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Aerodynamic interaction between static vehicles and wind barriers on railway bridges exposed to crosswinds

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Abstract. Wind tunnel experiments are used to investigate the aerodynamic interactions between vehicles and wind barriers on a railway bridge. Wind barriers with four different heights (1.72 m, 2.05 m, 2.5 m and 2.95 m, full-scale) and three different porosities (0%, 30% and 40%) are studied to yield the aerodynamic coefficients of the vehicle and the wind barriers. The effects of the wind barriers on the aerodynamic coefficients of the vehicle are analyzed as well as the effects of the vehicle on the aerodynamic coefficients of the wind barriers. Finally, the relationship between the drag forces on the wind barriers and the aerodynamic coefficients of the vehicle are discussed. The results show that the wind barriers can significantly reduce the drag coefficients of the vehicle, but that porous wind barriers increase the lift forces on the vehicle. The windward vehicle will significantly reduce the drag coefficients of the porous wind barriers, but the windward and leeward vehicle will increase the drag coefficients of the solid wind barrier. The overturning moment coefficient is a linear function of the drag forces on the wind barriers if the full-scale height of the wind barriers $h \le 2.5$ m and the overturning moment coefficients $C_O \ge 0$.

Keywords: wind barrier; aerodynamic effect; crosswinds; wind tunnel test; vehicle; railway bridge

1. Introduction

Bridges are a major segment of railways. For example, bridges make up 86.5% of the Beijing-Shanghai high-speed railway. The wind speed over a bridge deck will be higher than that over ground, so the wind loads on the vehicles will be larger than the wind loads of the vehicles on the ground. Under strong crosswind conditions, it becomes difficult to run trains and accidents may occur (Charuvisit *et al*. 2004). To avoid this, wind barriers are applied in many highway and railways (Štrukelj *et al*. 2005, Wang *et al*. 2007, Bobi *et al*. 2009). In past research, the crosswinds, vehicle and bridge were considered to be wind-vehicle-bridge (WVB) system that contains three interaction systems: wind-vehicle system, vehicle-bridge system and wind-bridge system. The WVB system is a complex system (Li *et al*. 2005. Cai and Chen 2004). This current work focuses on the vehicle against the crosswinds using the wind barrier, which is a part of the WVB system.

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Here we review the effects of the wind barrier on vehicles.

Several researchers have studied the protective effect of wind barriers on highways and railways using the aerodynamic forces on vehicles. Coleman and Baker (1992) tested the aerodynamic forces acting on a 1/50th scale vehicle model behind wind barriers. The results indicated that the drag coefficient and lift coefficient acting on the vehicle were significantly reduced. Chu *et al*. (2012) used simulations to study the effects of porous wind barriers on the protection of vehicles on a bridge. The results showed that porous wind barriers could significantly reduce the side force coefficient of the vehicle, and the side force on the vehicles on the windward lane of the bridge is smaller than that on the leeward lane. Xiang *et al*. (2014) showed that the wind barrier with a defined height could change the lift-drag ratio of the train and increase the lift coefficients of vehicle. Kozmar *et al*. (2012) examined the protective effects of wind barriers on a bridge by wind tunnel tests. Their results showed that the wind barriers caused a large wind speed jump and formed a vorticity behind them. Kwon *et al*. (2011) also studied the protective effects of wind barriers by wind tunnel tests focusing on the wind speed distributions behind the wind barriers.

Some researchers have used the vehicle responses to study the protective effects of wind barriers. Charuvisit *et al*. (2004) tested the aerodynamic forces of a moving vehicle by wind tunnel tests and analyzed the dynamic responses of the vehicle. The results indicated that the responses such as the side acceleration and yaw angular acceleration were reduced. Zhang *et al*. (2013) applied the method of coupling vibration to WVB system and obtained the evaluation index. They then studied the height and porosity rate of the wind barriers. However, the vehicle responses under crosswinds are obtained by simulations, and it is difficult to prove the accuracy of the vehicle responses. The measurement of the response needs a complex experimental system (Yi *et al*. 2013) and the vehicle may be overturned by crosswinds.

Even though the above-mentioned studies offer good information about the performance of wind barriers on the ground and bridge, they were focused on highway wind barriers, or the aerodynamic forces on vehicles. For railways, the trains and the bridges also have significant aerodynamic interactions. The wind barriers will increase the drag forces on the bridges and reduce the drag forces on the vehicles. However, the aerodynamic effects between wind barriers and trains have not been studied much.

The aerodynamic coefficients of the wind barrier and the vehicle under crosswinds can be obtained by the moving vehicle model test as well as the numerical simulation. However, the moving vehicle tests have some difficulty in terms of repeatability. Because the time window associated with each moving model test is very small and requires many repetitions (Bocciolone et al. 2008). The accuracy of the numerical simulation has not been extensively validated. Indeed, the aerodynamic coefficients of the train far from the nose are functions of the crossflow velocity at large yaw angles because trains have a high aspect ratio (Chiu and Squire 1992). The wind barrier must be subjected to wind forces due to the crosswinds and the train-induced wind forces. But the train-induced wind forces are not control factors. Crosswinds dominate the design of wind barriers (Xiang 2013). Therefore, the aerodynamic forces on the static vehicle and wind barriers on railway bridges are tested by wind tunnel experiments in this work. The effects of various barrier parameters such as height and porosity on the aerodynamic forces on the vehicle are presented. The effects of the vehicle on the aerodynamic coefficients of the wind barriers are also analyzed. Finally, the relationship between the drag forces on the wind barriers and the aerodynamic coefficients of the vehicle are discussed.

2. Wind tunnel tests

The rail-vehicle, bridge and wind barrier can be considered as line-like structures. Thus, the 2D section model in Fig. 1 can be utilized to test the aerodynamic forces on the vehicle and the wind barrier. The tests are conducted in a XNJD-3 wind tunnel with a top speed near 16.5 m/s. The turbulence intensity of the free stream flow I_x is less than 1.5%. The length, width and height of the wind tunnel are 36.0 m, 22.5 m and 4.5 m, respectively.

The CRH2 model with a scale of 1/15th is utilized. A train model contains three vehicles. The middle vehicle is the test object and the other vehicles are transition parts. The height, width and length of the scale vehicle are 0.233 m (H), 0.225 m (B) and 1.0 m (L), respectively. On high-speed railways, the most common bridge section is the box girder. The height, width and length of the scale bridge model in Fig. 1 are 3.51B, 1.1B, and 13.3B, respectively.

The wind barriers with five heights and three porosities are investigated. The three porosities are 0%, 30% and 40%. The five full-scale heights of the wind barriers (*h*) are 0 m, 1.72 m, 2.05 m, 2.5 m and 2.95 m. The lengths of the wind barriers are 4.4 B. The different shapes of open area of the wind barriers have some impacts on the protective effects (Yeh *et al*. 2010). In this work, the openings, uniformly distributed on the wind barriers, are of circle with a diameter of 0.049B (see Fig. 2).

The main effect of wind barriers is the reduction of the accident risk for the vehicle under crosswinds. Thus the forces and moments on the vehicle are tested by the balance that is installed in the vehicle (Xiang *et al*. 2014). The range of balance is 5kg and the accuracy is 0.5%. The diagram of the aerodynamic forces and moments is shown in Fig. 1. The wind speed of the free stream is from 4.6 to 14.1 m/s, the sampling frequency is 100 Hz, the sampling time is 30s. The average of forces and moments are used to calculate the aerodynamic coefficients. The aerodynamic coefficients of the vehicle are defined by (Li *et al*. 2005)

$$C_{\mathrm{D}} = \frac{F_{\mathrm{D}}}{\frac{1}{2}\rho U^2 HL} \tag{1}$$

$$C_{\mathrm{L}} = \frac{F_{\mathrm{L}}}{\frac{1}{2}\rho U^2 BL} \tag{2}$$

$$C_{\mathrm{M}} = \frac{M_z}{\frac{1}{2}\rho U^2 B^2 L} \tag{3}$$

where, F_{D}, F_{L} and M_{Z} are the drag force, lift force and roll moment, respectively. Terms C_{D}, C_{L}, C_{M} represent the drag coefficient, lift coefficient and roll moment coefficient, respectively. Term U is the velocity of the upper stream and ρ is the air density. H, B and L are the height, width and length of the vehicle, respectively.

The overturning moment M_{O} reflects the overturning performance of the vehicle under the cross winds. The overturning moment coefficient of the vehicle (see Fig. 1) is expressed as

$$C_{\mathrm{O}} = \frac{HyC_{\mathrm{D}} + BxC_{\mathrm{L}} + C_{\mathrm{M}}B^2}{B^2} \tag{4}$$

where, x and y are the arms of the lift force and the drag force, respectively.

The aerodynamics of the windward wind barriers are tested by a balance (see Fig. 3), and the drag coefficient of the wind barrier is given by

$$C_{\mathrm{DW}} = \frac{F_{\mathrm{DW}}}{\frac{1}{2}\rho U^2 H_W L_W} \tag{5}$$

where, F_{DW} is the side drag force of the wind barrier (see Fig. 3). Term H_{W} is the height of the wind barrier model, and L_{W} is the length of the wind barriers.

Test cases are given in Table 1. Column 2 is the test object. Column 3 is the number of trains. One train implies only a train on the bridge (see Fig. 1). Two trains imply two trains meeting each other; Column 4 is the porosity of the wind barrier, and column 5 is the full-scale height of the wind barrier. In the wind tunnel test, the wind is perpendicular to the vehicle and the bridge. The forces and the moments are tested at different wind speeds, and the Reynolds number Re ($=UH/v$, $v=1.5\times10^{-5}$) is between 7.1×10^4~2.2×10^5.

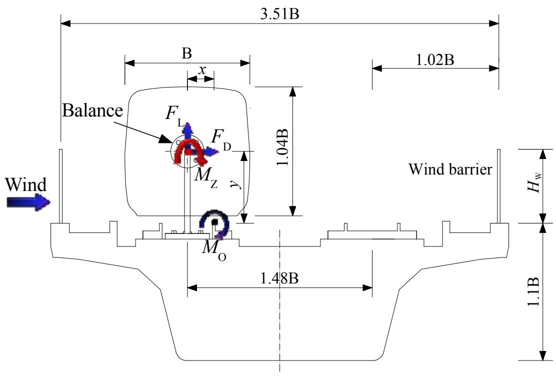


Fig. 1 Schematic diagram of the test vehicle

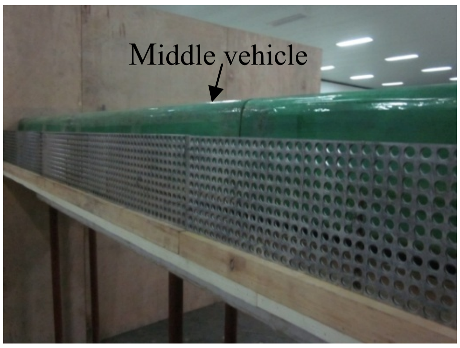


Fig. 2 Shape of wind barrier

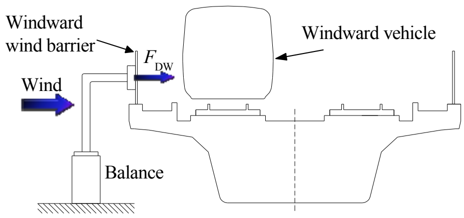


Fig. 3 Schematic diagram of wind barrier's aerodynamics

Table 1 Test cases

No.	Test objects	Train number	*α*	*h* (m)
1	windward vehicle	one train	30%	0.0, 2.95
2	windward vehicle	one train	0%	0.0, 1.72, 2.05, 2.50, 2.95
3	leeward vehicle	one train		
4	windward vehicle	two train	0%	
5	leeward vehicle	two train		
6	windward vehicle	one train	0%, 30%, 40%	
7	leeward vehicle	one train		
8	windward wind barrier	one train on windward	0%, 30%, 40%	0.0, 1.72, 2.05, 2.50, 2.95
9		one train on leeward		
10		without train		

α is the porosity; *h* is the full scale height of wind barrier

3. Results and discussion

3.1 Aerodynamic coefficients of vehicle

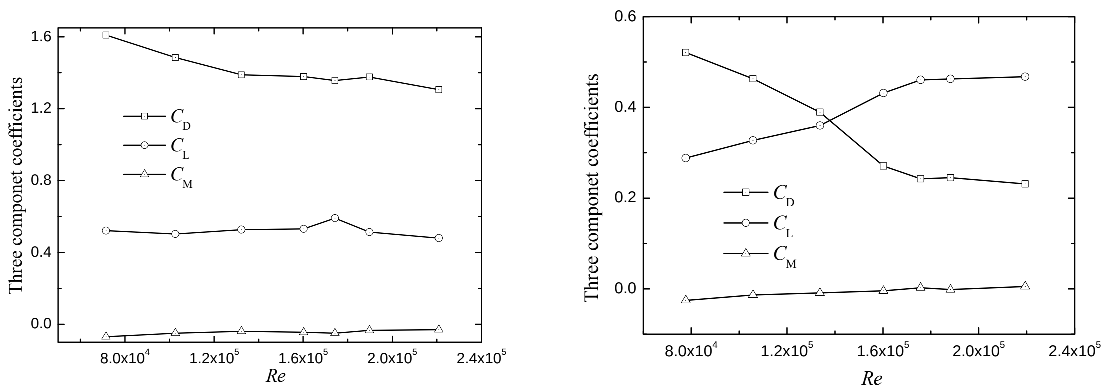
Coleman and Baker (1992) pointed out that the drag coefficients of vehicles with a curved surface roof are strongly depending on the Reynolds number. To investigate the effect of Reynolds number, the aerodynamic coefficients in case 1 are shown in Fig. 4 with a Reynolds number of 7.1×10^4~2.2×10^5. In Fig. 4(a), we see that the Reynolds number has some effect on the drag coefficients in the absence of wind barriers. After installing the wind barrier with a height of 2.95 m and a porosity of 30%, the drag coefficients is reduced with increasing Reynolds number, and the lift coefficients increase with increasing Re number (see Fig. 4(b)). Because the vehicle has a blunt body with a curved surface roof. When the flow gets through the wind barriers, a shear layer and an accelerated flow over decks are formed (Coleman and Baker 1992, Xiang *et al*. 2014).

These acts on the curved vehicle roof, which can replenish the energy loss by the stream separation on the roof, and may change the position of separation points on the vehicle roof in different Re number. The roll moment coefficients increase with increasing Re number in the absence and presence of wind barriers, but the absolute value of the roll moment coefficients in the presence of wind barrier is smaller than that without wind barrier. Because the coefficients in the high Reynolds number case are closer to the actual situation, the coefficients in the maximum Reynolds number are discussed in the next context.

To investigate the effects of the wind barriers on the vehicle, the aerodynamic coefficients in cases 2 and 3 are shown in Fig. 5. The aerodynamic coefficients in cases 4 and 5 are shown in Fig.6, and the drag coefficient and the lift coefficient in cases 6 and 7 are shown in Fig. 7. In Fig. 7, the right column is drag coefficients, and the left column is lift coefficients.

In Fig. 5, it is clear that the drag coefficients of the windward vehicle are reduced by the wind barriers. After installing the solid wind barriers with heights of 1.72 m~2.95 m, the drag coefficients have negative values. Because the flow gets through the solid wind barriers, a low pressure zone and reverse flow exists over the decks. The bridges and solid wind barriers constitutes a U-shaped groove structure, the effect of reverse flow on the aerodynamic coefficients will be weakened with increases in wind barrier height. However, the drag coefficients with a negative value mean that the vehicle may be over-protected. The windward vehicle has a high-lift after installing the wind barrier and the lift coefficients is larger than the drag coefficients for the leeward vehicle as well (see Fig. 5(b)).

The sudden change of wind loads for two trains meeting each other is the controlling factor in the WVB system (Li *et al*. 2013). From Figs. 5 and 6, we see that the leeward vehicle has little effect on the aerodynamic coefficients of the windward vehicle in the presence and absence of wind barriers. However, the windward vehicle has an obvious effect on the aerodynamic force coefficients of the leeward vehicle. In the absence of wind barriers, there is a larger sudden change in drag and lift coefficients of the leeward vehicle (see Figs. 5(b) and 6(b)), this is disadvantageous for train safety. After installing wind barriers with heights of 1.72 m~2.95 m, the value of the sudden change is obviously reduced and enhances safety when two trains pass each other.



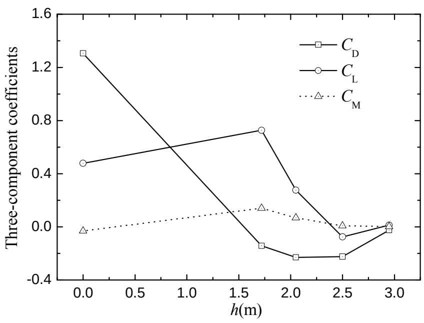
(a) Absence of wind barrier (b) Presence of wind barrier (30%, 2.95)

Fig. 4 Aerodynamic coefficients in case 1

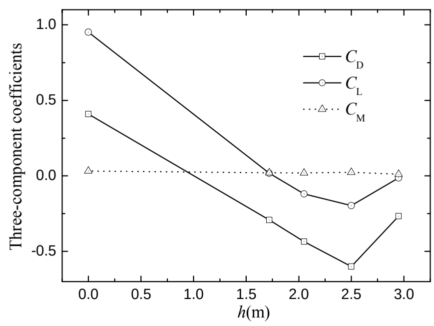
In Fig. 7, we see that the drag coefficients and lift coefficients of a vehicle reduce significantly after installing the porous wind barriers. In Fig. 7(a), the porous wind barrier does not reduce the lift coefficient of the windward vehicle. Instead, a high-lift phenomenon exists for every porous wind barrier, but this is negative for the vertical comfort of the trains. When the porosity of wind barrier is 40%, the drag coefficient C_D in h=2.95 m is larger than that wind barriers with heights of 1.72 m ~2.5 m, the Reynolds number effect may be the major determinant. Because the Re number of free flow is similar, but the local Re around vehicles is different when we installed the wind barrier with different heights and porosity.

3.2 Aerodynamic coefficients of wind barrier

The wind barrier is equivalent to a drag force, and the reduction of the wind force behind the wind barrier is transferred to the wind barrier. To some degree, the drag force on the wind barrier is related to the protective effect of the wind barrier (Miller *et al*. 1975). Additionally, the aerodynamic coefficients of the wind barrier are important parameters for the wind barrier design. We measured the drag coefficients of the wind barriers in cases 8, 9 and 10 to investigate the effect of the vehicles (Table 2).

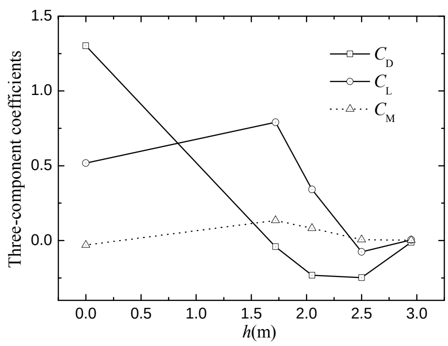


(a) Case 2

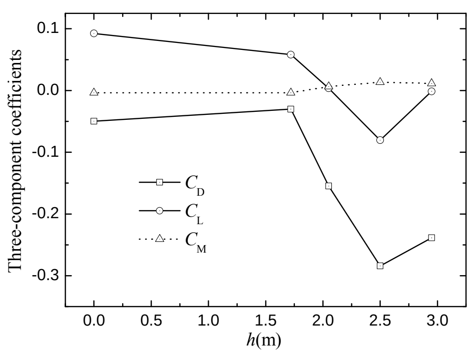


(b) Case 3

Fig. 5 Aerodynamic coefficients in cases 2 and 3

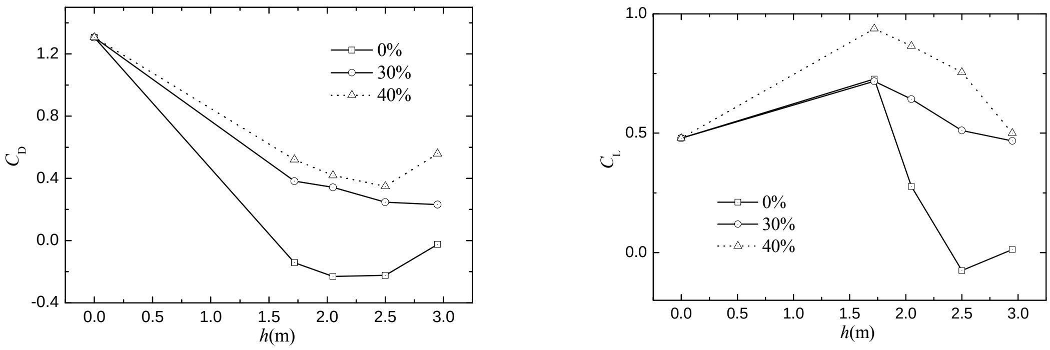


(a) Case 4

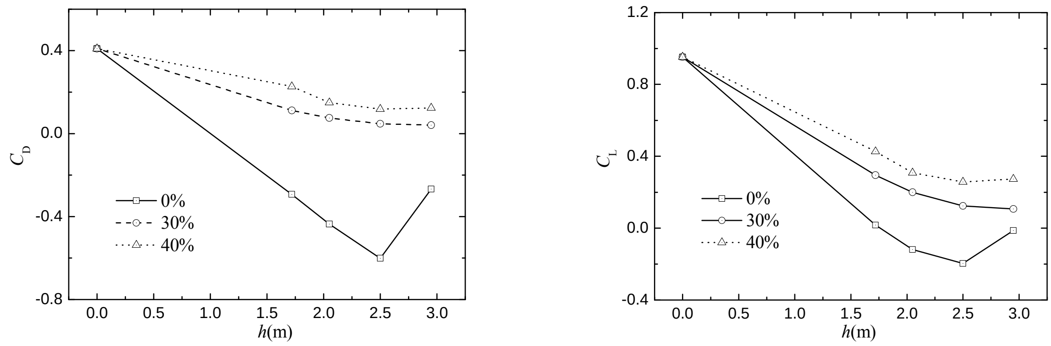


(b) Case 5

Fig. 6 Aerodynamic coefficients in cases 4 and 5



(a) Case 6



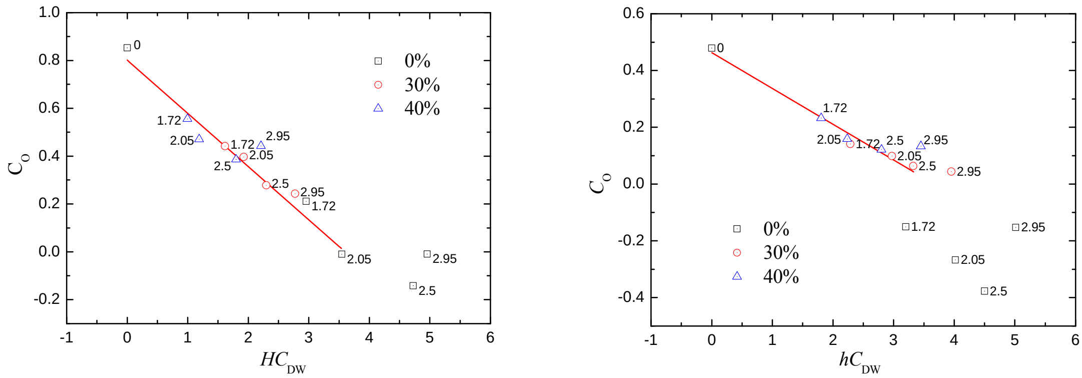
(b) Case 7

Fig. 7 The effects of porosity on aerodynamic coefficients

Table 2 Drag coefficients of the wind barrier

h (m)	Case 8			Case 9			Case 10		
	0%	30%	40%	0%	30%	40%	0%	30%	40%
1.72	1.72	0.94	0.58	1.86	1.33	1.05	1.44	1.35	1.15
2.05	1.73	0.94	0.58	1.96	1.45	1.09	1.60	1.32	1.18
2.50	1.89	0.92	0.72	1.80	1.33	1.12	1.65	1.36	1.16
2.95	1.68	0.94	0.75	1.70	1.34	1.17	1.66	1.35	1.24

In Table 2, if the vehicle is close to the porous wind barrier on the windward side, the drag coefficient of the porous wind barrier is significantly reduced. Because the jet through the holes of the wind barrier are “clogged” by the vehicle, and the pressure difference between the two sides of the wind barrier are reduced. If the wind barrier is a solid wall, the drag coefficient of the wind barrier will be increased. In this situation, the solid wind barrier and the vehicle are composed of a U-shaped groove. This increases the pressure difference between the two sides of the wind barrier. This also shows that the windward vehicle and windward wind barrier have significant aerodynamic interactions.



(a) windward (b) leeward

Fig. 8 Overturning moment coefficients vs. hC_{Dw}

3.3 Overturning moment coefficient vs. drag force on wind barrier

The wind speed over a bridge deck will be higher than that over ground. Thus, the wind loads on wind barriers on a bridge will be larger than the wind loads on ground. Therefore, it is necessary to reduce the wind loads on the wind barriers, and the vehicle can run safely under crosswinds at the same time. To investigate the relationship between the wind barrier and the aerodynamic coefficients of vehicle, we plotted the overturning moment coefficient of the vehicle with parameter hC_{DW} of the wind barrier (see Fig. 8). Here hC_{DW} reflects the drag force on the wind barrier under the cross wind, and the legend around data is wind barrier height.

From Fig. 8, we see that the overturning moment coefficient is a linear function of hC_{DW} if $h \leq 2.5$ and $C_O \geq 0$. When the solid wind barrier has a height of 2.05 m, the overturning moment coefficients of the windward vehicle will be close to 0. If the height of the porous wind barrier continues to increase, then the overturning moment coefficient of the vehicle cannot be reduced obviously (see Fig. 8). If the height of the solid wind barrier continues to increase, the overturning moment coefficient of the vehicle becomes negative. However, the wind barrier cannot be optimal for both the windward and leeward vehicles. As hC_{DW} approaches 3.5, the overturning moment coefficient of the windward and leeward vehicle will be close to 0.

4. Conclusions

Wind tunnel tests are conducted to investigate the aerodynamic effects between wind barriers and static vehicles. The aerodynamic coefficients of the vehicles and wind barriers are tested.

- Experimental results show that the drag coefficients of the vehicle with a curved surface roof are Reynolds number dependent. After installing the porous wind barrier, the dependence of the drag coefficients on Reynolds number is stronger.
- The wind barrier can significantly reduce the drag coefficients of the vehicles, but the lift coefficients of the windward vehicle increased significantly after installing the porous wind barriers. This is disadvantageous for the vertical comfort of the trains.

- There are many interactions between the vehicle and the wind barrier. The windward vehicle will obviously reduce the drag coefficient of the porous wind barrier, and the vehicle will increase the drag coefficient of the solid wind barrier. If $h \leq 2.5$ and $C_O \geq 0$, the overturning moment coefficient is a linear function of hC_{DW}.

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