A CFD analysis of the aerodynamics of a high-speed train passing through a windbreak transition under crosswind

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ABSTRACT
In areas with strong wind, windbreaks are built along railways to reduce the impact of wind on trains. However, because of the restrictions imposed by actual terrain, windbreak structures are often not uniform, such as from a cutting to an embankment, resulting in a discontinuous transition region. When a train runs through this region, a distinct yawing phenomenon occurs. This study numerically explored the aerodynamic features of a train running through a rectangular windbreak transition region. The variations in the pressure, side force, and moment of a train were analyzed, and the flow field features were clarified. Furthermore, the yawing motion of the car body with time was described. Finally, based on EN14067-6, the critical wind speed was obtained using the safety assessment of a train running through a windbreak transition region.

1. Introduction
The aerodynamic characteristics of a train under crosswind depend not only on the shape of the train but also the infrastructure around the train, such as bridges, cuttings, embankments, and windbreaks. Baker (2010) investigated the effect of crosswind on train dynamic systems, and Cui, Zhang, and Sun (2014) considered the effects of attitude change on aerodynamics to ensure train safety under crosswind. Using a crosswind generator, Dorigatti, Sterling, Baker, and Quinn (2015) explored the different pressure distributions obtained from static and dynamic experiments using an innovative physical model. Specifically, they examined the wind-induced forces and pressure by a 1:25 scale model of a Class 390 Pendolino at a 30° yaw angle. Luo, Hu, Yang, and Hu (2013) explored the effects of different embankment incline angles on the aerodynamics of a high-speed train under crosswind. As the inclination angle of the embankment increased, the side force coefficient on the head car of the train first increased slightly and then decreased. Diedrichs, Sima, Orellano, and Tengstrand (2007) used experiments and computational fluid dynamics (CFD) to study the crosswind stability of a high-speed train on a 6 m high embankment subjected to a resultant wind of 30°. Both experiments and calculations showed that the train in the leeward case (LWC) was more critical than that in the windward case (WWC). Using a validated CFD model to consider different scenarios of a double track with ballast and rail (DTBR), an embankment, and wind barriers, Bocciolone, Cheli, Corradi, Muggiasca, and Tomasini (2008) conducted extensive wind tunnel tests on scale models of trains to study the effects of turbulence intensity and train motion on the aerodynamic coefficients.

In a strong wind environment, windbreaks are important for avoiding the risk of overturning for high-speed trains. Avila-Sanchez, Lopez-Garcia, Cuerva, and Meseguer (2016) used particle image velocimetry (PIV) to measure the flow field above a two-dimensional railway bridge equipped with a solid windbreak in a wind tunnel. The authors found that the inclusion of a second windbreak on the trailing edge restrains the location of the separation bubble to the bridge deck. Through wind tunnel analysis, Avila-Sanchez, Pindado, Lopez-garcia, and Sanzandres (2014) also studied the shelter effect of a windbreak in a railway embankment. Wang, Chen, Li, and Liu (2016) researched the effect of a windbreak gap on the aerodynamic characteristics of an electric multiple units (EMU) train. The authors found that as the cars pass the gap, the aerodynamic force coefficients reach their maximum values and then rapidly decrease to their minimum values. After the cars pass the gap, the coefficients return to their steady state, and the head car is the least safe. Tomasini, Giappino, Cheli, and Schito (2016) conducted wind tunnel tests on different types of windbreaks in the ground, and they compared...
two types of windbreaks with holes in detail. Li, Tian, and Liu (2011) optimized windbreaks with holes for a high-speed railway and found that 30% transmittance greatly optimizes the EMU aerodynamic performance. Li, Zhang, and Zhang (2012) researched the dynamic performance of a high-speed train passing a windbreak under crosswind, and they developed a windbreak with buffer equipment to significantly improve train safety and comfort. Zhang and Liu (2012) studied the slope angle of an earth-type windbreak for a Xinjiang single-track railway and proposed that the windward and leeward slope angles for the earth-type windbreak are 69°–72°. Catanzaro, Cheli, Rocchi, Schito, and Tomasini (2016) analyzed the train aerodynamic force coefficients for an embankment under different wind angles, and they compared the static and dynamic states in the embankment. In addition, the authors compared the train aerodynamics with and without a windbreak for the DTBR under different wind angles.

Certain features, such as windbreak setting, shape, and opening rate, have been extensively researched for plat ground, embankments, and bridges in previous studies. The literature shows that the conditions studied in the past were idealized, and different scenarios were studied separately. However, in an actual railway line, because of the effects of complex terrain conditions, a windbreak is built discontinuously. In a full-scale test, Lu, Zhou, Zhou, Xiong, and Yang (2014) found that the aerodynamic performance and dynamic index of a vehicle system showed sudden changes and frequently became worse solely in the position of the discontinuous transition region of windbreak. For example, the Lanzhou–Xinjiang passenger railway is a double line in China with a total length of 1776.9 km and was the first railway to be built through an area with strong wind (Li, 2012). Part of the railway line that passes through the strong wind area is in mountainous terrain, which also results in many cuttings, embankments, and transition regions along this line, as shown in Figure 1. When trains pass through this windbreak transition region, a ‘yawing’ phenomenon occurs (Lu et al., 2014), affecting both passenger comfort and operational safety.

Therefore, this paper analyzes the aerodynamic performance and operational safety of a China Railway High-speed Train 2 (CRH2) under crosswind from a cutting to an embankment, particularly in the rectangular windbreak transition region.

2. Numerical method and model setup

2.1. Numerical method

In the current study, an aerodynamics computational model is established based on a highly irregular actual landform with complex structures. The Reynolds-averaged Navier–Stokes (RANS) equation is used in most numerical studies involving these conditions to describe the time-averaged flow; the results obtained by this equation are also valid for determining the pressure field, velocity field, and aerodynamic forces (Cheli, Ripamonti, Rocchi, & Tomasini, 2010; Cui et al., 2014; Haque, Katsuchi, Yamada, & Nishio, 2015). According to a previous study (Morden, Hemida, & Baker, 2015), the Shear Stress Transport (SST) \( k - \omega \) approach can reduce computational expense with a slight reduction in accuracy in predicting forces and surface pressures. Therefore, the three-dimensional incompressible unsteady RANS equations and the SST \( k - \omega \) turbulence model (Menter, 1994) are used in this paper. The constants in the turbulence model are \( \sigma_{k_1} = 0.85, \sigma_{\omega_1} = 0.65, \beta_1 = 0.075, \sigma_{k_2} = 1, \sigma_{\omega_2} = 0.856, \beta_2 = 0.0828, \beta^* = 0.09, \) and \( a_1 = 0.31. \) The commercial software package Fluent 6.3.26 is used in this study, and the governing equations are discretized by the finite volume method (FVM). The convection and diffusion terms are discretized by the second-order upwind scheme, and the time derivative is discretized by the second-order implicit scheme for unsteady flow calculations. The velocity-pressure coupling and solution procedures are based on the SIMPLE algorithm.

![Figure 1](image-url) **Figure 1.** Windbreak rectangular transition between cutting and embankment: (a) structure toward rail line and (b) structure outward rail line.
2.2. Model description and computational setup

Figure 2(a) presents the CRH2 model, where C1, C2, and C3 represent the head car, middle car, and tail car, respectively. The landforms studied in this paper are shown in Figure 2(b), and the basic dimensions of the cutting and embankment are shown in Figure 3 and Figure 4, respectively.

Figure 5 shows the CFD domain and boundary conditions. Face DCGH is a uniform velocity inlet; faces ABCD, EFGH, and ABFE are set as pressure outlets; the upper face AEHD is a slip wall; and the lower face BFGC and the surface of the vehicle are no-slip walls. In this work, a moving mesh is used to more accurately capture the relative motion between the train and surrounding terrain; a constant train speed is assigned to the moving mesh, which is defined as IJKL-MNOP. The boundary conditions of faces IJKL and MNOP are pressure outlets, and the remaining faces are interface boundary conditions. The surface JKON remains close to the bottom of the wheel, and surface JKON is separated from the ground by a certain physical distance to simulate the air flow underneath the train. For the decomposed moving mesh method, information transfer is addressed with an interface between the moving train and the other stationary regions. As shown in Figure 6, in terms of Zone 1 (train), which is in motion, and Zone 2 (landforms), which is stationary, the boundary face of Zone 2 is composed of A-C-E-G; the boundary face of Zone 1 is composed of B-D-F-H; and the public face a-b-c-d-e-f-g is generated. The boundary information of Unit 3 is obtained from the public face b-c-d by interpolating Unit 1, Unit 2, and Unit 4. The boundary information of Unit 1, Unit 2, and Unit 4 is obtained from the public face a-b-c-d-e by interpolating Unit 3, Unit 5, and the other units in Zone 1.

For the dimensions of the computational domain, the height of the train model (3.7 m) is considered the characteristic dimension and is denoted by $H$. In
the full-scale test, the terrain becomes an approximately uniform landform beyond 150 m in the width direction. Therefore, the distances from face ABFE and DCGH to the longitudinal center of the train are both 54H, and the height of the computational domain is 40.5H. For the length of the computational domain, to obtain a steady flow field and the initial train aerodynamics, as shown in Figure 7(a), the length from the train tail to the boundary is fixed at 40H. The cutting is lengthened for three cases in which the distance from the nose to the rectangular transition is 50H, 100H, or 120H. To compare these three cases uniformly, the initial time of Case 1 is regarded as the reference point. As shown in Figure 7(b), the side force coefficient $C_y$ of the head car is used for comparison; this coefficient is defined as

$$ C_y = \frac{F_y}{0.5 \rho U^2 S} \quad U^2 = v_t^2 + v_w^2 $$

where $F_y$ is the side force, $\rho$ is the density of air (1.225 kg/m$^3$), $U$ is the relative speed of the train speed $v_t$ and crosswind speed $v_w$, and $S$ is the reference area; here, the train cross-sectional area is 11.29 m$^2$. It can be observed that the side force coefficients of the three
cases in the transition region and embankment are similar, whereas a shorter cutting length leads to an unsteady characteristic of $C_v$. With increasing cutting length, the side force coefficient in the cutting becomes relatively stable. Other aerodynamic coefficients have a similar characteristic but are not elaborated upon here. Therefore, the length of Case 3 is chosen as the computational dimension for the cutting. The initial time of the result analysis is taken after the train has been moving for 3.2 s; thus, in the discussion in Section 4, the initial time of 0 s represents an actual time of 3.2 s.

3. Numerical details

3.1. Computational mesh and mesh sensitivity

A tetrahedral grid is used to fill the complex geometry of the domain because of its characteristic advantage for treating complex objects. The regions around the train and windbreak are refined to ensure accurate results. In addition, to obtain mesh-independent results, numerical simulations are performed with three different meshes: coarse, medium, and fine meshes consisting of 15 million, 18 million, and 20 million cells, respectively. The initial flow field is calculated first. Then, the adaptive mesh technique is used, and relatively satisfactory results are obtained; the non-dimensional wall distance $y^+$ is approximately 10. Figure 8(a) shows the 22 measurement points around the center cross section of the middle car. The pressure coefficients $C_p$ of these 22 points are calculated with three meshes when the train is held stationary in the cutting with a 30 m/s crosswind. $C_p$ is defined as $C_p = (P - P_0 / 0.5 \rho U^2)$, where $P_0$ is the reference pressure, which is 0, and $P$ is the static pressure on the train surface (Luo et al., 2013).

Figure 8(b) shows the results obtained from the three meshes: The medium mesh results closely match the fine mesh results, whereas the results of coarse mesh clearly differ from the other results. Therefore, the resolution of the fine mesh is adequate, and no further mesh refinement is performed. Other cross sections have similar grid independence characteristics but are not elaborated upon here. Therefore, the CRH2 aerodynamic performance is analyzed using the fine mesh. Figure 9 shows the mesh of the computational model.

3.2. Result validation

In the full-scale test, the train surface pressure is obtained using a vehicle-mounted pressure test system (Xiong, Liang, Gao, & Liu, 2006; Xu, 2010). There are eight cars in the train, and the pressure sensors are arranged on the head car, tail car, and one middle car (the fourth car). Figure 10 shows the measurement arrangement and a photograph of the actual setup for the middle car. There are three cross sections: No. 1, No. 2, and No. 3. The pressure sensor installation at cross sections No. 1 and No. 3 are shown in Figure 10(a); their arrangements on the left and right sides are symmetrical, and there are no pressure sensors on the top or bottom. The pressure sensor installation of cross section No. 2 has the same arrangement as that shown in Figure 8(a) in Section 3.1.

To verify the reliability of the calculation results, two field test conditions are selected. Figure 11 shows the results when the train ran in the cutting reaches a train speed of 220 km/h and an average crosswind speed of 18.6 m/s. Figures 11(b), (c), and (d) show the results of the numerical simulation and the full-scale test at planes No. 2, No. 1, and No. 3, respectively. Figure 12 shows the results obtained when the train passes the embankment at a speed of 110 km/h and an average crosswind speed of 22.3 m/s. Figures 12(b), (c), and (d) present the results of the numerical simulation and the full-scale test at planes No. 2, No. 1, and No. 3, respectively. It can be observed that the numerical simulation results agree fairly well with the full-scale test results. However, the difference for the bottom measurement points is greater than that in other areas; this difference may result from the complex bogie and device cabin structures, which are somewhat simplified in the numerical simulation, and the surface

Figure 8. (a) Measurement points of the center cross section of the middle car (units: mm) and (b) pressure coefficient curves with different mesh resolutions.
Figure 9. The computational mesh: (a) the mesh of the computational domain, (b) the mesh around the transition region, (c) a magnification of the windbreak mesh, and (d) a magnification of the train surface mesh.

Figure 10. Middle car pressure sensor arrangement: (a) schematic and (b) photograph of the full-scale test. (units: mm)

of the geometric model being smoother than that of the actual train body. Therefore, the negative pressure on the bottom of the car body is greater than that in the full-scale test. Overall, the maximum error between the simulation and the experiment is 9.4%, and considering effects mentioned above, the agreement between the results is deemed adequate.

4. Results and discussion

4.1. Pressure coefficient and side force coefficient

Figure 13 shows the time histories of the pressure coefficients for each car, in the case of a crosswind velocity of 30 m/s and a train speed at 250 km/h. The pressure measurement points are located on the windward side (WWS) and leeward side (LWS) at the central cross section of each car (2.28 m above the top of the rail). The time history of pressure coefficient for each car can be divided into three parts: cutting, windbreak transition region, and embankment. Because of the shielding effect of the windbreak, the train body is essentially surrounded by a negative pressure area (Avila-Sanchez et al., 2016). The time marks in Figure 13 represent the period during which the car passes the transition region. WWS and LWS represent the windward side and leeward side pressure coefficients, respectively, and W-L represents the difference between them. The LWS
Figure 11. (a) Train running through the cutting and (b) results of the full-scale test and numerical simulation at cross sections No. 2, (c) No. 1, and (d) No. 3.

Figure 12. (a) Train running through the embankment with a flat windbreak and (b) results of the full-scale test and numerical simulation at cross sections No. 2, (c) No. 1, and (d) No. 3.

pressure coefficient variation profiles for each car in the cutting and embankment are consistent with those of the WWS. However, they differ in the transition region: the WWS exhibits clear peak values of the pressure, whereas the LWS shows no such change. In the cutting and embankment, the W-L values of each car are relatively stable (Gao & Duan, 2011). In the transition region, the W-L values without wind show very small changes because the windbreak is closer to the car body, whereas the WWS and the W-L values change significantly under the crosswind of 30 m/s, which induces an additional side force and other relative aerodynamic effects for the train passing through this transition region.

To determine the macroscopic aerodynamic load effects on the train, the side force coefficient $C_y$ of the train is obtained by integrating the pressure. Figure 14 shows the side force coefficient of each car, which reflects the total pressure difference. Therefore, the variation of the side force coefficient is similar to that of the W-L pressure coefficient in Figure 13. With wind, the side force coefficients of each car are also relatively stable in the cutting and embankment, although the fluctuation
Figure 13. Time history of the pressure coefficients of the measurement points on the train surface: (a) head car, (b) middle car, and (c) tail car.

Figure 14. Time history of the side force coefficients of the head car, middle car, and tail car.

is slightly greater than in the case without wind. In the transition region, the side force coefficient for the head car changes from a large positive value to a large negative value firstly and then increases to a slightly positive value again; the side force coefficients of the middle car and tail car change from a slightly negative value to a more negative value and then rapidly increase to a large positive value. Therefore, their variation trends are similar. The peak-to-peak values of the side force coefficients for the head, middle, and tail cars in the windbreak transition region are 0.68, 0.48, and 0.49, respectively. The value is the greatest for the head car, which is 41.7% and 38.8% greater than the values obtained for the middle and tail cars, respectively. The changes in the side force coefficient and pressure coefficient can be attributed to the varying flow field around the train, which is induced by the irregular landforms and the different windbreak heights and shapes in the transition region.

4.2. Flow fields around the high-speed train

The aerodynamic coefficients for the head car under crosswind are relatively greater than those for the middle car and tail car, as discussed in Section 4.1, and similar results have been obtained in other studies (Luo et al., 2013; Mao, Ma, & Xi, 2011). Therefore, the following descriptions are all based on the head car unless otherwise noted.

Figure 15 shows that the flow separates behind the windbreak, forming a vortex. The vortex $V_1$ exists from $t = 0.8$ s to $t = 2.48$ s, when the train is running in the cutting, and the distance between the center of vortex $V_1$ and the train is relatively constant over time (Zhang, Gao, Liu, & Li, 2015). The air velocity on the WWS of the train is similar to that on the LWS; thus, the two pressure coefficients in the cutting are also similar. This process is accurately reflected in Figure 13(a).

The airflow near and in the transition region is mainly characterized by two low-pressure and unstable vortices. When the middle cross section of the head car moves near the transition region at $t = 2.64$ s, a new vortex $V_2$ appears near the LWS of the train. The oscillations of the high and far part of the vortex $V_1$ and the low and close part of the vortex $V_2$ are $180^\circ$ out of phase and independent of each other. An upward airflow is generated and decreases the pressure equally on the LWS and the WWS; therefore, the W-L pressure difference coefficient remains...
constant at approximately zero. The plane of the middle cross section of the head car is entirely in the transition region at \( t = 2.8, 2.96 \) and \( 3.12 \) s. The vortices \( V_1 \) and \( V_2 \) disappear in this plane, and two new vortices \( V_3 \) and \( V_4 \) appear. \( V_4 \) is formed by the shedding vortex of the vortex \( V_3 \). The oscillations of \( V_3 \) and the lower part of the ring vortex of \( V_4 \) are in phase. The position of the lower center of \( V_4 \) is relatively stable compared with that of the higher part of \( V_3 \). The upper part of \( V_3 \) is not stable but oscillates against the streamwise direction and moves along the \( z \)-axis direction, moving from the LWS to the WWS over time. During this process, the pressure of the LWS varies only slightly between \( t = 2.8 \) s and \( t = 2.96 \) s and decreases at \( t = 3.12 \) s because of the effect of vortex \( V_4 \). The pressure of the WWS at \( t = 2.96 \) s is slightly lower than that at \( t = 2.8 \) s but greatly increases at \( t = 3.12 \) s because of the considerable impact and oscillation effect of \( V_3 \). Therefore, a lower W-L peak value occurs at \( t = 2.85 \) s, and a higher peak W-L value occurs at \( t = 3.16 \) s.

When the plane of the middle cross section of the head car is near the embankment at \( t = 3.28 \) s, the vortex \( V_4 \) disappears, and \( V_5 \) occurs where \( V_1 \) previously existed. In addition, \( V_3 \) moves away from the train. The pressure around the train surface decreases, but the pressure difference between the WWS and LWS is very small; thus, W-L is approximately zero. The last three figures present the plane streamlines when the middle cross section is in the embankment. The flow in the embankment is regular and stable, consisting of a series of stable vortex structures, and the train is surrounded by a smaller negative pressure. The vortex \( V_5 \) changes only slightly over time. The vortex \( V_6 \) is split into two small counter-rotating parts on the LWS of the windbreak. Therefore, the flow field is stable in the embankment, and the pressure difference coefficient W-L is steady and smooth.

Figure 16 shows the corresponding planes colored by the static pressure distributions at different times. In the areas where the pressure variation in the transition region is smaller and disordered, the pressure in the cutting and the embankment also vary, but the pressure variation gradient is small. Therefore, the effect of the pressure variation caused by the windbreak transition on the...
vibration of the car body is studied further in the next section.

4.3. **Pressure coefficient of different z-planes in the windbreak transition region**

Figure 17 presents the W-L values along the length of the head car in the planes \( z = 1.5, 2, 2.25, 2.5, 2.75, 3, 3.25, 3.5, \) and 3.75 m at time intervals of \( t = 0.16 \) s. The train pressure nephogram inside the figure shows the position of the head car at different times. Because the length of the streamlined head of CRH2 is 9 m, the W-L pressure difference coefficients fluctuate more intensely along the length of the head car at lengths less than 10 m.

At \( t = 2.8 \) s, the \( z \)-planes, except for those at 3.5 and 3.75 m, exhibit a negative pressure difference coefficient along the length of the head car, and W-L at lengths less than 10 m is greater than that in the rear area. Therefore, a pressure difference exists between the front and rear parts of the head car body. A yawing motion rotates around the end position of the streamlined head. The motion state of the head car at \( t = 2.96 \) s is different from that at \( t = 2.8 \) s, when the streamlined head is characterized by a positive pressure difference coefficient and most of the \( z \)-planes are negative in the rear part of the head car. As a result, a stronger yawing motion rotates around the end position of the streamlined head. After 0.16 s, the streamlined nose is near the embankment windbreak, where the car body motion state is similar to the state at \( t = 2.8 \) s, but the yawing center is different. At this time, the yawing center is in the rearward position and located at approximately 15 m along the car body length. As the head car leaves the transition region from \( t = 3.28 \) to 3.44 s, the pressure difference coefficient of the streamlined head region and the front part of the car body changes from negative to positive. The rear part of the head car experiences exactly the opposite effect: The pressure difference coefficient becomes more negative. The yawing phenomenon is obvious at \( t = 3.44 \) s, and the yawing center is closer to the tail of the car body at approximately 18 m along the car body length.

The varying W-L leads to different motion states, which are presented in Figure 18(a) based on an analysis of Figure 17. As previously discussed, the head car
shows a rather distinct yawing motion as the head car moves through the transition region. However, the yawing center varies as the car advances. This process is also reflected by the side force variation of the head car shown in Figure 14 and the yaw moment time history shown in Figure 18(b). The variation of the side force coefficient is similar to that of the yaw moment. The yaw moment coefficient is defined as

\[ m_z = \frac{M_z}{0.5 \rho U^2 S l} \]  

where \( M_z \) represents the yaw moment and \( l \) represents the reference height of the wind pressure center, which is \( l = 2 \text{ m} \) (Zhang, Liang, Liu, & Lu, 2011).

In Figure 18(b), the three cars show similar behavior in the transition region, and the yaw moment coefficient has high positive and negative peaks compared with the case without wind. These peaks are caused by the aerodynamic forces acting on the front and rear halves of the car as the train moves into and out of the transition region. The peak-to-peak values of the yaw moment coefficient in the transition region for the head, middle, and tail cars are 2.35, 2.04, and 1.12, respectively. Thus, the value of the head car is 15.2% and 109.8% greater than the values of the middle car and tail car, respectively. This result further shows that when the train runs from the cutting to the embankment, the aerodynamic performance of the head car is worse in the rectangular windbreak transition region.

### 4.4. Safety assessment of a train in the windbreak transition region

Based on EN14067-6 (2010), this section presents a safety assessment of the wheel unloading ratio \( f_{\Delta Q} \) for a train
speed of 250 km/h, a crosswind speed varying from 0 to 60 m/s, and a wind direction of 90° (Giappino, Rocchi, Schito, & Tomasini, 2016). In EN14067-6, to determine the characteristic wind curve, the moment of equilibrium towards the rail is calculated. This procedure relies on four fundamental quantities: the restoring moment $M_m$ due to the vehicle mass; the moment $M_{la}$ due to the uncompensated lateral acceleration; the moment $M_{CoG}$ due to the lateral movement of the center of gravity (CoG) of the suspended masses (due to sway and lateral displacement); and the aerodynamic moment $M_{x,lee}$ due to the wind load.

Using the coordinate system defined in EN14067-1 (2003), the moment of equilibrium towards the leeward rail is given by

$$\sum M = f_{\Delta Q} \cdot \frac{1}{f_m} \cdot M_m + M_{CoG} + M_{la} - M_{x,lee} = 0$$  \hspace{1cm} (3)

The moments in Equation (3) are calculated according to Equations (4) to (9).

$$M_m = m \cdot g \cdot b_A$$  \hspace{1cm} (4)

$$M_{la} = m \cdot a_{q} \cdot z_{CoG}$$  \hspace{1cm} (6)

$$M_{x,lee} = 0.5 \cdot \rho \cdot U^2 \cdot S \cdot l \cdot C_{Mx,lee}(\beta)$$  \hspace{1cm} (7)

$$m = m_0 + m_1 + m_2$$  \hspace{1cm} (8)

$$z_{CoG} = \left( \frac{m_0 \cdot z_{CoG,0} + m_1 \cdot z_{CoG,1} + m_2 \cdot z_{CoG,2}}{m} \right)$$  \hspace{1cm} (9)

Considering the uncertainties in the method, the method factor $f_{\Delta Q}$ is set to 1.2. The railway line studied in the present work is a straight line; thus, the moment $M_{la}$ due to uncompensated lateral acceleration is zero. The parameters of Equations (4)–(9) are listed in Table 1.

However, Equation (3) differs from the equation presented in EN 14067-6. In the reference, the factor $f_{\Delta Q}$ is fixed to a maximum safety value of 0.9, and Equation (3) is used to calculate the characteristic wind speed $v_w$. In this study, the characteristic wind speed $v_w$ is given as 0–60 m/s, and Equation (3) is used to calculate $f_{\Delta Q}$; thus, the critical wind speed is obtained when $f_{\Delta Q}$ is greater than the maximum safety value.

Table 2 shows the maximum aerodynamic force coefficients in the transition region under different wind speeds.

Table 1. The parameters of the Equations (4)–(9).

| Parameters                               | Value | Unit |
|------------------------------------------|-------|------|
| Unspring masses $m_0$                    | 2.1   | t    |
| Primary suspended masses $m_1$           | 2.6   | t    |
| Secondary suspended masses $m_2$         | 26.1  | t    |
| The half of the lateral contact spacing $b_A$ | 0.75  | m    |
| Flexibility coefficients used for the lateral movement of the center of gravity of the primary suspended mass $y_1$ and that of the secondary suspended mass $y_2$ | 1.187 | –    |
| The uncompensated lateral acceleration $a_{q}$ | 0     | m/s² |
| The height of the center of gravity of the unsprung masses $z_{CoG,0}$ | 0.43  | m    |
| The height of the center of gravity of the primary sprung masses $z_{CoG,1}$ | 0.51  | m    |
| The height of the center of gravity of the secondary suspended masses $z_{CoG,2}$ | 1.52  | m    |

Table 2. The aerodynamic forces coefficients under different wind speeds.

| $v_w$ (m/s) | $C_y$  | $C_z$  | $C_{Mx,lee}(\beta)$ |
|-------------|--------|--------|----------------------|
| 0           | 0.223  | –0.087 | –0.287               |
| 10          | 0.339  | –0.128 | –0.070               |
| 15          | 0.341  | –0.130 | 0.290                |
| 20          | 0.402  | –0.144 | 0.547                |
| 25          | 0.445  | –0.158 | 0.897                |
| 30          | 0.486  | –0.170 | 1.148                |
| 35          | 0.560  | –0.213 | 1.608                |
| 40          | 0.551  | –0.236 | 1.715                |
| 45          | 0.687  | –0.292 | 1.908                |
| 50          | 0.689  | –0.282 | 2.442                |
| 55          | 0.776  | –0.332 | 2.713                |
| 60          | 0.771  | –0.338 | 2.997                |
wind speeds obtained from the numerical simulation. $C_{Mx,lee}(\beta)$ is the lee rail rolling moment coefficient; $C_z$ is the lift force coefficient, $C_z = (F_z/0.5\rho U^2 S)$; $F_z$ is the lift force; and $\rho$, $U$, and $S$ are the same as defined for $C_y$. According to Equation (3), Figure 19(a) shows the time history of $f_{AQ}$ for a train speed of 250 km/h and a wind speed of 30 m/s. Similarly to the aerodynamic force coefficient discussed in Sections 4.1 and 4.3, for a crosswind of 30 m/s, $f_{AQ}$ is relatively stable in the cutting and embankment; however, a distinct change suddenly occurs in the rectangular windbreak transition region, and the peak value of $f_{AQ}$ is 0.49. Figure 19(b) shows the variation in $f_{AQ}$ as the wind speed varies from 0 m/s to 60 m/s when the train runs at a speed of 250 km/h. With increasing wind speed, the wheel unloading ratio $f_{AQ}$ increases, and $f_{AQ}$ exceeds the allowable value when the wind speed reaches 50 m/s.

5. Conclusion and future work

In this study, a numerical investigation was conducted to determine the aerodynamic performance of a CRH2 running from a cutting to an embankment with a rectangular windbreak transition. It was observed that when the train runs in the cutting and embankment, the train’s aerodynamic performance remains in a relatively steady state; however, when the train runs through this transition region under crosswind, the pressure, force, and moment coefficients increase clearly and suddenly. The train shows a continuous yawing motion, which affects both passenger comfort and operational safety, and the head car experiences the worst sway phenomenon. The peak-to-peak values of the side force coefficients for the head, middle, and tail cars in the windbreak transition region are 0.68, 0.48, and 0.49, respectively. The peak-to-peak values of the yaw moment coefficient in the transition region for the head, middle, and tail cars are 2.35, 2.04, and 1.12, respectively. Relatively stable vortices occur in the cutting and embankment; in contrast, the disordered and relatively strong vortices in the windbreak transition region cause the aerodynamic force coefficients to suddenly change and cause the car body to sway.

The method presented in EN 14067-6 was slightly altered and applied in the present study. The operational safety was shown to be worse when the train runs through the windbreak transition region. At a train speed of 250 km/h and a wind angle of 90°, the wheel unloading ratio $f_{AQ}$ exceeds the safety value after the wind speed reaches 50 m/s.

This paper analyzed the variation in the pressure and load of a high-speed train with varying windbreak structures and landforms under a crosswind. Future studies could optimize a windbreak structure or transition region to reduce both the flow field variations and the peak values of the train aerodynamic force and to improve the train’s operational safety.

Disclosure statement

No potential conflict of interest was reported by the authors.

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