A Numerical Study of the Effect of Wind Barriers on Traffic and the Bridge Deck

Zhang, Yuxiang[1], Cardiff, Philip[2], Keenahan, Jennifer[1]
[1]School of Civil Engineering, University College Dublin, Belfield, Dublin 4, Ireland
[2]School of Mechanical and Materials Engineering, University College Dublin, Belfield, Dublin 4, Ireland
email: yuxiang.zhang1@ucdconnect.ie, jennifer.keenahan@ucd.ie

ABSTRACT: Wind actions can have a great impact on both bridges and traffic on bridges. However, structures designed to shelter the traffic from wind can influence the aerodynamic performance of the bridge deck, especially for long-span bridges. This study compares the effect of non-perforated walls and perforated walls used as wind barriers for traffic by conducting Computational Fluid Dynamics (CFD) simulations on three-dimensional geometries of a four-lane bridge deck. Steady-state simulations employ the Reynolds-Averaged Navier Stokes (RANS) method with the k-epsilon turbulence model and all simulations use parallel computing. An open-sourced software OpenFOAM is used.

KEY WORDS: Wind; Bridges; CFD Modelling.

1 INTRODUCTION

Traditionally, wind-tunnel tests are used to simulate a wind environment where scaled models with sensors are installed within the wind tunnel and data collected from these sensors is analyzed to draw conclusions. However, the use of wind tunnels is costly and often has scaling issues. In recent times, an increase in the use of CFD models and simulations has occurred, particularly in the field of wind engineering. Computers have gained sufficient computational power to conduct sophisticated CFD simulations and with lower cost and higher efficiency, CFD has a promising future.

The crosswind effect on vehicles can bring critical safety issues to drivers. Therefore, bridges in areas of complex wind environments usually have wind-shield structures to shelter vehicles from the wind. Researchers have conducted many wind-tunnel tests to determine the cross-wind effect. Dorigatti et al., 2012 [1] focused on using wind tunnels to investigate the risk of high-sided vehicles overturning on long-span bridges under gust-winds with different yaw angles. Xin et al., 2012 [2] performed an experiment to study how dynamic winds affected the bridge deck section.

While some researchers have focused on wind tunnel studies, others have used CFD modelling to analyse the wind environment. Fintelman et al., 2015 [3] have studied the aerodynamic issues of motorbikes subject to crosswind effects on freeways by applying the CFD method. Golovanevskiy et al., 2012 [4] used the CFD approach and wind tunnel tests to determine the optimal model for open cargo railway trains. Khalighi et al., 2012 [5] investigated the aerodynamic performance of a sports utility using the CFD method and validated their results against models in a wind tunnel. Alonso-Estébanez et al., 2017 [6] simulated bus models subject to winds with different yaw angles on bridge decks, which is of high value in the future of bridge road design. Kozmar et al., 2012 [7] investigated the sheltering efficiency of wind barriers on bridges under wind with different yaw angles. They emphasized that it is of high importance to study wind characteristics since wind-induced instability is one of the most common problems witnessed in large bridges. This study is especially beneficial to bridge constructions in areas that have severe wind issues, such as Italy and Croatia in which strong bora wind seasonally occurs [7]. Giannoulis et al., 2012 [8] discussed the permeability of wind barriers on bridges and suggest that further studies on such barriers are necessary

The purpose of this research is to study the efficiency of traffic sheltering structures by comparing different wind-shield walls using CFD simulations. 3D models of these structures are sketched in AutoCAD and OpenFOAM is applied to mesh the geometry and calculate the wind velocity and wind pressure using the Reynolds-Averaged Navier-Stokes (RANS) method. Final results were visualized in ParaView. Comparisons will be drawn on the performance of the different wind-shield walls. A simulation of perforated wind-shield walls against extreme weather conditions in Ireland is also conducted to demonstrate the necessity of wind-shield structures. Conclusions from this research will help improve the design of wind-shield structures.

2 MODELLING METHODOLOGY

2.1 Bridge Model

The geometry of the bridge model is shown in Figure 1. It is a simplified model with a width of 31 meters, a length of 50 meters and a height of 15 meters. Considering the simulation focuses on how wind affects the behaviour of vehicles, this model will satisfy the requirement of the research. As shown in Figure 1, the model is a segment of a continuous bridge.

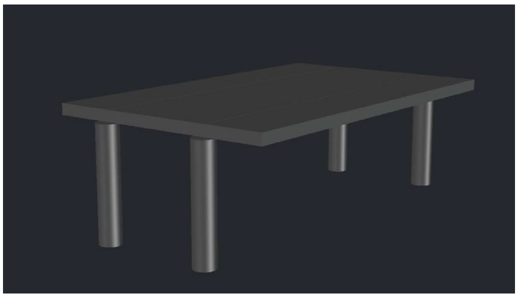


Figure 1. Overview of the bridge model

2.2 *Modelling the Vehicle*

An overview of the vehicle model is shown in Figure 2. This model has a height of 1.82 meters, a width of 1.8 meters and a length of 4.4 meters. The wheel of the model has a radius of 0.16 meters and a width of 0.205 meters. It represents an ordinary van on the road, which has an average size of larger vehicles and small-scale family cars.

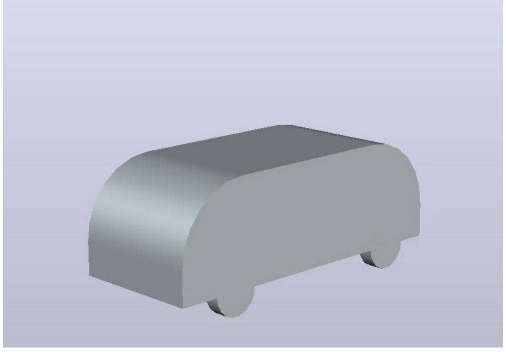


Figure 2. Overview of the vehicle model

2.3 *Modelling of the wind-shield wall*

The wind-shield wall is an essential part of the model in the simulation. It is a commonly used structure on bridges, especially in areas that have complex wind environments. To make a comparison among different wind-shield walls, a series of walls that have different dimensions are sketched for this research. Details of these walls are listed in Table 1.

Table 1. Dimensions of wind shields.

Number	Type	Height (m)	Length (m)	Width (m)
1	Non-perforated	1.5	50	0.25
2	Non-perforated	2	50	0.25
3	Non-perforated	4	50	0.25
4	Perforated	4	50	0.25

Bridge models with different wind-shield walls and vehicle models are assembled and shown in Figure 3. These models were tested in the virtual domain of OpenFOAM. The purpose of building these models with slight variations is to compare whether the shape of wind-shield wall will have a significant influence on wind behaviour around vehicles on bridges. Comparisons will be drawn using the control variate method.

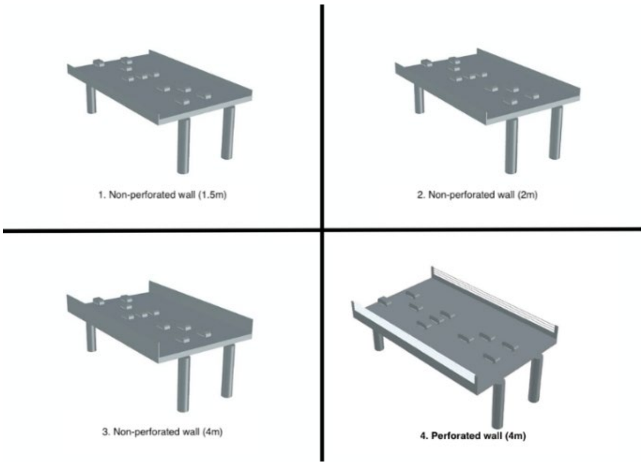


Figure 3. Overview of assembled geometries

2.4 *Wind velocity*

The wind speed is determined from a statistical analysis of Irish historical weather data. Figure 4 [9] shows the mean annual wind speed on the island of Ireland. The wind speed varies from 4 m/s to 7 m/s depending on locations. In coastline areas, the wind speed is approximately 6 m/s on the east and 7m/s on the west. These values are average ones, which will underestimate the wind velocity. Met.ie, 2018 [9] highlights the presence of gale gusts, which is a gust wind of over 17 m/s, in its report. This wind speed can be used as a threshold value to tell if the condition is critical. Therefore, this 17 m/s wind velocity will be applied in most simulations of this study. Met.ie, 2018 [9] also reports an extreme velocity of 45m/s for the gust wind. This velocity is used in the simulation of extreme weather condition.

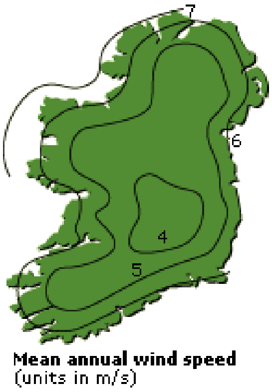


Figure 4. Mean annual wind speed of Ireland [9]

2.5 *Boundary Conditions*

The domain is chosen to be a similar size to the average wind tunnel used in wind tunnel tests. Since it is a virtual testing space, there is more flexibility for modification. The domain selected for this research is a cuboid one, which has a length of 70 meters, a width of 65 meters, and a depth of 50 meters. The domain has four surfaces of wall-type patches, which will stop air flowing through. These wall-type patches are painted blue in Figure 5. The red surface in Figure 5 is the inlet patch, where airflow initiates. The surface opposite to the inlet patch is the outlet patch, which only permits the air inside the domain to discharge.

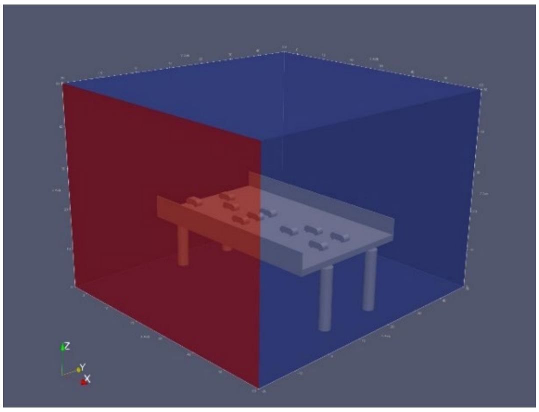
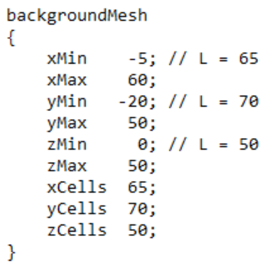


Figure 5. Overview of the testing domain

2.6 *Meshing and Solver*

The meshing procedure begins with generating background mesh using utility *blockMesh* in OpenFOAM. The background mesh scheme is shown in Figure 6. There are 65 cells in the x-direction, 70 cells in the y-directions, and 50 cells in the z-direction so that each cell is a cubic block with a width of 1m. The internal volume meshes are refined by the utility *SnappyHexMesh* in OpenFOAM. The total cell counts for most simulations are around eight million which makes it time-consuming to perform these simulations locally. Therefore, all simulations are run in parallel on the UCD cluster server with 64 cores.



```
backgroundMesh
{
    xMin    -5; // L = 65
    xMax    60;
    yMin   -20; // L = 70
    yMax    50;
    zMin     0; // L = 50
    zMax    50;
    xCells  65;
    yCells  70;
    zCells  50;
}
```

Figure 6. Background mesh scheme

OpenFOAM provides various solvers for different tasks. In this research, the RANS solver named simpleFoam was used. It can conduct steady-state simulations of incompressible flows. In this case, it can meet the requirement of simulating air behaviour. SimpleFoam can also calculate the turbulent model with acceptable accuracy for vehicle-and-bridge models.

2.7 *Post-processing*

Simulation results are visualized in ParaView as OpenFOAM does not have a graphic user interface. Figure 7 shows the cross section with one vehicle model, which is selected to study the crosswind effect on the vehicle model. Two sampling lines are generated by the utility named *plotOverLine* in Paraview to extract the wind velocity and wind pressure at different heights above the road surface. Locations of these lines are listed in Table 2. The wind velocity and wind pressure extracted are later plotted against the y-axis to get a clear view of the wind profile along the selected cross section.

Table 2: Locations of sampling lines

Number	Start point (x y z)	End point (x y z)	Distance to the road surface (m)
1	(13 -20 17.5)	(13 50 17.5)	1
2	(13 -20 18.5)	(13 50 18.5)	2

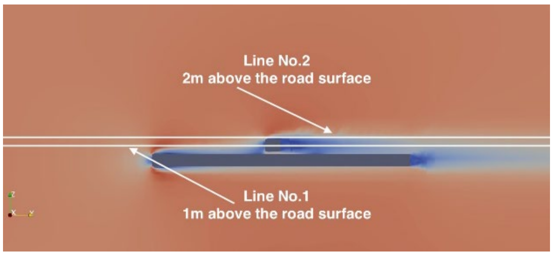


Figure 7. The cross-section with sampling lines

3 RESULTS

3.1 *Comparison of Simulations between non-shielded model and models with wind shields*

In this comparison, the dimensions of the domain, the wind velocity (17 m/s), the geometry of bridge and vehicle models are fixed. The only variable is the wind-shield walls. Figures 8 to 13 show the wind velocity at the selected cross section of five models with different wind-shield walls.

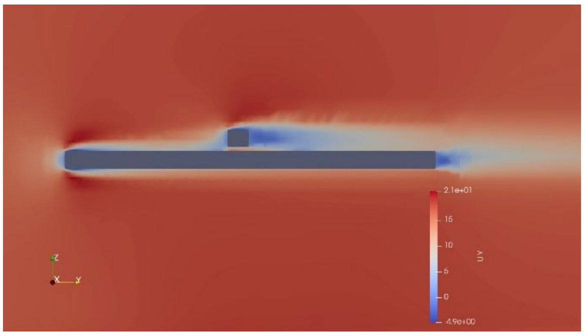


Figure 8. Cross section of the non-shielded model

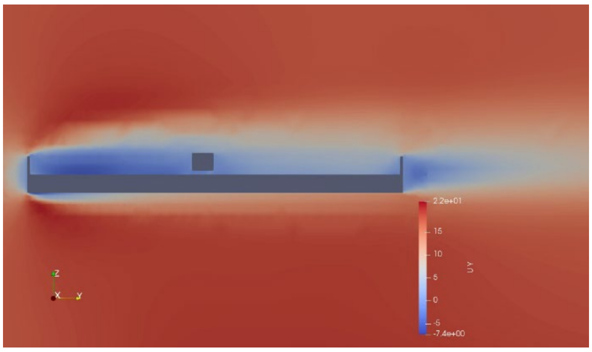


Figure 9. Cross section of the model with the 1.5m wall

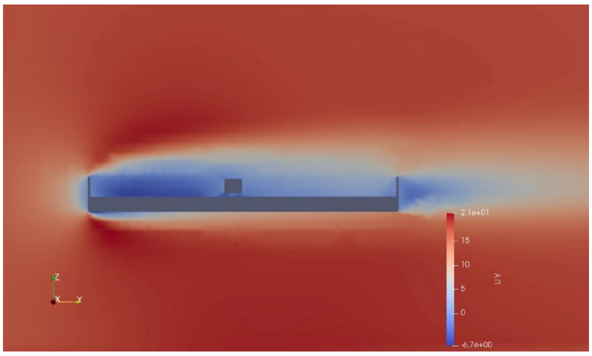


Figure 10. Cross section of the model with the 2m wall

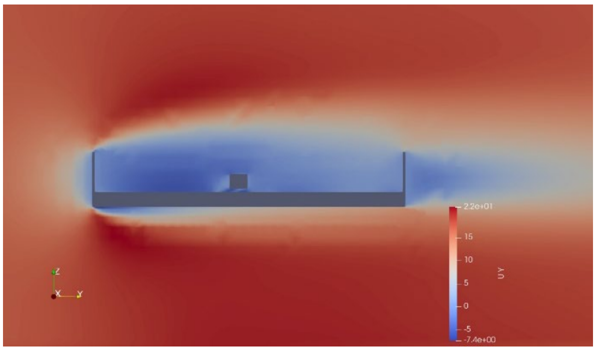


Figure 11. Cross section of the model with the 4m wall

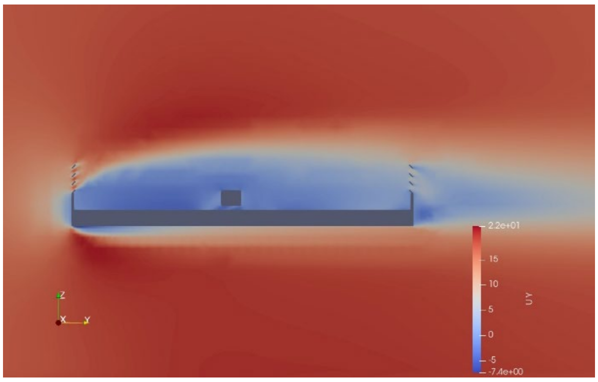


Figure 12. Cross section of the model with the perforated wall

Figures 9 to 12 show the wind velocity and wind pressure at the two sampling lines of five simulations with different the wind-shields. The positions of the vehicle models are indicated in these figures.

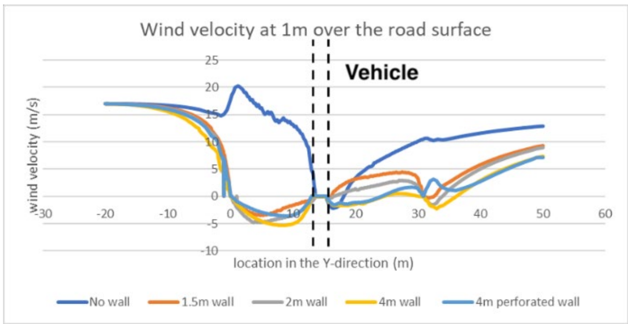


Figure 13. Wind velocity at 1m over the road surface

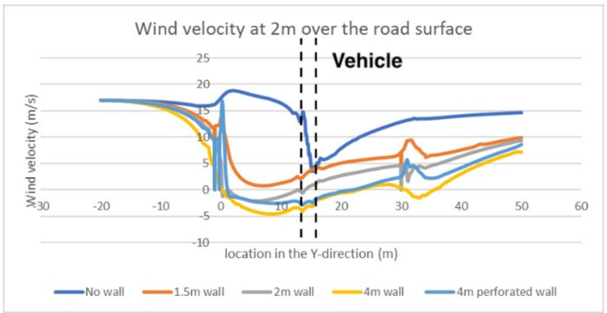


Figure 14. Wind velocity at 2m over the road surface

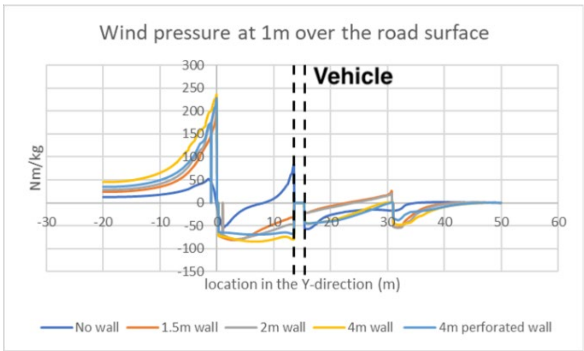


Figure 15. Wind pressure at 1m over the road surface

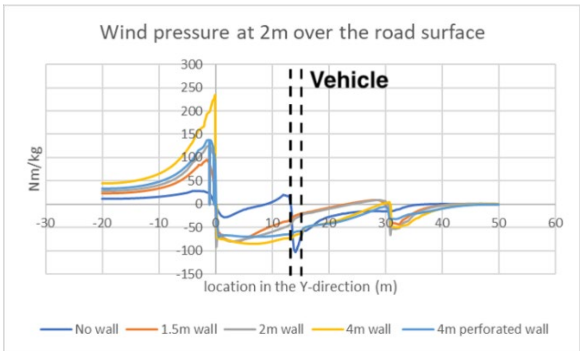


Figure 16. Wind pressure at 2m over the road surface

It is clear in Figure 13 and Figure 14 that the wind velocity of models with a wind-shield wall is much lower than the wind velocity of the model without wall. As the non-perforated wall gets higher, the wind velocity at the location around the vehicle tends to get lower and then forms a negative wind velocity. When the height of the non-perforated wall continues to increase, the absolute value of the negative wind velocity becomes higher. However, the 4m perforated wall has a lower absolute value of the wind velocity than that of the 4m non-perforated wall. According to Figure 15 and 16, the model with 4m perforated wall generally has a lower absolute value of the wind pressure than 4m non-perforated wall. All these results indicate that wind-shield walls can effectively reduce the wind velocity around the vehicle. However, higher walls might increase the intensity of eddies around the bridge deck.

3.2 Simulation of the perforated barrier against extreme weather conditions in Ireland

In this simulation, the wind velocity is set as 45m/s. The model with a perforated wind-shield wall is compared with the basic model without a wall. The wind velocity at the selected cross section of the two models are shown in Figures 17 and 18. The wind velocity at two sampling location is presented in Figure 19 and Figure 20. Figure 19 shows that the wind at the height of 1m over the road surface has a velocity of around 10m/s before reaching the vehicle model when there is no wind-shield wall. When the bridge is shielded with a 4m perforated wall, the wind velocity at the left side of the vehicle is almost zero. Figure 20 shows that the wind velocity of the shielded model at the location above the top of the vehicle is over 20 m/s lower than that in the non-shielded model. This proves that the 4m perforated wind-shield wall can effectively protect the vehicle from wind-induced problems.

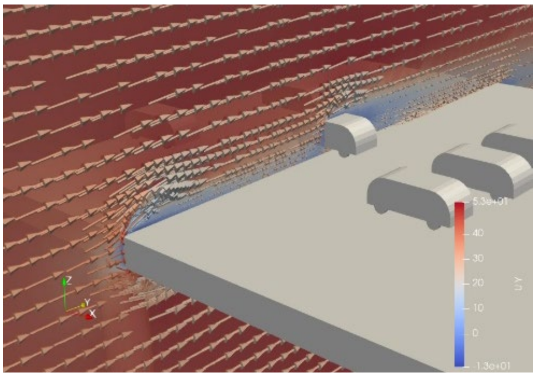


Figure 17. Cross section of the non-shielded model

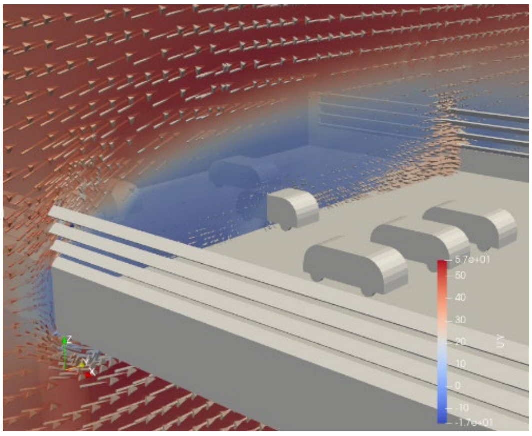


Figure 18. Cross section of the model with the perforated wall

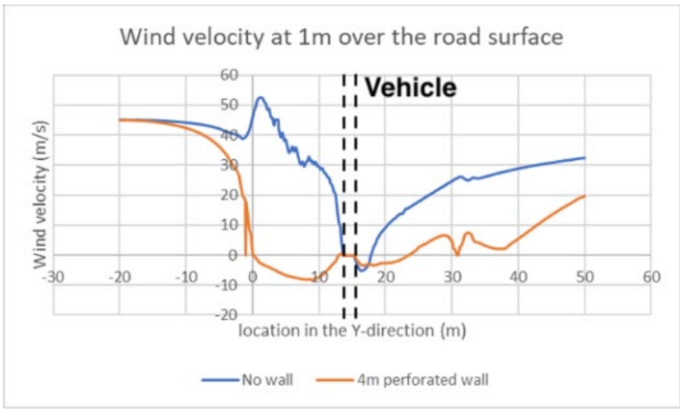


Figure 19. Wind velocity at 1m over the road surface

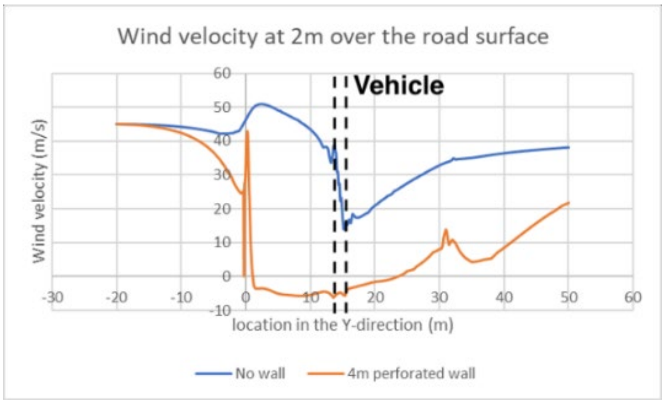


Figure 20. Wind velocity at 2m over the road surface

4 CONCLUSIONS

It can be concluded from the results that the non-perforated wind-shield walls can significantly reduce the wind velocity around the vehicle. The non-perforated wind-shield wall will also simulate eddies, which might cause vortex-related problems. As the wall gets higher, this effect will become more significant. The perforated wall can also effectively reduce the wind velocity. It also causes relatively smaller eddy-related issues than non-perforated walls with the same height. This study has shown the convenience of extracting data from CFD simulations. More relevant parameters will be compared in future research. As parallel computing techniques continue to develop, simulations based on complex geometries will be more affordable. Also, it is important to verify the new techniques used in CFD simulations. Therefore, there will be more comparisons between simulations and wind tunnel tests in this area.

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