Study on modulation technology of highway regional wind field

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Abstract. In this paper, through numerical simulation, the modulation effect of trees on the wind field of the highway and the wind load of the traffic is studied. Two tree species were selected, and the effects of different tree species and arrangement numbers on the wind speed on the embankment and the wind pressure on the driving surface were studied, by simulating the single-row distribution of a single tree species and the mixed multi-row distribution of two tree species. The results show that trees play a significant role in wind field modulation, and different tree species have different effects; Compared with the modulation of single tree species, the mixed modulation effect is more effective, and gradually increases with the number of rows, but the trend of enhancement gradually slows down.

1. Introduction

Serious traffic accidents caused by high winds are common, and extreme weather conditions often cause traffic accidents or cause highway outages.

Some researchers have carried out numerical simulations or wind tunnel tests on the driving of vehicles under wind measurement[1–4]. Gawthorpel[5] and Baker[6] studied the factors that may cause driving safety problems when the vehicle is under the crosswind, including the increase in resistance when the vehicle is driving, the deviation of the driving direction. Gawthorpel pays more attention to the problems that may be encountered when conducting model tests and numerical simulations.

The modulation method can be used to change the wind field of the highway area and reduce the wind speed in the area[7]. At present, the most commonly used modulation methods are to install wind barriers and plant windshield. The use of wind barriers to modulate the wind field has quick results, strong operability, and is suitable for almost all environments, but the cost is relatively high. And it is limited by the strength of the material itself and the problem of easy aging. Once the wind barrier structure itself is damaged in a strong wind environment, it is easy to cause unexpected traffic accidents due to the wind barrier dumping, which is contrary to the original intention of the design[8]. Planting a windshield for modulation can achieve a better modulation effect while meeting greening requirements, and the primary forest can also be directly used to save costs when the primary forest exists. However, it is greatly affected by the surrounding environment of the highway, and it is difficult to use it in bridges, tunnels and mountain areas[9].

Yang et al.[10] and Zeng et al.[11] used the additional source term method to simulate the canopy area, and analyzed the windshield effect and related parameters of the trees through numerical
simulation calculations. Mulati Yusaiyin et al. [12] found the windshield has a significant effect on reducing the wind speed in the area behind it. The wind speed decreases by 15% - 22% as the width of the windshield increases.

This article assumes that the fluid is incompressible. The commercial software FLUENT is used to numerically simulate the wind field around the embankment. The dynamic grid is used to realize the vehicle driving on the embankment at a speed of 25m/s. For the simulation of trees, the additional source term method and Consider it. Taking two tree species as an example, the influence of a single tree species on the wind load on the embankment wind field and traffic, and the effect of the number of arrays on the modulation effect when using multi-row mixed modulation are studied. And give suggestions on the choice of modulation method.

2. Numerical model
The CFD software uses the finite volume method to solve the continuity equation and momentum equation, so as to obtain the information of the external flow field of the structure.

2.1. Governing equation
In the numerical simulation study in this paper, it is assumed that the fluid is incompressible, so the continuity equation and momentum equation in this paper are

$$\nabla \cdot \mathbf{u} = 0$$

and

$$\frac{\partial}{\partial t} \mathbf{u} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho} \nabla p + \nu \nabla^2 \mathbf{u}$$

Where \( \mathbf{u} \) is the velocity vector of the fluid, \( \rho \) is the density of the fluid, \( t \) is the time, \( p \) is the pressure, and \( \nu \) is the dynamic viscosity of the fluid. The standard \( k - \varepsilon \) turbulence model is adopted.

2.2. Geometric model and computing domains
In this paper, the numerical model of highway embankment is built on the basis of the G204 ring road standard embankment in Rizhao City, Shandong Province, China. The embankment model cross-section is shown in Figure 1. The embankment is 8m high and 25.5m wide, with a slope \( H/L \) of 1:1.5, and 4-lane dual carriageway. The middle isolation bandwidth is 3.0m, the traffic lane is 4×3.75m.

The vehicle model uses the GTS vehicle model proposed by the Sandia National Laboratory in 1996 as a prototype for numerical simulation. This vehicle with a total length of 19.8m, a width of 2.6m, and a height of 4.1m. The height of the bottom of the vehicle from the ground is 0.5m. The front of the vehicle is streamlined, as shown in Figure 2. At the same time, the necessary simplification of the vehicle model is also made to reduce the calculation cost. Although the distance between the head and the body is ignored, the overall structural characteristics of the vehicle are maintained.

The tree model in this paper is to add additional source terms \( S_i, S_k, S_\varepsilon \) to the momentum equation, \( k \) equation and \( \varepsilon \) equation respectively[10,13]:

$$S_i = -C_d A |u| u_i$$

Figure 1. Embankment section.

Figure 2. Vehicle model.
\[ S_k = C_d A \left( \beta_p |u|^3 - \beta_d |u|^k \right) \]  
\[ S_\varepsilon = C_d A \left( C_{\varepsilon d} |u|^3 - C_{\varepsilon e} \beta_d |u|^\varepsilon \right) \]

Where \(|u| = (u_i^2)^{1/2}\), \(\beta_p, \beta_d, C_d, C_{\varepsilon d}, C_{\varepsilon e}\) are empirical constants, and the values are 1.0, 5.03, 0.24, 1.5, 1.5 respectively. \(A\) is the leaf area density, which is defined as the sum of the leaf area per unit volume in the canopy. This article takes two common tree species (cedar and dragon cypress) common in Rizhao as an example[14]. Tree species 1 is cedar, length 2m, width 2m, tree height 12m, trunk width 0.2m, height under branch 6m, leaf area density 0.72 m²/m³; tree species 2 is dragon cypress length 1m, width 1m, tree height 8m, no branch height, Leaf area density 1.8 m²/m³. Cedar and dragon cypress represent two typical tree species with or without distance between the crown and the ground, which directly affects the flow field generated when the wind blows through the trees.

The calculation domain is set to 280m (x axis) x 150m (y axis) x 80m (z axis), where the x-axis is the direction of incoming flow and the z-axis is the direction of height. The embankment height \(h = 8\) m. The inlet is 85m away from the embankment slope foot, about 10\(h\); the outlet from the embankment slope foot is 145m, about 18\(h\); the top surface is 72m, 9\(h\) from the embankment top surface, the vehicle is in the outer lane.

2.3. Meshing and boundary conditions
In terms of meshing the model, the tetrahedral unstructured grid is used near the embankment area, and the minimum size is 0.25m. The remaining area uses a hexahedral structure grid and the density changes from the calculation domain boundary to the embankment direction.

The boundary condition of the entrance to the calculation domain is set to velocity-inlet, Wind speed selects the form of exponential wind profile:
\[ \bar{V}(z) = V_{10} \left( z/10 \right)^{0.15} \] (6)

Where, \(V_{10}\) is the average wind speed at a standard height of 10m. Relying on the actual measured data of the project, this model takes \(V_{10} = 10\) m/s.

The boundary conditions of the top surface and both sides of the calculation domain are set as solid-wall and the outlet boundary conditions are set as free outflow. The embankment surface, the vehicle surface and the bottom surface of the calculation domain adopt solid-wall and non-slip wall.

3. Results and discussion
In this paper, two tree species are taken as examples to simulate the modulation of a single tree species and the mixed modulation of two tree species separately. Among them, the modulation of single tree species studied the influence of each tree species on the modulation effect, and the mixed modulation studied the influence of the number of rows on the modulation effect.

3.1. Modulation effect of single tree species
The distance between the tree model and the foot of the embankment slope is defined as \(L_1\), and a row of tree species 1 and tree species 2 are symmetrically arranged at a distance of \(L_1 = 5\) m from the embankment slope foot. Figure 3 shows the calculated path of the wind speed in this paper, which is 2.5m above the road surface and 10m in front of the front of the vehicle.

\[ x=0 \]
\[ 10.5m \]
\[ \text{Calculate path} \]

\[ 10m \]
\[ \text{Calculate path} \]

**Figure 3.** Schematic of wind speed calculation path.

Define the wind load \(P\) on the vehicle as the sum of the windward pressure, leeward pressure and crosswind shear of the vehicle.
Dimensionless the wind load for comparison, and define the wind load change rate $\lambda$ as:

$$\lambda = \frac{|P_0| - |P|}{|P_0|} \times 100 \%$$  \hspace{1cm} (7)

where $P_0$ is the wind load on the vehicle without modulation, $P$ is the wind load on the vehicle after modulation. Define the rate of change of wind speed $\eta$ as:

$$\eta = \frac{V_0 - V}{V_0} \times 100 \%$$  \hspace{1cm} (8)

where, $V_0$ is the wind speed at a certain point when modulation is not performed, $V$ is the wind speed at that point after modulation.

![Figure 4](image1.png)  \hspace{1cm} ![Figure 4](image2.png)

(a) Tree species 1 modulation  \hspace{1cm} (b) Tree species 2 modulation

**Figure 4.** Contour map of horizontal wind speed at $z = 10.5$m when modulated by a single tree species.

![Figure 5](image3.png)  \hspace{1cm} ![Figure 5](image4.png)

(a) Comparison of wind speed $V$  \hspace{1cm} (b) Comparison of wind speed $\eta$

**Figure 5.** Comparison of wind speed $V$ and wind speed change rate $\eta$ on the modulation calculation path of a single row of tree species.

Without modulation, the wind load on the vehicle $P = 17.17$kN; when using the tree species 1 modulation, $P = 16.13$kN, wind load change rate $\lambda = 6.1\%$; when the tree species 2 modulation, $P = 14.90$kN, $\lambda = 13.2\%$. That is, when a single tree species is modulated, the wind pressure modulation effect of tree species 2 is better than that of tree species 1.
Figure 4 is a contour map of wind speed 2.5m above the road surface (z = 10.5m) when modulated by a single tree species. It can be seen that when using tree species 1 modulation, due to its wind-reducing effect, a low wind speed area is formed in the tree area on the windward side, and the wind speed is 6m/s ~ 8m/s; When using species 2 for modulation, since the cut plane is still 2.5m away from the top of species 2, there is no significant change in wind speed above and around the area, but the wind speed is less than when no modulation is performed. The method of single tree species modulation is similar to that when the vehicle is not modulated. The wind speed around the vehicle is relatively large, close to the driving speed of the vehicle itself, and the low-speed area is still behind the leeward side of the vehicle.

Figure 5 shows the comparison of the wind speed and the change rate of the wind speed on the calculation path without modulation and single-row tree species modulation. After modulation, the wind speed is reduced. On the calculation path above the embankment slope, the tree species 1 has a better modulation of the wind reduction effect; on the calculation path above the road surface, the tree species 2 has the better modulation on the wind reduction effect.

3.2. Mixed modulation effect
When planting windshield trees in actual projects, windrow modulation is often carried out by using multiple rows to form a windbreak, so it is necessary to discuss and analyze the modulation effect when planting multiple rows of trees. This section mainly analyzes the modulation effect when planting one to seven rows of trees in mixed modulation.

The mixed modulation model is to arrange the corresponding row tree species 2 symmetrically at the distance $L_1 = 5m$ from the embankment slope foot, and then arrange the corresponding row tree species 1 symmetrically at the distance $L_2 = 5m$, as shown in Figure 8.

![Figure 6. Variation of wind load change rate $\lambda$ with the number of rows of trees.](image)

Figure 6 shows the change of the wind load change rate $\lambda$ with the number of arrangements. The wind load change rate increases with the number of arrangements, but the trend gradually slows down. Before the number of rows is increased to four rows, each additional row will have a significant improvement in wind pressure modulation effect, and after the number of rows is more than four rows, increasing the number of planting rows can still improve the effect of wind pressure modulation, but the increase is significantly reduced.

Due to space limitations, Figure 7 is a contour map of the wind speed of one-row and seven-row where the mixed modulation is 2.5m above the road surface (z = 10.5m).

In the case of multi-row modulation, with the increase of the number of rows, the wind-reducing area of the windward tree species 1 area becomes larger and larger, and the wind speed value...
gradually decreases from 6m/s to 8m/s in the case of one-row mixed modulation to seven-row mixed modulation 2m/s~6m/s. In the area around the embankment, the wind reduction area behind the vehicle side decreases continuously as the number of rows increases, and the wind speed in other areas except the wind reduction area also decreases as the number of rows increases, and the overall wind field in the embankment area increases as the number of rows increases It tends to be flat. The wind speed around the vehicle is relatively high, approaching or slightly exceeding the speed of the vehicle itself. As the number of rows increases, the wind speed around the vehicle also decreases.

(a) One-row mixed modulation
(b) Seven-row mixed modulation

**Figure 7.** Contour map of horizontal wind speed at z = 10.5m when mixed with different rows.

![Contour map of horizontal wind speed](image)

(a) Comparison of wind speed $V$
(b) Comparison of wind speed change rate $\eta$

**Figure 8.** Comparison of wind speed $V$ and wind speed change rate $\eta$ on the modulation calculation path when mixed with different rows.

Figures 8 shows the comparison of the wind speed and the change rate of the wind speed in the multi-row mixed modulation calculation path. The maximum wind speed on calculation path above the road surface is on the shoulder on the windward side. As the number of rows increases, the wind speed on the calculation path decreases significantly. After the number of rows is more than four rows, increasing the number of rows reduces the effect of reducing the wind.

When the number of rows is less than four rows, the wind reduction effect on calculation path increases significantly for each additional row; After four rows, the effect of reducing the wind on each additional row is very small. Increasing the number of rows significantly improves the wind
reduction effect. It is recommended to plant four rows of tree species 2-tree species 1 for wind speed modulation.

4. Conclusion and outlook
In this paper, the numerical simulation is used to study the modulation effect of trees modulating the wind field and the wind load on the highway. Four parameters, wind load $P$, wind load change rate $\lambda$, wind speed $V$ and wind speed change rate $\eta$, are defined to analyze the effects of wind pressure modulation and wind speed modulation. Based on the two trees, the tree species 1, tree species 2 models are established, and their modulation effects are discussed. Through numerical simulation, it is found that when a single tree species is used for modulation, the decompression effect of tree species 2 and the wind reduction effect above the road surface are better; When using tree species 1 and tree species 2 for mixed planting for modulation, it was found that the mixed tree species had a better modulation effect. By analyzing the effect of multi-row mixing modulation, it is found that when the number of planting rows is less than four rows, the modulation effect increases significantly for each additional row; After the number of rows is greater than four rows, the modulation effect still increases for each additional row, but the increase is significantly reduced.

Finally, it is recommended to use a mixed modulation method. When conditions permit, planting more than four rows of tree species 2-tree species 1 for modulation can significantly improve the modulation effect.

In this paper, only two types of tree species are studied as examples, and only the wind load of the vehicle driving in the outer lane at a speed of 25m / s is studied. Due to the large differences between different tree species, future research can be further studied on different canopy heights and leaf area density, the vehicle’s driving position and speed. For vehicles, refined modelling can be carried out in the future to improve the accuracy of the results. In addition to the huge contribution of trees in affecting the wind field of highways, they have great research value in improving automobile exhaust, underground runoff, and affecting the surrounding biological communities.

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