Study on the Influence of Crosswind Angle and Longitudinal Spacing on Buses in a Platoon

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Abstract. The influences of crosswind angle and longitudinal spacing on bus platoon are studied by methods of theoretical analysis and numerical simulation. The results show that the wind resistance coefficient of the bus increases first and then decreases with the increase of crosswind angle. The maximum wind resistance coefficient is about 2.3 times of that without crosswind when the crosswind angle is 30°. When buses in a platoon at a crosswind angle of 20°, the pressure increase on the windward side of the rear bus is much greater than that on the windward side without crosswind. This shows that crosswind shortens the distance between the two buses at high fuel economy.

1. Introduction
A bus running along the road is often affected by crosswind due to the uncertainty of wind direction, and compared with the bus platoon without crosswind, the aerodynamic moment and aerodynamic force upon the bus will increase with the action of crosswind, and riding comfort of the driver and passengers as well as the driving and handling stability of the bus will obviously change[1]. In addition, for large buses, when they drive fast or along a mountainous road, their safety and stability will be greatly reduced if they encounter the high-speed crosswind[2].

With the increasing number of vehicles in operation, traffic jam is getting increasingly serious, and sometimes several vehicles need to be running in platoon, or forming a temporary fleet under some special circumstances. During the actual driving of the fleet, the flow field between vehicles will act upon each other, thus changing the aerodynamic characteristics of the vehicles. Moreover, under the influence of the front vehicle, the wind resistance coefficient of the rear one can be reduced to a certain extent, which is conducive to saving energy, reducing emission and lowering the transportation cost[3]. The research results of relevant literatures show that[4,5], the fuel economy of vehicles can be effectively improved if they are running in platoon, and the comprehensive transportation capacity and economic benefits of transportation system can also be enhanced, thus offering a good prospect.

In recent years, researches on crosswind and distance between vehicles have become a key issue concerning a running fleet. Xu Xianggang[6] uses the method of numerical simulation to analyze the aerodynamics characteristic of a single vehicle under the influence of crosswind, as well as the fuel economy of vehicles running in the 2-vehicles and 3-vehicles platoon at different crosswind angles and with different distances between vehicles. The research results show that the wind resistance coefficient of a single vehicle increases first and then decreases with the increase of crosswind angles; and when the angle is 30°, the wind resistance coefficient is the largest. As to the condition of two vehicles running in platoon, the change of crosswind angles and distance between vehicles has greater influence upon the fuel economy and wind resistance coefficient of the rear bus. The rate of fuel saving reducing with the increase of crosswind angle and distance between vehicles. Jiang Luming[7] studies the aerodynamic
characteristics of the bus and van fleet under the influence of crosswind. The results show that the change of crosswind angles imposes greater impact upon the lift force of a van, the increase of crosswind angles causing the lift to rise. In comparison with the van, the bus endures greater impact on the lateral force with the change of crosswind angles.

In the paper, theoretical analysis combined with numerical simulation are used in order to analyze the aerodynamic characteristics of buses under the impact of crosswind. The Influence of crosswind angle and longitudinal spacing upon the buses in platoon is studied, and the variation laws of intensity of pressure upon buses, flow field and wind resistance coefficient are summarized and analyzed.

2. Fluid Control Equation and Turbulence Model

2.1. Energy Conservation Equation[8]
The law of conservation of energy means that the sum for the increasing amount of kinetic energy and the increase in internal energy of a fluid tiny element in a unit time is equal to the product of the deformation rate and surface force of the fluid tiny element plus the work of the volume force acting on the fluid tiny element in a unit time. The specific equation is shown as below:

\[
\frac{\partial \rho T}{\partial t} + \text{div}(\rho U T) = \text{div}(\frac{k}{C_p} \text{grad} T) + S_f
\]

T-temperature, K-heat transfer coefficient, C_p-specific heat capacity, S_f-viscous dissipation term.

Since in the paper, only the pressure field and velocity field are analyzed, and temperature field is not analyzed, the energy conservation equation is not involved.

2.2. Momentum Conservation Equation[9]
The momentum conservation equation, also known as Navier-Stokes equation, is used to describe the momentum conservation of incompressible viscous fluid. The specific formula is shown as below:

\[
\begin{align*}
\rho \frac{du}{dt} &= -\frac{\partial p}{\partial x} + \rho X + \mu \Delta u \\
\rho \frac{dv}{dt} &= -\frac{\partial p}{\partial y} + \rho Y + \mu \Delta v \\
\rho \frac{dw}{dt} &= -\frac{\partial p}{\partial z} + \rho Z + \mu \Delta w
\end{align*}
\]

u, v and w-the velocity component of fluid in 3 directions as x, y and z at a certain moment; \( \rho \)-density of fluid; \( \mu \)-dynamic viscosity; P-pressure; X, Y and Z-components of external force in the 3 directions; \( \delta \)-Laplace operator.

2.3. Mass Conservation Equation[8]
The mass conservation equation means that the increase of fluid mass in a tiny element in a unit time is equal to the net mass flowing into the tiny element in the unit time. The specific formula is shown as below:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

u, v and w-velocity component of fluid in the 3 directions as x, y and z at a certain moment; \( \rho \)-density of fluid.

If the fluid is stable, \( \rho \) does not change with time. The equation is:

\[
\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

If the fluid is incompressible, \( \rho \) is a constant. The equation is:

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]

2.4. Standard k-\( \varepsilon \) Model
The standard k-\( \varepsilon \) model can be adopted for the numerical simulation calculation of fluid under the state of complete turbulence; the standard k-\( \varepsilon \) model is composed of 2 equations, i.e. k (turbulent kinetic energy equation) and \( \varepsilon \) (turbulent dissipation rate equation).

K (turbulent kinetic energy) transport equation:
\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho ku_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon
\]

\varepsilon \text{ (turbulent dissipation rate) transport equation:}
\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon}{k} \left( C_{\varepsilon 1} G_k - C_{\varepsilon 2} \rho \varepsilon \right)
\]

\[
G_k = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j}
\]

\(C_{\varepsilon 1}, C_{\varepsilon 1}, \sigma_k, \sigma_\varepsilon\) - empirical constant; \(G_k\) - generation term of turbulent kinetic energy.

3. **Research on the Numerical Simulation of Single Vehicle**

3.1. **3D Model of Bus and Computational Domain Modeling**

In the paper, a 3D model is established in accordance with the bus produced by an enterprise. The dimension scale between the 3D model and real bus is 1:1, and the length, width and height of the bus is 12.2m, 2.4m and 2.9m respectively. In order to shorten the convergence time of the numerical simulation and ensure smooth calculation, the 3D model of the bus is appropriately simplified in the paper, but the parts such as rear-view mirror which can greatly impact wind resistance coefficient are still retained. The 3D model of the bus is shown in Figure 1.

![Figure 1. 3D Model of the Bus.](image)

When a numerical simulation research of buses is carried out, it is necessary to first determine the size of the computational domain. Whether the computational domain is reasonable or not will greatly affect the accuracy and convergence time of the results. In this paper, the computational domain of virtual wind tunnel is selected. The cross section of the computational domain is 10 times wider and 7 times higher than the bus respectively, so the blockage ratio is 1.43%. The research shows that[10], if the blockage ratio is less than 2% in the computational domain of wind tunnel, the experimental error caused by blocking interference is not necessary to be corrected. Therefore, the scheme design of computational domain of the numerical simulation is in line with the requirements.

3.2. **Numerical Simulation Scheme of Single Vehicle**

During the research on the numerical simulation of a single vehicle, the crosswind angle \(\alpha\) in the paper increases from 0° to 45° by 5° in turn. If the air velocity at the inlet of the wind tunnel is \(V_x\), the speed of the bus is \(-V_x\), and \(V_z\) is the speed perpendicular to the driving direction set in the numerical simulation software, so the actual speed of crosswind is \(V\). The schematic diagram is shown in Figure 2.

![Figure 2. Schematic Diagram of Numerical Simulation of Buses under the Influence of Crosswind.](image)

It can be seen from Figure 2, the actual speed of crosswind is \(V=V_x/cos\alpha\), and speed in the perpendicular direction is \(V_z = V_x \cdot tan\alpha\). In the experiment, the bus is running at 20m/s, and the crosswind speed corresponding to various angles is shown in Table 1.
3.3. Analysis on the Influence of Crosswind upon Wind Resistance Coefficient of Buses

First, the impact of crosswind upon the wind resistance coefficient of buses is analyzed in the paper. Figure 3(a) and 3(b) show respectively the experimental results of the Reference 6 and 11, and the results show that with the increase of crosswind angle, the wind resistance coefficient of a bus goes up first and then down. It is also pointed out in Reference 11 that the wind resistance coefficient is the largest if crosswind angle is within the scope of 20° to 35°. Figure 3(c) shows the numerical simulation result of wind resistance coefficient and changes of crosswind angle in the paper, the variation trend basically consistent with the results shown in the above 2 figures. In the numerical simulation result, the maximum value of wind resistance coefficient is about 2.3 times more than that when there is no crosswind, and the crosswind angle corresponding to the situation with the largest wind resistance coefficient of bus is 30°, which is between 20° and 35°. The above analysis indicates that the numerical simulation result is credible.

3.4. Analysis on the Influence of Crosswind upon Velocity Field of Buses

Figure 4 shows the velocity distribution of symmetrical section of a bus when the crosswind angles are 0°, 30° and 45° respectively. The 3D model diagram of the bus is omitted in the Figure. As can be seen in Figure 4(a), due to the inhibition of the bus head to the airflow, when the crosswind angle is 0°, i.e. no crosswind, the airflow velocity in the middle of the head will be obviously reduced, air will flow to the roof, bottom, left and right side of the bus and a high flow velocity area will be formed in the upper part of the head due to the change of shape. The air flows along the surface of the body to the rear. After it reaches to the rear of the bus, the airflow in all directions begins flowing to the middle due to the loss of flowing attachments. The airflow on the roof that flows downward, airflow on the bottom that flows upward and the one flowing to both sides of the body gather and then form multiple vortexes at the rear of the bus; the clockwise vortexes will be formed on the top of the rear, while the counterclockwise vortexes formed at the bottom of the rear. As a result of vortexes, the pressure difference between the head and rear of the bus is increased, which is an integral part of aerodynamic drag of the bus.

The velocity field shown in Figure 4(b) and 4(c) respectively is obviously different from those without crosswind, which indicates that crosswind can affect the velocity field of airflow. When the crosswind angle is 30°, vortex is closer to the rear of the bus where air flows faster, thus reducing the static pressure at the rear. This series of changes increase the pressure difference between the front and rear of the bus, enhancing the wind resistance coefficient in the end. When the crosswind angle is 45°, the vortex at the rear is less noticeable, and meanwhile the air at the rear flows even faster.

Table 1. Crosswind Speed Corresponding to Each Crosswind Angle.

| α (°) | 0° | 5° | 10° | 15° | 20° | 25° | 30° | 35° | 40° | 45° |
|-------|----|----|-----|-----|-----|-----|-----|-----|-----|-----|
| VX (m/s) | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 | 20 |
| VZ (m/s) | 0 | 1.75 | 3.53 | 5.36 | 7.28 | 9.33 | 11.55 | 14 | 16.78 | 20 |
| V (m/s) | 20 | 20.08 | 20.31 | 20.71 | 21.28 | 22.07 | 23.09 | 24.42 | 26.11 | 28.28 |

Figure 3. Relationship between Crosswind Angle and Wind Resistance Coefficient in Different Experiments.
3.5. Analysis on the Impact of Crosswind upon the Pressure Field of Bus
Figure 5 shows the pressure field on the windward side of the bus head when crosswind angle is 0°, 30° and 45° respectively. It can be seen from the Figure that under the impact of airflow, a positive pressure area is formed on the bus head, and with the change of the crosswind angle, the shape of pressure field at the head as well as the maximum positive pressure area are also changing. When there is no crosswind, the positive pressure on the windward side of the bus head is the smallest. With the crosswind angle increasing, the maximum positive pressure area on the head will be gradually shifting along the direction of crosswind, positive pressure area of the head decreasing, and pressure upon the sides of the body increasing with the increase of crosswind angle.

Figure 6 shows the pressure field on the rear of bus when crosswind angle is 0°, 30° and 45° respectively. As can be seen from the Figure, a negative pressure area is formed at the rear of the bus. With crosswind angle increasing, the range of negative pressure area at the rear is gradually expanding, while negative pressure at the rear gradually decreasing.

In accordance with the above analysis results, when there is no crosswind, the positive pressure on the windward side of the front is the smallest, while the negative pressure at the rear is the largest, so the pressure resistance and wind resistance coefficient are both the smallest at this moment. When crosswind angle reaches 45°, the positive pressure area on the windward side of the head is further narrowed than when the crosswind angle is 30°; and since the main factors influencing the change of wind resistance coefficient are positive pressure area and positive pressure, the wind resistance coefficient is larger when crosswind angle is at 30°.

4. Numerical Simulation Research of Buses Running in Platoon
4.1. Numerical Simulation Scheme of Buses Running in Platoon
On the basis of the previous researches on single bus, a numerical simulation research on buses running in platoon is carried out, during which, the 0° and 20° crosswind angle are selected, and the distance
between the two buses is 10m, 20m and 30m respectively. Other conditions are consistent with the single-bus numerical simulation scheme.

4.2. Analysis of Influence of Buses Running in Platoon on Pressure Field

Figure 7 shows the distribution diagram of pressure field of two buses running in platoon under the condition of no crosswind. With the gradual increase of the distance between the two buses, the pressure field on the windward side of the head has no obvious changes, while the pressure upon the windward side of head of the bus running behind gradually increases and the maximum pressure range further expands. This is mainly because, with the increase of the distance between the two buses, the barrier action of the front bus on the rear one gradually decreases, but the pressure borne by the rear one is still smaller than that by the front one, which is conducive to the enhancement of fuel economy. As for the rear of the bus, with the gradual increase of distance between the two buses, the negative pressure area at the rear of the bus gradually expands and negative pressure gradually decreases but to a limited extent.

![Figure 7. Pressure Field of Two Buses Running in Platoon with No Crosswind.](image)

4.3. Analysis on the Influence of Crosswind on Pressure Field of Buses Running in Platoon

Figure 8 shows the distribution diagram of pressure field of two buses running in platoon when crosswind angle is 20°. With the gradual increase of the distance between two buses, the pressure field on the windward side of the head has no obvious changes, while the pressure upon the windward side of head of the bus running behind gradually increases and the maximum pressure range further expands. This is mainly because, with the increase of the distance between the two buses, the barrier action of the front bus on the rear one gradually decreases. As for the rear of the bus, with the gradual increase of distance between the two buses, the negative pressure area at the rear of the bus gradually expands while negative pressure is gradually diminishing.

![Figure 8. Pressure Field of Two Buses Running in Platoon When Crosswind Angle at 20°.](image)

By comparing Figure 7 with Figure 8, it can be seen that with the gradual increase of the distance between two buses, the pressure upon the windward side of the bus running behind is increased on a much larger degree with crosswind than that without crosswind. Under the condition that the distance between two buses is 30m, the pressure distribution on the windward side of head of the front and rear bus is almost same in the presence of crosswind, while the pressure upon the windward side of head of the bus running behind is still relatively smaller in the absence of crosswind. The above results show that crosswind shortens the distance between the two buses which at this time boast high fuel economy.

5. Conclusion

a) Crosswind can affect the wind resistance coefficient of the bus. With the crosswind angle increasing, the wind resistance coefficient of the bus shows a trend of increasing first and then decreasing, and when
the crosswind angle reaches 30°, the wind resistance coefficient is the largest, which is about 2.3 times more than that when there is no crosswind.

b) Crosswind can affect the speed field and pressure field of the bus. With crosswind angle increasing, the maximum positive pressure area on the bus head gradually shifts along the direction of crosswind, positive pressure area of the head decreases, and pressure upon the sides of the body increases with the increase of crosswind angle. As the crosswind angle goes up, the negative pressure area at the rear of the bus gradually expands, while negative pressure at the rear gradually decreases.

c) Under the circumstance that the buses run in platoon without crosswind, the barrier action of the front bus to the rear one gradually decreases with the enlargement of the distance between two buses, but the pressure borne by the rear bus is still lower than that by the front one, which is conducive to the improvement of fuel economy.

d) When buses are running in platoon at a crosswind angle of 20°, the pressure increase on the windward side of the rear bus is much greater than that on the windward side without crosswind with the enlargement of the distance between two buses. This shows that crosswind shortens the distance between the two buses at high fuel economy.

References
[1] Chadwick A, Garry K, Howell J. (2001) Transient Aerodynamic Characteristics of Simple Vehicle Shapes by the Measurement of Surface Pressures. SAE Paper: 2001-01-0876.
[2] Fu Limin. (1994) An Investigation to the Effects of Add-on Devices on Reducing Aerodynamic Drag of Domestic Trucks. Automotive Engineering, 1994: 144-148.
[3] Alam A A, Gattami A, Johansson K H. (2010) An Experimental Study on the Fuel Reduction Potential of Heavy Duty Vehicle Platooning. In: 13th International IEEE: Annual Conference on Intelligent Transportation Systems Madeira Island. Portugal. pp. 306-311.
[4] Fu Limin, Wu Yunzhu, He Baoqin. (2006) Aerodynamic Characteristics of Vehicle Platoon. Journal of Jilin University (Engineering and Technology Edition), 36:871-875.
[5] Jiang Bo. (2007) Computational Simulation of External Flow Field of Truck in Tandem and Research on Its Fuel Economy. Hunan University, Changsha.
[6] Xu Xianggang. (2016) Research on the Effect of Lateral Wind and Longitudinal Spacing on Trucks in a Platoon. Jilin University, Changchun.
[7] Jiang Luming. (2016) Research on Aerodynamic Characteristics of Vehicle Platoon within Crosswind. Jilin University, Changchun.
[8] Versteeg H K, Malalasekera W. (1995) An Introduction to Computational Fluid Dynamics: The Finite Volume Method.Wiley. Epfl, 20: 400.
[9] Sun Wence. (1995) Engineering Fluid Mechanics. Dalian University of Technology Press, Dalian.
[10] Hammache M, Michaelian M, Browand F. (2002) Aerodynamic Forces on Truck Models Including Two Trucks in Tandem. SAE Paper: 2002-01-0530.
[11] Altinisik A, Yemenici O, Umur H. (2015) Aerodynamic Analysis of a Passenger Car at Yaw Angle and Two-Vehicle Platoon. Journal of Fluids Engineering, 137: 1107-1110.