Study on the reasonable tilt angle of ventilation shafts in Xidianwan Tunnel, China

Dapeng Xue1, Guoping Zheng2*, Hongyu Guo3, Jiongke Chen2 and Yizhou Zhuang2

1 College of Civil Engineering, Shaoxing University, Shaoxing, Zhejiang, 312000, China
2 College of Civil Engineering and Architecture, Zhejiang University of Technology, Hangzhou, Zhejiang, 310014, China
3 Zhejiang Provincial Communications, Planning, Design & Research Institute Ltd.Co, Hangzhou, Zhejiang, 310030, China
*Corresponding author’s e-mail: g.zheng@uq.edu.au

Abstract. The "asthma effect" of shaft natural ventilation is common, which makes the actual air exchange volume impossible to be quantified and the pollutant concentration along the tunnel unable to be analyzed. In order to improve the ventilation effect of the ventilation shaft and realize the steady air flow in the air well, the reasonable tilt angle of the ventilation shaft is studied. Firstly, the numerical simulation software FLUENT is used to establish a tunnel model of a certain traffic volume based on dynamic grid technology, and to analyze the relationship between the shaft tilt angle and the air flow state, including intake and exhaust air volume, and air flow direction. Secondly, model experiments are carried out to verify the numerical simulation results, in which jet fan thrust pressure is substituted for traffic piston pressure. The result shows that the natural ventilation state with the proposed direction can be realized on condition that the shaft tilt angle is around 15 degrees. That means to discharge polluted air from one group of ventilation shafts and suck in fresh air from the other group of ventilation shafts. At the same time, by dividing the tunnel rationally, the calculation formula of pollutant concentration of the cross section along the tunnel under the condition of different diverging amounts caused by the change of tilt angle of the ventilation shafts is derived, which provides guidance and reference for determining whether the air quality in the tunnel meets the requirements of relevant specifications.

1. Introduction
As a relatively closed artificial space, moving vehicles in the tunnel release a large quantity of pollutants. There have been many studies on the ventilation mode of natural ventilation at the entrance and exit to reduce the pollutant concentration in the tunnel [1]-[7]. However, for relatively long tunnels in geographically complex locations, inadequate ventilation may occur for natural ventilation through the entrances and exits, increasing the pollutant concentration [8]. Ventilation shaft-type natural ventilation refers to the situation where ventilation shafts connected to the ground are set at the top of the tunnel to realize tunnel ventilation with the help of traffic wind pressure. At present, in China, ventilation shafts have been applied in Hongxing Road underpass Tunnel (800 m) in Chengdu,
Tongjimen Tunnel (890 m) in Nanjing, Xi'anmen Tunnel (1,410 m) in Xi'an, and Caihong Road Tunnel (3,260 m) in Hangzhou.

Many research projects on this new ventilation mode have been carried out, which provide a theoretical basis for engineering construction. For example, Yoon, C.H. used the thermal dynamic method to measure the natural ventilation pressure of a long highway tunnel in South Korea in winter and summer. It was found that the natural wind pressure of the tunnel with ventilation shafts was much higher than that of the tunnel without shafts, which proved the feasibility of natural ventilation through shafts [9]. Chen, T.Y. studied the velocity distribution of piston wind generated on both sides of the vehicle at different vehicle spacing, vehicle speed and single-direction and dual-direction traffic through the method of model experiment, which provided a reference for research on tunnel piston wind [10]. Sambolek, M. verified the existence of the critical Reynolds number in the self-mode area during the experiment by using model experiments combined with field measurements, and studied the traffic wind velocity and air volume generated by model cars at different speeds, thus providing theoretical support for model experiments of natural ventilation tunnels [11]. Nicolae Ilias et al. conducted a simulation study on the ventilation quality and flow distribution in tunnel ventilation shafts caused by the piston effect, and obtained the relationship between two-way ventilation volume and vehicle speed, vehicle position and the ventilation shaft cross-sectional area [12]. Takeuchi, S. et al. established a 1:20 scale tunnel model, studied the influence of parameters, such as shaft height, on pollutant discharge efficiency of a six-shaft underground tunnel, and obtained the shaft blocking height and the air circulation law of natural ventilation through shafts [13].

However, the airflow state of the natural ventilation shaft is in an unsteady flow state, which is due to the pressure crest (positive pressure) near the front and the pressure trough (negative pressure) behind the vehicle. The air inside the tunnel is not diffused before it is sucked into the tunnel after being extruded from the shaft, forming an "airflow short circuit". As for the law of air flow caused by vehicles in the tunnel, Bellasio, R has studied the flow field distribution in the tunnel, and concluded that the main influencing factors of air turbulence are vehicle movement and atmospheric advection, obtaining the diffusion differential equation under turbulence [14]. Katolický, J. et al. applied the euler-lagrange model to simulate the movement of cars in the tunnel and its influence on tunnel ventilation, and concluded that the traffic-induced turbulence had a non-negligible influence on the total flow inside the tunnel [15]. Aydin, E. M. et al. simulated the drag flow generated by the translation of the rough cushion surface in a limited space, and the research results supported the notion of universality of turbulent flow structure in the wall region, thus providing "the Couette flow" theory for the study of the motion of cars in the tunnel [16]. However, due to the low air pressure in the tunnel caused by vehicle movement and other factors, the ventilation shaft is easy to undergo frequent wind direction fluctuations, affected by the atmospheric pressure outside the tunnel, which is the "asthma effect" of the natural ventilation shaft tunnel. This problem leads to the fact that the air exchange volume of each group of shafts cannot be quantified and analytical solutions for the pollutant concentration along the tunnel cannot be obtained. Therefore, it is impossible to determine whether the air quality in the tunnel meets the requirements of relevant specifications. In order to solve this problem, numerical simulations and model experiments are adopted to obtain the constant airflow by changing the angle of the ventilation shafts, so as to realize the artificial ventilation mode with one group of shafts mainly responsible for exhausting air and another group of shafts mainly responsible for sucking air, to obtain the pollutant concentration distribution along the tunnel, in order to improve the ventilation efficiency of the natural ventilation tunnel with shafts.

2. Engineering background

The study used the Xidianwan tunnel in Ningbo, China of G228 as the background project. The tunnel is a two-way six-lane first-level highway tunnel with a total length of 1,590 m, and the designed speed is 80km/h. The predicted traffic volume in 2020 is 11,325 pcu/d, and that in 2,035 is 21,032 pcu/d. The model composition ratio is shown in Table 1.
| Type of Vehicle | Proportion |
|-----------------|------------|
| Passenger car   | 77.68%     |
| Medium truck    | 9.54%      |
| Large truck     | 4.27%      |
| Trailer         | 8.51%      |

The peak hour traffic volume coefficient is 0.11, the directional disequilibrium coefficient is 0.52, and the converted hybrid vehicle and the standard vehicle coefficient are about 1.85. Based on this, it can be seen that there are 13 vehicles in the forward single-hole tunnel through calculation.

Because the surrounding area has a high requirement for environmental control, and in order to avoid the noise problem caused by the axial flow fan, two groups of natural ventilation shafts are planned to be set outside the environmentally sensitive area. The starting point of the first group of ventilation shafts is set at 795 m from the tunnel entrance, while the starting point of the second group of ventilation shafts is 1,095 m from the tunnel entrance and the length of each group is 55 m. Each group is composed of five ventilation shafts, with the shaft head being 7 m in length, 2.5 m in width and 3.5 m in height (the vertical distance from the shaft head to the inner surface of the tunnel structure). The distance between adjacent shaft centers is 12 m, and the projected area of the natural ventilation shafts is 17.5 m².

3. Numerical simulation

3.1. Model
A dynamic mesh for the prototype tunnel is modeled by the FLUENT software, and the standard K-ε turbulence model is used for analysis. For the convenience of ventilation analysis, the low-speed airflow in the tunnel at room temperature is regarded as an incompressible continuous medium fluid. The holistic modeling is adopted. The tunnel area is 1,590 m long, and the pressure inlet boundary conditions are set at the entrance. The boundary conditions at the tunnel exit and ventilation shaft head are the pressure outlet boundary conditions, and the friction coefficient along the tunnel wall is 0.02. A total of 13 vehicles in the model entered the tunnel in turn, with spacing of 66.6 m between vehicles and a total fleet length of 803.2 m. The time required for the vehicles to pass by a group of ventilation shafts is 38.66s. The front of the car is the wall boundary condition, which is given a fixed moving speed by UDF. The side of the car body is used as a sliding mesh interface for data transmission with the air inside the tunnel. The tunnel section and the size of the ventilation shaft head are established according to the actual tunnel. The model is shown in Figure 1.
3.2. Simulation Analysis of Piston Wind Velocity in Tunnel
As the pressure source in the tunnel, the driving vehicles are the direct cause of the piston wind. The tunnel with 90° ventilation shafts is used as an example. Under the traffic piston wind, the wind velocity isoline distribution of the longitudinal section of the first group of ventilation shafts is shown in Figure 2, and the wind velocity isoline distribution of the cross-section of the first group of ventilation shafts is shown in Figure 3.

![Figure 1. Tunnel model.](image1)

![Figure 2. Wind velocity isoline distribution of the longitudinal section of the ventilation shafts.](image2)
Figure 3. Wind velocity isoline distribution of the cross section of the ventilation shafts.

The calculation results show that the wind velocity in the whole tunnel section is not evenly distributed. Driven by the vehicles near the road surface, the average wind velocity in the lower half of the tunnel section reaches 5 to 6 m/s. In Figure 3, the selected section is in the middle lane, and the wind velocity in the section is not uniform. Near the ground, the average wind velocity of the section between vehicles is about 6 to 8 m/s, while the wind velocity of the upper part of the tunnel is relatively small, only about 1 m/s. The average cross-sectional wind velocity of the tunnel is about 5 m/s under the steady traffic-flow air.

Figure 4. Variation of average wind velocity in tunnel section.

Figure 4 shows the variation of the cross sectional average wind velocity at 200 m from the entrance of the tunnel. It can be seen from the figure that when the first four vehicles in the fleet passed through the section, the sectional wind velocity showed a fluctuating upward trend (area I). When the fourth vehicle arrived at the section, the section wind velocity had basically reached the calculated wind velocity. Moreover, when the vehicles passed through, the air in the tunnel is squeezed by them, and the section wind velocity fluctuated near the calculated wind velocity (area II). When the last vehicle in the fleet left the section, the wind velocity of the section dropped rapidly (area III).
3.3. Analysis of the Influence of the Angle of Ventilation Shaft on the Inlet and Outlet wind velocity

When the vehicles passed by a group of ventilation shafts, the wind velocity data at the head of ventilation shafts were extracted. The average velocity within this period was used as the ventilation wind velocity \( v_i \) \((i=15°, 30°, 45°, 60°, 75°, 90°)\), of this group of ventilation shafts under the action of traffic piston wind.

The ventilation wind velocity at the head of the ventilation shafts with different angles from 15° to 75° was compared with that at the head of the ventilation shafts with a ventilation angle of 90°. The air-exhaust ratio is defined as \( K = \frac{v_i}{v_{90}} \). The calculation results of the air-exhaust ratios of two groups of ventilation shafts are shown in Figure 5.

![Figure 5. Air-exhaust ratios changing with ventilation shaft angles.](image)

The simulation results show that, at any angle, the first group of ventilation shafts always remained in the exhaust state during the process of vehicles passing by, and the average flow velocity at the head of the ventilation shafts increased with the increase of the tilt angle (from 90° to 15°). When the tilt angle of the ventilation shafts was within the range of 45° to 90°, the second group of ventilation shafts was exhausted during the process of vehicles passing by, and the exhaust air volume increased slightly with the increase of the tilt degree. When the tilt angle of the ventilation shafts was 15° and 30°, the second group of ventilation shafts was in the intake state during the process of vehicles passing by, and the air intake at 15° was higher than that at 30°.

4. Model experiment

4.1. Determination of traffic piston wind

The traffic piston wind refers to the ventilation force caused by the forward movement of air driven by the piston effect in the tubular tunnel, which is related to the obstruction ratio in the tunnel, the friction between the tunnel wall and the air, the driving speed of the vehicles, and the air resistance and others. Based on the energy conservation law of fluid mechanics and the assumption that the traffic flow is a steady flow, when the wind force of the traffic flow and the impedance force of ventilation are equal, the corresponding air volume is the air volume of the traffic piston, which can be obtained through the piston wind velocity \( v_i \) in the tunnel caused by the traffic flow wind [11]. The calculation formula of the traffic wind force \( \Delta p_i \) \((\text{N/m}^2)\) is as follows:
\[ \Delta p_r = \frac{A_r}{n} \cdot \frac{\rho}{2} \cdot (v_r - v_t)^2 \]  

(1)

In addition, the ventilation resistance force \( \Delta p_r \) (N/m\(^2\)) to the air circulation in the tunnel is calculated as follows:

\[ \Delta p_r = \left( 1 + \xi + \lambda_r \frac{L}{D_r} \right) \cdot \frac{\rho}{2} \cdot v_r^2 \]  

(2)

Where \( n \) is the number of vehicles in the tunnel in the same direction as \( v_r \), \( n = \frac{N \cdot L}{3600v_t} \); \( v_r \) is the tunnel design wind velocity (m/s), \( v_r = \frac{Q_r}{A_r} \); \( Q_r \) is the tunnel design air volume (m\(^3\)/s); \( A_r \) is the cross-sectional area of tunnel lane space (m\(^2\)); \( v_t \) is the vehicle speed under various working conditions in the same direction as \( v_r \) (m/s); \( A_w \) is the equivalent impedance area of the vehicle (m\(^2\)); \( \xi \) is the loss coefficient at the tunnel entrance; \( \lambda_r \) is the friction loss coefficient of the tunnel wall; \( \rho \) is the air density at the ventilation calculation point (kg/m\(^3\)); \( L \) is the length of the tunnel (m); \( D_r \) is the equivalent diameter of the tunnel section (m), \( D_r = \frac{4 \times A_r}{C_r} \); \( C_r \) is the perimeter of the tunnel section (m).

According to \( \Delta p_r = \Delta p_r \), the wind speed \( v_r \) in the tunnel can be obtained. Since no factors such as fans are considered, the result is the wind velocity under the action of traffic wind pressure in the tunnel. In order to facilitate the calculation of the traffic wind speed in the tunnel, the calculation method in "Guidelines for Design of Ventilation of Highway Tunnels" [17] is adopted, and then the parameters of the background engineering tunnel are applied to obtain the traffic wind speed in the natural ventilation tunnel. The Xidianwan Tunnel is used as an example. The cross-sectional area of the small bus is 2.13 m\(^2\), and the cross-sectional area of the large bus is 5.37 m\(^2\). According to the model scale, the equivalent car cross-sectional area is 2.8 m\(^2\), the length is 6 m, and the driving speed in the tunnel is 80 km/h (22.2 m/s). The theoretical wind velocity in the tunnel under the traffic wind pressure can be obtained, \( v_r = 5.06 \) m/s. The results are consistent with those obtained in the numerical simulation.

4.2. Experimental model

In the model experiment, the geometric similarity ratio of 1:20 was adopted. A metal plate and an angle iron were selected as materials to make the model in sections. The cross-section size of the model tunnel was 71.5 cm×33.75 cm, the height of the ventilation shaft was 17.5 cm, and the opening size was 12.5 cm×35 cm. After the model was made, the sectional box bodies were initially connected with bolts, and then transparent adhesive tape was applied at the joints to ensure the air tightness of the model. The ventilation shaft part was made separately, and can be installed in the opening at the top of the sectional box bodies in the same way as mentioned before, and it is easy to dismantle. The location of the tunnel and the ventilation shaft model and the wind speed measuring points are shown in Figure 7 and Figure 8.

Limited by the experimental site, the length of the model tunnel is 18.5 m. In the experiment, the calculated piston wind velocity of the prototype tunnel was used as the experimental reference wind velocity, and the local resistance of the grid was used to simulate the reduced loss along the tunnel.
As the main research object of this study was the ventilation shaft part, the experiment mainly tested the diverging effect of the ventilation shaft at different angles on the airflow inside the tunnel, as well as the velocity distribution at the ventilation shaft head.

Assuming an uninterrupted flow of tunnel traffic, through numerical simulation, the existing related theory studies showed, in one-way traffic tunnels with ventilation shafts at the top, inside the tunnel airflow pressure part is horizontally directional vector movement, only the static pressure part has an effect on the opening, and the ratio of the opening area at the top to the sectional area of the tunnel is relatively small, no matter whether an inlet or outlet air flow is produced at the opening, air flow velocity in different areas of the tunnel traffic fluctuates only near the theory of piston air velocity value. In this experiment, the influence of the ventilation shafts was considered, so the lift pressure of the axial flow fan was used instead of traffic wind pressure to simulate the inlet and outlet air condition of the ventilation shafts under a stable airflow. (Figure 8)
4.3. Experimental model

The similarity between the model and the prototype is the theoretical basis of the model experiment and the premise of deducing the results of the model experiment to the prototype. According to the necessary and sufficient conditions for the similarity of the two phenomena, as long as the four similar characteristic numbers are equal, the two incompressible viscous flows are similar. The four characteristic numbers are Reynolds number $Re$, Froude number $Fr$, Strouhal number $St$ and Euler number $Eu$ respectively.

However, it is difficult to have equal to four similar characteristic numbers in actual experiments. Usually, only the major similar characteristic numbers are the same, and the minor ones are ignored (or modified). This approach is a partial (approximate) simulation.

For the Strouhal ($St$) criterion does not work for the steady flow, the Froude ($Fr$) criterion may be ignored in the pressure flow, and the Euler ($Eu$) criterion is an amorphous criterion. Therefore, the only figurate criterion with the similar tunnel airflow is the Reynolds ($Re$) criterion. In order to ensure the similarity of the airflow movement, the same $Re$ (Reynolds number) for the model and the prototype is necessary, that is:

$$Re = \frac{\rho_p v_p l_p}{\mu_p} = \frac{\rho_m v_m l_m}{\mu_m} = 1$$

(3)

Kinematic viscosity $v$ can be expressed as the ratio of dynamic viscosity $\mu$ to fluid density $\rho$. Since the model and prototype media are both air, then:

$$\rho_p = \rho_m$$

(4)

And at room temperature:

$$\mu_p = \mu_m$$

(5)

Therefore, for the similar airflow movement in the experiment, the following is necessary:

$$v_p : v_m = l_m : l_p$$

(6)

To make the airflow movement in the model completely similar to that in the prototype, a high-speed airflow $\lambda$ times that of the prototype must be generated in the model. As vehicle motion is the power source of the airflow movement, it is difficult to generate enough power under experimental conditions. In existing studies, the Reynolds number ($Re$) is usually greater than the second critical
value, that is, the airflow state is in the self-mode area of the Reynolds number, as the basis for the similarity between the airflow in the model and the prototype airflow. The critical Reynolds number of the model can be determined through preliminary experiments.

In the preliminary experiment, airflow of a certain flow velocity was injected into the tunnel model by a variable-frequency fan. Then, two sections were selected to measure their respective wind velocity \( v \) and total pressure drop \( \Delta P \). The resistance coefficient \( \lambda \) of the tunnel model was calculated by using the Darcy formula \( \Delta P = \frac{\lambda l}{2d} \). The Reynolds number of the airflow under the wind speed \( v \) is calculated through the Reynolds number formula \( \text{Re} = \frac{vd}{\gamma} \).

Figure 9. Re - \( \lambda \) relation curve of the model tunnel.

Figure 9 shows the curve of the Re - \( \lambda \) relation under the conditions of wind velocity in different tunnels. It can be seen that when the Reynolds number is greater than 15,000, the resistance coefficient of the tunnel model basically does not change with the increase of flow velocity, which indicates that the airflow has entered the self-mode area.

Re = 15,000 is called the critical Reynolds number, and the corresponding airflow velocity \( v_c = 0.5822 \text{ m/s} \) is called the critical wind velocity. In the formal experiment, the wind velocity inside the tunnel should always be above the critical ventilation velocity, so as to ensure the similarity of the model and the prototype airflow. The average value of the resistance coefficient in the self-mode area is 0.02.

According to the experimental conditions, the basic scale of the model experiment was determined, mainly including:

The linear scale
\[
\lambda_l = \frac{l_p}{l_m} = 20
\]  

(7)

The velocity scale
\[
\lambda_v = \frac{v_p}{v_m} = 5
\]  

(8)

Subscript \( p \) represents the prototype parameters, and subscript \( m \) represents the model parameters. According to the velocity scale \( \lambda_v \), the piston wind velocity is 1.032 m/s.
According to the definition of parameters or the relationship of criteria, other derived scales can be obtained from the basic scale, including:

The area scale

\[
\lambda_A = \frac{A_p}{A_m} = \lambda_l^2 = 400
\]

(9)

The air flow scale

\[
\lambda_Q = \frac{Q_p}{Q_m} = \lambda_v \cdot \lambda_A = 2000
\]

(10)

4.4. Experimental model

The air volume data of ventilation shafts at different angles in the experiment are shown in Table 2.

**Table 2.** Air volume (m³/s) of cross-section of tunnel with ventilation shafts at different angles.

| Angle | Position of the Section | No. 1 shaft | First group of shafts | No. 5 shaft | No. 6 shaft | Second group of shafts | No. 10 shaft |
|-------|-------------------------|--------------|-----------------------|-------------|-------------|------------------------|-------------|
| 90°   | front                   | 0.2713       | 0.0351                | 0.2363      | 0.2387      | 0.0205                 | 0.2195      |
| 75°   | front                   | 0.2666       | 0.0322                | 0.2368      | 0.2349      | 0.0325                 | 0.2065      |
| 60°   | front                   | 0.2690       | 0.0337                | 0.2359      | 0.2349      | 0.0327                 | 0.2023      |
| 45°   | front                   | 0.2676       | 0.0226                | 0.2452      | 0.2433      | 0.0239                 | 0.2242      |
| 30°   | front                   | 0.2678       | 0.0375                | 0.2313      | 0.2319      | 0.0187                 | 0.2133      |
| 15°   | front                   | 0.2694       | 0.0446                | 0.2275      | 0.2261      | -0.0158                | 0.2424      |

When the tilt angle was large, the section area of the 15° ventilation shaft was reduced by about 75% compared with that of the 90° ventilation shaft (in the model experiment, the cross-section area of the 90° model ventilation shaft was 0.04375 m², and that of the 15° ventilation shaft was 0.01132 m²). The length of the ventilation shaft also changed greatly, with L=17.5 cm in the 90° model and L=67.6 cm in the 15° model. The equivalent diameter of the section of the ventilation shafts also changed from 0.1842 m to 0.105 m. The relationship between the exhaust air ratio and the angles of the ventilation shafts in the experiment is shown in Figure 11.
As can be seen from Figure 12:

(1) The exhaust air volume of the first group of ventilation shafts was always greater than that of the second group. Thus it can be seen that the tilt direction of the first group of ventilation shafts is conducive to the outflow of air inside the tunnel, while the second group of ventilation shafts has an opposite tilt direction, which is not conducive to the outflow of air;

(2) The first group of ventilation shafts was always in an exhausted state, and the variation trend of the air volume decreased first and then increased with the increase of the tilt angle of the ventilation shafts; When the tilt angle of the second group of ventilation shafts was 90°, 75°, 60°, 45° and 30°, the second group of ventilation shafts was in an exhausted state. Only when the tilt angle is 15°, the second group of ventilation shafts was in an air intake state;

(3) When the tilt angle of the first and second groups of ventilation shafts was 15°, the first group of ventilation shafts was exhausted with the maximum exhaust air volume, while the second group of ventilation shafts was in the state of air intake.

By multiplying the air volume measured in the experiment of the 90° ventilation shafts by the flow scale \(\lambda_Q = 2000\), the air volume of the ventilation shaft in the actual tunnel can be obtained, and the result is: that of the first group of ventilation shafts was 70.2 m³/s, and that of the second group was 41 m³/s. According to the theoretical calculation of the prototype tunnel, the total air volume at the entrance is 481.041 m³/s. At 90°, the first and second groups of ventilation shafts accounted for 14.6% and 8.5% of the total air volume at the entrance, which were their respective flow rate \(\eta\).

| Group      | Angle | 15° | 30° | 45° | 60° | 75° | 90° |
|------------|-------|-----|-----|-----|-----|-----|-----|
| Q (m³/s)   |       |     |     |     |     |     |     |
| Group 1    |       | 142.5 | 87.0 | 74.3 | 59.9 | 67.5 | 70.2 |
| \(\eta\)   |       | 29.6% | 18.1% | 15.4% | 12.5% | 14.0% | 14.6% |
| Q (m³/s)   |       | -15.6 | 27.0 | 24.9 | 20.9 | 22.5 | 41.0 |
| Group 2    | \(\eta\) |     |     |     |     |     |     |
| Q (m³/s)   | -3.2% (intake) | 5.6% | 5.2% | 4.4% | 4.7% | 8.5% |

When there are no ventilation shafts in the tunnel, all pollutants will migrate and diffuse to the exit of the tunnel along with the airflow. When there are some ventilation shafts, pollutants can be discharged along the way through the ventilation shafts, making the concentration of pollutants at the exit of the tunnel.
tunnel lower than that in the tunnel without ventilation shafts. The change of the ventilation shaft angle can change the flow rate of ventilation shafts to some extent (Table 3), and further, improve the air quality in the tunnel and at the exit.

5. Formula of pollutant concentration

The tunnel is divided into three calculation areas i: from the entrance of the tunnel to the back of the first group of ventilation shafts is Area 1; from the back of the first group of ventilation shafts to the front of the second group of ventilation shafts is Area 2; from the front of the second group of ventilation shafts to the exit of the tunnel is Area 3, as shown in Figure 10.

In each area, the emission of CO ($Q_{col}$ (m$^3$/s)) from vehicles in area i is

$$Q_{col} = \frac{1}{3.6 \times 10^6} \cdot q_{col} \cdot (\Pi f_i) \cdot L \cdot \sum_{m=1}^{N} (N_m \cdot f_m)$$  \hspace{1cm} (11)

$q_{col}$ is the standard displacement of the vehicles (m$^3$/km \cdot veh); $\Pi f_i$ is the product of various correction coefficients; $N_m$ is the amount of traffic designed for the corresponding vehicle type (veh/h); $N$ is the number of vehicle categories; $f_m$ is the coefficient of the vehicle type.

When there are no ventilation shafts, there is no air exchange from the entrance to the exit. In this case, the concentration at the exit of the tunnel is:

$$\delta_{exit} = \frac{Q_{col} + Q_{co2} + Q_{co3}}{Q_e}$$  \hspace{1cm} (12)

When the tilt angle of ventilation shafts was set to be 15°, the first group of ventilation shafts had air outflow with air volume of $Q_e$ (m$^3$/s), and the second group of ventilation shafts had air inlet with air volume of $Q_b$ (m$^3$/s), then

The concentration of section 1 is:

$$\lambda_i = \frac{l_p}{l_m} = 20$$  \hspace{1cm} (13)

The concentration of section 2 is:

$$\delta_{co2} = \frac{Q_{co2} + (Q_e - Q_e)/Q_e \cdot Q_{col}}{Q_e - Q_e}$$  \hspace{1cm} (14)

The concentration of section 3 is:

$$\delta_{co3} = \frac{Q_{co2} + Q_{co3} + (Q_e - Q_e)/Q_e \cdot Q_{col}}{Q_e - Q_e + Q_b}$$  \hspace{1cm} (15)

The CO concentration at other sections in the tunnel can also be calculated by the above-mentioned three calculation formulas, and thus the CO concentration distribution at all parts of the full-length tunnel can be obtained.

6. Conclusion

- Based on the above-mentioned analysis, the distributive law of the ventilation shafts obtained through the model experiment is basically consistent with that obtained through numerical simulation. When the tilt angle of the ventilation shafts decreases, the intake air rate of the first group of ventilation shafts and the exhaust air rate of the second group of ventilation shafts both increase. When the tilt angle is 15°, the expected artificial ventilation effect can be achieved, that is, the first group of ventilation shafts is mainly responsible for air exhaust and the second group of ventilation shafts is mainly responsible for air intake, effectively reducing the pressure pulsation and the influence of "asthma effect" in the tunnel.
• By optimizing the tilt angle of the ventilation shafts, the orderly exchange of air inside and outside the tunnel is realized, and the quantitative calculation formulas of pollutant concentration at the outlet of the shaft and at the exit of the tunnel are obtained, which provide a basis for ventilation design and environmental evaluation.

• It should be pointed out that the conclusions drawn in this paper are mainly based on the geometric parameters of the Xidianwan tunnel, and it is advisable to carry out specific studies for specific projects.

Acknowledgments
This research was supported by National Natural Science Foundation of China (no.51678530).

References
[1] Oka, Y., Atkinson, G. T. (1995) Control of smoke flow in tunnel fires. Fire Safety Journal., 25(4): 305-322.
[2] Bellasio, R. (1997) Modelling traffic air pollution in road tunnels. Atmospheric Environment, 31(10): 1539-1551.
[3] Sambolek, M. (2004) Model testing of road tunnel ventilation in normal traffic conditions. Engineering Structures., 26(12): 1705-1711.
[4] Betta, V., Cascetta, F., Musto, M., Rotondo, G. (2009) Numerical study of the optimization of the pit angle of an alternative jet fan in a longitudinal tunnel ventilation system. Tunneling and Underground Space Technology., 24(2): 164-172.
[5] Bari, S., Naser, J. (2010) Simulation of airflow and pollution levels caused by severe traffic jam in a road tunnel. Tunneling and Underground Space Technology., 25(1): 70-77.
[6] Hashemkhani Zolfani, S., Hossein Esfahani, M., Bitarafan, M., Kazimieras Zavadskas, E., Lale Arefi, S. (2013) Developing a new hybrid MCDM method for selection of the optimal alternative of mechanical longitudinal ventilation of tunnel pollutants during automobile accidents. Transport., 28(1): 89-96.
[7] Chammem, T., Vauquelin, O., Mhiri, H. (2014) Performance evaluation of alternative tunnel longitudinal ventilation systems using two inclined jets. Tunneling and Underground Space Technology., 41: 53-61.
[8] Brousse, B., Vidal, B., Ponticq, X., Goupil, G., & Alary, R. (2005). Pollution dispersion at an urban motorway tunnel portal: Comparison of the small-scale predictive study with the actual conditions measured on the site. Atmospheric Environment, 39(13): 2459-2473.
[9] Yoon, C.H., Kim, M.S., Kim, J. (2006) The Evaluation of Natural Ventilation Pressure in Korean Long Road Tunnels with Vertical Shafts. Tunneling & Underground Space Technology Incorporating Trenchless Technology Research., 21(3): 472-472.
[10] Chen, T.Y., Lee, Y.T., Hsu, C.C. (1998) Investigations of Piston-Effect and Jet Fan-effect in Model Vehicle Tunnels. Journal of Wind Engineering and Industrial Aerodynamics., 2(2): 99-110.
[11] Sambolek, M. (2004) Model testing of road tunnel ventilation in normal traffic conditions. Engineering Structures., 26(12): 1705-1711.
[12] Ilias, N., Lanchava, O., Nozadze, G. (2020) Numerical simulation of air flow in short metro ventilation shafts caused by a piston effect. MATEC Web of Conferences., 305 00050.
[13] Takeuchi, S., Aoki, T., Tanaka, F., & Moinuddin, K. A. M. (2017). Modeling for predicting the temperature distribution of smoke during a fire in an underground road tunnel with vertical shafts. Fire Safety Journal, 91, 312-319.
[14] Bellasio, R. (1997) Modelling traffic air pollution in road tunnels. Atmospheric Environment., 31(10): 1539-1551.
[15] Katolický, J., Jicha, M. (2005) Eulerian-Lagrangian model for traffic dynamics and its impact on operational ventilation of road tunnels. Journal of Wind Engineering and Industrial Aerodynamics., 93(1): 61-77.
[16] Aydin, E. M., Leutheusser, H. J. (1991) Plane-Couette flow between smooth and rough walls. Experiments in Fluids., 11(5): 302-312.
[17] People's Republic of China industry recommended standards. (2014) Guidelines for Design of Ventilation of Highway Tunnels (JTG/T D70/2-02-2014). China Communications Press, Beijing.