Mathematical Modeling and Experimentation of Airflow Disturbance in Tramcar-roadway System

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Abstract. This paper analyzes the variation law of equivalent air resistance in a mine car-roadway system, establishes the index system of influencing factors of airflow disturbance. Using experimental system of mine ventilation simulation, the characteristics of air supply of the roadway, blocking coefficient and disturbance of air resistance in roadway are studied. Furthermore, the mathematical model for calculating the equivalent disturbance air resistance is built in the different tramcar positions. The result shows that the tramcar-roadway system has a positive disturbance effect when the tramcar’s speed is greater than the air velocity of the roadway, and it is equivalent to air regulation by addition of pressure of the mine ventilation system. The negative disturbance effect is equivalent to air regulation by addition of resistance. It has the stronger disturbance effect if the air velocity or the roadway section is small. The maximum disturbance variation of air resistance occurs at the moment while the tramcar mine car enters or leaves the roadway. The error between the mathematical model and the measured data is 8.12 %. The research results can provide theoretical basis for intelligent regulation of mine ventilation system.

Keywords: Disturbance air resistance, Tramcar, Airflow disturbance of roadway, Mine ventilation network.

1. Introduction
Safe and stable operation of mine ventilation system is an important prerequisite and guarantee for mine safety production. According to the theory of optimum regulation of mine ventilation network, mine car is the most common disturbance factor of air flow. The roadway running mine car is usually located in the maximum resistance line of mine ventilation network. When the equivalent resistance of mine car-roadway system changes greatly, it causes the redistribution of air flow in some roadways of the ventilation system, resulting in insufficient air supply at the place where the air is used. Especially for the diagonal roadway, the phenomenon of breeze and no air is easy to occur, which reduces the safety and stability of mine ventilation system, and even leads to mine safety accidents.

In the research of safe, stable and reliable operation of mine ventilation system, the methods of fuzzy comprehensive evaluation, neural network evaluation and variable weight fuzzy comprehensive...
evaluation of mine ventilation system are put forward, and the macro static evaluation of mine ventilation system is realized [1-2]; the catastrophic failure types and changing rules of mine ventilation system after mine fire, coal and gas outburst and other disasters are analyzed [3-5], and the influence of catastrophic disturbance on mine ventilation system is studied. The research on the influence of airflow disturbance in the car-tunnel system mainly focuses on the field of metro tunnel. By analyzing the piston effect produced by high-speed train running in roadway, the mechanism of piston wind formation is studied. The influence of piston wind on tunnel wind resistance coefficient is determined by field measurement [6-9] and numerical simulation [10] based on dynamic grid method and momentum source term method when one-way driving [11] and vehicle staggering [12-13]. However, the mine ventilation system has many characteristics, such as more branch nodes, higher complexity of structure, and the speed of mine car is much lower than that of tunnel vehicle [14-15]. Therefore, the research results of piston effect cannot be directly applied to solve the problem of air flow safety and stability in mine ventilation system.

With the improvement of monitoring technology, it is of great significance to effectively analyze the basic parameters of mine ventilation system monitoring, study the basic characteristics of airflow disturbance, and put forward the adaptive regulation technology for the development of mine intelligent ventilation system. By studying the characteristics of airflow disturbance in mine car-tunnel system, this paper puts forward the main influencing factors of airflow disturbance in mine roadway, establishes relevant mathematical models, and provides theoretical basis for intelligent control of mine ventilation system.

2. Air Flow Disturbance Model and Characteristic Parameters of Mine Car-roadway System

The parameters describing air flow in mine ventilation network mainly include branch air volume, pressure and resistance. The branch air resistance is a parameter reflecting the geometric characteristics of the mine roadway assuming the density of the branch remains unchanged, and its value is constant after the formation of the roadway. The method of measuring ventilation resistance is usually adopted. The equivalent wind resistance of the mine car-roadway system changes during the operation of the mine car in the underground roadway, and the variation is related to the physical parameters and the operation state of the mine car.

\[
V_{\text{car}} = \begin{cases} \frac{V_{\text{air}} V_{\text{car}}}{V_{\text{air}}} & \text{The tramcar runs in the same direction as the wind flow} \\ \frac{-V_{\text{air}} V_{\text{car}}}{V_{\text{air}}} & \text{The tramcar runs in the opposite direction of the wind} \\ 0 & \text{Stationary state} \end{cases}
\]

Where, \( V_{\text{car}} \) is the tramcar running speed, m/s; \( V_{\text{air}} \) is the roadway wind speed, m/s. The direction of roadway wind speed depends on the pressure difference at both ends of roadway. When the roadway pressure difference is positive, the velocity is positive; when the roadway pressure difference is negative, the velocity is negative; when the pressure difference is zero, the velocity is 0. Coupling of mechanical energy of tramcar with wind field, energy exchange occurs. When the tramcar travels in the same direction as the wind flow in the roadway and \( V_{\text{car}} > V_{\text{air}} \), the mechanical energy of the tramcar works positively on the wind field and increases the energy of the air flow, which is equivalent to pressurizing the ventilation system. Other circumstances lead to the increase of roadway wind resistance, that is, the ventilation system is adjusted to increase the resistance. Therefore, the disturbance of ventilation system caused by mine car-roadway system has positive and negative bidirectional characteristics.

From two aspects of roadway parameters and mine car parameters, the index system of mine car-roadway air flow disturbance factors is established as shown in Figure 1. The wind resistance, cross-sectional area of roadway, length of roadway, cross-sectional area and length of mine car are fixed physical constants. The parameters of wind speed, resistance loss, traveling speed, traveling time and running state of mine car can be obtained by monitoring system. On the basis of these, three
parameters, disturbance wind resistance, blocking coefficient and relative position of tramcar in roadway, are proposed to characterize the characteristics of air flow disturbance in tramcar-roadway system. Blocking coefficient $\alpha$, the ratio of tramcar cross-sectional area $S_0$ to roadway cross-sectional area $S$, $\alpha=S_0/S$, $\alpha \in [0, 1]$, is used to describe dimensionless parameters of effective ventilation cross-section. The relative position of the tramcar is a function of the length of the roadway $l$, the length of the tramcar $l_0$, the tramcar speed $v_0$ and the traveling time $t$. According to the position of the mine car in the roadway, its operation state can be divided into: (1) The tramcar does not run in a certain roadway; (2) Running in a roadway of mine car body: When the roadway is short, it is possible to run in two or more roadways at the same time; (3) The whole body of the mine car runs in a certain roadway. The disturbance wind resistance of the roadway is defined as a variable of the wind resistance of the roadway where the tramcar-roadway are located, which is related to the wind speed, wind resistance, resistance loss, the relative position of the tramcar and the blocking coefficient of the roadway.

![Figure 1. Index system of airflow disturbance factors.](image1)

3. Experimental Research on Air Flow Disturbance in Mine Car-roadway System

In order to reduce the influence of other disturbances on mine ventilation system, the simulation monitoring experimental system of mine ventilation is used to study the parameters of wind flow variation during the operation of mine trucks. The wind speed sensor and pressure sensor are installed in the system, and the variable frequency fan is used to control the air supply precisely and obtain the air flow parameters of the simulation system in real time.

In the experimental roadway, the model of tramcar is selected as the main roadway with the length of 4.5 m, the cross section of the roadway is rectangular, the length is 0.3 m, the width is 0.3 m, and the tramcar is replaced by rectangular module. Measurement of pressure difference variation at two ends of roadway by tilt differential pressure meter. The correction coefficient is 0.2. The schematic diagram of the experimental layout is shown in Figure 2, and the simulation experiment system of mine ventilation is shown in Figure 3.

![Figure 2. Schematic diagram of experimental design.](image2)
Figure 3. Simulation system of mine ventilation.

By adjusting the motor frequency of the frequency converter fan, the wind flow parameters of different locations when the mine car runs against the wind at a speed of 0.25 m/s in different roadways are determined respectively as shown in Table 1. The model length of the mine car is 0.1 m, width is 0.18 m, height is 0.18 m, and the blocking coefficient of the roadway is 0.36. The variation law of wind resistance with wind speed at different positions of mine car is obtained, as shown in Figure 4. From Figure 4, it can be seen that when the roadway wind speed is small, the influence of the tramcar on its wind resistance is greater. With the increase of the roadway wind speed, the wind resistance of the tramcar-roadway system decreases gradually. That is to say, the disturbance wind resistance of the tramcar-roadway system in the small wind speed roadway is greater than that in the high wind speed roadway. When the air supply is constant, the mine car from point B to point A, the wind resistance of the roadway changes little, showing a slowly decreasing trend. When driving out of point A, the resistance of the roadway drops sharply. Therefore, the maximum disturbance variation of the mine truck to the wind resistance of a roadway occurs at the time when the mine truck enters or leaves the roadway.

Table 1. Air flow parameters of mine roadways under different air supply conditions.

| Motor frequency /Hz | Wind speed /m·s⁻¹ | Tilt gauge reading /mmH₂O |
|---------------------|-------------------|--------------------------|
|                     |                   | Section A | Section 1 | Section 2 | Section 3 | Section B |
| 15                  | 2.88              | 6         | 8         | 7.5       | 7         | 8         |
| 20                  | 4.09              | 5.5       | 10        | 11        | 12        | 12        |
| 25                  | 5.46              | 6         | 13.5      | 15        | 16        | 17        |
| 30                  | 7.04              | 9         | 5         | 20        | 23        | 22        |
| 35                  | 8.34              | 13        | 30        | 31        | 31        | 32        |
| 40                  | 9.75              | 21        | 41        | 42        | 43        | 42        |

Figure 4. Air resistance of roadway under different air velocity

According to the range of roadway wind speed, the frequency of fan motor is selected as 25 Hz. The pressure difference of Section 2 is measured. The change of roadway wind flow in the static state...
is shown in Table 2. The relationship curve between the blocking coefficient and the roadway wind resistance is calculated as shown in Figure 5.

| Tramcar section (Width × Height) / m | Blocking coefficient | Tilt gauge reading/mmH2O | Wind speed /m·s⁻¹ | Air resistance /kg·m⁻⁷ |
|-------------------------------------|----------------------|---------------------------|--------------------|------------------------|
| 0                                   | 0                    | 2.5                       | 3.31               | 55.21                  |
| 0.09×0.05                           | 0.05                 | 4                         | 3.25               | 91.64                  |
| 0.09×0.09                           | 0.09                 | 6                         | 3.21               | 140.90                 |
| 0.18×0.09                           | 0.18                 | 9                         | 3.15               | 219.48                 |
| 0.18×0.15                           | 0.3                  | 13.5                      | 3.1                | 339.92                 |
| 0.18×0.18                           | 0.36                 | 15                        | 3.07               | 385.11                 |

From Figure 5, it can be seen that the relationship between the blocking coefficient and the wind resistance of the roadway is linear increasing. With the increase of the cross-section of the tramcar, the wind resistance of the roadway increases gradually. That is to say, the disturbance of the tramcar running in the small cross-section roadway to the tramcar-roadway system is greater than that of the large cross-section roadway. Therefore, high wind speed and large cross-section roadway should be preferentially selected in the design of underground mine truck transportation.

![Figure 5. Relationship between blocking coefficient and air resistance.](image)

### 4. Mathematical Modeling of Air Flow Disturbance in Tramcar-roadway System

#### 4.1. Calculating Model

The air flow in the mine satisfies the unsteady Bernoulli equation. The schematic diagram of relative position of tramcar in the ventilation network is shown in Figure 6. According to the running position of the mine car, the branching disturbance wind resistance $\Delta R_{AB}$ calculation models are established.
Figure 6. Schematic diagram of relative position of tramcar.

The tram is not running on AB at position 1, marked #1. Under this condition, there is no disturbance in the roadway and the wind resistance of the roadway.

\[
R'_{AB} = \left( \xi + \frac{\lambda}{d} \right) \frac{\rho(v')^2}{2(vS)^2}
\]  

(2)

Where, \( R'_{AB} \) is the wind resistance of roadway AB, kg/m²; \( \xi \) is the local resistance coefficient; \( \lambda \) is the resistance coefficient along the roadway; \( l \) is the length of the roadway, m; \( d \) is equivalent diameter of roadway, m; \( S \) is roadway cross-section area, m²; \( \rho \) is roadway air density, kg/m³, density value in a mine roadway can be regarded as fixed value; \( v' \) is the roadway wind speed when the mine car is not running, m/s. At this time, the disturbance wind resistance \( \Delta R_{AB} \) is 0.

Part of the car body of the mine car drives into the roadway AB at position 2, marked #2. Taking the roadway as the reference frame, the tramcar satisfies the continuity equation of flow in the roadway,

\[
v_0 \cdot S_0 = v_s (S - S_0) + v \cdot S
\]  

(3)

Where, \( v \) is the wind speed of the roadway, m/s; \( v_0 \) is the traveling speed of the mine car, m/s; \( v_s \) is the velocity of space airflow consisting of mine car section and roadway section, m/s; \( S_0 \) is the cross-sectional area of the tramcar, m².

Let \( \alpha = S_0/S \) be the blocking factor of mine car and roadway system,

\[
v_s = (\alpha v_0 - v)/(1 - \alpha)
\]  

(4)

The roadway AB is cut by the front section of the mine car. The unsteady flow bernoulli equation of the airflow between the head section 1 of the mine car and the starting section A of the roadway and the end section B of the roadway is as follows,

\[
\begin{cases}
P_a + \frac{\rho v^2}{2} + \rho gh_a = P_1 + \frac{\rho v^2}{2} + \rho gh + \rho x \frac{dv}{dt} \\
P_1 + \frac{\rho v^2}{2} + \rho gh = P_b + \frac{\rho v^2}{2} + \rho gh_b + (1-x) \rho \frac{dv}{dt}
\end{cases}
\]  

(5)
Where, $P$ is aerostatic pressure, Pa; $g$ is gravitational acceleration, 9.8 m/s$^2$; $h$ is node elevation, m; $l_0$ is mine truck length, m; $x$ is the length of the AB part of the roadway where the mine car enters (point A is zero), m, $x \leq l_0$. Solution (5) makes $T = P_A - P_B + \rho g (h_A - h_B)$ available.

Combining with the formula of wind resistance calculation, let $K_i = (\xi_i + \lambda_i x / d_s) / (1 - \alpha^2)$, $i = 1, 2, 3, 4$.

Where, $\xi_1$ and $\lambda_1$ are the local and along resistance coefficients of the remaining space of the tramcar section and roadway section respectively, and $d_s$ is the equivalent diameter of the space in this area, m. The formulas for calculating the wind resistance of the mine car after disturbance are obtained.

$$\Delta R_{AB} = R_{A1} + R_{B1} - R_{AB} = \frac{\rho}{2S^2} \left[K_1 \left(\frac{v_0}{\alpha} - 1\right)^2 - \lambda \frac{x}{d_s}\right]$$ (7)

The part of the car body of the mine car drives out of a roadway at position 3, marked #3. According to the same method mentioned above, the calculation models of wind resistance variation of roadways at 3 and 4 positions of tramcar can be calculated respectively. Taking section 4 as the cut surface, the roadway can be divided into two parts: car and no car. Let $y$ be the length of AB part (point B is zero), m, $y \leq l_0$. The bernoulli equation for unsteady flow is,

$$\begin{cases}
P_1 + \frac{\rho v_1^2}{2} + \rho g h_1 = P_3 + \frac{\rho v_3^2}{2} + \rho g h_3 + (l - y) \rho \frac{dv}{dt} \\
P_1 + \frac{\rho v_1^2}{2} + \rho g h_1 = P_4 + \frac{\rho v_4^2}{2} + \rho g h_4 + y \rho \frac{dv}{dt}
\end{cases}$$ (8)

By combining Equations (4) and (8), the following equation can be obtained.

$$\frac{dv}{dt} = \frac{T - \alpha \rho (v_0 - v) \left[\alpha (v_0 - v) - 2v\right]}{2(1 - \alpha)^2 \rho (2y - \alpha y - 1) / (1 - \alpha)}$$ (9)

The calculation formula of the wind resistance change value of the disturbed roadway by the tramcar operation is as follows,

$$\Delta R_{AB} = \frac{\rho}{2S^2} \left[K_1 \left(\frac{v_0}{\alpha} + 1\right)^2 - \lambda \frac{y}{d_s}\right]$$ (10)

The whole body of the mine car runs in a certain roadway, at position 4, marked #4. When $l_0 \leq l$, the mine car does not fill the roadway, as shown in Figure 3. The roadway is divided into three sections at position 4. If the distance between section 2 at one end and section A is $z$, the distance between section 3 and section B is $l - l_0 - z$, and the wind resistance value after disturbance of the operation of the mine car is obtained, as shown in Equation (11). When $l_0 \geq l$, the tramcar occupies the whole roadway, then the air flow in the roadway belongs to the steady flow. The wind resistance value after disturbance of
the operation of the mine car is obtained, as shown in Equation (12).

\[ \Delta R_{AB} = R_{A2} + R_{C3} + R_{B3} - R_{AB} = \frac{\rho}{2S^2} \left[ K_3 \cdot \left( \frac{\nu \cdot v_0}{\nu} \right)^2 - \left( 2\xi - \lambda \frac{l}{d} \right) \right] \]  

(11)

\[ \Delta R_{AB} = \frac{\rho}{2S^2} \left[ K_2 \cdot (1-\alpha)^2 - \lambda \frac{l}{d} \right] \]  

(12)

Combined (2), (7), (10), (11) and (12), the resistance variation of roadways at different times can be calculated according to the running state of the tramcar. \( K \) can be simplified by formula Абрамовец as follows:

\[ K = \frac{\alpha}{(1-\alpha)} + \frac{0.0512x}{(1-\alpha)^3S} \]  

(13)

Where, \( x \) is the length of the mine car in the roadway, m. The wind speed \( v \) of the mine car-roadway system can be calculated by formula (6) and formula (9). Because of the blocking factor \( \alpha \) of the roadway, the height difference \( h_A \) and \( h_B \) at both ends of the roadway are fixed. The air density of each roadway can be regarded as a constant. Therefore, the variation of wind resistance can be calculated by measuring the running speed of the mine car \( v_0 \), running time \( t \), static pressure \( P_A \) and \( P_B \) at both ends of the roadway. The variation of air resistance of roadway can be calculated.

4.2. Model Validation

Taking the experimental data as an example, the potential energy of the roadway is 0, the differential pressure meter reading at both ends of the roadway is 15 mmH₂O, and \( P=29.4 \) Pa is calculated. \( \alpha=0.36, V_0=0.25 \) m/s and \( \rho=1.2 \) kg/m³ in the tramcar-roadway system. When the tramcar runs to section 2, \( x=1.0 \) m. The roadway wind speed is calculated by formula (6), and the boundary condition is \( \nu|_{\nu_0}=\nu' \). The wind speed \( v=5.95 \) m/s is calculated by using the software of Matlab, and the measured wind speed is 5.46 m/s, with an error of 8.23 %.

The coefficient of friction resistance of roadway is 0.001. When \( \lambda=0.0066, \xi=0.3, d=0.34 \) m, \( K=1.59 \) is calculated. \( \Delta R_{AB}=48.04 \) kg/m can be obtained by formula (11). \( R_{AB}'=63.82 \) kg/m, the measured wind resistance is 121.75 kg/m, and the error of calculation is 8.12 %. Therefore, the mathematical model can meet the accuracy requirements.

5. Conclusion

(1) The variation law of equivalent wind resistance of wind disturbance in mine car-roadway system is analyzed. When the tramcar travels in the same direction as the wind flow in the roadway, and the speed of traveling is greater than the speed of the wind, the tramcar-roadway system is equivalent to the boost regulation of the mine ventilation system, which belongs to the positive disturbance; the resistance regulation of the ventilation system belongs to the negative disturbance.

(2) The index system of influencing factors of air flow disturbance is established, and the blocking coefficient, disturbance wind resistance and relative driving position of the mine car are put forward to characterize the characteristic parameters of air flow disturbance in the mine car-roadway system.

(3) The characteristics of air supply, blocking coefficient and disturbance of air resistance in roadways are studied. It is concluded that the disturbance wind resistance of small wind speed and small cross-section roadway is greater than that of large wind speed and large cross-section roadway; the maximum disturbance variation of mine car to a certain roadway wind resistance occurs at the time when the mine car enters or leaves the roadway.
(4) A mathematical model for calculating the equivalent disturbance wind resistance of the mine car-roadway system at different operation positions is established. The solving method of the model is studied. The error between the calculated wind resistance and the measured data is 8.12%.

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