Prediction of dispersion behavior of typical exhaust pollutants from hydraulic support transporters based on numerical simulation

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Received: 3 August 2021 / Accepted: 1 December 2021 / Published online: 24 January 2022
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Abstract
We investigated the impact of exhaust emissions from hydraulic support transporters on the air quality in roadways in mines. The dispersion distribution of diesel exhaust pollutants emitted by hydraulic support transporters was simulated with a dynamic mesh and computational fluid dynamics (CFD) simulations. More specifically, the dispersion and distribution of the main exhaust pollutants CO, HC, and NOx emitted by vehicles under the influence of the roadway wind flow were simulated with CFD simulations; in addition, the dispersion characteristics of exhaust pollutants from hydraulic support transporters during multiple driving phases in an alleyway (from transporting material, being unloaded at idle speed, to driving off without load) were predicted. The simulation results show that exhaust pollutants emitted by moving hydraulic support transporters can pollute the air in roadways and negatively affect the performance of gas monitoring devices in the roadway. Therefore, coal mining companies should optimize the ventilation design scheme to improve the air quality in roadways: they should increase the ventilation volume to dilute the emitted pollutants; in addition, the positions of underground gas monitoring devices should be adjusted to prevent interference from exhaust pollutants emitted by vehicles. This paper provides the theoretical basis and results of a preliminary investigation of the dispersion and transportation characteristics of exhaust pollutants emitted by vehicles in roadways. The results in this paper can serve as guidance for reducing the risk of occupational diseases.

Keywords Hydraulic support transporters · Numerical simulation · Diesel engine · Exhaust pollutants · Dispersion and distribution of exhaust pollutants · Environmental pollution

Introduction
In operation since the twentieth century, trackless rubber-tire vehicles can be easily loaded and unloaded and have a high load capacity and good transportation efficiency; their use in coal mines has indirectly improved the economic efficiency of coal mines (IARC 2014). However, exhaust emissions from trackless rubber-tire vehicles can pollute the surrounding air, as shown in Fig. 1. Because the underground tunnel environment is a relatively confined space, air circulation is poor, particularly, in digging tunnels and tunnels with low ventilation rates. Hence, tail gas pollutants accumulate more easily when coal mining vehicles are traveling through tunnels (Lyon, 2012; AIOH, 2013). Exhaust emissions from diesel mining vehicles are an acknowledged type of pollutants that degrade the air quality in underground environments (Attfield et al., 2012).

Many computational fluid dynamics (CFD) techniques have widely been used to solve mining-related issues. At this stage, CFD simulations are used to evaluate downhole fluid dynamics and to study the dispersion characteristics of exhaust from coal mining vehicles in underground mines to identify the areas with high particulate matter concentrations and reduce the risk of occupational diseases. For instance, Silvester et al. modeled the effects of flow ventilation, underground crushing installations, and dump trucks for loading...
and unloading mining materials with CFD simulations (Silvester et al., 2007). Zheng and Tien et al. used CFD software to investigate the distribution characteristics of exhaust emissions (Zheng and Tien, 2009). Xu et al. used FLUENT to analyze the dispersion process of exhaust particulate matter from underground mining vehicles (Xu et al., 2018). In addition, Ping et al. analyzed the DPM dispersion and distribution characteristics at an underground development face with an onsite experiment and CFD simulations (Ping et al., 2020). Silvester, Zheng, Xu, and Ping have demonstrated that numerical simulations can accurately predict the dispersion characteristics of particulate matter from vehicles in tunnels. However, they have only analyzed the dispersion distribution of tailpipe particulate matter and have neglected the fact that emissions from coal mining vehicles also contain gaseous pollutants. These gaseous pollutants contain CO, NO, CH, and other toxic and harmful gas components; they can pollute the air underground and, thereby, negatively affect the cardiopulmonary function of mine workers (Nitta H et al., 1993; Ruiz et al., 2011; M Garelnabi et al., 2013).

However, only very few researchers have studied the diffusion and distribution characteristics of exhaust pollutants in tunnels. Chang et al. reviewed existing exhaust pollution theory and stated that pollutants emitted by underground vehicles significantly pollute tunnel environments (Chang et al., 2017). In addition, Zhang et al. used FLUENT software to simulate the gas dispersion process in road tunnels (Zhang et al., 2013). They showed that CFD simulations can accurately predict the airflow behavior at underground mining sites. Moreover, Jundika et al. analyzed the airflow and methane dispersion characteristics in tunnels with CFD simulations (Jundika et al., 2013). Liu et al. used the standard k–ε turbulence model and component transport equation to simulate the diffusion of motor vehicle exhaust in a roadway with 45° slope to study the concentrations in different sections (Liu et al., 2016). However, these researchers have only analyzed the dispersion behavior of pollutants emitted by a stationary point source; a moving source has not been considered (Xue et al., 2016; Wang et al., 2018).

In summary, first, researchers who have studied exhaust emissions from coal mining vehicles have focused on the dispersion of particulate matter and neglected the effects of gaseous pollutants typically found in exhaust gases (e.g., CO, NOx, and HC). Second, researchers who have studied downhole pollution dispersion have only considered the dispersion of gaseous pollutants from relatively stationary or stationary sources. The research results presented in this paper fill the gap between the two aforementioned considered scenarios. Furthermore, different types of trackless rubber-tire vehicles are used in mines. Many scholars have focused on trackless rubber-tire vehicles with exhaust pipes at the tails while neglecting those with exhaust pipes on the sides; in addition, they have not analyzed the diffusion and distribution characteristics of diesel particulate matter when trackless rubber-tire vehicles are traveling in mines. The dispersion and distribution characteristics of exhaust gas emitted by moving mining trucks in tunnels are an urgent research topic. In this study, a more reproducible 3D physical model was established, and the gas diffusion model with the numerical simulations was applied to analyze the diffusion range of exhaust pollutants emitted from a driving vehicle in an alleyway and the identification of the areas with high concentrations of tailpipe pollutants. Coal mining companies can adjust the activities of miners during the operation of vehicles according to the simulation results to prevent miners from inhaling large amounts of turbid exhaust pollutants.

According to the Chinese Coal Mine Safety Regulations (Table 1), the maximum allowable concentrations of CO and NOx underground are $24 \times 10^{-5}$ and $25 \times 10^{-7}$ kg/m$^3$, respectively. To protect underground miners, it is important to divide the high exhaust pollutant concentrations areas to

![Fig. 1 Vehicles emitted large amounts of exhaust pollutants](image)
avoid miners’ activities in this area of high concentration of exhaust particulate. In this paper, this value is also used as the exhaust pollutants limit of CO and NOx.

Establishment of models

Establishment of mathematical model

To analyze more thoroughly the distribution and dispersion characteristics of exhaust pollutants emitted by vehicles, a complete tunnel model, 3D vehicle models, numerical simulation methods based on the RNG k–ε turbulence model, and the gas dispersion and mixture multiphase flow models were used to simulate the coupled scenario and diffusion distribution of the emissions with respect to the tunnel airflow.

Owing to the effects of the airflow in the tunnel and piston wind on exhaust dispersion, the airflow can be considered an incompressible fluid with turbulent flow; it can be described with the RNG k–ε equation model for an incompressible fluid with constant turbulence. Therefore, the airflow can be expressed as a continuous flow (Hu et al., 2015). Because the airflow and gas experience changes in their momenta, masses, energies, and species transport characteristics, the following assumptions can be made (Luo and Yu 2021): (1) the effect of the natural airflow at the tunnel entrance is negligible because the subsidiary transportation roadway in the mine is long; the airflow in the tunnel is an incompressible fluid, regardless of the force between the fluids; (2) the effect of the temperature on exhaust dispersion is negligible, and the wall surface of the mine is adiabatic; (3) there are no secondary reactions during exhaust dispersion; the gas dispersion process does not involve chemical and phase change reactions; (4) there are no other pollutants in the tunnel except the exhaust from vehicles (Chang et al., 2019a, b). Because it was assumed that the exhaust does not experience reactions during dispersion, the chemical reaction item in the Species Model in FLUENT was not selected; the dispersion of pollutants was described as follows (Yang et al., 2019; Wang et al., 2019):

\[
\frac{\partial}{\partial t}(\rho Y_i) + \nabla (\rho \mathbf{v} Y_i) = -\nabla J_i + S_i
\]  

(1)

where \( Y_i \), \( S_i \), and \( J_i \) denote the mass concentration, production rate, and mass dispersion flux of the \( i \)-th material, respectively.

The tunnel air comprises oxygen, water vapor, and exhaust. Their interaction is represented by the mixture density, which obeys the incompressible-ideal-gas law given by the general transport equations for the turbulence kinetic energy \( k \) and turbulence dissipation rate \( \epsilon \) of the RNG k–ε turbulence model (Nazif and Basirat 2013; Li et al., 2020; Liu et al., 2021a):

\[
\frac{\partial}{\partial x_i} \left( \rho k \mathbf{u}_i \right) = \frac{\partial}{\partial x_j} \left( \alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right) + G_K + G_b - \rho \varepsilon \tag{2}
\]

\[
\frac{\partial}{\partial x_i} \left( \rho \varepsilon \mathbf{u}_i \right) = \frac{\partial}{\partial x_j} \left( \alpha_k \mu_{eff} \frac{\partial \varepsilon}{\partial x_j} \right) + \frac{G_{\varepsilon}}{k} (G_K + C_{3k} G_b) + C_2 \rho \frac{\varepsilon^2}{k} - R_c \tag{3}
\]

where \( G_k \) is the generation rate of turbulence kinetic energy due to the mean velocity gradients, \( G_b \) the generation rate of turbulence kinetic energy due to buoyancy, and \( \alpha_k \) and \( \alpha_\varepsilon \) are the inverse effective Prandtl numbers for \( k \) and \( \varepsilon \), respectively; \( \mu_{eff} \) is the effective viscosity, and \( C_{1k}, C_{2k}, \) and \( C_{3k} \) are the turbulence model constants. The term \( R_c \) in the equation represents the effects of the rapid strain and streamline curvature, which affects the anisotropy of large-scale eddies (Jundika et al., 2013; Wang et al., 2019).

The fluid phase is treated as a continuum by solving the Navier–Stokes equations; thus, the conservation equations of mass (4) and momentum (5) in the case of incompressible, stationary turbulence can be expressed in the Cartesian-tensor notation (Yan et al., 2021):

\[
\frac{\partial U_i}{\partial X_i} = 0 \tag{4}
\]

\[
U_i \frac{\partial U_i}{\partial X_j} = -\frac{1}{\rho} \frac{\partial p}{\partial X_j} + \frac{\partial}{\partial X_j} \left( \nu \left( \frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i} \right) - u_i u_j \right) \tag{5}
\]

where \( \rho \) is the static pressure, \( \nu \) the kinematic viscosity, \( U_i \) the instantaneous velocity in the \( X_i \) direction, \( U_i \) the average mean flow velocity, and \( u_i \) the turbulence velocity fluctuation such that \( u_i = U_i + u_i' \). The term \( u_i' u_j' \), which is known as the Reynolds stress tensor, must be determined with a turbulence closure model (Hu et al., 2016; Niu et al., 2021).

In this study, the continuity equation, momentum conservation equation in the airflow direction, energy conservation equation, and dispersion equation of the pollutant were formulated. The continuity equation in the airflow direction can be written as follows (Lotrecchiano et al., 2020):

\[
\frac{\partial p}{\partial t} + \rho \left\{ \frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} \right\} = 0 \tag{6}
\]

where \( p \) denotes the exhaust flow rate, \( \rho \) the gas mass, and \( v_x, v_y, \) and \( v_z \) denote the flow velocities of the gas in the \( x, \)
\begin{equation}
\n\nabla \cdot \rho U = 0
\end{equation}

\begin{equation}
\n\nabla \cdot \rho U = -\nabla p + \nabla \cdot \left[ \left( \mu + \mu_t \right) \left( \nabla U + \left( \nabla U \right)^T \right) - \frac{2}{3} \left( \mu + \mu_t \right) \left( \nabla \cdot U \right) I + \rho k I \right] + \rho g
\end{equation}

\begin{equation}
\n\nabla \cdot \left( \rho C_p U T \right) = \nabla \cdot \left( \rho D_{i,\text{eff}} + \frac{C_p \mu t}{P r_t} \right) \nabla T
\end{equation}

\begin{equation}
\n\nabla \cdot \left( \rho \omega_i U \right) = \nabla \cdot \left( \rho D_{i,\text{eff}} + \frac{\mu t}{S c_t} \right) \nabla \omega_i
\end{equation}

where \( V \) denotes the kinematic viscosity, \( D \) the molecular diffusivity, and \( \mu \) the dynamic viscosity.

**Establishment of physical model**

The research objects are the WC55Y hydraulic support transport vehicles with high pollutant emission rates in the Sanjiaohe coal mine in Linfen, Shanxi Province, China. The selected route is the “subsidiary transportation tunnel—B3-6011 roadway—B3-6012 roadway.” SOLIDWORKS was used to build a full-scale model for accurate simulation results. The three-dimensional model of the vehicle in the roadway is shown in Fig. 2; its length, width, and height are 9560, 3650, and 1824 mm, respectively. The exhaust pipes are located at the outer side of the left front wheel at the vehicle front (Hua et al., 2021; Wang et al., 2021; Liu et al., 2019). Moreover, the vehicle includes, for example, a front frame assembly, power system, steering system, load-supporting part, and hydraulic system; this vehicle type is a hydraulic support transporter with a high load capacity and long transfer distance; its application effectively improves the operation efficiency. The width of the tunnel is 6.5 m, the height is 2.4 m, and the top is round. There are (0.6-m diameter) press-in ducts at the top of the tunnel, 1 m from the roof and 0.7 m from the right wall. According to the actual on-site measurement results, the wind speed at the entrance of the subsidiary transportation tunnel is 2.4 m/s. The model used in this study has the same scale as the field vehicle and...
roadway to obtain more reproducible results. This study is innovative because it combines multiple research fields: the analysis and application of a gas diffusion model to a dispersion model of exhaust pollutants from underground vehicles; in addition, a more accurate dynamic grid is applied for the division of the physical model, and the dispersion of exhaust pollutants from moving vehicles is analyzed (Sun et al., 2021; Huang et al., 2021a).

Model validation

ICEM software was used to calculate and divide the mesh of the model. Because the model of the hydraulic support transporter has a complex structure, dividing its mesh structure is difficult. Thus, a hybrid mesh was used. The simulation accuracy and calculation time largely depend on the mesh density; therefore, the independence of the mesh model had to be assessed (Ma et al., 2020; Guo et al., 2020). To ensure linear independence of the simulated data of the grid, the model was simulated with three different grid densities, and their wind speed values were compared: the coarse mesh “A” (number of mesh points = 4,564,433), medium mesh “B” (number of mesh points = 3,246,886), and fine mesh “C” (number of mesh points = 2,078,356). A 10-m line on the model’s central axis (i.e., above the vehicle) parallel to the wind flow direction was selected. The wind speeds on the line of the three different mesh points are compared in Fig. 3. Evidently, the number of mesh points in mesh B deviates by 1% from that in mesh A. The results of mesh C deviate by approximately 9% from those of mesh B. Consequently, mesh B was used for the numerical simulations (Xu et al., 2019; Chu et al., 2020; Juganda et al., 2020; Xu et al., 2021).

In addition, the parameters of mesh B were used as a reference (the maximum size of the vehicle model grid was set to 0.15, and the minimum size of the lane grid was set to 0.75); the mesh of the overall model was divided accordingly, and the resulting mesh was imported in FLUENT for the calculations (Ray et al., 2020). The RNG $k$–$\varepsilon$ turbulence model and Mixture multiphase flow model were used to determine the solution. Subsequently, open options for the species transport, inlet diffusion, and diffusion energy source were selected; the wind speed at the entrance of the model and the relative turbulence intensity and vehicle exhaust port boundary-type for the mass flow rate outlet were chosen (Huang et al., 2021b; Cai et al., 2021). The walls were modeled with no-slip conditions, and the vehicle driving speed was set according to the actual situation on site. To ensure the validity of the simulation results, the physical model must be verified. The wind flow velocity and concentrations of gas components around idle WC55Y hydraulic supporters at idle speed in the unloading phase to be simulated were measured on site to verify the validity of the model.

To minimize measurement errors, the measured exhaust pollutant concentrations were averaged and compared to the results of the established model. The measurement location is shown in Fig. 4; the ventilation wind speed in the tunnel is 1.31 m/s. Two cross-Sections. 2 m from the front and rear of the car and four measurement points in each cross-section...
were selected to measure the wind speed; in addition, the concentrations of toxic and harmful gases in the exhaust gas were measured at a point 50 cm from the exhaust pipes. Figure 4 shows the field measurement results; an anemometer (TSI-9545) was used to measure the wind flow speed inside the tunnel (Zhang et al., 2021; Xiu et al., 2020). When the idle vehicles were unloaded (i.e., the airflow movement is almost stable), the anemometer’s probe was installed at the measuring points. In the next step, the light strips at the end of the probe were used to determine the airflow direction; the direction of the probe was parallel to the airflow. Finally, the data on the display (i.e., the measured airflow velocity) were recorded. Figure 5 and Table 2 compare the measured and simulated airflow velocities. Evidently, the average relative error between the measured and simulation results was 9.42%, which confirms the effectiveness of the airflow simulation; this verifies the validity of the wind flow simulation (Chang et al., 2019b; Hua et al., 2020). To compare the simulation and measurement data, the exhaust gas concentration near the monitor was studied. Owing to the limitations of the actual field experiments and the available monitor (Khan and Gillies 2019), the measuring point was 50 cm from the exhaust pipe outlet of the hydraulic support transporters. The reasons are as follows: as shown in Fig. 5, the underground environment in the mine was fairly complex, and the detector could experience an unstable airflow, which could affect the accuracy of the measurement results; in addition, human factors can affect the measurement results (Ping et al., 2019; Liu et al., 2021b).

The LB-5Q automobile exhaust gas analyzer was used for non-dispersive infrared absorption measurements. In addition to real-time measurements, the instrument automatically ensures that the testing process is in accordance with the Chinese national standard “GB 18,285–2018 Limits and measurement methods for emissions from gasoline vehicles under two-speed idle conditions and short driving mode conditions.” This special program for double-idle conditions has been written to control automatically the testing process. Moreover, the small and lightweight device can store 500 sets of measured emission data. The working principle of the LB-5Q-type automobile emission gas analyzer is based on undifferentiated infrared absorption; the device can directly measure HC, CO, and NOx concentrations in exhaust gas of motor vehicles through microcomputer analysis; the NOx and O2 concentrations in the exhaust gas were determined with an electrochemical sensor, and the excess air coefficient \( \lambda \) was determined based on the measured CO, NOx, HC, and O2 concentrations. The exhaust pollutant concentrations were measured four times for 1 min at intervals of 15 s; Fig. 5b and Table 2 compare the measured and simulated data. In contrast to the simulation data, the errors between the measured and simulated data of the CO, HC, and NOx concentrations did not exceed 10%, which is within an acceptable range. Thus, the dispersion of exhaust gas from WC55Y hydraulic support transporters can be predicted with FLUENT (Khan and Gillies 2019; Ping et al., 2019).
Simulation results and analysis

The vehicle is traveling

While the vehicle is moving in the roadway under the influence of its own body structure, the piston wind moves along the edge of the vehicle body; the airflow velocity around the vehicle body changes evidently, and the airflow velocities above and on both sides of the vehicle exceed the roadway wind velocity; thus, the gas flow velocities around the vehicle body vary (Bao et al., 2020; Liu et al., 2021c). Different vehicle driving speeds lead to different wind flow velocities around the vehicle body, which in turn affect the dispersion of exhaust pollutants (Ding et al., 2010). As shown in Figs. 6 and 7 and in Tables 3 and 4, in most cases, the exhaust pollutants emitted by vehicles move toward the roadway wall.
surface owing to momentum dispersion; subsequently, they diffuse along the roadway walls on both sides. When the vehicle’s speed exceeds 16 km/h, the exhaust pollutants spread directly to the rear end of the vehicle under the influence of the piston wind. Therefore, the changes in the wind flow field in the roadway that are caused while the vehicle is moving were analyzed in this study.

For an efficient transport system, WC55Y hydraulic support transporters are usually driven at high speeds in roadways. As shown in Figs. 6–1 and 6–6, when the vehicle runs at 12 km/h, the engine runs at a high load, the fuel combustion rate increases, and more exhaust pollutants are emitted (Zhu Shiguang, 1998). These exhaust pollutants diffuse to the wall of the tunnel and disperse; a part of the exhaust pollutants diffuses to the car front, and another part diffuses to the rear under the influence of the wind flow near the tunnel bottom; only a small amount of surface exhaust pollutants is diluted by the wind flow. The dispersion distances of CO and HC are long, and their concentrations exceed 10^4.0 and is diluted by the wind flow. The dispersion distances of CO are better dispersed; the dispersion distances and minimal concentrations of CO, HC, and NOx are 10.94, 3.13, and 52.4 mg/m^3, respectively. Because NOx is easily reduced at high temperature, the dispersion area of NOx is relatively small and low; the concentration in the outer layer of the aggregation area exceeds 80.6 mg/m^3. The wind velocity around the car body is low because the wind in the tunnel is slower in the 6–6 stage than in the 6–1 stage; hence, the dispersion distance of the exhaust pollutants is relatively short, and their concentration in this area is high in this stage (the CO, HC, and NOx concentrations are 116.7, 41.8, and 97.6 mg/m^3, respectively). These high concentrations gather at the tunnel bottom and are not easily diffused and diluted by the wind flow. They pollute the pedestrian areas of the aisles on both sides of the tunnel, thereby endangering the health of coal mine workers and affecting the normal operation of monitoring devices.

As shown in Figs. 6–2 and 6–7, when the vehicle is moving at 5 km/h, the engine runs in a lower power state, and the amount of exhaust emissions is lower (Zheng et al., 2015). In addition, influenced by the structure of the vehicle, vortexes form next to the vehicle, thereby causing the exhaust pollutants to accumulate next to the vehicle. Owing to the tunnel wind flow and piston wind, the accumulated volume of exhaust pollutants mainly diffuses laterally in the tunnel, and the concentration of exhaust pollutants in the horizontal-axis cross-section gradually decreases along the radial direction, thereby showing regular radial flow characteristics (Fayad et al., 2021). The tail gas pollutants exhibit higher concentrations in the vertical-axis cross-section; the pollutants diffuse farther vertically and accumulate in higher concentrations, which negatively affect the performance of the gas monitoring device at the corner. In the dispersion area of the tailpipe pollutants, the NOx dispersion distance is relatively short; however, the concentration changes more evidently (the lowest concentration is 60.4 mg/m^3). CO and HC disperse over long distances, with minimal concentrations of 52.4 and 20.4 mg/m^3, respectively. These high concentrations disperse after the vehicle has moved away and, thus, pollute the alleyway.

Subsequently, the vehicle accelerates; as the speed increases, the engine output power and air/fuel ratio of the engine increase. Although the amount of exhaust pollutants increases with increasing engine output, the dilution effect becomes more evident owing to the influence of the piston wind. As shown in Figs. 6–3 to 6–5 and Table 3, the vehicle speed gradually increases to 6, 8, 10, and 12 km/h; the concentrations and dispersion distances of CO and HC in the exhaust gradually decrease; the NOx concentration gradually decreases, whereas the dispersion distance gradually increases. Through these comparisons, one can easily see that when the vehicle is moving at 10 km/h, the exhaust is better dispersed; the dispersion distances and minimal concentrations of CO, HC, and NOx are 10.94, 3.13, and 3.27 m and 19.3, 8.4, and 21.2 mg/m^3, respectively. In this stage, the exhaust is better diluted, the concentrations of the different pollutants are low, and the surrounding air is only slightly polluted.

In Fig. 6–8, the vehicle travels at 5 km/h close to the unloading site. Owing to the engine wind flow and piston wind, a vortex is formed in front of the vehicle body, and most exhaust pollutants move to the vehicle front; these factors result in a long, highly concentrated pollution area in front of the vehicle. In the contaminated area, the minimal CO concentration is 48.7 mg/m^3 (at 6.3 m distance); the minimal HC concentration is 18.7 mg/m^3 (at 2.6 m distance); and the minimal NOx concentration is 58.9 mg/m^3 (at 1.4 m distance). As the vehicles approach the unloading site, the high concentrations of exhaust pollutants will endanger the health of the staff who tries to dismantle the hydraulic support.

| Time (s) | Gas (mg/m^3) | CO  | NOx | HC   |
|---------|--------------|-----|-----|------|
| 15 Num  | Numerical simulated | 260 | 312.5 | 30.5 |
|         | Field measured | 250 | 309.4 | 32.8 |
| 30 Num  | Numerical simulated | 364 | 420.5 | 43.1 |
|         | Field measured | 358 | 428.5 | 48.8 |
| 45 Num  | Numerical simulated | 378 | 458 | 49.8 |
|         | Field measured | 389 | 462 | 48.8 |
| 60 Num  | Numerical simulated | 395 | 471 | 51.2 |
|         | Field measured | 397 | 472 | 50.1 |

| Stage of 6–1 and 6–2 | Stage of 6–3 and 6–4 | Stage of 6–5 and 6–6 | Stage of 6–7 and 6–8 |
|----------------------|----------------------|----------------------|----------------------|
| Field measured       | Numerical simulated  | Field measured       | Numerical simulated  |
| 397                  | 395                  | 471                  | 472                  |
| 472                  | 471                  | 51.2                 | 50.1                 |
Roadway airflow

Piston airflow

The exhaust pollutants aggregation area

Dilution effect of piston wind

Low airflow-velocity region

Vortex

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The diffusion distance of the exhaust pollutants to the front of the vehicle decreases with the vehicle speed.
When the unloading process has finished, the vehicle returns on the original route to the surface yard. Because the on-board load has been reduced, the dispersion distance and concentration of tailpipe pollutants are reduced. As shown in Fig. 7–1, the sidewall and tail wind flow velocities of the empty vehicle vary more than those of the loaded vehicle in the roadway. In addition, the dilution of exhaust pollutants is more evident, the horizontal dispersion distance of the exhaust pollutants is shorter, their concentrations are lower, and the roadway is less polluted. Regarding the case with the constant driving speed, the engine must provide more power in the 6–8 loaded driving stage than in the 7–1 unloaded driving stage; this leads to a higher cylinder pressure and temperature in the engine cylinders, which promote the combustion and cracking of hydrocarbons in the fuel. Consequently, the dispersion distances of HC and CO are longer, and their concentrations in the tailpipe exhaust volume of stage 6–8 are higher. Because NOx is easily reduced at high temperature, the NOx dispersion distance is shorter, and its concentration is lower.

As shown in Figs. 7–2 and 7–6, when the unloaded vehicle is moving at 5 km/h, the vehicle steering system needs additional power from the engine (Zheng et al., 2015); consequently, the amount of exhaust pollutants emitted by the engine increases. Under the influence of the tunnel wind flow and piston wind, a winding flow is generated around the car body, which limits the horizontal dispersion of exhaust pollutants. This results in accumulations of exhaust pollutants at the corners of the tunnel; the CO, HC, and NOx concentrations in this area exceed the safety limit. First, these exhaust pollutants negatively affect the performance of the monitoring devices in the tunnel; second, the flow around the vehicle body in this stage causes the exhaust pollutants to spread vertically; hence, the cab is surrounded by high

### Table 3  Diffusion of various components of exhaust pollutants during the loading transportation stage

| Gas  | CO   | HC    | NOx  |
|------|------|-------|------|
| Scenario |      |       |      |
| Stage  | Velocity | Horizontal diffusion distance (m) | Minimal concentrations (mg/m³) | Horizontal diffusion distance (m) | Minimal concentrations (mg/m³) | Horizontal diffusion distance (m) | Minimal concentrations (mg/m³) |
| 6–1   | 12 km/h | 15.73  | 104   | 7.66  | 39.2  | 4.97  | 80.6   |
| 6–2   | 5 km/h  | -      | 52.4  | -     | 20.4  | -     | 60.4   |
| 6–3   | 6 km/h  | 14.12  | 54.1  | 6.43  | 33.7  | 0.68  | 61.8   |
| 6–4   | 8 km/h  | 12.78  | 36.7  | 4.86  | 19.4  | 1.36  | 41.6   |
| 6–5   | 10 km/h | 10.94  | 19.3  | 3.13  | 8.4   | 3.27  | 21.2   |
| 6–6   | 12 km/h | 13.61  | 116.7 | 41.8  | 6.19  | 97.6   |
| 6–7   | 5 km/h  | -      | 58.3  | -     | 25.7  | -     | 62.7   |
| 6–8   | 5 km/h  | 6.3    | 48.7  | 2.6   | 18.7  | 1.4   | 58.9   |

### Table 4  Diffusion of various components of exhaust pollutants during the unladen transportation stage

| Gas  | CO   | HC    | NOx  |
|------|------|-------|------|
| Scenario |      |       |      |
| Stage  | Velocity | Horizontal diffusion distance (m) | Minimum concentration (mg/m³) | Horizontal diffusion distance (m) | Minimum concentration (mg/m³) | Horizontal diffusion distance (m) | Minimum concentration (mg/m³) |
| 7–1   | 5 km/h  | 8.73  | 43.5  | 2.78  | 15.3  | 2.64  | 34.8   |
| 7–2   | 5 km/h  | -     | 45.6  | -     | 18.3  | -     | 42.5   |
| 7–3   | 8 km/h  | 9.87  | 76.4  | 2.84  | 38.4  | 3.05  | 73.8   |
| 7–4   | 12 km/h | 11.39 | 51.7  | 4.91  | 29.7  | 4.57  | 49.6   |
| 7–5   | 16 km/h | 13.28 | 20.9  | 5.97  | 19.4  | 5.23  | 24.7   |
| 7–6   | 5 km/h  | -     | 44.8  | -     | 17.1  | -     | 39.4   |
| 7–7   | 18 km/h | 14.22 | 46.8  | 6.19  | 24.2  | 5.64  | 49.5   |
| 7–8   | 20 km/h | 15.07 | 72.6  | 6.94  | 31.4  | 1.36  | 86.7   |
| 7–9   | 22 km/h | 16.87 | 112.4 | 7.35  | 48.6  | 3.27  | 91.3   |
exhaust pollutant concentrations, which endanger the health of mine workers.

When the unloaded vehicle accelerates, as the speed increases, the air/fuel ratio of the engine increases, thereby reducing the CO and HC emissions; the continuous increase in the engine cylinder temperature reduces the NOx emissions. As shown in Figs. 7–3 to 7–5 and Table 4, as the speed of the vehicle increases, the airflow rate around the vehicle body increases, and the dispersion characteristics of the exhaust pollutants and their concentrations change: first, the exhaust pollutants are gradually diluted by the wind flow; although the dispersion distance of the exhaust pollutants is longer, the concentration decreases in a stepwise manner. Second, the dispersion of exhaust pollutants to the vehicle front is suppressed. This dispersion distance decreases with the vehicle speed; when the speed of the vehicle increases to 16 km/h, the exhaust pollutants directly diffuse with the piston wind to the rear of the vehicle.

When the unloaded vehicle leaves the lane at a higher speed, the engine runs at high speed, which results in the incomplete combustion of hydrocarbons in the fuel and increased emissions of exhaust pollutants; thus, the CO and HC concentrations in the exhaust volume increase significantly. As shown in Figs. 7–7 to 7–9 and Table 4, as the vehicle speed increases, the dispersion distance of the exhaust pollutants and the concentrations of the individual components increase. In stage 7–7, when the vehicle is moving at 18 km/h, the concentration of exhaust pollutants increases with respect to that of stage 7–5, and the CO, HC, and NOx concentrations in the exhaust increase. In stage 7–8, when the vehicle accelerates to 20 km/h, the higher engine power increases the temperature and pressure of the engine cylinder, which cause the engine to overheat. The results are deflagration, early combustion, and the generation of more NOx and exhaust pollutants. In stage 7–9, when the vehicle is moving at 22 km/h, owing to the high engine load, the exhaust gas volume in the engine cylinder increases, thereby producing more CO and HC; the increased CO and HC concentrations evidently exceed that of NOx in this stage (Zhu Shiguang, 1998). In the previously presented scenario, the tail gas pollutants are influenced by the piston airflow and accumulate at the bottom of the tunnel; only the concentration of the tail gas pollutants on the surface layer is reduced, and the accumulated tail gas pollutants negatively affect the

Fig. 8 Diffusion scenario of exhaust pollutants during the idle stage
performance of the gas monitoring device in the mine. When the vehicles are driven away, the gathered exhaust pollutants can easily spread in the roadway; a lot of time is required to dilute them completely. The polluted underground environment endangers the health of coal mine workers.

Idle unloading phase

Because the crew is near the car while it is dismantling the hydraulic support, the area contaminated by exhaust pollutants must be predicted with numerical simulations (Xu et al., 2018). Because the roadway in which the hydraulic support will be installed is long, seven equidistant locations in the roadway were selected to predict the dispersion characteristics of exhaust pollutants emitted by vehicles at the different locations with numerical simulations. As shown in Fig. 8, when the idle vehicle is being unloaded, it emits more CO and small amounts of HC and NOx because the engine is running at a lower speed; consequently, the gas exchange rate is low, and the amount of residual exhaust gas in the cylinder increases, which results in the incomplete combustion of fuel and, therefore, the generation of CO. The main exhaust component in this process is CO; less HC and NOx are emitted, and the pollutant concentration decreases with decreasing dispersion distance. In addition, the wind flow in the tunnel promotes the lateral dispersion of exhaust pollutants after contacting the tunnel wall, and a vortex region is formed in front of the car body. First, this leads to the accumulation of exhaust pollutants in front of the car body; second, the forward dispersion distance of the exhaust pollutants is prolonged. According to Figs. 8–1 to 8–7, the wind flow around the car body gradually increases as the unloading position of the vehicle approaches the inlet alley. The dispersion characteristics of HC and NOx are relatively stable, and the high-concentration area is mainly located near the exhaust pipes. The outer concentrations are below 18 and 23 mg/m³, respectively, which are lower than the safety limit of the mine. Because of their low concentrations and relatively short dispersion distances, they have little influence on the roadway air and underground construction personnel. The CO dispersion characteristics are more complex; when the discharge position of the hydraulic support transporter changes, the CO dispersion distance on the cross-section of the horizontal axis increases along the radial direction, and the concentration distribution shows the conventional radial flow characteristics. That is, when the vertical section of the exhaust pipes corresponds to the center, the CO concentration near the exhaust pipes is higher; most CO concentrations exceed 240 mg/m³ and decrease in a stepwise manner in the horizontal direction. However, the CO dilution effect becomes more evident with increasing speed of the wind flow around the vehicle. Although there is no clear pattern, one can easily see that the CO concentration decreases in a jet-like manner with increasing wind speed around the vehicle in stage 8–7 compared with that in stage 8–1. In addition, the area in which the CO concentration exceeds 160 mg/m³ gradually decreases; most CO concentrations are diluted to 53 mg/m³, and the surface CO concentrations are diluted to 20 mg/m³.

In general, these vehicles emit mostly CO when idle; the HC and NOx concentrations are relatively low and within the standard range (US.EPA, 2002). In addition, as the wind speed around the car increases, the concentration of exhaust pollutants gradually decreases, and the surface CO concentration decreases to 20 mg/m³ owing to the wind flow; this concentration is lower than the safety limit of the coal mine. Hence, the roadway environment is less polluted. Some areas around the vehicle have CO concentrations between 20 and 24 mg/m³; nevertheless, mine workers can mitigate negative effects on their health by wearing gas masks with better filtration properties.

Recommended measures and conclusions

A prediction model for the dispersion of exhaust gases from trackless rubber-tire mining vehicles operating under different conditions in alleyways of mines is proposed. The results of this model were verified with experiments. According to the simulation results of moving WC55Y hydraulic support transporters, the exhaust pollutants that spread in the tunnel easily accumulate under the influence of the roadway wind flow and piston wind; they pollute the roadway environment and negatively affect the performance of underground gas monitoring devices. Therefore, mine personnel must control the dispersion of exhaust pollutants emitted by vehicles in roadways. This study provides the following contributions:

a) Gas equations were used to describe the distribution of CO, HC, and NOx in automobile exhaust in an enclosed space. The dispersion results provide guidance for suppressing the dispersion of exhaust pollutants from moving coal mining vehicles in tunnels.

b) According to the numerical simulation results, when the vehicle is traveling, the exhaust pollutants interfere with the performance of the gas monitoring devices in the mine. The negative effects of CO, HC, and NOx pollutants can be prevented with the help of the simulation results to prevent false alarms. Thus, the location of the device should be chosen such that exhaust pollutants emitted by vehicles do not reach the device.

c) According to Figs. 6–1 and 6–6 and the comparison with the dispersion characteristics of exhaust pollutants from the idle vehicle (Fig. 8), the wind flow around the vehicle affects the dispersion of exhaust pollutants when the vehicle is traveling at constant speed; in addition, they are more efficiently diluted when the wind flow speed is greater. Mining
companies can optimize the mine ventilation design based on this point; that is, toxic and harmful gases emitted by vehicles can be diluted by increasing the ventilation volume. According to Figs. 7–8 and 7–9, a vehicle moving at high speed emits more exhaust pollutants, which are not easily diluted by the wind flow; thus, mine managers should adjust the upper limit of the vehicle speed to 16 km/h to reduce exhaust. When the vehicle is being unloaded at idle speed, the main exhaust pollutant is CO. Although some exhaust accumulates near the exhaust pipes and the CO concentration exceeds 140 mg/m³, the highly polluted area is mainly located at the height of the exhaust pipes on the discharge side. Most of the CO amount becomes evidently diluted owing to the airflow in the tunnel; the operators should wear gas masks with better filtration characteristics.

**Author contribution** XL: software, original draft preparation, writing; WN: conceptualization, methodology, writing—reviewing, editing, writing; YH: investigation; CL: data curation; LG: validation.

**Funding** This work has been funded by the National Natural Science Foundation of China (NO. 52174191 and 51874191), the national Key R&D Program of China (2017YFC0805201), Qinghuang Science and Technology Project of Shandong Province University (2020KJD002), and Taishan Scholar Project Special Funding (TS20190935).

**Data availability** All data generated or analyzed during his study are included in this published article.

**Declarations**

**Ethics approval and consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

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