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Research on the evacuation of people from a road tunnel fire based on a mathematical model

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ABSTRACT

A mathematical model for the evacuation of people from a road tunnel is created, taking into account various factors such as the speed at which people move, the density of the flow of people, and the outcome of the fire. This model allows for the precise calculation of the evacuation time and the optimization of the evacuation route in a fire scenario. The constructed mathematical model was used to determine how long it would take for people to evacuate this road tunnel, and the findings of the Pathfinder simulation were compared. The findings demonstrate a relationship between the model's evacuation time and the human flow density, movement velocity, and fire product characteristics. The evacuation time is closer to the outcome of the actual fire scene when the impact of the fire environment on the speed of evacuation is quantified. The mathematical model of human evacuation's calculation of the evacuation time is essentially accurate when compared to the Pathfinder simulation's calculation, with an error of only 0.77 %. The model provides recommendations for optimizing the evacuation of people from a road tunnel in the case of a fire by not only predicting where the crowding would occur but also by calculating the duration of the crowding.

1. Introduction

The average annual growth rate of road tunnels since the turn of the century is up to 20 %, and the rate of rise is growing every year [1]. Although they make traveling more convenient, road tunnels also make it difficult to evacuate workers in an emergency because of how easily smoke and heat may build up in the small, constrained spaces [2]. When there is a lot of traffic, it is quite simple to block the city highway tunnel's traffic flow. If there is a fire, it will spread quickly amongst the vehicles and pose a major threat to the lives of everybody within. In order to plan the emergency rescue of road tunnels, it is crucial to research the personnel evacuation time in the event of a fire.

The subject of evacuation models for areas like road tunnels has been thoroughly studied by academics both domestically and overseas. A dynamic model of the emergency evacuation system was created by Liu Chang et al. [3] using evacuation simulation software, based on the relationship curve between the flow of evacuees and walking pace. In order to construct the personnel evacuation dynamics equation, Seike et al. [4] studied the movement speed of individuals in a crowded environment and came up with a relationship equation between crowding degree and speed. SEIKE M et al. [5] established a novel empirical model for calculating the evacuation time of tunnel people based on variables including tunnel length, width, and traffic volume in order to precisely determine the evacuation time of tunnel personnel. The association between the smoke extinction coefficient and regular walking speed and

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emergency evacuation speed of workers was studied by SEIKE M et al. [6–8]. Arshad et al. [9] proposed an ant colony algorithm-based personnel evacuation solution for the ship escape path planning problem with consideration of fire spread. However, most studies failed to fully consider factors such as fire products and blocked tunnel exits, and studies related to the movement speed law of people could not quantify the evacuation time, making it difficult to simulate the evacuation of people under fire scenarios.

During fire evacuation and escape, smoke poisoning is the main cause of casualties, the significant harm of CO in smoke to people has been recognized and highly valued in the field of fire science. However, in recent fire research, most scholars usually set certain temperature and harmful gas concentration thresholds, or only consider the injury value under the separate action of temperature and CO, as the criteria for safe evacuation of personnel, which is highly inconsistent with the reality. According to the relevant statistics of the National Fire Protection Association, the death of people in the fire is mainly caused by poisoning and suffocation, with the general proportion of 80 % from toxic smoke, 13 % from high temperature, and 7 % from other causes [10]. Kathy A et al. [11] calculated and analyzed the available safe evacuation time under different temperature, visibility, CO volume fraction and other scenarios based on Monte Carlo method method, and clarified the impact of different threshold parameters of fire on the uncertainty of available safe evacuation time; Jin, Rantzich, and Nilsson [12–14] conducted experiments on visibility and movement speed, and found that movement speed decreases with reduced visibility; Wei Wei [15] modified the traditional FED disability model and for the first time provided a formula for determining personnel evacuation considering smoke toxicity. He found that an increase in smoke concentration would reduce personnel movement speed. When the concentration increased to a certain extent, evacuees could even experience symptoms such as shock; Wang Dong [16] derived the safe escape distance and safe escape area for personnel in highway tunnel fires under the combined action of temperature and CO based on the Krani formula and FED model. The above studies all indicate that the movement speed of evacuees in fire scenarios is influenced by fire products such as CO concentration, visibility, and temperature.

LIU Shao bo [17], AIK [18] and other studies have found that during the evacuation process, a large number of pedestrians gather in front of the safety exit and compete before the exit. The density of people around the exit is an important factor affecting pedestrian exit selection. Therefore, it is necessary to consider the impact of personnel density on evacuation efficiency in personnel evacuation research.

Based on this, this article quantifies the effects of fire products and personnel density on the speed of personnel evacuation movement through formulas, and constructs a mathematical model suitable for personnel evacuation time in tunnel fires. Taking a highway tunnel in Hangzhou as an example, a mathematical model and Pathfinder software were used to study personnel evacuation, and the results of the two were compared and analyzed to verify the effectiveness of the mathematical model. The research results have revealed the rules of personnel evacuation in highway tunnels under fire conditions, providing certain reference and guidance value for optimizing evacuation routes under fire conditions. Mathematical model construction for personnel evacuation.

2. Relevant parameters of evacuation model

In a tunnel fire scenario, the evacuate action speed of people is mainly affected by smoke, temperature, fire products such as CO, and the density of human traffic. The movement speed of people in a fire scenario is reduced because the smoke from the fire reduces the field of view of evacuees and gases such as CO can affect the health of evacuees. However, most of the existing evacuation studies focus on fire-free evacuation, which is far from the actual evacuation of people in tunnel fires, and the results obtained are difficult to meet the needs of evacuation studies in fires.

2.1. Effect of fire products on the evacuation speed of people

The influence of fire products on the evacuation speed of personnel, introduced the concept of equivalent speed in the evacuation process [19], and quantified the influence of fire products on the evacuation speed of personnel as the temperature influence coefficient $f_1(T_s)$, and the CO concentration influence coefficient $f_2(\rho_{co})$, and the visibility influence coefficient$f_3(K_s)$, and the calculation formula are given. Equivalent speed is the evacuation speed of people in a fire environment obtained by quantifying the effect of the fire environment on evacuation behavior. Yuan Chunyan et al. [20] considered the incentive behavior and mutual aid behavior of groups in fires, modified the formula proposed by Yi Liang et al. and set the upper tolerance limit of personnel to toxic gas CO concentration from 0.25 % to 0.4 %, and the upper tolerance limit of personnel to smoke temperature from 120 °C to 192 °C, which is consistent with the actual human tolerance limit in fires [21], and the modified equivalent velocity and velocity discount The modified equivalent velocity and velocity reduction values are shown in Eq:

$$v_1 = v_0 \bullet \delta \tag{1}$$

$$\delta = f_1(T_s) \bullet f_2(\rho_{co}) \bullet f_3(K_s) \tag{2}$$

In the formula, v_1 is the equivalent velocity, m/s; v_0 is the velocity of free traffic flow during evacuation, m/s, take 1.20 m/s; δ is the velocity discounted value.

When a fire occurs, the thermal radiation of the flame and the thermal convection of smoke will lead to an increase in temperature around the fire, and the high temperature will affect the body functions of personnel, making them feel hot, dizzy, and nervous, reducing the evacuation speed. The influence of temperature on the evacuation speed of personnel is calculated according to formula (3) [22].

$$f_1(T_s)=\begin{cases} 1\ T_0 \le T_s < T_{\text{cr1}} \\ \dfrac{(v_{\max}-v_0)\left(\dfrac{T_s-T_{\text{cr1}}}{T_{\text{cr2}-T_{\text{scr2}}}}\right)^2}{v_0}+1\ \ T_{\text{cr1}} \le T_s < T_{\text{cr2}} \\ \dfrac{v_{\max}}{v_0}\left[1-\left(\dfrac{T_s-T_{\text{cr1}}}{T_{\text{cr2}-T_{\text{scr2}}}}\right)^2\right] T_{\text{cr2}} \le T_s < T_{\text{dead}} \end{cases} \tag{3}$$

In the formula, T_s is the fire temperature, $^\circ C$; v_0 is the velocity of free traffic flow during evacuation, m/s, taken as 1.20 m/s; v_{max} is the maximum escape velocity, m/s, taken as 1.27 m/s; T_{cr1} is the temperature at which people feel uncomfortable, $^\circ C$, taken as 30 $^\circ C$; T_{cr2} is the temperature at which harm is caused to people, $^\circ C$, take 60 $^\circ C$; T_{dead} is the lethal temperature, $^\circ C$,take 192 $^\circ C$.

In addition to the influence of temperature, the evacuation speed is also related to the toxic fumes generated by combustible materials, such as CO, HCL and other inorganic gases and some organic toxic gases, among which CO is the main gas that causes casualties and may cause serious injuries or even death by prolonged inhalation. The influence coefficient of CO on the evacuation speed of personnel is calculated according to equation (4).

$$f_2(\rho_{co})=\begin{cases} 1\ \rho_{co}< 0.1 \\ 1-(0.2125+1.788\rho_{co})\,\rho_{co}\text{t} \quad 0.1 \le \rho_{co}< 0.4 \\ 0 \quad 0.4 \le \rho_{co} \end{cases} \tag{4}$$

In the formula, ρ_{co} is the CO concentration, %; t is the exposure time, min.

Smoke from a fire can reduce the visibility of evacuees and affect the range of vision during evacuation, thus affecting the escape speed of personnel. The influence of visibility on the evacuation speed is calculated according to formula (5).

$$f_3(K_s)=\begin{cases} 1\ K_s< 0.35 \\ 1\ -\ 0.3025K_s \quad 0.35 \le K_s< 1.2 \\ 0.25 \quad 1.2 \le K_s \end{cases} \tag{5}$$

In the formula, K_s is the light reduction coefficient, m^{-1}.

2.2. Crowd density

Fegress [23] considered the crowd density as the horizontal projected area of people on the evacuation channel per unit area. Assuming that the maximum number of people carried on each evacuation route during evacuation is a constant value, the corresponding crowd density p_0 on the evacuation route is of size

$$p_0=\frac{nf}{((n-1)d_0+nb_0)w/2} \tag{6}$$

In the formula, n is the total number of people in a certain area; f is the unit horizontal projection area, m^2; d_0 is the human flow spacing, m; b_0 is the thickness between human flows, m; w is the width of the evacuation route, m.

Fegress divides the evacuees within the flow of people into three categories of people according to their ages: young people, middle-aged people, and elderly people. The projected area of evacuees in the three age groups can be measured according to the actual situation and then averaged, and then a weighted average is sought according to the proportion of each type of people in the evacuee flow.

$$f=xa+yb+zc \tag{7}$$

In the formula, f is the unit horizontal projection area, m^2; x, y, z are the average single horizontal projection area of young people, middle−aged people and elderly people, m^2; a, b, c are the percentages of young people, middle-aged people and elderly people in the evacuation flow, respectively.

The crowd density p_m on evacuation partition m is the ratio of the total number of people in evacuation partition m at a certain moment (excluding those passing through the evacuation channel) to the area of evacuation partition m as [24]:

$$p_m=\frac{S_m-\sum\int_0^t p_0 v_2 u dt}{A_m} \tag{8}$$

In the formula, S_m is the maximum number of persons to be accommodated in partition m; A_m is the area of partition m, m^2.

2.3. The speed of the flow of people in the evacuation channel in case of emergency

As a key factor in the overall evacuation process, many studies have focused on measuring the walking speed of crowds in various buildings under normal conditions, however, people will walk faster than normal under emergency conditions. According to Predtechenskii Milinskii [25], the velocity of pedestrian flow in a horizontal evacuation corridor under normal conditions is as follows:

$$v=\frac{\left(112p_0^4-380p_0^3+434p_0^2-217p_0+57\right)}{60} \tag{9}$$

The equation for the travel speed of the human flow in the horizontal channel in an emergency situation satisfies [25]:

$$v_2=v\mu_1 \tag{10}$$

In the formula, $\mu_1 = 1.49 - 0.36p_0$.

2.4. Evacuation time

After a fire, the first reaction of personnel is to evacuate to a safe area in time. Let the evacuation time of people in the horizontal place be t_1 [26].

$$t_1=\frac{a}{v_1} \tag{11}$$

In the formula, a is the maximum distance from the evacuation flow to the safety exit, m.

The blockage time for evacuees on evacuation partition m to pass through the evacuation route is t_2.

$$\frac{w}{p_m}=\frac{8.04}{{t_2}^{1.37}} \tag{12}$$

$$t_2=\left(\frac{8.04p_m}{w}\right)^{\frac{1}{1.37}} \tag{13}$$

In the formula, w is the effective width of evacuation route.

The time for a single person to walk through the horizontal passage is t_3.

$$t_3=\frac{l}{v_2} \tag{14}$$

In the formula, l is the horizontal channel length, m.

The total evacuation time T_m or all evacuees on evacuation partition m is:

$$T_m=t_1+t_2+t_3+t_4 \tag{15}$$

In the formula, t_4 is the evacuation response time, s.

2.5. Personnel evacuation mathematical model equation coupling

In order to improve the shortcomings of the original personnel evacuation model, which only focuses on non fire evacuation, the impact of fire products on personnel evacuation speed is quantified. The impact of fire products on personnel evacuation speed is calculated by using formulas (3) to (5), and it is substituted into formula (1) to obtain personnel evacuation speed under fire scenarios. Coupling the crowd velocity equation (1) and equations (9) and (10), the crowd density equations (6)–(8) and the evacuation time equation (11)–(14), and substituting into equation (15) to obtain the total crowd evacuation time T_m for the horizontal evacuation site partition m as:

$$T_m=\frac{a}{v_1}+\left(8.04\frac{S_m-\sum\int_0^t\frac{nfu(1.49-0.36p_0)\left(112{p_0}^4-380{p_0}^3+434{p_0}^2-217p_0+57\right)}{30((n-1)d_0+nw)b_0}dt}{wA_m}\right)^{\frac{1}{1.37}}+\frac{60l}{(1.49-0.36p_0)(112{p_0}^4-380{p_0}^3+434{p_0}^2-217p_0+57)}+t_4 \tag{16}$$

3. The effect of fire products on the evacuation speed of people

Fire products can have an impact on personnel evacuation speed, mainly because fire smoke and high-temperature heat plumes can reduce personnel's physiological motility and affect their choice of escape routes. To reflect the degree of influence of fire products on evacuation speed, the discounted values of fire smoke concentration, visibility and temperature on personnel evacuation speed were quantified. The fire smoke, temperature and visibility data are obtained by detecting the hazardous location of the building, and the relationship between the fire products and time is used to obtain the discounted evacuation speed values and time.

3.1. Building the model

(1) Overview of the building

A selected road tunnel in Hangzhou is a two-lane road tunnel, 810 m long, 15.2 m wide, 8 m clear height, with an open boundary at the entrance and exit, and the lining material is selected as concrete. There are two evacuation channels, evacuation channel A and B, the width of the evacuation passage is 2 m, as shown in Fig. 1 (a), and the distance between adjacent cross channels is 250 m according to the Highway Tunnel Design Specification (JTG D70-2004) [27].

(2) Geometric model of the tunnel

A tunnel model is built in FDS with a centralized smoke exhaust at the top of the tunnel, the main body is divided into two parts, the travel lane and the smoke exhaust, connected by smoke exhaust valves, and the tunnel cross-section is shown in Fig. 1 (b). The fire point is set at the centre of the tunnel. Considering the impact of fire detectors on fire detection delay and fan startup delay in actual situations, the mechanical smoke exhaust system cannot be started immediately when a fire occurs, the smoke valve is opened by the automatic smoke induction system 60s after the fire, and the smoke from the fire enters the top exhaust tunnel from the traffic lane through the smoke valve, and smoke fans are installed at both ends of the exhaust tunnel and connected to the tunnel shaft to discharge the smoke. The safety zone. The top of the model is set as a velocity boundary at both ends to replace the realistic jet fans, and all other structural dimensions are based on the actual road tunnel.

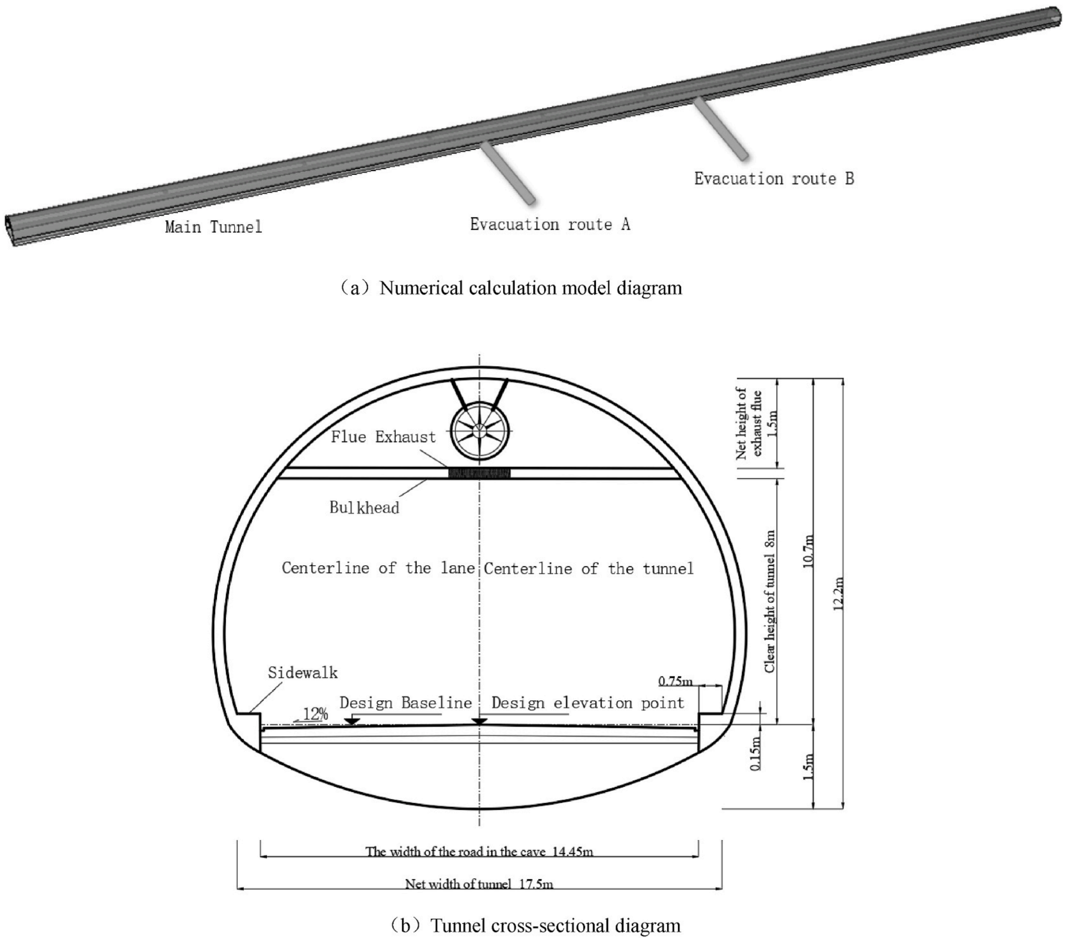


Fig. 1. Schematic diagram of the tunnel model
(*a*)Numerical calculation model diagram
(b)Tunnel cross-sectional diagram.

(3) Fire source setting

Due to the low headroom of the tunnel, when a fire occurs inside the tunnel, the vehicles involved in the fire will generate a large amount of radiation heat towards their adjacent vehicles. If the critical radiation heat flux of adjacent vehicles is less than the radiation heat received, the vehicles involved in the fire will ignite the adjacent vehicles, expanding the scale of the fire.

The rate of heat release from a fire is critical to the generation of fire smoke. Wang, W. L [28] found through research that the heat release rate of a large-scale fire in a highway tunnel is 50 MW, set according to the most unfavorable fire source. In the early stages of the fire, a t^2 fire growth model is generally used with a fire growth factor of 0.1876. The simulated fire material is assumed to be petrol, the fire size is 2 m × 1 m, it is a non-stationary volumetric heat source, and the fire source is located at the middle end of the tunnel at the centre.

(4) Grid Settings Analysis

The accuracy of numerical calculation of tunnel fires is closely related to grid division. Among them, the characteristic diameter of the fire source is the main parameter for evaluating the grid, as shown in equation (17).

$$D* = \left(Q/\left(\rho_\infty \bullet C_p \bullet T_\infty \bullet \sqrt{g}\right) \right)^{0.4} \tag{17}$$

in the grid division, considering the drastic changes in smoke flow in the tunnel fire area, the grid near the fire source area was locally densified. Considering the large length to width ratio of highway tunnels, the grid size can be appropriately scaled up in areas far from the fire source. The grid size in the no fire source area is 1.0 m × 0.5 m × 0.5 m, grid refinement in the fire source area [29,30], using 0.2 m × 0.5 m × A grid of 0.5 m.

(5) Location of measurement points

The characteristic height of the human eye is generally between 1.2 and 1.8 m. A height of 1.6 m above ground level on the center line of the tunnel was selected as the location for monitoring the characteristic line. 18 characteristic points were further selected upstream and downstream of the fire, as shown in Fig. 2, and this was used to analyse the changes in fire smoke height, visibility, temperature and CO concentration at the characteristic height of the human eye.

(6) Initial and boundary conditions

The model wall is considered as an adiabatic surface, The thickness is 0.3 m, Its physical parameters are as follows: thermal conductivity of 1.8 W/(m·K)、specific heat of 1.04 kJ (kg·K)、density of 2280 kg/ m^3, the ambient temperature is set to 20 °C, the relative humidity to 50 % and the ambient pressure to 101.3 kPa, the gravity acceleration value is 9.81 m/ s^2, and the direction is vertical and downward, other defaults. The exhaust air outlet is defined as the velocity boundary "exhaust" and the velocity is 4 m/s 0.9 kg/m^2 is chosen as the air density for calculation, the simulation duration is set to 900s.

3.2. Discounted evacuation speed

FDS is used to calculate smoke spread, visibility and temperature distribution in case of fire in the tunnel. According to the "China Fire Protection Manual, Volume III, Fire Protection Planning, Public Fire Protection Facilities, and Building Fire Protection Design", the criteria for determining the available safe evacuation time are that the smoke temperature at the characteristic height within the tunnel does not exceed 60 °C, the visibility is not less than 10 m, and the CO concentration does not exceed 0.1 %, which is considered as the safe range that personnel can withstand, and exceeding this range will cause harm to personnel's physical health.

Fig. 3 shows the smoke dispersion cloud map of the tunnel fire, from the figure can be seen in the early stage of the fire, the fire smoke has not yet gathered, the temperature has not obviously risen, the speed of personnel discount value change is not large, can be ignored; 300s later the smoke spread throughout the tunnel, the air CO concentration increased, the temperature obviously rose, visibility reduced, personnel evacuation speed is affected. From equation (3) to (5), it can be seen that when the attenuation coefficient exceeds 0.35, the CO concentration exceeds 0.1 %, and the smoke temperature reaches 60 °C, the smoke causes great harm to human psychology and physiology, and personnel affected by CO will suffer from poisoning and respiratory burns, and the evacuation speed is significantly reduced, and one discount value is recorded; When the attenuation coefficient exceeds 1.20, the CO concentration rises to 0.4 %, and the smoke when the light reduction factor exceeds 1.20, the CO concentration rises to 0.4 % and the temperature of the smoke reaches 120 °C, it is enough to pose a threat to the life of the personnel and a discount value is recorded.

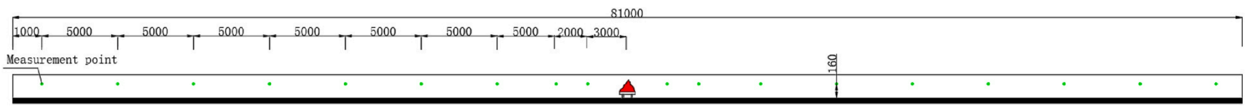


Fig. 2. Tunnel model measurement point layout.

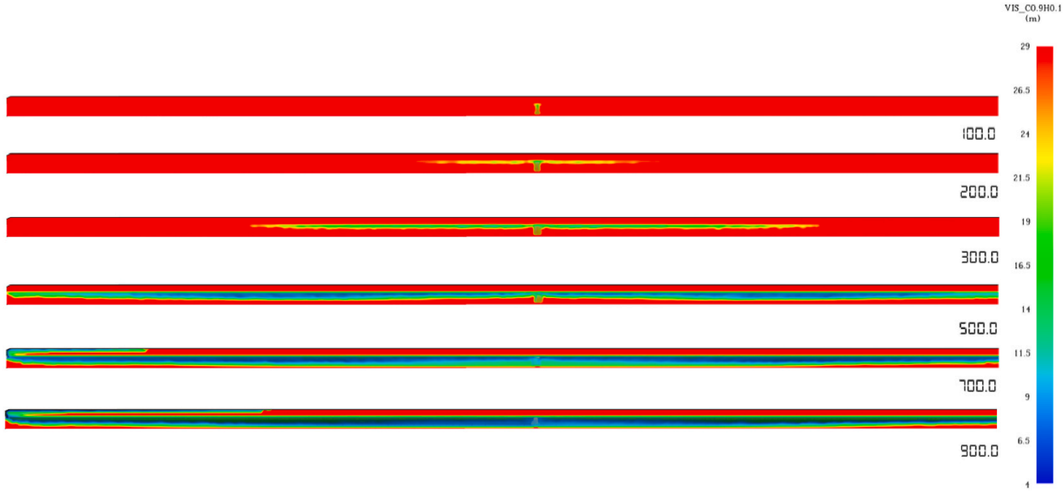
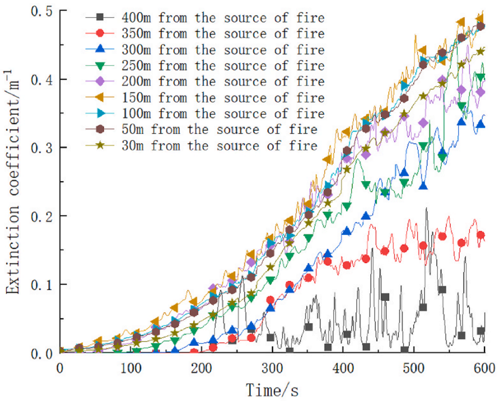
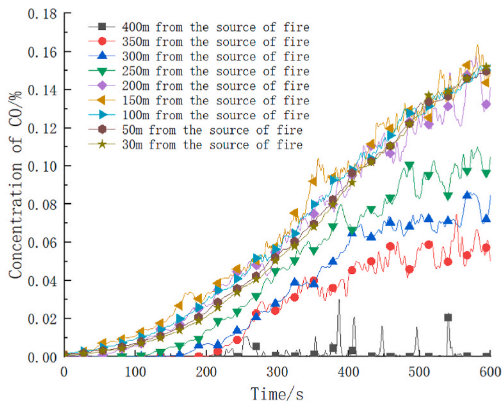


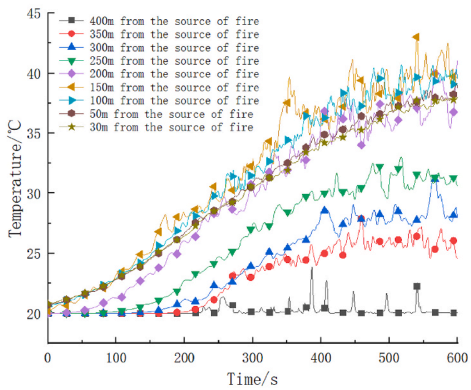
Fig. 3. Tunnel fire smoke dispersion cloud.



（a）Variation of extinction coefficient at different distances from the fire source



（b）Variation of CO concentration at different distances from the fire source



（c）Graph of temperature variation at different distances from the fire source

Fig. 4. Plot of fire products versus time at different moments away from the fire source
(*a*)Variation of extinction coefficient at different distances from the fire source
(b)Variation of CO concentration at different distances from the fire source
(c)Graph of temperature variation at different distances from the fire source.

By analyzing the results of the numerical fire simulation, the relationship between fire product and time is derived as shown in Fig. 4 (a)~(c), which is then combined with equation (2) ~ (5) to derive the discounted evacuation velocity δ at different locations at different distances, as shown in Table 1 from Fig. 4 (b) it can be seen that at 680s the CO concentration reaches 0.1 % at 30 m from the fire source, the evacuation of personnel is affected by the fire products and the evacuation speed is significantly reduced, a discount factor needs to be recorded, according to equation (3)~(5) it is calculated that at this time $f_1(T_s) = 0.932, f_2(\rho_{co}) = 0.821, f_3(K_s) = 0.834$, from equation (2) it is calculated that at 540s the distance from the fire source The discounted value of velocity at 30 m $\delta = 0.638$.

4. Mathematical model solving and simulation verification

4.1. Evacuation model assumptions

A road tunnel in Hangzhou is used as the object of study and the above mathematical model is applied to study the evacuation of people. To facilitate the study, the following basic assumptions are made on the model:

(1) The location of evacuees in the tunnel is randomly distributed.
(2) The reaction time of all personnel after a fire is consistent and they have some awareness of the escape route.
(3) The evacuation speed of all evacuees under comfortable conditions is set according to their age group, and the specific evacuation speed is shown in Table 3.
(4) The effect of the side rails of the evacuation platform on the evacuation process is ignored.

4.2. Determination of evacuation zones and setting of personnel parameters

The mathematical model developed above is used to study the evacuation of people from a specific tunnel. It is assumed that in the event of a fire in a tunnel, traffic is blocked, vehicles cannot move and people have to get out of their cars to escape, the safety of evacuation depends mainly on the available safe evacuation time ASET and the necessary safe evacuation time RSET.

The RSET in an emergency includes the fire detection alarm time, the personnel pre-action time and the personnel evacuation movement time, the first two of which are usually referred to collectively as the personnel evacuation response time. A "domino" phase effect was introduced, dividing the tunnel into different response time zones according to the location of the fire source [31]. The area closest to the source of the fire, where personnel detect the fire by smelling the odour or seeing the flames and smoke and respond quickly, with a response time set at 30s [32]; People in other areas are mainly detected by fire alarms. The fire detection alarm time is set to 60s and the average value of the pre-action time is increased by 13s in turn, and the evacuation response time for each area is considered to be a maximum of 120s when the tunnel is fully equipped. The evacuation zones are divided according to the evacuation response time, the overall length of the tunnel and the distribution of evacuation routes. The corresponding evacuation response time is shown in Table 2.

According to the research results of Capote J A [33], the evacuation response time is divided by a length of 40 m, and the evacuation zones are divided according to the evacuation response time. When the fire burning position is at the midpoint of the simulation interval, personnel can only choose the nearest pedestrian passage for evacuation based on their own location. At this time, the longest evacuation distance for personnel is the most unfavorable situation. See Fig. 5 for evacuation zones and personnel evacuation directions.

According to the 2019 National Economic and Social Development Statistical Bulletin [34], the personnel composition and

Table 1
Discounted evacuation speed at different locations from the fire source.

Location	Time/s	Speed discount decrease in speed	$f_1(T_s)$	$f_2(\rho_{co})$	$f_3(K_s)$	δ
30 m from the source of the fire	280	Significantly lower	0.932	0.821	0.834	0.638
	510	Pose a threat to life	0.685	0.373	0.344	0.1
50 m from the source of the fire	287	Significantly lower	0.905	0.823	0.869	0.647
	515	Pose a threat to life	0.686	0.319	0.303	0.1
100 m from the source of the fire	380	Significantly lower	0.942	0.805	0.864	0.655
	511	Pose a threat to life	0.682	0.332	0.331	0.1
150 m from the source of the fire	361	Significantly lower	0.915	0.812	0.860	0.639
	590	Pose a threat to life	0.675	0.362	0.342	0.1
200 m from the source of the fire	490	Significantly lower	0.944	0.839	0.861	0.682
	559	Pose a threat to life	0.717	0.399	0.429	0.123
250 m from the source of the fire	420	Significantly lower	0.936	0.820	0.883	0.685
	559	Pose a threat to life	0.742	0.447	0.518	0.172
300 m from the source of the fire	420	Significantly lower	0.902	0.814	0.889	0.653
	600	Pose a threat to life	0.752	0.647	0.720	0.350
350 m from the source of the fire	450	Significantly lower	1	0.803	0.917	0.736
	600	Pose a threat to life	1	0.801	0.909	0.728
450 m from the source of the fire	486	Significantly lower	1	0.896	0.922	0.734
	600	Pose a threat to life	1	0.922	0.997	0.919

Table 2
Evacuation response times by region.

Region	Longitudinal distance from source of fire/m	Fire detection Alarm time/s	Personnel pre-action Operating hours/s	Evacuation response Time t_4/s
m_5、m_6	0–40	–	30	30
m_4、m_7	40–80	60	43	103
m_3、m_8	80–120	60	56	116
m_2、m_9	120–200	60	60	120
m_1、m_{10}	200–400	60	60	120

Table 3
Proportion of different types of personnel and movement parameters.

Type of personnel	Young people	Middle age	Old age
Proportions	60 %	20 %	20 %
Movement speed/m/s	1.2	1.1	0.9
Lift height and shoulder width/cm	178/41.7	170/38.2	167/35.6

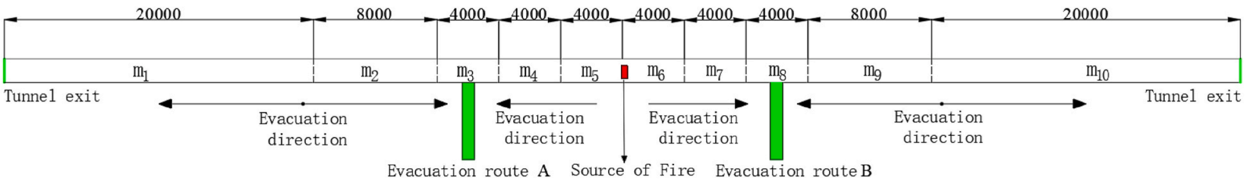


Fig. 5. Diagram of the distribution of evacuation regions and evacuation directions.

proportion are set at 36 % for males, 35 % for females, 17 % for children, and 12 % for the elderly. Evacuation speed values for different types of personnel are obtained based on the recommended walking speed and physical characteristics in the UK SFPE Handbook for Fire Engineering [35]. The specific parameters are shown in Table 3.

During the simulation, blocked vehicles serve as obstacles, taking into account the most unfavorable conditions for personnel evacuation under traffic congestion. The passenger capacity of the vehicles is set based on the research results of Wang Jie et al. [36]. The distance between vehicles is set to 1.5 m and 2.0 m respectively according to the size of the vehicle model. The types and proportions of vehicles in the tunnel are shown in Table 4.

4.3. Calculation of evacuation time

Using the real situation in this tunnel with the fire simulation data, the evacuation time is solved according to equations (1)–(16). The width of the evacuation passageway w is known to be 2 m, and the overall width of the tunnel is 15.2 m. Based on the distribution of evacuation zones in the tunnel in Table 2, the area A of each evacuation zone can be calculated A_m.

The actual measurement shows that the average thickness b_0 of young people is 0.25 m, the average projection area is 0.16 m^2, the average projection area of middle-aged and elderly people is 0.14 and 0.12 m^2 respectively, then the evacuees projection area f = 0.148 m^2, the free walking distance between the crowd d_0 is taken as 0.5 m.

According to hypothesis (1), the random distribution of evacuees in the tunnel and the types and proportions of no accessible vehicles in Table 4, the random distribution of vehicles in the tunnel is carried out, and the number of passengers in each evacuation zone is obtained. By substituting the data into formula (8), the population density p in each evacuation zone can be calculated p_m , please refer to Table 5 for details.

According to the distribution of each evacuation zone in Table 2, the maximum distance a from each evacuation zone to the tunnel exit can be calculated. At the same time, combining the movement speed of evacuated personnel under normal conditions in Table 3 with the speed reduction coefficient value delta of each evacuation zone under the influence of fire products in Table 1, and substituting it into Formula (1), the evacuation movement speed of personnel under fire scenarios can be calculated v_1.According to

Table 4
Types and proportions of vehicles.

Type of vehicle	Pickup truck	Medium goods vehicle	Large truck	Minibus	Medium bus	Coach	Private Car
Number	24	9	12	20	16	16	72
Length of car/m	4.5	6.0	12	6.0	8.0	12.0	3.5
Max. number of passengers/person	2	2	2	6	24	50	4

Table 5
Crowd density by evacuation zone p_0

Evacuation Zones	Number of people in evacuation zones/n	Pedestrian spacing d_0/m	Intercrowd thickness b_0/m	Width of evacuation route w/m	Density of foot traffic p_0
m_1	291	0.5	0.25	2	0.197
m_2	242				0.198
m_3	122				0.198
m_4	108				0.199
m_5	119				0.198
m_6	128				0.198
m_7	124				0.198
m_8	121				0.198
m_9	231				0.198
m_{10}	287				0.198

formula (11)$t_1 = \frac{a}{v_1}$, It is possible to calculate the time for personnel in each evacuation zone to move to the evacuation passageway in the event of a fire t_1, the specific results are shown in Table 6.

From Table 5, it can be seen that the density of evacuated people in evacuation zone m_2 is 0.198, and the evacuation speed v_2 of evacuated people in evacuation zone m_2 is 0.668 m/s in the horizontal channel in case of emergency by substituting formula (10); the effective width of evacuation channel A is 2 m; then the blocking time t_2 of people in evacuation zone m_2 at the entrance of evacuation channel by substituting formula (13) is 132.56s.

Table 5 shows that the total number of people in the evacuation zone m_2 is 242; the total length of the evacuation channel is 20 m; then substituting into equation (14) gives the time $t_3 = 29.94$s for evacuees to pass through the horizontal evacuation channel in case of emergency.

Substituting the above calculation results into Equation (16), the total evacuation time T_m for this road tunnel in a fire scenario is:

$$T_m = t_1 + t_2 + t_3 + t_4 = 476.54s$$

4.4. Evacuation simulation verification

Compare the simulation process and results with the results calculated by the mathematical model of personnel evacuation. Based on the actual size of the highway tunnel, a single hole bidirectional highway tunnel evacuation model with a length of 810 m and a width of 15.2 m is constructed using Pathfinder software. According to hypothesis (3), randomly place vehicles and maintain a distance of 1.5 m between the front and rear of the large vehicle and 1 m between the front and rear of the small vehicle. By setting parameters such as the number of people inside the vehicle, vehicle size, and quantity in Table 4, a total of 1773 people were evacuated from the tunnel. At the beginning of evacuation, when a fire occurs and the vehicle stops in the middle of the section tunnel, the evacuees must first evacuate to the outside of the vehicle, and then select the corresponding evacuation passageway based on the distance from themselves to the exit.

The evacuation of people is simulated by Pathfinder, a software based on evacuation dynamics, which provides a virtual simulation of the movement of people by setting the appropriate parameters (walking speed, shoulder width, exit selection, etc.) for each evacuee in the group and setting the mode of escape of people. In Pathfinder 2019, a new function of area personnel speed modifier has been added, as shown in Fig. 6. In order to establish the evacuation model of personnel under the influence of fire products, the velocity discount value \delta obtained from Table 1 is input into the velocity modifier module of Pathfinder software, and the evacuation response time of personnel in each partition is set according to Table 2.

To achieve the safety goal of ensuring personnel evacuation, that is, to ensure that when a fire occurs, all affected personnel in the fire tunnel section can leave the fire hazard control area and reach a safe location through a safe path before the danger arrives. During the simulation, when highway tunnel personnel evacuate through the evacuation passageway within the available safety time in the event of a fire, it is considered that the personnel have reached a safe location and completed the evacuation goal. The evacuation

Table 6
Evacuation time in horizontal places under fire scenarios t_1

Evacuation Zones	Speed discount factor values δ	Speed of movement v_1/m^2	Maximum distance to exit a/m	t_1/s
m_1	0.656	0.787	150	197.87
m_2	0.682	0.818	155.74	194.04
m_3	0.639	0.767	25.12	36.31
m_4	0.655	0.786	61.90	89.40
m_5	0.638	0.766	101.15	134.22
m_6	0.656	0.787	150	199.84
m_7	0.682	0.818	155.74	195.21
m_8	0.639	0.767	25.12	39.70
m_9	0.655	0.786	61.90	88.43
m_{10}	0.638	0.766	101.15	137.71

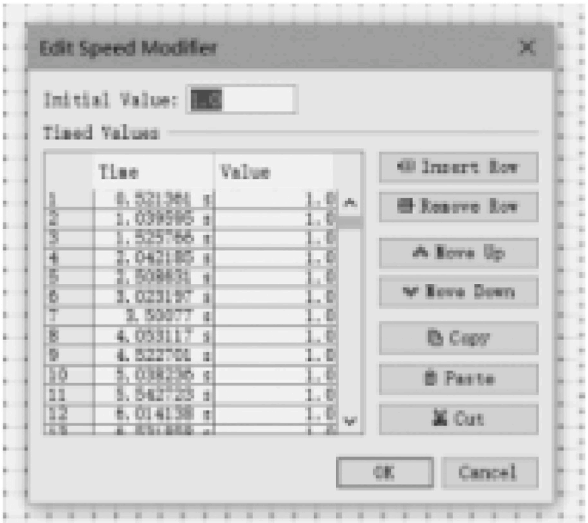
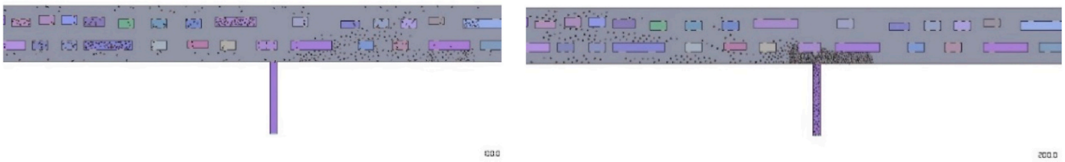


Fig. 6. Speed modifier.



（a）Evacuation situation at evacuation route A at 100s （b）Evacuation situation at evacuation route A at 200s

Fig. 7. Simulation of evacuation process
(*a*)Evacuation situation at evacuation route A at 100s (b)Evacuation situation at evacuation route A at 200s.

simulation process is shown in Fig. 7(a)and (b).

As can be seen in Fig. 8 the total evacuation time is 480.3 s. The simulation results are consistent with the calculated time of 472.91 s from the mathematical model, with an error of 1.54 %. The evacuation rate is basically the same within 280.0 s from the beginning of the evacuation. After 280.0 s, the visibility value decreases and the evacuation rate starts to decrease due to the rapid spread of fire smoke.

As can be seen from Fig. 9- Fig. 11, the evacuation channel evacuation is divided into 4 stages: (1) when the evacuation just started, the response time of the personnel in evacuation partition m_5、m_6 is short, and they are the first to start evacuating. As can be seen in Fig. 9 103s later, the rest of the evacuation partition personnel discover the fire through the fire alarm and evacuate to the safety area one after another, at this time, the density of personnel at the entrance of the evacuation channel is low, there is no blockage phenomenon, and the evacuation time is not affected by the density of personnel The evacuation time is not affected by the density of people, but by the evacuation speed and distance. (2) With the increase of time, a large number of people move to the evacuation channel, the crowd density at the entrance of the evacuation channel rises rapidly and the crowding phenomenon begins to appear, the evacuation channel A starts to block at 139.7s, and the evacuation channel B starts to block at 135.3s. As can be seen from Fig. 10, the crowding phenomenon is more serious at the entrance of the evacuation channel at this time, while the density of people at the far end is low, and the evacuation time still depends on the evacuation speed and distance. (3) As the density of people continues to increase, the evacuation time depends on the blockage time. The blocked crowd forms an externally closed arch-shaped crowd structure, as shown in Fig. 11, at which time the arch-shaped crowd structure is in dynamic equilibrium. Once people enter the evacuation channel inside the arch-shaped structure, the dynamic equilibrium is broken, after which the blocked flow quickly moves forward to form the arch-shaped structure again and restore the equilibrium. (4) As the number of evacuees increases, the crowd density at the entrance of the evacuation channel decreases, the arch-shaped crowd structure disappears, the dynamic equilibrium is broken, and the evacuation time is again determined by the evacuation speed and distance. It is recommended to optimize the emergency broadcasting system in the tunnel, broadcast regularly after a fire, guide evacuation personnel near the fire source to evacuate to other relatively unobstructed exits, alleviate congestion, improve the utilization rate of other evacuation channels, and reduce personnel evacuation time. At the same time, measures should be taken to control the scale of fires in a timely manner and avoid their spread. Strong smoke exhaust facilities should be used to prevent the worsening of disasters from causing panic among evacuees and exacerbating congestion. Case studies have shown that establishing a fire compartment smoke exhaust strategy is the most effective measure to assist in emergency evacuation of platform fires

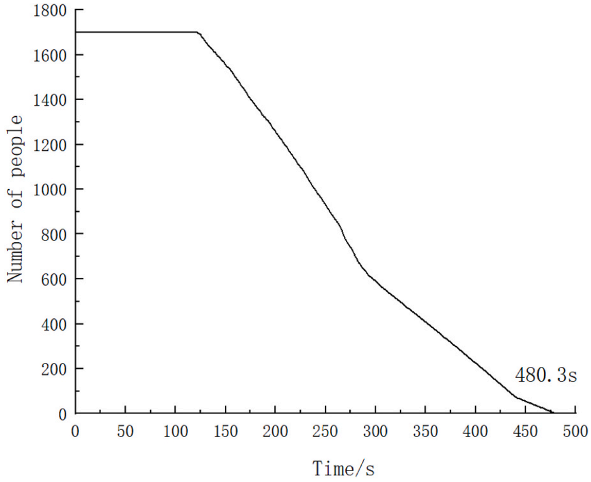


Fig. 8. The number of evacuees as a function of time.

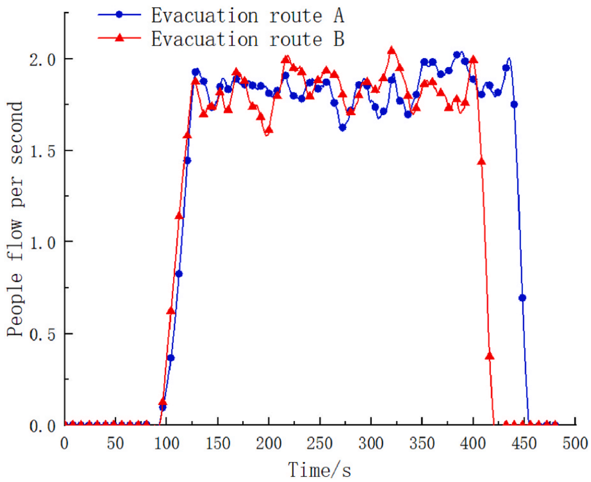


Fig. 9. The relationship between the change of human flow at evacuation channel A and B.

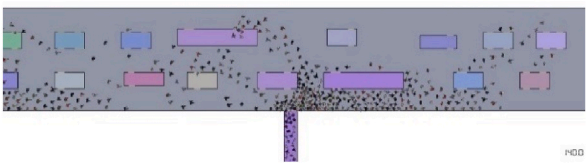


Fig. 10. Density of people at evacuation route A at 140s.

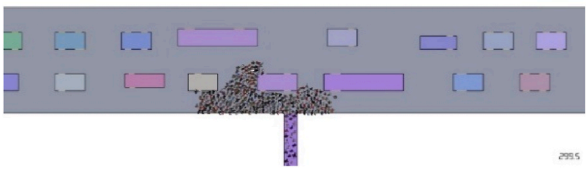


Fig. 11. Arch-shaped pedestrian flow structure at evacuation channel A.

The location of the crowdіng phenomenon can be predicted by equation (9) in the evacuation mathematical model, and the crowding phenomenon occurs when the crowd density exceeds 0.92 [16], and the duration of the crowding phenomenon can be calculated according to equation (13). In this tunnel model, the crowd density at the exit of the left and right ends of the tunnel is always lower than 0.92, and there is no crowding phenomenon; the crowd density reaches 0.969 at 137.9s in evacuation passage A, and 0.942 at 135.3s in evacuation passage B. The crowding phenomenon occurs, and the duration of crowding phenomenon t_2 is calculated according to Equation (13) as 300.07s and 277.71s, which is basically consistent with the crowding duration of 300s and 283s from Pathfinder simulation, confirming the reasonableness of the established mathematical evacuation model.

5. Conclusion

(1) Based on the effects of movement speed and personnel density on the evacuation of road tunnel personnel, the degree of injury to human body by fire products is quantified by the formula, and the mathematical model of evacuation of road tunnel personnel under the influence of fire products is established, the model calculation is simple and convenient, and this method can be closer to the results of personnel evacuation in real fire scenarios.

(2) The evacuation time calculated through examples is basically consistent with the time simulated by Pathfinder, with an error of only 0.77 %, indicating that the established model is reasonable and can provide guidance for emergency evacuation of highway tunnel fires. (3)Research findings the road tunnel evacuation process is divided into four phases:① Smaller density of people at evacuation routes, evacuation time determined by the speed and distance of movement; ② The density of people at the entrance of the passage increases, but the overall density of people is still lower than the capacity of the evacuation passage, and the evacuation time still depends on the movement speed and distance; ③ When the density of people reaches a certain level, gradually forming an arch-shaped pedestrian flow structure, evacuation time mainly depends on the blockage time; ④ As the number of evacuees increases, the arch-shaped crowd structure gradually disappears and the evacuation time is again determined by the evacuation speed and distance. By analyzing the four processes of highway tunnel evacuation, it can provide certain reference for daily fire supervision and personnel evacuation guidance in emergency situations.

(4) The model can not only predict the location of the crowding phenomenon by equation (9) in the evacuation mathematical model, but also calculate the duration of the crowding phenomenon according to equation (13) when the crowding density exceeds 0.92. Provide theoretical support for optimizing personnel evacuation plans in highway tunnels.

(5) Research has shown that using formulas to quantify the reduction of evacuation speed in the fire environment is a simple and feasible method. Based on the degree of harm caused by fire smoke to the human body, it is converted into equivalent speed, changing the previous constant setting of evacuation speed, and providing reference for subsequent evacuation research under multiple factors. The research mainly focuses on the impact of fire products and personnel density on evacuation speed, and there are many factors that affect evacuation efficiency. In subsequent research, psychological changes of evacuation personnel, such as panic psychology and negative psychology, can also be comprehensively considered to affect evacuation speed.

CRediT authorship contribution statement

Shuchuan Zhang: Conceived and designed the experiments. **ziyan Zhu:** Conceived and designed the experiments, Contributed reagents, materials, Formal analysis, Wrote the paper. **Zheng Haotian:** Analyzed and interpreted the data. **Zhang Huanhuan:** Performed the experiments; Contributed reagents, materials, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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