Study on Tunnel Fire Smoke Control and Transverse Passageway Interval under Traffic Congestion

Shuai Liu*
1China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd., Chongqing, 400067, China
*Corresponding author’s e-mail: liushuai@cmhk.com

Abstract: When there are traffic jams in the tunnel, if the critical velocity is used for longitudinal smoke exhaust, it will pose a threat to the vehicles and people congested downstream. Using FDS + EVAC for numerical simulation, this paper has studied the fire smoke control strategies and transverse passageway intervals. The results show that: (1) When there is congestion at the downstream of the fire source, excessive longitudinal smoke exhaust will reduce the available safe evacuation time (ASET) in the downstream area of the fire source, and the longitudinal velocity should be controlled within 1 m/s. (2) When the transverse passageway for vehicles cannot be used for evacuation, the time necessary for safe evacuation increases by 43%. In order to ensure the safe evacuation, the transverse passageway intervals should be no more than 400m, and the transverse passageway for vehicles should have the function of pedestrian evacuation.

1. Introduction
With the rapid development of city construction, the population gradually grows, and the land for construction is increasingly in urgent need. In order to ensure the rapid and efficient running of the city, more and more tunnels have been built. Although the tunnel greatly relieves the pressure of urban traffic congestion, it also brings potential safety hazards to operations. Among them, fire is one of the biggest threats to the safety operation of tunnels. Tunnel is a long and narrow semi-closed structure. If the high temperature and dense smoke generated by fire are not discharged quickly, it will often lead to casualties. In order to solve this problem, the tunnel is usually equipped with smoke exhaust system and escape exit. Most tunnels are equipped with jet fans, and the smoke flow is controlled by longitudinal smoke exhaust [1]. Transverse passageways between two adjacent traffic lanes of the tunnel are used for escape and evacuation [2]. The longitudinal smoke exhaust system forms longitudinal airflow in the tunnel to ensure that the fire smoke does not flow back to the upstream of the fire source. Under normal circumstances, people at the upstream of the fire source can be evacuated to the adjacent tunnel through the transverse passageway, while those at the downstream of the fire source can be evacuated to the outside of the tunnel by driving. The longitudinal velocity should be greater than the critical velocity [3].

However, with the rapid growth of car ownership in cities, traffic congestion in tunnels occurs frequently, especially in the morning-evening rush hours. When there is congestion in the tunnel, a large number of vehicles move slowly or even come to a standstill, which greatly changes the smoke flow environment in the tunnel. This will lead to the change of the smoke spreading characteristics of tunnel fire [4]. By means of numerical simulation and scale test, a series of studies have been conducted previously on the influence of vehicle obstacles on longitudinal smoke exhaust when there...
is a fire in a longitudinal ventilation tunnel. Through numerical simulation, Junli Luo et al. discussed the influence of traffic congestion on smoke spreading in longitudinal ventilation tunnels, including the influence of different area ratio, position and length of congestion on smoke spreading [5]. Through scaled (1:5) model test and numerical simulation, Na Meng et al. studied the influence of congestion on critical velocity and counterflow length in the fire breaking out in longitudinal ventilation tunnels[6]. F. Tang et al. studied the influence of the distance between the obstacle and the fire source on the highest temperature and the thickness of the smoke layer at the top[7]. W. Tang et al., by conducting experiments in a model tunnel, studied the influence of congestion upstream of the fire source on the counterflow length and critical velocity of smoke in a longitudinal ventilation tunnel, and provided a global prediction model[8]. Through numerical simulation, Merve Altay et al. studied the influence of congestion at the upstream and downstream of the fire source on the smoke spreading and counterflow length respectively, and estimated the critical velocity when there is congestion in a tunnel fire[9]. Through numerical simulation, Soufien Gannouni et al. studied the influence of the height of the obstacle upstream of the fire source from the ground on the critical velocity and counterflow length[10]. Through scaled tests, L.H. Hu et al. obtained the non-dimensional equation of the highest temperature of the top smoke layer with different obstacles and distances from the fire source[11]. Through numerical simulation, S. Bari studied the spreading of smoke from burning vehicles and exhaust pollutants from jammed vehicles in tunnels[12]. In fact, the above-mentioned studies mainly consider the influence of jammed vehicles upstream of the fire source on smoke spreading. However, when there is congestion downstream of the fire source, vehicles downstream of the fire source can no longer drive out of the tunnel quickly. If the smoke control plan under normal circumstances is adopted again, it will pose a threat to the safety of people downstream of the fire source. There are no relevant studies on how to control fire smoke under such circumstances.

In this paper, FDS + EVAC is used for numerical simulation. First, the available safe evacuation time of congested tunnel fires at different longitudinal smoke exhaust velocity is calculated, and then the evacuation time is calculated to obtain the smoke control strategy of tunnel fires under traffic congestion. Considering the smoke control effect, a plan for setting the transverse passageway intervals is proposed.

2. Model Establishment and Working Condition Design

2.1 Simulation Computation of Smoke Movement

The section of the numerical simulation computation model of smoke movement is set according to the full size of the actual section of the tunnel, with a height of 7.25 m and a width of 11.75 m. The length of the model takes into account both the smoke spreading range and the amount of numerical simulation computation, adopts 1100m, as shown in Figure 1. The length of congestion is 1000m. The fire source is located at X=120m with the size of 12m (length) × 2.5 m (width) × 4m (height). As a large truck is simulated to catch fire, the maximum heat release rate is 30MW. The growth curve of heat release rate adopts ultra-fast t^2 growth fire. The size of computational grid is 0.5 m (length) × 0.25 m (width) × 0.25 m (height). The computation working conditions mainly consider the change of longitudinal smoke exhaust velocity. The specific computation conditions are shown in Table 1.
| Serial No. | Fire Size (MW) | Smoke Exhaust Velocity (m/s) |
|-----------|---------------|-----------------------------|
| A-1       | 30            | 0                           |
| A-2       | 30            | 0.5                         |
| A-3       | 30            | 1                           |
| A-4       | 30            | 1.5                         |
| A-5       | 30            | 2.0                         |
| A-6       | 30            | 2.5                         |
| A-7       | 30            | 3.0                         |
| A-8       | 30            | 3.5                         |

2.2 Simulation Computation of Evacuation

The evacuation simulation computation scenario adopts the same fire scenario as the previous fire smoke movement simulation computation, with a total model length of 1100m and a congestion distance of 1000m. The distance between congested vehicles is considered as 2m, the proportion of vehicle type is determined according to the actual traffic flow, and the length of different vehicle types is determined based on the realities. Considering the most unfavorable situation, it is assumed that each vehicle is fully loaded with passengers, specifically, each truck carrying 2 people, each small bus carrying 5 people, and each big bus carrying 48 people. After calculation, it shows the number of people who need to be evacuated due to congestion in the tunnel, which is as shown in Table 2. The evacuation computation model is as shown in Figure 2.

| Item               | Pickup truck | Medium truck | Big truck | Trailer | Small bus | Big bus |
|--------------------|--------------|--------------|-----------|---------|-----------|---------|
| Proportion of vehicle type | 16.11%       | 10.16%       | 17.58%    | 7.32%   | 36.62%    | 12.21%  |
| Length of single unit vehicle(m) | 6            | 8            | 12        | 18      | 6         | 13      |
| Number of vehicles | 30           | 18           | 32        | 13      | 67        | 23      |
| Number of people in each vehicle | 2            | 2            | 2         | 2       | 5         | 48      |
| Total number of people in tunnel | 1577         |              |           |         |           |         |

Figure 2 Computation Model of Tunnel Fire Evacuation

In the simulation computation of evacuation, the computation working conditions mainly consider the transverse passageway intervals. Table 3 shows the specific computation working conditions. B1 ~ 6 in Table 3 mainly consider different transverse passageway intervals. In actual projects, the tunnel is equipped with both pedestrian passageways and vehicle passageways, and usually one vehicle passageway is provided every two pedestrian passageways. The vehicle transverse passageway is equipped with fire resistant shutter which is used to prevent smoke moving from fire tunnels to non-fire tunnels. If people need to be evacuated through the pedestrian transverse passageways, the fire-resistant shutter of the vehicle transverse passageways must be opened, which may easily cause the fire smoke enter the non-fire tunnels. Therefore, designing the B-7 working condition, this study...
considers not to open the fire-resistant shutter, and explore whether the evacuation through pedestrian passageway alone can meet the safety requirements when the vehicle transverse passageways are not used for evacuation,

| Serial No. | Number of people evacuated | Transverse passageway interval (m) | Notes |
|------------|----------------------------|-----------------------------------|-------|
| B-1        | 1577                       | 250                               |       |
| B-2        | 1577                       | 300                               |       |
| B-3        | 1577                       | 350                               |       |
| B-4        | 1577                       | 400                               |       |
| B-5        | 1577                       | 450                               |       |
| B-6        | 1577                       | 500                               |       |
| B-7        | 1577                       | 250, 500, 250                     |       |

Table 3. Computation Working Conditions of Tunnel Evacuation.

3. Results Analysis

The available safe evacuation time ASET can be obtained through FDS by calculating when the internal environmental parameters in the tunnel exceed the critical safety index. The critical safety index is as shown in Table 4. When the tunnel environmental conditions exceed any safety index, it is considered that the critical value of safe evacuation is reached, and this moment is regarded as the available safe evacuation time. Table 5 shows the calculation results of available safe evacuation time when different longitudinal smoke exhaust velocity is adopted under the condition of tunnel congestion.

| Serial No. | A-1 | A-2 | A-3 | A-4 | A-5 | A-6 | A-7 | A-8 |
|------------|-----|-----|-----|-----|-----|-----|-----|-----|
| Available evacuation time (s) | 660 | 559 | 557 | 388 | 383 | 381 | 363 | 359 |

Table 4. The Critical Safety Index of Evacuation.

| Item        | Criterion                                                                 |
|------------|---------------------------------------------------------------------------|
| Temperature| The temperature at a height of 1.8 m above the ground is less than 60℃. |
| Toxic gas  | At a height of 1.8 m above the ground, the volume concentration of CO is less than 1500ppm. |
| Visibility | At a height of 1.8 m above the ground, it is no less than 10m.             |

Table 5. Calculation Results of Available Safe Evacuation Time.

The available safe evacuation time is obtained by EVAC calculation. The calculation process is as shown in Figure 3 and the calculation result is as shown in Table 6.

Figure 3. Tunnel evacuation route map.

| Serial No. | B-1 | B-2 | B-3 | B-4 | B-5 | B-6 | B-7 |
|------------|-----|-----|-----|-----|-----|-----|-----|
| Available evacuation time (s) | 346 | 374 | 399 | 433 | 460 | 495 | 495 |

Table 6. Calculation Results of Necessary Time for Safe Evacuation in the Tunnel.

In terms of evacuation time, with the increase of transverse passageway interval, REST increases accordingly. Particularly, when the transverse passageway (the transverse passageway interval is 250 m) for vehicles cannot be used for evacuation, the time necessary for safe evacuation increases by
Considering the available safe evacuation time, when the smoke exhaust velocity is no more than 1 m/s, the ASET is longer than 557 s. When the transverse passageway interval is no more than 500 m, the necessary time for safe evacuation in the tunnel must be less than 500 s. That is to say, theoretically, when the transverse passageway interval of the tunnel is between 250 m and 500 m, and the smoke exhaust velocity of the tunnel is no more than 1 m/s, people in the tunnel have sufficient time to evacuate to the safety zone. However, when the transverse passageway interval is greater than or equal to 400m or the vehicle transverse passageways cannot be used for evacuation, there is relatively less safety margin time for evacuation from the tunnel. It means that in order to ensure the safe evacuation, the transverse passageway intervals should be no more than 400m, and the transverse passageway for vehicles should have the function of pedestrian evacuation.

4. Conclusions

1. When there is congestion at the downstream of the fire source, excessive longitudinal smoke exhaust will reduce the available safe evacuation time (ASET) in the downstream area of the fire source, and the longitudinal velocity should be controlled within 1 m/s.

2. When the transverse passageway (the transverse passageway interval is 250 m) for vehicles cannot be used for evacuation, the time necessary for safe evacuation increases by 43%. In order to ensure the safe evacuation, the transverse passageway intervals should be no more than 400 m, and the transverse passageway for vehicles should have the function of pedestrian evacuation.

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