AHP and Casualties Calculation Based Research on Road Tunnel Fire Risk Evaluation

Yangyuyu Xia1*, Bufan Wang2 and Fei Ma1
1China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd., Chongqing, 400067, China
2Chongqing Jiaotong University, Chongqing 400074, China
*Corresponding author’s e-mail: xiayangyuyu@163.com

Abstract: On the basis of classic risk theories this paper proposes a more pertinent and practical fire evaluation model for road tunnels. According to causes for tunnel fire, an index system for assessment of tunnel fire probability and rating criteria are established based on tunnel properties, environmental conditions, traffic status and vehicle performance. By fine modelling of tunnel fire smoke spread and personnel escape behaviour, a calculation method and rating criteria for consequences of tunnel fire are established. The research results suggest this method is a feasible means to assess road tunnel fire risks.

1. Introduction

As of the end of 2017 a total of 16,229 highway tunnels covering 15285.1km had been in service in China, and highway tunnels are increasing at a rate of more than 10% a year [1]. The number of urban tunnels had exceeded 1,000. As cities grow the number and length of tunnels will keep increasing in quite a long time. Currently China has the most urban tunnels and the greatest total length of tunnels in operation in the world.

A tunnel is a semi-concealed structure with almost-enclosed space. In the event of a tunnel fire, personnel escape and rescue are more difficult than from other buildings. In addition, the poor ability to dissipate heat and remove smoke from the tunnel increases the destructiveness and hazard level of tunnel fire accidents [2]. It is therefore necessary to study how to assess road tunnel fire risk and increase operating safety of the tunnels.

Existing research on assessment of road tunnel fire risk is generally divided into two categories. One is to conduct study of influencing factors of fire accidents, select key indicators to establish corresponding assessment criteria and then establish an index system for assessment [3, 4]. However, such methods cannot take into account specific fire scenes and their assessment results cannot correspond to accident consequences such as casualties. The other is to introduce classic theories, obtain probability characteristics through statistical analysis of past fire accidents, study consequences of fire accidents and make assessment using the definition of risk [5, 6]. Basic data for such methods are sometimes difficult to obtain; meanwhile, application of large sample data to specific system objects may lead to misleading estimate.

Based on the above two categories of methods and classic risk theories, this paper proposes a new risk assessment model for road tunnel fire to provide reference for scientific and suitable assessment of road tunnel fire risk.
2. Process of Tunnel Fire Risk Assessment

Risk is a combination of adverse event probability and consequences. The fire risk level of road tunnel should be assessed taking into account the fire probability level and consequence level in 4 steps.

Step 1. Establish an index system for tunnel fire probability assessment and assess the tunnel in question to obtain fire probability level.

Step 2. Select typical accident scenes based on tunnel traffic mix and features.

Step 3. Build smoke spread model and personnel evacuation model in each scene to obtain the number of deaths in each typical scene and tunnel fire consequence level.

Step 4. Assess tunnel fire risk level through risk matrix using fire probability level and consequence level, as shown in Table 1.

| Table 1. Fire risk rating |
|--------------------------|
| Probability level | 1 | 2 | 3 | 4 | 5 |
| Consequence level | | | | | |
| 1 | I | I | II | II | III |
| 2 | I | II | II | III | III |
| 3 | II | II | III | III | IV |
| 4 | II | III | III | IV | IV |
| 5 | III | III | IV | IV | IV |

3. Assessment of Tunnel Fire Probability Level

3.1. Analysis of factors influencing tunnel fire

Based on statistics of fire accidents[2], main causes for tunnel fire include: (1) vehicle fault such as circuit fault and engine ignition in small vehicles and ignition in large trucks due to brake overheat, making up 63% of all causes of fire accidents; (2) traffic accidents such as vehicle collision, making up 18%; (3) spontaneous combustion of cargo, making up 7%; (4) unknown causes, making up 12%. Overall, spontaneous combustion of vehicles is the direct cause of tunnel fire.

Vehicle performance is the internal cause of spontaneous combustion of a vehicle while external environment conditions are inducement. Accordingly, tunnel fire probability is mainly influenced by vehicle performance, tunnel use and ambient conditions of the tunnel. Tunnel use is dictated by tunnel length and traffic conditions; tunnel environment includes traveling conditions such as tunnel alignment, pavement conditions, lighting conditions as well as natural conditions such as weather.

3.2. Index system for assessment of tunnel fire probability

By dividing influencing factors of tunnel fire probability into tunnel property, environmental factor, traffic conditions and vehicle performance and giving assessment criteria for each indicator, we establish an index system for assessment of tunnel fire probability [7, 8], as shown in Table 2.

3.3. Tunnel fire probability level

According to the tunnel fire probability evaluation index system in Table 1, the tunnel in question is assessed item by item and its fire risk probability P is calculated using Eq. (1).

\[ P = \sum U_{ij} \times \gamma_{ij} \]  

Where \( U_{ij} \) is the points of assessment indicator; \( \gamma_{ij} \) is corresponding weight factor to be obtained by AHP (Analytic Hierarchy Process) or Expert Investigation Method. (i = 1,2,3,4; j=1,2,…,n, n is the number of indicators corresponding to class i)

Having obtained the value of R, the tunnel fire probability level is determined according to Table 3.
Table 2. Fire probability evaluation index system

| Category          | Assessment indicator | Assessment criteria                                      | Points   | Weighting |
|-------------------|----------------------|----------------------------------------------------------|----------|-----------|
| Tunnel property   |                      |                                                          |          |           |
| L11               | **Tunnel length U**   |                                                          |          |           |
|                   | L>3000               |                                                          | 75~100   |           |
|                   | 1000<L≤3000           |                                                          | 50~75    |           |
|                   | 1000<L≤500            |                                                          | 25~50    |           |
|                   | L≤500                 |                                                          | 0~25     |           |
|                   | **Tunnel alignment U**| Poor alignment combination or α>5%                       | 75~100   |           |
|                   |                       | Unreasonable alignment combination or 3%≤α<5%           | 50~75    |           |
|                   |                       | Improper alignment combination or 1%≤α<3%               | 25~50    |           |
|                   |                       | Good alignment combination or α<1%                       | 0~25     |           |
| Environmental    |                      |                                                          |          |           |
| Factor            | **Pavement condition U**| Uneven pavement or SFC<0.3                            | 75~100   |           |
| U22               |                      | Relatively uneven pavement or 0.3≤SFC<0.4               | 50~75    |           |
|                   |                      | Relatively even pavement or 0.4≤SFC<0.5                 | 25~50    |           |
|                   |                      | Even pavement or SFC≥0.5                                | 0~25     |           |
| Traffic state     |                      |                                                          |          |           |
| U3                | **Annual Average Daily Traffic (AADT) U**| AADT>30000                                              | 75~100   |           |
|                   |                      | 10000<AADT≤30000                                         | 50~75    |           |
|                   |                      | 4000<AADT≤10000                                          | 25~50    |           |
|                   |                      | AADT≤4000                                                | 0~25     |           |
|                   | **Proportion of Heavy Goods Vehicle (HGV) U**| HGV>40%                                                  | 75~100   |           |
|                   |                      | 40%<HGV≤20%                                              | 50~75    |           |
|                   |                      | 10%<HGV≤20%                                              | 25~50    |           |
|                   |                      | HGV≤10%                                                  | 0~25     |           |
|                   | **Hazardous chemical**| Permitted to pass                                        | 75~100   |           |
| Category | Assessment indicator | Assessment criteria | Points | Weighting |
|----------|----------------------|---------------------|--------|-----------|
| vehicle control U35 | Limitation on some goods or quantities | 50–75 |
| | Allowed to pass with time restriction | 25–50 |
| | Prohibited | 0–25 |
| Vehicle performance U4 | Accidents/million vehicle kilometers traveled U41 | CR>0.5 | 75–100 |
| | 0.30<CR≤0.50 | 50–75 |
| | 0.15<CR≤0.30 | 25–50 |
| | CR≤0.15 | 0–25 |

Table 3 Fire Probability Level

| Fire probability level | P |
|------------------------|---|
| 1                      | P≤20 |
| 2                      | 20<P≤40 |
| 3                      | 40<P≤60 |
| 4                      | 60<P≤80 |
| 5                      | P>80 |

4. Rating of Tunnel Fire Consequences

4.1. Selection of tunnel fire scenes
The major consideration in selecting tunnel fire scenes is the type of vehicles passing through the tunnel, based on which fire size is determined. By reference to French characteristic disaster investigation method and PIARC fire scenes and considering the type of vehicles in China, Table 4 gives the size of fire accidents caused by different types of vehicles. The fire scenes are selected according to the type of vehicles passing through the tunnel under evaluation.

| Type of fire source | Heat generated (MW) | Fire size | Maximum heat release duration | Type of expressway toll |
|---------------------|---------------------|-----------|-------------------------------|-------------------------|
| Ordinary small vehicle | 5                   | Small     | 163.1s                        | Class I vehicle         |
| Small passenger bus and truck | 10                  | Small and medium | 230.7s                       | Class II vehicle        |
| Ordinary passenger bus and truck | 20                  | Medium    | 326.3s                        | Class III vehicle       |
| Large truck or hazardous goods vehicle | 100                 | Large     | 729.7s                        | Class IV or V vehicle   |

4.2. Numerical modeling of tunnel fire consequences
According to the tunnel structure under evaluation, FDS software is used to model smoke spread under fire scenes inside the tunnel and determine the limit escape time at different locations inside the tunnel in the event of a fire, using CO and O2 limit conditions as criteria for personnel escape. The limiting value of CO concentration is set to 200ppm and that of O2 concentration to 9.6% [9-11].
Fig 1. Personnel evacuation model

After collecting proportions of various types of vehicles passing through the tunnel under evaluation, Pathfinder software is used to simulate personnel escape behavior considering the configuration of tunnel escape route to obtain the number of people who fail to escape within the time limit under various scenes as the consequence of the respective fire scene. The Pathfinder simulation takes into account the moving speed of different people, and congestion when people try to escape. With improved calculation method for escape time, it makes the escape simulation more accurate.

4.3. Tunnel fire consequence level

The tunnel fire consequence is assessed assuming the anticipated deaths caused by one fire accident. Tunnel fire consequence $R$ is calculated using Eq. (2).

$$R = \sum C_t S_t$$

(2)

Where $C_t$ is the number of deaths in each fire scene; $S_t$ is the weight of this fire scene, $\sum C_t = 1$.

From the previous statistical analysis, the major cause of tunnel fire is spontaneous combustion of vehicles. Consequently, the weight of each fire scene is approximated by the proportionality coefficient of the type of vehicle causing this fire scene.

Having obtained the value of $R$, the tunnel fire consequence level is determined according to Table 5.

| Fire scene level | $R$         |
|------------------|-------------|
| 1                | $R \leq 0.1$|
| 2                | $0.1 < R \leq 0.3$|
| 3                | $0.3 < R \leq 1$|
| 4                | $1 < R \leq 3$|
| 5                | $R > 3$     |

Table 5. Fire scene

Fire risk level is obtained from fire probability level and fire consequence level.

5. Case Study

An expressway tunnel in Guangzhou has been in operation for nearly 5 years with increasing traffic flow. Peak daily traffic volume reaches 90,000 vehicles. In addition, harsh climatic conditions in the mountains increase the hazard of secondary accidents, causing certain safety concerns. Therefore, it is necessary to evaluate its fire risk, understand its operational safety status and provide basis for facility improvement.
Information on this tunnel is collected. According to the tunnel fire probability evaluation index system in Table 2, the tunnel in question is assessed item by item; the weight of each indicator is obtained by AHP; fire risk probability $P$ is calculated, as shown in Table 5.

According to Table 5, the fire probability level of this tunnel is determined to be Level 3. This tunnel does not impose restrictions on vehicles. Based on the types of vehicles actually passing through the tunnel, fire scenes of 5MW, 10 MW, 20 MW and 100 MW are selected. The type of fire source is set to be extremely rapid fire; see Table 4 for parameter configuration. The tunnel section wind speed is measured at 0.8m/s.

The tunnel cross section is 8.25m high and 15.8m wide, assuming the fire source is located at the door to pedestrian cross passage. The detector is 1.8m off the ground and on the centerline of the inspection walkway. FDS is used to simulate fire smoke spread. Based on CO and O2 limit criteria, the limit escape time at different locations upstream of the fire is obtained, as shown in Table 7.

### Table 7. Limit escape time at different locations upstream of the fire

| Location | 10m | 20m | 30m | 50m | 80m | 120m |
|----------|-----|-----|-----|-----|-----|------|
| 5MW      | 153.6 | 187.8 | 244.8 |     |     |      |
| 10MW     | 127.2 | 160.8 | 212.4 | 241.2 |     |      |
| 20MW     | 117.2 | 141.3 | 195.6 | 220.8 | 259.2 |      |
| 100MW    | 33.6  | 52.2  | 92.6  | 133.8 | 187.8 | 262.8 |

Note: 5MW fire affects 30m upstream of the fire source; 10MW fire affects 50m upstream of the fire source; 20MW fire affects 80m; and 100WM fire affects 120m. After the fire occurs in the tunnel, vehicles downstream of the fire move out of the tunnel and the impact on personnel downstream is not considered.

The tunnel has a design speed of 80km/h. The proportion of various types of vehicles is taken from 2017 statistics. AADT for this tunnel is 28,133 vehicles with Class I: II: III: IV and V vehicles =0.68: 0.03: 0.06: 0.23. Table 7 gives the deduced blocked vehicles and people to be evacuated inside the tunnel in the event of a fire.

Based on relevant literature, Human Dimensions of Chinese Adults (GB/T 10000-1988) and Human Dimensions of Chinese Minors (GB/T 26158-2010), people mix, shoulder width and moving speed are determined as shown in Table 8[12-13].
## Table 8. Blocking vehicles and evacuation personnel

| Item                          | Class I vehicle | Class II vehicle | Class III vehicle | Class IV or V vehicle |
|-------------------------------|-----------------|------------------|-------------------|-----------------------|
| Number of vehicles/vehicle   | 65              | 4                | 7                 | 22                    |
| Number of people in a single vehicle/people | 2               | 10               | 24                | 2                     |
| Total number of people to be evacuated |                  |                  |                   | 382                   |

## Table 9. Staff composition and moving speed

| People                          | Proportion | Shoulder width (cm) | Moving speed (m/s) | Number |
|---------------------------------|------------|---------------------|--------------------|--------|
| Children                        | 8%         | 40.0                | 0.92               | 31     |
| The aged                         | 15%        | 40.5                | 0.85               | 57     |
| Young and middle-aged men        | 42%        | 41.5                | 1.1                | 160    |
| Young and middle-aged women      | 35%        | 41.0                | 0.95               | 134    |

By collating Pathfinder data, the time at which people pass different locations can be obtained, as illustrated in Fig. 2 below.

![Personnel escape curve](image)

Fig 2. Personnel escape curve

As seen from Fig. 2, in the cases of 5MW, 10MW and 20MW fires all occupants are able to escape; in the case of 100MW fire, 3 people die at a distance of 20m–30m upstream of the fire source.

Considering the proportion of various types of vehicles, Eq. (2) is used to calculate the tunnel fire consequence $R = 3 \times 0.23 = 0.69$. According to the table, the tunnel fire consequence level is determined to be Level 3.

Based on the fire probability level and consequence level of this tunnel, its fire risk is determined to be of Level III. The risk is high and accepted conditionally. Risk mitigation measures must be put in place and emergency response plans must be prepared.

### 6. Conclusions

On the basis of classic risk theories this paper has proposed a more pertinent and practical fire risk evaluation model for road tunnels. On the basis of tunnel fire causes, an index system for assessing
tunnel fire probability has been established and assessment criteria for fire probability level has been obtained. The proposed model finely simulated escape behavior of people. A calculation method for tunnel fire consequence has been developed using simulation of tunnel smoke spread and people escape. This method has been applied to fire risk assessment for a tunnel in Guangzhou; its effectiveness has been demonstrated. The research results provide a new idea and method for assessment of road tunnel fire risk and have reference value for study on road tunnel fire risk in China.

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