The Setting of Road Tunnel Cross Passages Based on Risk Analysis

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Abstract. Cross passages are critical infrastructure for evacuation and rescue in fire accidents of road tunnels. Reasonable cross channel design is conducive to improving the efficiency of evacuation and rescue. In this paper, a key parameter setting method of highway tunnel cross-passages based on risk assessment is established. Aiming for safe evacuation of people and vehicles in the tunnel, this method is based on risk evaluation and involves comprehensive analysis of the effects of tunnel properties, traffic conditions, cross passage parameters and evacuation guidance measures so as to support the development of an optimum design of cross passages. This paper describes in detail its design approach, parameter determination process and risk evaluation method and taking an actual tunnel as example, demonstrates the process of determining key parameters of tunnel cross passages on the basis of risk evaluation.

1. Introduction

Tunnels are control works in a highway project and have a special semi-closed long structure. In the event of a fire, fumes are hard to disperse, and rescue is difficult, often leading to mass deaths and casualties [1]. For example, the 2014 fire incident in Yanhua Tunnel of Jincheng-Jiyuan Expressway in Shanxi caused 40 deaths and 12 injuries. The 2019 fire incident in Maoliling Tunnel of G15 Shenyang-Haikou Expressway resulted in 5 deaths and 31 injuries. The best first response for a tunnel fire incident is the evacuation and self-rescue of drivers and passengers in the initial stage of the fire, known as the prime time for tunnel emergency rescue. A suitable design of cross passages of the tunnel holds the key to effective utilization of this prime time to make evacuation and rescue more efficient. Cross passages are critical safety facilities to ensure safe evacuation of tunnel occupants and quick arrival at the incident site by first responders. They consist of pedestrian and vehicle cross passages [3-4].

China's current Specifications for Design of Highway Tunnel: Section 1 - Civil Engineering (JTG 3370.1-2018) recommends a spacing of cross passages of 250m which shall not be greater than 350m on the basis of past engineering experience in China and relevant foreign codes. However, it does not give specific calculation and verification methods and its theoretical basis is insufficient. Reported research results mostly focus on the spacing of cross passages using the following method: on the basis of performance-based design philosophy, numerical modeling and comparison of Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET) are used to determine the suitability of cross passage spacing by assessing evacuation safety [5-10]. Current codes and reported research results
suggest tunnel designers and researchers mainly consider the spacing of cross passages. In fact, the angle between vehicle cross passage and main tunnel, the relative location of vehicle cross passage and emergency parking strip, evacuation guidance provisions (such as cross passage indicators and emergency broadcast), etc. also have some effect on evacuation efficiency. However, prior design and research did not take these factors into account when determining cross passage parameters.

This paper introduces the concept of risk evaluation to AHP-based consideration of the influences of tunnel length, number of lanes, traffic flow, pedestrian/vehicle cross passage configuration and other evacuation guidance features on safe evacuation of people and vehicles so as to determine suitable key parameters for cross passages.

2. Setting of Road Tunnel Cross Passages Based on Risk Analysis

2.1. Idea on determining key parameters of cross passages
Key parameters of cross passages include spacing and width of cross passages, the angle between vehicle cross passage and main tunnel, the relative location of vehicle cross passage and emergency parking strip, and evacuation guidance provisions (such as cross passage indicators and emergency broadcast) in the event of an emergency. During design of cross passages, the comprehensive risk level of cross passages shall be considered in addition to individual parameters meeting specification requirements. Consequently, the basic idea of determining cross passage key parameters is to preliminarily determine relevant parameters of cross passages based on tunnel basic information in accordance with design code requirements, then evaluate safety risks of people and vehicle evacuation using risk evaluation method, and finally adjust relevant parameter based on risk evaluation results to finalize key parameters of cross passages.

2.2. Procedures for determining key parameters
Key parameters of tunnel cross passages can be determined in 4 steps: collect basic data on the tunnel; preliminarily determine design parameters of cross passages; evaluate safety risks of tunnel evacuation; and analyze risk evaluation results. The flowchart is given in Fig. 1.

1. Collect and organize tunnel related data
Collect and organize basic data on the tunnel including tunnel length, number of lanes, traffic volume and types of vehicles by means of data access, field measurement, calculation, Q&A and informal discussions.

2. Preliminarily determine design parameters of cross passages
Preliminarily determine design parameters of cross passages including spacing and width, the angle between vehicle cross passage and main tunnel and configuration of tunnel evacuation guidance facilities, in accordance with applicable specification requirements on the basis of basic information on the tunnel.

3. Evaluate safety risks of tunnel evacuation
Aiming for safe evacuation, perform risk evaluation on the preliminary design scheme for the tunnel to determine preliminary evacuation risk level.

4. Analyze risk evaluation results
Analyze risk evaluation results. If the risk level is acceptable then the preliminary design scheme meets safety requirements. If the risk level is unacceptable then the scheme is adjusted according to contribution of each risk factor and re-evaluated until the risk level is acceptable.
3. Risk Evaluation Method for Road Tunnel Evacuation

3.1. Establishment of assessment indicator system

An assessment indicator system is the basis for risk evaluation. Tunnel safety assessment systems in prior work mainly generalize and classify risks in tunnel basic information, traffic conditions, civil structure, E&M system, management system and organization and operating environment. Overall, each of these assessment indicator systems has its own advantages and disadvantages and focuses on different aspects depending on assessment goal or emphasis.

In this study, the tunnel evacuation safety risk assessment system is considered in 3 aspects: tunnel traffic conditions, tunnel evacuation conditions and evacuation guidance features. Tunnel traffic conditions dictate the number of people and vehicles to be evacuated in the tunnel. The specific assessment indicators include traffic volume, traffic mix and passage of hazardous chemicals. Tunnel evacuation conditions dictate the inherent evacuation capacity of the tunnel including tunnel basic information such as tunnel length and number of lanes; configuration of pedestrian cross passages such as spacing and width; configuration of vehicle cross passages such as spacing, width, the angle between vehicle cross passage and main tunnel and its location with regard to emergency parking strip and the presence or absence of ear-shaped cavity for personnel evacuation. Tunnel evacuation guidance features dictate utilization of tunnel evacuation facilities including cross passage indication signs, evacuation indication signs and emergency broadcast.

To sum up, according to the purpose and principle of establishing the assessment indicator system a tunnel evacuation safety risk evaluation system is established in 5 aspects: tunnel information, traffic conditions, pedestrian cross passages, vehicle cross passages and evacuation guidance, as shown in Fig. 2.
3.2. Determination method for indicator weight

In order to determine assignment of weight to indicators, analytic hierarchy process (AHP) is used in this study to perform analysis and well-known experts in the industry are asked to complete questionnaires for survey. Specific steps of AHP are as follows:

(1) Build a hierarchical structure model

First, build a hierarchical structure model that consists of three layers - target layer, criterion layer and indicator layer, as detailed below:

1) Target layer
   Evacuation safety for road tunnel is denoted by $U$.

2) Criterion layer
   $U = \{ \text{tunnel basic information } U_1, \text{ traffic conditions } U_2, \text{ pedestrian cross passage } U_3, \text{ vehicle cross passage } U_4, \text{ evacuation guidance } U_5 \}$

3) Indicator layer
   Tunnel basic information $U_1 = \{ \text{tunnel length } U_{11}, \text{ number of lanes } U_{12} \}$;
   Traffic conditions $U_2 = \{ \text{traffic volume } U_{21}, \text{ Proportion of large vehicles } U_{22}, \text{ Proportion of hazardous goods vehicles } U_{23} \}$;
   Pedestrian cross passage $U_3 = \{ \text{spacing and width of cross passages } U_{31}, \text{ cross passage indication sign } U_{32} \}$;
   Vehicle cross passage $U_4 = \{ \text{spacing and width of cross passages } U_{41}, \text{ angle between vehicle cross passage and main tunnel } U_{42}, \text{ location of vehicle cross passage with regard to emergency parking strip } U_{43}, \text{ ear-shaped cavity for people evacuation } U_{44} \}$;
   Evacuation guidance $U_5 = \{ \text{evacuation indication sign } U_{51}, \text{ emergency broadcast } U_{52} \}$.

(2) Create assessment matrix

According to the subordination relationship between upper and lower layers as established by the hierarchical structure, Expert Investigation Method is used to compare the importance of lower layer indicators relative to upper layer indicators and create assessment matrices in conjunction with T. L. Satty scales 1-9 (as defined in Table 1). This converts qualitative assessment to quantitative result. Values of elements in the assessment matrix directly reflect relative importance of factors. For example, $U_i$ is influenced by $U_{k1}, U_{k2} \text{ and } U_{k3}, ..., U_{k n}$ in the lower layer. Two factors $U_{ki}$ and $U_{kj}$ are taken for comparison each time. $a_{ij}$ denotes the ratio between relative importance of $U_{ki}$ and $U_{kj}$ to $U_k$. Thus the assessment matrix created is as shown in Table 2.
### Table 1. Assessment matrix scale and meaning

| Scale | Meaning |
|-------|---------|
| 1     | Two factors are equally important. |
| 3     | One factor is slightly more important than the other one. |
| 5     | One factor is apparently more important than the other one. |
| 7     | One factor is significantly more important than the other one. |
| 9     | One factor is extremely more important than the other one. |
| 2, 4, 6, 8 | Medians between the above adjacent scales |

### Table 2. Assessment matrix

| $U_k$ | $U_{k1}$ | $U_{k2}$ | ... | $U_{kn}$ |
|-------|---------|---------|-----|---------|
| $U_{k1}$ | $a_{11}$ | $a_{12}$ | ... | $a_{1n}$ |
| $U_{k2}$ | $a_{21}$ | $a_{22}$ | ... | $a_{2n}$ |
| ... | ... | ... | ... | ... |
| $U_{kn}$ | $a_{n1}$ | $a_{n2}$ | ... | $a_{nn}$ |

$$ A = \begin{pmatrix} a_{11} & \ldots & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \ldots & a_{nn} \end{pmatrix} = A \left( a_{ij} \right)_{n \times n} $$

$$ a_{ij} > 0, a_{ij} = \frac{1}{a_{ji}}, a_{ii} = 1 (i, j = 1, 2, 3, \ldots, n) $$

(3) Calculation of relative weight

After creating the assessment matrix $A$ for $U_{ki}$ importance relative to $U_{kj}$ under criterion $U_k$ using the above method, maximum characteristic value of the matrix and its corresponding characteristic vector are calculated.

$$ AW = \lambda_{max} W $$

Thus maximum characteristic value $\lambda_{max}$ and the corresponding characteristic vector $W = (W_1, W_2, \ldots, W_n)^T$ are obtained. If the matrix is determined to meet consistency requirements, then through normalization processing $\omega = (\omega_1, \omega_2, \ldots, \omega_n)^T$ is derived as the weight coefficient of $U_{ki}$ under criterion $U_k$.

(4) Check the consistency of assessment matrix

Because people's understanding of complex and diversified objective things is subjective, the assessor cannot give the accurate value of $a_{ij}$ but only can give an estimated value. This cannot ensure the consistency of the assessment matrix, so it is necessary to check the consistency of the assessment matrix. Consequently, consistency check is required to identify any potential conflict between indicator weights. The steps are given below:

1) Calculate consistency indicator $CI$

$$ CI = \frac{\lambda_{max} - n}{n - 1} $$

where $n$ is the order of the assessment matrix.

2) Look up the corresponding mean stochastic consistency indicator $RI$. The mean stochastic consistency indicator is obtained from Table 3.
Table 3. Values of mean stochastic consistency indicator

| n  | 2    | 3    | 4    | 5    | 6    | 7    | 8    | 9    |
|----|------|------|------|------|------|------|------|------|
| RI | 0    | 0.58 | 0.90 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 |

3) Calculate consistency ratio $CR$

$$CR = \frac{CI}{RI}$$

If $CR < 0.10$ then the matrix meets the consistency requirement; otherwise the consistency value of the matrix needs adjustment.

(5) Weight calculation of evacuation safety indicators for road tunnels

To ensure the scientificity of expert investigation results, 15 leading experts in the industry were invited to score indicators in the hierarchical structure model; and weighted arithmetic mean values of the score results were derived to obtain the final indicator weight. The calculation results are given in Table 4.

Table 4. Indicator weight calculation results

| Criterion layer          | Weight coefficient | Indicator layer | Comprehensive weight coefficient |
|--------------------------|--------------------|-----------------|---------------------------------|
| Tunnel basic information | 0.059              | Tunnel length $U_{11}$ | 0.033                          |
|                          |                    | Number of lanes $U_{12}$ | 0.027                          |
| Traffic conditions       | 0.319              | Traffic volume $U_{21}$ | 0.082                          |
|                          |                    | Proportion of large vehicles $U_{22}$ | 0.093                          |
|                          |                    | Proportion of hazardous goods vehicles $U_{23}$ | 0.143                          |
| Pedestrian cross passage | 0.267              | Spacing and width of pedestrian cross passages $U_{31}$ | 0.098                          |
|                          |                    | Pedestrian cross passage indication sign $U_{32}$ | 0.169                          |
| Vehicle cross passage    | 0.089              | Spacing and width of vehicle cross passages $U_{41}$ | 0.039                          |
|                          |                    | Angle between vehicle cross passage and main tunnel $U_{42}$ | 0.011                          |
|                          |                    | Location of vehicle cross passages with regard to emergency parking strip $U_{43}$ | 0.012                          |
|                          |                    | Ear-shaped cavity for people evacuation in vehicle cross passage $U_{44}$ | 0.027                          |
| Evacuation guidance      | 0.266              | Evacuation signs $U_{51}$ | 0.129                          |
|                          |                    | Emergency broadcast $U_{52}$ | 0.137                          |

3.3. Assessment indicator risk score

Assessment of individual factors in the indicator layer is the basis for comprehensive evacuation safety risk evaluation for road tunnels. On the basis of summarizing research results, this paper gives indicator risk scores as follows.

(1) Tunnel basic information

A longer tunnel means a longer evacuation distance to outside the tunnel for people and vehicles and more difficult evacuation, hence higher risk. For a unidirectional tunnel, more lanes mean safer vehicle operation, i.e. the larger the number of lanes, the safer vehicles are operated and the lower the probability of an incident. In addition, with the same volumes of traffic, more lanes afford more space for evacuation, especially when vehicle evacuation is needed. more lanes are more beneficial to vehicle evacuation. Risk scores of tunnel information are presented in Table 5.
Table 5. Risk scores of tunnel basic information

| Assessment indicator | Assessment criteria | Risk score |
|----------------------|---------------------|------------|
| Tunnel length $U_{11}$ (m) | $L \leq 1000$ | 20         |
| $1500 \leq L > 1000$ | 40         |
| $3000 \leq L > 1500$ | 60        |
| $5000 \leq L > 3000$ | 80        |
| $L > 5000$ | 100 |
| Single-tube two-lane | 100 |
| Two lanes | 80 |
| Three lanes | 60 |
| Four or more lanes | 40 |

Number of lanes $U_{12}$

| Assessment criteria | Risk score |
|---------------------|------------|
| Single-tube two-lane | 100 |
| Two lanes | 80 |
| Three lanes | 60 |
| Four or more lanes | 40 |

(2) Traffic conditions

In the event of a fire or leakage of hazardous goods, higher Annual Average Daily Traffic (AADT) means more potential casualties and more difficult evacuation. The impact of traffic mix on tunnel evacuation is mainly due to large vehicles especially large trucks. With an increasing proportion or number of trucks, the probability of serious fire incidents increases. Serious incidents may result from improper treatment by field personnel at the tunnel or improper measures taken by tunnel operators. A traffic accident involving hazardous goods vehicles may result in serious disasters due to explosion, combustion and leakage of toxic gas. Consequently, the proportion of hazardous goods vehicles in the vehicles passing through the tunnel has a significant influence on the probability of risk and severity of consequences. The assessment criteria are shown in Table 6.

Table 6. Risk scores of traffic condition indicators

| Assessment indicator | Assessment criteria | Risk score |
|----------------------|---------------------|------------|
| AADT $U_{21}$ (unit: vehicles/day) | $0 < T_v \leq 2000$ | 0 |
| $2000 < T_v \leq 4000$ | 10 |
| $4000 < T_v \leq 8000$ | 30 |
| $8000 < T_v \leq 12000$ | 50 |
| $12000 < T_v \leq 20000$ | 70 |
| $20000 < T_v \leq 40000$ | 90 |
| $40000 < T_v$ | 100 |
| Proportion of large vehicles $U_{22}$ (unit: %) | $0 < T_l \leq 0.1\%$ | 0 |
| $0.1 < T_l \leq 5\%$ | 10 |
| $5\% < T_l \leq 10\%$ | 30 |
| $10\% < T_l \leq 15\%$ | 50 |
| $15\% < T_l \leq 20\%$ | 70 |
| $20\% < T_l \leq 30\%$ | 90 |
| $30\% < T_l$ | 100 |

| Proportion of hazardous goods vehicles $U_{23}$ (unit: %) | $0 < T_g \leq 0.1\%$ | 0 |
| $0.1 < T_g \leq 0.5\%$ | 10 |
| $0.5\% < T_g \leq 1\%$ | 30 |
| $1\% < T_g \leq 3\%$ | 50 |
| $3\% < T_g \leq 4\%$ | 70 |
| $4\% < T_g \leq 5\%$ | 90 |
| $5\% < T_g$ | 100 |

(3) Pedestrian cross passage

More closely spaced cross passages mean smaller evacuation distance and less time needed for evacuation. More prominent indication signs of cross passages are more beneficial to people evacuation, thus assisting with self-rescue in the event of a tunnel fire. Table 7 gives the risk scores of pedestrian cross passage indicators.
Table 7. Risk scores of pedestrian cross passage indicators

| Assessment indicator | Assessment criteria | Risk score |
|----------------------|---------------------|------------|
| Spacing of cross passages $U_{31}$ (m) | $L \leq 200$ | 60 |
|                      | $200 < L \leq 250$ | 70 |
|                      | $250 < L \leq 300$ | 80 |
|                      | $300 < L \leq 350$ | 90 |
|                      | $L > 350$ | 100 |
| Cross passage indication sign $U_{32}$ | Enlarged cross passage wall painted sign + LED strobe guidance light + conventional electro-optic indication sign for pedestrian cross passage | 60 |
|                      | LED strobe guidance light + conventional electro-optic indication sign for pedestrian cross passage | 70 |
|                      | Enlarged cross passage wall painted sign + conventional electro-optic indication sign for pedestrian cross passage | 80 |
|                      | conventional electro-optic indication sign for pedestrian cross passage | 90 |
|                      | Without indication signs | 100 |

(4) Vehicle cross passage

The main purpose of vehicle cross passages is to allow rescue vehicles to rapidly arrive at the incident site in the tunnel from the adjacent incident-free tunnel or to allow obstructed vehicles to evacuate after the fire has been put out. A smaller spacing of these cross passages is more beneficial to rescue. A smaller angle between vehicle cross passage and main tunnel is more beneficial to movement of rescue vehicles. Suitably located vehicle cross passages relative to emergency parking strips can assist with vehicle movement especially for a two-lane tunnel. Providing an ear-shaped cavity for people evacuation at the fire resisting shutter of the vehicle cross passage can aid in safe evacuation of people and prevent fire smoke spreading to non-incident tunnel from the incident tunnel. Table 8 gives the risk scores of vehicle cross passage indicators.

Table 8. Risk scores of vehicle cross passage indicators

| Assessment indicator | Assessment criteria | Risk score |
|----------------------|---------------------|------------|
| Spacing of cross passages $U_{41}$ (m) | $L \leq 750$ | 60 |
|                      | $750 < L \leq 800$ | 70 |
|                      | $800 < L \leq 900$ | 80 |
|                      | $900 < L \leq 1000$ | 90 |
|                      | $L > 1000$ | 100 |
| Angle between vehicle cross passage and main tunnel $U_{42}$ | $45^\circ$ | 50 |
|                      | $60^\circ$ | 60 |
|                      | $90^\circ$ | 100 |
| Location of vehicle cross passages with regard to emergency parking strip $U_{43}$ | End wall of emergency parking strip aligned with the center of vehicle cross passage | 70 |
|                      | End wall of emergency parking strip $\leq 5$m from the center of vehicle cross passage | 80 |
|                      | The center of emergency parking strip aligned with the center of vehicle cross passage | 90 |
|                      | End wall of emergency parking strip $> 5$m from the center of vehicle cross passage | 100 |
| Ear-shaped cavity for people evacuation at the vehicle cross passage $U_{44}$ | Yes | 60 |
|                      | No | 100 |
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(12) Evacuation guidance

Sound evacuation guidance features have a significant influence on people evacuation safety in the event of a tunnel fire. Inadequate guidance features may lead to the following problems: (1) blocked people may stop to wait or even become onlookers at the incident scene; (2) blocked people far from the incident scene do not know what happened ahead and how to react correctly; (3) evacuees may be unaware of the location or even the existence of nearby emergency exit. Table 9 gives the score criteria for evacuation guidance indicators.

Table 9. Risk scores of evacuation guidance indicators

| Assessment indicator | Assessment criteria | Risk score |
|-----------------------|----------------------|------------|
| Evacuation signs $U_{51}$ | Yes, and the signs are clear. | 60 |
|                        | Yes, but the signs are not clear enough. | 80 |
|                        | No. | 100 |
| Emergency broadcast $U_{52}$ | Yes, and the directions are clear. | 60 |
|                        | Yes, but the directions are not clear enough. | 80 |
|                        | No. | 100 |

3.4.1.4 Comprehensive risk level and calculation method

(1) Comprehensive risk level

The assessed risk level of road tunnel evacuation safety $M$ is defined as a number ranging from 0 to 100. In this paper the safety level of road tunnels is divided into 5 classes, as shown in Table 10.

Table 10. Risk level classification for road tunnel evacuation safety

| Tunnel evacuation risk level | I | II | III | IV | V |
|------------------------------|---|----|-----|----|---|
| Assessment risk              | Extremely low risk | Low risk | General risk | High risk | Extremely high risk |
| Risk score $M$               | $M<60$ | $60 \leq M < 70$ | $70 \leq M < 80$ | $80 \leq M < 90$ | $90 \leq M$ |

(2) Comprehensive risk calculation method

In this paper the tunnel evacuation safety risk score is obtained by weighted sum method, i.e. deriving a comprehensive assessed value through weighted sum of factors in the indicator layer. The calculation method is as follows:

$$M = \sum_{i}^{n} \omega_i U_i$$

where $n$ is the number of factors in the indicator layer; $\omega_i$ is the weight of each factor in the indicator layer as given in Table 4; $U_i$ is the risk score of each factor as calculated per Section 3.3.

4. Case Study

4.1. Project overview

An expressway tunnel is 6492/6482.63m long with unidirectional two lanes in each of the two tubes. The design speed is 100km/h. According to construction drawing design documents, its forecast traffic volume and traffic mix are shown in Tables 11-12. Pedestrian cross passages are perpendicular to main tunnel and spaced 300m apart; vehicle cross passages form an angle of about 60° with main tunnel (left and right tubes) and are spaced 895m apart at maximum; the end wall of emergency parking strips is 5m from the center of vehicle cross passage.
Table 11. Forecast traffic volume through the tunnel

| Design target year | 2025 | 2038 |
|--------------------|------|------|
| Daily traffic volume | 23100 | 45959 |
| Peak hourly volume  | 1142  | 2271  |

Table 12. List of types of vehicles

| Year     | Small truck | Medium truck | Large truck | Trailer | Minibus | Large bus |
|----------|-------------|--------------|-------------|---------|---------|-----------|
| 2025     | 13.3%       | 13.23%       | 20.43%      | 15.36%  | 27.51%  | 10.17%    |
| 2038     | 10.49%      | 10.06%       | 21.57%      | 16.35%  | 30.48%  | 11.05%    |

4.2. Risk analysis

According to tunnel data and assessment criteria, individual indicator risks and comprehensive risks of tunnel evacuation safety are determined as shown in the table below:

Table 13. Risk scores of individual indicators

| Risk assessment indicator                                      | Indicator weight | Risk score of individual indicator |
|----------------------------------------------------------------|------------------|------------------------------------|
| Tunnel length                                                  | 0.033            | 100                                |
| Number of lanes                                                | 0.027            | 80                                 |
| Traffic volume                                                 | 0.082            | 90                                 |
| Traffic composition                                            | 0.093            | 100                                |
| Passage of hazardous chemicals                                 | 0.143            | 50                                 |
| Spacing and width of pedestrian cross passages                 | 0.098            | 80                                 |
| Pedestrian cross passage indication sign                        | 0.169            | 90                                 |
| Spacing and width of vehicle cross passages                    | 0.039            | 80                                 |
| Angle between vehicle cross passage and main tunnel            | 0.011            | 60                                 |
| Location of vehicle cross passages with regard to emergency parking strip | 0.012 | 80                                 |
| Ear-shaped cavity for people evacuation in vehicle cross passage| 0.027            | 100                                |
| Evacuation signs                                               | 0.129            | 60                                 |
| Emergency broadcast                                           | 0.137            | 60                                 |
| **Comprehensive risk**                                         |                  | **75.74**                          |

Thus, comprehensive risk score of the tunnel evacuation safety is 75.74. According to the risk level classification criteria, the tunnel evacuation safety risk is Class III, meaning general risk.

4.3. Optimization of design scheme

From individual indicator risk scores it can be seen that the risk scores of spacing of pedestrian cross channels, cross passage indication sign and ear-shaped cavity for people evacuation in vehicle cross passage are high. Therefore, the design scheme can be optimized by targeting these 3 aspects as follows: adjust the spacing of pedestrian cross passages to 250m; add enlarged cross passage wall painted sign + LED strobe guidance light; and add ear-shaped cavity for people evacuation at the vehicle cross passages. After optimization, the tunnel evacuation safety risk is re-evaluated to derive a comprehensive risk score of 68.61 which means Class II risk (low risk).
5. Conclusions
This paper presents a risk evaluation based configuration method for cross passages of a road tunnel. Aiming for safe evacuation of people and vehicles in the tunnel, this method is based on risk evaluation and involves comprehensive analysis of the effects of tunnel properties, traffic conditions, cross passage parameters and evacuation guidance measures so as to support the development of an optimum design of cross passages. This paper describes in detail its design approach, parameter determination process and risk evaluation method and taking an actual tunnel as example, demonstrates the process of determining key parameters of tunnel cross passages on the basis of risk evaluation.

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