Index Weight Determination for Road Tunnel Fire Risk Assessment Based on Fuzzy Analytic Hierarchy Process

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Abstract. Road tunnel, as an underground engineering, is characterized by unpredictability which has high fire risks in operation process. In recent years, major fire accidents have happened around the world in road tunnel operation process, causing enormous casualties and economic losses. Therefore, it is very necessary to assess fire risks during the road tunnel operation process. In this paper, an index system of road tunnel fire risk assessment with different categories of assessment indexes is established. Index weight is introduced to show the importance of each assessment index for assessment object. This paper adopts fuzzy analytic hierarchy process (FAHP) to express index weight with qualitative description language through pairwise comparison. Qualitative description language given by experts are indicated by correlative triangular membership function. Finally, through defuzzification and normalization, triangular fuzzy numbers are converted into final weights to establish the fire risk assessment index system during the road tunnel operation process.

Key words: road tunnel, fire risk assessment, fuzzy analytic hierarchy process, index weight.

1. Research Background
With the constant acceleration of urbanization process, road tunnel construction is developing rapidly. In recent years, the cross-river-and-ocean tunnel has become a milestone in world road construction. While road tunnel brings convenience to people's life, the probability of fire accident also creeps. In recent years, major fire accidents have happened around the world in road tunnel operation process, causing enormous casualties and economic losses [1-3]. Therefore, it is necessary to carry out fire risk assessment in road tunnel operation period for improving tunnel safety and eliminating fire hazards and risks.

There are many risk assessment methods, including qualitative, quantitative and semi-quantitative risk analysis methods. Many methods need to determine assessment index weights in the assessment process. In the 20th century, Professor Saady from University of Pittsburgh, America, put forward a comprehensive qualitative and quantitative systematic analysis method. It could deal with the comprehensive assessment of multiple factors in complex assessment objects, especially the factors that cannot be quantitatively described. It is namely analytic hierarchy process (AHP) [4]. Fuzzy analytic hierarchy process (FAHP), based on AHP, fully considers subjective fuzziness, combines fuzzy mathematic theory, and uses triangular fuzzy numbers to represent the mutual importance degree.
between index factors through fuzzy mathematic operation and least square method, getting judgment matrixes of all index factors. In this connection, routine AHP is extended to FAHP under the condition of uncertainty [5, 6].

2. Establishment of Fire Risk Assessment Index System in Road Tunnel Operation Period

The establishment of the assessment index system generally follows a concrete-abstract-concrete dialectical process. In the process, the characteristics of road tunnels and the fire risks during the operation period should be fully considered, and the index system should be constantly modified and improved [7].

In this paper, the qualitative analysis method of fault tree, expert evaluation method and other methods are used to establish the road tunnel fire risk assessment index system, which consists of 3 factors in criterion layer and 20 factors in index layer, as shown in table 1.

| Table 1. Road Tunnel Fire Risk Assessment Index System |
|-----------------------------------------------|
| **Criterion Layer**                          | **Index Layer**                          |
| Personnel and Management                      | Personnel fire safety awareness $c_{11}$ |
|                                                | Personnel escape self-help ability $c_{12}$ |
| $C_1$                                          | Fire safety management $c_{13}$          |
|                                                | Fire emergency plan $c_{14}$             |
|                                                | Fire safety training and fire emergency drill $c_{15}$ |
|                                                | Fire protection publicity and education $c_{16}$ |
|                                                | Daily fire safety inspection $c_{17}$    |
| Fire-fighting Facility and Equipment $C_2$    | Fire-fighting equipment maintenance $c_{18}$ |
|                                                | Tunnel hydrant system $c_{21}$           |
|                                                | Automatic fire alarm system $c_{22}$     |
|                                                | Ventilation and smoke control system $c_{23}$ |
|                                                | Automatic fire extinguishing system $c_{24}$ |
| Tunnels and Environment $C_3$                  | Fire extinguishers $c_{25}$              |
|                                                | Evacuation facilities $c_{26}$           |
|                                                | Fire electrical system $c_{27}$          |
|                                                | Tunnel fire load $c_{31}$                |
|                                                | Tunnel service life $c_{32}$             |
|                                                | Fire risks of adjacent buildings $c_{33}$ |
|                                                | Distance from the fire stations $c_{34}$ |
|                                                | Local rescue force $c_{35}$              |

3. Assessment Index Weight Determination based on FAHP

3.1. Main Steps

Based on FAHP, the main steps to determine the weights of the road tunnel fire risk assessment index system are as follows:

1. According to the purpose and content of road tunnel fire risk assessment, an assessment index system is established (See Table 1);
2. Index factors are compared in pairs. Triangular fuzzy numbers are used to establish membership function of assessment indexes and objects. Transformation standard is expressed by three fuzzy numbers in accordance with 1-9 scaling method in AHP [8], as shown in Figure 1.
According to the transformation standard, the judgment matrix is constructed. It is assumed that the assessment object has \( n \) index factors, and the index \( C_i \) is compared with \( C_j \), and the degree of importance is obtained. After all indexes are compared in pairs, a judgment matrix is obtained:

\[
M = (a_{ij})_{n \times n} = \begin{bmatrix}
    a_{11} & a_{12} & \cdots & a_{1n} \\
    a_{21} & a_{22} & \cdots & a_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    a_{n1} & a_{n2} & \cdots & a_{nn}
\end{bmatrix}, \quad i, j = 1, 2, 3, \ldots, n
\]  

(1)

Among them, \( a_{ij} = [l_{ij}, m_{ij}, u_{ij}] \), \( a_{j} = [\frac{1}{u_{ij}}, \frac{1}{m_{ij}}, l_{ij}] \) are triangular fuzzy numbers. When there are \( T \) experts make judgments, each expert’s judgment is expressed by \( a_{ij}^{	ext{e}} = [l_{ij}^{	ext{e}}, m_{ij}^{	ext{e}}, u_{ij}^{	ext{e}}] \) and all the judgments are synthesized by the formula below.

\[
a_{ij} = \frac{1}{T} \otimes \sum_{\text{e}=1}^{T} a_{ij}^{	ext{e}}
\]  

(2)

(3) The triangular fuzzy weights are determined. For the synthetic fuzzy judgment matrix, the geometric mean value is taken, and the synthetic fuzzy number of each line index weight is obtained.

\[
\bar{a}_i = (\bar{l}_i, \bar{m}_i, \bar{u}_i) = \left(\frac{1}{n} \prod_{j=1}^{n} l_{ij}, \frac{1}{n} \prod_{j=1}^{n} m_{ij}, \frac{1}{n} \prod_{j=1}^{n} u_{ij}\right)
\]  

(3)

Then the fuzzy index weight value of line \( i \) is:

\[
w_i = (l_i, m_i, u_i) = \left(\frac{\bar{l}_i}{\sum_{j=1}^{n} u_j}, \frac{\bar{m}_i}{\sum_{j=1}^{n} m_j}, \frac{\bar{u}_i}{\sum_{j=1}^{n} l_j}\right)
\]  

(4)

(4) Weight defuzzification. The defuzzification formula is adopted to transform the angular fuzzy number into the standard weight value.

\[
S(M) = \frac{1+2m+u}{4}
\]  

(5)

(5) Weight normalization. The standard weight is normalized and the relative weight is obtained.
\[ WF_i = \frac{S(w_i)}{\sum_{j=1}^{5} S(w_j)} \]  \hspace{1cm} (6)

### 3.2. Index Weight Determination

According to the road tunnel fire risk assessment index system, experts from tunnel operation and management companies, fire departments and scientific research institutes are invited to make a comparative analysis of the importance of indicators at all levels by using FAHP. The index judgment matrix is established and FAHP is adopted to determine weights of all index hierarchy.

(1) The indexes weights determination of tunnel and environmental criterion layer is taken as an example, the calculation process is as follows:

Firstly, the fuzzy judgment matrix of the indexes is established according to the expert score. Then, Formula (2) is used to calculate the comprehensive judgment values of the indexes, and the comprehensive judgment matrix of the index factors is established, as shown in Table 2. Then, according to Formula (3), the comprehensive fuzzy numbers of index weights in each line in the fuzzy judgment matrix is determined.

#### Table 2. Indexes Synthetic Judgment Matrix in Tunnel and Environment Criterion Layer

| \( c_{ij} \) | \( c_{11} \) | \( c_{12} \) | \( c_{13} \) | \( c_{14} \) | \( c_{15} \) |
|----------------|----------------|----------------|----------------|----------------|----------------|
| \( c_{31} \) | (1, 1, 1) | (1.63, 2.08, 2.81) | (1.38, 2.25, 3.77) | (0.71, 0.77, 0.95) | (0.24, 0.32, 0.52) |
| \( c_{32} \) | (0.96, 1.15, 1.61) | (1, 1, 1) | (0.88, 1.03, 1.19) | (0.21, 0.27, 0.44) | (0.18, 0.22, 0.29) |
| \( c_{33} \) | (0.54, 0.71, 0.75) | (1.63, 2.33, 3.06) | (1, 1, 1) | (0.2, 0.26, 0.42) | (0.17, 0.21, 0.27) |
| \( c_{34} \) | (1.75, 2.38, 3.08) | (3.36, 4.5, 5.25) | (0.66, 4.56, 5.63) | (1, 1, 1) | (1.88, 2.33, 3.06) |
| \( c_{35} \) | (2.25, 3.5, 4.34) | (4.05, 5.25, 6.43) | (3.49, 5.3, 6.11) | (0.67, 0.94, 1.13) | (1, 1, 1) |

\[ \bar{a}_1 = \left( \bar{l}_1, \bar{m}_1, \bar{u}_1 \right) = \left( \frac{s}{\sum_{j=1}^{5} l_{1j}}, \frac{s}{\sum_{j=1}^{5} m_{1j}}, \frac{s}{\sum_{j=1}^{5} u_{1j}} \right) = (0.83, 1.03, 0.39) \]

In a similar way, \( \bar{a}_2 = (0.50, 0.59, 0.75), \bar{a}_3 = (0.50, 0.62, 0.76), \bar{a}_4 = (2.10, 2.58, 3.08), \bar{a}_5 = (1.84, 2.47, 2.86) \).

Then, according to formula (4), the average fuzzy weight value for each line index is calculated to be \( w_1 = (l_1, m_1, u_1) = \left( \frac{\bar{l}_1}{\sum_{j=1}^{5} \bar{m}_1}, \frac{\bar{m}_1}{\sum_{j=1}^{5} \bar{m}_1}, \frac{\bar{u}_1}{\sum_{j=1}^{5} \bar{u}_1} \right) = (0.09, 0.14, 0.24) \), \( w_2 = (0.06, 0.08, 0.13) \), \( w_3 = (0.06, 0.09, 0.13) \), \( w_4 = (0.24, 0.35, 0.54) \), \( w_5 = (0.21, 0.34, 0.50) \).

According to formula (5), the triangular fuzzy number is transformed into a standard weight value \( S(w_i) \):

\[ S(w_1) = \frac{l_1 + 2m_1 + u_1}{4} = 0.15, S(w_2) = 0.09, S(w_3) = 0.09, S(w_4) = 0.37, S(w_5) = 0.35. \]

Finally, the standard weight of each index in fire-fighting facility and equipment criterion layer is normalized as shown in Table 3.

#### Table 3. Weights of Each Index Factor in Tunnel and Environment Criterion Layer

| Criterion Layer | Index Layer | Weight |
|-----------------|-------------|--------|
| Personnel and Management | Tunnel fire load | 0.15 |
| Personnel and Management | Tunnel service life | 0.08 |
| Personnel and Management | Fire risks of adjacent buildings | 0.09 |
| Personnel and Management | Distance from the fire stations | 0.35 |
| Personnel and Management | Local rescue force | 0.33 |

Similarly, the weight of each indicator in the criterion layer of personnel, management as well as repair facilities and equipment can be obtained, which are shown in table 4 and table 5 respectively.
Table 4. Weights of Each Index Factor in Fire-fighting Facility and Equipment Layer

| Criterion Layer (Grade I Indexes) | Index Layer (Grade II Indexes)                | Weight |
|-----------------------------------|----------------------------------------------|--------|
| Fire-fighting Facility and Equipment | Tunnel hydrant system                        | 0.07   |
|                                    | Automatic fire alarm system                  | 0.11   |
|                                    | Ventilation and smoke control system         | 0.33   |
| Fire-fighting Facility and Equipment | Automatic fire extinguishing system         | 0.24   |
|                                    | Fire extinguishers                          | 0.03   |
|                                    | Safe evacuation facilities                  | 0.19   |
|                                    | Fire electrical system                      | 0.03   |

Table 5. Weights of Each Index Factor in Personnel and Management Layer

| Criterion Layer (Grade I Indexes) | Index Layer (Grade II Indexes)                | Weight |
|-----------------------------------|----------------------------------------------|--------|
| Personnel and Management          | Personnel fire safety awareness              | 0.04   |
|                                    | Personnel escape self-help ability           | 0.07   |
|                                    | Fire safety management                       | 0.11   |
|                                    | Fire emergency plan                         | 0.08   |
|                                    | Fire safety training and fire emergency drill| 0.10   |
|                                    | Fire protection publicity and education      | 0.04   |
|                                    | Daily fire safety inspection                 | 0.24   |
|                                    | Fire-fighting equipment maintenance         | 0.32   |

After the weights of factors in index layer are determined, the same method is adopted to calculate the weights of criterion layers when regards the fire safety of the road tunnel as the target. Finally, the weights of criterion layers are determined as shown in Table 6.

Table 6. Weights of criterion layers

| Criterion Layer                        | Weight |
|----------------------------------------|--------|
| Personnel and Management               | 0.32   |
| Fire-fighting Facility and Equipment   | 0.47   |
| Tunnels and Environment                | 0.21   |
To sum up, the fire risk assessment system in the operation period of road tunnel is established; it is composed of 3 criterion layer factors and 20 index layer factors with different weights, as shown in Table 7.

| Table 7. Road Tunnel Fire Risk Assessment System |
|-----------------------------------------------|
| Criterion Layer | Weight | Index Layer | Weight |
| Personnel and Management $C_1$ | 0.32 | Fire safety training and fire emergency drill | 0.10 |
| | | Fire protection publicity and education | 0.04 |
| | | Daily fire safety inspection | 0.24 |
| | | Fire-fighting equipment maintenance | 0.32 |
| | | Tunnel hydrant system | 0.07 |
| | | Automatic fire alarm system | 0.11 |
| Fire-fighting Facility and Equipment $C_2$ | 0.47 | Ventilation and smoke removal system | 0.33 |
| | | Automatic fire extinguishing system | 0.24 |
| | | Fire extinguishers and others | 0.03 |
| | | Safe evacuation facilities | 0.19 |
| | | Fire electrical system | 0.03 |
| | | Tunnel fire load | 0.15 |
| | | Tunnel service life | 0.08 |
| Tunnels and Environment $C_3$ | 0.21 | Fire risks of adjacent buildings | 0.09 |
| | | Distance from the fire stations | 0.35 |
| | | Corporate rescue force | 0.33 |

4. Conclusion
On the basis of fire risk evaluation index system during the road tunnel operation period, this paper adopts FAHP and transforms the qualitative evaluation of importance degree between two factors into triangular fuzzy function for establishing the judgment matrix of road tunnel fire risk indexes. The relative weights of the fire risk assessment indexes are finally determined through fuzzy mathematic operation that makes the fire risk assessment system of the road tunnel in operation more accurate and complete.

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