Safety Evaluation of Large-size Transportation Bridges Based on Combination Weighting Fuzzy Comprehensive Evaluation Method

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Abstract. The load of large-size vehicles has not been clearly defined in the existing bridge design codes in our country. When large-size vehicles cross the bridge, the bridge has certain safety hazards. At present, there are not many evaluation methods for the driving safety of large-size transportation bridge structures. In order to scientifically evaluate the traffic safety of the large-size transportation bridge structure, this paper considers the factors of bridge, traffic and environment, and establishes the evaluation index system for the operation safety of the large-size transportation bridge structure, using the comprehensive weighting method of the G1-entropy weight method. Calculating the weight and combining the fuzzy comprehensive evaluation method to evaluate the traffic of the large-scale transportation bridge in Huanglong County, Shaanxi Province, the results show that the traffic safety level of the bridge is level II, which has good safety.

1. Introduction

In recent years, with the rapid development of the national economy, many key construction projects related to the national economy and people's livelihood have begun to be put into construction, and large-scale transportation has emerged at the historic moment\textsuperscript{[1]}. In the process of large-scale transportation, the safe passage of vehicles through bridges is one of the cores of large-scale transportation.

Due to the huge load, large transportation vehicles will cause bridge structure vibration when passing through the bridge, and the bridge vibration in turn affects the vehicle vibration. The vibration under the influence of this interaction is called vehicle-bridge coupled vibration\textsuperscript{[2]}. Yang et al.\textsuperscript{[3]}, Zou et al.\textsuperscript{[4]}, respectively elaborated on the development of vehicle-bridge coupled vibration theory and the evolutionary history of simulation models. Li Xiaozhen\textsuperscript{[5]} proposed the Newmark-\( \beta \) method to solve the established vehicle-bridge coupled vibration equation, and solved the vehicle-bridge coupled vibration response of the steel-analyzed composite main girder cable-stayed bridge of the Nanjing Cross-River Bridge on the Beijing-Shanghai High-speed Railway. With the improvement of the
computer level, modern vehicle-bridge coupling research can more accurately simulate the bridge structure and vehicle vibration and the coupling numerical relationship between them.

Since the 1980s, scholars at home and abroad have conducted extensive research on the safety evaluation of bridge driving under the action of vehicles, and proposed methods such as analytic hierarchy process, grey relational analysis and variable weight synthesis[6-8]. For small and medium-sized bridges, the commonly used evaluation methods in my country are the Comprehensive Evaluation Method of "Code for Maintenance of Highway Bridges and Culverts" (JTJ H11-2004)[9] and the highway bridge management system developed by the Research Institute of the Ministry of Communications in the 1990s[10].

Most of the existing bridge safety evaluations focus on the detection and individual evaluation of each part of the bridge, lacking a comprehensive evaluation of the overall safety of the bridge, and there are very limited researches on the safety of large transportation bridges. This paper takes a large-size transportation bridge in Huanglong County, Shanxi Province as the engineering background, and establishes the driving safety evaluation of the large-size transportation bridge based on the "Code for Maintenance of Highway Bridges and Culverts"[9-11] and other related road bridge specifications, combined with the coupling relationship between vehicles and bridges The system uses the combination of G1-entropy weighting method and fuzzy theory to comprehensively evaluate the safety of vehicles.

2. Numerical analysis method of vehicle-bridge coupled vibration

2.1. Bridge model establishment

This paper selects the research object of a large transportation bridge in Huanglong County, Shaanxi Province. The upper part adopts (1×9.0) m reinforced concrete cast-in-situ monolithic slab, and the lower part adopts mortar-masonry stone abutment. The width of the bridge is 8.0m, and the horizontal layout: 0.5 m (guardrail) + 7.0m (carriageway) + 0.5m (guardrail). The Abaqus software is used to establish the finite element model of the reinforced concrete simply supported beam bridge. The bridge is simulated by solid45 elements, the grid is divided by C3D8R, and the reinforcement is T3D2 Truss. Figure 1 shows the three-dimensional model of a reinforced concrete simply supported beam bridge.

![Figure 1. Modeling example of reinforced concrete slab bridge.](image)

2.2. Establishment of simulation model of large-size transportation vehicles

The large-size transportation vehicle is an eight-axle vehicle model composed of 19 centralized quality systems such as a car body and eight wheel pairs. The vehicle model is shown in Figure 2, and the vehicle simulation model parameters are shown in literature [12].

\[ m_c \text{ is the mass of the car body; } m_i \text{ is the mass of each wheel; } J_{ci} \text{ is the moment of inertia of each side roll of the car body, } K_{si}, C_{si} \text{ are the stiffness coefficients of the upper springs and the damping coefficients of the upper springs; } K_{li} \text{ and } C_{li} \text{ are the stiffness coefficients of the lower springs and the damping coefficients of the lower springs, respectively; } L_i \text{ are the distances of the axles from the center of gravity.} \]
2.3. The establishment of the model of the unevenness of the bridge deck
This paper focuses on the C-level highway bridge, and the irregularity of the bridge surface is simulated by the triangular series superposition method. Figure 3 is a sample curve of simulated bridge deck irregularity.

2.4. Vehicle-bridge coupling dynamic response
This article takes the large-scale transportation reinforced concrete slab bridge in Huanglong County, Shaanxi Province as an example, considers the unevenness of the bridge deck and uses the vehicle-bridge coupling model, the dynamic response of the bridge is analyzed when large-size transportation vehicles pass at speeds of 40km/h, 60km/h, and 80km/h. Figures 4 and 5 show the vertical acceleration of the car body and the vertical displacement at the mid-span node of the bridge when the driving speed is 40km/h. The maximum values of various indexes such as bridge stress, bridge mid-span deflection and vehicle acceleration at different speeds are summarized in Table 1:

3. Safety evaluation system for large-size transportation bridges
3.1. Establishment of indicator system
The establishment of the evaluation index system is mainly about the selection of indexes and the determination of the structural relationship between indexes. For a complex system such as a vehicle safety evaluation system for large transportation bridges, the selection of indicators and the determination of the relationship between indicators will directly affect the reliability of the evaluation
results. The traffic safety evaluation system of large-size transportation bridges is a two-level three-tier evaluation system. Three types of factors such as bridge factor T1, traffic factor T2, and environmental factor T3 are the main factors that affect the traffic safety of highway bridges. The specific index system is shown in Figure 6.

![Figure 6. Safety evaluation system of large-size transportation bridge structure](image)

The value of the secondary index is very important to the evaluation result. In order to have a corresponding theoretical basis when judging the traffic safety level of large transportation bridges and reduce subjective assumptions, this article combines the "Highway Bridge and Culvert Maintenance Specifications", "Highway Bridge Technical Condition Evaluation Standards" and other specifications, to define and classify the secondary indicators of driving safety evaluation, and Table 2 shows the classification standards.

Table 2. Secondary index classification standard for traffic safety evaluation of large transport bridges

| Secondary indicators | I  | II  | III | IV  | V  |
|----------------------|----|-----|-----|-----|----|
| Bridge stress        | Bridge stress change value (ΔT) | 0≤ΔT≤5% | 10≤ΔT≤15% | 20≤ΔT≤25% | 30≤ΔT≤35% | ΔT≥5% |
| Bridge deflection    | Maximum deflection of bridge span (y) | — | — | y≤calculated span/1000 | Calculated span/1000<y≤calculated span/600 | y>calculated span/600 |
| Bridge damage        | Bridge Defect Degree | No | Slight defect | Moderate defect | Severe defect | More severe defects |
| Carrying capacity    | R/γ₀S | 0.855≤R/γ₀S≤1 | 0.81≤R/γ₀S≤0.855 | 0.675≤R/γ₀S≤0.815 | R/γ₀S<0.675 |
| Driving acceleration | Driving acceleration (A) | 0≤A≤0.3 | 0.315≤A≤0.55 | 0.55≤A≤0.63 | 0.63≤A≤1.25 | A≥1.25 |
| Driving speed        | Running speed coordination | Great | better | Moderate | Poor | Poorer |
| Unevenness of bridge | Irregularity grade | Class A | Class B | Class C | Class D | Class E |
| Fog                  | Impact on bridge driving safety | No | Slight | Moderate | Severe | More severe |
| Rainwater            | Impact on bridge driving safety | No | Slight | Moderate | Severe | More severe |
| Ice and snow         | Impact on bridge driving safety | No | Slight | Moderate | Severe | More severe |
3.2. G1 method subjective empowerment

The G1 method is also known as the order relationship analysis method. This method can overcome the shortcomings of the analytic hierarchy process such as large amount of calculation, cumbersome calculation process, and the need for consistency testing. It is an improved analytic hierarchy process [13]. G1 must first sort the evaluation indicators, then compare and judge the importance of adjacent indicators, and finally get the weight coefficient of each indicator. The specific steps are as follows:

1. Determine the order. According to the influence on the evaluation result, the expert determines the order relationship of the evaluation index $X_1, X_2, X_3, ..., X_n$ relative to a certain criterion level (target level): $X_1^* > X_2^* > ... > X_{n-1}^* > X_n^*$.

2. Judging the importance of adjacent indicators. The degree of importance between two adjacent evaluation indicators $X_{i-1}^*$ and $X_i^*$ is represented by $r_i$, which is recorded as:

$$ r_i = \frac{o_i}{o_i^*}, i = n, n - 1, ..., 3, 2 \tag{1} $$

In the formula, $o_i^*$, $o_i$ —— represent the weight coefficient of the evaluation index $X_{i-1}^*$ and $X_i^*$, respectively.

See Table 3 for the values of $r_i$.

| Importance              | Extreme important | Strong important | Obvious important | A little important | Same important |
|-------------------------|-------------------|------------------|-------------------|--------------------|----------------|
| Value of $r_i$          | 1.8               | 1.6              | 1.4               | 1.2                | 1.0            |

3.3. Entropy objective weighting method

Entropy is a concept in thermodynamics, which was later introduced into information theory to measure the degree of disorder of a system. When the system is more orderly, the information entropy is lower, and the system is more disorderly, and the information entropy is higher. The entropy weight method is an objective assignment method that uses the amount of information provided by the entropy value of each indicator to determine the weight of the indicator [14]. Specific steps are as follows:

1. Standardize the raw data.

Assuming that there are m evaluation items and n evaluation indicators, the original data matrix can be obtained as:

$$ X = [x_{ij}]_{m \times n} \quad (0 \leq i \leq m, 0 \leq j \leq n) \tag{4} $$

This article uses the range transformation method to standardize the original data.

For positive indicators:

$$ y_i = \frac{x_{ij} - \min x_{ij}}{\max x_{ij} - \min x_{ij}} \tag{5} $$

For negative indicators:
\( Y'_i = \frac{\max x_i - x_i}{\max x_i - \min x_i} \)  \hspace{1cm} (6)

2. Calculate the proportion of the index value of the i-th item under the j-th index:
\( p_{ij} = Y'_i \sum_{i=1}^{m} Y'_{ij} \)  \hspace{1cm} (7)

3. Calculate the entropy value of the j-th index:
\( e_j = -\frac{1}{\ln m} \sum_{i=1}^{n} p_{ij} \ln p_{ij} \)  \hspace{1cm} (8)

4. Calculate the entropy weight of the j-th index:
\( \omega_j = \frac{1-e_j}{n-\sum_{i=1}^{n} e_j} \)  \hspace{1cm} (9)

3.4. Comprehensive weight method based on G1-entropy weight method
In this paper, the multiplicative normalization method is used to obtain the comprehensive weight of the j-th index. Assuming that the weight obtained by the G1 method is \( \omega_n^* \), and the weight obtained by the entropy weight method is \( \omega_j^* \), the comprehensive weight of the j-th index is:
\( \omega_j = \frac{\omega_n^* \omega_j^*}{\sum_{j=1}^{n} \omega_n^* \omega_j^*} \)  \hspace{1cm} (10)

Then the comprehensive weight vector of all indicators:
\( W_j = [\omega_1 \omega_2 \cdots \omega_n]^T \)  \hspace{1cm} (11)

3.5. Fuzzy comprehensive evaluation
Fuzzy comprehensive evaluation is based on fuzzy mathematics, which quantitatively expresses the objective attributes of some uncertain things and then evaluates. The specific process of evaluation is as follows:

1. Select the bridge driving safety evaluation index system, and establish the evaluation index set \( U \):
\[ U = \{ u_1, u_2, \cdots, u_n \} \]  \hspace{1cm} (12)

2. Establish a standard set of evaluation indicators for bridge driving safety:
\[ V = \{ v_1, v_2, \cdots, v_n \} \]  \hspace{1cm} (13)

3. Calculate the combined weight: According to the multiplicative synthesis normalization method, the subjective weight obtained by the G1 method and the objective weight obtained by the entropy weight method are combined to obtain a comprehensive weight vector.

4. Constructing the evaluation matrix: starting from a single factor for evaluation, determining the degree of membership of the evaluation object to the evaluation level set, making a single-factor fuzzy evaluation, and then combining the single-factor evaluation sets to obtain a multi-factor evaluation set.
\[ R = \begin{bmatrix}
R_1 \\
R_2 \\
\vdots \\
R_n
\end{bmatrix} = \begin{bmatrix}
r_{11} & r_{12} & \cdots & r_{1n} \\
r_{21} & r_{22} & \cdots & r_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
r_{m1} & r_{m2} & \cdots & r_{mn}
\end{bmatrix} \]  \hspace{1cm} (14)

5. Calculation of fuzzy comprehensive evaluation value:
In the formula, B is the fuzzy comprehensive evaluation set; W is the weight of the index; \( b_i \) is the fuzzy comprehensive evaluation index.

The evaluation of the driving safety of the bridge starts from the lowest level of influencing factors, then a comprehensive evaluation is carried out layer by layer, and finally according to the principle of maximum membership degree, the comprehensive value of the road bridge driving safety evaluation is obtained, and its safety level is determined.

4. Case analysis

In order to verify the feasibility and scientficity of the method, the large-scale transportation reinforced concrete slab bridge in Huanglong County, Shaanxi mentioned in the above article is taken as an example, and the driving safety of the bridge is comprehensively evaluated.

4.1. Determine the index set \( U \) and comment set \( V \)

According to the bridge driving safety index system shown in Figure 6, the factor set \( U = \{ u_1, u_2, \ldots, u_{10} \} \) is established. The evaluation level is divided into five levels: dangerous, dangerous, critical, safer, and safer, namely the comment set \( V = \{ 2, 4, 6, 8, 10 \} \).

4.2. Determination of indicator weight

The comprehensive weights of indicators calculated by the combination weighting method of G1-entropymethod described in Section 2 of this article are shown in Table 4.

| Weights | Evaluation index          | Subjective weight | Objective weight | Comprehensive Weights |
|---------|----------------------------|-------------------|------------------|-----------------------|
| Bridge factor 0.2557 | Bridge stress 0.2479 | 0.2936 | 0.2908 |
|         | Bridge deflection 0.2479 | 0.2579 | 0.2954 |
|         | Bridge damage effect 0.2066 | 0.2188 | 0.1806 |
|         | Bridge carrying capacity 0.2975 | 0.2297 | 0.2731 |
|         | Driving acceleration 0.4051 | 0.2315 | 0.2876 |
| Traffic factor 0.4206 | Driving speed 0.3116 | 0.5163 | 0.4934 |
|         | Unevenness of bridge 0.2833 | 0.2521 | 0.2190 |
| Environmental factor 0.3237 | Fog 0.2591 | 0.2063 | 0.1492 |
|         | Rainwater 0.4041 | 0.5586 | 0.6298 |
|         | Ice and snow 0.3368 | 0.2351 | 0.2210 |

4.3. Fuzzy comprehensive evaluation

According to the content of Table 2, each qualitative index is quantified through the expert consultation method, and the quantitative index is obtained by the Abaqus simulation described in the first section of this article. This study chooses a reasonable membership function, calculates the membership degree of each index, and obtains the membership evaluation matrix of each index which can be seen in Table 5-7.
Table 5. Membership degree of bridge factors (R1)

| index                | Evaluation grade |
|----------------------|------------------|
|                      | I    | II   | III  | IV   | V    |
| Bridge stress        | 0.5  | 0.5  | 0    | 0    | 0    |
| Bridge deflection    | 0    | 0    | 1    | 0    | 0    |
| Bridge damage effect | 0    | 0.667| 0.333| 0    | 0    |
| Bridge carrying capacity | 0    | 0.667| 0.333| 0    | 0    |

Table 6. Membership degree of traffic factors (R2)

| index                  | Evaluation grade |
|------------------------|------------------|
|                        | I    | II   | III  | IV   | V    |
| Driving acceleration   | 0.107| 0.893| 0    | 0    | 0    |
| Driving speed          | 0    | 0.933| 0.067| 0    | 0    |
| Unevenness of bridge   | 0    | 0    | 0.733| 0.267| 0    |

Table 7. Membership degree of environmental factors (R3)

| index                  | Evaluation grade |
|------------------------|------------------|
|                        | I    | II   | III  | IV   | V    |
| Fog                    | 0    | 0.267| 0.733| 0    | 0    |
| Rainwater              | 0    | 0    | 0.867| 0.133| 0    |
| Ice and snow           | 0    | 0    | 1    | 0    | 0    |

(1) First-level fuzzy evaluation:

\[ B_1 = W_1 \tilde{R}_1 = \begin{bmatrix} 0.145 & 0.448 & 0.407 & 0 & 0 \end{bmatrix} \quad B_2 = W_2 \tilde{R}_2 = \begin{bmatrix} 0.031 & 0.717 & 0.194 & 0.058 & 0 \end{bmatrix} \]

\[ B_3 = W_3 \tilde{R}_3 = \begin{bmatrix} 0 & 0.040 & 0.876 & 0.084 & 0 \end{bmatrix} \]

(2) Second-level fuzzy evaluation:

\[ R_B = \begin{bmatrix} B_1 \\ B_2 \\ B_3 \end{bmatrix} = \begin{bmatrix} 0.145 & 0.448 & 0.407 & 0 & 0 \\ 0.031 & 0.717 & 0.194 & 0.058 & 0 \\ 0 & 0.040 & 0.876 & 0.084 & 0 \end{bmatrix} \quad B = WR_B = \begin{bmatrix} 0.050 & 0.429 & 0.469 & 0.052 & 0 \end{bmatrix} \]

(3) System score calculation:

Combining the comment set and calculating the value, the total score of the traffic safety evaluation of the large-size transportation bridge can be obtained: \[ G = 0.05 \times 10 + 0.429 \times 8 + 0.469 \times 6 + 0.052 \times 4 + 0 \times 2 = 6.954 \], the result shows this The driving safety of large-size transportation bridges belongs to Class II, which has good safety.

5. Conclusion

Due to the uncertainty of the load of large vehicles, when large vehicles cross the bridge, the bridge has certain potential safety hazards. This article explores the safety of bridges under the load of large transportation vehicles.

(1) Taking the large-scale transportation reinforced concrete slab bridge in Huanglong County, Shaanxi Province as the engineering background, the large-scale vehicle-bridge coupling model was established using Abaqus finite element software. Under the condition of C-level bridge deck irregularities, Under the condition of C-level bridge deck irregularity, the vibration characteristics under the coupling action of vehicle and bridge are calculated.
(2) Considering the three factors of bridge, traffic and environment, the evaluation index system for driving safety of large-size transportation bridge structure has been established. The G1 method (Subjective empowerment method) and the entropy method (Objective empowerment method) are combined to determine the comprehensive weight of the index and established a fuzzy comprehensive evaluation model for the driving safety of the large-size transportation bridge structure.

(3) Combined with an engineering example, namely, a large-scale transportation reinforced concrete slab bridge in Huanglong County, Shaanxi, the fuzzy comprehensive evaluation model for the driving safety of the large-scale transportation bridge structure is used to determine the driving safety level of the bridge structure as Class II.

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