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A Large Bridge Traffic Operation Status Impact Assessment Model Based on AHP–Delphi–SVD Method

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Abstract: As an important component of road traffic facilities, bridges play a crucial role in daily traffic operations, and changes in their status can have an impact on traffic operation. The existing research mainly focuses on monitoring the status of bridges themselves or analyzing the operation status of road traffic, and rarely considers the changes in traffic operation status caused by changes in bridge status. Therefore, in order to evaluate the impact relationship between the two, this article designs an algorithm that combines the Analytic Hierarchy Process (AHP), the Delphi method, and Singular Value Decomposition (SVD) based on the traditional evaluation of bridges and road traffic operation status, and establishes a bridge traffic operation status impact assessment model. Then, simulation analysis and actual data verification will be conducted based on the specific situation of Ma'anshi Bridge on the Chongqing Wuhan Expressway. The experimental results show that the evaluation model established in this paper conforms to the characteristics of traffic operation, can reflect the impact of bridge state changes on traffic operation status well, effectively promote the automation level of bridge traffic impact management, and has high reliability and accuracy.

Keywords: bridge traffic operation; evaluation model; analytic hierarchy process; Delphi method; singular value decomposition

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1. Introduction

China is a country with complex terrain and numerous mountains and rivers. In order to improve transportation efficiency and meet the needs of economic construction, China has built a large number of bridges in highway and railway construction projects. Bridges are indispensable infrastructure for road transportation, alleviating the difficulties caused by complex terrain in China's transportation development and ensuring the sustainable development of various industries and economies [1]. Significant achievements have been made in technology related to roads and bridges in our country, gradually moving towards maturity and promoting the continuous development of our social economy [2]. With the continuation of the operation of bridge facilities and factors such as environmental and climate changes, the status of these facilities will inevitably undergo certain changes, thereby affecting the operation status of transportation. Therefore, a real-time understanding of bridge status and an effective scientific evaluation of the impact of bridges on traffic during operation are of great significance for traffic safety and the economy.

In some developed countries, the construction of road traffic networks has been effectively completed, and a relatively mature and complete analysis and evaluation system has been established for various components of highways. They use existing infrastructure to analyze and evaluate the operation status of highways, improve the quality and service level of high-speed highway operations, which is the direction of future transportation development. However, research into an evaluation system for traffic operation status in

China started relatively late. If the assessment of bridge traffic impact is not strengthened, more bridge traffic accidents will occur, causing incalculable impacts on traffic operation. With the deepening of people's understanding of transportation issues and the increasing emphasis on the role of bridges in traffic operations, a large amount of related research has also been conducted.

In one study [3], a long-term oriented full bridge traffic load monitoring system was proposed for the long-term monitoring of the distribution of full bridge traffic load on large-span bridges. The authors of [4] proposed a stochastic traffic flow simulation method that considered the correlation between vehicle arrival order and axle load. The results show that the correlation of these traffic flow parameters has a significant impact on the response of large-span suspension bridges. The study carried out in [5] uses the generalized extreme value theory to predict and evaluate the extreme value effects of bridges under heavy load random traffic loads in Wuhan during different regression periods. The study carried out in [6] establishes a fitting relationship model for coordination of traffic operations on large-span bridge sections under crosswind action by analyzing the relationship between traffic accidents on bridges and the distribution pattern of crosswinds. In order to effectively determine and identify abnormal driving vehicles, the study carried out [7] has proposed a highway traffic safety estimation model based on vehicle operation status. In order to solve the problem of traffic congestion in the context of smart cities, the study carried out in [8] establishes a traffic ontology called "TrafCsOnto" using OWL language and the protégé tool. The study carried out in [9] proposed an innovative model that utilizes Convolutional Neural Networks (CNNs), Bidirectional Long Short Term Memory (BiLSTM), and an Attention Mechanism (AM) to predict highway traffic flow with high accuracy and feasibility. The study carried out in [10] constructs a bridge digital twin system connected by measured traffic flow loads to evaluate the health status of bridge structures during operation. The experimental results showed that the system integrates the response coordination relationship between various components within the overall structure in the finite element model and the real change law of the structure in the monitoring data, and is capable of carrying out the health status assessments of bridge structures throughout their entire life cycle. The study carried out in [11] proposed a probabilistic fatigue assessment method based on the simulation of random traffic flow and on-site measured strain influence lines, and verified the effectiveness of the proposed method through a case study of a large-span suspension bridge. The study carried out in [12] proposed a truck queue load model and a mixed traffic flow simulation method to study the load effect level of different truck queues and the impact of mixed traffic flow formed with ordinary vehicles on bridge structures, and evaluated the applicability of current regulations. The study carried out in [13] proposed a method for evaluating the dynamic influence factor (IM) from the dynamic response of bridges considering local surface damage in traffic flow. The method was validated by applying it to two existing bridges with different road surface damage and traffic conditions.

In summary, the above-mentioned research is still focused on the evaluation of bridges themselves and traffic operation status, or the impact of traffic flow on bridge structures, lacking an assessment of the impact of changes in bridge status on traffic operation status. However, a timely and accurate understanding of bridge information, effective evaluation of the impact of changes in bridge status on traffic conditions, and the timely adoption of effective measures play an important role in ensuring the safe and reliable operation of traffic and improving the operational efficiency of the highway network. Therefore, this article starts with the impact of bridges on traffic operation, and uses an algorithm model that combines Analytic Hierarchy Process (AHP), Delphi method, and Singular Value Decomposition (SVD) to establish a model for evaluating the impact of bridge traffic operation status, which is applied in practical engineering projects. This model can timely and accurately understand bridge information, effectively evaluate the impact of changes in bridge status on traffic conditions, and play an important role in ensuring the safe and reliable operation of traffic and improving the operational efficiency of the highway network.

2. Requirements for Detection Indicators of Bridge Facility Operation Status

In actual bridge monitoring, real-time monitoring is preferred for large bridges, and this monitoring method generates many data indicators that need to be screened for indicators related to traffic operation status. This article designs a Hierarchical Bridge Evaluation model, as shown in Figure 1.

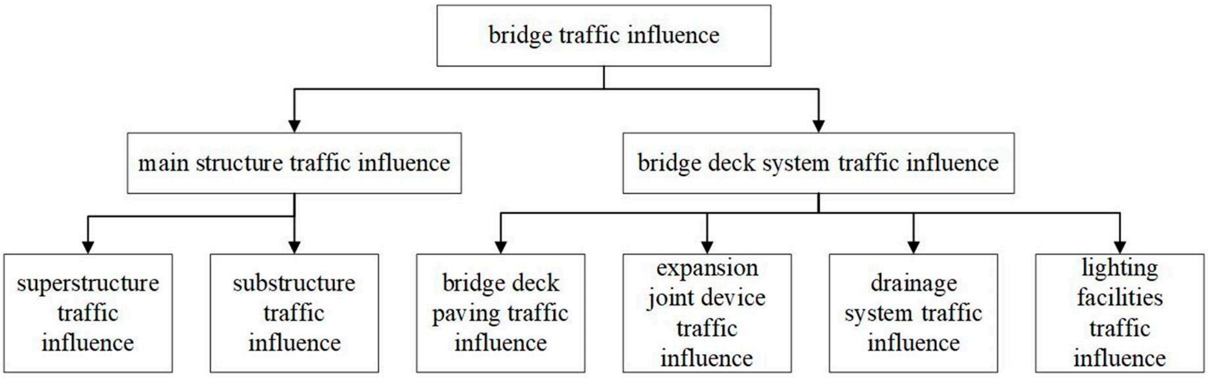

Figure 1. Hierarchy of bridge traffic impact assessment.

2.1. Determination of Existing Information and Analysis of Factors Affecting Traffic Operation Status

The existing information about large bridges is defined as the data for the current evaluation object held in various information systems included in the road network. From the perspective of information access, analysis and processing, and system evaluation, the existing information about large bridges can be divided into two categories: static information and dynamic information:

(1) Static information refers to the data of regarding the attributes of routes and bridges included in the road network, which are generally not changed after the completion of the bridge.

(2) Dynamic information refers to the real-time monitoring results of the dynamic monitoring system for large bridges in the highway network, the detection results of the maintenance, management, and monitoring of systems, and various results of daily inspections. This part of the data usually has a certain update frequency according to management needs.

The factors affecting bridge traffic are mainly divided into two categories: the impact of each component of the main structure and each component of the bridge deck system on traffic.

Among them, the impact of each component of the main structure on traffic includes:

(1) Superstructure traffic-influencing factors refer to the detection results of the bridge located above the support, including the bridge span structure and bridge deck structure.

(2) Substructure traffic-influencing factors refer to the detection results of the supporting structure of the bridge located below the support.

The impacts of various components of the bridge deck system on traffic include:

(1) Traffic-influencing factors of bridge deck paving refer to the detection results for bridge deck pavement.

(2) Traffic-influencing factors of expansion joint devices refer to the detection results for expansion joint devices in bridge deck systems.

(3) Traffic-influencing factors of drainage system refer to the results of an inspection of the drainage system in the bridge deck system.

(4) Traffic-influencing factors of lighting facilities refer to the results of an inspection of the lighting facilities on bridge decks.

2.2. Classification of Existing Factors Influencing Information Transportation

The existing information types and various traffic-influencing factors that have been identified can be basically divided into two categories based on their impact on traffic operation status. One category is considered to have direct influencing factors, and the other category is considered to have indirect influencing factors. When determining the weight of the impact of infrastructure on traffic, the weight determination methods can be divided into two categories: the expert scoring method and experimental determination method.

Determine the weights of the impacts of various traffic-influencing factors on existing information using expert scoring and experimental analysis methods. Among them, the expert scoring method mainly focuses on determining the weights of the impacts of traffic-influencing factors that are closely related to other factors, such as the long detection cycle of bridge pavement scales. The experimental analysis method mainly focuses on the traffic influencing factors that can be measured in the field and lead to direct changes in vehicle speed and driving. By measuring relevant parameters and designing corresponding experimental processes, the weights of the impacts of the above traffic-influencing factors can be measured.

This article analyzes various traffic influencing factors of existing information, and combines experimental data from the analysis method and expert scoring results to obtain the traffic influencing factors and degree of bridge infrastructure, as listed in Table 1. The degree of impact increases from 0 to 1. The classification and definition of each scale standard in this Table are consistent with the current "Technical Condition Evaluation Standards for Highway Bridges".

Table 1. Factors and degrees of impact on bridge infrastructure traffic.

Influencing Factors	**Traffic Influence Degree (0–1)**				
	Class 1	**Class 2**	**Class 3**	**Class 4**	**Class 5**
superstructure	0.00	0.15	0.25	0.40	1.00
substructure	0.00	0.15	0.25	0.40	1.00
bridge deck paving	0.00	0.10	0.20	0.25	-
expansion joint device	0.00	0.10	0.20	0.30	-
drainage system	0.00	0.05	0.15	0.30	-
lighting facilities	0.00	0.05	0.10	0.15	-

Note: A degree of impact of 0 indicates no impact on traffic, while a degree of impact of 1 indicates a significant impact on traffic and the need to interrupt it.

2.2.1. Traffic-Influencing Factors of the Superstructure

The results of the inspection of the superstructure of the bridge are classified into Class 1–5 based on their technical condition evaluation level, as shown in Table 2:

Table 2. Traffic-influencing factors of bridge superstructure inspection results.

Superstructure Inspection Results	**Specific Meaning**
Class 1	The technical condition of the main components of the superstructure is intact, and the evaluation results are all Class 1.
Class 2	The technical condition assessment results of the main components of the superstructure are Class 2 or below, with good technical condition of each component, no obvious deformation, only a small number of cracks, no defects or detachment, and no impact on normal driving.

Table 2. *Cont.*

Superstructure Inspection Results	Specific Meaning
Class 3	The technical condition assessment result of the main components of the superstructure is Class 3 or below, with obvious downward deflection, deflection less than the limit value, or individual components experiencing bending deformation, slight vibration or shaking when driving.
Class 4	The technical condition assessment result of the main components of the superstructure is Class 4 or below, and the components have obvious permanent deformation, defects or deformations less than or equal to the specification value.
Class 5	The technical condition assessment result of the main components of the superstructure is Class 5, with deflection or other deformations greater than the limit value, causing significant permanent deformation of the structure and significantly affecting driving safety.

2.2.2. Traffic-Influencing Factors of the Substructure

The results of the inspection of the substructure of the bridge are classified into Class 1–5 based on their technical condition evaluation level, as shown in Table 3:

Table 3. Traffic-influencing factors of bridge substructure inspection results.

Substructure Inspection Results	Specific Meaning
Class 1	The technical condition of the main components of the substructure is intact, and the evaluation results are all Class 1.
Class 2	The technical condition assessment results of the main components of the substructure are Class 2 or below, with good technical condition of each component, no obvious deformation, only a small number of cracks, no defects or detachment, and no impact on normal driving.
Class 3	The technical condition assessment result of the main components of the substructure is Class 3 or below, with obvious downward deflection, deflection less than the limit value, or individual components experiencing bending deformation, slight vibration or shaking when driving.
Class 4	The technical condition assessment result of the main components of the substructure is Class 4 or below, and the components have obvious permanent deformation, defects or deformations less than or equal to the specification value.
Class 5	The technical condition assessment result of the main components of the substructure is Class 5, with deflection or other deformations greater than the limit value, causing significant permanent deformation of the structure and significantly affecting driving safety.

2.2.3. Traffic-Influencing Factors of the Bridge Deck Paving

The results of the inspection of the bridge deck paving are classified into Class 1–4 based on their technical condition evaluation level, as shown in Table 4:

Table 4. Traffic-influencing factors of bridge deck paving inspection results.

Bridge Deck Paving	Specific Meaning
Class 1	The evaluation results of the technical condition of the bridge deck paving are all on Class 1 and in good condition.
Class 2	The evaluation of the technical condition of bridge deck paving has reached Class 2, with local cracks, damages, and deformations, but within a reasonable state.

Table 4. *Cont.*

Bridge Deck Paving	Specific Meaning
Class 1	The evaluation results of the technical condition of the bridge deck paving are all on Class 1 and in good condition.
Class 2	The evaluation of the technical condition of bridge deck paving has reached Class 2, with local cracks, damages, and deformations, but within a reasonable state.

2.2.4. Traffic-Influencing Factors of the Expansion Joint Device

The results of the inspection of the expansion joint device are classified into Class 1–4 based on their technical condition evaluation level, as shown in Table 5:

Table 5. Traffic-influencing factors of expansion joint device inspection results.

Expansion Joint Device	Specific Meaning
Class 1	The evaluation results of the technical condition of the expansion joint device are all on Class 1 and in good condition.
Class 2	The evaluation of the technical condition of expansion joint device has reached Class 2, with local cracks, damages, and deformations, but within a reasonable state.
Class 3	The evaluation of the technical condition of expansion joint device has reached Class 3, with some cracks, damages, and deformations, reaching or approaching the standard values.
Class 4	The evaluation result of the technical condition of the expansion joint device has reached Class 4, with significant cracks, damages, and deformations, the number of which is greater than the standard value.

2.2.5. Traffic Influencing Factors of the Drainage System

The results of the inspection of the drainage system are classified into Class 1–4 based on their technical condition evaluation level, as shown in Table 6:

Table 6. Traffic-influencing factors of drainage system inspection results.

Drainage System	Specific Meaning
Class 1	The evaluation results of the technical condition of the drainage system are all Class 1 and in good condition.
Class 2	The evaluation result of the technical condition of the drainage system has reached Class 2, and there are local drainage blockages, blockages, or damages in the drainage system, but within a reasonable state.
Class 3	The evaluation result of the technical condition of the drainage system has reached Class 3, with some local drainage problems such as obstruction, blockage or damage, reaching or approaching the standard values.
Class 4	The evaluation of the technical condition of the drainage system has reached Class 4, and there are obvious local drainage blockages, blockages, and damages in various components of the bridge deck, with a quantity greater than the standard value.

2.2.6. Traffic-Influencing Factors of the Lighting Facilities

The inspection results of the lighting facilities are classified into Class 1–4 based on their technical condition evaluation level, as shown in Table 7:

Table 7. Traffic-influencing factors of lighting facilities inspection results.

Lighting Facilities	Specific Meaning
Class 1	The evaluation results of the technical condition of the lighting facilities are all on Class 1 and in good condition.
Class 2	The evaluation result of the technical condition of the lighting facilities has reached Class 2, and there are a few deficiencies in the lighting facilities, but within a reasonable state.
Class 3	The evaluation result of the technical condition of lighting facilities has reached Class 3, and there are many deficiencies in the lighting facilities, reaching or approaching the standard value.
Class 4	The evaluation result of the technical condition of lighting facilities has reached Class 4, with a large number of lighting facilities missing and exceeding the standard value.

3. Impact Assessment Model for Traffic Operation Status of Large Bridges

Based on the established indicators of infrastructure, the degree of impact of each indicator item on traffic, and the weight values of each traffic impact indicator, this paper proposes a traffic state impact model that combines the Analytic Hierarchy Process (AHP), the Delphi method, and Singular Value Decomposition (SVD) to evaluate the impact of infrastructure state changes on traffic operation status. The overall process of this evaluation system is shown in Figure 2.

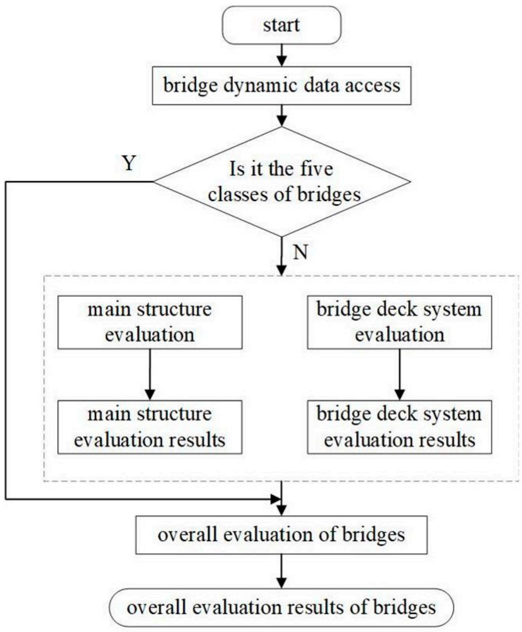

Figure 2. Flowchart of bridge traffic impact assessment system.

3.1. Calculation of Traffic Impact on the Bridge

The weights of the influence of different components of the bridge are $\omega_i,\ i = 1, 2 \ldots$.
The results of the inspection of different components of the bridge are $a_i,\ i = 1, 2 \ldots$.
Then, the impact of the bridge on traffic is:

$$y(f) = 1 - \sum_{i=1}^{n} \omega_i a_i \tag{1}$$

The maximum traffic capacity of the road section is:

$$C_s = C \times (1 - y(f)) \tag{2}$$

Among them, C_s is the current maximum traffic capacity of the evaluated section, C is the traffic capacity designed for the evaluated section, and $y(f)$ is the traffic impact value from the evaluation section.

The degree of traffic impact on different influencing factors of bridges is $f_{bi},\ i = 1,2$. The weights of the influence of different influencing factors are $\beta_i,\ i = 1,2$. The traffic impact result is recorded as f_2. The value of the impact f_2 of the bridge on traffic can be calculated using the following formula:

$$f_2 = \begin{cases} 1 - \sum_{i=1}^{2} \beta_i (1 - f_{bi}) & f_{b1} < 1.0,\ f_{b2} < 1.0 \\ 1 & f_{b1} = 1.0 \end{cases} \quad (3)$$

In the formula, $f_{b1} = 1.0$ refers to the maximum impact of the main structure inspection results on traffic, and f_{b2} refers to the impact of the bridge deck system inspection results on traffic.

3.2. Calculation of Traffic Impact on the Main Structure

The different influencing factors of the main structure of the bridge and the degree of impact of the traffic are $x_i,\ i = 1,2$, respectively. The weights of the influence of different influencing factors are $\beta_{1i},\ i = 1,2$. The traffic impact result is recorded as f_{b1}. The value of the impact f_{b1} of the main structure of the bridge on traffic can be calculated using the following formula:

$$f_{b1} = \begin{cases} 1 - \sum_{i=1}^{2} \beta_{1i} (1 - x_i) & x_i < 1.0 \\ 1 & x_i = 1.0 \end{cases} \quad (4)$$

In the formula, $x_1 < 1.0$ represents the maximum impact of the superstructure detection results on traffic, and $x_2 < 1.0$ represents the maximum impact of the substructure detection results on traffic.

3.3. Calculation of Traffic Influencing Factors for Bridge Deck Systems

The degree of impact on transportation of different influencing factors in bridge deck systems is $x_i,\ i = 1,2,3,4$. The influence weights of different influencing factors are $\beta_{2i},\ i = 1,2,3,4$. The traffic impact result is recorded as f_{b2}. The impact value f_{b2} of the bridge deck system on traffic can be calculated using the following formula:

$$f_{b2} = 1 - \sum_{i=1}^{4} \beta_{2i} (1 - x_i) \quad (5)$$

The traffic impact degree values of each component of the bridge deck system are expressed as a percentage, and the weighted sum of the impact weight and impact degree is used to obtain the overall impact degree value of the bridge deck system.

4. Theory and Method of Traffic Operation Status Evaluation

According to the analysis of the traffic-influencing factors mentioned earlier, the dynamic evaluation of bridge traffic operations mainly includes the real-time operation status and the impact of the bridge itself on the operation status. In the long run, the working status of various components of the bridge is in a dynamic and changing state, which will generate a series of dynamic parameter data about the bridge; however, in a relatively short period of time, the state of various components of the bridge can be seen as unchanged to a certain extent. If there is a sudden change under certain conditions, it will have a significant impact on the traffic operation status of the bridge in a short period of time.

The key to multi-objective system evaluation lies in how to scientifically and reasonably weight and comprehensively calculate various indicators, and integrate a multi-objective problem into a single-indicator form [14]. This article improves the Analytic Hierarchy Process (AHP) and Delphi combined with Singular Value Decomposition (SVD) to obtain the weight values of each evaluation-influencing factor in the evaluation model. A partial pseudocode of the algorithm can be found in Appendix A.

4.1. AHP

The Analytic Hierarchy Process (AHP) decomposes elements related to decision-making into levels such as goals, criteria, and plans, and makes decisions based on these levels. The method is concise and flexible. The Analytic Hierarchy Process (AHP) is a comprehensive evaluation method that combines qualitative and quantitative analysis. Its main idea is to decompose complex problems into several levels and compare the importance of each two indicators, create a judgment matrix, and calculate the weight values of different factors in the system by calculating the eigenvalues and eigenvectors of the judgment matrix [15].

In the impact assessment of bridge traffic operation status, according to the theory of AHP, the influencing factors of the bridge components to be evaluated can be divided into n different levels of factor sets, $U = \{u_1, u_2, \ldots, u_n\}$. The corresponding weight set is $W = \{w_1, w_2, \ldots, w_n\}$.

In addition, in order to effectively evaluate the overall impact of the bridge on traffic, based on the importance of the impact on traffic, the overall traffic impact of the bridge is divided into two categories: the results of the main structure inspection and the results of the bridge deck system inspection. As shown in Table 8:

Table 8. Traffic-influencing factors in lighting facilities inspection results.

Influencing Factors	Specific Meaning
Main structure inspection results	The results of daily, regular, special, and specialized inspections of the upper and lower structures of bridges are classified into Class 1–5.
Bridge deck system inspection results	The inspection or testing results of various components of the bridge deck system are divided into Class 1–4.

Establish a comment set $V = \{v_1, v_2, \ldots, v_n\}$ based on the above table. Based on the factor set and comment set, define the evaluation result set $R = \{r_1, r_2, \ldots, r_n\}$, which includes:

$$r_i = \sum_{j=1}^{n} \sum_{k=1}^{m} v_{ij} w_{jk} \tag{6}$$

In the formula, the selection of weight vector W is carried out using the Delphi method.

4.2. Delphi Method

The Delphi method, also known as the expert inquiry survey method, is a decision-making method that involves conducting several rounds of anonymous consultations to concentrate the opinions of expert groups and ultimately make conclusions that are in line with development trends [16]. The prediction and evaluation leadership group summarizes and organizes the opinions in each round, and sends them as reference materials to each expert for analysis and judgment for them to propose new opinions. After repeated attempts, the opinions tend to be consistent, resulting in a more reliable and unified conclusion. The essence of the Delphi method is to use the knowledge and experience of a collective of experts to seek multiple opinions from a group of relevant experts for complex problems that cannot be directly quantitatively analyzed, and to obtain measurement conclusions [17].

Due to the anonymity, feedback, and statistical characteristics of the Delphi method, the statistical analysis and feedback of expert opinions during the survey process fully reflect the role of information feedback and information control [18]. Therefore, this article uses the Delphi method to determine the weight of bridge traffic impact. The specific flowchart is shown in Figure 3:

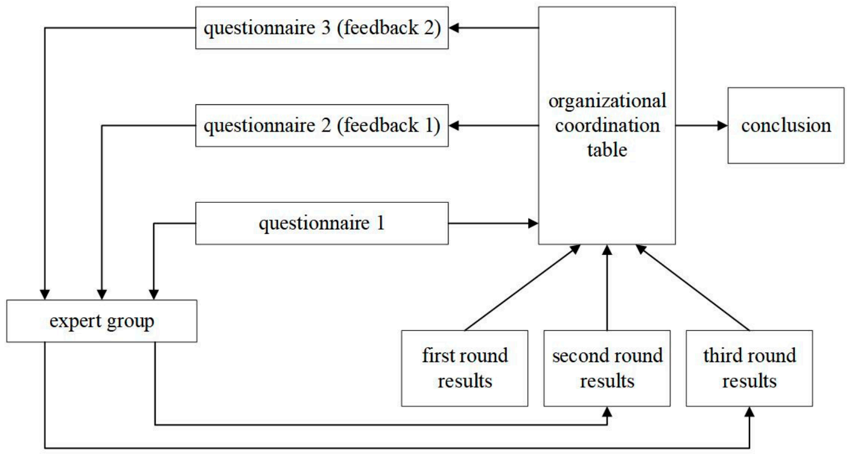

Figure 3. Application flowchart of Delphi method.

Based on the results of the Delphi method, the traffic impact weights of the influencing factors of the bridge, the main structure of the bridge, and the bridge deck system are finally determined. The specific steps are as follows:

(1) Define judgment matrix $B = (b_{ij})_{n\times n}$ and $b_{ij} = 0;\ i, j = 1, 2 \ldots n$, and eigenvectors $\beta = (\beta_1, \beta_2, \ldots \beta_n)^T$ and $\beta_i = 0,\ i = 1, 2 \ldots n$:
(2) Based on the expert experience database, compare different traffic influencing factors $A_1, A_2 \ldots A_n$ pairwise and rank them in a non-decreasing manner, denoted as $A_1 \geq A_2 \ldots \geq A_n$;
(3) Compare the sorted non-decreasing sequence $A_1 \geq A_2 \ldots \geq A_n$ with A_i and A_{i+1} based on $i = 1, 2 \ldots n-1$, and write the scaling value t_i;
(4) Construct judgment matrix B:
Assign initial values to i, j; let $i = 1, j = 1$, and $i, j = 1, 2 \ldots n$;
If $i = j$, then $b_{ij} = 1$;
If $i \neq j$, then $b_{ij} = t_i \times t_{i+1} \times \ldots \times t_{j-1}, (i \neq j)$, and $b_{ij} = \frac{1}{b_{ji}}$;
(5) Solve the matrix to obtain the maximum eigenvector $\lambda_{\max}$ and its corresponding eigenvector β;
(6) Normalize feature vectors, whose corresponding values are the weights in the non-decreasing sequence $A_1 \geq A_2 \ldots \geq A_n$.

Based on the results of the expert scoring method, establish a judgment matrix B. Using the above method, determine the traffic impact weights of each factor in the bridge deck system, as listed in Tables 9–11.

Table 9. Bridge-influencing factors and traffic impact weights.

Influencing Factors	Traffic Influence Weight
main structure	0.8
bridge deck system	0.2

Table 10. The influence weight of the main structure of the bridge.

Influencing Factors	Traffic Influence Weight
superstructure	0.5
substructure	0.5

Table 11. The influence weight of the bridge deck system.

Influencing Factors	Traffic Influence Weight
bridge deck paving	0.40
expansion joint device	0.25
drainage system	0.20
lighting facilities	0.15

4.3. SVD

The Singular Value Decomposition (SVD) is an important matrix factorization method in linear algebra, which has important applications in signal processing, statistics, and other fields [19].

In the establishment of the bridge traffic impact assessment model, the relative importance values of each evaluation factor are obtained through the Delphi method. In order to facilitate the calculation of the impact degree later, decoupling and normalization processing are needed, and the SVD method is used here [20].

Firstly, construct the initial matrix. The data obtained from the Delphi method expert scoring are a set of relative importance values, which are a set of one-dimensional data. In order to apply the SVD algorithm, a two-dimensional matrix needs to be constructed. If the original data are $b_i(i = 1, 2, \ldots, r)$ and r is the number of evaluation model factors, then the constructed matrix is $A \in R^{r \times r}$. The construction method is as follows:

(1) $a_i = 1(i = 1, 2, \ldots, r)$. The diagonal elements of the matrix have values of 1;
(2) If $i \neq j(i, j = 1, 2, \ldots, r)$, set $k = i : 1 : j - 1(i, j = 1, 2, \ldots, r)$, then $a_{ij} = a_{ij} * b_k$;
(3) If $a_{ji} \neq 0$, then $a_{ij} = 1/a_{ji}$.

This constructs an $r \times r$ matrix and also solves the problem of data coupling in the original one-dimensional array. By solving matrix $A \in R^{r \times r}$, a set of independent data are obtained.

Secondly, the singular value decomposition algorithm is applied to decompose matrix $A \in R^{r \times r}$. In order to maintain the sum of the weights of each factor as 1, after performing singular value decomposition on the matrix, the results also need to be normalized. The implementation steps are as follows:

(1) Solve the eigenvectors pv and the eigenvalues po of the matrix;
(2) Find the maximum eigenvalue and the eigenvector corresponding to the maximum eigenvalue;
(3) Normalize the eigenvector.

By following the steps above, the weight values of each evaluation factor in the evaluation model can be calculated. Since the model is implemented using the Analytic Hierarchy Process, this method has been used more than once in model evaluation, and will not be repeated here.

5. Simulation and Results of Impact of Parameters on Bridge Traffic Operation

5.1. Classification of Bridge Traffic Impact Levels

According to some regulations in the "Technical Condition Evaluation Standards for Highway Bridges", the impact of changes in the main structure and deck system of bridges on traffic is divided into four levels.

Level 1: Changes in the status of road and bridge infrastructure have a minor impact on traffic, with the bridge capacity changing from 90% to 100% of its original design capacity.

Level 2: Changes in the status of road and bridge infrastructure have a certain impact on traffic, with the bridge capacity changing from 80% to 89% of its original design capacity.

Level 3: Changes in the status of road and bridge infrastructure have a significant impact on traffic, with bridge capacity changing from 70% to 79% of its original design capacity.

Level 4: Changes in the status of road and bridge infrastructure have a significant impact on traffic, with the bridge capacity changing by less than 69% compared to the original design capacity.

5.2. Introduction to Simulation Environment

This article chooses to simulate the section of road from Yujiawan in Yubei District to Beibei, with a length of approximately 23 km, including the Ma'anshi Bridge. The simulation experiment is conducted using TransModeler software (version 6.0) [21,22], with a simulation time of 1 h (10:00–11:00). The occurrence of each obstacle started at 10:20 and ended at 10:40. The free flow speed of the Chongqing Wuhan Expressway is set to 120 km/h, with a free flow speed of 70 km/h for the bridge. The simulation time is from 10:00 to 11:00, and the entrance flow of the simulated section is 2500 vehicles/h and the exit flow is 2500 vehicles/h.

To simulate and analyze the impact of changes in road infrastructure on traffic capacity, changes in sensor data are used to simulate changes in bridge status on simulated road sections. Three traffic conditions are set for road capacity, excellent, good, and poor, and the impact of changes in traffic operation influencing factors on traffic operation status is verified. The specific meanings of the different road traffic capacities are as follows:

(1) Excellent: The road and bridge facilities have not undergone any changes, or have undergone minor changes, and these changes have almost no impact on the vehicles driving on the road. Vehicle traffic is basically smooth, and variables such as traffic flow, speed, and lane occupancy rate change steadily.

(2) Good: The road and bridge facilities have undergone certain changes. By changing the sensor data on the road, the state of the bridge facilities can be simulated to change. For example, obstacles can be set between sensors, and the maximum speed for passing through this obstacle is set to 60 km/h. However, the impact is not significant, and vehicle traffic is relatively smooth. The variables of traffic flow, speed, and occupancy rate change steadily, with occasional small changes, but the fluctuations are not significant.

(3) Poor: There have been significant changes in road and bridge facilities, such as a malfunction in a section of the road between sensors, resulting in a speed of 0 km/h and a significant impact on vehicle traffic, leading to poor traffic flow. The variables of traffic volume, speed, and occupancy rate have shown obvious abrupt changes.

5.3. Simulation Results and Analysis

We simulated three different conditions of road capacity, compared the conditions of good and bad traffic conditions with the conditions of excellent traffic conditions, and added a comparison of adjacent lane changes. Figures 4–7 show the comparison results of the number of vehicles and average speed collected during good traffic conditions with excellent traffic capacity:

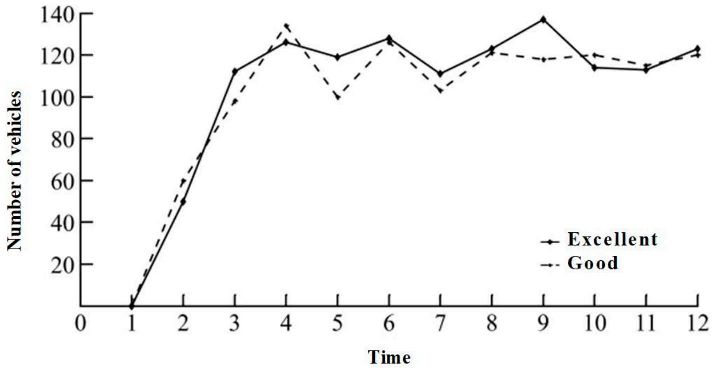

Figure 4. The number of vehicles recorded by sensor 378 when the traffic status is excellent or good.

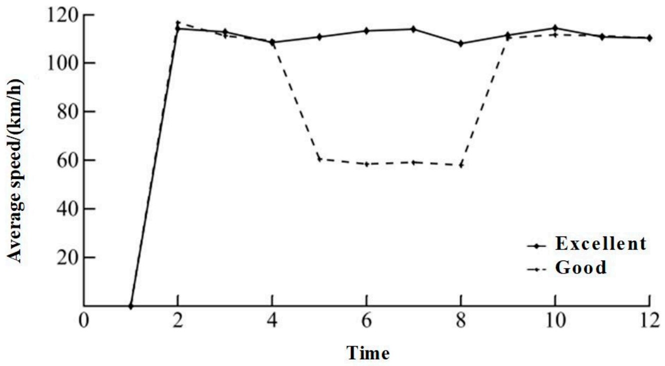

Figure 5. The average vehicle speed recorded by sensor 378 when the traffic status is excellent or good.

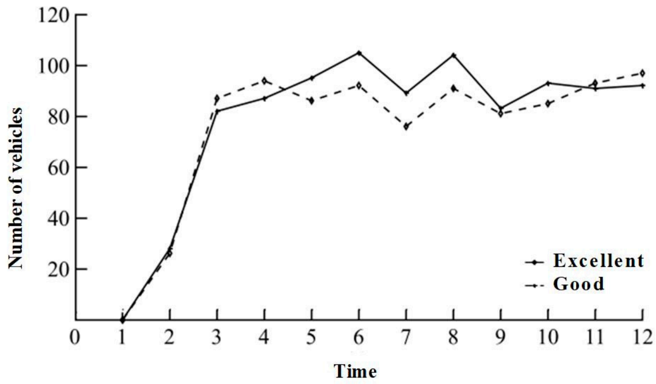

Figure 6. The number of vehicles recorded by sensor 379 when the traffic status is excellent or good.

It can be clearly seen from Figures 4 and 5 that, when there are slight changes in road and bridge facilities, the number of vehicles passing through the road does not change significantly and the changes are relatively stable. It has had a certain impact on the speed of the vehicle, with some changes occurring, but the changes are not significant, which can ensure the normal passage of the vehicle. From Figures 6 and 7, it can be seen that, when there are slight changes in the highway bridge facilities, they also have a certain impact on adjacent lanes, but the changes are not significant, and vehicles can pass through relatively smoothly.

In summary, when there are minor changes in bridge facilities, it will not have a significant impact on the driving conditions of vehicles, and they can pass smoothly as a whole. The number of vehicles passing through remains stable, and the speed is also higher than the minimum speed specified for highways (60 km/h).

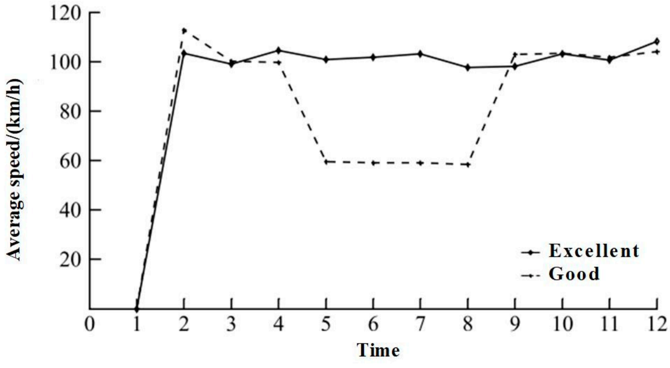

Figure 7. The average vehicle speed recorded by sensor 379 when the traffic status is excellent or good.

Figures 8–11 reflect the comparison of results of the number of vehicles and average speed collected when the traffic capacity is poor compared to when the traffic capacity is excellent:

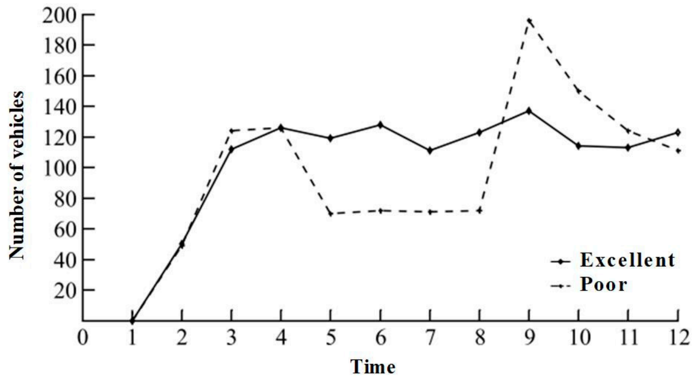

Figure 8. The number of vehicles recorded by sensor 378 when the traffic status is excellent or poor.

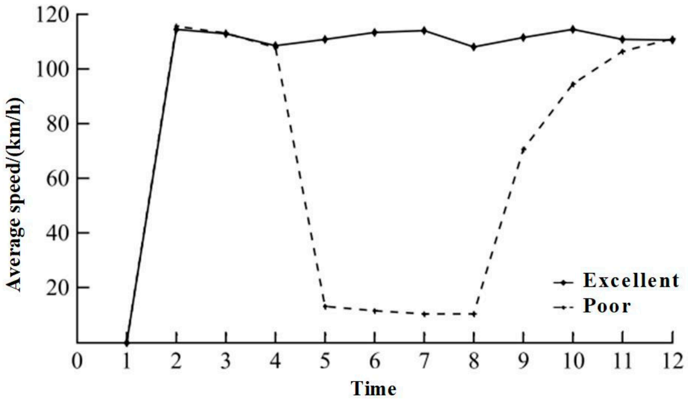

Figure 9. The average vehicle speed recorded by sensor 378 when the traffic status is excellent or poor.

From Figures 8 and 9, it can be seen that when there are significant changes in road and bridge facilities, the number of vehicles passing through the road undergoes a sudden change, and the number of vehicles rapidly increases, resulting in significant road congestion and seriously affecting the efficiency of vehicle traffic. From Figures 10 and 11, it can be seen that when the bridge infrastructure undergoes significant changes, it also has a significant impact on adjacent lanes, causing vehicle traffic to be obstructed and resulting in congestion.

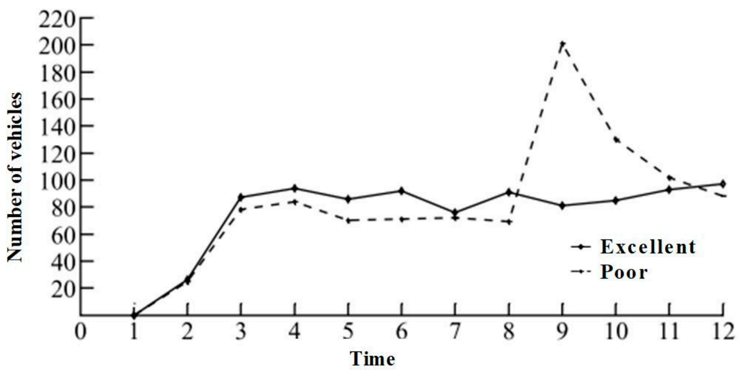

Figure 10. The number of vehicles recorded by sensor 379 when the traffic status is excellent or poor.

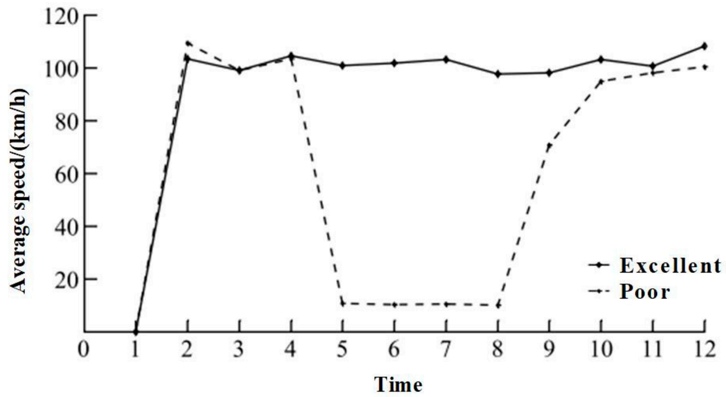

Figure 11. The average vehicle speed recorded by sensor 379 when the traffic status is excellent or poor.

In summary, when there are significant changes in bridge infrastructure, it has a significant impact on the driving conditions of vehicles. Overall, the traffic efficiency is low, the number of vehicles passing through is small, and it leads to serious congestion in adjacent lanes, resulting in a sharp decrease in vehicle passing speed.

Looking at the simulation results of the entire traffic model, it can be seen from the data collected by sensor 378 that when there are slight changes in the road and bridge infrastructure, the road capacity will be affected to a certain extent, but the overall impact is not significant and the recovery is relatively fast. When there are significant changes in the infrastructure of roads and bridges, the road capacity will undergo drastic changes, which will have a huge impact on vehicles and traffic, and the recovery of traffic will also be relatively slow.

According to the data recorded by sensor 379 arranged for adjacent lanes, when there are significant changes in bridge infrastructure, the road capacity of adjacent lanes will also be affected. This conclusion conforms to the general rules of transportation operation and has high reliability and accuracy.

6. Conclusions

This article aimed to promote the automation of bridge traffic impact management, effectively evaluate the impact of bridges on traffic operation status, maintain bridges in a timely manner, and avoid traffic accidents by modeling the bridge traffic impact assessment system, screening evaluation model factors, and processing parameters. On this basis, a bridge traffic operation status evaluation model is proposed based on existing bridge data, with the Analytic Hierarchy Process (AHP) as the main model structure, combined with the Delphi and Singular Value Decomposition (SVD) methods. However, the current research on the operation status of bridge traffic is still not sufficient, and improvements can be made to the following aspects in the future: Firstly, there is still significant room for optimization in terms of the accuracy and applicability of the model, and parameter refinement can be carried out according to different regions and types of roads and bridges. Secondly, reference can also be made to the actual road conditions and relevant standards of different countries and industries to further consider more traffic influencing factors and achieve more accurate assessments.

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Appendix A

Algorithm A1: Traffic Impact Assessment of Large Bridges

Input: X
Output: F

1. Initialization: β
2. **for** i = 1:n
3. **for** j = 1:m
4. $\text{fbj} = 1 - \sum_{1}^{j} \beta j(1 - xj)$
5. **End for**
6. $\text{fi} = 1 - \sum_{1}^{i} \beta i(1 - \text{fbi})$
7. **End for**
8. **Return** F

Algorithm A2: Determination of Bridge Traffic Impact Weights

Input: A
Output: W

1. Initialization: A
2. **for** i = 1:n
3. Sort (A) --> A1 ≥ A2 ≥ A3 . . . ≥ An
4. **End for**
5. **For** i = 1:n
6. Compare (Ai, Ai + 1) --> T (t1, t2, t3 . . . tn)
7. **End for**
8. Compute (B):
9. **If** i = j, Bij = 1
10. **Else** Bij $= b_{ij} = t_i \times t_{i+1} \times \ldots \times t_{j-1}, (i \neq j)$
11. Eig (B) -- > β
12. W = Normalization (β)
13. **Return** W

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