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Evaluation Modeling of Regional Traffic Congestion Based on Fuzzy AHP

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Abstract

Studying the congestion condition of urban road networks is crucial for effective traffic management. To assess congestion levels, a fuzzy evaluation model is developed, integrating the Analytic Hierarchy Process (AHP) and fuzzy comprehensive evaluation theory. This model offers a structured approach, considering congestion from micro, meso, and macro perspectives. Using the AHP, a three-tiered evaluation index system is formulated, encompassing various congestion factors. A fuzzy consistency discriminant matrix is then used to determine the weights of these factors, establishing thresholds for congestion evaluation intervals. The congestion evaluation set is categorized into five grades: Smooth Traffic, Basically Smooth Traffic, Light Congestion, Moderate Congestion, and Heavy Congestion. To demonstrate the model's effectiveness, congestion data from 14 traffic districts in a specific area of Taiyuan City in 2023 are analyzed. The results confirm the feasibility and accuracy of the model, providing a valuable tool for traffic planners and policymakers. This approach enables informed decisions on infrastructure investments, traffic control strategies, and urban development, ultimately leading to more efficient and sustainable urban road networks.

Keywords

Traffic jam, fuzzy analytic hierarchy process, evaluation model, membership degree calculation

Introduction

Traffic congestion, categorized as frequent or occasional, often occurs in urban areas due to demand exceeding road capacity. Studies suggest that traffic flow failure at bottlenecks [1], both occasional (e.g., accidents, road maintenance) and recurrent (due to factors like demand, driving behavior, and design), is the primary cause of expressway congestion. With the rise of transportation big data, user-generated traffic data can be used to analyze and predict road conditions. This article establishes congestion evaluation indicators, combines survey data with map platform data, and examines the relationship between congestion factors and traffic jams. The evaluation method's feasibility was validated using survey data from 14 transportation communities in Taiyuan City during peak hours on a weekday in October 2023.

1. Evaluation Index System of Regional Traffic Congestion

In order to reflect the traffic operation state of the study area comprehensively, the validity, accuracy and objectivity of the evaluation index should be emphasized when selecting the evaluation index. Meanwhile, the data acquisition of the evaluation index should be convenient, and the function calculation of the evaluation index should be simple.

From the microscopic point of view, traffic volume, saturation, average queue length, service level, delay, etc. are common indicators to describe the operation state of road intersections; from the mesoscopic point of view, link travel time, link traffic volume, average speed, lane change rate, etc. can be used to describe the traffic operation state; from the macroscopic point of view, road network travel time and road network efficiency index can be used to describe the regional traffic operation state.

When selecting evaluation indicators, we also need to consider the feelings of traffic participants. Vehicle drivers, as the main traffic participants, can intuitively feel the influence of travel time and driving speed on traveling. Therefore, these two factors should be considered in the selection of evaluation indicators. In addition, in practical application, some evaluation indexes are not easy to obtain, and the operability of the evaluation model is poor. This index can be discarded in practical operation.

1.1 Construction of traffic congestion evaluation index

The Analytic Hierarchy Process (AHP) is a decision-making framework that organizes and quantifies decision-making processes in alignment with cognitive and psychological principles [2]. It offers a quantitative foundation for analysis, decision-making, forecasting, or control, leveraging mathematical techniques. This approach integrates qualitative and quantitative decision-making methods. In the process of traffic congestion risk assessment, the first step is to determine a reasonable, objective, and scientific measurement index system. On the basis of analyzing the influencing factors of road traffic flow operation and following the principle of hierarchical analysis, a road traffic congestion evaluation index system with 3 levels and 11 indicators is established, as shown in Table 2.

2. Fuzzy Evaluation Model of Regional Traffic Congestion

Fuzzy Comprehensive Evaluation (FCE) is a decision-making method that integrates fuzziness and uncertainty into the evaluation process. This approach is widely used in engineering, management, and social sciences to deal with complex problems involving multiple criteria and uncertain or imprecise information. The core concept of FCE is the use of fuzzy numbers or fuzzy sets to represent evaluation criteria and their associated weights. This method provides a more comprehensive and flexible evaluation method for the processing of inaccurate or subjective data [2].

2.1 Determining the Weight Coefficient of Congestion Risk Evaluation Index by Fuzzy AHP

Fuzzy AHP utilizes fuzzy consistent relations and matrices to structure optimization problems hierarchically [3, 4], identifies evaluation indices, and constructs a priority matrix transformed into a fuzzy consistent one. Ranking indicators across levels is facilitated by a hierarchy diagram organizing objectives, objects, and relationships. A judgment matrix, with pairwise comparisons, avoids qualitative weight determinations, and its elements aim to possess specific properties.

$$a_{ij} = \frac{1}{a_{ji}} \tag{1-1}$$

Hierarchical single sorting

Step 1: Calculate the product *Mi* of each row element in the judgment matrix

$$M_i = \prod_{j=1}^{m} a_{ij} \, (j = 1, 2, 3 \cdots m) \tag{1-2}$$

Step 2: Calculate the *n-th* root *Wi* of the product *Mi*

$$W_i = \sqrt[n]{M_i} \, (i = 1, 2, 3 \cdots n) \tag{1-3}$$

Step 3: Normalize the *n-th* root *Wi* to obtain the feature vector *wi*

$$w_i = \frac{W_i}{\sum_{j=1}^{m} W_j} \, (j = 1, 2, 3 \cdots m) \tag{1-4}$$

Step 4: Calculate the maximum eigenvalue of the judgment matrix λ Max

$$\lambda_{\max} = \sum_{i=1}^{n} \frac{[Aw_i]}{nw_i} \tag{1-5}$$

Consistency testing of judgment matrices

To maintain consistency among experts' evaluations, consistency checks on the judgment matrix are crucial. Complete consistency results in zero eigenvalues, while incomplete consistency leads to non-zero eigenvalues exhibiting a specific relationship.

$$\sum_{i=2}^{n}\lambda_i = n - \lambda_{\max} \tag{1-6}$$

In this case, a negative mean is introduced in the AHP to determine the remaining eigenvalues of the matrix beyond the maximum eigenvalue, which serves as an indicator to measure the deviation of the judgment matrix from consistency

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{1-7}$$

To measure the size of CI, the random consistency index RI is introduced,

$$RI = \frac{CI_1 + CI_2 + \cdots + CI_n}{n} \tag{1-8}$$

In practical applications, the influence of random reasons can lead to deviation in consistency. Therefore, when testing whether the judgment matrix has satisfactory consistency, it is necessary to compare the CI with RI, as shown in equations 2-9.

$$CR = \frac{CI}{RI} \tag{1-9}$$

If $CR < 0.1$, the judgment matrix passes the consistency test, otherwise it will not have satisfactory consistency.

2.2 Fuzzy comprehensive evaluation modeling of regional traffic congestion

The fuzzy comprehensive evaluation method uses indicator weights to assess the fuzziness of influencing factors in target evaluation, employing fuzzy mathematics for quantitative analysis. It involves defining evaluation elements (U), evaluation sets (V), determining weights (W), and constructing an evaluation matrix (R). The final comprehensive evaluation is obtained by combining W and R using a fuzzy operator.

$$B = W \circ R = (b_1, \ b_2, \cdots, \ b_m) \tag{1-10}$$

Calculate the corresponding grade scores for each factor in the criterion layer as follows:

$$F = \sum_{i=1}^{n} v_i B (i = 1, 2, \cdots, n) \tag{1-11}$$

Calculate the corresponding level scores for each factor in the criterion layer, and then correspond to the score range of the comment set to obtain the corresponding congestion evaluation level.

2.3 Fuzzy comprehensive evaluation membership degree calculation

This article mainly evaluates objective things based on quantitative analysis, so linear analysis method is chosen. Assuming that the evaluation factor of a certain evaluation object is *x* and the membership function is, then the membership degree of this factor to the evaluation of traffic operation status is $\mu_{1(x)}$, $\mu_{2(x)}$, …, $\mu_{L+1}(x)$, which is:

$$\mu_1(x) = \begin{cases} 1 & x \le s_1 \\ \dfrac{s_2 - x}{s_2 - s_1} & s_1 < x < s_2 \\ 0 & other \end{cases} \tag{1-12}$$

$$\mu_2(x) = \begin{cases} 1 - \mu_1(x) & s_1 < x < s_2 \\ \dfrac{s_3 - x}{s_3 - s_2} & s_2 < x < s_3 \\ 0 & other \end{cases} \tag{1-13}$$

$$\mu_{L+1}(x) = \begin{cases} 1 & s_{L+1} \le x \\ 1 - \mu_L(x) & s_L < x < s_{L+1} \\ 0 & other \end{cases} \tag{1-14}$$

3. Cases

In order to reduce the complexity of traffic control and management systems and improve system reliability, urban road network traffic zones have been divided. The selected road network area is shown in Figure 1, and the road network is divided into 14 transportation communities for research.

To assess the scientific and numerical rationality of a fuzzy neural network model for regional traffic congestion, a review group of 10 experts from various transportation-related fields was assembled to investigate traffic conditions in Taiyuan City [7]. Evaluation indicators were chosen, and their weight coefficients were determined. These were then integrated into the congestion evaluation model to assess the traffic status of the study area.

3.1 Determine indicator weights

(1) Construct a first level indicator judgment matrix.

Determine the weights of regional traffic congestion evaluation indicators based on the Analytic Hierarchy Process. Using a questionnaire survey method to score each indicator, taking the average, the judgment matrix A is obtained as:

$$A=\begin{bmatrix} 1 & 0.5 & 1.8 \\ 2 & 1 & 1.5 \\ 0.566 & 0.667 & 1 \end{bmatrix}$$

According to formulas (2-2)-(2-5), calculate the eigenvectors and eigenvalues as follows:

$$M \Rightarrow \begin{bmatrix} 1\times 0.5\times 1.8 \\ 2\times 1\times 1.5 \\ 0.566\times 0.667\times 1 \end{bmatrix} \Rightarrow \begin{bmatrix} 0.9 \\ 3 \\ 0.3708 \end{bmatrix}$$

The nth root *Wi* of *M* is:

$$W_i=\begin{bmatrix} 0.9655 \\ 1.4422 \\ 0.7185 \end{bmatrix}$$

(2) The feature vector *wi* is:

$$w_i=\begin{bmatrix} 0.3088 \\ 0.4614 \\ 0.2298 \end{bmatrix}$$

Calculate maximum eigenvalue:

$$(Aw)_i=\begin{bmatrix} 1 & 0.5 & 1.8 \\ 2 & 1 & 1.5 \\ 0.566 & 0.667 & 1 \end{bmatrix}\times\begin{bmatrix} 0.3088 \\ 0.4614 \\ 0.2298 \end{bmatrix}=\begin{bmatrix} 0.95314 \\ 1.4237 \\ 0.70925 \end{bmatrix}$$

(3) According to formula (2-7), the index CI is calculated as:

$$CI=\frac{\lambda_{\max}-n}{n-1}=\frac{3.0861-1}{3-1}=0.0431$$

(4) According to Table 3, the average random consistency index RI for the judgment matrix is:

$$RI(3)=0.58$$

(5) According to formula (2-10), calculate the CR as follows:

$$CR=\frac{CI}{RI}=\frac{0.0431}{0.58}=0.0742$$

CR<0.1, meets the consistency test standards, and the data is reasonable.

In summary, the evaluation indicators and their weights for road congestion in the study area are shown in Table 3.

3.2 Calculation of membership degree

The evaluation of regional traffic congestion involves indicators of membership degree division, including average speed of road sections, road saturation, proportion of congested road sections, road network congestion index, and road network efficiency index.

1) Determination of the membership degree of average speed on road sections

Different levels of road sections have different discriminant indices for their operational status.

Table 1. Classification of Congestion Levels During Rush Hour Based on Average Travel Speed in Different Regions(partial data)

Zoon ID	1 Smooth Traffic	2 Basically Smooth Traffic	3 Light Congestion	4 Moderate Congestion	5 Heavy Congestion
1	＞49	(35, 49]	(28, 35]	(21, 28]	≤21
2	＞56	(40, 56]	(32, 40]	(24, 32]	≤24
3	＞46	(33, 46]	(26, 33]	(20, 26]	≤20
4	＞47	(34, 47]	(27, 34]	(20, 27]	≤20
5	＞50	(36, 50]	(29, 36]	(22, 29]	≤22

According to Table 1 above, the membership degrees of the evaluation set corresponding to the average speed of road sections during peak hours for five traffic operation states (Smooth Traffic, Basically Smooth Traffic, Light Congestion, Moderate Congestion, Heavy Congestion) are as follows: (Taking Traffic zoon 1 in the study area as an example for explanation)

$$\mu_A = \begin{cases} 1 & x > 49 \\ 0 & x \le 49 \end{cases} \tag{2-1}$$

$$\mu_B = \begin{cases} (x-35)/14 & 35 < x \le 49 \\ 0 & x \le 35 \ or \ x \ge 49 \end{cases} \tag{2-2}$$

$$\mu_C = \begin{cases} (x-28)/7 & 28 < x \le 35 \\ (49-x)/14 & 35 < x \le 49 \\ 0 & other \end{cases} \tag{2-3}$$

$$\mu_D = \begin{cases} (x-21)/7 & 21 < x \le 28 \\ (35-x)/7 & 28 < x \le 35 \\ 0 & other \end{cases} \tag{2-4}$$

$$\mu_E = \begin{cases} 1 & x \le 21 \\ (28-x)/7 & 21 < x \le 28 \\ 0 & x \ge 28 \end{cases} \tag{2-5}$$

3.3 Weights and Congestion Rating Statistics

To improve the clarity and brevity of congestion evaluations, the study divides the congestion set into five grades with defined coupling intervals. Each grade receives a score determined by the minimum value within its interval for evaluation purposes. According to the calculated indicators, take zoonl 1 in the study area as an example, and carry out the following evaluation calculation process.

$$B = W \bullet R = \begin{bmatrix} 0.3102 \\ 0.4576 \\ 0.2322 \end{bmatrix}^T \bullet \begin{bmatrix} 0 & 0.45505 & 0.39932 & 0.14563 & 0 \\ 0.05874 & 0.425923 & 0.565527 & 0 & 0 \\ 0 & 0.559996 & 0.440004 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0.0269 \\ 0.4661 \\ 0.4848 \\ 0.0452 \\ 0 \end{bmatrix}^T$$

$$F = \sum_{i=1}^{n} v_i B = 0 \times 0.0269 + 2 \times 0.4661 + 4 \times 0.4848 + 6 \times 0.0425 + 8 \times 0 = 3.143$$

According to the calculation results, the zoon 1 in the study area is basically unblocked. Similarly, the operation status of other traffic cells can be obtained as follows (Table 3):

Table 2. Statistical Table of Weights and Congestion Level Evaluation Indices for zoon 1

First-level indicators	Weight	Secondary indicators	Weight	Total weight	evaluation				
					Smooth Traffic	Basically Smooth Traffic	Light Congestion	Moderate Congestion	Heavy Congestion
Micro level	0.3102	Average Delay Time	0.2127	0.0660	0	0.5	0.4	0.1	0
		Intersection Traffic Volume	0.1689	0.0524	0	0.6	0.2	0.2	0
		Average Queue Length	0.2874	0.0892	0	0.4	0.4	0.2	0
		Intersection Saturation	0.3310	0.1027	0	0.4	0.5	0.1	0
Meso level	0.4576	Travel Time on Road Segment	0.1264	0.0579	0.2	0.4	0.4	0	0
		Traffic Volume on Road Segment	0.1673	0.0766	0.2	0.5	0.6	0	0
		Saturation Of Road Segment	0.2099	0.0961	0	0.5	0.5	0	0
		Average Speed Of Road Segment	0.1975	0.0904	0	0.31	0.69	0	0
		Percentage Of Congested Road Sections	0.2989	0.1368	0	0.42	0.58	0	0
Macro level	0.2322	Road Network Congestion Index	0.3333	0.0774	0	0.64	0.36	0	0
		Road Network Efficiency Index	0.6667	0.1548	0	0.52	0.48	0	0

Table 3. Congestion Evaluation Levels for Each Traffic Zone

Zoon ID	Membership Degree $[V_1,V_2,V_3,V_4, V_5]$	Rating Score	Congestion Level
1	[0.0269, 0.4661, 0.4848, 0.0452, 0]	3.143	2
2	[0, 0.1804, 0.4734, 0.3286, 0.0176]	4.367	3
3	[0, 0.0713, 0.4824, 0.4232, 0.0231]	4.796	3
4	[0, 0.6813, 0.3121, 0.0066, 0]	2.647	2
5	[0, 0.6518, 0.3482, 0, 0]	2.696	2
6	[0, 0.4238, 0.3574, 0.2010, 0.0178]	3.625	2
7	[0, 0.2827, 0.4874, 0.1683, 0.0616]	4.018	3
8	[0, 0.5208, 0.3426, 0.1366, 0]	3.232	2
9	[0, 0.2855, 0.4036, 0.2952, 0.0157]	4.082	3
10	[0, 0.2925, 0.4273, 0.2372, 0.043]	4.062	3
11	[0, 0.4255, 0.4173, 0.1572, 0]	3.463	2
12	[0, 0.1923, 0.5565, 0.2512, 0]	4.118	3
13	[0, 0.4518, 0.3521, 0.1961, 0]	3.489	2
14	[0, 0.4176, 0.3258, 0.2145, 0.0421]	3.762	2

Through modeling analysis, it can be concluded that the congestion state of 14 traffic cells involved in the investigation area of Taiyuan City in this period is consistent with the actual situation.

4. Conclusion

Taking road traffic congestion evaluation as the overall goal, this paper establishes an evaluation index system of road traffic congestion, which includes three levels: intersection, road section and road network and 11 indexes. According to the types of land use and geographical location, the evaluation index membership function of 14 traffic zones in the study area is determined, and the congestion index and saturation degree membership function are refined. The classification of road traffic congestion evaluation index is designed, and the coupling intervals of different grades are determined. An example analysis is carried out by using the evening peak data of Taiyuan City in October 2023. The results show that the fuzzy evaluation model for regional traffic congestion has good applicability and can be applied to traffic congestion evaluation in other areas of Taiyuan City.

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