Research on the Design of Toll Square Based on Comprehensive Evaluation Model

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Abstract

This article is based on the 2017 American college students mathematical modeling contest B, in order to design a reasonable toll plaza, we consider three factors of the toll station throughput, cost and accident prevention to establish a comprehensive evaluation index system. And these three factors are refined into six evaluation indexes of traffic flow, vehicle density, land and Road construction costs, other costs, accident frequency and vehicle lane index. According to the improved FAHP model, the weight of each index is 0.374, 0.124, 0.245, 0.054, 0.156, 0.047 respectively. Finally, the equation of the comprehensive index Q of comprehensive evaluation system is Q = 0.498Q$_1$+ 0.299Q$_2$ + 0.213Q$_3$ = 1.186252X+0.061752Y + 0.073255M + 1.016146N + 0.033228K + 0.010011L. CLC number: U412.1+3 Document code: A.

Keywords

Improved FAHP;Overview;Toll plaza.

1. Introduction

The highway will be set to collect fees to charge a certain square high-speed fee, the United States charges less highway, but the toll road in the toll plaza settings there also exists some problems. How to set up the merge mode becomes a restrictive problem when the vehicle is imported into the conventional lane from the toll lane. The design of the toll plaza determines the toll throughput, the cost and the occurrence of the accident. By combining these elements, the reasonable design will better serve the national and serve the society.

2. Evaluation system

The main factors influencing the design of toll plaza are throughput, cost and accident prevention. In this regard, the influence degree of the evaluation system on three influencing factors is analyzed qualitatively and quantitatively. Three influencing factors are used to describe the influencing factors, the weight of the response factors of the degree reflects the influence, thus establishing a hierarchical structure model. In this paper, we adopt the improved FAHP model, which is simpler and more effective than FAHP model.

2.1 Improved FAHP to determine the index weight

The modified model steps are as follows:

1.Build a hierarchical model. Based on the relationship between indicators to establish a hierarchical model.

2.Establish the priority relation matrix F. In order to more accurately compare the importance of the various indicators, using the three-scale method to establish a priority relationship matrix $F = (f_{ij})_{n\times m}$, among them

$$f_{ij}=\begin{cases}0.5 & c_i=c_j\\ 1 & c_i>c_j\\ 0 & c_i<c_j\end{cases}$$

Explanation: c_i—The relative importance of f_i

c_j—The relative importance of f_j

3.The sum of all rows in the matrix $r_i = \sum_{k=1} f_{ik}$, and by using the conversion formula $r_{ij} = \frac{r_i - r_j}{2n} + 0.5$, F is converted into complementary judgment matrix by $R = (r_{ij})_{n\times m.}$

4.Using the root square method to get the sorting vector $W^{(0)} = (w_1, w_2, \cdots w_n)^T$.

5.The transformation matrix $e_{ij} = r_{ij}/r_{ji}$ is used to transform the complementary judgment matrix R into the reciprocal matrix $E = (e_{ij})_{n\times m}$.

6.The iterative initial value of $W^{(0)}$ as the eigenvalue method V^0,Using the iterative formula $V^{(k+1)} = EV^{(k)}$ to find the characteristic vector $V^{(k+1)}$,And obtain $V^{(k+1)}$ and $||V^{(k+1)}||_\infty$.If satisfied judgment formula $\left| \left\| V^{(k+1)} \right\|_\infty - \left\| V^{(k+1)} \right\|_\infty \right| < \varepsilon$ (ε for calculation accuracy, $\varepsilon \le 0.001$, $||V^{(k+1)}||_\infty$ is the largest eigenvalue λ_{max}, And the vector which is normalized by $V^{(k+1)}$ is the final sort vector $W^{(k)}$, $W^{(k)} = V^{(k+1)}$,Iteration end. Otherwise,$V^{(k+1)} = V^{(k+1)}/\,||V^{(k+1)}||_\infty$, $V^{(k+1)}$ will be standardized with $V^{(k+1)}$, as a new initial value, iterate again.

7.Calculate the weight of each index in the index layer.

The calculation procedure based on the above steps is as follows:

(1) The hierarchy model of each index is as follows:

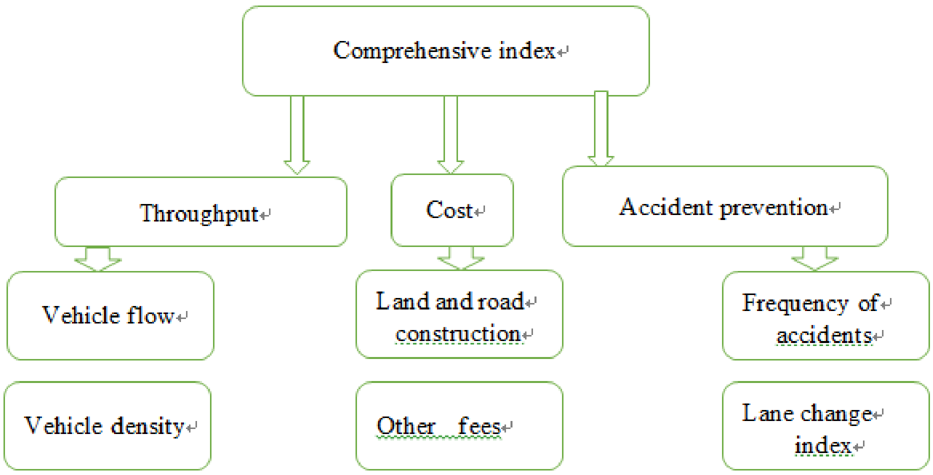


Figure 1. Hierarchical graph

(2) Priority judgment matrix:

$$F = \begin{bmatrix} 0.5 & 1 & 1 \\ 0 & 0.5 & 0 \\ 0 & 1 & 0.5 \end{bmatrix} \quad F_1 = \begin{bmatrix} 0.5 & 1 \\ 0 & 0.5 \end{bmatrix} \quad F_2 = \begin{bmatrix} 0.5 & 1 \\ 0 & 0.5 \end{bmatrix} \quad F_3 = \begin{bmatrix} 0.5 & 1 \\ 0 & 0.5 \end{bmatrix}$$

Among them, F is the first level judgment matrix,F_1, F_2 are the priority judgment matrix of the two level.

(3) The priority relation matrix F is transformed into complementary judgment matrix R .Available:

$$R = \begin{bmatrix} 0.15 & 0.83 & 0.67 \\ 0.17 & 0.5 & 0.33 \\ 0.33 & 0.67 & 0.5 \end{bmatrix} \quad R_1 = \begin{bmatrix} 0.5 & 0.75 \\ 0.25 & 0.5 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 0.5 & 0.75 \\ 0.25 & 0.5 \end{bmatrix} \quad R_3 = \begin{bmatrix} 0.5 & 0.75 \\ 0.25 & 0.5 \end{bmatrix}$$

(4) Using the root mean square method to get the order vector of the index layer is:

$W = (0.45, 0.21, 0.34)^T \quad W_1 = (0.59, 0.41)^T$

$W_2 = (0.59,0.41)^T$ $W_3 = (0.59,0.41)^T$

(5) The complementary judgment matrix R is transformed into the reciprocal judgment matrix E, give the result as follows:

$$E = \begin{bmatrix} 1 & 4.88 & 2.03 \\ 0.20 & 1 & 0.49 \\ 0.49 & 2.03 & 1 \end{bmatrix} \quad E_1 = \begin{bmatrix} 1 & 3 \\ 0.33 & 1 \end{bmatrix} \quad E_2 = \begin{bmatrix} 1 & 3 \\ 0.33 & 1 \end{bmatrix} \quad E_3 = \begin{bmatrix} 1 & 3 \\ 0.33 & 1 \end{bmatrix}$$

(6) Calculation accuracy $\varepsilon \le 0.001$,The ranking vector $W^{(0)} = (0.45,0.21,0.34)^T$ is used as the initial value of the eigenvalue method. After two iterations, the normalized vector $W^{(3)} = (0.59,0.13,0.28)^T$,The calculation precision is $|||V^{(k+1)}||_\infty - \left\|V^{(k+1)}\right\|_\infty| < \varepsilon$,The elements in $W^{(2)}$ as W_i Similarly, we can getthe two level of the index after the iteration of the normalized vector were $W_1{}^{(2)} = (0.75,0.25)^T$, $W_2{}^{(2)} = (0.75,0.25)^T$, $W_3{}^{(2)} = (0.75,0.25)^T$. Note that the elements in $W_i{}^{(\prime)}$ are $W_{ij}{}^{(\prime)}$.

(7) According to the formula $W_{ij}{}^{(\prime\prime)} = W_i \times W_{ij}{}^{(\prime)}, W_i \; and \; W_{ij}{}^{(\prime)}$ into the formula, we can get the weight of each indicator is as follows:

Table1. Indicator Weight

$W_{11}{}^{(\prime\prime)}$	$W_{12}{}^{(\prime\prime)}$	$W_{21}{}^{(\prime\prime)}$	$W_{22}{}^{(\prime\prime)}$	$W_{31}{}^{(\prime\prime)}$	$W_{32}{}^{(\prime\prime)}$
0.374	0.124	0.245	0.054	0.156	0.047

2.2 Establishment of the equation

In order to accurately depict the relationship[4] between the index and the three influencing factors, we use the indicator weight to get the equations for throughput, cost, and accident prevention, and then get the comprehensive index of the evaluation system according to the three equations. The flow chart is as follows:

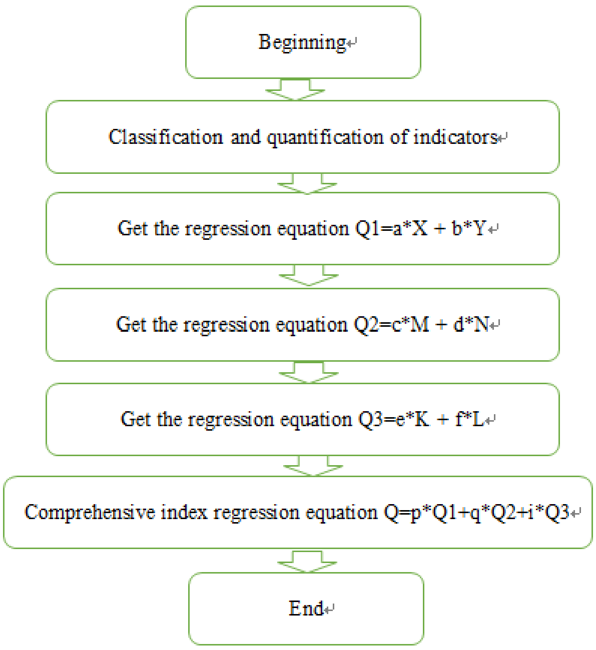


Figure 2. flow chart

2.3 Establishment of Quantification Standard

The comprehensive index evaluation system is more reasonable[5] and practical, we quantify the following six indicators.1-10 to quantify[6] the level of the six indicators of the unified numerical quantification, quantitative criteria are as follows:

Table 2. Vehicle flow

Traffic flow/min	0-5	6-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50
The quantization value	1	2	3	4	5	6	7	8	9	10

Table 3. Vehicle density

Vehicle density/km^2	0-100	101-200	201-300	301-400	401-500	501-600	601-700	701-800	801-900	901-1000
The quantization value	1	2	3	4	5	6	7	8	9	10

Table 4. Land and road construction and other expenses

cost/million	4.5-5.0	4.0-4.5	3.5-4.0	3.0-3.5	2.5-3.0	2.0-2.5	1.5-2.0	1.0-1.5	0.5-1.0	0-0.5

Table 5. Accident frequency

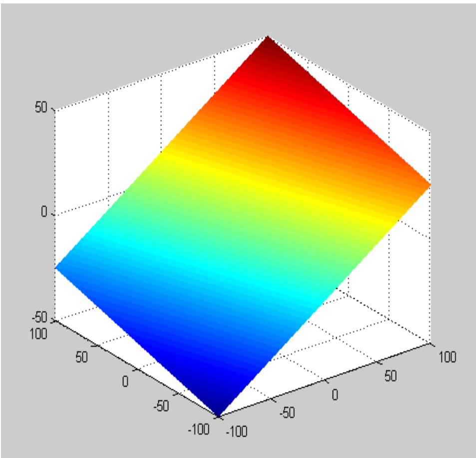
Frequency of accidents/%	9-10	8-9	7-8	6-7	5-6	4-5	3-4	2-3	1-2	0-1
The quantization value	1	2	3	4	5	6	7	8	9	10

Table 6. Lane change index

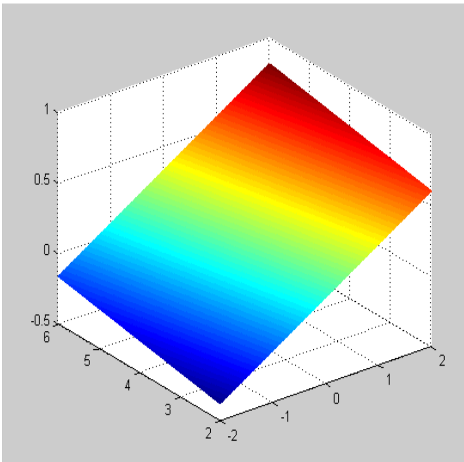
Lane change index	0.9-1.0	0.8-0.9	0.7-0.8	0.6-0.7	0.5-0.6	0.4-0.5	0.3-0.4	0.2-0.3	0.1-0.2	0-0.1
The quantization value	1	2	3	4	5	6	7	8	9	10

2.4 Determination of Composite Index

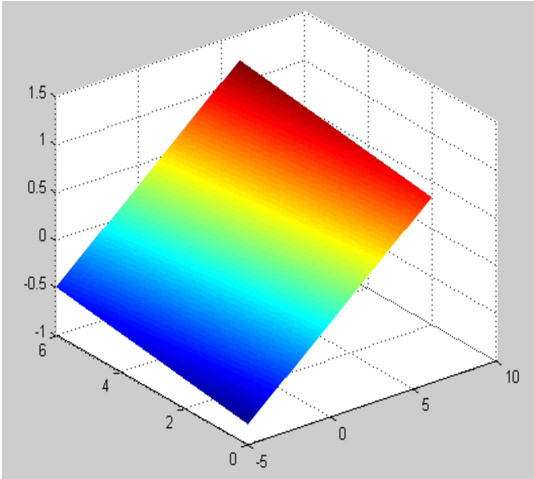
The weight of the index obtained by the improved fuzzy analytic hierarchy process is described as three factors: throughput, cost[8] and accident prevention. The resulting equation and the relational image are as follows:



(a)



(b)



(c)

Figure 3. (a) Throughput equation Q1=0.374X+0.124Y. (b) Cost equation Q2=0.245M+0.054N. (c) Accident prevention equation Q3=0.156K+0.047L.

The improved fuzzy analytic[9] hierarchy process(AHP) uses fuzzy mathematics and analytic hierarchy process to get the weights of six indexes more accurately. This makes the three main factors that affect the design of toll stations can be reasonably explained by the numerical value. From the above set of quantitative indicators, we only need to clear the value of each index, you can calculate the throughput, cost and value of accident prevention.

In order to obtain the comprehensive[10] index coefficient of toll station intuitively, in order to analyze and compare the toll station and the toll station. We can set the comprehensive index Q to describe the comprehensive index of toll station design. We obtain the relationship between the comprehensive index Q and the throughput Q1, cost Q2 and accident[11] prevention Q3 and the relational image as follows:

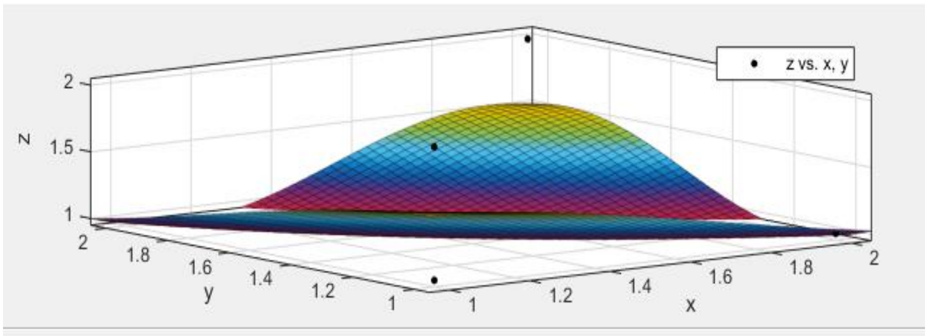


Figure 4. Composite index equation Q=0.498Q1+0.299Q2+0.213Q3

The comprehensive[12] index Q has played a role in evaluating the overall performance of toll stations may not be able to perfect the toll station design to evaluate, but also reflects some problems of the design. In the evaluation of the new design, we can compare the new design of the toll station and the existing toll station according to the size of a comprehensive indicator, a larger overall index was a better one. The comprehensive index Q will provide a reasonable[13] basis for judging whether[14] the design is good or bad. In the next design and comparison process, we will judge[15] the design of toll station with the comprehensive indicators.

3. Conclusion

By using the equation of comprehensive evaluation index system, we can get the comprehensive index Q of the existing straight-line plane-style toll plaza and elliptic gradient type, octagonal gradient type and straight-line style toll plaza, which are 1.85244, 2.025201, 2.211453 and 2.291222 respectively. The bigger the comprehensive index, the better the comprehensive performance of the toll plaza. It can be seen that the performance of the toll plaza is the best, followed by the octagonal gradient type, the elliptical gradient type and the straight plane type. It can be seen from the new design of the three toll plaza than the original straight-line flat-charge Square has been greatly improved.

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