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The Comprehensive Research on Scheme Evaluation of Urban Expressway

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Abstract

This paper studies the evaluation system of urban expressway schemes. By comparing the most widely-used evaluation methods, analytic hierarchy process method is selected to build the framework of the indexes system. After the classification and screening, technical indexes, economic indexes, construction indexes and environmental indexes are selected as the first grade containing second representative indexes. The methods to define and to quantify these qualitative evaluation indexes and determination of the weight of each index are studied in this paper. Next, the evaluation value is calculated by establish mathematical model with fuzzy evaluation method and gray correlation analysis method, so the optimal scheme can be gained by sorting analysis. Finally, an urban expressway of Nantong as an example is evaluated according this system to verify the correctness of this evaluation method. In general, the research presents a specific method of urban expressway scheme evaluation, quantifies each scheme into specific value in order to make comparison easy, and provides a reference for future evaluation.

Keywords: Urban Expressway; Evaluation Index System; Fuzzy Comprehensive Evaluation; Grey Relational Evaluation

1. BACKGROUND:

Urban expressway is defined as traffic artery in or near downtown area with multi-lane (two lanes or more) on one-way, which has large capacity and is fast for the traffic services of the city and its satellite towns. As the main skeleton of the urban road network, urban expressway is the main artery for external

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traffic and traffic between the regions of the city. Urban expressway can be divided into four types based on its section type and the location of the main and side road; they are ground integral, viaduct alignment, graben and underground. Different design schemes are available for the same project because of various types of urban expressway. Urban expressway schemes selection is a complex system involving multi schemes and multi factors. It is not overall and systematic using single traditional single-index method to research the problem. In fact, most past researches of expressway programs are analyzed in a qualitative way, and it is likely to cause distortion of the evaluation since its subjectivity and randomness. Therefore, as a multi-objective decision problem, urban expressway scheme evaluation from the point of view of the system, is needed to use the method of mathematics analysis to make accurate, scientific and objective evaluation.

2. EVALUATION METHODS SELECTION:

Urban expressway scheme selection is a complicated process, and establishing a comprehensive evaluation system can evaluate the schemes information effectively, and make a comprehensive and accurate scientific judgment for urban expressway scheme quality. Based on different mathematical theories, evaluation methods can be divided into types: expert scoring method, analytic hierarchy process, fuzzy comprehensive evaluation method, data envelopment analysis, grey relation analysis, artificial neural network evaluation method and the method of comprehensive use.

Analytic Hierarchy Process is used in the paper which can analyze the relative factors of the scheme and measure the relative importance of the indicators. However, it is a drawback of Analytic Hierarchy Process that qualitative analysis accounts for a large part while quantitative analysis lacks. Therefore, the membership function and fuzzy statistical method in the fuzzy comprehensive evaluation are used to quantify the effective evaluation indicators. On the other hand, since the limited number of expressway scheme, the evaluation indexes do not necessarily meet the statistical regularity, so grey relational evaluation is needed. Grey relational analysis is a non-statistical method, so that it can be more practical especially when the amount of data does not meet the statistical requirements. Above all, a mixed evaluation method is needed in this study. With the mutual authentication of the two methods, the evaluation result is more persuasive.

3. EVALUATION SYSTEM ESTABLISHMENT

Table 1. Urban Expressway Evaluation System

First-level indexes	Second-level index	Index properties	Optimal value
Technical indexes U1	Traffic capacity	Quantitative index	Maximum
	Average delay	Quantitative index	Minimum
	Running time	Quantitative index	Minimum
	Traffic Conflict	Quantitative index	Minimum
Economic indexes U2	Area covering	Quantitative index	Minimum
	Construction cost	Quantitative index	Medium
	Amount of demolition	Quantitative index	Minimum
Construction indexes U3	Impact of construction	Qualitative index	Minimum
	Ease of construction	Qualitative index	Minimum
	Convenience of management and maintenance	Qualitative index	Maximum
Environmental indexes U4	Social environmental impact	Qualitative index	Maximum
	Natural environmental impact	Qualitative index	Maximum

The reasonableness of the chosen of evaluation indexes plays a critical role on the evaluation result. Choosing too much indexes may easily lead to the repeated superposition; on the contrary, choosing insufficient indexes shall cause the lack of representation and comprehension. By analyzing its operation and management characteristics, the evaluation indexes of expressway are divided into four categories: technical indexes, economic indexes, construction indexes and environmental indexes. Regard to the significant difference of the schemes, we screen the indexes and select as few as possible to ensure the efficiency of the index system. After screening, the specific indexes under the four index categories, the analysis of the characteristics of the indexes and the optimal values are shown in Table 1.

4. Evaluation Indicators Quantization

Technical indexes

Since the capacity of the main road differs from that of auxiliary road, the whole capacity of expressway is the sum of them. And then quantify it with the membership functions of the traffic capacity which is shown as follows:

$$u(x) = \begin{cases} 1 & x \geq N_{max} \\ \dfrac{x - N_{min}}{N_{max} - N_{min}} & N_{min} \leq x < N_{max} \\ 0 & x < N_{min} \end{cases} \quad (1)$$

x presents the capability of calculating scheme, and N_{min} stands for the lowest capacity of all the schemes (pcu/h), and N_{max} stands for the highest capacity of all the schemes (pcu/h).

Delay is an index which can reflect the operating efficiency of the traffic flow and the average delay is the average of the delay of all vehicles in the road for a certain time period. It is usually caused by traffic interference and traffic management. The membership function of the average delay is as follows:

$$u(x) = \begin{cases} 1 & x < T_{min} \\ \dfrac{T_{max} - x}{T_{max} - T_{min}} & T_{min} \leq x < T_{max} \\ 0 & x \geq T_{max} \end{cases} \quad (2)$$

x presents the delay of calculating scheme, and T_{min} indicates the minimum delay of all the schemes and T_{max} indicates the minimum delay of all the schemes.

Running time refers to the actual time a vehicle needs to get through a section. Due to the independence of the evaluation index, the running time that getting through the node is selected as the evaluation object. Its membership function is as follows:

$$u(x) = \begin{cases} 1 & x < t_{min} \\ \dfrac{t_{max} - x}{t_{max} - t_{min}} & t_{min} \leq x < t_{max} \\ 0 & x \geq t_{max} \end{cases} \quad (3)$$

x presents the delay of the calculating scheme, and t_{min}indicates the shortest running time of all the schemes and t_{max} indicates the longest running time of all the schemes.

Traffic conflicts refer to the conflict of the running track of different road users. It can reflect the running state of the vehicle and is also a non-accident statistics traffic safety evaluation method. In the study, we use the number of traffic conflicts to describe this property. The membership function of traffic conflict is as follows:

$$u(x)=\begin{cases}1 & x<n_{min}\\ \dfrac{n_{max}-x}{n_{max}-n_{min}} & n_{min}\le x<n_{max}\\ 0 & x\ge n_{max}\end{cases} \quad (4)$$

x presents the traffic conflicts of the calculating scheme, and n_{min} indicates the smallest number of traffic conflict of all the schemes and n_{max} indicates the largest number of traffic conflict of all the schemes.

Economic indexes

Construction cost is a very important factor to consider when selecting the schemes. Construction, operation and maintenance cost are essential that should be taken into consideration. In addition, the concept of "life cycle cost" should be established which advocates achieving optimization and savings throughout the life cycle of the expressway. Therefore establish cost membership function is as follows:

$$u(x)=e^{-k(x-a)^2} \quad (5)$$

x presents the construction cost of the calculating scheme, and a stands for the mean value of the construction cost of all the schemes: $a=\frac{1}{m}\sum_{i=1}^{m}C_i$ (m is the scheme number). C_i represents the construction cost of the i th scheme (million). k is the undetermined coefficients ($k>0, k=\frac{m-1}{\sum_{i=1}^{m}(C_i-a)^2}$)

In the most cases, the city expressway is transformed from the original road. The road width is limited, thus the expressway should be as compact as possible to reduce the area the road occupies. Therefore, the membership function of the area of each scheme is as follows:

$$u(x)=\begin{cases}1 & x<A_p\\ \dfrac{A_{max}-x}{A_{max}-A_p} & A_p\le x<A_{max}\\ 0 & x\ge A_{max}\end{cases} \quad (6)$$

x presents the area of the calculating scheme, and A_p stands for the area covering of original road (acres). And A_{max} stands for biggest area covering of all the schemes.

Amount of demolition is an important index which should be taken into consideration. The urban expressway scheme should minimize the amount of demolition. The membership function of the area of each scheme is as follows:

$$u(x)=\begin{cases}1 & x=0\\ \dfrac{a_{max}-x}{a_{max}-0} & 0<x<a_{max}\\ 0 & x\ge a_{max}\end{cases} \quad (7)$$

x presents the construction cost of the calculating scheme, and a_{max} means the largest demolition area of all the schemes.

Construction indexes

During the expressway transformation of the original road, part of the road would be closed because of the construction. It will seriously affect the traffic operation, as a result, the speed of vehicles reduced, delays increased and it may cause the vehicles queuing. Therefore, the rational organization of traffic running is essential, and its quantitative standard is shown in Table 2.

Table 2. Quantization of Evaluation Indexes Effected by the Construction

Evaluation factors			Quantization value
Influence on the running vehicles	The influence on the intersecting road	Construction time	
Greater influence or prohibit access	Prohibit access and detour large distance	Long	9
			7
Little influence, keep smooth flow	Able to access, large delay	common	5
			3
Had no influence	Little influence	Short	1

2, 4, 6, 8 are the intermediate value of the two.

Ease of construction is a relative index which has an important effect on the assurance of construction quality and optimization of resources utilization. Its quantitative standard is shown in Table 3.

The membership function of the above two indexes are as follows: (10 is the optimal value, x is quantized score)

$$u(x) = \frac{10 - x}{10} \quad (8)$$

Table 3. Quantization of Ease of Construction

Evaluation factors		Quantization value
Scheme complexity	Construction technology level	
Complex, such as graben	Poor	9 7
Ordinary, such as viaduct alignment	General	5 3
Simple, such as ground integral	Excellent	1

2, 4, 6, 8 are the intermediate value of the two.

Convenience of management and maintenance mainly include ease of management and conservation convenience. Its membership function is as follows: (10 is the optimal value, x is quantized score)

$$u(x) = \frac{x}{10} \quad (9)$$

Table 4. Quantization of Convenience of Management and Maintenance

Evaluation factors		Quantization value
Conservation convenience	ease of management	
Convenient	Convenient	9 7
Ordinary	Ordinary	5 3
Inconvenient	Inconvenient	1

2, 4, 6, 8 are the intermediate value of the two.

Environmental indexes

Environmental indexes include two aspects: one is the natural environmental impact and the other one is social environmental impact. The impact on the social environment mainly includes convenient situation on both sides of the region, economic development and other effects. Their quantitative criterion is shown in Table 5.

Table 5. Quantization of Social Environment Impact

Evaluation factors			Quantization value
Regional exchanges	Economic development	Other effects	
Little influence, easy travel	Obvious effect	Beneficial effects	9 7
Ordinary, need to bypass	Ordinary	Ordinary	5 3
Great influence, far detour	Little promoting	Adversely affected	1

2, 4, 6, 8 are the intermediate value of the two.

The impact of urban expressway construction on the natural environment mainly include environmental design, aesthetic and historical value of the road. The study mainly considers the landscape, ecosystem destruction and environmental pollution and the quantitative criteria as shown in Table 6.

Table 6. Quantization of Natural Environment Impact

Evaluation factors			Quantization value
landscape	ecosystem destruction	environmental pollution	
Meet the landscape aesthetics	Less ecological damage, and better recovery	Little influence, have emergency measures	9 7
Ordinary	General, have protection measures	Ordinary	5 3
Contrary to the aesthetic requirements	No promoting	Adversely affect	1

2, 4, 6, 8 are the intermediate value of the two.

The membership function of the above two indexes is as follows: (10 is the optimal value, x is quantized score)

$$u(x) = \frac{x}{10} \quad (10)$$

5. Analytic Hierarchy Process (AHP) To Determine Index Weights

The weights division of first grade index

Though first-level indexes comparison, judgment matrix is gained as table 7.

Table 7 the Judgment Matrix of the First-level Indexes.

Indexes	Technical indexes	Economic indexes	Construction indexes	Environmental indexes
Technical indexes	1	1	3	2
Economic indexes	1	1	2	2
Construction indexes	1/3	1/2	1	1/4
Environmental indexes	1/2	1/2	4	1

Normalize the vector to get the weight vector.

$$W = (\overline{W_i} / \sum_{i=1}^{4} \overline{W_i})_{1\times4} = (0.342, 0.317, 0.108, 0.233)$$

Calculate the largest eigenvalue $\lambda_{max} = \frac{1}{4}\sum_{i=1}^{4}\frac{[AW]_i}{W_i} = 4.200$

Examine its consistency indexes: $CI = \frac{\lambda_{max}-n}{n-1} = \frac{4.200-4}{4-1} = 0.067$(n=4, RI=0.8931), $CR = \frac{CI}{RI} = \frac{0.024}{0.8931} = 0.074 < 0.1$. Thus, the result meets the principle of consistency.

The weights division of second grade indexes

Table 8 the Judgment Matrix of the Technical Indexes

	Traffic capacity	Average delay	Running time	Traffic Conflict
Traffic capacity	1	1	6	5
Average delay	1	1	3	5
Running time	1/6	1/3	1	1/2
Traffic Conflict	1/5	1/5	2	1

In line with the calculation method of the first-level indexes, we can easily gain the weight of the second-level indexes and their consistency judgment. The weights of each index of the second grade are shown in Table 8~11.

Table 9 the Judgment Matrix of the Economic Indexes

	Area covering	Construction cost	Amount of demolition
Area covering	1	1/6	1/5
Construction cost	6	1	2
Amount of demolition	5	1/2	1

Table 10 the Judgment Matrix of the Construction Indexes

	Impact of construction	Ease of construction	Convenience of management and

			maintenance
Impact of construction	1	1/3	1/4
Ease of construction	3	1	1/2
Convenience of management and maintenance	4	2	1

Table 11 the Judgment Matrix of the Environmental Indexes

	Social environmental impact	Natural environmental impact
Social environmental impact	1	1
Natural environmental impact	1	1

Their calculation results is shown as follows:

$$W_1 = (0.438, 0.376, 0.082, 0.104), \lambda_{max} = 4.142, CR = 0.053 < 0.1$$

$$W_2 = (0.082, 0.575, 0.343), \lambda_{max} = 3.029, CR = 0.03 < 0.1$$

$$W_3 = (0.123, 0.320, 0.557), \lambda_{max} = 3.018, CR = 0.018 < 0.1$$

$$W_4 = (0.500, 0.500), \lambda_{max} = 2, CR = 0 < 0.1$$

The accurate weight of each index

According to the above analysis, the weight of each index in Table 12 is the final result which will be used in evaluation model.

Table 12. the Accurate Weight of Each Index

The first grade index	The weights division of first grade index	The second grade index	The weights division of second grade index	Absolute weight
Technical indexes U1	0.342	Traffic capacity	0.438	0.150
		Average delay	0.376	0.129
		Running time	0.082	0.028
		Traffic Conflict	0.104	0.036
Economic indexes U2	0.317	Area covering	0.082	0.026
		Construction cost	0.575	0.182
		Amount of demolition	0.343	0.109
Construction indexes U3	0.108	Impact of construction	0.123	0.013
		Ease of construction	0.320	0.035
		Convenience of management and maintenance	0.557	0.060
Environmental indexes U4	0.233	Social environmental impact	0.500	0.117
		Natural environmental impact	0.500	0.117

6. MATHEMATICAL ANALYSIS MODEL

Multilayer Fuzzy Evaluation Model

In the single-layer fuzzy evaluation mathematical model, the evaluation vector is $V = W^{\circ}R = (V_1, V_2, \ldots, V_m)$. In the formula, ° is the generalized fuzzy operator, and *m* is the number of pending evaluation program, and *R* is the judgment matrix of the first-grade indexes. There have been infinite variety of generalized fuzzy operator °, and the weighted average type is chosen in this study. So that, each factor has contributed to the comprehensive evaluation and it can also reliably reflect the actual situation of the evaluation object.

Multilayer fuzzy evaluation model established according to APH, contains *p* first-layer indexes, and its corresponding evaluation matrix is *R* and the weight vector is *W*. i^{th} index in the first layer has *q* (*q* is uncertain) second-layer indexes with corresponding evaluation matrix R_i and weight vector W_i.

$$R_i = \begin{bmatrix} r_{11} & \cdots & r_{1q} \\ \vdots & \ddots & \vdots \\ r_{m1} & \cdots & r_{mq} \end{bmatrix}$$

The evaluation vector of the second grade index of i^{th} first-layer index is:

$$U_i = W_i \circ R_i^T = (U_{i1}, U_{i2}, \dots, U_{im})$$

The first level evaluation matrix $R = [U_1, U_2 \cdots U_p]^T$. Thus, the evaluation vector of the first level indexes fuzzy comprehensive evaluation is:

$$V = (V_1, V_2, \dots, V_m) = W \circ R = W \circ [U_1, U_2 \cdots U_p]^T = W \circ [W_1 \circ R_1, W_2 \circ R_2 \cdots W_p \circ R_p]^T$$

When $V_O = max\{V_j\}$, j^{th} scheme is the optimal scheme of all the schemes.

Multilayer Gray Relational Analysis Model

Multilayer gray relational analysis model established according to APH, contains p first-layer indexes, and its corresponding evaluation matrix is C and the weight vector is W. i^{th} index in the first layer has q (q is uncertain) second-layer indexes with corresponding evaluation matrix C_i and weight vector W_i.

$$B_i = \begin{bmatrix} b_{01} & \cdots & b_{0q} \\ b_{11} & \cdots & b_{1q} \\ \vdots & \ddots & \vdots \\ b_{m1} & \cdots & b_{mq} \end{bmatrix}$$

According to the formula $\xi_{ij} = \frac{\Delta_{min} + \rho\Delta_{max}}{\Delta_{ij} + \rho\Delta_{max}} (\rho = 0.5)$

$$\Delta_{ij} = |b_{ij} - b_{0j}| (i = 0,1,2, \dots m;\ j = 1,2, \dots q)$$

get the incidence matrix: $C_i = \begin{bmatrix} \xi_{11} & \cdots & \xi_{1q} \\ \vdots & \ddots & \vdots \\ \xi_{m1} & \cdots & \xi_{mq} \end{bmatrix}$

Calculate to get the incidence matrix: $Q_i = W_i \times C_i^T = (Q_{i1}, Q_{i2}, \dots, Q_{im})$

Incidence matrix of the first grade indexes: $C = [Q_1, Q_2 \cdots Q_p]^T$, then the incidence matrix of the first grade indexes, or the evaluation vector is $V = W \times C = (V_1, V_2, \dots, V_m)$.When $V_O = max\{V_j\}$, j^{th} scheme is the optimal scheme of all the schemes.

7. CASE ANALYSIS

Table 13. the Original Score of the Evaluation Indexes

first grade index	second grade index		schemes NO.1	NO.2	NO.3	NO.4	NO.5
Technical indexes		Traffic capacity（pcu/h）	15200	13600	13200	15200	15800
		Average delay (s)	206.3	184.6	238.3	206.5	151.2
		Running time (s)	84.8	83.9	130.8	82.1	40.1
		Traffic Conflict	5345	4230	7315	5214	3892
Economic indexes		Area covering（acres）	429.72	372.99	461.1	429.72	533.07
		Construction cost（ten thousand yuan）	46805.19	99527.44	20013.59	49557.06	131878.3
		Amount of demolition（m^2）	6024.6	4812	9576.1	6024.6	19709.3
Construction indexes	Impact of construction	Influence on the running vehicles	3	6	4	6	7
		The influence on the intersecting road	5	5	2	8	7
		Construction time	6	7	5	7	6
	Ease of	Scheme complexity	5	6	2	8	7

	construction	Construction technology level	5	5	5	5	5
	Convenience of management and maintenance	Conservation convenience	5	4	7	2	3
		ease of management	5	4	6	4	6
Environmental indexes	Social environmental impact	Regional exchanges on both sides	5	3	6	5	7
		Economic development	4	3	8	5	4
		Other effects	5	5	5	5	5
	Natural environmental impact	landscape	4	2	6	8	2
		ecosystem destruction	7	6	5	3	4
		environmental pollution	5	3	6	7	2

Five schemes are put forward according to the function, service targets, geographical location and the urbanization trends of the regions along the road. According the system, the original score of the five options is shown in Table13.

After quantization and calculation according the evaluation system, the evaluation vector V obtained by fuzzy comprehensive evaluation is *V=(0.602, 0.505, 0.332, 0.603, 0.508)*, while the evaluation vector obtained by gray relational analysis is: *V=(0.772, 0.714, 0.660, 0.779, 0.769)*. It can be seen from the vectors obtained with the two methods above that the scores of all schemes show a certain difference, whereas 4^{th} scheme is better relatively. Thus 4^{th} scheme is the best optimal choice。 We can also see from the example that the results of the fuzzy comprehensive evaluation method and gray relational analysis are consistent with each other in order. In addition, when the project was actually put into implement, experts chose 4^{th} scheme which is consistent with the result of the evaluation system.

8. CONCLUSION

The research presented in this paper studies the multi-level mixed evaluation method to establish mathematical evaluation system that reflects the characteristics of urban expressway construction project. This study provides a specific method to evaluate the urban expressway schemes, and provide a theoretical basis for scheme choose .The conclusion of the case analysis and expert appraisal conclusion is consistent, indicated that the comprehensive evaluation indicator system is basically reasonable feasible and accurate. So that, the system in the urban expressway construction project work can be used in scheme comparison, and further optimization is needed to be closer to the actual situation.

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