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Application of Analytic Hierarchy Process in Network-level Pavement Maintenance Decision

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Abstract

This paper proposes a method based on Analytic Hierarchy Process (AHP) to determine the weight of decision-making factors, consider their relative importance and make an overall ranking for each road section. Taking the priority of highway network maintenance as an example to illustrate the proposed steps, the five relevant factors that the CCP considers pavement maintenance decision-making include pavement performance, pavement structure strength, traffic load, pavement life, and road slope. The weight of the five factors is quantified through the analytic hierarchy process. Then, the comprehensive ranking index value Ui is determined, which represents the maintenance priority of the road section in the network-level decision-making. From the perspective of maintenance costs, the sensitivity analysis results are consistent with the weights of different maintenance decision factors. Pavement maintenance costs are very sensitive to changes in pavement performance. This study shows that the applicability and rationality of the decision-making method based on AHP theory can be used as a guiding principle for road maintenance institutions.

Keywords

Asphalt pavement, network level, maintenance decision-making, analytic hierarchy process, factor weight, priority.

1. INTRODUCTION

With the development and expansion of the expressway network, more and more expressways are deteriorating. Pavement maintenance has attracted the attention of more and more road maintenance engineers. However, due to the limited annual maintenance budget, it is difficult to meet all the road surface maintenance needs. Therefore, considering various factors is an important issue for highway agencies to optimize pavement maintenance strategies. Due to the lack of historical pavement conditions, traffic data, and analysis methods, there are very few domestic road maintenance decision-making research results. Currently, the highway load system has been widely used in China, and it can provide comprehensive axle load data. By systematically collecting road-related data, it makes sense to incorporate all these factors into road maintenance decisions.

Pavement maintenance decision-making is to consider the various performances of all road sections and determine the maintenance priority of the road network section. Therefore, this is a multi-factor and multi-standard issue. Considerations include pavement structure, traffic load, pavement performance, pavement service life, etc. On the one hand, various maintenance treatments are carried out to maintain a high level of pavement performance to meet the needs of road users; on the other hand, it is also necessary to minimize road maintenance costs. Due to limited road maintenance costs, it is unlikely to meet the maintenance requirements of all

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road sections. A scientific process is needed to sort the maintenance priorities of all road sections reasonably.

Determining the weight of each factor is the key to solving problems in the decision-making process. Since the relationship between the factors is qualitative, it is difficult to determine the weight of the factors. The Analytic Hierarchy Process (AHP) is a typical system engineering method that transforms qualitative analysis into quantitative analysis. It can determine the weight of each factor. It is widely used to solve decision-making problems with complex structures, many decision-making standards, and difficult to quantify. This study chooses the analytic hierarchy process to determine the weight of each factor, and obtains the comprehensive ranking index of road sections in the road maintenance decision-making at the network level.

The purpose of this research is to develop a network-level road maintenance decision-making process based on AHP theory. The applicability of the AHP theory is demonstrated through the analysis of the decision-making case of the network level maintenance in Jiangsu Province. Various decision-making factors are considered, including road performance, road structure, road age, traffic level and road grade. The analytic hierarchy process is used to determine the weight of each decision factor, and the comprehensive ranking index of the selected highway section is obtained. Sensitivity analysis can verify the accuracy and effectiveness of AHP weight analysis.

2. CHOICE OF INFLUENCING FACTORS

Network-level maintenance decisions involve many factors, each of which may be related to the maintenance process in different ways. It is impractical to monitor all of this. Therefore, it is very important to determine the key factors that have the most important impact on the maintenance decision-making process [1]. Through literature review, expert opinion survey and information analysis in the database, key factors are selected in the first round. In this study, a group of 10 asphalt pavement maintenance experts participated in the improvement and revision of the index selection. Each expert listed factors related to maintenance decisions. Factors with higher frequency in the extraction list, including road performance, road structure strength, traffic level, road age and road slope.

2.1. Pavement Quality Index

The performance indicators of asphalt pavement include Pavement Condition Index (PCI), Driving Quality Index (RQI), Rutting Depth Index (RDI), Anti-Slip Index (SRI), and Road Quality Index (PQI)) By the formula:

$$PQI=\omega PCIPCI+\omega RQIRQI+\omega RDIRDI+\omega SRISRI \quad (1)$$

Among them, ωPCI, ωRQI, ωRDI, and ωSRI are the weighted values of PCI, RQI, RDI, and SRI, which are 0.10, 0.35, 0.40, and 0.15, respectively.

2.2. Pavement Structure Strength

Generally speaking, difficulties develop slowly on roads with good sports quality and reasonable hierarchical structure. Sections with better pavement structure will last longer. Therefore, the ability of pavement structure is considered to be another important factor that affects pavement maintenance decisions [2]. Unlike PCI or RQI, the structural capabilities of the road cannot be directly seen or perceived. In order to quantify the pavement structure capability, it is necessary to determine the indicators that can represent the strength of the pavement

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structure based on instrument testing. According to the China Highway Performance Evaluation Code, the strength of asphalt pavement structure can be measured by the Pavement Structure Strength Index (PSSI). PSSI can be calculated by the formula:

$$\text{PSSI}=\frac{100}{1+a_0\exp(a_1 SSI)}\eta \tag{2}$$

$$\text{SSI}=\frac{l_R}{l_0} \tag{3}$$

Where SSI is the structural strength index; design road deflection; is the representative deviation actually measured; η is the correction factor; and is the calibration factor. In this article, is 15.71 and is -5.19.

2.3. Traffic Load

Traffic refers to the traffic flow of vehicles passing through a certain section of road within a unit time, including various vehicles and axle loads. Due to the large difference in axle load, the cumulative equivalent single axle load (ESAL) is usually used to characterize the traffic level based on the measured traffic flow. By installing a Weighing Movement (WIM) station in Jiangsu Province, detailed axle loads can be obtained and a more accurate ESAL can be calculated. The traffic volume includes various vehicles and axle loads, and 100kN two-wheel single axle load is used as the standard single axle load. When the predicted road surface deformation and the tensile stress at the bottom of the asphalt layer are used as design criteria, the equivalent axle load (N) can be calculated by the formula:

$$\text{N}=\sum_{i=1}^{K} C_1 \bullet C_2 n_i \left(\frac{P_i}{P}\right)^{4.35} \tag{4}$$

Where N is the equivalent axle load repetition times; Pi is the axle load of different models; ni is the axle load repetition times of all models; P is the standard axle load 100KN; C1 is the wheel coefficient, the single wheel group is 6.4, the double wheel group Is 1, the four-wheel group is 0.38; C2 is the axis number coefficient.

When the axle distance is greater than 3 meters, it should be calculated as a single axle, and the axis number coefficient is 1. When the axle distance is less than 3 meters, it should be calculated as dual or multi-axle, and the axis number coefficient calculation formula:

$$\text{C2}=1+1.2\ (\text{m}-1) \tag{5}$$

Where m is the number of axes.

As shown in Table 1, asphalt pavements with different traffic levels can be classified according to the cumulative ESAL repeatability of a lane in the design life.

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Table 1. Traffic classification of asphalt pavement

Traffic level	Types of	Cumulative ESAL (×106/lane)	Nn axle weight is greater than 40KN (number/day/lane)
low	A	<1.5	<300
light	B	1.5-4.0	300-1000
In	C	4.0-12.0	1000-4000
Weight	D	12.0-30.0	4000-10,000
overweight	E	>30.0	> 10,000

In addition, the analysis period of the expressway traffic load is limited to 15 years.

2.4. Road Life

Pavement life is also one of the important factors influencing road maintenance decision-making. The design life of Chinese expressways is between 15 and 20 years, and most expressways have not yet reached the design life. For long-term maintenance expressways, their pavement age is close to the design life, and they need higher maintenance priority [3].

2.5. Road Class

The highway network in Jiangsu Province includes national and provincial highways. Since two highways have the same road conditions, such as performance, traffic volume, etc., national highways often have a higher priority for maintenance. Similar to risk analysis, higher performance level requirements and maintenance priorities are usually assigned to highways with higher traffic or relative importance. The expressway network includes national highways and provincial highways. National highways often have a higher priority for maintenance, ranking first, and provincial highway maintenance priority is low, ranking second.

3. ANALYTIC HIERARCHY PROCESS

The weight value reflecting the status or role of various factors in the evaluation process directly affects the decision result. Subjective evaluation only relies on experience and cannot accurately reflect the actual situation. The assessment results may be "distorted." On the contrary, several methods to determine the weight value have been developed, including expert consultation, analytic hierarchy process, frequency statistics, etc. AHP was originally developed by Saaty in the 1970s [9]. It is suitable for decision-making problems involving complex levels and multiple indicators. The analytic hierarchy process can deal with the qualitative and quantitative factors of the decision-making process, and it is practical, systematic and concise. It determines the relative importance or weight of alternatives based on each criterion involved in a given decision problem. This study uses the analytic hierarchy process to determine the weight value of each decision-making influence factor, and determines the weight of the alternative plan according to each criterion involved in a given decision-making problem, including four steps [4]: (1) establish a hierarchical model; (2)) Construct a judgment matrix; (3) Ranking and consistency test; and (4) Synthesis and consistency test.

3.1. Hierarchical Model

By building a hierarchical model, the decision-making problem becomes hierarchical and the complexity is decomposed. The hierarchical model usually consists of three levels: (1) the top level represents the overall goal for determining the importance ranking; (2) the middle level contains the criteria that affect the goal and is used to evaluate alternatives; (3) the bottom level includes alternatives to achieve the goal. The top layer is the target layer, denoted as A, the

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middle layer containing n criteria is denoted as C1, C2, C3,... and Cn, the bottom layer containing m alternatives is denoted as P1, P2, P3,... And Pm. The layered model is shown in Figure 1:

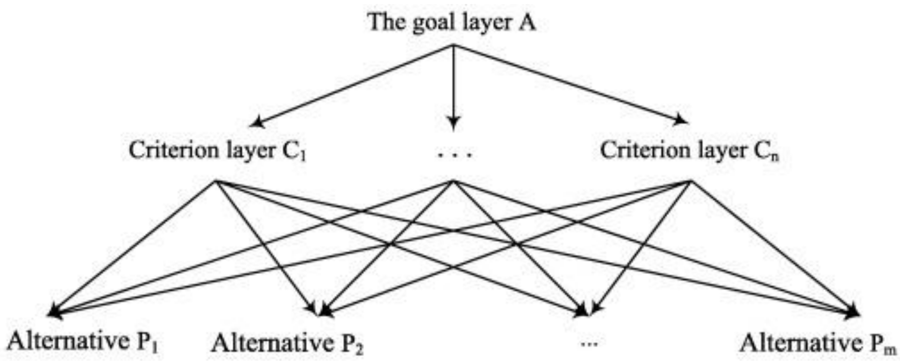

Fig 1. Analytical hierarchical process model

3.2. Pairwise Comparison Judgment Matrix

The judgment matrix is constructed by comparing two elements pairwise. Pairwise comparison is used to determine the relative importance of each option in terms of each criterion. The decision-maker must determine the relative importance of each option according to the 9 levels shown in Table 2. Compare the value for analysis. For the second layer, the comparison result can be described by the matrix $A_{n\times n}=(aij)_{n\times n}$ $A_{n\times n}$ is called the pairwise comparison judgment matrix from layer A to C, and the judgment from layer C to layer P can also be constructed Matrix, which includes:

Table 2. Relative importance ratio

Degree of relative importance	definition
1	Equally important
3	Medium important
5	Very important
7	Determine important
9	Absolutely important
2,4,6,8	The middle value between two adjacent judgment values
Pairwise comparison value	The judgment value of the importance of elements i and j is rij, and the reciprocal value is 1/rij

3.3. Ranking and Consistency Check

After constructing the comparison matrix, the relative importance of each element of a layer to the elements of the above layer can be extracted. For the comparison matrix, the relative importance can be calculated by normalizing the feature vector corresponding to the main feature value of the judgment matrix.

The established judgment matrix quantifies the judgment process. However, when many paired comparisons are made, some inconsistencies may occur. For example, suppose that 3 criteria are considered, and the decision maker evaluates that criterion A is more important than criterion B, and criterion B is more important than criterion C. If the third criterion is more important than the first, there will be inconsistencies.

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For the comparison matrix, the relative importance is calculated by normalizing the feature vector corresponding to the main feature value of the judgment matrix [5]. However, when many paired comparisons are made, some inconsistencies may occur. The purpose of the matrix consistency check is to check the consistency of the evaluation, and to ensure the rationality of each judgment and avoid conflicting results. Perfect consistency rarely occurs in practice. If the corresponding consistency ratio (CR) is less than 10%, the judgment matrix is considered to be sufficiently consistent [6]. First, the consistency index (CI) can be calculated by a formula based on the maximum eigenvalue λmax:

$$CI=\frac{\lambda max - n}{n - 1}, n=1, 2, \ldots, 9 \tag{6}$$

Then, as shown in Table 3, divide CI by the random consistency index (RI) to obtain CR.

$$CR=\frac{CI}{CR} \tag{7}$$

Table 3. RI value

Factor	1	2	3	4	5	6	...
RI	0	0	0.58	0.9	1.12	1.26	...

3.4. Synthesis and Consistency Check

The final hierarchical priority ranking is to calculate the ranking weight of the relative importance of all elements of a certain layer to the top level [7]. For this article, the decision-maker needs to construct N judgment matrices of M×M order and a judgment matrix of N×N order. According to the scheme of all standard combinations, the final priority expressed by W_{P1}, W_{P2}, ..., W_{Pi} is calculated according to the equation:

$$W_{Pi} = \sum_{j=1}^{n} W_{Cij} W_j \text{, i=1, 2, ..., m} \tag{8}$$

Where W_j is the overall ranking weight of each element in the above C layer; WC_{ij} is the ranking weight of the layer corresponding to C_j, and the consistency of the final ranking weight is checked as follows:

$$CR = \frac{\sum_{j=1}^{n} W_j CI(j)}{\sum_{j=1}^{n} W_j RI(j)} \text{, j=1, 2, ..., n} \tag{9}$$

Where CI(j) is the consistency index CI of standard j; RI(j) is the average random consistency index RI of standard j.

4. SENSITIVITY ANALYSIS

The results of pavement maintenance decisions are affected by a variety of pavement-related factors. The purpose of sensitivity analysis is to explore which factors have a significant impact on road maintenance decisions from two aspects of service life and cost [8]. Sensitivity analysis

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takes the remaining service life and maintenance cost of the pavement as indicators. The service life of the pavement infrastructure can be determined according to the performance curve (based on historical data) and the pavement performance threshold. Maintenance costs mainly depend on the type of maintenance activities carried out on the road. Each maintenance treatment strategy is determined by the specific maintenance behavior, work content, unit cost and the treatment effect of existing facilities [9]. The unit cost of each treatment is achieved by investigating historical average facility construction and maintenance costs. Life Cycle Cost Analysis (LCCA) has been widely used to evaluate the cost-effectiveness of road surfaces. Maintenance items on different roads are usually applied in different years, using equations to explain the impact of inflation:

$$PW = F\frac{1}{(1+i)^n} \tag{10}$$

Where PW is the present value; F is the future cost or current cost; i is the discount rate; n is the duration of the maintenance project;

$$EUAC = PW\frac{i(1+i)^p}{(1+i)^p - 1} \tag{10}$$

Among them, p is the analysis period related to the maintenance project, which can be regarded as the service life of the maintenance treatment.

For sensitivity analysis, the basic values of PQI and PSSI are set to 80, the road life is 10 years, and the cumulative ESAL in the design service life (15 years) is 10×106 per lane. The impact of one indicator on changes in maintenance costs and remaining life of the road surface can be explained by changing its value, while other indicators remain unchanged. According to the history of road maintenance, it can be found that the maintenance priority of national roads is different from that of provincial roads, but there is no significant difference in the results of choosing the maintenance treatment based on road grade [10]. Therefore, different road grades are not considered in this sensitivity analysis, and road maintenance costs are most sensitive to changes in road performance. In addition, the road structure and traffic level have similar effects on maintenance costs. When the road surface age changes, the road maintenance cost does not change much, but the remaining service life varies greatly. The maintenance cost analysis results are consistent with the weights of different decision-making factors [11].

5. CONCLUSION

Network-level infrastructure maintenance decision-making is a multi-factor and multi-standard problem. This article chooses Analytic Hierarchy Process (AHP) to determine the weight of each decision factor. Considering their relative importance and generating an overall priority ranking index for each section, it can incorporate all possible maintenance related factors. A total of five pavement maintenance decision-making factors are considered, and the weight values of the five factors are determined through the analytic hierarchy process. After quantifying the weight values of the five factors, the comprehensive ranking value Ui is determined, which indicates the maintenance priority of the road section in the network-level decision-making process [12]. From the perspective of maintenance costs, the sensitivity analysis results are consistent with the weight values of different maintenance decision

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indicators. It can be found that road maintenance costs are very sensitive to changes in road performance.

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