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ABSTRACT

This paper proposes an Analytic Hierarchical Process (AHP) theory based method to determine the weight of the decision-making influence factors, considering their relative significance and generating an overall ranking for each road section. A case study on the highway network maintenance priority was conducted to illustrate the proposed procedure. A total of five pavement maintenance decision-making related factors were considered in the study, including pavement performance, pavement structure strength, traffic loads, pavement age and road grade. The weightings of the five factors were quantified through AHP method. Then, the comprehensive ranking index value Ui was determined, which indicated the maintenance priority of a road section in network level decision-making. From the aspect of maintenance cost, the sensitivity analysis results were in accordance with the weightings of different maintenance decision-making factors. The pavement maintenance cost was significantly sensitive to the change of pavement performance. The case study clearly demonstrated the applicability and rationality of the AHP theory based decision-making method and it can be used as a guideline for pavement maintenance agencies.

Keywords: Asphalt pavement; Network level; Maintenance decision-making; Analytic Hierarchical Process; Factor Weight, Priority

INTRODUCTION

Most of the highways in Jiangsu Province were built more than 10 years ago and distresses with various types and severity levels have occurred on the pavement surface. With the development and expansion of highway network, more and more highways meet varying degrees of deterioration. Pavement maintenance, which aims to restore the safe and comfortable riding for road users, has drawn more and more attentions of pavement maintenance engineers. However, due to the limited annual maintenance budget*)* and it is difficult to meet the demand of all the highway pavement maintenance. Therefore, it is an important issue for highway agencies to optimize pavement maintenance strategy considering various factors.

Due to the lack of historical pavement condition and traffic data, and analysis methods, only limited findings on pavement maintenance decision-making in china were attained. Nowadays, highway weight charge system has been extensively used in China and comprehensive axle loads data are available. Routine pavement performance survey is carried out by the highway management agency every year and the pavement condition data have been recorded in the developed Pavement Management System (PMS) in Jiangsu Province. Detailed information of pavement structure, weather, environment, traffic level, axle loads and pavement performance detection are also included in the PMS. With those systematically collected pavement related data available, it is of great interests to incorporate all of those factors into pavement maintenance decision-making.

Network level pavement maintenance decision-making is to determine the maintenance priority of road sections in a highway network, considering the performance and other characteristics of all the road sections. Therefore, it is a multi-factor and multi-criteria problem. Considered factors include pavement structure, traffic loads, pavement performance, pavement age and etc. Moreover, the maintenance plan is based on multiple goals, which are often not coordination and even contradictory. On one hand, various maintenance treatments were carried out to maintain high level pavement performance to meet the requirement of road users; on the other hand, it is the goal of the pavement highway agencies to minimize pavement maintenance costs. With limited pavement maintenance budget, it is unlikely to meet the maintenance requirements of all road sections. A scientific process is needed to rationally rank maintenance priority of all the road sections according to specific criteria, including performance, traffic volume, relative significance of road sections and etc.

Determining the weight of each item factor is the key to solve the problem in the decision-making process. It is difficult to determine the weight of the factors, as the relationship between each factor is qualitative. Analytic Hierarchical Process (AHP) is a typical system engineering method transforming qualitative analysis into quantitative analysis. It can effectively avoid the difficulties and determine the weight of each factor, considering both quantitative and qualitative factors. It has been widely used to solve decision-making problem with complicated structure, more decision criterion, and factors which are difficult to quantify. AHP method can help keep the consistency of the judging process, and it is widely used for determining the weight expressing the relative importance of a set of alternatives on the basis of multiple criteria. In this study, AHP was selected to determine the weight of each factor, in order to get a comprehensive ranking index of the road sections in network level pavement maintenance decision-making.

RESEARCH OBJECTIVE

The objective of the presented study is to develop a network level pavement maintenance decision-making process based on the AHP theory. A case study of network level maintenance decision-making in Jiangsu Province was conducted to demonstrate the applicability of the AHP theory. Various decision-making factors, including pavement performance, pavement structure, pavement age, traffic level, and road grade were considered. Hierarchical analysis method is used for determining the weight of each decision-making factor, in order to get a comprehensive ranking index of the selected road sections of the highways. The accuracy and effectiveness of the AHP weighting analysis could be verified through sensitivity analysis.

SELECTION OF DECISION-MAKING INFLUENCE FACTORS

There were many factors involved in network level maintenance decision-making and each of them could be related in different ways to the maintenance processes. It is not practical to monitor all of them. Therefore, it is important to identify the key factors which would have the most important effects on the maintenance decision-making process. The key factors were selected in the first round through literature review, survey of the experts' opinions and analysis of the information in the database. In this study, a panel of 10 experts in asphalt pavement maintenance participated for refining and revising the selection of the indices. Each expert gave a list of maintenance decision-making related factors. The factors with high frequency on the list were extracted, which were pavement performance, pavement structure strength, traffic level, pavement age, and road grad.

Pavement Quality Index

It is generally believed that pavement performance is the most significant factor in the maintenance decision-making process. According to the Chinese specification for highway performance assessment, the performance indices for asphalt pavement include Pavement Condition Indicator (PCI), Riding Quality Index (RQI), Rutting Depth Index (RDI), Skid Resistance index (SRI). The Pavement Quality Index (PQI), calculated by Equation (1), was used to characterize the overall pavement performance.

$$PQI = \omega_{\mathrm{PCI}}\, PCI + \omega_{\mathrm{RQI}}\, RQI + \omega_{\mathrm{RDI}}\, RDI + \omega_{\mathrm{SRI}}\, SRI \tag{1}$$

Where, ω_{PCI}, ω_{RQI} , ω_{RDI}, and ω_{SRI} are the weighting values of RQI, RDI, SRI, and PCI; and 0.35,0.40, 0.15, and 0.10 were used in this study, respectively.

Pavement Structure Strength

Generally, distresses develop slowly on pavements with better quality material and rational layer structure. Road sections with better pavement structure have longer service time. Therefore, the pavement structural capacity is considered to be another important factor affecting the network level pavement maintenance decision-making.

Unlike PCI or RQI, the structural capacity of pavement cannot be directly seen or perceived. To quantify the pavement structural capacity, an index which could represent the strength of the pavement structure needs to be determined based on instrument detection. According to the Chinese specification for highway performance assessment, the highway asphalt pavement structure strength can be measured by the Pavement Structure Strength Index (PSSI). PSSI is an average value of relative deflections measured by the falling weight deflectometer at multiple positions. It can be calculated by Equation (2) and (3).

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

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

Where, SSI is the structure strength index; l_{R} is designed pavement deflection, mm; l_0 is the actual measured representative deflection, mm; η is the correction coefficient; a_0 and a_1 are calibration coefficients. In this study, a_0 is 15.71 and a_1 is -5.19.

Traffic Load

Traffic means the vehicle traffic flow that goes through to a certain lane of a certain section of the road in unit time and consists of a variety of vehicles and axle loads. Due to the large variance of axle loads, the cumulative Equivalent Single Axle Loads (ESALs) is usually used to characterize traffic level based on measured traffic flow. With the installation of weigh-in-motion (WIM) stations in Jiangsu Province, detailed axle loads can be obtained and more accurate ESALs can be calculated.

According to the Chinese Specification for Design of Highway Asphalt Pavement, the 100 kN single axle load with dual wheels is used as the standard single axle load. Axle loads less than 40 kN are neglected due to their little impact on the pavement. When the predicted pavement surface deflection and tensile stress at bottom of asphalt layer are used as the design criteria, the equivalent axle load repetitions (N) can be calculated by Equation (4).

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

Where, N is the equivalent axle load repetitions; P_i is the axle load of different vehicle type (KN); n_i is axle load repetitions of all vehicle types; P is the standard axle load, 100 KN; C_1 is wheel set coefficient, 6.4 for single wheel set, 1 for dual wheel set, 0.38 for four wheel set; C_2 is axle number coefficient.

When the distance between axles is greater than 3 m, it shall be calculated as a single axle, and axle number coefficient is 1; when the distance between axles is less than 3 m, it shall be calculated as dual axles or multiple axles, and the axle number coefficient is calculated by Equation (5).

$$C_2 = 1 + 1.2(m-1) \quad (5)$$

Where, m is axle number.

As shown in Table 1, asphalt pavements with different traffic levels can be classified based on cumulative ESAL repetitions of one lane in the design service life.

Table 1 Traffic Level Classification on Asphalt Pavements

Traffic level	Type	Cumulative ESALs($\times 10^6$/lane)	N_n of axle load greater than 40kN (number/day/lane)
Low	A	<1.5	<300
Light	B	1.5-4.0	300-1000
Moderate	C	4.0-12.0	1000-4000
Heavy	D	12.0-30.0	4000-10000
Extra heavy	E	>30.0	>10000

Moreover, the data of the annual traffic load growth rate can be obtained from the PMS. Because most of the designed service life of highways in Jiangsu Province is 15 years, the analysis period of traffic load of all highways is set as 15 years. The cumulative equivalent axle load repetitions during the analysis period could be calculated based on which the ranking value of all road sections can be acquired.

Pavement Age

Pavement age is also one of the most significant influence factors for pavement maintenance decision-making. Many highways in Jiangsu Province were built more than 10 years ago. The design life of highways in China is between 15 to 20 years, and most of the highways have not reached their design lives yet. For those highways which have been servicing for longer years, their pavement age are close to the design life and they need higher priority of maintenance.

Road Grade

The highway network in Jiangsu province includes national and provincial highways. For two highways have the same pavement condition such as performance, traffic volume, and etc., national highway often has a higher priority of maintenance. Similar with the risk analysis, higher performance level requirement and maintenance priority are usually assigned to highways with higher traffic volume or relative importance. Based on the results of expert consultation, and the overall status of the highway network, the national highway has higher priority of maintenance and the ranking value was set as the first. The provincial highway has lower priority of maintenance and the ranking value was set as the second.

ANALYTIC HIERARCHY PROCESS

The weighting values, which reflect the status or role of various factors in the evaluation process, directly affect the decision-making results. Subjective evaluation only relies on experience and cannot accurately reflect the actual situation. The evaluation result may be "distorted". Instead, several methods of determining the weighting values were developed, including expert consultation, AHP, frequency statistics, and etc.. In this study, the method of AHP was used to determine the weighting value of each decision-making influence factor.

AHP was originally developed by Saaty in the 1970s. It is applicable to decision-making problems that involve complex hierarchies and multiple indices. AHP can deal with qualitative and quantitative factors of the decision-making process, and it is practical, systematic and terse. It determines the relative importance, or weight, of the alternatives in terms of each criterion involved in a given decision-making problem. Generally speaking, four steps are involved to determine the weight of the factors in network level decision-making: 1) building the hierarchical model; 2) constructing the judgment matrix; 3) ranking and consistency check; and 4) synthesis and consistency check.

Hierarchical Model

By building the hierarchical model, a decision problem becomes hierarchical and the complexity is decomposed. The problem is explored at levels from general to detailed and then expressed in a multileveled way. The hierarchical model usually consists of three layers according to their relationships and attributes: 1) the top level represents the overall goal to determine the ranking of importance; 2) the middle level contains the criteria that influence the goal and are used for evaluating the alternatives; 3) the bottom level, which includes alternatives to achieve the goal. The top layer is the goal layer, denoted as A. The middle level containing n criteria, is denoted as C_1, C_2, C_3,..., and C_n. The bottom layer containing m alternatives is denoted as P_1, P_2, P_3,..., and P_m. The hierarchical model is shown in Figure1.

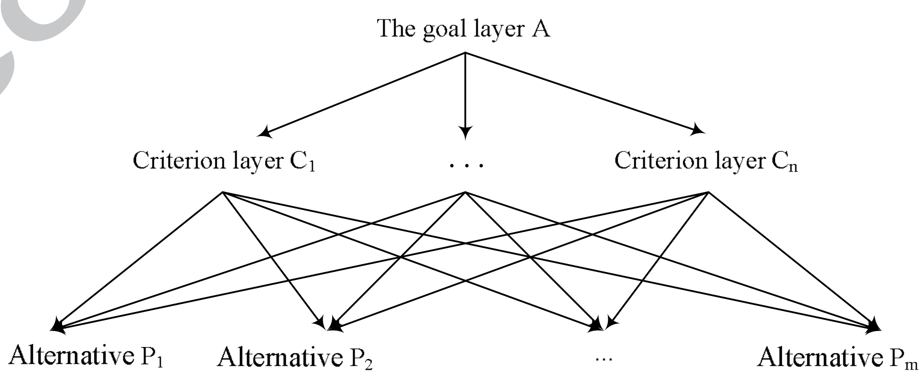

Figure 1 Analytic hierarchical process model.

Pairwise Comparison Judgment Matrix

A judgement matrix is constructed by pairwise comparing two elements. Pairwise comparisons are used to determine the relative importance of each alternative in terms of each criterion. The decision-maker has to express his opinion about the value of one single pairwise comparison at a time, on the basis of 1-9 scale as shown in Table 2. For the second layer, the comparison result can be described by the matrix $A_{n\times n}= (a_{ij})_{n\times n}$. $A_{n\times n}$ is called the pairwise comparison judgment matrix from layer A to *C*. The judgment matrix from the layer C to P can also be constructed, which involves *m* elements. The *m* elements can be pairwise compared and assigned with the specific values, which form the matrix $(C_{\mathrm{i}})_{m\times m}$ (i= 1, 2, 3,..., n).

Table 2 Scale of Relative Importance

Intensity of relative importance	Definition
1	Equal importance
3	Moderate importance
5	Strong importance
7	Demonstrated importance
9	Absolute importance
2、4、6、8	Intermediate values between two adjacent judgement values
The reciprocal value	The judgement value of the importance of the element *i* and *j* is r_{ij}, and the reciprocal value is $1/r_{ij}$.

Ranking and Consistency Check

After constructing the comparison matrix, the relative importance of each element of one layer to the element of the above layer can be extracted. For a comparison matrix, the relative importance can be calculated by normalizing the eigenvector corresponding to the principal eigenvalue of the judgment matrix.

The established judgment matrices quantify the judgment process. However, when many pairwise comparisons are performed, some inconsistencies may arise. For example, assume that 3 criteria are considered, and the decision maker evaluates that the criterion A is more important than B criterion, while the B criterion is more important than C criterion. An inconsistency arises if the third criterion is more important than the first criterion.

The purpose of matrix consistency check is to check the consistency of the evaluation, and to ensure each judgment is rational and avoid no conflicting results. Perfect consistency rarely occurs in practice. The judgment matrix is considered to be adequately consistent if the corresponding consistency ratio (CR) is less than 10%. Firstly, a Consistency Index (CI) can be calculated by Equation (6) based on the maximum eigenvalue$\lambda_{\max}$:

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

Then, *CR* is obtained by dividing the *CI* by the Random Consistency Index (*RI*) as shown in Table 3.

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

Table 3 The RI Values

Elements	1	2	3	4	5	6	7	8	9	…

RI	0	0	0.58	0.9	1.12	1.26	1.36	1.41	1.45	…

Synthesis and Consistency Check

Final hierarchy priority ranking is to calculate the ranking weights of the relative importance of all the elements of a certain layer to the top layer. For a problem with M alternatives and N criteria as shown in this paper, the decision maker is required to construct N judgment matrices (one for each criterion) of order M*M (for m factors) and one judgment matrix of order N*N (for n criteria). The final priorities, denoted by W_{P1}, W_{P2},..., W_{Pi}, of the alternatives in terms of all the criteria combined are determined according to Equation (8).

$$W_{p_i} = \sum_{j=1}^{n} W_{c_{ij}} W_j \text{ , } i=1\text{ , }2\text{ , }\dots\text{ , m} \quad (8)$$

Where, W_j is the overall ranking weight of each element of the above layer C; W_{Cij} is the ranking weight of the layer corresponding to C_j.

The consistency check of the final ranking weight is shown in Equation (9).

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

Where, $CI(j)$ is the consistency index CI of criterion j; $RI(j)$ is the average random consistency index RI of criterion j.

PROJECT CASE STUDY

Collection of Road Sections

Twenty six road sections on thirteen highways in need of maintenance were selected from the PMS for the case study. Most of the road sections need immediate maintenance. The five influence factors of the twenty six road sections till 2014 were obtained and calculated from the PMS. The pavement performance indices and pavement structure strength of the selected road sections in 2014 are summarized in Table4. Table 5 shows the cumulated ESALs till 2014 and the annual growth rate. Table 6 shows the pavement ages and road grade of investigated Highways. The national equals to the Interstates whereas the provincial equals to State Routes.

Table 4 Asphalt Pavement Performance Indices and Structure Strength

Road Name	Road Code	No.	Direction	PCI	RQI	RDI	SRI	PQI	PSSI
Yan Jing	S29	1	North Bound	95	92	90	94	93	83.96
		2	South Bound	92	89	86	93	90	84.71
Ning Xu	S49	3	North Bound	94	90	86	92	91	83.14
		4	South Bound	90	87	84	91	88	83.65
Lian Xu	G3	5	West Bound	85	84	80	86	84	65.43
		6	East Bound	87	89	80	90	87	73.91
Xi Guang	G2	7	North Bound	87	84	80	90	85	74.62
		8	South Bound	85	83	77	85	83	71.80
Jing Hu	G2	9	North Bound	86	83	79	89	84	80.82
		10	South Bound	82	80	75	81	80	73.55
Zhen Li	G4011	11	North Bound	90	89	83	94	89	87.93
		12	South Bound	94	92	87	93	92	88.63
Ning Chang	S38	13	West Bound	95	96	91	97	95	87.04
		14	East Bound	95	92	89	96	93	86.99
Fen Guan	G15	15	North Bound	94	92	91	96	93	81.85

		16	South Bound	88	83	81	89	85	79.04
Ning Tai	S38	17	West Bound	90	85	82	92	87	87.19
		18	East Bound	93	90	86	95	91	87.36
Ning Hang	G25	19	West Bound	91	87	83	89	88	86.59
		20	East Bound	92	91	87	94	91	64.26
Xi Yi	S48	21	North Bound	94	90	90	96	92	80.44
		22	South Bound	93	88	88	91	90	81.85
Hu Ning	G42	23	West Bound	88	83	80	90	85	66.70
		24	East Bound	93	91	89	97	92	70.03
Lian Tong	G15	25	North Bound	94	93	90	94	93	81.24
		26	South Bound	91	88	85	92	89	79.87

Table 5 Cumulative ESALs till 2014 and Traffic Load Growth

Road name	Road code	No.	Direction	Lane number	Cumulative ESALs($\times 10^6$)	Traffic Load growth rate
Yan Jing	S29	1	North Bound	2	3.59	13.9%
		2	South Bound	2	3.84	12.0%
Ning Xu	S49	3	North Bound	2	4.26	4.3%
		4	South Bound	2	9.43	8.8%
Lian Xu	G3	5	West Bound	2	17.03	8.3%
		6	East Bound	2	14.16	10.1%
Xi Guang	G2	7	North Bound	3	24.18	3.0%
		8	South Bound	3	38.50	7.0%
Jing Hu	G2	9	North Bound	2	39.57	6.8%
		10	South Bound	2	62.60	4.5%
Zhen Li	G4011	11	North Bound	3	7.05	5.0%
		12	South Bound	3	6.45	3.7%
Ning Chang	S38	13	West Bound	3	1.22	6.85%
		14	East Bound	3	1.39	10.0%
Fen Guan	G15	15	North Bound	2	13.53	4.9%
		16	South Bound	2	24.70	5.3%
Ning Tai	S38	17	West Bound	2	12.26	5.8%
		18	East Bound	2	11.86	3.5%
Ning Hang	G25	19	West Bound	3	15.36	3.4%
		20	East Bound	3	10.95	4.8%
Xi Yi	S48	21	North Bound	2	8.60	4.7%
		22	South Bound	2	8.73	2.9%
Hu Ning	G42	23	West Bound	4	22.57	4.5%
		24	East Bound	4	15.34	3.6%
Lian Tong	G15	25	North Bound	3	4.05	2.1%
		26	South Bound	3	7.71	1.6%

Table 6 Pavement Ages and Road Grade of Highways

Road name	Road code	Opening time	Designed service life (years)	Pavement age(years)	Road grade

Yan Jing	S29	2001.11	15	13	Provincial
Ning Xu	S49	2001.12	15	13	Provincial
Lian Xu	G3	2001.12	15	13	National
Xi Guang	G2	1999.09	15	15	National
Jing Hu	G2	2000.12	15	14	National
Zhen Li	G4011	2007.09	20	7	National
Ning Chang	S38	2007.09	20	7	Provincial
Fen Guan	G15	2002.10	15	12	National
Ning Tai	S38	2004.11	15	10	Provincial
Ning Hang	G25	2004.09	20	10	National
Xi Yi	S48	2003.09	20	11	Provincial
Hu Ning	G42	2005.12	15	9	National
Lian Tong	G15	2005.11	30	9	National

Determination of Factor Weighting

When using AHP method to determine priority ranking of network level pavement maintenance activities, the comprehensive ranking index can be set as the goal. As the analysis of comprehensive ranking index should cover rationality and feasibility of the factors, the two criterions were employed, referred as C_1 and C_2. The five influence factors in maintenance decision making can be set as the bottom alternatives layer, which are pavement performance (P_1), pavement structure strength (P_2), traffic load (P_3), pavement age (P_4) and road grade (P_5). The hierarchical structure model is shown in Figure 2.

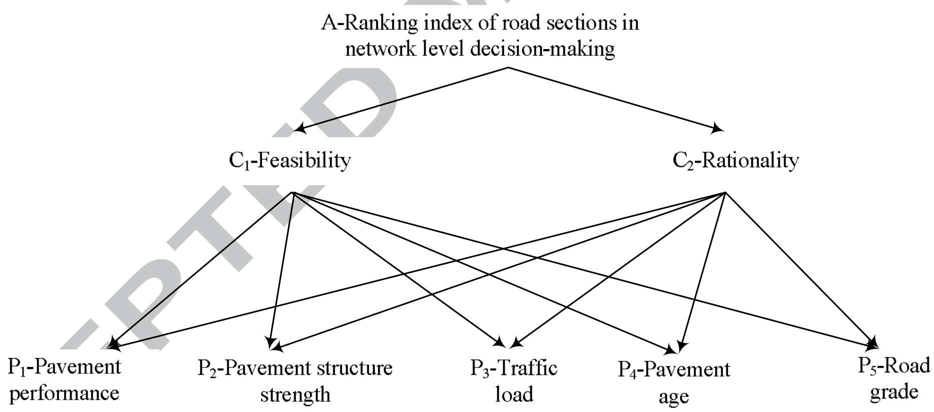

Figure 2 Hierarchy model of factor weighting analysis in network level decision-making.

According to the hierarchy model, the judgment matrix $A_{2\times2}$ with respect to the goal A to C was built, including two elements: feasibility and rationality. The judgment matrix was constructed by collecting experts' rating, analysing the importance of the two factors and assigning specific values. Then, the judgment matrix $(C_{\mathrm{i}})_{5\times5}$ with respect to the two criteria C was also constructed. They were pairwise compared and assigned with the specific values, which form the matrix $(C_1)_{5\times5}$ and $(C_2)_{5\times5}$ (i = 1, 2, 3,..., n). In this study, the experts from the highway management departments, highway research institute and highway construction departments, with each group of about 10 people and a total of 30 people, independently complete the questionnaire to establish the comparison matrix. The pairwise comparison matrices are shown in Equation (10).

$$A=\begin{bmatrix}1 & \frac{1}{3}\\ 3 & 1\end{bmatrix}\quad C_1=\begin{bmatrix}1 & 5 & 5 & 7 & 9\\ 1/5 & 1 & 3 & 5 & 5\\ 1/5 & 1/3 & 1 & 4 & 5\\ 1/7 & 1/5 & 1/4 & 1 & 3\\ 1/9 & 1/5 & 1/5 & 1/3 & 1\end{bmatrix}\quad C_2=\begin{bmatrix}1 & 6 & 6 & 8 & 8\\ 1/6 & 1 & 2 & 5 & 5\\ 1/6 & 1/2 & 1 & 4 & 5\\ 1/8 & 1/5 & 1/4 & 1 & 2\\ 1/8 & 1/5 & 1/5 & 1/2 & 1\end{bmatrix} \tag{10}$$

Firstly, the consistency of matrix A was checked. As the matrix A had two factors, it was complied with the consistency principle. The principle eigenvalue wasλ_{max}=2, the corresponding eigenvector W was $W=[W_1, W_2]^T=[0.25, 0.75]^T$. The consistency of matrix C_1 and C_2 was also checked. The weights of the five factors were calculated and shown in Table 7.

Table 7 Weights of the Five Factors and the Consistency Check

Factor weight	W_{i1}	W_{i2}	W_{i3}	W_{i4}	W_{i5}	λ_{max}	CI_i	RI_i	CR_i
W_{C1}	0.5565	0.2187	0.1324	0.0583	0.0341	5.4392	0.1098	1.12	0.0980
W_{C2}	0.5958	0.1839	0.1327	0.0502	0.0373	5.3631	0.0908	1.12	0.0811

From Table 7, it is can be seen that the matrix $C_1$and C_2 passed the consistency check and they are effective matrices. The consistency of the overall ranking is checked as follows:

CI=0.25*0.1098+0.75*0.0908=0.0956,

RI=1.12,

CR=0.0854<0.1.

It can be seen that the overall ranking passed the consistency check. The final weight vector of factors P_1, P_2, P_3, P_4 and P_5 is $W_P = [W_{P1}, W_{P2}, W_{P3}, W_{P4}, W_{P5}]^T$=[0.5860, 0.1926, 0.1326, 0.0522, 0.0365]^T.

Application of Factor Weighting

Based on the discussion above, the ranking values of the twenty six road sections corresponding to the five maintenance decision-making influence factors are calculated and summarized in Table 8. The smaller the ranking value, the higher priority the road section has in pavement maintenance. By applying the weighting of the five factors, which is $W_P = [W_{P1}, W_{P2}, W_{P3}, W_{P4}, W_{P5}]^T$ =[0.5860, 0.1926, 0.1326, 0.0522, 0.0365]^T, the comprehensive ranking index U_i and the maintenance priority could be determined as also shown in Table 8. The comprehensive ranking index U_i shows the urgency and priority of a road section in network pavement maintenance planning. For example, road section 10 had the minimum ranking value and should be assigned with the highest maintenance priority. In this study, when the road sections had the same value of comprehensive ranking index U_i, the road section with smaller value of PQI was assigned with higher maintenance priority. The results of priority ranking reflected the urgency and importance of each road section in pavement maintenance. The road sections in highest need of maintenance treatment could be selected in line with the maintenance budget in the next year. The results can be used as a guideline for highway agencies in their pavement maintenance decision-making process.

Table 8 Single Factor Ranking and Comprehensive Ranking of Road Sections

Road name	Road code	No.	PQI	PSSI	Traffic load	Pavement age	Road grade	U_i	Priority
Yan Jing	S29	1	10	18	24	3	2	12.74	23
		2	7	19	23	3	2	11.04	21
Ning Xu	S49	3	8	16	21	3	2	10.78	19
		4	5	17	14	3	2	8.29	11

Road name	Road code	No.	PQI	PSSI	Traffic load	Pavement age	Road grade	U_i	Priority
Lian Xu	G3	5	3	2	5	3	1	3.00	3
		6	5	7	11	3	1	5.93	8
Xi Guang	G2	7	4	8	6	1	1	4.77	6
		8	2	5	4	1	1	2.75	2
Jing Hu	G2	9	3	12	2	2	1	4.48	4
		10	1	6	1	2	1	2.02	1
Zhen Li	G4011	11	6	25	12	8	1	10.38	18
		12	9	26	16	8	1	12.86	24
Ning Chang	S38	13	11	22	25	8	2	14.49	26
		14	10	21	26	8	2	13.84	25
Fen Guan	G15	15	10	14	10	4	1	10.13	17
		16	4	9	3	4	1	4.72	5
Ning Tai	S38	17	5	23	7	6	2	8.67	13
		18	8	24	9	6	2	10.89	20
Ning Hang	G25	19	5	20	8	6	1	8.19	10
		20	8	1	13	6	1	6.95	9
Xi Yi	S48	21	9	11	17	5	2	9.98	16
		22	7	15	18	5	2	9.71	15
Hu Ning	G42	23	4	3	15	7	1	5.31	7
		24	9	4	20	7	1	9.10	14
Lian Tong	G15	25	10	13	22	7	1	11.68	22
		26	6	10	19	7	1	8.36	12

SENSITIVITY ANALYSIS

The results of the pavement maintenance decision-making are influenced by multiple pavement related factors. The purpose of the sensitivity analysis is to explore which factor has significant effects on pavement maintenance decision-making from the aspects of both service life and cost. The pavement residual service life and maintenance cost were used as the responses in the sensitivity analysis.

Pavement infrastructure service life, i.e., time taken for the pavement to deteriorate to a threshold value or rehabilitation can be determined based on performance curves (developed from historical data) and a pavement performance threshold. Residual service life of an infrastructure is the rest service life which is the whole service life with deduct of the age. Maintenance costs mainly depend on the type of maintenance activities that are performed on the pavement. Each of the maintenance treatment strategies is defined by specific maintenance action, work content, unit cost and treatment effect on the existing facilities. The unit cost for each of the treatments was attained by investigating the historical average facility construction and maintenance costs in Jiangsu province. The life cycle cost analysis (LCCA), has been widely used to evaluate cost-effectiveness of pavement, which recommends using Equivalent Uniform Annual Cost (EUAC) to compare the different costs. Maintenance projects at different pavement sections were usually applied in different years. In order to compare their costs, the present value is determined using Equation (11) to account for inflationary effects.

$$PW = F\frac{1}{(1+i)^n} \tag{11}$$

Where, PW is the present worth, ¥/m^2; F is the future cost or current cost, ¥/m^2; i is the discount rate, and the value can be adopted as 6% in China; n is the age of the maintenance project, years. Where, PW = the present worth, ¥/m^2;

$$EUAC = PW \frac{i(1+i)^p}{(1+i)^p - 1} \quad (12)$$

Where, p = analysis period associated with the maintenance project, years, and it can be adopted as the maintenance treatment service life.

For sensitivity analysis, the basic value of PQI and PSSI was set as 80, pavement age was 10 years, and the cumulative ESALs in designed service life (15years) were 10×10^6 per lane. The influence of one index or factor on the change of maintenance cost and the pavement residual life can be illustrated by changing its value, while holding other factors constant. According to the pavement maintenance history, it can be found that the maintenance priority of national highway was different with that for provincial highway. However, there was no significant difference in selecting maintenance treatment result based on road grade. Therefore, different road grade was not considered in this sensitivity analysis. Table 9 shows the sensitivity analysis results. It can be seen that pavement maintenance cost had the most sensitive response change of pavement performance. Furthermore, pavement structure and traffic level had similar influence on maintenance cost. When the pavement age changed, the pavement maintenance cost had little change, but the residual service life varied a lot. From the aspect of maintenance cost, the analysis results were in accordance with the weightings of different decision-making influence factors discussed above.

Table 9 Influences of Factor Variations on Maintenance Cost and Residual Service Life

Influence factor	Index value Change Rate	EUAC Change Rate	Absolute value of Change Rate Ratio	Residual Service Life Change Rate	Absolute value of Change Rate Ratio
Pavement Quality Index	+10%	-10%	1.00	+15%	1.50
	-10%	+10%	1.00	-15%	1.50
Pavement Structure Strength	+10%	-2%	0.20	+11%	1.10
	-10%	+3%	0.30	-12%	1.20
Cumulative ESALs	+10%	+2.5%	0.25	-7%	0.70
	-10%	-3%	0.30	+6%	0.60
Pavement Age	+10%	+1%	0.10	-20%	2.00
	-10%	-1%	0.10	+20%	2.00

APPLICATION OF THE METHOOD

The objective of network-level decision support for pavement maintenance is to help managers allocate funding for a network of highway and to decide on the best timing for the maintenance activities. The decisions at the project-level decision support are a key input for the network-level decision making process. To apply this AHP based priority ranking methods, the highway maintenance managers submit a plan on annual maintenance budget of next year based on project-level decision every year. Usually, the cost needed for all the maintenance activities is higher than the available. Then, the budget should be allocated to the road sections based on the overall priority.

CONCLUSIONS

Network level infrastructure maintenance decision-making is a multi-factor and multi-criteria problem. It used to be determined based on limited factors and subjective judgment. Analytic Hierarchy Process (AHP) method was selected for determining the weighting of each decision-making factor in this study. It is capable of incorporating all the potential maintenance related factors, considering their relative importance and generating an overall priority ranking index for each road section.

A case study on network level pavement maintenance decision-making for the highways was conducted to demonstrate the application of the AHP method. A total of five pavement maintenance decision-making factors were considered, including pavement performance, pavement structure strength, traffic loads, pavement age and road grade.The weighting values of the five factors were determined through AHP method.

After the quantification of weighting values of the five factors, the comprehensive ranking value U_i was determined, which indicated the maintenance priority of a road section in network level decision-making process. From the aspect of maintenance cost, the sensitivity analysis results were in accordance with the weighting value of different maintenance decision-making indices. It can be found that the pavement maintenance cost is very sensitive to the change of pavement performance.

There are also several problems that can be improved for the application of AHP method. The five indices considered in this study are generally the pavement structural, functional and conditional factors. Several other potentially important factors, including pavement structure type, climatic condition, details of the surface materials, could also be included when the data is available.

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