Optimal pre-maintenance timing decision for asphalt pavement based on TOPSIS and combination weighting method

Huishan Li [1], Biling Niu [1, 2]

[1]School of Civil Engineering, Lanzhou University of Technology, Lanzhou, Gansu, China, 730050

[2]2245672928@qq.com

Abstract. With the continuous growth of highway quantity in China, the post-maintenance of highways has become a focus of highway management, attracting widespread attention in the industry. Selecting an appropriate maintenance timing is of significant importance for highway maintenance. Based on the TOPSIS theory and the deterioration law of asphalt pavement performance indicators, this study takes cost, effectiveness, energy consumption, and carbon emissions as research indicators. Combined with the entropy weighting method and the analytic hierarchy process, the study establishes a decision model for determining the optimal preventive maintenance timing for asphalt pavement. This model determines the best timing for preventive maintenance of asphalt pavement through the values of relative closeness. Finally, by analyzing a practical maintenance case of a highway in Jiangsu Province, it is found that when the Pavement Condition Index (PCI) equals 90, it is the optimal timing for preventive maintenance of asphalt pavement, which verifies the rationality of the decision model and provides a scientific reference for selecting maintenance timing.

Keywords: Road Engineering, Maintenance Timing, TOPSIS Comprehensive Evaluation Model, Analytic Hierarchy Process-Entropy Weighting Method, Cost-Benefit Analysis.

1. Introduction

Highway construction in China has entered a golden age of development in recent years thanks to the country's brisk economic expansion, which has led to the creation of a highway network that spans the entire country. The post-maintenance of highways has evolved into a project that places a significant demand on finances and has growing negative effects on the environment. As a direct result of this, the nation has mandated low-carbon emission standards for the building industry and has rolled out a number of environmental regulations that are congruent with these standards [1]. At the moment, the most important method for maintaining asphalt pavement is called preventive maintenance. When it comes to asphalt pavement care, choosing the right timing for preventative maintenance is a vital problem. This is especially true when the state of the pavement is taken into consideration. There is a lack of objectivity and a scientific basis for the selection of maintenance timing in China, which leads to problems such as high maintenance costs, insignificant maintenance benefits, prominent environmental impacts, and severe resource waste [2].

Extensive research has been carried out by academics from a variety of countries, both in the United States and worldwide, with the purpose of determining the most effective preventive maintenance schedule and maintenance techniques. Previous research mostly concentrated on determining pavement performance indicators, the benefits of maintenance, and the costs of maintenance. Yao Yuling and colleagues [3] constructed a decision model that was based on the cost-effectiveness ratio. The model used the ratio to identify the ideal schedule for preventative maintenance and used the ratio to predict the cost of performing the repair. A decision approach for calculating the appropriate preventive maintenance scheduling of asphalt pavement based on aging indicators of the asphalt pavement was proposed by Dong Ruikun et al. [4]. This method was developed by Dong Ruikun et al. This approach carried out significant experimental study and analysis on the aging indicators of asphalt materials from the point of view of internal molecular structure. As a result, it was able to determine the approximate range of the ideal preventative maintenance scheduling for asphalt pavement. However, this technique is only capable of determining a general time range for asphalt pavement repair; it is unable to specify an exact period at which maintenance should be performed. On the basis of a cost-benefit analysis, Wang Xiaofeng et al. [5] analyzed the comprehensive benefits and costs, and formed four decision indicators with different focuses. These decision indicators were as follows: comprehensive benefit value, equal annual cost value, benefit index, and variation in pavement service life. These decision indicators were used to determine the optimal preventive maintenance timing. In order to identify the appropriate timing for maintenance and measures, R.G. Hicks et al. [6] presented decision trees and decision matrices. This method formulated criteria determined by pavement performance indicators, which resulted in the formation of a complicated decision matrix for the timing and procedures of maintenance.

In summary, the currently available strategies for determining when to perform maintenance only take into account a single vantage point; they do not take into account the environment, the resources, or any other factors comprehensively. In the case of the cost-effectiveness decision model, for instance, the cost-effectiveness ratio is the one and only research indication that is used. The decision-making process for the timing of pavement maintenance, on the other hand, is a challenge that involves multiple attributes and dimensions. The outcomes of the decision should strive to maximize total advantages along several dimensions.

This article is based on the TOPSIS theory, establishes a multi-indicator system including cost, effectiveness, energy consumption, and carbon emissions, and combines the entropy weighting method and the analytic hierarchy process to analyze and determine the weights of each indicator from both subjective and objective perspectives. The results of this analysis and determination are presented in this article. Because of this, the indicator weights have increased credibility, and a TOPSIS complete decision model has been established. The relative closeness values in the model are used to calculate, as a last step, the best period for the pre-maintenance of asphalt pavement. This model gets around the problem that traditional methods of decision-making have with just having a single indication by utilizing the benefits that the TOPSIS technique offers in the context of multi-objective and multi-attribute decision-making [7]. In addition to optimizing the cost-effectiveness of the decision, it reduces the negative effects on the environment, maximizes the rational use of resources, and ultimately produces the best possible outcome for the decision. This model offers a scientific reference for making decisions regarding the scheduling of asphalt pavement maintenance. The goal of the model is to maximize the amount that the service life of asphalt pavement can be extended while simultaneously limiting the expenses of maintenance, the negative effects on the environment, and the amount of resources that are used.

2. Constructing Decision Model

Establishing an evaluation index system, determining the weights of the indexes using the AHP-entropy method, employing the TOPSIS comprehensive decision model, and conducting a comprehensive evaluation are the fundamental steps involved in the construction of the decision model for determining the optimal preventive maintenance timing for asphalt pavement. These steps are as follows: establishing an evaluation index system, determining the weights of the indexes, and conducting an evaluation that is comprehensive.

2.1. Establishing the Evaluation Index System

It is important that the evaluation technique that is chosen to determine the best time for preventative maintenance on asphalt pavement be one that is both thorough and reflective of the entire system. At the moment, the majority of approaches for selecting the best time to do maintenance concentrate on the indications of benefits and costs. However, in recent years, because construction activities are having an increasingly negative influence on the environment, carbon emissions and energy consumption have now been included in the scope of the research [8]. As a result, a comprehensive index system centered around benefits, costs, carbon emissions, and energy consumption has been developed, denoted as C = {C1, C2, ..., Cm}.

2.2. Determining the Weights of Indexes Using AHP-Entropy Method

The decision outcomes on the scheduling of asphalt pavement preventative maintenance might be impacted by the use of various weighting methods for indexes. As a result, in order to increase the credibility of the results of the decision-making process, it is required to give acceptable weights to each index. In this study, the AHP-entropy method was chosen to calculate the relative importance of each indicator, taking into account both the subjective and the objective points of view. This technique may somewhat overcome the subjectivity of the Analytic Hierarchy Process (AHP), and it combines the advantages of the entropy weight method, which results in trustworthy weights for each index. Additionally, this method can partially overcome the subjectivity of the entropy weight method. The steps involved in the algorithm are as follows:

2.2.1. AHP Determines the Weights of Indexes

(1) Construct a hierarchical structure model.

(2) Consult relevant experts and use the importance scale table 6 to compare and score the evaluation indexes pairwise, establishing the judgment matrix B. Calculate the normalized relative importance vector T of the judgment matrix B according to Equation (2).

$$T^{'} = \left(\prod_{j=1}^{n} [\![(a_{ij})^{\frac{1}{n}}]\!] \right) \tag{1}$$

$$T = \frac{T^{'}}{\sum_i T^{'}} \tag{2}$$

($i = j$ = 1,2, ..., n, a_{ij} represents the relative importance scale value of the i-th index compared to the j-th index)

(3) Calculate the maximum eigenvalue $\lambda_{\max}$ and eigenvector of the judgment matrix, then normalize the eigenvector to obtain the weight vector. Perform a consistency check, where a consistency ratio $C.R < 0.1$ indicates effective weights, otherwise, the judgment matrix needs to be reconstructed. The formulas are as follows:

$$\lambda max = \frac{1}{n} \sum_{i=1}^{n} \frac{(BT)_i}{T_i} \tag{3}$$

$$C.I = \frac{\lambda_{max} - n}{n - 1} \tag{4}$$

$$C.R = \frac{C.I}{R.I} \tag{5}$$

2.2.2. Entropy Weight Method for Weight Modification. Normalize the judgment matrix obtained from the AHP by using the entropy weight method to modify the weights obtained from the AHP. This involves calculating the information entropy H_j, entropy weight E_j, and modified weight W_j for each evaluation index. The formulas are as follows:

$$H_j = -\frac{1}{lnn}\sum_{i=1}^{n} p_{ij} \ln p_{ij} \tag{6}$$

$$E_j = \frac{1 - H_j}{\sum_{j=1}^{n}(1 - H_j)} \tag{7}$$

$$W_j = \frac{T_j E_j}{\sum_{i=1}^{n} T_j E_j} \tag{8}$$

(a_{ij} values in the judgment matrix are changed to p_{ij} after normalization)

2.3. TOPSIS Comprehensive Evaluation Model

The technique known as TOPSIS, which stands for "Technique for Order Preference by Similarity to Ideal Solution," is a decision-making process that can be applied to issues involving multiple attributes and multiple objectives. It evaluates a select set of potential alternatives and ranks them according to how close they are to the idealized aim. It is a strategy for making decisions that chooses the most advantageous option from among a number of potential outcomes.

2.3.1. Determining Comparative Alternatives and Index Quantification. Based on the actual situation, n comparative alternatives are determined as D_1, D_2, ..., D_n. To highlight the differences among the alternatives, the research indexes need to be quantified. Efficiency refers to the quantified response of pavement performance improvement throughout its entire lifecycle after implementing preventive maintenance measures. The Road Quality Index (RQI), Pavement Condition Index (PCI), and Skid Resistance Index (SRI) are selected for evaluating the efficiency [9]. For the analysis and calculation of the maintenance costs of actual cases, to reflect the dynamic economic effects of funds over the entire lifecycle, the cost present value is chosen as the fund evaluation index. The cost quantification method calculates the cost present value used for maintenance per kilometer over the entire lifecycle, with the unit being 10,000 RMB/km. Carbon emissions and energy consumption are quantified based on the lifecycle evaluation theory [10]. The production, processing, transportation, and construction of raw materials are the three main sources of carbon emissions in the maintenance process. The quantification of carbon emissions and energy consumption is based on the construction quotas corresponding to the actual preventive maintenance technical measures adopted in engineering maintenance cases, with the units of energy consumption being MJ per functional unit and carbon dioxide emissions being kg per functional unit. The values of each index are quantified, and a decision matrix A is established.

2.3.2. Establishing Decision Matrix and Weighted Normalization Matrix. After determining the comparative alternatives and index system, and quantifying the indexes, a corresponding decision matrix A is established as shown in Table 1. The decision matrix A is standardized using formulas (9) and (10), which are the normalization formulas for efficiency-type and cost-type indexes, respectively. Then, formula (11) is used to obtain the weighted normalization matrix A_1, as shown in Table 2.

Table 1. Decision Matrix A.

Scheme \ Criterion	C_1	C_2	...	C_m
W_j	W_1	W_2	...	W_m
D_1	a_{11}	a_{12}	...	a_{1m}
D_2	a_{21}	a_{22}	...	a_{2m}
...	...	...	...	...
D_n	a_{n1}	a_{n2}	...	a_{nm}

Table 2. Weighted Normalization Matrix A_1.

Scheme \ Criterion	C_1	C_2	...	C_m
D_1	h_{11}	h_{12}	...	h_{1m}
D_2	h_{21}	h_{22}	...	h_{2m}
...	...	...	...	...
D_n	h_{n1}	h_{n2}	...	h_{nm}

$$x_{ij} = \frac{a_{ij}}{a_j^{max}} \tag{9}$$

$$x_{ij} = 1 - \frac{a_{ij}}{a_j^{max}} \tag{10}$$

$$h_{ij} = W_j x_{ij} \tag{11}$$

2.3.3. Determining Ideal Solution, Euclidean Distance, and Relative Closeness. From the weighted normalization matrix A1, the ideal solution and negative ideal solution for each alternative (i) can be obtained using formulas (12) and (13), respectively. Then, using the positive and negative ideal solutions, the Euclidean distance from alternative (i) to the ideal solution and negative ideal solution can be calculated using formulas (14) and (15), respectively. Finally, the relative closeness value (C_i) for alternative (i) can be calculated using formulas (16).

$$x_i^* = max\{x_{ij}\} \tag{12}$$

$$x_i^0 = min\{x_{ij}\} \tag{13}$$

$$d_i^* = \left[\sum_{j=1}^{n}\left(x_{ij} - x_i^*\right)^2\right]^{\frac{1}{2}} \tag{14}$$

$$d_i^0 = \left[\sum_{j=1}^{n}\left(x_{ij} - x_i^0\right)^2\right]^{\frac{1}{2}} \tag{15}$$

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$$C_i = \frac{d_i^0}{d_i^0 + d_i^*} \tag{16}$$

2.4. Comprehensive Evaluation

The value of C_i represents the degree of relative closeness of the i-th maintenance timing alternative. A larger C_i indicates that the alternative is closer to the ideal maintenance timing and farther from the negative ideal state. The optimal alternative corresponds to the maximum C_i value, indicating the most comprehensive optimization in terms of maintenance cost, efficiency, energy consumption, and carbon emissions, while maximizing the service life of the pavement.

3. Case Study

3.1. Project Overview

The pavement performance data used for case study and model validation are obtained from a highway in Zhejiang Province, China. The basic information of the highway is as follows:

The highway was opened to traffic at the end of 2015, with a total length of 47.920 km and a design speed of 100 km/h. The study focuses on the right carriageway of a 10 km section (from K11+474 to K21+474) of the highway. No major maintenance activities have been carried out on the highway since its construction. The actual measured values of pavement performance indicators for the years 2015 to 2018 are shown in Table 3. Based on the Grey-Markov theory model, the future pavement performance data for several years are predicted, as shown in Table 4.

Table 3. Actual Measured Values of Pavement Performance Indicators.

Year	2015	2016	2017	2018
PCI	99. 300	97. 541	95. 834	92. 871
RQI	96. 601	96. 421	93. 521	93. 643
SRI	97. 203	98. 762	94. 603	95. 901

Table 4. Predicted Values of Pavement Performance Indicators.

Year	2019	2020	2021	2022	2023	2024
PCI	89 .632	86 .840	83 .341	79 .542	75.000	71.000
RQI	90 .392	89 .273	87 .165	85 .554	82.902	79.131
SRI	91 .332	88 .414	86 .143	84 .730	81.000	76.209

As shown in Table 3, the *PCI* deterioration rate is faster and has a larger numerical range compared to *RQI* and *SRI*. When *PCI* is in the range of 80-90, both *RQI* and *SRI* are above 80, and their decay values also fall within the desired range for preventive maintenance. Therefore, *PCI* is chosen as the research indicator for calculating maintenance benefits [11, 12]. Threshold values of *PCI*, namely 90, 87, 83, and 80, are selected as the starting points (D_1, D_2, D_3, D_4) for preventive maintenance. Considering the actual conditions, microsurfacing is chosen as the preventive maintenance technique for this highway [13]. Thus, this case study focuses on the decision analysis of the optimal timing for preventive maintenance using microsurfacing. The *PCI* values after implementing microsurfacing are shown in Table 5. Since the design service life of the highway is generally 15 years, the analysis period for the entire maintenance project is set as 15 years.

Table 5. PCI Values after Implementing Microsurfacing.

Year	Year 1	Year 2	Year 3	Year 4	Year 5
PCI	99.071	97.430	94.300	90.264	87.313

3.2. AHP-Entropy Method for Weight Determination

First, the Analytic Hierarchy Process (AHP) is used to determine the weights of each criterion. Twenty experienced experts were invited to score the pairwise comparisons of evaluation criteria according to the scale of importance (shown in Table 6). The highest and lowest scores were removed, and the remaining data were averaged to obtain the judgment matrix (Table 7). The eigenvector of the judgment matrix, which represents the weights of each criterion, was calculated using Equations (1) and (2) and is shown in Table 8. The maximum eigenvalue $\lambda_{\max}$ was calculated as 4.261 using Equation (3), and the consistency ratio $C.R$ was calculated as 0.098<0.1 using Equations (4) and (5), indicating that the weights are valid after passing the consistency test.

Table 6. Scale of Importance.

Importance Scale Value	Definition
1	Equally important
3	Slightly more important
5	Comparatively more important
7	Very important
9	Absolutely important
2, 4, 6, 8	Intermediate values between the above judgments
Reciprocal	If the two are compared in reverse, the corresponding value is the reciprocal

Table 7. Judgment Matrix.

	Benefit	Cost	Energy Consumption	Carbon Emission
Benefit	1	3	6	6
Cost	1/3	1	5	5
Energy Consumption	1/6	1/5	1	1/3
Carbon Emission	1/6	1/5	3	1

Table 8. Criterion Weights.

	Benefit	Cost	Energy Consumption	Carbon Emission	Multiplication	Fourth Root	Weight
Benefit	1	3	6	6	108	4 .224	0.555
Cost	1/3	1	5	5	25/3	1.699	0.292
Energy Consumption	1/6	1/5	1	1/3	1/90	0.325	0.056
Carbon Emission	1/6	1/5	3	1	1/10	0.562	0.097

The judgment matrix B was normalized to obtain matrix B_1 as shown in Equation (17). Using Equations (6) and (7), the information entropy of each criterion was calculated as H_1=0.785, H_2=0.632, H_3=0.891, H_4=0.734. The entropy weights of each criterion were calculated as E_1=0.224, E_2=0.384, E_3=0.114, E_4=0.278 using Equation (8). The modified weights were calculated as W_1=0.460, W_2=0.416, W_3=0.024, W_4=0.100.

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$$B_1 = \begin{bmatrix} 0.600 & 0.683 & 0.400 & 0.486 \\ 0.200 & 0.227 & 0.333 & 0.405 \\ 0.100 & 0.045 & 0.067 & 0.027 \\ 0.100 & 0.045 & 0.200 & 0.081 \end{bmatrix} \tag{17}$$

3.3. Model Verification

3.3.1. Establishing the Decision Matrix and Weighted Normalization Matrix. The criteria of cost, benefit, energy consumption, and carbon emission were determined as the research indicators and quantified to establish the decision matrix A (Table 9). The matrix was standardized using Equations (9) and (10) and weighted to obtain matrix A_1 using Equation (11) (Table 10).

Table 9. Decision Matrix A.

Criterion / Scheme	Benefit	Cost	Energy Consumption	Carbon Emission
W_j	0.460	0.416	0.024	0. 100
D_1	141.126	4070.070	189541.690	1697.193
D_2	122.474	4062.87 1	964073.443	32248.091
D_3	108.797	4068.874	642715.632	21498.730
D_4	79.138	4087.210	480677.854	31741.882

Table 10. Weighted Normalization Matrix A_1.

Criterion / Scheme	Benefit	Cost	Energy Consumption	Carbon Emission
D_1	0.460	0.002	0.019	0.095
D_2	0.399	0.003	0.000	0.000
D_3	0.355	0.002	0.008	0.033
D_4	0.258	0.000	0.012	0.002

3.3.2. Determining the Positive and Negative Ideal Solutions. From the weighted normalization matrix, the negative ideal solution and ideal solution of each alternative were determined, resulting in the following results:

$$x_i^0 = min\{0.258,0.000,0.000,0.000\} \tag{18}$$

$$x_i^* = max\{0.460,0.002,0.019,0.095\} \tag{19}$$

3.3.3. Determining the Euclidean Distance and Relative Closeness of Each Alternative. Using Equations (5), (6), and (7), the distance and relative closeness of each alternative to the ideal and negative ideal solutions were calculated, as shown in Table 11.

Table 11. Distance and Relative Closeness of Each Alternative to Ideal and Negative Ideal Solutions.

Scheme	d_i^*	d_i^0	C_i
D_1	0 .001	0 .224	0 .996
D_2	0 .114	0 .141	0 .553
D_3	0 .122	0 .103	0 .456
D_4	0 .223	0 .012	0 .052

3.4. Comprehensive Analysis and Evaluation

From the calculation results, it can be observed that C_1 has the highest value. Therefore, D_1 is identified as the optimal timing for preventive maintenance, indicating that the best starting time for preventive maintenance on asphalt pavement is when the *PCI* value is equal to 90.

By using this decision model for comprehensive evaluation, the complexity of multi-objective decision-making can be addressed. According to the results calculated in Table 11, Scheme 1 has the highest relative closeness with a value of 0.996, indicating that it is closest to the ideal solution and farthest from the negative ideal solution. In terms of the distance to the negative ideal solution, the distance to the ideal solution for Scheme 1 can be considered negligible. Therefore, Scheme 1 approaches the ideal solution's criteria closely, resulting in the maximum overall benefits. As we move to the subsequent alternative schemes, the relative closeness decreases, indicating that the later the pavement maintenance starting time, the farther the alternative scheme deviates from the ideal solution and approaches the negative ideal solution, resulting in a smaller overall benefit. From Scheme 1 with *PCI*=90 to Scheme 2 with *PCI*=87, the difference in maintenance starting time is only one year, but there is a significant change in relative closeness. On the other hand, from Scheme 2 to Scheme 3 with *PCI*=83, although the time interval is also one year, the change in relative closeness is minimal. This indicates that when the pavement condition index (*PCI*) is within the range of [85, 90], it is a critical period for preventive maintenance of asphalt pavement. In summary, it is recommended to perform preventive maintenance on the pavement when the *PCI* is equal to 90, under the condition of a good pavement condition. This approach can yield the maximum comprehensive benefits in terms of economics, society, and environmental aspects.

4. Conclusion

Traditional selection of preventive maintenance timing for asphalt pavement is often based on a single criterion, such as cost-effectiveness analysis. However, the decision regarding the timing of preventive maintenance for asphalt pavement should consider comprehensive and multiple attributes. The TOPSIS decision model allows for decision-making from multiple perspectives and utilizes the AHP-Entropy method to assign weights to indicators from both subjective and objective aspects, thereby ensuring the decision results are more comprehensive and accurate. Finally, the decision model is validated through an actual maintenance case study. The results show that the optimal starting time for preventive maintenance is when the *PCI* value is equal to 90, which is consistent with the concept of preventive maintenance. Implementing preventive maintenance on the pavement when it is in good condition can optimize various indicators, maximizing benefits, minimizing costs, energy consumption, and carbon emissions. This also confirms the accuracy of the decision model. The case study demonstrates that the model is applicable for determining the optimal timing of preventive maintenance for asphalt pavement.

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