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A multi-criteria decision framework for selecting preventive maintenance measures on asphalt pavement: a case study of the Liuzhou North Ring Expressway

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Highlights:

- Preventive maintenance decision model for asphalt pavements is proposed.
- AHP-based multi-level optimization model supports maintenance decisions.
- Model parameters better match actual pavement maintenance needs.
- Sensitivity analysis confirms applicability of the proposed AHP framework.

Abstract: In recent years, the rapid development and proliferation of highways in China have made asphalt pavement maintenance increasingly complex, requiring maintenance management departments to make practical choices of preventive maintenance measures within limited budgets. To improve comprehensiveness, scientific rigor, and the economy of decision-making, the Analytic Hierarchy Process (AHP) was employed to conduct a decision-optimization study of preventive maintenance measures for asphalt pavements. Taking the preventive maintenance project of the Liuzhou North Ring Expressway in Guangxi as a case study, maintenance measures were initially selected through road condition assessment and investigation. A multi-level, multi-objective decision-making AHP model was constructed, including an objective layer, a criterion layer, an indicator layer, and a scheme layer. By comprehensively considering maintenance needs and assigning values to multi-level factors, the weights and priorities of each maintenance measure were determined. The results show that the ranking and weight calculation of measures such as ultra-thin cover, composite seal coat, micro-surfacing, thin layer cover, and seal coat are relatively rational, and the theoretical analysis results are in good agreement with actual needs.

Keywords: asphalt pavement; highway maintenance management; preventive maintenance; analytic hierarchy process; decision-making model; multi-objective optimization

1. Introduction

With the rapid expansion and continuous ageing of China's expressway network, asphalt pavement maintenance has become an urgent and complex systemic challenge. By the end of 2024, the total length of highways requiring maintenance nationwide reached 5.4904 million kilometers, accounting for 97.3% of the total highway mileage, with an average annual maintenance cost of approximately US$6 billion [1]. Given the limited budget and concentrated maintenance needs, how to scientifically select preventative maintenance measures to extend pavement service life and optimize life-cycle benefits is a core challenge for management departments [2,3]. This decision-making process is inherently multi-objective, multi-attribute, and semi-structured, but its complexity stems not only from the need to simultaneously weigh multiple criteria, such as technical performance, but also from frequent conflicts between objectives [4]. The best technical solution may not be the most economical, and accurately quantifying some indicators for long-term performance prediction is difficult. Internationally, the implementation of preventive maintenance has been proven to significantly prolong pavement life and improve economic returns, as illustrated in Figure 1, which depicts the relationship between pavement condition index and service life [5].

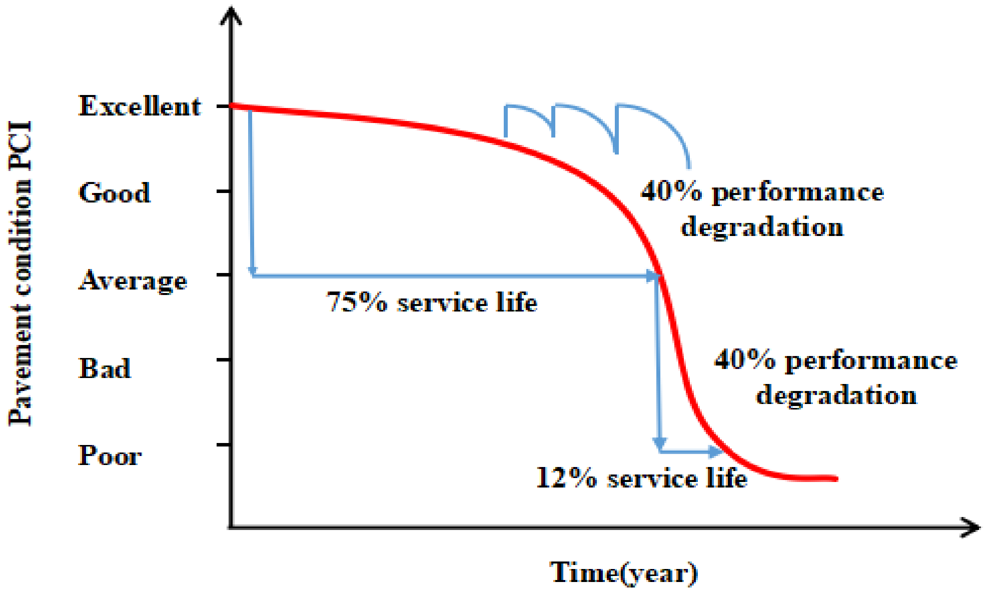

Figure 1. Correlation between pavement condition index and service life [5].

Furthermore, existing decision-making models often struggle to balance practicality and scientific rigour. Highly complex mathematical models require large amounts of data and are computationally intensive, while experience-driven methods lack systematicity and objectivity, making them difficult to apply widely in practical engineering [6,7]. To address these challenges, scholars both domestically and internationally have developed various decision-making methods. Early research mainly relied on empirical models and deterministic indicators, such as the Current Service Capacity Index (PSI) model proposed by the American Association of State Highway and Transportation Officials (AASHTO) in the

United States [8], as well as decision trees [9] and decision matrices used by various states [10]. These methods are intuitive but highly subjective. Subsequently, mathematical programming and stochastic models were introduced, such as 0-1 integer programming [11], Monte Carlo simulation [12], and Markov decision processes [13]. Although these methods improved the degree of structuring, their applicability in the field was often limited by computational complexity and high data requirements. In terms of life cycle cost-benefit analysis, scholars have proposed a full-cycle optimization model with the benefit-cost ratio as its core [14]. However, its integration of multiple attribute indicators is still insufficient, and the determination of weight largely depends on subjective judgment. In recent years, multi-criteria decision-making methods (MCDM) have gradually become a research hotspot. Among them, the AHP has been applied to maintenance priority ranking due to its ability to systematically handle qualitative and quantitative indicators [15–17]. However, most of these studies focus on local factors and fail to establish a complete mapping system from decision criteria to specific measures and lack a hierarchical indicator framework tailored to regional characteristics. Meanwhile, intelligent algorithms, represented by genetic algorithms and neural networks [17], can improve predictive capabilities with the help of big data, but their "black box" nature and high data requirements limit their application in early decision-making or data-scarce scenarios.

Existing research still shows limitations in model practicality, objectivity of multi attribute weighting, and the balance between advanced computational methods and engineering feasibility [18,19]. For regional pavement maintenance in China, there remains a need for a systematic, transparent, and practical decision support framework that integrates technical, economic, and environmental objectives [20–22]. Although AHP has been widely used in pavement maintenance decision-making, several limitations remain. Many existing models do not clearly separate screening indicators, such as pavement structural condition, from ranking indicators, such as cost, service life, environmental impact, and construction feasibility [23,24]. In addition, the normalization direction of benefit and cost indicators is often insufficiently explained, which may affect the final ranking of maintenance alternatives [25]. Furthermore, few studies provide a clear connection between measured pavement condition, preliminary treatment selection, expert judgment, consistency testing, and final treatment ranking [26–28]. To address these gaps, this study develops an improved AHP based decision framework for selecting preventive maintenance measures for asphalt pavements. The proposed framework first screens pavement sections using technical condition indicators and then ranks feasible preventive maintenance treatments through weighted technical, economic, and environmental criteria. The Liuzhou North Ring Expressway in Guangxi is used as a case study to demonstrate the applicability of the proposed model and to provide highway maintenance agencies with a transparent and practical decision-making tool.

2. Methodology

This study focuses on developing a decision-making formulation for preventive maintenance measures for asphalt pavements. The primary selection of measures is made by assessing and investigating the road conditions using testing vehicles to get pavement performance data. Following this, a multilevel mathematical model based on the AHP is introduced for decision-making. The optimal priority order of measures is obtained by calculating the weights through the model structure. The research methodology of this study is shown in Figure 2.

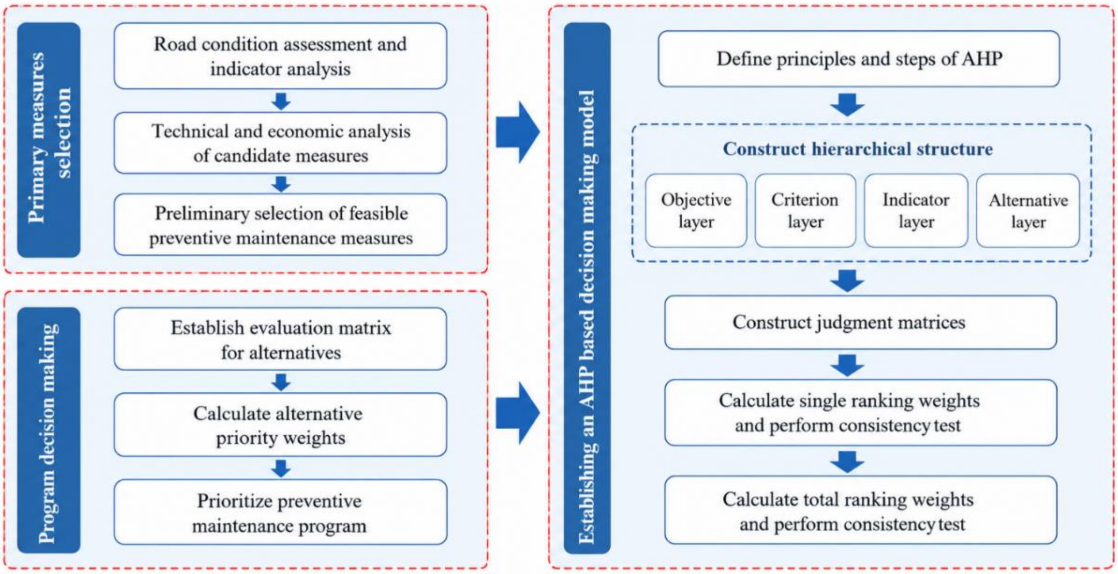

Figure 2. Research workflow for selecting preventive maintenance measures using pavement condition assessment and AHP based multi criteria decision making.

2.1. Primary preventive maintenance measures selection

The decision regarding preventive maintenance for asphalt pavement is based on an assessment of the technical condition of the road. According to the road condition assessment survey, the pavement must meet preventive maintenance standards. To obtain a preliminary selection of preventive maintenance methods, studying the road surface conditions and analyzing relevant factors related to pavement distresses is crucial.

2.1.1. Road condition assessment and indicator analysis

The investigated section is located between K912 and K958 on the G78 Liuzhou North Ring Expressway. The chainage length of the section is approximately 46 km. Considering both carriageway directions, the evaluated pavement length is reported as 92 km. This distinction is important because the pavement condition statistics and maintenance quantity estimation are based on the total evaluated carriageway length. The assessment is mainly based on the evaluation methods and requirements specified in the Technical Specification for Maintenance of Asphalt Pavements (JTG 5142-2019), using the Multi-functional Road Condition Rapid Detection System (CiCS as shown in Figure 3a), and the pavement lateral force coefficient testing vehicle (road surface lateral force testing vehicle as shown in Figure 3b), The main road condition evaluation includes seven technical aspects: road damage, smoothness, rutting, jumping, wear, anti-skid performance, and structural strength. The pavement structural strength is the precondition for the implementation of preventive maintenance, mainly obtained by converting the test data from the automatic bending sediment meter installed on the testing vehicle. The evaluation unit for the basic road section is set at 1000m. The pavement quality index (PQI) indicators mainly include the pavement condition index (PCI), riding quality index (RQI), skidding resistance index (SRI), rutting depth index (RDI), and pavement structure strength index (PSSI). These indicators determine the need for preventive pavement maintenance and be used to develop maintenance engineering plans and strategies.

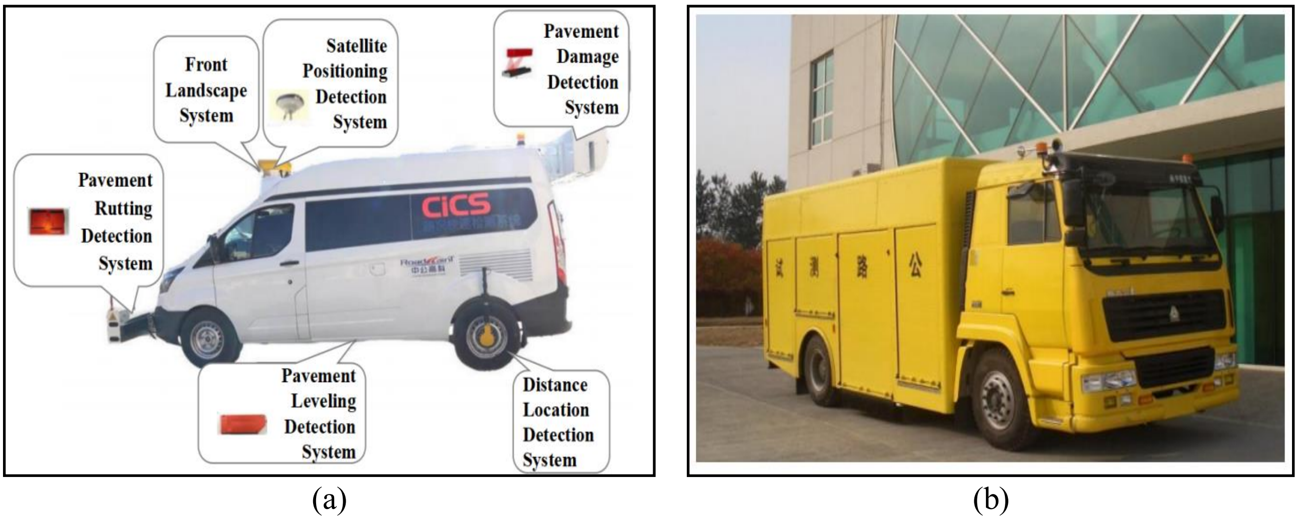

Figure 3. Pavement condition data collection equipment used in the case study: **(a)** multi-functional road condition detection system (CiCS); **(b)** Pavement transverse force coefficient test vehicle.

According to the Technical Specification for Maintenance of Asphalt Pavement on Highways, road sections are evaluated as “excellent” or “good” by the PQI, along with numerous sub-indicators of asphalt pavement, which are eligible for daily maintenance, preventative, and repair. Table 1. displays the “excellent and good” grading levels for roadway pavements. These levels are determined based on Highway Technical Condition Assessment (HTCA) grades and evaluations conducted by various academics.

Table 1. Classification of highway technical conditions [28,29].

Evaluation Index	Acronyms	Excellent	Good
Pavement Quality Index	PQI	≥ 90	$80 \leq x < 90$
Ride Quality Index	RQI	≥ 90	$80 \leq x < 90$
Rut Depth Index	RDI	≥ 90	$80 \leq x < 90$
Pavement Bearing Index	PBI	≥ 90	$80 \leq x < 90$
Pavement Width Index	PWI	≥ 90	$80 \leq x < 90$
Surface Roughness Index	SRI	≥ 90	$80 \leq x < 90$
Pavement Surface Strength Index	PSSI	≥ 90	$80 \leq x < 90$
Pavement Condition Index	PCI	≥ 92	$80 \leq x < 92$

Note: PQI, PCI, RQI, RDI, SRI, and PSSI were used in this study because they directly describe pavement surface condition, riding quality, rutting, skid resistance, and structural adequacy. PSSI was used as the structural precondition for preventive maintenance selection because preventive treatments are suitable only when the pavement has adequate load bearing capacity.

According to the Technical Specification for Maintenance of Asphalt Pavement, the technical condition index of asphalt pavement should meet the requirements as shown in Table 2.

Table 2. Technical requirements for highway asphalt pavement [20].

Technical Performance Index	PQI	PCI	RQI	RDI	SRI
Highway	≥ 80	≥ 80	≥ 80	≥ 75	≥ 75

Considering that preventive maintenance is applied to pavements with sound structural performance and contributes minimally to enhancing structural capacity, the PSSI serves as a suitable precondition for treatment selection. Current specifications, however, lack a unified threshold. For instance, the Shanghai Highway Bureau Technical Specifications for Asphalt Pavement Preventive Maintenance recommend PSSI ≥ 85 as a qualifying criterion. Conversely, the Technical Manual for Preventive Maintenance of Asphalt Pavement on High-Grade Highways in Guangdong Province excludes sections with PSSI < 80 from preventive maintenance consideration. To ensure conservative and effective intervention, this study adopts PSSI ≥ 85 as the structural precondition for preventive maintenance.

2.1.2. Preventive maintenance measures analysis and selection

The adequacy of preventive maintenance measures is evaluated based on their effectiveness in addressing pavement distress and their overall contribution to pavement performance, thereby determining how well they meet maintenance needs and management expectations. By analyzing the type and extent of pavement distress alongside the applicable conditions of available measures, appropriate preliminary preventive maintenance techniques for a given road section can be identified.

Currently, a variety of preventive maintenance measures are commonly used both in China and internationally [21,22]. According to China's Technical Specification for the Preventive Maintenance of Highway Asphalt Pavement (JTG 5142-01-2021), nine widely adopted techniques include fog seal, chip seal, thin slurry seal, micro-surfacing, composite seal coat, thin layer cover, ultra-thin layer cover, sealing layer cover, and hot in-place recycling. Furthermore, the Technical Specification for Maintenance of Asphalt Pavements (JTG 5142-2019) issued by the Ministry of Transport states that indicators such as road classification and pavement performance serve as preconditions for deciding whether to undertake preventive maintenance. Consequently, these precondition indicators are not included in the AHP decision-making framework for selecting specific measures.

Additional evaluation criteria considered include environmental impact-covering resource conservation, energy efficiency, noise, air, and water pollution-and traffic disruption factors, such as construction efficiency, duration, lane closure time, and traffic management arrangements. Aesthetic aspects, primarily related to pavement appearance and color, are also considered. The technical and economic applicability of each measure is summarized in Table 3.

When choosing pavement preventive maintenance measures, selecting technologies based on specific maintenance purposes and deterioration characteristics is crucial. There are also mature maintenance materials and technologies internationally [24]. Priority should be given to preventive maintenance technologies that have been successfully applied in local engineering practice and have demonstrated reliable performance under similar traffic, climatic, and construction conditions.

Table 3. Technical and economic analysis of preventive maintenance measures [5,26].

Maintenance Measures	Features & Performance	Service life (year)	Unit cost (US$/m²)	Applicability	Construction difficulty
Fog seal	Prevent cracking and loosening, and delay aging	2	4.15	Suitable for longitudinal and transverse cracks, block cracks, and loose asphalt pavement	Low
Chip seal	Heal network cracks, increase crack resistance, and improve anti-seepage ability	3–5	6.87	Low longitudinal and horizontal cracks and block cracks, loose, weathered, aging	Middle
Thin slurry seal	Preventive effect on aging, cracks, smoothness, and looseness	4	5.5	Mild longitudinal and horizontal cracks, block cracks, aging, and seepage pavement	Low
Micro-surfacing	Repair minor pavement distress such as ruts, mild loose oiling, and cracks, and can be quickly solidified and formed	5	9.87	Pavement with mild longitudinal and transverse cracks, as well as pavement with mild unevenness, light to moderate oiliness, and water seepage	Middle
Composite seal coat	Combine two or more curing techniques to enhance the curing effect	6–8	8.24	Suitable for multiple distresses to coexist	High
Thin-layer cover	Improve the smoothness, restore the anti-skid performance, correct the contour, and the cost is low	6	9.62	Suitable for low-grade roads or roads with low traffic volume	Middle
Ultra-thin cover	Repair minor cracks, improve loose aging conditions, improve slip resistance, and the cost is high	7	7.99	The surface is damaged, the anti-slip resistance is insufficient, and the water and oil are slightly seeped, suitable for roads with low traffic volume	Middle
Sealing layer cover	It can repair road ruts and minor distresses, improve flatness and anti-skid performance	5–7	8.37	Mild longitudinal and transverse cracks, oily deep-water rutted pavement	High
Hot in-place recycling	Used for repairing some distresses and restoring surface function	10	13.74	Can be used on high-grade highways; It can be used on highways of various traffic load classes	High

2.2. Establishing an AHP-based decision-making model

The decision-making process for asphalt pavement preventive maintenance involves multiple objectives and attributes. Evaluating these attributes requires various indicators connected to preventive maintenance decision-making [22,23]. The MCDM methods have been widely applied in infrastructure management and pavement maintenance planning. Common approaches include the AHP, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE), and VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR, meaning multi-criteria optimization and compromise solution). Each method has its own advantages and limitations depending on the decision context. The TOPSIS and VIKOR are distance-based methods that rank alternatives by measuring their identicality to an ideal solution. The PROMETHEE is a subjective and complex method. In contrast, the AHP is particularly suitable for problems characterized by hierarchical structures and limited quantitative data [27].

This paper develops an AHP-Based Decision-Making model based on preliminary measures. The decision-making indicators are first analyzed, and a hierarchical structure is established. Then, the indicators are assigned and calculated to determine their weight for the objective. The AHP is a multi-criteria decision-making method for quantitative analysis of qualitative problems proposed by an American operations researcher named Saaty [24,28]. In addition, it is an important method for analyzing and making decisions in system engineering. The method offers clear advantages in analyzing and evaluating systems with multi-objective and multi-criteria, enabling effective decision-making on the objectives [25–27].

2.2.1. Introduction of decision-making factors

This study thoroughly considers several variables while developing a framework for decision-making in preventative maintenance methods [29]. According to the specification and previous studies, it is essential to thoroughly consider technical, economic, and environmental factors when making decisions [30]. Weights in this study can be applied to regional highways of the same type, where the traffic conditions, climatic factors, management and maintenance patterns of the pavements are basically similar, and the maintenance decision-making factors are similar, and the results of the study are regionally generalized. When evaluating technical factors, it is crucial to examine the quality of construction, the quality of material, and the feasibility of construction. Meanwhile, it is essential to consider the economic factors while evaluating the cost of the project and its service life [31]. The primary elements contributing to traffic interruption are environmental considerations, such as environmental protection and aesthetics. These concerns are interconnected and may even conflict with one another. For example, the pursuit of technological advancement will result in a rise in expenses. Therefore, the first task involves identifying and assigning suitable weights to these determining factors or criteria according to their attributes when selecting solutions. The measures should be grouped and organized hierarchically. There are two main types of criteria: qualitative and quantitative. Qualitative criteria are intangible and may be subjectively measured, while quantitative criteria are concrete and can be objectively measured. Despite their lack of quantifiability, subjective factors must be considered and cannot be excluded from decision making. Subjective criteria can be more important than objective criteria in some decision-making situations. If these criteria are not properly weighed and considered collectively, decision-making may be biased, as is often seen in maintenance decision-making.

2.2.2. Principles and steps of modeling

The AHP involves breaking down the decision-making problem into different hierarchical structures according to the order of the total objective, sub-objectives of each level, evaluation criteria, and plans. Then, the method of solving the eigenvectors of the judgment matrix is employed to obtain the priority weight of each element at each level relative to an element from the previous level. Finally, the weighted sums of the final weight of each alternative to the total objective will be combined sequentially, and the alternative with the largest final weight will be deemed the optimal measure. It is characterized by using less quantitative information to apply mathematical principles to decision-making. This is done by thoroughly investigating the complex decision-making problem, the influencing factors, and their intrinsic relationship. Its use aims to construct a judgment matrix and determine its maximum eigenvalue, and its corresponding eigenvector (W). This matrix is then normalized to get the relative importance weight of a certain level of indicators for a related indicator in the previous level. The steps of applying hierarchical analysis to analyze preventive maintenance decision-making are shown in Figure 4.

Figure 4. Decision-making hierarchical steps.

2.2.3. Establishment of model structure

Asphalt pavement preventative maintenance decision-making aims to select the best maintenance measure according to the specified specifications. Firstly, the decision objectives are organized in layers, with the highest layer consisting of the decision objectives, followed by the decision criteria and secondary criteria indicators, and finally, the alternative maintenance measures. Therefore, a hierarchical structure is established consisting of the objective layer, criterion layer, indicator layer, and scheme layer. The target layer is generally located at the highest level of the model, usually consisting of only one element. The criteria layer in decision-making establishes the standards by which the problem is evaluated. In cases of increased complexity, the criteria layer elements can be further separated into several indicators for consideration. Typically, the criteria layer is generally located in the middle of the model. The hierarchy criteria mainly consider the impact, including the technical element (B1), economic element (B2), and environmental element (B3). In the indicator layer, the details of the quality of the material (C1), the quality of the construction (C2), construction feasibility (C3), service life (C4), unit cost (C5), traffic disruption(C6), environmental impact (C7), and aesthetics impact (C8) are considered. The scheme layer at the bottom of the model provides alternatives for decision-making. The plans in the plan layer are from Table 3, which follows the selection of the preliminary measures. The AHP decision-making structure is established as shown in Figure 5.

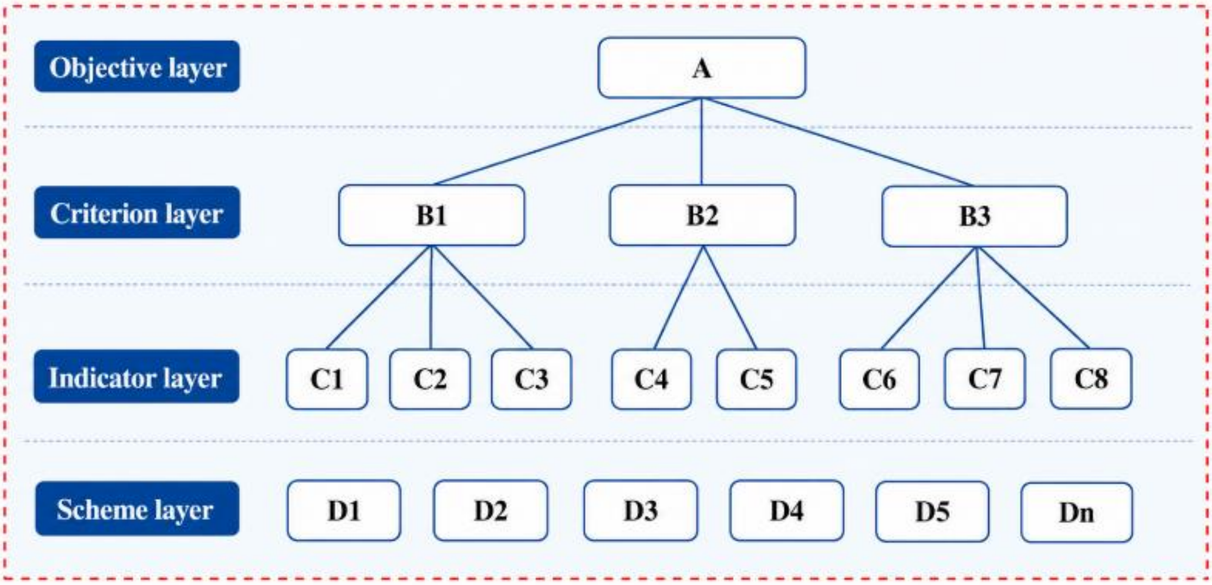

Figure 5. General AHP decision making model.

2.2.4. Establishment of judgment matrix

After the AHP-based model structure has been constructed, it is necessary to compare the relative importance of the lower elements to the upper elements as a benchmark. The matrix used for comparing the mutual importance of elements at the same level is called the judgment matrix, as shown in Equation (1).

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{bmatrix} \approx \begin{bmatrix} w_1/w_1 & w_1/w_2 & \cdots & w_1/w_n \\ w_2/w_1 & w_2/w_2 & \cdots & w_2/w_n \\ \cdots & \cdots & \cdots & \cdots \\ w_n/w_1 & w_n/w_2 & \cdots & w_n/w_n \end{bmatrix} \quad (1)$$

In the matrix, every element a_{ij} in the judgment matrix indicates the relative importance of the i-element compared to the j-element in the previous target layer. The measurement of relative importance is generally measured using the relative importance of scale, as presented in Table 4. The pairwise comparison scale follows the standard Saaty 1–9 scale, where numerical values directly indicate the relative importance between two criteria. The reciprocal property $a_{ij} = 1/ a_{ij}$ is strictly satisfied.

Table 4. Relative importance of scale of AHP [32].

Scale	Meaning	Explanation
1	Equal importance	Both factors contribute equally to the objective.
3	Moderate importance	Experience and judgment slightly favor X_i over X_j
5	Strong importance	Experience and judgment strongly favor X_i over X_j
7	Very strong importance	X_i is favored very strongly over X_j; its dominance is demonstrated in practice.
9	Extreme importance	The evidence favoring X_i over X_j is of the highest possible order of affirmation.
2, 4, 6, 8	Intermediate values between adjacent scales	Used when a compromise is needed between two judgments.
Reciprocals	If factor X_i receives scale a_{ij} when compared to X_j, then j compared to I receives $1/ a_{ij}$	Represents the opposite relative importance.

Note: When performing calculations, fractional values may be used for reciprocals.

2.2.5. Calculation of hierarchical single-ranking weights

The judgment matrix for each layer was created using the scores based on the invited experts, with senior professional titles, including at least one economic expert, two professors or researchers specializing in road maintenance, one representative of the maintenance project owner, and senior engineers specializing in road design and maintenance. Each expert individually filled up a pairwise comparison matrix. The final judgment matrix was generated using the geometric mean method.

The geometric mean of each row of the judgment matrix was calculated as:

$$M_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{1/n} \tag{2}$$

The normalized priority weight of each indicator was calculated as:

$$W_i = \frac{M_i}{\sum_{i=1}^{n} M_i} \qquad i = 1,2,3 \ldots .n \tag{3}$$

The maximum eigenvalue was calculated as:

$$\lambda_{max} = \frac{1}{n}\sum_{i=1}^{n}\frac{(AW)_i}{W_i} \tag{4}$$

The obtained new vector W = [W_1, W_2, ..., W_i] ^{T} is the priority vector of the desired target element. The maximum characteristic root λ_{max} specified as:

$$\lambda\sum_{i-1}^{n}\frac{(Aw)_i}{nw_i}\frac{1}{n}\sum_{i-1}^{n}[(\sum_{i-1}^{n}a_{ij}w_j)/w_i]_{max} \tag{5}$$

The consistency index was calculated as:

$$CI = \frac{\lambda_{max} - n}{n-1} \tag{6}$$

The consistency ratio was calculated as:

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

A judgment matrix was considered acceptable when $CR < 0.10$.

2.2.6. Consistency test

Prior to adapting the matrix, testing the consistency of the judgment matrix is essential due to the intricate nature of the objective factors, which frequently causing it challenging to achieve coherence between its sections. The consistency index (CI) and consistency ratio (CR) are usually used for testing. Table 5 presents the Random Consistency Index (RI) that is a predefined value based on the size of the matrix (n). If the CR value < 0.1, then, the a_{ij} value passes the consistency test.

Table 5. Random consistency index (RI) values for various matrix sizes (n) [25].

n	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
RI value	0	0	0.58	0.89	1.12	1.26	1.36	1.41	1.46	1.49	1.52	1.54

2.2.7. Calculation of total ranking weights for hierarchy

To consider the influence of the indicator layer on the target layer, a total ranking of the hierarchy is required. The synthetic weight w(n) of the elements on the n layer to the total criterion on the top layer can be calculated using Equation (8), where P(n) represents the synthetic weight of the nth layer on the elements on the (n-1) layer.

$$W^{(k)} = (w_1^{(k)} + w_2^{(k)}, \cdots, w_{nk}^{(k)})^T = P^{(k)} w^{(k-1)} \tag{8}$$

$$P^{(k)} = (P^{1(k)} + P^{2(k)}, \cdots, P^{n_k-1(k)})_{n_k \times n_k - 1} \tag{9}$$

The ranking weight of the indicator layer for the highest target layer is calculated through a comprehensive ranking of the hierarchy, resulting in a matrix of indicator weights known as the weight matrix.

2.3. Decision-making for maintenance approach

The benefits of implementing preventive maintenance measures are multifaceted; therefore, it is necessary to set up multiple aspects to evaluate the framework. According to the evaluation criteria of the decision-making model, this study primarily evaluates indicators, including technology, economy, and environment. However, some indicators can be accurately measured during the actual review process. While some indicators are not accurately measured, which could only be qualitatively described. Therefore, it is necessary to standardize these qualitative indicators and quantitative indicators to obtain values [5]. Table 6 categorizes the evaluation of preventive maintenance decision-making indicators as excellent, good, moderate, passing, and failing based on the requirements of the specification. The quantitative indicators are service life and unit cost. Service life is a benefit-based index, while unit cost is a cost-based index. A more significant service life is considered better, while a smaller unit cost is considered better. For a detailed technical and economic analysis, as presented in Table 3.

Table 6. Reference scores for decision-making indicators [22].

Indicator	**Score**
Excellent	0.8–1
Good	0.6–0.8
Moderate	0.4–0.6
Passing	0.2–0.4
Failing	0–0.2

After completing the normalization of quantitative and qualitative indicators, the affiliation evaluation matrix was created for each preventive maintenance measure and evaluation indicator. The weight matrix of the indicators and the evaluation matrix were multiplied to obtain the comprehensive weight of the measures using Equation (10). Finally, the optimal preventive maintenance measures were determined based on the calculated values of the weights of each preventive maintenance measure.

$$U = W \times R \tag{10}$$

where U represents the priority of each preventive maintenance plan, W represents the priority of each evaluation index, and R represents the weight matrix of each preventive maintenance plan for each evaluation index.

3. Results and discussion

3.1. Preliminary measures selection

The Liuzhou North Ring Expressway in Guangxi province was completed and officially opened for public use in 2006. The 2022 Pavement Technical Condition Assessment test revealed that the pavement condition indicators on the expressway G78 K912-K958 were good. This section spans a total of 92 km and consists of dual lanes. The PQI statistics are shown in Figure 6.

From the assessment results in Table 7, the pavement demonstrated excellent overall quality, as seen by the high average value of PQI of 95.31. Additionally, the excellent and good road rates of 98.92% and 100% further confirmed the excellent quality of the overall pavement. These findings suggested that the PSSI ≥ 85. The assessment data demonstrated the high quality of the Liuzhou North Ring Highway, suggesting that preventive maintenance is mainly needed to solve minor problems and prolong the service life of the pavement. The selected maintenance measures aim to prevent the occurrence of small cracks, improve pavement conditions, and increase skid resistance. Implementing these measures will ensure the long-term durability and safety of the highway.

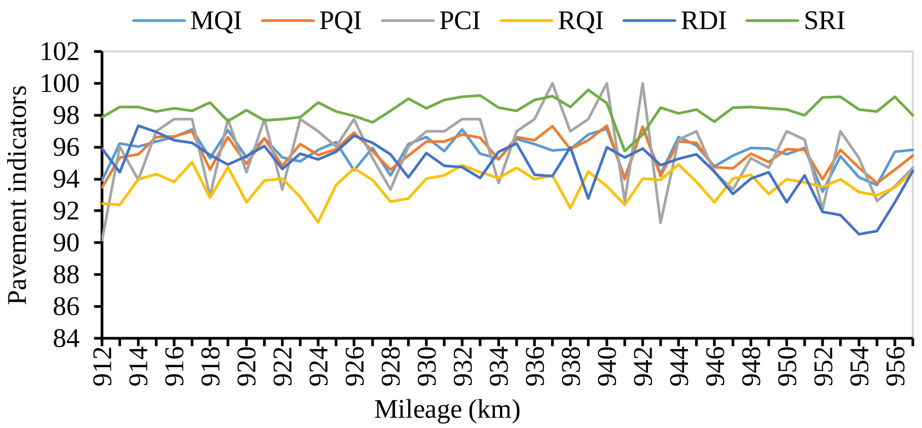

Figure 6. Spatial variation of pavement technical condition indicators along the investigated expressway section.

Table 7. Pavement maintenance quality index assessment.

Evaluation Indicators	Excellent	Good	Average	Bad	Poor	average value	Superior road rate %	Good road rate %
PQI	91.77	1	0	0	0	95.31	98.92	100
PCI	81.39	11.39	0	0	0	95.10	87.73	100
RQI	91.77	1	0	0	0	93.43	98.92	100
RDI	92.77	0	0	0	0	94.75	100	100
SRI	92.77	0	0	0	0	98.13	100	100
PBI	91.77	0	0	0	0	99.73	98.92	98.92
PSSI	91.12	0	0	0	0	96.1	98	100

Therefore, five main preliminary options for preventive maintenance measures were selected: ultra-thin cover, composite seal coat, micro-surfacing, thin layer overlay, and sealing layer cover. The main reasons and comparisons are analyzed in Table 8.

By examining road conditions and distress analysis, initial measurement decisions can be made quickly. This method is more efficient and comprehensive compared to previous research, considering a broader range of technical and economic indicators. The initial measure can be selected swiftly based on the specific wording of the road condition indicators.

Table 8. Results of preliminary measures selection.

Maintenance Measure	Causes addressed	Reasons for comparison
Ultra-thin cover	Minor surface stacks: due to aging and minor structural issues, aging and looseness: surface becomes loose and less cohesive over time	Highest cost among overlays but provides excellent surface renewal, best for roads with specific surface damage and low traffic volume
Composite seal coat	Multiple distress treatment: effective for addressing a variety of surface issues simultaneously, enhanced durability: combines benefits of multiple techniques	Higher cost but longer service life, suitable for complex maintenance needs with multiple surface issues
Micro-surface treatment	Minor rutting: caused by traffic load, leading to depressions in the wheel paths, surface imperfections: light oiling and water seepage that compromise surface integrity	Balances cost, longevity, and effectiveness for minor to moderate surface issues, quick to solidify, and effective for small repairs
Thin-layer overlay	Surface wear: general wear and tear from traffic and environmental exposure, skid resistance: loss of texture and skid resistance over time	Offers a longer service life with moderate cost, ideal for restoring smoothness and skid resistance on low-traffic roads
Sealing layer cover	Rutting and minor distress: effective for minor structural issues and improving surface, characteristics, and anti-skid performance enhances surface friction for safety	Longer service life and highly effective for rutting and minor structural repairs. Higher cost and complexity

3.2. Outcomes of the established AHP-based model

3.2.1. Model's structure

The preliminary measure selection includes the framework layers, which are the composite seal coat, micro surfacing (micro-surface treatment), ultra-thin cover, thin layer cover, and sealing layer cover. Thus, a multilevel structural model containing the objective, criterion, indicator, and scheme layers is established, as shown in Figure 7. Based on the preliminary selection of feasible preventive maintenance measures, a case specific AHP hierarchy was established for the Liuzhou North Ring Expressway. The objective layer represents the selection of the most suitable preventive maintenance measure. The criterion layer includes technical, economic, and environmental indicators. The indicator layer further divides these criteria into material quality, construction quality, construction feasibility, service life, unit cost, traffic disruption, environmental impact, and aesthetic impact. The scheme includes five candidate measures, namely composite seal coat, micro surfacing, ultrathin cover, thin layer cover, and sealing layer cover. This structure provides the basis for constructing judgment matrices, calculating weights, and ranking the maintenance alternatives.

This hierarchical analysis model contains a multilevel structural model of the target, criterion layer, sub-criterion, and alternative layers. The criterion layer comprehensively considers technical, economic, and environmental factors, whereas the indicator layer specifies factors such as material quality, construction quality, service life, and unit cost.

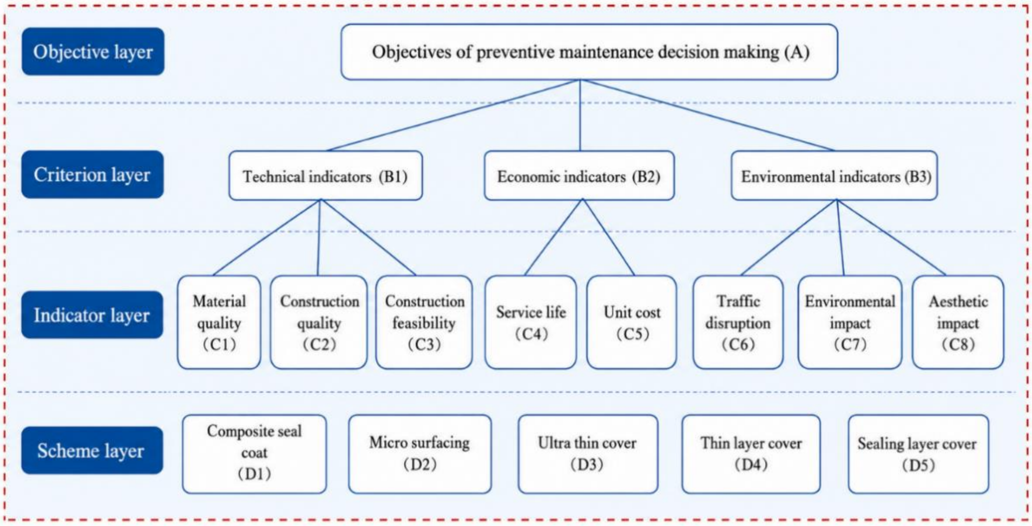

Figure 7. Actual AHP model structure used in this study.

3.2.2. Judgment matrix

To ensure the reliability and accuracy of the weight calculations, a total of five experts specializing in various domains related to highway maintenance management, preventive maintenance construction, highway design, and pavement performance evaluation were consulted. This diverse group of experts was carefully selected to guarantee comprehensive and authoritative scoring results. The scoring process adhered to a unified normalization approach to establish the judgment matrix.

Based on the hierarchical structure model established in Figure 7, experts were invited to score the indicators at each level according to the rating rules provided in Table 4. This process involved pairwise comparisons to assess the relative importance of the economic, technical, and environmental criteria. A judgment matrix was constructed to compare the criteria. For instance, a score of 0.2 when comparing technical (B1) to economic (B2) indicators reflects that technical aspects are considered significantly less important than economic factors. A score of 0.3333 indicates that environmental criteria are more important than technical ones. Furthermore, a score of 0.5 signifies that economic indicators hold greater weight than environmental indicators. These comparisons yield a relative prioritization of the criteria as evaluated by the experts, establishing a quantitative foundation for multi-faceted decision-making. The resulting judgment matrix is summarized in Table 9.

Table 9. Judgment matrix for target layer and criterion layer.

Decision (A)	**Technical indicators (B1)**	**Economic indicators (B2)**	**Environmental indicators (B3)**
Technical indicators (B1)	1	0.2	0.3333
Economic indicators (B2)	5	1	2
Environmental indicators (B3)	3	0.5	1

Similarly, judgment matrices were constructed to evaluate the indicators within each criterion layer, including technical, economic, and environmental aspects. The judgment matrix for the technical indicators is presented in Table 10. In this matrix, a value of 2 in the row for material quality (C1) indicates that it is considered twice as important as construction quality (C2). Conversely, the corresponding value of 0.5 in the row for construction quality reflects its half-importance relative to material quality.

When comparing material quality (C1) to construction feasibility (C3), the value of 0.5 signifies that material quality is moderately less important. The value of 0.3333 for the comparison between construction quality (C2) and construction feasibility (C3) indicates that construction quality is considerably less important. Consequently, construction feasibility (C3) emerges as the most significant technical indicator, prioritized above both material quality and construction quality. Among the three, material quality (C1) holds intermediate importance, while construction quality (C2) is the least significant. These relative weights clarify the priority of technical indicators, guiding where greater attention and resources should be directed during the decision-making and planning phases.

Table 10. Judgment matrix for technical indicators.

Technical Indicators (B1)	Material quality (C1)	Construction quality (C2)	Construction feasibility (C3)
Material quality (C1)	1	2	0.5
Construction quality (C2)	0.5	1	0.3333
Construction feasibility (C3)	2	3	1

In the economic dimension, the judgment matrix for economic indicators is presented in Table 11. A value of 0.3333 indicates that service life (C4) is considered less important than unit cost (C5), specifically one-third as significant. Correspondingly, the value of 3 in the unit cost row signifies that unit cost is three times as important as service life. Thus, within the economic criteria, unit cost carries substantially greater weight than service life. This result suggests that in decision-making and planning, cost efficiency should be prioritized over extending service life. Such insights help clarify the focus of economic considerations, indicating that greater attention should be directed toward managing and reducing costs rather than predominantly emphasizing longevity.

Table 11. Judgment matrix for economic indicators.

Economic Indicators (B2)	Service life (C4)	Unit cost (C5)
Service life (C4)	1	0.3333
Unit cost (C5)	3	1

For the environmental aspect, the judgment matrix of the corresponding indicators is presented in Table 12. A value of 0.5 when comparing traffic disruption (C6) to environmental impact (C7) indicates that traffic disruption is half as important. Conversely, the value of 2 in the environmental impact row signifies that it is twice as important as traffic disruption. Furthermore, a value of 2 in the traffic disruption row shows that it is considered twice as important as aesthetic impact (C8). These comparisons reveal that, within the environmental criteria, environmental impact holds the highest priority, followed by traffic disruption, with aesthetic impact being the least critical. This hierarchy provides clear guidance for incorporating environmental considerations into project planning and decision-making.

Table 12. Judgment matrix for environmental indicators.

Environmental Indicators (B3)	Traffic disruptions (C6)	Environmental impact (C7)	Aesthetic impact (C8)
Traffic disruptions (C6)	1	0.5	2
Environmental impact (C7)	2	1	3
Aesthetic impact (C8)	0.5	0.3333	1

3.2.3. Single-ranking weight and consistency

The criterion layer is responsible for calculating the weights and conducting consistency tests for the judgment matrix of the target layer. The weights of each criterion element of the criterion layer, relative to the target layer, are calculated from Table 9 and are shown in Figure 8a. It shows that economic indicators hold the highest weight at 0.5813, followed by Environmental at 0.3092 and Technical at 0.1096.

The weights of the technical indicators calculated from Table 10 are shown in Figure 8b. This weight demonstrated that material quality had a significant but not the highest level of significance among the technical indicators. Specifically, it accounted for approximately 29.73% of the total importance among the technical indicators. Due to its low importance, the construction quality had the lowest weight of 0.1638, which was the least significant factor among the technical indicators. Construction feasibility, with the highest weight of 0.5390, was the most significant technical indicator. It accounted for about 53.90% of the total importance, indicating that it is the primary concern in the technical evaluation. These weights provided a quantified basis for making balanced decisions that appropriately reflect the relative importance of different technical criteria.

Figure 8c displays the weights of economic indicators calculated from Table 11. Service life shows moderate importance among the economic indicators. Specifically, it accounts for approximately 25% of the total importance among the economic indicators. With the highest weight of 0.75, unit cost exhibited the most significant economic indicator. This suggested that around 75% of the total importance was attributed to unit cost, making it the primary concern in economic evaluations. Unit cost (C5) is the most critical factor to consider, as it holds the highest weight. This means that managing and reducing costs should be the top priority in decision-making regarding economic indicators. The importance of service life (C4) is relatively lower in priority compared to the unit cost. This indicates that prioritizing cost efficiency should be supported by the goal of prolonging the service life. Practically, cost-benefit analysis and budgetary restrictions frequently have a significant impact on road repair decisions in China. As a result, in expert assessments, economic indicators are inherently given more weight.

Figure 8d presents the weights of the environmental indicators calculated from the judgment matrix in Table 12. Environmental impact (C7) exhibited the most important indicator with a weight of 0.5389 compared to others. Followed by traffic disruptions (C6) as the second most important factor with a weight of 0.2972. Aesthetic impact (C8) showed the least important indicator with a weight of 0.1638. This suggests that decision-makers should prioritize environmental impact considerations in any projects or initiatives. While traffic disruptions are significant, it is less critical compared to environmental impact. This implies that aesthetic considerations should be given the least priority compared to the other two indicators.

The calculation results revealed that the model demonstrated the highest economic weight among the technical, economic, and environmental indicators. This indicates that the economic indicators held the greatest importance, aligning with the key considerations of road maintenance management in preventive maintenance decision-making [5,22]. The analysis suggests that the decision-makers prioritize economic considerations over environmental ones while valuing environmental factors more than technical ones. The results of the consistency test for the indicators are shown in Table 13. From the results, the maximum characteristic root of the target judgment matrix was λmax of 3.0037 with a CI value of 0.0018 and a CR value of 0.00316 < 0.1. The maximum characteristic root of the technical judgment matrix was λmax of 3.0092 with a CI value of 0.0046 and a CR value of 0.0079 < 0.1. As for the economic judgment matrix, the maximum characteristic root was $\lambda max = 2$ with a CI value of 0 and a CR value of 0 < 0.1. The maximum characteristic roots of the environmental judgment matrix were λmax of 3.0092 with a CI value of 0.0046 and a CR value of 0.0079 < 0.1. All judgment matrices with a CR value < 0.1 had passed the consistency test. The consistency test assessed the reliability of the judgment matrix, and the consistency ratio CR < 0.1 indicates no inconsistencies when comparing the indicators. These results suggested this model is reliable and the consistency is satisfactory. It also showed that decision-makers have a common understanding of the criteria and alternatives.

Table 13. Consistency test results for judgment matrices.

Indicators	Target indicators	Technical indicators	Economic indicators	Environmental indicators
λmax	3.0037	3.0092	2	3.0092
CI	0.0018	0.0046	0	0.0046
RI	0.58	0.58	0	0.58
CR	0.00316	0.0079	0	0.0079

The established hierarchical structure model consists of target, criterion, sub-criterion, and alternative layers. The judgment matrix was constructed, and the weight calculation and consistency test were carried out to ensure the scientific and rational nature of the model. This approach further validates the effectiveness of AHP in complex decision-making problems.

3.2.4. Total ranking weight

Based on the hierarchical model, the overall weight of each indicator relative to the decision-making target was calculated by synthesizing its weight within the criterion layer and the weight of that criterion relative to the target layer. The resulting overall weight matrix R is as follows: material quality (0.0326), construction quality (0.0179), construction feasibility (0.0590), service life (0.1453), unit cost (0.4360), traffic disruption (0.0964), and environmental impact (0.1516) (Figure 8e). These values reflect the relative priority of each indicator in the overall decision framework. The results show that unit cost (0.4360) is the most heavily weighted factor, underscoring the paramount importance of cost efficiency in the decision-making process. Environmental impact (0.1516) and service life (0.1453) also carry considerable weight, highlighting the role of sustainability and durability. In contrast, material quality and construction quality have minimal influence on the overall priority, indicating that in this preventive maintenance context, economic and environmental considerations outweigh pure technical specifications.

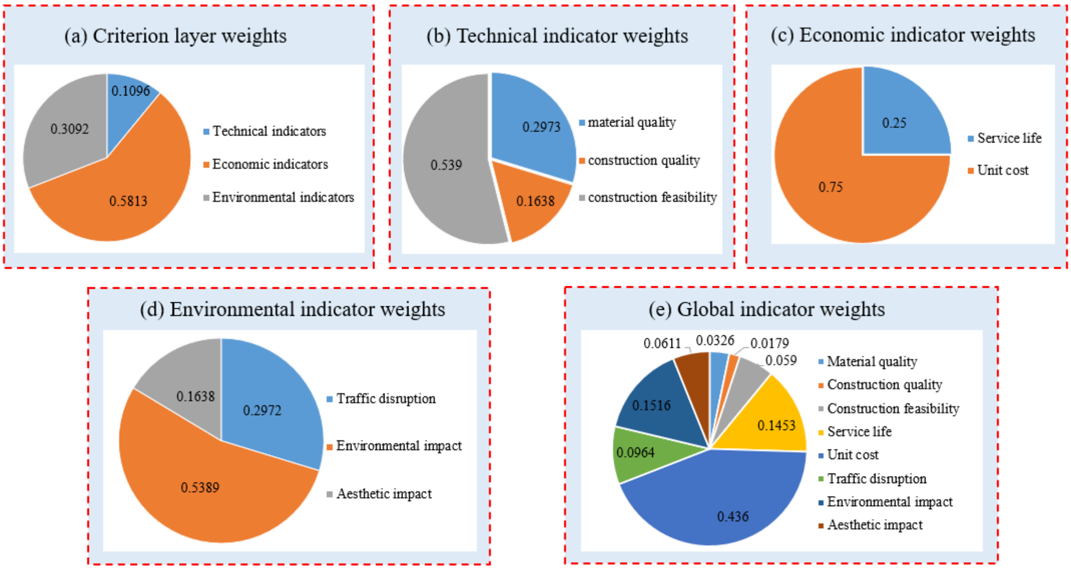

Figure 8. AHP weight distribution across criterion, indicator, and global decision levels.

3.3. Outcome of maintenance methods decision-making

According to the analysis in Table 6, an evaluation matrix (W) has been established to assess measures. Qualitative and quantitative indicators of the measure framework are scored and assigned values by experts. The magnitude of these values represents the impact of the indicators. After numerical processing, the indicator layer evaluation matrix (W) of each framework is presented in Table 14. The results revealed the notable performance of the composite seal coat and ultra-thin cover measures in critical indicators such as material quality, construction quality, and service life. While excelling in essential areas, these approaches may entail a higher cost and environmental impact. On the other hand, micro-surfacing offered strong environmental benefits and feasibility, making it a suitable option for environmentally conscious projects. Thin and sealing layer covers provided more moderate performance, catering to specific project needs and constraints.

Table 14. Evaluation matrix for framework indicators.

Indicator	Composite seal coat	Micro-surfacing	Ultra-thin cover	Thin layer cover	Sealing layer cover
Material quality	0.85	0.75	0.90	0.60	0.70
Construction quality	0.80	0.65	0.85	0.55	0.60
Construction feasibility	0.70	0.80	0.75	0.65	0.50
Service life	0.90	0.70	0.85	0.75	0.60
Unit cost	0.60	0.50	0.70	0.55	0.65
Traffic disruptions	0.50	0.55	0.45	0.60	0.50
Environmental impact	0.75	0.85	0.80	0.70	0.65
Aesthetic impact	0.85	0.65	0.75	0.70	0.60

Note: Service life and unit cost were normalized from the quantitative values reported in Table 3. Service life was treated as a benefit indicator, while unit cost was treated as a cost indicator. Other indicators were scored using expert judgment according to the reference score intervals in Table 6.

The synthetic weights of the five maintenance methods were calculated as 0.7280 (ultra-thin cover), 0.6896 (composite seal coat), 0.6247 (micro-surfacing), 0.6233 (thin layer cover), and 0.6171 (sealing layer cover), establishing the priority order presented in Figure 9. The ultra-thin cover ranked highest primarily due to its superior performance in material quality (0.90), construction quality (0.85), and service life (0.85), which offset its moderate scores in unit cost (0.70) and environmental impact (0.80). The composite seal followed closely, excelling in service life (0.90) and material quality (0.85), though it also entails higher costs. In contrast, the sealing layer cover received the lowest priority largely due to its poor construction feasibility (0.50), which significantly affected its overall score despite moderate performance in other indicators. These outcomes reflect the weighted influence of each indicator within the decision framework, where cost and environmental impact played dominant roles. The results provide a structured basis for selecting maintenance strategies that balance technical performance, economic efficiency, and environmental sustainability under conditions similar to the Liuzhou North Ring Expressway.

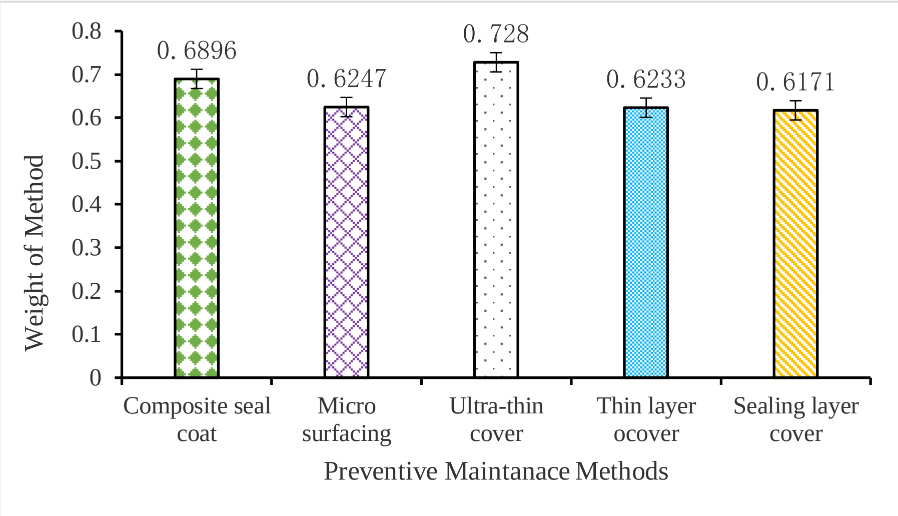

Figure 9. Final priority scores of preventive maintenance alternatives based on the AHP evaluation framework.

3.4. Sensitivity analysis of AHP weights

To evaluate the stability of the proposed AHP based decision framework, a sensitivity analysis was conducted by varying the weights of the technical, economic, and environmental criteria. This analysis is necessary because the baseline results show that the economic criterion has the highest weight in the decision model. Therefore, the final ranking of preventive maintenance measures may be affected if decision makers assign greater or lower importance to cost related factors.

In the baseline AHP model, the criterion weights were 0.1096 for technical indicators, 0.5813 for economic indicators, and 0.3092 for environmental indicators. Different weighting scenarios were then examined to represent possible changes in maintenance management priorities. These scenarios included technical emphasis, economic emphasis, environmental emphasis, balanced criteria, and reduced economic weight. For each scenario, the local weights of the indicators within each criterion group were kept constant, while the criterion level weights were varied. The final scores of the maintenance alternatives were recalculated to determine whether the ranking of the preferred treatment changed.

The results of the sensitivity analysis are shown in Table 15. Under all tested scenarios, ultra-thin cover remained the first ranked alternative, while composite seal coat consistently ranked second. This indicates that the proposed decision result is stable under rational changes in criterion weights. Micro surfacing generally ranked third, except under the economic emphasis scenario, where sealing layer cover moved to third position due to the stronger influence of cost related scoring. These results suggest that the selection of ultra-thin cover is robust and is not solely dependent on the baseline expert weighting structure. However, the close ranking of the lower alternatives indicates that secondary treatment choices should still be interpreted with consideration of project budget, construction conditions, and environmental requirements.

Table 15. Sensitivity analysis of maintenance method ranking under different criterion weight scenarios.

Scenario	Technical weight	Economic weight	Environmental weight	Rank 1	Rank 2	Rank 3	Decision implication
Baseline AHP weights	0.1096	0.5813	0.3092	Ultra-thin cover	Composite seal coat	Micro surfacing	Baseline result confirms ultra-thin cover as the preferred treatment.
Technical emphasis	0.2000	0.5000	0.3000	Ultra-thin cover	Composite seal coat	Micro surfacing	Ranking remains stable when technical performance receives higher priority.
Economic emphasis	0.0800	0.7000	0.2200	Ultra-thin cover	Composite seal coat	Sealing layer cover	Ultra-thin cover remains first, but the third ranked option changes due to stronger cost influence.
Environmental emphasis	0.1000	0.4500	0.4500	Ultra-thin cover	Composite seal coat	Micro surfacing	Ranking remains stable when environmental criteria receive higher weight.
Balanced criteria	0.3333	0.3333	0.3333	Ultra-thin cover	Composite seal coat	Micro surfacing	Equal weighting does not change the first and second ranked alternatives.
Reduced economic weight	0.1500	0.4000	0.4500	Ultra-thin cover	Composite seal coat	Micro surfacing	The preferred alternative remains unchanged despite reduced economic dominance.

3.5. Discussion and evaluation of the proposed model

The results indicate that economic considerations dominate the preventive maintenance decision for the Liuzhou North Ring Expressway. This finding is realistic considering preventive maintenance is typically implemented under budget constraints and requires treatment options that provide acceptable performance at manageable cost. The dominance of unit cost also indicates that the final ranking is highly sensitive to the normalization method used for cost evaluation. Therefore, careful treatment of cost type indicators is necessary to avoid biased ranking outcomes.

The relatively high weights of environmental impact and service life show that the decision framework does not rely only on short term cost. Instead, it also captures sustainability and durability concerns. This is important for expressway maintenance as treatments with low initial cost may not always provide the best value when traffic disruption, environmental effects, and treatment durability are considered. By utilizing quantitative data, such as pavement condition indices and service life analysis, decision-makers can prioritize maintenance based on objective criteria rather than subjective observations, providing a solid foundation for decision-making.

The proposed AHP framework has practical value for the reason that it converts expert judgment and pavement condition data into a transparent ranking process. However, the model has slight limitations. Whereby, the expert panel size is small, and expert judgments may vary by region, agency policy, and budget conditions. In addition to that, the case study is limited to one expressway section, which restricts the general transferability of the final weights. Moreover, the treatment scores require stronger justification, especially for qualitative indicators. Future work should include more case sections, compare AHP results with actual maintenance performance, and test alternative multi criteria methods such as TOPSIS, VIKOR, and fuzzy AHP.

4. Conclusions

This study developed an AHP based decision framework for selecting preventive maintenance measures for asphalt pavements. The Liuzhou North Ring Expressway was used as a case study, and pavement condition indicators confirmed that the investigated section was suitable for preventive maintenance. Five candidate treatments were evaluated based on the technical, economical, and environmental criteria.

The AHP results showed that economic indicators show the highest criterion weight, followed by environmental and technical indicators. At the global indicator level, unit cost, environmental impact, and service life were the most influential factors. The final treatment ranking identified ultra-thin cover and composite seal coat as the leading alternatives under the adopted weighting and scoring conditions.

The study provides a transparent decision support procedure for pavement maintenance planning. However, the final ranking depends strongly on the scoring and normalization of quantitative indicators, especially unit cost. Therefore, future work should include corrected cost type normalization, sensitivity analysis, larger expert panels, and validation using post maintenance pavement performance data.

Data availability statement

The data or datasets that support the findings of this study are available from the corresponding author upon reasonable request.

Declaration of generative AI and AI-assisted technologies

During the preparation of this manuscript, the authors used generative AI tools only to improve language and readability. Specifically, the authors used DeepL for translation in limited sections. The authors take full responsibility for the content of the manuscript.

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Authors' contribution

Zhen Wu: conceptualization, methodology, formal analysis, investigation, data collection, analysis, interpretation, writing—original draft preparation and modification; Mohd Rosli Mohd Hasan: supervision, project administration, software guiding, visualization, writing—review and editing, funding acquisition; Oumar Orozi Sougui: formal analysis, chart; Diyar Khan: formal analysis, data curation, writing—review and editing; Hainian Wang and Hui Wang: validation, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

Conflicts of interest

The authors declare that they have no conflicts of interest in this paper.

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