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Assessment of Intelligent Unmanned Maintenance Construction for Asphalt Pavement Based on Fuzzy Comprehensive Evaluation and Analytical Hierarchy Process

Gensheng Hu [1], Gongzuo Shi [1], Runhua Zhang [2,3], Jianfeng Chen [1], Haichang Wang [2,3] and Junzhe Wang [2,3,*]

1 Zhejiang Communication Investment Expressway Operation Management Co., Ltd., Hangzhou 310020, China; 13757144113@163.com (G.H.); shigongzuo@163.com (G.S.); 15180182073@163.com (J.C.)
2 China Academy of Transportation Sciences, Beijing 100029, China; 17801128125@163.com (R.Z.); 15901377101@163.com (H.W.)
3 Testing Technology (Beijing) Co., Ltd. of China Academy of Transportation Sciences, Beijing 100029, China
* Correspondence: wangjunzhe@motcats.ac.cn

Abstract: Conventional human-involved maintenance methods for asphalt pavement pose significant challenges when applied to high-traffic road sections, often leading to congestion and safety risks, as well as reduced maintenance efficiency. In recent years, explorations into unmanned construction technology for newly constructed expressways have yielded beneficial and encouraging results. However, its application in road maintenance in more complex environments still needs to be expanded. In this study, an intelligent unmanned maintenance technology for asphalt pavement was applied to the Lilong Highway in Zhejiang Province, China, and the compactability, thickness, surface smoothness, permeability coefficient, and constructure depth of maintenance road sections were measured. Then, based on fuzzy comprehensive mathematics and the analytic hierarchy process, a comprehensive evaluation was performed on the intelligent unmanned maintenance technology, considering the aspects of road quality, safety, application, and socio-economic benefits. The results show that the road quality of intelligent unmanned maintenance technology can meet the road specification requirements. In addition, the membership degree of unmanned maintenance technology in the excellent grade is the highest, reaching 0.805, and the quantified value for the overall evaluation of the application effectiveness of unmanned maintenance technology is 92.10. This means that the final comprehensive evaluation result of unmanned maintenance technology is rated as excellent. The research findings provide decision-makers with valuable insights into the unmanned automation maintenance challenges faced by asphalt pavement, enabling them to implement appropriate measures to elevate the maintenance standards of road transportation.

Keywords: road engineering; asphalt pavement; unmanned maintenance; fuzzy comprehensive evaluation; analytical hierarchy process

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1. Introduction

With the rapid growth of highway mileage and the increase in road service life, highways have entered a period where construction and maintenance are equally important [1–4]. Common drawbacks associated with conventional engineering construction and maintenance methods include low productivity and high costs, largely attributed to heavy reliance on manual labor. With the rapid advancement of digitalization, automation, artificial intelligence, big data, and other technologies, the landscape of engineering construction and maintenance is gradually shifting towards intelligent systems [5–7]. Consequently, as a vital component of transportation infrastructure, pavement construction and maintenance urgently require the adoption of new technologies, techniques, and solutions to alleviate the workload of workers and enhance construction efficiency.

In road construction, effective paving and compaction techniques will ensure road quality and traffic safety. In the development of intelligent pavement paving and compaction technology, scholars have conducted extensive research. For pavers, Liang and Guan [8] devised an intelligent automatic leveling control system for asphalt pavers, leveraging ultrasonic distance-measuring technology. This innovative system automatically adjusts the speed of the hydraulic cylinder in response to road elevation deviations and autonomously verifies the accuracy of the measured data. Consequently, it mitigates human effects on achieving a smooth road surface during construction. Qi et al. [9] developed a specialized paving control device and control method for the construction of curved sections with super-large lateral inclinations. They programmed a reference control line into the paver's operational control device and adjusted the machine's lateral displacement deviation to align its data with the travel route, thus enabling precise control over the forward trajectory of the paving machine. For rollers, Chen et al. [10] proposed an intelligent control system for asphalt pavement compaction quality. Through on-site measurements and analysis, they investigated and verified the correlation and applicability of two proposed indicators for controlling compaction quality with compactness and smoothness. Lu et al. [11] proposed an intelligent technology for roller path tracking and mapping in pavement compaction. Based on laboratory and field tests, the proposed technology can achieve comparable accuracy to GPS for rollers' lateral position estimation and a satisfactory accuracy for longitudinal position estimation. Meanwhile, in addition to intelligently optimizing equipment parameters, the devices themselves have been endowed with more intelligent functionalities. For instance, 3D intelligent paving technology involves the use of non-contact electronic guidance systems to guide pavers in laying surfaces without the need for strings. In terms of controlling the direction and elevation of the paver, global positioning system (GPS) and laser radar technology have replaced strings, increasing accuracy to the millimeter level [12,13]. Researchers in France and other countries have delved into "Computer-Integrated Road Construction Projects" supported by relevant research initiatives in the European Union. By amalgamating high-precision positioning technology and laser guidance technology, they achieved precise positioning guidance for road rollers and pavers [14]. Ye et al. [15] conducted comparative tests between the 3D paving control system and the conventional paving control system using specific engineering examples. They found that the use of 3D intelligent paving technology reduced the measurement workload by approximately 40%, increased paving accuracy by around 30%, and improved work efficiency by approximately 50%.

Furthermore, current research and development efforts for paving and compaction equipment are moving towards unmanned vehicle fleets. This technology for unmanned construction involves construction machinery operated from a distance, along with supporting equipment for remotely controlling the operation of this machinery. Bian et al. [16] proposed a path-tracking control method based on the fuzzy algorithm to solve the path-tracking error of unmanned vibration rollers during automatic rolling operations and confirmed the effectiveness and superiority of this method. Xie R. [17] provided a detailed introduction to the unmanned paving and compaction intelligent construction system. This system utilizes the BeiDou Navigation Satellite System and, with the assistance of a 3D laser leveling system, automatically plans the travel paths of pavers and compactors for newly constructed asphalt pavement. Wang et al. [18] analyzed the statistical results of road condition indicators for unmanned construction sections and indicated that unmanned construction machinery based on road trajectory data can ensure construction accuracy within 2 cm and achieve a pass rate of over 90%. Compared to conventional manual construction methods, they found a 50% reduction in the need for auxiliary personnel, resulting in improved construction quality and efficiency.

In summary, unmanned intelligent road construction technology has promising prospects. However, the technology is currently in the research stage and is only used in new road engineering constructions on a small scale, and its application in highway maintenance projects still needs to be assessed. Compared with a newly constructed highway project, a maintenance project in operating expressway experiences more complex situations and the quality requirements of pavement surface conditions are much stricter. Specifically, the current maintenance of highways faces two prominent issues: (1) Maintenance operations on high-traffic sections are difficult to carry out, leading to congestion and lower construction efficiency. Organizing traffic during maintenance operations is complex, and there are significant safety risks for workers involved in these activities. (2) The level of intelligence in maintenance equipment is not high. Some maintenance machinery and equipment have low levels of automation, resulting in many maintenance operations still being labor-intensive. The degree of reliance on information technology for quality management is not high enough to meet current maintenance needs. In this study, unmanned intelligent road construction technology is used in the maintenance construction of a practically engineered structure. The engineering technical indicators of asphalt pavements after intelligent unmanned maintenance and conventional manual maintenance are investigated and compared. Finally, based on fuzzy comprehensive mathematical methods and the analytic hierarchy process, an evaluation index system for the effectiveness of unmanned maintenance technology is established, considering road quality, safety, technology application, and socio-economic benefits.

2. Project Overview

2.1. Study Area

In this study, to comprehensively evaluate the application effectiveness of intelligent unmanned road construction technology in maintaining road sections, a local road to be repaired in Jinyun County, Zhejiang Province, was selected as the study area to complete the field tests. The road is situated in the Lishui section of the Longli Expressway. The Longli Expressway spans a total length of 85,056 km and was constructed in accordance with bidirectional four-lane expressway standards. The roadbed maintains a standard width of 24.5 m, and the mainline road surface, during construction, comprises a typical structure with three asphalt concrete layers (4 cm top layer + 6 cm middle layer + 8 cm bottom layer), a water-stable crushed stone base layer, and a sub-base layer. The expressway was completed and opened to traffic in December 2006.

Table 1 outlines the specific details of the road sections maintained using intelligent unmanned maintenance technology in this study. Sections 7 and 8 are specifically designated for completing unmanned maintenance work at night. In addition, to further assess and validate the maintenance quality of sections under unmanned maintenance technology, the road sections utilizing conventional manual maintenance methods are selected, as shown in Table 2. The expressway's "up" and "down" directions are determined based on the expressway milepost, with "up" denoting the direction of increasing expressway mileposts and "down" indicating the direction of decreasing highway mileposts.

Table 1. Description of unmanned maintenance sections.

Road Section Number	Direction	Starting Milepost	Ending Milepost	Length/km
W1	Up	K445 + 050	K445 + 444	0.394
W2	Down	K461 + 306	K460 + 606	0.7
W3	Down	K460 + 460	K459 + 760	0.7
W4	Down	K466 + 308	K465 + 991	0.317
W5	Up	K431 + 803	K432 + 503	0.7
W6	Up	K432 + 494	K433 + 250	0.756
W7	Up	K475 + 244	K475 + 977	0.733
W8	Down	K94 + 422	K93 + 928	0.494

Table 2. Description of conventional maintenance sections.

Road Section Number	Direction	Starting Milepost	Ending Milepost	Length/km
C1	Up	K415 + 282	K415 + 975	0.693
C2	Up	K437 + 296	K438 + 171	0.875
C3	Up	K443 + 622	K445 + 031	1.409
C4	Up	K445 + 527	K446 + 179	0.652
C5	Up	K474 + 619	K475 + 241	0.622
C6	Down	K467 + 230	K466 + 308	0.922
C7	Down	K463 + 136	K462 + 046	1.09
C8	Down	K438 + 605	K437 + 960	0.645

2.2. Intelligent Unmanned Maintenance Technology

In these maintenance activities, the asphalt overlayers are used for strengthening the existing pavement structure, correcting surface defects, and improving pavement serviceability. The unmanned maintenance process for the asphalt overlayers primarily involves the paving and compaction of the asphalt mixture. The test road in this study is equipped with two unmanned asphalt pavers and five unmanned rollers. Additionally, two asphalt pavers and five double steel-wheel rollers were mobilized as emergency equipment to ensure the smooth progress of maintenance on the test section.

During the paving process, two unmanned automatic telescopic pavers operate in tandem, with adjacent lanes overlapping by a width of 0.1–0.2 m. The pavers are positioned and pre-adjusted to the desired curvature 30–60 min before paving. The smoothing plates were preheated to 120 °C prior to the paving process. According to the Technical Specification for Construction of Highway Asphalt Pavements (JTG F40-2004) [19], both pavers maintain consistent compaction hammer vibration frequencies, and the paving temperature of the asphalt mixture must not be kept lower than 160 °C. In the initial 10–20 m from the starting point of the pavement section, manual operation mode is employed for paving, and manual leveling is conducted for joint areas. Once the paving machine stabilizes, it transitions into unmanned paving mode. The loose thickness is determined based on the measured loose coefficient. The paving machine uniformly, slowly, and continuously paves the material. The paving speed is controlled within the range of 2–4 m/min, avoiding arbitrary changes in speed or mid-process stops to enhance smoothness and reduce material segregation. At 10–20 m from the end point of the paving section, the system switches to manual control mode and remains under manual control until it passes the joint.

Simultaneously, the compaction of the asphalt mixture is undertaken. For the initial 10–20 m of the joint starting section, the compaction of the asphalt pavement is manually controlled. After the initial compaction is completed, it transitions to unmanned compaction mode to start the unmanned compaction operation. During the initial compaction, the roller closely follows the paver, applying static pressure while moving forward and vibratory pressure while moving backward. A relatively short initial compaction zone is maintained to quickly complete the compaction, minimizing heat loss. Each paver is followed by two rollers. Following the completion of paving by the first paver, an approximately 0.5 m joint is left without compaction temporarily. This serves as a reference surface for the movement of the floating screeds of the second paver. Once the second paver completes its paving, compaction is then applied to the joint. The roller's secondary compaction is carried out immediately after the initial compaction, without arbitrary pauses. The recommended length for the roller's compaction is 50–80 m. After the secondary compaction, on-site technicians use a three-meter straightedge to inspect the smoothness. If any suboptimal points are identified, the roller is directed for spot vibratory compaction by a manually operated small roller. The final compaction is conducted immediately after the secondary compaction and should be carried out in segmented rolling, until all roller marks are eliminated. According to the JTG F40-2004, the travel speeds for initial compaction, secondary compaction, and final compaction are 2–3 km/h, 3–5 km/h, and 3–6 km/h, respectively.

2.3. Performance Tests

Following the completion of pavement construction on the test section, the assessments of road quality were conducted to compare the maintenance quality of different maintenance technologies. Firstly, based on the Field Test Methods of Highway Subgrade and Pavement (JTG 3450-2019) [20], core samples were collected on-site from the unmanned maintenance section and the conventional maintenance section. Then, the performances of the test road, including compactability, thickness, smoothness, permeability coefficient, and construction depth, were measured.

2.3.1. Compactability

To obtain the compaction degree of the asphalt pavement, the real-time density ρ_s of the core samples is obtained using the test method in the Standard Test Methods of Bitumen and Bituminous Mixtures for Highway Engineering (JTG E20-2011) [21]. Simultaneously, the standard density ρ_0 is determined according to the JTG F40-2004. Finally, compactability K is calculated by Equation (1) according to the T 0924-2019 in the JTG 3450-2019.

$$K = \frac{\rho_s}{\rho_0} \tag{1}$$

The compactability of two maintenance sections is shown in Figure 1. It can be observed that, upon completion of paving and compaction on the test section, the compactability for each section under conventional maintenance mode can meet the specification requirements. However, the unmanned maintenance sections achieve a compactability meeting the specified standards at a rate of 75%, suggesting room for improvement in the qualification rate. Interestingly, there is notable variability in data within the starting and ending points of unmanned maintenance Sections 3 and 6. This is attributed to the transition between manual and unmanned maintenance modes in these regions, introducing a certain level of impact on data stability. After excluding data with significant variability within the starting and ending regions, the compactability across various unmanned maintenance sections meets the specified standards at a rate of 88%. In addition, the compactability for unmanned maintenance sections after two months greatly exceeds the design values, meeting the specification requirements, which indicates the feasibility of the unmanned maintenance technology.

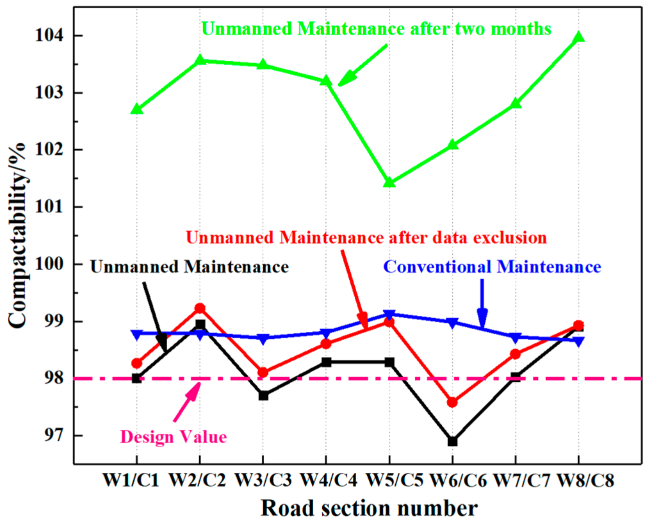

Figure 1. Compactability of unmanned and conventional maintenance sections.

2.3.2. Thickness

In accordance with the T0912-2019 in the JTG 3450-2019, to obtain the thickness of the core sample, a vernier caliper was used to measure the height between the surface and bottom along four symmetrical directions across the circumference of the core sample. Then, the average value of the four positions was calculated. The average thickness and qualification rate of the core samples are depicted in Figure 2. As shown in Figure 2a, it is evident that, in comparison with the design values, the average thickness of the unmanned maintenance section, particularly in Section 4, is lower than the design value, while the average thickness of other maintenance sections is higher than the design value. As shown in Figure 2b, regarding qualification rates, Sections 2 and 6 under the unmanned maintenance sections exhibit relatively low rates, at 80% and 83.3%, respectively. Conversely, under the conventional maintenance mode, the average thickness values for each section surpass the design values, and the qualification rates are all 100%. This implies that the thickness evaluation results for the conventional maintenance sections are slightly superior to those for the unmanned maintenance sections. This is attributed to the fact that some sections maintained by unmanned methods exhibit uneven thicknesses, primarily concentrated at the starting and ending points of construction, with a thinner thickness. Consequently, this non-uniformity results in the overall average thickness of the section being lower than the design value.

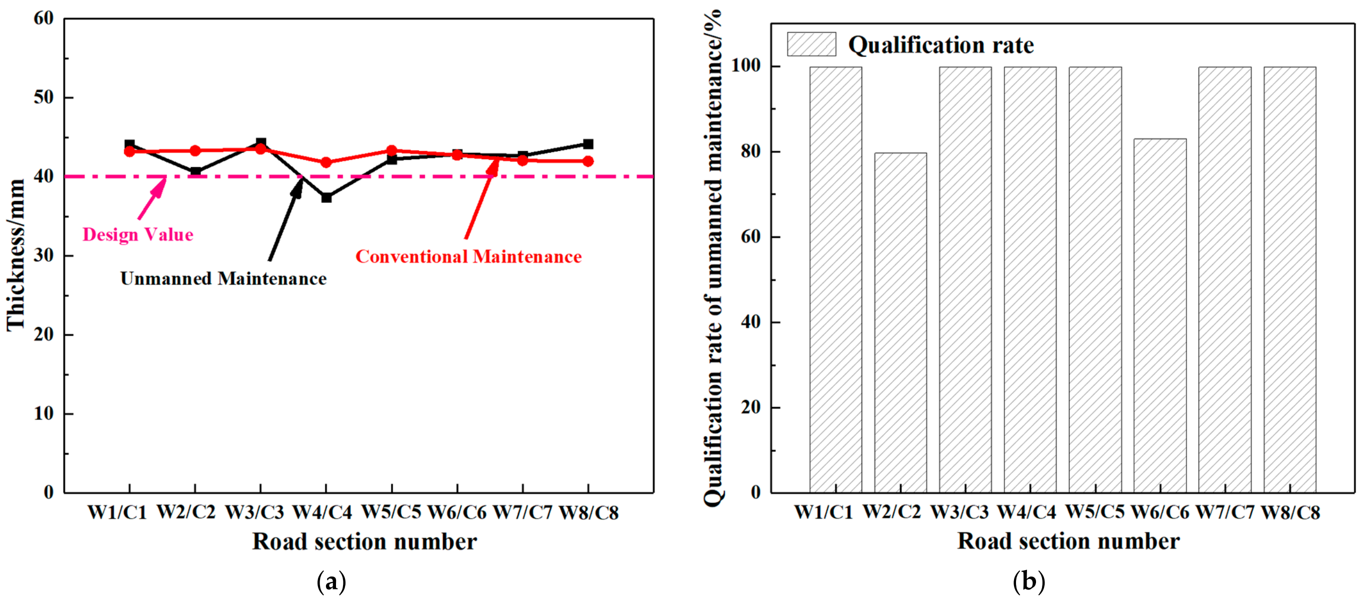

Figure 2. Thickness and qualification rate of unmanned and conventional maintenance sections. (**a**) Thickness of two maintenance method sections. (**b**) Qualification rate of unmanned maintenance sections.

2.3.3. Surface Smoothness

In accordance with the T0934-2008 in the JTG 3450-2019, the vehicle-mounted laser profiler was used to measure the International Roughness Index (*IRI*) of the main lane and passing lane. The speed of the vehicle was kept at 50–80 km/h. Once the vehicle exited the testing section, the testing personnel ceased data collection and recording. At the same time, in accordance with the Highway Performance Assessment Standards (JTG 5210-2018) [22], the Riding Quality Index (*RQI*) was calculated by Equation (2).

$$RQI = \frac{100}{1 + \alpha_O e^{\alpha_1 IRI}} \quad (2)$$

where α_O (0.026) and α_1 (0.65) are the parameters.

The results of *IRI* and *RQI* of unmanned maintenance sections are shown in Table 3. The test results indicate that the overall average *IRI* for the main lane construction section is 1.23 m/km, with an *RQI* average of 94.50. For the pass lane construction section, the overall average *IRI* is 1.30 m/km, with an *RQI* average of 94.26. The smoothness index is assessed as excellent in both lanes.

Table 3. IRI and RQI of unmanned maintenance sections.

Road Section Number	Main Lane		Pass Lane	
	IRI	*RQI*	*IRI*	*RQI*
W1	1.35	94.13	1.11	94.93
W2	1.23	94.53	1.39	93.98
W3	1.13	94.86	1.42	93.85
W4	1.30	94.31	1.39	93.96
W5	1.31	94.25	1.47	93.66
W6	1.19	94.68	1.40	93.93
W7	0.98	95.32	1.12	94.90
W8	1.40	93.93	1.13	94.87

In addition, in accordance with the Inspection and Evaluation Quality Standards for Highway Maintenance Engineering Section 1 Civil Engineering (JTG 5220-2020) [23], the qualification rate of the *IRI* for the section (the ratio of the number of points in each section meeting the specification requirements to the total number of test points) was calculated, as shown in Figure 3. It can be observed that the qualification rates for unmanned maintenance sections and conventional maintenance sections are quite close, but both show cases where the qualification rate for the *IRI* does not reach 100%. This is mainly due to the lack of qualification of the *IRI* in the starting and ending areas of the sections. Thus, it can be concluded that the quality control of smoothness at the starting and ending sections of construction sections is a weak link in unmanned maintenance. Additionally, the multiple repairs conducted in localized areas of the main lane before starting the unmanned maintenance have a negative impact on road smoothness, so the qualification rate for the smoothness of the main lane is lower than the pass lane.

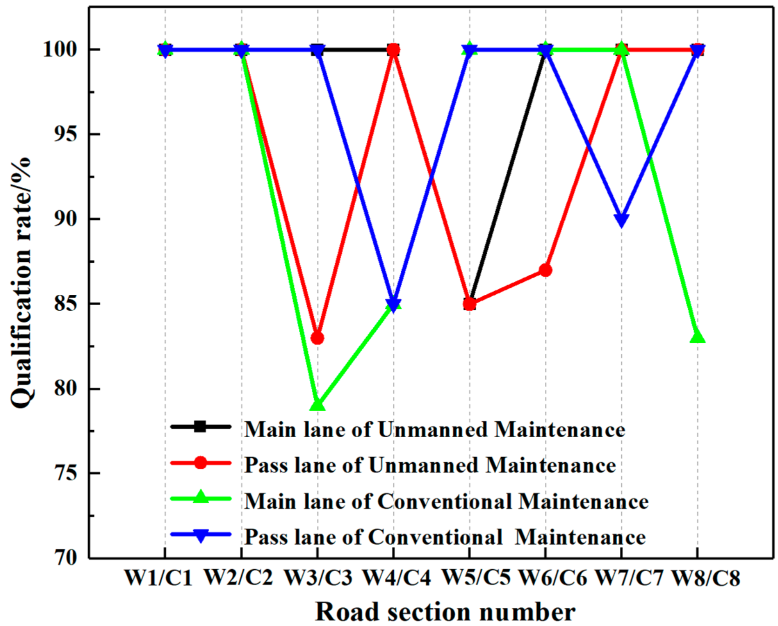

Figure 3. Qualification rate of the *IRI* of unmanned and conventional maintenance sections.

2.3.4. Permeability Coefficient and Constructure Depth

The permeability of asphalt pavement reflects an indirect indicator of the gradation composition of asphalt mixtures on the road surface. It is also a crucial parameter for the water stability of asphalt pavements. In accordance with the T 0971-2019 in JTG 3450-2019, the permeability coefficient of the maintenance sections was measured. In this test, a pavement permeability tester was used. The instrument had a volume of 600 mL, with calibration lines at 100 mL and 500 mL. Firstly, water was poured into the graduated cylinder up to the 100 mL calibration lines, and then the stopwatch was immediately started to begin timing. When the time reached 3 min, the volume of water was recorded, and the test was stopped simultaneously. If the time elapsed was less than 3 min and the volume of water had already dropped to 500 mL, the time was immediately recorded, and the test was stopped simultaneously. The permeability coefficient C_w can be calculated by Equation (3):

$$C_w = \frac{V_2 - V_1}{t_2 - t_1} \times 60 \quad (3)$$

where V_1 is the volume of water for the first time; V_2 is the volume of water for the second time; t_1 is the time for the first time; and t_2 is the time for the second time.

The construction depth of the road surface is a significant indicator of surface roughness, primarily used to assess the macro-roughness, drainage performance, and skid resistance of the road surface. In accordance with the T 0966-2008 in JTG 3450-2019, the vehicle-mounted laser profilometer was used to obtain the pavement constructure depth. The results of the permeability coefficient and construction depth measurements for the unmanned and conventional maintenance sections are shown in Figure 4. The detection data indicate that both the unmanned maintenance section and conventional maintenance section exhibit satisfactory results for the two parameters. The permeability coefficient and construction depth compliance rates reach 100%, which aligns with the design requirements, indicating that both maintenance methods effectively meet the specified standards. This suggests that intelligent unmanned maintenance technology yields comparable results to conventional manual maintenance methods in terms of these critical parameters, affirming its suitability for use in road construction projects.

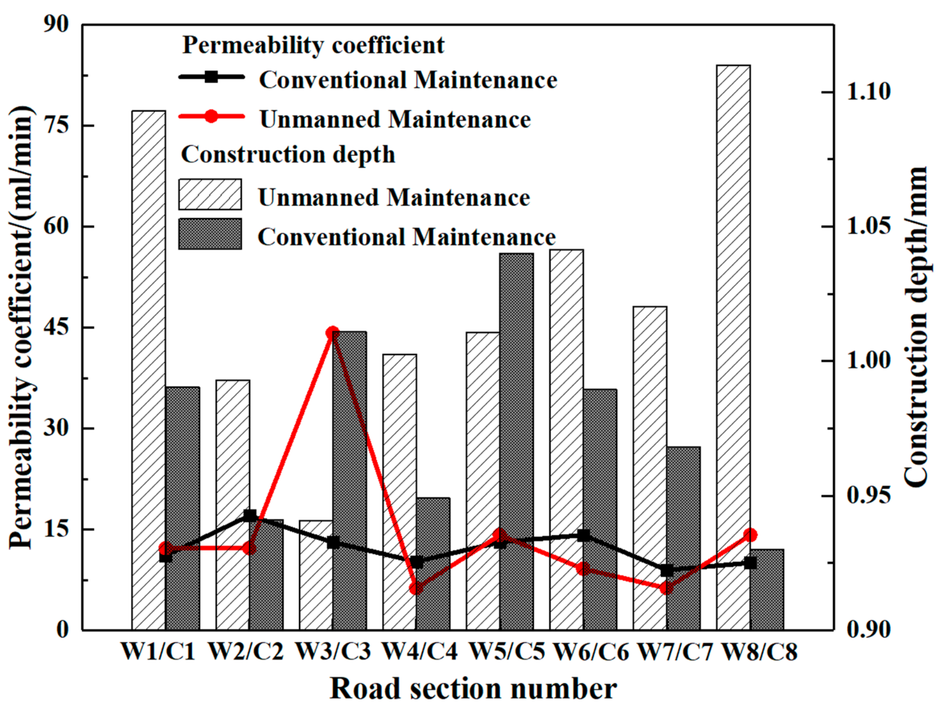

Figure 4. Permeability coefficient and construction depth of conventional maintenance sections.

2.3.5. Performance Comparison of Unmanned Maintenance between Daytime and Nighttime

In this study, Sections 1–6 are designated as daytime maintenance sections, while Sections 7 and 8 are nighttime maintenance sections. To further compare the level of unmanned maintenance under different working conditions during the day and at night, the detection data from Sections 1–6 are averaged to represent the quality assessment results of daytime unmanned maintenance, while the detection data from Sections 7 and 8 are averaged to represent the quality assessment results of nighttime unmanned maintenance for comparative analysis, as shown in Table 4. It can be observed that the thickness, construction depth, and permeability coefficient of the nighttime all meet the specification requirements and show little difference compared to the daytime. The compaction index of the nighttime construction sections is slightly lower than that of the daytime construction. However, the coefficient of variation of the *IRI* calculated from the original data per hundred meters shows that the coefficient of variation (0.12) during nighttime is higher compared to that during daytime (0.07), indicating greater difficulty in controlling the smoothness during nighttime maintenance. Nighttime maintenance is more susceptible to environmental factors such as temperature and wind speed, which may lead to a rapid decrease in the temperature of the asphalt mixture, thereby affecting compaction and smoothness indices. Further optimization of maintenance processes during nighttime can be carried out to make them more suitable for nighttime environments.

Table 4. Comparison of road quality between unmanned maintenance at daytime and nighttime.

Type	Daytime	Nighttime	Standard Value
Compactability	96.8	95.5	/
Thickness	41.7	43.3	>40 mm
Smoothness	94.5	94.6	/
Permeability coefficient	16.0	10.0	<80 mL/min
Construction depth	1.06	1.12	>0.55 mm
Coefficient of variation for *IRI*	0.07	0.12	/

3. Fuzzy Comprehensive Evaluation of Intelligent Unmanned Maintenance Technology

3.1. Establish Evaluation Index System

The evaluation index system is shown in Figure 5. The road quality, safety, technology application, and socio-economic benefits were selected as the criteria layer evaluation indicators to evaluate unmanned maintenance technology. This is because road quality is an important indicator for measuring the success of unmanned maintenance construction technology. High-quality roads ensure stable and durable facilities post-construction, thereby reducing maintenance costs and the need for subsequent repair work. Furthermore, the safety of the operators and the working environment during the road construction process are equally important indicators. Evaluating safety can consider indicators such as accident rates and the effectiveness of safety management measures to ensure the safety of personnel and equipment during maintenance. Additionally, unmanned maintenance technology typically relies on the support of information technology, such as sensors, drones, and artificial intelligence. Assessing the application of information technology can reflect technological proficiency and innovation, which are significant for enhancing construction efficiency and reducing costs. Lastly, the application of unmanned maintenance technology not only concerns its technical performance but also encompasses its impact on socio-economic factors. Evaluating socio-economic benefits can consider indicators such as project costs, construction periods, and the efficiency of human resource utilization to determine the technology's contribution to overall socio-economic benefits.

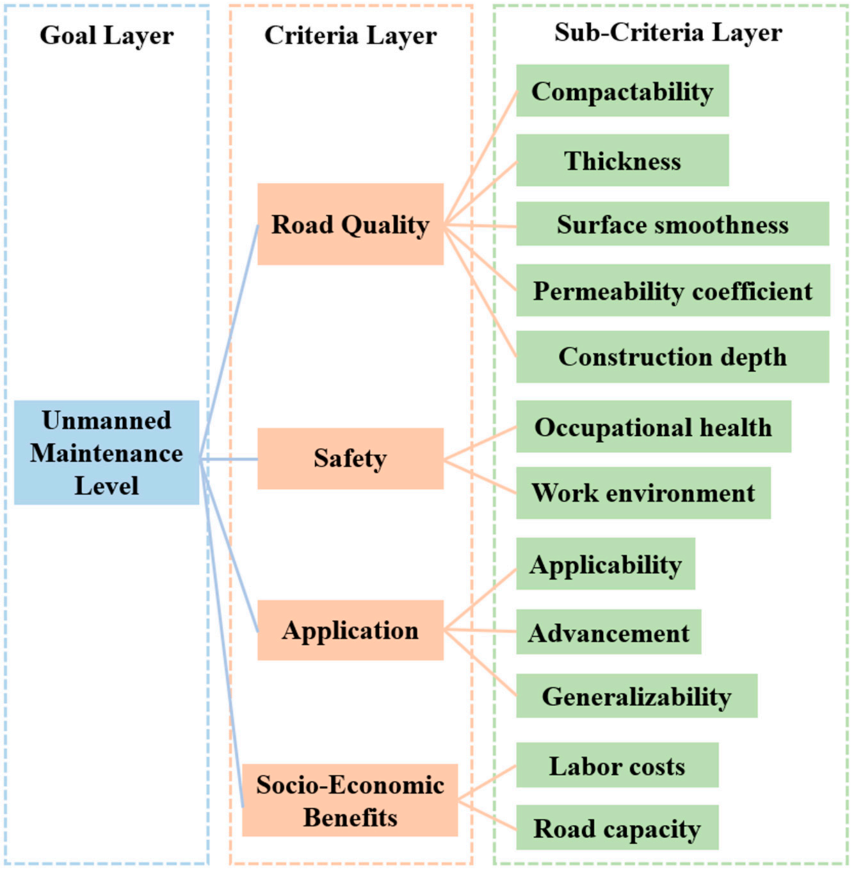

Figure 5. Evaluation index system.

In addition, the reason for selecting compactability, thickness, surface smoothness, permeability coefficient, and construction depth as secondary evaluation indicators for road quality is that these indicators directly reflect the quality of road construction. Indicators such as compactability, thickness, and surface smoothness can measure the structural stability and smoothness of the road surface, while permeability coefficient and construction depth relate to the durability and anti-permeability ability of the road surface. The reason for selecting workplace safety and occupational health safety as secondary evaluation indicators for safety is that workplace safety and occupational health safety are critical factors in ensuring the life safety and health of construction workers. Workplace safety includes safety management and environmental protection at the construction site, while occupational health safety focuses on various health risks faced by construction workers during work. The reason for selecting applicability, advancement, and generalizability as secondary evaluation indicators for technology application is that these indicators can comprehensively evaluate the actual effects and promotion potential of technology in road construction. Applicability considers whether technology can adapt to different construction environments and needs, advancement focuses on whether the technology is at the industry forefront, and generalizability considers whether the technology has the potential for promotion and application in different regions and projects. The reason for selecting labor cost and road capacity as secondary evaluation indicators for socio-economic benefits is that these indicators involve the impact of road construction on the socio-economic aspects. Labor cost directly affects construction costs and efficiency, while road traffic capacity relates to the impact of road construction on traffic flow and travel efficiency, thereby affecting the realization of socio-economic benefits.

3.2. Evaluation Method

In engineering practice, engineers frequently encounter decision-making challenges. The objects under evaluation are influenced by multiple factors and exhibit fuzzy characteristics. Fuzzy refers to concepts with unclear and ambiguous boundaries, such as the relative beauty or ugliness of decorative materials [24]. Hence, there is a need for an evaluation method to consider all relevant factors and address the ambiguity of boundaries. The commonly used evaluation methods include the analytic hierarchy process (AHP), fuzzy comprehensive evaluation method (FCE), Principal Component Analysis, Grey Comprehensive Evaluation Method, etc. The FCE method is one of the most fundamental approaches in fuzzy mathematics, allowing for the evaluation of multiple indicators of an object's state at a comprehensive evaluation level. It is based on the theory of membership degree, which can convert qualitative indicators into quantitative indicators and comprehensively evaluate the membership degree levels of the evaluated objects based on multiple parameters and dimensions. The fuzzy rule base of fuzzy comprehensive evaluation is a fundamental component that governs the decision-making process in detail [25]. It comprises a set of rules that define the relationship between input variables and output assessments within a fuzzy logic system. These rules are typically formulated based on expert knowledge or empirical data. Each rule specifies how input variables, which may have uncertain or imprecise values, contribute to the overall evaluation outcome. By employing fuzzy logic techniques, the rule base accommodates the inherent ambiguity and uncertainty in real-world scenarios, allowing for a more flexible and nuanced decision-making process. Furthermore, in the practical application process of the evaluation system, this study combines the fuzzy comprehensive evaluation method with AHP [26], decomposing factors related to decision-making into objectives and criteria, and conducting qualitative and quantitative analyses on this basis, allowing experts to provide important levels for pairwise comparison of indicators, thereby ensuring higher reliability.

3.2.1. Fuzzy Comprehensive Evaluation

The establishment process of the FCE model includes six main steps: defining the evaluation indicator set, establishing the set of evaluation grades, constructing the membership functions, determining the fuzzy matrix, and forming the fuzzy evaluation vector. The specific steps are shown as follows:

The first step is to establish an evaluation indicator set, which is a collection of various factors that constitute the assessment objects. For the evaluation of maintenance effectiveness, a comprehensive judgment is required from multiple aspects such as road quality, implementation safety, the degree of information technology application, generated socio-economic benefits, etc. All these factors form the set of the evaluation indicator system, namely the evaluation factor set, denoted as $U = \{U_1, U_2, \cdots, U_n\}$. Here, $U_i = (i = 1, 2, \cdots, n)$ represents an evaluation factor, and n is the number of individual factors at the same level.

The second step involves establishing the set of evaluation grades. This is necessary due to the different evaluation values associated with each indicator, often resulting in varying levels such as excellent, good, fair, poor, and so forth, for assessing maintenance effectiveness. It is denoted as $V = \{V_1, V_2, \cdots, V_m\}$. Here, V_j ($j = 1, 2, \cdots$, m) represents the evaluation level standards, providing different grades for each indicator.

The third step is to construct membership functions. After constructing the set of evaluation factors, it is necessary to quantitatively characterize these factors. This involves determining the degree of membership of each factor to the set of evaluation grades, thereby obtaining the fuzzy matrix.

Firstly, the fuzzy evaluation matrix $R_i = (r_{i1}, r_{i2}, \cdots, r_{im})$ is constructed, where R_i is the fuzzy matrix for the ith indicator in the evaluation factors corresponding to each evaluation grade V_i, V_2, $\cdots$, V_m. For the safety, information technology application, and socio-economic benefit indicators, the membership degrees are calculated using the expert scoring method. The same evaluation grade is used for each indicator. Finally, the evaluation data from 20 experts are taken to calculate the membership degrees. The calculation equation for r_{ij} is as follows [26]:

$$r_{ij} = \frac{c_{ij}}{\sum_{j=1}^{m} c_{ij}} \tag{4}$$

where c_{ij} represents the number of occurrences where the ith factor U_i receives the jth comment V_j; r_{ij} (i = 1, 2, $\cdots$, n; j = 1, 2, $\cdots$, m; n is the number of evaluation factors, m is the number of evaluation grades) represents the proportion of occurrences of the indicator factor U_i receiving the comment V_j. For the road quality indicators, membership degrees are calculated using testing data.

The fourth step is to construct a fuzzy matrix based on the membership degree subset, as shown in Equation (5) [27].

$$R = \begin{pmatrix} R_1 \\ \vdots \\ R_n \end{pmatrix} = \begin{pmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nm} \end{pmatrix} \tag{5}$$

The fifth step is to form the fuzzy evaluation vector, which can be calculated by multiplying the weight vector W by the fuzzy matrix R, as shown in Equation (6) [27].

$$B = W \cdot R = (w_1,\ w_2, \ldots, w_n) \begin{bmatrix} r_{11} & \cdots & r_{1m} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{1m} \end{bmatrix} \tag{6}$$

3.2.2. Analytic Hierarchy Process

To obtain the fuzzy evaluation vector, the weight vector W should be obtained. In general, the roles played by various evaluation indicators in a comprehensive evaluation are not the same. The results of the comprehensive evaluation depend not only on the assessments of each factor but also largely on the impact of each factor on the overall evaluation. This requires determining a weight allocation among the evaluation indicators, represented as a fuzzy vector W = (W_1, W_2, $\cdots$, W_n) on set U = {U_1, U_2, $\cdots$, U_n}, where Wi is the weight of the ith evaluation indicator. In this study, the AHP is applied to quantitatively analyze the importance of each indicator and determine the weights of each indicator. The weight calculation can be carried out according to the following steps:

(1) Establishing hierarchical structure model: This step is used to construct a hierarchical organizational model for the evaluation of the application effectiveness of intelligent unmanned maintenance technology, as shown in Figure 5.

(2) Constructing judgment matrix: This step involves constructing the judgment matrices to obtain the relative importance of different evaluation indicators. For each pair of evaluation indicators to be compared, a scale is used to express the relative importance between them. Five basic scales (1, 3, 5, 7, and 9) of absolute numbers can be used, representing equal importance, moderate importance, strong importance, very strong importance, and extreme importance, respectively. The numbers between these scales (2, 4, 6, and 8) express intermediate importance. This method decomposes the evaluation objectives into multiple levels, assessing the relative importance of different factors within each level of the objectives. This study establishes a judgment matrix by inviting experts to quantitatively score the importance of each indicator.

(3) Calculate the maximum eigenvector (λ_{max}) and corresponding eigenvector (α): These parameters can be calculated by Equation (7) [28]:

$$\lambda_{max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(P\alpha)_i}{n\alpha_i} \tag{7}$$

where n is the order of the judgment matrix.

(4) Consistency ratio check. In this step, the consistency index (CI) and consistency ratio (CR) are calculated to conduct a consistency check on the judgment matrix, aiming to enhance the reliability of the AHP, as shown in Equations (8) and (9) [26].

$$CR = \frac{CI}{RI} \quad (8)$$

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (9)$$

where RI is a random consistency index. Generally, if the CR is less than an accepted threshold (typically 0.1), the judgment matrix is considered consistent; otherwise, a reevaluation of the relative importance of pairwise comparisons is necessary.

Finally, the judgment matrices are used to calculate the weight vectors. Finally, obtain the weight values (W_i) and the weight vector $W = (W_1, W_2, \cdots, W_n)$, where $\sum_{i=1}^{n} w_i = 1$.

4. Results and Discussion

4.1. Determination of Evaluation Factors Set and Evaluation Grade Set

As shown in Figure 6, in this study, four criteria layer evaluation indicators, including road quality, safety, application, and socio-economic benefits, were selected to evaluate unmanned maintenance technology. These evaluation indicators were labeled from U_1 to U_5, respectively. Four grades, namely, excellent (V_1), good (V_2), normal (V_3), and poor (V_4), were used to set up the evaluation set. To further quantify the application effect of unmanned maintenance technology, specific scores are assigned to each evaluation grade, resulting in $P = \{P_1, P_2, P_3, P_4\} = \{100, 80, 60, 40\}$. V_1 signifies a very high level of achievement for each indicator, with an excellent application effect of unmanned maintenance technology. V_2 represents a relatively good level of achievement for each indicator, with a good application effect of unmanned maintenance technology. V_3 denotes a normal level of achievement for each indicator, with an average application effect of unmanned maintenance technology, requiring improvement. V_4 indicates a poor application effect of the technology.

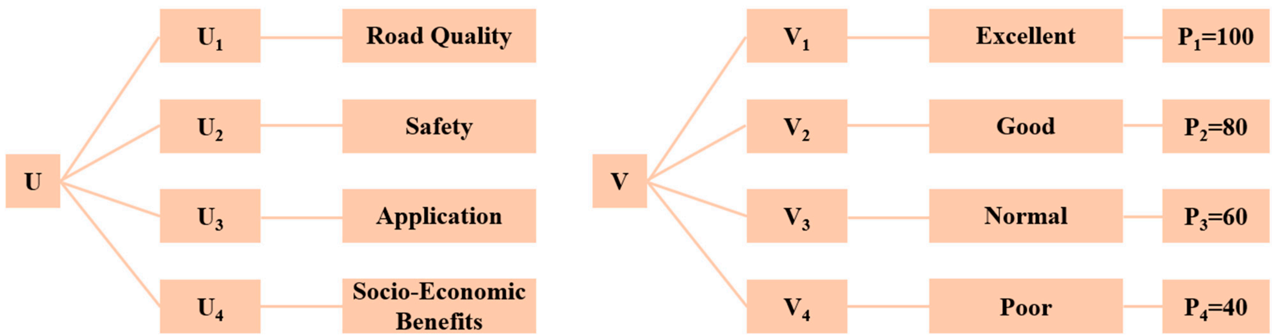

Figure 6. Set of evaluation indicators and evaluation grades.

4.2. AHP for Weight Determination

A panel of 10 experts and 10 on-site maintenance engineering technicians, all involved in the project, are invited to form an evaluation group. Based on the constructed evaluation index system, experts and technicians conduct pairwise comparisons of the indicators at the same level and with the indicators of the previous level. They assign values representing the relative importance, resulting in judgment matrices. The weights for the single-level ranking of the criteria layer and sub-criteria layer evaluation factors are then calculated, and consistency checks are performed. According to the judgment matrix, the weight coefficients for each indicator are obtained, as shown in Table 5.

Table 5. Weight of evaluation factors.

Criteria Layer Evaluation Indicators	Weight	Sub-Criteria Layer Evaluation Indicators	Weight
Road quality	0.510	Compactability (N_1)	0.485
		Thickness (N_2)	0.227
		Surface smoothness (N_3)	0.143
		Permeability coefficient (N_4)	0.089
		Construction depth (N_5)	0.057
Safety	0.330	Occupational health (N_6)	0.25
		Workplace (N_7)	0.75
Application	0.100	Applicability (N_8)	0.623
		Advancement (N_9)	0.239
		Generalizability (N_{10})	0.137
Socio-economic benefits	0.059	Labor costs (N_{11})	0.667
		Road capacity (N_{12})	0.333

The weight set for the criteria layer is {0.51, 0.330, 0.100, 0.059}, indicating that the importance of the evaluation indicators is road quality (U_1) > safety (U_2) > application (U_3) > socio-economic benefits (U_4). This further emphasizes that road quality is the most crucial factor in evaluating the effectiveness of intelligent unmanned maintenance technology, ensuring that the technologies and measures applied in maintenance projects meet the required standards. Therefore, strict requirements should be imposed on the implementation process of the target project, with the quality of the road repeatedly checked. During the implementation process, there should be ample communication and discussion between management personnel and maintenance technicians to continuously optimize and improve, ensuring that the applied unmanned construction and maintenance technology meets the standards for maintenance construction. Safety (U_2) in maintenance projects holds the second-largest weight among the criteria layer evaluation indicators, indicating that highway maintenance projects prioritize safety. Managers should ensure safety through technical measures to guarantee the safety of project implementation.

From Table 5, for road quality (U_1), three indicators, including compactability, thickness, and surface smoothness, have relatively large weights, all exceeding 0.140. This suggests that when applying unmanned maintenance technology, attention should be focused on paving and compaction operations, strictly adhering to process requirements to ensure that all test indicators meet standard requirements. In the criteria layer indicator safety (U_2), the proportion of workplace safety is the largest, indicating that the safety of engineering facilities and the surrounding environment is a key focus during the implementation of highway maintenance projects. For the application of intelligent technology, the highest weight is assigned to applicability, highlighting the significant potential this technology holds for future utilization within the domain of road maintenance. In terms of socio-economic benefits, it is evident that labor costs carry significant weight, reflecting the substantial advantage of unmanned construction in reducing labor costs compared to traditional manual maintenance construction methods.

4.3. Fuzzy Comprehensive Evaluation

The membership degrees of the criteria layer evaluation indicators to different evaluation grades are illustrated in Figure 7. It can be observed that both safety and socio-economic benefits have membership degrees greater than 0.8, reaching the excellent grade (V_1). Especially for socio-economic benefits, there are no instances of the normal grade (V_3) and poor grade (V_4), and they have the highest membership degree (0.883) on the excellent grade among all evaluation indicators. It can be concluded that the socio-economic benefits generated by the application of unmanned maintenance technology are quite favorable. In addition, road quality has a membership degree of 0.785 in the excellent grade (V_1), which is the smallest among the four indicators. Moreover, the proportion of cases categorized as poor is relatively large, highlighting the need for further refinement and improvement.

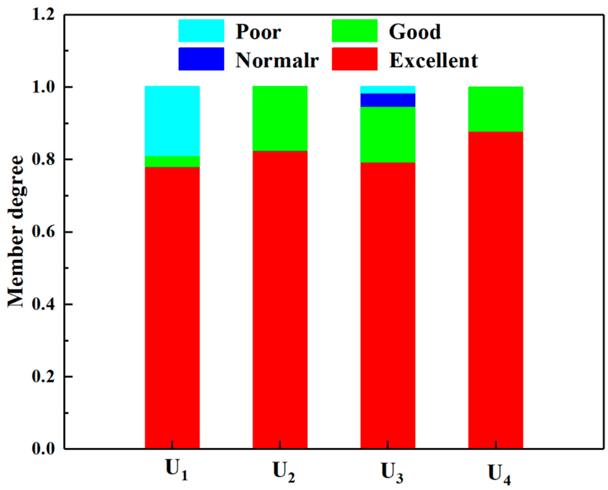

Figure 7. Member degrees of criteria layer evaluation indicators.

The membership degrees of the sub-criteria layer evaluation indicators to different evaluation grades are illustrated in Figure 8. It can be observed that compactability (N_1), thickness (N_2), surface smoothness (N_3), and generalizability (N_{10}) all exhibit a poor grade (V_4). Compactability and thickness are identified as weak indicators, and the permeability coefficient (N_4) and construction depth (N_5) belong to the excellent grade with a membership degree of 1, aligning with the analysis results of the inspection data. In addition, generalizability (N_{10}) has the lowest membership degree in the excellent grade (V_1), standing at only 0.5, indicating a need for significant optimization and improvement. Smoothness (N_3), occupational health and safety (N_7), and labor cost (N_{11}) show relatively high membership degrees for the excellent grade (V_1), indicating that unmanned maintenance technology for highway pavements performs well in terms of labor cost and occupational health and safety aspects.

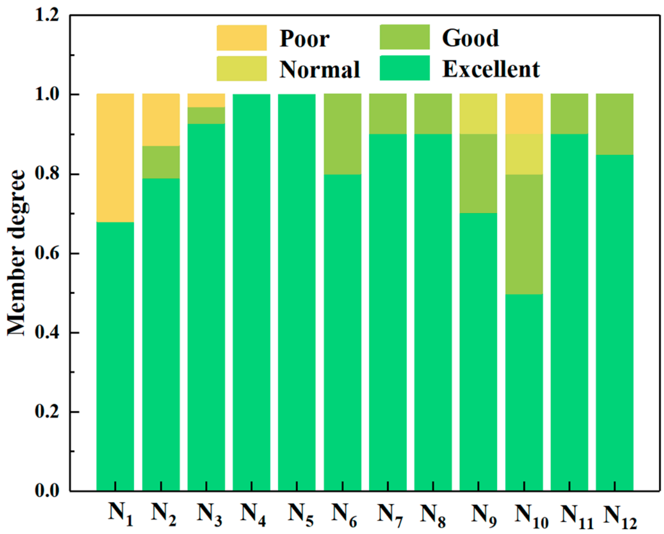

Figure 8. Member degrees of sub-criteria layer evaluation indicators.

Finally, the comprehensive evaluation vectors of all the involved criteria layer evaluation indicators are calculated, as shown in Equations (10)–(13), giving the comprehensive evaluation vectors of all the involved asphalt mastics:

$$U_1 = W_1 \times R_1 = (0.785,\ 0.026,\ 0,\ 0.189) \tag{10}$$

$$U_2 = W_2 \times R_2 = (0.825,\ 0.175,\ 0,\ 0) \tag{11}$$

$$U_3 = W_3 \times R_3 = (0.797,\ 0.151,\ 0.038,\ 0.014) \tag{12}$$

$$U_4 = W_4 \times R_4 = (0.883,\ 0.117,\ 0,\ 0) \tag{13}$$

So, the fuzzy matrix can be obtained, as follows:

$$R = \begin{pmatrix} 0.785 & 0.026 & 0 & 0.189 \\ 0.825 & 0.175 & 0 & 0 \\ 0.797 & 0.151 & 0.038 & 0.014 \\ 0.883 & 0.117 & 0 & 0 \end{pmatrix} \tag{14}$$

Combined with the weight vector $W = (0.51, 0.33, 0.1, 0.059)$ for the criteria layer indicators, the fuzzy vector B can be obtained:

$$\mathrm{B} = \mathrm{W} \times \mathrm{R} = (0.805,\ 0.093,\ 0.004,\ 0.098) \tag{15}$$

It can be observed that the membership degree of unmanned maintenance technology in the excellent grade is the highest, reaching 0.805. In other words, the final comprehensive evaluation result of unmanned maintenance technology is rated as excellent. To further quantify the application effect of unmanned maintenance technology, each grade level is assigned to specific scores, namely, four evaluation grades (V_1, V_2, V_3 and V_4) with assigned scores of 100, 80, 60, and 40, respectively. In this case, the comprehensive score F is calculated by Equation (16):

$$\mathrm{F} = \mathrm{B} \times \mathrm{P}^{\mathrm{T}} \tag{16}$$

The quantified value F for the overall evaluation of the application effectiveness of intelligent unmanned maintenance technology is 92.10. This indicates that the application's effectiveness is very good.

5. Conclusions

In this study, intelligent unmanned road construction technology is utilized to explore its potential in road maintenance engineering. The engineering technical indicators of asphalt pavement after unmanned maintenance are investigated and compared. Meanwhile, using the analytic hierarchy process (AHP) and fuzzy evaluation method, an evaluation index model that considered road quality, safety, technology application, and socio-economic benefits was established to assess the application effectiveness of intelligent unmanned maintenance technology. The main conclusions can be drawn as follows:

(1) The road quality of the unmanned maintenance method is inferior to traditional manual maintenance methods, especially in terms of the compactability and surface smoothness at the starting and ending points of the maintenance section, which need improvement. However, the quality of the unmanned maintenance method still meets specification requirements.

(2) The weight set of the four types of criteria layer evaluation indicators suggests that the importance of the evaluation indicators follows the order of road quality (U_1) > safety (U_2) > application (U_3) > socio-economic benefits (U_4). Consequently, stringent requirements must be placed on the implementation process of the target project, with continual monitoring of road quality.

(3) Regarding socio-economic benefits, labor costs hold considerable weight, underscoring the significant advantage of unmanned construction in reducing labor costs compared to traditional manual maintenance construction methods.
(4) Both safety and socio-economic benefits exhibit membership degrees exceeding 0.8, attaining the excellent grade (V_1). Furthermore, road quality attains a membership degree of 0.785 in the excellent grade (V_1), the lowest among the four indicators. Additionally, the proportion of road quality classified as poor is relatively high, emphasizing the necessity for further refinement and enhancement.
(5) The membership degree of unmanned maintenance technology in the excellent grade is the highest, reaching 0.805, and the quantified value for the overall evaluation of the application effectiveness of unmanned maintenance technology is 92.10. This means that the final comprehensive evaluation result of unmanned maintenance technology is rated as excellent.

The integrated technology used in this study enables the precise edge-rolling of road boundaries and the unmanned compaction of standardized road sections based on satellite positioning. However, in scenarios such as tunnels or under bridges where satellite signals are obstructed, the lack of high-precision location information leads to increased trajectory errors. In the future, a multi-sensor fusion positioning method can be used to address the localization issues of unmanned equipment in the absence of satellite signals, thus improving adaptability to different scenarios. In addition, it is necessary to align with the industry's development stages, thus optimizing and enhancing the established index system and evaluation methods.

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