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Application of Automated Pavement Inspection Technology in Provincial Highway Pavement Maintenance Decision-Making

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Abstract: Taiwan's provincial highways span approximately 5000 km and are crucial for connecting cities and towns. As pavement deteriorates over time and maintenance funds are limited, efficient pavement inspection and maintenance decision-making are challenging. Traditional inspections rely on manual visual assessments, consuming significant human resources and time without providing quantitative results. This study addresses current maintenance practices by introducing automated pavement damage detection technology to replace manual surveys. This technology significantly improves inspection efficiency and reduces costs. For example, traditional methods inspect 1 km per day, while automated survey vehicles cover 4 km per day, increasing efficiency fourfold. Additionally, automated surveys reduce inspection costs per kilometer by about 1.7 times, lowering long-term operational costs. Inspection results include the crack rate, rut depth, and roughness (IRI). Using K-means clustering analysis, maintenance thresholds for these indicators are established for decision-making. This method is applied to real cases and validated against actual maintenance decisions, showing that the introduced detection technology efficiently and objectively guides maintenance decisions and meets the needs of maintenance units. Finally, the inspection results are integrated into a pavement management platform, allowing direct maintenance decision-making and significantly enhancing management efficiency.

Keywords: automated pavement damage detection technology; K-means clustering analysis; maintenance decision-making; pavement management platform

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1. Introduction

This study first explores the current pavement inspection methods and maintenance decision-making approaches for provincial highways, referencing pavement maintenance decision methods from various countries. Subsequently, automated pavement damage detection methods are introduced, and corresponding maintenance decision-making approaches are developed. Practical case applications and validations are then conducted to ensure that the decision-making methods established in this study meet the needs of maintenance units. Finally, a pavement management platform is established that integrates the pavement inspection results and decision-making methods into the platform, enabling maintenance managers to manage pavements objectively and efficiently in the future.

1.1. Current Status of Provincial Highway Inspections

Currently, pavement damage detection on Taiwan's provincial highways primarily relies on visual inspections. This traditional method is time-consuming and labor-intensive, presenting significant economic, social, and environmental drawbacks. Economically, traditional methods require extensive manpower and time, leading to high costs and low efficiency. For instance, traditional inspections need three people and 12 h, whereas automated survey vehicles need only two people and 2 h. Additionally, traditional methods involve extensive post-processing, further increasing the time and labor costs. Socially, inspection personnel face prolonged exposure to traffic risks. The reliance on significant human resources and the low efficiency of traditional inspections impact overall decision-making, potentially delaying maintenance plans. Environmentally, traditional methods require substantial paper for data recording and analysis, burdening the environment. Therefore, advanced technologies are necessary to improve the inspection efficiency and effectiveness, reduce costs, minimize environmental impact, and enhance worker safety and efficiency [1,2].

1.2. Current Status of Pavement Maintenance for Provincial Highways

Provincial highways in Taiwan are positioned between expressways and urban roads in terms of road hierarchy. With traffic volume and speed requirements second only to expressways, these highways are crucial for connecting the northern and southern regions of Taiwan. Given the extensive demands for pavement inspection and maintenance, enhancing efficiency and reducing costs through advanced technologies has become a critical issue. In Taiwan, provincial highways primarily undergo regular inspections focusing on the International Roughness Index (IRI) and pavement damage. The IRI is measured using an inertial profiler, while pavement damage is visually inspected by engineers, including cracks, deformations, surface damage, and other defects [3]. Maintenance units analyze and evaluate the conditions based on the IRI and pavement damage, classifying road sections into "Maintenance Sections" and "Observation Sections". Maintenance work is performed on "Maintenance Sections", while "Observation Sections" continue to be monitored to observe their deterioration. This shows that the current pavement inspection and maintenance decision-making for provincial highways require substantial human resources and time costs.

1.3. Pavement Maintenance Strategies in Different Countries

In recent years, maintenance units in various countries have drawn on past experiences, selecting significant pavement indicators for inspection and establishing decision-making grading intervals for each indicator. Maintenance decisions are made based on these grading intervals. This section evaluates the pavement inspection and decision-making methods in different countries.

- The American Association of State Highway and Transportation Officials (AASHTO) collected 10 years of pavement observation data and formed a panel of pavement experts to evaluate these data. The panel identified parameters and performed mathematical analysis to establish the Present Serviceability Index (PSI), which is used in the AASHTO Guide for Design of Pavement Structures for pavement thickness design and overlay decision analysis. The PSI is calculated using the example in Equation (1) [4], which involves parameters such as pavement smoothness, surface cracking, repair level, and rutting.

$$\mathrm{PSI} = 5.03 - 1.91\log(1 + \mathrm{SV}) - 0.01\sqrt{\mathrm{C} + \mathrm{P}} - 0.21\overline{\mathrm{RD}}^2 \quad (1)$$

where:

SV = Smoothness Variation
C + P = Cracking and Patching Rate
RD = Rutting Depth

- In 2012, the United States passed the MAP-21 funding bill, which includes pavement maintenance strategies proposed by the Federal Highway Administration (FHWA) [5]. This strategy involves inspecting the IRI, crack rate, and rutting depth, setting grading intervals for these indicators into the "Good", "Fair", and "Poor" categories, as shown in Table 1.

Table 1. Grading intervals for various indicators.

Grading	IRI (m/km)	Crack Rate (%)	Rutting (mm)
Good	<1.5	<5	<5
Fair	1.5–2.7	5–10	5–10
Poor	>2.7	>10	>10

(Source: Compiled from FHWA-HIF-17-022, 2016 [5]).

- In South Korea, pavement inspections for the IRI, crack rate, and rutting depth are conducted, and the National Highway Pavement Condition Index (NHPCI) is calculated based on these results, using the example in Equation (2) [6]. Jin-Hoon Jeong analyzed data from South Korean highways [7], setting maintenance thresholds for the IRI, crack rate, and rutting depth at a 95% confidence level for different warranty periods (3, 5, and 7 years), as shown in Table 2.

$$\text{NHPCI} = \frac{1}{(0.33 + 0.003 \times X_{CR} + 0.004 \times X_{RD} + 0.0183 \times X_{IRI})^2} \tag{2}$$

where:

XCR = Crack Rate (%)
XRD = Rutting Depth (mm)
XIRI = IRI (m/km)

Table 2. Maintenance thresholds for pavement inspection indicators on South Korean highways.

Pavement Inspection Indicator	Warranty Period	Maintenance Threshold
Crack Rate (%)	3	15
	5	18
	7	20
Rutting (mm)	3	12
	5	14
	7	15
IRI (m/km)	-	3.7

(Source: Compiled from Jin-Hoon Jeong, 2014, [7]).

- In Japan, pavement inspections focus on the IRI, crack rate (including the surface repair rate), and rutting depth. The Ministry of Construction's Civil Engineering Research Institute uses historical data to develop the Maintenance Control Index (MCI) through multiple regression analysis, with the calculation shown in the example in Equation (3) [8]. Additionally, the Metropolitan Expressway Company in Japan develops maintenance strategies based on the IRI, crack rate (including the surface repair rate), and rutting depth inspection results [9]. The criteria for determining the inspection results are shown in Table 3, where the pavements are categorized into six grades (A, B1, B2, B3, C, and D) based on the average rutting depth, maximum rutting depth, average crack rate, and maximum crack rate. Maintenance status is broadly divided into three categories: "Good Condition" for grade D, "Track Required" for grades C and B3, and "Maintenance Required" for grades B2, B1, and A.

$$\text{MCI} = 10 - 1.48\text{C}^3 - 0.29\text{D}^{0.7} - 0.47\sigma^{0.2} \tag{3}$$

where:

C = Crack Rate (%)
D = Rutting Depth (mm)
σ = Smoothness Variation (mm)

Table 3. Criteria for determining pavement inspection results on the Metropolitan Expressway in Japan.

Grading	Maintenance Method	Crack Rate (%)		Rutting (mm)	
		Average Crack Rate (%)	Maximum Crack Rate (%)	Average Rutting Depth (mm)	Maximum Rutting Depth (mm)
A	Emergency Repair	-	>30	-	-
B1	Preventive Maintenance	>20	25–30	>20	>25
B2	Maintenance Required	18–20	20–25	18–20	20–25
B3	Track Required	16–18	16–20	16–18	16–20
C	Regular Tracking	12–16	12–16	12–16	12–16
D	Good Condition	<12	<12	<12	<12

(Source: Compiled from the Metropolitan Expressway Company, 2017 [9]).

- In summary, most countries currently inspect the IRI, crack rate, and rutting depth of pavements. Therefore, this study also collects relevant grading standards for these inspection indicators, including the ASTM D6433 [10] grading for rutting damage shown in Table 4. Additionally, referencing the World Bank Technical Report [11], the relationship between the road grade and pavement smoothness range is indicated in Table 5. "New Pavement", "Old Pavement", and "Damaged Road" were selected for subsequent decision comparison analysis.

Table 4. Rutting depth grading intervals.

Grading	Light Rutting	Moderate Rutting	Severe Rutting
Rutting Depth (mm)	6–13	13–25	>25

(Source: Compiled from ASTM D6433, 2023 [10]).

Table 5. Relationship between road grade and IRI.

Road Grade	IRI (m/km)
Airport Runways, Expressways	0.25–1.75
New Pavement	1.25–3.50
Old Pavement	2.25–5.75
Well-Maintained Unpaved Roads	3.25–10.00
Damaged Roads	4.00–11.00
Rough Unpaved Roads	>7.75

(Source: Compiled from World Bank Technical Paper, 1990 [11]).

1.4. Automated Pavement Inspection Methods in Different Countries

- Chin-Yuan Zheng [12] utilized a self-developed Automated Pavement Damage Image Detection System (APDIDS) for automated pavement surveys. The system includes two main designs: the first is a camera bracket fixed to the vehicle body and a camera housing mounted on the bracket, and the second is a distance sensor mounted on the wheel that rotates with it. After processing the pavement images obtained, steps such as pavement image synthesis, lighting correction, binarization, and damage enhancement are performed to obtain better images. Then, the pavement damage image extraction and classification methods are used for recognition, followed by relevant calculations and analysis of the recognition results, as shown in Figure 1. The system can recognize transverse cracks, longitudinal cracks, alligator cracking, patches, and potholes with a recognition rate of up to 91%.

- The Australian Road Research Board (ARRB) has been committed to the development of pavement inspection equipment for over 50 years. The Hawkeye Automated Detection Vehicle is highly functional, capturing road information used by engineers and road users. Its functions include highway pavement asset management, a pavement image capture system, a digital profile elevation system, a GPS/DGPS system, and a DIS system. Figure 2. shows the Hawkeye 2000 detection vehicle. The equipment includes two high-performance 3D laser elevation sensors mounted on the rear of the survey vehicle, positioned vertically above the pavement. Each laser elevation sensor includes a high-power laser and a 3D camera mounted on a rotating laser axis, where the laser light and camera images are used to measure pavement transverse profiles with a resolution of 0.5 mm [13].
- Shih-Ming Hsu [14] used images captured by a dashcam to recognize pavement damage, employing SLIC Superpixels as the main recognition principle. Through a two-stage image clustering process, pavement damage in the images is identified. The damage clusters are then classified to identify patches, potholes, longitudinal and transverse cracks, and alligator cracking, integrating PCI numerical calculations. The results show that this method closely matches manual inspection values and significantly reduces the labor and time costs of PCI measurement.
- Brian Mulry [15] applied the Laser Crack Measurement System (LCMS) to airport runways, using 3D sensors for automated measurements, as shown in Figure 3. The system can identify cracks, joints, pavement texture, patches, spalling, and roughness and can calculate rutting and depressions using laser-measured elevations. The detection speed can exceed 100 km/h.
- Ianca Feitosa explored the application of drones in pavement inspection technology [16]. The article reviews the existing literature, focusing on the use of drones in pavement inspection and future development trends. Drones equipped with high-resolution cameras and advanced image processing technology can generate three-dimensional surface models and detect various types of pavement defects, including longitudinal cracks, transverse cracks, alligator cracks, potholes, ruts, corrugations, and other surface deformations. Compared to traditional three-dimensional laser scanning, the use of drones offers several advantages, such as reducing on-site inspection costs, improving data collection accuracy, lowering ground operation risks, and accelerating data processing speeds.

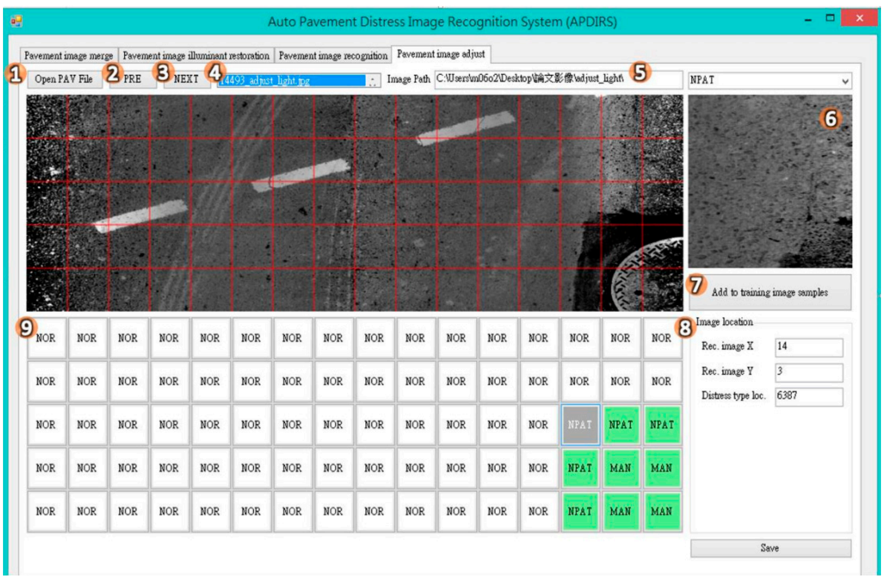


Figure 1. APDIDS pavement damage recognition results. (Source: Compiled from Zheng, J.-Y, 2014 [12]).

Figure 2. Hawkeye 2000 Detection Vehicle. (Source: Compiled from ARRB Systems, 2021, [13]).

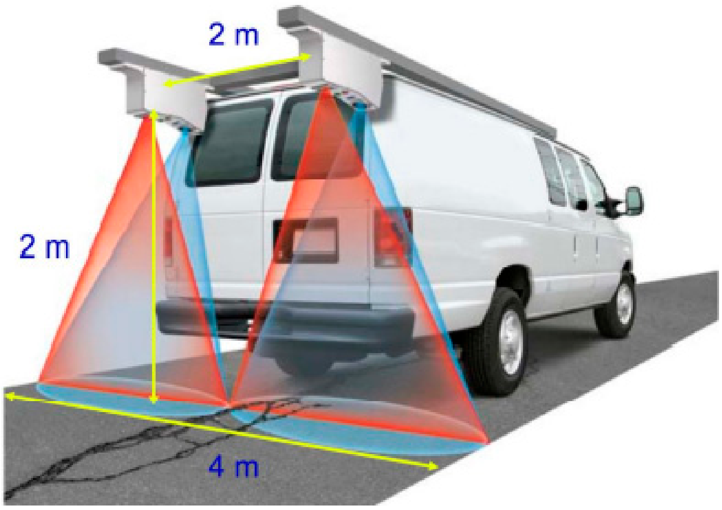


Figure 3. LCMS Detection Vehicle. (Source: Compiled from Brian Mulry, 2015, [15]).

2. Introduction of Efficient Pavement Inspection Methods

2.1. Pavement Inspection Indicators

This section compares the current inspection indicators used by provincial highway maintenance units with those used by various countries, as shown in Table 6, to establish better pavement inspection indicators. From the comparison results, it is evident that the inspection indicators can generally be categorized into two main types: pavement smoothness indicators and pavement damage indicators. Therefore, this study will further analyze these two types of indicators to establish a more comprehensive pavement inspection and maintenance decision-making method.

- Pavement Smoothness Indicators: The smoothness indicators used by various units include the International Roughness Index (IRI) and the smoothness variation. Considering that most pavement smoothness assessments currently use the IRI and that provincial highway maintenance units also use the IRI, this study will continue to use the IRI as the smoothness inspection indicator.
- Pavement Damage Indicators: The types of pavement damage indicators used by various units vary slightly. However, cracks, surface repairs, and rutting depth are commonly used in maintenance strategies and are also referenced by provincial highway maintenance units. Therefore, this study will use cracks, surface repairs, and rutting depth as pavement damage inspection indicators.

Table 6. Comparison of pavement inspection indicators.

Maintenance Strategy	Pavement Inspection Indicators	
	Pavement Smoothness Indicators	**Pavement Damage Indicators**
Provincial Highway Maintenance Units	IRI	Cracks, surface damage, deformations (ruts and depressions), and other damage.
Pavement Present Serviceability Index	Smoothness Variation	Cracks, surface repairs, rutting.
US Interstate Highway Maintenance Strategy	IRI	Cracks, rutting.
South Korea Pavement Maintenance Strategy	IRI	Cracks, rutting.
Japan Pavement Maintenance Strategy	Smoothness Variation	Cracks, surface repairs, rutting.

2.2. Pavement Inspection Methods

2.2.1. Automated Pavement Inspection Vehicle

This study introduces the use of an Automated Pavement Inspection Vehicle to enhance the inspection efficiency. The inspection vehicle is shown in Figure 4. Crack measurements are performed using linear laser scanning to capture binary image signals of the road surface; the rutting depth is measured using linear laser scanning combined with a high-speed camera to capture three-dimensional signals at fixed distances; the IRI is measured using displacement sensors combined with vertical accelerometers and distance sensors along the lane direction, with the IRI value calculated from these three devices' results [17]. Additionally, the inspection vehicle is equipped with a front camera to record the inspection conditions, covering a 5 m range in front of the vehicle. The maximum speed limit for inspection is 100 km/h. To avoid laser scattering errors caused by wet pavement, inspections must be conducted on dry surfaces. The accuracy requirements for the inspection vehicle used in this study are shown in Table 7. The study further divides the pavement into single lanes, with each 100 m as a unit (referred to as pavement units) for inspection and analysis.

Figure 4. Automated Pavement Inspection Vehicle.

Table 7. Accuracy requirements for the pavement inspection vehicle.

Item	Accuracy Range
Distance	Error within ±0.1% of the actual measurement.
Cracks	Identifiable width of 1 mm or more.
Rutting	Error within ±3 mm of the actual measurement.
IRI	Error within ±5% of the verification unit's IRI measurement.

2.2.2. Analysis of Inspection Results

Data collected by various devices on the Automated Pavement Inspection Vehicle are analyzed and integrated using pavement condition analysis software, producing a pavement condition report. An example of the inspection results is shown in Figure 5.

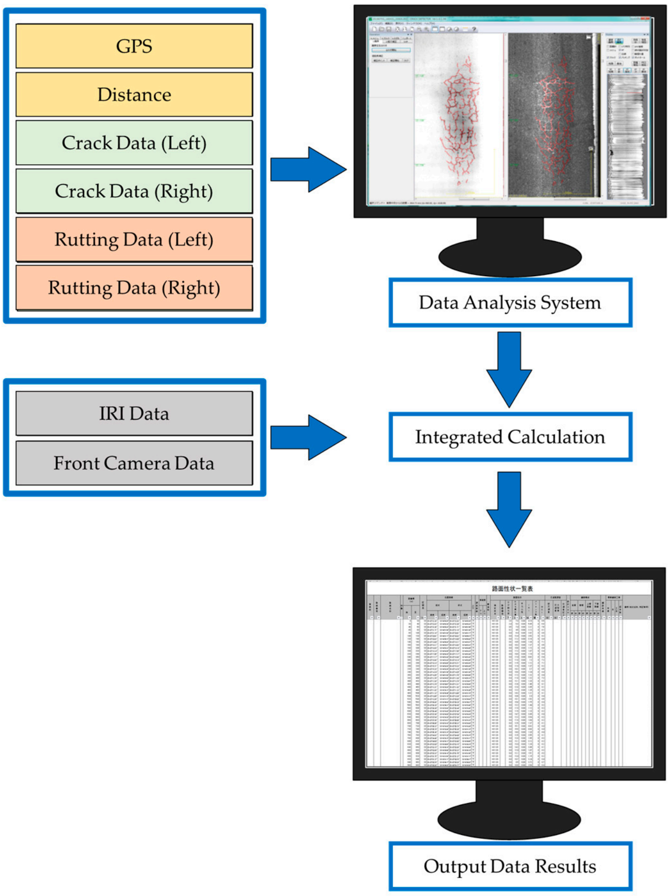


Figure 5. Data analysis process for Automated Pavement Inspection Vehicle.

- Crack Rate Inspection and Analysis

The crack rate calculation method is based on the area ratio. The steps are as follows: first, divide the inspected road into a grid of 0.5 m by 0.5 m. Next, calculate the number of cracks and the repair area ratio within each grid. Finally, compute the crack rate by multiplying the number of grids with the corresponding reduction rate, as shown in Table 8. An example of the calculation and the results are shown in Figure 6 and Table 9.

Table 8. Crack rate reduction rate.

Damage Type	Number or Ratio within Grid	Calculation Area (%)
Cracks (count)	1	60
	≥2	100
Repair Area (%)	0~25%	0
	25~75%	50
	≥75%	100

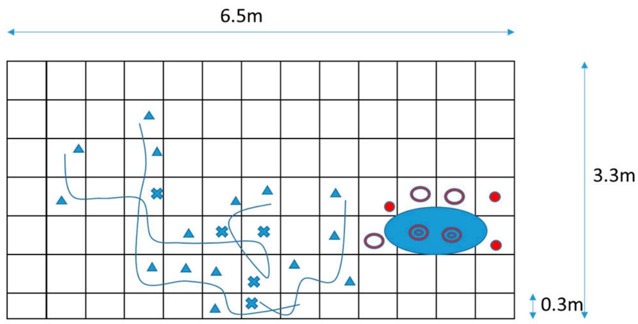


Figure 6. Pavement crack rate inspection example.

Table 9. Pavement crack rate calculation example.

Damage Type	Crack Area
≥2 cracks (✖)	0.25 m^2 (grid area) × 4 (grids) = 1 m^2
	0.15 m^2 (grid area) × 1 (grids) = 0.15 m^2
1 crack (▲)	0.15 m^2 (60% grid area) × 14 (grids) = 2.1 m^2
	0.09 m^2 (60% grid area) × 1 (grid) = 0.09 m^2
Repair Area 0–25% (●)	0 m^2 (0% grid area) × 3 (grids) = 0 m^2
Repair Area 25–75% (○)	0.125 m^2 (50% grid area) × 3 (grids) = 0.375 m^2
Repair Area ≥ 75% (◎)	0.25 m^2 (grid area) × 2 (grids) = 0.5 m^2
Crack Rate = 4.215 (crack area)/21.45 (total area) × 100 = 19.65%	

- Rutting Depth Inspection and Analysis

The rutting depth is measured using linear laser scanning technology to measure pavement elevation changes. The specific method is as follows: if the center elevation is higher than the side elevations, the raised center part is used as the reference line; if the center elevation is lower than the side elevations, the raised sides are connected as the reference line. The depth from this reference line to the deepest part of the wheel tracks (D1 and D2) is measured, and the maximum depth is taken as the rutting depth, as shown in Figure 7.

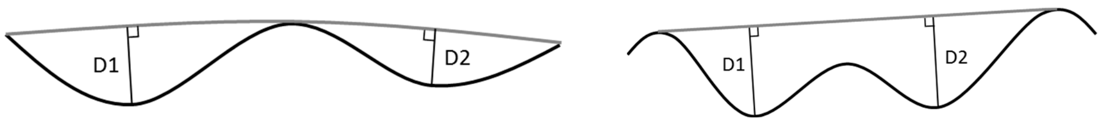


Figure 7. Rutting depth measurement example. (**a**) Center elevation higher than sides; (**b**) Center elevation lower than sides.

- IRI Inspection and Analysis

The IRI is defined based on the average rectified slope, simulating the cumulative elevation difference of a single wheel track as a vehicle travels at 80 km/h over the test road profile, divided by the test road length. This study uses a common inertial profiler for measurement, with the results expressed in meters per kilometer (m/km).

2.3. Benefits of Applying Automated Pavement Inspection Vehicles

- Improved Work Efficiency
  Automated Pavement Inspection Vehicles offer significant advantages in improving work efficiency. Traditional manual visual inspections require two inspectors and two

traffic control personnel to conduct walking inspections. Including data processing and analysis time, an average of 1 km can be inspected per day. In contrast, using an Automated Pavement Inspection Vehicle requires only one driver, and inspections can be performed at normal driving speeds. The backend system can automatically recognize and complete 4 km of inspection per day on average, improving the inspection efficiency by four times compared to traditional methods. Additionally, in terms of work safety, walking inspections require inspectors to walk on busy roads, increasing the risk of accidents. In contrast, Automated Pavement Inspection Vehicles can perform inspections safely under better protective measures, reducing the risk of inspectors being exposed to hazardous environments.

- Reliability of Inspection Results
  The application of Automated Pavement Inspection Vehicles also demonstrates higher reliability in the inspection results. Equipped with advanced technology, Automated Pavement Inspection Vehicles enhance the spatial and detection accuracy, and automated processing reduces human error. Compared to manual inspections, which rely on the experience and observational skills of personnel, Automated Pavement Inspection Vehicles provide more consistent and accurate data.
- Economic Benefits
  In terms of economic benefits, although the equipment cost and initial investment for Automated Pavement Inspection Vehicles are higher, their inspection speed and reduced manpower requirements lower the long-term operating costs. Analyzing the economic benefits based on the inspection testing fees commissioned by maintenance units, the cost per kilometer of inspection is compared in Table 10. Automated Pavement Inspection Vehicles can reduce inspection costs by 1.7 times compared to manual inspections. Analyzing the long-term operational benefits, Automated Pavement Inspection Vehicles indeed offer economic advantages and high competitive value.

Table 10. Inspection cost analysis.

	Inspection and Analysis Cost (USD/km)	Human Resource Cost (USD/km)	Total Cost (USD/km)
Traditional Manual Inspection	35	188	223
Automated Pavement Inspection Vehicle	85	47	132

3. Application of Pavement Inspection Indicators to Maintenance Decision-Making

3.1. Developing Maintenance Decision-Making Methods for Provincial Highways

This study focuses on pavement inspection indicators such as the crack rate, rutting depth, and IRI, referencing maintenance decision strategies from various countries. The US MAP-21 classifies inspection values into three categories: “Good”, “Fair”, and “Poor”, while Japan has six grading categories, broadly divided into “Good Condition”, “Requires Monitoring”, and “Requires Maintenance”.

Currently, provincial highway maintenance units classify maintenance strategies into “Maintenance Sections” and “Observation Sections”. To allocate maintenance resources effectively, this study refers to the US and Japanese maintenance strategies, further classifying sections into “Maintenance Sections”, “Continuous Monitoring Sections”, and “Good Condition Sections”. Considering the widespread application and reliability of the K-means clustering analysis method, this study adopts this method for grading pavement inspection indicators, classifying sections as “Maintenance Sections”, “Continuous Monitoring Sections”, and “Good Condition Sections” for the maintenance decision-making of Taiwan’s provincial highways.

3.2. Grading Analysis of Inspection Indicators

3.2.1. Clustering Analysis Method

The K-means clustering analysis method involves selecting K initial cluster centers, where K is the number of desired clusters. The method calculates the distance of each observation to each cluster center, assigning each observation to the nearest cluster. This process is repeated until no data points can be moved, as follows [18]:

- Initialization: Specify K clusters and randomly select K data points as cluster centers.
- Assign Data Points: Calculate the distance using simple Euclidean distance, assigning each data point to the nearest center.
- Calculate Averages: Recalculate the center point of each cluster.
- Clustering: Assign each point to the K clusters, ensuring each point is in the nearest cluster center.

3.2.2. Analysis of Inspection Data

- Inspection Range

This study selects the "Provincial Highway No. 2 from 4K+000 to 8K+000 and from 23K+000 to 27K+000", totaling 400 pavement units, for inspection based on the method in Section 2.2, including the crack rate, rutting depth, and IRI. The data are then subjected to K-means clustering analysis for grading the inspection indicators.

1. Provincial Highway No. 2 from 4K+000 to 8K+000, inner, middle, and outer lanes in both directions, totaling 240 pavement units.
2. Provincial Highway No. 2 from 23K+000 to 27K+000, inner and outer lanes in both directions, totaling 160 pavement units.

- Analysis Results of Inspection Indicators

This study evaluates the inspection results using the K-means clustering analysis method to analyze data for the crack rate, rutting depth, and IRI. Data from 400 pavement units on Provincial Highway No. 2 from 23K+000 to 27K+000 and from 4K+000 to 8K+000 are analyzed using K-means clustering, dividing each indicator into three clusters. The specific analysis process and results are as follows:

1. Data Collection and Organization:

Collect the crack rate, rutting depth, and IRI data from the mentioned sections, reflecting the condition and quality of the pavement.

2. K-means Clustering Analysis:

Use K-means clustering to divide the data points into three clusters, each representing a group of pavement units with similar characteristics. The analysis results are shown in Tables 11–13.

3. Cluster Grading Definition:
   - ➢ Define Cluster 1 as "Good", indicating sections in good condition with no immediate maintenance required.
   - ➢ Define Cluster 2 as "Continuous Monitoring", indicating sections that need monitoring to promptly detect pavement issues.
   - ➢ Define Cluster 3 as "Requires Maintenance", indicating sections in poor condition that need maintenance work.

Table 11. Crack rate clustering analysis results.

Clustering Analysis Results	Cluster 1	Cluster 2	Cluster 3
Maintenance Grading Definition	Good	Continuous Monitoring	Requires Maintenance
Crack Rate (%)	0–4.5	4.6–12.5	12.8–29.5

Table 12. Rutting depth clustering analysis results.

Clustering Analysis Results	Cluster 1	Cluster 2	Cluster 3
Maintenance Grading Definition	Good	Continuous Monitoring	Requires Maintenance
Rutting Depth (mm)	2.1–4.6	4.7–7.0	7.1–12.4

Table 13. IRI clustering analysis results.

Clustering Analysis Results	Cluster 1	Cluster 2	Cluster 3
Maintenance Grading Definition	Good	Continuous Monitoring	Requires Maintenance
IRI	1.4–3.11	3.13–4.42	4.5–7.00

3.3. Maintenance Decision-Making Based on Grading of Inspection Indicators

Based on the results of the K-means clustering analysis in Section 3.2, this study further sets grading thresholds for the crack rate, rutting depth, and IRI. The upper limit of Cluster 1 is set as the threshold for "Continuous Monitoring", and the upper limit of Cluster 2 is set as the threshold for "Requires Maintenance". Based on these thresholds, the inspection results are graded into "Requires Maintenance", "Continuous Monitoring", and "Good". The specific grading methods are as follows:

- Crack Rate (%)
    1. Good: Crack rate $\leq$ 4.5
    2. Continuous Monitoring: 4.5 < Crack rate $\leq$ 12.5
    3. Requires Maintenance: Crack rate > 12.5
- Rutting Depth (mm)
    1. Good: Rutting depth $\leq$ 4.6
    2. Continuous Monitoring: 4.6 < Rutting depth $\leq$ 7.0
    3. Requires Maintenance: Rutting depth > 7.0
- IRI
    1. Good: IRI $\leq$ 3.11
    2. Continuous Monitoring: 3.11 < IRI $\leq$ 4.42
    3. Requires Maintenance: IRI > 4.42

Subsequently, based on the grading results, a more effective maintenance decision-making model is established. Any pavement unit with any inspection indicator graded as "Requires Maintenance" is defined as a "Maintenance Section". Pavement units with all three indicators graded as "Good" are defined as "Good Condition Sections", and the remaining sections are defined as "Continuous Monitoring Sections". Corresponding maintenance strategies are developed for each grading, as shown in Table 14.

Table 14. Summary of maintenance decision-making grading.

Grading Conditions	Maintenance Grading Result	Maintenance Method
Any inspection indicator graded as "Requires Maintenance"	"Maintenance Section"	Conduct structural surveys and perform pavement maintenance work
All three inspection indicators graded as "Good"	"Good Condition Section"	Continue routine inspections
All other grading results	"Continuous Monitoring Section"	Continuously monitor the section to observe deterioration of pavement service indicators

4. Application of Pavement Management Platform and Validation with Practical Cases

4.1. Application of Pavement Management Platform

This study establishes a pavement management platform to manage pavement inspection and maintenance decision-making. It creates a database for each pavement unit based on the inspection indicators and integrates the maintenance decision-making methods developed in this study to assist managers in formulating maintenance strategies.

- Inspection Data Module

A database is established for the inspection indicators used in this study, as shown in Table 15, and imported into the management platform. Managers can use the system to query and analyze inspection data for tracking pavement inspection indicators. The platform interface is shown in Figure 8.

Table 15. Inspection database.

Direction	Pavement Unit	Lane	Year	Crack Rate (%)	Average Rutting Depth (mm)	IRI
Forward	16K+000~16k+100	1	2023	5.66	6.04	2.50
Forward	16k+100~16k+200	1	2023	6.92	6.06	2.70

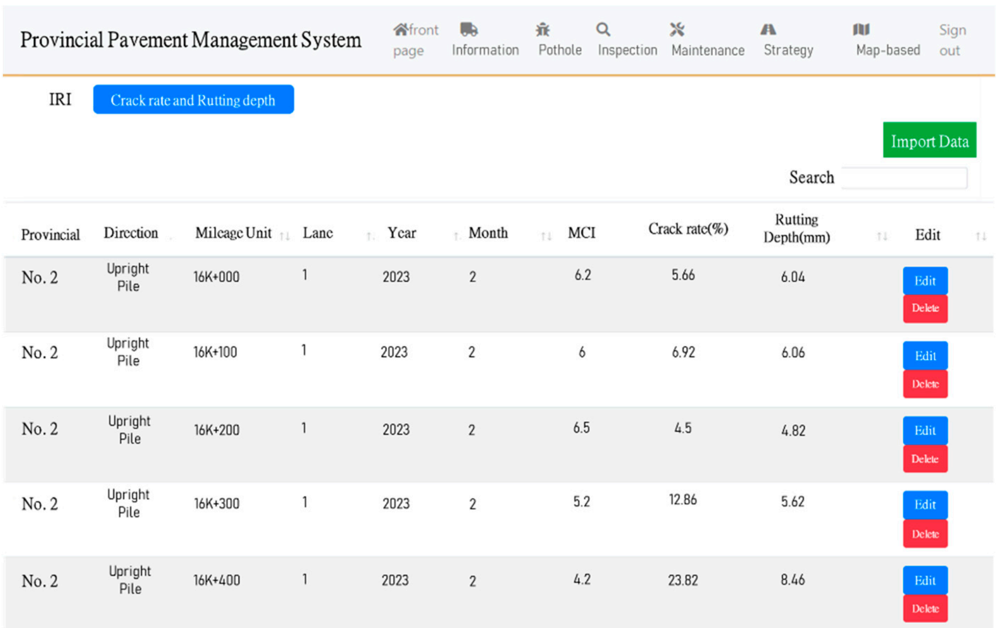


Figure 8. Importing inspection data into pavement management platform.

- Integration of Maintenance Decisions for Management

Next, the pavement management platform is used for maintenance decision-making. Managers input the grading thresholds from Section 3.3 into the platform, which can automatically filter pavement units into "Maintenance Sections", "Continuous Monitoring Sections", and "Good Condition Sections", effectively enhancing maintenance decision efficiency, as shown in Figure 9.

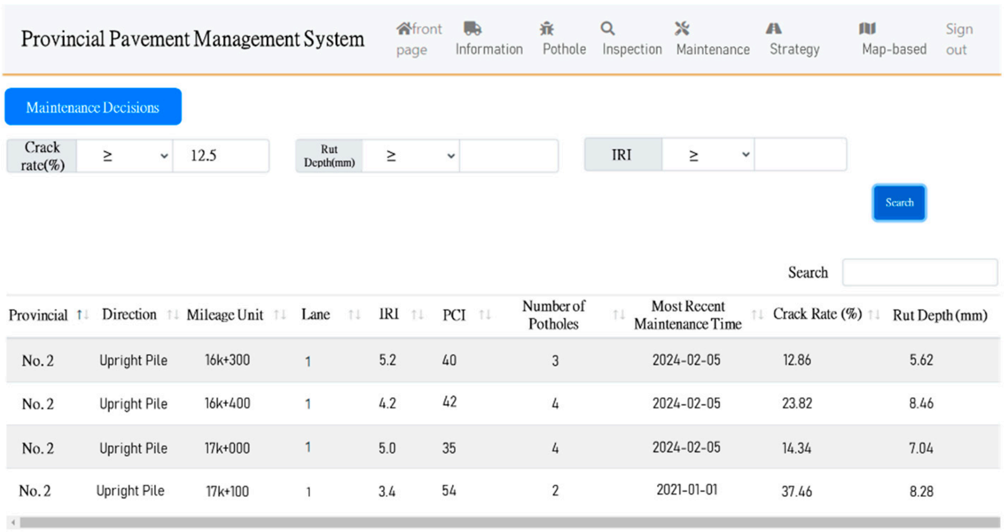


Figure 9. Integration of maintenance decisions into pavement management platform.

4.2. Practical Case Inspection and Validation

- Validation Case Range

This study selects "Provincial Highway No. 2 from 16K+000 to 19K+000, inner and outer lanes in the forward direction", totaling 60 pavement units, as the validation section.

- Application and Validation Methods

The maintenance units of provincial highways develop maintenance strategies for the validation section based on the traditional decision-making method described in Section 1.1, dividing the 60 pavement units into "Maintenance Sections" and "Observation Sections".

Using the inspection indicator grading developed in this study and the grading thresholds in Table 14, the 60 pavement units are classified into "Maintenance Sections", "Continuous Monitoring Sections", and "Good Condition Sections". Considering that the traditional decision-making method only results in two decision outcomes, for comparative analysis, the "Continuous Monitoring Sections" and "Good Condition Sections" are classified as "Observation Sections".

The accuracy of the decision results from the two methods is calculated using the example in Equation (4).

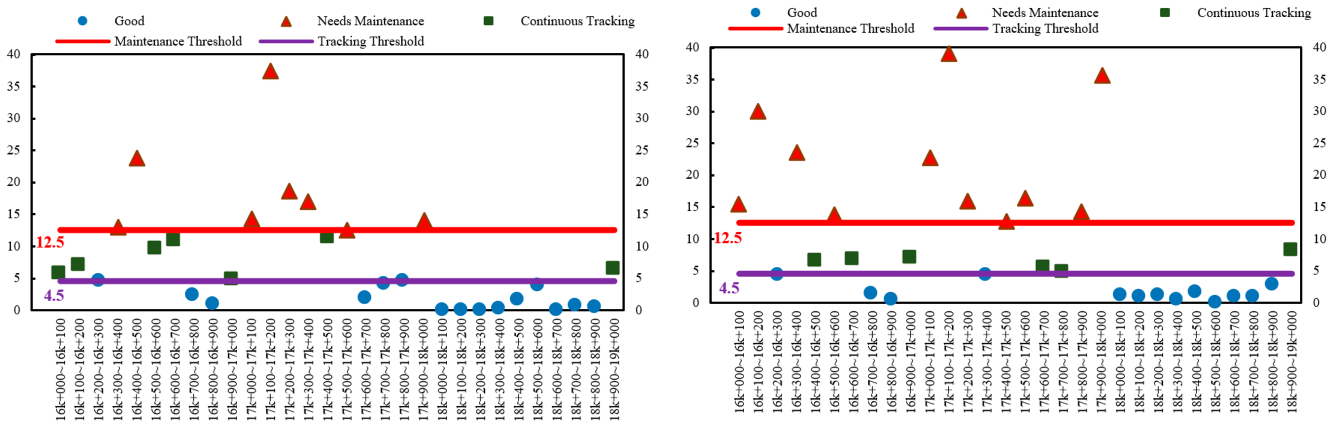
$$\text{Validation Accuracy} = 100\% \times (\text{Number of Accurate Decisions}/\text{Total Number of Sections}) \tag{4}$$

where:

Number of Accurate Decisions = Number of sections where both decisions are "Maintenance Sections" or "Observation Sections".
Total Number of Sections = 60 pavement units from 16K+000 to 19K+000 in the forward direction

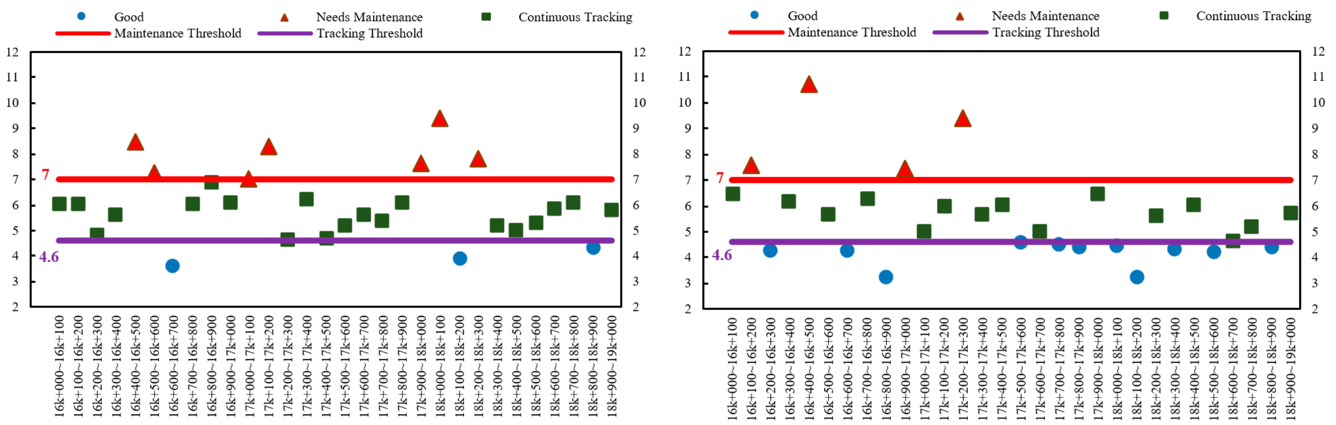
- Inspection Results

The crack rate, rutting depth, and IRI of 60 pavement units on "Provincial Highway No. 2 from 16K+000 to 19K+000, inner and outer lanes in the forward direction" were inspected. The inspection results are graded based on the method in Section 3.3. The grading results for the crack rate, rutting depth, and IRI are shown in Figures 10–12, respectively.



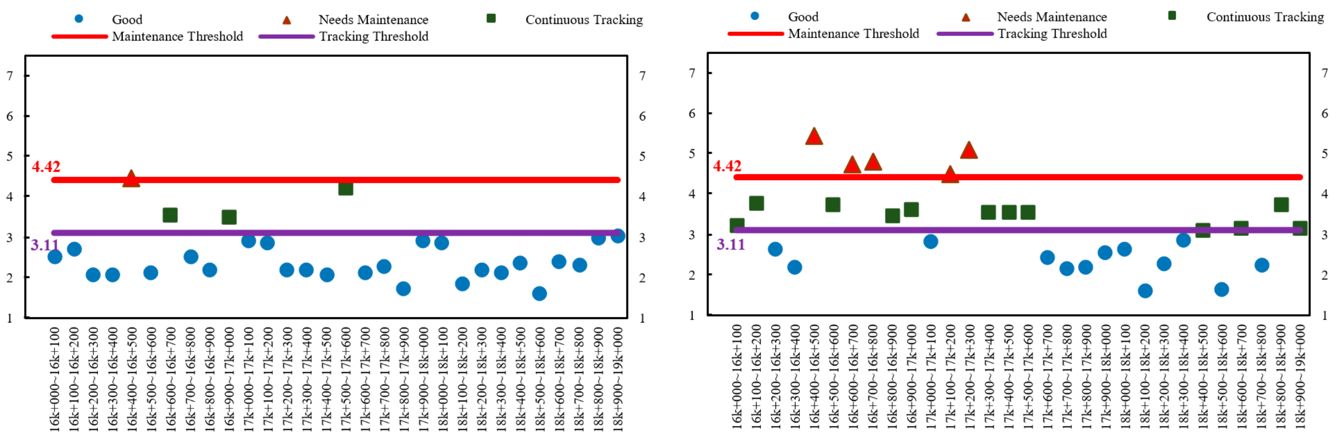
(**a**) (**b**)

Figure 10. Crack rate grading results. (**a**) Inner lane; (**b**) Outer lane.



(**a**) (**b**)

Figure 11. Rutting depth grading results. (**a**) Inner lane; (**b**) Outer lane.



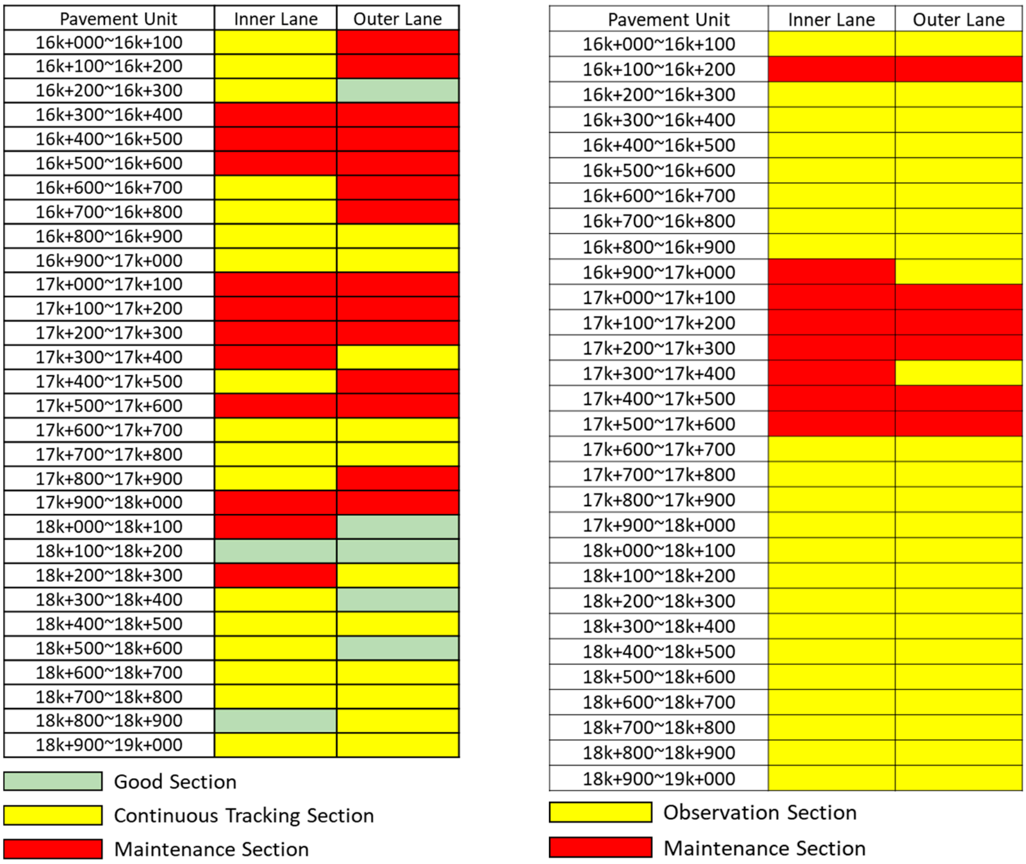
(**a**) (**b**)

Figure 12. IRI grading results. (**a**) Inner lane; (**b**) Outer lane.

- Validation Results

Subsequently, the maintenance decisions for 60 pavement units on "Provincial Highway No. 2 from 16K+000 to 19K+000, inner and outer lanes in the forward direction" are validated:

- Based on the inspection results of this study, the 60 pavement units are graded into "Maintenance Sections", "Continuous Monitoring Sections", and "Good Condition Sections", as shown in Figure 13a.
- The provincial highway maintenance units make maintenance decisions based on the traditional method, dividing the 60 pavement units into "Maintenance Sections" and "Observation Sections", as shown in Figure 13b.
- The "Continuous Monitoring Sections" and "Good Condition Sections" from this study are both classified as "Observation Sections", and the validation accuracy of maintenance decisions is analyzed using Equation (4).
- The calculation results are shown in Table 16. The final validation accuracy is 70%, indicating that the decision results of this study mostly align with the actual maintenance decisions of the provincial highway maintenance units. This demonstrates that the inspection and decision-making methods developed in this study meet the needs of actual maintenance units and can replace traditional methods for more efficient decision-making.



(**a**) (**b**)

Figure 13. Decision validation analysis. (**a**) Decision results of this study; (**b**) Actual maintenance sections by provincial highway maintenance units.

Table 16. Practical application validation results.

Validation Section	Total Number of Sections	Number of Accurate Decisions	Validation Accuracy
Provincial Highway No. 2 from 16K+000 to 19K+000, inner and outer lanes in the forward direction	60	42	70%

5. Conclusions

- This study conducted an in-depth exploration of pavement inspection methods and maintenance decision-making strategies for Taiwan's provincial highways, proposing improvements based on advanced pavement damage detection technology. By introducing automated detection technology to replace traditional manual visual inspections, the inspection efficiency and accuracy were significantly enhanced. Traditional methods could inspect 1 km per day, whereas automated pavement survey vehicles could inspect 4 km per day, increasing the efficiency by approximately four times. Additionally, the application of automated pavement survey vehicles reduced the inspection costs per kilometer by about 1.7 times compared to traditional methods, significantly lowering long-term operating costs.
- Using the K-means clustering analysis method, maintenance threshold values for these three indicators were established as the basis for decision-making. The results are as follows: any pavement unit with at least one indicator graded as "Requires Maintenance" is defined as a "Maintenance Section"; units with all three indicators graded as "Good" are defined as "Good Condition Sections"; the remaining units are defined as "Continuous Monitoring Sections".
    1. Crack Rate (%)
       Good: Crack rate $\leq$ 4.5
       Continuous Monitoring: 4.5 < Crack rate $\leq$ 12.5
       Requires Maintenance: Crack rate > 12.5
    2. Rutting Depth (mm)
       Good: Rutting depth $\leq$ 4.6
       Continuous Monitoring: 4.6 < Rutting depth $\leq$ 7.0
       Requires Maintenance: Rutting depth > 7.0
    3. IRI
       Good: IRI $\leq$ 3.11
       Continuous Monitoring: 3.11 < IRI $\leq$ 4.42
       Requires Maintenance: IRI > 4.42
- Through practical application and verification, the detection and decision-making methods proposed in this paper can objectively and efficiently conduct provincial highway maintenance decisions, significantly improving management efficiency and meeting the needs of maintenance units. For example, in the practical application for "Provincial Highway No. 2, 16K+000 to 19K+000, inner and outer lanes", comprising 60 pavement units, the decision accuracy rate reached 70%, demonstrating that this method meets the requirements of provincial highway maintenance units.
- By integrating the detection results into a pavement management platform, managers can make timely and accurate maintenance decisions, further enhancing the overall efficiency of maintenance work. In the future, it is hoped that the results of this study can be widely applied to more road maintenance management to improve road service quality and lifespan.

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