Teknisia

Vol. 30, No. 1, Mei 2025, pp.33-44
E-ISSN: 2746-0185

Prediction of pavement condition using markov chain method based on PCI and SDI assessment result

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Article Info
***Article history*:**
Received:
February 13, 2025
Revised:
June 11, 2025
Accepted:
June 11, 2025
Available online:
June 23, 2025

***Keywords*:**
Maintenance Cost
Markov Chain
Pavement Management System
Pavement Condition
Road Maintanance.

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Abstract

A pavement management system needs to be implemented as a form of road management to ensure that roads function properly. The Markov Chain model describes future pavement conditions to produce optimal highway maintenance. The research was carried out on Suprapto Street, Ahmad Yani Street, and Yos Sudarso Street in Indramayu Regency. Based on road conditions in 2024 by PCI and SDI assessment results, predictions are made by multiplying the initial condition vector by the transition probability matrix. Once the condition of the road is known, the proposed type of maintenance can be determined based on Ministerial Regulation of Public Work No. 13/PRT/M/2011, along with the costs required based on the maintenance cost history. The Markov Chain predictions show that road conditions will deteriorate and there will be an increase in severe damage over the years if no treatment is carried out. Maintenance action patterns vary; sections that experience a high level of damage will receive more serious treatment, and in the following year maintenance will decrease and then increase again according to the level of damage. The pattern of maintenance costs also follows the handling actions taken. Costs in the initial year were the highest, while most costs were spent on Suprapto Street.

Introduction

A pavement management system needs to be implemented as a form of road management to ensure that roads function properly. Road pavement conditions deteriorate over time, and many factors can contribute to road damage. Letjend. Suprapto Street, Jendral Ahmad Yani Street, and Yos Sudarso Street in Indramayu Regency are county roads that connect urban centers with national roads. These three sections often experience damage due to flooding in several areas. Although maintenance is frequently carried out, unavoidable road damage causes the pavement condition to deteriorate over time. The budget for road management often falls short of what is needed to maintain the existing road sections. Due to this issue, necessary road maintenance is delayed. Limited funding can impact the type of road maintenance that can be performed, so the type of maintenance must be adjusted according to the available funds. Therefore, damage prediction, maintenance planning, and maintenance cost budgeting are crucial to ensure that road maintenance programs can be implemented according to the level of damage.

The Markov Chain model represents the concept of future highway maintenance and

uses a nonlinear optimization method to generate optimal road maintenance plans with limited budgets. This decision-making policy is based on optimizing road maintenance with constrained costs while minimizing maintenance and rehabilitation expenses, which are limited by predetermined road maintenance needs. The first case is used to implement an optimal road maintenance and rehabilitation program that has been developed, while the second case is used for planning and budget reduction purposes (Abaza and Ashur, 1999). Based on the research conducted by Issa & Schoefs (2019), the Markov Chain model can also be applied to three types of pavements: rigid, semi-rigid, and composite. The results of the Markov Chain analysis showed that road damage increased in years when no repairs were made. Sazali (2019) in his research on the Application of the Markov Chain Model in Road Management in West Bangka Regency stated that during the five year period (2018–2022), road handling patterns showed a shift in the type of handling program from heavy work to lighter work.

Research on pavement prediction using the Markov Chain method has also been conducted by Clemmensen and Wang (2024), Alonso et al. (2023), Oliveira et al. (2022), Salman and Gursoy (2022), Wang et al. (2021), Issa and Schoefs (2019), Sati et al. (2019), Osorio et al. (2017), Pérez et al. (2017), Moreira et al. (2016), and Hong and Wang (2003). This method still needs to be explored for use in a variety of locations that differ in terms of regional characteristics and handling regulations. Based on previous research (Hakim et al 2024), this paper focuses on the prediction of Indramayu Regency Road conditions in the next five years using the Markov Chain Model, determining the proposed type of maintenance and predicting maintenance costs.

Research Method

In general, this research was conducted in three stages: data collection, analysis and discussion, and conclusions. The research flowchart can be seen in Figure 1.

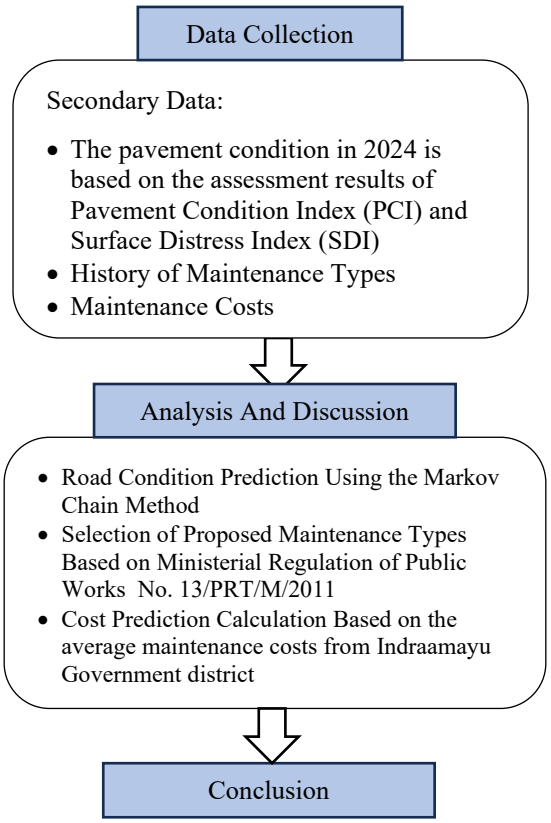

Figure 1. Research flow chart

The research process begins with data collection, the type of data used in this research is secondary data. The secondary data needed includes the pavement condition in 2024 is based on the assessment results of Pavement Condition Index (PCI) and Surface Distress Index (SDI), the history of road maintenance, records of road conditions, and maintenance costs from 2019 to 2023. The use of PCI and SDI Method to evaluate and determine pavement maintenance have reported by Hakim et al. (2024), Suprapto and Fauziah (2024), Fauziah and Febryawan (2017), Chasanah and Wijaya (2016), and Kemala (2022).

This study was conducted on several roads in Indramayu Regency. The three roads examined are primary collector roads with county status. The road section studied was Suprapto Street 2,150 m long, Ahmad Yani Street of 600 m long, and Yos Sudarso Street

of 950 m long. The total length of these three road sections is 3.7 km. The road section that will be the research object is shown in Figure 2.

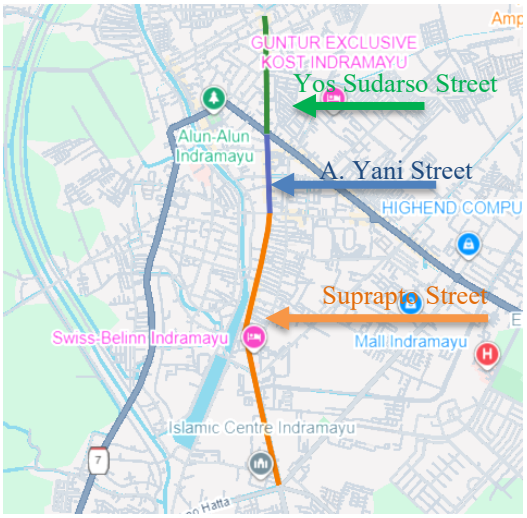

Figure 2. Research location

The next stage is data analysis. Predictions of road conditions are carried out to determine road conditions for the next five years using Markov Chain. According to Adams et al. in Mukti (2023), Markov Chain analyses the properties of a variable in the present based on its properties in the past to predict its properties in the future. In predicting road pavement performance using stochastic models, Markov properties can be used if future pavement conditions depend on current pavement conditions rather than past conditions. Future pavement conditions can be predicted using a formula, as shown in Equation (1) (Ortiz-Garcia et al. 2006).

$$a_t = at{-}1 \times P = a_0 \times P_t \quad (1)$$

a_t is distribution of condition at time, a_0 is distribution of conditions at time 0, which is the initial vector ($a_t{-}1$), P_t is transition probability matrix improved with time control, and t is time elapsed in years.

The formulation of transition probability matrix models changes in pavement conditions over time, which is represented by P. The general form of P is shown in Equation (2) (Ortiz-García et al. 2006; Pérez-Acebo et al. 2017).

$$\mathrm{P} = \begin{bmatrix} P_{11} & P_{12} & \dots & P_{1n} \\ P_{21} & P_{22} & \dots & P_{2n} \\ \vdots & & & \vdots \\ P_{n1} & P_{n2} & \dots & P_{nn} \end{bmatrix} \quad (2)$$

Distribution of pavement conditions based on the initial condition vector (a_0). The equation for the proportion of damage distribution can be seen in Equation (3).

$$\text{Proportion of distribution} = \frac{\text{damage condition}}{\text{total road length}} \quad (3)$$

Proposed types of maintenance can be carried out based on Ministerial Regulation of Public Work No. 13/PRT/M/2011. Road maintenance includes all preventive, correction and repair actions necessary to keep the road in optimal condition, ensuring it serves traffic efficiently and reaches the designated design life. Road maintenance includes routine maintenance, periodic maintenance and road rehabilitation, including complementary buildings and road equipment Bina Marga (2011). Treatment programs based on SDI and PCI values can be seen in Table 1.

The budget plan is based on the rates set by on Ministerial Regulation of Public Work in Indramayu Regency based on the level of road damage from good road conditions to seriously damaged by determining the price of work for road maintenance in the previous year taken from on Ministerial Regulation of Public Work in Indramayu Regency and for predictions using inflation data from the Indonesia's Central Bureau of Statistics, then calculating the average condition value each year and then multiplying it by the length and width and then multiplying the cost that has been obtained.

Table 1. Treatment programs based on SDI and PCI values

PCI Value*	SDI Value**	Road Condition	Damage Limitation Percentage	Maintanance Program
100-85	<50	Good (G)	< 6 %	Routine Maintanance
84-69	50 – 100	Moderate (M)	6 - < 11 %	Routine Maintanance /Periodic
70-54	100 – 150	Light Damaged (LD)	11 - < 15 %	Rehabilitation
<54	>150	Severe Damaged (SD)	>15%	Reconstruction

(Source: Shahin, (1994) *, Ministry of Public Work, (2011)**)

The results of the road condition predictions are compared based on the condition assessments using the PCI and SDI methods, and also by comparing the predicted road conditions with and without maintenance interventions. The discussion regarding types of maintenance and costs compares the types of maintenance and costs available from the two existing road condition assessment methods. Once the results and discussion are known, conclusions can be determined based on the research objectives and results obtained.

Result and Discussion

Pavement Condition Prediction Using Markov Chain

Markov Chain method is used to predict road damage in the next five years. To perform calculations, an initial condition vector and a transition probability matrix are needed. Table 2 shows the results of calculating the initial condition vector values based on PCI and SDI assessment by Hakim et al. (2024). Each segment is divided into west and east directions due to 2-way traffic flow.

Table 2. Initial distribution proportion based on PCI and SDI assessment in 2024.

Road	Initial Distribution Proportion							
	PCI				SDI			
	G	M	LD	SD	G	M	LD	SD
West Suprapto	0,37	0,28	0,14	0,21	0,88	0,12	0,00	0,00
East Suprapto	0,53	0,23	0,19	0,05	0,91	0,09	0,00	0,00
West A. Yani	0,67	0,33	0,00	0,00	1,00	0,00	0,00	0,00
East A. Yani	1,00	0,00	0,00	0,00	1,00	0,00	0,00	0,00
West Yos Sudarso	0,33	0,67	0,00	0,00	1,00	0,00	0,00	0,00
Est Yos Sudarso	0,67	0,33	0,00	0,00	1,00	0,00	0,00	0,00

G= Good, M= Moderate, LD= Light Damaged, SD= Severe Damaged

Source: Hakim et al. (2024)

The transition probability matrix is determined based on the maintenance history and road conditions that occurred from 2019 to 2020.

Transition probability matrix if not treated

$$\begin{bmatrix} 0,6 & 0,4 & 0 & 0 \\ 0 & 0,5 & 0,5 & 0 \\ 0 & 0 & 0,5 & 0,5 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Transition probability matrix for routine maintenance

$$\begin{bmatrix} 0,89 & 0,11 & 0 & 0 \\ 0 & 0,85 & 0,15 & 0 \\ 0 & 0,42 & 0,48 & 0,1 \\ 0 & 0 & 0,2 & 0,8 \end{bmatrix}$$

Transition probability matrix for periodic maintenance

$$\begin{bmatrix} 0,95 & 0,05 & 0 & 0 \\ 0,47 & 0,3 & 0,23 & 0 \\ 0 & 0,6 & 0,35 & 0,05 \\ 0 & 0,2 & 0,7 & 0,1 \end{bmatrix}$$

Transition probability matrix for rehabilitation

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0,83 & 0,17 & 0 & 0 \\ 0,7 & 0,3 & 0,3 & 0 \\ 0,65 & 0,35 & 0,35 & 0 \end{bmatrix}$$

Transition probability matrix for reconstruction

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

Based on equation 1, the predicted pavement condition is obtained without any treatment being applied to the three sections as shown in Figure 3 to 8.

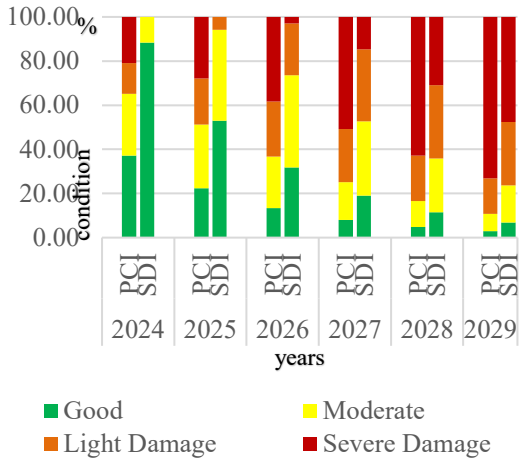

Figure 3. Condition Prediction of Supapto West Street using Markov Chain

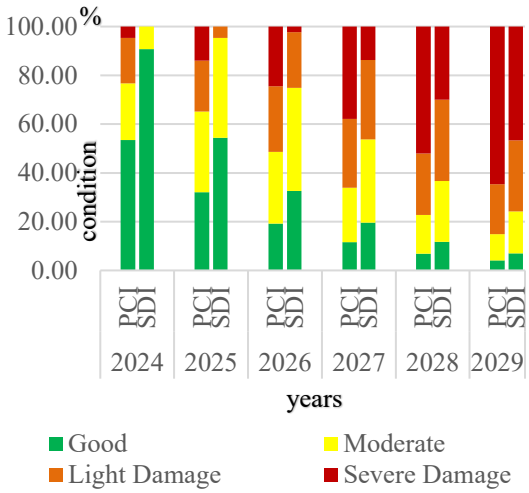

Figure 4. Condition Prediction of Suprapto East Street using Markov Chain

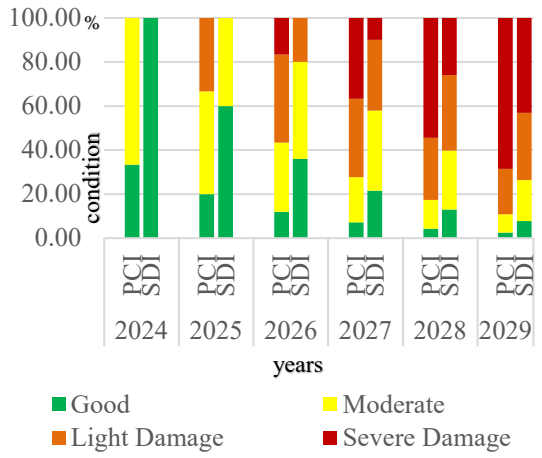

Figure 5. Condition Prediction of A. Yani West Street using Markov Chain

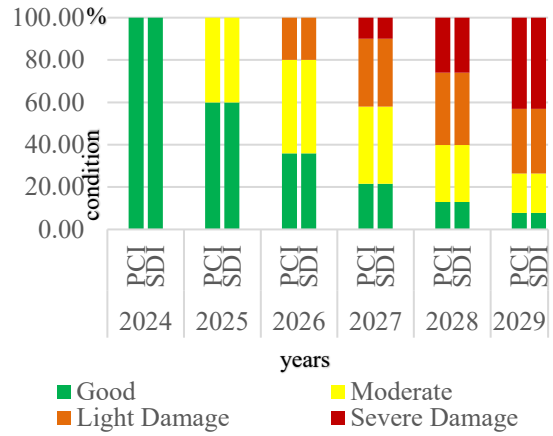

Figure 6. Condition Prediction of A. Yani East Street using Markov Chain

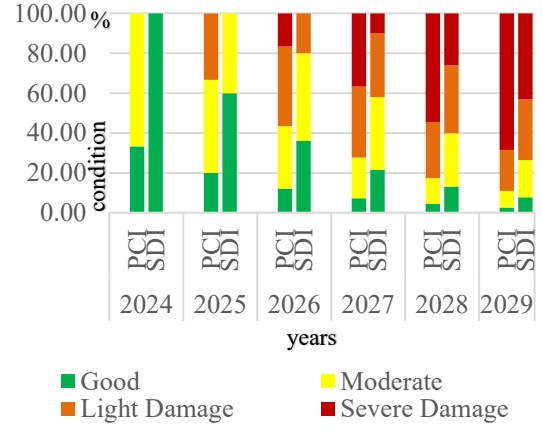

Figure 7. Condition Prediction of Yos Sudarso West Street using Markov Chain

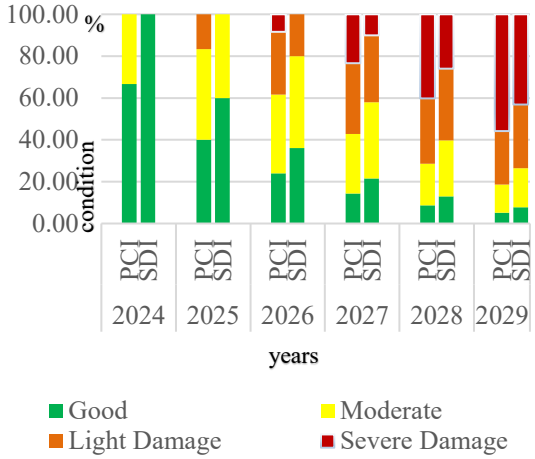

Figure 8. Condition Prediction of Yos Sudarso East Street using Markov Chain

In predicting road damage using the Markov Chain method, both the PCI and SDI assessment methods, as shown in Figures 3 through 8, indicate a similar trend of decreasing good conditions and increasing severe damage. This similarity arises because, despite using different assessment methods, both still utilize the same transition probability matrix.

The only difference between the methods is in the percentage of damage in the initial condition vector based on the road condition assessment results from 2024. This is similar to research conducted by Mukti, et al (2023) and Aulia, et al (2023) which states that if the pavement condition is not treated, then the condition will decline and damage will increase over time.

After predicting the condition of the pavement, the type of maintenance can be selected based on Ministerial Regulation of Public Works No. 13/PRT/M/2011 as in Table 1. Table 3 presents a summary of the proposed types of interventions for the three road sections based Ministerial Regulation of Public Works No. 13/PRT/M/2011.

Table 3. Proposed Type of Treatment Based on Ministerial Regulation of Public Works No. 13/PRT/M/2011

Street	Year	Type of Maintenance	
		Based on PCI Assessment	Based on SDI Assessment
Suprapto West	2024	RC	RM
	2025	NT	RM
	2026	RM	RM
	2027	PM	RM
	2028	PM	PM
	2029	RM	RH
Suprapto East	2024	RC	RM
	2025	NT	RM
	2026	RM	RM
	2027	RM	RM
	2028	RM	PM
	2029	PM	RH
A. Yani West	2024	RM	NT
	2025	RM	RM
	2026	RM	RM
A. Yani West	2027	PM	PM
	2028	PM	RH
	2029	PM	RM
A Yani East	2024	NT	NT
	2025	RM	RM
	2026	RM	RM
	2027	RM	PM
	2028	PM	RH
	2029	RH	RM
Yos Sudarso West	2024	NT	NT
	2025	RM	RM
	2026	RM	RM
	2027	RM	PM
	2028	PM	RH
	2029	PM	RM
Yos Sudarso East	2024	RM	NT
	2025	RM	RM
	2026	RM	RM
	2027	PM	PM
	2028	PM	RH
	2029	PM	RM

NT= No Treatment, RC= Routine Maintenance, PM= Periodic Maintenance, RH= Rehabilitation, RC= Reconstruction.

Based on Table 3, which details the types of maintenance conducted annually based on road damage assessment using the PCI method to keep pavement conditions in good shape, a graph is presented. This graph illustrates the difference between pavement conditions without any intervention and those with regular maintenance over the next five years. Figure 9 to 14 below shows a comparison graph of the condition of each street with and without maintenance over five years.

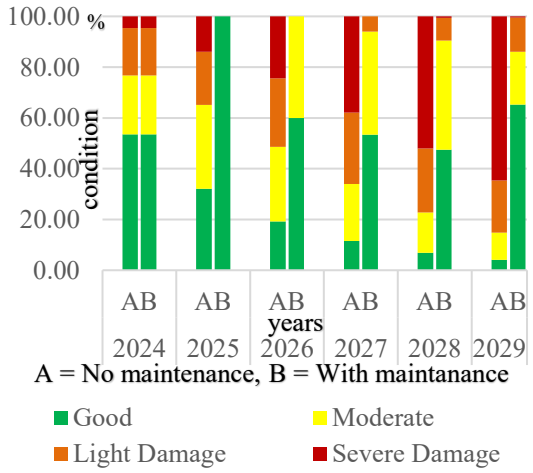

Figure 9. Comparison of Suprapto West Street Conditions with and without Maintenance Based on PCI Values

Based on figure 9 West Suprapto Street, reconstruction was carried out in 2024 because the road was in a severe damaged condition, with 21% of the road affected. As a result, by 2025, the road condition reached 100% good. No maintenance was conducted in 2025. In 2026, routine maintenance was performed as there were no minor or severe damages. In 2027 and 2028, periodic maintenance was carried out to prevent damage from exceeding 15%. In 2029, routine maintenance was conducted to maintain the road condition.

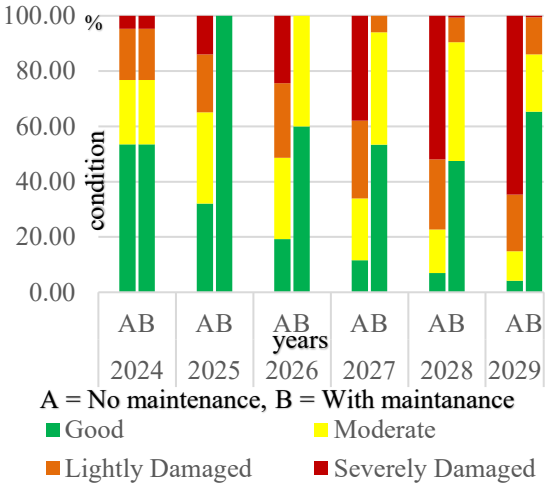

Figure 10. Comparison of Suprapto East Road Conditions with and without Maintenance Based on PCI Values

On East Suprapto Street, reconstruction was carried out in 2024 due to the road being in a light damaged condition (19%) and severely damaged (5%). Consequently, by 2025, the road condition reached 100% good. No maintenance was conducted in 2025. In 2026, routine maintenance was performed as there were no minor or severe damages. In 2027 and 2028, routine maintenance was carried out to keep damage from exceeding 15%. In 2029, periodic maintenance was conducted because the damage reached 14%.

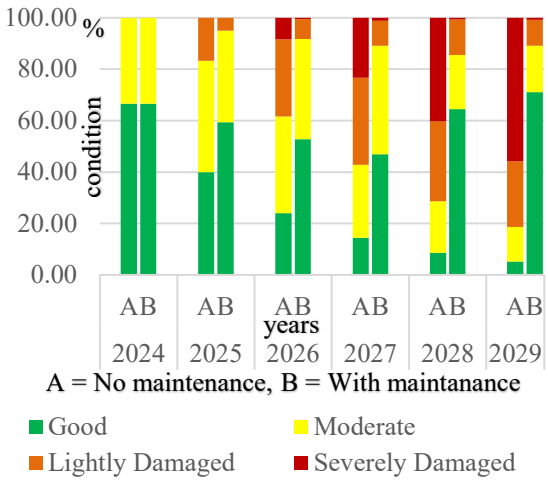

Figure 11. Comparison of A. Yani West Street Conditions with and without Maintenance Based on PCI Values

On West Ahmad Yani Road, routine maintenance was conducted in 2024 as there was no damage. In 2025 and 2026, routine maintenance was also carried out because the damage was below 11%. In 2027, periodic maintenance was performed due to 10% minor damage and 1% severe damage. In 2028 and 2029, periodic maintenance was conducted as damage exceeded 11%, to prevent it from reaching more than 15%.

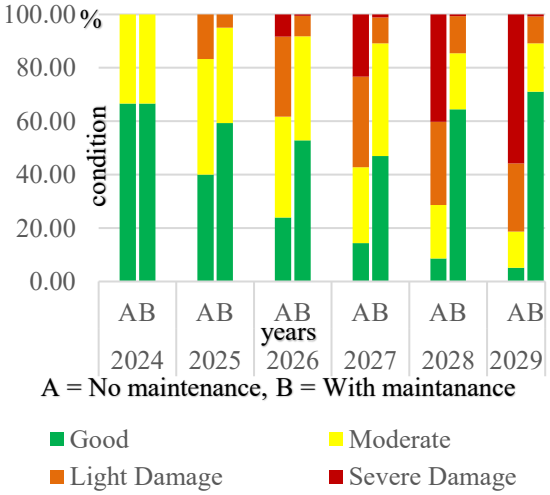

Figure 12. Comparison of A. Yani East Street Conditions with and without Maintenance Based on PCI Values

In Figure 12 East Ahmad Yani Road, no maintenance was conducted in 2024 because the road was still in 100% good condition. In 2025, routine maintenance was performed as there was no damage yet. In 2026 and 2027, routine maintenance was also conducted because the damage remained below 11%. In 2028, periodic maintenance was carried out due to 11% minor damage and 1% severe damage. In 2029, rehabilitation was conducted as the damage exceeded 15%.

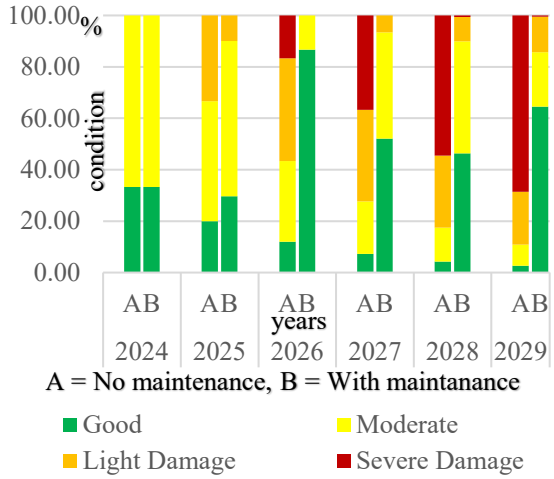

Figure 13. Comparison of Yos Sudarso West Street Conditions with and without Maintenance Based on PCI Values

On West Yos Sudarso Street, no maintenance was conducted in 2024 as the road was still undamaged. In 2025, 2026, and 2027, routine maintenance was performed because the damage remained below 11%. In 2028 and 2029, periodic maintenance was carried out to prevent damage from exceeding 15%.

In Figure 14 East Yos Sudarso Road, routine maintenance was conducted in 2024, 2025, and 2026 because the damage remained below 11%. In 2027, 2028, and 2029, periodic maintenance was performed to prevent the damage from exceeding 15%.

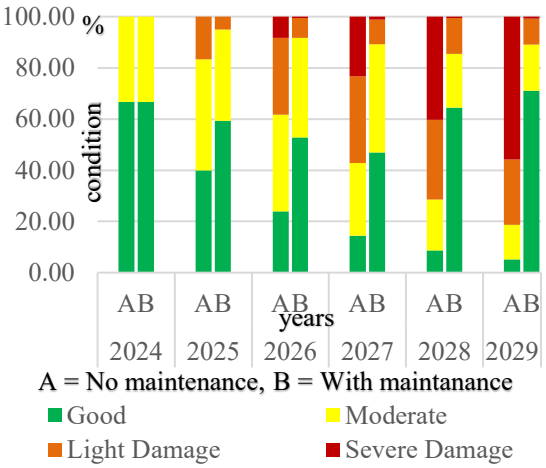

Figure 14. Comparison of Yos Sudarso East Road Conditions with and without Maintenance Based on PCI Values

The pattern of maintenance actions varies for each road segment; segments with higher levels of damage receive more intensive treatment, with maintenance levels decreasing in the following year before rising again in line with the extent of the damage. The findings of this study differ from those of Sazali et al. (2019), which show a shift in maintenance patterns from heavy to lighter work, specifically reconstruction– rehabilitation – periodic maintenance– routine maintenance.

According to research by Sati et al. (2020), using the Markov Chain method to predict pavement conditions proved 90% accurate. This indicates that the model can be effectively used to forecast future pavement conditions with a high level of accuracy. Such predictions can assist decision-makers in forecasting pavement conditions, ranking priorities, and preparing maintenance and rehabilitation needs at the right time based on these requirements.

Maintenance Cost

Figure 15 shows the difference in road maintenance costs between the PCI and SDI methods on the three road sections.

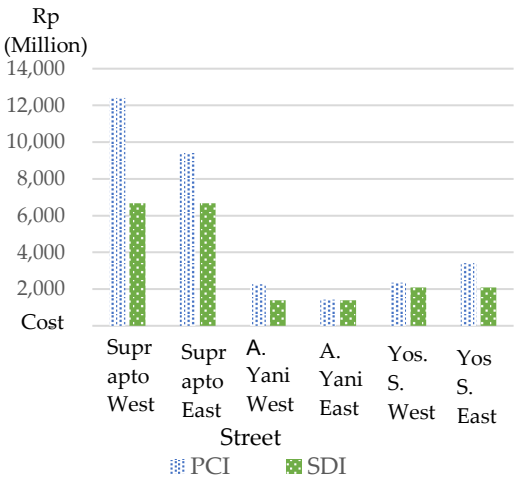

Figure 15. Road Maintenance Cost Based on Unit Prices from Indramayu Department of Public Works and Housing Indramayu

In Figure 15, it can be seen that based on the assessment of road conditions using the PCI method, Suprapto Street costs Rp. 21,821,000,000 for maintenance over five years, Ahmad Yani Street Rp. 3,697,000,000, Yos Sudarso Street Rp. 5,754,000,000. Meanwhile, based on assessing road conditions using the SDI method, Suprapto Street costs Rp. 13,340,000,000 for maintenance, Ahmad Yani Street Rp. 2,784,000,000, and Yos Sudarso Street Rp. 4,176,000,000. Suprapto West Street costs the most maintenance costs, whether assessed using PCI or SDI. This is because the Suprapto Street section has the longest section length among the three roads, damage factors also influence it so reconstruction needs to be carried out for this section.

The difference in costs carried out each year between damage assessments using the PCI and SDI methods is also shown in Figure 16. SDI method is better than PCI because of its low maintenance cost. However, PCI is better for comprehensive maintenance despite its high cost. The highest costs will be in 2024 based on assessing road damage using the PCI method, as both Suprapto West and East routes underwent reconstruction that year, leading to significantly high expenses.

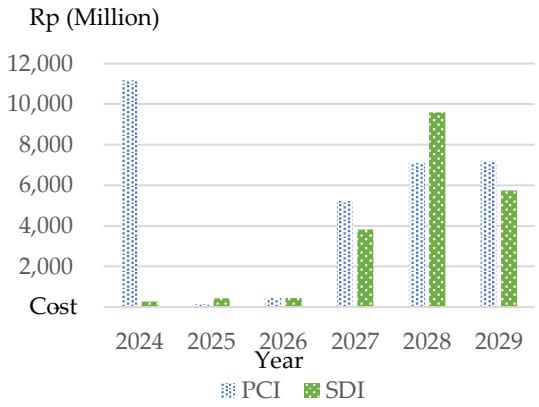

Figure 16. Road Maintenance Cost Based on Unit Prices from Indramayu Department of Public Works and Housing Indramayu from 2024 to 2029

By considering the transition probability matrix values and initial conditions according to the handling patterns and available road condition data, this can be used for other locations. Sections that are more than 1 km long should be divided into several sections so that the damage assessment is more specific. The type of treatment applied should not be uniform across an entire road section, because in one section there are various levels of damage. By applying varied treatment types, the costs incurred for a single section can be lower compared to using the same maintenance method throughout the entire section. The transition probability matrix can be obtained in various ways. The method for assessing road conditions can be carried out using the latest methods. To have better results, another road condition should be provided each year to compare the accurateness of the prediction using Markov Chain versus the real condition.

Conclusion

Predictions made using Markov Chain show that road conditions will experience a

decline in good condition and an increase in seriously damaged conditions from year to year if not treated. The pattern of maintenance actions varies for each section, sections that experience a high level of damage will receive more serious treatment, and in the following year maintenance will decrease and then increase again according to the level of damage. The pattern of maintenance costs follows the handling actions taken. Costs in the initial year were the highest, while most costs were spent on the Suprapto Road Section.

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