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Pavement Performance Prediction of Semarang–Solo Toll Road, Indonesia, using Markov Chain Model

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Abstract

Roads are one of the infrastructures that significantly impact a country's economic growth. The condition of the roads usually decreases due to increasing vehicle volumes. Predicting road conditions is essential for planning future maintenance. This study aims to evaluate the pavement conditions over five years using Markov chain model for five sections of the Semarang-Solo toll road, Indonesia. Two scenarios are selected in the simulation, without-handling and with-handling programs. The results show that the historical data used to compile the transition probability matrix (TPM) from the Markov model greatly influences the simulation results in both scenarios. In addition, the simulation results also indicate that the inner lane for all segments of Semarang - Solo direction is the most crucial because these segments have a relatively high rate of decline in road steadiness and a shorter cycle time for implementing the handling program.

INTRODUCTION

Toll road is a kind of infrastructure that positively impacts economic conditions at the national and regional levels. The construction of toll roads is one of the strategic work programs carried out by the Government of Indonesia, in which there has been a significant increase in the number and length of roads in recent years. The Toll Road Regulatory Agency (BPJT) stated that, until 2019, 516 km of toll roads were built and operational, with a plan that by the end of 2024, there will be 4,600 km of toll roads that are built and ready to operate in Indonesia [1]. One of the toll roads built and operational since 2011 is the Semarang - Solo toll road, Indonesia. Since the opening of the toll road, it has had a high traffic volume of 13,000 vehicles per day [2] and experienced a decline in condition. The decrease in the toll road condition could be attributed to increased traffic volume and loads yearly. The toll road condition, represented by the international roughness index (IRI), in the period of 2020 – 2022 was between 2.14 m/km and 3.8 m/km, while the common IRI value usually was in the range of 3.0 m/km to 3.8 m/km.

To guarantee a safe, comfortable, effective, and efficient toll road operation, a minimum service standard (SPM) is required to ensure the implementation of toll road operations. The SPM in the Regulation of the Minister of Public Works No. 16/PRT/M/2014 states that the IRI value for flexible and rigid pavements should not exceed 4.0 m/km [3]. Due to its ease and speed of measurement, the use of IRI as one of the parameters in the SPM greatly facilitates the quick assessment of surface quality, in terms of road roughness, for the purposes of road maintenance/ rehabilitation programs [4]. Road roughness can be caused by various factors such as traffic loads, environmental conditions, material quality, and the construction or maintenance process, which may act independently or together to shape the road's condition. On the other hand, traffic load and environmental factors are crucial for assessing the structural integrity of pavement and require additional measurements, but these are not included in the SPM.

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To implement the SPM, a good road network management system is needed so that toll roads can always be maintained steadily throughout the design life. One road network management system that focuses on pavement is the pavement management system (PMS). In its application, PMS requires good road performance modeling based on observations and accurate performance predictions to produce effective and efficient rehabilitation and maintenance planning [5].

One method that can be used to predict road pavement performance is the Markov chain, where the Markov chain model can predict changes in pavement conditions in the future depending on the current pavement conditions. In the process of its application, the Markov chain model requires a TPM (Transition Probability Matrix) to define changes in road pavement conditions from one condition to another [5–7]. With the prediction of toll road pavement performance using the Markov chain, it is hoped that it can provide information on road pavement performance conditions so that it can be used as a reference in preparing an optimal road management program to achieve a predetermined design life.

This study aims to evaluate changes in predicted pavement conditions over five years using the Markov chain model, with and without handling programs. The proposed yearly handling program aims to keep the toll road in a steady condition, with IRI less than 4.0 m/km as stipulated in the toll road SPM. The study areas used were five sections located on the Semarang - Solo toll road, namely Banyumanik - Ungaran, Ungaran - Bawen, Bawen - Salatiga, Salatiga - Boyolali and Boyolali - Kartasura sections, as shown in Figure 1.

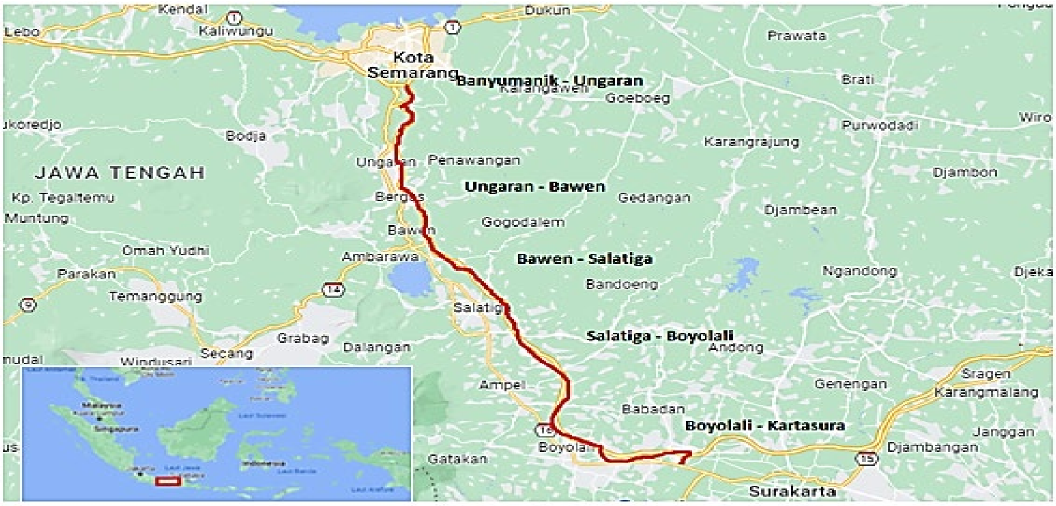

Figure 1. Toll Segments Evaluated in this Study

Literature Review

Markov Chain

Markov is a method used to make decisions based on current conditions. When applying the Markov Chain model, certain limitations must be considered, namely: (i) the process is discretely concerned with time, (ii) it has a computable or finite state, and (iii) it must fulfill the Markov property. Future pavement conditions can be predicted using the formula shown in Equation 1 [8]:

$$\alpha_t = \alpha_{t-1} \times P = \alpha_0 \times \quad (1)$$

in which: a_t is condition distribution at time *t;* a_0 is condition distribution at time 0, which is the initial vector; P^t is improved TPM (Transition Probability Matrix) with time control *t;* and *t* is time in years.

The position of TPM in the modeling process using Markov is very important because TPM has a function as a modifier to display changes in conditions from one state to another in the future. The general form of TPM can be shown in the equation 2 [9] as follows:

$$P = \begin{bmatrix} P_{1,1} & P_{1,2} & \cdots & P_{1,n} \\ P_{2,1} & P_{2,2} & \cdots & P_{2,n} \\ \vdots & \cdots & \cdots & \vdots \\ P_{n,1} & P_{n,2} & \cdots & P_{n,n} \end{bmatrix} \quad (2)$$

in which $P_{i,i}$ is the transition probability from state I to remain in state I, or the probability that the pavement remains in the same condition after one transition has passed, and i is the index to declare state or class I (i = 1, 2, 3, 4).

After determining the TPM, the next step is determining the initial vector. The initial vector will show the probability of a pavement under certain conditions or circumstances. The initial condition vector can be described as follows:

$$a_0 = (p_1\ p_2\ p_3\ p_4) \tag{3}$$

in which: p_i is the condition of the initial vector at the pavement age in year 0.

Road Handling Programs

The type of road handling program is determined based on the Regulation of the Minister of Public Works Number 13/PRT/M/2011 [10], as shown in Table 1.

Table 1. Types of Road Handling Programs based on Road Condition

Road Condition	% of Damage	Handling Program
Good (B)	<6%	Routine Maintenance
Moderate (S)	6 - <11%	Periodic Maintenance
Slight Damage (RR)	11 - <15%	Rehabilitation
Heavily Damage (RB)	>15%	Reconstruction

METHOD

There are two main stages of methodology in this study:

- Secondary and primary data collection. The secondary data needed in this study were IRI and road condition data for 2020–2022, obtained from PT. Trans Marga Jateng, the toll road company (BUJT) of the Semarang-Solo toll road. The primary data collection was conducted in terms of a road condition survey using outdoor video cameras along both directions of the Semarang – Solo toll road to adjust the IRI value of the road pavement conditions, if necessary.
- Data analysis. This stage was conducted by using the Markov chain method to determine changes in toll road pavement conditions in the future and consisted of four steps: (1) determination of state condition criteria; (2) preparation of the transition probability matrix; (3) calculation of the distribution of conditions; and (4) pavement condition prediction model.

RESULTS AND DISCUSSION

The Markov chain model is applied to toll roads through a simulation based on the implementation of the without-handling program (no treatment or only routine maintenance) and the with-handling program (minor rehabilitation). The first step of this study was to determine the IRI class using the IRI value, as seen in Table 2.

Table 2. States of the Road Condition used in This Study

State	IRI values
1	2.0 – 2.5
2	2.5 – 3.0
3	3.0 – 3.5
4	3.5 – 4.0

This study used IRI data from pavement years 2020–2022, with the initial condition vector (a_0) arranged based on the distribution of criteria or state conditions. There are four state conditions or classes, which were determined based on the frequency distribution of the IRI data. A total of 876 IRI measurements were collected from 5 segments and four lanes of toll roads, with minimum and maximum values of 2.14 m/km and 3.8 m/km, respectively. This results in 11 classes, each with a relatively small interval length, which complicates implementation. To address this, a simplification process is employed by merging three or four classes, thereby reducing the number of classes and enhancing the effectiveness of TPM development. The first class or state represents a road condition with an IRI value of 2.0 – 2.5, while the last class represents the worst condition with an IRI score of 3.5 – 4.0.

The second step of this study was to determine the transition probability matrix (TPM). Each TPM has to fulfill the following conditions: the number of inputs from each row is equal to 1, and all input values cannot be negative [11].

Pavement quality typically deteriorates during its service period, leading to damage. In Markov modeling, changes in the pavement due to damages can be denoted by the untreated or without-handling TPM, which is the probability of changing the pavement condition due to damages from time to time. The form of the probability matrix considers no handling programs [12], which can be seen in equation 4.

$$P = \begin{bmatrix} P_{1,1} & P_{1,2} & 0 & 0 \\ 0 & P_{2,2} & P_{2,3} & 0 \\ 0 & 0 & P_{3,3} & P_{3,4} \\ 0 & 0 & 0 & P_{4,4} \end{bmatrix} \quad (4)$$

$P_{1,2} = \frac{S_1^{(1)} - S_1^{(2)}}{S_i^{(1)}}$, $S_1^{(1)} \geq S_1^{(2)}$ $\quad$ $P_{3,4} = \frac{S_4^{(2)} - S_4^{(1)}}{S_3^{(1)}}$ $\quad$ $P_{4,4} = 1.00$

$P_{1,1} = 1 - P_{1,2}$ $\quad$ $P_{2,2} = 1 - P_{2,3}$

$P_{2,3} = \frac{S_2^{(1)} - S_2^{(2)} + S_1^{(1)} P_{1,2}}{S_2^{(1)}}$ $\quad$ $P_{3,3} = 1 - P_{3,4}$

To calculate TPM with handling programs in this study, the types of treatment in the form of periodic maintenance and rehabilitation or improvement were used. The form of the probability matrix considers periodic maintenance and rehabilitation programs [12], which can be seen in equation 5.

$$P = \begin{bmatrix} P_{1,1} & 0 & 0 & 0 \\ f_{2,1} & P_{2,2} & 0 & 0 \\ f_{3,1} & f_{3,2} & P_{3,3} & 0 \\ f_{4,1} & 0 & f_{4,3} & P_{4,4} \end{bmatrix} \quad (5)$$

$f_{3,1} = f_{4,1} = \frac{length\ of\ road\ to\ be\ rehabilitated}{total\ length\ of\ road}$ $\quad$ $P_{3,3} = \frac{S_3^{(2)} - S_4^{(1)} + S_4^{(1)}\ x\ f_{4,1} - S_4^{(2)}}{S_3^{(1)}}$

$f_{2,1} = \frac{S_1^{(2)} - S_1^{(1)} - S_3^{(1)}\ x\ f_{3,1} - S_4^{(1)}\ x\ f_{4,1}}{S_2^{(1)}}$ $\quad$ $P_{4,4} = \frac{S_4^{(2)}}{S_4^{(1)}}$

$P_{2,2,} = 1 - P_{2,1}$ $\quad$ $f_{3,2} = 1 - f_{3,1} - P_{3,3}$ $\quad$ $f_{4,3} = 1 - f_{4,1} - P_{4,4}$

in which: i is an index to declare state or class I (i = 1, 2, 3, 4); $P_{i,i}$ is the transition probability from state I to remain in state I or the probability that the pavement remains in the same condition after one transition has passed; $S_i^{(k)}$ is proportion of state or class i in the k-year transition and determined based on the percentage of road length in a specific condition or state, observed over two review periods, one year prior and the current year; and k is an index to express the transition year to k, k = 1,2.

The probability values below the main diagonal ($f_{i,j}$; $j < i$) represent the transition probabilities for improving pavement conditions as a result of maintenance and rehabilitation (M&R) programs. According to Abaza and Ashur [13], maintenance program (M) is applied to states 2, 3, and 4, specifically the variables $f_{2,1}$, $f_{3,2}$, and $f_{4,3}$, with no maintenance applied to state 1. These variables correspond to a one-step improvement from state i to state $i - 1$. In contrast, a rehabilitation program (R) is applied to pavements in states 3 and 4, specifically $f_{3,1}$ and $f_{4,1}$, and can result in multiple steps of improvement, moving the pavement from state i directly to state 1.

The TPM used in this model is the transition probability for the initial conditions in 2020–2022, where 2022 is the base year (t = 0). The probability values in these matrices are determined based on the percentage of road length in a specific condition or state observed over two review periods—one year prior and the current year. TPM for the application of Markov chain modeling on the Semarang - Solo toll road is presented in Tables 3 and 4. The two tables cover the TPM for two different lanes (inner and outer) and for two directions (Semarang – Solo and Solo – Semarang), each consisting of TPM for the five road segments evaluated (Banyumanik – Ungaran, Ungaran – Bawen, Bawen – Salatiga, Salatiga – Boyolali, and Boyolali – Kartasura). In Tables 3 and 4, the without-handling-program matrix is a matrix that contains historical data when no handling activities or only routine maintenance activities are carried out, and the handling-program matrix contains historical data when rehabilitation or improvement activities were carried out on the road section.

Table 3. TPM of Toll-road of Semarang-Solo Direction

Sections	Transition probability matrix based on the types of road handling			
	Inner lane		Outer lane	
	Without handling	With handling	Without handling	With handling
Banyumanik – Ungaran	$\begin{bmatrix}0.00 & 1.00 & 0.00 & 0.00\\0.00 & 0.46 & 0.54 & 0.00\\0.00 & 0.00 & 0.99 & 0.01\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.43 & 0.00 & 0.57 & 0.00\\0.43 & 0.00 & 0.57 & 0.00\end{bmatrix}$	$\begin{bmatrix}0.00 & 1.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.00 & 0.00 & 0.75 & 0.25\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.73 & 0.00 & 0.27 & 0.00\\0.73 & 0.00 & 0.27 & 0.00\end{bmatrix}$
Ungaran – Bawen	$\begin{bmatrix}0.00 & 1.00 & 0.00 & 0.00\\0.00 & 0.75 & 0.25 & 0.00\\0.00 & 0.00 & 0.75 & 0.25\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.85 & 0.00 & 0.15 & 0.00\\0.85 & 0.00 & 0.15 & 0.00\end{bmatrix}$	$\begin{bmatrix}0.75 & 0.25 & 0.00 & 0.00\\0.00 & 0.60 & 0.40 & 0.00\\0.00 & 0.00 & 0.80 & 0.20\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0 .00\\0.00 & 1.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\end{bmatrix}$
Bawen – Salatiga	$\begin{bmatrix}0.00 & 1.00 & 0.00 & 0.00\\0.00 & 0.63 & 0.37 & 0.00\\0.00 & 0.00 & 0.53 & 0.47\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.86 & 0.00 & 0.14 & 0.00\\0.86 & 0.00 & 0.14 & 0.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 0.63 & 0.37 & 0.00\\0.00 & 0.00 & 1.00 & 0.00\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\end{bmatrix}$
Salatiga – Boyolali	$\begin{bmatrix}0.60 & 0.40 & 0.00 & 0.00\\0.00 & 0.67 & 0.33 & 0.00\\0.00 & 0.00 & 0.94 & 0.06\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.79 & 0.00 & 0.21 & 0.00\\0.79 & 0.00 & 0.21 & 0.00\end{bmatrix}$	$\begin{bmatrix}0.92 & 0.08 & 0.00 & 0.00\\0.00 & 0.74 & 0.26 & 0.00\\0.00 & 0.00 & 1.00 & 0.00\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\end{bmatrix}$
Boyolali – Kartasura	$\begin{bmatrix}0.00 & 1.00 & 0.00 & 0.00\\0.00 & 0.75 & 0.25 & 0.00\\0.00 & 0.00 & 0.75 & 0.25\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\end{bmatrix}$	$\begin{bmatrix}0.00 & 1.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.00 & 0.00 & 0.75 & 0.25\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\end{bmatrix}$

Table 4. TPM of Toll-road of Solo-Semarang Direction

Sections	Transition probability matrix based on the types of road handling			
	Inner lane		Outer lane	
	Without handling	With handling	Without handling	With handling
Banyumanik – Ungaran	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 0.50 & 0.50 & 0.00\\0.00 & 0.00 & 0.83 & 0.17\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.40 & 0.00 & 0.60 & 0.00\\0.40 & 0.00 & 0.60 & 0.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.00 & 0.00 & 0.91 & 0.09\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.43 & 0.00 & 0.57 & 0.00\\0.43 & 0.00 & 0.57 & 0.00\end{bmatrix}$
Ungaran – Bawen	$\begin{bmatrix}0.71 & 0.29 & 0.00 & 0.00\\0.00 & 0.33 & 0.67 & 0.00\\0.00 & 0.00 & 1.00 & 0.00\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 0.80 & 0.20 & 0.00\\0.00 & 0.00 & 1.000 & 0.00\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\end{bmatrix}$
Bawen – Salatiga	$\begin{bmatrix}0.00 & 1.00 & 0.00 & 0.00\\0.00 & 0.92 & 0.08 & 0.00\\0.00 & 0.00 & 0.93 & 0.07\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.60 & 0.00 & 0.40 & 0.00\\0.60 & 0.00 & 0.40 & 0.00\end{bmatrix}$	$\begin{bmatrix}0.00 & 1.00 & 0.00 & 0.00\\0.00 & 0.71 & 0 .29 & 0.00\\0.00 & 0.00 & 0.89 & 0.11\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.75 & 0.00 & 0.25 & 0.00\\0.75 & 0.00 & 0.25 & 0.00\end{bmatrix}$
Salatiga – Boyolali	$\begin{bmatrix}0.40 & 0.60 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\0.00 & 0.00 & 0.80 & 0.20\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.23 & 0.77 & 0.00 & 0.00\\0.90 & 0.00 & 0.10 & 0.00\\0.90 & 0.00 & 0.10 & 0.00\end{bmatrix}$	$\begin{bmatrix}0.00 & 1.00 & 0.00 & 0.00\\0.00 & 0.82 & 0.18 & 0.00\\0.00 & 0.00 & 1.00 & 0.00\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.50 & 0.50 & 0.00 & 0.00\\0.91 & 0.00 & 0.09 & 0.00\\0.91 & 0.00 & 0.09 & 0.00\end{bmatrix}$
Boyolali – Kartasura	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 0.83 & 0.17 & 0.00\\0.00 & 0.00 & 0.75 & 0.25\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 0.75 & 0.25 & 0.00\\0.00 & 0.00 & 1.00 & 0.00\\0.00 & 0.00 & 0.00 & 1.00\end{bmatrix}$	$\begin{bmatrix}1.00 & 0.00 & 0.00 & 0.00\\0.00 & 1.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\\1.00 & 0.00 & 0.00 & 0.00\end{bmatrix}$

The third step was to determine the proportion of the initial condition. The proportion is obtained by comparing the length of the road segment in certain conditions with the total length of the road segment under review. The proportion of initial conditions for applying the Markov chain modeling on the Semarang - Solo toll road is presented in Table 5.

Based on Table 5, the road segment can be divided into two parts: Banyumanik - Ungaran - Bawen - Salatiga and Salatiga - Boyolali - Kartasura. Salatiga is the highest point along the toll road, influencing the level of road stability. The summary of Table 5 shows that the level of road steadiness is better on uphill roads (on average for inner lanes or outer lanes) by 58% for both Semarang - Solo and Solo - Semarang directions, while the level of road steadiness on downhill roads is only 46% and 49%, for the directions Semarang - Solo and Solo – Semarang, respectively. The length and high longitudinal slope contribute to the low road steadiness on downhills, which causes vehicles to have low to medium speed but with low distance headway [14].

Table 5. Proportion of Initial Condition on Different Lanes and Directions of Semarang–Solo Toll Road

No	Segments	The Proportion of Initial Conditions (a_0) in 2022			
		IRI 2.0- 2.5	IRI 2.5 - 3.0	IRI 3.0 - 3.5	IRI 3.5 - 4.0
	Inner-lane, Semarang-Solo Direction				
1	Banyumanik – Ungaran	0.17	0.43	0.39	0.00
2	Ungaran – Bawen	0.08	0.50	0.42	0.00
3	Bawen – Salatiga	0.12	0.47	0.41	0.00
4	Salatiga - Boyolali	0.17	0.26	0.52	0.04
5	Boyolali - Kartasura	0.25	0.25	0.50	0.00
	Outer-lane, Semarang-Solo Direction				
1	Banyumanik – Ungaran	0.22	0.52	0.17	0.09
2	Ungaran - Bawen	0.25	0.25	0.42	0.08
3	Bawen - Salatiga	0.06	0.41	0.53	0.00
4	Salatiga - Boyolali	0.29	0.25	0.46	0.00
5	Boyolali – Kartasura	0.00	0.38	0.63	0.00
	Inner-lane, Solo-Semarang Direction				
1	Kartasura – Boyolali	0.25	0.63	0.13	0.00
2	Boyolali – Salatiga	0.13	0.50	0.25	0.13
3	Salatiga – Bawen	0.06	0.41	0.35	0.18
4	Bawen – Ungaran	0.42	0.17	0.42	0.00
5	Ungaran – Banyumanik	0.09	0.26	0.57	0.09
	Outer-lane, Solo-Semarang Direction				
1	Kartasura - Boyolali	0.00	0.25	0.63	0.13
2	Boyolali - Salatiga	0.04	0.50	0.46	0.00
3	Salatiga – Bawen	0.06	0.41	0.53	0.00
4	Bawen – Ungaran	0.25	0.33	0.42	0.00
5	Ungaran - Banyumanik	0.09	0.39	0.52	0.00

Due to various road conditions encountered in all road segments evaluated (see Table 5), this study used hypothetical data to ease analyzing the prediction results produced by the Markov model. These two hypothetical data reflect two initial road conditions, which are derived from Table 5, that is, initial conditions at a medium level of road steadiness or hypothetical data A (a_0 = 0.250, 0.300, 0.350, 0.100) and at the low level of road steadiness or hypothetical data B (a_0 = 0.100, 0.250, 0.500, 0.100). Likewise, the scenarios applied to the two initial condition values were: (i) without-handling-program scenario (no treatment or routine maintenance) if the road steadiness with states 1 and 2 (see Table 2) is above 50%, and (ii) with-handling-program scenario (minor rehabilitation), if the road steadiness with states 1 and 2 is less than 50%,

Figures 2-5 depict the road condition prediction using the Markov model in terms of the steady condition of states 1 and 2, in which two scenarios, that is, without-handling-program and with-handling program scenarios, applied to two hypothetical initial condition data (at medium- and low-level of road steadiness).

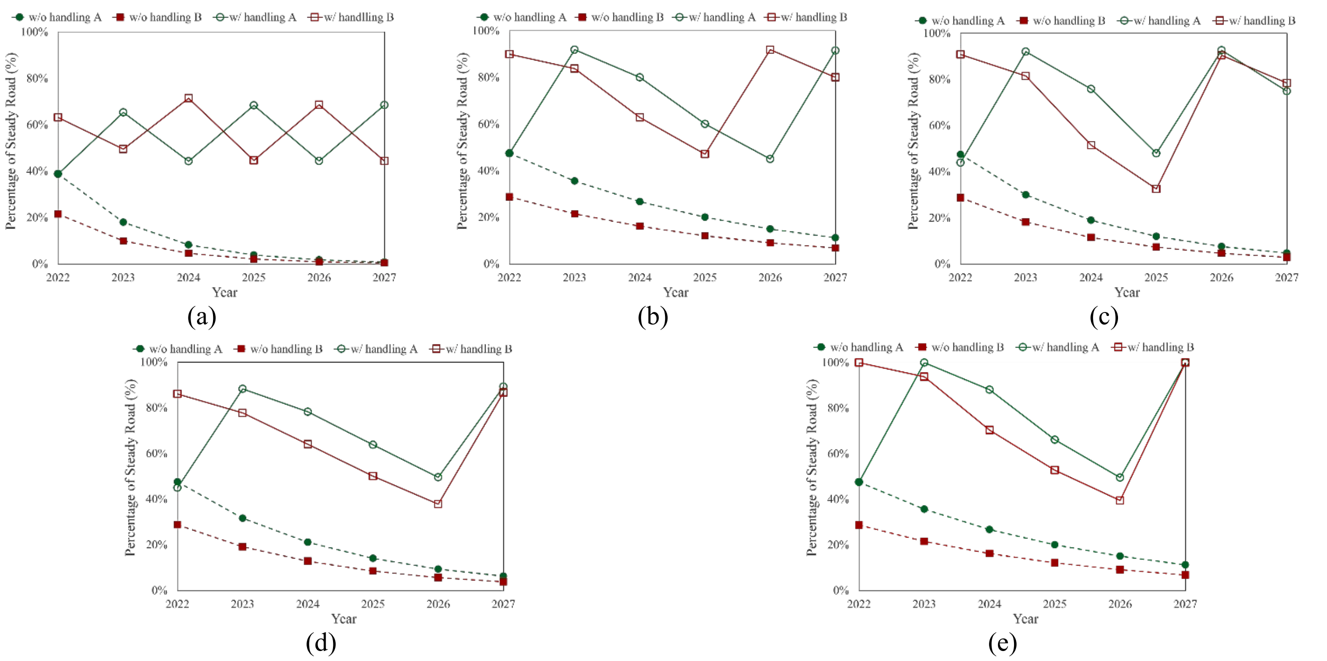

Figure 2. Percentage of Steady Condition of Inner-lane of Semarang–Solo Direction: (a) Banyumanik-Ungaran; (b) Ungaran-Bawen; (c) Bawen-Salatiga; (d) Salatiga-Boyolali; (e) Boyolali-Kartasura

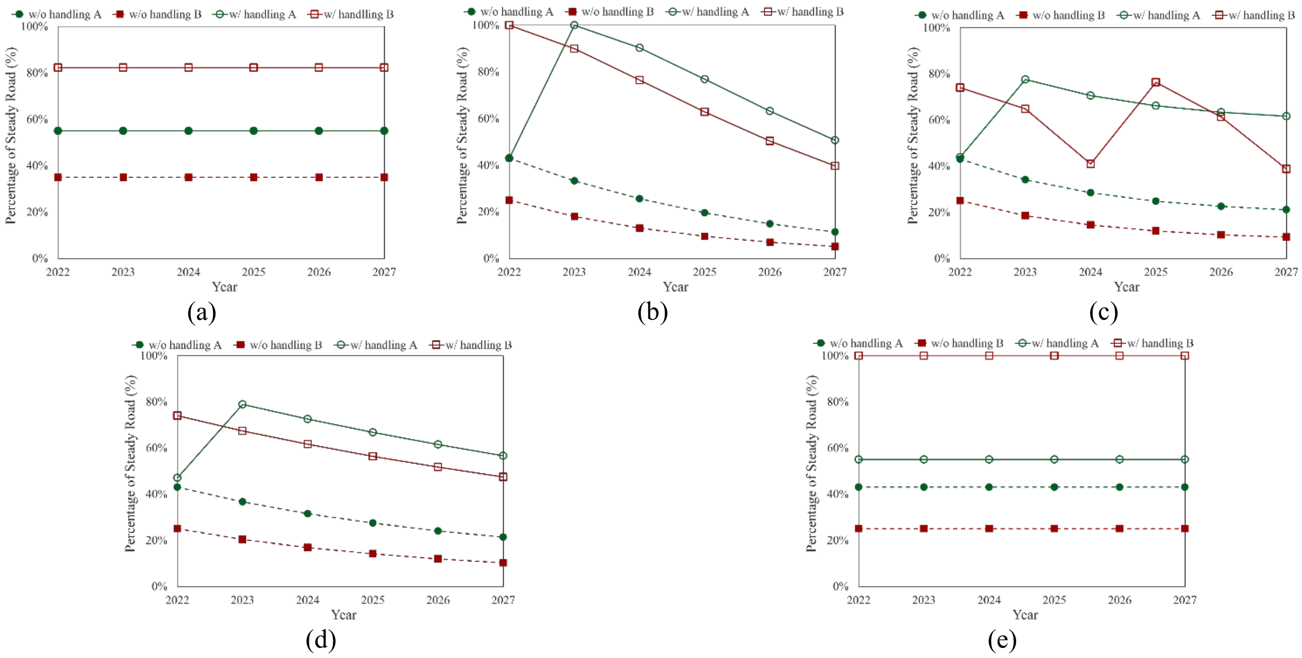

Figure 3. Percentage of Steady Condition of Outer-lane of Semarang–Solo Direction: (a) Banyumanik-Ungaran; (b) Ungaran-Bawen; (c) Bawen-Salatiga; (d) Salatiga-Boyolali; (e) Boyolali-Kartasura

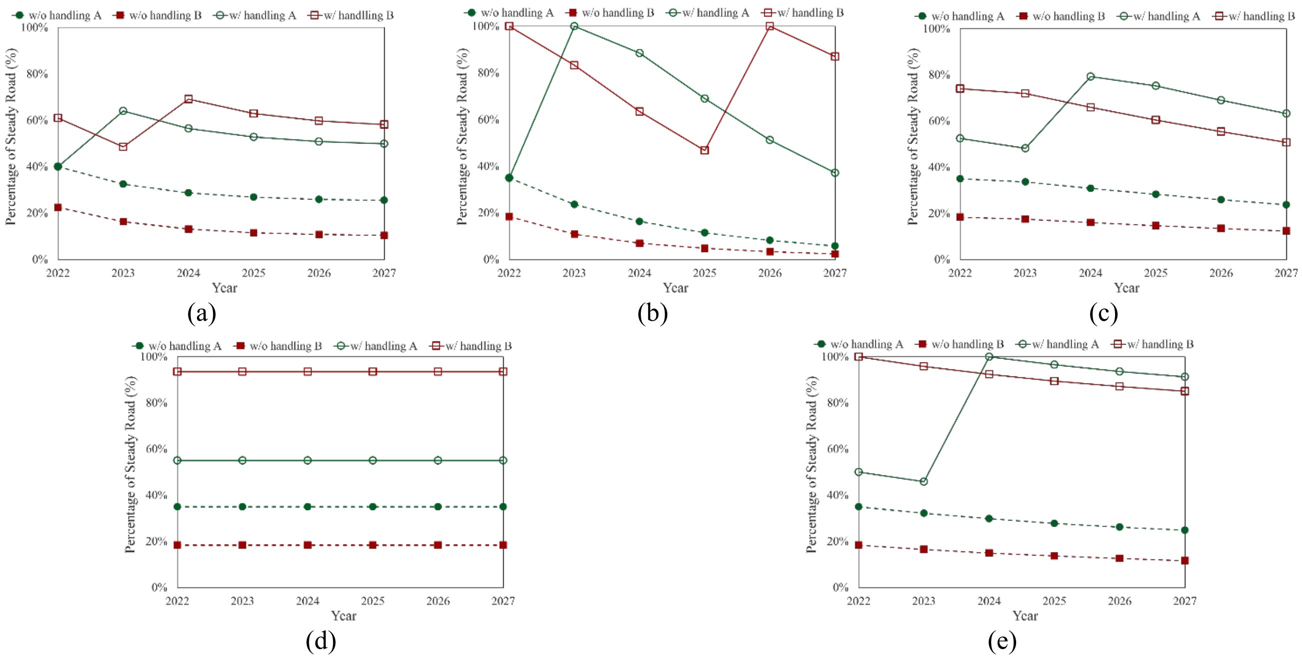

Figure 4. Percentage of the Steady Condition of the Inner Lane of Solo–Semarang Direction: (a) Ungaran-Banyumanik; (b) Bawen-Ungaran; (c) Salatiga-Bawen; (d) Boyolali-Salatiga; (e) Kartasura-Boyolali

The decreasing trend in Figures 2 – 5 indicates a decrease in the percentage of road steadiness in states 1 and 2 due to no treatment (or only routine maintenance). In contrast, an increasing trend indicates increased road steadiness in states 1 and 2 due to the handling (minor rehabilitation) program. There is also a trend of the same level of road steadiness throughout the predicted years (as in Figures 3(a), 3(e), 4(d), and 5(a)) shows that the road segments seem well maintained. However, it has to be observed that there is a possibility of an increase in severe damage conditions, but it is not shown on the graph because it is categorized as road steadiness in states 3 and 4.

The slope of the graphs in Figures 2 – 5 can provide indications regarding the level of decline of the road steadiness. A steep slope shows a drastic decrease in the road's steadiness, indicating that the road section has a higher priority for handling, so it can assist the Highway Agency in determining road handling priorities. Also, handling scenarios in this study help predict how soon handling work is required. Each section encountered different conditions if the scenarios were implemented because each section has its historical road handling data. Therefore, the Bawen – Salatiga section (Figure 2(c)) only requires two years for the subsequent handling program, while the Salatiga – Boyolali section (Figure 2(d)) needs three years.

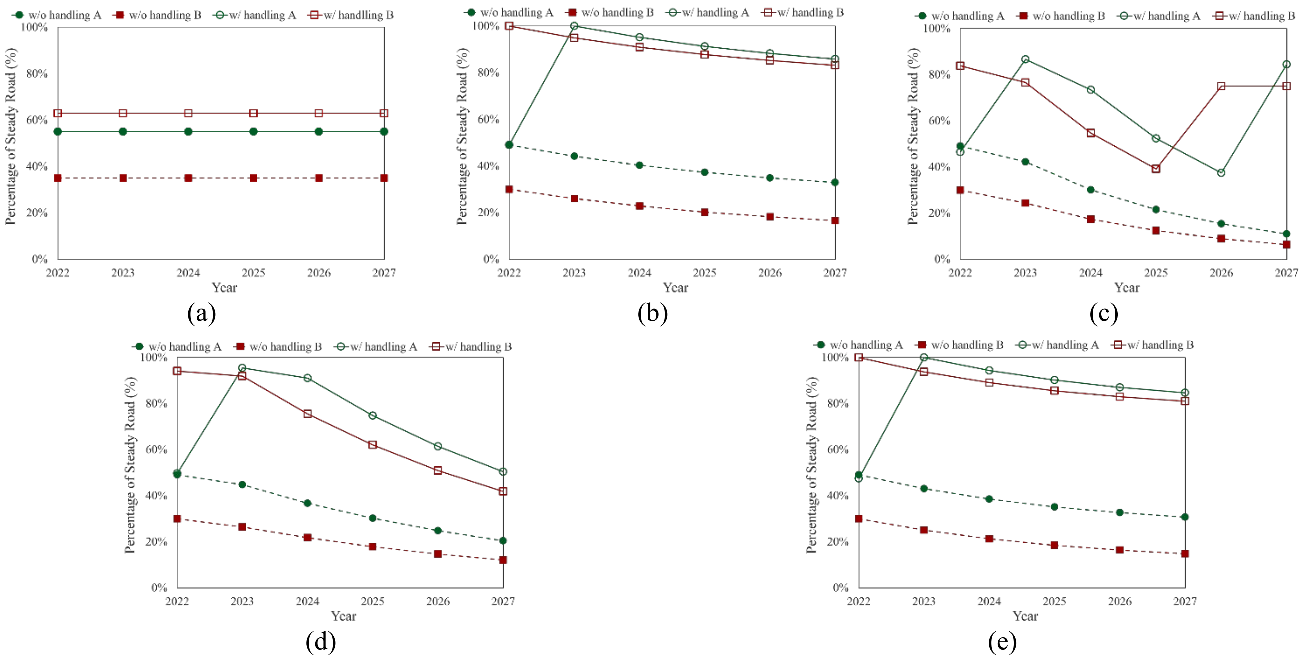

Figure 5. Percentage of the Steady Condition of the Outer Lane of Solo–Semarang Direction: (a) Ungaran-Banyumanik; (b) Bawen-Ungaran; (c) Salatiga-Bawen; (d) Boyolali-Salatiga; (e) Kartasura-Boyolali

Using two hypothetical data produced results as expected. That is, the road steadiness was higher on roads with medium initial conditions than those with low initial conditions. However, for a 5-year prediction, the cycle time required for a road section to obtain the next handling program is generally longer on roads with low initial conditions.

Further analysis of the simulation results using the Markov model can be obtained by referring to other required data, such as annual traffic volume data (see Table 6) and road geometric data in the form of longitudinal slope data (Table 7). Annual traffic volume data is based on toll road regulations in Indonesia. Traffic volume is divided into five groups: 1 for light vehicles and buses and 2 - 5 for trucks with various axle loads. The traffic volume data in Table 6 is the traffic volume data recorded at the toll gates of each segment.

Table 6. Annual Traffic Volume Data Recorded at Toll Gates in the Year 2021

Tollgate	No. of vehicles (veh./year)	
	Category 1	Category 2 - 5
Banyumanik	4,084,344	514,002
Ungaran	1,518,046	48,668
Bawen	2,630,628	375,588
Salatiga	687,922	112,047
Boyolali	727,972	55,211

Table 7. Longitudinal Slope for All Toll-road Segments

Toll-road segments	No. of vehicles (veh./year)		
	Average slope (%)	Max slope (%)	% slope more than 5%
Banyumanik – Ungaran	2.99	13.50	13.04
Ungaran – Bawen	5.35	14.58	36.36
Bawen – Salatiga	2.47	5.18	5.26
Salatiga – Boyolali	1.90	6.83	5.26
Boyolali – Kartasura	0.60	1.16	0.00

Both additional data (annual traffic volume and longitudinal slope) can be used to justify the historical road condition data and the prediction results produced by simulation using the Markov model. Generally, traffic volume consisting of a high percentage of trucks and a high longitudinal slope positively contribute to the low level of road steadiness. Figure 2-5 shows that the Banyumanik - Ungaran, Ungaran - Bawen, and Bawen - Salatiga segments are the segments with a higher rate of decline in road steadiness compared to the Salatiga - Boyolali and Boyolali - Kartasura segments. This trend can be seen in the without-handling graphs and is more obvious in the with-handling graphs.

In lane-position wise, the inner lane of Semarang - Solo direction has a steeper slope and a higher level of fluctuation compared to the outer lane, where this trend is only visible on Ungaran - Bawen and Bawen Salatiga. Meanwhile, in the Solo - Semarang direction, a similar trend is only visible in a few segments, i.e., the Bawen - Ungaran and the Salatiga - Bawen segments for the inner and outer lanes, respectively. This illustrates that the inner lane for all segments in the Semarang - Solo direction has the main priority of being monitored.

The simulation using the Markov method provides a good illustration of the level of road steadiness over years of observation, although limiting the prediction period is highly recommended because there is the possibility of unpredictable occurrences that are not considered in the simulation. Sazali et al. [15] reported that the Markov method's prediction accuracy, when compared to actual conditions over four consecutive years, had an average deviation of 5%, with a maximum deviation of 13% in the no-treatment scenario and up to 8% in the treatment scenario. If significant discrepancies are encountered between the Markov method's predictions and actual road steadiness conditions in a certain year, the non-homogeneous Transition Probability Matrix (TPM) can be considered [16] and recalculated using the previous year and the current IRI data collected by the toll road authority.

Further research on road condition prediction could explore the potential of non-Markovian effects by identifying memory effects within the system and understanding how past states influence future dynamics. This approach is expected to complement the Markov method, which assumes short-term memory in nature. Utilizing techniques such as longitudinal data analysis (time-series analysis or panel data models) [17] or predictive methods like machine learning [18] is highly recommended to enhance the accuracy and robustness of road condition predictions.

CONCLUSIONS

Applying the Markov chain model to the Semarang-Solo toll road, Indonesia, five-year period (2022–2027) used the TPM value of the road condition transitions in 2020–2022, and 2022 was used as the base year. A simulation using the Markov model was conducted on a five-segment Semarang-Solo toll road, with two scenarios, without-handling and with-handling programs, to evaluate the decreasing trend in the level of road steadiness during the evaluation period. The simulation results showed that the historical data used to compile the transition probability matrix (TPM) from the Markov model greatly influences the simulation results in the without-handling and with-handling programs. In addition, the simulation results also indicated that the inner lane for all segments of the toll road from Semarang - Solo direction is the most crucial segment because these segments have a relatively high rate of decline in road steadiness and a shorter cycle time for implementing the handling program.

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