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Nepal's National Highway Pavement Optimal Management through Life Cycle Cost Minimization

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Abstract

Nepal's National Highway (NH) network is vital to meet the country's transportation demands and socio-economic development. However, a big fraction of NH network faces rapid deterioration due to increasing traffic, harsh climatic conditions and inefficient maintenance planning. This study presents a data driven framework for road management planning, utilizing the Markov hazard model for pavement deterioration for two major pavement types – Surface Dressing (SD) and Asphalt Concrete (AC) across two major climatic conditions - Tropical Savannah (Aw) and Temperate Climate with Dry winter (Cw). The framework incorporates Surface Distress Index (SDI), traffic volumes, and life cycle cost analysis (LCCA) to evaluate the long-term effectiveness of various maintenance and upgrading strategies using the Markov model. The result shows that Combined Maintenance (CM) which involves integration of routine and recurrent maintenance activities significantly delay pavement deterioration process, reducing periodic maintenance costs and improving road network performance. Upgrading SD pavement with higher deterioration rates to AC proves highly effective for high traffic roads, improving durability and overall network condition. The study evaluates several maintenance and upgrading strategies, highlighting the balance between LCC and the good to fair road percentage, enabling road agencies to set performance targets within budget constraints. The findings provide valuable information for policymakers and road agencies, emphasizing the importance of proactive, data-driven decision-making in road maintenance planning. Future research could explore indirect benefits, such as vehicle operating cost savings and reduced travel times, to further enhance the decision-making framework.

Keywords: Markov pavement deterioration model; Markov pavement repair model; combined maintenance; life cycle maintenance cost; cost-condition relation.

1. Introduction

Nepal's road network plays a critical role in the country's economic development and daily connectivity. The 16th Five Year Plan of Nepal (2024/25 to 2028/29) has set ambitious targets to be achieved during this period, indicating significant growth over the next five years. This plan also focuses on the importance of developing mechanisms for road maintenance, ensuring organized and systematic maintenance work, mobilizing and managing resources (National Planning Commission, 2024). Despite these attempts in policy-level efforts, a significant portion of the National Highways (NH) faces rapid deterioration due to increasing traffic volumes, diverse climatic conditions, and inefficiencies in maintenance planning. This deterioration lowers road quality, leading to higher maintenance costs and vehicle operating costs (VOC). Present maintenance practices in Nepal are yearly and short term, it lacks a robust, data-driven framework, which supports the decision makers and road agencies to set the acceptable standards of network performance considering the associated cost factor.

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A key contribution of this study is the integration of Markov hazard model and repair models with climatic and mixed traffic conditions in developing countries to access pavement deterioration considering data base of Nepal's NH. This research evaluates the performance of two major pavement types—Surface Dressing (SD) and Asphalt Concrete (AC)—across two distinct climatic zones: Tropical Savannah (Aw) and Temperate Dry Winter (Cw) which are classified by modifying Köppen - Geiger (KG) climate classification systems to delineate the realistic climatic condition of Nepal. Additionally, the study introduces a cost-condition trade-off framework, which quantifies the relationship between life cycle cost analysis (LCC) and good to fair road percentages (Surface Distress Index (SDI) value ≤ 3). This framework evaluates various maintenance and upgrading strategies over a 24-year horizon, enabling road agencies to make informed decisions based on budget limitations and performance goals. These contributions provide practical tools for data-driven, cost-effective road maintenance planning in resource-constrained settings, with broad applicability to other developing countries facing similar challenges.

2. Literature Review

Referring to AASHTO pavement management guidelines, four types of models are commonly used to predict future pavement conditions: deterministic, probabilistic, Bayesian, and subjective (or expert-based) models (American Association of State Highway and Transportation Officials, 2012). The Markov hazard model, a probabilistic approach, derived from survival analysis principles, which are widely used in infrastructure management, has proven effective in predicting pavement deterioration by considering transition probabilities between condition states (Tsuda et al., 2006). Pavement deterioration process is progressive and depends on several factors such as traffic, environment, construction methods etc. and this probabilistic approach enables infrastructure managers to account for uncertainties in the deterioration process. The deterioration states are categorized into several ranks based on inspection results and their deterioration rates are estimated by the hazard models. The expected deterioration path, which characterizes the average deterioration process, is derived from the Markov transition probabilities. The transitions between condition states are governed by life expectancy computations for the life expectancy in each condition state and the total life expectancy is the sum of life expectancy in each condition state (Tony Lancaster, 1990).

However the Markov pavement repair process is a deterministic, demonstrating its ability to model the transition of pavement condition states after the repair activities (Angelo et al., 2023). In the context of Nepal, the SDI serves as a performance indicator to assess pavement conditions, adapted from the World Bank's recommendations (Department of Roads (DOR) & MRCU, 1995; Ministry of Works and Transport Department of Roads, 1995). The DOR strategy emphasizes on execution of planned maintenance comprising a program of routine, recurrent and periodic maintenance activities for roads that are in a maintainable condition The integrated routine and recurrent maintenance activities is termed as combined maintenance (CM) and the associated cost is the CM cost. (DOR, 2014; Ministry of Works and Transport Department of Roads, 1995).

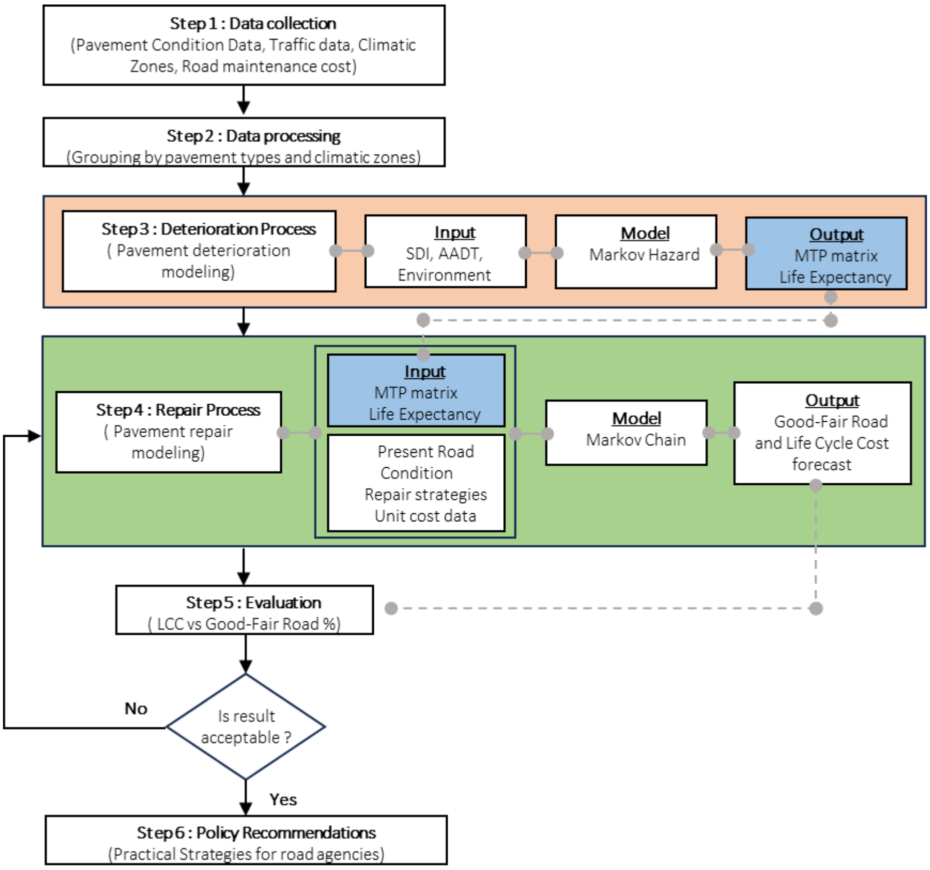
The life cycle cost of a road infrastructure is defined as the aggregation of initial costs and discounted future costs, such as maintenance cost, user cost, reconstruction, rehabilitation, restoring and resurfacing costs, over the life of the road project. (Federal Highway Administration (FHWA), 2024).

3. Methodology

This study presents a comprehensive, data-driven framework for road maintenance planning. Utilizing Markov hazard (Kobayashi et al., 2012) and Markov repair models (Angelo et al., 2023), the framework is outlined in Figure-1, examines pavement deterioration and evaluates maintenance strategies for two major pavement types: SD and AC. The methodology is divided into four main stages: data collection from road agency, data processing, model description, and analysis of repair strategies. Life cycle cost and predicted road condition is computed for various strategies. The unit cost for combined maintenance (CM), periodic maintenance (PM) and upgrading (U) is acquired from the IARMP 2022-23 national allocation summary. In developing countries like Nepal, roads have been constructed and upgraded by various road agencies and foreign donors, it is very difficult to define the initial construction cost. Instead, in this study LCC excludes the initial construction cost and focuses on the CM cost, PM cost and upgrading cost over the analysis period y.

3.1 Data Collection

The data utilized in this study were collected from periodic inspection reports recorded in the road register of the Highway Management Information System (HMIS) unit at DOR. This dataset includes information on pavement conditions and traffic volumes. DOR considers surface distress of pavement as an indicator to represent the pavement condition. The traffic survey involved traffic counting and analysis from 160 stations which are at



the major nodal locations on the strategic road network of Nepal. The traffic data is represented by the average annual daily traffic (AADT) expressed in Passenger Car Unit (PCU). These are used as an explanatory variable in the hazard model.

Figure 1. Pavement deterioration modelling and maintenance decision making framework.

3.1.1 Pavement Performance Indicator: Surface Distress Index (SDI)

SDI is a measurement of pavement distress which accounts for major defects such as wide cracks, scabbing, rutting, potholes, exposed base, long edge break, corrugations and minor defects such as narrow crack, line crack, bleeding, short edge break etc. Highway engineers and pavement experts conduct visual surveys and record the severity of the distress for each 1 km road section. This data is used to calculate the SDI value for the surveyed road section. In context of Nepal, SDI is expressed in rating scale from 0 to 5. The rating 0 indicates a pavement surface without any defects, whereas a rating of 5 indicates the maximum possible deterioration. This method adopted by DOR is a simplified procedure recommended by the World Bank which has been modified to suit the conditions in Nepal and the need for DOR.

Detail procedure for the determination of SDI value for each road link is described in “Road Pavement Management, MRCU” (Department of Roads (DOR) & MRCU, 1995). To implement the Markov hazard model, the condition ratings presented in Table 1 were used to assess the pavement conditions based on the SDI values. Condition state 1 denotes the best condition, whereas condition state 6 represents the worst pavement condition.

Table 1. Road condition based on SDI

SDI Value	Condition	Incidence of minor defects	Incidence of major defects	Condition State
0	Good	None	None	1
1	Moderate	1 to 200 sq.m. per km.	1 occurrence	2
2	Satisfactory	< 50% of the area	2 to 4 occurrences	3
3	Fair	≥ 50%	< 30% of area	4
4	Poor		30% or potholes and base exposed < 20% of the area	5
5	Bad		Potholes and exposed base = 20% of the area	6

3.2 Data Processing

The national highway network is group into different climatic zones as defined by New Climatic Classification of Nepal, Ramchandra Karki et al. This study identifies the five major types of climatic zones in Nepal by modifying Köppen - Geiger (KG) climate classification systems to delineate the realistic climatic condition of Nepal (Karki et al., 2016). Figure 2 shows the national highway sections under different climatic zones as defined by modified KG climatic classification system.

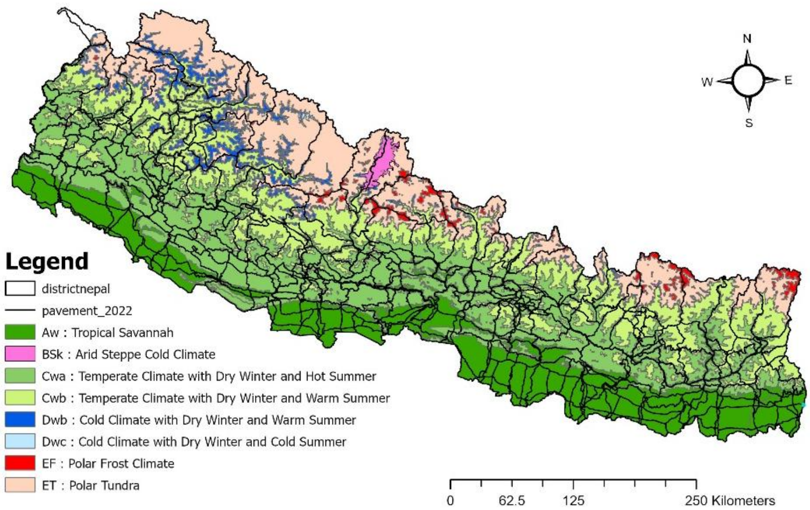


Figure 2. National highway network under different climatic zones.

3.3 Model Description

3.3.1 Markov pavement deterioration model

Markov pavement deterioration hazard model is derived from the survival analysis principle which is widely used for modelling infrastructure deterioration. It is a probabilistic model based on inspection data and taking uncertainty into account to determine the future conditions of the infrastructure. In this model the pavement deterioration process is progressive and depends on several factors such as traffic, environment, construction methods etc. The deterioration process is described by transition probabilities. The deterioration states are categorized into several ranks based on inspection results and their deterioration rates are estimated by the hazard models. For the application of the Markov hazard model, the following assumptions must hold true. Assumptions of the Markov model are : (a) there have been no maintenance and repair activities imposed and no measurement errors during the inspection period and (b) the deterioration process of the road section occurs naturally as its condition state getting worsens over the year (Tsuda et al., 2006).

The Markov transition probability is used to represent the uncertain transition of the condition state during two points in time. If the condition state observed at time $\tau_A = i$, a Markov transition probability, given a condition state $h(\tau_A) = i$ observed at time τ, defines the probability that the condition state at a future time τ_B will change to $h(\tau_B) = j$, that is

$$Prob[h(\tau_B) = j \mid h(\tau_A) = i] = \pi_{ij} \quad (1)$$

The multistage exponential hazard model has been defined as

$$\pi_{ij} = \sum_{k=i}^{j} \prod_{m=i}^{k-1} \frac{\theta_m}{\theta_m - \theta_k} \prod_{m=k}^{j-1} \frac{\theta_m}{\theta_{m+1} - \theta_k} exp(-\theta_k Z) \quad (2)$$

where,

$$\prod_{m=i}^{k-1}\frac{\theta_m}{\theta_m-\theta_k}=1, at\ (k\leq i+1)\ and\ \prod_{m=k}^{j-1}\frac{\theta_m}{\theta_{m+1}-\theta_k}=1\ at\ (k\geq j)$$

The hazard rate θ_i ($i=1,2,\ldots,\ J-1$) is defined as the function of explanatory variable and the unknown parameter beta ($\boldsymbol{\beta}_i$). The unknown parameter β_i ($i=1,2,\ldots,\ J-1$) is determined using the Bayesian estimation method. For detailed explanation of Bayesian method for estimation it is recommended to refer [Han D et al.] (Han et al., 2014). The Markov transition probabilities matrix can be defined by using the transition probabilities between each pair of condition states (i,j) as

$$\prod=\left(\begin{bmatrix}\pi_{11} & \cdots & \pi_{1J}\\ \vdots & \ddots & \vdots\\ 0 & \cdots & \pi_{JJ}\end{bmatrix}\right) \tag{3}$$

where,

$\pi_{ij}\geq 0$

$\pi_{ij}=0$ (when i > j) since the model does not consider the repair.

$\sum_{\mathrm{j=1}}^{\mathrm{J}}\pi_{ij}\ =1$

The final state of deterioration is expressed by condition state J, which remains an absorbing state in the Markov chain if no repair is carried out. In this case $\pi_{JJ}=1$.

However, in the model, the hazard rate θ_i^k($i=1,2,\ldots,\ J-1$) for the inspection sample $k=(1,\ldots,K)$ is considered to change in relation to explanatory variables $\mathbf{x^k}$ and the unknown parameter $\beta_i=\left(\beta_{i,1,}\ldots,\beta_{i,M}\right)$ such that :

$$\theta_i^k=exp(\boldsymbol{\beta}_{i,1}+\boldsymbol{\beta}_{i,2}\boldsymbol{x}_2^{\boldsymbol{k}}+\ldots,\boldsymbol{\beta}_{i,M}\boldsymbol{x}_{\boldsymbol{M}}^{\boldsymbol{k}}) \tag{4}$$

$$\theta_i^k=\ f(\boldsymbol{x^k}\colon\boldsymbol{\beta}_i') \tag{5}$$

3.3.2 Output of the deterioration prediction model.

Using the periodic inspection data, the model provides two major outputs. First is the Markov Transition Probability (MTP) matrix, which is primary output for forecasting the pavement deterioration process. The MTP matrix $\prod(Z)$ represents the probability of condition transition within a specific time interval Z. Therefore, the MTP matrix $\prod(nZ)$ after n interval can express in terms of the MTP matrix $\prod(Z)$ as:

$$\prod(nZ)=\{\prod(Z)\}^n \tag{6}$$

The second output is the life expectancy (LE) of each condition state which is then defined by means of survival function (Lancaster 1990). The life expectancy of the condition state i of the inspection sample k, LE_i^k can be expressed as :

$$LE_i^k\ =\ \int_0^\infty exp(-\theta_i^k y_i^k)dy_i^k\ \ =\frac{1}{\theta_i^k} \tag{7}$$

$$LE_i^J=\sum_{i=1}^{J-1}LE_i^k \tag{8}$$

The life expectancy from condition state i to J can be defined by the sum of life expectancies, and the deterioration curve can be attained by their relations. For more details, it is suggested to refer to Tsuda et al., 2006 (Tsuda et al., 2006).

3.3.3 Markov pavement repair model

The Markov pavement repair process is a deterministic process. The Markov repair or maintenance process has the following assumptions: (a) the repair interval and the repair type are decided by the road agency such as DOR. And (b) the repair process improves the condition state from worse to better (Angelo et al., 2023). For formulating the repair process, the transition from condition state i to j after the repair type is defined by r_{ij}.

$$r_{ij} = \begin{cases} 1, for\ \eta(i) = j \\ 0, for\ \eta(i) \neq j \end{cases} \tag{9}$$

In equation 9, $\eta(i)$ denotes the action vector such that $\eta = [\eta(1), \ldots, \eta(J)]$. The action vector indicates the change in condition state due to repair action. The repair action $\eta(i)$ stands for the transition from i to state $\eta(i)$. For example if $\eta(i) = j$ indicates the state transition from i to j due to repair action. If the repair is carried out for the road section, the condition state changes to a better condition state, otherwise it remains in its current state. Therefore, the Markov transition probability matrix for repair is expressed as R(η):

$$R(\eta) = \left(\begin{bmatrix} r_{11} & \cdots & r_{1J} \\ \vdots & \ddots & \vdots \\ r_{J1} & \cdots & r_{JJ} \end{bmatrix}\right) \tag{10}$$

If we suppose a road network with pavement condition state vector $S(t_r)$, at inspection time t_r will change its state to $S(\tilde{t}_r)$ after the repair assuming that the repair action is carried out after the inspection.

$$S(\tilde{t}_r) = S(t_r) * R(\eta) \tag{11}$$

The deterioration and repair process are continuous process, the condition state before and after the repair at the n^{th} inspection can be formulated using the initial condition state vector $S(t_0)$, the deterioration transition probability matrix Π and the repair transition probability matrix R(η) as follows:

$$S(\tilde{t}_n) = S(t_0)[\ \Pi . R(\eta\ )]^{n-1} . \Pi \tag{12}$$

3.3.4 Life Cycle Cost (LCC)

The DOR strategy emphasizes on execution of planned maintenance comprising a program of routine, recurrent and periodic maintenance activities for roads that are in a maintainable condition (DOR, 2014; Ministry of Works and Transport Department of Roads, 1995). The life cycle cost (LCC) of a road infrastructure is defined as the aggregation of initial costs and discounted future costs, such as maintenance cost, user cost, reconstruction, rehabilitation, restoring and resurfacing costs, over the life of the road project (Federal Highway Administration (FHWA), 2024). In context of DOR, the integrated annual cost for routine and recurrent maintenance activities is termed as combined maintenance cost (CM). Thus, LCC is sum of the initial construction cost, CM and periodic maintenance cost (PM) over the analysis period y years as shown in Figure 2. In the context of developing countries like Nepal, roads have been constructed and upgraded over time by various road agencies and foreign donor partners. In this situation, it is very difficult to define the initial construction cost. Focusing on the maintenance cost of the road infrastructure, in this study Life Cycle Cost (LCC) is defined as the sum of CM and PM.

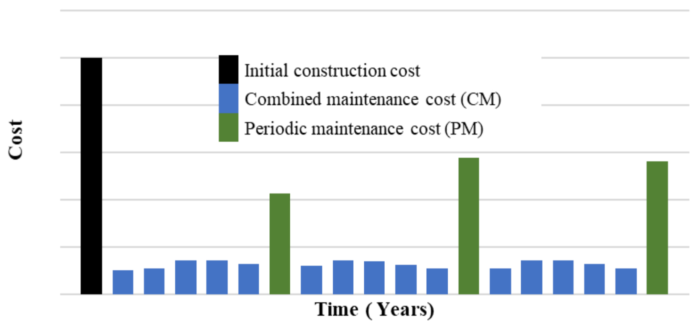


Figure 2. Life cycle cost for road infrastructure.

$$LCC = IC + \sum_{i=1}^{y} [CM_i + PM_i] \quad (13)$$

$$LCC_{Total} = LCC_{SD} + LCC_{AC} \quad (14)$$

3.4 Road maintenance activities

To keep the SRN in a serviceable condition DOR undertakes pavement maintenance activities. These maintenance based on the frequency can be classified into five categories (Department of Roads (DOR), 1994).

i. Routine Maintenance: This category of maintenance is labor intensive and involves activities to keep the road pavement and roadside structures clean and functional. The details of the activities are explained in "Length workers Related Handbook" published by DOR (Department of Roads (DOR), 2006).
ii. Recurrent Maintenance: This category of maintenance is done using hand tools, medium to heavy equipment for repairing potholes, patching, repairing edges and shoulders, crack sealing etc. The interval of recurrent maintenance is 6 months to 2 years. The CM is defined as the integration of routine maintenance and recurrent maintenance activities.
iii. Periodic Maintenance: This category of maintenance refers to the planned cyclic maintenance activity for resealing or resurfacing bituminous surfaced roads at an interval of 6 to 10 years taking account of their present condition, age, geographic location, traffic and their strategic importance. The details procedure for periodic maintenance are explained in " Standard Procedure for Periodic Maintenance Planning" published by DOR (Department of Roads (DOR), 2005).
iv. Emergency Maintenance: This category of maintenance is needed to relate to immediate actions during road closure to keep the traffic movement in SRN. This involves removal of debris and other obstacles; placement of warning signs and diversion works.
v. Preventative Maintenance: This maintenance involves maintenance activities such as slope netting, river training and bank protection works, bioengineering works etc. to preserve the road assets.

4. Empirical Study

For the empirical study the actual pavement inspection data for SRN of Nepal was employed. These road networks have two major types of pavement (a) surface dressing (SD) and (b) Asphalt Concrete (AC). The condition state is defined in Table 1. The data consists of two condition state – the initial condition state corresponds to the road condition from inspection in 2021 and the final condition corresponding to inspection in 2022 for every 1 km road section. The inspection interval is 1 year, and the traffic count is taken as the explanatory variable. The total 4024 data sets are grouped based on the climatic zone as defined by modified Köppen–Geiger climate classification systems. Table 2 shows the inspection data set in different climatic groups.

Table 2. Road section

S.No	Climatic Classification	Inspection data set (Actual)	Inspection data set (Satisfying Markov criteria)
1	Tropical Savannah (Aw)	1701	1669
2	Arid Steppe cold climate (Bsk)	-	-
3	Temperate climate with dry winter and hot summer (Cwa)	1863	1849
4	Temperate climate with dry winter and warm summer (Cwb)	506	506
5	Cold climate with dry winter and warm summer (Dwb)	1	-
6	Cold climate with dry winter and cold summer (Dwc)	-	-
7	Polar Tundra climate (ET)	-	-
8	Polar Frost climate (EF)	-	-

For this study, pavement deterioration was analyzed considering two major pavement types, SD and AC alongside two predominant climatic zones: Tropical Savannah (Aw) and Temperate Climate with Dry winter (Cw).

5. Results and Discussions

5.1.1 Average Markov transition probability matrix

The MTP matrix for each sample is estimated by using the exponential hazard model and the average MTP matric is determined. The MTP matrix for SD and AC pavement is presented in Table 3 and 4.

Table 3. MTP matrix from estimation results – SD

Rating	1	2	3	4	5	6
1	0.29	0.29	0.32	0.08	0.02	0.00
2	-	0.19	0.54	0.20	0.06	0.02
3	-	-	0.51	0.31	0.13	0.06
4	-	-	-	0.41	0.34	0.25
5	-	-	-	-	0.36	0.64
6	-	-	-	-	-	1.00

Table 4. MTP matrix from estimation results – AC

Rating	1	2	3	4	5	6
1	0.43	0.27	0.25	0.04	0.01	0.00
2	-	0.23	0.57	0.16	0.04	0.00
3	-	-	0.61	0.28	0.10	0.02
4	-	-	-	0.51	0.38	0.10
5	-	-	-	-	0.64	0.36
6	-	-	-	-	-	1.00

5.1.2 Life expectancy of pavement under various climatic conditions

The hazard rate for each transition is estimated using equation (5). The expected deterioration path, which characterizes the average deterioration process, is derived from the Markov transition probabilities. Considering that pavement deterioration is a progressive process, transitions between condition states are governed by life expectancy computations using equations (7) and (8) for the life expectancy in each condition state and the total life expectancy respectively. The average deterioration process during the life expectancy rating as shown in Figure 3. The results indicate that SD pavements deteriorate faster than the AC pavement in both Aw and Cw climatic zones.

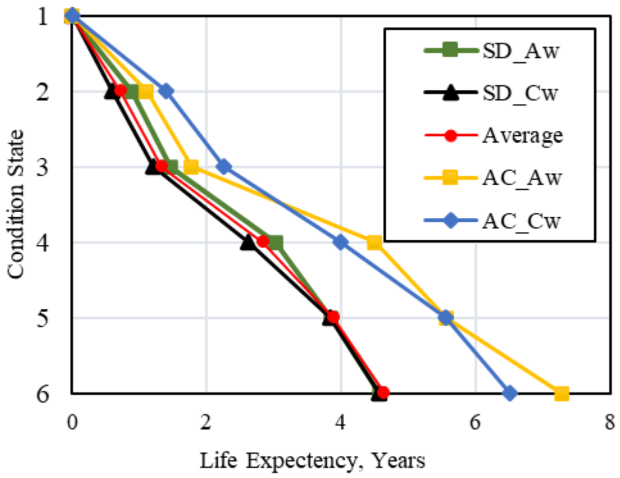
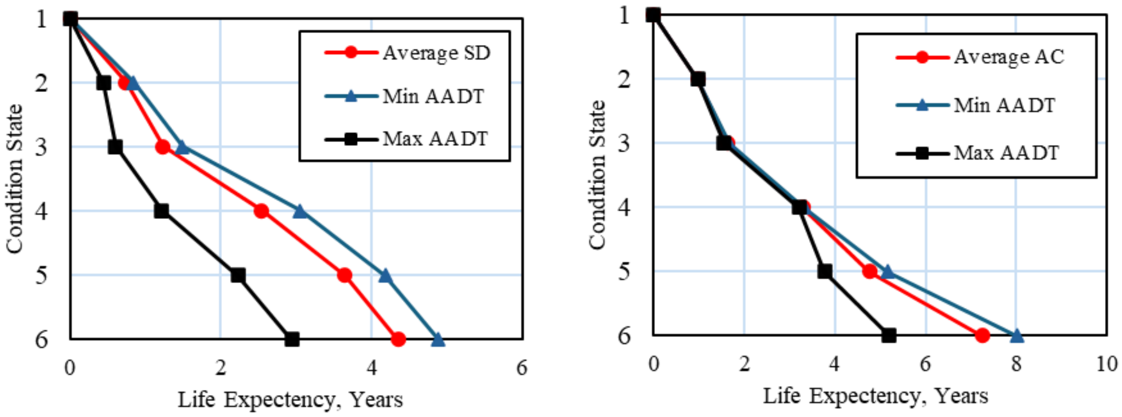


Figure 3. Expected deterioration path of pavement under various climatic conditions

5.1.3 Life expectancy of pavement under various traffic conditions



a. b.

Figure 4. Expected deterioration path of pavement under various traffic conditions- a. SD; b. AC

The results of the study for the effect of traffic on SD and AC pavement deterioration are presented in Figure 4. The result indicates that AC pavements demonstrated a higher average life expectancy of 7.25 years, while SD pavements deteriorated more rapidly with an average life expectancy of 4.35 years. The results indicate that traffic has a significant effect on the pavement. With the increase in traffic volume the pavement life is reduced significantly for both SD and AC pavement. The expected deterioration path of SD and AC pavements at minimum and maximum traffic volume is shown in Figure 4 (a) and 4 (b). Figure 4 (a) suggests that the SD pavement with higher traffic volume should be prioritized for upgrading to AC for improving the road condition. Figure 4 (b) indicates that on AC pavements, traffic has deteriorating effect only after it exceeds the fair condition.

5.1.4 Road Condition and associated costs with and without Combined Maintenance

In this study, 100 km of representative NH is considered for simulating the different maintenance strategies. The condition of the road network, represented as the proportion of pavement in each condition state was assessed for SD and AC pavement at the inspection year 2022. The pavement condition state vector for SD and AC pavement was determined as S $\left(t_{0,SD}\right) = (2.3, 3.79, 35.44, 24.74, 12.84, 14.23)$ and $S\left(t_{0,AC}\right) = (0.52, 0.56, 3.29, 1.51, 0.58, 0.20)$ respectively.

The repair actions are described by the repair matrixes. If no maintenance is performed, the road follows a deterioration process as shown in Figure 3 and Figure 4, represented by the identity matrix. Referring to equation (9), the repair action for combined maintenance is defined by $\eta(4) = 2$ indicates the state transition from 4 to 2 due to combined repair action. Based on this, the repair matrix for CM is defined as.

$$R_{CM}(\eta) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (15)$$

Similarly, when the road pavement is maintainable condition the PM (resealing or overlay) reinstates the pavement to best condition i.e. condition state 1(DOR, 2014; Ministry of Works and Transport Department of Roads, 1995). Therefore, the MTP matrix for repair by PM is defined as:

$$R_{PM}(\eta) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (16)$$

Combining the two repair strategies PM supplemented by CM, the MTP matrix for repair is defined as:

$$R_{CM+PM}(\eta) = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (17)$$

For applying equation (12) in case of SD pavements, the present pavement condition state vector is given by $S(t_{0,SD})$, the MTP matrix is described in Table 3, and the repair strategies $R(\eta)$ defined in equation (15-17). Similarly, for AC pavement, the present pavement condition state vector is given by $S(t_{0,AC})$, the MTP matrix is described in Table 4, and the repair strategies $R(\eta)$ defined in equation (15-17). The average unit cost for maintenance is acquired from the IARMP 2022-23 national allocation summary. The annual cost for CM and PM of SD and AC pavements are calculated. In Figure 5 the interval period for resealing is assumed to be 6 years and the figure shows the plot of yearly pavement maintenance cost with and without the CM. As shown in Figure 5, yearly CM cost is small compared to the PM cost. By introducing CM every year the PM cost is reduced significantly.

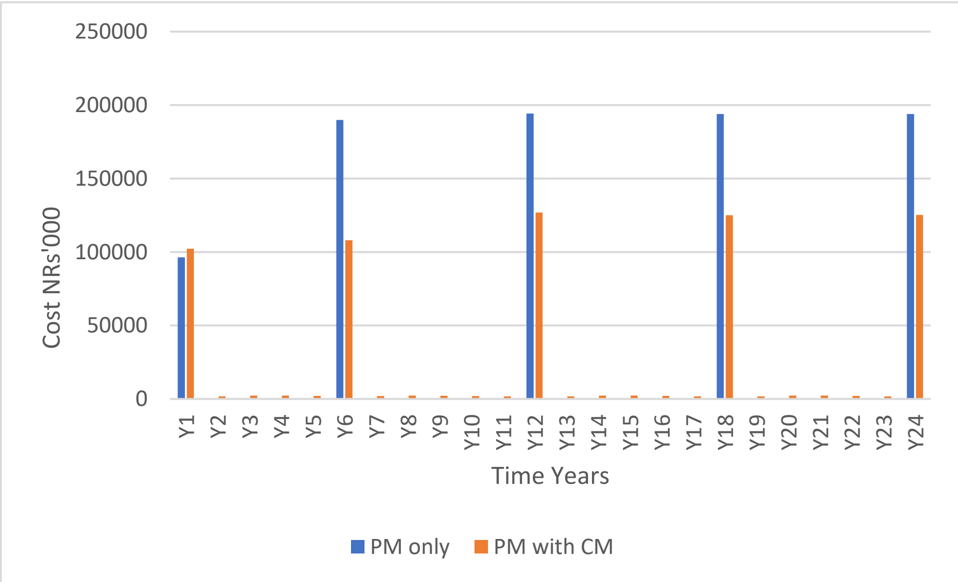


Figure 5. Annual Maintenance Cost for PM only and PM with CM.

Similarly, the associated yearly road maintenance cost for road network (SD pavements at different maintenance interval and AC pavement with 6 year interval) and the road conditions with and without CM are calculated. This yearly road maintenance cost is combined to determine the life cycle cost estimate for 24 years perspective period. Figure 6 illustrates the relationship between the good-fair road condition and the associated cost over different intervals, with and without CM i.e. PM with CM and PM only.

Figure 6 clearly shows that the percentage of good-fair roads increases significantly when combined maintenance is introduced. CM has proved crucial in increasing the service life of the pavement. The red triangles and green dots indicate the serviceable road percentage of road network with PM only and PM with CM respectively. For example, PM at the interval of 5 year, can maintain 22.90% of road network in good-fair condition. For the same interval of PM this percentage is increased to 52.32% when CM is introduced every year. As CM is carried out effectively every year, the service life of road is improved significantly resulting in increased good-fair roads at lower periodic maintenance cost. The red and green lines are the plot of LCC with PM only and PM with CM. This study indicates that at the interval of 5 years the LCC is minimum. The % of good-fair road is increased by 29.42% with reduction of 28.05% LCC. This study suggests that with CM, road conditions are maintained at a much higher percentage with overall lower LCC, suggesting better long-term performance quality.

From Figure 6 it can be inferred that for the study road network with 93.34% SD and 6.66% of AC pavement, the maximum % of serviceable road that can be maintained is 66.54%. This is attained only when the SD pavements with life expectancy less than the average life expectancy are resealed at the interval of 3 years. This may not be practically feasible with budget and time constraints. The challenge of faster deteriorating pavements can be solved by upgrading the pavement with higher construction standards. In this study the pavements with higher deterioration rates are proposed for upgrading to AC which has comparatively higher life expectancy than SD pavements.

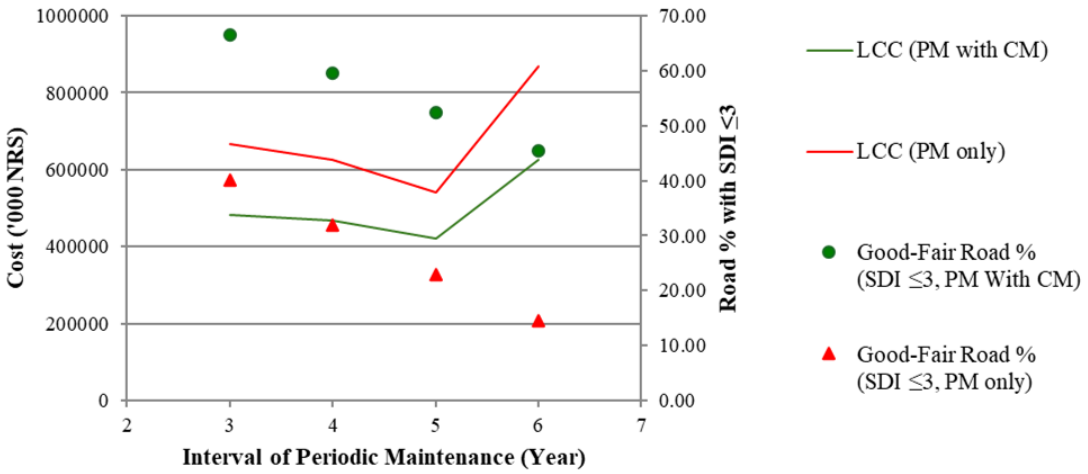


Figure 6. Life Cycle Cost Estimate for maintenance of 100 km road section for 24 years.

As shown in Figure 4 (b) the average life expectancy of AC is 7.25 years. We consider the minimum periodic maintenance interval for AC for this study to be 6 year. The maintenance strategies for upgrading and maintaining SD pavements are summarised in Table 5 .

Table 5. Maintenance Strategies

S.No	Strategy	Description
Strategy 1	U5 C P5	Upgrading 5%, Combined Maintenance and Periodic Maintenance at 5 year interval
Strategy 2	U10 C P5	Upgrading 10%, Combined Maintenance and Periodic Maintenance at 5 year interval
Strategy 3	U15 C P5	Upgrading 15%, Combined Maintenance and Periodic Maintenance at 5 year interval
Strategy 4	U20 C P5	Upgrading 20%, Combined Maintenance and Periodic Maintenance at 5 year interval
Strategy 5	U5 C P4	Upgrading 5%, Combined Maintenance and Periodic Maintenance at 4 year interval
Strategy 6	U10 C P4	Upgrading 10%, Combined Maintenance and Periodic Maintenance at 4 year interval
Strategy 7	U15 C P4	Upgrading 15%, Combined Maintenance and Periodic Maintenance at 4 year interval
Strategy 8	U20 C P4	Upgrading 20%, Combined Maintenance and Periodic Maintenance at 4 year interval
Strategy 9	U5 C P3	Upgrading 5%, Combined Maintenance and Periodic Maintenance at 3 year interval
Strategy 10	U10 C P3	Upgrading 10 %, Combined Maintenance and Periodic Maintenance at 3 year interval
Strategy 11	U15 C P3	Upgrading 15 %, Combined Maintenance and Periodic Maintenance at 3 year interval
Strategy 12	U20 C P3	Upgrading 20 %, Combined Maintenance and Periodic Maintenance at 3 year interval

The yearly maintenance cost for 12 maintenance strategies which upgrade SD pavements with higher deterioration rates to AC, is calculated. The LCC for 24 year perspective period is determined using equation (14). The summary of the results is presented in Figure 7 which shows the relationship between LCC and the good-fair road percentage for the different maintenance strategies

Figure 7 is a plot of cost along the x-axis and road % along the y-axis. In this study the cost is the LCC for maintenance strategy for perspective 24 years and road % is the average good-fair road (SDI $\leq$ 3) percentage. From the results of this study, referring Figure 7 it can be inferred that 52.3 % of good-fair road condition can be achieved at relatively low LCC with strategy 1. Strategies 11 and 12 show the best road conditions but have the higher LCC cost.

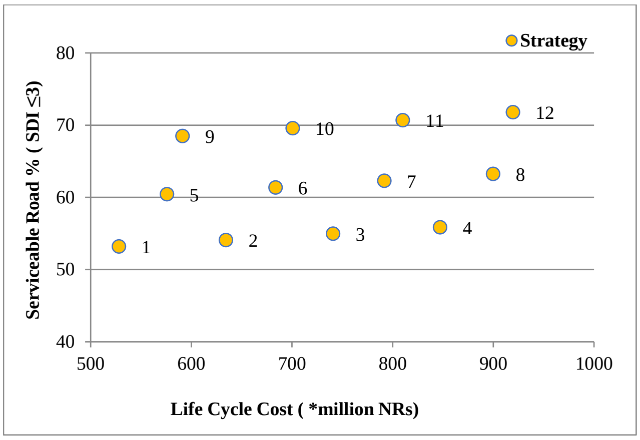


Figure 7. LCC and the serviceable road percentage for the different strategies.

As shown in Figure 7, if a road agency (DOR) sets a minimum acceptance criteria of 60% SRN road network to be in SDI ≤ 3. Based on the data analyzed the following Strategies 5-12 can be chosen. If cost minimization is the primary goal, Strategy 5 would be the most suitable option. However, if the authority is open to a higher investment for significantly better road conditions, Strategy 9 may be preferable, as it offers nearly 8% more roads in good condition for a relatively small additional cost. This extra expenditure can be justified by potential savings in Vehicle Operating Costs (VOC) and travel time due to improved road conditions.

6. Conclusion

This study presents an approach to apply Markov deterioration hazard model to study the deterioration of SD and AC pavement in Tropical Savannah (Aw) and Temperate Climate with Dry Winter (Cw). The study shows that the deterioration process is high with an average life expectancy of 4.22 years. This is similar in both Aw and Cw climate conditions. Similarly, with the increasing traffic volume the life expectancy of SD pavement is significantly reduced which indicates that SD pavements are a cost-effective option, making them suitable for roads with low to medium traffic volumes. On the other hand, AC pavement being superior pavement has higher durability for heavy traffic. Having higher life expectancy, AC can be a better pavement option for upgrading SD pavements with high deterioration rates.

Combined maintenance is a proactive maintenance strategy. The yearly cost is small when compared to periodic resealing cost. The activities during this maintenance process are effective to delay the deterioration process. As shown in Figure 5 and Figure 6, it can be accepted that the combined maintenance is beneficial both in terms of reducing costs and maintaining better pavement performance.

Long term maintenance planning and prioritizing the road sections for upgrading are very important tasks for the road agencies like DOR. The absence of practical guidelines, inadequate maintenance budget and ad hoc practices are valid reasons for poor road network condition of Nepal. A data driven approach can help road agencies make decisions depending on whether the priority is cost savings or maximizing road conditions. This study emphasizes the importance of data-driven decision-making in road maintenance planning. By utilizing cost and road condition data, road agencies can make more improved decisions that are well-supported by road quality outcomes. The results shown in Figure 5 is a clear trade-off between cost and road quality. Better road conditions lead to smoother travel, lower fuel consumption, and fewer vehicle repairs, which could offset the additional cost imposed during upgrading. Additionally, reduced travel times due to better roads could lead to significant economic benefits in terms of increased productivity, faster goods transport, and lower public transportation costs. The findings suggest that adopting a data-driven approach in road maintenance planning can lead to more efficient allocation of resources while ensuring road networks are kept in serviceable condition.

However, this study has some limitations that can be improved in the future studies. The key limitation of this study is the exclusion of the initial construction cost from the LCC analysis. Also, the data set is acquired from two consecutive inspection in 2021 and 2022. Due to the limitation of data in other climatic conditions the study limited to only these two climatic condition Aw and Cw. The traffic growth and the inflation rates are not considered during the perspective period. The direct maintenance cost is only considered for analysis but the indirect benefits, such as VOC and travel time reductions, to further enhance the decision-making process is not accounted. A separate study on VOC and travel time savings would be necessary to quantify these benefits.

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