OPTIMIZING ROAD NETWORK ASSET MANAGEMENT IN LAO PDR BY STOCHASTIC DETERIORATION FORECASTING

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This research aims to improve conventional road asset maintenance systems, particularly in developing countries like Lao PDR. It introduces a model based on the stochastic Markov decision process. The advantage of the model is that it shifts away from traditional reactive practices towards a proactive approach in terms of road condition prediction and resource allocation. In Lao PDR and similar nations, road maintenance has frequently been resource-intensive and reactive, posing challenges due to budget constraints and sustainability concerns. The proposed asset management model introduces an advanced methodology, providing decision-makers with tools for forecasting deterioration trends, optimizing maintenance strategies, and resource allocation. The model's merit lies in its ability to predict and plan maintenance needs based on probabilistic pavement deterioration trends and various budget scenarios. This leads to substantial cost reductions and better road network conditions. This research aims to introduce new concepts of sustainable road infrastructure management by working on improving the traditional approach to road maintenance in Lao PDR. It provides decision-makers with the insights and tools to transition from reactive to proactive strategies, resulting in optimal maintenance budgeting and required road performance.

Key Words: *Optimum Road Maintenance Strategy, Stochastic Markov Decision Process, Laos RMS.*

1. INTRODUCTION

(1) Road Asset Management in Lao PDR

In Lao PDR, the road maintenance system (RMS) utilizes the Highway Development and Management (HDM-4) model for long term planning to allocate maintenance funding and determine priorities [1, 2]. HDM-4 requires a lot of data, including pavement inventory, condition, type, traffic patterns, environmental factors, maintenance history etc., that is difficult to collect at once and is often utilized for specific projects. In the short term, provinces in Laos carry out condition inspections and present reports to the Ministry of Public Works and Transport (MPWT) for decisions on maintenance financing annually. The provincial reports are made based on condition surveys and provide one-time data used for planning which is reactive. Maintenance is also based on road importance/priority level [3].

The current Laos RMS utilizes various inputs, including road characteristics, traffic data, and pavement conditions, to assess overall road performance based on roughness, ride quality, and skid resistance. These indicators provide insights into the current road condition and facilitate the identification of areas requiring maintenance or improvements. However, the RMS does not provide direct predictions for road network conditions and should be used in conjunction with other information and models to support decision-making processes related to road network management and investment planning. Moreover, the Laos RMS incorporates a Pavement Management System (PMS) module to determine possible road maintenance; however, budgetary restrictions and a lack of technical resources hinder its efficiency.

The Laos national road network is categorized into six types (**Fig 1**): national, provincial, district, urban,

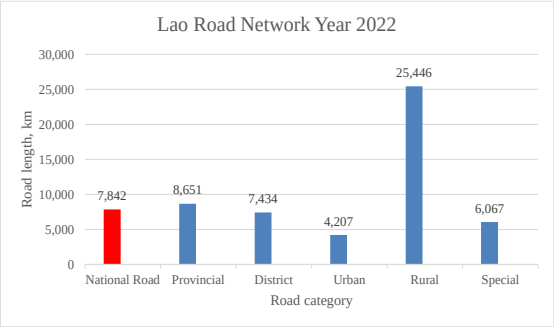


Fig 1. Lao PDR Road Network Length by Category in Year 2022.

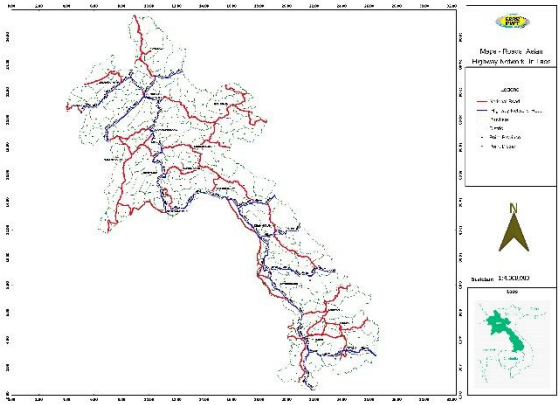


Fig 2. Laos National Road Network

rural, and special roads, with a total length of 59,645 km in 2022 according to the Laos Ministry of Public Works and Transport 3).

The national roads further have three core network levels: Core Network 1 for high-priority roads linking Laos to other Association of Southeast Asian Nations (ASEAN), Core Network 2 connecting major intranational towns, and Core Network 3 linking provincial to secondary towns with low traffic volume (**Fig 2**). Over the past decade, the Lao PDR road network has significantly expanded, but the implementation of road maintenance has faced challenges such as climate change-induced disasters, increased debt from a loan-based road financing model, and poor axle overload control. These challenges have resulted in longer reimbursement periods for contractors and higher project costs, leading to neglect of network sections, particularly those of lower priority.

The MPWT plays a major role in the development, maintenance, and rehabilitation of transportation infrastructure assets in Laos. The RMS encompasses health monitoring, planning, and road maintenance programming 4). The road management life cycle involves road network inspection, data collection and management, short- and long-term maintenance planning, as well as routine and periodic maintenance 5). Optimization of life cycle costs (LCCs) is crucial for efficient resource allocation and better preservation of roads 6).

Road pavement deterioration is often modeled as a Markov process. The last couple of decades have seen increasing numbers of statistical deterioration modeling methods using inspection data. Among the methods, the Markov deterioration hazard model proposed by 7) enables the estimation of transition probabilities using inspection records at two time points and overcame many challenges associated with the incompleteness of infrastructure inspection data. The model has been modified and augmented to account for specific types of challenges prevalent with inspection data such as a small sample size, measurement errors, different deterioration modes, composite deterioration structures, etc. 8, 9, 10, 11).

To improve the Laos RMS, this study applies the Markov Decision Process (MDP), a widely used methodology, to develop a stochastic MDP model and conduct LCC analysis using historical data under budget constraints. The main objective is to determine an optimal road maintenance plan and compare it to the current Laos RMS through LCC analysis. Optimal pavement management strategies and stochastic deterioration forecasting models have demonstrated their value in road asset management. Previous studies highlight the importance of considering uncertainties, such as stochastic deterioration and transition probabilities, when developing asset management strategies using two-point data instead of one-point data currently applied in the Laos RMS. These approaches enable decision-makers to make informed choices regarding maintenance, rehabilitation, and resource allocation, ultimately leading to improved road network performance, enhanced safety, and cost-effective asset management outcomes 12, 13, 14).

The Markov hazard model has been used to benchmark asset management in other developing countries including Vietnam 15, 16) and Uganda 14) with the goal of improving the estimation of infrastructure performance and management strategies. This study explores cost effective and efficient methods of enhancing the Laos RMS to improve road condition and boost economic growth.

(2) Maintenance budgets

The Road Maintenance Fund (RF) in Lao PDR, established in 2001, faces significant challenges due to its mounting debt of approximately 3,800 billion Kips (USD 200 million) as of 2021 17). This debt burden raises concerns about the fund's ability to finance road maintenance effectively, leading to deteriorating road conditions, increased repair costs, and compromised road safety. The RF's growing debt also limits its capacity to invest in necessary infrastructure improvements and road network expansions, hindering

the country's economic growth. To address this issue, prudent financial management and strategic maintenance planning are crucial. The government, particularly MPWT, must explore measures such as implementing cost-effective maintenance strategies, seeking alternative funding sources, improving revenue collection mechanisms, and optimizing resource allocation. These actions will help reduce the debt burden, ensure the RF's financial viability, and support the long-term sustainability of road network maintenance in Lao PDR. As a result, this study aims to calculate the road network's maintenance budget in order to maintain it at a level that satisfies the stochastic Markov model's predicted minimum acceptable requirement for road network conditions.

(3) Study Objectives

This study focuses on the development of a road asset management framework for Lao PDR that takes into account budget constraints and required road performance. The primary objectives of this research are:

1) Enhance the decision-making process within the Laos RMS by improving its capacity.
2) Prioritize road maintenance strategies by considering various scenarios in terms of budget constraints and road network performance.
3) Conduct a comprehensive framework to evaluate the long-term impact of different budget scenarios and policies for overall network performance.
4) Explore alternative strategies to overcome resource limitations while preserving or improving the condition of the road network in Lao PDR.

By achieving these objectives, this study aims to contribute to the improvement of the Laos RMS, particularly in terms of decision-making and efficient resource allocation. The incorporation of budget constraints into the road asset management framework will enable more effective prioritization of maintenance activities. Additionally, the comparison between the proposed stochastic model and the current RMS will provide insights into the potential benefits and advantages of adopting the new approach. Ultimately, this research aims to enhance the overall performance and sustainability of road asset management in Lao PDR.

2. METHODOLOGY

(1) Markov Decision Process

The MDP framework consists of decision epochs, states, actions, rewards, and transition probabilities[18]. In MDP, a road agency makes decisions based on the observed condition state of a road at each time step and selects an action to perform. The road's condition then transitions to a new state, and the agency/road user receives a reward. The objective is to maximize the cumulative reward over time.

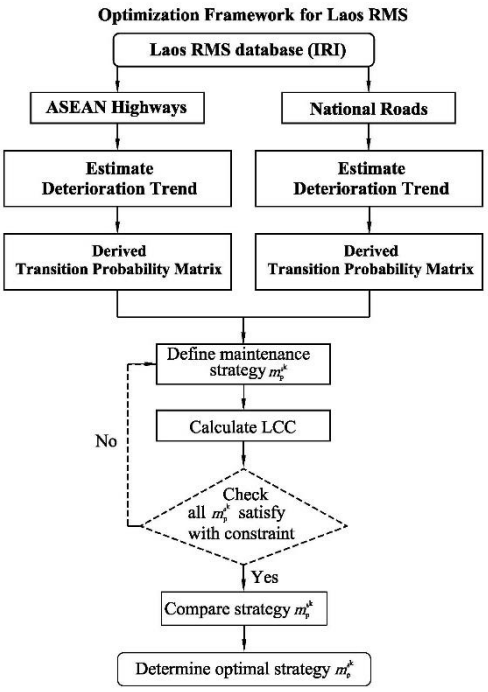


Fig 3. Model framework

Markov processes assume that the probability of transitioning to a new state depends only on the current state and action, not on any previous states or actions [18]. This property allows for the construction of Markov models using states, actions, transition probabilities, and rewards. MDP can be solved using algorithms such as dynamic programming, Monte Carlo methods, and reinforcement learning. These algorithms find optimal policies by mapping states to actions to maximize the expected cumulative reward[19,18].

The developed model incorporates condition states $i(i = 1, 2, 3, \dots, J)$ with J as the absorbing state, discrete time periods $t(t = 0, 1, 2, \dots)$, maintenance strategies (m_p), inspection intervals Z ($Z = 1, 2, 3, \dots$), and maintenance actions (A). The analysis considers a finite period from $t = 0$ to $t = T$.

Fig 3 illustrates the general framework of the model, which includes defining the network, estimating deterioration rates, proposing policies, estimating LCCs, and determining the optimal strategy that minimizes LCC. This framework guides the development of the stochastic MDP model for road asset management in Lao PDR.

(2) Markov Transition Probability (MTP)

The MTP models the transition of road conditions from $h(t) = i$ to $h(t + Z) = j$ after an interval Z, with periodic inspections at time t and $t + Z$ [7,21]. The probability of this transition is

$$\text{Prob}\,[h(t) = j | h(t + Z) = i] = \pi_{ij} \qquad (1)$$

As a function of hazard rates, the MTP

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

where θ_i is the hazard rate and, $\tilde{k}$ and $\tilde{m}$ are indices. The MTP matrix $\prod$ can be defined using transition probabilities between each pair of condition states (i, j)

$$\prod = \begin{bmatrix} \pi_{11} & \cdots & \pi_{12} \\ \vdots & \ddots & \vdots \\ 0 & \cdots & \pi_{JJ} \end{bmatrix} \qquad (3)$$

For Markov chain property, the following requirements should be met:

No maintenance or restoration projects should be done throughout the inspection period.

The deterioration of the road surface begins as soon as it is made available to the public.

The preconditions $\pi_{ij} \geq 0$ and $\sum_{j=1}^{J} \pi_{ij} = 1$ are defined to satisfy the axioms of probability. Since the model does not consider repairs, $\pi_{ij} = 0$ for $(i > j)$ and $\pi_{JJ} = 1$.

The hazard rate θ_i can be expressed as a function of explanatory variables $\boldsymbol{x^k}$ and unknown parameters $\boldsymbol{\beta_i}$ where $\boldsymbol{\beta_i} = (\beta_{i,1}, \dots, \beta_{i,M})$, $m\ (m = 1, \dots, M)$ is the number of explanatory variables and $k(k = 1, \dots K)$ is the number of inspected element groups.

$$\theta_i^k = f(\boldsymbol{x^k}; \boldsymbol{\beta_i}) = \exp(\boldsymbol{x^k \beta_i'}) \quad (i = 1, \dots, J-1) \qquad (4)$$

The unknown parameters $\boldsymbol{\beta_i}(i = 1, \dots, J-1)$ can be determined using an iterative method like Newton's method or through Bayesian estimation [22, 9].

The life expectancy LE_i^k in each condition state i can be defined by means of a survival function [23].

$$LE_i^k = \frac{1}{\theta_i^k} \qquad (5)$$

The average life expectancy from i to J can be estimated as $\sum_{i=1}^{J-1} LE_i^k$. For a detailed description of MTP derivation, it is recommended to refer to [7].

(3) Pavement Maintenance Model

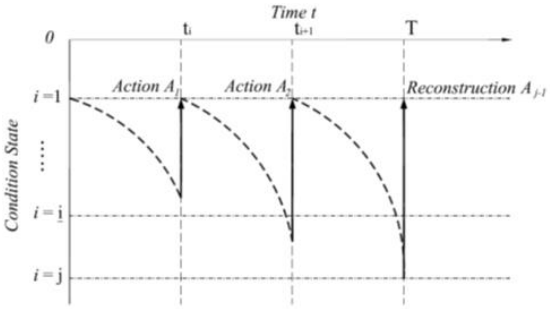


Fig 4. Uncertain deterioration considering repair

Road agencies need to implement optimal maintenance plans that provide the highest value. The optimal plan is one that keeps more roads in good condition while minimizing the overall LCCs. This study focuses on road agency costs and not user or social costs. The term "maintenance strategy" can be used to refer to a combination of road maintenance activities, including pothole patching, resurfacing, reconstruction and inspection.

Pavement maintenance activities denoted by $A(A_0, A_1, A_2, A_3, \dots, A_{J-1})$ are carried out in correspondence with the condition after inspection (time-dependent rule) or deterioration rate (condition-dependent rule) following [13, 14]. At the end of the planning period, time *T*, reconstruction A_{J-1} is considered for all sections. **Fig 4** illustrates the correspondence between observed condition and maintenance action. Once action is taken, pavement condition state i is assumed to improve to $\hat{\imath}$. This improvement is denoted by i_{rep}

$$i_{rep} = \begin{cases} i & \text{if } A_0 \text{ (no action)} \\ \hat{\imath} & \text{otherwise } (A_1, A_2, A_3, \dots, A_{J-1}) \end{cases} \quad (i = 1, \dots, J) \qquad (6)$$

Preventive maintenance actions can be performed on pavements before they reach the terminal state. The expected expenditure necessary for planning purposes is estimated from the maintenance plans. Inspected roads are grouped based on traffic volume into groups $k(k = 1, \dots \dots K)$ with pavement sections $s^k(s^k = 1, \dots S^k)$. The maintenance strategy $\boldsymbol{m_p^{s^k}}(\boldsymbol{m_{A\leftrightarrow i}^{s^k}}, \boldsymbol{Z^{s^k}})$ is a set of actions done in correspondence to condition $\boldsymbol{m_{A\leftrightarrow i}^{s^k}} = (A_0^{s^k} \leftrightarrow 1, \dots \dots A_{i-1}^{s^k} \leftrightarrow i)$ and inspection intervals $\boldsymbol{Z^{s^k}} = (Z_1^{s^k}, \dots \dots Z_T^{s^k})$. **Table 1** displays the attained condition after action. The repair activities are set by balancing the cost and frequency of repairs. It was assumed that patching and crack sealing improved condition by one step while overlay improved condition by two steps. Routine maintenance maintains the road in its current condition. Reconstruction (A_{J-1})

Table 1. Maintenance actions, costs and condition after repair.

Condition state, $\boldsymbol{i}$	Repair actions	Costs	Condition state after action, $\hat{\boldsymbol{\imath}}$
1	A_1 (routine)	C_{A1}	1
2	A_1 (routine)	C_{A1}	2
	A_2 (patching + sealing)	C_{A2}	1
	A_3 (overlay)	C_{A3}	1
3	A_1 (routine)	C_{A1}	3
	A_2 (patching + sealing)	C_{A_2}	2
	A_3 (overlay)	C_{A3}	1
…	…	…	…
$\boldsymbol{J}$	A_0	C_{A1}	J
	A_2 (patching + sealing)	C_{A2}	$J-1$
	A_3 (overlay)	C_{A3}	$J-2$
	…	…	…
	A_{J-1}	$C_{A_{J-1}}$	1

is done at the end of pavement service life (absorbing condition state). The maintenance cost C_{i-1} is an increasing monotone function with action.

$$C_{A_0} \le C_{A_1} \le C_{A_2} \le \cdots \le C_{A_{J-1}} \tag{7}$$

(4) Repair transition probability

When a road section is maintained, the transition probability will be modified because the pavement system has become newer. The MTP matrix will be multiplied with a repair matrix P_{rep}. The elements of the J x J repair matrix is denoted as $\pi_{ij}^{rep} = (i = 1, \dots J), (j = 1, \dots J)$. In case of no repair, the repair matrix will be an identity matrix $P_{rep} = I$. This is the default state of the repair matrix with all values in the major diagonal being 1 and all other matrix elements being 0.

$$P_{rep} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{8}$$

For all repair matrices, the values of π_{ij}^{rep} above the major diagonal must be 0 because it is not expected that any repair action will worsen pavement condition. the values on the major diagonal or below it can take the value of either 1 or 0. The condition $\sum_{j=1}^{j} \pi_{ij}^{rep} = 1$ must be met within P_{rep}. The repair probability.

$$\pi_{ij}^{rep} = \begin{cases} 1 & if\ i_{rep} = \hat{\imath} \\ 0 & otherwise \end{cases} \quad (i = 1, \dots J) \tag{9}$$

The transition probability matrix P_{trans} is a matrix with elements $\pi_{ij}^{trans} (i = 1, \dots, J), (j = 1, \dots, J)$

$$P_{trans} = \prod(Z) * P_{rep} \tag{10}$$

(5) Maintenance strategy

The maintenance strategy $\boldsymbol{m_p^{s^k}}$ is proposed by road managers within a finite planning horizon $(t = T)$. It is assumed that there is no salvage value at the end of T [24]. MDPs can be solved with a variety of algorithms such as value iteration, policy iteration, Monte Carlo methods [25]. This study optimizes the agency costs estimated from exogenously set strategies. The maintenance costs for each pavement section can be expressed as [14]

$$V_i^{t,s^k} = (1 + \rho^r)^{-t} * \pi_{ij}^{trans} * C_{A \leftrightarrow i}^{t,s^k} \tag{11}$$

where V_i^{t,s^k} is total agency costs at time t for section s^k, $C_{A \leftrightarrow i}^{t,s^k}$ is intervention cost, ρ^r is the discount rate and π_{ij}^{trans} is the transition probability.

(6) Optimization process

The LCCs of each maintenance strategy are the summation all agency costs for all sections $s^k (s^k = 1, \dots, S^k)$ assuming the salvage value at T, $C_v^{s^k} = 0$.

$$LCC = \sum_{t=0}^{T} \sum_{s^k=1}^{s^k} \sum_{i=1}^{J} V_i^{t,s^k} \tag{12}$$

The optimization problem to find optimum strategy $\boldsymbol{m_p^{s^k}}^*$ is expressed as

$$\min_{\boldsymbol{m_{A \leftrightarrow i}^{t,s^k}}, \boldsymbol{Z^{s^k}}} LCC \tag{13}$$

subject to

$$\sum_{k=1}^{K} \sum_{s^k=1}^{S^k} C_{A \leftrightarrow i}^{t,s^k} \in \Omega_t \qquad \forall t \tag{14}$$

where Ω_t is the budget limit at t

The greedy algorithm [26, 27] was used to solve the optimization problem. Sections with the worst predicted condition were prioritized.

(7) Road network condition estimation

The condition of the network in each state was estimated using:

$$CS_{t+Z} = p(Z) * CS_t \tag{15}$$

where CS_t is a $1 \times J$ vector of number of road sections per condition state at time t, and $p(Z)$ is the $J \times J$ MTP matrix. Knowing the proportion of sections in each condition state will support the decision-

making process for choosing the most appropriate maintenance strategy amidst budget constraints.

(8) Budget requirement based on performance road network condition requirement

Based on equation (11) and (15), to estimate the budget needed to achieve the set road network performance requirement, the total agency costs at time t for condition requirement at section s^k, can be estimated as follows:

$$V_i^{*t,s^k} = CS_{t+Z}^{*} * C_{A\leftrightarrow i}^{t,s^k} \quad (16)$$

subject to

$$CS_{t+Z}^{*} = p(Z)^{-1} * CS_t \quad (17)$$

where V_i^{*t,s^k} is total agency costs at time t for desired condition for section s^k, CS_{t+Z}^{*} is a vector $1 \times J$ of the desired condition, $C_{A\leftrightarrow i}^{t,s^k}$ is intervention cost. and $(p(Z))^{-1}$ is the inverse $J \times J$ MTP matrix transition probability.

The required budgets can be derived from the estimated undiscounted agency costs as these were assumed to only contain intervention costs

3. EMPIRICAL STUDY

(1) Data processing

In the empirical model application, Laos RMS historical inspection data and intervention unit costs were used in LCC estimation. Inspection data from 2014 to 2015 and 2020 was obtained from the Lao RMS database. Because it was difficult to determine maintenance history for the period 2015–2020 and pavement condition in 2020 was almost as good as in 2015, only datasets from 2014–2015 were used. The collected and analyzed data contained pavement materials, International Roughness Index (IRI), and average annual daily traffic (AADT) for 22 paved national roads.

The national road sections were grouped based on the Laos road classification into Network 1 and 2 with length 1,900 km and 869 km, respectively. These surveyed roads, 47.26% of the total national road network, are presented in **Table 2.**

Asphalt concrete pavement and surface treatment (single and double bituminous) are the two main types of pavements constructed in Laos. Traffic volume was obtained by counting the number of vehicles passing a specific location on each road section automatically or manually using a traffic count form. The vehicles were classified into 14 classes in order to generate adjustment factors to derive AADT [28].

(2) Definition of condition state

Table 2. Data summary for surveyed Laos national roads

Description	Core Network 1 (ASEAN)	Core Network 2 (National)
No. of road links	8	14
Total length surveyed (km)	1,900	869
Number of sample pairs	18998	860
Explanatory Variables	AADT, Road surface (AC/ST)*	AADT, Road surface (AC/ST)*
Length of AC/ST (km)	778/1,122	50/819

*AC=Asphalt concrete; ST=Surface treatment.

Table 3. No. of sections in each condition state for each network in year 2014-2015.

IRI (m/km)	Condition state	Core Network 1 (ASEAN)		Core Network 2 (National)	
		2014	2015	2014	2015
≤ 3	1.Excellent/Good	9612	4950	2648	1007
3<IRI≤ 5	2.Fair	8182	10177	4323	4178
5<IRI≤ 7	3.Poor	1086	3119	1340	2309
7<IRI≤ 9	4.Bad	85	478	267	771
>9	5.Failed	33	274	112	425

Road condition was quantified using IRI data obtained from 2014–2015 periodic inspections. In order to measure IRI, the dynamic response Vehicle Intelligent Monitoring System (VIMS) equipment, supported by the Japan International Cooperation Agency (JICA) in 2012, was used. The IRI was measured at a speed of around 80 km/h for each 100-meter segment [29, 30].

The IRI was classified into five condition states based on a preset criteria for roughness sufficiency to estimate MTP [31]. The number of sections per condition state, year and for each network are shown in **Table 3.**

(3) Estimation of deterioration rate and transition probability

The estimation for deterioration rate was done for the two networks using traffic volume, road surface type as explanatory variables. The hazard rate in exponential form can be expressed as:

$$\theta_i = \exp\left(\beta_{0,i} + \beta_{1,i}x_1 + \beta_{2,i}x_2\right) \quad (18)$$

$$x_2 = \begin{cases} 1 & \text{for } AC \\ 0 & \text{for } ST \end{cases} \quad (19)$$

where x_1 is standardized traffic volume, x_2 is the road surface type dummy variable. The estimation of

Table 4. Estimated β parameters and life expectancy in years.

	Core Network 1 (ASEAN)				Core Network 2 (National)			
State	β_0 *Absolute*	β_{1i} *Traffic*	β_{2i} *Pave-ment*	LE_i^k *Life*	β_0 *Absolute*	β_{1i} *Traffic*	β_{2i} *Pave-ment*	LE_i^k *Life*
1-2	-0.0005 (0.203) *	-	-0.661 (-0.915)	1.39	0.632 (0.719)	-	-0.934 (0.685)	0.93
2-3	-1.256 (-0.275)	0.284 (0.382)	-0.256 (-0.346)	3.67	0.017 (-1.455)	-	-0.051 (0.097)	2.63
3-4	-0.824 (-0.369)	-	-	3.20	-0.753 (-0.103)	-	-	2.34
4-5	0.497 (-0.342)	-	-	1.03	-0.630 (1.337)	0.257 (-1.946)	-	1.62

*The values in parentheses are the Geweke's diagnostic for β.

The hazard rate $\boldsymbol{\theta_i^k}$ can be estimated as the inverse of $\boldsymbol{LE_i^k}$ according to Equation (5).

the unknown parameters was carried out with the Markov Chain Monte Caro (MCMC) methodology using the Metropolis Hastings (MH) algorithm [32, 33]. MATLAB programming language was used to solve for the unknown parameters. MCMC was used because the formulated log-likelihood function was conditional on many unknown parameters and the merits of shorter computation time. The unknown β parameters converged as shown in **Table 4**. The *Geweke* diagnostic should fall within [-1.96, 1.96] limits with 0 denoting perfect convergence.

The positive β values mean that traffic strongly impacts deterioration rate in condition state 2 for Core Network 1 and 4 for Core Network 2 because

higher traffic loading causes faster deterioration. Road sections made of the thicker and stronger AC have longer life hence the negative β values. Other β values were excluded because of sign restrictions. The estimated condition performance curves show a higher life expectancy of 9.28 years for Core Network 1 (ASEAN) roads compared to 7.51 years for Core Network 2 (**Figure 5**). This better life performance for ASEAN roads is due to their stronger pavement materials. About 40.9% of ASEAN roads are constructed using AC and only 5.8% of the Core Network 2 is constructed with AC (**Table 2**). The MTPs for Core Network 1 and 2 are shown in Equation (17) and (18), respectively. The MTPs show that Core Network 2 undergoes faster deterioration with higher probabilities of transitioning to worse state.

$$\begin{bmatrix} 0.487 & 0.442 & 0.063 & 0.006 & 0.002 \\ 0 & 0.761 & 0.203 & 0.026 & 0.010 \\ 0 & 0 & 0.732 & 0.167 & 0.101 \\ 0 & 0 & 0 & 0.378 & 0.622 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (20)$$

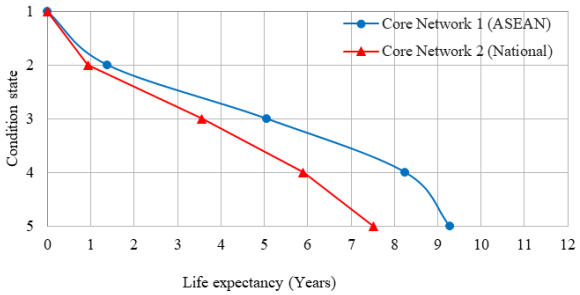


Fig 5. Performance curves for Core Network 1 and 2

$$\begin{bmatrix} 0.342 & 0.529 & 0.110 & 0.016 & 0.003 \\ 0 & 0.683 & 0.254 & 0.051 & 0.012 \\ 0 & 0 & 0.652 & 0.254 & 0.094 \\ 0 & 0 & 0 & 0.539 & 0.461 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \quad (21)$$

(4) Maintenance strategy for Laos

The study focused on investigating different maintenance strategies ($\boldsymbol{m_p^{s^k}}$) for the two core networks, considering budget and serviceability targets. The aim was to determine the optimal strategy by comparing the LCCs and condition performance of each strategy. The inspection interval for all strategies was set at 1 year. Three target policies were considered:

- Policy 1: Reactive Maintenance (Rt) - This approach involved road intervention when a road network reached condition 4 or 5. Reactive works were conducted in response to the deterioration of the roads to the worst states.
- Policy 2: Proactive Maintenance (Pr) - In addition to the works performed in policy 1, this policy included preventive maintenance works from condition 2 to 3. The goal was to prevent further deterioration and maintain the roads in better condition.

Table 5. Laos maintenance actions, costs and condition after repair.

Condition state i	Repair actions	Costs (Mil. Kips/m2)	Condition state after action, $\hat{i}$
1	A1 RM	0.0008	1
2	A1 RM	0.0008	2
	(A2 patching+ crack sealing)	0.065	1
	(A3 overlay)	0.072	1
3	A1 RM		3
	(A2 patching+ crack sealing)	0.065	2
	(A3 overlay)	0.072	1
4	A1 RM	0.0008	4
	(A2 patching+ crack sealing)	0.065	3
	(A3 overlay)	0.072	2
	(A4 reconstruction)	0.221	1
5	A0	0.0	5
	(A2 patching+ crack sealing)	0.065	4
	(A3 overlay)	0.072	2, 3
	(A4 reconstruction)	0.221	1

- Policy 3: No Major Repairs (Do Nothing) - This policy only involved routine maintenance (RM) for roads in conditions 1 to 4 and no RM for roads in terminal condition 5.

A greedy algorithm was employed to determine the maintenance actions, with priority given to sections that had deteriorated to the worst condition. Various maintenance actions were utilized, each associated with a specific cost **Table 5**. The study also considered the effect of prioritizing one network over another. In this study, four maintenance strategies (Equation 21 to 24) were defined, with two strategies for each policy (preventive or reactive). An optimal maintenance strategy was determined initially, assuming a limitless budget. The default strategy of "do nothing," where the repair matrix is an identity matrix, was also investigated. Following the selection of the optimal strategy, a budget limit was introduced, with priority given to ASEAN roads that connect nations.

$$\boldsymbol{Pr_1} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (22)$$

Table 6. LCC for Laos roads considering a limitless budget

Strategy $m_p^{s^k}$	Estimated LCC (Mkips)		
	Surveyed network (47.26%)		Whole network (100%)
	Core Network 1 (ASEAN)	Core Network 2 (National)	Total
$\boldsymbol{Pr_1}$	1,341,903.17	978,759.38	4,909,934.60
$\boldsymbol{Pr_2}$	2,680,382.03	1,651,018.12	9,164,146.41
$\boldsymbol{Rt_1}$	1,264,847.74	802,409.57	4,373,793.24
$\boldsymbol{Rt_2}$	1,554,660.95	1,118,096.58	5,654,878.45
Laos RMS	-	-	6,426,029

$$\boldsymbol{Pr_2} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (23)$$

$$\boldsymbol{Rt_1} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (24)$$

$$\boldsymbol{Rt_2} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (25)$$

4. RESULTS

(1) Determination of optimal strategy considering a limitless budget

The strategy selection was done considering preventive and reactive policies with a limitless budget. This was done for both core networks. The condition of the network at the end of the analysis period considering all policies and strategies was also determined. The surveyed Laos network (Core Network 1 and 2) was 47.26% of the total national roads network.

Among the strategies evaluated, the results of differences strategies application indicate the differences road condition performance at the final year of the analysis period. particularly strategy Pr_2 was found to maintain a larger proportion of the network in fair to good condition. Specifically, it resulted in 92.88% of Core Network 1 and 87.10% of Core Network 2 being in fair to good condition at the end of the analysis period (**Fig 6**). While strategy Pr_1 was the second order to maintain the proportion of the condition in fair to good, with the conditions at

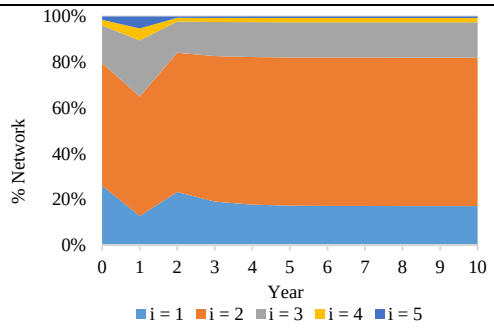
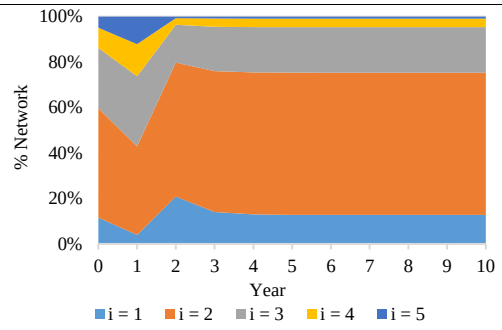
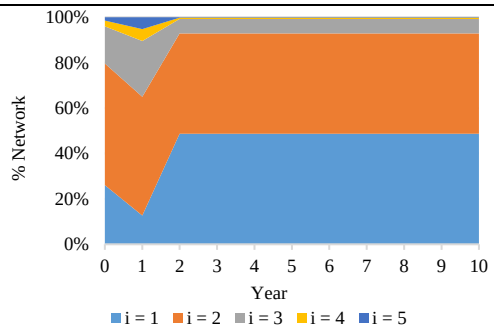
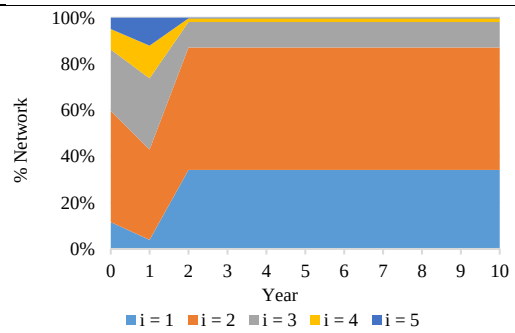
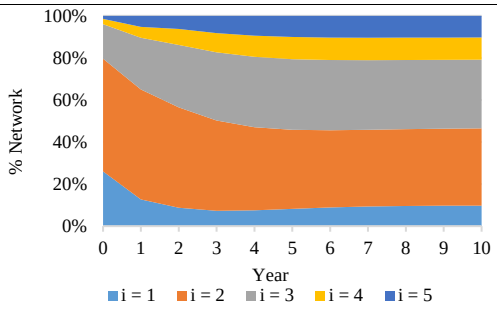
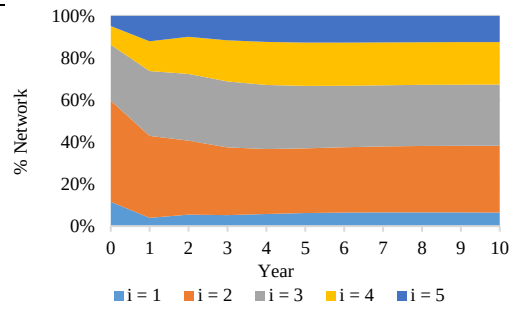
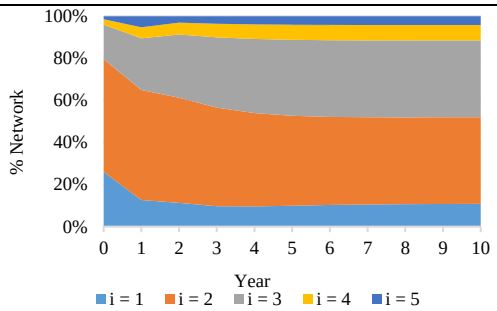
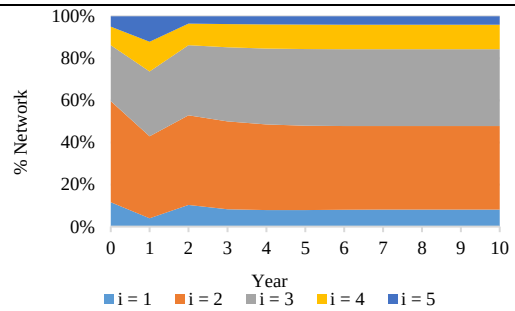
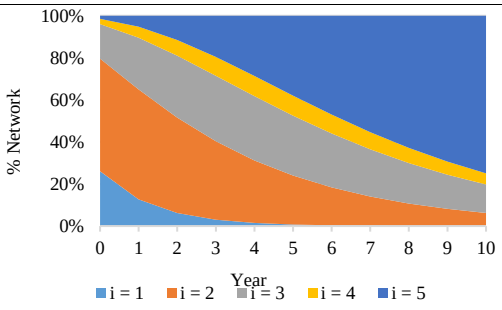
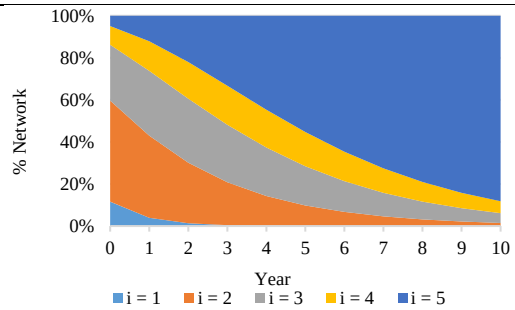
Strategy $m_p^{s^k}$	Core Network 1 (ASEAN)	Core Network 2 (National)
Pr_1		
Pr_2		
Rt_1		
Rt_2		
Do noth-ing		

Fig 6. Condition of network per strategy considering a limitless budget.

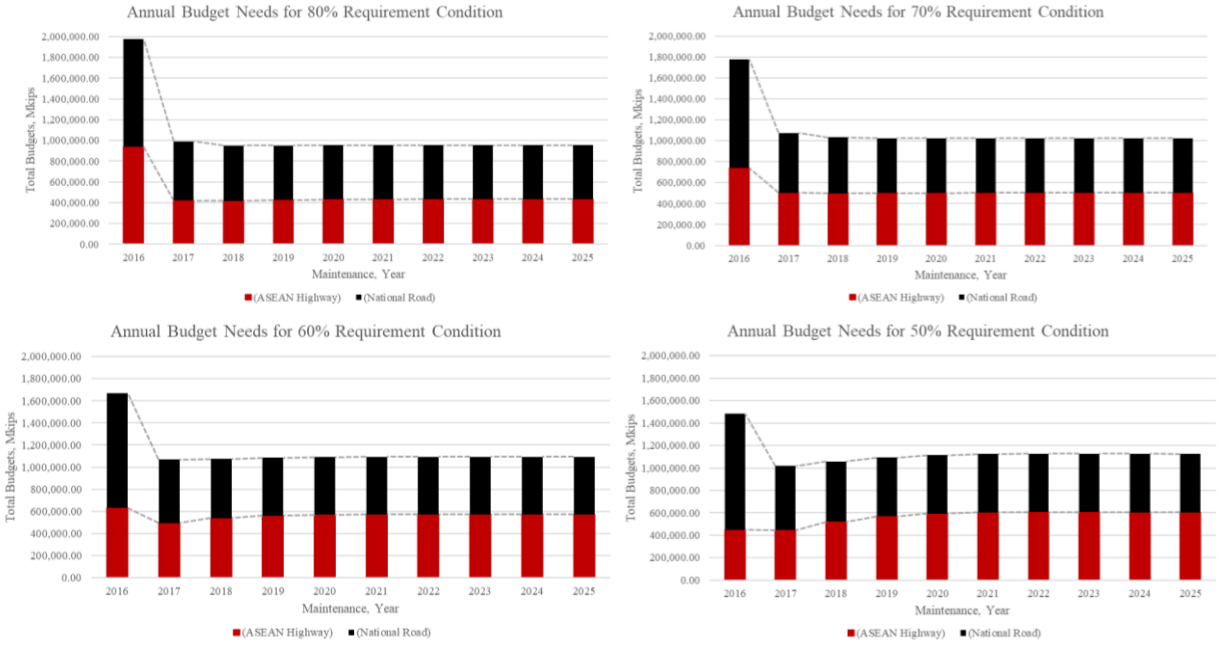


Fig 7. The annual comparative budget requirements for the required minimum performance levels

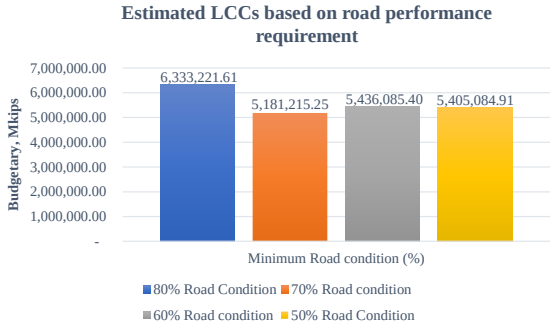


Fig 8. The Estimated total LCCs for minimum road network conditions performance

the end of the analysis period were 82.01% and 75.36% for Core Network 1 and Core Network 2, respectively. Additionally, the LCCs associated with these strategies were relatively lower than the total budget needs of the Lao RMS estimation.

On the other hand, the reactive strategies, particularly strategy Rt_1, had the lowest LCC estimation condition compared to others, with 46.50% of Core Network 1 and 38.23% of Core Network 2 deteriorating to poor, bad, and failed conditions. While strategy Rt_1, remained at 52.02% of Core Network 1 and 47.82% of Core Network 2, the proportion of the condition was fair to good. This indicates that simply minimizing LCC may not lead to the optimal strategy choice. It's important to consider improving the network condition while keeping the LCC reasonably low through preventive rather than reactive policies.

In summary, strategy Pr_1 was found to be the most favorable option considering both network condition and LCC, with a notable higher benefit-cost ratio (BCF) than other options (when we compare the investment with the benefit). This strategy effectively slowed down the degeneration of the network, resulting in a larger proportion of the network being in fair to good condition by 82.01% of Core Network 1 and 75.36% of Core Network 2, while maintaining a reasonably low LCC at 4,909,934.60 Mkips (**Table 6**).

(2) Estimation of budget requirements for minimum condition performance

An optimal policy, aimed at providing support for decision-makers, also incorporates a minimum acceptable condition performance threshold for the road network. This threshold sets the minimum road conditions as the baseline, serving traffic needs and national economic development goals. Specifically, the target conditions in fair to good condition for both international ASEAN roads and intranational Core Network 2 are set at 80%, 70%, 60% and 50% in good to fair condition in order to compare the performance and budgetary considerations at a satisfactory level of overall road network condition.

The comparative results (**Fig 7**) indicate the budgetary allocation necessary for road maintenance to preserve road condition above set performance targets. The lowest budget was required for a 70% performance target. A 70% performance target enabled preventive maintenance of a larger proportion of sections preserving better network condition compared to other performance targets cost effectively. The 80% performance target was much more expensive

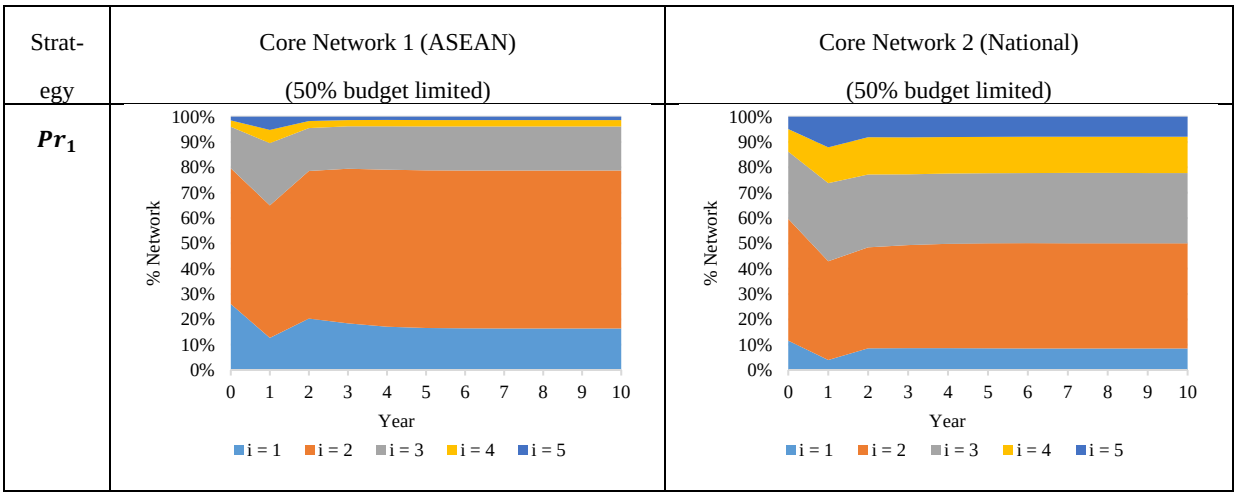


Fig 9. Condition of network considering a limited budget and optimal strategy.

to attain and lower budget levels resulted in poorer condition.

As a result, the overall LCCs requirement for achieving each performance requirement are shown in (**Fig 8**), The LCCs for 60% and 50% were increased and higher than 70% target requirement, as these required higher maintenance costs due to more rapid deterioration of road sections to worse condition.

(3) Considering a limited budget

In the case of a limited budget that can only cover 50% of the total Laos national roads budget needs, prioritization was implemented. The priority was considered given to improving 80% of Core Network 1, which consists of the international ASEAN roads, and the remaining 20% of the budget was allocated for the intranational Core Network 2 roads. This was because a larger proportion of foreign loans are currently specified to bettering the international roads. The optimal strategy Pr_1, which was previously determined, is assumed. The estimated total LCCs for both networks under this limited budget scenario is approximately 2,454,967.30 Mkips.

During the selection of candidates for intervention, it was determined that all sections in the worst state would be repaired. Additionally, 80% of the sections in each other improvable state for Core Network 1 and 20% for Core Network 2 would be worked on. As a result of this allocation, the proportion of sections in fair to good condition decreased for both networks. Specifically, the proportion decreased by 3.27% for Core Network 1 and 25.37% for Core Network 2 at the end of the analysis period (**Fig 9**).

This outcome highlights the importance of budget allocation based on the priority level of each network and the minimum condition performance requirements. Despite the optimal strategy Pr_1, being considered, the limited budget necessitated strategic decision-making regarding which sections to repair. The decrease in the proportion of sections in fair to good condition reflects the impact of the budget constraints on the overall condition of the networks.

When facing a limited budget, road agencies need to carefully determine the budget allocation by considering the priority level of each network and the minimum condition performance requirements. This strategic approach helps optimize the use of available resources while acknowledging the resulting impact on the network condition.

5. DISCUSSION

The results presented above provide valuable insights into the decision-making process regarding network maintenance and repair strategies when considering different budget scenarios. In the first scenario, where a limitless budget was assumed, strategy Pr_1 emerged as the optimal choice. This strategy not only maintained a larger proportion of both Core Network 1 and 2 in fair to good condition but also incurred relatively low LCCs. These findings emphasize the importance of preventive works in slowing down the deterioration of the networks.

On the other hand, the estimation of budgetary depend on minimum acceptable conditions performance for road networks under the minimum target policy of 80%, 70%, 60%, and 50% conditions in fair to good. The findings from the comparative analysis also indicate the importance of budgetary allocation for road maintenance to preserve road conditions at different levels. Particularly, preserving the road condition at the 70% minimum performance level

emerged as the most optimum as it maintains a higher proportion of network in fair to good condition at a relatively low LCC. The study considers both LCC and condition performance to determine optimum choice. It can be emphasized that the optimal strategy for road maintenance, the lowest budgetary, may lead to maximizing condition performance. This finding underscores the significance of strategic planning and resource allocation in achieving both cost efficiency and satisfactory road network conditions.

In additional, the study also introduced the reality of limited budgets. In this case, only 50% of the total needs could be covered. To address this constraint, a prioritization strategy was implemented, giving priority to repairing 80% of Core Network 1 (international ASEAN roads) and allocating the remaining 20% of the budget for Core Network 2 (intranational roads). The optimal strategy Pr_1 was still considered.

The results of this limited budget scenario demonstrated the necessity of strategic budget allocation. While the estimated total LCC was 2,454,967.30 Mkips, the proportion of sections in fair to good condition decreased for both Core Network 1 and Core Network 2. This reduction amounted to 3.27% for Core Network 1 and a significant 25.37% for Core Network 2. These findings highlight the trade-offs and challenges faced by road agencies when confronted with budget constraints. Tough decisions must be made regarding which sections to repair, and these choices inevitably impact the overall condition of the networks.

In practice, road agencies need to carefully consider various factors, including the priority level of each network, minimum condition performance requirements, and available budget, when determining the allocation of resources. It is essential to strike a balance between maintaining acceptable network conditions and optimizing the use of limited funds. Simply minimizing the LCC may not always result in the best outcome if it compromises the condition of the networks.

6. CONCLUSIONS

The analysis highlights the importance of considering both network condition and budget constraints when making decisions about road network maintenance and repair strategies. In a scenario with a limitless budget, strategy Pr_1 emerged as the optimal choice, effectively maintaining a larger proportion of the network in fair to good condition while keeping the LCC reasonably low. However, when faced with a limited budget that can only cover 50% of the total needs, prioritization becomes essential. Allocating resources to repair 80% of Core Network 1 and 20% of Core Network 2 resulted in a decrease in the proportion of sections in fair to good condition. These findings emphasize the challenges road agencies face in balancing network condition and budget limitations. On the other hand, the finding of budgetary needed to meet a minimum acceptable condition performance indicates the optimum LCC, which is dependent on the proportion of the road condition in poor or bad condition affecting the overall LCC.

In conclusion, the results from the scenarios with a limitless budget, minimum requirement road condition performance, and a limited budget underscore the importance of considering both network condition and budget constraints when making decisions about maintenance and repair policies. Road agencies should strive to find the optimal balance between these factors to ensure the effective utilization of available resources and the provision of reliable and safe road infrastructure. In addition, the consideration of a minimum acceptable condition performance further enhances the optimal balance between the minimum budget allocation and the maximum performance.

Future research and decision-making processes could explore more alternative strategies set endogenously and allocation models that further address resource limitations while aiming to maintain or improve the condition of road networks. Additionally, a comprehensive cost-benefit analysis could be conducted to evaluate the long-term impacts of different budget scenarios and policies on overall network performance and user satisfaction.

ACKNOWLEDGEMENTS

The Laos Ministry of Public Works and Transport (MWPT) is appreciated for providing roads data used in this study.

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