Establishing an Optimum Maintenance Strategy for a National Highway Using HDM-4: A Case Study of NH 66 Section in Kerala, India

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Abstract Timely maintenance of pavements is an essential requirement for the efficiency of any road network. Roads which are inadequately maintained most often require major rehabilitation works to be performed much earlier than those which are maintained on a regular basis. This could result in huge financial burdens on the economy. The requirements for pavement maintenance and repair are continuously increasing, but the resources and funds are limited. Hence, a proper pavement management system is necessary to preserve the road assets in a good condition, to achieve a more efficient allocation of the available funds and a more accurate evaluation of future needs. This paper presents the use of the World Bank developed HDM-4 model for deriving optimum maintenance standards for flexible pavements. The portion of NH66 passing through Thrissur district of Kerala was considered for the study. Required data was collected, and analysis was carried out at the project level for determining the optimum maintenance strategy, based on the criteria of maximization of ratio of net present value to cost. It is hoped that the results of this study shall be of use to the highway agencies in better decision making and effective management of the highway network.

Keywords Pavement management system · Road assets · Maintenance · Serviceability · HDM-4

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1 Introduction

Transportation infrastructure is like a baseline that ensures continuous and smooth flow of people and goods. Effective transportation is an indispensable element to achieve economic progress. Among the various transportation systems, road transportation is crucial to economic development and growth. Roads are of great significance that makes a country grow and develop by providing access to employment, social, education and healthcare services. They help stimulate social and economic development. And, for these reasons, road infrastructure is considered to be the most important of all public assets.

The road infrastructure becomes aged due to continuous use and time, and it requires maintenance, renewal and upgradation. Construction of road infrastructure necessitates huge investments, and as a result, it is critical to maintain these assets in good order. Adequate maintenance of the road infrastructure is essential to preserve and enhance its serviceability. Inadequate maintenance can cause irreversible deterioration of the road network, which could spread across the road systems very quickly resulting in rising costs and major financial burdens. Also, delay of maintenance and rehabilitation activities can lead to a fall in the level of pavement performance [14]. The importance of maintenance thus needs to be recognized by decision-makers. A proper management system is necessary to help preserve the road assets in a good condition and to balance the long-term need, thereby benefiting the stakeholders.

The actual resources available are also much less than what is actually needed. The pavements are simply maintained rather than being properly managed [8]. In India, the road maintenance and rehabilitation techniques are currently determined entirely based on the subjective judgment and expertise of the field engineers. The life-cycle costs and other management requirements are not given any thought. The root causes of road deterioration, as well as the ineffectiveness of various maintenance measures, are frequently ignored. This is mostly due to the lack of objective databases needed for the study of different activities such as design, construction and maintenance of pavements [17].

As a result of this, there occurs a complex problem with respect to the matching of resources, equipment, time, labor, funds, design and decision making, which consequently leads to the accumulation of gap between the allocation of resources and the actual requirements over a period of time [17]. But in today's economic environment, a more systematic approach for the determination of maintenance and rehabilitation techniques and priorities is needed. Pavement management systems are now being used by highway administrations worldwide to make systematic decisions regarding all the activities related to pavement development and maintenance [18]. However, developing countries such as India still require a systematic strategy to PMS implementation. Today's highway administrators have a number of tools that help them make the best use of available resources for highway pavement maintenance and rehabilitation, but they are not universally accepted. As a result, there is a lack of global acceptance and implementation of these tools [19]. The Highway Development and Management System (HDM-4) was therefore designed by the World

Bank as a universally recognized instrument for making timely and cost-effective maintenance management choices for road networks.

2 Literature Review

Pavement maintenance management systems promote an improvement in the quality and performance of pavements as well as a reduction in the costs through effective management practices. They offer a systematic way for inspecting and assessing pavement conditions in order to assure timely maintenance and, as a result, eliminate all undetected pavement faults. It assists decision-makers in determining best strategies for existing pavement conditions through pavement evaluation and maintenance in order to maintain acceptable serviceability for a specified duration. Pavement management systems (PMS) can be simply defined as a 'set of tools or methods that assist the decision-makers in finding out the optimum strategies for providing and maintaining the pavement in a serviceable condition over a given period of time' [15]. It is a comprehensive package that is used to assess the condition of pavement, recommend the best M&R strategy, create road maintenance investment plans and conduct economic analysis of road projects [19].

Sudhakar [17] developed PMS for a network of urban roads in Chennai. The project analysis application module of HDM-4 was utilized for determining the optimum maintenance strategy for the pavement sections considered based on the criteria of maximization of NPV/cost ratio.

Odoki and Khan [9] used the HDM-4 model for establishing optimal pavement maintenance standards for Bangladesh.

Mathew and Issac [10] attempted an optimization of maintenance strategy for a rural road network in the state of Kerala. Prior to the use of the software, the HDM-4 deterioration models were calibrated to suit low volume conditions, and the optimized strategy for the network was developed using the HDM-4 strategy analysis.

Jain et al. [7] conducted a comparative study of scheduled versus condition responsive maintenance strategies which in turn could result in an optimum utilization of the maintenance funds. Economic analysis was conducted for the pavement sections, and it was found that the condition responsive maintenance was more advantageous over the analysis period than scheduled maintenance. For some pavements the resurfacing was done as per the renewal cycle even when the pavement condition was good, while for some other sections that deteriorated quickly, the renewal was urgently required but was not covered by the maintenance cycle.

Jain et al. [8] developed a PMS for selecting an optimum M&R strategy for multilane highways. The optimum strategy was chosen based on the highest value of NPV/cost ratio, and the section having a higher value of this ratio would be maintained at a higher priority than other sections.

Girimath et al. [4] determined the optimum maintenance treatment for urban road network of Bangalore city, using the HDM-4 Project Analysis.

Gupta et al. [5] used the HDM-4 Project Analysis application module for the optimization maintenance and rehabilitation strategies for three urban road sections in Punchkula district of Haryana.

Yogesh et al. [19] developed a pavement management system for a network of 21 urban roads of Noida. The aim of the study was to make use of the HDM-4 strategy analysis to determine the required funding levels for a set of user defined maintenance standards. The evaluation was done based on two criteria: maximization of the net present value (NPV) and also minimization of the cost required to achieve a target level International Roughness Index (IRI). The strategy analysis was performed, and the optimum M&R strategy under both the criterions was determined. The selection of an optimum maintenance alternative is based on the selection criteria which the planner adopts. It is for this reason that the HDM-4 strategic analysis is considered to be a customized economic evaluation tool which could be utilized in better management of urban roads.

Chopra et al. [1] developed a PMMS for an urban road network comprising four road sections in Patiala district of Punjab, using the Highway Development and Management model.

3 Objective of the Study

The study focuses on the development of a pavement maintenance management system for a selected stretch of NH66 passing through Trissur district of Kerala using the HDM-4 model. The objective of the study is to find an optimum maintenance strategy for the road sections based on the criteria of maximization of net present value to cost ratio.

4 Overview of the Highway Development and Management Model (HDM-4)

The Highway Development and Management (HDM-4) is a globally recognized decision-making tool developed by the World Bank for evaluating the engineering and economic feasibility of the of potential road investment alternatives. It is an international standard which helps predict the future economic, social and environmental and technical implications of investment decisions concerning maintenance and management of pavements. HDM-4 was created as a result of a number of investigations conducted in various parts of the world. Despite the fact that it was founded by the World Bank in the late 1960s, several of the world's major research institutions have made significant contributions to its development during the past three decades. The HDM-4 system could be used to make good investment decisions at all levels of management.

4.1 HDM-4 Applications

The three basic areas of analysis that can be undertaken in HDM-4 are project analysis, program analysis and strategy analysis [19].

The project analysis can be utilized to compare the physical, functional and economic feasibility of various project alternatives against a base alternative of 'do nothing'. This can be done for the evaluation of M&R options for existing roads, for geometric improvement or pavement upgradation schemes, construction of new roads and so on.

The program analysis is largely concerned with prioritizing a long list of candidate road projects into a one-year or multi-year work schedule that is constrained by a budget. This tool has been integrated into HDM-4 to allow for quick examination of the entire road network in order to identify candidate road sections for maintenance during a certain budget period. The maximization of the NPV/cost ratio is adopted as the economic criteria for selection of the candidate road for maintenance under the constrained budget.

Strategic analysis refers to the analysis of a certain road network as a whole. The preparation of estimates of investment needs for road network development and maintenance under various budget conditions is a typical application of strategy analysis. Estimates are made for medium to long-term expenditure requirements ranging from 5 to 40 years. The applicability of program and strategy analysis is determined by the size of the road network under consideration as well as the length of the analysis period. Program analysis is usually favored for a smaller highway network and a shorter period of analysis, but strategic analysis is more effective for a bigger highway network and long-term strategic planning [19].

5 Methodology

The methodology adopted for the study is illustrated in the flowchart shown in Fig. 1.

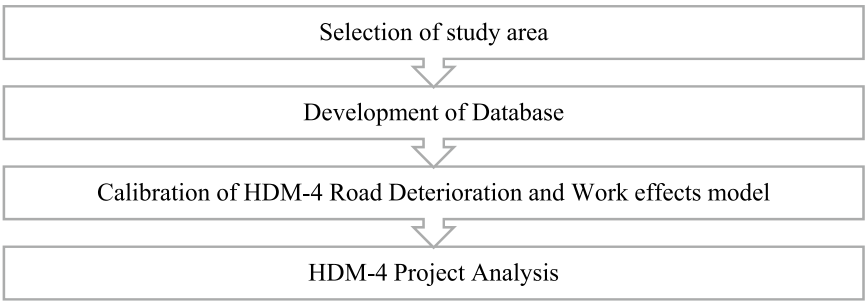

Fig. 1 Methodology of the study

Table 1 List of study sections

S. No.	Section ID	Section name	Length (m)
1	N1	Kottapuram–Chanthapura	800
2	N2	Chanthapura–Kottapuram	800
3	N3	Chanthapura–Mathilakam	1000
4	N4	Mathilakam–Moonupeedika	1000
5	N5	Moonupeedika–Thriprayar	1000
6	N6	Thriprayar–Vadanapally	1000
7	N7	Vadanapally–Chettuva	1000
8	N8	Chettuva–Chavakkad	1000

The first stage is the selection of the highway network for analysis. The second stage involves the collection of the required data. The third stage is to calibrate the road deterioration and work effects model of HDM-4 to suit the conditions of the study area. In the fourth stage, all the required data is given as input to the software, and project level analysis is carried out. The optimum maintenance strategy is selected based on the results of the economic analysis.

5.1 Selection of the Study Area

National Highway 66, commonly referred to as NH 66 is a 1608 km long busy National Highway running roughly north–south, parallel to the Western Ghats along the west coast of India. It connects Panvel in Maharashtra to Kanyakumari in Tamil Nadu and passes through the states of Maharashtra, Goa, Karnataka, Kerala and Tamil Nadu.

For the study, the portion of NH 66 passing through Thrissur district of Kerala, starting from Kottappuram and ending at Chavakkadu, is selected. The total length of the stretch of NH 66 selected for the study is 49.7 km. The total study stretch was then divided into homogenous sections from which 8 sections (6 sections of 1 km each and 2 sections of 800 m) were demarcated for further data collection. Table 1 shows the list of study sections. Figure 2 shows the study stretch.

5.2 Data Collection

The data requirements for analysis using HDM-4 can be categorized into the following four categories:

- Road network data
- Vehicle fleet data

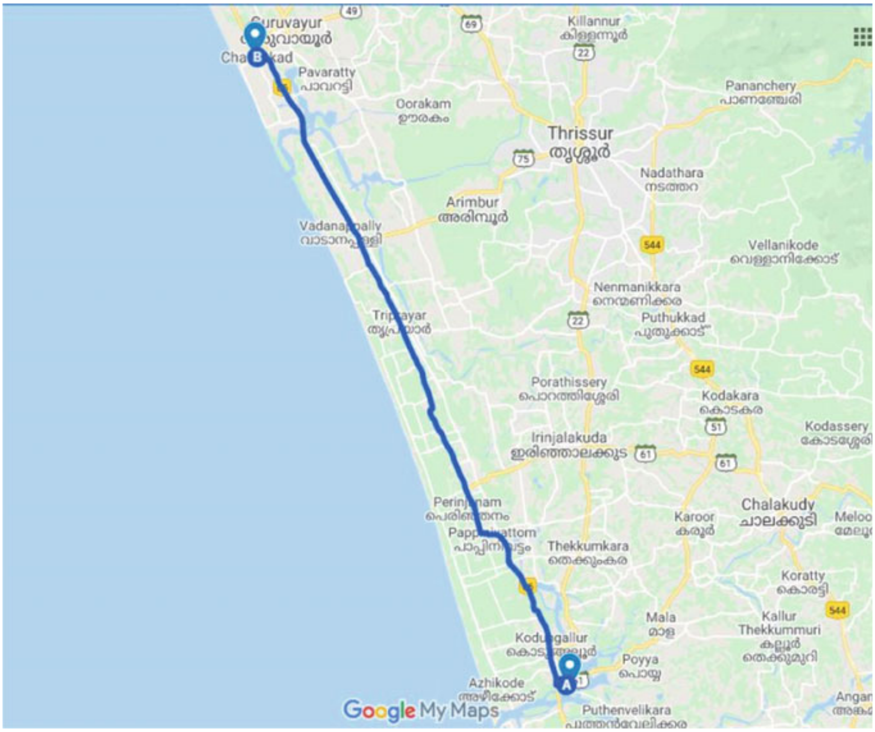

Fig. 2 Map view of the study stretch. *Source* Google Maps

- Maintenance and rehabilitation works data
- Cost data.

Road Network Data: The road network data collection involves the road inventory data and the pavement structural and functional condition data. Inventory data includes details like length and width of the sections, shoulder width, drainage conditions, details of maintenance and rehabilitation works, etc. The structural condition of the test sections was assessed in terms of their rebound deflection values by performing the Benkelman beam deflection survey. The functional condition was assessed in terms of pavement condition as well as roughness. The roughness survey was performed using ARRB Roughometer. Pavement condition survey was conducted to determine the extent and severity of different distresses present on the pavement. The predominant distresses that were observed on the test sections include longitudinal, transverse and edge cracking, alligator cracking, raveling, potholes and so on. The characteristics of the study sections are summarized in Table 2, and the pavement condition survey data is shown in Table 3.

Vehicle Fleet Data: This comprises the details like basic characteristics of vehicles, economic cost details of vehicles, vehicular compositions and growth rates.

Table 2 Road network data

S. No.	Section ID	Carriageway width (m)	Roughness IRI (m/km)	Characteristic deflection (mm)	Traffic volume (veh/day)
1	N1	7	3.45	0.639	17,638
2	N2	7	3.55	0.532	17,638
3	N3	7	3.15	0.380	34,576
4	N4	7	2.75	0.303	35,816
5	N5	7	3.55	0.328	41,755
6	N6	7	2.95	0.287	26,642
7	N7	7	2.60	0.305	26,970
8	N8	6	3.00	0.353	20,599

Table 3 Pavement condition data

Section ID	Cracking area (%)	Raveled area (%)	Potholes (%)	Depression (%)	Patchwork (%)
N1	13.76	0.126	0	0.073	0.82
N2	1.24	0.246	0	0.01	1.97
N3	0.1	0.187	0	0	0
N4	0	0.0025	0	0	0
N5	0	0.375	0	0	0
N6	0	0.005	0	0	0
N7	0.011	0	0	0	0
N8	0	0.013	0	0	0

The vehicle fleet for the present study consists of only motorized vehicles, as non-motorized transport is not very common in the study area.

Maintenance and Rehabilitation Works Data: *Maintenance Serviceability Levels*: The maintenance serviceability levels considered for the study are based on the recommendations of IRC: 82–2015 [6]. The serviceability levels and the allowable levels of defects in terms of roughness and distresses like cracking, raveling and pothole are shown in Table 4.

Cost Data: *Cost of Maintenance and Rehabilitation Works*: The costs of various maintenance items were obtained from the 'Report of the Committee on Norms for Maintenance of Roads in India', MoRTH 2001 [12]. These costs were updated to the base year 2020–2021 by using the mathematical model for updation of norms. The updated costs for the different maintenance activities are shown in Table 5.

Road User Cost: One of the most important components in the life-cycle cost analysis of pavements is road user cost, which is the expense incurred by vehicle operators and the traveling public. The vehicle operating cost, the time cost and the cost of a

Table 4 Serviceability levels for highways

Serviceability indicator	Level 1 (Good)	Level 2 (Fair)	Level 3 (Poor)
Cracking (%)	< 5	5–10	> 10
Raveling (%)	< 1	1–10	> 10
Potholes (%)	< 0.1	0.1–1	> 1
Roughness (max permissible)	1800 mm/km	2400 mm/km	3200 mm/km
Equivalent IRI	2.52 m/km	3.26 m/km	4.21 m/km

Source IRC: 82–2015 [6]

Table 5 Costs data for various maintenance activities

Type of maintenance activity	Unit costs for the base year 1999–2000 (Rs per sqm)	Updated costs for 2020–2021 (Rs per sqm)
Routine maintenance		
Crack repair	30	93.9
Pothole patching	37.8	118.3
Periodic maintenance		
25 mm DBSD	75.14	295.15
40 mm BC	171.44	672.0
50 mm DBM	172.01	674.31

road accident make up the road user cost. The price that has to be spent by the user in moving a vehicle per unit distance on the road is known as vehicle operating cost. The monetary worth of the time spent by people traveling and the time consumed by freight in transit is referred to as time cost. The cost of a traffic accident includes human life and property losses, which are difficult to quantify in monetary terms. Among these components, the VOC is the largest component and is considered in this study. The VOC components include cost of new vehicle, fuel cost, lubricating oil cost, tyre replacement costs and so on.

5.3 *Calibration of HDM-4*

The HDM-4 pavement deterioration models were developed as a result of a large number of field experiments carried out in various locations across the world. As a result of this, if the default equations are used without proper calibration, the predicted performance of the pavement may differ from what is actually observed on the road sections. So, in order to improve the accuracy of pavement performance predictions and vehicle resource consumption, proper calibration of HDM-4 is required. Prior to using HDM-4, it is assumed that the pavement performance models will be calibrated

Table 6 Calibration factors

Model	Calibration factors
Roughness progression	0.2
Cracking progression	0.7
Raveling progression	0.3
Pothole progression	0.7

to match the observed rates of deterioration on the pavement sections where the models will be applied [2].

Prior to the study, the deterioration models of HDM-4 were calibrated using secondary data collected from National Transportation Planning and Research Centre (NATPAC), Trivandrum [13]. Calibration was done for roughness progression model, cracking progression model, raveling progression model and pothole progression model, and the obtained calibration factors are shown in Table 6.

The calibration of HDM-4 models revealed that the progression of deterioration for the study stretch is at a slower rate than that predicted by the HDM-4 models. The obtained calibration factors were also compared with works carried out within and outside Kerala [2, 3, 11, 16], and it was observed that the values were comparable with the obtained results.

5.4 Maintenance Strategies Considered

The M&R alternatives considered for the study and the intervention criteria adopted are shown in Table 7. Four alternatives along with routine maintenance as the base alternative is considered. The intervention criteria were fixed based on the serviceability levels as per IRC: 82-2015 [6].

Table 7 M&R alternatives considered

Alternative	Works standard	Description of work	Intervention criteria
Base alternative	Routine maintenance	Crack sealing and patching	Scheduled annually
Alternative 1	Resealing	25 mm DBSD	Total damage area >= 10%
Alternative 2	Resealing	25 mm DBSD	Total damage area >= 10%
	Overlay	40 mm BC	IRI >= 3.26 m/km
Alternative 3	Overlay	40 mm BC	IRI >= 3.26 m/km
Alternative 4	Mill and Replace	Remove 90 mm surface and provide 50 mm DBM + 40 mm BC	Total carriageway cracked area >= 10% IRI >= 4.21 m/km

Routine maintenance activities like crack sealing and patching are to be performed on an annual basis. The resealing is to be done with 25 mm double bituminous surface dressing (DBSD). For triggering resealing of the pavement surface, the total damage area comprising cracking, raveling, and potholing area was considered as the controlling factor, while for overlays, roughness in terms of IRI was considered. For the study overlay using 40 mm bituminous concrete (BC) was considered. In case of the mill & replace alternative, total percentage of carriageway cracked was also considered along with the roughness criterion. Here, the top 90 mm of the surface will be removed and replaced with 50 mm Dense Bituminous Macadam (DBM) followed by 40 mm bituminous concrete.

5.5 *Project Analysis*

The project analysis was set up with routine maintenance as the base alternative with which all other alternatives were compared. Economic analysis was conducted at a discount rate of 12% and for a period of 10 years. The maintenance and rehabilitation work reports and the economic analysis summary reports were generated. A sample of M&R work report and the associated costs for section N1 are shown in Tables 8 and 9. The economic analysis summary for the entire project is shown in Table 10.

5.6 *Selection of the Optimum Maintenance Strategy*

Based on the results of the economic analysis, it is observed that Alternative 3, i.e., 40 mm BC overlay, has the maximum value of net present value/cost ratio. The internal rate of return is also higher for this alternative. So, overlay with 40 mm bituminous concrete is suggested as the optimum maintenance strategy for the pavement sections under study.

6 Conclusions

The objective of this paper was to overcome some of the limitations in the current maintenance and rehabilitation practices and to provide a better aid in decision making. The Highway Development and Management Model (HDM-4) developed by the World Bank can be used as a very powerful tool in this respect. In this paper, an attempt was made to optimize the maintenance strategies for the pavement section under study based on the criteria of maximization of net present value to cost ratio. The software was calibrated prior to the study so as to suit the conditions of the study area. Five different alternatives along with their intervention criteria were defined,

Table 8 Sample of M&R work report for section N1

Year	Base alternative	Alternative 1	Alternative 2	Alternative 3	Alternative 4
2021	Patchwork and crack sealing	25 mm DBSD	40 mm BC	40 mm BC	***
2022	Patchwork and crack sealing	***	***	***	***
2023	Patchwork and crack sealing	***	***	***	***
2024	Patchwork and crack sealing	25 mm DBSD	***	***	Mill and replace
2025	Patchwork and crack sealing	***	40 mm BC	40 mm BC	***
2026	Patchwork and crack sealing	25 mm DBSD	***	***	***
2027	Patchwork and crack sealing	***	***	***	***
2028	Patchwork and crack sealing	25 mm DBSD	25 mm DBSD	***	***
2029	Patchwork and crack sealing	25 mm DBSD	25 mm DBSD	***	***
2030	Patchwork and crack sealing	25 mm DBSD	40 mm BC	40 mm BC	***

*** indicates that 'no M&R work is assigned in that particular year'

Table 9 Sample of cost report for section N1

	Cost of works in Million Rupees				
Year	Base alternative	Alternative 1	Alternative 2	Alternative 3	Alternative 4
2021	0.0097	1.652	3.763	3.763	0.00
2022	0.0156	0.00	0.00	0.00	0.00
2023	0.0143	0.00	0.00	0.00	0.00
2024	0.0132	1.652	0.00	0.00	7.543
2025	0.0186	0.00	3.763	3.763	0.00
2026	0.0218	1.652	0.00	0.00	0.00
2027	0.0217	0.00	0.00	0.00	0.00
2028	0.0215	1.652	1.652	0.00	0.00
2029	0.0212	1.652	1.652	0.00	0.00
2030	0.0191	1.652	3.763	3.763	0.00
Total cost	0.1767	9.917	14.595	11.289	7.543

Table 10 Economic analysis summary for the pavement sections

Alternative	Increase in agency cost (C)	Decrease in user cost (B)	Net present value (NPV = B − C)	NPV/cost ratio	Internal rate of return (IRR)
Base alternative	0.00	0.00	0.00	0.00	0.00
Alternative 1	73.699	885.836	812.136	11.020	451.1
Alternative 2	95.200	1965.943	1870.743	19.651	559.9
Alternative 3	53.470	1673.138	1619.668	30.291	575.1
Alternative 4	33.900	881.456	847.556	25.001	421.9

and economic analysis at the project level was carried out using HDM-4. The alternative '40 mm BC overlay' was obtained as the optimum maintenance strategy based on the results of economic analysis, and the intervals of application of the overlay were also obtained from the work reports.

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