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A Network Level Pavement Maintenance Optimisation Approach Deploying GAMS

V. U. Rejani[1] · **V. Sunitha[1]** · **Samson Mathew[1]** · **A. Veeraragavan[2]**

Abstract

Pavement Management Systems (PMS) can benefit the highway agencies in several ways both at network and project levels, especially in selecting cost-effective alternatives. Whether it is new construction, maintenance, or rehabilitation, PMS helps the authorities attain the best possible utilisation of available resources and public money. This investigative paper proposes a network level PMS for the roads of Tiruchirappalli city, India. Data pertaining to inventory, traffic, maintenance history, and serviceability of the study roads are gathered at regular intervals for a period of 7 years. The pavement sections are grouped into homogeneous clusters by k-means clustering, and Multiple Linear Regression Models are developed for the clusters to predict pavement performance. Based on the pavement condition, different maintenance treatments are identified through expert opinion surveys. An optimisation programme UPMMS-GAMS is developed using Generic Algebraic Modelling System (GAMS) software, to consolidate the city's PMS. Pavement condition, age, maintenance options, and maintenance cost are given as model inputs. Minimum performance levels and the maximum number of maintenance activities are constraints that must be guaranteed. The optimisation programme defines the maintenance and rehabilitation strategies to be employed each year to maintain the pavement sections above a minimum desired level.

Keywords Urban pavement maintenance · Pavement management system · Pavement deterioration models · Optimisation · GAMS · UPMMS-GAMS

1 Introduction

The pavement deteriorates at a relatively slow rate during the early years of its life, but as it approaches the end of its design life, the rate of deterioration accelerates. Intervention, with appropriate maintenance treatments, at the appropriate times, can substantially delay the deterioration cycle and consequently reduce the overall cost of maintaining the pavement. Maintenance and Rehabilitation (M&R) strategies must be so chosen to maximise the serviceability of the road through cost-effective interventions. A Pavement Management System (PMS) can facilitate such decisions. A PMS has been defined as "A coordinated set of activities, all directed toward achieving the best value possible for the available public funds in providing and operating smooth, safe, and economical pavements" [1]. The PMS helps to increase the effectiveness of the decision-making process, assess the outcomes of the decisions made, coordinate the activities, and standardise the decisions made at various administrative levels.

Executing a well-designed PMS primarily depends on three aspects: consistent data, accurate models that organise the data, and user-friendly software for processing the inputs and predicting the outputs. The deteriorating urban roads and limited budgets are principal issues faced by the local governments. The systems of objective measurement of distress, along with visual surveys, are used for deciding maintenance and rehabilitation measures, which, in the course of time, have been fine-tuned to offer prompt, objective measures to

✉ V. U. Rejani
  rejanivu@gmail.com

  V. Sunitha
  sunitha@nitt.edu

  Samson Mathew
  sams@nitt.edu

  A. Veeraragavan
  av@iitm.ac.in

1   Department of Civil Engineering, NIT Tiruchirappalli, Tiruchirappalli, India

2   Department of Civil Engineering, IIT Madras, Chennai, India

set up maintenance preferences. Data regarding the pavement condition, such as roughness and distress are used to prioritise the projects for maintenance and rehabilitation. In highway agencies with limited funds, where the detailed quantitative assessment of pavement condition is restricted, a subjective yet scientifically performed evaluation would be a practical substitute. If pavement condition surveys cannot be conducted periodically, the condition of each pavement section may be predicted using suitable pavement condition prediction models. Also, if financial limitations compel an agency to delay the pavement rehabilitation programme, the deterioration of the sections can be predicted using the models for the budget planning of the subsequent years.

The idea of PMS was conceived towards the end of 1960s and the systems approach for pavement management was introduced [2], ensued by advancements in related technologies in the 1970s, and the information was presented in a book on Pavement Management Systems [3]. In the 1980s, the World Bank developed HDM-III, which brought in the vehicle operating costs in the lifecycle cost analysis, to offer highway agencies an aid for planning M&R strategies [4]. In the 1990s, the techniques used in pavement management were completely altered with the availability of personal computers. The optimisation techniques used in PMS are broadly categorised as single-objective and multi-objective optimisation. While the former attempts to satisfy a particular objective, such as minimising the maintenance cost or maximising the benefits [5], the latter aims to derive an optimal solution, optimising different objective functions satisfying multiple constraints.

Various techniques like the weighting sum method [6], analytic hierarchy process [7], genetic algorithms (GAs), and evolutionary algorithms [8] have been deployed in the pavement management sector for solving optimisation problems. Li [9] presented an integrated PMS based on Markov prediction models. Fwa et al. [10] established the adaptation of GAs to resolve pavement management problems. The general framework of the GA model can be employed to address a variety of PMS problems by appropriately coding the problem parameter, and the solution technique can admit different objective functions identified by the user. Ferreira et al. [11] developed a PMS which uses a deterministic deterioration model, which explores the application of GA and GIS and the research was further expanded by Morcous et al. [12] using probabilistic models for pavement deterioration in bridge pavements. Mathew and Issac [13] presented a multi objective optimisation model for the maintenance planning of the rural road network of the Indian state of Kerala, which focus on the minimisation of cost and maximisation of effectiveness of treatment over the planning period. Meneses and Ferreira [14] developed and implemented a multi-objective optimisation model for the PMS of Portugal with the objectives of cost minimisation, and maximisation of the residual value of pavements. Saha and Ksaibati [15] presented an optimisation methodology for Wyoming's county roads to choose the best combination of maintenance strategies within limited funds, maximising the traffic and PSI, and minimising the risk. The decision-rule preference model proposed by Augeri et al. [16] allows the analyst to interact with the policymaker so that the analyst can organise the treatment alternatives and allocate the budget in accordance with the previously defined objectives. A model for optimising the M&R strategies of Iran's national road network based on the cloud decision tree (CDT) theory was presented by Mataei et al. [17].

Ever since the introduction of PMSs, prioritisation, and optimisation models have been used in the decision support systems to plan the M&R strategies [18]. In prioritisation models, all the pavements are prioritised based on various parameters like the category of road, condition of road surface, traffic volume, age, etc., and M&R funds are allocated according to the ranking. The prioritisation is done using the present condition data of the pavements. Therefore, this approach does not warrant that the best maintenance strategy is chosen, nor does it permit planning for longer durations. On the other hand, optimisation models aim at an optimal or near-optimal solution. Optimisation approaches can be broadly classified into two: top–down approaches and bottom–up approaches. In top–down methods, the road sections are investigated in separate classes, and the sections in each class are considered to deteriorate identically [19]. As the same treatment is given to all sections in a group, it is not possible to recommend explicit strategies to each section. On the other hand, section-wise distress data and deterioration rates are considered in bottom–up approaches. The M&R optimisation aims at proposing the timing and type of maintenance plan for sections, over a sufficiently long period.

Generally, two main approaches are followed for fixing the treatment plan for a particular section of pavement: plans based on condition threshold and those based on user cost. Many authors have employed condition thresholds for simplifying the optimisation problem [20, 21]. Even though the approach in the present study also employs condition thresholds for sections, they are used only as a lower limit for optimising the maintenance treatments. Many PMSs merge short pavement sections into homogeneous ones of 1–5 kms to simplify the optimisation problem and this may lead to inaccurate condition prediction, causing an overestimation or underestimation of serviceability on short sections [22]. On the other hand, the accuracy of prediction is affected by variations in data. The accuracy of performance prediction of pavement sections can be improved by grouping them into homogeneous clusters. The clustering may be done based on their similarities with respect to various parameters. The clustering approach can be effectively adopted for grouping pavement sections in different phases of pavement

management like road network planning, prioritisation, pavement deterioration prediction etc. [23–25].

The simulation tools have become one of the most crucial components of optimisation, as these tools allow planners to analyse various solutions for the problem under consideration. Recently various researchers have made their contribution in developing multiple tool boxes for different areas of interest. Various commercial software applications are available for optimisation, which includes Generic Algebraic Modelling System—GAMS [26, 27][28], AMPL [29], LINGO [30], Python [31] and MATLAB packages [32, 33], etc. GAMS is a high-level modelling system for programming and optimisation of mathematical models, particularly intended for linear, nonlinear, and mixed integer optimisation problems.

GAMS offers many advantages over conventional computer optimisation systems. It is customised for intricate, extensive modelling applications and can be used to develop large deployable models which can adapt to new circumstances. In GAMS, the model is formulated using concise algebraic statements, making it easy to read for computers and humans alike. GAMS belongs to the genus of math programming languages specially tailored for optimization problems making it better than general purpose numerical analysis languages like MATLAB. Since GAMS is a language specialised in math programming, it is particularly equipped to define the optimisation problem, provides access to various solvers, helps to develop the problem gradually and transform it from linear to nonlinear to discrete or an equilibrium problem easily. The major advantages of GAMS are its ease of execution, portability and trouble-free technical updation. Works have already been done on the application of GAMS to solve optimisation problems in various fields [34, 35] and it is used for pavement maintenance optimisation in the present study.

From the literature review it was found that most of the studies deploy either Pavement Condition Index (PCI) or International Roughness Index (IRI) of pavement for analysis and a combination of these may be more effective in predicting the performance characteristics of pavements. The performance prediction of pavement sections can be done more accurately if they are grouped into homogeneous clusters. Clustering of pavements based on parameters relevant to urban roads is necessary. Many of the PMSs merge short pavement sections into long ones of 1–5 kms, to simplify the optimisation problem. Merging the sections may lead to inaccurate condition prediction. In many of the previous works clustering is done based on one or two factors for a short period of one or two years and the clustering results may vary with the planning period. In the present study, clustering is done based on the PCI, IRI, Age and Traffic of the sections for a period of seven years.

This paper investigates the performance of selected urban road sections, group them into homogeneous clusters, generate performance prediction models for the sections in each cluster, and identify the various alternate maintenance treatments duly considering Pavement Condition Index. A decision support system is then presented for optimising the maintenance strategies of urban roads within the budget constraints. The PMS includes a database of the selected road network, a performance assessment system, pavement deterioration models, and a maintenance optimisation system. The distress data, collected before and after the monsoon seasons for a long period of seven years, helps substantially eliminate anomalies. The roads are divided into short sections of 25 m and the Pavement Condition Indices are determined considering the distress parameters pertaining to the urban roads of India. A deterministic deterioration model is developed to estimate the pavement condition during the analysis period. An Urban Pavement Maintenance Management system called UPMMS-GAMS (named by authors) was developed to consolidate the PMS of the city of Tiruchirappalli (India). The optimised maintenance treatment for each section of the selected roads for the study is found using the GAMS (Generic Algebraic Modelling System) software. The objective is not just to optimise the effectiveness or to minimise the cost, but to find optimum treatment solutions to keep the sections above the minimum desired PCIs, based on the budget constraints using GAMS.

2 Methodology

The condition of the pavement is assessed in terms of pavement distresses and its serviceability in terms of pavement roughness. Each lane of the road is divided into of 25 m long sections for data collection. The pavement distress data is collected through visual condition surveys and the pavement condition is presented as PCI, found using the Deduct Curve method from US Army Corps of Engineers' Technical Manual [36]. Visual evaluation being subjective in nature, an objective evaluation of the pavement condition in terms of the roughness, expressed as IRI, is executed using Roughometer III. Traffic volume data of the study roads is obtained by manual counts.

Homogeneous clusters of road sections are formed considering its PCI, IRI, age, and traffic volume of the study roads. Multiple Linear Regression Models are formulated to predict pavement performance of each cluster. The maintenance options to be considered in the optimisation programme and the corresponding increase in PCI values are identified through expert opinion surveys.

An optimisation model is developed for the maintenance activities of the road network using General Algebraic Modelling System (GAMS). In the optimisation model,

pavement condition data, age of pavements, maintenance options, and the cost of each maintenance option are given as model inputs and the future serviceability of pavements are predicted using the performance prediction models. The objective of the model is to minimise the funds required to maintain all the pavement sections above the desired performance levels. Basically, the urban pavement maintenance management system, UPMMS-GAMS developed for the PMS of the city of Tiruchirappalli (India), defines the maintenance and rehabilitation strategies to be employed to the pavement sections each year. The methodology is pictorially represented in Fig. 1.

3 Study Area and Data Collection

The arterial and sub arterial road network of Tiruchirappalli (Trichy) district of the state of Tamil Nadu, South India, is selected for the study. The roads selected for study are listed in Table 1. The road inventory, traffic volume, maintenance records, distress, and roughness data are collected section-wise for the study roads.

Data regarding the year of construction and nature and time of maintenance activity are obtained regularly from the Tiruchirappalli Corporation office. After undergoing a major rehabilitation (strengthening with Dense Bituminous Macadam + Bituminous Concrete or an overlay of more than 40 mm), the pavement PCI is assumed to increase to 100, and it can be treated as a new pavement. The age of the

Table 1 Road network selected for the study

Sl. no.	Road name	No. of lanes	Length (km)	No. of sections**
1	Anna Nagar Main Road	4	1.000	160
2	Bharathidasan Road	4	1.300	208
3	Bishop Road	2	1.050	84
4	Collector Office Road	2	1.675	134
5	Convent Road	2	0.525	42
6	Hospital Road	2	0.550	44
7	Lawson's Road	2	0.500	40
8	Mc Donald's Road	2	0.350	28
9	Pattabiraman Street	2	0.850	68
10	Puthur EVR Road	4	0.725	116
11	Puthur Main Road*	4/2	0.725	84
12	Reynold's Road	2	0.375	30
13	Rockins Road	2	0.525	42
14	Royal Road	2	0.625	50
15	Salai Road	2	1.250	100
16	Sastri Road	2	1.025	82
17	Thillai Nagar Main Road	2	1.050	84
18	Victoria Road	2	0.275	22
19	William's Road	2	0.875	70
Total			15.250	1488

*Puthur Main road is a four-lane road up to a length of 400 m and changes to a two-lane road afterwards

**A single lane of road stretch, 25 m long, is mentioned as one section. (For example, a two-lane road of one km length has 1000/25 × 2 = 80 sections)

Fig. 1 Methodology
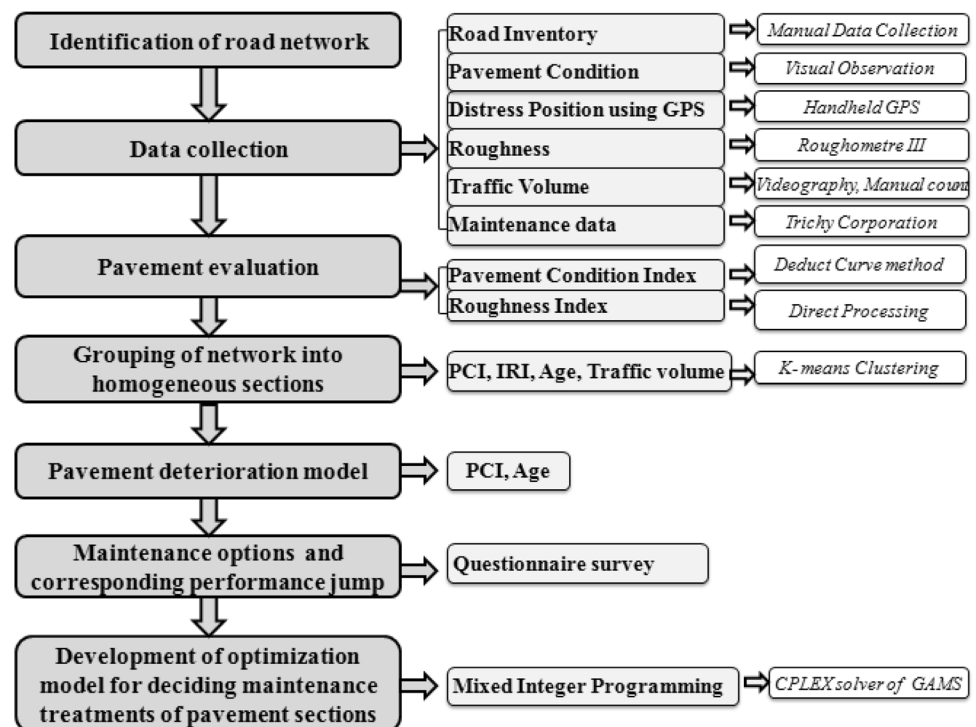
pavement, therefore, decreases to zero after a major rehabilitation and increases by one every year, for any other treatment or if no treatment is done. The pavement age, therefore, is the number of years after the last major rehabilitation. If a pavement segments has not received any major rehabilitation, age is defined from the year of construction.

A 24-h manual count was conducted for each road during weekdays, and the traffic volume is represented in Commercial Vehicles per Day (CVPD). Videographs were also taken during peak hours on roads with heavy traffic. For shorter roads without major intersections in between, the variation in traffic volume along the length of road was very less, and hence, the traffic data was collected only at the middle of each road. For longer roads with major intersections, traffic volume was collected at different points and the volume is assumed to be same between two intersections.

The distress data are collected twice a year, before and after the monsoon, for thirteen seasons, through walkthrough visual surveys as per the guidelines of IRC 82-1982 [37]. The distresses include alligator cracking, transverse cracking, longitudinal cracking, rutting, potholes, depression, patching, and ravelling. The PCI is determined using Deduct Curve method from US Army Corps of Engineers Technical Report [35]. The deduct values (DV) are determined from deduct value curves for each distress type and severity. The Total Deduct Value (TDV) is obtained by adding the individual DVs. The Corrected Deduct Value (CDV) corresponding to the TDV is found out from the Corrected Deduct Value chart. The PCI of the section is determined using the equation:

$$PCI = (100 - CDV).$$

4 Clustering

Clustering is the task of grouping the data points which are bound together by certain similarities. *K*-means clustering is a reliable unsupervised machine learning algorithm for unlabelled data. It is an established method for large datasets and can be implemented easily. In the present study, the pavement sections are grouped into homogeneous clusters, so that each cluster consists of portion of the network that possess similar characteristics. The grouping is done based on the PCI, IRI, age, and traffic volume of the pavement sections. A subjective score of the pavement condition is obtained from the PCI whereas the functionality of the pavement is measured using the IRI. Traffic volume and age vary considerably for different roads in the study area and affect the deterioration pattern. The 1438 road sections of the study area are considered for analysis, leaving behind 50 sections where continuous data could not be collected. The grouping is done by means of K-means

clustering using XL-STAT, which is a user-friendly data analysis add-in for Microsoft Excel. The number of clusters is varied from 2 to 10 and the optimum number of clusters is found such that the within class variance is minimised (keeping the elements of a cluster as similar as possible) or between class variance is maximised (minimise the similarity between different clusters). The optimum number of clusters is found to be three by the elbow method [38] as shown in Fig. 2.

The properties of road sections in each cluster are studied and it is observed that majority of roads with heavy traffic fall into cluster 2 category, whereas, the roads with poor maintenance history, i.e. higher age, are grouped under cluster 3. Cluster 1 consists of roads with moderate traffic and moderate maintenance history. Even though data are collected section wise, it is observed from the clustering results that the entire pavement sections of each road falls in the same cluster.

5 Pavement Deterioration Model

From the review and analysis of different prediction models [39], the authors have inferred that a multiple linear regression model is most appropriate for the present study, and pavement deterioration models are developed for each cluster using the PCI and age data of the sections for a period of seven years. To analyse the effect of clustering, a single model for the whole network is also developed using the non-clustered data. These models can be used for the planning of maintenance strategies and allocation of budgets to maintain the pavements above a desired performance level.

The general structure of the model is:

$$PCI_n = a + b \times PCI_{n-1} + c \times Age_n, \tag{1}$$

where PCI_n and PCI_{n-1} are the PCI values for the year *n* and *n*−1, respectively, Age_n is the age of the pavement in the *n*th year, and *a*, *b*, *c* are constants.
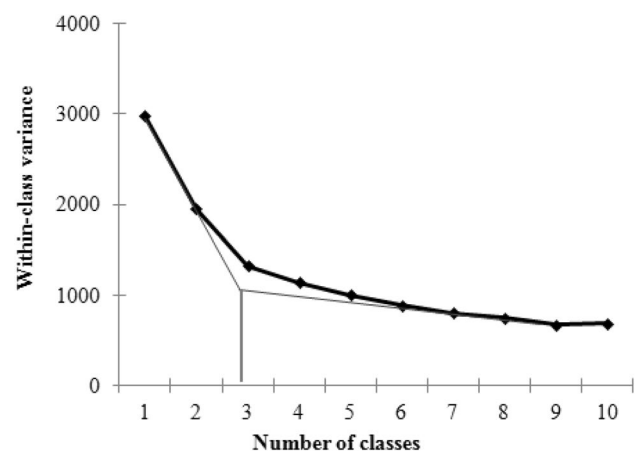

Fig. 2 Optimum number of clusters

The coefficients of (1) for different clusters and that for the non-clustered group are shown in Table 2.

An ANOVA test conducted for the models, and the low p values in all cases at a significance level of 0.05 indicates their goodness of fit. The condition of pavements during a year in terms of PCI is predicted from the data of the previous year using the performance prediction models. Prediction is done using both clustered and non-clustered models and a comparison is made between the predicted values and the observed values for the same year. The Mean Absolute Percentage Error (MAPE) is computed form the models to estimate the variation between the observed and predicted values. It is observed that the MAPE is lesser for the models for clustered data confirming that the accuracy of prediction can be increased by grouping the road sections into homogeneous clusters. The predicted PCI values for various clusters and non-clustered sections based on the pavement condition model for an initial PCI of 100 are graphically represented in Fig. 3, for comparison.

Figure 3 indicates that in all the cases the pavement condition prediction by the non-clustered model results in higher or lower values compared to that by the clustered models.

More details of data collection, clustering, and pavement deterioration model are not included in the paper due to space constraints and are explained by Rejani et al. [38].

6 Optimisation of Pavement Maintenance

Pro-active maintenance of pavements prevents destruction of the asset value and manages expectations of all key stakeholders. In many situations, budgets often fall short to keep the pavement at the pristine condition. Therefore, it becomes a tight balancing act in prioritising various maintenance activities so as to achieve the agreed goals by the optimal use of the allocated funds. Multiple constraints (e.g., available funds, condition of pavements, expected performance level, etc.) have to be integrated in the formulation of the optimisation problem. Generally, the goal of M&R optimisation is to maximise pavement performance, keep the performance level above a desired limit, or to minimise the operational costs by choosing the most appropriate maintenance strategy, subject to the constraints (e.g., budget).
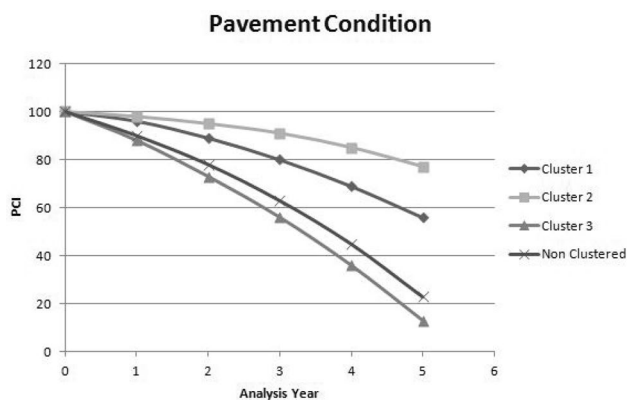

Fig. 3 Prediction of pavement condition using clustered and non-clustered models

6.1 Optimisation Using GAMS

The General Algebraic Modelling System (GAMS) is a modelling approach for mathematical programming and optimisation. GAMS is used to model extensive and complex modelling problems and build large maintainable models which have the flexibility to adapt to new situations. The general steps to implement a mathematical model using GAMS optimization package is as follows:

1. The decision variables are defined using reserved words: VARIABLES, INTEGER VARIABLES, POSITIVE VARIABLES or BINARY VARIABLES. The type of decision variables depend on the nature or type of the optimization model i.e. Linear programming (LP), Nonlinear programming (NLP), Mixed-integer linear programming (MIP), Mixed-integer nonlinear programming (MINLP) among others.
2. The set of necessary equations are defined using the reserved word "EQUATIONS". First, the names of the equations are defined and then their mathematical expressions are written.
3. The name of the model is defined using the reserved word "MODEL": MODEL < model name >.
4. The mathematical model is solved using the commands: SOLVE < model name > USING < model type > MAX-

Table 2 Coefficients of deterioration models for K-means clusters

	Size	Coefficients of deterioration models			R^2	p value
		A	b	c		
Cluster 1	601	− 17.089	1.116	− 0.753	0.715	< 0.0001
Cluster 2	289	− 30.120	1.286	− 0.507	0.744	< 0.0001
Cluster 3	548	− 23.502	1.182	− 0.742	0.727	< 0.0001
Non-clustered	1438	− 31.41	1.220	− 0.134	0.578	< 0.0001

IMIZING or MINIMIZING < objective function variable >.

5. The solutions or variables of interest can be seen as output using the reserved word DISPLAY: DISPLAY z.1.

The full version of GAMS can be purchased, or a demo version for academic purposes with some restrictions on the number of variables and solvers is available at the website www. gams.com.

In the present study, the CPLEX solver of GAMS is used for optimisation. CPLEX solver facilitates programmers to blend the high-level modelling abilities of GAMS with the potentials of CPLEX optimisers. Mixed Integer Programming (MIP) is done to minimise the budget keeping the PCI values above the minimum desired value.

6.2 Maintenance Treatments

A questionnaire survey was conducted to get expert opinions regarding the different maintenance options that can be given to the distressed pavements and the corresponding improvement in pavement condition. Questionnaires were sent to academicians, scientists and practicing engineers in the field of Transportation Engineering. Maintenance treatments and the expected improvements in PCI are suggested for the study area based on the opinion of the experts as given in Table 3.

The yearly budget required for maintenance treatment activities of the sections for five years is calculated as per the Schedule of Rates, Govt. of Tamil Nadu. The coding for the maintenance treatment activity in the optimisation model and the corresponding costs are shown in Table 4.

Table 4 Code for maintenance treatment activity and costs considered in programming

Sl. no.	Code	Maintenance treatment activity	Cost per km per lane (in million INR)
1	DN	Do nothing	0
2	RM	Routine maintenance	0.15
3	RS	Resurfacing	0.75
4	ST	Strengthening	3
5	MR	Major rehabilitation	3.75

6.3 Optimisation Model

There are two approaches of maintenance strategies available—first, one which is driven by optimisation models, and the second, one which leverages on the knowledge-based expert systems. As transportation networks have expanded, it is important that an optimisation modelling approach is used for the maintenance processes.

The optimisation of the maintenance strategies is done under two scenarios. The first one is to minimise the maintenance funds necessary to keep the PCI of all the pavement sections above a fixed value and is referred to as Necessary Funds Model (NFM). The second one is to maximise the benefit area within the budget limitations and is referred to as Budget Bound Model (BBM). The Budget Bound Model is beyond the scope of this paper and is not discussed here. The Necessary Funds Model presented in this study proposes a comprehensive maintenance strategy for the pavement segments during each year of the analysis period defined by the user. The optimal solution is expected to satisfy the following conditions:

Table 3 Maintenance treatments identified

Sl. no.	PCI range	Maintenance treatment	Description	Expected improvement in PCI
1	81–100	Routine maintenance	Roadside maintenance Pothole filling Shoulder dressing Drain desilting Minor crack sealing	Up to about 10 points
2	61–80	Resurfacing	Routine maintenance + Surface treatment Rout and seal cracks Overlay of less than 40 mm	Up to about 30 points
3	41—60	Strengthening	Routine maintenance + Overlay of 40 mm or more	Up to about 60 points
4	≤ 40	Major rehabilitation	Strengthening (75 mm DBM + 40 mm BC)	Up to about 100 points

- The total cost of maintenance for all the pavement segments considered is kept at a minimum.
- Pavements segments are maintained throughout the analysis period above a minimum level defined by the user.

The concept of necessary funds model adopted in the study is illustrated below:

- The PCI values at the beginning of the analysis period, threshold PCI, age of pavement sections, the cluster to which it belongs, the maintenance options, costs and the corresponding increase in PCI are given as inputs of the optimisation programme.
- The condition of all the pavement sections after treatment should therefore be above threshold PCI.
- From the initial PCI, the maintenance treatment required for each section to keep the PCI above the threshold value is selected from the maintenance options using the optimization programme.
- The PCI after treatment and the maintenance costs for the year are also calculated.
- The PCI of the next year is calculated for each section using the deterioration model for the cluster to which it belongs.
- The process is done for a period of 5 years.
- The PCI after treatment, the deterioration during the next year and the treatment costs for the successive years depend on the treatment option selected for each year. Various combinations of treatment options are checked for each pavement section by the optimization programme.
- The optimum combination of treatment options for each pavement section for a period of 5 years which gives the minimum total maintenance cost is found out by the optimisation programme.
- Maintenance and rehabilitation plan for a period of 5 years, The PCI before and after maintenance during each year and the budget requirements during the planning period are obtained as outputs of the programme.

The details of the optimisation model are shown in Table. 5.

The objective functions and constraints in the NFM model are discussed below.

7 Necessary Funds Model

Problem problem:

$$\text{Minimize} \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{j=1}^{J} C_{ijt} X_{ijt}, \tag{2}$$

$$\text{s.t.} \quad \text{PCIF}_{ijt} \geq \text{PCI}_{\text{threshold}} \quad \text{for all } i, j, t, \tag{3}$$

$$\sum_{j=1}^{J} X_{ijt} = 1 \quad \text{for all } i, t, \tag{4}$$

$$X_{ijt} \in \{0, 1\} \quad \text{for all } i, j, t, \tag{5}$$

where I is the pavement sections, t is the planning periods, j is the maintenance actions for each pavement section during the period, C_{ijt} is the cost of alternative 'j' for pavement section 'i' in period 't', PCIF_{ijt} is the PCI of the section 'i' after maintenance treatment 'j' has been applied during period 't', X_{ijt} is the variable indicating the application of a maintenance activity on a pavement section. The objective function (2) minimises the total cost of maintenance activity for the system. The constraint (3) indicates that the PCI of the section after applying M&R activity should be greater than or equal to the specified Threshold PCI. The constraint (4) indicates the alternative selection constraint and ensures that only one strategy is chosen for each pavement section in any time period. (Strategy '1' stands for 'do-nothing' activity). Constraint (5) shows that $X_{ijt} = 1$ if alternative 'j' for pavement sections 'i' in period 't' is selected, and it is equal to 0 otherwise.

Table 5 Details of the optimization model

Objective	Minimisation of total cost of maintenance activity for the system
Data and models	Performance prediction models
	PCI of pavements
	Age of pavements
	M&R actions and its unit costs
	Minimum performance levels to be maintained
Constraints	The minimum performance levels should be maintained
	The number of M&R actions during the planning period should not exceed the maximum permitted
Results	Maintenance and rehabilitation plan
	Functional quality improvement report
	Costs report

The calculation time depends on the number of sections, analysis period and the features of the system used. In a 1.6 GHz Intel core i5 processor, 8 GB RAM system, it takes around 10 min to run the optimisation programme for 1438 sections for 5 years.

7.1 Results from Optimisation Programme

The optimisation programme UPMMS-GAMS has been developed for the study roads for a period of five years from the analysis year. From the deterioration model, the optimised maintenance treatment for each section of the selected roads for the study is found. The minimum budget required for a period of five years to maintain the sections at a serviceable PCI level of 80 is determined by the NFM. Based on the type of maintenance activity carried out, performance jump criteria are included in the optimisation programme. As an example, the results for ten sections of Convent Road from the optimisation programme for K-means Clustered Data by Necessary Funds Model are shown in Table 6. A sample deterioration curve for Sect. 6 is given in Fig. 4.

The yearly budget required in each planning year and the total budget required to keep all the sections above a threshold PCI of 80 as obtained from the programme is given in Table 7.

It can be seen that the budget necessary to maintain the pavement sections above the threshold PCI is greater for the non-clustered model for the roads selected for study.

7.2 Sensitivity Analysis

Sensitivity analysis aims at measuring the impact of changes in parameters of a mathematical model or system on its target output or performance. To calculate sensitivity, each of the system parameters is altered by a particular percentage individually while keeping all of the other parameters constant, and the percentage change of the output is examined.

The budget required in the Necessary Funds scenario depends on the initial PCI of the roads considered and the threshold PCI value targeted after maintenance. Keeping all the other constraints unchanged, the threshold PCI, which is a main constraint in the model, is varied from 50 to 90. The sensitivity of the threshold PCI in the

Table 6 Maintenance treatment activities for ten sections

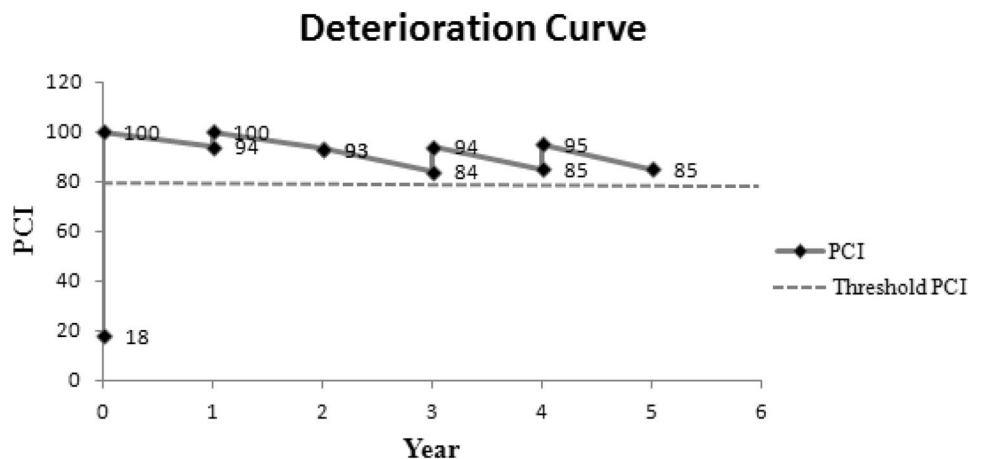| Section	PCI—year 0	Maintenance treatment				
		Year 1	Year 2	Year 3	Year 4	Year 5
1	33	ST	DN	RM	RM	RM
2	60	RS	RM	RM	RM	RM
3	82	RM	RM	RM	DN	RM
4	43	ST	RM	DN	RM	DN
5	59	RS	RM	RM	RM	RM
6	18	MR	RM	DN	DN	RM
7	70	RS	DN	RM	RM	DN
8	44	ST	RM	DN	RM	DN
9	13	MR	RM	DN	RM	DN
10	25	ST	RM	RM	RM	RM

Fig. 4 Sample deterioration curve

Table 7 Yearly budget required for a threshold PCI of 80

	Budget required (Million Rs./km/lane)					Total Budget required for 5 years (Million Rs./km/lane)
	Year 1	Year 2	Year 3	Year 4	Year 5	
Clustered model	0.80	0.13	0.14	0.09	0.07	1.23
Non clustered model	0.81	0.20	0.19	0.12	0.09	1.40
% Variation	1.07	36.15	28.50	19.93	23.09	12.77

Table 8 Sensitivity analysis of threshold value in NFM

Sl. no.	Threshold PCI	K means cluster model		Non-cluster model		% variation in budget
		Budget (Million Rs./km/lane)	Benefit*	Budget (Million Rs./km/lane)	Benefit*	
1	50	0.65	12,376.61	0.83	12,241.44	21.3
2	60	0.79	13,411.32	0.94	13,354.81	15.4
3	70	0.97	14,449.03	1.13	14,533.62	14.5
4	80	1.23	15,600.77	1.40	15,641.41	12.8
5	90	1.55	16,641.18	1.73	16,847.94	10.4

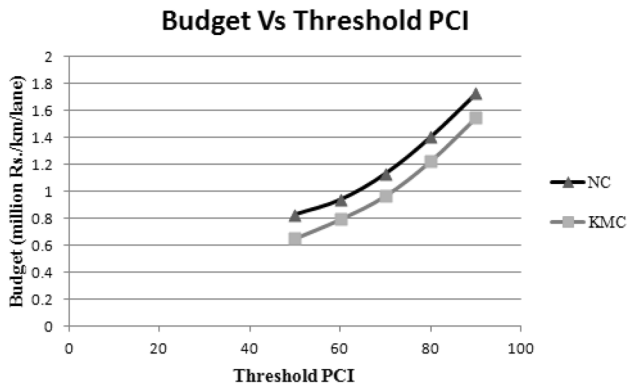*In terms of area under performance curve

Fig. 5 Budget required for various threshold PCIs

optimisation results is found out for clustered and non-clustered models. The results are shown in Table 8. The budget required for various values of threshold PCIs for a period of five years is given in Fig. 5.

It can be observed that the funds necessary to sustain all the pavement sections above the threshold PCI are greater for the non-clustered model in all the cases for the roads selected for the present study. The percentage variation in budget reduces as the budget limit increases. Thus it can be observed that the clustered model is more important in a limited budget scenario for the study roads.

8 Conclusions

Pavement condition surveys and roughometer surveys are carried out for the study of roads, and Pavement Condition Indices (PCIs) and the International Roughness Index (IRI) values are determined. Considering the PCI, IRI, traffic volume, and age of the pavement sections, they are grouped into homogenous clusters using K-means clustering. Multiple linear regression models are developed for these clusters to predict the pavement deterioration for the future years. For comparison, another model is formulated considering the whole network without clustering. On validation of the model, it is found that the accuracy of prediction is increased when the roads are grouped into homogeneous clusters. A questionnaire survey is conducted to get an expert opinion regarding the different maintenance options that can be given to the distressed pavements and the corresponding improvement in pavement condition.

The optimisation programme UPMMS-GAMS has been developed for the study area. The CPLEX solver of GAMS is used for optimisation. Mixed Integer Programming was done to maintain the PCI values above the threshold PCI and minimise the budget. The optimised maintenance treatment for each section of the roads selected for the study and the minimum yearly budget required for a period of 5 years to maintain the sections at a serviceable PCI level of 80 is determined by the NFM. Total Budget required for 5 years is found to be 12.77% less for

the optimisation model using clustered data, the yearly reduction in budget varying from 1.07 to 36.15%. The total budget required for a period of 5 years for various values of threshold PCIs and the total benefits for the budgets are found out. It can be observed that the funds needed to maintain all the pavement sections above the threshold PCI is lesser for the clustered model in all the cases for the study roads. The reduction in budget varies with the threshold PCI, the percentage reduction being 10.4% for a threshold PCI of 90, and 21.3% for a threshold PCI of 50. It can be observed that considering all the roads as a single group results in under estimation or over estimation of the maintenance treatments and the required budgets. The study establishes the necessity and the significance of clustering of pavement sections for planning and executing the maintenance strategies.

The research may be extended using other clustering methods such as latent class clustering and using other modelling techniques. Also, the maintenance strategies may be optimised based on the budget constraints (Budget Bound Model). The sections, after finding optimised treatment, may be grouped in such a way that at least 100 m length of road (or total length of a particular road, whichever is lesser) should have the same treatment measure.

Declarations

Conflict of interest Not applicable.

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V. U. Rejani is a Research Scholar in the Department of Civil Engineering, NIT Tiruchirappalli. She holds an M.E. in Highway Engineering from University Visvesvaraya College of Engineering (UVCE), Bangalore University. She joined NSS College of Engineering, Palakkad, India, as Assistant Professor in 2003 and has been working there as faculty member since then. She has published articles on Pavement Evaluation, Pavement Management Systems, Clustering etc. Her research and publication interests include Pavement Engineering and Pavement Management Systems.

V. Sunitha did her Ph.D. from IIT Madras. She joined National Institute of Technology, Tiruchirappalli in the year 2003 as Research Associate and later as Assistant Professor in 2006. She has completed two sponsored projects and currently co-ordinating two sponsored projects sponsored by Coir Board, Ministry of MSME, Government of India and one of the coordinator of Centre of Excellence in Transportation Engineering (CETransE). She is a member of State Technical Agency of Prime Minister Gram Sadak Yojana (PMGSY) program for Tamilnadu and Pondicherry. Her research interest is on pavement materials and pavement management systems.

Samson Mathew holds a Ph.D. from University of Calicut. He received the young scientist award for the year 1994. He joined National Institute of Technology, Tiruchirappalli in the year 1994 and is currently the Professor of Civil Engineering. His teaching and research areas include Transportation Planning, Traffic Engineering, Road Safety, Pavement Management and ITS. He has published 36 papers in International/National journals, 29 papers in International conferences and more than 70 papers in National level conferences. He has successfully completed projects sponsored by Ministry of Human Resources Development, Govt. of India, National Rural Road Development Agency, Coir Board etc. He was also the head of Centre of Excellence in Transportation Engineering (CETransE) at NIT Tiruchirappalli. Currently he is working as Director, NATPAC, Thiruvananthapuram, under deputation.

A. Veeraragavan is currently Professor in the Department of Civil Engineering at the Indian Institute of Technology Madras, Chennai, India. He has over four decades of experience in teaching, research and industrial consultancy. He has published over 100 research papers in National and International Journals and over 150 papers in Conference proceedings. He has co-authored four books on: Surveying, Highway Engineering (11th edition-under print), Highway Materials and Pavement Testing (5th edition) by M/s Nem Chand & Bros. Roorkee, and a book on 'Pavement Drainage – Theory and Practice' by CRC Press, Taylor & Francis Group, UK. He is a Fellow of the Institution of Engineers (India) and a Fellow of the International Society for Engineering Asset Management. He is a member of the editorial board of the International Journal of Pavement Research and Technology and the Infrastructure Asset Management Journal from ICE publishing.