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Development of a Budget-Prioritized Pavement Management System based on Engineering Criteria

Suraj Gowda[1], Sumit Jain[2], K. S. Patil[3], Krishna Prapoorna Biligiri[4+], and B. E. Prabhakar[5]

Abstract: The main objective of this study was to develop a budget-prioritized pavement management system (BpPMS) capable of selecting the most appropriate maintenance activities considering the corresponding cost-based priority for pavement maintenance and rehabilitation in Bangalore city, State of Karnataka, India. A total of 69 km of arterial roadway stretch covered with asphalt concrete pavements in one of the six zones of the city was used for pavement condition assessment and development of pavement condition indices. Since there were no previous records of pavement condition assessment, engineering criteria was recommended and developed based on the prevalent field conditions and pavement distresses. The pavement condition parametric indices were estimated using the engineering criteria based threshold indices, which were used as major inputs in the development of a BpPMS computer program. A unique feature of the ranking-prioritization based system toolkit is that it helps an agency to prefer to maintain only selective roadway network sections that are in dire need of maintenance and plan to defer actions for the rest of the sections as part of future maintenance. Overall, the approach taken in this study is a promising assessment concept which will aid an agency to implementing a network level BpPMS for the best upkeep of the region's roadway infrastructure that would deteriorate otherwise owing to monetary constraints.

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Introduction

A good roadway network is absolutely essential for the development of any country. Pavements are the most frequently used mode of transportation in the world. With the major issues relevant as regards pavement condition; pavement performance assessment and maintenance is absolutely essential without which pavements will deteriorate well before the end of their design lives. The surface condition of a pavement section at any given time reflects the degree of damage caused by traffic and environmental conditions. More so, traffic and environmental parameters are useful in predicting the remaining service life of a pavement. Based on the prediction, the appropriate maintenance and rehabilitation strategies can be recommended. A comprehensive system tool that can assist the roadway engineers in making appropriate decisions to maintaining the network of roads in a given region over a period of time is termed Pavement Management System (PMS). In other words, PMS is a toolkit that helps an agency to maintain a network of safe and serviceable pavements in a cost-effective manner. When most agencies refer to the term PMS, it usually means a computerized system where pavement condition information is stored, analyzed, and represented along with the maintenance strategies and cost recommendations.

While the database is the central hub of a PMS, it is not useful unless it is presented in a meaningful way. As early as 1980s, Kulkarni *et al* [1] developed a PMS optimization algorithm for Arizona Department of Transportation using large mainframes which helped organize data, estimate indicators of the Arizona State road network, and recommend pavement rehabilitation strategies. With the advent of new technologies and sophisticated computer tools, large mainframes gave way to smaller but faster computers that could handle huge amount of data through the later years. During the mid-1980s until the early 1990s, researchers at the Illinois Department of Transportation developed the Illinois Pavement Feedback System and the Illinois Roadway Information System to basically collect and store roadway inventory and condition data as well as assess and predict future performance of the existing roadway sections through the development of pavement condition models [2, 3].

Since the late 1990s, several researchers in the United States of America formulated computer-assisted methodologies which could be used to address the pavement condition database for developing refined deterioration models and PMS tools [4-7]. Recently, researchers also assessed the influence of the different pavement preservation treatments on pavement surface characteristics such as friction and its long term performance [8, 9].

In Europe, PMS consisting of three basic modules: a road network database; a quality evaluation tool; and a decision-aid tool to minimize the expected agency discounted costs of pavement management strategies have been developed over the last three decades [10-12]. These PMS tools provided a generic framework for combining the systematic collection of data with the

[1] SECON Private Limited, Plot No.147, 7B Road, Export Promotion Industrial Park (EPIP), Whitefield, Bangalore, Karnataka 560 066, India.
[2] L & T Constructions (Transportation Infrastructure IC), Mount Poonamallee Road, Manapakkam, P.B. No.979, Chennai, Tamil Nadu 600 089, India.
[3] Department of Civil Engineering, SRM University, Modi Nagar, Delhi NCR 201 204, India.
[4] Indian Institute of Technology Kharagpur, West Bengal 721 302, India.
[5] Bruhat Bengaluru Mahanagara Palike, Bangalore, Karnataka 560 001, India.
[+] Corresponding Author: E-mail kpb@civil.iitkgp.ernet.in
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decision-making processes necessary to optimize resources for the maintenance and renewal of pavements, including the generation of programs of works and corresponding budgets. Furthermore, advanced optimal signal processing algorithm for pavement inspection was developed by researchers to assess pavement damage that may be used in road management [13].

The researchers in Australia and New Zealand also developed and implemented national PMS in the respective countries taking into account the current pavement conditions and cost strategies required for repair and rehabilitation of the deteriorated pavements [14-16].

In the Asian region, researchers have produced effective PMS tools that have managed projects of a PMS with limited budgets for historically managed roadway networks [17-20]. The systems are based on the optimization techniques that help prioritize the maintenance activities of the different pavements evaluation criteria of pavement serviceability and structural strength of the pavements with optimization techniques to prioritize the maintenance activities.

In the Indian context, the disparity between the growth of the road network and the growth in the number of registered vehicles has resulted in the shortfall of roadways' function and structural capacity to sustain high magnitude stresses imposed by heavier axle loads and ultimately premature failure of pavements [21]. It is noteworthy that India has one of the largest roadway network systems in the world with a total length of 4.7 million km of classified roads. However, very limited research has been conducted in India with regard to the development and implementation of PMS. Researchers have conducted distress surveys to check for major pavement distresses along rural and urban roads in India, and used Pavement Condition Index (PCI) as a parameter to assess the conditions of the deteriorated roads [22-27]. As part of these studies, pavement performance models were either developed or used from other sources such as the highway development and management (HDM-4) software tool to understand the structural capacity of the deteriorated roads. However, currently, there is no budget-prioritized PMS which will help an agency entrusted to construct and maintain roads to easily implement at the state or national level. Furthermore, there is a need to develop a PMS that covers a simple priority lists based on engineering judgment to complex budget-based optimization algorithms.

In essence, the components of PMS are fundamentally identification of pavement distresses through extensive surveys and/or prediction models for future forecast, provision of alternative maintenance and rehabilitation strategies, and corresponding budgetary allocations for a specific project. To accomplish these tasks, several analytical procedures are required, which considers time series analyses. However, this is possible if and only if field observations are made over several years and recorded. For an agency that is in the initial stages of PMS development, the procedure will become intricate and rather impossible to develop quantitative prediction equations to capture pavement distresses and corresponding maintenance alternatives. Consequently, in these situations, due to lack of historical data, techniques that can utilize engineering criteria to estimate pavement conditions and corresponding maintenance strategies will certainly need to be developed based upon current pavement performance characteristics and traffic conditions. Furthermore, for the agencies that have limited budget or constraints in general, prioritization of maintenance strategies owing to those road sections that require utmost attention becomes necessary to be applied first than those that have just started to show signs of deterioration.

Research Objectives and Scope of the Effort

The main purpose of this study was to develop a PMS program (toolkit) for an arterial roadway network capable of selecting the most appropriate maintenance activities considering the corresponding budgetary priority for pavement maintenance and rehabilitation in Bangalore city, State of Karnataka, India. It is important to note that at present, there is no PMS with the Bangalore city corporation (called Bruhat Bengaluru Mahanagara Palike or BBMP). In addition, since there were no historical data showing past records of maintenance and rehabilitation of the road stretches, the PMS was developed using engineering criteria and budget prioritization techniques. The approach taken in this study is first of its kind within the framework of PMS research and development in India. Furthermore, the developed program is capable of providing appropriate maintenance treatments at appropriate time scales to defer the rate of pavement deterioration, thus reducing the overall maintenance costs. The scope of the effort included:

- Review of the existing literature pertinent to PMS and corresponding software tools at both national and global levels
- Identify and select pavement locations of a zone in the City of Bangalore where the identified locations will be representative of the local community's generic pavement deterioration patterns, i.e., at the ward (project) level
- Collect and develop a PMS database for the selected locations, including: pavement type, pavement condition assessment using manual survey, and traffic patterns
- Establish a methodology to estimate the PCI for the selected road sections based on engineering criteria; estimate and incorporate PCI into the PMS database
- Recommend maintenance alternatives and/or rehabilitation strategies where appropriate based on the estimated PCI
- Define the costs associated with the maintenance alternatives for each section
- Formulate and develop the budget constrained prioritization based PMS tool
- Recommend the devised approach to advance it to a network level for the city

Study Design Methodology

The PMS tool developed in this study was designed and formulated encompassing collection of the pavement distress data, adopting and setting the engineering criteria to estimate PCI, assigning the corresponding maintenance strategies and prioritizing maintenance work based on the budgetary constraints. Note that this PMS was developed keeping in mind the local conditions, distress types of the existing pavements, and available resources for maintenance. Therefore, this tool or the algorithm by itself may have to be adjusted for local conditions for efficient functioning of the program elsewhere. The details of the design methodology of this study are presented next.

Methodology

The study methodology outline is shown in Fig. 1. As illustrated, the PMS study methodology included the development of a pavement condition information database, which was established in such a way to store the information needed for good pavement maintenance decision making. It included a pavement condition survey to identify the major distresses and related surface characteristics. Once the database was established, the data was used for analysing each street (between intersections or shorter where necessary), major or minor maintenance identification, ranking the maintenance work, and prioritizing these maintenance works based upon different funding scenarios. Various methods are available which could be effectively used to prioritize a system such as ranking, optimization, artificial intelligence techniques and analytical hierarchy process [28-30]. Specifically for this study, ranking method based strategy for maintenance of arterial roads for a particular zone in Bangalore city was formulated. The ranking of pavement sections for maintenance was accomplished based on the priority index calculated by combining different pavement condition indices. These indices were estimated by considering parameters such as pavement distresses, ride quality, traffic, geometric details, and engineering judgement. The following sections illustrate the methodology adopted in the study to develop a budget-prioritized PMS.

Distress Identification

Table 1 was prepared using the criteria listed in [31]. As seen in the Table, a total of 12 major asphalt concrete pavement distresses were identified and grouped under three categories: cracking, surface and support. Pavement distress extent and severity were also measured with the help of guidelines presented in the manual.

Engineering Criteria based PCI

PCI is a numerical rating of the pavement condition that ranges from 0 to 100 with 0 being the worst possible condition and 100 being the best possible condition [31]. Although PCI can be estimated using the American Society for Testing and Materials standard [32] charts and equations or through expert judgment based on an opinion survey that complements the existing data [29]; engineering criteria and judgment was adopted in this study to estimate PCI owing to the uncertainty of the ASTM procedure to suit the actual field site conditions in Bangalore, India as well as lack of historical records of pavement distress surveys, and dearth of pavement management experts in the region. In the engineering criteria based PCI estimation process, a primary decision criterion called threshold deduct value is established that indicates at what distress level an action would be required at a particular severity and extent level for a specific distress type. The deduct value (DV) for that level of distress should be such that the resulting PCI would be about the midpoint in the index range (say 50 in the range of 0 and 100). The threshold value beyond which, the condition of the pavement is considered unacceptable. Once threshold values are decided, DVs for the different distresses are obtained with which PCI can be calculated. The step-wise procedure used to obtain the PCI for each roadway segment based on the engineering criteria is listed under:

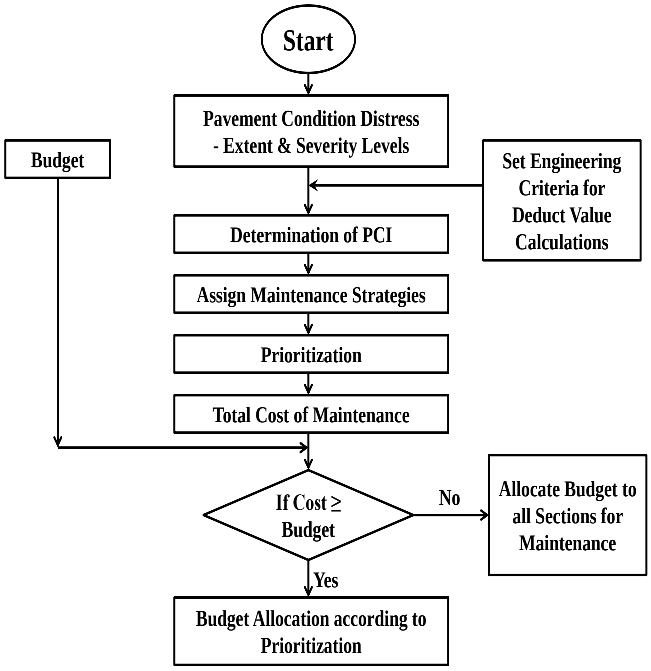


Fig. 1. Research Methodology Outline.

- Selecting index scale: index scale is a classified numerical scale (example: 0-100, 0-10, 0-5), wherein each class represents the condition of the pavement. The index scales used in the study was 0-100
- Setting threshold value: threshold value is a particular index value representing unacceptable pavement condition, typically taken as middle value of an index scale, such as 50 for 0-100 index scale used in the study
- Setting engineering criteria: is fundamentally based on the extent and severity of the distresses for the whole network of the study area under investigation. It depends on the network's distress levels (severity and extent) which are considered unacceptable. In simple words, once distress crosses these levels then action is to be taken to correct it. Numerically, these levels may or may not be different for various types of distresses. However, each distress had a specific criterion defined to it in this study for easy investigation
- Developing plots of deduct values versus extent of distress: relationship between deduct values (on y-axis) and extent of distress (on x-axis) for all the different distresses were drawn. For a particular distress type, all the three severity levels (i.e., low, moderate and high) started at 0 and passed through the threshold value of 50 since index scale considered was 0-100. The same procedure was repeated for the other distresses
- Estimation of PCI: after all the DVs in a particular segment of a road were estimated, they were totaled and the final resulting PCI was equal to 100 – $\sum$DV

It is very important to note that the PCI and the DV curves of the specific distresses obtained in this study may not be similar to the ones listed in the FHWA distress manuals and included in the ASTM standard. However, the study does not mean to redefine the fundamental principles of obtaining PCI.

Table 1. Major Asphalt Concrete Pavement Distress Identification Criteria Based on [31].

	Type	Severity			Remarks
		Low	Moderate	High	
CRACKING	Fatigue / Alligator (sq. m.)	An area of cracks with no or only a few connecting cracks	An area of interconnected cracks forming a complete pattern	An area of moderately or severely spalled interconnected cracks forming a complete pattern	Many sided sharp edge pieces, In Low & Moderate Pumping is not evident but it is in high
	Block (sq. m.)	Cracks with a mean width 6 mm	Cracks with a mean width > 6 mm & <= 19 mm	Cracks with a mean width > 19 mm	Rectangular blocks ranging from 0.1 to 1 m^2
	Edge / Random (m / sq. m.)	Cracks with no breakup or loss of material	Cracks with some breakup & loss of material for up to 10 % of the length of the affected portion	Cracks with considerable breakup & loss of material for more than 10 % of the length of the affected portion	Located within 0.6 m of the pavement edge
	Longitudinal (m)	A crack with a mean width 6 mm	Cracks with a mean width > 6 mm & <= 19 mm	Cracks with a mean width > 19 mm	Cracks predominantly parallel to pavement centerline
	Transverse (m)	A crack with a mean width 6 mm	Cracks with a mean width > 6 mm & <= 19 mm	Cracks with a mean width > 19 mm	Cracks predominantly perpendicular to pavement centerline
SURFACE	Weathering / Raveling (sq. m.)	Very little coarse aggregate has worn away some loss of fine, coarse aggregate is exposed	Surface has an open texture.Considerable loss of fine and some coarse aggregate	Most of the surface aggregate has worn away. Surface is severely rough and may be completely removed in places	Raveling should not be rated on chip seals
	Bleeding (sq. m.)	Free bitumen is slightly noticeable at the pavement surface	Both coarse aggregate and free bitumen are noticeable at the pavement surface	Surface appears black with very little aggregate noticeable	
	Patching (number & sq. m.)	Patch area with any low severity distress including rutting <= 6 mm	Patch area with any moderate severity distress including rutting > 6 & <= 12 mm	Patch area with any High severity distress including rutting > 12 mm	Patch Area >= 0.1 m^2
	Potholes (number & sq. m.)	<=25 mm deep	> 25 mm to <= 50 mm deep	> 50 mm deep	Minimum plan dimension is 150 mm
SUPPORT	Rutting (mm)	Depth <= 6 mm	Depth > 6 mm & < 25 mm	Depth >=25 mm	Longitudinal surface depression in the wheel path
	Shoving / Corrugations (sq. m.)	Noticeable effect on ride but no effect on comfort	Moderate ride discomfort is noticeable and driver can easily control the vehicle	Vehicle vibration is severe, speed reduction is necessary for comfort and to maintain vehicle control	Generally caused by braking or accelerating vehicles
	Settlement (m)	Noticeable effect upon ride, driver able to maintain vehicle control easily	Some discomfort to passengers, driver able to maintain control	Definite effect upon ride quality; Profile dip > 150 mm	Settlement should not be confused with corrugation

Pavement Maintenance Strategy

Once the pavement is constructed and opened to traffic, the life of the pavement starts diminishing. In other words, life decreases as deterioration increases. For this reason, strategies are proposed considering the budgetary constraints so as to extend the life of a pavement. Although several types of pavement maintenance strategies were suggested in this study as will be listed later on, all of them were grouped under three major types of pavement maintenance strategies: (a) preventive maintenance using surface treatments and operations intended to retard progressive failures; (b) corrective maintenance mainly performed after a deficiency occurs in the pavement, and (c) complete rehabilitation performed after extensive severity in distresses are found in a segment.

Costs of Maintenance

In the present study, cost for maintenance was calculated from the schedule of rates prepared by BBMP for the current year as listed in [33]. This unit cost was used to estimate the actual maintenance costs for each distress and a particular segment. In this way, the total cost of the project location was estimated for each corresponding maintenance strategy. The use of the unit costs is presented in later sections.

Data Collection

Based on the roadway network system, the City of Bangalore in India is divided into six zones covering a total of approximately

Table 2. Summary of Flexible Pavement Distress Evaluation of the 69 km Roadway Segments.

Section	Width (m)	Lanes	Major Distresses	Ride Quality	PCI
1	14	4	Rav, Po	4	98
2	4.5	2	B, Pa, Po	4	85
3	4.5	2	EC, Rav, B, Po	3	81
4	3.5	1	FC, EC, Rav, B, Pa, Po	2	39
5	12	4	Rav, Po	4	92
6	10	2	Rav, B	4	99
7	4.5	2	EC, Pa, Po, Se	3	93
8	3.5	1	FC, EC, BC, Rav, Po, Se	2	30
9	9	2	EC, Rav, Po	3	91
10	3.5	1	EC, Pa, Po, Se	3	78
11	3.5	1	EC, Pa, Po, Se	4	78
12	3.5	1	EC, Pa, Po, Se	4	89
13	3.5	1	EC, Pa, Po	4	93
14	14	4	FC, LC, Rav, Pa	4	81
15	10	2	FC, Rav, Pa, Po, Cor, Se	3	71
16	14	4	Rav	4	99
17	15	4	Rav, Pa, Po	4	84
18	10	2	Rav, Pa, Po	4	91
19	9	2	FC, LC, TC, Rav, Pa, Po, Se	3	48
20	10	2	Rav, Pa	4	93
21	10	2	TC, Rav, Pa, Po	4	82
22	5.5	2	LC, Rav, Pa, Po, Se	2	39
23	12	4	Rav, Po	3	91
24	7	2	FC, EC, LC, Rav. Pa, Po	3	77
25	5	2	FC, EC, LC, Rav, Pa, Po	3	34
26	9	2	LC, Rav	4	92
27	9	2	Pa	4	99
28	4.5	2	FC, Rav, Pa, Po	1	51
29	4.5	2	FC, Rav, Pa, Po	2	60
30	7	2	Rav, Pa, Po	2	83
31	6	2	Rav, Pa	4	89
32	7	2	FC, Rav, Pa, Po	3	46
33	7	2	LC, Pa, Po	3	88
34	5.5	2	FC, LC, Rav, Pa, Po, Rut, Se	1	26
35	5	2	FC, LC, Rav, Pa, Po, Se	1	11
36	5	2	LC, Rav, Pa, Po, Rut, Se	2	54
37	5	2	LC, Rav, Po, Rut, Se	1	65
38	5	2	FC, Rav, Pa, Se	4	86
39	8	2	Rav, Po	4	93
40	8	2	TC, Rav, Pa	3	67

Legend: FC: Fatigue Cracking; EC: Edge Cracking; LC: Longitudinal Cracking; TC: Transverse Cracking; BC: Block Cracking; Rav: Ravelling; B: Bleeding; Pa: Patching; Po: Potholes; Rut: Rutting; Cor: Corrugations; Se: Settlement.

1940 km, including, 923 km of arterial road length and 1017 km of sub-arterial roads. Almost 98% of the roadway stretches are covered with asphalt concrete pavements with only certain pockets overlaid with cement concrete. In this study, one of the six zones: Byatarayanapura-Dasarahalli was considered for pavement evaluation and subsequently for the development of PMS. Byatarayanapura-Dasarahalli zone consists of 25 stretches of arterial roads covering approximately 309 km and 38 stretches of sub-arterial roads encompassing approximately 166 km. Out of the 166 km of sub-arterial roads, 69 km of roadway length was selected for this pilot study as this network covered Byatarayanapura area in the combined Byatarayanapura-Dasarahalli zone. Note that the selected roadway sections were overlaid with only asphalt concrete flexible pavements and cement concrete rigid pavements were not present in the total network zone.

As part of the preliminary data collection, the details pertinent to roadway geometry, maps, number of lanes, and approximate traffic counts were collected and assembled in the database. Further, based on the flexible pavement distress type, severity, and extent, pavements were evaluated for their distress conditions using the prepared survey sheet. The survey summary sheets provided three broad pavement distress elements, which are based on cracking, surface and support related distress types. Further, each distress element comprised of different distresses under the group with low, moderate and high severities and percent area of extent of the distress.

In total, the 69 km roadway network was compiled into forty different roadway segments and a thorough pavement distress evaluation was undertaken for each segment separately using the survey sheet through visual manual surveys. Based upon the severity and extent magnitudes of the different pavement distresses, PCI was estimated for each roadway segment using engineering criteria as will be illustrated in the following section. Table 2 presents a summary of the flexible pavement distress evaluation of the 69 km roadway segments, including: roadway section identification (ID), width, number of lanes, distresses recorded in each segment, visual ride quality and estimated PCI.

The obtained PCI was then included in the PMS database and the corresponding maintenance strategies were accorded. The unit costs for each maintenance strategy were obtained from BBMP to calculate the total cost of pavement maintenance, which is shown in Table 3. The estimation of PCI, provision of the corresponding maintenance strategy and budgetary allocation for maintaining the roadway network for future from both total expenditure and budget-prioritization perspectives are documented next.

Budget-Prioritized Pavement Management System (BpPMS) Program

The PMS tool developed in this study consists of five distinct modules: a road network database, a quality pavement distress evaluation system, suitable maintenance strategies, total cost expenditure, and prioritization of maintenance work provided budgetary constraints. The BpPMS program was developed using the Microsoft® Excel platform. The salient features of the program are as follows:

- Domain: provides a systematic and consistent approach to evaluate the present surface condition of each pavement segment under investigation
- Function: helps determine the proper type of maintenance strategy according to the pavement condition level and distress types
- Outcome: aids in prioritizing the necessary repairs and/or rehabilitation within the roadway project level network

The following sections describe the chronology of the development of the PMS program along with the step-wise procedure to use the tool to determine the pavement condition and corresponding cost-associated maintenance strategies

Estimations of Engineering Criteria based PCI

A comprehensive pavement condition evaluation was conducted prior to the development of the PMS program. As already mentioned, the condition evaluation involved determining the types, severity and extent of all pavement distresses in the roadway network. The collected raw data was used to estimate the PCI purely based on engineering criteria. Table 4 shows the summary of the deduct values for the different distresses, which were used in drawing relationships between deduct values and the extent of distresses for each type of distress found during visual pavement evaluation. Note that deduct values were estimated for lower than 1% extent also mainly since there were many segments which had very low extent of distress. To avoid incorrect estimations of the final PCI, two lower extents (0-0.5% and 0.5-1%) were also considered for each distress type.

Figs. 2, 3 and 4, respectively, present the engineering criteria set, respectively for cracking, surface and support types of distresses found in the study roadway network. As mentioned earlier, y axis represents deduct values and x axis represents the relative area of the extent of the distress. Different textured lines represent severity levels of the distress and threshold is set as 50 as it was decided that beyond this value the condition of pavement will be unacceptable. The y versus x relationship in each Figure is used in the PMS modules to calculate the deduct values for extent and severity for a particular distress type. Using the engineering criteria deduct values (Table 4), PCI for each road segment was calculated whose final estimates are shown in Table 3.

Provision of Suitable Maintenance Strategies

Using the estimated PCIs for each road segment, suitable maintenance strategies were suggested based on the observed distress extent and severity levels. The generic suggested maintenance strategies for the distresses corresponding to extent and severity levels used in the study is shown in Table 5. It should be noted that all the strategies mentioned here are subjected to changes based on the availability of the sources and also on final decision by the engineer-in-charge of the site. However, a provision was provided in the developed PMS program wherein the user would be able to choose his/her choice of the maintenance strategy, whose details are provided in the next section. The basis for the provision of the suggested maintenance strategies in this study was formulated from the general considerations documented using engineering criteria and costs that were obtained from the schedule of rates from BBMP mentioned earlier.

BpPMS Software Program

BpPMS database and software program created in this study mainly comprises of the asphalt pavement evaluation distress summaries for forty roadway segments covering 69 km, deduct values and PCI estimations using engineering criteria for each of the forty sections, corresponding suitable pavement maintenance strategies and cost estimations to maintain the deteriorated roadways. Thus, the BpPMS program consists of the following components. A total of 100 separate raw pavement distress evaluation worksheets were prepared in the program as input summaries. Several other worksheets were assigned for estimations of PCI, maintenance strategy recommendation and cost allocation for each strategy in the roadway network. Each pavement evaluation input worksheet consists of section inventory details which includes length and width of the section, pavement temperature, street identifications, ride quality index and pavement maintenance rating. The user will be able to enter the pavement distress extent details based on the severity of each distress. Once this step is complete, the program is capable of automatically calculating the deduct values for each distress. Simultaneously, the PCIs are estimated for each segment and correspondingly a suitable condition rating is assigned. Further, the program will automatically suggest various maintenance strategies for the identified distresses and the total cost for maintenance corresponding to each distress extent area are determined. The following subsections enlist the various modules of the BpPMS program developed in this study.

Module 1: Instructions

The first module of the BpPMS consists of the standing instructions given to the user to navigate through the various inputs and outputs for a pavement network. An important note is coded with yellow colour in the program, which basically states that only those cells that are yellow

Table 3. Unit Costs of Maintenance Strategies Used as Input in the Study [33].

Maintenance Strategy	Units	Cost in Indian Rupees*
Dusting	sq. m.	1
Crack Filling	m	3.4
Crack Seal	sq. m.	7
Fog Seal	sq. m.	15
Single Chip Seal	sq. m.	38
Slurry Seal	sq. m.	38
Double Chip Seal	sq. m.	52
Thin Patching	sq. m.	90
Thick Patching	sq. m.	140
Micro Surfacing	sq. m.	165
Thin Overlay	sq. m.	190
Thick Overlay	sq. m.	457
Reconstruction	sq. m.	815

**1 INR = 0.020 USD*

coded are used as inputs and the rest of the other cells are automatically generated. Examples of inputs are raw data of pavement condition obtained from visual inspection, user priority maintenance strategies, unit costs for maintenance strategies, and annual amount allocated for maintenance by an agency.

Module 2: Raw Data

The second module of the BpPMS consists of raw data sheet embedded for 100 different segments in the roadway network in the survey sheet. In the raw data sheets, the manually calculated distress extent values could be entered in the cells corresponding to their severity level, which are based on visual inspection for each type of distress. Once the raw data is input for all the segments in the project, by default the program suggests the user to carry out a particular maintenance strategy specific for a distress with any severity and classified extent levels. Based on the user inputs and for a chosen specific maintenance strategy, the program then calculates the maintenance cost to be incurred by the user and/or agency for the section(s) under consideration. For example, for an input 4% extent level against fatigue / alligator cracking under 0-5% extent level, the program by default gives a maintenance strategy to be Crack Seal that costs Indian Rupees 5997.60 under the maintenance strategies recommended and cost of maintenance columns. It is important to note that in the same sheet, deduct values are also estimated that are directly taken from a spreadsheet embedded in the program based on the summary shown in Table 4.

Module 3: Maintenance Strategy

The third module consists of different components of maintenance strategy used in the BpPMS program. The details of the sub-modules are provided as under.

- *User priority maintenance strategy*: In case the user is not satisfied by the strategy defined by the program (module 2), a user priority maintenance strategy could be chosen from the drop-down menu provided by the program. By choosing the appropriate strategy, the user may be able to curtail the expenditure on the maintenance work subject to the availability of funding. An example calculation is shown in Fig. 5(a). As observed, in row 7 of the calculation sheet, the program by default suggests the user to adopt crack seal maintenance but if the user is not satisfied with this strategy, then another of the strategies could be chosen appropriately from the drop-down box shown as Author: 0, 1, 2, 3 for None, Crack Filling, Crack Seal and Thin Overlay, respectively.
- *Maintenance type*: As mentioned in Section 2.4, three major types of maintenance strategies are commonly adopted for any project. In the BpPMS program as well, once the raw data for a particular roadway section is entered, the program calculates PCI and corresponding maintenance type. For the maintenance type (here: corrective maintenance), the pavement condition (here: poor) is also displayed as shown in the Fig. 5(b).

Module 4: Zone Summary

The fourth module of the BpPMS presents the total cost of maintenance for all the roadway segments in the project. While Fig. 5(b) showed the cost of maintenance for a single segment, the total costs estimated for all the segments are shown in Fig. 6(a) depicted as zone summary module. This particular module of the program includes the default total cost as well as user defined total cost for all the sections along with the estimated PCI and pavement condition. Note that the Fig. 6(a) shows the zone summary cost for all the 40 sections considered in this study.

Module 5: Reconstruction

One of the salient features of the BpPMS program is that the tool helps the user to prioritize if a section completely needs to be reconstructed considering it being given the utmost importance than relatively lesser problematic sections in the network. Thus, a provision has been made in the program to calculate the cost of reconstruction involved in these types of low PCI sections. Fig. 6(b) shows the estimates of reconstruction cost for certain sections that need a complete rehabilitation maintenance.

Module 6: Budget Constraint Prioritization

Huge sums of money are required for total restoration of the road network. Hence, an agency would normally prefer to maintain few sections of a network in the first year and rest in the subsequent years depending on which of the sections require immediate attention. This prioritization process has been considered while developing the program mainly so the agency decides how much

Table 4. Total Deduct Values Based on Engineering Criteria Developed in the Study.

	Distress Types	Severity		Total Deduct Values					
				0-0.5%	0.5-1%	1-5%	6-25%	26-50%	51-100%
Cracking	Fatigue/Alligator (Square Meters)	1	Low	0.1	0.4	1	9	21	42
			Moderate	0.5	1.5	5	31	76	100
			High	0.8	0.8	8	52	100	100
	Edge/Random (Meters/Square Meters)	2	Low	0.1	0.4	2	9	21	42
			Moderate	0.4	1.3	5	26	63	100
			High	0.6	1.9	8	39	95	100
	Longitudinal (Meters)	3	Low	0.1	0.4	1	8	19	39
			Moderate	0.3	0.9	3	19	48	94
			High	0.6	1.9	6	39	95	100
	Transverse (Meters)	4	Low	0.1	0.4	1	8	20	40
			Moderate	0.3	0.8	3	16	38	76
			High	0.5	1.5	5	31	76	100
	Block (Square Meters)	5	Low	0.1	0.4	1	8	20	40
			Moderate	0.3	0.8	3	17	42	84
			High	0.5	1.5	5	31	76	100
Surface	Raveling (Square Meters)	6	Low	0.1	0.4	1	8	20	40
			Moderate	0.3	0.8	3	16	38	76
			High	0.4	1.3	4	26	63	100
	Bleeding (Square Meters)	7	Low	0.1	0.4	1	8	19	38
			Moderate	0.2	0.6	2	13	32	63
			High	0.3	0.8	3	16	38	76
	Patching (Number and Square Meters)	8	Low	0.1	0.4	1	8	19	39
			Moderate	0.2	0.6	2	13	32	63
			High	0.4	1.1	4	22	54	100
	Potholes (Number and Square Meters)	9	Low	0.2	0.6	2	13	32	63
			Moderate	0.6	1.9	6	39	95	100
			High	1.0	3.1	10	65	100	100
Support	Rutting (Milimeters)	10	Low	0.1	0.4	1	8	21	41
			Moderate	0.3	0.9	3	19	48	94
			High	0.5	1.5	5	31	76	100
	Shoving / corrugations (Square Meters)	11	Low	0.1	0.4	1	8	20	39
			Moderate	0.2	0.7	2	14	35	69
			High	0.3	0.9	3	19	48	94
	Settlement (Meters)	12	Low	0.1	0.4	1	8	20	40
			Moderate	0.3	0.8	3	17	42	84
			High	0.4	1.3	4	26	63	100

Table 5. Generic Suggested Maintenance Strategies for the Distresses Corresponding to Extent and Severity Levels used in the Study

Distress	Extent		0 - 25%	26 - 50%	51 - 100%
Fatigue/Alligator (Square Meters)	1	Low	Crack Seal	Crack Seal	Thin Overlay
		Moderate	Single Chip Seal	Single Chip Seal	Thick Overlay
		High	Thick Patching	Reconstruction	Reconstruction
Edge/Random (Meters/Square Meters)	2	Low	Crack Filling	Crack Filling	Single Chip Seal
		Moderate	Crack Filling	Single Chip Seal	Single Chip Seal
		High	Thick Patching	Micro Surfacing	Micro Surfacing
Longitudinal (Meters)	3	Low	Crack Filling	Crack Filling	Single Chip Seal
		Moderate	Crack Filling	Thin Patching	Thin Overlay
		High	Thick Patching	Thick Overlay	Thick Overlay
Transverse (Meters)	4	Low	Crack Filling	Crack Filling	Single Chip Seal
		Moderate	Crack Filling	Thin Patching	Thin Overlay
		High	Thick Patching	Thick Overlay	Thick Overlay
Block (Square Meters)	5	Low	Crack Seal	Crack Seal	Chip Seal
		Moderate	Single Chip Seal	Single Chip Seal	Slurry Seal
		High	Thin Overlay	Thin Overlay	Thick Overlay
Ravelling (Square Meters)	6	Low	Fog Seal	Slurry Seal	Slurry Seal
		Moderate	Fog Seal	Slurry Seal	Micro Surfacing
		High	Slurry Seal	Thin Overlay	Thick Overlay
Bleeding (Square Meters)	7	Low	Dusting	Dusting	Dusting
		Moderate	Dusting	Dusting	Dusting
		High	Dusting	Dusting	Dusting
Patching (Number and Square Meters)	8	Low	No Maintenance	No Maintenance	Single Chip Seal
		Moderate	Single Chip Seal	Double Chip Seal	Double Chip Seal
		High	Double Chip Seal	Double Chip Seal	Double Chip Seal
Potholes (Number and Square Meters)	9	Low	Thin Patching	Thin Patching	Micro Surfacing
		Moderate	Thick Patching	Thick Patching	Thin Overlay
		High	Thick Patching	Thick Overlay	Reconstruction
Rutting (Milimeters)	10	Low	Thin Patching	Thin Patching	Micro Surfacing
		Moderate	Thin Patching	Micro Surfacing	Thin Overlay
		High	Thick Patching	Reconstruction	Reconstruction
Shoving / corrugations (Square Meters)	11	Low	No Maintenance	No Maintenance	Single Chip Seal
		Moderate	No Maintenance	Single Chip Seal	Single Chip Seal
		High	Double Chip Seal	Double Chip Seal	Reconstruction
Settlement (Meters)	12	Low	Thin Patching	Thin Patching	Micro Surfacing
		Moderate	Thick Patching	Thin Overlay	Thin Overlay
		High	Thick Patching	Thick Overlay	Reconstruction

money needs to be sanctioned immediately and for future. In this direction, the BpPMS program module 6 presents the capability of prioritizing budget maintenance work for three consecutive years. The three steps followed for yearly prioritization is listed under.

i. Enter the budget allocated for three consecutive years (Fig. 7(a))
ii. Once the budget is allocated, the PCI value which is already estimated is to be sorted in an increasing order (Fig. 7(b)).

This is done by using sort smallest to largest option present in the Microsoft® Excel options

iii. Finally, the maintenance work to be carried out in three consecutive years with the allocated money for those three years is calculated as shown in Fig. 7(c). The column highlighted in green informs the user which section should be considered yearly as well.

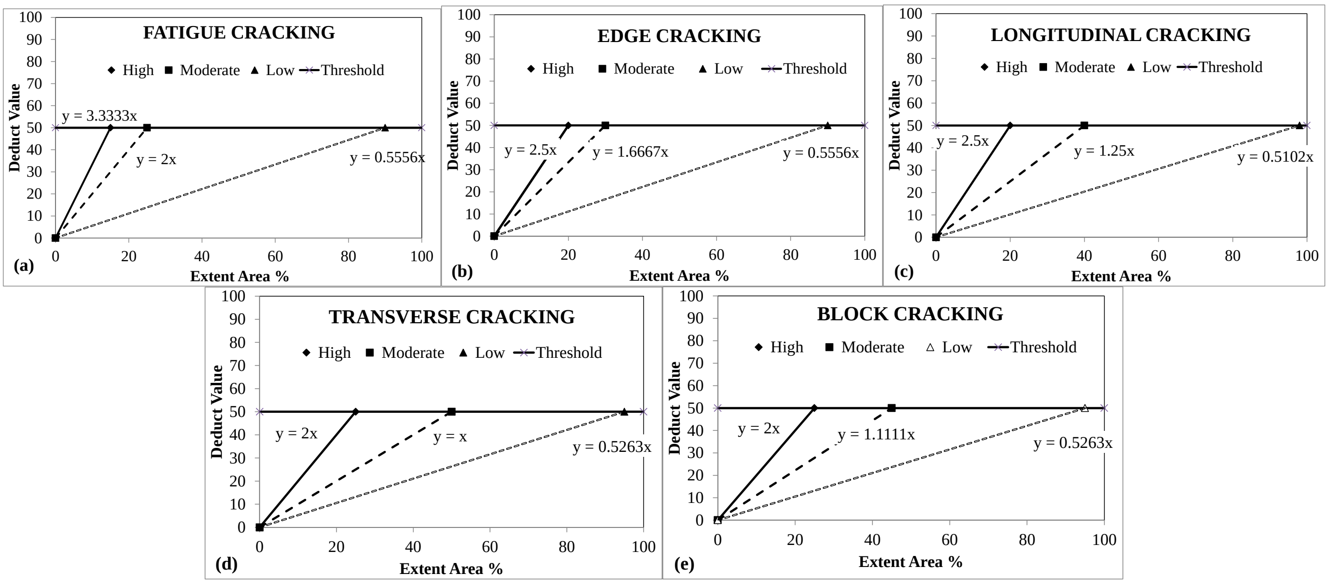


Fig. 2. Engineering Criteria for Cracking Distresses: (a) Fatigue Cracking; (b) Edge Cracking; (c) Longitudinal Cracking; (d) Transverse Cracking; (e) Block Cracking

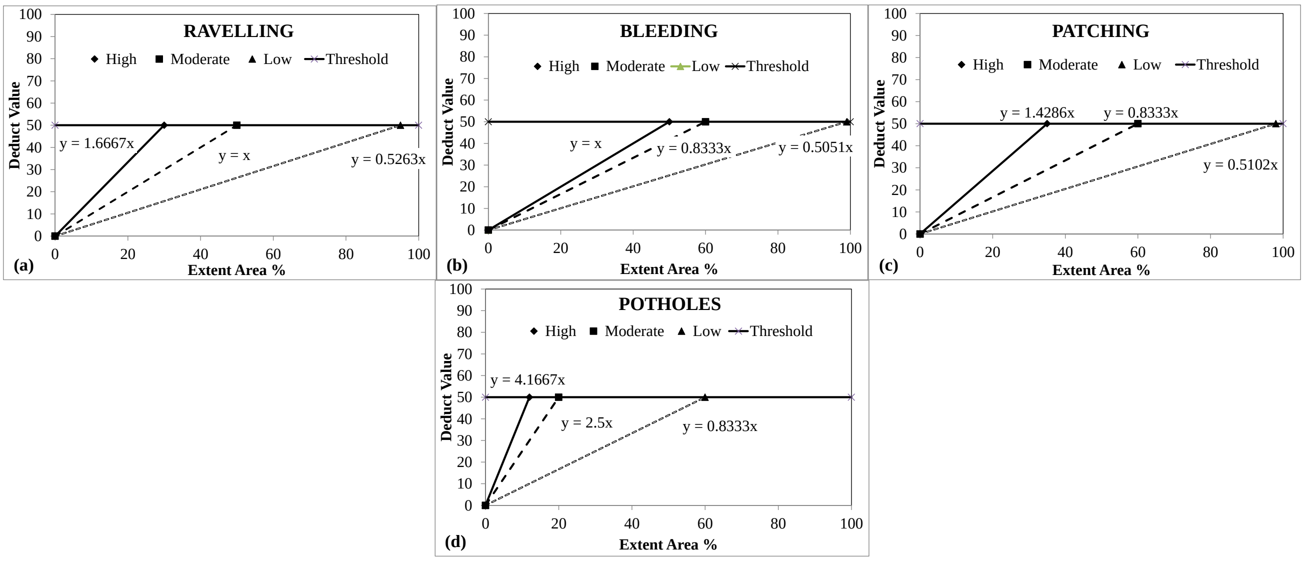


Fig. 3. Engineering Criteria for Surface Distresses: (a) Ravelling; (b) Bleeding; (c) Patching; (d) Potholes.

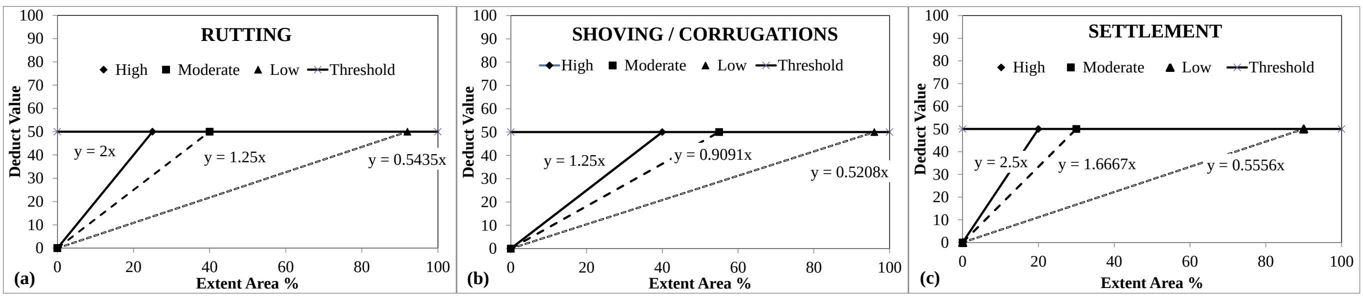


Fig. 4. Engineering Criteria for Support Distresses: (a) Rutting; (b) Shoving / Corrugations; (c) Settlement.

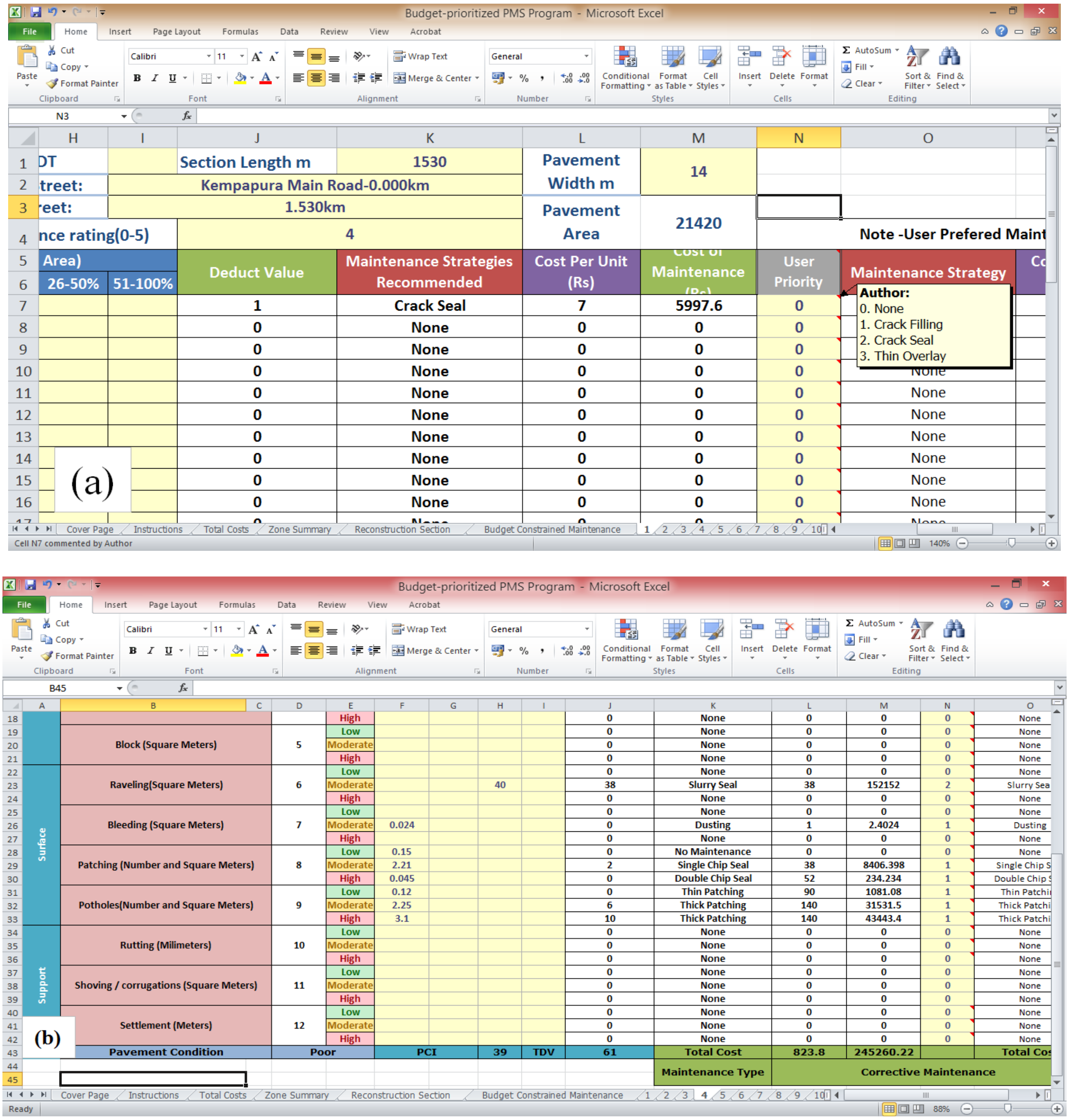


Fig. 5. Budget-Prioritized Pavement Management System Program Module 3: (a) User Priority Example, (b) Pavement Maintenance Output.

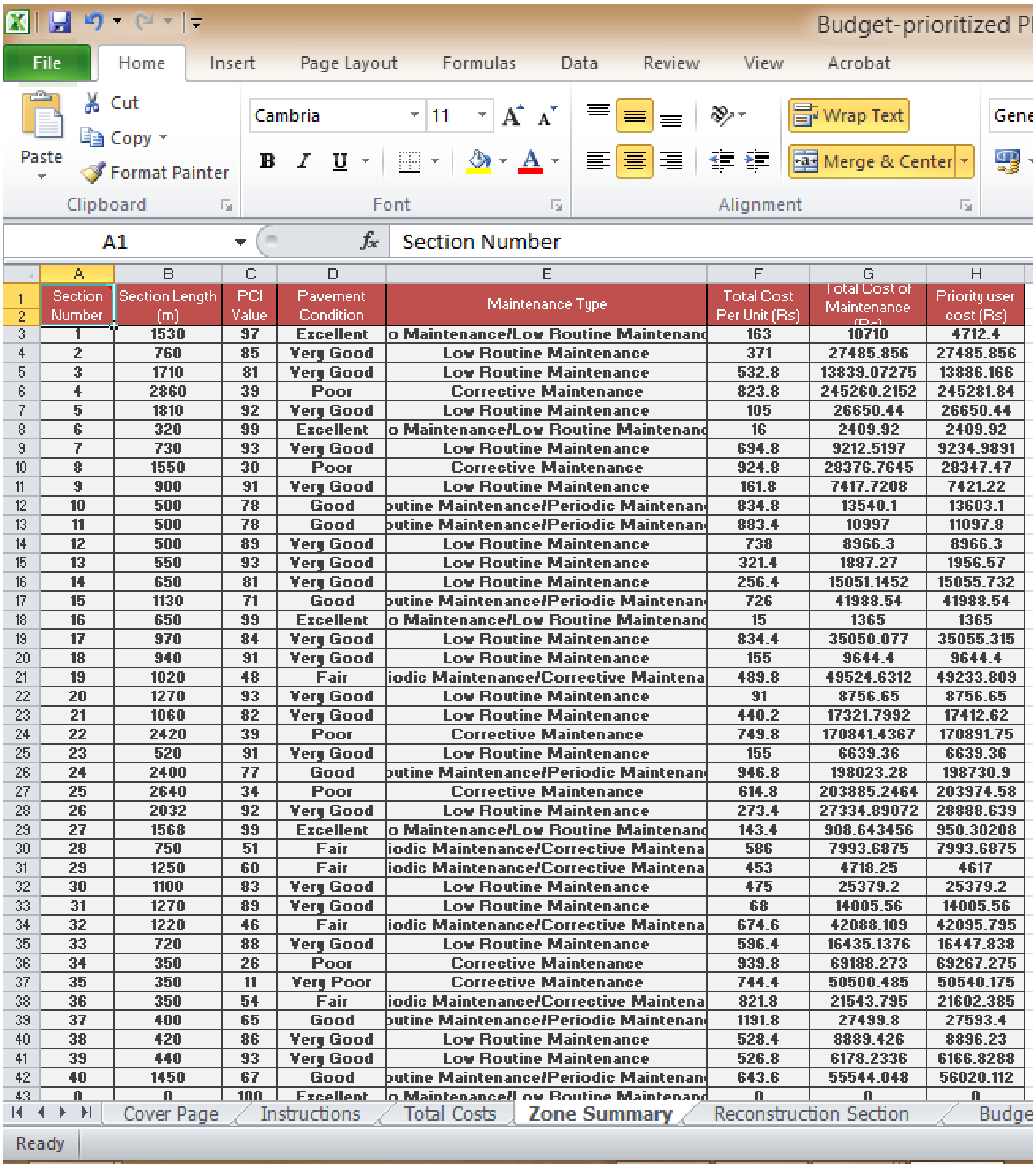
Module 7: Total Costs

The final module (module 7) of the BpPMS program displays the total cost of maintenance incurred for three consecutive years when budget is not a constraint as well as when budget is a constraint. Both default and user priority maintenance strategy based costs are also displayed in this module.

Discussion

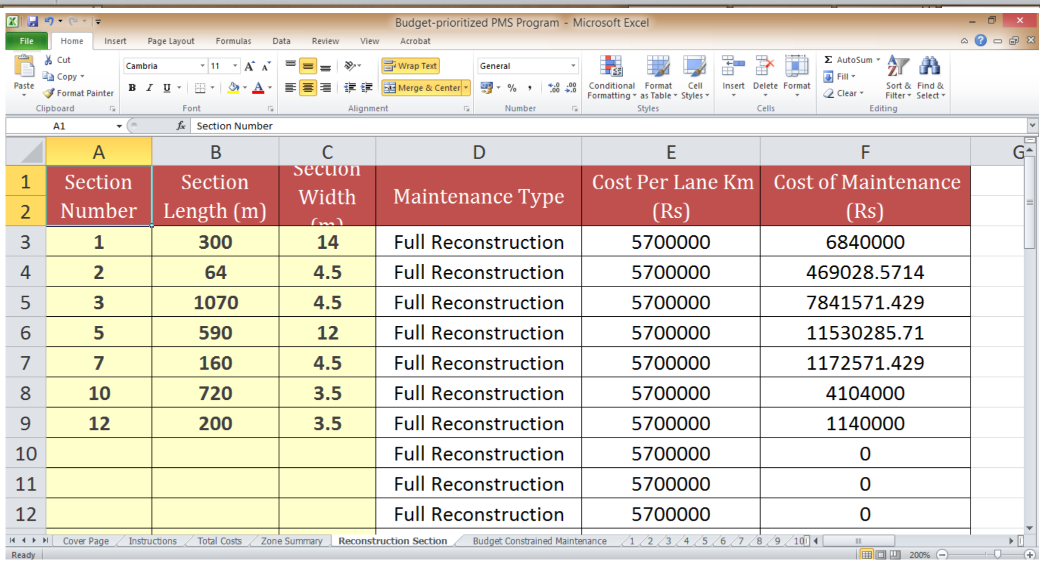
A significant and exclusive contribution of this study is that the BpPMS program could be well-utilized as a scientific tool measure towards a comprehensive assessment of the pavement conditions of roadway networks. This toolkit could be useful under the following major heads in future works in the PMS areas:

- Concept: The framework of this study by itself is practical in nature. This supports the basic theories of pavement evaluation and assessment pertinent to roadway condition characteristics. The development of this concept is truly based on visual inspection and its practical aspects. PCI, which is one of the most important pavement condition assessment parameters renders tremendous amount of information as regards pavements-related structural and functional performance characteristics. However, this parameter by itself cannot be



	Section Number	Section Length (m)	PCI Value	Pavement Condition	Maintenance Type	Total Cost Per Unit (Rs)	Total Cost of Maintenance (Rs)	Priority user cost (Rs)
3	1	1530	97	Excellent	o Maintenance/Low Routine Maintenanc	163	10710	4712.4
4	2	760	85	Very Good	Low Routine Maintenance	371	27485.856	27485.856
5	3	1710	81	Very Good	Low Routine Maintenance	532.8	13839.07275	13886.166
6	4	2860	39	Poor	Corrective Maintenance	823.8	245260.2152	245281.84
7	5	1810	92	Very Good	Low Routine Maintenance	105	26650.44	26650.44
8	6	320	99	Excellent	o Maintenance/Low Routine Maintenanc	16	2409.92	2409.92
9	7	730	93	Very Good	Low Routine Maintenance	694.8	9212.5197	9234.9891
10	8	1550	30	Poor	Corrective Maintenance	924.8	28376.7645	28347.47
11	9	900	91	Very Good	Low Routine Maintenance	161.8	7417.7208	7421.22
12	10	500	78	Good	outine Maintenance/Periodic Maintenan	834.8	13540.1	13603.1
13	11	500	78	Good	outine Maintenance/Periodic Maintenan	883.4	10997	11097.8
14	12	500	89	Very Good	Low Routine Maintenance	738	8966.3	8966.3
15	13	550	93	Very Good	Low Routine Maintenance	321.4	1887.27	1956.57
16	14	650	81	Very Good	Low Routine Maintenance	256.4	15051.1452	15055.732
17	15	1130	71	Good	outine Maintenance/Periodic Maintenan	726	41988.54	41988.54
18	16	650	99	Excellent	o Maintenance/Low Routine Maintenanc	15	1365	1365
19	17	970	84	Very Good	Low Routine Maintenance	834.4	35050.077	35055.315
20	18	940	91	Very Good	Low Routine Maintenance	155	9644.4	9644.4
21	19	1020	48	Fair	iodic Maintenance/Corrective Maintena	489.8	49524.6312	49233.809
22	20	1270	93	Very Good	Low Routine Maintenance	91	8756.65	8756.65
23	21	1060	82	Very Good	Low Routine Maintenance	440.2	17321.7992	17412.62
24	22	2420	39	Poor	Corrective Maintenance	749.8	170841.4367	170891.75
25	23	520	91	Very Good	Low Routine Maintenance	155	6639.36	6639.36
26	24	2400	77	Good	outine Maintenance/Periodic Maintenan	946.8	198023.28	198730.9
27	25	2640	34	Poor	Corrective Maintenance	614.8	203885.2464	203974.58
28	26	2032	92	Very Good	Low Routine Maintenance	273.4	27334.89072	28888.639
29	27	1568	99	Excellent	o Maintenance/Low Routine Maintenanc	143.4	908.643456	950.30208
30	28	750	51	Fair	iodic Maintenance/Corrective Maintena	586	7993.6875	7993.6875
31	29	1250	60	Fair	iodic Maintenance/Corrective Maintena	453	4718.25	4617
32	30	1100	83	Very Good	Low Routine Maintenance	475	25379.2	25379.2
33	31	1270	89	Very Good	Low Routine Maintenance	68	14005.56	14005.56
34	32	1220	46	Fair	iodic Maintenance/Corrective Maintena	674.6	42088.109	42095.795
35	33	720	88	Very Good	Low Routine Maintenance	596.4	16435.1376	16447.838
36	34	350	26	Poor	Corrective Maintenance	939.8	69188.273	69267.275
37	35	350	11	Very Poor	Corrective Maintenance	744.4	50500.485	50540.175
38	36	350	54	Fair	iodic Maintenance/Corrective Maintena	821.8	21543.795	21602.385
39	37	400	65	Good	outine Maintenance/Periodic Maintenan	1191.8	27499.8	27593.4
40	38	420	86	Very Good	Low Routine Maintenance	528.4	8889.426	8896.23
41	39	440	93	Very Good	Low Routine Maintenance	526.8	6178.2336	6166.8288
42	40	1450	67	Good	outine Maintenance/Periodic Maintenan	643.6	55544.048	56020.112
43	0	0	100	Excellent	o Maintenance/Low Routine Maintenanc	0	0	0

(A)



	Section Number	Section Length (m)	Section Width (m)	Maintenance Type	Cost Per Lane Km (Rs)	Cost of Maintenance (Rs)
3	1	300	14	Full Reconstruction	5700000	6840000
4	2	64	4.5	Full Reconstruction	5700000	469028.5714
5	3	1070	4.5	Full Reconstruction	5700000	7841571.429
6	5	590	12	Full Reconstruction	5700000	11530285.71
7	7	160	4.5	Full Reconstruction	5700000	1172571.429
8	10	720	3.5	Full Reconstruction	5700000	4104000
9	12	200	3.5	Full Reconstruction	5700000	1140000
10				Full Reconstruction	5700000	0
11				Full Reconstruction	5700000	0
12				Full Reconstruction	5700000	0

(B)

Fig. 6. Budget-Prioritized Pavement Management System Program (a) Module 4: Zone Summary; (b) Module 5: Reconstruction.

used for complete understanding of the many pavement maintenance problems. In this study, PCI was well-utilized to investigate the surface characteristics of the already in-service roadway surfaces and a concept was developed to evaluate its power and applicability to formulate engineering-criteria based PMS research framework for an urban area. It is noteworthy that although the study made use of only few kilometers of road stretches, there is no reason why this study could not be extended to conceptualize other regions or a city in another country in a similar manner.

- Formulation: Based on the fundamental PMS principles, the salient pavement condition assessment parameters such as distresses identification, PCI, maintenance strategies, cost allocations, and budget prioritizations and manual optimization were employed to formulate the relevant PMS computer program, both at project and capable of extending it to a network level. The formulation of the budget prioritized PMS program within a zone of a major city in the country is an important step to creating a venue for scientific assessment of the other zones. The formulation of the problem assessment strategy of this study basically yields a user-friendly algorithm.
- Computer toolkit: A host of automatic estimations that are intertwined between the different PMS parameters were developed in this study with the basic understanding that each parameter is important. The toolkit works based on ranking and prioritization of maintenance strategies subject to budgetary constraints which will help assist an inexperienced agency to only reap the benefits of allocating annual maintenance budget for those that require immediate attention and save wasteful expenditure. The different modules of the program exemplified the actual site conditions of the study area corresponding to their prevalent pavement conditions.

  There is no doubt that extensive work needs to be carried out in future to develop summaries of conditions for the other zones in the city, but this study illustrated that it is certainly possible to advancing the state-of-the-art and knowledge appropriate to PMS research.
- Findings: Apart from the inbuilt program functions, a major contribution of this study was to investigate the pavement condition indices and its relationship to the classic pavement life cycle of deterioration during its service. It is very important to note that the PCIs genuinely determine the position of the current state of the roadway condition. Nevertheless, the study clearly depicted that periodic pavement condition assessment is extremely consequential and is of utmost significance in PMS. However, efforts will be made to disseminate the findings of this study through training the relevant personnel handling pavement evaluation and maintenance in the roadway construction agencies of the various States of India.

Conclusions and Recommendations

The main objective of this study was to develop a budget-prioritized PMS program for an arterial roadway network of 69 km capable of selecting the most appropriate maintenance activities considering the corresponding budgetary priority for pavement maintenance and rehabilitation in Bangalore city, State of Karnataka, India. The approach taken in this study is first of its kind within the framework of PMS research and development in India. Furthermore, the developed program is capable of providing appropriate maintenance treatments at appropriate time scales so that the rate of pavement deterioration can be deferred to a great extent, thus reducing the overall maintenance costs. The major conclusions of this practical study are as follows:

- Parametric indices: for an agency with no historical records of pavement condition assessment, engineering criteria was recommended and developed based on the prevalent field pavement conditions and different distresses, which helped estimate the actual pavement condition parametric indices. PCIs were estimated using the threshold indices developed based on engineering criteria beyond which the pavement conditions were unacceptable, and the deduct values formulated for prevalent site conditions. These deduct values for the different distresses are flexible in that they need to be only adjusted to suit a particular local condition in other regions.
- BpPMS program: a simple but a user-friendly computer based PMS program was developed incorporating features such as the current pavement condition, PCIs, maintenance strategies and cost allocations. The numerous features of the BpPMS program will only help save money rationally that is required for total restoration of the roadway network. Using the program, an agency can prefer to maintain only a few sections of a network in the first year and rest in the subsequent years depending on which of the sections require immediate attention. The ranking-prioritization process was considered mainly so the agency can decide the sum of money needed for immediate maintenance as well as help make appropriate decisions for future maintenance of the rest of the sections.
- Future scope of work: The findings of the study revealed that there is definitely a need to understand the future conditions of the pavements starting from the current assessment. This only means that numerical models are required to predict future state of affairs of those sections through mathematical formulations, integration of Geographic Information System (GIS) with pavement conditions, and life cycle cost assessment. Furthermore, there is also a need to incorporate the routine maintenance history of the sections in some form for a thorough understanding of the behavioural pavement condition response. It is noteworthy that although the current program allows the user to manually select sections for maintenance by optimization process, future tool(s) should be made automatic in identifying sections for maintenance by adopting both optimization and prioritization processes making the outcomes more robust. Further, the basis would be to consider the differences of consecutive PCIs rather than just using the ranking of PCIs.

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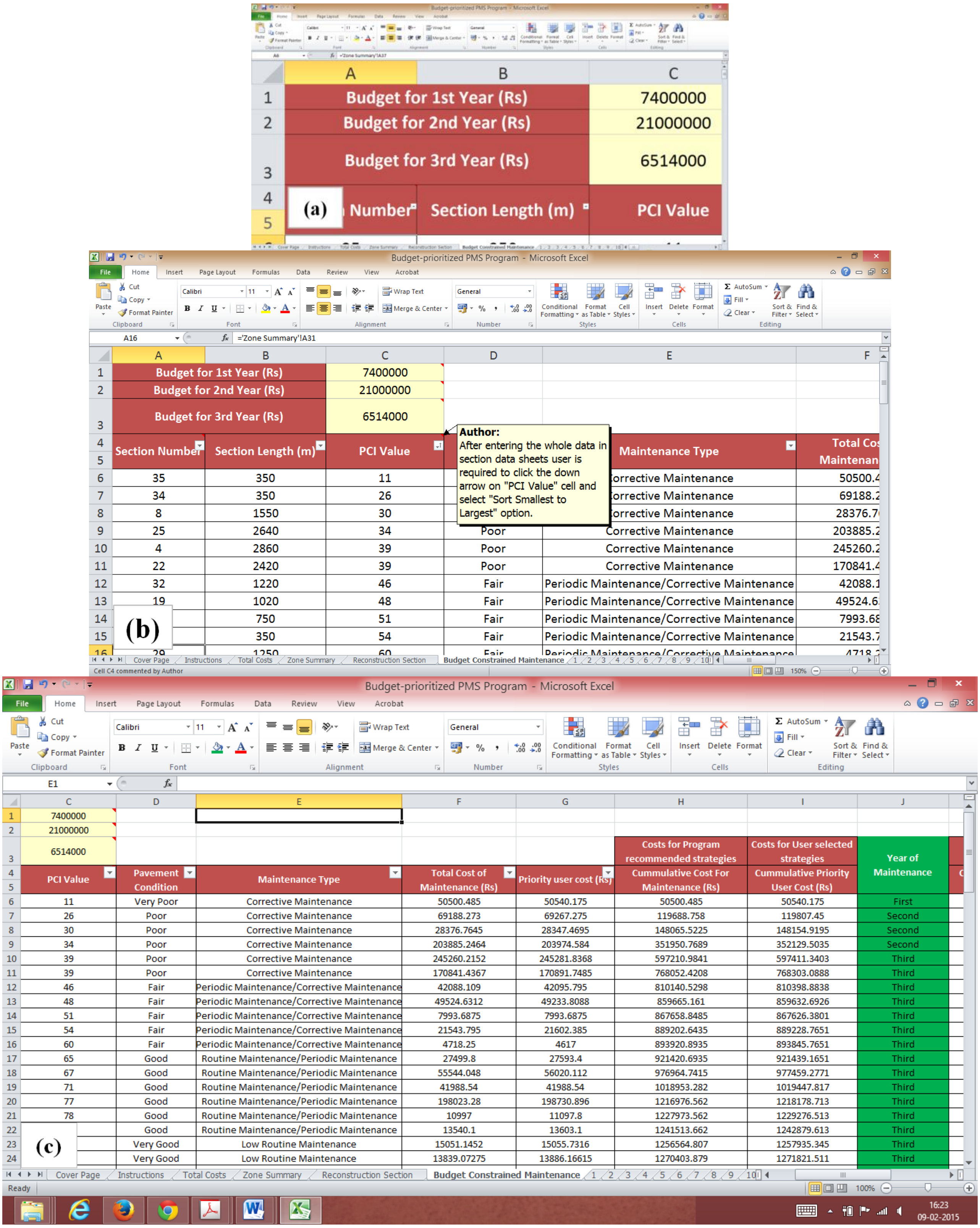

Fig. 7. Budget-Prioritized Pavement Management System Program Module 6: (a) Yearly Budget Allocation; (b) PCI Sorted Smallest to Largest; (c) Prioritizing Yearly Maintenance.

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