A Critical Review of Prioritization Models for Pavement Maintenance Management Decisions

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A primary purpose of a pavement management system (PMS) is to provide information so that roadway improvements can be priority ranked. Ideally, prioritization is a consistent and justifiable process. It should involve minimizing life cycle costs subject to minimum levels of serviceability and budget constraints. Prioritization is a complicated process that requires sound engineering judgment and a good understanding of local conditions. Current fiscal crises and rising roadway improvement costs have made prioritization decisions more important than ever. Priority analysis is a systematic process that determines the best ranking list of candidate sections for maintenance based on specific criteria such as pavement condition, traffic level, pavement functions, etc. Various methods are used for priority analysis ranging from simple listing based on engineering judgment to true optimization based on mathematical formulations.

This paper examines theoretical and pragmatic problems surrounding the prioritization process. This study report a detailed review of various prioritization techniques and models developed for flexible pavements at global level. This will help in evaluating the usefulness of the various models in some particular condition having the similar prioritization parameters. A discussion on the limitations of the different models is also given in this study.

Keywords: Pavement management system, prioritization models.

1. Introduction

Pavements are the important component of the inland transport system. It’s a challenging job for engineers and scientists to augment the performance of roads to meet the needs of growing urban communities. It is very important to maintain the existing pavement network in its serviceable condition within the available resources. And this can be achieved by adopting appropriate maintenance strategy for the road network under consideration. Managing the pavements is a systematic approach, which includes different activities like pavement performance evaluation, determination of maintenance and rehabilitation (M&R) requirements, optimization of resources and prioritization of pavement sections for timely and resource effectively maintenance. These activities collectively create the pavement management system (PMS).

Priority ranking, as used in PMS, is a process used to rank the pavement sections in an order of urgency for maintenance and repair. The prioritization process is the main step of PMS, before the decision maker’s takes final decision on execution of maintenance program.

The quality of priority-setting is directly influencing the effectiveness of available resources which are, in most cases, the primary judgment of the decision maker (Sharaf & Mandeel 1998). The priority ranking process depends on various factors like pavement condition, traffic volume, environmental effects, desired performance standards, and budgetary constraints. Since maintenance actions affect the scheduling of work and allocation of resources, proper selection of such actions (priorities) is crucial to the most efficient use of limited resources. In the present study an effort has been made to broadly classify various approaches/methods for prioritization of pavement maintenance and the applications of these models made by different researchers at global level. A discussion on the limitations of the different models is also given in this study.

2. Prioritization Methods / Approaches

Priority setting techniques as used in the PMS cover a wide spectrum of methods and approaches ranging from simple priority lists based on engineering judgment to complex network optimization models as shown in Table 1 (Haas et al. 1994). These prioritization methods can be further divided as: (i) Ranking Methods (ii) Optimization Methods (iii) Artificial Intelligence Techniques (iv) Analytical Hierarchy Process Method.
2.1 Ranking Methods

2.1.1 Composite Index Ranking Method

The ranking of pavement sections for maintenance is done on the basis of the priority index calculated by combining different pavement indices. These indices are estimated by considering parameters like pavement distresses, riding quality, traffic conditions, economic analysis, functional class, accident details, geometric deficiencies, structural capacity, skid resistance, pavement age, engineering judgement, etc.

The prioritization program should not only be based on current pavement condition, for making it efficient future pavement condition should also be considered. As generally the treatments are applied at least one year after the condition surveys are carried out, giving the time to require for relative prioritization and organizing for funds.

There are different approaches to develop a priority combined index for pavement maintenance. These approaches include unique sum approach, utility theory, Delphi method, factorial rating method, and fuzzy set theory. The application of few methods is discussed in following sections.

2.1.2 Economic–based Methods

The prioritization methods based on economic analysis can be of two types: (i) using optimal benefit/cost ratio (ii) using incremental benefit/cost ratio. In the first method, prioritization process uses the optimal M&R recommendations and corresponding benefit/cost ratios (or effectiveness/cost (E/C) ratio) for each pavement section of the network produced from the dynamic programming. The higher the E/C ratio of a section, the higher the priority of that section for repair. The available budget is allocated to the pavement sections as per the priority list till the budget is completely exhausted.

The second methodology is a heuristic method for budget optimization. In this method all feasible M&R alternatives of a section are identified and the corresponding inflated initial cost, present-worth costs, and weighted benefits are obtained. This information is then used in the program to produce optimal M&R recommendations for each pavement section, including initial cost and type of treatment. The budget optimization also gives the total network-weighted benefits corresponding to optimal M&R recommendations (Butt et al. 1994).

2.2 Optimization Methods

Priority programming by optimization is conceptually different from others methods. It combines the function of priority programming, program formulation, and project scheduling into one operation which gives the optimum schedule of projects through precise analytical techniques such as linear and dynamic programming. Generally, these method uses maintenance cost minimisation or maintenance benefits maximization to generate the optimal maintenance plans.

2.3 Artificial Intelligence Techniques

Artificial intelligence techniques include fuzzy mathematical programming, ANNs, and evolutionary computing (including genetic algorithms). These techniques are particularly appropriate for pavement management because the information may be uncertain and incomplete. The data may involve combinations of objective measurements, subjective rating, and expert
inputs, such as those data used to create M, R&R decision criteria and policy tables. Artificial neural networks and fuzzy systems have been used for needs analysis as alternatives to the traditional priority ranking tools, such as decision trees.

2.4 Analytical Hierarchy Process Method

Analytical hierarchy process (AHP) is one of the multi criteria decision making methods (MCDM) used to scale and quantify measurements. AHP theory was developed by Saaty in 1970. Fig. 1 shows a typical schematic hierarchy of prioritization process. The first step is the formation of the problem components (hierarchy); the second phase of the AHP is the evaluation which is based on the concept of paired comparisons. The parameters considered at each level of hierarchy are compared in relative terms as their importance or contribution to a given criterion. This process of comparison yields a relative scale of measurements of priorities or weights of the elements. These relative weights sum to unity. For project-level evaluations where a few sections are to be considered simultaneously, AHP is an effective method for analysis.

Chen et al. (1993) developed a prioritization procedure as a part of an Urban Roadway Management System (URMS) at network level. The procedure combined two matrices and an equation for computing priority index (PIX). PIX was taken as a function of PCI, pavement age, mixed traffic and street class. The process is shown in Fig. 2.

Fig. 1 Typical hierarchy structure for prioritization

3. Studies on Pavement Maintenance Prioritization

3.1 Based on Subjective Ranking

Fwa and Chan (1993) illustrated the feasibility of using neural network models for priority assessment of highway pavement maintenance needs. A simple backpropagation neural network with three different priority setting schemes viz. a linear function relating priority ratings to pavement conditions, a nonlinear function, and subjective priority assessments obtained from a pavement engineer, was tested using general purpose micro-computer based neural network software known as Neural Works. The validation analysis was carried out for all three schemes as described below:

Chen et al. (1993) compared three methods for priority ranking. In the first model the priority index was estimated as follows:

\[
Priority \ Index = \frac{defect \ length}{traffic \ factor \times defect \ factor}
\]  

(1)

The traffic levels were classified as less than 2500 vehicle per day (vpd), between 2500-10,000 vpd, and more than 10,000 vpd and the corresponding traffic factors were selected as 1.0, 0.5 and 0.1 respectively. The defect factor (values between 0.1 to 1.0) was assigned on the basis of the distress type and required treatment (lower values for major treatments). The sections were then ranked in descending order after calculating the section priority index, and converted to a cost list by using appropriate maintenance treatment unit cost. The second model was a modification of the first, where the pavement sections were arranged according to road type (i.e. desert or agricultural roads) and traffic level into four classes. Also in this model the budget shares were reserved for different maintenance treatments. In the third model, the distribution of budget among all the sections was done on the basis of optimization method.

Jain et al. (1996) selected four sections of flexible pavement on NH-21 & NH-22 in state of Himachal
Pradesh and eight sections in state of U.P. on NH-2, SH-45 & MDR-121 for maintenance prioritization. Various field studies like measurement of surface deflection, roughness, rut depth, cracks & cracking patterns, pot holes and axle load studies were performed on all pavement sections. Based on the collected data M&R investment strategy for design life of 5 years was suggested. Priority fixation for M&R was done based on following factors:

i. Importance of road (i.e. road type and commercial traffic);
ii. Characteristic deflection (Dcs) value;
iii. Road condition based on roughness, cracks, rutting and potholes;
iv. Investment needs for maintenance and rehabilitation.

Suma et al. (2000) developed a simplified ranking methodology based on distresses to prioritise the pavements for maintenance management. Data pertaining to pavement distress viz., cracking and patching along with their severity levels, unevenness (roughness), and pavement condition ratings were collected and weightages were assigned to each type of distress based on the severity level and extent and deduct value curves were developed. Pavement Condition Indices were then determined and the pavement sections were ranked for maintenance.

Agarwal et al. (2004) presented a rational approach using AHP for prioritization of highway sections for maintenance on the basis of present highway condition, future highway condition and the highway importance. The functional condition of highway sections was evaluated considering the (i) safety (ii) efficiency of traffic operation and (iii) riding comfort. The relative weights of these factors have been conceived from the expert opinion of field engineers which were analysed using AHP. For evaluation of structural condition a simple and cost effective statistical model based on Long Term Pavement Performance (LTPP) database of US Department of Transportation was developed. The highway importance is assessed considering the (i) highway class (ii) importance to community and (iii) political importance. The relative weights of these factors have also been conceived from the expert opinion of field engineers and using the AHP. A total of 15 factors are considered and identified by thicker borderline of the text boxes in Fig.3. The developed approach was employed for prioritizing the sections for maintenance in a small highway network.

Chandran et al. (2007) formulated the prioritization technique of low-volume pavement sections for maintenance using fuzzy logic. Eight pavement sections each of 500m length with different deterioration levels
were selected in the Trivandrum and Kollam Districts in Kerala State. Fuzzy condition indices (FCI) were used to prioritize the pavement sections by suitable fuzzy ranking methods. Fuzzy membership functions were formulated for severity, extent, and relative importance of each distress with respect to maintenance. The common index aggregating above parameters in form of fuzzy condition index (FCI) was computed using following expression:

\[ FCI = \sum_{i=1}^{3} w_{ki} A_{ki} S_i \]  

(2)

Where \( w_{ki} \) = subjective weight of distress \( k \) at severity level \( i \), \( A_{ki} \) = subjectively assessed extent of distress \( k \) at severity level \( i \), and \( S_i \) = subjective assessment of severity level \( i \).

Fuzzy condition indices were developed for each pavement section by using MATLAB software. The FCI so obtained for various sections are shown in Fig. 4.

The ranking based on PCI values were also compared with FCI ranking.

\[ e_{ij} = \frac{S_{ij}^+}{S_{ij}^+ + |S_{ij}^-|} \]  

(4)

Where, \( (S_{ij}^+ + |S_{ij}^-|) = \) Total area of \( (\bar{p}_i - \bar{p}_j) \)

The road link which had highest Priority Index (PI) was given top priority and vice versa. A code was developed in MATLAB in order to calculate the PI for the present study.

Zhang (2004) presented an Analytic Hierarchy Process (AHP) based quantitative approach to the prioritization of data requirements for pavement management. Using the Weighted Sum technique, the importance and frequency of usage of data items were combined to yield their comprehensive ranking score. The overall methodology is illustrated in Fig. 6. The process of establishing the hierarchy to prioritize pavement data collection using AHP is illustrated in Fig. 7.

Farhan & Fwa (2009) made an attempt to explore the use of an analytic hierarchy process (AHP) for the prioritization of pavement maintenance activities. Three forms of AHP were examined, namely, the distributive-mode relative AHP, the ideal-mode relative AHP, and the absolute AHP. For analysis purpose, three road functional classes, three distress types and three levels of distress severity were considered which gave 27 possible combinations of maintenance treatments. The hierarchy structure used for the AHP analysis is as shown in Fig. 8. The study concluded that the absolute AHP was suitable for the pavement maintenance prioritization process, on the basis of its ability to provide priority assessments for pavement maintenance activities in good agreement with the priority assessments obtained by the direct assessment method and its operational advantage in evaluating a large number of maintenance activities.
Moazami et al. (2010) generated AHP and Fuzzy logic modelling for prioritization of pavement rehabilitation. The developed models were executed for 131 sections of urban streets of district No. 6 of Tehran municipality. The modelling was done in two steps, in the first step analytical hierarchy process was employed to compute the relative weights of parameters. The pairwise comparison between the following criteria and sub-criteria as given in Table 2 was done by considering ideas of about 200 PMS experts. Finally, with rating approach in Expert Choice software prioritization was done.

In the next step, fuzzy logic modelling was used to obtain satisfactory precision. The three fuzzy sets were defined and following Gaussian membership function were used for demonstration of being high, medium and low fuzzy sets.

$$\mu(X) = \exp \left[ -\frac{1}{2} \left( \frac{X-G}{\sigma} \right)^2 \right]$$  \hspace{1cm}  (5)

where, $\mu(X)$ = Value of Membership of Variable $X$ to Fuzzy Set, $G$ = Mean of Gaussian Function, $\sigma$ = Gaussian Function Bell Radius. The Singleton Fuzzifier, a product inference engine was used to calculate the priorities of the sections using fuzzy logic. The analysis was done using the fuzzy toolbox of MATLAB 7.0 software and coded M-files.

It was concluded that, in AHP pairwise comparison between criteria and sub-criteria is arbitrary, while gauss mean and sigma matrixes constitutions are based on reality. Also it was shown that AHP method cannot differentiate between two almost identical sections. Consequently, fuzzy logic programming was considered as the best choice in the study.

### Fig. 6 Overall process of the methodology

(Source: Zhang 2004)

### Fig. 7 Application of AHP to prioritizing pavement data collection

(Source: Zhang 2004)

#### 3.2 Based on Composite Condition Index

Karan (1981) described the pavement management implementation project for Prince Edward Island (PEI), Canada covering a road network of 500km. It included the field inventory, identification of needs for pavement improvements, evaluating the rehabilitation alternatives, priority analysis and budget analysis. The Condition Index (CI) was computed considering the severity of 10 different distresses on road sections. The overall Serviceability Index (SI) was calculated for all road sections using following expression:

$$SI = a \cdot (RCI) + b \cdot (SAR)$$  \hspace{1cm}  (6)
where, $SI =$ serviceability index (Rating Scale: 0-10, 0 – totally unacceptable pavement, 10 - perfectly smooth and strong pavement), $RCI =$ Riding Comfort Index (Rating Scale: 0 – 10, 0 - worst riding comfort & 10 – perfectly smooth pavement), $SAR =$ Structural adequacy rating (Rating Score: 0 – 10, 0 - 4.9 indicates structural adequate pavement, 5-10 indicates structural inadequate pavement), $a, b =$ weighting factors ($a + b = 1.0$) 

The calculated values of CI, RCI, SAR, SI was given as an input for development of PMS at network level. One of the components of PMS was establishing the pavement improvement priorities. A mathematical-optimization (linear-programming) model was adopted to set priorities based on benefit maximization and budget constraints.

![Hierarchy structure for AHP analysis](Source: Farhan & Fwa 2009)

**Table 2. Criteria and sub-criteria for AHP process**

<table>
<thead>
<tr>
<th>Level - 1 Criteria</th>
<th>PCI</th>
<th>Types of Urban Roads (Road Width m – both direction)</th>
<th>Traffic Volume (pcu/hr/ direction)</th>
<th>M &amp; R Cost (USD per red)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Level - 2 Sub-Criteria</strong></td>
<td></td>
<td>Local (5.5 - 6.5)</td>
<td>Low Volume (&lt;433)</td>
<td>Very Low (&lt; 2000)</td>
</tr>
<tr>
<td></td>
<td>0 – 10</td>
<td>Minor Arterial (5.5 - 21)</td>
<td>Medium Volume (433-2660)</td>
<td>Low (2000-20000)</td>
</tr>
<tr>
<td></td>
<td>25 – 40</td>
<td>Other (90 – 100)</td>
<td>Others (&gt; 6200)</td>
<td>Omit High (50000-100000)</td>
</tr>
<tr>
<td></td>
<td>40 – 55</td>
<td></td>
<td></td>
<td>Very High (&gt;100000)</td>
</tr>
<tr>
<td></td>
<td>55 – 70</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>70 – 85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>85 – 100</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(Source: Moazami 2010)
Zhang et al. (1993) developed a comprehensive ranking index for flexible pavements using Fuzzy sets theory. The model developed was named as overall acceptability index (OA1) is given as follows:

$$OAI = \left( \frac{W_1}{\sum W_i} \right) A_1 + \left( \frac{W_2}{\sum W_i} \right) A_2 + \left( \frac{W_3}{\sum W_i} \right) A_3 + \left( \frac{W_4}{\sum W_i} \right) A_4 \quad (7)$$

Where \(W_1, W_2, W_3, W_4\) are the weighing factors for roughness, distress, structural capacity and skid resistance respectively. The sum of all weighing factors, \(\sum W_i = 1.0\). The membership functions for each parameter are developed using nonlinear regression analysis for a subjective opinion survey about the level of acceptance for selected pavement attributes and their relative importance, are given in Table 3.

Table 3. Membership functions and weights for secondary roads

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Membership Function</th>
<th>(R^2)</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness (PSI)</td>
<td>(A_1 = 1 - \exp\left(\frac{-0.01274*PSI^2}{0.0000082}\right))</td>
<td>0.970</td>
<td>0.306</td>
</tr>
<tr>
<td>Distress (D)</td>
<td>(A_2 = \exp\left(\frac{-0.0000185*D^3}{0.00000185}\right))</td>
<td>0.971</td>
<td>0.244</td>
</tr>
<tr>
<td>Structural Capacity (SC)</td>
<td>(A_3 = 1 - \exp\left(\frac{-0.207*(CS/50)^2}{0.207}\right))</td>
<td>0.960</td>
<td>0.225</td>
</tr>
<tr>
<td>Skid Resistance (CF)</td>
<td>(A_4 = \frac{-0.22 + 1.6308*CF}{1.6308})</td>
<td>0.979</td>
<td>0.231</td>
</tr>
</tbody>
</table>

(Source: Zhang et al. 1993)

Andres (1994) details the prioritization methodology of local roadway improvements for the town of Eastham, Massachusetts. The system used a composite performance based index to assess priorities. The index was formed by first determining an effectiveness ratio. This is accomplished by dividing “benefits” (areas under deterioration curves after treatment is assigned) by the cost per square yard of treatments. This effectiveness ratio was then weighted by functional class. This measure of the influence of traffic volume on priority assessment can be modified by user. The weighted effectiveness ratio was then used to prioritize road segments in each category. The prioritization was done considering different budget scenarios like zero funding, full funding, moderate budget cut and severe budget cuts.

Flintsch et al. (1998) presented the formula to prioritize pavement rehabilitation projects based on expert’s opinion. It was used for the 5 yr pavement preservation program of Arizona Department of Transportation (ADOT). The preliminary list of candidate projects were prioritized using a “rate” number computed according to the following equation:

$$\text{Rate} = Cr + 0.2*Rg + 2*Rut + 0.0015*MC \quad (8)$$

where; \(Cr = \text{cracking} \), \(Rg = \text{roughness (Maysmeter units)} \), \(Rut = \text{rutting (in.)} \), and \(MC = \text{average maintenance cost for last 3 years (dollars per year)} \). Pavement experts were instructed to examine carefully all pavement sections presented in the questionnaire and to assign a priority rating to each of the sections using a scale from 1 to 10. A priority of 1 indicated the pavements most in need of a preservation treatment. The average response for each section was used for the analysis. The average proposed treatment was computed by averaging the numeric values corresponding to all treatments recommended for each section. The average was rounded and converted back to a treatment recommendation. The average priority values computed for each pavement section were used to obtain an alternative prioritization formula. The following model was selected to calculate the priority for pavement sections:

$$\text{Priority} = 4.82 - 0.83A - 0.64B - 0.50C - 0.82D - 0.81E - 1.11F \quad (9)$$

Where, \(\text{Priority} = \text{priority value}, A = \text{functional classification code (Inter-state or State route)}, B = \text{traffic code}, C = \text{maintenance cost code}, D = \text{roughness code}, E = \text{cracking code}, \text{and } F = \text{rutting code}. This model includes all the variables in the rate formula plus two more: roadway classification and rutting. A model for selection of maintenance treatment to pavement sections was also developed as shown below:

$$\text{Treat} = 2.28 + 0.33A + 0.14B + 0.32D + 0.34E + 0.56F - 0.06G - 0.26EF \quad (10)$$

Where, \(\text{Treat} = \text{type of treatment, } A = \text{functional classification code, } B = \text{traffic code, } D = \text{roughness code, } E = \text{cracking code, } F = \text{rutting code, and } G = \text{structural number code}. The result of the analysis were then implemented in a computer program that automatically computes the recommended treatment for each homogeneous pavement section in the preliminary list of candidate sections using a default assignment matrix that can be modified by the user. The program also assigned a priority value based on the alternative pavement prioritization formula (priority) and sorts the projects by priority within each roadway group (roadway classification, traffic, and region). The sections with the highest priority within each group are funded until they
reach the budget recommendation provided by the network optimization system, increased by a coefficient.

Ramadhan et al. (1999) used Analytical Hierarchy Process for priority ranking of pavement maintenance. The priority index (PI) used in this study for pavement maintenance priority has the following form:

\[ PI = \Sigma W_j \times F_j \]  

Where, \( PI \) = Priority index for any section (out of 100); \( W_j \) = Factor “j” weight of importance to priority ranking; \( F_j \) = Factor “j” value (out of 100); and \( SW_j = 1.0 \).

A questionnaire was prepared in four parts for collecting the respondent’s opinion about the weight of importance of the seven priority factors. The seven factors considered for priority ranking were road class, pavement condition, operating traffic, riding quality, safety condition, maintenance cost and importance to community. The procedure followed in the preparation of this questionnaire is detailed in Ramadhan (1997).

The factor weights were computed using the AHP method by analyzing the data collected. The factor weights so obtained were further adjusted for the individual experience factor, in the following manner:

\[ CW_i = \frac{\Sigma_{j=1}^{n} w_j \times E_j}{\Sigma_{j=1}^{n} E_j} \]  

where, \( CW_i \) = corrected overall weight of factor \( i \); \( w_j \) = factor weight as estimated by individual \( j \); \( E_j \) = individual experience factor for individual \( j \), \( i \) = factor number (one to seven for priority factors, and one to six for sub-factors); and \( j \) = individual number out of the total number of individuals \( n \).

The final form of the developed maintenance priority ranking procedure was given as:

\[ PI = \Sigma CW_i \times F_i \]  

It was concluded that the developed procedure can adequately and efficiently rank a huge number of pavement sections for maintenance.

Bandara and Gunarante (2001) tested a methodology developed for pavement maintenance prioritization based on rapid visual condition evaluation using fuzzy logic, on the major pavement network of Sri Lanka. Four commonly observed distress types and their severity levels chosen in this study are given below.

1. Alligator cracking [low severity (AL), medium severity (AM), high severity (AH)]
2. Potholes [low severity (PL), medium severity (PM), high severity (PH)]
3. Edge failures [low severity (EL), medium severity (EM), high severity (EH)]
4. Raveling [low severity (RL), medium severity (RM), high severity (RH)]

The concept of triangular fuzzy numbers (TFNs) with a linear membership function as described in the Fig. 9 was used for analysis. The mathematical equations for the membership function for TFN that has been adopted are given as follows:

\[ \mu_A(x) = 0; \ x < l \]  
\[ \mu_A(x) = \frac{x - l}{m - l}; \ l < x < m \]  
\[ \mu_A(x) = 1; \ x = m \]  
\[ \mu_A(x) = \frac{h - x}{h - m}; \ x > h \]  
\[ \mu_A(x) = 0; \ x > h \]  

The efficient fuzzy weighted average (EFWA) algorithm was employed to compute the weighted fuzzy pavement condition index with slight adjustments to suit the study. The employed aggregation method can be expressed as follows:

\[ WC_i = \frac{\Sigma_{j=1}^{n} w_j \times E_j}{\Sigma_{j=1}^{n} E_j} \]  

Further a ranking index was defined for each pavement section \( i \) using the FCI values and the rating difference matrix, given as follows:

\[ R_i = \frac{\Sigma_{j=1}^{n} (d_{ij} - 0.5)}{2} \]  

Where, \( d_{ij} \) = element indicating the degree of difference between the respective fuzzy condition ratings of the \( i^{th} \) and \( j^{th} \) pavement sections. The ranking for maintenance as per the current rehabilitation urgency was done based on these ranking indexes (\( R_i \)). Also a fuzzy pavement condition forecasting model was developed by incorporating subjective probability assessments regarding pavement condition deterioration rates, in the Markov transition process. And the re-ranking of same sections was done based on ranking indexes (\( R_i \)) for the forecasted pavement condition in the second year.
Reddy and Veeraragavan (2001) proposed a priority ranking methodology based on overall distress index model and traffic adjustment factors. A schematic flow chart of the proposed priority ranking model is as shown in Fig. 10.

The degree of acceptability on a 0 to 1 scale was determined, for pavement distresses of different extent based on the expert opinion survey. The degree of acceptability and the extent of distress were correlated to obtain best fit function as the membership functions. Table 4 shows the mathematical relationships developed as a member ship functions and the relative weightage assigned to each of distress based on expert’s opinion.

\[ PDI = \left[ 1 - \sum (AL_i \times w_i) / \sum w_i \right] 100 \quad (21) \]

Where, \( AL_i \) = acceptability level of any distress, \( i \), \( w_i \) = weightage of distress \( i \). Based on above equation, PDI values have been assigned as 0 to very good pavement and 100 to completely deteriorated pavement. Further the prioritization factors (F) based on functional class and average daily traffic were also considered as given in Table 5. These factors were used to adjust the PDI values in order to assign greater priority to the higher functional class roadways and also to roadways with higher traffic levels within a given functional class. The Priority Index (PI) for a pavement section was computed as:

\[ PI = F \times PDI = F \times \left[ 1 - \sum (AL_i \times w_i) / \sum w_i \right] 100 \quad (22) \]

Using this priority index, different maintenance strategies were assigned to pavement sections. Also, the developed model identified the availability of budget and compared with the total cost required for strengthening. It was concluded that the Priority Ranking Model (PRM) so developed provides a consistent, reliable and facile method of evaluating pavements at network level.

Table 5. Prioritization factors based on functional class and average daily traffic

<table>
<thead>
<tr>
<th>Functional Class</th>
<th>Level</th>
<th>No. of Commercial Vehicles</th>
<th>Prioritization Factor (F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>National Highway (NH)</td>
<td>High</td>
<td>&gt;3000</td>
<td>1.00</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>3000–5000</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>&lt;3000</td>
<td>0.80</td>
</tr>
<tr>
<td>State Highway (SH)</td>
<td>High</td>
<td>&gt;3000</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>1500–3000</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>&lt;1500</td>
<td>0.70</td>
</tr>
<tr>
<td>Other Roads (OR)</td>
<td>High</td>
<td>&gt;1500</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>500–1500</td>
<td>0.70</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>&lt;500</td>
<td>0.60</td>
</tr>
</tbody>
</table>

(Source: Reddy and Veeraragavan 2001)

Cafiso et al. (2002) provided a Multicriteria analysis (MCA) framework for pavement maintenance management. An AHP method of MCA was implemented to compute the ranking values (RV) for the maintenance alternatives. The overall computational procedure for implementation MCA within HDM-4 to compute the ranking vector is as shown in Fig. 11. The HDM-4 was used to produce outputs that can be used as attributes for each road section and investment alternative (i.e., the average IRI values in Figure: Part b). The above procedure produced a matrix of “Multicriteria ranking numbers” for every year (or the whole analysis period), and for all road sections included in the study. The alternative with highest RV was selected in case of unconstrained budget. When there is budget constraint, as is always the case in practice, this need to be considered by applying further analysis of prioritization or optimization.

Narasimha (2003) defined a procedure prioritizing roads in a network for periodic maintenance based on the subjective rating technique as per the guidelines of Asphalt Institute (AI), USA. The field surveys on various categories of roads (SH, MDR & ODR) were conducted and data regarding the present serviceability conditions were collected for about 22 km of road length from a total of 160.334 km under study area, in
Tamil Nadu. The pavement condition survey was carried out, by identifying and evaluating thirteen types of distresses as defined by AI and then the pavement condition rating (PCR) of each stretch of road was computed. The distresses considered with their rating score were: Transverse crack (Rating : 0-5), Longitudinal crack (Rating : 0-5), Alligator crack (Rating : 0-10), Shrinkage crack (Rating : 0-5), Rutting (Rating: 0-5), Corrugations (Rating :0-5), Shoving (Rating: 0-5), Potholes and Patching (Rating: 0-10), Excess bitumen (Rating: 0-10), Polished aggregate (rating: 0-10), Deficient drainage (Rating: 0-10), Riding quality (Rating : 0-10). For all rating scores lowest value indicated good pavement condition and highest value indicate worst pavement condition.

Finally, the PCI value was calculated using the charts given in AI and the prioritization of maintenance for road sections was done.

Kumar (2004) developed a methodology for priority ranking of highway pavements for maintenance of certain roads in Thiruvananthapuram city based on composite criteria. The approach included the opinions from the users in first step and opinions from the experts in the second step. The questionnaire for user opinion survey consisted two parts one with trip information and second with pavement condition. Average response of each user was found out using Excel Macro Programming. Analysis of Variance technique was used to decide that minimum sample size should be 30 so that there is no variation between users.

From the user opinion different pavement section was ranked for priority maintenance. In next step functional evaluation of pavement sections was done and following parameters were analyzed:

(i) Visual rating was done and sections were rated on a scale of 0 – 5. The riding quality assessment was done by driving the vehicle at uniform speed of 30kmph and a subjective rating scale of 0-5 was adopted.

(ii) Crack measurement was done and crack index was computed based on width of crack.

\[
\text{Crack Index (CI) for each km} = \frac{\text{C}_1 \times 0.75 + \text{C}_2 \times 1 + \text{C}_3 \times 1.5}{w \times 100} \times 100 \tag{23}
\]

where, \( \text{C}_1 = \text{area of cracks with width 1mm or less} \), \( \text{C}_2 = \text{area of cracks with width 1 to 3 mm} \), \( \text{C}_3 = \text{area of crack with width greater than 3 mm, } w = \text{pavement width in m} \).

The Crack Index (CI) for each km was computed by assigning weightages to the different severity levels.

\[
\text{Crack Index} = (\text{Crack Percentage} \times WF) \times 100 \tag{24}
\]

Where, \( WF = \text{weightage factor} = 0.5 \) for low severity level = 1.0 for high severity level.

(iii) The number of small, medium and large potholes per km of roads was recorded and the percentage of potholes was compute as:

\[
\text{Percentage of Potholes} = \frac{S \times 1.0 + M \times 3 + L \times 6}{w \times 1000 \times 0.76} \times 100 \tag{25}
\]

where, \( S = \text{number of small potholes, } M = \text{number of medium potholes, } L = \text{number of large potholes, } W = \text{pavement width in m} \).

Then percentage of potholes were converted to Pothole Index (PI) is calculated by assigning weightages to the different severity levels. The PI is calculated as:

\[
\text{PI} = (\text{Crack Percentage} \times WF) \times 100 \tag{24}
\]
Pothole Index = (% of pothole x WF) x 100 \hspace{1cm} (26)

Where, WF = weightage factor = 0.5 for low severity level = 0.75 for medium severity level = 1.0 for high severity level.

(iv) Roughness value in terms of Unevenness Index (UI) was calculated indirectly by using the mean of ride rating values termed as Present Serviceability Rating (PSR). The following model developed at Bangalore University was adopted:

\[
\text{PSR} = -1.9326 \log_e(\text{UI}) + 14.3765 \hspace{1cm} (27)
\]

Based on above functional evaluation indices second questionnaire was prepared and expert opinions were taken for fixing priority for maintenance. Finally the priority obtained from user and experts were compared.

Pantha et al. (2010) developed a Geographic Information Systems (GIS)-based highway maintenance prioritization model for major link of 53.2 km to the capital city of Kathmandu, Nepal. The highway sections were prioritized considering the pavement and roadside slope stability condition. Using the bivariate statistical method (Information Value Method) also know as statistical index method, the weight value for a parameter class affecting the landslide and pavement condition were calculated. Finally an integrated maintenance priority index (MPI) was computed by adding pavement maintenance prioritization index and roadside slope maintenance prioritization index after multiplying by weighted value of each component, as given in following expression.

\[
\text{MPI} = \text{PMPI} \times W_p + \text{RMPI} \times W_r \hspace{1cm} (28)
\]

where, PMPI is the pavement maintenance prioritization index, RMPI is the roadside slope maintenance prioritization index, \(W_p\) is the weight given to pavement maintenance and \(W_r\) is the weight given to roadside slope maintenance. The selection of maintenance sections were done based on these calculated MPI.

Khadem et al. (2010) presented a combined Conference-Delphi-analytic hierarchy process (AHP) model employed to prioritize the low-class roads in Gilan, Iran. The main three objectives defined for this study was determining the high-priority low-class roads for maintenance (MA), improvement (IM), and upgrading (UP).
Each part of the designed Conference-Delphi-AHP decision-making model function interdependently through a series of systematic steps was as shown in the Fig. 12.

The first step included the creation of data bank for road network in Arc View, GIS software. Then, three categories for the prioritization were formed by the classifying algorithm as shown in Figure 33 for three objectives viz. MA, IM & UP. And all the sections of low-class road network are tested by the algorithm and placed in these three categories. Next step included to finalize the decision criteria and list of decision makers to participate in AHP. This was done by conducting conference and Delphi Survey. The AHP hierarchies decided to make the decisions for MA, IM & UP were as shown in Fig. 14.

Lastly, the final weight of alternative number \( n \) was calculated by the following equation with regard to all of the criteria in the hierarchy:

\[
W_n = \sum_{i=1}^{i} \left( w_i \times \sum_{j=1}^{j} \left( w_{ij} \times \sum_{k=1}^{k} \left[ w_{ijk} \times a_{ijkn} \right] \right) \right)
\]

where \( i \) =number of the criteria in Level 1; \( j \) =number of the criteria in Level 2 whose parent criterion is the \( i \)th criterion in Level 1; and \( k \) =number of criteria in Level 4 whose parent criteria are the \( j \)th criterion in Level 3 and the \( i \)th criterion in Level 2.
Kaysi et al. (2010) prioritized the National Road sections based on a multi-criteria analysis (MCA) approach, the linear additive model, which evaluates each scheme on a set of criteria derived from the various national goals and objectives of the Saudi authorities.

The framework designed and implemented to set the priorities was explained by flow-chart as shown in Fig. 15. To set the priority an exhaustive set of criteria’s been decided. The selected criteria were grouped into 5 main criteria (Group Criteria) reflecting the broad objectives of the key players: A- Road Network Development; B- Socio-Economic Development; C- Economic Efficiency; D- Serving Hajj and Umrah; and D- Other Criteria including Security, Safety, and Environment. Each main criterion was then divided into primary criteria, some of which were divided further into secondary criteria, thus resulting in a three level hierarchy as given in Fig. 16.

In the next step the relative weights of each criterion were derived using AHP method by developing the questionnaire. The following Linear Additive model was used to calculate the overall value score of a proposed road scheme by adding its weighted score on a set of criteria:

\[ S_i = \sum_{j=1}^{n} w_j S_{ij} = w_1 S_{i1} + w_2 S_{i2} + \ldots + w_n S_{in} \]  

where \( S_i \) is the total value score of scheme i; \( w_j \) is the relative weight of criterion j; \( S_{ij} \) is the value score of scheme i on criterion j; and n is the total number of criteria. The schemes were then divided into two groups based on the road category: primary and secondary roads. The schemes were then ranked based on the calculated total scores. The sensitivity analysis was also carried out to evaluate the robustness of the Saudi Arabian Road Prioritization (SARP) model.
3.3 Based on Economic Analysis

Livneh and Craus (1990) suggested an economic-based model for prioritizing the maintenance of pavement sections. The model had a following mathematical form:

\[ P\% = k \times SN^{3.72} \times (5 - PSI) \times \left(\frac{AADT}{1000}\right) \]  \hspace{0.5cm} (31)

Where \( P\% \) = the first year rate of return, \( SN = \) structural number = 5 - 0.04DR, where DR is a distress grade (0-100), \( PSI = \) serviceability grade (0-5), \( AADT = \) annual average daily traffic, and \( k = \) numeric constant.

The first year rate of return was estimated for a given rehabilitation investment, that is the agency and road user’s costs (before and after upgrading), and the benefits gained from investment in the maintenance and rehabilitation work. The governing factor of this model was AADT.
Sharaf & Mandeel (1998) analyzed three techniques for priority setting. The first technique was a simple ranking based on four ranking measures viz.: (i) lowest life cycle cost; (ii) worst condition first; (iii) highest traffic and (iv) highest benefit/cost ratio. The second technique was a combined ranking technique based on relative weights assigned to the above mentioned four ranking measures. Finally, the third technique was a linear programming optimization model which considers both time (current and future) and space (entire network). A comparison between the three techniques in terms of network condition over time and in terms of budget deficit over time was presented. The results indicated a considerable difference in future network performance under the three techniques with the optimization technique produced the best results.

Veeraragavan (2000) presented a methodology of prioritizing the highway sections for maintenance based on the current structural and functional condition of the pavement and the traffic intensity. An economic analysis was done to evaluate the benefit/cost ratio and net present value. Based on the highest value of the economic criteria, the pavement sections were selected for treatment and the highway sections were ranked on priority for maintenance.

Roy et. al. (2003) evaluated the uses of HDM-4 as a versatile tool to study the economic viability of alternative road projects and to prepare road investment programmes for the selected sections of State highways of Kerala. The M&R strategies were selected for sections based on IRR and B/C values.

Aggarwal et. al. (2004) prioritized the yearly M&R works for the National Highways based on the decreasing NPV/Cost ratio. The ‘Project Analysis’ component of HDM 4 was used for doing the analysis.
and computing the NPV/cost ratio for different pavement sections of NH under study. A section with higher NPV/Cost ratio was considered first for maintenance.

Singh and Sreenivasulu (2005) used programme analysis of HDM-4 for prioritizing the maintenance of road sections, under different budget scenarios. The NPV/Cost ratios were determined for all candidate sections and were prioritized accordingly.

Parida et al. (2011) & Shah et al. (2012) compared the two methods for priority ranking of urban road maintenance, viz. (a) ranking based on subjective rating and (b) ranking based on economic indicator. The subjective ranking was done using maintenance priority index (MPI) which was a function of road condition index, traffic volume factor, special factor and drainage factor. The second ranking method was based on economic indicator in which NPV/Cost ratio was calculated for each pavement section using the HDM-4 software.

4. Discussion and Conclusions

The main aim of this paper was to build knowledge about the pavement maintenance prioritization methods and to present the research studies developed in this area by different researchers at global level. It can be concluded that the selection of prioritization method is a case specific and not applicable everywhere. The selection of pavement sections on the bases of fund constraints, may lead to road condition deterioration for other sections not in priority list. At the same time, prioritization based on optimization is able to maintain or even improve road conditions of the overall network.

Also it has been observed that:
- The complexity is added to the calculations as we move on from simple engineering judgment based to complex network optimization models, as a prioritization method.
- Ranking based methods requires less data collection, than other methods, where data like future traffic projection, future funding, forecast of effects and durability of maintenance and pavement deterioration models need to be studied.

References


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