EVALUATION OF ENVIRONMENTAL SUSTAINABILITY OF PAVEMENT PRESERVATION STRATEGIES USING ANALYTIC HIERARCHY PROCESS

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ABSTRACT

Pavement management involves satisfying goals that are often multiple and conflicting such as minimizing environmental, societal, economic impacts, and maximizing safety, level of service, condition etc., and cannot be achieved simultaneously. Decision makers are required to select a single maintenance strategy which closely meets their objectives and selection criteria. The set of criteria may involve economic as well as environmental aspects, some of which may not be easily quantifiable, thus requiring the use of qualitative judgments. Ranking approaches assign priorities to either distresses or maintenance treatments, and arrive at a maintenance program based on a selected set of criteria or preferences. A commonly used technique, in operations research, for prioritization of alternatives is known as Analytic Hierarchy Process (AHP). Its ability to embrace both quantitative and qualitative data through assignment of numerical values to qualitative data, and the significance of its role as a decision making tool for building a targeted model makes this the preferred method for prioritization. Therefore, this study explores the use of analytic hierarchy process (AHP) for prioritization of pavement rehabilitation treatments involving multiple criteria such as treatment cost, serviceability, and environmental implications. A Hypothetical numerical example is presented to illustrate the proposed framework for prioritizing 5 pavement rehabilitation techniques, namely, cold in-place (CIR), hot in-place (HIR) surfacing, hot in-place repaving, hot in-place remixing, and hot mix asphalt (HMA) overlay.

Keywords: pavement preservation, recycling, environment, sustainability, AHP

1. INTRODUCTION

Highway infrastructure not only provides critical infrastructure services to society but also poses significant impacts related to high material consumption, energy input, and capital investment. Conventionally, agency costs are used by highway agencies to compare different rehabilitation strategies. Energy consumption, greenhouse gas emissions, and environmental damages are often excluded from the decision making process (Wilde et al., 2001; Huang, 2004). As the pavements age and deteriorate, preservation treatments (i.e. maintenance and rehabilitation) are required to restore their structural integrity, level of safety and service.

Various rehabilitation treatments are currently employed, depending on the existing pavement structure. They include cold in-place (CIR), hot in-place (HIR) surfacing, hot in-place repaving, hot in-place remixing, and hot mix asphalt (HMA) overlay. One of the most prevalent rehabilitation treatments, for pavements subjected to heavy traffic, is the placement of an overlay on top of the existing pavement (DOT, 1989). An overlay is known to protect and strengthen existing pavement structure, retard the rate of pavement deterioration, and correct surface deficiencies. However, the use of traditional asphalt mix overlay (HMA) presents significant environmental implications.

This paper presents a framework for prioritization of various rehabilitation strategies, from economic, serviceability, and environmental perspective, using Analytic Hierarchy Process (AHP). A hierarchy is structured incorporating multiple criteria, such as serviceability, treatment cost, and CO_2, NO_x, SO_2, PM_{10}, and TOC emissions, and various rehabilitation treatments as alternatives.

2. CONCEPT OF ANALYTIC HIERARCHY PROCESS

The Analytic Hierarchy Process (AHP) is a mathematical technique for multicriteria decision making developed by Saaty (1980) in the 1970s to facilitate decision makers in selecting the best alternative. AHP has been used to compare between alternatives on a ratio scale, and permits qualitative data to be included in addition to quantitative data (Saaty 1980, 1994). AHP involves the following phases: (a) structuring of a hierarchy, (b) prioritization based on pairwise comparison, (c) synthesis of pairwise priorities to form a priority vector, and (d) checking for consistency of the preference judgments.
A hierarchy decomposes a problem into individual independent elements. According to Saaty (1980), a hierarchy is “an abstraction of the structure of a system to study the functional interactions of its components and their impacts on the entire system.” It consists of an overall goal at the top or first level, a set of alternatives, at the bottom or last level, for reaching the goal, and a set of criteria, at mid-level, that relate the alternatives to the goal. Normally, the criteria are further broken down into sub-criteria, sub sub-criteria, and so on, depending on the complexity of the problem.
The next phase is pairwise comparison of criteria. Findings from psychological studies by Miller (1956) have shown that individuals are unable to effectively apply a rating scale of more than seven (plus or minus two) points. AHP as recommended by Saaty (1980) uses a nine-point scale to determine the comparative difference in a pairwise comparison of two elements. The preference judgment is made by assigning a value of 1 to the elements if they are of equal importance, 3 to a weakly more important element, 5 to a strongly more important element, 7 to a very strongly important element, and 9 to an absolutely more important element.

The outcome of each set of pairwise comparisons is expressed as a positive reciprocal matrix $A = (a_{ij})$ such that $a_{ii} = 1$ and $a_{ij} = 1/a_{ji}$ for all $i, j \leq n$,

$$A = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ . & . & \dots & . \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix} \tag{1}$$

where n denotes the number of alternatives being compared within one set of pairwise comparisons, a_{ij} denotes the importance of alternative i over alternative j, and a_{ji} denotes the importance of alternative j over alternative i.

Synthesis is the next step that translates the priorities, assigned to each pair of elements, in the matrix A into a priority vector w, that contains the priority weight of each element. Saaty’s eigenvector method (EM) is often employed to derive the priorities of the alternatives, and computes w' as the principal eigenvector, a vector that corresponds to the largest eigenvalue called the principal eigenvalue λ_{max} of the matrix A.

$$Aw' = \lambda_{\max} w' \tag{2}$$

The priority vector w is obtained by normalizing the principal eigenvector w', and is also called the normalized principal eigenvector. The priority vector is the normalized principal eigenvector of the pairwise comparison matrix. It is established for each criterion, sub-criterion, as well as the alternatives under each sub-criterion. The overall priority weight of alternatives is computed as follows (Belton, 1986),

$$V_i = \sum_j W_j X_{ij} \tag{3}$$

where V_i = overall priority weight of alternative i, W_j = weight assigned to criterion j, and X_{ij} = weight of alternative i given criterion j.

AHP allows for 10 percent inconsistency in human judgments (Saaty, 1980). To check for consistency in judgments of a decision maker, Saaty (1994) defined the consistency ratio CR which is a comparison between Consistency Index CI and Random Consistency Index RI as follows,

$$CR = \frac{CI}{RI} \tag{4}$$

where CI is given by,

$$CI = \frac{\lambda_{\max} - n}{n-1} \tag{5}$$

where n is the size of the matrix. RI is obtained by computing the CI value for randomly generated matrices. A matrix is considered consistent, only if $CR \leq 0.1$ (Saaty, 1980).

3. ILLUSTRATIVE EXAMPLE

The proposed framework is illustrated considering 5 possible rehabilitation options for each pavement segment: (1) CIR, (2) HIR-Surfacing, (3) HIR-Repaving, (4) HIR-Remixing, (5) HMA-Overlay. The evaluation of environmental implications of various rehabilitation treatments is based on the preliminary results presented by Horvath (2004), as shown in Table 1.

3.1 Structuring a Hierarchy

Once the list of pavement rehabilitation techniques, along with the necessary cost, service life, and environmental emission information, has been identified, the next step is to decompose the problem into individual independent elements by developing a hierarchy. Placed at the top level in the hierarchy, as shown in Figure 1, is the overall objective to prioritize pavement rehabilitation techniques. Next, the factors influencing the objective are translated as criteria, such as cost, service life, and environmental implications, and are placed at the second level. The next level is represented by the individual greenhouse gases as the sub-criterion to the environmental emissions. The final level gives all the alternatives available for rehabilitation.

3.2 Prioritization and Synthesis

Prioritization involves pairwise comparisons between elements residing at the same level in the hierarchical structure. It is recognized that currently there does not exist any theoretical or analytical method that can make pairwise comparisons and determine the relative priorities, therefore a questionnaire survey is proposed for that purpose. Once the priorities are established, the collected data is entered into spreadsheet files, prepared following Saaty's eigenvector method (Millet, 1990) explained earlier, for synthesis and analysis according to Eqs. (1) and (2). All pairwise comparison matrices were checked for consistency using the consistency ratio defined in Eqs. (4) and (5).

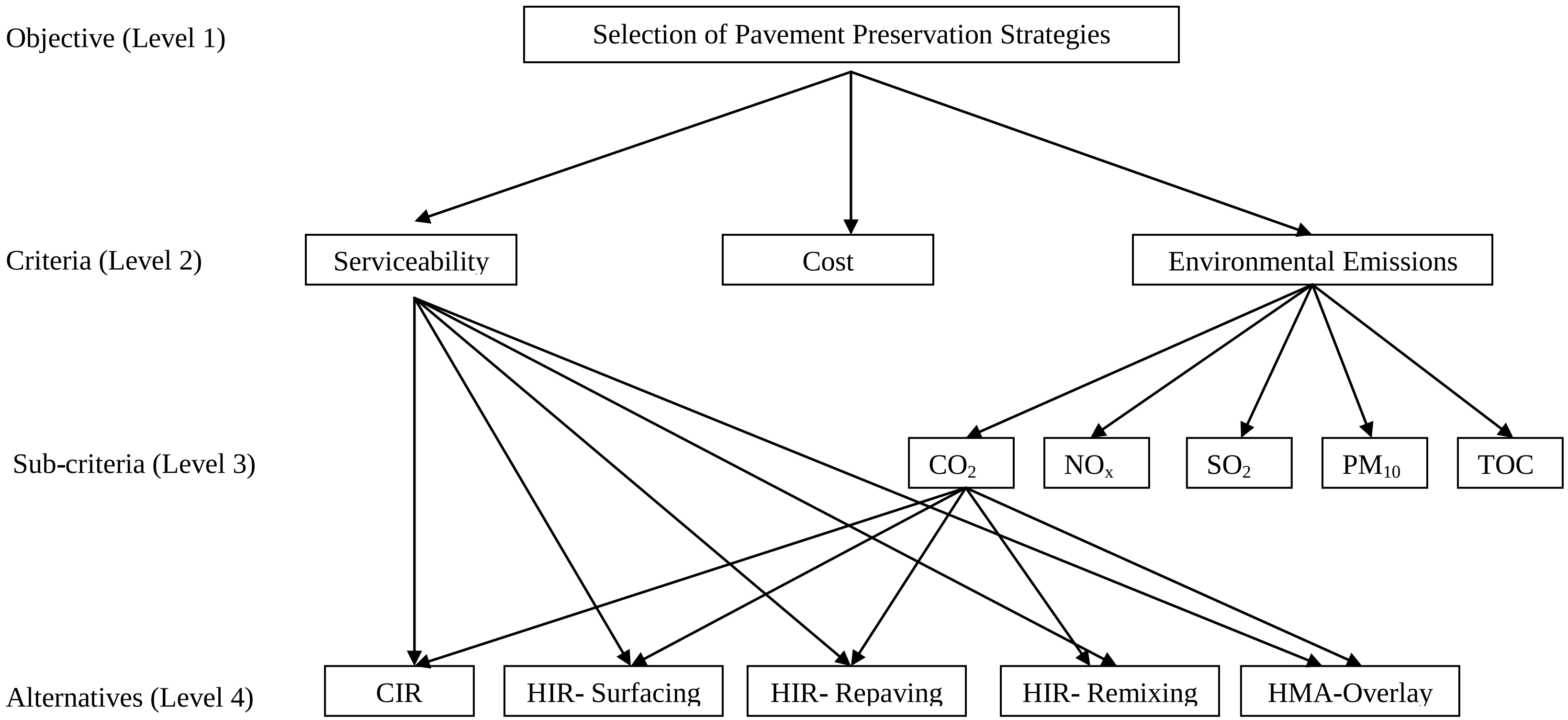

Figure 1: Hierarchy structure for selection of pavement preservation strategies in AHP

Table 1: Comparison of Different Preservation Treatments for Asphalt Pavements

Pavement Preservation Treatments	Parameters				Total Emissions (g/m^2)				
	Treated Depth (mm)	Overlay Depth (mm)	Serviceability (years)	Cost ($/m^2)	CO_2	NO_X	SO_2	PM_{10}	TOC
CIR	101.6	50.8	10	3.09	23,599	16	4	6	4
HIR-Surfacing	25.0	-	5	2.50	172	5	0.30	0.32	0.4
HIR-Repaving	25.0	25.0	8	4.28	11.695	10.1	2.0	3.1	2.1
HIR-Remixing	40.0	19.0	8	3.58	8,964	7.9	1.6	2.4	1.6
HMA-Overlay	-	25.0	6	2.10	12,323	27.1	3.20	4.3	3.5

Source: Horvath (2004)

4. RESULTS AND DISCUSSION

Five pavement engineers were asked to provide priority ratings for the rehabilitation treatments using the AHP method. Each expert was approached independently to perform a rating survey, and subsequently all pairwise comparison matrices were checked for consistency using the consistency ratio defined by Eq. (4). The average priority ratings and ranks obtained from the 5 experts are used in the analysis. Some of the matrices were found to be inconsistent, and the experts concerned were requested to revise their judgments by redoing the survey.

Table 2: Priority Ratings and Rankings of Pavement Preservation Treatment

Pavement Preservation Treatments	Priority Rating	Priority Ranking
CIR	0.23	2
HIR-Surfacing	0.14	5
HIR-Repaving	0.24	1
HIR-Remixing	0.22	3
HMA-Overlay	0.15	4

The results from the AHP prioritization method, in the form of priority ratings and rankings, are tabulated in Table 2. As in the table, HIR-Repaving is ranked as the most preferred rehabilitation treatment followed by Cold In-Place recycling as second, HIR-Remixing as third, HMA-Overlay as fourth, and HIR-Surfacing as the least preferred treatment option.

5. CONCLUSION

This study explored the use of analytic hierarchy process (AHP) for prioritization of pavement rehabilitation treatments involving multiple criteria such as treatment cost, serviceability, and environmental implications. Alternative pavement rehabilitation strategies and their attributes with respect to criteria constitute a hierarchical structure in the AHP method. The proposed procedure was illustrated with an example problem considering 5 possible rehabilitation options. Based on the results from the analysis, HIR-Repaving is ranked as the most preferred rehabilitation treatment followed by Cold In-Place recycling, HIR-Remixing, HMA-Overlay, and HIR-Surfacing. It can be concluded that the analytic hierarchy process can be used to prioritize pavement rehabilitation treatments involving multiple criteria.

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