Status of Pavement Management Systems and Data Analysis Models at State Highway Agencies

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The state of pavement management as practiced by state highway agencies (SHAs) is explored. A survey was conducted of each SHA to determine the stated and implicit objectives of its statewide pavement management system; if the SHA uses a ranking system for priority ranking and selecting projects, what are the mechanics and variables of the ranking system? If the SHA uses an optimization methodology for selecting projects, what is the methodology, what constraints are used, and what is the objective function? At the time of the survey (fall 1991), about a third of the SHAs had developed and were operating a pavement management system that includes network optimization. Sophisticated pavement management systems apply a mixture of the sciences of pavement design, highway maintenance/rehabilitation, and systems analysis. Clearly, SHAs understand the conventional sciences of pavement design and highway maintenance and rehabilitation. However, SHAs are less familiar with system analysis and the science of pavement management systems. As a result, the promotion of the science of pavement management is recommended, as is the development of standard terminology, standard data collection procedures, and structured analysis methodologies. In general, the same is true for the promotion of the science of maintenance management of all types of public infrastructure.

In March 1989 FHWA set a policy requiring that each state highway agency (SHA) have a pavement management system (PMS) (*1*). Each PMS must be based on concepts described in the AASHTO publication *Guidelines on Pavement Management*: "A PMS is a systematic approach to providing highway administrators and engineers with the types of information needed to effectively and efficiently manage their highway pavements" (*2*).

The FHWA policy states that SHAs were to have a PMS operational by January 13, 1993. This paper reports the findings from a survey of SHAs and evaluates the current status (the survey was completed during the fall 1991) of PMS implementation as SHAs work to meet the 1993 deadline.

Besides evaluating the state of the practice, the paper also provides a benchmark for the maturing science of pavement management as practiced by state agencies. As more agencies practice and learn about pavement management, the science of pavement management will be applied more extensively and improved. Structuring a science for pavement management implies developing standard terminology, standard data collection procedures, and structured analysis methodologies.

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Most simply, PMSs can be structured into three components:

- A data base containing information on the pavement inventory; pavement condition data; construction, maintenance, and reconstruction history; traffic data; maintenance, rehabilitation, and reconstruction (MR&R) cost data; and possibly other data (e.g., accident data).
- A data analysis package that uses information in the data base to allocate resources to potential MR&R projects. The data analysis systems used by SHAs vary in sophistication from structured engineering judgment to mathematical programming coupled with statistically based pavement condition forecasts.
- A feedback process to verify and improve the reliability of the PMSs.

Drawing from questionnaires returned by SHAs, the paper explores the state of the practice of the pavement management. Besides determining the progress SHAs are making toward implementing PMSs, the paper identifies the objectives used by SHAs for maintenance resource allocation and identifies the processes used within the data analysis components to allocate resources (usually a ranking system or an optimization model).

METHODOLOGY

Fifty-two questionnaires, each containing four open-ended questions, were mailed to pavement management engineers at the 50 SHAs and the highway agencies in Washington, D.C., and Puerto Rico. Thirty-nine agencies returned the questionnaire, and eight SHAs were interviewed by telephone. The remaining five SHAs did not respond either to the initial letter or to the follow-up telephone contacts. It was thought that the five nonresponsive SHAs were likely to still be in the initial developmental stages of implementing a PMS. The nonresponsive SHAs tend to bias the results, but a 90 percent response rate provides adequate information for assessing the state of the practice.

The questionnaire contained the following questions:

1. Is there a precise objective for your state's pavement management process? If so, what is it?
2. Is there an implicit objective for your state's pavement management process? If so, in your judgment, what is it? (Please do not identify abstract objectives like obtaining

the best pavements for the taxpayers' investment. Please be specific.)

3. How does your state's pavement management process prioritize the allocation of resources to alternative projects? If you have priority-ranking criteria or a ranking matrix, please send a copy to the Iowa Transportation Center.

4. Does your PMS contain a network optimization model (i.e., a mathematical model, such as a linear program)? If it does, what is its objective function? What mathematical programming technique does it use? What are the constraints?

Some SHAs submitted reports documenting their PMSs instead of answering the questions. As a result, the data collected are based on the researchers' interpretation of those reports instead of direct answers to the questionnaire.

For each SHA, a summary sheet was completed with all the answers to the questions. Once a summary sheet was completed for each response, a data base was developed using a spreadsheet program. The data base included 50 columns and 47 rows. Each row corresponded to a SHA, and each column represented specific information. The columns were divided into the following sections:

1. The first section identified whether the SHA has a PMS and, if so, what type of algorithm is used to allocate resources (i.e., prioritization scheme or a network optimization).
2. The second section identified factors used to priority rank projects, if a prioritization system is used.
3. The third section identified the methodology used to predict pavement performance. Generally, pavement performance predictions models are used to generate inputs for multiyear programs developed by network optimization models.
4. The fourth section specified the mathematical programming techniques used in the PMS's optimization models, if an optimization is used.
5. For SHAs using optimization models, the fifth section identified the constraints used in each optimization model.
6. For SHAs using optimization models, the sixth section identified the objective function of the model.
7. In most cases, a state will have general purpose for developing a PMS. For example, one state developed a PMS to help defend itself from accusations of prejudicial resource allocation decisions. These purposes were coded in the seventh section.

Each section was divided into all the possible outcomes for the question dealing with each section issue. For example, in Section 3, the columns were titled linear programming, integer programming, dynamic programming, nonlinear programming, incremental benefit-cost analysis, and marginal cost-effectiveness analysis. These are six optimization techniques employed by PMSs. When an SHA indicated which optimization technique it used, a 1 was placed in the corresponding column; otherwise the cell was left blank.

PRIORITIZATION AND OPTIMIZATION

Several methodologies are used to allocate MR&R resources, and agencies have generated their own unique terminology for these methods. They include pavement ranking criteria, pavement condition analysis, priority assessment models, network-level optimization models, prioritization models, and identification of MR&R strategies (*1–5*). The terminology is somewhat confusing and some agencies have developed unique names to identify similar techniques. However, for the purpose of this paper, methodologies are divided into two categories: project prioritization methods and network optimization.

Project prioritization is a method of data analysis that combines pavement condition data into a score or index that represents overall pavement condition. The pavement score is generally expressed on a scale of 10 to 100. All pavement sections are ranked and categorized by type of pavement, traffic volume, road classification, and other factors related to the pavement section. Some SHAs have more complex ranking criteria for which various factors such as friction, structural capacity, and geometric deficiencies are used to establish pavement section ranking (factors most commonly used for prioritization are identified later in the paper). MR&R resources are allocated on the basis of the pavement section's ranking and the priority assigned to it.

A network-level optimization model identifies the network MR&R strategies that maximize the total network benefits (or performance) or minimize the total network cost subject to network-level constraints such as budget limits and desired performance standards (*2*). The pavement section condition values are used as model parameters, decision variables represent the application of selected MR&R strategies to sections, and resource limits and minimum pavement condition or overall minimum pavement network performance are constraints. The model's decision variables determine which treatments are to be applied to which pavement sections.

Most optimization models consider future pavement condition and allocate resources over a span of several years. Therefore, pavement condition prediction models provide technical input to pavement management network optimization models. The performance prediction methods (used by SHAs) will be discussed later.

Table 1 gives the percentage of the SHAs that are or will be capable of performing each level of data analysis. The percentages in the third column of Table 1 total to more than 100 percent because SHAs that use an optimization model often also have a prioritization methodology.

Of the surveyed SHAs, 77 percent priority rank projects and 2 percent plan to implement a prioritization model. Twenty-eight percent of the responding SHAs have network-level optimization models, and an additional 19 percent will have optimization models in the future. Four of the 47 SHAs did

TABLE 1 Agencies with Data Analysis Capabilities

Data Analysis Capability of Agency	Number	Percentage
No PMS	4	9
Prioritization model	36	77
Plans for prioritization model	1	2
Optimization model	13	28
Plans for optimization model	9	19

not have a PMS implemented (as of fall 1991) but were working with a consultant or in-house to develop one.

FACTORS USED TO PRIORITY RANK PROJECTS

Several models exist for developing priority indexes. Usually they are composites of several pavement section condition measures. SHAs were found to use one or more of the condition measures listed in the following; the frequency of their use is identified in Table 2.

- Pavement distress: The evidence of defects in the pavement (e.g., ruts, cracks, potholes, faulting, and blow-ups) is considered pavement distress.
- Ride or pavement roughness: Roughness is a measurement of a vehicle's response to roughness of the pavement profile.
- Traffic: Traffic is generally taken into account through using the average daily traffic volume or estimating equivalent single-axle loadings that a pavement has received. Pavement sections with higher traffic volumes usually receive higher priorities.
- Economic factors: When a treatment is assigned to a project on the basis of life-cycle cost analysis, several economic factors may be used in prioritization, including benefit-cost ratios and cost-effectiveness ratios.
- Functional class: Although several functional classification schemes are used by SHAs, functional classification is sometimes used in prioritization and results in higher-classification roadways' receiving a higher priority.
- Accidents: Accident rates are often taken into consideration when ranking projects, especially with regard to safety-related maintenance activities.
- Friction or skid resistance: Skid resistance is a major component when safety-related maintenance is evaluated.
- Geometric deficiencies: Some SHAs consider the number of specific geometric deficiencies that could create safety problems when selecting MR&R projects. This assumes that the geometric deficiencies could be corrected through MR&R activities. Typical geometric deficiencies used are the number of narrow structures per mile, shoulder width, number of substandard stopping sight distances, lane width, and substandard horizontal curves per mile (*6*).
- Structural capacity: Most SHAs measure the structural capacity of a pavement through measuring the deflection or curve of the pavement that results from a static or repeated load.
- Engineering judgment: Some agencies structure their priority-ranking criteria to include engineering judgment or to be primarily based on engineering judgment.
- Age: When age is taken into account, it generally enters the priority analysis through measuring the number of years the pavement's performance will remain acceptable (remaining service life concept).
- Location: Some SHAs will provide a higher priority to a pavement on the basis of its strategic location. For example, highways that serve production centers, schools, and military facilities must be maintained in good condition without risking possible road closing.

TABLE 2 Factors Used To Priority Rank Projects

Factor	Number	Percentage
Distress	27	57
Ride	21	45
Traffic	19	40
Economics	8	17
Functional classification	7	15
Accident rate	6	13
Friction	5	11
Geometric deficiencies	5	11
Structural capacity	4	9
Engineering judgment	3	6
Age	3	6
Location	1	2

As presented in Table 2, distress, ride, and traffic are the most common factors used in pavement section priority indexes. However, it is clear that there is a great diversity in the conditions included in the priority indexes. Only distress is used by more than half of the SHAs surveyed.

MATHEMATICAL PROGRAMS USED IN OPTIMIZATION MODELS

Thirteen SHAs use network optimization models. Only four strategies are in use, however, and other mathematical program techniques, including dynamic programming, have been proposed (*7*). The distribution of the four approaches are as follows:

Technique	*Number*	*Percentage*
Linear programming	7	55
Integer programming	2	15
Incremental benefit-cost	2	15
Marginal cost-effectiveness	2	15

Linear and integer programs are two widely used mathematical programming techniques and are commonly applied to solve a range of problems in all sectors of government and business. They are naturally suited to issues dealing with resource allocation. Incremental benefit-cost is a recursive algorithm and seeks to allocate each increment of resources to projects that provide the largest possible increment of benefit. A close cousin to incremental benefit-cost is marginal cost-effectiveness. The primary difference in the two methods is the terminology used (benefits versus effectiveness). However, both should result in the same solution.

PAVEMENT PERFORMANCE PREDICTION METHODOLOGIES

Performance is the "ability of a pavement to fulfill its purpose over time" (*2*). A prediction method is "a mathematical description of the expected values that a pavement attribute will take during a specified analysis period" (*2*). Prediction models provide parameters to pavement management optimization so that they can base the selection of future MR&R programs on the forecasted conditions.

Although most prediction models are deterministic, probabilistic models are being implemented in SHAs. The prediction models identified in the survey are as follows:

- Performance curves: A performance curve defines variations of pavement attributes over time. SHAs create performance curves for their particular conditions. An SHA will have as many performance curves as different pavement types exist in its jurisdiction. In other words, a bituminous pavement with high traffic and low subgrade strength may have a different performance curve than a concrete pavement with low traffic and medium subgrade strength. Performance curves normally calculate expected serviceability and age relationship over the entire design period (*3*). Other attributes or indexes can also be used to establish new relationships. These include structural capacity versus age, skid resistance versus age, and a measure of distress versus age. The relationship between the variables is commonly estimated using regression.
- Markov chain: The Markov chain is a probabilistic model that accounts for the uncertainties present with respect to both the existing pavement condition and future pavement deterioration. The underlying concept of this method is that a pavement section may be in one of several states or conditions and that unless maintenance or rehabilitation is undertaken, the condition of the pavement will worsen over time. The amount of pavement deterioration in a given period, such as a year, is a random variable depending only on the most recent state of the pavement and the amount and type of traffic loading that the pavement accrues during that period of time.

One of the difficulties of using a Markov chain model for predicting performance is that it predicts the proportion of the entire pavement network falling into each pavement condition category during each future period. Because it forecasts the distribution of future pavement conditions, it does not predict the specific condition of a specific section and does not allow any later project-level analysis. A Markov chain model is only useful for network-level analysis.

- Survival rate: When an MR&R treatment is applied, a pavement section increases its condition rating. The potential gain of rating is defined as the net expected increase of pavement rating of the section. To predict the effects of MR&R treatments over a chosen planning period, the potential rating gain is affected by a pavement survival rate. For each section, a pavement survival matrix, which that contains the survival probability for each distress type and MR&R treatment, is developed. The term "survival" indicates that the pavement condition is still expected to rate high enough that it will not require additional MR&R work at a future specified point (*8*). For each specific highway section, each particular MR&R strategy, and each distress, the survival probability (or rate) decreases with time. For example, for Year 0, when the treatment is applied, the survival probability is 1; at Year 2, it could be 0.8; at Year 4, 0.5, and so forth. If, for example, the rating change of a particular pavement section is desired 3 years after a certain treatment is applied, the potential gain of the pavement section due to the treatment application at Year 0 is multiplied by the survival probability for that section and treatment for Year 3.

This prediction method is quite data-intensive. Data sets must be collected to develop each pavement survival matrix for each pavement category. This information is managed in the form of vectors and matrices when all the sections, distresses, and MR&R strategies are analyzed together. This method of prediction looks at the effect of each MR&R treatment on each type of distress of a pavement section. Therefore, it is used in optimization models that look for maximum maintenance effectiveness.

The following table shows the number of SHAs that use each of the three prediction models:

Performance Prediction Method	*Number*	*Percentage*
Performance curve	6	46
Markov chain	5	38
Survival rate	1	8
Did not identify	1	8

The choice of pavement prediction modeling methodology is linked to the optimization method selected and the objective of the pavement management optimization. As mentioned, the Markov chain is a prediction tool only for network-level optimization and thus linked to network-level analysis, network objectives, and specific optimization techniques.

CONSTRAINTS USED IN OPTIMIZATION MODELS

When selecting projects, SHAs are constrained by different factors. All proposed projects cannot be funded in a single year or even through a multiyear funding plan. Some SHAs did not identify a specific constraint and others specified more than one. The following constraints were identified in SHAs with optimization models:

- Budget: The budget is the maximum level of funding available in 1 year or in several years over a multiyear plan. The constraint would ensure that the solution does not exceed the available budget.
- Minimum pavement condition requirement: This constraint could be either a minimum average network performance or a maximum percentage of sections allowed below the minimum acceptable value.
- Resources: Resources for pavement MR&R can be categorized as materials and supplies, equipment, or personpower (*8*). Similarly to a budget constraint, a resource constraint does not allow the solution to exceed the amount of available resources.
- Others: Some SHAs included constraints such as the number of days available to perform construction activities (this is particularly important in Snow Belt states where cold weather restricts the number of days in which maintenance can be performed), local legislative requirements, and political issues (e.g., equal distribution of funds to geographic districts of a state).

The following table summarizes the frequency with which each type of constraint is used by the 13 SHAs that operate a network optimization model:

Constraint	*Number*	*Percentage*
Budget	13	100
Minimum pavement condition requirement	5	39
Resources	2	15
Other	5	39

OBJECTIVE FUNCTIONS USED IN OPTIMIZATION MODELS

Each of the mathematical programming techniques requires a specific objective function. Mathematical programs select solutions to decision variables that optimally satisfy the objective function subject to the identified constraints. Four categories of objective functions were employed by SHAs using network optimization:

- Minimize cost: When various MR&R strategies are available for each project in the analysis period, the alternatives that satisfy the constraints and generate the lowest overall cost are selected.
- Maximize area under performance curve: When an MR&R strategy is assigned to a pavement section, a performance curve for this section is predicted. The area under this curve is a measure of effectiveness and is a surrogate for the benefit of applying the treatment. The optimal combination of strategies will be those that maximize the combined increase in the area under all the performance curves while satisfying the optimization's constraints.
- Minimize disutility: Instead of predicting pavement performance, some agencies predict the severity of distress, the level of maintenance costs, or the user cost. The area under these curves is called disutility. The objective function defines the selection of treatments that minimize disutility.
- Maximize maintenance effectiveness: This is the ability of a treatment strategy to eliminate a particular distress type for as long as possible (*8*). For example, in a pavement section for which rutting is a problem, the treatment that eliminates the ruts from the pavement for the longest amount of time will be the one selected. An optimization model can use this objective function when survival rates are used to predict the performance of each pavement section for each distress type.

The following table summarizes the objective functions used by the 13 SHAs that operate network-level PMSs (because some optimization models can use more than one objective function, the percentages do not total 100):

Objective Function	*Number*	*Percentage*
Minimize cost	8	62
Maximize area under performance curve	5	39
Minimize disutility	1	8
Maximize maintenance effectiveness	1	8

CONCLUSIONS

The state of the practice in pavement management is still in the developmental stages. All SHAs either have a PMS or are working to achieve an acceptable PMS. Roughly a quarter of the SHAs have advanced their PMSs to the network optimization level. The results presented here, however, indicate that more states use a network optimization model than was previously estimated (*4*).

Given the widespread use of pavement management, it seems clear that there is a need to promote the development of the science of pavement management. More specifically, a mature science of pavement management should have a common terminology, standard data collection procedures, and comparable data analysis methods. To the contrary, through the survey it was found that different agencies sometimes use incomparable terminology, that some agencies did not appear to understand the objectives of the analysis models imbedded within their own PMS computer software, and that little technical information on the science of PMSs appears to be shared between states. At the national level, the researchers believe that it is time to promote the science of pavement management. It is probably also true that the science of maintenance management of all types of public infrastructure needs to be developed into a more formal and structured field of knowledge. In prior research, we have noted that maintenance management training is painfully lacking in conventional engineering education and continues to be an area desperately needing improvement (*9*).

One of the more specific conclusions is that there appears to be no unanimity in the inputs to the pavement management process or to the analysis methods and objectives used. SHAs have selected diverse analysis tools and methods for use within their PMSs. For example, in the development of a composite measure for priority ranking pavement MR&R work, there is little consensus on which factors are important. Distress is the most frequently used factor in pavement priority indexes, but only about half of the SHAs used distress in their prioritization methodology. Inputs to the prioritization process include one or more of 11 categories of pavement condition measures and other economic, traffic, or safety factors. Even though only 13 SHAs have reached the level of performing network optimization, four fundamentally different methodologies are being applied and other optimization methodologies are being proposed or developed (*7*).

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