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Highway Asset Management

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66.1 Introduction

The United States has nearly 4 million miles of highways and streets and more than 550,000 bridges of at least a 20-ft span. Constituting the largest government-owned asset in the country, highways are associated with annual investment levels exceeding $1 trillion [FHWA and AASHTO, 1996]. Transportation agencies at all levels of government have the responsibility of effectively managing the performance and usage of their physical assets so that such assets can be kept in acceptable condition to provide desirable levels of service with available resources. Given the ever-increasing commercial and personal travel demands vis-à-vis limited resources, this task is more critical than ever before. Management of highways has come of age because of changes in the transportation environment, changes in public expectations, and extraordinary advances in technology. Defined as a systematic process of maintaining, upgrading, and operating physical assets cost-effectively [FHWA, 1999], highway asset management combines engineering principles with sound business practices and economic theory and provides a tool to facilitate a more organized, logical, and integrated approach to decision making. The recent issuance of Governmental Accounting Standards Board Statement 34 (GASB34) established new financial reporting requirements for state and local governments to ensure safekeeping and appropriate use of public resources and operational accountability [GASB, 1999]. GASB34 therefore helped usher in a new era in highway asset management. While most state and local highway asset management systems are in their nascent stages of development, the various component management systems that will ultimately constitute an overall highway management system are fairly well developed in most states. These include pavement, bridge, maintenance, traffic, and safety management systems. A discussion of the three dimensions (physical facilities, operational functions, and system objectives) that are associated with the various management systems is presented in this chapter.

66.2 Financial Accounting Issues

Historically, public agencies have not calculated the value of their infrastructure for three reasons: (i) provision of the infrastructure was for the benefit of individuals and groups external to the providing agency, (ii) agencies were not held accountable for the stewardship of the value of their infrastructure, and (iii) revenue was not often linked to maintaining the value of the infrastructure. GASB34 provided a new financial model for state and local governments and required all such agencies to provide a value of the infrastructure assets, among others. Considered the most significant pronouncement in the history of government financial reporting, GASB34 constitutes a vital part of overall financial accounting standards and government accounting standards. These standards are aimed at assessing public accountability for resources collected and spent, identifying how the choices of state and local governments affect their financial positions, assessing the levels of service that can be provided, and determining whether the governments can meet obligations when they are due.

It is expected that GASB34 will result in the generation of useful information that will educate and guide the public, including issuers, auditors, and users of government financial reports — citizens and their representatives, the municipal bond industry, and investors among them. The relationship between GASB34 and highway asset management is reflected in the requirement that government-wide financial statements should include a statement of net assets that includes highway infrastructure. Furthermore, highway infrastructure expenditure is no longer treated as sunk costs but is considered as a capital cost or expense item, therefore providing a new accounting perspective of such costs. The key elements of infrastructure reporting for GASB are an inventory of the assets (type and extent) and a valuation of the assets. The valuation of highway assets, apart from satisfying the requirements of GASB34, is expected to ensure accountability of stewardship responsibilities of such assets, enable cross-category investment comparisons, ensure budget justification and requests, and foster strategic investment decision making [Maze, 2001]. There are two major approaches for assessing the value of highway assets: the modified approach and the depreciation approach [GASB, 1999].

The Modified Approach for Highway Asset Valuation

This approach assumes that the asset is preserved approximately at or above prescribed condition standards through timely maintenance and rehabilitation. Agencies that use this approach do not have to account for depreciation if they can demonstrate that the asset is being preserved. For financial reporting purposes, initial construction and major improvement costs are capitalized, while preservation and maintenance outlays are treated as expenses. This approach focuses attention on asset management practices and preservation outcomes. It is expected that asset preservation can be demonstrated by maintaining up-to-date records of the inventory, condition, and costs (budgeted and incurred) to preserve the assets.

The Depreciation Approach for Highway Asset Valuation

This approach assumes gradual deterioration of the asset over its service life and consequently reduces the recorded value of the asset on the balance sheet through depreciation. In this approach, initial construction, improvement, and preservation costs are capitalized, while maintenance is considered an expense. The current value of the asset is established using an appropriate deterioration function. The depreciation approach requires data such as initial costs, estimated salvage value, expected service life, current age of the asset, and remaining service life.

Summing up, it is apparent that GASB34 provides a major impetus for applying financial asset management practices to state and local infrastructure and has far-reaching implications on the management of highway assets. For instance, it is envisaged that state and local governments will demand greater authority over allocation of federal aid funds and that valuation-based securitization of infrastructure expenditure will help pay for compliance efforts and rehabilitation [Dornan, 2001]. Furthermore, the establishment of a common framework for developing a comprehensive database and decision support system is foreseen. Through such developments, it is expected that highway asset management will support economic development in a more visible and cost-effective manner. It is also envisaged that highway assets will be better planned, designed, and maintained to ensure maximum possible levels of service at minimum possible life cycle cost (LCC). Other expectations are that bond financing for highway assets will become more feasible as the value of the assets become known, predictions of life cycle costs will be more reliable, and private sector financial discipline can be infused into highway asset management. Finally, as the public sector gets more and more involved in highway asset management through outsourcing of line functions, financial participation, or possible asset ownership or operation, overall costs could be lowered and funding for asset repair or replacement would be made more available.

66.3 Dimensions of Highway Asset Management

Sinha and Fwa [1989] defined the concept of a comprehensive highway system management, which can be considered in terms of a three-dimensional matrix structure, with dimensions representing highway facilities, operational functions, and system objectives, as shown in Fig. 66.1.

Highway Physical Facilities

Any highway system involves a number of physical facilities, such as pavements, bridges, drainage structures, traffic control devices, and roadside elements. Each facility plays a unique role in the delivery of transportation services. For instance, pavements, bridges, and drainage structures carry traffic. Traffic control devices foster smooth traffic flow and safety, and roadside elements enhance convenience and aesthetics. Each highway physical facility is associated with one or more component management systems of highway asset management. Activities performed on pavements, bridges, and drainage structures unavoidably affect flows of traffic and cause delay to road users. Maintenance and rehabilitation activities related to roadside elements and some traffic control devices may, however, be managed without major traffic disruption. The differences between highway facilities are reflected in their life cycle spans. The varied life cycle spans among the facilities, coupled with the differences in the types of services they provide, necessitate the adoption of different management strategies for each facility. Consequently, it is common practice in field operations to consider management of different facilities independently. Furthermore, the multiple-element structure of highway facilities implies that several facilities compete for funds and other resources available to a highway agency. The overall effectiveness of the highway system depends on the levels of service provided by the individual facilities. As resources are limited, optimal

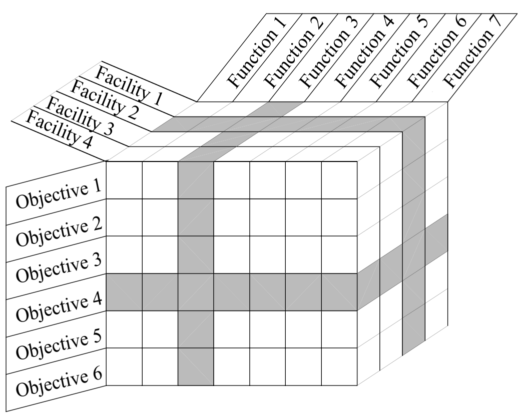

FIGURE 66.1 Three-dimensional matrix structure of a highway asset management system.

allocation among the various facilities must be ensured. Any activity on each facility element has an impact in the realization of system objectives of highway asset management. Therefore, the relative importance of each facility element needs to be assessed for a logical resource allocation.

Operational Functions

An operational function is an activity carried out on or related to a highway facility in order to achieve a system objective. In the management of each highway facility element, the following operational functions are involved: planning, design, construction, condition and usage monitoring and evaluation, maintenance, rehabilitation, and data management. Each operational function is related to one or more component management systems of highway asset management. The planning phase involves the preparation of capital expenditure programs for highways based on overall network needs, such as facility expansion and system preservation. This phase also covers demand analysis and estimation of facility needs to accommodate the current and future traffic. There are several priority programming methods available for selecting highway capital projects. However, project selection is currently often carried out on the basis of historical trends or regional needs estimates. The operational functions associated with design generate alternative facility configurations, analyze the alternatives, and evaluate and select the optimal configuration. Construction involves the management of funds, time, manpower, materials, and equipment to transform designs into physical realities. The major aspects of the construction function are preparation of specifications and contract documents, scheduling of construction activities, control of costs and quality of construction, and monitoring of work progress. Operational functions relating to facility condition and usage monitoring and evaluation, as well as to facility maintenance and rehabilitation, are currently the main focus of most facility management systems in the United States. Condition evaluation includes facility condition survey, analysis and prediction of facility performance, and decision analysis on actions required.

System Objectives

System objectives are specified levels of selected performance indicators relating to the condition or usage of the physical facility. The highway asset management process is associated with multiple objectives. Such objectives include specified levels of service for traffic congestion and safety, preservation of the facility condition at or above a desired level, minimization of agency and user costs, maximization of socioeconomic benefits, and minimization of energy use and environmental impacts. To facilitate the task of highway management programming, system objectives may be assessed quantitatively by means of highway performance indicators. As performance indicators provide indications of the degree of fulfillment of system objectives, priority ranking of facilities can be established based on the relative values of performance indicators. Such indicators may be used for comparison of the effectiveness or adequacy of alternative strategies within pavement, bridge, safety, or congestion management. They can also easily be incorporated into a mathematical optimization programming model for highway management. As in any complex multiple objective system, difficulties may exist in achieving desired levels of system objectives within a given period of time.

Within each of its component management systems, highway asset management incorporates information from each of the three dimensions to select specific operational functions (e.g., maintenance) to be carried out on a physical facility (e.g., pavements) such that maximum possible levels of system objectives (e.g., minimize total network roughness) are realized within given constraints. For this task to be carried out properly, it is necessary, among other requirements, to determine any trade-off relationships that may exist between various operational functions for a given facility or across facility types. An example is the tradeoff between rehabilitation frequency and maintenance expenditure [Labi, 2001]. Given its multidimensional nature and the multiplicity of elements in each dimension, it is vital that the ideal highway management system be comprehensive and coordinated yet flexible and sensitive enough to adjust to changes in the highway transportation environment and public perceptions. Management systems that developed over the last two decades and play a role similar to asset management, albeit in a disintegrated fashion, are described below.

66.4 Component Management Systems for Highway Asset Management

In a bid to enhance their ability to diagnose existing and potential problems throughout the entire surface transportation network, and to evaluate and prioritize alternative strategies, several states have developed various management systems. These management systems include the pavement management system (PMS), bridge management system (BMS), traffic congestion management system (CMS), highway safety management system (SMS), and intermodal management system (IMS). In addition, many states have developed maintenance management systems (MMS) to aid in planning and evaluating in-house maintenance work on pavements and bridges. PMS, BMS, and MMS are oriented toward the physical state of the highway assets, as their primary purpose is to inventory, track, and address the conditions of the various components of the highway network and assist in establishing cost-effective strategies to sustain acceptable conditions of such facilities. On the other hand, SMS and CMS focus on the operation and performance of the transportation network.

The integration of the various component management systems for overall highway asset management has been aptly recognized, implicitly or explicitly, by various researchers [Sinha and Fwa, 1989; Markow et al., 1994]. With effective coordination among various component management systems, it is expected that the impacts and tradeoffs of current and future alternative policies or investments within or across management systems can be evaluated. The various management systems are described in the following sections.

Pavement Management Systems

A pavement management system is a set of tools that assist decision makers in finding optimum strategies for providing and maintaining pavements in a serviceable condition over a given period of time. In its broad sense, pavement management includes all activities involved in planning and programming, design, construction, maintenance, and rehabilitation of the pavement element of a highway. There are three principal components in a PMS: data collection and management, analysis, and feedback and updates [Haas et al., 1994]. The function of a PMS is to improve the efficiency of decision making, expand the scope of the decisions, provide feedback on the consequences of decisions, facilitate the coordination of activities within the agency, and ensure the consistency of decisions made at different management levels within the same organization. Pavement management must be capable of being used in whole or in part by various technical and administrative levels of management in making decisions regarding individual projects or entire highway networks. At the network level, agency-wide programs for new construction, maintenance, or rehabilitation are developed such that overall cost-effectiveness is maximized over a given analysis period. At the project level, detailed consideration is typically given to alternative design, construction, maintenance, or rehabilitation activities for a particular section or project within the overall program that will provide the desired benefits or service levels at the least total cost over the analysis period.

Usefulness of Pavement Management Systems

PMS outputs required at various levels are considerably different in detail and format. Midlevel end users of PMS outputs typically require detailed information, while top-level management requires information that is relatively more concise and graphic in nature, highlighting only salient features such as overall (or average) pavement condition and expenditure by functional class, spatial and temporal trends in pavement condition and expenditure, monetary backlogs, and amount of travel and user costs. PMS outputs are useful for identifying pavement network extent, usage, and other pavement-related attributes and also for analyzing current and historical pavement conditions as well as the impacts of alternative funding options. A PMS generates data that are needed for the development of single- and multiyear programs, establishing treatment selection methodologies, applications in construction, design and materials, applications in maintenance, and applications in research. Other uses of a PMS include its role in effective pavement-related decision making and marketing, interaction between top management and politicians, and interaction between the public, legislators, and top management.

Legislators have final authority over allocation of funding for state operation, including rehabilitation of highway infrastructure. As representatives of their constituencies, they also have the responsibility to represent their constituencies in the best manner possible and to ensure that their road network is in good condition and deficient roads are rehabilitated. Legislators and state management are ultimately accountable to the public for their actions, especially those in regard to money and priorities. Therefore, top-level state highway management needs to be responsive to the political environment and its own public image. In that regard, a PMS can be a useful tool by providing a means of marketing pavement needs, demonstrating accountability, and justifying project priorities; it can also help in image building and in the credibility of management.

A PMS produces a single- or multiyear rehabilitation program through various methodologies. The simpler ones include ranking by at least one distress type, prioritization, and optimization. All such methodologies seek to develop a program that represents the best value for the money, often called an optimum program. As state and local PMS evolve over time, their database modules accumulate performance and other pavement-related data. Such data have led to a better understanding of the performance of various rehabilitation treatments on different types of existing pavement structures and are therefore useful for pavement maintenance and rehabilitation decision making. Decision mechanisms are then used by highway districts or central offices to recommend rehabilitation treatments for various road segments. Performance data can also be, in turn, fed back into the PMS to make future predictions and applications of the system more accurate and reliable. With regard to pavement construction, a PMS enables the evaluation of the effectiveness of various alternative construction techniques and materials. Regarding pavement design, a PMS can be used for the evaluation of different pavement rehabilitation designs and to generate data for the design of new pavement structures. Pavement maintenance activities affect pavement performance and, consequently, service life. Information obtained from a pavement management system is vital in the determination of tradeoffs between maintenance expenditure and rehabilitation cycle length. Such tradeoffs are important aspects of overall highway asset management.

Data Collection and Management

As a PMS database is a critical part of the PMS decision support system, PMS data requirements have to be properly identified. Therefore, a statistically adequate data collection system needs to be established to meet these requirements, and a database structure has to be designed, followed by acquisition of the necessary hardware and software for the database operation. The physical and logical design of the database should ensure data integrity, reliability, and security.

PMS Data Types

The data items to be collected and included in the database will depend on the management analysis needs of the agency, which in turn will depend on the types of infrastructure, the available resources, and the organizational units that will use the data. Data needs of a typical PMS are classified as follows:

Road inventory data: Road classification data include items such as functional class of road, identification codes, location, and reference points. Such data may also include geometric characteristics such as number of lanes, lane widths, and shoulder widths.

Pavement structure and subgrade data: Pavement data items include pavement type, layer thickness, and material characteristics. Subgrade characteristics such as drainage coefficients, modulus of resilience, particle size distribution, and consistency limits and indices should also be taken into account. Data may also include groundwater levels and moisture content.

Traffic-related data: Traffic volume and classification data are obtained from traffic counts and surveys. Such data include annual average daily traffic (AADT), vehicle classifications, lane distribution, and directional distribution. Also, available data on the axle load levels and distributions should be included in the database.

TABLE 66.1 Surface Distress Types for Asphalt Pavements

Distress Type	Unit of Measure
Cracking	
Fatigue cracking	Square meters
Block cracking	Square meters
Edge cracking	Meters
Wheel-path longitudinal cracking	Meters
Non-wheel-path longitudinal cracking	Meters
Reflection cracking at joints	
Transverse reflection cracking	Number, meters
Longitudinal reflection cracking	Meters
Transverse cracking	Number, meters
Patching and Potholes	
Patch/patch deterioration	Number, square meters
Potholes	Number, square meters
Surface Deformation	
Rutting	Millimeters
Shoving	Number, square meters
Surface Defects	
Bleeding	Square meters
Polished aggregate	Square meters
Raveling	Square meters
Miscellaneous Distress	
Lane-to-shoulder drop-off	Millimeters
Water bleeding and pumping	Number, meters

Source: SHRP, *Distress Identification Manual for the Long-Term Pavement Performance Studies*, National Research Council, Washington, D.C., 1993.

Pavement condition data: Pavement condition may be represented by measures based on aggregate data (such as roughness) or disaggregate data (such as present serviceability index, which accounts for the occurrence frequencies and severities of various individual distresses). Tables 66.1 to 66.3 show surface distress types for asphalt pavements, jointed concrete pavements (JCP), and continuously reinforced concrete (CRC) pavements, respectively [SHRP, 1993].

Other indicators of pavement condition include skid resistance, which is measured by a coefficient of friction and depends on the nature of and the amount of water on the pavement surface. The load-carrying capacity of an in-service pavement can be measured directly by full-scale load tests or indirectly by measuring material properties of each pavement layer, to be used subsequently in load-response calculation. Also, measurement of pavement material properties can be carried out by means of field tests, laboratory tests of cored samples, or nondestructive tests using modern equipment and advanced technology such as deflection equipment.

Climatic and Environmental Data — Data on climatic conditions, such as precipitation and temperature-related factors (freeze index, freeze–thaw cycles, and depth of frost penetration), are useful in the development of pavement deterioration models. Also, relationships that enable the estimation of pavement temperature from air temperature are useful.

Maintenance and Rehabilitation Data — These include information on work activity type, types and levels of resources used (equipment, manpower, and materials), and cost of any routine or periodic pavement maintenance carried out in-house or by contract. Such data may be transformed to reflect work done per lane mile, and costs involved need to be brought to the constant dollar to address the changing values of money over time.

Data for Economic Evaluation — Alternatives are evaluated by comparing their costs and benefits. Cost data for maintenance, rehabilitation, and replacement actions are essential to estimate agency costs and

TABLE 66.2 Surface Distress Types for Jointed Portland Cement Concrete Pavements

Distress Type	Unit of Measure
Cracking	
Corner breaks	Number
D cracking	Number of slabs, square meters
Longitudinal cracking	Meters
Transverse cracking	Number, meters
Joint Deficiencies	
Transverse joint seal damage	Number
Longitudinal joint seal damage	Number, meters
Spalling of longitudinal joints	Meters
Spalling of transverse joints	Number, meters
Surface Defects	
Map cracking	Number, square meters
Scaling	Number, square meters
Polished aggregate	Square meters
Pop outs	Number, square meters
Miscellaneous Distress	
Blowups	Number
Faulting of transverse joints and cracks	Millimeters
Lane-to-shoulder drop-off	Millimeters
Lane-to-shoulder separation	Millimeters
Patch/patch deterioration	Number, square meters
Water bleeding and pumping	Number, meters

Source: SHRP, *Distress Identification Manual for the Long-Term Pavement Performance Studies*, National Research Council, Washington, D.C., 1993.

TABLE 66.3 Surface Distress Types for Continuously Reinforced Concrete Pavements

Distress Type	Unit of Measure
Cracking	
D cracking	Number of slabs, square meters
Longitudinal cracking	Meters
Transverse cracking	Number, meters
Surface Defects	
Map cracking	Number, square meters
Scaling	Number, square meters
Polished aggregate	Square meters
Pop outs	Number, square meters
Miscellaneous Distress	
Blowups	Number
Transverse construction joint deterioration	Number
Lane-to-shoulder drop-off	Millimeters
Lane-to-shoulder separation	Millimeters
Patch/patch deterioration	Number, square meters
Punch-outs	Number
Spalling of longitudinal joints	Meters
Water bleeding and pumping	Number, meters
Longitudinal joint seal damage	Number, meters

Source: SHRP, *Distress Identification Manual for the Long-Term Pavement Performance Studies*, National Research Council, Washington, D.C., 1993.

budget requirements. For activities performed in-house, data on benefits can be combined with unit cost data to obtain estimates of costs of alternatives. Benefits include user and nonuser benefits. User benefits include reductions in vehicle operating costs, travel time, delay, accidents, and pollution. Data regarding the different components of vehicle operating costs, as well as travel time, delay, crashes, and pollution, are used to estimate user benefits.

Sampling Techniques for Data Collection

Due to the typical large size and wide coverage of state highway networks, it is often considered impractical to collect data for the entire network. It is common practice to apply the statistical sampling theory in data collection so that a sufficient number of pavement segments representative of the overall network are determined for survey and testing [Mahoney and Lytton, 1978]. Some of the common sampling techniques are as follows:

Simple random sampling method: In this method, all highways considered in a survey are first divided into segments of either equal length or uniform pavement characteristics. Each pavement segment constitutes a sampling unit in the sampling process. A random sampling is then carried out to select the pavement segments for the survey. Each segment has an equal probability of being chosen. This method is more likely to be used at the project level, where pavement segments with similar characteristics are usually involved.

Systematic random sampling method: This method requires all sampling units of equal length or of uniform pavement characteristics to be randomly ranked, and every rth element of the ranked list is selected. The first sampling unit is sampled at random between 1 and r, say the mth unit. The final sample will therefore consist of sample unit number m, $(r + m)$, $(2r + m)$, $(3r + m)$, and so on. The use of this method is associated with limitations similar to those with simple random sampling.

Stratified random sampling method: This method first divides all pavement segments into different groups or strata on the basis of certain selected characteristics, such as function class or pavement type. The next step involves random sampling within each stratum to select the desired number of pavement segments. This method ensures that pavements of all highway functional classes and pavement types are represented in the sample.

Single-stage cluster sampling method: This method involves two steps. First, pavement segments are grouped into different clusters. Next, a random sampling process selects the clusters to be included in the survey. The pavement segments in the selected clusters are sampled. This method is useful for selecting subdivisions of a network for a survey.

Multistage cluster sampling method: This is an extension of the single-stage cluster sampling method. After clusters are randomly selected in the first step, another random sampling is performed within each selected cluster to sample subclusters for the survey. This process can be carried out repeatedly as desired.

Sample Size Requirements for Data Collection

The objective of sample size selection is to achieve a balance between data precision and cost of collecting data. There is no clear-cut criterion for the selection of optimum sample size, as it depends on the precision set by the pavement agency as well as the level of funds available [Mahoney and Lytton, 1978].

Sample Size for Time Variation of Pavement Condition — Time variations of different pavement condition measurements are an important consideration in pavement management. The time rate of change of a pavement condition measure provides useful information to engineers involved in decision making concerning pavement maintenance and rehabilitation. Therefore, the magnitude of sample size selected must be able to detect a certain minimum variation at the confidence level. The following equations can be used as a guide:

$$m = \frac{Z^2}{2\left(P_1 - P_2\right)^2}$$

$$n = \left(\frac{m}{m + N}\right)N$$

where P_i = the proportion of the total road mileage studied at time period i that has a distress greater than the acceptable level, a ride quality lower than the specified minimum, or a skid resistance lower than the minimum level ($i = 1, 2, \ldots$)

n = the number of pavement segments required to detect a change equal to $(P_1 - P_2)$ of specified pavement condition

N = the total number of pavement segments considered

Z = the normal distribution statistics, equal to 0, 1.645, and 1.96 for confidence levels of 50, 90, and 95%, respectively.

Number of Tests Required per Pavement Segment — In order to provide a sufficiently precise estimate of the mean and standard deviation of the pavement response investigated, the number of test measurements to be conducted in each pavement segment need to be decided. More precise estimates can be achieved by increasing the number of tests, but at a higher cost. The statistical relationship between precision and the number of tests can be expressed mathematically as

$$R_\alpha = Z_\alpha \left(\frac{\sigma}{\sqrt{n}} \right)$$

where R_α = a measure of the limit of precision at significance level α, $0 < \alpha < 1$

Z_α = the standard normal statistic

σ = the standard deviation of the pavement response being considered

n = the number of test measurements

The above equation implies that if $\bar{x}$ is the mean pavement response from the n test measurements, then the confidence that the true mean of the pavement response lies within the range of $\bar{x} \pm R_\alpha$ is $100(1 - \alpha)$%.

Defining Pavement Segments for Data Collection

Pavement data are collected and stored for discrete units typically referred to as segments. For data to be compatible, it is necessary for such segments to be well defined. Two approaches for defining pavement segments are generally used: the equal length method and the uniform characteristics method.

Equal Length Pavement Segments — The use of equal length pavement segments is convenient both for data collection purposes and for representation in the database. However, it is possible that some segments have unequal lengths. For network-level analyses, the characteristics of equal length segments are uniform enough within each segment to obtain results of sufficient accuracy. For project-level analyses, more accuracy is required. Therefore, shorter segment lengths or segments with uniform characteristics should be used.

Pavement Segments with Uniform Characteristics — There are a number of approaches to identify pavement segments with uniform characteristics: the pavement classification–based approach, the pavement response–based approach, and the cumulative difference approach. With the classification-based approach, pavement characteristics are chosen and segments are identified so that the pavement characteristics are uniform within each segment. Usually these are characteristics that influence the deterioration of the segment and the type of rehabilitation action to be applied to the segment. Such pavement characteristics are pavement type, material type, layer thickness, subgrade type, highway classification, and traffic loading. An advantage of this approach is that pavement segments delineated on this basis retain their uniform characteristics over time, until major rehabilitation or reconstruction changes such characteristics. Figure 66.2 gives an example of pavement segment delineation with the classification-based approach.

With the response-based approach, a number of pavement response variables are chosen and segments are identified so that the response variables remain fairly constant within each segment. Pavement response variables that can be chosen include roughness, rut depth, skid resistance, some surface distresses, and structural characteristics such as deflection. These variables are chosen according to their

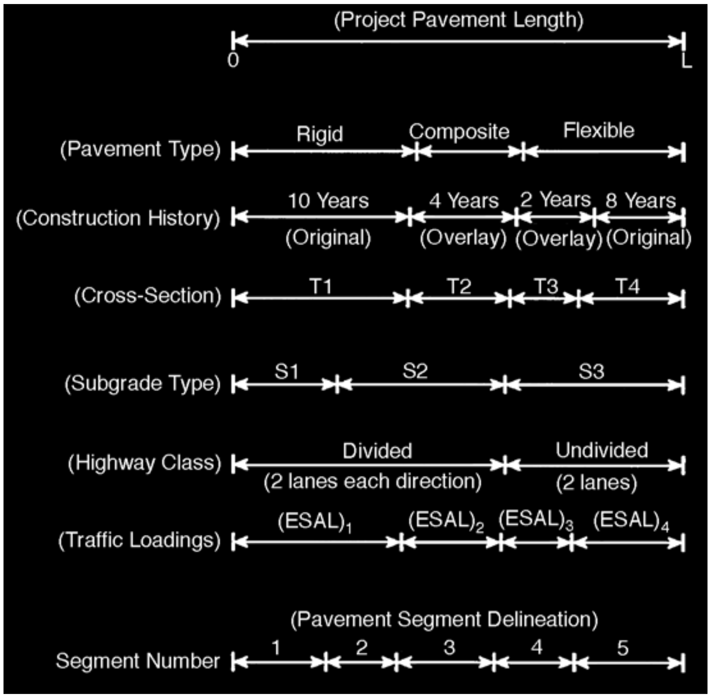

FIGURE 66.2 Pavement segment delineation with the classification-based approach.

importance for predicting pavement deterioration and for determining the type of rehabilitation action to be implemented. Because these characteristics change over time, this approach has the disadvantage that segments might have to be redefined regularly. Statistical tests can be used to test whether the characteristics of adjacent segments are different enough to classify them as separate segments. Assuming the characteristics are normally distributed in both segments with the same variance, the following *t* test can be used to test for statistically significant difference:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\left[\frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2}\right]\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}}$$

where $\bar{X}_1$ = the average characteristic for segment 1
$\bar{X}_2$ = the average characteristic for segment 2
s_1 = the sample standard deviation of segment 1
s_2 = the sample standard deviation of segment 2
n_1 = the sample size of segment 1
n_2 = the sample size of segment 2

The calculated *t* value can be compared with the critical *t* value, $t_{n_1+n_2-2,\ \alpha/2}$, at a significance level of α. If $-t_{n_1+n_2-2,\ \alpha/2} < t < t_{n_1+n_2-2,\ \alpha/2}$, the characteristic is not significantly different between the two segments and the segment can be combined. Figure 66.3 presents an example of pavement segment delineation with the response-based approach. The response used in this illustration is pavement deflection.

The cumulative difference approach identifies the boundary between adjacent segments as the point where the cumulative pavement characteristic versus distance function changes slope. It is recommended by the American Association of State Highway and Transportation Officials (AASHTO) for pavement segment delineation. Figure 66.4(a) shows how pavement characteristics may change with distance along

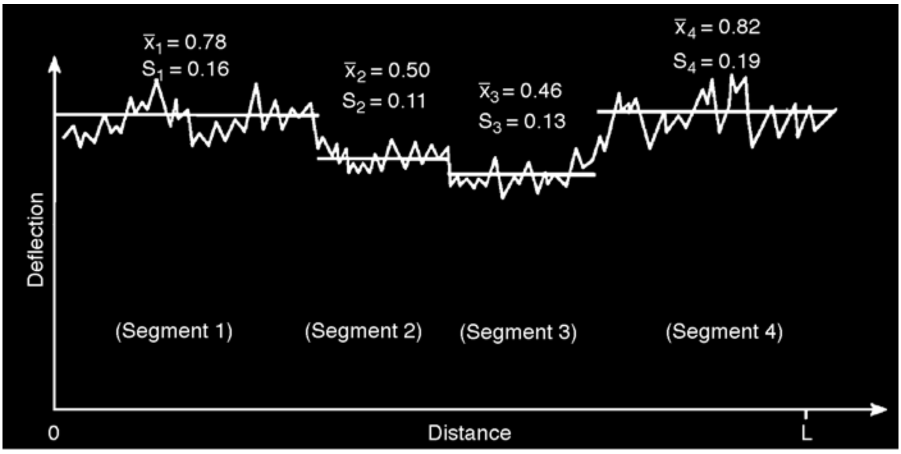

FIGURE 66.3 Pavement segment delineation with the response-based approach.

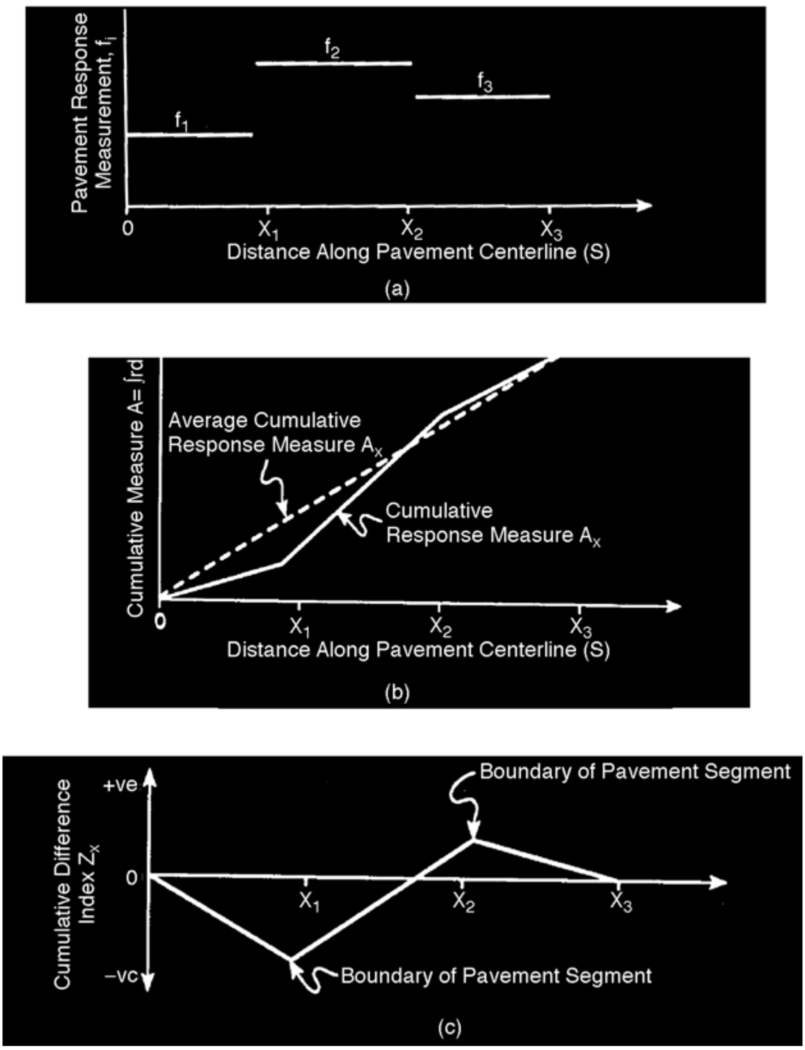

FIGURE 66.4 Pavement segment delineation with the cumulative difference approach.

the length of a pavement, while Fig. 66.4(b) shows the cumulative value of the characteristic along the length of the pavement. For a continuous function, the cumulative function is given by

$$A(x) = \int_0^x f_1(s)ds \qquad \text{for } 0 \le x \le x_1$$
$$= \int_0^{x_1} f_1(s)ds + \int_{x_1}^x f_2(s)ds \qquad \text{for } x_1 \le x \le x_2$$

Pavement characteristics are usually measured at discrete points. The cumulative function can be calculated by using the trapezium rule as follows:

$$A(x) = \frac{1}{2}\sum_{i=1}^{n}\left(f_{i-1} + f_i\right)\left(x_i - x_{i-1}\right)$$

where n = the total number of measurements
f_i = the characteristic value of the ith measurement
f_{i-1} = the characteristic value of the $(i-1)$th measurement
x_i = the distance along the pavement of the ith measurement
x_{i-1} = the distance along the pavement of the $(i-1)$th measurement

Figure 66.4(b) also shows a broken line connecting the cumulative function values at the two endpoints. The slope of this line therefore represents the average characteristic value over the length of pavement. If $\bar{A}(x)$ denotes the cumulative value given by the broken line, the cumulative difference index $Z(x)$ is then given by $Z(x) \equiv A(x) - \bar{A}(x)$.

Figure 66.4(c) shows a plot of $Z(x)$ versus distance. The boundaries of pavement segments are given by the points where the slope of the $Z(x)$ distance plot changes sign. The boundaries and their stability over time will depend on the characteristic chosen for segment delineation.

Data Collection Technologies

Specialized equipment is used to determine position, measure pavement friction, and determine ride quality or roughness, pavement distress, and structural properties.

Location Determination — Systems with mileposts or mile reference markers are common. The vehicle for pavement condition collection has the ability to determine distance fairly accurately. After the necessary corrections, relative distances are used to determine the positions of points where condition data measurements are made. A newer development is the Global Positioning System (GPS), which can determine position automatically and accurately with radio signals and satellites. This technology holds even more promise when combined with the Geographic Information System (GIS).

Pavement Friction Measurement — The locked wheel friction tester is the most common device used to measure pavement friction. Disadvantages are low testing speed, high testing costs, and high wear and tear of equipment. Alternative equipment in use or in development are the mu-meter, the locked-wheel skid tester, the spin-up tester, and various devices for collecting and processing video and laser images of pavement texture [FHWA, 1989].

Pavement Roughness — There are various measures of roughness and, consequently, various equipment types for roughness measurements. Basic methods include the rod and level survey and the dipstick profiler. As the use of such manual devices is very time consuming, they are mostly used to profile roughness calibration segments to calibrate other types of devices.

Profilographs are mostly used for construction quality control of portland concrete cement (PCC) pavements. Response-type road roughness meters (RTRRMs) measure the dynamic response of a mechanical system with specified characteristics traveling at a specified speed over the pavement, as a measure of pavement roughness. The disadvantages of RTRRM equipment are that they do not directly measure pavement profile, but rather dynamic response as a proxy, and that they require frequent calibration to obtain consistent relationships between pavement characteristics and dynamic responses.

A number of profiling devices have been developed that measure pavement profile. Most of such devices consist of accelerators (which are used to determine relative vertical displacement with time), a distance-measuring instrument to measure distance along the vehicle path, and an ultrasonic, optical, or laser system to measure the height of the device above the pavement surface. The pavement profile $p(x)$ at any point x along the vehicle path is then given by device vertical displacement $y(x)$ minus the height of the device above the pavement surface $h(x)$, or $p(x) = y(x) - h(x)$. Raw data are noisy and must be smoothed or filtered and then processed further to convert the profile data to the required roughness indices. Software packages have been developed to carry out such tasks [FHWA, 1991].

Rut Depth — Rut depths are measured using basically the same technology used for profiling pavement surfaces. Most equipment types have a transverse rut bar with three or five ultrasonic or laser sensors. Laser sensors are more accurate and reliable than ultrasonic sensors but are much more expensive. The heights between the sensors and the pavement surface are measured at regular intervals. The transverse profile and a measure of rutting can then be constructed using the height measurements for each cross section [FHWA, 1991].

Various Surface Distresses — Most surface distress data are collected with visual inspections. These manual methods are time consuming, are expensive, and rely on subjective evaluations. Efficiency can be improved with clear and standardized manuals, training of inspectors, and inspection aids such as portable computers and specialized survey keyboards. A number of technologies using laser, radar, or video are being developed to improve inspections. Laser devices can detect some cracking but are less reliable and repeatable and do not produce visual records [FHWA, 1991]. Radar devices help to identify locations and sizes of voids under PCC pavements. Video equipment can be used to detect distresses such as surface cracks, potholes, and rutting. Video equipment is easier to use, is inexpensive, and involves reusable storage media. In the use of such technologies, much effort is expended in processing of recorded images for data extraction. As such, research is being carried out to automate image processing tasks [FHWA, 1989].

Structural Capacity — Pavement structural capacity influences the sizes of permissible loading patterns on a pavement and is therefore an important factor influencing the remaining service life of a pavement. Deflection of the pavement under various static and dynamic loads is usually taken as a measure of pavement structural capacity. Pavement deflection is influenced by many factors, including size and duration of the load; pavement type; stiffness of the pavement; local defects such as joint cracks, moisture, frost, and temperature; and proximity of structures, which have to be taken into account when analyzing deflection data. Types of deflection equipment are static deflection, steady-state dynamic deflection, and impulse deflection equipment.

Static deflection equipment measures pavement deflection under slowly applied loads. The best known device of this type is the Benkelman beam, which yields a single deflection measurement. Other static deflection devices are the curvature meter and plate-bearing test equipment. Other equipment includes automated beam equipment, such as the traveling deflectometer. Steady-state dynamic deflection equipment applies a steady-state sinusoidal force to the pavement after the application of a static preload. The change in deflection (vibration) is then measured and compared with the amplitude of the dynamic force. The Dynaflect and the more versatile Road Rater are well-known devices of this type. Limitations of this equipment are the limited amplitudes of the dynamic loads compared with the static preloads. Impulse deflection equipment applies an impulsive force to the pavement, usually with a falling weight. The size of the force can be varied by varying the drop height and the mass of the weight. The Dynatest Falling Weight Deflectometer is a widely used device of this type [FHWA, 1989].

The collection and analysis of pavement condition data form the foundation of any effective PMS, as decisions based on objective data are vital for proper budgeting. Current trends in pavement data collection and analysis point to increasing use of automation, therefore decreasing the element of subjectivity in pavement condition monitoring while ensuring the safety of condition-monitoring personnel and road users during such data collection.

Management Strategy Development

Program Development Processes

Each year, state highway agencies are faced with the task of developing a single-year program that optimizes resources allocated to that year. In order to achieve this objective, projects are prioritized for the year under consideration. Every organization has a process by which it develops a program. The process, which generally reflects the management style within the organization, typically fits into any one of the following three organizational structures [AASHTO, 1990]:

Centralized program development process: The most often used process for developing a program is one in which the central office programming unit develops a program with some consultation with the districts. The rules and goals of the central office generally prevail in this type of a program.

Semidecentralized program development process: In this process, the districts in a state are asked to rank projects and recommend a program of construction for projects that the districts would like to see implemented. Such ranked lists are often developed by considering projects that could not be carried out in previous years, in addition to projects that meet the programming criteria in the current year. In this type of organizational structure, the central office may use rules and goals that are different from those of individual districts. Rules and goals may also vary from one district to another.

Decentralized program development process: In this process, districts are considered autonomous units. A budget is allocated to each district by the central office. Each district is completely free to develop its program according to its own set of rules and goals.

Project Selection Methods

Single-Year Prioritization — The first step in developing a single-year program is to determine what pavement segments should be considered for rehabilitation that year. In most cases, the managers of a network establish pavement condition criteria that will trigger minor or major rehabilitation. The second step in the program development process is to determine what factors will be used to identify a project that is in need of rehabilitation. Some of the criteria used by different highway agencies for this purpose include a project's overall condition (such as distress index, roughness, and performance index), a project's individual distress (such as cracking, rutting, spalling, etc.), and the rate of deterioration of the project. The level of current condition at which an agency considers a pavement as a candidate for a specific action is referred to as a "trigger point." Trigger points may vary according to the importance, use, or classification of a facility. A district may use additional criteria to determine trigger points for the selection of candidate projects. For instance, maintenance requirements of a project may be at such high levels that rehabilitation would be more appropriate. Also, preventive action at an early point in a pavement's life may save a large expenditure of funds over the life of the project. General practice is such that a combination of many the above objectives are used as trigger points to select candidate projects in a single-year prioritization program.

After current needs have been identified through the use of trigger points, the next step in the program development process is to determine what treatment should be applied to each project. There are several methods of treatment selection that are currently in use. These include various combinations of the following: policy and experience, decision trees, design methods, initial cost, least-present cost, and cost effectiveness. For each set of candidate projects, the best treatment for each candidate project is identified and the corresponding cost is determined. The next step involves prioritization of the candidate projects according to a given set of rules or guidelines. Certain methods of ranking include prioritization by parameters such as distress or performance, or by composite criteria (such as a ranking function combining condition, geometry, traffic, maintenance, safety factors, etc.), initial costs, least-present costs, and benefit–cost ratio or cost effectiveness. The treatment selection procedure and the ranking procedure make available a ranked list of projects to be carried out, the treatment and costs associated with each project, and a cutoff line that is established based on the level of funding available.

Deficiencies of Single-Year Prioritization — As alternative treatment timings are not considered in single-year prioritization, the long-term impacts of the decisions are not adequately addressed. Therefore, the true costs of the rehabilitation approach over time may not be given due consideration. Currently, many agencies use this approach to program their pavement repair activities.

Multiyear Prioritization — Multiyear prioritization is a more sophisticated approach to project selection that is closer to an optimized solution for addressing pavement network scheduling and budgeting needs. This method requires the use of performance prediction models or remaining service life estimates. It also requires the definition of trigger points to identify needs and provisions that allow the acceleration or deferral of treatments during the analysis period. There are three common approaches used to perform this prioritization: marginal cost-effectiveness approach, incremental benefit–cost approach, and remaining service life analysis.

Cost-Effectiveness Approach — The cost-effectiveness approach is a method of assessing the trade-offs of a project by providing information about costs, benefits, and impacts in such a manner as to facilitate prudent, broad-based decisions. This approach first identifies feasible treatments for each analysis based on the projected condition and established trigger levels and then calculates the respective effectiveness (area under performance curve multiplied by some function of traffic) and costs in terms of net present values of costs of each combination and selects the treatment alternative and the time for each segment with the highest cost-effectiveness ratio. The marginal benefit–cost approach, which involves determination of costs and benefits (effectiveness), is considered superior to the benefit–cost approach.

Incremental Benefit–Cost Approach — The main difference between the incremental benefit–cost approach and the marginal cost-effectiveness approach is the monetary aspect that is placed on the benefits. In the incremental benefit–cost approach, not only are the costs associated with a project considered, but also the benefits. As it is typically difficult to determine the monetary benefits of road repair investments, specified values are assigned to such benefits on the basis of how long the benefits are expected to last. In this approach, the efficiency frontier represented by successive line segments, with which the slopes are the incremental ratios of benefits and costs from one strategy to the next, is established.

Remaining Service Life Approach — This approach uses the expected remaining life of the pavement as an indirect measure of the work needed on a pavement. In this approach, the relationship between remaining service life and life cycle costs is established. The network life cycle costs are considered the sum of the annual preservation costs that are accumulated over the life cycle analysis period. They are calculated based on the need of an agency to minimize the total costs of pavement preservation and the need to control the relationship between costs of preservation and the network's condition over long periods of time.

Multiyear prioritization differs from single-year prioritization in a number of ways. First, a number of different strategy alternatives (treatment types and timings) are considered in multiyear prioritization. The use of a benefit calculation generally identifies the treatment that provides the most benefit to an agency, while a single-year prioritization approach typically considers only one assigned option for a specified condition level. Another difference lies in the complexity of analysis. In a single-year prioritization, the most common factors considered are the current condition and the existing traffic levels. In a multiyear prioritization, an agency is able to simulate future conditions through the use of performance prediction models and to consider other factors in the analysis. Furthermore, with the multiyear prioritization, the option of timing of maintenance, rehabilitation, and reconstruction can be included in the analysis process. Also, the capability of finding an optimum combination of projects, alternatives, and timing for any budget level can be incorporated. The impact of various funding levels also can be assessed. Naturally, the reliability of the results of multiyear prioritization is dependent on the predictive accuracy of the performance models.

Optimization — Through the use of mathematical programming methods, such as linear programming, dynamic programming, discrete optimization, and multicriteria optimization, optimal solutions are developed in accordance with goals established, such as maximizing total agency benefits or minimizing agency costs to achieve certain condition levels. Optimization analysis, unlike prioritization, yields outputs that are provided in terms of percentage of miles of roads that should be mobilized from one condition to another rather than in terms of identification of specific projects. The optimization approach addresses several important considerations that are not covered in prioritization analysis, such as the incorporation of interproject trade-off analyses during strategy selection. Furthermore, optimization guarantees that the selection of strategies adheres to budgetary limits. Also, optimization allows the conduction of multiyear network-level planning and programming aimed at moving the overall system toward a defined performance level.

Performance Analysis

Prediction models are developed to predict future pavement condition, and ultimately to assist in the estimation of the type and timing of maintenance activities and optimization of the pavement condition, for life cycle cost analysis. Pavement performance is generally predicted using deterministic and probabilistic models through regression analysis, Markov transition probabilities, and Bayesian methodology [FHWA, 1991]. These modeling techniques are briefly described below.

Regression Analysis — Regression is a statistical tool that is used to derive a relationship between two or more variables. Important parameters that can be used to judge how well an equation fits the actual data or the predictive power of the model include coefficient of determination, root mean square error, and hypothesis tests on regression coefficients. An advantage of regression analysis is that it provides a simple mathematical method to analyze performance data and to develop performance prediction models that can be updated using future analysis results and engineering judgment. However, regression analysis requires an accurate and abundant set of data and needs to consider all significant variables affecting pavement deterioration.

Markov Transition Probabilities — The basic Markov assumption is that current pavement condition is dependent only on its prior condition. Furthermore, future pavement condition is dependent only on current pavement condition. Probability transition matrices developed upon these premises can be used to estimate probabilistic performance prediction models. The advantages of such models lie in their relatively simplicity of implementation and in their ability to provide a network-level assessment of facility condition. Their greatest disadvantage, however, is that the major assumption associated with the development of the transition matrices may be invalid.

Bayesian Methodology — This methodology allows both subjective data (opinions) and objective data (generated from mechanistic models) to be combined to develop and predictive (regression) equations. In traditional regression analysis, the unknown regression coefficients are based on the observed data and are assumed to have unique values. In Bayesian regression analysis, the regression parameters are assumed to be random variables with associated probability distributions analogous to a mean and a standard deviation.

Institutional Issues

Communication within an agency is one of the most important items in a PMS. Without effective communication, decisions would be made without all of the information needed. The main objective is to ensure rapid and effective flow of information within the agency and to aid the decision makers in making cost-effective decisions. A good PMS enhances flexibility in the reporting of information.

Bridge Management Systems

A bridge management system is a systematic approach to assist in making decisions regarding cost-effective maintenance, rehabilitation, and replacement plans for bridges. Such systems seek to identify current and future deficiencies, estimate the backlog of investment requirements, and project future requirements. A BMS also helps to identify the optimal program of bridge investments over time periods, given particular funding levels. With a BMS, substantial savings for both agency and user costs can be achieved and bridge improvement programs can be readily and effectively explained to the public, legislative bodies, and budget decision makers. Also, BMSs play an important role in risk management, as evidence to counter possible claims alleging negligence for the agency's failure to upgrade a bridge in light of changed conditions and current design standards can be provided. A BMS includes four basic components: a database, cost and deterioration models, optimization models for analysis, and updating functions. The database component contains information from regular field inspections. Deterioration models predict the future condition of bridge elements. Agency cost models are associated with maintenance and improvement of bridge components, while user cost models relate more directly to bridge safety and serviceability. Using results from the cost and deterioration modeling, an optimization model determines the least-cost maintenance and improvement strategies for bridge elements. A life cycle cost analysis considers bridge improvements over its entire service life.

A top-down or bottom-up approach can be used to optimize a BMS. The top-down approach determines the desired goals for the entire network and then selects individual bridge projects. The bottom-up approach determines the optimal action for each bridge and then selects which projects will be completed based on the network optimization. The top-down approach typically works faster because the individual projects are determined after the network goals are set, but it requires a large number of facilities (bridges) to provide meaningful results. The bottom-up approach uses more computer time to optimize the individual bridge projects and often proves cumbersome for a large number of bridges. Finally, the BMS generates summaries and reports for planning and programming processes. Deterioration and cost models need to be continually updated to represent current conditions.

Data Needs, Data Collection, and Database for BMS

Data Types

Selection of data items needed to operate a BMS on the intended functions of the system generally consists of the following four categories [Sinha et al., 1991]:

Inventory data: To provide a bridge inventory, data items such as location, number and length of spans, structure and material, type of deck, superstructure, substructure, and age are needed.

Condition and usage data: Data on bridge condition, environmental conditions, and traffic load are required for condition monitoring, evaluation, and prediction.

Agency cost data: To estimate agency costs, the above inventory and condition data, as well as data on maintenance, rehabilitation, and reconstruction dates, types, and costs, are needed.

User cost data: To compute user costs, data on the distribution of vehicle types, heights, and weights on various road functional classes; vehicle operating costs; average lengths of detours; and bridge-related accident rates and costs are required.

Data Collection and Database Development

Some of the above data items need not be collected by a data collection effort dedicated to acquiring BMS information but can be obtained from existing data sources, such as statewide traffic counts conducted under the highway traffic monitoring system, PMS databases, or published information. Data items related to implemented maintenance, rehabilitation, and reconstruction actions are typically collected as the actions are performed. Bridge condition data are typically collected during regular bridge inspections.

A BMS database typically contains all bridge-related information necessary for project selection and for preparing various network summary reports. BMS data items can also be categorized into four modules: condition rating, bridge traffic and safety, improvement activities, and impact identification [Kleywegt and Sinha, 1994].

Condition Rating Module — The bridge condition rating is a key parameter in determining types of repairs needed for a bridge. This, together with other inspection data, constitutes basic input data needed for the ranking and optimization procedures. It is important that the condition rating be carried out in a consistent manner for all bridges. In this module, a bridge is divided into three major components:

deck, superstructure, and substructure. This approach of reducing a complex structure into simpler elements is called the problem reduction approach in knowledge engineering. The subdivision of a bridge into simpler subcomponents can be accomplished by adopting the bridge items listed in a standard field inspection form. Finally, as a result of objective measurements (such as measured values of subcomponent condition) and subjective judgment (such as importance factors for the subcomponents using a fuzzy set approach), consistent condition ratings of state-owned bridges can be derived and kept in this module.

Bridge Traffic Safety Evaluation Module — Traffic safety can be one of the factors for recommending bridge improvement activities. Bridge traffic safety can be affected by many factors, and subjective judgments are often made to assess it. The overall traffic safety rating of a bridge hinges on the bridge inspector's assessment of the importance of the safety evaluation factors considered and the actual safety deficiencies of the components of a bridge.

During bridge inspection, each of the safety factors can be assigned a safety rating depending on specific conditions of the bridge. The rating may be one of the following terms: very critical, critical, moderately critical, not critical, and highly not critical. The weight of each of the safety factors can be assessed through a questionnaire survey of the district bridge inspectors. The ratings and weights of all the factors can then be combined to obtain the weighted average rating or bridge safety index. Factors to compute safety index may include roadway width, shoulder width, vertical clearance, approach guardrails and bridge rails, approach sight distance, approach roadway curvature, approach gradient, volume–capacity ratio, truck percentage, lighting, signing and delineation, presence of nearby ramps or intersections, and presence of nearby lane drops or pavement transitions.

Improvement Activity Identification Module — Severity and extent of distresses present at the bridge structure call for specific types of improvement. In order to develop a computerized improvement alternative selection process, it is necessary to develop distress improvement relations by highway class, condition rating, and traffic volume. For this purpose, a database must be created that can accumulate the information of all improvement activities performed for each bridge in the system over a period of time. The improvement activity recording and monitoring module, based on the activity history database, would serve as the data bank for future analysis.

Impact Identification Module — The use of a structurally deficient or functionally obsolete bridge has significant impacts on the highway agency, road user, and surrounding community. To the highway agency, the effect of a structurally deficient bridge would be measured in terms of the cost of an immediate investment to upgrade the bridge. The highway user is impacted directly by the relatively longer distances and travel time and increased potential for traffic accidents associated with detour roads. The impacts on the surrounding people involve the inconvenience created by a sudden upsurge of local traffic volumes. These impacts are considered significant due to the typically long construction period for bridge rehabilitation or replacement. To assist in the identification of magnitudes of various impacts and to translate such impacts into qualitative and quantitative effects, detour length is a necessary data item.

Data Analysis

Condition Data Analysis

The condition of a bridge can be represented in several ways. One of the most common methods is to construct condition indices, which aggregate data on the condition of component bridge elements to obtain indices for larger elements, such as a deck, superstructure, or substructure, or for a bridge or a network of bridges. The level of aggregation will be determined by the purpose of the indices, especially the intended users or audience [Jiang and Sinha, 1990]. Prediction of future condition and remaining service life can be carried out using any of several statistical techniques.

Regression Analysis — Regression analysis is applied in many areas of bridge management systems. Equations are estimated to predict the future conditions of bridge elements as a function of the current condition, the age of the element, material types, maintenance practices, environmental features and deicing chemical use, traffic volume, and past rehabilitation actions. These predicted conditions are then used to estimate future agency and user costs, to evaluate different rehabilitation and replacement alternatives, to choose strategies under budget and other constraints, to predict the impacts of different budgets, and to plan work over the medium and longer term. A commonly used form of equation in regression analysis, due to the ease with which the parameters of such an equation can be estimated, is the linear regression equation

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon$$

where Y = the dependent variable
X_i = the independent variables, $i = 1, 2, \ldots, n$
β_i = the unknown parameter to be estimated, $i = 1, 2, \ldots, n$
ε = the random error

The dependent variable might be the future condition of a bridge component, and independent variables might include the current condition, time since the previous major rehabilitation, type of rehabilitation implemented, material type, and environmental features. The random error term is included since the equation will never be a perfect representation of the underlying phenomenon. Different methods can be used to obtain parameter estimates that will make the equations fit the data as well as possible. The simplest and most common method is ordinary least squares (OLS). A more versatile method is maximum likelihood. The "goodness of fit" of the regression model can be evaluated in different ways. The most popular statistic used for model evaluation is the coefficient of determination, which measures the closeness of the observed data to the theoretical model.

Markov Chains — If the conditions of bridge elements are classified into discrete states, the deterioration process can be modeled as a Markov chain. A Markov chain describes a process that undergoes transitions from a state at one stage to a state at the next stage. The state of each element or the proportion of elements in each state can be measured during an inspection. An underlying assumption of Markov chains is that given the present state of the process, the future states are independent of the past. This assumption might not be satisfied if the state of an element is defined based on the condition of the element only, because the probabilities of the deterioration, and therefore transition probabilities, will be influenced not only by the current condition of the element but also by such factors as age of the element, past rehabilitation of the element, condition of other elements, and traffic loading. To make better use of Markov chains for condition prediction, the states of an element would have to be defined on the basis of the current condition of the element and the factors significantly influencing the element's deterioration. In order to make provision for changing transition probabilities over an element's age, different transition matrices can be used for elements of different ages. One approach is to estimate regression models having the state as a dependent variable, assume a probability distribution for the random error term, and then convert interval probabilities to transition probabilities. To use a Markov chain, individual states must be defined as intervals on a continuum. Alternative models like multinomial logit models can also be used. Another approach, as suggested by the developers of the PONTIS bridge management system, is to use subjective judgment of bridge maintenance experts to obtain estimates of transition probabilities in Markov chains and to update and improve the initial estimates based on regular inspections using the Bayesian estimation technique [FHWA, 1987].

Bayesian Estimation — Bayesian estimation can be used for updating the estimate probabilities of future conditions. It is particularly well suited for updating the estimates of transition probabilities in Markov chain analysis as additional data become available with inspection. Under suitable assumptions, the updated estimate (called posterior mean) equals a weighted average of the previous estimate (called prior mean) and the mean of the new data. The weights represent the value attached to the data from which the prior mean is estimated relative to the new data. Usually, the relative numbers of observations are used as weights. If the prior mean was estimated from judgmental methods, as suggested by PONTIS, it has to be valued as an equivalent number of observations, representing the amount of data on which the expert's judgment is based. When the estimates are later updated, the posterior values become the prior values for the new estimates. In this way, the effects of initial estimates are reduced as new data become available.

Fuzzy Set Theory — Many bridge inspection data items are of a subjective nature. The quality of these subjective data can be improved through better training of bridge inspectors, carefully designed uniform procedures and measures, quality control and quality assurance programs, and better inspection manuals. An innovative technique is the theory of fuzzy sets. Unlike classical set theory where an element is either a member of a set or not, degrees of membership are provided for in fuzzy set theory. For instance, a bridge element can be in both a fair and a poor condition, and to different degrees. This technique yields a more realistic and flexible method to represent the subjective ratings of bridge elements.

Latent Variable Approach in Regression Analysis — The approach of latent variables considers the infrastructure condition as a set of unobservable or latent variables that depend on other variables, such as previous maintenance, environmental features, and traffic loading. The observed characteristics, such as the measured distresses, in turn simultaneously depend on the underlying latent variables. Because variables such as various distresses and structural capacity are measured with a large degree of error, the observed variables can be modeled as functions of the true values as well as stochastic measurement errors. The model also can be enhanced by using lagged variables and by simultaneously modeling deterioration and maintenance. This treatment is especially important in that deterioration tends to increase with decreasing maintenance, all other factors held constant. However, maintenance tends to increase with increasing deterioration.

Latent Markov Decision Process — This method explicitly takes into account uncertainty associated with facility inspection and incorporates this into a Markov decision process framework. It augments the definition of states to incorporate all information available up to each stage, including all previously measured conditions and implemented actions. This causes the state space to grow very rapidly with the number of stages, making this method computationally very cumbersome. This approach is required to enable the recursive calculation of the conditional probabilities of the actual condition, given all information up to that stage. With an appropriate cost function based on element condition and implementation action, the strategy selection problem can be formulated as a dynamic programming problem to find the optimal solution over a finite horizon with no budget constraints.

Life Cycle Cost Analysis

To manage bridge infrastructure efficiently, the cost implications of alternative actions have to be considered. These costs are used in the comparison of alternatives for project-level decisions and also in ranking and optimization routines for network-level decisions. For a system of bridges, overall costs include direct and indirect costs incurred by the agency and the road users. Regression analysis has been found useful for estimating agency and user costs as functions of bridge element conditions, deficiencies, and traffic loading. Agency costs include costs associated with materials, manpower, and equipment used in bridge-related repair activities (maintenance, rehabilitation, and replacement). To estimate the costs of these activities, a good cost-accounting system is essential. The type of action performed on each bridge element, the costs incurred for the bridge element, and the condition of the bridge element before and after each repair activity should be recorded.

Maintenance Costs — The costs associated with routine maintenance of bridge elements can be estimated directly or indirectly. These costs could be estimated directly as a function of the material type, condition, location, traffic, highway classification, and other important factors for each bridge element. On the other hand, such costs could be estimated indirectly by first estimating the quantity of different routine maintenance activities performed on a type of element per year, as a function of element condition, material type, traffic, highway classification, environment, and other factors. The unit cost of each type of maintenance activity is also estimated as a function of material type, highway classification, and other factors. Then the overall routine maintenance costs are determined given the level and unit costs of routine maintenance activities.

Element Rehabilitation Costs — The costs associated with the rehabilitation of bridge elements are typically estimated for different types of elements and their respective rehabilitation alternatives. A cost-accounting database provides accurate and up-to-date cost estimates classified by individual element rehabilitation activity. Unit costs of deck reconstruction and overlay alternatives can be estimated using regression analysis as a function of climate, road functional class, traffic volume, bridge length, deck area, percent of area needing patched, and other variables.

Element Replacement Costs — Unlike the case for bridge rehabilitation, bridge element replacement costs are estimated separately. Superstructure replacement costs can be modeled for different superstructure types as a function of bridge length and deck width, while substructure replacement costs can be modeled for different substructure types as a function of bridge length, deck width, and vertical clearance. Approach construction costs can be calculated as a function of approach length and earthwork quantity.

Bridge Replacement Costs — Bridge replacement cost can be estimated by decomposing the total project into its constituent cost items and then using historical contract costs for similar items on similar projects. Bridge replacement costs depend on bridge dimensions, number of spans, material and type of superstructure and substructure, and bridge location and the crossing feature, i.e., road, rail, or river.

Additional User Costs — User costs include all additional costs incurred by road users over those costs that would have been incurred if the bridge system had been in a specific predefined "ideal" status. User costs are therefore incurred even if there is no bridge in place and when a bridge suffers from structural or functional deficiencies. Additional user costs can be incurred to the road users by detouring made necessary by insufficient vertical clearance or loading capacity. To estimate the additional user costs due to detours for life cycle cost analysis, future traffic is estimated using regression techniques based on time series data. Then loading capacity is predicted directly using either regression techniques or Markov chains or indirectly by using these techniques to predict the conditions of the applicable structural elements and then to derive the load capacity from these element conditions. Elementary descriptive statistics can be used to estimate the distribution of different vehicle types on different routes, the distribution of vehicle weight and height for each vehicle type, the number of different types of vehicles detoured due to insufficient vertical clearance or bridge loading capacity, the vehicle operating costs per distance for different types and weights of vehicles, and the additional vehicle operating costs and time costs because of bridge deficiencies.

Crash Costs — To estimate bridge-related crash costs, the rates of occurrence of various crashes and their corresponding costs need to be estimated. The expected rates of different crash types at each bridge as a function of its deficiencies is typically estimated based on highway crash statistics. The costs of the different types of crashes related to bridges can be estimated by separately considering the direct and indirect crash costs. Direct costs include more "tangible" costs, such as medical, property damage, and legal costs. Indirect costs include the value of the more intangible losses, such as pain, loss of quality of life, and loss in future production and income. The rates of different crash types and their associated costs together give an estimate of the expected crash costs due to bridge deficiencies.

Additional User Costs during Bridge Work — Bridge repair activities typically influence traffic flow on the bridge as well as surrounding roads. Congestion levels associated with various alternatives differ in terms of severity, duration, and frequency. For instance, routine maintenance may cause less severe and short-lived congestion compared to rehabilitation or replacement, which leads to more frequent congestion. Additional user costs are incurred by road users on the bridge and the surrounding road network due to congestion arising from bridge repair activities. Furthermore, the additional use of alternative routes during bridge repair may lead to accelerated deterioration of pavements and bridges on such routes.

Identification of Promising Alternatives

More than one bridge maintenance, rehabilitation, and replacement alternative may be feasible for each scenario (combination of deficiencies, element material types, bridge structural types, climatic feature, and traffic volume). For practical purposes it is desirable to develop a reduced list of more promising alternatives for each situation. Each alternative is then analyzed with its activity profiles and cash flows for project-level decisions or with the promising alternatives of other bridge projects for network-level decisions. The detail with which alternatives are formulated will depend on the level permitted by available data and the level at which one alternative is considered distinct from the other.

Activity Profiles and Cash Flows

The next step in analyzing different alternatives is to construct the activity profile associated with each alternative. This involves collating the results of the analyses described above. The current condition and traffic volume influence current agency and user costs as well as the identification of currently feasible alternatives. The models developed to predict condition are used to predict the long-term condition trends associated with each alternative. These are then used with the models for agency and user costs to estimate the associated costs for each alternative activity profile and to derive the corresponding cash flow. The cash flow of each activity profile is then analyzed with the techniques of interest accounting.

Impact Analysis

Even with programs for systematic data collection and analysis in place, it may take many years before sufficient data is collected to apply techniques such as regression analysis, Markov chains, or Bayesian estimations. Simplified impact estimation techniques are therefore needed to support decisions that have to be taken as a BMS gradually evolves. A common approach is to obtain the judgment of bridge experts regarding the impact of alternatives.

Priority Ranking

Ranking methods developed to assist in priority setting for bridge repair activities typically involve the use of a composite ranking index or indices for each bridge or each project. Priority ranking for bridge repair can also be conducted according to the level of service based on deficiency points. More advanced project selection tools for bridge management include concordance analysis, linear programming, and analytic hierarchy processes. Such methods may be cumbersome when dealing with a large number of alternatives but are greatly facilitated by the use of computer technology.

Assignment of Relative Weights

The analytic hierarchy process (AHP) constructs a hierarchy and uses pair-wise comparisons at each level of the hierarchy [Saaty, 1977]. System goals, objectives, criteria, and alternatives are related by the hierarchy. Relative weights are assigned to activities on the same level in the hierarchy for measuring their contribution to an activity on an adjacent higher level. For a BMS, the first level may be the goal to maximize system effectiveness. The second level may consist of objectives based on achievement of the goal to be measured, such as bridge condition, agency costs, user costs, and external impacts. The third level may involve the criteria in terms of which each objective is measured. The criteria for user costs may consist of additional vehicle operating costs due to detours, excess loss in travel time, and crash costs. The fourth level may be composed of individual alternative projects. A unique feature of the AHP method lies in the derivation of relative weights. The activities at each level are compared in a pair-wise fashion to produce relative weights. Then these relative weights are arranged in a reciprocal matrix for each higher level activity. If the pair-wise comparisons are consistent, an eigenvector corresponding to the largest eigenvalue will yield a set of relative weights for all of the activities.

Utility Functions — As bridge management typically involves the evaluation of several alternatives, the task of pair-wise comparison can be enormous. This problem can be resolved by developing utility functions for the bridge characteristics, such as remaining service life, which will be impacted by alternatives. To compare alternative projects, the characteristics of the bridge can be directly converted to utility values without having to resort to pair-wise comparison between the alternatives.

Optimization — The purpose of optimization is to find the optimal set of actions to be implemented on a network of bridges, at various points in time and subject to a variety of constraints. Some commonly used approaches are briefly discussed below.

Minimization of Life Cycle Costs — One approach is to conduct a life cycle cost analysis for each bridge or type of bridges in the system for each promising alternative that can be employed at each programming period. However, this approach does not find a true global optimum strategy, because it does not simultaneously take into account network-wide effects such as budget constraints. Furthermore, future choices and their impacts are unknown at the time of selecting the best alternative. Therefore, the choice of the "optimum" alternative under such conditions is associated with simplifying assumptions about future alternatives.

Linear and Mixed-Integer Programming

One of the most versatile optimization techniques is linear programming (LP) [Sherali et al., 1992]. In such a program the values of decision variables are sought that will maximize or minimize a linear objective function, subject to linear constraints such as budget constraints. The decision variables should be such that they can realistically be regarded as continuous variables. Often the decision variables are discrete, such as whether an alternative will be implemented or not (represented by 0/1 integers), resulting in mixed-integer programming (MIP). In such problems, the objective functions and constraints are assumed to be linear functions of the decision variables. In reality, such assumptions may be unduly restrictive. However, formulating the optimization problem as a nonlinear one with nonlinear objective functions and constraints significantly complicates the problem computationally.

Dynamic Programming

An optimization approach with more desirable computational properties is dynamic programming (DP) [Denardo, 1981]. It is based on the principle of optimality that in this context means that optimal alternatives or policies over time consist of optimal subalternatives or subpolicies over shorter periods of time. In general, this is true in bridge management. Thus, optimal policies can be constructed by recursively finding optimal subpolicies for successive programming periods. One method of applying DP is to do the analysis over a finite, but long, time horizon. A terminal value or cost is assigned to each state at the end of the analysis period. A cost is associated with being in each state at each stage and with the implementation of each alternative in each state. The optimal alternative can be calculated recursively for each state at each stage. The transition probabilities can be given as the transition matrix of a Markov chain, as long as the underlying assumptions of a Markov chain are satisfied.

Network and Heuristic Method

Due to the computational complexity of the optimization models described above, heuristic approaches may be used. An example is the implementation of lexicographic optimization proposed for an investment-staging model for bridge replacement [Garcia-Diaz and Liebman, 1983]. This model specifically addresses the replacement and scheduling of rural bridges, which explicitly takes into account the user costs of alternative routes due to bridge loading capacity deficiencies. By separately scheduling bridge replacement projects over different subhorizons, the road user cost–minimizing problem subject to agency budget constraints is approximated by this form of decomposition. The subhorizons are then ordered in a priority sequence.

Bridge management is a continuous process and seeks to adapt to changes that occur in the transportation and technological environments. For instance, deteriorating bridge elements are maintained, rehabilitated, or replaced; traffic levels change over time; costs change; and available resources change. Data collection and performance modeling should be carried out on a regular basis so that the BMS can yield outputs that are effective and economically sound for overall highway asset management.

Maintenance Management Systems

Infrastructure maintenance carried out in-house by highway agencies is associated with significant levels of resources. Maintenance management systems seek to utilize limited resources for in-house maintenance cost effectively and to improve the coordination of maintenance and rehabilitation programs so that tradeoffs between maintenance and rehabilitation actions can be evaluated. MMS activities are performed on a more decentralized basis, whereas pavement and bridge management activities tend to be more centralized [Markow et al., 1994].

Components and Features of a Maintenance Management System

A computer-based MMS incorporates a number of important components and features, as shown below [Markow et al., 1994]:

Activity definition and list: In designing an MMS, work activities should be defined to facilitate planning, scheduling, and control requirements, including the definition of appropriate accomplishment units and inventory units. Activities typically included in maintenance programs are maintenance of roadway and shoulder surfaces, maintenance of drainage facilities, roadside maintenance, bridge maintenance, winter maintenance, maintenance of traffic control devices, emergency maintenance, and public service. It is recommended that the list of activities accommodate the needs of both high- and low-level maintenance management. High-level management is concerned with policy, planning, programming, and budgeting. At the lower level of the maintenance organization, managers involved in day-to-day field operations need more details to facilitate decentralized decision making.

Feature inventory: A roadway feature inventory is a file of maintenance-related road features and their respective quantities, providing the physical basis for estimating annual maintenance work requirements by activity. A typical MMS roadway inventory organizes data on roadway features in a way that is consistent with the definition of maintenance activities defined. It also maintains a quantity of items requiring maintenance by location and management unit and provides a basis for estimating annual or biennial maintenance work requirements. Inventories of physical assets to be maintained should be accomplished by data on their condition and functional obsolescence. Inventories of maintenance features that are nonphysical assets should be accompanied by data on the level of service being achieved.

Performance standards: A performance standard is developed for each work activity. The standards include the measures for work accomplishment and for feature inventory, accomplishment quantities per inventory unit for each road class, productivity values in terms of either average daily production or accomplishment quantity per labor hour, resources required for an efficient operation, a standard crew size, and costs for the activity. In addition, the purpose of each activity and the quality standards associated with the activity are generally included in an operations manual. There are typically two sets of performance standards: a set suitable for planning, programming, budgeting, and allocating resources to districts or subdistricts, and a set prepared by districts or subdistricts to reflect local conditions and the most efficient work methods.

Work programs: MMS work programs provide physical targets as well as target resource allocations and limitations. A program estimate is developed for each applicable work activity. The work quantity for the activity is computed for each road class using the feature inventory for the activity and the quantity standards from the performance standard. The number of crew days of work needed for the year is computed using the annual work quantity and the average daily production from the standard. Labor hours are computed using the standard crew size and the working hours per day. The work programs formulated should be capable of quick and realistic adjustment in accordance with budget limitations or other considerations.

Performance budget: Performance budgets are work programs with cost estimates tied to individual activities and work quantities. As such, performance budgets represent a performance objective as well as the basis for allocating funds.

Work calendar: This is an annual plan showing seasonal or monthly amounts of work to level the maintenance workload; it serves as a guide to the development of schedules, plus it provides the basis for evaluating progress throughout the year. The work calendar should be able to address demand-responsive needs, particularly those that are seasonal in nature and can contribute to an imbalance in workload over the year.

Resource requirements: This is a month-by-month listing of resources needed, including labor and equipment by classes and materials by types, to guide the allocation of specific labor, equipment, and materials. The MMS should be capable of adjusting the resource requirements based on the degree of contracting expected to occur.

Scheduling: The scheduling systems generally provide ways for supervisors to make field notes of work that needs to be done and to match these needs with the work program and calendar. These systems also provide for the supervisors to decide specifically when and where each activity is to be performed and in combination with what other activities on a given day to make effective use of personnel and equipment. Many of the systems use crew-day cards as an aid to scheduling and thereby enable maintenance supervisors to select activities from the work calendar, to request for service or emergency work, and to address leftovers from previous schedule periods.

Work reporting: The essential information to be entered into an MMS is the actual resources used and the accomplishments for each item of work. The crew-day card is often used for this purpose, with the added advantage of allowing for an easy and immediate review of progress. All of the working reports, including accomplishments, resource usage, time sheets, and roadway feature inventory updates, are typically generated from the crew-day cards. However, it is often recommended that such information be entered locally to facilitate local use.

Management reports: An MMS provides numerous reporting options. In general, these reports are divided into two categories: planning and evaluation. Planning reports describe the results of the work planning process and present planned activities, quantities of work to be performed, required resources, and the budget for the work program. The planning reports include work program and budget, deferred maintenance, workload distribution, work calendar, resource requirements, activity listing, etc. Evaluation reports compare planned work with actual accomplishments. Most evaluation reports contain current month and period-to-date performance values and costs. The evaluation reports include performance, on-screen activity performance, budget status, work calendar status, resource utilization, location maintenance, and work request completion analysis.

Database Development

To ensure consistency integrity, data needed for maintenance management should be incorporated into the overall highway asset management database. In this way, highway network inventory data used for pavement management are available for maintenance management and condition data collected as part of the routine maintenance process become available for pavement and bridge management, as well. Other types of data needed for maintenance management include condition, level-of-service characteristics of maintainable elements, traffic volumes and composition, accident statistics, budget and cost parameters for labor, materials, equipment, etc. These data are used in conjunction with inventory and condition information to develop, analyze, and evaluate work plans to be carried out by the maintenance staff.

The inventory information for an MMS should reside in databases, photo logs, or plan sheets, using location for referencing inventory data elements. The Geographic Information Systems would provide consistent and accurate representation of maintenance on the road network, including data pertaining to its location, coverage, and elements involved. The creation of highly accurate cartographic base maps for GIS generally depends on improved mapping technology, especially that based on the satellite Global Positioning System. For example, the exact location of a unique road segment or structure can be established by coupling its latitude and longitude coordinates obtained using GPS.

Maintenance Needs Assessment

The first step of maintenance needs assessment is an inspection or a condition survey of physical highway assets. Such data should be incorporated into an agency's regular data collection program. Next, given the collected condition and other data, appropriate maintenance activities can be chosen. The most appropriate treatment may depend on the condition, traffic loading, climate features, available resources, and competing maintenance requirements. Maintenance managers need to be able to identify proposed maintenance expenditures whose benefits exceed costs, regardless of funding availability. As a result, a short list of proven cost-effective alternatives can be compiled and standardized for all maintenance units of the highway agency. Scarce resources are taken into account during the priority setting and optimization phase (namely, constrained analysis phase) of the management process.

Resource Needs Assessment

For the purposes of cost estimation, priority setting, optimization, programming and scheduling, and budgeting, it is necessary to estimate the resources needed to perform each of the identified maintenance alternatives. One approach is to first identify a measurement unit of each maintenance treatment. Next, estimates are obtained for the types and size of manpower needed, the number of man-hours for each labor type or the number of crew days, the types and quantities of equipment needed, and the types and quantities of materials needed, per unit of the maintenance activity. These standard resource requirements should be incorporated into the database to ensure automated resource needs and cost estimation.

Cost Analysis

Cost analysis for MMS involves the combination of the level of maintenance activity, types and amounts of resources needed per unit of the maintenance activity, and the unit costs of each type of resource. Unit costs should be incorporated in the database and kept up to date to ensure the reliability of cost estimates.

Optimal Programming and Scheduling

Due to limited resources, usually it will not be possible to perform all of the required maintenance activities. A scheme for priority setting and optimization is therefore needed to effectively allocate scarce resources. Similar to the priority setting and optimization for pavement and bridge management, such procedures as benefit–cost analysis (e.g., incremental benefit–cost analysis and cost-effectiveness analysis) and mathematical programming (linear programming, mixed-integer programming, dynamic programming, multicriteria optimization, etc.) can also be used for maintenance management [Steuer, 1986]. Typical constraints to be incorporated into mathematical programming models include minimum and maximum maintenance production requirements, manpower availability, equipment availability, materials availability, budget constraints, and constraints to coordinate maintenance and rehabilitation programs. One way of coordinating these programs is by suspending routine maintenance activities a certain time period before scheduled major rehabilitation work is to commence on the same facility.

Programming, Scheduling, and Budgeting

The results of the above phases of the maintenance management process provide the input for the programming and scheduling of maintenance activities at all levels, as well as for compiling budgets at both the decentralized and centralized levels.

The Evolving Roles of Highway Maintenance Management

Recent trends in highway programs suggest that maintenance will occupy an increasingly important role, entailing a more sophisticated treatment in future roadway management, operations, data collection, and research [Markow et al., 1994; Reno et al., 1994]. Existing maintenance systems have been an important and effective mechanism over the past two decades in helping to plan, budget, monitor, and control maintenance work and in establishing standard and productivity guidelines. However, many changes have occurred since then — in the highway programs themselves, in the road managers' expectations, and in the state of the art of managing the transportation network in terms of techniques, tools, and technology now available. These systems need to continuously make changes to accommodate these additional categories of information and to build on emerging management capabilities.

Integration

At the strategic planning and operational levels, MMSs need to be more integrated with other types of planning and decision making regarding capital improvements and operations. For instance, MMSs rely on the assumption of steady-state work requirements from one year to the next, as embodied in the quantity standards. Whereas pavement and bridge programming systems may employ a decision-making procedure that balances the costs of a project against its benefits, MMSs make no attempt to quantify the benefits of the work performed. Also, PMSs analyze long-term alternatives in pavement actions and recommend not only the appropriate capital rehabilitation and reconstruction projects and their timing and location but also the appropriate level of routine and periodic maintenance. These recommendations could be included into the MMSs as planning and budgeting guidelines. One key change to MMSs that will allow for better integration is incorporating the ability to consider specific road segments in planning and scheduling. Another is to base maintenance work planning on an expended set of information, including condition ratings, traffic and accident levels, treatment histories, and planned construction project status.

Decentralization and the Use of Technology

Data processing and reporting methods in current MMSs are time consuming for field personnel and unable to produce sufficient timely reporting of results for effective management use. There is a need to shift planning and management responsibility to levels closer to the subdistricts where the work is accomplished. Many states have done so, but there is also the need to provide interactive computerized tools to assist maintenance personnel in the subdistricts to carry out their tasks more efficiently.

Flexibility

Effective linkages among budgets, work plans, and work accomplishments in the existing MMSs are vital. With time, however, there is a need to allow for possible replanning of work and for granting greater freedom to maintenance managers to reschedule activities or shift resources across categories of activities. Such increased flexibility would also allow for easier coordination with nonmaintenance activities in highway asset management.

Sophistication

Feature inventories should be expended to include additional information such as condition ratings, types of damages, traffic conditions, congestion levels, accident histories, and past treatments that affect maintenance decision making. Currently, MMS performance standards in most states represent average conditions and need to be refined to take into account different work circumstances, as reflected in an expended feature inventory. In addition to engineering and managerial tools now being used, improved operational planning and scheduling methods and economic analysis need to be introduced to the MMS. The details are discussed below:

Maintenance capital tradeoffs: The tradeoffs between maintenance expenditure and the level or frequency of capital improvement of pavements and bridges need to be explored by life cycle cost analysis.

Level-of-service tradeoffs: The advantages and disadvantages of maintenance expenditure on nonphysical assets such as ditch cleaning and deicing should be addressed by analytical procedures such as utility analysis and conjoint analysis for assessing level-of-service tradeoffs.

Agency and user cost analysis: Agency costs may be estimated on the basis of historical data and expert judgment. User costs are important for assessing delays associated with maintenance work zones and for calculating benefits of road and bridge improvements.

Optimal resource allocation: Methods for determining the best set of maintenance and improvement actions over time, given a budget constraint, can provide estimates of optimal future spending. Additional problems such as short-term scheduling of labor, materials and equipment for daily maintenance operations, and the optimal level of service for various maintenance activities, given a budget constraint, can also be addressed.

Maintenance management systems play a useful role in overall highway asset management. This is because the operational functions associated with this management system have far-reaching implications on other management systems, including risk management.

Congestion Management System

Traffic congestion has become a major concern on existing highways, and the situation is deteriorating at an alarming rate. Detrimental consequences of traffic congestion include longer travel time, higher fuel consumption, and increased air pollution and are associated with annual congestion costs exceeding $70 billion [TTI, 1998]. Obviously, highway asset management needs to include the management of congestion; otherwise, many system objectives of asset management will not be realized. Many states have established congestion management systems to combat the problem of traffic congestion. A CMS is defined as "a systematic process that provides information on transportation system performance and alternative strategies to alleviate congestion and enhance mobility of persons and goods" [NARA, 1993]. Congestion management implies a direct customer orientation to planning and investment and can be tailored to provide a mechanism to measure the economic and environmental consequences of current system performance and proposed future investments.

A CMS is generally composed of nine elements:

1. identification of targeted CMS locations or networks
2. definition of congestion performance measures
3. selection of performance objectives and standards
4. system monitoring and evaluation
5. identification of system deficiencies
6. selection and evaluation of appropriate congestion mitigation strategies
7. implementation of selected strategies
8. effectiveness evaluation of implemented strategies
9. establishment of a process to periodically update a CMS

CMS is often described as a unique management system because it provides a direct formal link to planning required under the 1990 Clean Air Act amendments.

Possible congestion mitigation measures related to physical assets may include road or lane widening, high-occupancy vehicle (HOV) facilities, traffic signals and related devices, and Intelligent Transportation Systems technologies, including detectors, sensors, and traffic control centers. Choocharukul and Sinha [2000] provide a congestion management system geared to physical assets. As changes in roadway facilities can affect the level of service and vice versa, there is a direct connection between CMS and other management systems.

Safety Management System

High rates of highway crashes make it necessary to identify highway facility problem areas so that necessary remedial safety-enhancing investments can be carried out. Regulation of highway use through policy formulation and implementation is another way to enhance highway safety but is of less relevance to highway asset management than investments made on physical facilities. Also, SMS integrates vehicle, driver, and roadway elements into a comprehensive approach to solving highway safety problems. However, the role of roadway elements is of particular relevance to highway asset management. Many states have developed safety management systems to address the issue of highway safety. An example is the highway safety management system developed for the state of Indiana [Farooq et al., 1995].

An SMS is defined as a systematic process that has the goal of reducing the number and severity of traffic crashes by ensuring that all opportunities to improve highway safety are identified, considered, implemented as appropriate, and evaluated in all phases of highway planning, design, construction, maintenance, and operation, and by providing information for selecting and implementing effective highway safety strategies and projects [NARA, 1993].

SMSs typically seek to promote widespread collaboration around highway safety issues and broaden the range of organizations involved in such efforts by including public health, emergency medical services (EMS), and law enforcement agencies in the development and implementation of the systems. A safety management system generally consists of the following elements: definition of safety performance measures and standards, identification of existing and potential safety problems, identification and evaluation of safety-enhancing measures, evaluation of the effectiveness of implemented measures, and review of the SMS on a continuing basis.

From the operational function dimension of asset management (Fig. 66.1), activities carried out on highway facilities with the objective of enhancing safety include the construction or repair of road signs and guardrails, the laying of new pavement surfaces to improve friction, and pothole repair. Safety management systems provide not only decision support tools for policy makers to allocate resources to solve safety-related highway problems but also data that enable the conduction of tradeoff analyses between investments in highway safety on one hand and investments in highway facility condition or other areas of highway usage on the other. Furthermore, costs and occurrence levels of various highway crash types are monitored using SMS databases to determine the extent to which asset management system objectives, such as highway safety, are being achieved.

Closely related to highway safety management is risk management. A risk management system is a collection of operational procedures to minimize loss due to tort liability. Risk management systems have been developed to address the rapid upsurge in tort claims following the loss of sovereign immunity [Yu and Demetsky, 1992; Gittings, 1989]. Risk management operational procedures include facility improvement, legal measures, and highway policy implementation. Of these procedures, facility improvement is linked directly to highway asset management.

66.5 General Requirements of Highway Asset Management System

The primary function of a highway asset management system is to serve as a decision-making tool for highway agencies. Toward this end, the system must satisfy the following criteria [Sinha and Fwa, 1989; FHWA and AASHTO, 1996]:

Comprehensiveness: A highway asset management system must address all major issues affecting the performance of highways. Elements from each dimension of the asset management matrix structure should be considered. Because of the multiobjective nature of the system, solutions developed for individual subsystems or for a single objective are unlikely to be globally optimal for the total highway asset management system.

Flexibility: The management system must be flexible to accommodate variations in different regions of a highway network. Such variations include highway functional class, unit costs of highway activities, priorities among system objectives, preferences over different highway functional activities, differences in climatic and environmental conditions, and so on. Management system needs also change with time as responsibilities shift, infrastructure elements change, organization and budget compositions are restructured, and new technologies are developed. A management system should therefore be capable to the type of agency it is intended to serve and flexible to changing requirements.

Sensitivity: To be a good strategic decision-making aid, the highway asset management system must be capable of analyzing the impacts of changing macroeconomic factors such as inflation, energy price and availability, changes in automobile and truck characteristics, and changes in type and intensity of traffic loadings. It should also be capable of analyzing the implications of different highway policy decisions.

Coordination: Most state highway agencies currently operate management systems that could provide valuable information for highway asset management. These systems are intended to cyclically monitor the condition, measure real-life performance, predict future trends, recommend candidate projects and preservation treatments, and monitor the implications of investments (or lack thereof) on system objectives, such as safety and congestion.

In a primer for asset management [FHWA, 1999], it is stated that asset management should be guided by principles of customer focus, system orientation, long-term planning, and flexibility, among others.

Conclusion

Highway asset management combines the various management systems into a single integrated system, thus enabling the evaluation of impacts of operational function decisions made in one system on performance measures in another system. For instance, it makes possible the determination of system-wide increases in crash rates if annual expenditure on roadside safety–enhancing facilities is decreased in favor of pavement repair. Highway asset management systems provide decision-making tools to improve highway transportation services with limited resources. As transportation needs and facilities of communities differ vastly, so do the management systems of their highway agencies. Important factors influencing the type and scope of management systems are the nature of the facilities to be provided and maintained and the available funds, equipment, and manpower. Highway asset management is an evolutionary process that is expected to be responsive to the needs of road users and highway agencies. Operational functions such as data collection, analysis, optimization, and strategy selection should be pursued continuously, and tools and technologies used in asset management need to be regularly updated and improved. The component management systems of asset management need to be updated as needed, such as improvements in data quality and relationships to other management systems. It is important that highway asset management systems are flexible, keeping abreast of the changing needs of highway transportation, yet robust enough to be applicable in a wide variety of areas related to asset management.

Defining Terms

Asset valuation — The use of depreciation or other approaches to determine the value of a highway asset at a given point in time.

Bayesian estimates — A statistical technique used to update estimates when new data become available.

Cash flow — The sequence of benefits and costs over time, associated with an alternative (not all of which need to involve monetary transactions).

Distress — Deterioration in the condition of a physical highway asset, such as cracking or rutting of a highway pavement.

Dynamic programming — The technique used to formulate and solve optimization problems by recursively solving subproblems.

Geographic Information Systems — A database with capabilities to manipulate, analyze, and display spatial data.

Global Positioning System — Technology developed by the military that uses satellites to determine the latitude and longitude of a position anywhere in the world.

Heuristic optimization — Techniques used to find satisfactory, not necessarily optimal, solutions to optimization problems. Some heuristic techniques provide solutions with values that differ from the optimal solution value by not more than a provable bound.

Linear programming — The techniques used to formulate and solve optimization problems in which the decision variables are continuous and the objective function and constraints are linear.

Location referencing system — A system that uniquely describes the geographical location of a feature with respect to some projection or other position referencing system.

Markov chain — A stochastic process in which the present state of the system determines the future evolution of the process independently of the past.

Mixed-integer programming — The techniques used to formulate and solve optimization problems in which at least some decision variables are discrete and the objective function and constraints are linear.

Network-level analysis — The evaluation of dependent or independent alternatives for a set of highway asset facilities.

Network-level optimization — The techniques used to formulate and solve optimization problems in such a way that the polynomial time algorithms developed for some network problems can be used.

Ordinary least squares — A technique for calculating the regression equation that minimizes the sum of the squares of the error terms, that is, the differences between the observed and predicted values for the dependent variable.

Pavement profile — The vertical shape of the pavement surface.

Pavement segment — A length of pavement that forms the basic unit for which data is collected, stored, and analyzed and for which alternatives are evaluated and decisions are taken.

Programming — The determination and scheduling of activities to be performed and the resources needed to implement the program.

Project-level analysis — The evaluation of mutually exclusive alternatives for a single physical highway asset.

Regression analysis — The technique of mathematically estimating the parameters of functions describing a process to fit the functions to data.

Sampling technique — The method used to choose units of physical highway assets to include in the sample, with the objective of obtaining a statistically adequate, representative sample at reasonable costs.

Abbreviations

AADT	Annual average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
AHP	Analytic hierarchy process
BMS	Bridge management system
CMS	Congestion management system
CRC	Continuously reinforced concrete
DP	Dynamic programming
FHWA	Federal Highway Administration
GASB	Governmental Accounting Standards Board
GIS	Geographical Information Systems
GPS	Global Positioning System
JCP	Jointed concrete pavement
LCC	Life cycle cost
LOS	Level of service
LP	Linear programming
MIP	Mixed-integer programming
MMS	Maintenance management system
OLS	Ordinary least squares
PCC	Portland cement concrete
PMS	Pavement management system
RTRRM	Response-type road roughness meter
SMS	Safety management system

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