Analytical Approach to the Development of a Bridge Management System

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A study to determine feasibility and define the general structure of a bridge management system (BMS) for the Texas State Department of Highways and Public Transportation's 47,000 highway bridges is described. The decentralized nature of bridge management in the SDHPT's district offices suggests that a BMS for Texas should have primary applicability at the district level. Specific recommendations for the characteristics and scope of a BMS are presented. Development of the recommended BMS is planned to culminate with implementation in September, 1992, followed by a period of evaluation and refinement.

INTRODUCTION

A bridge management system (BMS) can be defined as a comprehensive method for making decisions about bridge management activities in a systematic manner. According to such a definition, the bridge management activities of most state transportation departments can be termed bridge management systems. The term BMS implies somewhat more, however. The FHWA defines a comprehensive BMS as "an integrated set of formal procedures for directing or controlling all activities related to bridges," (1). In this paper, the term BMS is used to mean *a computerized decision-aiding system incorporating both rational models and expert knowledge of bridge deterioration processes and effectiveness of management activities, and economic models of life-cycle costs, including an economic accounting of user as well as agency benefits and costs, in a process designed to provide a predefined level of service to the public at a minimum cost.* In the past few years, a significant amount of study has been directed at development of methods to accomplish bridge management with systems which approximate the above definition. Based on recent federal data, it appears that approximately forty percent of the states have developed, are developing, or are planning development of some form of a BMS (2). It is clear that the needs of the various states are different, and these differences are reflected by the various approaches taken in the development of the various BMS which have been reported in the literature. The FHWA is encouraging the various States to develop their own bridge management systems (1), and it is generally recognized that bridge management decisions supported by BMS will carry increased credibility in the federal Bridge Replacement and Rehabilitation Program (BRRP).

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SCOPE OF THE PROBLEM

There are at present approximately 46,783 bridges on Texas highways. This figure includes nearly 32,000 bridges "on system", or on highways designated as eligible for federal-aid, with the remaining approximately 15,000 bridges designated as off-system bridges, for which primary responsibility for maintenance belongs to a county, city or some other entity rather than the State Department of Highways and Public Transportation (SDHPT) (3). The approximately 47,000 bridges is easily the largest number of bridges of any state in the United States. Recent studies (3) have concluded that approximately 19.8 percent of all on-system bridges in Texas are classified as substandard due to structural deficiency or functional obsolescence. A much higher fraction of the off-system bridges are so classified. Projected needs for rehabilitation of existing bridges peak in the five-year period beginning 1995, at $2 billion/5 years or $400 million per year. This is more than 2.5 times the entire bridge expenditures by the Department in 1988, and will undoubtedly require additional sources of revenue.

The magnitude of the projected rehabilitation needs emphasizes the importance of good bridge management to Texas. The advantages of an operational BMS for Texas are anticipated to include:

- Better data and better access to data on bridge deterioration rates,
- More rational definition of level of service goals,
- Identification of optimal activities and budgets for both short and long-range planning scenarios,
- Better understanding of effectiveness of maintenance and management activities,
- Future integration with pavement management system (PMS) into a roadway management system (RMS),

- More uniform application of bridge management strategies across geographically and politically diverse districts, and
- More rational means for programming improvements and forecasting needs.

To study the feasibility of developing a BMS for Texas, and to define the recommended scope and content of a BMS, an SDHPT-sponsored study conducted by the Texas Transportation Institute (TTI) was initiated in September 1988. The recommendations of this two year study are reported in this paper. It is the present goal of the SDHPT to implement a BMS by September 1992.

DESCRIPTION OF THE STUDY

The primary objective of the study was to design a plan to achieve a cost-effective, comprehensive bridge management system which meets the needs of the SDHPT. To accomplish this objective, the research team worked closely with an advisory committee consisting of bridge managers from several districts, and various individuals in the bridge and maintenance divisions of the SDHPT. The purpose of the advisory committee was to obtain feedback on the effectiveness of present bridge management practices and to obtain expert advice on the needs and problems of bridge management at both the district and state levels. A review of bridge management systems and related literature nationwide was also accomplished, which included discussions with FHWA personnel and bridge managers and researchers associated with successful or evolving bridge management systems in other states, including North Carolina, California, Indiana, Pennsylvania, and New York.

In reviewing the needs expressed by district and state personnel, it was determined that many could be satisfied directly through implementation of a comprehensive bridge management system. Listed below is a summary of some of the key needs identified in the study that can be aided by development of a BMS for Texas:

- A supplement to the sufficiency rating system for setting planning priorities,
- An analytical approach to identification of bridge needs,
- Consideration of user benefits and level of service in making funding decisions,
- Consideration of life-cycle costs in programming activities at the state and federal level
- An intermediate-range plan for scheduled maintenance to accompany the replacement and rehabilitation funding programs,
- A method of gauging maintenance effectiveness, and
- A method of evaluating alternatives, including maintenance, over a network as well as for single bridges.

With these needs and goals in mind, a plan for the development and implementation of a comprehensive BMS was formulated. In the course of performing this research, several major tasks were accomplished, including:

- Identification of specific data required for the BMS,
- Establishment and evaluation of a list of cost-effective maintenance and rehabilitation work items, and
- Identification of suitable and necessary models and algorithms for incorporation into the BMS, including deterioration, life-cycle cost, and optimization procedures.

DETAILS OF PROPOSED BMS

The BMS recommended to the SDHPT includes the following elements: databases containing inventory data and unit costs data, deterioration models, feasible improvements knowledge-based system, life-cycle costs models, and optimization procedures. Each of these proposed elements will be addressed below.

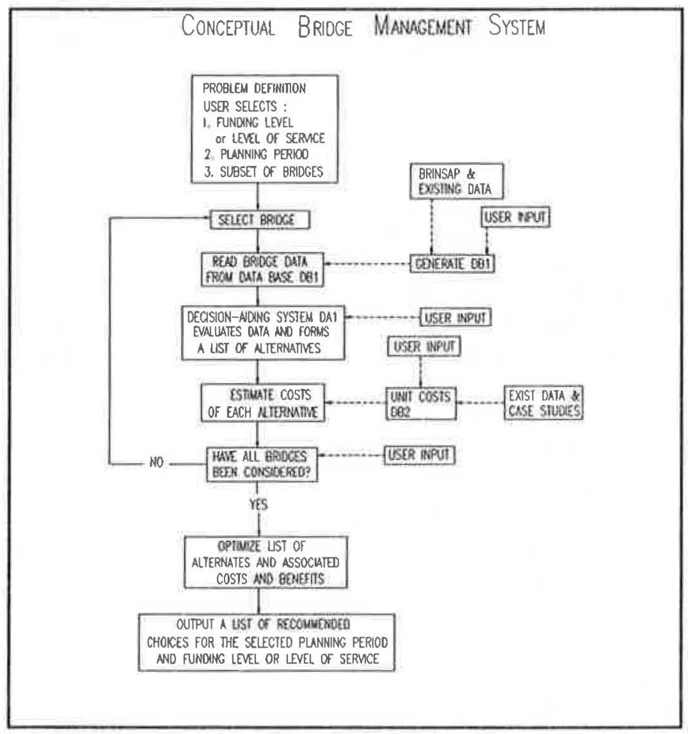

FIGURE 1 Flow chart illustrating recommended BMS for Texas.

The interaction between the elements is as described in FIGURE 1. The BMS may be activated by the user, for purposes of this discussion, a district bridge engineer, in one of two modes; short-term program planning, or long-term needs prediction. These two modes are distinguished by the different unknowns which will be determined by the BMS in each case. In the case of short-term program planning, it is assumed that the planning period is one or two years, and that the budget available for that period is known and constrains the problem. In this case the problem becomes a determination of the optimal selection of projects and bridge management activities yielding the greatest economic benefit subject to the budget constraint. In the case of long-term needs prediction, the user is seeking to determine the required funding level to provide a predefined level of service for a longer period, such as five, ten, or twenty years. The user also enters the BMS with a user-defined subset of bridges under consideration. In the default case, this subset will be all the on-system bridges in the district, but other subsets can be defined by the user for specific studies.

The BMS considers each bridge in the selected subset individually, in turn, determining the required condition data from the database DB1. With the knowledge represented by this data, along with any other runtime data input by the user for specific bridges, the decision-aiding system DA1 synthesizes several feasible alternative bridge management activities. This list of feasible alternatives may be supplemented by user-generated alternatives in the case where the user desires to force economic consideration of some specific activity for a selected bridge. For each of the synthesized activities an initial cost and a life-cycle cost are generated. The agency benefits of the alternative are determined by comparison of the present value life-cycle cost with a reference life-cycle cost, and the user benefits are computed and summed with the agency benefits. The optimizing routine then determines the optimal selection of alternatives for that bridge. Once all bridges have been considered, the BMS outputs the recommended list of bridge management activities for the predetermined planning period, along with the initial costs and calculated benefits.

The user interface for the BMS is planned to allow runtime user interaction in both pre- and postprocessing modes. Through this interface, the user will be able to make queries to the databases, manipulate output reports, and provide input that might otherwise not be considered by the BMS. A geographic information system (GIS) is one viable alternative for meeting these pre- and postprocessing needs.

Bridge Inventory Data

A comprehensive and effective BMS requires a database or system of databases which is capable of supporting the various analyses involved in the various submodels of the BMS. As part of the development of a BMS, it was thus necessary to first identify the expected users of the BMS--in this case the various SDHPT district bridge management personnel, and the data needed by them, and also determine what types of BMS analyses can be accomplished utilizing the data items available in the existing databases.

There are basically three major types of data required to implement a comprehensive BMS: bridge inventory, condition and rating data; cost data; and improvement activity data, including replacement, rehabilitation and maintenance data. At the Texas SDHPT, the primary database containing such data is the Bridge Inventory, Inspection, and Appraisal Program (BRINSAP) database. An evaluation of the adequacy of the BRINSAP database included a study of the database structure itself and the relevance or usefulness of its data contents for incorporation into a BMS. One of the goals of this effort was to determine whether BMS analyses using only the existing data could yield useful results, or whether any additional data is needed. This question is still under study. As part of the BMS, a core database DB1 will be created primarily from the existing BRINSAP database to provide necessary bridge inventory, condition and rating data for analyses within the BMS.

Texas' Bridge Inventory, Inspection and Appraisal Program (BRINSAP)

In an effort to perform bridge planning, programming, project decision-making, as well as implement the National Bridge Inspection (NBI) standards as issued by the Federal Highway Administration (FHWA), a manual of procedures was prepared by the SDHPT (4) defining maintenance of the department's BRINSAP file. BRINSAP uses a computerized database to record, store, and update all data related to inventory, inspection, and appraisal activities on each bridge and tunnel on Texas public roads. While the main electronically-stored data is maintained by the department's headquarters in Austin, Texas, SDHPT District Engineers also keep a complete, accurate, and sometimes more detailed file on each bridge located in their respective districts.

The bridge inventory data in BRINSAP consists of items identifying the bridge type, location, general description, age, functional classification, condition ratings, etc. In addition to the basic NBI items, BRINSAP includes modifications to suit the Department's own needs, similar to databases kept by DOTs in other states, including New York and North Carolina (5). This is especially apparent in the case of condition ratings; NBI includes six condition ratings, but BRINSAP contains ten possible condition ratings (0 - 9) for each item, and additional details are also recorded during the bridge field inspection.

BRINSAP allows the bridge inspector to record the condition rating after condition assessment of the bridge, allocating a rating out of a possible ten values (0 - 9) as stipulated by the National Bridge Inventory Coding Guide (6). The condition rating of a major component (SI & A Item) is derived by selecting the lowest rating of any element of that component as illustrated in FIGURE 2. In addition to the ratings, the inspector may record comments on the condition of the component or its elements. While these comments and individual ratings are useful for detailed bridge analyses, only the overall component condition ratings are stored on the computerized BRINSAP database; the remaining information can be accessed only manually, through the individual bridge folders maintained by the Districts.

TEXAS BRINSAP INVENTORY ITEM 58 - ROADWAY

Minimum		Condition Rating
1	Deck ______	______
6	Wearing Surface ______	______
6	Joints, Expansion, Open ______	______
6	Joints, Expansion, Sealed ______	______
6	Joints, Other ______	______
6	Drainage System ______	______
6	Curbs, Sidewalks & Parapets ______	______
6	Median Barrier ______	______
6	Railings ______	______
7	Railings Protective Coating ______	______
7	Delineation (curve markers) ______	______
6	Curbs, Sidewalks & Parapets ______	______
	Other ______	______

Component Rating ______

Comments: ______

FIGURE 2 Excerpt from Texas' BRINSAP inspection form 1085-1.

Since any form of network analysis requires computer accessibility to the data required, the level of detail of any analysis conducted using the current data in BRINSAP will be limited to a consideration at the bridge component level only. To illustrate this point, consider the SI & A Item 58--Roadway. The condition performance of sealed joints, railings, etc. which are elements of this component, cannot be monitored on a network basis; the required condition rating of the joint or railing has been overridden by the available single overall rating of the Roadway component. In order to improve the current level of detail in network analyses, the element's specific condition ratings should be included in BRINSAP. Since these data items are already collected at the time of regular bridge inspection, no additional cost would be incurred; only a slight modification of the BRINSAP database structure is needed to accommodate this change. Moreover, these additional data items will give a more complete picture of the bridge condition and the maintenance and rehabilitation needs. The need for such data was initially identified during one of the research team's interviews with SDHPT District bridge personnel.

With the aid of a coding guide, the items in the computerized BRINSAP database were interpreted and reviewed to evaluate their relevance to the development of a comprehensive and effective BMS. An example listing some of the many items being considered for inclusion in the core database DB1 for the proposed BMS framework are shown in TABLE 1, along with a description of the relevance of each item.

The database DB1 is designed to interface with the main framework of the proposed BMS, with the option of user input provided to override or validate the data items generated from BRINSAP. The deterioration submodel and the knowledge-based feasible improvements generator will be able to read bridge data directly from this database.

Improvement Costs Database

Many of the analyses to be done within the proposed BMS will require cost data. To facilitate this, two steps will be taken in building a database DB2 which will contain unit costs of feasible bridge improvement and maintenance activities. First, it is necessary to identify the various possible bridge maintenance and rehabilitation (M&R) activities which are being performed, or which should be performed, and to evaluate the effectiveness and frequency of application of each of these activities on Texas bridges. Secondly, unit costs for each of the M&R activities will be developed, using historical data where available, or expert opinion when historical data is lacking. It may also be necessary to establish a procedure to capture future bridge maintenance and rehabilitation cost data.

Sources of available data on bridge-related expenditures at the SDHPT include the BRINSAP database, the Construction Projects' Average Low Bid Listings, Bridge Projects' Bid Listings, the Design and Construction Information System (DCIS), the Financial Information Management System (FIMS), and the newly developed Maintenance Management Information System (MMIS).

Bridge Improvement Activities

The only formal system for monitoring maintenance activities on the Texas Highway System is the recently developed Maintenance Management Information System (MMIS). In its original form, the MMIS was designed to monitor 21 highway maintenance functions, with none specifically designated for bridge maintenance (7). MMIS has recently been modified to monitor the ten bridge-related maintenance and rehabilitation functions shown in TABLE 2.

While these activities may be adequate for a summary level analysis of bridge expenditures, a network level bridge management scheme will require the monitoring of M&R activities at a more detailed level. There is a vast number of possible bridge rehabilitation and maintenance activities. For example, the bridge management systems used by the transportation agencies of Pennsylvania and North Carolina monitor 71 and 40 activities respectively (8, 9). While efforts are underway to increase the current number of bridge maintenance activities monitored by the SDHPT, the activities recommended for consideration by a BMS should be limited to the most commonly applied activities.

To achieve this goal, first, a "raw" list of possible bridge improvement activities was generated through a literature

TABLE 1 SAMPLE LISTING OF BRINSAP ITEMS FOR BMS CORE DATABASE DB1

BRINSAP Item	Relevance to a BMS
Items 5.1 - 5.6 (Principal Route)	Level of Service (LOS) Criteria
Items 6.1 - 6.2 (Principal Route)	LOS Criteria
Item 10.4 (Widening projects' history)	Rehabilitation Effectiveness
Item 19 (Bypass, Detour Length)	User Costs/Benefits
Item 20 (Toll)	Life-Cycle Cost Analyses
Item 24 (Federal Aid System)	LOS Criteria
Item 27 (Year built/last rehab.)	Deterioration/Rehabilitation Study
Item 28 (Lanes on structure)	LOS Criteria
Item 29 (Average Daily Traffic)	LOS Criteria and Deterioration Study
Item 32 (Approach Roadway Width)	Estimate Improvement Costs
Item 36 (Traffic Safety Features)	LOS Criteria and User Costs/Benefits
Item 41 (Operational Status)	User Costs/Benefits
Item 43 (Structure Type)	Deterioration Study and Feasible Improvement Strategies
Item 58 (Roadway Condition)	Deterioration Study
Item 59 (Superstructure Condition)	Deterioration Study
Item 60 (Substructure Condition)	Deterioration Study
Item 63 (Estimated Remaining Life)	Deterioration Study
Item 66 (Inventory Rating)	LOS Criteria
Item 67 (Structural Condition)	LOS Criteria
Item 68 (Roadway Geometry)	LOS Criteria
Item 69 (Vert/Lateral Clearance)	LOS Criteria
Item 70 (Safe Load Capacity)	LOS Criteria
Item 71 (Water Adequacy)	LOS Criteria
Item 72 (Approach Rdwy Alignment)	LOS Criteria

survey and review of historical data on bridge activities - SDHPT's Average Bid Listings, Bridge Cost Data Files, etc. Secondly, the initial raw list was refined to a shorter list using a structured opinion survey of the SDHPT bridge engineers and inspectors. At this stage, the importance of each activity was assessed based on the expert's own experience with bridge engineering and management in Texas. Because the feasibility study revealed a scarcity of bridge cost records, old bid records on bridge projects and expert opinions of SDHPT bridge personnel, regarding the relative importance and frequency of application of the activities, were determined in order to select and recommend the most important bridge rehabilitation activities to be monitored by the Texas BMS.

The MMIS should provide data and statistics on work performed as well as costs expended on various maintenance activities. It will also be a useful tool in analyzing and improving the productivity and efficiency of bridge maintenance programs. Since the system is designed to track activities on a highway by milepost location, it may be necessary to modify the MMIS database structure in order to track bridge maintenance activities. This problem is apparent in the case of two adjacent bridges on a divided highway; the two bridges have the same milepost. Possible solutions are to use bridge structure number instead of the milepost, or use milemarkers instead of mileposts. The MMIS appears to be flexible enough that such changes and addition of maintenance functions could be easily accommodated. In the future, it may be necessary to add to the ten MMIS bridge maintenance and rehabilitation functions, because of the many activities which may impact the decision processes in a BMS.

In addition to its current link with three other databases maintained by the SDHPT--Salary and Labor Distribution (SLD), Equipment Operating System (EOS), and Material Supply and Management System (MSMS)--MMIS could potentially be linked to other pertinent SDHPT systems such as BRINSAP, DCIS, FIMS, and the Roadway Information System (RIS). A similar integrated system has been successfully implemented by the Pennsylvania Department of Transportation (8).

TABLE 2 BRIDGE FUNCTIONS IN THE TEXAS MMIS

Texas MMIS Function No.	Bridge M&R Activity
610	Bridges, Movable Span
620	Channel Maintenance
625	Channel Maintenance (Under Bridge)
630	Bridges, Rail
640	Bridges, Joints
650	Bridges, Deck
660	Bridges, Superstructure
670	Bridges, Substructure
970	Bridges, Inspection (BRINSAP)
971	Bridges, Routine Inspection (non-BRINSAP)

Unit Costs Estimates

As mentioned above, for a comprehensive BMS to function accurately, it is necessary to develop unit costs for each of the considered bridge improvement activities. This could be done through statistical analyses of historical data where available; otherwise preliminary cost estimates could be used. Preliminary cost estimates of bridge replacement or major rehabilitation projects are usually obtained through the aggregation of unit costs of different work items as retrieved from low bid listings for past similar projects. The total project unit cost, or major component--deck, superstructure, or substructure--unit costs can be estimated using the bridge deck area as a unit of measurement. Simplicity aside, it is not practical to use a common unit cost value for all bridges, even for the same type of improvement activity. This is simply because bridge improvement projects are often unique to specific classes of bridges, especially substructure rehabilitation projects. It will therefore be necessary to categorize project unit costs by bridge type, improvement activity type, and also by geographic location. In a similar fashion, unit costs for each bridge maintenance activity can be estimated using preliminary cost estimates.

It will be necessary to establish a procedure and framework to capture appropriate cost data as costs accrue during the service life of the bridge. Hopefully, the MMIS will be modified to be capable of capturing bridge maintenance cost data on a regular and historical basis. After collecting this data on a historical basis, it will then be feasible to conduct case studies on bridge maintenance expenditures, which will contribute to the refinement of a comprehensive bridge management system for Texas.

Deterioration Models

Models of bridge condition deterioration may be classified as empirical, mechanistic, or stochastic. Empirical or regression based models are models in which the condition of a component is assumed to deteriorate at a prescribed rate determined by fitting quantitative data, sometimes supplemented with the use of expert knowledge. Regression models are the most commonly used models in existing BMS (5, 9, 10, 11, 12, 13, 14, 15), although examples of mechanistic models (16), and stochastic models (17, 18, 19) may also be found in the literature. Because of the present lack of comprehensive mechanistic models, it is not practical at present to base a deterioration model solely on a mechanistic approach, no matter how aesthetically appealing that may be.

The most commonly used stochastic model for representing the bridge deterioration process is the Markov chain approach. One mathematical limitation of deterioration models using stationary Markov chains is that the probability of transition from one state to the next is independent of the time that the bridge has occupied the present state. In reality, bridges stay in a specified condition state many years, and the probability of transition to a lower condition state will increase with time in any given state. Non-stationary semi-Markov processes are more suitable, but have not yet been applied to this problem.

The most sophisticated and realistic of the existing regression models is the nonlinear model developed by West et al. (15). The basis of the model is a condition rating function which depends on time in the following manner:

$$CR(t)=(1-X)\beta_1 e^{-\frac{t}{\beta_2}}+X(\beta_1 e^{-\frac{t_r}{\beta_2}}+\beta_3)e^{\frac{-(t-t_r)}{\beta_4}}$$

where

CR(t) = component condition rating,
t = age of the bridge,
t_r = age at time of major rehabilitation,
β_1 = initial condition rating,
β_3 = improvement due to rehabilitation,
β_2, β_4 = reciprocal decay coefficients (yr), and
X = 0 before rehabilitation, 1 after rehabilitation.

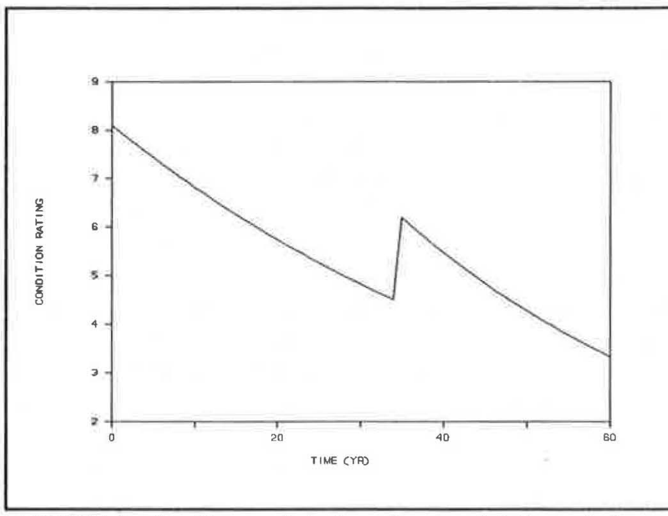

FIGURE 3 Nonlinear deterioration model for reinforced concrete bridge decks on prestressed concrete girders, with rehabilitation at 35 years (15).

This model is represented in FIGURE 3, with the parameters recommended by West et al. (15) for concrete bridge decks on prestressed concrete girder bridges carrying average daily traffic (ADT) in excess of 10,000 vehicles.

In its most detailed form, the model is a six-parameter nonlinear model which can include the effects of two different types of rehabilitation; a rehabilitation after 25 years of service being considered to have slightly different effects on the resulting increase in condition rating and on the subsequent condition rating deterioration than a rehabilitation accomplished before 25 years of service.

Because of the simplicity and availability of regression models, the use of regression models from the literature, fit to Texas bridge condition data supplemented where needed by expert knowledge obtained of Texas SDHPT bridge engineers, is recommended for incorporation into the proposed BMS.

Feasible Improvements Model

The feasible improvements model will be a knowledge-based system which will synthesize a list of feasible alternatives for each bridge under consideration. Rules for such a knowledge-based system are available. The present SDHPT practice for identifying bridges eligible for rehabilitation and replacement have been incorporated into a series of computer programs (20) to allow an automated listing of bridges eligible under FHWA guidelines as defined in Texas SDHPT's Roadway Information System User's Manual (21). From this existing procedure, a series of rules will be developed which will approximate the existing procedure, generating a feasible alternative from the following set: do nothing, rehabilitate, or replace. The present procedure does not include more detailed alternatives, nor does it include consideration of different levels of maintenance effort. However, along with the rules developed from existing practices, other expert knowledge such as that suggested by Harper et al. (22) and Zuk (23), will be used to generate additional alternatives.

In the current SDHPT process, each bridge is assigned a weighted score, which is a linear combination of five variables; ADT, the average daily traffic; CPV, the cost of the proposed improvements divided by ADT; SR, the FHWA's sufficiency rating; DSS, the minimum value of the deck, superstructure and substructure condition ratings; and BWC, the bridge width condition, which is a binary-valued measure of the adequacy of the roadway width for ADT. The rules forming the basis for this process involve comparison of the weighted scores with user-defined limits for qualifying/marginal and marginal/non-qualifying bridge categories. In the present method, the bridges classified in qualifying and marginal categories are then ranked by increasing initial improvement cost, normalized by ADT. In the proposed procedure, the life-cycle costs and benefits will be compared for all feasible alternatives for all bridges under consideration, to select an optimal program of improvements.

As mentioned above, knowledge-based rules derived from the present logic used by the SDHPT, as well as rules suggested by Harper et al. (22), Zuk (23) and others, will be employed to assure that the set of feasible alternatives includes the optimal solution. Harper et al. (22) define a series of 84 rules which synthesize feasible maintenance and rehabilitation options from among approximately 40 possible scopes of work. The possible scopes of work include various feasible permutations of routine maintenance, repairs, rehabilitation and replacement of deck, superstructure, and substructure components. Zuk (23) describes an expert system with a set of 32 knowledge-based rules. These rules are fundamentally based on the sufficiency rating, but include consideration of historical significance, roadway width adequacy, replacement of obsolete bridges that inherently cannot be widened, strengthening of bridges to improve load capacity, terminal maintenance of bridges which are to be replaced in the near future, detour length during rehabilitation, replacement of bridges requiring frequent major repairs, timing of bridge replacement for bridges in areas of rapid ADT growth, and limited network considerations.

Life-Cycle Costs Model

In order to evaluate the alternative improvement strategies for every bridge on a network system, it is necessary to consider the corresponding costs to be incurred by the highway agency. These costs include the first or initial one-time cost, periodic maintenance costs, and possibly a rehabilitation or replacement cost as the bridge approaches the end of its service life.

While many of the current bridge project selection methods consider only the first or initial construction costs (5), it is more appropriate that the entire life-span costs, or simply the life-cycle costs associated with each alternative, be considered. Life-cycle cost analysis is particularly suitable for evaluating multiple alternatives which have unequal life expectancy, level of service, and/or maintenance costs. Based on the expected deterioration rate, costs required to bring a bridge back to a desired level of service are utilized to generate a life-cycle profile. Since life-cycle costs include future costs, a discount rate must be selected in order to combine future and present costs.

In the economic analysis, the cost of a bridge improvement alternative will be taken as the initial capital cost, or first cost, of the project. In addition, two types of benefits will be considered: agency benefits and user benefits.

Agency Benefits

Agency benefits are categorized as reductions in life-cycle cost resulting from actions of the agency, such as preventive maintenance, certain types of rehabilitation, and any other actions that effectively extend the service life of the bridge. More specifically, agency benefits are defined as the present worth of future cost savings to the department due to a bridge expenditure (5).

To determine agency benefits, the present worth of all future costs to the agency over the life of the bridge, such as maintenance, rehabilitation, and replacement expenditures, are calculated for two different life-cycle cost scenarios. The first assumes no improvement is made to the bridge, thus the service life is not extended and replacement takes place at the end of the bridge's remaining life. This scenario constitutes the base line or reference life-cycle cost. The second case assumes that an expenditure is made to extend the life of the bridge for a specified number of years. This scenario determines the life-cycle cost for the improvement activity. The net benefits are thus equal to the life-cycle costs for the replacement alternative minus the life-cycle costs for the extended life alternative.

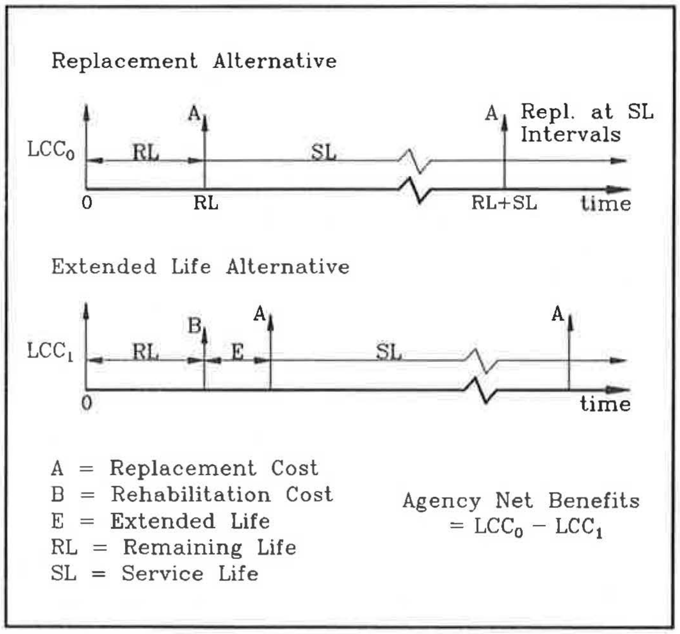

FIGURE 4 Calculation of agency benefits using life-cycle cost analysis (5).

Consider, for example, the illustration shown in FIGURE 4. There are two possible courses of action: (1) replacement of the bridge, or (2) rehabilitation and maintenance of a bridge to postpone eventual replacement. For a life-cycle cost comparison of these alternatives, the following information is needed:

E = the extended life of the bridge due to rehabilitation and maintenance.
LCC_0 = Present worth of life-cycle costs for the replacement case.
LCC_1 = Present worth of life-cycle costs for the extended life case.

The agency net benefit, B_a, associated with the extended service life case is computed as the difference between the two life-cycle costs involved, that is,

$$B_a = LCC_0 - LCC_1$$

If the rehabilitation expenditure is in fact determined to be of net benefit to the agency, the reduction in future agency costs, discounted, will be greater than the expenditure. If such a benefit is not feasible, the alternative was not of net benefit, and the agency should search for other options.

User Benefits

The second type of benefits to be considered by the BMS is user benefits. These are the benefits to the public resulting from actions that reduce user costs. User costs can be generated due to narrow width, low clearance, poor alignment, and reduced load capacity. Likewise, improvements that functionally upgrade a bridge, such as straightening the approach alignment, removing a load posting restriction, or increasing horizontal and/or vertical clearances all serve to reduce user costs. In general, any improvement that alleviates user costs prior to the end of a bridge's economic life is taken as a user benefit (5). These benefits are calculated by subtracting the user costs before an improvement from the user costs after the improvement. The user costs are generally computed annually and then discounted to a present worth in the same manner as agency costs. The benefits that will be considered primarily fall into three categories:

- Reductions in accident costs,
- Savings in vehicle operating costs, and
- Reductions in travel times.

In the last several years major advancements have been made in life-cycle cost analysis procedures and methods of calculating user costs for bridge alternatives. Two references present the state of the art in this analysis very well. The first of these is Federal Highway Administration's procedure for analyzing bridge alternatives (5). The second is the research done in North Carolina, particularly the report by Chen and Johnston (9). These life-cycle cost procedures represent advancements in the state of the art for bridge management and will provide the basic framework for the BMS described herein.

Accident Costs

Savings in accident costs result from bridge improvements that eliminate width restrictions and poor approach geometry. Several studies have shown that bridge width, roadway width, bridge rail design, roadway marking and signing, and roadway geometry are important in determining accident rates and severity. However, a review of these bridge studies showed that several had emphasized the importance of bridge and roadway width in determining the accident rate

(24). That is, vehicles tend to strike the bridge rail or bridge rail end when the bridge is narrow, either absolutely, or relative to the roadway width.

A more recent review of the literature (25) and a recent study of a large number of bridge accidents (26) confirmed this relationship and developed improved estimating procedures. The latter study used all reported accidents from the states of Arizona, Michigan, Montana, and Texas over a 3-year period, occurring on or within 500 feet of a bridge. This included 11,880 bridges and 24,809 accidents.

Other recent research has developed improved estimates of bridge-related accident costs (27). This research showed that fatality and injury rates for bridge-related accidents were among the highest cost accidents. The annual accident benefits of bridge widening are calculated as follows:

Annual Accident Benefits = (Change in Accident Rate) (ADT) (365) (Cost/Accident)

Time and Vehicle Operating Costs Associated With Detours

The cost of detouring vehicles when the load capacity or size of a bridge requires such action includes the extra time and vehicle operating costs associated with traveling the alternative route instead of using the preferred route. The benefit of not having to detour is equal to this cost and is calculated using the following two formulas (5):

Vehicle Operating Cost Savings From Not Detouring:
Savings = (ADT) (365) (Change in Fraction of Trucks Detoured) (Change in Distance Traveled by Trucks Detoured, in Miles) (Operating Cost Per Mile).

Value of Time Savings:
Savings = (ADT) (365) (Change in Fraction of Trucks Detoured) (Change in Distance Traveled by Trucks Detoured in Miles) (Value of Time Per Hour)/ (Speed in Miles Per Hour)

The FHWA manual uses vehicle operating costs developed in a New York study in 1981. Truck and passenger values of time have also recently been developed by McFarland and Chui (28). In addition, very detailed procedures for estimating the number of trucks that will be detoured for load limits and size restrictions have been developed by North Carolina (29). The above estimation procedures have been proposed for use in the BMS for Texas. However, the procedures for calculating time and vehicle operating costs associated with detours use average values and, consequently, are rough approximations of the expected costs of detours. Therefore, in order to provide more accurate calculations in cases where these costs are especially significant, it has been further proposed to supplement these procedures with an improved method that is based on research conducted at TTI.

This improved procedure was originally developed for evaluating highway bypasses and uses traffic relationships in the new highway capacity manual. It can be used in both rural and urban areas, and can be used to model the effects of closing one or more lanes, including complete shutdown of the bridge during major rehabilitation. This ability will allow the estimation of user cost savings experienced from building a new bridge at a different location while keeping the old bridge open to traffic during construction. This may be very significant if a critical bridge with a high traffic volume must be closed during rehabilitation.

Since general modeling procedures have already been developed for estimating the user costs described above, emphasis will be placed on refining these procedures. Special attention will be placed on developing procedures for each type of bridge alternative. Attention will also be devoted to evaluating procedures for estimating user costs during rehabilitation requiring bridge or lane closures.

Once the agency and user benefits for a prescribed alternative, have been determined, the total net benefits can be simply determined. For any proposed improvement activity,

Total Net Benefits = Agency Benefits + User Benefits

Optimization Routine

The bridge rehabilitation/replacement model is actually a special case of discrete optimization models. Discrete optimization problems abound in all situations concerning the management and efficient use of scarce resources to increase productivity. Particularly, in the last few years, applications of discrete optimization have rapidly developed because of the widespread use of microcomputers and the data provided by information systems.

The purpose of the optimization routine is to select one maintenance, rehabilitation, or replacement activity, including the do-nothing alternative, for each bridge of a given system, such as a state, district or part of a district. This is done in such a way that the total benefit derived from the implementation of the selected projects is maximized without exceeding a known budget. It is assumed that the following information is available:

- The group of bridges to be considered,
- A set of feasible alternatives for each bridge, and
- The cost and benefit associated with each alternative.

The basic bridge alternative selection model can be mathematically formulated as follows:

$$\text{Maximize} \quad Z=\sum_{i=1}^{n}\sum_{j\epsilon s_i} b_{ij}X_{ij}$$

$$\text{Subject to} \quad \sum_{j\epsilon s_i} X_{ij} = 1 \text{ for each bridge } i$$

$$\sum_{i=1}^{n}\sum_{j\epsilon s_i} c_{ij}X_{ij} \leq B$$

$$X_{ij}=0,1 \quad \text{for all } i,j$$

where the following notation is used:

n = number of bridges,
S_i = set of alternatives for bridge i,
b_{ij} = benefits associated with bridge i, alternative j,
c_{ij} = cost of bridge i, alternative j,
B = specified budget for a given planning horizon, and
X_{ij} = 1 if alternative j is chosen for bridge i; else 0.

The objective function maximizes the benefits resulting from a set of feasible bridge alternatives. The first set of constraints allows only one alternative to be selected for each bridge. The last constraint ensures that the total budget available is not exceeded. The above mathematical model is an integer programming model. A computationally efficient solution for the model can be obtained from a branch-and-bound integer programming procedure due to Nauss (30) or a special-purpose methodology based on a systematic analysis of incremental costs and benefits due to McFarland, et al. (31). Optimization routines based on these two procedures have been coded in FORTRAN and are referred to as INTPROG and INCBEN, respectively.

The computational requirements of INCBEN and INTPROG for the optimization of bridge-improvement alternatives for single-period problems have been investigated in a microcomputer environment. Both programs have been used successfully with hypothetical bridge data to identify an optimal set of bridge-improvement alternatives for up to 5,000 bridges with up to seven alternatives each. A comparison of the optimality of the solutions was accomplished, as well as a comparison of the computation time and hardware requirements for the two methods. Although INCBEN requires up to 1.5 times the memory storage capacity of INTPROG, INCBEN runs up to 3 times faster than INTPROG for certain data sets. For all practical purposes, the accuracy of the solution sets were identical for all data sets and budget constraints used in the investigation.

Description of Basic INCBEN Procedure

The basic procedure of the INCBEN algorithm (31) is summarized below. This algorithm ensures that the optimal set of bridge alternatives will be chosen for any cumulative cost:

1. For each bridge arrange all alternatives in increasing order of cost.

2. If there are several alternatives having the same cost for the same bridge, delete all alternatives except the one resulting in the largest benefit.

3. Calculate the ratio of incremental benefit to incremental cost for each remaining alternative for each bridge.

4. Delete any alternative for which the incremental benefit-cost ratio is less than one. This step is optional, and its applicability depends on accuracy of the quantified benefits.

5. For each bridge, compare the incremental benefit-cost ratio of the first alternative to that of the second one. If the second ratio is larger than the first ratio, combine the two increments to form a marginal benefit-cost ratio. Leave the first alternative in the array in case that budget limitations exclude the second alternative while allowing the first. Then compare the marginal benefit-cost ratio of the first and second alternatives to the benefit-cost ratio of the next lower cost alternative, and repeat this basic procedure. This will yield an "average" benefit-cost ratio.

6. Arrange all alternatives, along with their relevant corresponding marginal costs, in decreasing order of their relevant incremental benefit-cost ratios.

7. Initially, choose alternatives in order from highest to lowest incremental benefit-cost ratios, accumulating the corresponding marginal costs to determine which alternatives to include in a budget. Only the most attractive alternative is chosen for each bridge, and all less expensive alternatives for the same bridge are then excluded.

8. The last bridge alternative selected is dropped from the list of chosen projects, and the selection process continues adding as many projects as the remaining budget will allow. After this process is completed, the total net benefit of the initial set of bridge alternatives is compared to the total net benefit of the second set. The set having the larger total benefit is selected as the optimal solution.

Multi-Period Optimization

The above basic model can be efficiently used to develop the most cost-effective, or the most beneficial, bridge rehabilitation/replacement alternatives for a short-range scenario. If the problem of interest, however, is determining optimal bridge decisions for each period of a long-range planning horizon, then it is necessary to combine the basic model with a dynamic programming approach in which the stages correspond to the periods.

In this multi-stage optimization problem, the state variables are defined as the budget remaining and the bridge conditions at each stage. The decision variables are binary variables indicating which strategy should be selected for each bridge in each period of the planning horizon. Since the condition of a bridge changes from period to period, the bridge condition deterioration process must be incorporated into the optimization methodology to take into consideration the effect of selecting or not selecting improvement projects for each bridge. This multi-period optimization approach exhibits the following attractive features:

- It allows the study of the interaction between periods, since a decision made in one period may affect decisions made in future periods,
- It is suitable for the investigation of several funding levels in each period of the planning horizon, and
- It accepts input from the bridge deterioration process for each intermediate period of the planning horizon.

The following notation will be used in the formulation of the dynamic programming recursive relationship for a multi-period optimization model:

A_t = amount available at the beginning of period t,
X_t = set of projects to choose from in period t,
$b(X_t)$ = total benefit for period t,
$c(X_t)$ = total cost for period t,
R_t = bridge conditions at the beginning of period t, and
$P_t(R_t)$ = set of feasible projects for period t.

Using the above notation, the subproblem for period t can be formulated as follows:

$$g_t(B_t) = \max_{0 \le A_t \le B_t} [f_t(A_t) + g_{t-1}(A_t + c(\vec{X}^*_{t-1})]$$

where

X^*_{t-1} = most benefit-effective decision at period t-1
$f(A_t)$ = max $b(X_t)$

subject to

$$c(\vec{X}_t) \le A_t$$

$$\vec{X}_t \in \vec{P}_t$$

In the above formulation, $f(A_t)$ can be determined in one pass of the INCBEN algorithm for all desirable values of A_t.

Geographic Information System

Geographic Information Systems, or GIS, provide an innovative approach for managing the large and diverse information required to support decisions concerning the highway and bridge infrastructure. A GIS can integrate the data collected by a transportation agency for use in both analytical and graphical applications. This technology is rapidly gaining popularity and is expected to play an increasingly major role in the daily operations of state transportation organizations in the immediate future. In fact, there are already several state agencies that are sponsoring projects related to the development and implementation of a GIS. These include the transportation departments in Texas (32), North Carolina (33), Pennsylvania (34), Colorado (35), and Alaska (36). The California Transportation Agency has digitized its entire highway network and can now graphically display every highway for which it is responsible. In addition to the activities at the state level, there are also ongoing efforts at the federal level by the FHWA and the American Association of State Highway and Transportation Officials (AASHTO) directed toward development of GIS technology and its applications in the area of transportation.

A GIS can be defined as a method of representing tabular data in a visual format as that information relates to a physical geographic location. Any type of data--physical, economic, demographic or other applied data--can be spatially defined within a georelational reference system. Layers of thematic data such as bridges, roadways, watercourses, district boundaries, county or municipal divisions, soils, and soils can be entered into the system as a series of map databases. The information is then joined or related to a series of tabular databases, such as inventory and cost databases, for analytical purposes.

The maps in the GIS are input as a series of arcs and nodes. Closed arcs form polygons which contain common thematic types such as soils, geologic formations, or ownership boundaries. This then becomes known as a polygon coverage. The area and perimeter of each polygon is automatically calculated by the program. A coverage which contains arcs representing linear data such as roads or streams is a line coverage. Nodes are placed at the intersection of arcs which represent roadway intersections, bridges, etc. Both distance and direction between nodes, or along a route, can be automatically calculated. Thus, within the context of a bridge management system, the GIS could be used to determine alternate routing around an obstruction such as a construction site, and to determine the length of that alternate route. Possible applications of these features include detouring traffic around a bridge rehabilitation project or rerouting oversize loads around low clearance or load-posted bridges.

Visual impact adds a second dimension to tabular data. A list of all bridges twenty-five years old with four lanes that have not had preventative maintenance in the last five years is an easy search within a database. With the GIS, answers to such questions are readily accessible, and the locations of each of the structures satisfying a given set of variables are immediately available on a computer screen. Visual proximity analysis can lead to more cost effective repair schedules by optimizing the location of work crews and equipment. Examples of specific GIS applications include:

- Production of color coded maps showing bridge structures satisfying certain selection criteria or possessing certain attributes (e.g., deck condition rating < 3 and average daily traffic > 10,000), and
- Graphic representation of recommended activities such as scheduled maintenance, rehabilitation, or replacement.

In the proposed BMS for Texas, a GIS is being considered for use as both a pre- and postprocessor. Use of a GIS will enable the user to interface with the system and its various databases to obtain graphic images in response to various input and output queries and to automatically input the variables needed to run the model for a selected network of bridges. The results from the BMS can be made available in both tabular and visual format. In the pre-processing mode, the system can aid the bridge manager in selecting and visualizing a particular network of bridges. In the post-processing mode, the GIS can enable the bridge manager to query the tabular output from the BMS in order to visualize the answers to pertinent management questions, such as which bridges on a particular route need to have a concrete deck replaced, or be replaced entirely.

Another major advantage of the GIS system is its ability to establish a relational link among multiple databases. Once established within the bridge management system, the GIS could be linked with other databases within the SDHPT. Although beyond the scope of the proposed study, this type of communication among systems is feasible and would be the first step in the development of a total roadway management system.

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