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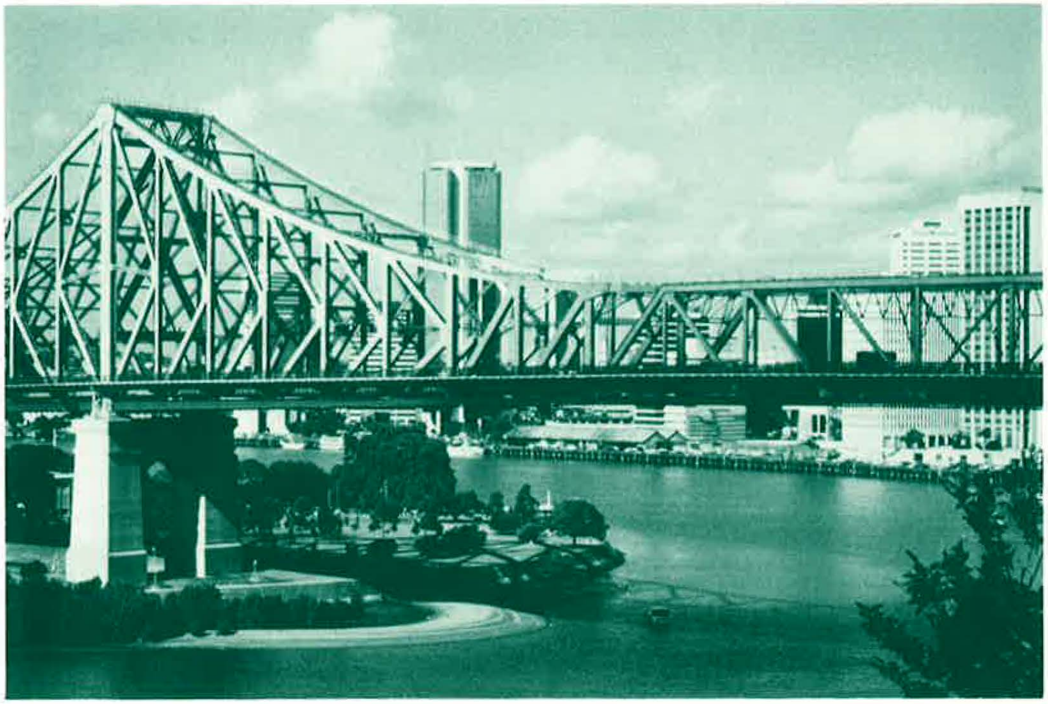
Characteristics of Bridge Management Systems



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CHARACTERISTICS OF BRIDGE MANAGEMENT SYSTEMS

Presentations from the
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FOREWORD

The Seventh Conference on Bridge Management was sponsored by the Transportation Research Board Committee on Structures Maintenance and Management in cooperation with the Texas Department of Transportation and the Federal Highway Administration in Austin, Texas, September 15-17, 1993. The objective of the Conference was to provide a forum for the exchange of information about the state-of-the-art in bridge management support systems. The proceedings of this Conference are included in this *Circular* and are grouped into four categories:

- Bridge Management Decision Support Process;
- National and Provincial Bridge Management Systems;
- State and Local Approaches to Bridge Management; and
- Development and Implementation Issues in Bridge Management Systems.

The first category contains three papers that describe the basic components of the bridge management support process: data needs and collection, data analysis, and decision support. The second category includes four papers that describe the two U.S. national systems, Pontis and BRIDGIT, followed by examinations of Denmark's bridge management system (BMS) and Ontario's project BMS. The third category has seven papers, the first five describe systems in Alabama, Connecticut, Indiana, North Carolina, and Pennsylvania. The last two papers provide a city's and a county's view of the bridge management process. The fourth category contains four papers, the first describes a method for developing National Bridge Inventory (NBI) condition ratings from a BMS, the second and third papers address issues involved in user costs, and the last paper examines the future prospects for bridge management.

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BRIDGE MANAGEMENT SYSTEM DATA NEEDS AND DATA COLLECTION

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ABSTRACT

This paper examines the types of data needed for operation of bridge management systems (BMSs). It traces the historical development of the National Bridge Inspection Standard (NBIS), which requires the collection of bridge data by all highway agencies. However, NBIS data are limited and do not supply the detailed information needed to make decisions regarding allocation of bridge resources. Many states have begun to supplement the NBIS data for bridge management purposes. The authors conducted a survey of bridge data collection by state highway agencies in 14 states. A wide variety was noted for both data collection and BMS practices. The strongest finding was that the states were collecting much more data than required by the NBIS. Data types, data uses, and collection methods are reviewed in the paper. The paper also outlines data needs for typical BMS functions such as preventing bridge failures, determining functional obsolescence, establishing maintenance requirements, determining future conditions through deterioration modeling, and operating bridge-cost models. Cost-effective management requires the use of sophisticated techniques and comprehensive data to provide bridges for tomorrow on today's limited budgets.

INTRODUCTION

The Silver Bridge between Point Pleasant, West Virginia and Gallipolis, Ohio collapsed during rush hour traffic in 1967. Many vehicles were stopped on the structure for a traffic signal when the instantaneous fracture of an eyebar led to the loss of 46 lives. This disaster was highly publicized and drew attention to the aging condition of the nation's bridges. The United States Congress added provisions to the Federal-aid Highway Act of 1968 which required the Secretary of Transportation to establish a NBIS and to develop a bridge inspection program. The standard was issued in April 1971. Since then the bridge inspection program has been continuously improved.

This paper examines data needed for operation of a BMS. It briefly traces the history of the NBIS and examines the type of data required. These data must be collected by all highway agencies, but are not necessarily the data needed to make bridge management decisions. BMS data are more comprehensive and include topics not covered by the NBIS. Such data are identified and discussed in this paper.

BRIEF HISTORY OF BRIDGE INSPECTION

When Congress mandated the creation of a bridge inspection program, there was much work to be done. There were no accepted procedures for inventorying nor criteria for inspecting structures. These had to be developed and tested. The Federal-aid Highway Act of 1968 required the Secretary of Transportation to create the NBIS. It also called for the states to inventory, inspect and report on the condition of their bridges. By the end of 1973, the states had inventoried most of the 274,000 bridges on the Federal-aid Highway System. The inventory data were reported to the Federal Highway Administration (FHWA) which merged it to form the National Bridge Inventory (NBI) file. The Surface Transportation Assistance Act of 1978 expanded the inventory/inspection program to include all bridges on other public roads, and the number of structures rose to 577,000. Today, 98 percent of the structures on other public roads are included in the NBI.

When the NBIS criteria were adopted, they were placed in the *Code of Federal Regulations* (*1*). 23 CFR 650 defines which structures are included in the program, establishes qualifications of inspection personnel, and specifies standard inspection report forms. Section 650.311 specifies that each state is to "prepare and maintain an inventory of all bridge structures" which are subject to the NBIS. It goes further to indicate that FHWA will list the required data items in its publication, *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, hereafter called *Coding Guide*. NBIS criteria were made available to highway agencies through the *Federal-aid Highway Program Manual* (*2*). FHWA published the *Coding Guide* in 1971 following several drafts. Because of rapid changes during the start up phase of the program, a revised *Coding Guide* was published in 1972 (*3*). The third version (*4*) was issued in 1979. The changes from version to version may be traced using Table I. With each new edition, the *Coding Guide* required more data items and storage space. In 1988 the FHWA published the fourth version of the *Coding Guide* (*5*). The number of items was expanded to 116, and there were significant changes in the definitions of some items, in inspection procedures, and in condition rating procedures. It is reasonable to expect that periodic revisions to the *Coding Guide* will continue in the future.

The States are not required to make their bridge inspection programs identical to that described in the *Coding Guide*. Agencies can devise their own procedures, codes and databases. However, they must be able to convert their unique databases into the NBIS format for reporting to FHWA. This is necessary so all states' data can be combined to form the NBI. The 1979 guide indicated that,

> "The use of this Guide is optional; i.e., each state may use its own code scheme. However, when data are requested, whether in tabular or in computer readable form, the format will be based on the codes in the Guide."

The same implication was included in the 1988 *Coding Guide*. The 1988 guide went further to state

> "... a complete, thorough, accurate, and compatible database is the foundation of an effective bridge management system and will require collection of additional items over those contained in this guide."

Major factors in bridge data collection have been the documentation of good inspection procedures and the preparation of training materials. It would be difficult to have a meaningful NBI if all states did not report using the same data definitions and inspection procedures. Both FHWA (*6*) and the American Association of State Highway and Transportation Officials (AASHTO) (*7*) prepared basic training manuals, and FHWA prepared a bridge inspector training course that has been taught continuously since 1970. As needed, FHWA has prepared inspection guidance documentation for a series of special emphasis items like culverts, moveable bridges, scour and fracture-critical bridge members. These documents have provided uniformity in data definitions and collection procedures.

EXPANSION OF BRIDGE DATA COLLECTION

The minimum number of inspection items gathered by any State are those of the NBIS. As shown in Table I, the number of items has increased over time and there have been changes in the content and character of the items. The number of inspection items has increased for reasons other than the NBIS. Typical reasons include the following:

- Individual states have sometimes been required by FHWA to begin keeping non-NBIS data. A typical example might be when a state had a wide spread or severe deficiency, and FHWA felt that additional data were necessary to identify and treat it. A unique type of bearing might have failed prematurely on several structures, and the FHWA might require the state to collect and report data on the condition of all similar bearings.
- Special emphasis programs created by FHWA require additional data. Examples include scour investigation, fracture-critical members and underwater inspection.
- States have found that supplemental data are needed for their own unique reasons. One agency routinely measures expansion joint movement as a way to decide when joint failure is approaching.
- The creation of bridge management systems has been, by far, the greatest reason that highway agencies have begun to collect additional data. Information must be secured for deterioration modeling, maintenance decisions, optimization of funds and other special needs. NBI data are usually insufficient for these purposes.

These are a few illustrations of the reasons that highway agencies have expanded their bridge databases. There are many additional reasons for such expansions, including the specific BMS tool requirements of AASHTO and FHWA.

TABLE I EVOLUTION OF FHWA CODING GUIDE

Date	No. Items	Not Used/ Blank/ Deleted	Net Coded Items	Digits of Data	Digits of Storage
Apr 1971	84	5	79	293	320
Jul 1972	84	4	80	300	320
Jan 1979	90	2	88	327	360
Dec 1988*	116	26	90	354	400

* Twenty-five items were deleted in 1988 Edition.

AASHTO BMS Guidelines

The need for additional data has been recognized by many parties. The AASHTO *Guidelines for Bridge*

Management Systems (*8*) indicate that a BMS must have a comprehensive database that contains "inventory, inspection, and appraisal data as well as complete historical information and codes indicating the dates and nature of detailed, special and supplemental inspections." The *Guidelines* state that essential data elements include many NBI data items, but also other information, especially more-detailed inventory and condition data on the elements of each structure. The AASHTO document goes further to describe several types of data needed for BMS functions such as modeling deterioration, identifying feasible actions for treatment of each bridge, establishing level-of-service criteria, determining agency costs, evaluating user costs, minimizing maintenance costs, and performing multi-period optimization. Much of this data is not available in the NBI. The states must develop their own data definitions and data values to perform the BMS functions described in the AASHTO *Guideline*.

Proposed FHWA Rules for Bridge Management Systems

Another voice calling for increased bridge data stems from the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) which requires state highway agencies to implement six types of management systems, one of which is a BMS. The notice of proposed FHWA rulemaking (*9*) indicates that

> "Each of the management systems will require data to define and monitor the magnitude of the problems, identify needs, analyze alternative solutions, and measure the effectiveness of the implemented actions."

This implies additional data past that found in the NBI. The proposed rules require that state BMSs incorporate NBI data. They also mandate collection of at least four additional types of data for bridges both on and off Federal-aid highways: 1) element condition, 2) cost information, 3) traffic and accident, and 4) historical. Additionally, state BMSs must include a system for monitoring the status of actions recommended by the BMS, including construction and maintenance reporting and cost tracking processes. The proposed FHWA BMS rules indicate that condition data are to be used to characterize the severity and extent of deterioration of bridge elements. Cost data are to be used to estimate costs of bridge treatment actions. Traffic and accident statistics are to be used to estimate user cost savings. Historical data on bridge conditions (excluding minor or incidental maintenance) and actions taken are to be used to model deterioration. Few highway agencies currently collect data in sufficient detail to meet the proposed rules. Most agencies will have to expand their inspection programs to meet the intent of the ISTEA management systems.

STATE HIGHWAY AGENCY DATA COLLECTION PRACTICES

There are distinct differences in bridges from state to state. This reflects variations in topography, design practices and budgets. Where a mid-western state might be most concerned that structures be wide enough to allow passage of wheat combines, an Appalachian state might be most concerned that load capacity of rural bridges not limit movement of heavy coal trucks, or an eastern state might be most concerned over age and deterioration of structures. These are why BMS data and data collection practices vary. The authors reviewed the bridge data items, item definitions, and data collection practices of a sample of 14 states. They were selected as a representative cross section. A short questionnaire was administered through facsimile and telephone interviews. The responses reflect the independent nature of bridge inspection and bridge management in the individual states.

Number of Bridges

As shown in Table II, the 14 states administer over 250,000 structures, about 44 percent of all of the nation's bridges. The average number of bridges was 17,972 for the 14 states. The greatest number was 47,800 and the least number was 3,550, collected by Texas and New Mexico, respectively. Thus, one state collected data from 14 times as many bridges as its neighbor state. A more complete picture of bridge inspection practices involves the numbers of "on-system" structures, and the states' practices regarding off-system structures. Approximately half of all structures in the states surveyed were on-system. The percent of on-system structures ranged, however, from 28 percent for Minnesota to 97 percent for North Carolina. The percent of off-system bridges that were inspected by state forces showed even more variability. One-third of the states did not inspect off-system bridges and another third inspected all of the off-system bridges. The remaining states inspected some but not all of the off-system bridges. Also, only two of the 14 state highway agencies perform maintenance for off-system structures.

TABLE II STATE BRIDGE COMPARISON

State	NBIS Bridges	Number State-Owned	% State-Owned	Non-State % State Maintained	Non-State % State Inspected
AL	15,461	5,411	35	0	0
CA	24,600	12,300	50	0	83
CO	8,012	3,658	46	0	100
FL	10,700	5,800	54	0	0
IN	17,870	5,562	31	0	0
LA	14,000	8,000	57	0	100
MN	13,270	3,674	28	0	50
NM	3,550	2,950	83	0	100
NY	19,600	7,700	39	3	100
NC	17,551	16,971	97	0	0
OH	28,741	11,300	39	16	5
PA	23,000	16,200	70	0	0
TX	47,800	33,300	70	0	100
WA	7,450	3,150	42	0	9
Average	17,972	9,713	57	1.5	46

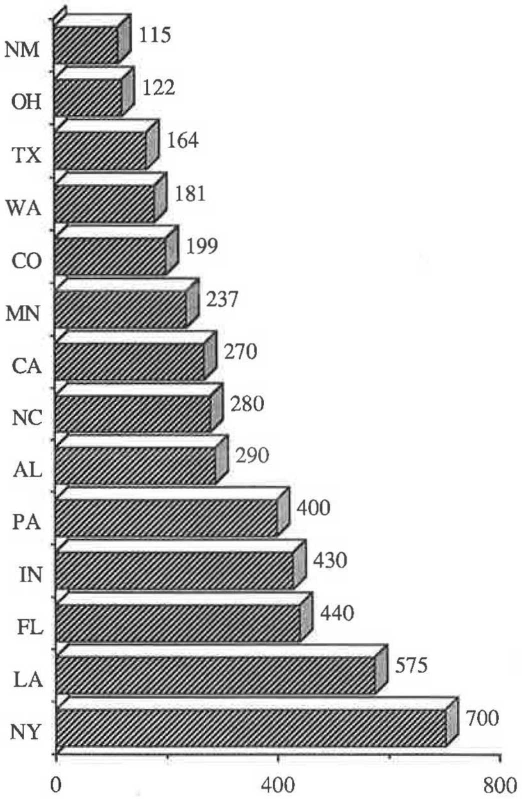

FIGURE 1 Number of data items per bridge.

Number of Data Items

The number of bridge data items collected by the sample states is shown in Figure 1. The median number of items lies between 270 items (California) and 280 items (North Carolina). New York collects the most data items (700) and has been collecting these items for the past eight years. At the other extreme, two states collect at or near the minimum level of only NBIS data items. A couple of interesting conclusions may be drawn from Figure 1. First, the figure illustrates the diversity of state data collection practices. Second, the trend is toward collection of more data items. New York collects six to seven times more supplemental data than NBIS data. Nine states in the survey collect more supplemental data items than NBIS items.

Labor Requirements

Collection of additional data items would seem to imply that more time is required to inspect structures, and that more labor must be devoted to it. The states were asked to estimate the average time required to inspect bridges. The average response was approximately 4.6 hours per structure. Of this, slightly more time was spent in the field than in the office. The minimum time was two hours, estimated by five different states. The maximum time was 16 hours by New York, which also has the largest number of data items. Many reasons exist for the differences between states, for example California uses one-person inspection teams while most states use multi-person teams. Another reason involves the variation in the number of data items from state to state. A third reason involves whether data are collected for each span as opposed to only once for an entire structure. New York has the largest number of data items and collects rather complete data for each span; consequently, they require more inspection time per structure.

Data Cost Effectiveness

The expense for collecting data is growing. Only one state, Louisiana, reported that it had examined use and cost-effectiveness of data. Because of its review, Louisiana deleted several data items that had experienced little or no use. It would seem reasonable that all states should be conducting more of these studies. A large amount of data is being collected, often without regard to the frequency or manner in which it might be used.

Frequency of Data Collection

Closely allied to the cost effectiveness of data collection is the frequency of collection. The NBI items must be included in every cyclic inspection, but many of them (such as deck width) do not change from cycle to cycle. The same is true for supplemental data items now being added by states. The states were asked to supply off-the-cuff estimates of the percentage of items requiring input each inspection cycle as opposed to only once per bridge life. On average, the states reported that 58 percent of the bridge data was collected only once, 17 percent was collected infrequently, and 25 percent was collected each inspection cycle. Be careful in interpreting these results because the responses were varied (see Figure 2). This could be because the initial question was awkwardly worded, although part of the cause is variability in state practices. Regardless, more than half of the items in BMS databases have to be input once, and about one-quarter of the items require examination each inspection cycle. Thus, the labor involved in bridge inspection probably does not increase in direct proportion to the increase in the number of data items utilized by the inspection agency.

Data Collection Methods

With the number of data items increasing in most states and the data becoming more complex (i.e., the evaluation of deterioration for individual elements or members), the states have searched for more efficient data collection methods. All of the survey states collect field data by filling in paper forms. Most states furnish their forces with the previous inspection report so the inspector needs only to indicate which information has changed. Several states have their computer print special data forms before inspection to ensure that the most recent data are available. Ohio does this, but does not give the inspectors the previous condition ratings for bridges so as not to prejudice their rating.

Of the surveyed states, inspectors in only five of 14 currently enter field data directly into a personal computer. However, all but one state indicated they eventually want to enter all inspection data electronically. A good example is Florida, which is implementing a program to have all of its bridge inspectors enter inspection data directly into personal computers. Several states indicated that while many bridge inspectors readily adapt to computer data entry, some prefer to enter data on paper forms. Typically, current data are down-loaded onto a portable computer just before the inspector examines a structure. The inspector has only to correct items that have changed and to enter comments while in the field. It is awkward to carry portable computers while walking around on a bridge. A very small computer may be strapped to a clipboard or placed on the inspector's arm to overcome this difficulty. However, the keyboard and viewing screen are so small that data entry can be very difficult. These small computers are called note pads, palm pads, wrist pads, grid pads and similar names. Florida, Louisiana, Minnesota, Pennsylvania and New Mexico have investigated the use of such computers. Louisiana is currently developing its own software for use with grid pads.

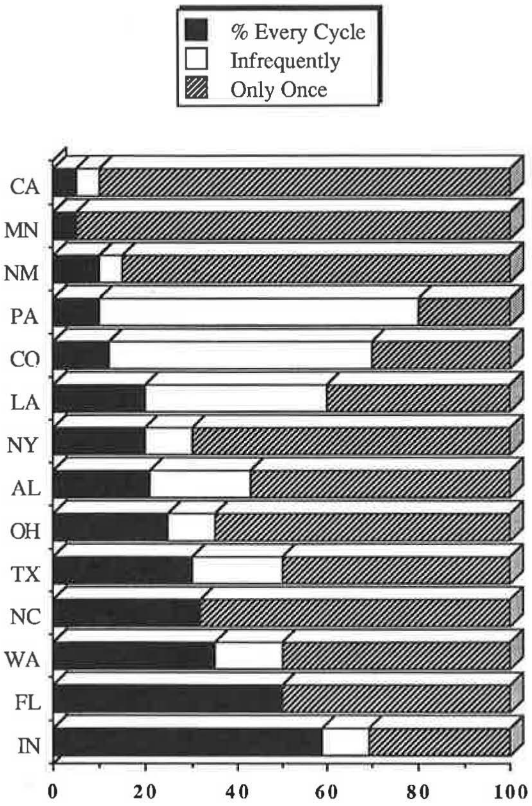

FIGURE 2 Percentage of BMS data items.

Little bridge data are collected automatically by computer by accessing other databases. States collected 5 percent on average of the total bridge data in this way (responses ranged from 0 to 20 percent). Although bridge inspectors in every state use data from other databases, i.e., traffic counts, most of the time they read the data from a printout or computer screen and then enter the data manually. BMSs can transfer data between electronic files and offer promise of improvements in future data collection efficiency.

Several states plan to scan photos and sketches by the bridge inspector into the bridge database. California is scanning as-built plans and 60 years of bridge inspection reports into its database. One benefit cited by California is that in the event of a bridge failure, anyone connected to the database can access the bridge plans. Several states commented on the usefulness of narratives, sketches and photos when planning maintenance or replacement for a bridge. It is becoming more popular to leave data fields or entire data screens available for narrative information as a routine part of the BMS database.

BRIDGE DATA NEEDS

A comprehensive bridge management plan recognizes that today's actions affect the condition of tomorrow's bridges. Systematically accounting for these effects is a major goal of BMSs. Unfortunately, it is difficult to predict the future conditions and costs of bridges. While bridge management experts grapple with these prediction problems, state highway agencies can use BMSs to organize their large bridge databases and to provide support for many important bridge management decisions.

Decisions on Immediate Needs

Many bridge management decisions can be based directly on raw bridge data. This was the state-of-practice before computer BMSs entered the scene. Decisions like closing structurally deficient bridges, replacing functionally obsolete bridges, and scheduling maintenance for deteriorating bridges can all be made by examining NBI data, i.e., bridge condition ratings and bridge geometry, or by reviewing bridge inspector's comments on needed maintenance. Such decisions can be made by direct comparison or rank ordering, but this becomes very difficult when there are multiple factors or many bridges to consider. BMSs can help by providing important decision support to highway agency managers through simple database functions such as sorting, tabulating and graphing selected bridge data. Even with this type of help from BMSs, bridge managers have recognized that such simplistic methods have limitations and more powerful tools are needed. This paper discusses three of the most obvious types of data that serve immediate BMS decision needs. These are used as examples and include: preventing bridge failures, determining functional obsolescence, and establishing maintenance needs.

Prevent Bridge Failures

One of the primary purposes of bridge inspection is to detect conditions threatening the structural integrity. Deck, superstructure and substructure condition ratings (described in the *Coding Guide*) were intended for this very purpose. Past bridge collapses due to failure of fracture-critical members, failure of underwater members and scour of foundation soils have attracted attention to these failure modes. As a result, highway agencies now use special inspection procedures and gather special data to monitor these possible bridge-threatening conditions. The following paragraphs briefly review data requirements of several such efforts.

Condition Ratings The primary NBI data item for prevention of failure is still the condition rating. Bridge inspectors use the "0 to 9" rating scale in the *Coding Guide* to indicate the integrity of the primary structural components. The NBI requires condition ratings for only three major bridge structural components: deck, superstructure and substructure. These condition ratings indicate the urgency of an impending loss of structural integrity, but provide little information about the type and location of the possible failure. Most states have added supplemental data items for rating the condition of specific elements of each major structural component. For example, the inspector normally rates the condition of bearings, floor beams and stringers separately while determining the overall condition rating for the superstructure. Electronic storage of this additional information allows studies to guide management in what type of bridge repair is necessary, and possibly the extent of needed repair. Some states (Florida, Ohio, and New York, for example) use separate condition descriptions for each major type of bridge component (for example, steel stringers, concrete T-beams and timber stringers). Ohio includes quantities in its descriptions (5-10 percent section loss on steel beams, for example).

To insure consistency between inspectors, many states perform field audits on a sample of previously inspected bridges using a central office inspection team. New York reports good consistency between inspectors due in part to thorough training and extensive use of photographs in their bridge inspection manual. The photographs show examples of bridge condition ratings for each element in the database.

Fracture-Critical The *Coding Guide* requires states to determine whether special inspection intervals are necessary for bridges with critical features, such as fracture-critical details (Item 92 of the *Coding Guide*). FHWA has made this an emphasis area, developed a training course, and published a supplement to its bridge inspector training manual. The states still have liberty to develop their own unique programs for fracture-critical inspection. Pennsylvania and Alabama identify fracture-critical members in their bridge inventory by categorizing the type of fracture-critical structure, fracture-critical member and fracture-critical detail. Pennsylvania also includes the fatigue crack susceptibility (based on the AASHTO fatigue stress category) and the material type in its BMS database.

Scour This is an emphasis item for which FHWA has developed special instructions and training materials. Currently, the *Coding Guide* requires states to rate each bridge according to its observed or potential vulnerability to scour. The states have approached this topic in several ways. For example, Alabama recently developed a scour program that records stream bed soundings made during the biennial bridge inspections and graphically displays the stream bed profile. The bottom elevations of the foundations and the maximum expected scour profile based on hydraulic analysis are also depicted graphically .

Other Data Other data used to prevent bridge failures includes earthquake vulnerability, load rating (from analysis or load tests) and vulnerability to collisions. New York has developed a comprehensive bridge safety assurance program that assesses bridge vulnerability for six different failure modes. An algorithm is being developed which draws inventory and condition information from the bridge database and assigns a vulnerability rating for each failure mode. The vulnerability rating will be used to flag bridges needing urgent attention.

Determine Functional Obsolescence

Unfortunately the decision facing bridge managers is not whether a functionally obsolete bridge needs to be replaced, but which of the obsolete bridges most needs replacement. The states are struggling to decide how to best use scarce financial resources, and have begun to generate and use several types of new data to help with these decisions.

Level of Service Goals Level of service (LOS) goals, introduced by Johnston and Zia (*10*), are statewide standards for critical items like load capacity, bridge width and vertical clearance. Higher standards are set for bridges expected to provide a higher LOS to users. Bridges carrying interstate traffic, for example, have more stringent LOS goals than bridges carrying only local traffic. The LOS concept has been practiced implicitly by district bridge maintenance engineers for years. What's new is that LOS goals are explicit, agreed-upon standards that can be applied uniformly across the entire state. By comparing the characteristics of each bridge (i.e., load capacity, width, vertical clearance) to the appropriate LOS goals, a measure of the bridge's functional adequacy is obtained. The degree of adequacy may be quantified for each bridge in the form of deficiency points or, more ambitiously, user costs. However, supplemental data must usually be gathered to make these comparisons.

Deficiency Points Deficiency points provide a relative measure of a bridge's functional adequacy and are useful for producing a direct comparison between all bridges in a certain category, for example, all concrete bridges, or all bridges in a geographic district. Deficiency point algorithms subtract the value of a bridge characteristic (load capacity, for example) from the appropriate LOS goal and multiply the difference by factors proportional to traffic volume and detour length. Much of the data for deficiency point algorithms, such as operating ratings, vertical clearances, and roadway widths, are in the NBIS database. Alabama calibrated its deficiency point algorithm on the judgement of experienced bridge inspectors and maintenance engineers. The calibration process revealed the need for several information items not in the NBIS database, such as the load ratings of strengthened bridges, the local importance of the bridge (for example, located on a school bus route), and whether or not the bridge is currently under contract to be replaced.

User Cost Models User cost models attempt to predict the expense a motorist incurs from using a bridge that falls below LOS goals. Examples of user costs include extra travel costs from detouring around a load-restricted bridge, or extra costs resulting from an accident on a narrow bridge. Models to predict user costs based on existing data (load capacity, detour length, traffic volume and similar factors) are still rather crude. Data supplemental to the NBIS data are needed to construct accurate user cost models, for example bridge-related accident rates, truck operating costs, and costs associated with bridge-related accidents.

Unfortunately, data are not readily available on the number of over-width, over-height or over-weight vehicles using certain routes, the number of accidents experienced by individual structures and similar user-cost topics. Surrogate data may have to be used, or data must be "borrowed" from other states or developed from the consensus opinion of experts. Once reasonable user cost models are constructed, user costs can be included with replacement costs and maintenance costs to determine the optimal set of bridge actions on a cost-effectiveness basis.

User cost formulas are similar to deficiency point formulas but include an additional unit cost factor. These costs are very difficult to quantify with confidence. Highway agencies may want to use deficiency points in place of user costs until better user cost models are developed. The identification and collection of relevant data are important in the accuracy of these models.

Determine Maintenance Needs

Many highway agencies currently ask their bridge inspectors to indicate whether a bridge needs maintenance. Six of the states surveyed indicated that the bridge inspectors' information is adequate for scheduling maintenance without a revisit by the maintenance supervisor. Another six states indicated that the bridge inspector's information is used to draw attention to needy bridges, then the maintenance supervisor visits the structure to determine what type and quantity of maintenance are necessary.

Maintenance Actions Often bridge inspectors indicate the type and quantity of needed maintenance by writing a short description on the bridge inspection form. To facilitate the tracking of needed and completed bridge maintenance via computer, states have developed several general categories of bridge maintenance activities (for example, resurfacing decks, repainting steel stringers). These maintenance activity categories are called different names by different states, but in this paper will be called "maintenance action items." When indicating a maintenance action item, the inspector also indicates a quantity (for example, deck resurfacing, 100 square meters). Table III shows the approximate number of maintenance action items for each state surveyed. Of the states with 20 or more maintenance action items, all but one enter or plan to enter the maintenance needs into their computer database. By also entering unit costs for each of the maintenance action items, a highway agency can determine the total statewide cost of needed bridge maintenance. Some states surveyed were planning to implement the FHWA bridge management program, Pontis. The Pontis maintenance module includes a wide range of maintenance action items and has maintenance optimization capabilities. Many states enter completed maintenance action items into the computer database. This step closes the loop and allows an agency to compare needed maintenance against completed maintenance any time during the year. It also provides an effective mechanism for updating maintenance unit costs for each action item.

TABLE III MAINTENANCE ACTION ITEMS

State	No. of Maintenance Items	Entered In Computer
PA	75	yes
FL	70	yes
NM	64	no
MN	45	yes
NC	42	yes
AL	38	yes
NY	35	yes
LA	25	yes
CA*	20	yes
OH	13	no
IN	5	no
TX	narrative	no
WA	narrative	no
Average	40	

* California normally uses only 20 items out of a possible 3127.

Maintenance Optimization There are several maintenance questions for which answers are highly desired. For example, what are the appropriate types and amounts of maintenance to ensure minimum life cycle costs for structures? What is the minimum acceptable level of maintenance during times of restricted budgets—a perpetual reality for highway agencies? How much, if any, is a bridge's condition improved by good maintenance practices? How long does this improvement last? Which data items and how much data are required to determine bridge maintenance effectiveness? Few states have assembled meaningful data files with which to begin answering these questions. Several years (5-10) of complete data will be required before statistical validity can be obtained. This is one reason that the FHWA's proposed rules for BMSs require that the states keep historical data files. The minimum maintenance data appear to be a categorical tabulation of needed maintenance items by type of structure and units of needed work, the estimated cost of the work or similar economic measures, a record of completed work, and records of expenses related to completed work so unit costs may be computed. These data should be archived for future studies to establish trends and to conduct optimization analyses.

Decisions on Future Needs

Bridge management systems are intended to help highway agencies make cost-effective decisions about topics like bridge maintenance and replacement. Because decisions to maintain or replace bridges today will affect the condition of the bridge system tomorrow, the best decision is the one which minimizes costs over the long run while providing the desired level of service. Much of what is new in BMSs involves mechanisms for predicting the future effects of today's decisions. The theory behind these prediction tools can be complex and will require many years to implement effectively. All the prediction tools, however, have one factor in common: they are based upon a computer database of bridge information and are, in fact, no better than the quality and extent of that data. This paper discusses the data requirements for two major prediction tools, bridge deterioration models and bridge-related cost models.

Predict Bridge Deterioration

The goal of a deterioration model is to predict the condition of a bridge element at some time in the future. Successful prediction depends upon determining all factors that have a major influence on the element's condition over time, and then measuring and recording data depicting those factors. For example, if a deterioration model is formed to predict the condition of bridge decks in the northern U.S., then an important factor to consider is the presence or absence of deicing salts. A deterioration model formed without considering deicing salts would predict the same deterioration for bridge decks subject to salts as for decks free from salts. Although such a model may be useful for predicting the average condition of all bridge decks (assuming no change in deicing practices), it may be inaccurate at predicting the condition of bridge decks subject to large quantities of deicing salts. A model to predict the deterioration of a specific structure must consider the current condition state of that structure (good, poor, etc.), then consider the deterioration caused beyond that state by each contributing factor.

Deterioration models use several cycles of condition data to identify trends, then extrapolate the trends to predict condition at some year in the future. An absolute minimum of three or four cycles of inspection data is required before a deterioration model can be formed. (As an alternative interim measure, a highway agency can survey a group of experienced maintenance engineers and bridge inspectors and form deterioration models based on a consensus of their "expert" opinions.) An earnest attempt should be made to identify the major factors affecting the deterioration of the state's bridges as early as possible. Only then can the relevant data items be collected to form the database for building reliable deterioration algorithms.

The factors that affect bridge deterioration vary from state to state, but some are common to all states. Element type and material, maintenance history, and environment are examples of the major factors that affect deterioration. Other factors may be prevalent for certain types of bridges or in certain geographic regions. In Ohio, the source of concrete aggregate has been determined to affect the deterioration of concrete bridge elements. And in New Mexico, the condition of the deck-joint seals has been found to affect the deterioration of the girder ends and pier caps below.

The BMS program Pontis uses a unique approach to model deterioration. Pontis models the deterioration of the corroded end of a steel stringer separately from the non-corroded midsection of the stringer. This requires the bridge inspectors to record the quantity of each structural component (steel stringers, for example) in each of several condition states (no corrosion, surface rust and advanced corrosion, for example). Since the current condition of a component strongly affects its deterioration rate, the Pontis approach should lead to more accurate deterioration models. When implementing the Pontis system, an initial inventory of the quantities of all relevant structural elements must be performed for each bridge. California performed the inventory in the office using bridge plans (*11*). The inventory required an average of 6.3 hours per bridge. California also reports slightly more time was required by the inspectors in the field to record the first-cycle of Pontis data. Inspection time is expected to drop, however, in future inspections. A Pontis CORE Element Task Group has recently prepared a draft report (*12*) listing Commonly Recognized Pontis elements. This standard list of elements will allow states to exchange and compare important data including deterioration rates. The finished report will be available through AASHTOware^{TM} with the next version of Pontis.

Predict Bridge-Related Costs

Bridge management systems are driven by costs. Everything eventually is compared in terms of costs. Costs are the common denominator in bridge management systems. Since a BMS is intended to help a highway agency make cost-effective life-cycle decisions, it must predict the costs of replacing and maintaining bridges. In a BMS, the number of bridges to replace or the quantity of deck area to maintain are calculated and then multiplied by the cost per bridge or quantity of deck area. Development of accurate, current unit costs is a crucial step in providing a fully-functional BMS. Accurate unit cost models are best derived from actual cost data. For example, by tracking construction costs of different type bridges and maintenance costs for different activities, the highway agency can construct unit cost models. Optimally, construction and maintenance costs for each bridge can be tracked automatically by the BMS through accessing appropriate databases. Since each state highway agency has its own project management, maintenance and accounting procedures, the cost tracking features of BMSs must be tailored to each state. The level of detail needed in tracking bridge-related costs depends on the accuracy required by the unit cost models. Considerations include isolating bridge construction costs from right-of-way, mobilization and other construction costs, distinguishing between type of bridge construction (grade separations versus major river crossings, for example), and tracking maintenance work performed by both contractors and state forces.

Finally, the reliability of the agency's unit cost models must be checked to ensure the accuracy of BMS predictions. Bridge costs are highly dependent upon historical data. The bridge manager must use historical data (short term history if possible, if not, long term) to find unit costs. It is difficult and time consuming to collect the necessary cost and condition data from historical files. However, these data are necessary and the proposed FHWA rules require that the states acquire them. New York analyzes contractors' bids every six months to update their equations for predicting bridge construction costs. These costs models are currently used by bridge design engineers to calculate the projected cost of each bridge, but will be adapted to New York's bridge management system in the near future.

DECISION CRITICAL DATA

States that have the most experience with BMSs have arrived at a consensus—NBI data are often not sufficient for crucial decisions. That theme has been echoed throughout this paper. Arun Shirole, New York State Department of Transportation Deputy Chief Engineer (Structures), coined the phrase "decision critical data" to describe data items that have significant impact in management decisions. The sample states were asked about which data items were considered to be "decision critical." The respondents apparently had different understandings of the question, but three useful conclusions can still be drawn. The results of the survey question are summarized in Table IV. First, condition codes were the data item most frequently identified by respondents as decision critical. Condition codes are used primarily for monitoring structural integrity and for preventing bridge failures. Second, half of the states identified maintenance costs and almost a third identified maintenance needs as important decision critical data. Highway agencies are paying greater attention to maintenance, since spending more money on maintenance probably means less replacement costs in the future. They are realizing that additional data must be captured before maintenance optimization becomes a reality. Third, most of the remaining answers relate to functional obsolescence and level of service. To summarize, the most frequently listed decision critical data were: condition ratings, maintenance costs and needs, and functional obsolescence.

SUMMARY

This paper has discussed the data needed to drive bridge management systems. One portion of the data may be extracted from the National Bridge Inventory (NBI). The NBI is limited, however, and does not supply the detailed information needed to make crucial decisions regarding allocation of bridge resources. Many states have begun to supplement NBI data for such purposes. A limited survey traced the data collection practices of 14 states. They were found to be taking varied approaches to data collection and to bridge management in general. Most states now collect more data than required by FHWA, up to seven times as much supplemental data as NBI data. These items are needed to inventory and monitor the condition of the states' bridges at a level of detail sufficient not only for preventing bridge failures, but also for cost-effective management of the bridge system. Cost-effective management requires system management tools that are new to most state highway agencies, such as

TABLE IV SURVEY OF DECISION CRITICAL DATA ITEMS

Decision Critical Item	No. of States
Condition Codes	10
Maintenance Costs	7
Maintenance Needs	4
Deterioration Prediction	3
Load Rating	3
Traffic Volume	3
Clearances	3
Roadway Width	3
Age	2
Functional Classification	2
Detour Length	2

deterioration models and agency and user cost models. The paper discusses the need for several types of supplemental data for decisions on immediate needs such as preventing bridge failures, determining functional obsolescence and establishing current maintenance needs. Supplemental data are needed also to determine future conditions and needs via deterioration models and bridge-related cost models. Overall, state highway agencies must identify crucial decision data items and begin to accumulate historical files of these items. This is necessary to provide bridges for tomorrow on today's limited budgets.

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TOOLS FOR BRIDGE MANAGEMENT DATA ANALYSIS

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ABSTRACT

The objective of bridge management is to allocate and use the limited resources in an optimal way for the provision of service. Data collection and data analysis are essential components of a bridge management process. Without these two activities, strategy selection and implementation cannot function efficiently. Data collection and analysis are therefore conducted not for their own sake, but to enable the other activities in the process to be well executed. An important purpose of data analysis is the prediction of the impact of different strategies on the system objectives. This involves predicting future conditions of bridge elements, agency costs of different projects and activities, and user and nonuser consequences expressed as user costs, user time, accident rates and other impacts. In this paper the application of several data analysis techniques, such as regression analysis, Markov chains, Bayesian estimation and fuzzy set theory for the prediction of bridge element condition, agency costs and user costs, is discussed. Whatever techniques are used, the point is stressed that the success of data analysis depends ultimately on the quality and sufficiency of data gathered. The objective of data analysis is not the analysis but better strategy selection. To assist in strategy development, several prioritization and optimization procedures exist that can be usefully applied. Some common techniques for priority setting and optimization, such as the analytic hierarchy process, linear and integer linear programming, dynamic programming and network techniques, are briefly discussed.

INTRODUCTION

The central role played by data and data analysis in bridge management is clear—without them the bridge management process would be not much more than ad-hoc reactions to the most urgent crises, in stead of a well-planned, pro-active process. It is also true that data collection and data analysis are not objectives in themselves. These activities should always be conducted with a clear view of the ultimate objectives of the bridge management process. Some purposes of data collection and data analysis are as follows:

- Provide an inventory of bridges, bridge elements, traffic volumes and other characteristics of the system.
- Reflect the current condition of bridge elements.
- Provide a record of implemented maintenance, rehabilitation and replacement actions, and their associated impacts and costs.
- Enable deterioration prediction—the forecasting of the future condition of bridge elements.
- Predict the impacts of different alternatives.
- Estimate the costs associated with different alternatives—for the agency, users and nonusers.
- Enable the evaluation of different alternatives for a bridge—project level analysis.
- Optimize allocation and use of resources on a network-wide basis—network level analysis.

Data needs and collection practice for bridge management systems are discussed in the paper by Turner and Richardson (*1*). The present paper discusses several analysis techniques that can be used to achieve the above objectives.

CONDITION DATA ANALYSIS

Current Condition

Current condition can be represented several ways. One of the most common methods is to construct condition indices, which aggregate data of the conditions of individual 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 index, especially the intended users or audience.

Condition Prediction and Remaining Life

Regression Models

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 conditions and deicing chemical use, traffic volume, and rehabilitation action taken. 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. The collection of the necessary data such as current condition and maintenance actions, to make these forecasts is discussed in the paper by Turner and Richardson (*1*). Examples of regression models of bridge deck, superstructure and substructure deterioration can be found in the Indiana Bridge Management System (IBMS) (*2,3*). Agency and user costs also can be predicted with regression equations. This is discussed in Life Cycle Cost Analysis Section of this paper, and in the paper by Johnston, et. al. (*4*).

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. A linear regression equation can be stated as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \epsilon$$

where,

Y ≡ dependent variable
X_j ≡ independent or explanatory variable; $j = 1,2,...,k$
β_j ≡ unknown parameter to be estimated; $j = 1,2,...,k$
ϵ ≡ random error term

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, the type of rehabilitation implemented, material type and environmental conditions. The random error term ϵ is included since the equation will never be a perfect representation of the underlying phenomenon. Certain statistical assumptions are made regarding these random errors. If these assumptions are violated, poor models might be obtained.

An important issue is the specification of the functional form of the regression equation. Unfortunately, there are no statistical recipes available to accomplish this. On the contrary, trying out many functional specifications and then choosing one solely based on goodness-of-fit or any other statistical measure, is strongly discouraged. Specification of the functional form should be based on a deeper understanding of the underlying principles governing the performance of the system. Only then is there any assurances that a regression model, that fitted a particular set of data well, will provide good predictions based on different values of the independent variables. This is especially true if the regression model is used for extrapolation, as is usually the case in bridge management systems.

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. A more versatile method is maximum likelihood. The "goodness-of-fit" of the regression model can be evaluated in different ways. The most popular is the coefficient of determination, R^2, which measures the closeness of the equation to the data. As a single measure it has limited value. Most real-world systems cannot usefully be modeled with a single equation. Realistic regression models are therefore often systems of simultaneous equations. Techniques for the estimation of simultaneous equation systems, such as two-stage least squares are discussed in the literature. Additional issues such as the identification problem, arise with the estimation of simultaneous equation systems which have to be resolved before all parameters can be estimated.

Markov Chains

If the conditions of bridge elements are classified into discrete states, for example condition index represented by the numbers one to nine, then the deterioration process can be modeled as a Markov chain. The state of each element or the proportion of elements in each state can be measured during an inspection. A Markov chain describes a process that undergoes transitions from a state at one stage to a state at the next stage. Transitions are usually regarded as probabilistic events, with associated transition probabilities, represented by a transition matrix. A transition probability can be interpreted as either the probability that a single element will undergo a specific transition or the long-run proportion of elements that will undergo the transition.

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. This is because the probabilities of deterioration, and therefore transition probabilities, will not be influenced only by the current condition of the element but also by such factors as age of the element, past rehabilitation of the element, the conditions of other elements, and the external forces such as traffic load applied. To make better use of Markov chains for condition prediction, the states of an element therefore have to be defined based the element's current condition and on the factors that have a significant influence on its deterioration.

This might cause the number of possible states of each element to become very large. For example, with three factors, such as current condition, level of maintenance and traffic load, each with five levels, the element has 5 x 5 x 5 = 125 possible states. If transition probabilities P_{ij} from each state i to each other state j have to be estimated, then 125 x 125 = 15,625 transition probabilities have to be estimated. If this has to be done for each type of bridge, and each set of environmental conditions, then this approach is not very practical. Fortunately, the problem is not always as severe as this. Many transition probabilities can be assumed to be zero (0). To make provision for changing transition probabilities as an element ages, (to take care of the assumption of time homogeneity), different transition matrices can be used for elements of different ages. Transition probabilities, P_{ij}, have to be estimated. One approach is to estimate regression models having the state as dependent variable, assume a probability distribution for the random error term, and then to convert interval probabilities to transition probabilities. To use a Markov chain, individual states have to be defined as intervals on a continuum. This approach requires a large amount of applicable data which are not yet available at most transportation agencies. Alternative models, such as multinomial logit models, also can be used.

Another approach, suggested by the developers of Pontis, is to use the subjective judgment of bridge maintenance experts to obtain estimates of transition probabilities (*5,6*). As data are collected through regular inspections, these initial estimates are updated and improved. The updating technique draws on the principles of Bayesian estimation.

Bayesian Estimation

Bayesian estimation can be used for updating the estimated 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 inspections. It was incorporated into the Pontis bridge management system (*5,6*).

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 was 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, then it has to be valued as an equivalent number of observations, representing the amount of data on which the expert's judgment is based. This is the approach suggested by the developers of Pontis (*5,6*). When the estimates are later updated, the posterior values become the prior values for the new estimates. In this way, the effect of initial estimates are reduced as new data become available.

Other Approaches in Condition Analysis Methods

Application of 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. Such quality assurance procedures were developed for the Pennsylvania Department of Transportation (*7*). An innovative technique to utilize these less exact data items, 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. A bridge element can, for example, be in both a fair and a poor condition, and to different degrees. This gives a more realistic and flexible method to represent the subjective ratings of bridge elements. The theory of fuzzy sets was applied at Purdue University to assess the condition of bridge components (*8,9*), and to construct a Bridge Safety Index for bridges (*10*).

The Latent Variable Approach in Regression Analysis The approach of latent variables considers the infrastructure "performance" or "condition" as a set of unobservable or latent variables, which depend on other variables such as previous maintenance, environmental conditions and traffic load. 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. The last option is especially important, because deterioration tends to increase with decreasing maintenance, all other factors held constant. However, maintenance tends to increase with increasing deterioration. If these two relationships are not modeled explicitly and simultaneously, the wrong model might be estimated. This wrong model might very well indicate that deterioration increases as maintenance increases, all other factors held constant, because the model that is estimated might be closer to maintenance as a function of deterioration, than to deterioration as a function of maintenance. These "strange" results have been reported in the literature (*11*).

Latent Markov Decision Process This method explicitly takes the uncertainty (e.g., due to measurement errors) associated with facility inspection into account, and incorporates this into a Markov Decision Process framework. It augments the definition of states to incorporate all information available up to each stage (all previous measured conditions and implemented actions). This causes the state space to grow very rapidly with the number of stages which makes 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 (*12*). With an appropriate cost function based on element condition and implemented action, the strategy selection problem can be formulated in terms of a dynamic program to find the optimal strategy over a finite horizon with no budget constraints (*12*).

LIFE CYCLE COST ANALYSIS

To manage the infrastructure efficiently, the cost implications of alternative actions have to be known (or estimated) and 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, the costs that have been considered are direct and indirect costs that will be incurred by the agency and the public. Costs incurred by the public should be given as much weight as those incurred by the agency, even if they are less tangible and more difficult to estimate, because costs incurred by the public make up most of the total costs, and the ultimate mission of the agency should be to provide the best service to the public. Costs incurred by the public can be divided into user and nonuser costs. Usually only user costs are considered because it is unclear to what extent the alternative actions taken by the agency can be regarded as the sole cause of nonuser costs, such as pollution, and because of the possibility of double counting of costs and benefits as with economic development effects. Regression analysis is especially useful for estimating agency and user costs as functions of bridge element conditions, deficiencies, and traffic volume, as will become clear.

Agency Costs

Agency costs include the resources such as funds, worker and equipment time, and materials consumed in bridge related activities, such as routine 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 the activity, and other relevant data should be recorded. Data needs to predict bridge related costs are discussed in this *Circular* by Turner and Richardson (*1*).

Routine Maintenance Costs

The costs associated with the routine maintenance of bridge elements can be estimated directly or indirectly. Directly, these costs would be estimated as a function of the material type, condition, location, average daily traffic (ADT), highway classification, and other important factors for each bridge element. Indirectly, these costs can be estimated 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, ADT, highway classification, environment and other factors. The unit cost of each type of maintenance activity is also estimated as a function of such factors as material type, highway classification, and other factors. Together, the quantity of routine maintenance activities per year and their unit costs give an estimate of the routine maintenance costs. With the necessary data, regression analysis can be used to estimate both the quantity of work to be done and unit costs for each type of work. An example can be found in the study by Purdue University for the Indiana Department of Transportation (*13*).

Element Rehabilitation Costs

The costs associated with the rehabilitation of bridge elements should be estimated for different types of elements and the different rehabilitation alternatives applicable for each element type. A good data base/cost accounting system is essential to provide accurate and up-to-date cost estimates, broken down to individual element rehabilitation level. Unit costs of the deck reconstruction and overlay alternative were estimated with regression analysis for the Indiana DOT with the following factors: region of the state, highway system, traffic volume, bridge length, deck area, and percent of area needing patching (*13*).

Element Replacement Costs

The principles involved in estimating element replacement cost are the same as those for element rehabilitation cost. The element replacement costs should be estimated separately to recognize element replacement as a separate alternative action and because the funding options for element replacement might be different from those for element rehabilitation. In a study by Purdue University for Indiana DOT, superstructure replacement cost was modeled for different superstructure types as a function of bridge length and deck width. Substructure replacement cost was modeled for different substructure types as a function of bridge length, deck width and vertical clearance. Approach construction cost was modeled as a function of the approach length and the amount of earthwork. Other costs and total bridge costs were modeled as a function of bridge length and deck width (*13*).

Bridge Replacement Costs

Bridge replacement cost estimation should be done by breaking the total project down in the different cost items, and then using historical contract costs for similar items on similar projects to estimate these cost items. For preliminary estimation, simplified methods can be used. Bridge replacement cost would depend on the length, width and height of the bridge, the number and length of the individual spans, the superstructure and substructure material and structural type, as well as the bridge location and the feature (e.g., road, rail or river) being crossed. Using the deck area to estimate replacement "base cost" is proposed in the paper by Chen and Johnston (*14*).

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" state. User costs are therefore incurred even (and especially) if there is no bridge in place, and when a bridge suffers from deficiencies, such as insufficient load capacity. The development of user costs for bridge management systems is discussed by Johnston et al. (*4*), and only a few points are mentioned here.

Additional User Costs Due to Detours

User costs can be incurred because vehicles have to take detours because of insufficient vertical clearance or load capacity. These costs will consist of additional vehicle operating costs and the value of the time lost. The additional congestion and pavement damage caused in the rest of the transportation system also should be considered, if this effect is likely to be significant. To estimate these user costs for life cycle cost analysis, the following data analysis techniques can be used:

- Estimate the future traffic using a time series or regression analysis. For a simplified analysis the historic traffic growth rate along the same or a similar route is usually extrapolated over the analysis period.
- Load capacity can be predicted directly using techniques such as regression analysis or Markov Chains, or indirectly by using these techniques to predict the conditions of the applicable structural elements and then derive the load capacity from these element conditions.
- With the necessary data, elementary techniques from 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 numbers of different types of vehicles detoured due to insufficient bridge load capacity or vertical clearance, the vehicle operating costs per distance for different types and weights of vehicles, and the additional vehicle operating costs and time costs due to bridge deficiencies.

Accident Costs

To estimate the costs due to bridge related accidents, the following have to be done:

- Estimate the expected rates of different types of accidents at each bridge as a function of its deficiencies. Accidents involving bridges are on average more serious than general vehicle accidents on the open highway (*14*). Therefore highway accident statistics should not be used to estimate rates of different severity levels of bridge related accidents. With sufficient data, regression analysis can be used to estimate rates of different accident types as a function of bridge deficiencies.
- Estimate the costs of the different types of accidents related to bridges. This is usually done by separately considering the direct and indirect accident 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 losses in future

production and income. Two approaches to determine accident costs are discussed in the paper by Chen and Johnston (*14*).

The rates of different accident types and their associated costs together give an estimate of the expected accident costs due to bridge deficiencies. Often the necessary data to estimate the costs of bridge related accidents as a function of bridge deficiencies will not be available. The effect of deficiencies on accidents also can be considered in a more qualitative way by constructing a "Bridge Safety Index" as described in a publication by Murthy and Sinha (*10*). In this study, bridge inspectors provided the subjective judgments. These subjective ratings were then regarded as elements of a fuzzy set and transformed to fuzzy numbers. Bridge characteristics, approach roadway and environmental conditions were the factors considered as influencing bridge safety.

Additional User Cost During Bridge Work

Bridge work, whether routine maintenance, rehabilitation or replacement, usually influences traffic flow both across the bridge and on surrounding roads. The congestion caused by different alternatives can differ in terms of severity, duration and frequency. Routine maintenance might cause less severe congestion for a shorter period than rehabilitation, but this congestion will occur more frequently. Bridge work therefore causes additional user cost due to increased congestion. These additional user costs are incurred by users of the bridge and by users of the surrounding road network that have to put up with the additional congestion during periods of bridge work. The additional use of alternative routes during bridge work also may cause accelerated deterioration of the roads and bridges along these routes.

Identification of Promising Alternatives

Many bridge maintenance, rehabilitation and replacement alternatives may be feasible for each situation. Although ideally all alternatives should be considered, for practical purposes it is desirable to develop a reduced list of more promising alternatives for each situation. The situation can, for example, be a combination of deficiencies, element material types, bridge structural types, climatic environment, and ADT. 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. An example of such an exercise is the study conducted for the Pennsylvania DOT to identify cost-effective bridge maintenance and rehabilitation alternatives (*15*). In another study for Pennsylvania DOT, it was found that even if the maintenance requirements are assessed on a broad basis, detailed needs have to be quantified for each bridge. A list of potential bridge maintenance activities was later developed (*15*).

The detail with which alternatives are formulated will depend on the level that the available data will permit and the level at which the analyst wants to make distinctions between different alternatives. Results specifying specific actions for each bridge can obviously not be expected if data of sufficient detail were not collected and the alternatives were not specified with the necessary level of detail. It also should be kept in mind that if the analysis does not include a sufficient level of detail, the results may be so crude that they are almost useless, and a manual, judgmental procedure might have achieved better results, even for network level analysis. In a study for Indiana DOT it was found that the level of distinction between bridge rehabilitation activities was too broad and an enlarged list was suggested (*13*).

Activity Profiles and Cash Flows

The next step in analyzing different alternatives is to construct the activity profile associated with each alternative. For this all the results of previous analyses are brought together. The current condition and ADT determines current agency and user costs, and which alternatives are currently feasible. The models developed to predict condition are used to predict the condition for different alternatives. These are then used with the models for agency and user costs to estimate the associated costs for each alternative activity profile, and thereby to derive each associated cash flow. The cash flow of each activity profile can then be analyzed with the techniques of interest accounting.

Commonly used criteria for selecting or ranking alternatives are Net Present Value, Equivalent Uniform Annual Cost, Incremental Benefit/Cost Ratio, and Incremental Internal Rate of Return. If the analysis is done correctly, these criteria should lead to the same preferences of alternatives relative to each other. Many reference works describe the application of these techniques, such as Grant, et. al. (17). Several issues have to be addressed when conducting these analyses. The first is the choice of a minimum acceptable rate of return. Theoretically, the chosen rate should be the rate of return that can be earned on projects or investments with a similar level of risk. The rate of return to be used is often suggested to be the yield rate on some type of long term government bond adjusted for inflation. The way in which inflation is to be considered is described in the literature, e.g., Grant, et. al. (*17*). Usually the service lives of alternatives will be different. One approach is to use the same cutoff date for all alternatives, after a long analysis period. Differences between alternatives after this cutoff date are then represented by different residual or salvage values. Another approach is to assume that each life cycle after bridge replacement is repeated into perpetuity. If this approach is followed, the ADT has to be stabilized at some value. Another issue to be addressed is exactly which costs should be considered. Agency and user costs, as influenced by the alternatives, have to be included. Nonuser costs, such as those associated with air and noise pollution, aesthetics and ecological disturbance, are difficult to relate to alternatives and to estimate. Most studies currently ignore these cost elements or take these effects into account in a more qualitative way. These factors will become more important in the future.

Impact Analysis

Even where programs for systematic data collection and analysis have been instituted, it may take many years before sufficient data have been collected to apply techniques such as regression analysis and Markov chains. A need therefore exists for simplified impact estimation to support decisions that have to be taken in the meantime. A common approach is to obtain the judgment of bridge experts regarding the impact of alternatives. Such an approach was followed by the Pennsylvania DOT to identify a list of cost-effective maintenance and rehabilitation alternatives with their impacts on costs and safety (*15*). The developers of Pontis suggested such an approach as an interim measure to obtain estimates of deterioration rates and condition impacts (*5,6*).

In a study conducted for the Indiana DOT by Purdue University the Delphi technique was used to obtain judgmental impact estimates by iteratively building a consensus among bridge experts. This technique was used to obtain estimates of the impact of routine maintenance only, deck patching, deck reconstruction and deck replacement, on the remaining service life of bridges (*8*).

PRIORITY SETTING AND OPTIMIZATION

Several approaches and techniques have been developed to assimilate data and analysis results to make better decisions. One approach is that of priority setting, usually done by ranking projects according to some criteria to obtain a priority order list of projects. Another approach is that of optimization, where the objective is maximized/minimized subject to constraints by choosing the best values of the decision variables.

Priority Setting

Many ranking methods have been developed to aid in priority setting. Most ranking methods develop a composite index or indices for each bridge or each project. Bridges or projects are then ranked according to the values of these indices. One such method is the sufficiency rating which is developed according to the FHWA's *Structure Inventory and Appraisal Guide* (*18*). This makes provision for the calculation of indices reflecting the structural adequacy and safety, the serviceability and functional obsolescence, the essentiality for public use and the overall sufficiency rating.

Bridges also can be ranked according to level-of-service criteria. Such a method that ranks bridges according to deficiency points, was proposed by Johnston and Zia for North Carolina DOT (*19*). The method takes load capacity, clear deck width, vertical overclearance and underclearance, remaining service life and the costs of alternatives into account.

There are many methods based on pairwise comparisons between bridges and alternatives. Concordance analysis is such a method that has been used to select transit improvement alternatives and in bridge evaluation (*8*). Another method was developed using linear programming to estimate the weights of multiple attributes in constructing a composite criterion (*8*). The analytic hierarchy process is a pairwise comparison method and will be briefly discussed. A disadvantage of all these pairwise comparison methods is that the number of pairwise comparisons become very large as the number of alternatives increases.

Assignment of Relative Weights

The analytic hierarchy process (AHP) constructs a hierarchy and uses pairwise comparisons at each level of the hierarchy. System goals, objectives, criteria and alternatives are related by the hierarchy. Relative weights are given to "activities" on the same level in the hierarchy for measuring their contribution to an "activity" on an adjacent higher level. For a bridge management system, the first level might be the goal to maximize system effectiveness. The second level might consist of objectives based on achievement of the goal to be measured, such as bridge condition, agency costs, user costs, safety and external impacts. The third level might then consist of the criteria, in terms of which each objective is measured. The criteria for user costs might consist of additional vehicle operating costs due to detours, value of time lost, additional congestion caused and accident costs. The fourth level might then consist of individual alternative projects.

The above hierarchical structuring is very general, and similar structures are used in many ranking methods. What makes the AHP method different is the way in which the relative weights are derived. The activities on each level are pairwise compared to produce relative weights. Then these relative weights are arranged in a reciprocal matrix for each higher level activity. If the pairwise comparisons are consistent, an eigenvector corresponding to the largest eigenvalue will give a set of relative weights for all the activities. Alternatives can then be ranked according to these weights. More information on the AHP can be obtained in Saaty (*20*).

Utility Functions

Many alternatives might have to be compared in bridge management. Making pairwise comparisons between all alternatives with respect to each criterion might therefore be an enormous task. In the bridge management system developed by Purdue University for Indiana DOT, this problem was resolved by developing utility functions for the bridge characteristics, such as remaining service life, that will be impacted by alternatives. To compare alternative projects, the characteristics of the bridges can be directly converted to utility points without having to make pairwise comparisons between all alternatives (*8*).

Optimization

The purpose of optimization is to find the optimal set of actions to be implemented at different times on a network of bridges subject to a variety of constraints.

Minimization of Life Cycle Costs

One approach is to do a life cycle cost analysis for each bridge or type of bridge in the system, for each promising alternative that can be implemented at each programming period. This reduces to continuing with routine maintenance until one of the rehabilitation or replacement alternatives is better than routine maintenance. A similar approach was followed by North Carolina State University in their study for North Carolina DOT (14), and by Wisconsin DOT (*21*). This approach does not find a "true global" optimum strategy, because it does not simultaneously take network-wide effects such as budget constraints into account, and at the point in time that an alternative is chosen, future choices are not yet determined. To choose the optimum alternative under these conditions, some simplifying assumptions about future alternatives usually have to be made.

Linear and Integer Linear Programming

One of the most versatile optimization techniques is linear programming (LP). In such a program, the values of decision variables are sought that will maximize/minimize a linear objective function, subject to linear equality/inequality constraints, such as budget constraints. The decision variables should be such that they can realistically be regarded as continuous variables. The Pontis MR&R models, including the deck maintenance models and the substructure-superstructure optimization models, were formulated so that they can be solved with linear programming. Decision variables for the different models include expected discounted cost, and the limiting probability that an element will be in a state and an action will be chosen (*5,6*). These are all continuous variables.

Often the decision variables are discrete, such as whether an alternative will be implemented ($x=1$) or not ($x=0$), resulting in an integer linear program (ILP). One very simple version is as follows:

$$\min \sum_{t=1}^{T} \sum_{i=1}^{I} \sum_{a=1}^{A} c_{ait} \, x_{ait}$$

$$\text{subject to}$$

$$\sum_{i=1}^{I} \sum_{a=1}^{A} b_{ait} \, x_{ait} \leq B_t \qquad \forall t = 1,\ldots,T$$

$$\sum_{a=1}^{A} x_{ait} \leq 1 \qquad \forall i = 1,\ldots I,\ t = 1,\ldots,T$$

$$\sum_{u=t}^{t+\tau} x_{aiu} \leq 1 \qquad \forall a = 1,\ldots,A,\ i = 1,\ldots,I,\ t$$

$$x_{ait} = 0 \text{ or } 1 \qquad \forall a,i,t$$

Each alternative a for each bridge i for each programming period t is associated with a decision variable x_{ait}, associated total (agency and user) costs c_{ait} and associated budget requirement b_{ait}. Each decision variable x_{ait} indicates whether the alternative is chosen ($x_{ait} = 1$) or not ($x_{ait} = 0$). The objective function minimizes the total costs over a finite time horizon, T.

The first constraint ensures that the budget for each programming period *t* is not exceeded. Budget constraints also can be split between various sources and accounts. The second constraint ensures that at most one alternative is chosen for each bridge in each programming period. The third constraint ensures that the same alternative is not implemented more than once for a specific bridge during a time window. Similar constraints can be formulated for mutually exclusive as well as for interdependent projects. An ILP model was proposed for the improvement model of Pontis (*5,6*), as well as for the Indiana BMS (*2*).

Advantages of LP and ILP are:

- These techniques are very versatile, easy to understand, and can be used to formulate and solve a wide variety of optimization problems. Formulations can be changed to adjust to changing needs and circumstances.
- Software for linear and integer linear programming is available.
- Linear programs with hundreds of thousands of decision variables have been solved.

Disadvantages of LP and ILP are:

- The size of *integer* linear programs that are solvable in reasonable time is much more restricted than that for linear programs.
- Objective functions and constraints are restricted to linear functions of the decision variables. Some nonlinear functions can be approximated by piecewise linear functions, but this complicates the exercise. Nonlinear objective functions and constraints also can be handled with the techniques of nonlinear programming. This is computationally much more demanding.

Dynamic Programming

An optimization approach with more desirable computational properties is dynamic programming. It is based on the Principle of Optimality which in this context means that optimal alternatives/policies over time consist of optimal subalternatives/subpolicies over shorter periods. This is in general true for bridge management. Thus, optimal policies can be constructed by recursively finding optimal subpolicies for successive programming periods. One method of applying dynamic programming is to do the analysis over a finite, but long, time horizon. At each stage a bridge element can be in several different states. A terminal value/cost is assigned to each state at the end of the analysis period. A cost is also 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. Such an approach has been suggested for several pavement and bridge management systems (*5,6,2*). If optimal alternatives are consistently implemented, the state of the system will move towards an optimal steady state. A useful analysis is therefore to determine the optimal steady state and associated alternatives. Because the system will not be in this optimal steady state, an associated problem is the optimal way of moving towards the optimal steady state. Both the optimal steady state problem and the optimal transition stage problem were formulated as linear programs for Pontis (*5,6*). An optimization model developed by Purdue University for Indiana DOT combines dynamic programming and integer linear programming. Different budgets for each stage are incorporated in the dynamic program's state space. At each stage the optimal set of projects for each budget is selected with integer linear programming. The objective is to maximize a measure of system effectiveness that takes ADT, bridge element conditions, traffic safety and community impact into account (*2*).

Network and Heuristic Methods

Because realistic optimization models are computationally demanding to solve, heuristic procedures might hold promise. Limited study has been done in this field. An example is an investment staging model for bridge replacement proposed by Garcia-Diaz and Liebman (*22,23*). This model specifically addresses the replacement and scheduling of rural bridges. It explicitly takes the user cost into account especially the cost of alternative routes due to bridge load capacity deficiency. It minimizes road user cost subject to agency budget constraints. The problem is simplified by a form of decomposition by separately scheduling bridge replacement projects over different subhorizons. The subhorizons are ordered in a priority sequence—an application of lexicographic optimization (*22,23*). Heuristic methods might be more effective due to the complexity of bridge management.

CONCLUSION

The nature and sophistication of an agency's bridge management system, and data analysis in particular, will be determined by the system of bridges for which the agency is responsible, and the available resources. Some larger cities with many bridges with a heavy traffic load might have bridge management system needs similar to those of state highway agencies, whereas some small cities might have only a few bridges to take care of, and very few resources. For such small cities bridge management would be mostly at the project level. Network level analysis would add little additional value. Some counties might have many bridges, but few resources to take care of those bridges. The bridge management needs of such counties would differ from those of states and cities.

Bridge management is a continuous process. Changes are continuously occurring—bridge elements deteriorate are rehabilitated or replaced, traffic levels change, costs change and available resources change. Bridge management activities should therefore be conducted on a continuing basis - data collected, database updated, reports generated, models developed, conditions and impacts predicted, alternatives evaluated and optimal strategies selected. Due to this dynamic nature of the bridge management process, systems should be frequently improved—new data analysis techniques developed, better models estimated, better optimization techniques developed and better decision making methods implemented.

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BRIDGE MANAGEMENT DECISION SUPPORT

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ABSTRACT

Bridge Management Systems (BMSs) are designed to assist the bridge manager in cost-effectively addressing the bridge infrastructure needs. Typical decision support include access and retrieval of bridge related information, assessment of bridge needs, evaluation and cost estimating of alternate strategies for inclusion in optimized capital and maintenance programs, network and project level forecasting, and trend analysis. This paper specifically focuses on major bridge related decisions managers face, at the network and project level, and the types of decision support needed for assuring appropriateness and cost-effectiveness of those decisions. It also discusses the data sources that can provide this decision support.

INTRODUCTION

Henry Ford made automobiles affordable and created an unprecedented need for expansion and improvement of roadway and bridge networks. As the automobile population grew, roadways were paved and bridges built. Depression era public works programs helped to meet much of this need, but most of that help ended with World War II. With all the growth, the U.S. never achieved a stable, steady-state bridge population. When these bridges became due for major preservation work, another major expansion program, the Interstate Highway Program, came along. That program replaced some of the worst bridges, added many new bridges and diverted our attention away from needed preservation work. Then, the country entered a new phase that it was not prepared to manage: the maturity of a highly diverse highway system. In its past enthusiasm to build and expand, timely maintenance of what was being built took a back seat to other local and national priorities. Deferred maintenance was thought of as a good way to stretch shrinking budgets. When attention was finally focused on bridge condition due to the catastrophic failure of some bridges (e.g., Point Pleasant, West Virginia), a sizeable portion of the bridge network needed substantial repairs.

The backlog of repair and replacement needs was large and new needs were also being identified with each new inspection and each improvement in the quality of the inspections. It became obvious that a better job had to be done in managing bridge networks. New technologies were available to aid in the systematic collection and processing of bridge data: to store, analyze, summarize, and retrieve vast quantities of bridge information; and to organize that information in ways to improve the decision making abilities of bridge managers. The use of such technology has been called a "Bridge Management System."

Most bridge agencies have reasonable confidence in their knowledge of their bridges, but not the same level of confidence in their ability to decide what is most appropriate for those bridges at a given point in time or at specific times in the future. Consequently, many of these agencies have recognized their need for assistance in making bridge-related decisions. As a result, BMSs have been receiving considerable attention in this country within the last decade. While there can be many benefits to a BMS, the major benefit is comprehensive data based assistance to the bridge manager. To a large extent, the specific assistance a particular BMS provides is determined by its developing agency and operational users.

This paper identifies types of decision support, presents what many larger bridge management agencies in the U.S. and Canada consider the most important decision support capabilities, and recommends a group of critical decision support capabilities that should be part of a comprehensive BMS. Besides capabilities that should be incorporated, it also must be recognized that some capabilities should not be built into a BMS. One such capability is decision making. A BMS must never make decisions. This is a pitfall where BMS developers can easily stumble. The analytical processes can often fool the developer and the user into believing that the system knows best. Bridges cannot be managed without the practical, experienced and knowledgeable input from the Engineer/Manager. A practical way to help ensure that a BMS would not be used as a decision maker is to build in user adjustments at all the critical decision areas. A user adjustment would require the user to either accept the recommendation of the BMS or change it based on the user's knowledge. Without positive user action, the system should not be able to complete the analysis routine.

BRIDGE MANAGEMENT SYSTEM - BASIC COMPONENTS

Agencies responsible for bridges are very enthusiastic about the prospects for BMSs. The reason for this enthusiasm is that bridge managers understand and believe that the BMSs will significantly improve their ability to manage their bridges. Help can be provided by the simple automation of current bridge management procedures. This automation will enable managers to deal more effectively with many bridges, multiple competing needs and complicated issues. Besides the automation of current procedures, expanded and/or newly developed analysis procedures also will help the manager by providing information that was not available in the past.

In any BMS there are only three basic components: data, data analysis, and decision support. Another way of describing this, is: input (data that are necessary for the decision process), processing (the analysis routines to which the data are subjected), and output (the results of the analysis routines that will assist the user in making balanced bridge management decisions, i.e., reports and summaries). In the development of a BMS, these three components do not occur in the order presented. The first activity is the recognition of the areas of need for decision support. The second is the identification of the types of analysis to be used to obtain the desired decision support. The last is the identification and collection of essential data for these analyses. When BMS formulation and development were in their infancy, it was widely accepted that any BMS would never have sufficient information in its database to make decisions. The missing information is mostly intangibles, such as: political considerations, engineering experience and local needs. These and other intangibles are essential for the final decision. However, the proposed BMSs were recognized as being able to provide valuable assistance by organizing and analyzing the available bridge data. The decision making would be left to the Engineer/Manager.

One area that was often overlooked in the BMS planning stages was how difficult it is to produce deterioration rate estimates for groups of bridges. The experience in New York State confirms how difficult condition deterioration prediction can be. One can make reasonably good predictions of the network condition of an infrastructure group for the near future, but predictions for a particular bridge have not been so successful. The cost of bridge work is similarly difficult to predict. Even after bridge projects have been designed, there can be significant differences between the engineer's estimate and what the bidders submit. A variation of plus or minus 10% is not uncommon. Therefore, we cannot and should not believe we can calculate precise benefit/cost data for various alternatives on one or many bridges. Thus, prioritization and optimization efforts have to be kept in the proper perspective. The quality and precision of the data that they rely on are insufficient to support sophisticated calculations.

COMPREHENSIVE BRIDGE MANAGEMENT - CAPABILITIES

Most dictionaries define comprehensive as "large in scope or content," or "marked by or showing extensive understanding in...." These two ways of defining the word "comprehensive" are subjective. Comprehensive bridge management also is subjective because it includes capabilities that are usually tied to the agency's needs. These needs are identified in the agency's goals, policies and standards. Therefore, what a particular BMS does for an agency is dependent on that agency's operational philosophies and the extent to which these philosophies are incorporated in the development of the system. A system exclusively developed for use by an agency will naturally be specifically tailored for that agency's goals, objectives, policies and procedures. A system developed for multiple agencies may not provide all the capabilities that each individual agency desires. The New York State Department of Transportation (NYSDOT) distributed a questionnaire to solicit information on the BMS development plans of major bridge management agencies. The results of that questionnaire (*2*) indicated that 37 (70 percent) of the responding agencies were anticipating adopting a system developed outside their agency. This shows that those agencies believe an externally developed system can support, or can be modified to support, their individual bridge management philosophies. BMSs, therefore, are likely to vary significantly in their construct and capabilities. Each system, however, should have some basic capabilities that are generally considered necessary for a comprehensive BMS. They are:

- Comprehensive bridge database and ease of access;
- Assessment ability for bridge condition, vulnerability and serviceability needs at the project and network level;
- Ranking/prioritization ability;
- Ability to develop and/or evaluate alternate work and program strategies based on cost effectiveness; and
- Ability to assess the effectiveness of decisions for optimal use of available resources.

In addition, a comprehensive BMS should provide the user with the ability to control various aspects of the program's operation and to "adjust" the results provided by the BMS, based upon the user's knowledge of unique or special considerations. These abilities are specifically focused on the user, not the system, as the decision maker. It is equally important to recognize that agencies are unique and their needs differ significantly. Consequently, a BMS without all the capabilities indicated above, although possibly viewed as not being comprehensive by many, may still satisfy all the needs of an individual agency.

BRIDGE MANAGEMENT DECISION SUPPORT

Bridge management decisions are related to either a group of bridges (Network Level Decision) or an individual bridge (Project Level Decision). Further, decisions at either level may include capital improvements and operating maintenance activities. The goal of a comprehensive BMS is to integrate these decision processes to attain the lowest possible and practical life cycle costs at the network and project level.

The principal purpose of a BMS is to provide properly analyzed information that will assist the user in selecting the best alternative action for a bridge or a network of bridges. Therefore, a BMS should present information to help the user coordinate bridge work activities, improve cost effectiveness of decisions and maximize benefits within constrained budgets.

The capabilities provided by a BMS for decision support are as many as the user and the bridge management agencies needs. Obviously, more appropriate capabilities can be included in the BMS when an agency is developing or controlling the development of that system rather than adopting a BMS developed by another agency. However, even in previously developed systems, a group of generally accepted basic core capabilities are included. Turner and Richardson (*1*) present data in terms of logical and practical groupings of data needs that are particularly useful when considering important decision support. The groupings are presented and described in Table I.

The NYSDOT is developing its own BMS. As part of the development process, the Department considered it important to identify those BMS capabilities that other transportation agencies deemed important for bridge management decision support. To satisfy this interest, questionnaires were sent to the Transportation Agency in the States, the District of Columbia, and several Canadian provinces. The results of the questionnaires provided a comprehensive list of desirable decision support capabilities. The results are tabulated in Table II.

Table III identifies the information areas, analytical requirements and sources for each of these decision support capabilities for both network and project levels. It is evident from the first two columns in Tables III that two basic information sources are needed by all BMS decision support capabilities: 1) the root BMS database containing new and historic condition, inventory, work and cost data, and 2) the agency's goals, policies, standards and procedures. The first shows the need for basic data, while the second shows the basic reliance on the organization's operating philosophy.

A BMS has two other basic information needs. Resource availability (column 4 in Table III) controls the amount and type of work that can be done both within the agency and by contract, by establishing allocations. This availability is under the control of various legislative and other political entities. The needs analyses (column 3) are limited applications of the agency policies and standards to the bridge database to identify all potential problem instances. These are appropriate as an input because they are not subject to negotiation within the BMS. A bridge either meets agency standards or it does not. It is subject to a particular policy, or it is not. The program that the BMS process produces may or may not address these needs. These first four columns represent data inputs.

The last four columns in Tables III are examples of iterated outputs that require evaluation by the agency. These outputs describe the currently selected work program. If the agency is satisfied with the results, then the BMS process is complete. If the results are not satisfactory, then adjustments have to be made to the BMS parameters and a new program generated.

Table IV indicates the sources for the decision critical information and the processed information (outputs) that were shown as the columns in Tables III. As expected, BMS information is derived from data sources, while analysis inputs require data sources combined with models, criteria and analytical methods. Based upon the responses to a NYSDOT survey (*2*), the Turner and Richardson paper (*1*), and other sources, bridge management decision support is desirable in the areas of condition assessment and forecasting, program and budget development, monitoring and analysis, and vulnerability to failure. The bridge failure and deterioration groups referred to by Turner and Richardson clearly encompass the condition assessment, forecasting and vulnerability features identified as desirable by the NYSDOT survey results. Level of Service (functional obsolescence) is also a desirable and important consideration in program development

TABLE I GROUPINGS OF DATA NEEDS FOR BRIDGE MANAGEMENT DECISION SUPPORT

Prevent Bridge Failures	Data to prevent bridge failures are identified as data areas that affect the structural integrity of a bridge. These include condition, fracture critical, and scour data. These data, and other vulnerability data (i.e., hydraulics, earthquakes, collisions, overloads), can provide input to a decision support feature that would help the bridge manager in determining the urgency of structural integrity needs and help identify possible work strategies to address these needs. However, bridges identified as having such needs would very likely be "high priority" candidates and have few (if any) alternative actions.
Determine Functional Obsolescence	Data to determine functional obsolescence are data that help assess the ability of a bridge to function as it was originally designed. These data include information on bridge width, vertical clearance (on and over), load posting, and user costs (includes detour costs). These data can be used to determine the severity of functional deficiencies, identify the consequences of any deficiency, and help develop possible work strategies to address these needs.
Determine Maintenance Needs	Data to determine maintenance needs are directed at identifying the traditional operational needs of a bridge. This operational work is associated with minor condition corrective type work and preventive types of work that will arrest or reduce the rate of deterioration. These data can be used to identify maintenance need areas and to help identify and evaluate possible work strategies and work plans to address these needs.
Predict Bridge Deterioration*	Data to predict bridge deterioration are data relating to the condition of a bridge and its elements over time. These data include bridge condition data tracked over time and historical environmental information pertaining to the environment that those bridges were subjected to. Some of these data can be difficult to gather. These data are necessary to predict the future condition of bridges so all potential work strategies can be evaluated. This is a very difficult capability and that should be kept in mind when applying the results of any analysis.
Predict Bridge Costs*	Data to predict bridge related costs are data to enable the user to develop costs for all types of potential bridge work strategies. These data include the historical bid information pertaining to bridge and project costs, type of improvement work, and specific details for each bridge. These data are necessary to predict the cost of proposed work recognizing the difficulty with cost predictions in general.

* Information in these groupings considered to be approximate.

TABLE II BRIDGE MANAGEMENT DECISION SUPPORT CAPABILITIES SELECTED BY TRANSPORTATION AGENCIES

Decision Support Capabilities	Selected by Responding Agencies[*] (%)
NETWORK LEVEL	
Analysis of Short/Long Term Capital & Operating Budgets Evaluate the effect of both long and short term capital and operating (maintenance) budgets and compare the results to agency goals and objectives.	79
Current Systemwide Assessment of Bridge Condition Provide bridge network assessment using the agency's condition methodology.	77
Forecasting Systemwide Assessment of Bridge Condition Project bridge network condition into the future using deterioration models.	75
Ability to Select the Most Prudent and Cost-Effective Mix of Capital/ Operating Improvements Based on Life-Cycle Costs Provide information on the advantages and disadvantages of alternative improvements.	75
Project Selection Select potential projects for inclusion in capital/operations program.	75
Program Development Develop a capital/operations program with capability to evaluate alternative "what if" scenarios.	74
Optimization of Improvement Action Evaluate advantages and disadvantages of improvement alternatives with ranking of individual projects.	68
Monitoring Bridge Improvement Program (Capital & Operating) Track the status of capital and operations programs.	60
Statewide Assessment of Bridge Service Restrictions Evaluate all bridges with respect to various levels of service for load carrying capacity, vertical clearance, and bridge width.	53
Vulnerability to Sudden Failure (scour, earthquake, etc.) Evaluate susceptibility of bridges to failure caused by scour, fatigue, earthquake, overload, collision impact, concrete/steel detail, etc., and analyze impact of alternative improvements.	43
Information Center Accessible to Others Availability of bridge data/information to others.	32
PROJECT LEVEL	
Definition of Individual Capital & Operating Needs Assessment of major needs (condition, vulnerability, serviceability and preservation) of individual bridges.	74
Prediction of Remaining Service Life of Improvements Identify remaining service life of a bridge using deterioration models and impacts of improvement activities.	55
Individual Project Cost Estimation: Capital and Operating Capital and operations cost estimates developed from component/element level data and associated costs for highway and utility work, construction inspection, etc.	51
Support for Structural Capacity Analysis (Load Rating) Analyze structural capacity of a bridge to produce load rating.	36
Project Design Support Develop project concepts, and structure design and detailing.	23

[*] Fifty-three Responding Agencies

TABLE III DECISION CRITICAL INFORMATION AREAS FOR NETWORK AND PROJECT LEVEL DECISION SUPPORT

	Information Sources				Processed Information			
	(1) Current & Historic Inspection, Inventory, Work & Cost Data	(2) Organizational Goals, Policies, Standards & Procedures	(3) Condition, Vulnerability & Serviceability Needs	(4) Resource Availability	(5) Program Cost Estimates	(6) Project Cost Estimates	(7) Forecast of Resulting Network Needs with/without Program	(8) Forecast of Resulting Project Needs with/without Program
NETWORK LEVEL								
Analysis of Short/Long Term Capital & Operating Budgets	X	X	X	X	X	X	X	X
Current Systemwide Assessment of Bridge Condition	X	X						
Forecasting Systemwide Assessment of Bridge Condition	X	X					X	
Ability to Select Cost-Effective Mix of Capital/Operating Improvements Based on Life-Cycle Costs	X	X	X					
Project Selection	X	X	X	X	X	X	X	X
Program Development	X	X	X	X	X	X	X	X
Optimization of Improvement Actions	X	X	X	X	X	X	X	X
Monitoring Bridge Improvement Program (Capital & Operating)	X	X			X	X		
Systemwide Assessment of Bridge Service Restrictions	X	X	X					
Vulnerability to Sudden Failure (scour, earthquake, etc.)	X	X	X					
Information Center Accessible to Others	X	X	X					
PROJECT LEVEL								
Definition of Capital & Operating Needs	X	X	X					
Prediction of Remaining Service Life of Improvements	X	X						X
Individual Project Cost Estimate: Capital and Operating	X	X				X		
Support for Structural Capacity Analysis (Load Rating)	X	X						
Project Design Support	X	X						

TABLE IV DATA SOURCES FOR DECISION CRITICAL INFORMATION

	DECISION CRITICAL DATA SOURCES											
	(1) Current & Historic Bridge Inspection and Inventory Data	(2) Current & Historic Work Cost Data (Capital & Operating)	(3) Vulnerability to Catastrophic Failure Data	(4) Serviceability Data	(5) Economic Indicator Data	(6) Deterioration/Improvement Model	(7) Cost Prediction Models	(8) Ranking/Prioritization Criteria	(9) Optimization Criteria	(10) Alternate Work Actions with Cost & Life Expectancy Estimates	(11) Service Life Models with/without Improvements	(12) External Agencies (i.e., FHWA & AASHTO)
INFORMATION SOURCES												
Current & Historic Inspection, Inventory, Work Histories, & Cost Data	X	X	X	X								
Organizational Goals, Policies, Standards, & Procedures	X	X	X	X	X	X	X	X	X	X	X	X
Condition, Vulnerability & Serviceability Needs	X		X	X								
Resource Availability												X
PROCESSED INFORMATION												
Program Cost Estimates	X	X	X	X	X	X	X	X	X	X	X	
Project Cost Estimates	X	X	X	X			X					
Forecast of Resulting Network Needs with/without Program	X		X	X		X					X	
Forecast of Resulting Project Needs with/without Program	X		X	X		X					X	

capability. Bridge costs are always a major part of program and budget development, monitoring, and analysis. These independent sources of information have been useful in providing a good understanding of which bridge management decision support capabilities are important.

Another major feature is the reporting capability. Without it, agencies would simply not be able to use the results of the BMS process. Reporting needs are individualized and vary from agency to agency as well as from time to time. It is equally important to note here that the basic conclusions reached in this paper are compatible with two previously released BMS documents. These documents are: American Association of State Highway and Transportation Officials' *Guidelines for Bridge Management Systems* (*3*) and *National Cooperative Highway Research Program Report 300*, "Bridge Management Systems" (*4*). Therefore, the core of BMS decision support capabilities is essentially unaltered from the beginnings of bridge management conceptual development.

SUMMARY

There are many capabilities that should be included in a comprehensive BMS. These are dependent on the desires of the bridge management agency. These capabilities can be combined into major areas that represent core features of any BMS. These major network and project level core capabilities are

- bridge needs assessment,
- bridge needs forecasting,
- optimization, and
- report capability.

The following principles should be kept in mind throughout the development and use of any BMS:

- BMS's should be compatible with agency philosophies;
- Systems should provide user adjustments/decisions;
- Quality and precision of the data requirements for prioritization and optimization are insufficient to support complex routines, therefore, these efforts should be kept in proper perspective and expectations for these areas set at reasonable levels; and
- A BMS is a decision support tool, not a manager!

Considering all we know today, a more appropriate name for a BMS should be a "Bridge Management Decision Support System" (BMDSS).

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PONTIS

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ABSTRACT

Pontis is a network-level Bridge Management System (BMS) to aid in the optimization of budgets and programs for the maintenance and improvements of each state's inventory of structures. The system includes several important innovations in bridge inspection procedures, life-cycle cost estimation, economic optimization, deterioration modeling, and software engineering. With a large collection of customization and "what-if" analysis features, the system is highly adaptable to the diverse needs of the states. It can operate in a client-server environment in tandem with mainframe or personal computer bridge inventories, and can be subdivided into components useful for inspectors, district offices, and local governments to support their individual portions of a state's total BMS. All 50 of the states have requested the software for evaluation, and a recent American Association of State Highway and Transportation Officials (AASHTO) solicitation indicates that at least 38 states have agreed to participate in a proposed AASHTOware^{TM} project to support and enhance the system. Many local, federal, and international agencies are also evaluating it. Initial development of the system was completed in February of 1992, and it is currently undergoing a set of minor software enhancements along with a process of standardizing the definitions of bridge elements to be inspected.

BACKGROUND

The National Bridge Inventory (NBI) contains inventory and condition appraisal information of the Nation's highway bridges both on and off the federal aid system. A review of the NBI shows that more than 400,000 of the nation's 570,000 bridges are more than 50 years old. Typically, these older bridges were designed for less traffic, slower speeds and lighter loads than they are subjected to today, to the point where many of these bridges are functionally obsolete. Due to the gradual effects of weather, deicing salts and inadequate maintenance policies, the structural integrity of many of the nation's bridges is being compromised. Today approximately 40 percent of the nation's bridges are, by reasons of their condition or appraisal, eligible candidates for the federal Highway Bridge Replacement and Rehabilitation Program (HBRRP). The amount of money needed to rehabilitate or replace the bridges eligible for the HBRRP has been increasing faster than the allocation of the HBRRP moneys. This gap between bridge needs and available bridge moneys continues to increase.

To reduce adverse effects of the widening gap between bridge needs and available money, sound bridge management decisions must be implemented. In 1986, as an effort to aid bridge owners to develop sound bridge management decisions, Federal Highway Administration (FHWA) Demonstration Project Number 71 (DP71) was initiated. The first phase of this project held a series of workshops in 47 states and published the DP71 Bridge Management Systems Report. After assembling a Technical Advisory Committee (TAC) which included bridge managers from six State Departments of Transportation (California, Minnesota, North Carolina, Tennessee, Washington, Vermont), the FHWA, and Transportation Research Board, the second phase of DP71 was initiated. In September 1989, a 27-month contract was awarded through a competitive bid process to the joint venture of Optima Incorporated and Cambridge Systematics Incorporated with the objective to develop a state-of-the-art, network BMS and accompanying computer software. Technical guidance of the project was provided by the TAC, including the development of the inspection procedures and some engineering submodels, while the State of California administered the contract. This second phase of DP71 ultimately became known as the Pontis project. The name "Pontis" was selected by the TAC after a series of "name the BMS" discussions among participants. Pontis is the Latin word meaning "pertaining to bridges."

The early portion of the contract was spent developing system concepts. A few of the key features of the modeling approach were:

- Separation of Maintenance, Repair and Rehabilitation (MR&R) actions from Improvement actions. In Pontis, MR&R activities are those activities that are in response to deterioration, while Improvement activities are in response to functional problems.

- Analyze each bridge according to its constituent elements. This approach coincided with the TAC's recognition that the existing NBI condition ratings for the Superstructure, Substructure and Deck were insufficient to make informed bridge repair decisions and a more detailed condition assessment of the bridge would be needed.
- View bridge deterioration as probabilistic (subject to uncertainty) rather than deterministic (known for certain), and automatically update deterioration predictions as historical inspection data are obtained. The probabilistic approach was very appealing to the bridge engineers in the group, who recognized that deterioration predictions are uncertain, but that this uncertainty plays a central role in decision making.

Of primary concern during the development process was that any data required must be easily obtained and simple to maintain. It was important to develop a system that was not so data-intensive that it would be impractical to manage. This became a major objective of the project team.

DATA NEEDS

To meet the project objectives of developing a simple yet more detailed approach to condition assessment took months of research, many meetings and lots of correspondence to develop a list of bridge elements that would behave in a consistent and predictable manner. What was developed is an element level condition assessment, or inspection system, which tracks not only the severity of a problem but also its extent. This new way of tracking condition data can be accomplished without much, if any, additional effort to the existing NBI condition rating procedures.

In the current version of Pontis there are 160 different elements. Each of these elements has a specified unit of measure, and up to five unique condition states described in engineering terms, three MR&R actions for each condition state, and four environments. This sounds complicated and highly data intensive, however, there are usually no more than six to eight elements for any one bridge. In California, where over 16,000 of 24,000 bridges have been assessed for Pontis elements the distribution of elements per bridge is shown in Table I. Not only are the element condition assessment procedures developed for Pontis innovative, but so is the way Pontis views deterioration. The Pontis approach to deterioration is probabilistic instead of the more conventional deterministic approach. What this means is that Pontis attaches a "confidence" factor to the occurrence of a certain event. Here the event is further deterioration. For example, instead of saying a bridge will take 30 years to deteriorate to a certain condition level, a probability of this event taking place is developed, since it is known that not every bridge follows the same deterioration pattern. If this probability was established at 100 percent, conventional deterministic results would be obtained.

TABLE I DISTRIBUTION OF PONTIS ELEMENTS IN CALIFORNIA BRIDGES

Number of Elements	Number of Bridges
1	69
2	161
3	882
4	4,527
5	4,344
6	3,258
7	1,572
8	761
9	363
10	155
11	86
12 or more	43

Although Pontis will automatically update its own deterioration predictions using historically obtained data, the historical data must be developed over the course of a few inspection cycles and is not currently available. To compensate for the limited historical data, Pontis provides an elicitation procedure that can be used to develop deterioration data. The Pontis elicitation procedure asks questions in a deterministic manner (since most engineers find these questions easier to answer) then converts the answer to a transition probability. For example, the engineer can specify that the median amount of time from the onset of freckled rust on a painted steel girder, until the paint system becomes totally ineffective, is 25-30 years, and the software can calculate from this that five percent of the inventory experiencing freckled rust will undergo this type of deterioration in any two-year period. The elicitation procedure also can be used to compare different experts' results and combine their results if needed.

Besides condition and deterioration data, Pontis requires MR&R cost data before it can perform an optimization. These cost data must be provided for each feasible action in units consistent with the element's unit of measure. For example, if the unit of measurement for a steel girder is linear-feet (LF) then the cost of a feasible action, say to paint, must be furnished in $ per LF. Unfortunately, few agencies have collected historical cost data in a way that can feed directly into Pontis. Because of this, efforts are currently underway to determine if a more automated approach to cost tracking and updating (much like the deterioration updating procedures) can be developed.

Because the condition, deterioration and cost data that drives the Pontis MR&R optimization are more detailed and objective, the optimization model can operate on sound economic principles rather than significant amounts of engineering judgment. This gives Pontis the unique ability to evaluate options based on network objectives. Engineering judgment is applied where it belongs after the economic analysis.

The data required for the Improvement model are based on actual geometric dimensions, load capacity values, and traffic conditions of each bridge. Pontis obtains this information directly from NBI data and uses it to evaluate user-specified level of service goals (the default level of service values in Pontis are those presented in the FHWA proposed rule-making on level of service apportionment). For bridges not meeting the desired level of service because they are either too narrow, too low, or not strong enough, agency specific costs must be provided before Pontis can complete the improvement optimization and determine benefits. These agency specific costs include the "hard" costs of doing the improvement, such as the cost to widen or strengthen a bridge, and the "soft" costs, such as vehicle operating detour, and accident costs. Although Pontis has automatic procedures to determine level-of-service deficiencies and their associated improvement costs, these procedures should be reviewed by an agency to insure they conform to that agency's needs. Once satisfied that the data available conform to its needs, an agency can begin to take advantage of the innovative and sophisticated analysis tools available in Pontis. Also included in the improvement model is a replacement criterion, which recommends replacement if this proves to be more cost-effective than the initially-recommended MR&R and improvement actions.

DATA ANALYSIS PROCEDURES

One critical function of a BMS is to translate bridge needs, as developed by engineering and planning processes, to economic quantities understandable by budgeting personnel, administrators, and elected officials. Because of limitations on funding availability, the network-wide bridge program is not the sum of project needs, but is instead the result of a long-term analysis that maximizes the long-term economic benefit of the bridge program (as seen by road users and society) achievable with the available budget. Since planning inputs, future budgets, and bridge deterioration are not known with certainty, network-level analysis is much less deterministic than project-level design. That is why diagnostic or rule-based models have not been widely used. What is needed instead, and what Pontis provides, is a set of economic evaluation and probabilistic optimization tools, usable in an exploratory, scenario-testing manner.

Figure 1 shows how Pontis organizes these tools as independent modules operating from a central database. A collection of modules, of which the most important are deterioration and cost models, feeds basic engineering and economic data and policy guidance into the database. Two main optimization modules and a program integration module process these inputs, along with additional policy and budget data, to yield action recommendations, economic costs and benefits, and a budget-constrained schedule of projects. Because of the need for program integration, all of the economic analysis must be performed in a consistent manner. In the long term, all modules have an infinite time horizon, reflecting the fact that most structures in the inventory must be kept in service for an indefinite period. In the short term, all models operate in two-year increments with costs incurred at the beginning and benefits received at the end, then discounted to the beginning. The two-year convention was chosen because this period is short enough to resolve individual projects in the bridge program, but long enough that network-wide deterioration effects can be observed.

The optimization model for maintenance, repair, and rehabilitation (MR&R) develops policy recommendations, project needs, and economic indicators for all agency responses to deterioration, ranging from spot painting and patching, up to replacement of whole elements of a structure. In the long-term portion of the model, a linear program finds the lowest-cost MR&R policy (set of chosen actions for every possible condition of every possible bridge element) which is indefinitely sustainable, yielding condition targets for the inventory. The short-term

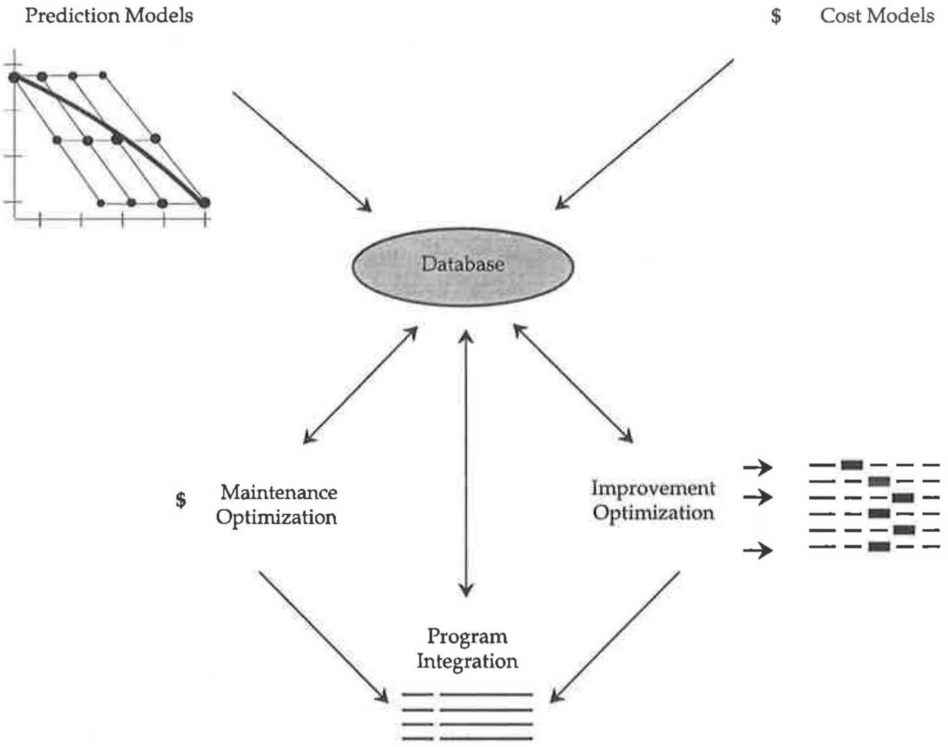

FIGURE 1 Overall structure.

portion chooses actions that can be done now and are consistent with eventually reaching the long-term condition targets. It identifies a program of needed actions for each bridge, and calculates the long-term cost of delaying the recommended actions. This is the measure of benefits used in priority-setting.

The deterioration models in Pontis are Markovian, which means that they divide time into discrete, equal periods; forecast next period's condition based only on this period's condition, without regard to earlier conditions; and perform this prediction by use of transition probabilities among the condition states. Figure 2 shows graphically the paths of deterioration that a family of bridge elements may take over time. For any individual bridge, the model allows for multiple outcomes. Over an entire inventory of bridges, the model predicts the fraction of bridges that will follow each possible path.

Transition probabilities are generated in two ways. When an agency is starting to use the system, and has no historical condition data, the prediction models must be based on expert judgement. Pontis has an expert judgement elicitation program, a computerized questionnaire, to help engineers and inspectors to enter the initial models. After Pontis has been in use for two or more succeeding inspections, an automatic updating module will extracts transition probabilities directly from the historical data and use these to improve its predictive capability. Over the years, as more inspections are conducted, the deterioration models continually improve. The system is therefore self-teaching.

The functional improvement model in Pontis is based on three primary ingredients:

- Level-of-service standards, which determine when a bridge is functionally deficient;
- Design standards, used in estimating the cost of improvements; and
- User cost models, which quantify the impact of deficiencies on road users, and therefore provide the benefit of improvements.

Level-of-service standards are a statement of policy for many state DOTs. They were proposed, though not adopted, as a basis for federal funding apportionment. In the standard level-of-service model provided in Pontis (which was based on the federal proposed rule making) each bridge is evaluated by comparing its operating rating, clear deck width, and vertical clearances against a set of standards, which vary depending on such factors as functional class, traffic volume, and traffic

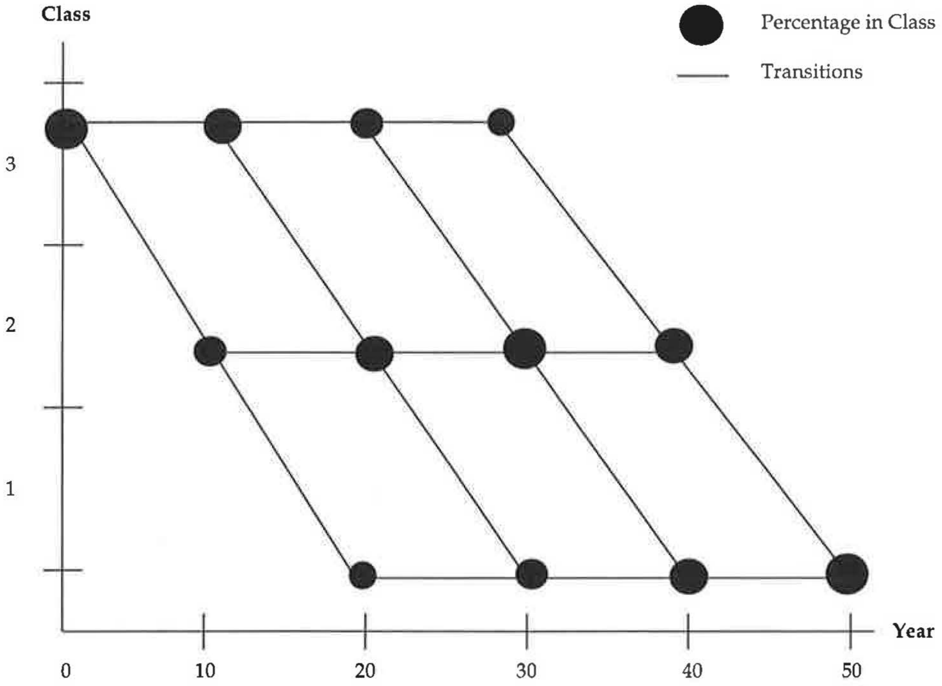

FIGURE 2 Prediction models.

configuration. These provide a screening mechanism, to reduce the number of bridges to be considered. In practice, few agencies have budgets large enough to meet all the needs identified by the level-of-service standards.

Design standards determine what actions will be taken to relieve functional deficiencies, including the estimation of cost. The design standards built into Pontis are based on the AASHTO Green Book, but can readily be modified to fit any state's policy or to analyze design policy alternatives. User cost models in Pontis, which are based on North Carolina research, measure the cost per hour and per mile of truck detours caused by bridge deficiencies, and the cost of higher accident rates associated with deficient geometrics. Replacement is evaluated for every bridge whose total MR&R and improvement needs or benefit-cost ratio approach those of replacement. The cost of replacement is calculated from a deck-area swell factor, and the benefit is calculated for improvements under the assumption that all functional deficiencies are removed. All these assumptions can be overridden on a systemwide or site-specific basis.

What results from the two main optimization models is a prioritized list of bridge needs, without regard to budget. Pontis program integration capabilities allow the preparation of a project schedule that maximizes the benefits achieved from the needs list at any given budget level. For any projects that cannot be implemented right away, due to budget constraints, Pontis simulates bridge deterioration and traffic growth over a two-year delay period, then generates and prioritizes a new needs list. This is repeated for each subsequent period in the program.

Both the MR&R and improvement models are structured in a way that first decides the best action for each bridge (based on network-level considerations), and then the best timing of actions. For each bridge, the primary decision issue of the project programming model is whether to take the optimal action now, or to wait until its priority has increased and higher priority needs have been met. Other than very routine maintenance (such as deck washing) and emergency repairs to critically deficient structures, the model framework does not normally allow "stopgap" or halfway measures. However, users may introduce overrides to schedule remedial work on bridges that might not otherwise be programmed. This provision allows fast and flexible prioritization by benefit-cost ratio.

DECISION SUPPORT

Management of an inventory of bridges is a cyclical process of planning, implementating, and monitoring, as depicted in Figure 3. Within the planning phase, there is a network-level component that determines total policy guidelines for the selection and scheduling of bridge actions, identifies structural and functional needs,

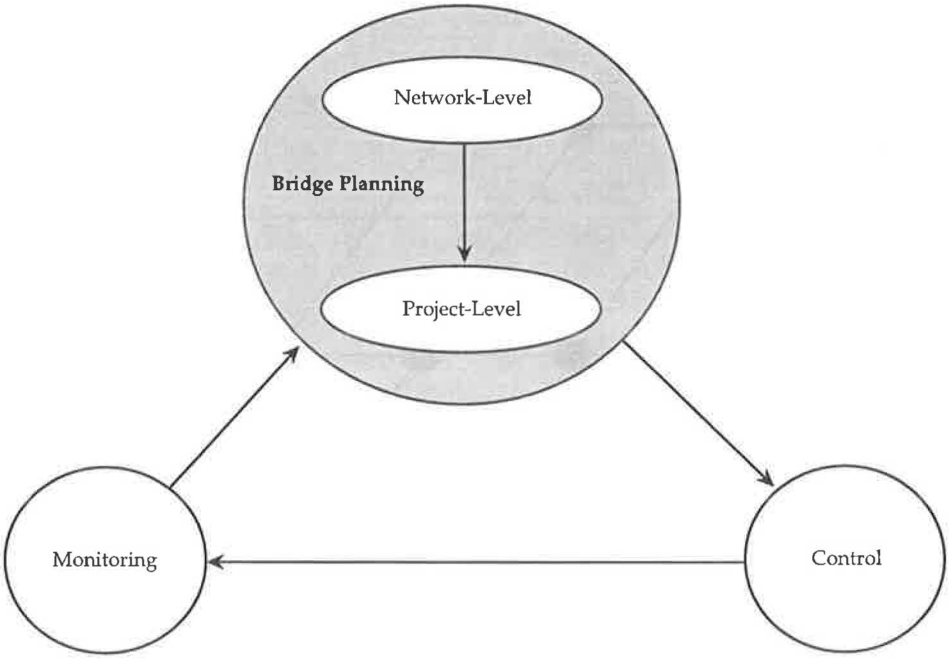

FIGURE 3 Bridge management cycle.

allocates limited funding, sets priorities, and establishes work schedules over multiple years. Projects programmed at the network level go to project-level design, and then to implementation. Project-level planning tools for structural analysis and computer-aided design are in use by many agencies, as are maintenance and contract management systems for project implementation. Most agencies have regular bridge inspection (monitoring) programs, which record the outcome of past bridge actions and feed condition data back to the network-level planning phase, where future needs are identified. Pontis is a network-level planning tool, a decision support system that helps bridge managers to make use of the database of bridge inspections and other data to make more informed policy and programming decisions.

BMSs occupy a unique position on the interface between the disciplines of bridge engineering, highway maintenance, budgeting, and policy. They are key communication tools, allowing the engineering considerations inherent in bridge program decision making, to be expressed in economic terms for the benefit of managers and elected officials who are not engineers. Many Pontis models are designed specifically to minimize the communication gaps among these disciplines, and many output reports feature both engineering results (such as bridge condition) and economic results (such as savings in future MR&R and user costs).

The top-down analytical structure of Pontis, which optimizes network-level policy first, before addressing project-level actions, makes the network-level tradeoff of engineering and economic concerns very efficient. Speed is essential to a BMS, not just for convenience, but also for credibility. Like most complex tools, users gain confidence in a BMS by experimentation, testing the envelope of the system's capabilities to see where it succeeds and where it fails. If the system is sufficiently fast, this testing activity, which involves using the system under a variety of plausible data inputs, can be a valuable experience in learning about quantitative bridge management. The system must be able to provide quick feedback of reasonable results to win support. Only by finding the limits of the system can a user be sure that any particular situation does not exceed these limits.

Optimization in a BMS is never optimal; a model is only as valid as its underlying assumptions, which in a BMS are simplifications of reality. Optimization is extremely effective as a mechanism for reducing the large amount of data input to a BMS into a concise description of the key decision tradeoffs. A BMS is never, in practice, used to find the one best policy among the possible choices. Instead, managers use the BMS as a tool to evaluate various policy initiatives based on their engineering and economic performance, to help inform the political choices available. This is often called "what-if" analysis: what if the budget was five percent less than expected, or what if we succeed in containing unit costs to this year's levels? Again, speed of the system is a necessary attribute if this kind of analysis is to be feasible and timely.

Pontis is currently operable on high-end Personal Computers (80386 or above) under MSDOS®, and is written entirely in the C language, including all database, user interface, statistical, and optimization routines. Custom-development of the system and all its components has resulted in extremely fast performance, even for inventories of 50,000 bridges.

Normal usage of Pontis is via a standard pull-down menus and a built-in help system. All Pontis modules also can be executed from MS-DOS® batch files, bypassing the menu system. Although its database is a highly-compressed format proprietary to Pontis, it does have a complete set of import/export capabilities, and has extremely flexible editing and reporting modules. Consistent with the principle of exploratory, scenario-testing analysis, the system gives users complete control of the workflow of model-building, allows multiple versions of all files, and provides access to all intermediate results of all submodels.

Since Pontis is intended for use by a wide range of national, state, and local agencies, flexibility is a prime requirement. One way in which Pontis provides this flexibility is through "formula files," which are text files containing mathematical statements, if-then-else logic, and commands. Formula files control the formats of reports and data entry-screens, provide a systematic way of selecting bridges for reporting or modeling, and specify calculations whose results are stored in the database. Users are free to create and maintain as many formula files as they need. Since many of the system's important models, such as the improvement optimization, are set up as formula files, agencies can easily customize and refine these models any time.

IMPLEMENTATION STATUS

Interest in Pontis has been gaining momentum since the completion of the project in February 1992. This interest has been fueled by the 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) which requires each state to implement a BMS. Because of the interest in Pontis and the importance to determine its stability and flexibility, a beta test was performed by 13 State DOTs and the City of San Jose. The purpose of the beta test was to exercise the full range of the software and modeling procedures in Pontis, and was completed in December 1992 without discovering any major flaws or bugs. Although nearly all agencies involved in the beta test felt that they would use all, or at least portions, of Pontis as their BMS, it was apparent that Pontis could not satisfy all the needs of every agency. The beta test found that some minor enhancements to the software were needed to improve the adaptability of Pontis across agency boundaries. In addition to minor software enhancements there was a strong need to find a long term solution for the maintenance and future enhancements of Pontis and a need to identify a group of commonly recognized elements that would be consistently used by all agencies so data sharing between agencies could be realized.

It was decided that AASHTO would best provide the long term solution for maintenance and enhancements. To determine the feasibility of participating in the long term support of Pontis, AASHTO surveyed its member departments. The results of this survey showed there was interest in the continued support of Pontis. Because of this, AASHTO has recently solicited its member departments for participation in an AASHTOware™ project to complete some identified software enhancements and provide maintenance support of the Pontis software.

To handle the effort of identifying a group of Commonly Recognized (CoRe) elements a CoRe task force was created. This task force was made up of members from six of the beta states (California, Colorado, Minnesota (Chair), Oregon, Virginia and Washington) and the FHWA. A final report that identifies the CoRe elements and many issues related to them is available.

Concurrent with the national activity Pontis is experiencing, at least half of the states are busy implementing Pontis. In California this implementation began with a pilot study of the Pontis inspection requirements before the completion of the Pontis project. Satisfied that the inspection efforts were no more time-consuming than the existing inspection procedures, California decided to begin a full scale implementation of Pontis. This implementation included the decision to modify California's existing mainframe bridge database, Structures Maintenance System (SMS), to hold the Pontis element data. This allowed SMS to continue providing the Department's bridge data management needs and also allow for periodic downloading of data to a personal computer (PC) so the optimization and analytical tools of Pontis can be used.

One significant activity associated with the implementation of Pontis is the identification and collection of the bridge element data necessary for a Pontis inspection. This activity is divided into two parts: the initial quantity assessment of elements, where each bridge is divided into its elements, and the approximate quantity of each element (e.g., 280 LF of girders) is recorded; and the actual inspection and condition assessment of those elements. In California, it was decided to perform the initial assessment for the bridges (i.e., identify the type and quantities of elements on a bridge) in the office instead of the field where the assessment could be accomplished with a normal inspection. This decision was made to save the inspection staff's time when in the field and reduce their "resistance to change." The decision to do the initial assessments in the office along with the need to evaluate and enhance the new inspection process as it matured caused California to gradually engage its inspection staff to the Pontis system. This phased-in approach was originally targeted to have all the inspection areas engaged in Pontis by January 1994 which would mean all 24,000 bridges in the state would be inspected by January 1996. Currently the implementation is six months ahead of schedule.

California's experience with the implementation of Pontis shows that 2,700-person hours were required to perform the initial assessment of 17,000 bridges. Responses from the inspection staff have been supportive and constructive criticism identified decencies in the condition state language on distresses. These distresses (deck cracking, fatigue problems, etc.) are now included as part of the CoRe element concept and, as such, the Pontis inspection procedures have been improved. California's experience also suggests that the first cycle of Pontis inspections requires approximately 10 percent more effort to quantify each element into its individual condition states. It is anticipated that subsequent cycles will save time since the initial quantification will be complete and only changes in condition will be noted. Considering the significant change in procedures, the implementation activities have progressed smoothly. Criticism has been constructive and the inspection staff appreciates the quality of the more detailed information since now both severity and extent are obtained with little, if any, additional effort required.

FUTURE DIRECTIONS

The beta testing process conducted in 1992 was extremely informative. Because of heavy user involvement during the system's development, the 14 beta-testing agencies were overwhelmingly satisfied with the product. Still, a lengthy list of major and minor enhancements was identified for consideration in future years. The major issues under consideration include:

- More detailed consideration of project-level issues in project programming. This would entail more flexible use of formulas to adjust costs and benefits to account for mobilization costs, new needs generated by traffic growth, and work zone user costs.
- Automatic updating of cost models. Most of the agencies implementing Pontis have commented that cost data are very difficult to acquire. A cost tracking system and automatic updating facility would simplify model development.
- Enhanced database features. Several new database tables and features have been requested.
- New user interface model. A study of how Pontis users interact with the system suggests that a non-procedural interaction would be more effective.
- Element modeling issues. Certain bridge elements, i.e., deck, exhibit multiple interacting distresses. Other elements may experience sufficient criticality of distress that risk effects and user costs effects may need further consideration in the MR&R models. Model enhancements would accommodate these effects. In the long-term, there is high interest in including explicit fatigue and scour models in Pontis. The general modeling framework of Pontis can accommodate these issues, but more research and data collection are needed. The minor Pontis enhancements now under development include new elements for the recording of fatigue information.

BRIDGIT BRIDGE MANAGEMENT SYSTEM SOFTWARE

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ABSTRACT

BRIDGIT is a micro-computer based bridge management system (BMS) being developed under NCHRP Project 12-28(2)A to meet the operational needs of state and local DOT bridge authorities as well as requirements being proposed by the Federal Highway Administration (FHWA).

The Phase I portion of the work has resulted in a software program named BRIDGIT. The system includes several modules that permit bridge agencies to store and modify inventory, inspection and maintenance information for bridges and culverts. An unlimited number of inventory data items can be created by the agency if desired. BRIDGIT also can produce a multi-period optimization analysis of the network or any subset of it to estimate and prioritize bridge improvement needs for both the constrained and unconstrained budget cases. Both costs to the agency as well as to users are included in the evaluation of feasible maintenance, rehabilitation and replacement options. The analysis also considers level of service goals for removing functional deficiencies due to geometric and load capacity deficiencies.

BRIDGIT provides routines to enable agencies to transfer information into the system from databases stored in other external systems. In addition, the system can automatically convert condition information uploaded from other systems, such as the NBIS (National Bridge Inventory System), to the condition rating format used in BRIDGIT.

Phase I of this project began in January 1992 and was completed in July of 1993. A second phase is in progress to develop some enhancements to the system and is scheduled for completion in early 1994.

PROJECT BACKGROUND

In 1985, NCHRP Project 12-28(2), Bridge Management Systems was initiated with the objective of developing a model form of effective bridge management at the network level. The specific project objectives were as follows:

- Develop methods to assess present and future needs of existing bridges;
- Establish guidelines for determining cost-effective alternatives both with and without financial constraints;
- Develop priority treatment of needs using generalized work activities (from posting and preventive maintenance through replacement);
- Provide flexibility to accommodate a variety of policy approaches;
- Provide flexibility to accommodate future expansion to the project level; and,
- Establish methods to ascertain standards of data reliability.

The project resulted in the identification of various modular elements required in a model bridge management system as well as the development of some of the engineering concepts necessary to operate such a system. The final phase of the project involved the development of an IBM PC-based computer program. Later testing and evaluation of the software by four state transportation departments identified several enhancements to the system which needed to be addressed before it could be accepted for use by state agencies.

Several research efforts in the areas of optimization, economic analysis, application of user costs, levels of service and deterioration models have been accomplished since the publishing of *NCHRP Report 300*,"Bridge Management Systems" and the development of the model BMS software. As a result, there was a need to review this information and to evaluate the possibility of incorporating applicable results into the BMS program. In addition, the initial system was not developed with any consideration for anticipated future requirements to be imposed by the Federal Highway Administration as part of its aim towards implementing Bridge Management Systems in all state transportation agencies by the year 1995.

The principal objectives of the current NCHRP Project 12-28(2)A, which began in January 1992, was to develop, validate and document a fully operational micro-computer based bridge management system software package that could be readily used by transportation agencies. The system is based on the conceptual design presented in *NCHRP Report 300* as well as the recommendations identified in the "Guidelines for Bridge Management Systems" which resulted from NCHRP Project 20-7, Task 46.

HARDWARE REQUIREMENTS

BRIDGIT is designed to operate as a single user system although a multi-user version is being developed as part of the Phase II portion of the project. It is assumed that a Local Area Network (LAN) will be used for the operating environment of the multi-user system.

The following is the recommended hardware configurations for operating BRIDGIT. The minimum configuration shown is designed to be a least cost system for smaller bridge agencies. The optimal configuration will provide better system performance as well as the capability to handle large bridge populations.

- Minimum Configuration
  - 80386 (Type DX) or 80386 (Type SX) based IBM PC or compatible
  - 3 MB RAM
  - 80 MB Hard Drive
  - 3½ inch Floppy Disk Drive, 1.44 MB
  - EGA or Hercules monochrome graphics card
  - EGA or Monochrome monitor
  - Keyboard and mouse
  - Dot matrix printer (for hard copy output)
  - DOS 5.0 or better
- Optimal Configuration
  - 80486 (Type SX) or 80486 (Type DX) based IBM PC or compatible
  - 8 MB RAM Memory to 32 MB RAM Memory
  - 80487 math co-processor (for 80486 Type SX CPU only)
  - Minimum 200 MB Hard Drive
  - 3½ inch Floppy Disk Drive, 1.44 MB
  - VGA or SVGA color graphics card
  - VGA or SVGA color monitor
  - Keyboard and mouse
  - Laser printer (for hard copy output)
  - DOS 5.0 or better

Hard Disk Capacity

The performance of a hard disk drive is determined by its average seek time and data transfer rate. Seek time, measured in milliseconds (MS), is the average time that a drive takes to manoeuvre the disk reading head to the start of the data block to be read. This seek time should be as brief as possible, preferably not exceeding 16 MS. The data transfer rate, measured in megabytes (MB) per second, should be higher for systems with large bridge populations; in the range of 1.2 MB/sec on average.

The minimum recommended hard disk configuration is a storage capacity of 80 MB for a bridge inventory not exceeding 2000 bridges. A maximum configuration would require a 300 MB disk for a bridge inventory not exceeding 10,000.

Random Access Memory

BRIDGIT is designed to utilize any available "extended" memory, resulting in increased data processing speed. Eight to 32 megabytes of Random Access Memory (RAM) should be incorporated into the BRIDGIT computer hardware. Although a math co-processor improves the speed of most optimization analysis routines, in most cases additional RAM memory has a greater impact on improving overall program performance and would therefore be a better investment choice.

SOFTWARE INCORPORATED IN BRIDGIT

The following software packages were used in the development of the BRIDGIT program and have been incorporated in the compiled source code. Therefore, purchase of these packages is not necessary to operate BRIDGIT unless it is desirable to modify the source code in the future:

Database Management Software (DBMS) - FoxPro

FoxPro 2.5 (Copyright © Microsoft Corporation) is the primary software language used to develop BRIDGIT. It is a fully relational fourth generation database language. Upcoming versions of FoxPro will include capabilities to operate in a variety of other operating systems such as Windows, Unix and Apple Macintosh.

Text Report Generation Software - Foxfire

To permit users to create and generate reports in a user friendly manner, Foxfire 1.02 (Copyright © Micromega Systems Inc.) was incorporated into BRIDGIT. This package enables users to define simple as well as complex filtering expressions to produce customized reports.

Graphics Development Software - dGE Graphics

To provide visual representation of database information, BRIDGIT provides several on-screen as well as hard copy graphs. To accomplish this, a graphics applications package called dGE Graphics 5.0 (Copyright © Bits per Second & Pinnacle Publishing) was used. This package produces user-friendly and fast generating color graphics capable of outputting to a variety of dot matrix, laserjet and ink jet printers.

DESCRIPTION OF BRIDGIT SYSTEM FEATURES

This section provides a brief overview of BRIDGIT and details some of the key features included in the software. The main menu of BRIDGIT displays a pull-down menu which provides access to the following eight modules:

- System
- Inventory
- Inspection
- MR&R (Maintenance, Rehabilitation & Replacement)
- Analysis
- Models
- Other
- Reports

Navigation through the system is accomplished either through keyboard or mouse controlled functions.

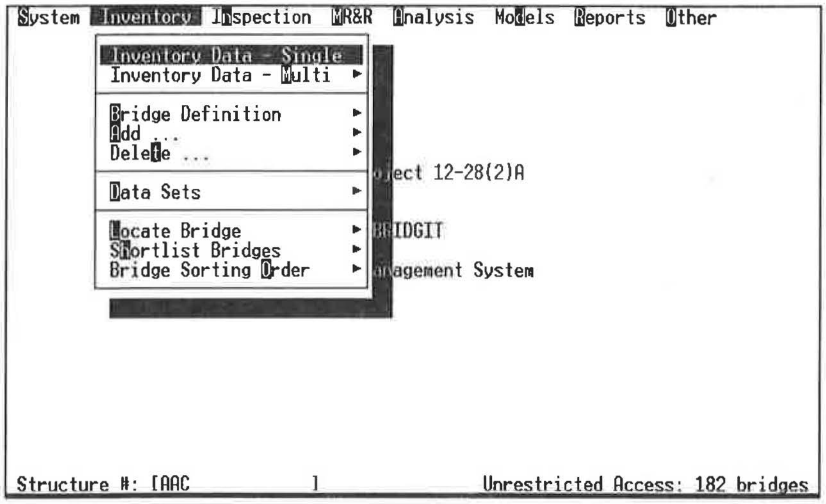
Module 1: System

The System module contains routines to permit users to configure the system interface (screen colors, sizes, video modes) to suit personal preferences. It is also possible to use on-screen tools such as a calculator or calendar/diary.

Module 2: Inventory

The main menu of the Inventory module is shown in Figure 1. BRIDGIT provides a very flexible inventory database which allows agencies to create an unlimited number of data items to be recorded for each bridge or crossing in the network, as well as for individual spans, piers, abutments, joints and bearings of a bridge. For example, it may be desirable to keep track of the height, width and thickness of each pier of a bridge. This can be accomplished by creating three data items in the PIERS database. To track this information for each bridge pier, users must identify all the pier locations associated with a particular bridge (i.e., Pier 1, Pier 2, East Pier, West Pier, Temporary Pier in Span 1). BRIDGIT is supplied with a set of data items common to most agencies, including all FHWA mandated National Bridge Inventory (NBI) items.

The Bridge Definition Routine is used to define the physical make-up of each bridge or crossing in the network. Bridges may be divided into any number of *segments* permitting condition information to be reported for selective parts of a bridge. The various elements and protection systems which are comprised in each segment must also be defined. Bridge elements are categorized by deck, superstructure, pier, abutment, railing, joint and bearing groups. Protection systems are categorized by paints and overlays.



Structure #: [AAC] Unrestricted Access: 182 bridges

FIGURE 1 INVENTORY module main menu.

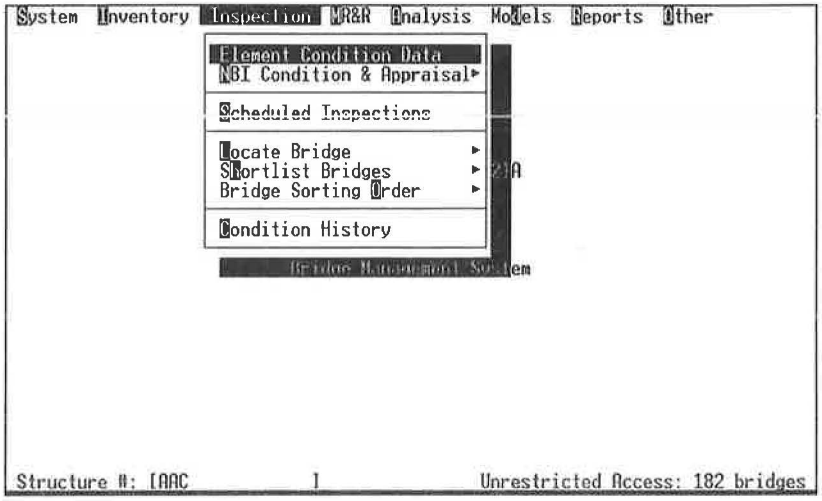


FIGURE 2 INSPECTION module main menu.

The Inventory Module also includes a routine for creating and selecting subsets (or shortlists) of the bridge network. This is useful for viewing or editing only selective inventory and inspection data as well as for performing an optimization analysis.

Module 3: Inspection

The main menu of the Inspection module is shown in Figure 2. This module permits agencies to view or edit inspection information for each bridge element or protection system as well as to view summarized historical data for the overall bridge population. Users are also able to store information concerning future routine and special inspections for a bridge.

BRIDGIT incorporates the same type of condition rating system used in the FHWA sponsored Pontis software (*1, 2*) to identify the nature and extent of deterioration of all bridge elements and protection systems in the network. Condition information to be input includes the quantities of element reported in each of the condition states defined for that element. Condition states for an element or protection system are described by types of physical as well as functional performance defects. Users may enter condition state quantity data by percentage of the total element quantity or by units of quantity (i.e., linear feet, square feet).

BRIDGIT also permits users to break down the reported condition state quantities into *portions*. For example, the deck element and protection system in the "East Approach" segment can be reported for groups of spans (i.e., Span 1, Spans 2 to 6). In this way, condition deficiencies in specific portions of a bridge segment can be identified.

Module 4: MR&R (Maintenance, Rehabilitation & Replacement)

The MR&R module provides the capability for agencies to plan, schedule and monitor multi-year work programs. Agencies will also be able to track historic work actions and related costs for individual bridges in the network. It is not intended that this module be used as a maintenance management system to report labor and material costs, however, it is possible to transfer information available in such systems into BRIDGIT.

Routines have been provided to:

- schedule and track MR&R Activities carried out by in-house as well as contracted forces;
- record a historical log of MR&R activities completed for each bridge in the network;
- provide a Project Cost Estimate routine to allow users to create detailed cost estimates for MR&R or improvement projects; and,
- maintain a standard list of MR&R Activities to be tracked.

Module 5: Analysis

The main menu of the Analysis module is shown in Figure 3. This is the most sophisticated module in BRIDGIT and draws on information stored within the Inventory module, Inspection module and Models module to produce optimized work plans for all or part of the bridge population, over a defined analysis horizon. Users may define the following parameters to be used in the optimization analysis:

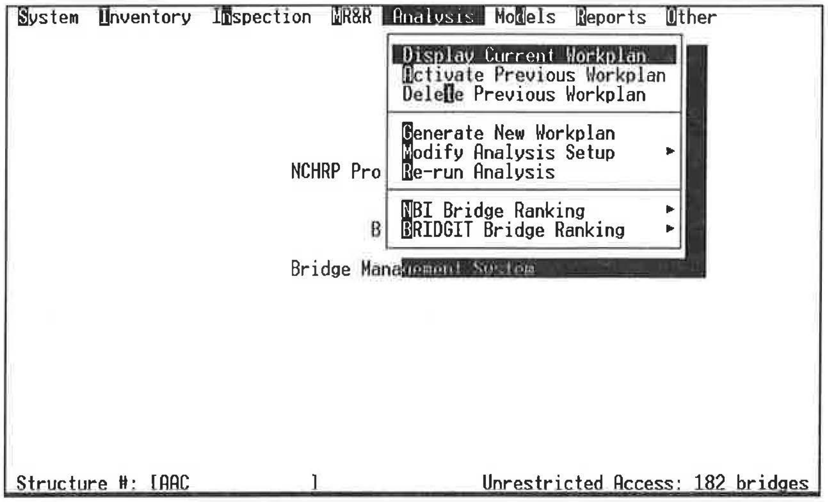


FIGURE 3 ANALYSIS module main menu.

- Level of Service Goals. In addition to evaluating bridge improvement actions due to condition related deficiencies, the optimization analysis also considers improvement actions to remove functional performance deficiencies. To accomplish the latter, agencies must define acceptable and desirable level of service goals for bridge deck width, vertical clearance and load capacity. In addition, the programming horizon (i.e., Immediately, 10 year, 20 year or "Only if Economical") in which these goals are to be satisfied must be input. BRIDGIT will select appropriate rehabilitation actions to remove all functional deficiencies within the defined time horizon providing sufficient funds have been budgeted.
- Available Annual Budgets. Users are required to identify the budgets available for each year of the analysis horizon of 20 years through an on-screen table. It is possible to define either the Total Annual Budget or multiple annual budgets portioned into Maintenance, Rehabilitation and Replacement amounts.

The optimization model performs an analysis in two steps. First, different life cycle activity profiles are developed for each bridge in the network, or selected shortlist, to estimate the present and future costs of various improvement options. Second, an optimization analysis is performed to prioritize needs and to select the most cost effective improvement options satisfying the defined constrained or unconstrained budget cases as well as the level of service goals.

Module 6: Models

The main menu of the Models module is shown in Figure 4. This module permits users to view or modify the various models and tables to be used in the optimization analysis. This enables a bridge agency to customize BRIDGIT to suit the uniqueness of its own bridge network and to identify its Maintenance, Rehabilitation and Replacement (MR&R) and Functional Improvement policies.

The following routines are included in the Models module:

Element & Protection System Models Routine

BRIDGIT allows an agency to create an unlimited number of bridge elements and protection systems. Elements are used to define the physical make-up of each bridge in the network and are categorized into seven groups:

- Decks
- Joints
- Railings
- Superstructure
- Bearings
- Piers
- Abutments

In addition, various types of paint and overlay protection systems may also be defined. The reason for distinguishing protection systems from elements is that the maintenance and replacement of protection systems are prioritized differently from elements. Protection systems do not influence the structural performance of a bridge.

BRIDGIT has been initially loaded with a set of 109 elements, 9 paint protection systems and 5 overlay

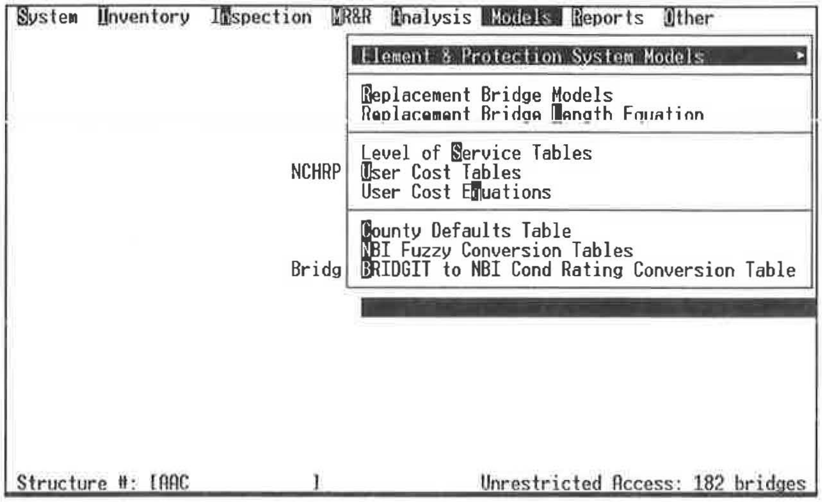


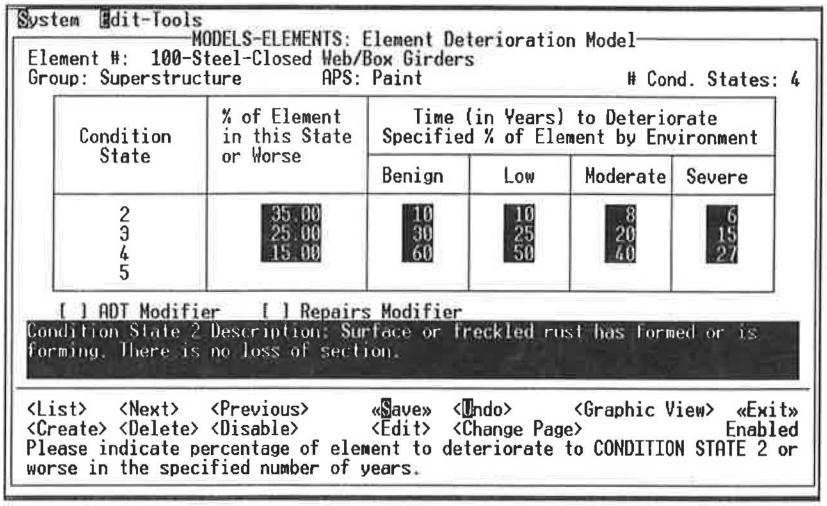
FIGURE 4 MODELS module main menu.

protection systems. Using these combinations, all of the 158 elements used in the FHWA sponsored Pontis software may be represented. While it will not be possible to delete any of these core system models, agencies can also create an unlimited number of additional models if desired.

The following information is required to define an element or protection system model:

- Identification & Units: To create an element or protection system model, users must provide a model name, identification number, the number of possible condition states and the units of quantity (i.e., linear feet of girder, square feet of deck, etc.) to be reported during inspection. In addition, a description of the element must be provided as well as a description of each condition state.
- Condition State Actions, Costs, Thresholds & A/M/U Factors: For each condition state, an improvement action and associated unit cost may be defined. (NOTE: BRIDGIT automatically considers the replacement and "Do-Nothing" alternatives for an element or protection system, therefore it is not necessary to define these actions). It is assumed that an improvement action will restore a condition state quantity to a State 1 level. BRIDGIT will use this information to calculate the costs associated with maintenance or rehabilitation of the element based on the quantities of element reported in each condition state during inspection. In addition, a Threshold Value must be defined to represent the maximum permissible quantity (in percentage) of an element which may be present in its worst condition state before a rehabilitation action should be triggered. This value will be used by BRIDGIT to determine the timing of certain condition improvement actions for an element or protection system.

  The A/M/U Factor is an indicator which identifies whether a condition state is considered to be Acceptable, Marginally acceptable or Unacceptable as defined by the agency. For example, Condition State 1 usually represents a condition which would not require any remedial actions and is always considered to be acceptable. Condition State 2 may represent only a small amount of deterioration and would involve only preventive maintenance actions. It would also be considered acceptable. Condition State 3 may represent significant deterioration but with no loss of structural capacity or performance. It would be considered Marginally acceptable. In other words improvement actions will be performed only if sufficient funds are available. Condition state 4 may represent significant deterioration with loss of structural capacity or performance. This state would no doubt be considered unacceptable and would require rehabilitation action if the reported quantity of element exceeds the Threshold Value defined for the element.
- Maintenance Actions & Costs: Agencies may define preventive maintenance actions and costs associated with each condition state of an element or protection system. This information is used to calculate the annual routine maintenance costs for each bridge in the network.
- Element Deterioration Models: For each element and protection system, a deterioration model must be defined. It is necessary to specify the percentage quantity of element that will be present in each lower condition state (or worse) after a specified number of



MODELS-ELEMENTS: Element Deterioration Model

Element #: 100-Steel-Closed Web/Box Girders

Group: Superstructure APS: Paint # Cond. States: 4

Condition State	% of Element in this State or Worse	Time (in Years) to Deteriorate Specified % of Element by Environment			
		Benign	Low	Moderate	Severe
2	35.00	10	10	8	6
3	25.00	30	25	20	15
4	15.00	60	50	40	27
5					

[ ] ADT Modifier [ ] Repairs Modifier

Condition State 2 Description: Surface or freckled rust has formed or is forming. There is no loss of section.

Please indicate percentage of element to deteriorate to CONDITION STATE 2 or worse in the specified number of years.

FIGURE 5 Deterioration model: steel open girders/stringers.

years. Figure 5 shows a sample deterioration model for a Steel Open Girders/Stringers element. For a moderate environment, 25% of the total quantity of element in an average bridge is expected to be in Condition State 3 or worse after 20 years. Stated another way, it will take 20 years for 25% of the element to deteriorate from Condition State 1 to Condition State 3 or worse. This type of information will be required for each condition state as well as for the four possible environment locations (Benign, Low, Moderate, Severe) that the element may be affected by.

For deck elements and overlay protection systems, it is also necessary to specify a factor to represent the increase in the rate of deterioration of an element due to the effects of average daily traffic and due to previous repairs. In the latter case, the development of life cycle costs for a bridge, BRIDGIT uses this factor to accelerate the deterioration of any deck elements or overlays that are reported to have been previously repaired.

The information defined for the model is used to calculate the quantity of element which will transition from a particular condition state to the next lower one, in any year. This is accomplished by employing the Markov Chain Process to calculate the transitional rates for each condition state of an element. The following assumptions have been made to adapt the Markovian model for application to BRIDGIT's bridge element deterioration models.

- Deterioration between states is a single step function. Therefore a quantity of element can only move to the next lower condition state in any year (i.e. state 1 to 2, 2 to 3, etc.).

- The transitional rate is not time dependent. Thus, the possibility of moving to a lower condition state is not a function of how long it has been in its current state.

The purpose of calculating the transitional rates is to project the quantities of a bridge element which will move to a lower condition state in a defined time horizon. This information is essential for estimating the deterioration of an element or protection system over time and the cost effectiveness of different MR&R improvement actions. Because little information is currently available to assist agencies in initially defining deterioration model parameters, BRIDGIT will be providing a routine for automatically updating the models from an analysis of historical inspection data. This feature is being developed as part of the Phase II portion of this project.

Replacement Bridge Models Routine

This routine permits the bridge agency to define standard Replacement Bridge models for different route classifications and for different ranges of span lengths. These models are used to develop the Replacement Life Cycle Activity Profiles (LCAPs) for each bridge in the network during the optimization analysis.

Level of Service Tables Routine

This routine permits agencies to view or modify the acceptable and desirable Level of Service goals for each of the parameters listed below. This information is recorded in a tabular format, classified by type of route.

- Load Capacity
- Vertical Clearance
- Bridge Clear Deck Width
- Number of Lanes

User Cost Tables Routine

This routine accesses and allows modification of the following information associated with the calculation of user costs for each MR&R alternative to be considered during the optimization analysis:

- Rate of increase of Average Daily Traffic (ADT) for different route classifications;
- Percent of vehicles detoured for different levels of bridge posting;
- Percent of dual axle trucks and truck-tractor semi trailers detoured for different ranges of vertical clearance;
- Estimated ADT for different road classifications;
- Estimated percent truck-traffic for different ADT's;
- Rate of load capacity reduction for different superstructure types in tons per year (assuming only routine maintenance is carried out);
- Unit accident costs;and,
- Vehicle operating cost tables (in $/mile) for vehicles weighing three tons or less, and vehicles weighing the maximum permissible vehicle load.

Also, the User Costs routine permits users to view the algorithms which are used by BRIDGIT to calculate accident costs and detour costs. The bridge agency can directly modify the constant values used in these formulas through tables. Modification of the formulas themselves may be accomplished by modifying the FoxPro source code.

Fuzzy Conversion Tables Routine

The Models Module also includes a routine containing Fuzzy Conversion Tables to be used to perform the following condition data conversions:

- Conversion of NBI condition ratings to BRIDGIT element condition states and estimated quantities;
- Conversion of any Agency defined condition ratings to BRIDGIT element condition states and estimated quantities; and,
- Conversion of BRIDGIT element condition states and reported quantities to NBI ratings for decks, superstructures, substructures and culverts.

Module 7: OTHER

This module is used to transfer information into and out of BRIDGIT from other systems as well as to provide tools for overall system administration. The following routines are included:

Import Data Routine

The Import Data routine is used to transfer information to system databases from the following external sources:

- NBIS ASCII File: This routine uploads data from an NBI ASCII file stored on a floppy disk, tape or a hard drive directory. It will not be possible to overwrite any existing information which has already been input into BRIDGIT. Therefore, this feature is intended to be used only to initially load data into the BMS.
- Other ASCII Files: This routine uploads data from a properly prepared ASCII file. It will be necessary for the agency to prepare the ASCII files with upload data in a prescribed ASCII file format. It may be desirable to upload to the BMS databases for the following reasons:

  - data is to be transferred from another existing bridge management system or from other information systems;
  - inspection results have been entered into an external data collection device or into a remote computer station and must be uploaded into BRIDGIT.

Export Data Routine

The Export Data routine is used to transfer information from BRIDGIT's databases to the following external sources:

- Create System Backup: This routine produces a backup of current BMS databases onto tape or hard disk directory, for data security or for future reference. Data files will be backed up in compressed format to minimize disk storage requirements.
- NBI ASCII File: This routine creates an ASCII file in the 400 character NBIS format specified by the FHWA, for any subset of the bridge network.
- Other ASCII Files: This routine creates an ASCII file for any set of BRIDGIT data items. This can be used to transfer data into other information systems used by the agency.

System Administration Routine

All the system administration functions necessary for managing BRIDGIT are found in the System Management routine. For security reasons, this routine is accessible only to the System Manager(s) who will be responsible for executing the following sub-routines:

- System Access: The access privileges of all system users is controlled by the System Access routine and are stored in an encrypted database. Through this sub-routine it is possible to assign a subset of the bridge network to individual users as well as to restrict access to specific BRIDGIT modules or routines.
- Database Maintenance: This sub-routine permits agencies to carry out maintenance of the hard disk to clean up data items marked for deletion and condense database file sizes.
- Data Validation : When data will be uploaded from external sources, important data irregularities may be present. The Data Integrity sub-routine cross checks all system databases to reconcile data contradictions that may exist in these databases after data has been imported into the system.
- Agency Setup: This sub-routine permits agencies to define several system setup parameters. These include a list of names and numbers of counties and districts associated with the agency as well as other items such as name of the agency, the date format to be used by the system, etc.

NBI Condition Data Transfer Routine

This routine allows an agency to convert NBI Condition Rating data items for superstructure, substructure, deck and culvert elements into the BRIDGIT condition rating system (condition states and quantities). This feature will facilitate initially producing condition information in the format required by BRIDGIT.

Module 8: REPORTS

BRIDGIT is capable of producing on-screen, ASCII and hardcopy output reports in either text or graphical format. Several pre-formatted reports are available for outputting inventory, condition, MR&R, models and analysis information. In addition a routine has been provided for created reports in a format which can be easily customized by the user.

BRIDGIT OPTIMIZATION ANALYSIS

The BRIDGIT optimization strategy is largely based on the methodology developed by North Carolina State University (*3,4,5*) for application to the needs of North Carolina Department of Transportation (NCDOT). As part of this effort, North Carolina State University has developed an analysis system named Optimum Bridge Budget Forecasting and Allocation System (OPBRIDGE) to support the bridge maintenance and improvement decision making process. The primary objectives of this software are to:

- Determine optimum use of funds at the bridge level considering both user costs and agency costs in life-cycle cost analyses;
- Predict optimum future funding needs;
- Determine optimum actions and uses of constrained funds; and,
- Predict performance of the bridge system under constrained funding.

OPBRIDGE considers Agency costs and User costs to determine the optimum improvement action and timing for each bridge in a network under various level-of-service goals and funding constraints over an analysis horizon. The optimization objective is to maximize reductions in equivalent uniform annual costs to the ultimate owner, the user-taxpayer.

At the end of each year of the analysis horizon, OPBRIDGE ages bridges one year and predicts condition ratings, Average Daily Traffic. etc. This allows the system to do the analysis for the following year. OPBRIDGE can produce detailed bridge-by-bridge output showing recommended current and future actions and tabular and graphical outputs showing future performance level of the bridge system over the horizon. Actions can be forced to assure that bridges are maintained to a minimum element condition level and/or to assure inclusion of bridges which do not meet user level-of-service needs. The optimization is at the bridge level for the entire bridge network or some designated subset of bridges.

The costing models used in BRIDGIT to develop LCAPs for different bridge improvement options incorporates several of the principals used in OPBRIDGE, however several modifications and enhancements were required to accommodate differences between the two systems. For example, there are seven groups of bridge elements and two groups of protection systems which must be considered in

BRIDGIT. OPBRIDGE only considers deck, superstructure and substructure groups. In addition, the condition rating system used in BRIDGIT requires that inspectors report the quantities of element or protection system in each condition state. The rating system used in OPBRIDGE is based on the NBI 0 to 9 scale.

The optimization model developed for BRIDGIT employs the same general optimization objectives as in OPBRIDGE but is unique in that it performs a multi-year analysis rather than a succession of single year analysis. This permits BRIDGIT to consider the option of delaying improvement actions to a later year where it would be more cost-effective. Therefore, if unlimited budgets are available, it is possible to determine the optimum period in which selected improvement alternatives should be scheduled rather than perform all actions in the first year.

Development of Life Cycle Activity Profiles

As part of the optimization analysis, BRIDGIT compares the cost-effectiveness of different improvement options between bridges by determining the present value of life cycle costs and benefits for each option. Costs in any year of the life cycle are calculated from the estimated user costs, annual routine maintenance costs as well as the costs of any bridge repair or improvement actions. The following sections describes each of these cost components in greater detail.

User Costs

BRIDGIT calculates user costs in each year of the LCAP based on projected future average daily traffic volumes to produce a total present value user cost. Two types of costs are incurred by users due to functional deficiencies of a bridge; accident costs and detour costs. Bridges having narrow deck width or low vertical clearance have a higher occurrence of accidents than bridges without these deficiencies. Bridges with low vertical clearance or insufficient load capacity will force a certain volume of truck traffic to be detoured to alternate routes, resulting in increased vehicle operating costs. As the volume of traffic increases, the number of accidents or detours will also increase.

Annual Routine Maintenance Costs

BRIDGIT will estimate the Total Present Value Cost associated with routine maintenance of a bridge over its service life. To calculate Routine Maintenance Costs for a bridge in any year of an LCAP, BRIDGIT will multiply the quantities of element or protection system reported in each condition state by the unit maintenance costs defined in the element or protection system model.

Bridge Repair & Improvement Costs

For any bridge, the initial costs of repair actions are determined by multiplying the unit improvement costs defined in the element and protection system models by the actual condition state quantities. The costs for bridge widening or replacement alternatives are calculated from information provided in the Bridge Replacement Models defined by the agency. To estimate bridge raising costs, BRIDGIT applies a user defined unit for each foot of vertical deficiency.

The various alternatives to be considered for economic analysis will be selected from knowledge based decision rules which will examine overall improvement strategies over the life-cycle of a bridge. BRIDGIT considers four possible improvement options for a bridge.

- Minor Repair to all bridge elements
- Major Repair to all bridge elements
- Rehabilitation (Major Repair and removal of all Functional Deficiencies)
- Replacement

For each of the above improvement alternatives, BRIDGIT calculates a Life Cycle Activity Profile for every bridge in the network or selected shortlist. The development of the LCAP's includes the costs associated with immediate as well as future improvement actions. BRIDGIT will project the future condition of elements and protection systems to calculate future improvement costs. BRIDGIT also projects future average daily traffic levels to determine future user costs. The LCAP models select feasible MR&R and functional improvement actions and determine the appropriate timing of such actions over the life cycle of each bridge.

As part of the optimization analysis, BRIDGIT compares the present value of costs associated with each of the feasible LCAP alternatives with the present value cost of the "Do-Nothing" LCAP. To develop this base case, it is assumed that no bridge improvement actions will be performed to the bridge during the optimization analysis horizon of 20 years. Two different scenarios can result from this assumption:

- Case 1 - Bridge Becomes Deficient During the Analysis Horizon: If at the beginning of the planning analysis horizon, a bridge has at least one key bridge element in deficient condition, the bridge could become totally unusable during the analysis horizon due to insufficient load capacity (i.e. load capacity is less than 3 tons). If this occurs, routine maintenance costs become zero and user costs due to vehicle detours become significant (depending on ADT and % truck traffic), thereby making the Do-Nothing Alternative undesirable.

At the end of the 20 year analysis horizon, the bridge will require either a major rehabilitation or replacement when either a Replacement Bridge LCAP or a Rehabilitation LCAP will be applied.

- Case 2 - Bridge Does Not Become Deficient During the Analysis Horizon: If at the end of the analysis horizon some key bridge element quantities are in either marginal or acceptable condition states, a Minor or Major Repair LCAP will be initiated.

BRIDGIT Optimization Analysis Model

The BRIDGIT Optimization Analysis Model will select optimal MR&R and functional performance improvement actions for each bridge in the network over a multi-year analysis horizon. In addition, the system considers both constrained and unconstrained budget cases. For the constrained budget case, users are also able to define budgets for maintenance, rehabilitation and replacement portions in any year of the analysis horizon.

BRIDGIT performs an optimization analysis over a horizon of 20 years. To minimize computational effort, this horizon is divided into 5 analysis periods; years 1 & 2, 3 to 5, 6 to 10, 11 to 15 and 16 to 20. At a representative year for each period, all bridges in the network are aged and the condition of bridge elements determined. BRIDGIT will evaluate the available annual budgets defined for that period by the user. If insufficient funds have been provided to match the selected MR&R needs, BRIDGIT will evaluate other lower cost MR&R alternatives using an incremental benefit/cost approach. Those with the highest Cost Effectiveness Indexes (CEI) are iteratively selected until the budget constraints are satisfied. Once optimization has been completed for a specific analysis period, BRIDGIT distributes the selected actions (in order of CEI) to each year in the period to expend the annual budgets previously specified by the user.

If the budget is unlimited, BRIDGIT selects the bridge alternatives with the highest CEI's, and allocates them to the period of the analysis horizon in which they should optimally be implemented.

The Cost Effectiveness Index is the rate of internal return between two alternatives. For each bridge improvement alternative being considered, BRIDGIT compares the Present Value Cost of agency and user life cycle costs, with the Present Value Cost of the Do-Nothing Alternative.

The calculation of the CEI for bridge i and improvement alternative j can be expressed as:

$$CEI(i,j) = \frac{PVDN(i) - PV(i,p,j) + IC(i,p,j)/(1+RRRR)^t}{IC(i,p,j)/(1+RRRR)^t}$$

where:

CEI(i,p,j) = Cost Effectiveness Index of alternative j in period p for bridge i;

PVDN(i) = Present Value Cost of the Do-Nothing alternative for bridge i;

PV(i,p,j) = Present Value Cost of improvement alternative j for bridge i calculated in period p;

RRRR = Real Required Rate of Return;

IC(i,p,j) = Initial Cost of alternative j in period p for bridge i incurred at the beginning of the representative year for period p;

For each bridge in the network, BRIDGIT determines the CEI's of all feasible alternatives to be considered in each period of the optimization analysis horizon. The alternative with the highest CEI over the analysis horizon is the optimal choice for that bridge.

The approach used in BRIDGIT regards the year when an improvement alternative is being considered as an additional variable within the optimization analysis and therefore evaluates the entire analysis horizon of 20 years as if it were one period. This permits alternatives in one analysis period to compete with others in a different period.

CONCLUSION

The Phase I portion of this NCHRP project was completed in July 1993. Work is continuing to develop enhancements to the system as part of a second project phase. Some of these enhancements will included expanding the system to permit operation in a multi-user environment with full network capabilities as well as a routine for automatically updating element deterioration models based on an analysis of historical inspection data. In addition, BRIDGIT will provide routines for developing bridge work plans and detailed cost estimates, permitting agencies to schedule and monitor MR&R work carried out by in-house forces or by contract.

A key objective of this project has been to develop a BMS which meets all of the requirements proposed by the FHWA in their rulemaking for bridge management systems. It is the intention of NCHRP to have the BRIDGIT system endorsed by the FHWA as a product that fully satisfies these requirements.

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DISCLAIMER

The opinions and conclusions expressed or implied in this paper are those of the research agency. They are not necessarily those of the Transportation Research Board, the National Research Council, the Federal Highway Administration, the American Association of State Highway and Transportation Officials or of the individual states participating in the National Cooperative Highway Research Program.

UNIQUE CHARACTERISTICS OF DENMARK'S BRIDGE MANAGEMENT SYSTEM

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ABSTRACT

Bridge Management System (BMS) is an area in rapid development. Although we have been working with this subject for nearly 20 years in Denmark, we are still adding new parts to our system. Experience obtained from working with bridge management in other countries also has influenced our system development. Thus, what we present today is a step forward from what we were able to show a few years ago. Since the last presentation of the work in Thailand, we have developed new modules for optimization and also preventive maintenance, long-term budges and a price book. We are currently working on an experience module. This paper describes the various components of our system and the status of our development. It also describes how the system is used as a tool in the road administration when dealing with the multiple tasks that have to be taken care of in the daily work.

INTRODUCTION

Three important issues of BMS are: data needs and data collection techniques, data analysis procedures, and decision support. We will try to deal with all three issues. However before we jump into a description of how we are handling these matters in our system, we find it is vital to discuss the background for BMS: why, for whom, and how? Some may find it a step backwards, because now we want to discuss the systems and how they are working. However, it is important to have the purpose of the system in mind always. We have to realize that today is it possible to build in many fancy gadgets into a BMS. This may be very tempting, but without a constant eye on the goal we may end up with a toy and not a tool.

So again, why are we building and using BMS? We normally say that a BMS is a tool that helps us with the following activities:

- Maintaining traffic safety;
- Preserving the road network capacity;
- Minimizing maintenance costs;
- Optimizing allocated funds; and
- Forecasting the budget needs.

It can be answered in many more complicated ways, but it can also be described with the key words *to save money*. Therefore, we should always be able to see the benefit of what we are doing, maybe not shortly but in the long run. This leads to another issue worthy of mentioning. The bridge owners have two main tasks:

- to maintain existing bridges, and
- to construct new bridges.

The system should help us to get the best out of our dollars in both cases. The system will give us experience from the old bridges, so that we can construct the new bridges in such a way that they will last longer for less money. If this is the case, we have to realize that we cannot use the service life prediction from the old bridges on the new ones.

For whom are we making the BMS? The system is made for the bridge owner's use. This has to be taken in the widest sense. It should be a tool that can support everyone who is working with bridge management.

Then comes the "how?" How can we construct a BMS that will fulfil our demands and be so user-friendly that everyone involved in bridge management will use it? First the concept has to be developed in cooperation with the future users. Here we are thinking of practical engineers, who have experience in bridge management. We also believe it be fundamental that it is built up in modules that can be tested as prototypes. Secondly we have to realize that it is not possible to hit the target right in the bull's eye at the first try. We have to go back and modify already developed modules from the experience we get from using the system. Finally, and partly because of the second point, the system has to be dynamic and constantly under improvement and development.

What makes the Danish system unique is the way it combines the project level and the network level. Optimization, budgeting and planning are all done on network level but the basis for these is information collected at the project level. This means that the optimization directly identifies the works to be carried out at project level. The optimization also considers the consequences of insufficient funds, and if necessary selects alternative solutions to keep within the budget.

The system deals with all aspects of bridge management, from preventive maintenance and daily administration to forecasting development of the bridge stock. All activities are described in manuals. Bridge management is thus integrated into one system, which is unusual.

DATA NEEDS AND DATA COLLECTION TECHNIQUES

Data Needs

When we look at the data needs, we have to categorize the data according to their future use. The use of the data can be for one of the following purposes:

- preventive maintenance;
- daily administration;
- planning of rehabilitation works;
- forecasting of future budgetary needs ; and
- policy for research and development.

Data can be related to the bridges, or external factors. Some data are static, some are changing over time. According to our experience the collection of data must be kept to an absolute minimum. This because data have to be maintained and this is time consuming. Thus only data we know we need are collected. We may here run into the problem that some data required according to codes or regulations are not very useful for us. If so, the best we can do is to try to have these regulations changed.

The requirement for reliability is different for all data. If we get garbage into the system we also get garbage out. However, to keep the workload at a reasonable level, we should also specify the quality of the data we require, e.g., we should not measure length or width in tenths of inches. For the same reason we should ensure that the updating is done at appropriate intervals.

The static data we need will be information of a technical and administrative nature related to the design and construction of the bridges. These data are collected at the inventory.

Dynamic data required will be data on deterioration, repairs and maintenance connected with the bridges and data such as traffic, accidents, maintenance costs, repair costs, tender prices and budgets connected to external factors. The first of these are collected during inspections, the rest are from other sources.

Preventive Maintenance

Preventive maintenance we define as minor works that comprise remedy of pollution effects and aging or wear caused by climate or traffic. They are often neglected or overlooked despite the benefit given by regular planning and execution of these tasks. For this activity we need the information from the following sources:

- inventory, and
- planning of maintenance (budgets includes superficial inspections and costs).

Daily Administration

The daily administration of our bridges consists of the tasks that keep the shop running. These are, e.g., updating of databases, tendering, writing of contracts, budget control, quality control, maintaining route maps for special transports, classifying existing bridges and special transports. We use in the daily administration data from:

- inventory,
- principal inspection,
- repair costs,
- tender prices, and
- budget policy.

Planning of Rehabilitation Works

Within the given maintenance budget for our bridges a certain part is set aside for preventive maintenance and the rest is used for rehabilitation works. These works are of a size that requires them to be tendered out. The rehabilitation works are planned based on data from:

- Inventory,
- Special investigation,
- Repair costs, and
- Tender prices.

Forecasting of Future Budgetary Needs

Both for the near and far term, we have to produce reliable figures for what the budgetary needs will be if we have to keep the bridges at an acceptable standard. The data we use for our forecasting come from:

- inventory,
- principal inspection,
- special investigation, and
- repair costs.

Policy for Research and Development

To determine which research projects and development projects on materials to support we need data from:

- inventory,
- principal inspection,
- special investigation, and
- repair costs.

Data Collection Techniques

Data can be collected with techniques ranging from simple visual observation to the fully automated one where built-in instruments automatically register the data and transfer them to computers for processing. We believe that there is a place for most of these techniques in a well-developed BMS. Again, we need to use the right technique for the right purpose. We have found that visual inspections are sufficient for our normal superficial inspections and principal inspections. We have tried to build-in detectors under bridge pavements to detect when they were leaking. The sad conclusion was that the detectors failed before the pavements. However we use advanced techniques when we monitor our cable-stayed and suspension bridges. These we have instrumented so than we can follow movements of cables, joints and bearings. On our project in Mexico we are using global positioning system (GPS) instruments to determine the position of the bridges.

We have been using small dictaphones for collection of data in Denmark. During a project in Portugal we used a computer installed in our vehicle. Now we are testing out the use of a video camera where we can collect pictures and data on the sound track. We have also tried using a data logger, which looks like a good solution for specific purposes. If we find severe defects during our visual inspections we call for a special investigation. During these types of investigation all types of testing are used from non-destructive testing (NDT) to retrieving specimens for laboratory tests. Of the NDT tests potential measurement is one of the most used. We are now starting the testing of ultrasonic equipment for special concrete problems.

DATA ANALYSIS PROCEDURES

The analysis procedures to be used for the various bridge management purposes mentioned above will be discussed in the following. We have the computer part of our system divided into the modules shown.

Inventory	Principal Inspection	Long Term Budget	Experience	Price Catalogue	Optimi-zation	Budget Module	Maintenance Module

Preventive Maintenance is supported by the maintenance module that can be used for keeping accounts on the maintenance works and the maintenance products and writing out work orders. It is also possible to make analysis on the maintenance works on the bridge components.

Daily Administration is supported by the Inventory, Principal Inspection, Optimization, and Budget Modules.

Inventory data are among others used to give various overviews of the bridge stock. A new feature in our inventory module is a digital bridge map connected to the databases. It is used to locate one or more bridges with the same characteristics such as type, construction year, load bearing capacity. All bridges are plotted by coordinates but they are also defined in the system by their stationing. Thus, it is possible to find a bridge along a given route.

The principal inspection reports that are automatically printed out from the inspection module contain inventory and inspection data. Now we are supplementing the inspection module with a picture database so video photos from the inspection can be shown on the screen and printed out as part of the report.

Optimization of the repair works is done within given budget limits and the budgets for the works are monitored. The optimization carried out by the system is described in the following, as this subject is considered a key issue by many American engineers. It makes use of both a project approach and a network approach. Road user costs are considered in the optimization.

Because of a special investigation, our consultant works out two to three different repair strategies for the bridge under investigation. The strategies cover a period of 25 years and are of different types, e.g., one may call for a complete retrofit now and a little work later, another for minor works in the first years and a replacement later. The consultants also have to consider the same strategies delayed five years and the consequences of the delay. The system will by a linear interpolation find the costs of the strategies if they are delayed one to four years. We may now end with three time six (3 x 6) solutions for a bridge and the system will now calculate the net present values of these. These 18 values are arranged in order of increasing present values and included further calculation optimization of the structures to be repaired. The present value of the optimum solution N_1 is determined within each individual strategy from the formula:

$$N_1 = MIN. \left(\sum_{n=1}^{25} (I_n+T_n)\ (1+r)^{-(n-1)} - R\ (1+r)^{-(25-1)}\right)$$

where,

I_n = Investment in year n
T_n = Road-user cost in year n
R = Residual value in year 25
r = Calculated rate of interest
n = Actual year

The system will, if we have no budget restraints, select the best solution for each bridge. On network level the system will combine the chosen strategies for all the bridges we have fed into the system. The investment outlay involved in the repair solutions chosen above is determined and placed within the years in which it is to be paid. Only the investments are relevant to the budget limits, so road-user costs are disregarded in these calculations. When the investments are summed up, the optimum temporal distribution of expenses is determined year by year.

If we have budget limits for the first five years it is investigated if the sum of investments in the first five years is under the budget limits. If so, the calculations are completed, and optimum repair is possible under the given economic limits, i.e., the following requirements are fulfilled in all years:

$$\left(B_n - \sum_{i=1}^{A} I_{n,i} \right) \leq 0$$

where,

B_n = Budget limit in year n
$I_{n,i}$ = Investment in year n in optimum solution for structure i
A = Number of structures

The budget limits are exceeded when the above requirements are not fulfilled. If the budget limits are exceeded, the system will go on working on network level and by an iteration process postpone the bridges where the costs of postponements are lowest until the total budgets for the first five years are below the budget limits. In this process the system may change the strategy for a bridge when the work is postponed. The year with the greatest difference between need for capital and budget limit is determined, i.e., the year with the maximum negative figure. For all structures contributing to the expenditure in this year, the solutions with the second lowest present value are found. For each structure the relative economic additional expenditure for replacement of the optimum solution by the second best solution is calculated, i.e., the calculation includes both investments and road-user costs. The following formula is used:

$$\frac{N_{2,i} - N_{1,i}}{N_{2,i}}$$

where,

$N_{1,i}$ = Present value of optimum solution for structure i
$N_{2,i}$ = Present value of second best solution for structure i

For the structure with the lowest relative additional expenditure, the optimum solution is replaced by the solution with the second lowest present value. The purpose is to find another temporal distribution of expenses. This is done by first postponing the structures involving a minimum additional expenditure, i.e., reduction of additional expenses, and by investigating whether the economy allows the repair to be carried out in another year. An iteration is performed, and it is again investigated if the budget has been exceeded. The iteration continues until the repair costs of all structures are under budget limits.

The social consequences of not carrying out repairs at the optimum time are calculated as additional costs. The following formula is applied:

$$\sum_{i=1}^{A} (N_{n,i} - N_1)$$

where,

N_i = Present value of optimum solution for structure i

$N_{n,i}$ = Present value of chosen repair solution for structure i

i = Actual structure

A = Number of structures

The correct way to find the optimal solution is by using integer programming. However, even large computers use an unacceptable amount of time for this type of calculation. Therefore, the simplified model has been developed which gives the results in a few seconds. This simplified model consistently given results close to the optimal found by integer programming.

The budget module controls the spending from the first day when a price is calculated to the day the rehabilitation work is completed. The budget for the single bridge is constantly updated when a change in the basis of the price occurs. Thus, it is possible any time to get a printout of the budget and take action if needed.

Planning of Rehabilitation Works is done with the inventory data, the price catalogue, the data from the special inspection and the final list from the optimization.

Forecasting of Future Budgetary Needs is done in different stages. During our principal inspections the inspectors estimate rehabilitation works to be done in the next 10-year period. They have to estimate the quantities and select the repair type. The system will then calculate the costs from the built-in prices. This gives us the first rough forecast. They have had an extensive training in these works, and the procedures to follow are described in detail in manuals and a handbook for inspection. Approximately 40 standard repair methods are incorporated in the system, but it is possible to use a lump sum for nonstandard works. We get a better but shorter forecast from our optimization module. With the data from the special investigations this module gives us the needs and the consequences if our needs are not covered.

Finally our long-term budget module gives us a forecast for a long period, say 50 years. This module based on deterministic forecasts, contains all bridges divided in the standard components we use. Quantities and construction data for the bridges are funneled into the module from the inventory module. By adding estimates for service life and maintenance costs for all bridge components it is possible to get the forecast from the system. These estimates are based on statistics from the inventory part. However it is the intention to use the experience module to establish better service life predictions, from exact knowledge of the bridge components, their quality and the influence of the environment. It is possible to integrate the data from the principal inspections in the long-term budget module.

The quality of the different types of forecasts matches their purpose. The data from the special investigation used in the coming years' budgets are the most reliable. The data from the principal inspections cover the following years and are, as in the first type, based on findings in the field. They are used for short term prediction. The data from the long term module are based on statistics only and therefore the most unreliable. For the long term prediction, we only need the approximate level of the budget.

The Policy for Research and Development is founded on the data on service life for bridge components that we obtain from our experience module. In this module bridge data from construction and from later stages as they are found during special investigation are combined with data on the impact from traffic and environment. Models to estimate interaction between the internal and external factors are set up. The module is still under development, but we find the work promising.

DECISION SUPPORT

The processed data from BMS supports decisions in bridge management. Lists for activities due to be carried out help in the preventive maintenance.

- The daily administration follows procedures planned for the activities that are part of our BMS. Information on problems that need special attention show up in reports and statistics. As a result actions are taken to prevent accidents and change inexpedient ways of constructing and maintaining structures.

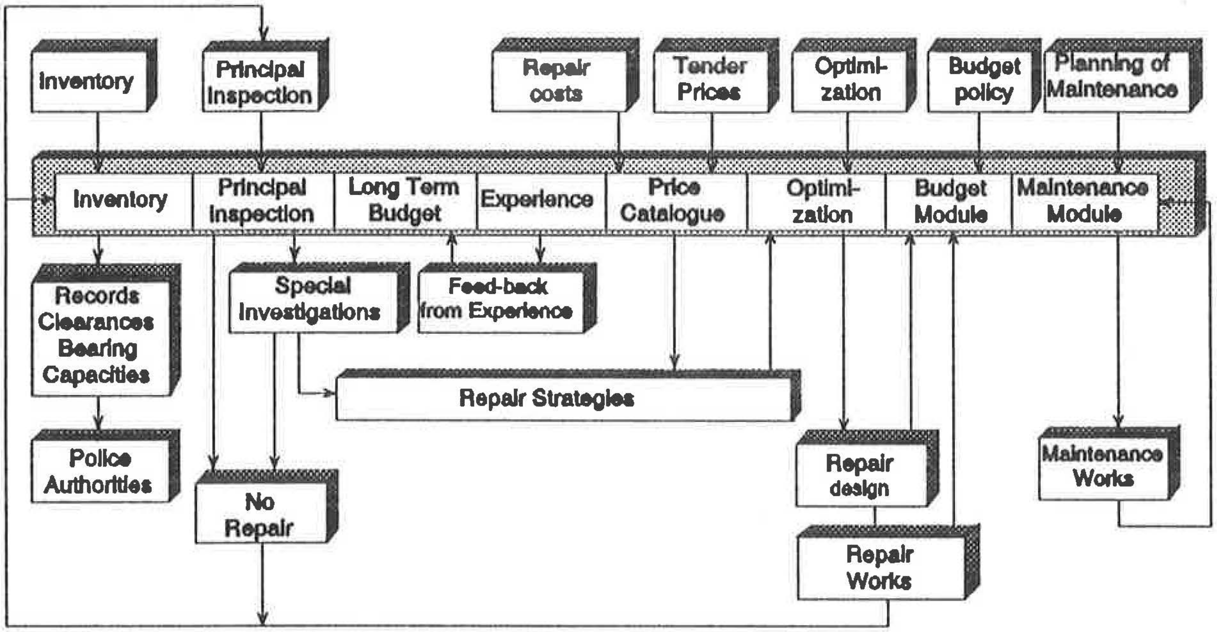

FIGURE 1 Flowchart of bridge management system.

- Rehabilitation works are based on the strategies proposed by the system. The optimized list of works to be carried out gives the head of the maintenance department a support for his planning.
- The forecasts on future budgetary needs are presented for our decision makers as a background for their budget planning and for their dialogue with the politicians.
- Finally we plan our research and development on the digested data from the experience module and the long-term budget module.

The ways data flow through the system and how activities are combined are shown on the flow chart below:

FURTHER DEVELOPMENT OF THE SYSTEM

Now we are working on a module for special transports. It is the intention that the hauler who has to make a transport from *A* to *B* should be able to get a permit and a route map written out from a computer, when contacting the local authorities with the specifications of his transport. This will be a development from our digital map. The major problem in this project, as far as we can see, is to ensure that the system is always updated when conditions on the roads are changed.

CONCLUSION

Our system has been installed on highways in Denmark, Thailand, Saudi-Arabia and Mexico, but each country uses its own tailor-made version. We have different applications due to different local conditions and different organizations. The organization and the system have to fit each other. Our experience from working abroad has been that most countries have good engineers who are willing to work with BMS. However, it has taken time to get bridge management organization established to take care of the daily works after a system has been implemented. Also preventive maintenance has been neglected, as it has taken some efforts to convince the authorities that funds for this purpose are essential.

Collecting data and maintaining them are far more costly than the cost of the development of the system. Thus only needed data should be collected and maintained. On the other hand the system should be designed so that we can easily incorporate new types of data into the system if the need arises. The system should be dynamic and not static. However, new applications should be released only so often that the users feel it is a pleasure.

In the introduction we risked saying that all efforts with BMS are made *to save money*. We believe it is true today, because we can only compare needs and requirements if we use money as a common denominator. This may not be so in the future. Research projects have been started where fuzzy logic will be used to interpret and compare the different requirements in another way. If they succeed, a demand may arise for another modification to our system, which will be another challenge. While we are waiting for the result, we will stick to our well-proven denominator.

PROJECT BRIDGE MANAGEMENT IN ONTARIO

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SUMMARY

A bridge management system is required to ensure the safety of bridges and to optimize the resources available for maintenance and rehabilitation. This paper describes the bridge management practices in Ontario at the project level and outlines the work in progress toward the development of a comprehensive bridge management system at the network level. The visual inspection condition data collected on bridges are supplemented with data from detailed condition surveys that include nondestructive and destructive sampling and testing. The results of those inspections and surveys are assessed to determine appropriate methods and options for rehabilitation. As an economic evaluation is an important step in the decision making process for work that involves major expenditures, the costs for alternative levels of improvements to a bridge are compared to determine the most economical option for the bridge based on a present value analysis and incremental benefit/cost ratio analysis. One benefit of this approach to bridge rehabilitation is significant improvements in the selection of rehabilitation options through detailed life-cycle analysis to determine optimal cost-effective options.

INTRODUCTION

A bridge management system consists of a logical sequence of events to ensure the safety of structures, to establish priorities for maintenance and rehabilitation, and to optimize the budget for these activities. This paper describes the project level bridge management practices in Ontario and the progress made to integrate these practices into a comprehensive bridge management system (BMS).

The Ministry of Transportation of Ontario owns and maintains approximately 3,200 bridges on the Provincial Highway system. About 50% of these bridges were built before 1960, and require an increasing amount of maintenance and rehabilitation. Approximately 30% of the bridges were built between 1961 and 1970. The distribution of these bridges by type of construction is shown in Figure 1. Figure 2 shows the annual bridge rehabilitation program in the province since 1985. In the mid to late 1980's, over 100 bridges were rehabilitated annually. This figure has decreased recently due the successful efforts of the past and partly due to recent budget constraints. Currently about 80 bridges are rehabilitated annually.

BRIDGE MANAGEMENT IN ONTARIO

The provincial highway network in Ontario is considered mature. Consequently, there are few bridges being added to the network, and bridge construction is normally the result of local capacity improvements or the replacement of deficient or deteriorated structures. The changing needs, combined with budget restraints, have resulted in the shift from expansion of the network in the 1960's to the preservation and improvement of the existing network in the 1970's and into the 1990's. Bridge management practices in Ontario, over the past 25 years, have resulted in a bridge population in good condition with few deficient bridges. The BMS developed for the provincial highway bridges is primarily concerned with the preservation and improvement of the existing network.

PROJECT LEVEL BRIDGE MANAGEMENT

Of all the components in a bridge, the bridge deck has exhibited the most rapid deterioration. This is particularly true in North America, where the heavy use of deicing chemicals and frequent freeze-thaw cycles, combined often with exposed concrete surfaces and insufficient concrete cover to the reinforcement, have resulted in rapid deterioration. Most authorities are having to undertake a comprehensive bridge rehabilitation program. This has been the case in Ontario, where in extreme cases, major deck rehabilitation has had to be carried out within 10 years of construction. The need to rehabilitate many bridges with limited resources led to the development of procedures to ensure that the optimum method of rehabilitation is chosen for each structure. Similar deterioration in concrete piers and abutments, beams and slabs are now taking up a larger share of the rehabilitation budget. The bridge project rehabilitation process consists of: data collection, option analysis and selection of the method of rehabilitation, design and preparation of contract documents, and construction.

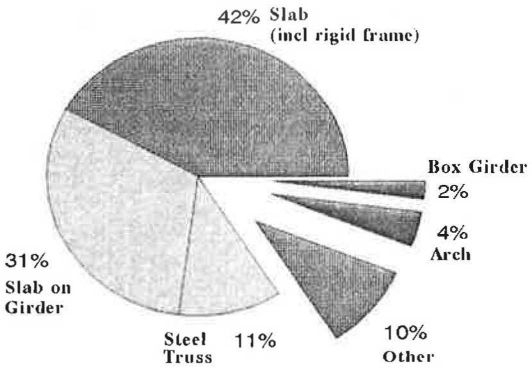

FIGURE 1 Types of bridges in Ontario.

Inventories, Data Collection and Databases

The basis of Ontario bridge information system is an extensive computerized *Ontario Structural Inventory System* (OSIS) (*1*). This inventory includes all structures in the province, and contains general design information. It is being extensively changed to meet current requirements as part of the Ministry's bridge management needs. A separate inventory, Ontario's *Bridge Clearance and Loads Information System* (BCLIS) (*2*), is maintained for clearances and load limits on the provincial highway system.

Besides the inventory data, every bridge on the provincial highway system is subject to a biennial routine detailed visual inspection. The extent and severity of any defects as well as an assessment of their effect on the performance or proper functioning of the component are recorded following the procedures given in the *Ontario Structure Inspection Manual* (OSIM) (*3*). Condition ratings are assigned and recorded on an individual span basis for each span in the structure and for all components. Components are rated on a scale of one to six with six being excellent condition. Separate condition rating systems are used to assess the material and performance conditions of individual components of a structure, and the performance condition rating of the entire structure. General guidelines for assigning appropriate material and performance condition ratings are given in Figure 3 and Table I, respectively. The rating of the performance defect is not necessarily the same as that of the material defect; therefore, the same component may have different material and performance condition ratings. The *Ontario Structure Inspection Management System* (OSIMS) (*4*), is the computerized system for managing the inspection data collected, and for obtaining reports. These reports are used to help in the prioritizing of repairs and rehabilitation. The retrieval of data and reporting from data in OSIS and OSIMS is very flexible and can be tailored to the end use. The condition of bridges along with the recommendations for additional investigations or repairs and rehabilitations also can be extracted from OSIMS.

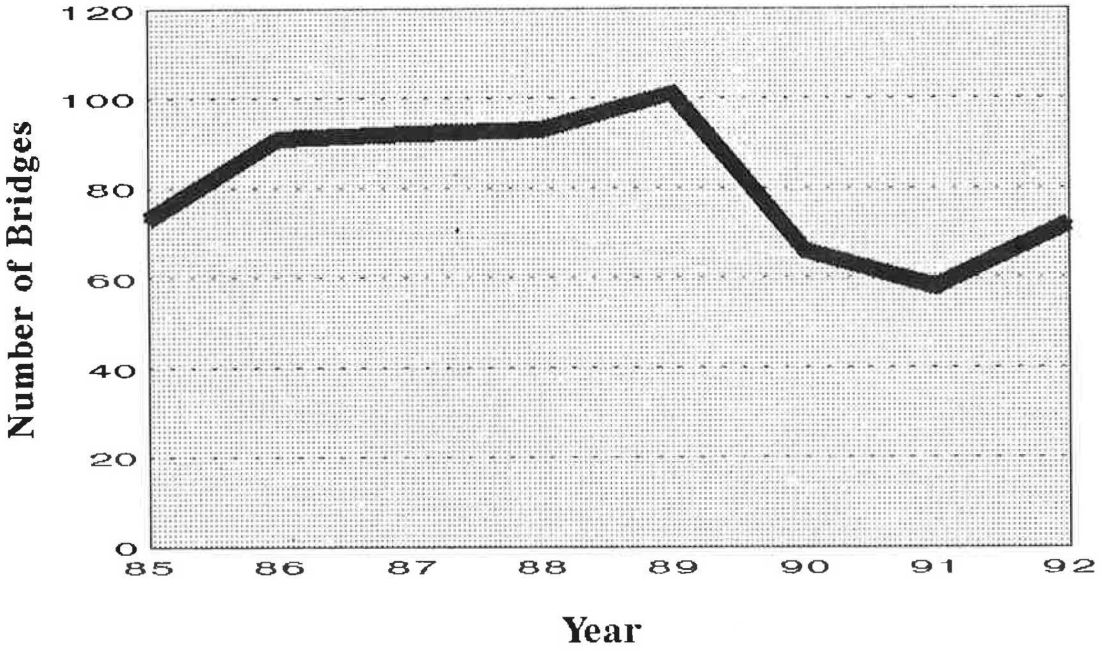

FIGURE 2 Bridge rehabilitation in Ontario.

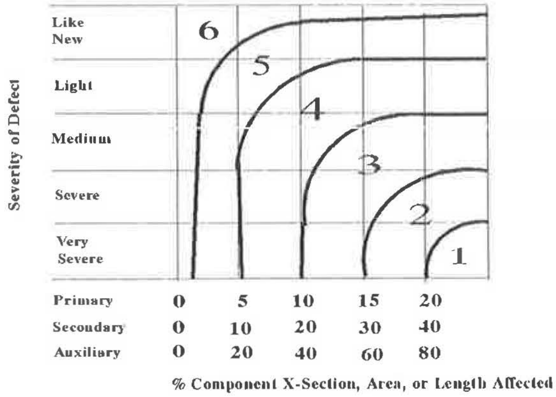

FIGURE 3 Material condition rating system.

TABLE I PERFORMANCE CONDITION RATING SYSTEM

Rating	Performance Condition of Components	Guidelines for the Approximate Reduction in the Capacity of the Component to Perform its Intended Function, %		
		Primary Components	Secondary Components	Auxiliary Components
6	Very Good	0 to 1	0 to 2	0 to 5
5	Good	1 to 5	2 to 10	5 to 20
4	Fair	5 to 10	10 to 20	20 to 40
3	Poor	10 to 15	20 to 30	40 to 60
2	Urgent	15 to 20	30 to 40	60 to 80
1	Critical	over 20	over 40	over 80

Detailed Condition Surveys

Approximately two years before a scheduled rehabilitation, a detailed condition survey is carried out. The purpose of the detailed condition survey is to determine the extent and severity of defects and deficiencies in the structure components. The data collected are used to determine and assess viable methods for rehabilitation. Both destructive and nondestructive testing and sampling methods are used. The procedures for carrying out detailed condition surveys, the description of the rehabilitation methods used by the Ministry, and criteria for the selection of technically viable methods are detailed in Ontario's *Structure Rehabilitation Manual* (*5*). A detailed condition survey involves a significant amount of work and cost, and is not carried out unless there is a need to rehabilitate the structure and the structure has been identified for rehabilitation. Some factors considered include: extent of defects and deterioration observed by routine detailed biennial inspections, age of the bridge, poor design or construction details, and repair history of the bridge. In addition, where the bridge is within the limits of a road or other rehabilitation contract, it is also considered for rehabilitation and a survey carried out.

For exposed concrete surfaces, the survey usually consists of:

- a thorough visual survey to record the extent and severity of cracks, scaling and spalling and patched areas;
- measurement of corrosion potentials (taken on a 1.5 m x 1.5 m grid);
- measurement of concrete cover (taken on a 1.5 m x 1.5 m grid);
- taking cores from sound and deteriorated areas of the concrete; and
- photographing significant deterioration.

On decks with a bituminous wearing surface, one must drill through the wearing surface to measure corrosion potentials; and, it is not possible to measure concrete cover and delamination. It is also more difficult to determine the condition of the deck slab, more cores may be taken. Further, sections of the bituminous wearing surfacing (approximately 250 mm x 250 mm) known as a sawn samples are removed to examine the condition of the underlying concrete deck surface.

All the cores are sketched, photographed, and subjected to a visual examination, and some are selected for testing for compressive strength, chloride content, and air-void system. A report is prepared for each structure and includes a description and analysis of all the on-site and laboratory testing. A summary of the sampling and testing requirements for concrete cores, and for the sampling requirements for asphalt sawn samples is given in Table II.

The other components of the structure are inspected visually. Where deterioration is found in the other substructure or substructure components, one must decide whether to include the work in the deck rehabilitation contract or by separate contract. Often, steel beams and girders will exhibit deterioration of the coating system, requiring recoating. This work is often carried out in a later contract for several reasons, such as: to prevent possibly damaging the new coating during concrete rehabilitation; to limit the extent of road rerouting and public inconvenience; and to facilitate contract administration as this work is usually carried out by specialized contractors. However, where later coating work will be necessary, those areas that will be exposed during concrete removals, which would be inaccessible after the rehabilitation are included as part of the work. These areas are typically under and around the expansion joints. Requirements for condition surveys and nondestructive and destructive sampling and testing are currently being developed for steel and wood components.

Selection of Rehabilitation Treatment and Option Analysis

The selection of the rehabilitation method is the crucial step in bridge rehabilitation. It includes consideration of many factors, some of which are technical, some economic, and some purely practical. The following factors most influence the selection of the rehabilitation method:

- life cycle costs of the different rehabilitation options compared to the cost of replacement;
- nature and extent of the deterioration;
- anticipated remaining life of the structure;
- location of the structure and its importance in the highway network;
- AADT at the site and the impact of lane closures on traffic flow;
- load-carrying capacity of the structure;
- history of deterioration and previous repairs;
- future reconstruction program near the structure; and
- the type of structure, its size and geometry.

Any rehabilitation option must ensure that the completed structure will be structurally adequate to carry all applied service loads. It is therefore necessary to establish that the component can be repaired, rather than replaced, and that all the components of the structure will support any additional loading resulting from the rehabilitation. These may be additional permanent loads, i.e., overlays, or may be construction loads in coating contracts, where work platforms and environmental protection may be suspended from the structure. This evaluation is carried out according to the *Ontario Highway Bridge Design Code* (OHBDC) (*6*).

Further, rehabilitation options considered are those that will prolong the life of the component by 10 years or more. Consequently, temporary repairs, such as patching or epoxy injection, are considered routine maintenance items rather than rehabilitation. Consideration is also limited to work which will be done by contract awarded through a competitive tender process. The choice of which method to use on any particular bridge deck or component depends on its condition, as determined from detailed condition surveys. Where rehabilitation is delayed more than four years from the date of the condition survey, then a new condition survey is normally carried out and the method of rehabilitation reassessed and contract documents updated as needed.

TABLE II REQUIREMENTS FOR SAMPLING AND TESTING BRIDGE DECKS

REQUIREMENTS FOR CORE SAMPLES

Percentage of deck area with corrosion potential more negative than -0.35V and with delaminated concrete	Number of Cores Required				Minimum Number of Cores	
	First Survey		Update Surveys		First Survey	Update Surveys
	Asphalt Covered Deck	Exposed Concrete Deck	Asphalt Covered Deck	Exposed Concrete Deck		
0 to 10%	1 core per 100 m^2	1 core per 200 m^2	1 core per 500 m^2	1 core per 500 m^2	6	3
10 to 25%	2 cores per 100 m^2	1 core per 150 m^2	2 core per 500 m^2	1 core per 500 m^2	6	3
more than 25%	3 cores per 100 m^2	1 core per 100 m^2	3 core per 500 m^2	1 core per 500 m^2	6	3

REQUIREMENTS FOR TESTING OF CORES

Test	Deck Area	Number of Cores		
		First Survey		Update Surveys
		Min	Max	
Compressive Strength	< 500 m^2	1	2	1 optional
	500 to 2000 m^2	2	4	
	> 2000 m^2	4	6	
Chloride Content	< 500 m^2	1	2	1
	500 to 2000 m^2	2	3	
	> 2000 m^2	3	4	
Air Void System	< 250 m^2	1	1	1 optional
	250 to 1000 m^2	2	2	
	> 1000 m^2	3	3	

REQUIREMENTS FOR SAWN SAMPLES

Percentage of deck area with corrosion potential more negative than -0.35V and with scaled or delaminated concrete	Number of Sawn Samples Required			Minimum Number of Samples	
	First Survey	Update Surveys			
		Deck Waterproofed	Deck not Waterproofed	First Survey	Update Survey
0 to 10%	1 per 200 m^2	1 per 500 m^2	1 per 200 m^2	6	3
10 to 25%	1 per 200 m^2	1 per 500 m^2	1 per 150 m^2	6	3
more than 25%	1 per 200 m^2	1 per 500 m_2	1 per 100 m^2	6	3

The technical consideration in selecting the method of rehabilitation can conveniently be dealt with by examining the relative advantages and disadvantages of the different options. Decision matrix tables and flow charts to assist in the selection of the rehabilitation methods for concrete decks and other components are given in the *Structure Rehabilitation Manual* (*5*). These are used with the results of the condition survey, other relevant available data and sound engineering judgement to select appropriate methods and strategies for rehabilitation. A typical decision matrix for a bridge deck in poor condition is illustrated in Figure 4.

- The methods considered for the rehabilitation of decks are:
  - Concrete patching with waterproofing and bituminous paving;
  - Normal concrete overlay with waterproofing and bituminous paving;
  - Latex modified concrete overlay;
  - Latex modified concrete overlay with waterproofing and bituminous paving;
  - Silica Fume concrete overlay;
  - Cathodic protection using coke mix and bituminous paving;
  - Cathodic protection using coke mix with a concrete overlay and bituminous paving;
  - Cathodic protection using anode mesh in concrete overlay, waterproofing and bituminous paving; and
  - Full depth replacement.
- The methods for rehabilitation considered for other concrete components are:
  - Concrete patching;
  - Concrete re-facing or encasement;
  - Latex modified shotcrete;
  - Silica Fume shotcrete;
  - Full depth replacement; and
  - Cathodic protection.
- The methods for rehabilitation considered for structural steel components are:
  - Strengthening or replacement of components;
  - Adding shear studs to make the beams composite with the deck; and
  - Applying a protective coating system.

The criteria for the selection of coating systems for coating structural steel components are given in the *Structural Steel Coating Manual* (*7*), and illustrated in Table III. Most of the methods used have been in place since 1978 and have been working well. However, modifications in the policy on concrete removal have been made in some areas to improve the durability of the repair or rehabilitation. Currently, concrete is removed in all deteriorated areas and all areas where half-cell readings are more negative than -0.35 volts, even if the concrete is otherwise sound. This has improved both the estimates of concrete removal and the product. Concrete is removed to sound concrete or to at least a minimum specified uniform depth of 25 mm below the first or top layer of reinforcement, and for an additional depth of 25 mm just around the bars in the next layer of steel. These practices have improved the durability of patches, overlays and shotcrete repairs. The policy for removal of high half-cell areas does not apply to rehabilitation by cathodic protection as it is not necessary in that case.

Financial Analysis

The criteria for the selection of the rehabilitation method or coating system deal with the technical and practical considerations, exclusive of cost. While costs are important, the cost of the rehabilitation method is only part of the total cost of a contract. This occurs because items such as traffic control, and mobilization can be a considerable portion of the total cost. This is particularly true if the extent of the rehabilitation or components needing rehabilitation is limited. Where many rehabilitation methods are feasible, or where the choice between rehabilitation and replacement is not obvious, then a life cycle costing between competing options is carried out to help make the choice. The methodology of carrying out life cycle financial analysis is given in the *Structural Financial Analysis Manual* (SFAM) (*8*). Analyses are carried out on a computer using Lotus, 1-2-3^{TM}. Guidelines are given in the SFAM on the life cycles of various rehabilitations based on the experience on major freeways in Ontario. They can be modified for local conditions and experiences. Considerable research is needed to refine these but as long as consistent data are used the analysis leads to valid choices.

Present Value Analysis Using PRVAL Program

PRVAL is a template overlay developed to perform financial analysis for bridge rehabilitation projects. The life cycle costs of viable rehabilitation options and strategy are carried out. These are compared to replacement costs, and/or may include replacement of part or all of the bridge at some time. The present value of estimated expenditures over the remaining life of the structure for each of the rehabilitation strategies is then calculated, and that option with the least present value is chosen as the preferred option and strategy to

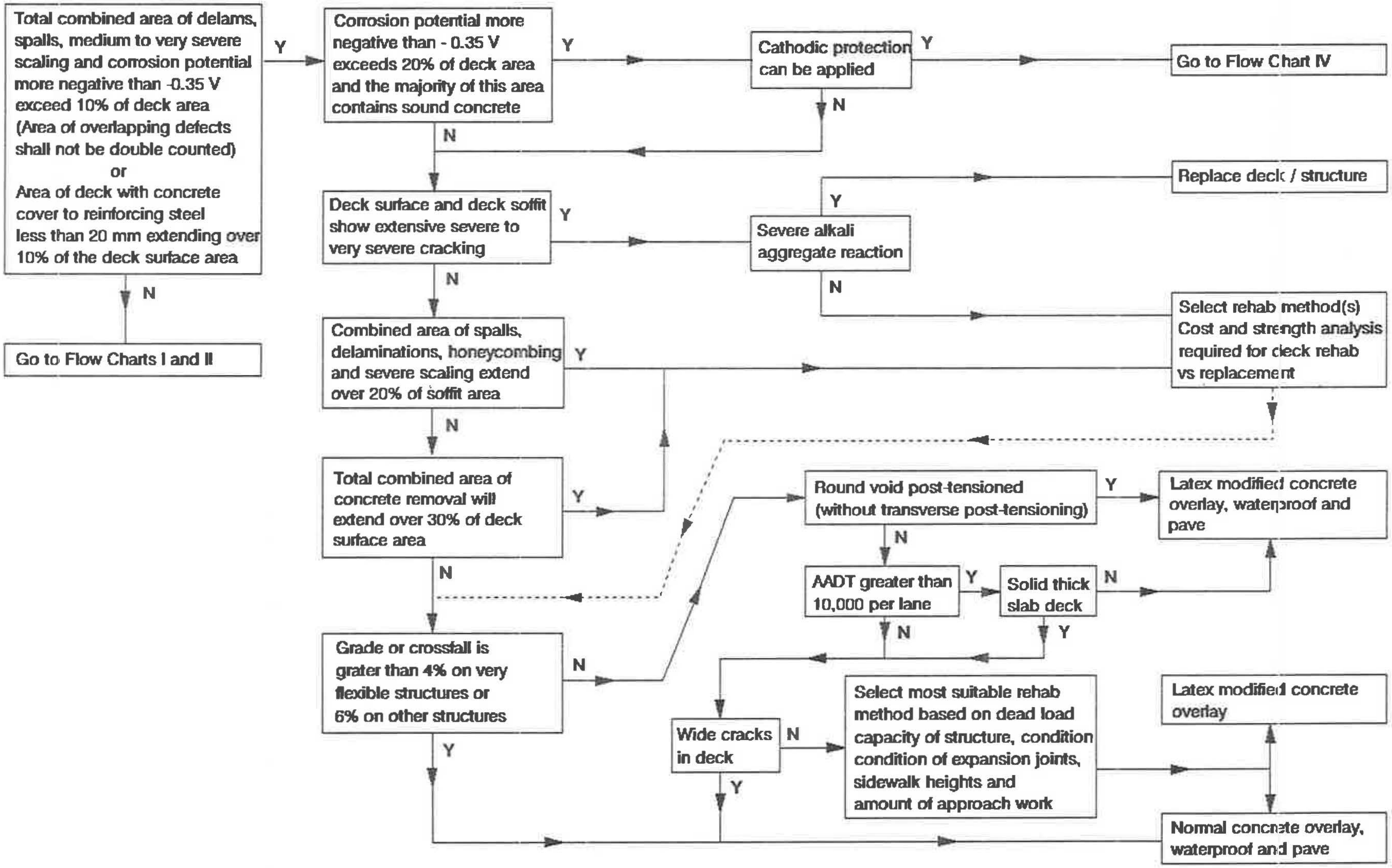

FIGURE 4 Selection of deck rehabilitation method (for deck in poor condition).

TABLE III COATING SYSTEM SELECTION CRITERIA

Coating System (total dry film thickness)	Optimum Utilization	Remarks
Inorganic Zinc/Vinyl (200 - 215 um)	Girder type structures. Use on Class A highways justified by its service life.	Not compatible with other paints. Will not tolerate inadequately cleaned surfaces that may occur on truss structures.
Epoxy Zinc/Vinyl (225 um)	Truss type Structures Use on Class A highways justified by its service life.	The epoxy-zinc will tolerate less than ideal surface cleanliness as may be encountered on a truss type structure.
Coal Tar Epoxy (400um)	Steel Piling.	Black in color.
Aluminum Epoxy Mastic (225 um)	All structure types.	Only to be used for spot cleaning/coating by Bridge crews.
Metallizing (200 um)	Steel posts or attachment brackets on concrete posts.	Suitable for all components including girders. Zn/Al alloy wire is used. Must be "seal" coated, usually with vinyl top coat.
Hot Dip Galvanizing (87 um)	Standard steel handrails.	Has also been used successfully on Ministry bridge girders.

follow for that bridge. There are four levels of sophistication for carrying out the financial analysis. These are analyses that consider: only capital costs; capital costs and residual values; capital costs, residual values and maintenance costs; and, analyses that incorporate given percentages or probabilities for uncertainty in costs.

Incremental Benefit/Cost Ratio Analysis Using COSBEN Program

COSBEN is a program developed to perform incremental benefit-cost analysis for bridge rehabilitation projects. The analysis can be carried out with or without user costs. Here, the option with the highest benefit/cost ratio greater than one is chosen.

Theory of Present Value Analysis

The present value analysis involves the calculation of the cost of alternative options in present day monetary terms, i.e., the amount required in today's value to obtain goods and services at any future date. It allows for the comparison of alternative options on an equitable basis. The present value *PV* of expenditure *C* in year *n* at a discount rate *r* is given by the expression:

$$PV=\frac{C}{(1+r)^n}$$

The present value of several expenditures $C_{\underline{n}}$ over *n* years is similarly given by:

$$PV=\sum_{n=1}^{n}\frac{C_n}{(1+r)^n}$$

The incremental benefit/cost ratio, *IB/IC,* is the ratio of the additional benefits realized in moving from one improvement option to another, divided by the corresponding difference in costs. This method not only optimizes the selection of options efficiently but also ranks the projects beginning with the most net benefit. It is used both at the project and network levels. Figure 5 shows the total benefit and first cost curves plotted for the various options for a bridge. Initially, the increment of benefit, *IB*, is higher than the increment of cost, *IC*; however, as costs increase the incremental benefits typically decline and are less than the incremental costs. The slopes of these benefits and first cost curves support the theory of diminishing returns. For a particular level of improvement there exist points on the benefit and cost curves, where the slopes of the two curves are equal, i.e., *IB* = *IC*. At this level of improvement the net benefit is a maximum. This is illustrated in Figure 6. Any option below this level where *IB/IC* > 1 is a desirable option. The procedure is to list rehabilitation options in order of increasing costs and calculate the *IB/IC* ratio for each option. Options for which *IB/IC* ratio is less than 1.0 are discarded. The options are then sorted in descending order of *IB/IC*. For a limited budget, the order of preference is the order from the highest to the lowest *IB/IC* ratio. The following should be estimated for each option in constant monetary terms:

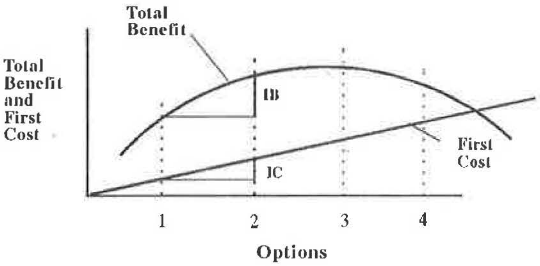

FIGURE 5 Total benefit and first cost.

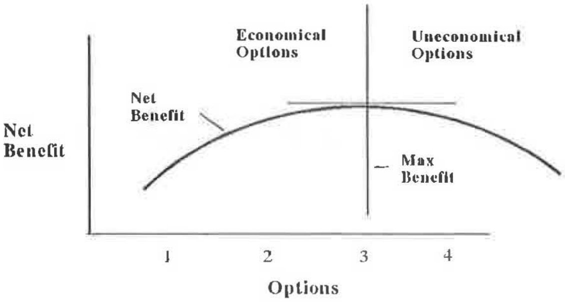

FIGURE 6 Net benefits.

- Engineering design cost;
- Construction cost;
- Miscellaneous costs such as, demolition, traffic control, work on approaches, utilities, stream-diversion, detours, etc.; and
- Maintenance and future rehabilitation costs.

Costs associated with maintenance are the routine maintenance costs. These would include minor repairs, maintenance, touch up painting, etc., carried out on a regular basis.

The life cycles for the rehabilitation methods, is the time between two successive rehabilitations or replacements, and have to be determined. Preferably, these should be based upon data collected in the field; however, as this type and volume of data may be limited, these may be estimated based upon available data and experience. The bridge may also have useful remaining life at the end of the period for any particular option. This is called the residual life. There are no specific methods of assessing this; therefore, a thorough knowledge of the performance of past rehabilitations, experience and sound engineering judgement are probably the best way of assessing the useful residual life. From the residual life, the residual value of the structure for the particular option can be determined. There are several methods available for determining the residual value. The method used here is the second cycle replacement method.

The discount rate depends on several factors (*9*), such as the magnitude of investment return, inflation and capital market conditions, preferences for current and future consumption, etc. A discount rate of 6% is recommended for government projects, which may be different for other agencies. Sensitivity analysis may be carried out by varying these rates.

For the incremental benefit/cost analysis, the following additional parameters are required: agency costs and benefits, and user costs and benefits. Agency costs are the same as for the present value analysis. Agency benefits are given in terms of the cost savings between rehabilitation and replacement, and of the cost of the rehabilitation. Maintenance and various types of rehabilitations extend the useful life of the bridge. These expenditures would postpone major expenditures for replacement. The difference between the discounted future cost of a rehabilitation option and that of a replacement option is the agency net benefit. The agency net benefit plus the cost of the rehabilitation is the agency total benefit. User costs are costs incurred by the user due to deficiencies or substandard conditions at the bridge. The following are the user costs:

- Accident Costs—costs resulting from accidents at bridges due to width restrictions, poor approach alignment, etc.; and
- Functional restriction costs—costs due to load restrictions and detours for certain classes of vehicles increase travel time and, therefore, operating costs. These vary for different locations and countries.

User benefits of a bridge rehabilitation option are the reduction in costs to the users due to the rehabilitation. In determining user benefits it is assumed that deficiencies will be eliminated when the bridge is repaired or replaced. The reduction in the number of accidents due to a certain type of improvement is used as a measure of user benefit for that type of improvement. The dollar value placed on different types of accidents is crucial in estimating user benefits. These may vary for different countries. The change in accident rate is measured by the difference in the number of accidents per million vehicles. The accident cost depends on the severity of the accident. Two methods for assessing accident costs considered are the Human Capital Approach and the Willingness to Pay Approach. The Human Capital Approach considers the direct and indirect costs, but does not consider the intangibles offered to the society and the loss in the quality of life. The Willingness to Pay approach includes the value of life in the estimates. As such, the latter approach is more conservative.

FUTURE WORK, IMPROVEMENTS AND ENHANCEMENTS

The rehabilitation policies and procedures in Ontario have developed over many years to the point that they are well documented in Ministry's manuals. The number of bridges rehabilitated each year and the funds spent on them are such that most of the needs on the provincial network are being met without undue inconvenience to the public. The project bridge management system that is currently in place is satisfying immediate needs but is continuing to be developed. Work is currently underway in the following areas to address future needs and enhancements to the system:

- merge all information on bridges under a single database management system;
- continue research and investigations to determine the life cycles of the various rehabilitation methods;
- identify, develop and implement other modules needed for a complete bridge management system of the provincial bridges at the network level;
- develop and incorporate expert systems for selection of rehabilitation methods and options analysis for project level bridge management; and
- develop and incorporate expert systems for network bridge management.

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DEVELOPMENT OF A BRIDGE MANAGEMENT SYSTEM IN ALABAMA

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ABSTRACT

This paper describes the development of Alabama's bridge management system (ABIMS) by the Alabama Department of Transportation (Department). Unique features of ABIMS development include its comprehensive committee structure and efficient software development procedure. Specific information is given regarding important ABIMS functions such as bridge resource tracking, needed and performed maintenance reporting, and scour monitoring. After hiring the University of Alabama as a consultant, the Department organized several committees to oversee, review, and develop ABIMS. The committees were composed of personnel from many branches and levels within the Department, the Federal Highway Administration (FHWA), and city and county representatives, which ensures ABIMS will interface as smoothly as possible with existing systems and will meet the needs of all users. Early, the Department decided to develop its own bridge management system (BMS) rather than use an off-the-shelf system. ABIMS was designed by pulling information and ideas from many sources and molding a BMS to custom-fit Alabama's needs. The detailed system design was performed by the bridge management engineer and the computer-program analyst assigned full-time to the project. Software development for ABIMS followed a three-phase procedure in which the function of every component was first fully-defined before proceeding with the actual computer programming. Several of ABIMS components or modules are up and running, including its unique scour module. This module displays stream-bottom profiles based on sounding data from biennial inspections. The graphical display allows bridge inspectors and maintenance engineers to spot developing scour problems.

INTRODUCTION

In today's struggling economy, all transportation agencies are faced with the same difficulty of striving to maximize the use of available dollars to handle the immense needs of our aging highway system. The old cliché of "the hurrieder I go, the behinder I get" applies here. Therein lies the need for bridge management. And, as one of our colleagues would say, "We have to do the best we can with what we've got"; this is exactly the purpose of bridge management. The Department strives to be proactive, rather than stand by and wait. We want to participate in the group that makes things happen. The Department recognizes the need to preserve the taxpayers' investment in the existing bridge system in Alabama. Toward this end, the Department began development of a bridge management system in 1989. Called the Alabama Bridge Information Management System (ABIMS), the system will provide ready access to a wealth of information concerning Alabama's bridges. When complete, ABIMS will go beyond information management. Instilled with the Department's level of service goals, maintenance policies, and replacement criteria, ABIMS will help the Department develop cost-effective bridge maintenance, rehabilitation, and replacement policies.

This paper presents an overview of the development of ABIMS. It describes how the project began with the hiring of an outside consultant and the organizing of supervisory, user, and working committees within the Department. Through combined efforts of the consultant and the Department, time was spent reviewing the existing FHWA guidelines on BMSs, surveying available literature and visiting states that had BMSs in place.

PROJECT ORGANIZATION

The first commitment made by the Department was to hire the University of Alabama (University) to help with the design and development of the system. Second, the Department established three committees to monitor and give direction in the development efforts of ABIMS. The composition of each committee is outlined in Figure 1. The Steering Committee is the highest in authority and consists of five representatives. This committee has the authority to allocate special funds, hire additional personnel, purchase special equipment to support the system, or make policy or procedural changes in the Department. One of the Steering Committee's first actions upon receiving the University's first interim report was to appoint a Bridge Management

Steering Committee	
1	Administrator
2	Bureau Chiefs (Maintenance & Computer Services)
1	University of Alabama Representative
	Bridge Management Engineer
User Committee	
7	Bureau Chiefs (Accounting, Bridge, Construction, Design, Maintenance, Secondary Roads, State Planning)
4	Division Representatives
2	County Representatives
1	City Representative
2	University of Alabama Representatives
1	FHWA Representative
	Bridge Management Engineer
Project Committee	
7	Bureau Representatives (Maintenance, Bridge, Computer Services, Secondary Roads)
1	County Representative
2	University of Alabama Representatives
1	FHWA Representative
	Bridge Management Engineer

FIGURE 1 Composition of supervisory and working committees.

Engineer. The User Committee is second in authority and consists of eighteen representatives from several bureaus in the Department, from the FHWA and from a county and a city. This committee reviews what has been planned and proposed for the system and ensures that ABIMS will meet the needs of all users and will interface smoothly with other bureaus and agencies. The Project Committee is the working committee and is composed of twelve people from the most-affected Department bureaus and includes an FHWA representative and a county representative. These people brainstorm ideas and work on the logistics of the system. The User and Steering Committees must review and approve the proposals of the Project Committee before proceeding with software development. Occasionally, the Project Committee had to make many decisions within a very short time. When this occurred, several task committees were named from the Project Committee members and from other Department employees who have the necessary expertise to help with the technical issues. By delegating specific tasks to subcommittees the progress of the system development was expedited.

This plan of development has worked very well for Alabama. It allows people to be directly involved with the hands-on development of ABIMS without demanding so much of their time. It also prevents any one group from dominating the design of the system. For example, since ABIMS will be housed in the Maintenance Bureau, it would be easy for maintenance personnel to tailor the system to accommodate only their needs and desires at the expense of others' needs.

DESIGN PROCEDURE

After receiving the contract in 1989, the University conducted a literature review and presented several seminars to brief the Department on the state-of-the-art in BMSs. Most helpful was an overview of BMSs by FHWA (*1*) and several publications describing the North Carolina BMS (*2,3*). Key concepts explained during the seminars included level of service, user costs, deterioration prediction, and system optimization.

The Project Committee visited the highway agencies of three other states to learn firsthand how these states ran their BMSs. Much useful information was exchanged during the visits to Pennsylvania, North Carolina and Virginia. During the visits, Department personnel often paired-up with their counterparts from the other state and shared specific information about bridge management and other pertinent topics. The Project Committee returned home and discussed the strengths and limitations of each state's BMS.

Preliminary Design

Before designing Alabama's BMS, ABIMS team members met to outline the needs and desires of the Department. Suggestions were solicited from all members of the Steering, User and Project Committees. After identifying the basic tasks for ABIMS, the Project Committee defined individual components or modules to perform the tasks. Figure 2 is a schematic layout developed by the University which shows conceptually some tasks to be performed by the software.

The University conducted a significant amount of research in the preliminary design stages and completed several interim reports (*4,5,6,7,8*) to document their efforts and findings. In Interim Report No. 1, it was recommended to the Department administrative staff that approval be granted for the preliminary design. The administrators readily approved the recommendations and detailed development began.

In the early stages of the detailed development, approximately fifteen programs or modules were identified for ABIMS. As the Project Committee

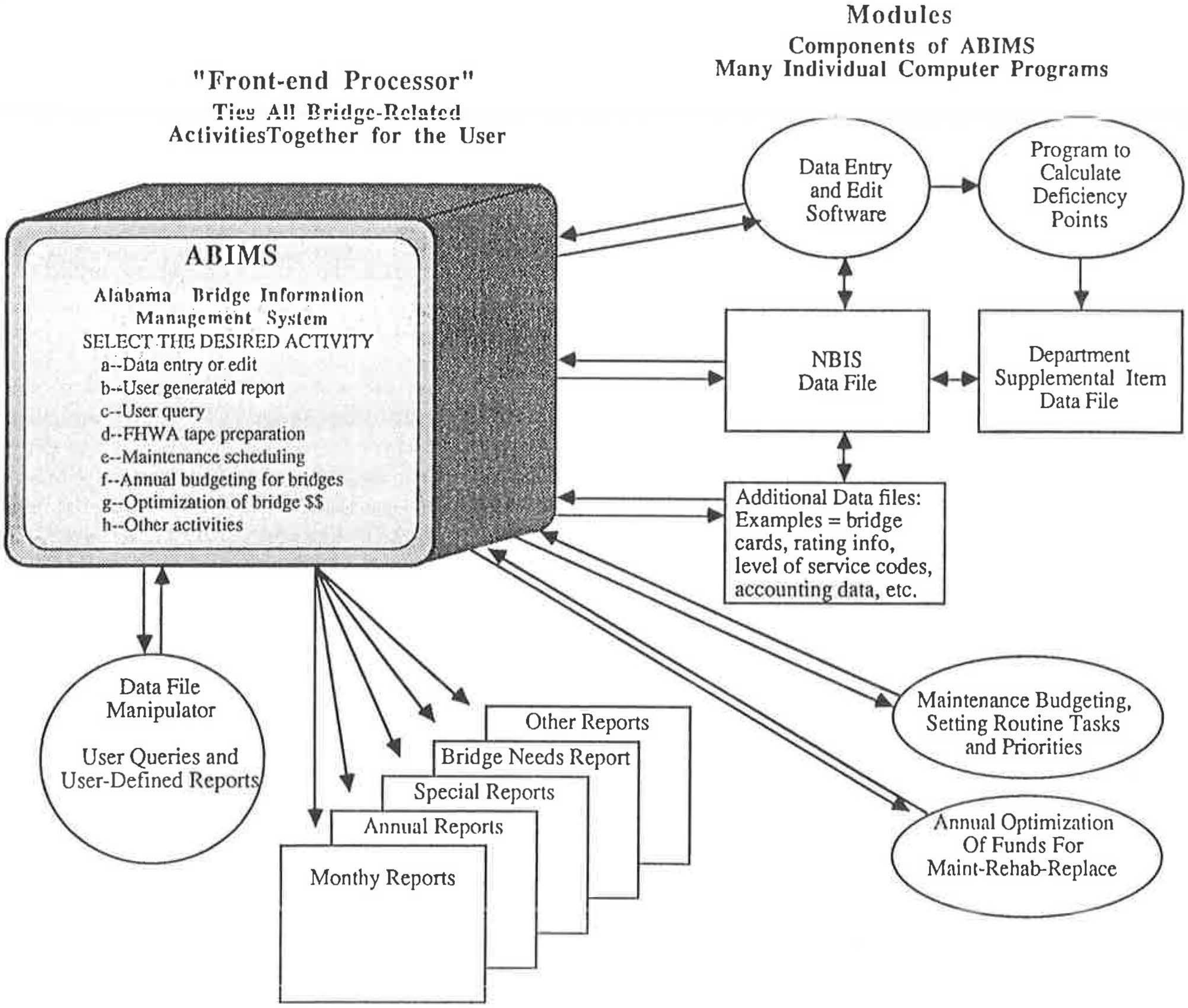


FIGURE 2 Preliminary schematic diagram for Alabama's bridge management system.

worked through what was expected from the system and how these expectations would be met, additional modules were identified and ultimately twenty-two modules were defined for ABIMS. In Figure 3, a list is provided with the modules grouped by their primary function.

Early, the Department made the decision to develop its own BMS, customized to fit its unique needs and programmed by its own computer services personnel. Once this decision was made, one programmer/analyst was named the ABIMS representative. This person was to be responsible for the software development of the system and would coordinate the programming of all modules of the system to cause it to be implemented most productively within the total plan. In the Department's Computer Services Bureau, there were approximately 10 programmers available to work on the ABIMS. Thus far, approximately eight of these programmers have been involved in writing software for the system.

Software Development Procedure

The strategy adopted for software development was recommended by the Computer Services Bureau. Based on the success in the development of another complex computer program, it was agreed to work through a three-phase development procedure.

Functional Specifications

The first development phase was the writing of the functional specifications. Functional specifications simply consist of a brief paragraph for each module in the system. This paragraph includes the purpose of the module, the type of information necessary to drive the module and what type of output is expected. In the functional specifications, the committee clearly established the type of modules to be included in the system, the amount of data to be collected, and the type of data manipulation required to obtain the desired results.

General System Specifications

The second phase of software development was to write general system specifications for each program module. These specifications were much more specific and included information such as which data items were required for input, where these data came from, what types of calculations and formulas were necessary, which modules interfaced with this module, and what type of output was required (for example reports or electronic storage).

Detailed System Specifications

The final phase of software development before actual coding of the program was to write the detailed system specifications. These specifications are detailed in nature and specify such things as size of data in bytes and whether data are alpha or numeric. Occasionally, modules with redundant tasks were removed and new modules were added to do mundane but necessary tasks such as recovery and security. Once the plan was completed and approved by the committees, any changes to the original plan were reviewed and approved by the committees. The functional specifications were written by delegating the modules to different task committees. This allowed parallel development of many of ABIMS's modules, shortening development time. The modules were implemented on a staggered schedule, allowing users to become familiar with each part of the system separately. This caused the users to be more receptive to the system without being overwhelmed by the amount of data required and the amount of data generated by the system.

STATUS OF IMPLEMENTATION

The Department is now 100 percent complete with development of the functional specifications, about 60 to 65 percent complete with the general system specifications and about 25 to 30 percent complete with the detailed design specifications. An overview of the 22 modules in ABIMS is presented below, followed by short discussions of selected modules.

Incidental Modules
- Front End Program
- On-Line Help
- Security
- Training
- Recovery

Data Capturing Modules
- Conversion
- NBI File Maintenance
- Element Rating Entry
- Maintenance Needs Estimate
- Maintenance Reporting
- Supplemental Data
- Scour Profile Plotting/Hydrology
- Deficiency Points
- Data Access in Other Fields

Data Analysis/Manipulation Modules
- Bridge Status Display Screens
- FHWA Edit Program
- Resource Tracking
- Maintenance Budgeting & Prioritizing
- Deterioration Models
- Optimization Program
- User Query
- Standard Request & Reports

FIGURE 3 Alabama bridge information management system modules.

Overview of Modules

Twenty-two modules have been identified for ABIMS. These modules are listed in Figure 3 where they are grouped according to function. Incidental modules do tasks necessary for any large program to be user friendly and reliable. Eight modules are devoted to data capture in ABIMS. Data enters ABIMS from many different sources such as bridge inspectors, maintenance crews, hydrologists, the project office, the National Bridge Inventory (NBI) file, the supplemental data file, and the accounting files. Data analysis and manipulation modules manipulate the massive bridge database and generate a multitude of display screens and reports for users at all levels.

Supplemental Data Items

Preliminary research by the University showed some states were collecting over 400 data items per bridge. This was significantly more than the 128 data items collected in Alabama at the time. Project committee members became concerned about the significant expense of collecting and maintaining a large amount of additional data, and the usefulness of the additional data. Reviewing data items collected by several other states, a task committee identified approximately 200 additional data items as necessary for the complete implementation of ABIMS. The definition of each item, the type of data (alpha or numeric), and the number of characters or digits in the data field were specified for each data item. An extensive set of codes was developed for many data items. For example, bearing type is entered as one of 21 possible codes with each code corresponds to a specific type of bearing. As development of other modules proceeds, additional data items are sometimes added to the supplemental data items. Data items are occasionally dropped when redundant data are discovered or the data item is no longer considered useful.

Bridge Number

One of the first tasks the Department faced was determining a method of uniquely identifying bridges that would be permanent for the life of the bridge. The current method for numbering state-owned structures is linked to the state route and the milepost distance from the county line. Both items can change over the life of the structure if a route realignment is completed or if structure ownership is transferred from one governing authority to another. Also, counties and cities in Alabama identify their structures by a different method. Because a unique bridge number was necessary for ABIMS as well as for the accounting reference systems and project management reference systems, a bridge identification number, or BIN, was established. This unique six-digit number bears no significance to the route or milepost and will not change for the life of the structure.

Bridge Resource Tracking

Currently under development, the bridge resource tracking module will collect data necessary for determining the expenditures on a specific structure at any point in time. The current eight bridge-related maintenance activities were expanded to 38 to provide more detailed data. Expenditures such as labor, equipment and materials will be tracked for individual structures by this module. Data from this module will be used to update the unit costs for labor and equipment. In the future, data from this module will be used to study the effect of maintenance activity on bridge deterioration. Much of the data to support this module is collected via the maintenance reporting module described below. Additionally, this module will collect and store data on the cost of construction of new bridges and the rehabilitation of existing bridges.

Maintenance Needs Estimate and Maintenance Reporting

FHWA wants state highway agencies to have a follow-up procedure for maintenance work reported as needed. Currently, once Alabama inspectors identify work to be done, they do not have a formal procedure for checking that the work is done. The maintenance needs and maintenance reporting modules will provide an automated procedure for identifying work needed on a bridge, tracking all maintenance activity on the bridge, and then documenting work accomplished for the bridge.

Maintenance Needs Module

The bridge inspectors are the primary source of data for the maintenance needs module. They will identify what type and how much maintenance the bridge needs by indicating one or more of the 38 possible maintenance activities and estimating the quantity (in appropriate units) associated with each needed activity. The inspector also will suggest a priority using one of four categories: emergency, urgent, priority or routine. The division maintenance engineer can adjust the suggested priority when considering the maintenance needs across the entire division. Information from the maintenance needs module can be used for several management activities. Once entered, ABIMS will assign information on needed maintenance to the appropriate bridges. A breakdown on the required maintenance for each bridge can be displayed on a computer screen. Anticipated costs will be displayed by ABIMS using unit costs calculated from the previous year's accounting data. An example of a bridge status display screen showing needed maintenance is shown in Figure 4.

Maintenance Reporting Module

The crew leader will record the data for the maintenance reporting module (crew leader may be the district engineer, a bridge inspector, a bridge repair crew supervisor, or similar personnel). The amount of labor, equipment, and materials used on each bridge and the activity accomplishment will be coded on the form. Information from the maintenance reporting module will be used to prepare payroll, material requisitions, and equipment usage reports. Also, the crew chief will check the box titled "Job Completed" to show the maintenance activity is complete. This is necessary to resolve discrepancies between the actual number of work units

NEEDED MAINTENANCE

B.I.N.: Bridge No.:

ACT. CODE	DESCRIPTION	QUANTITY PLANNED	ACT UNITS	EST. COSTS	DATE ENTER	MAINT PRIORITY
B29	Drift Removal	300	MH	$3,655	02 92	U
B14	Major Super Rpr--Steel	3,000	MH	$255,000	02 92	R
B23	Bridge Painting--Spot	1,100	SF	$485	01 92	R
B02	Curb/Rail/Fence Repair	2,500	LF	$37,500	12 91	R*
B17	Minor Sub Rpr--Steel	1,800	MH	$135,000	12 91	R
B31	Accident Repair	144	MH	$4,320	11 91	U
B04	Joint Repair--Sealed	450	LF	$13,500	10 91	R*
	Total Estimated Costs =			$449,460		

* Maintenance underway but not completed

FIGURE 4 Example display screen showing needed maintenance on a particular bridge.

COMPLETED MAINTENANCE

B.I.N : Bridge No:

ACT. CODE	DESCRIPTION	QUANTITY COMPLETED	ACT. UNITS	ACTUAL COSTS	DATE COMPLT	MAINT BY
B08	Major Deck Rpr--Steel	3,200	SF	$208,000	01 92	C
B03	Joint Repair--Open	3,211	LF	$212,000	09 91	D
B31	Accident Repair	120	MH	$4,000	04 91	D
B24	Bridge Painting--Partial	200,000	SF	$88,264	06 90	D
B11	Minor Super Rpr--Steel	452	MH	$22,600	09 88	C
B30	Slope/Shore Protect Rpr	367	MH	$5,505	08 87	D
B28	Light/Nav Light Repair	93	MH	$2,325	06 87	D
B17	Minor Sub Rpr--Steel	2,400	MH	$180,000	09 86	C
B32	Vandalism Repair	150	MH	$5,000	04 86	D
B04	Joint Repair--Sealed	320	LF	$9,600	02 85	D

30 OTHER MAINTENANCE JOBS FOR $ 11,516,288 COMPLETED SINCE 1961

LAST INSPECTION CYCLE MAINTENANCE COST = $ 512,264/yr
LAST INSPECTION CYCLE MAINTENANCE COST PER SQ FT = $ 65/yr
AVG INSP CYCLE MAINT COST, LAST TEN YEARS = $405,360/yr
AVG INSP CYCLE MAINT COST PER SQ FT, LAST TEN YEARS = $ 58/yr

FIGURE 5 Example display screen showing completed maintenance for a particular bridge.

and the estimated number of work units reported by the bridge inspector. An example of a bridge status display screen for completed maintenance is shown in Figure 5. This module also will include provisions for tracking maintenance work performed by both Department personnel and outside contractors. Maintenance not marked "Job Complete" will appear on a monthly report of remaining maintenance. If needed maintenance identified by the bridge inspector is not performed by the next inspection, the bridge inspector can clear the maintenance request and enter a new updated request if the bridge has further deteriorated.

Bridge Element Condition Rating

The bridge element rating module allows the entry, update, retrieval, and display of information from the bridge inspection report (Alabama's BI-5 Form). The BI-5 form is a detailed inspection sheet used by bridge inspectors for rating the condition of individual bridge elements. Adapted from a form distributed by FHWA in the early 70's, the BI-5 form contains approximately 75 data items for rating the condition of deck, superstructure, and substructure elements as well as culverts, channels and channel protection, and expansion joints. Other information includes traffic safety features, approach roadways, and the inspector's signature and certification number.

Deficiency Point Module

The deficiency point module will compare selected bridge characteristics against the appropriate level of service goals for each bridge in the database. The module will extract nine pieces of information from the NBI for each bridge (load rating, roadway width, vertical clearance, deck, superstructure, and substructure conditions, traffic volume, detour length and functional class). It also will use several supplemental data items and then compute a deficiency point number stored in the database for each bridge. The deficiency point equation was calibrated in Alabama by comparing lists of bridges picked by the deficiency point module against bridges selected by experienced maintenance engineers and bridge inspectors from several divisions and counties. After adjustment, the deficiency point algorithm showed excellent agreement with the engineers and bridge inspectors. The calibration procedure established the credibility of the deficiency point algorithm and established a uniform criterion for evaluating all bridges in the state. The algorithm can be adjusted in the future to reflect policy changes in the Department.

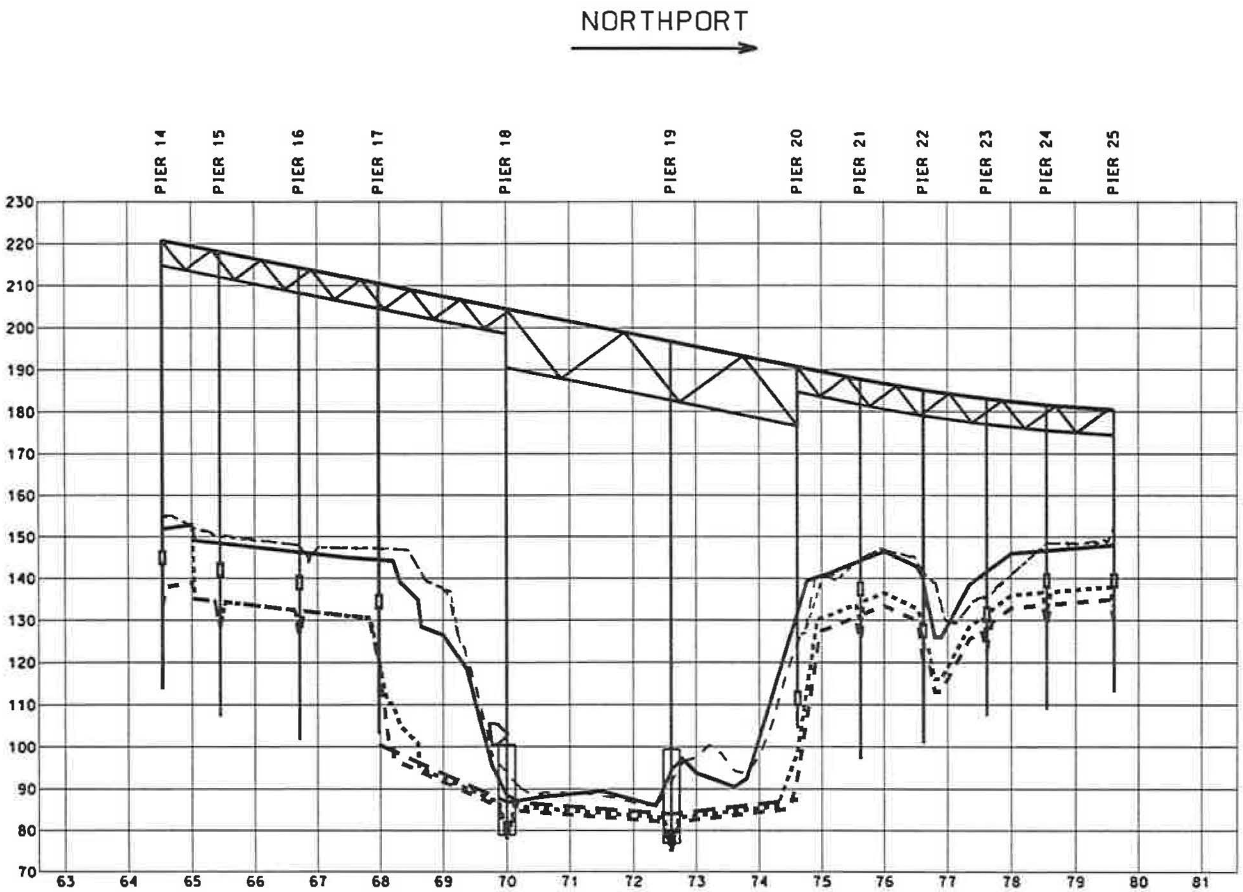
Scour Module

The scour module graphically displays foundation elevations and stream bed sounding data from several years. It was designed to detect changes in the stream bottom which may lead to undermining of the foundations. The scour module, the first completed module in ABIMS, was ranked high on the priority list once the FHWA began to schedule deadlines for the different phases of the states' scour programs. Because the Department chose not to classify any structure as low risk until an evaluation was complete, it faced a difficult deadline for completing the scour analyses on existing structures. The scour module provides a means for doing a visual evaluation of the stream bed and foundation elevation data and increases the user's confidence when classifying a structure as low risk.

The bridge inspectors are responsible for collecting the approximately 100 data items for this module. Data include bridge deck stations and elevations, stream bed soundings across the stream, superstructure thickness, and foundation types and elevations. The module displays an elevation view of the bridge showing the bridge deck, the bottom of the superstructure, the pier locations, and the bottom of the foundations. A typical plot generated by the scour module is shown in Figure 6. Information from soundings is displayed to show previous stream bed profiles and the current stream bed profile. The anticipated scour profile calculated by the hydraulics section also can be displayed for several flood frequencies. The scour module has been well received throughout the Department and highly praised for a 'job well done.' Besides the graphical presentation of the data, users can generate a report in tabular format listing the stations and elevations of the bridge, the original stream bed, the current stream bed, and the potential scour profile. The module uses graphics software (Intergraph's MicroStation) running on personal computers located in division and county offices throughout the state. The personal computers are linked (using File Transfer Protocol, NFS and Inter-link software) to the mainframe computer in the Department's central office.

Optimization Module

Currently under development, the optimization module will inform Department administrators about future budget requirements, support cost-effective allocation of current bridge funds, and provide other system-wide decision support. Because North Carolina served as the primary model for much of ABIMS design, (performed during 1990 and 1991), the Project Committee decided to adapt North Carolina's optimization program OPBRIDGE (*9*). The cooperation of Dr. David Johnston and the North Carolina DOT in sharing the program source code and example data files have been appreciated. The Project Committee is inserting Alabama's Level of Service goals, deterioration rates, accident rates, and other factors into the OpBridge program.



BIN: 10773. SN: 0000 0 069 63 016 5 0
DIVISION: 5. DISTRICT: 2
TUSCALOOSA
RIVER RD.MN AV.WARRIOR
TUSCALOOSA COUNTY
LEFT SIDE OF BRIDGE

ESTIMATED SCOUR												Q100
PIER NUMBER	14	15	16	17	18	19	20	21	22	23	24	25
CONTRACTUAL SCOUR (FT)	0	14	14	14	2	12	10	10	10	10	10	10
PIER SCOUR												
PIER SCOUR (FT)	0	6	5	10	8	8	23	5	5	5	5	5
TOTAL SCOUR (FT)	0	20	19	24	10	20	33	15	15	15	15	15

ESTIMATED SCOUR												Q500
PIER NUMBER	14	15	16	17	18	19	20	21	22	23	24	25
CONTRACTUAL SCOUR (FT)	14	14	14	14	3	13	13	13	13	13	13	13
PIER SCOUR												
PIER SCOUR (FT)	5	6	6	11	8	8	26	6	6	6	5	5
TOTAL SCOUR (FT)	19	20	20	25	11	21	39	19	19	19	18	18

NOTE: THE SOUNDINGS OF 1991 ARE NOT COMPLETE. THIS DRAWING ONLY INCLUDES THE TWO OVERBANK AREAS.

FIGURE 6 Typical plot from ABIMS scour module showing bridge elevation view and stream profiles.

Other Modules

The Standard Request/Reports module is being developed as other modules are implemented. This module generates standard reports for other modules. Other incidental modules are being developed concurrently with the major ABIMS modules. The Front End module, the Security module, the Training module and the Recovery module all perform important tasks to make ABIMS user-friendly and to safeguard the data in ABIMS.

CLOSING

Though ABIMS is far from the finish line, portions are already on line. Several reports and graphical output files can be generated to support decision-making efforts. Many output reports which will be implemented soon aim to make work efforts more efficient and productive. Considering the expanse of inspection and maintenance work facing the Department, improved efficiency will be much appreciated. In the short time that the scour module has been operational, many requests have been submitted for recommended changes and enhancements to the program. As the users become more familiar with the ABIMS scour module, they realize the potential and begin to suggest ways to make it better. We hope users will embrace the other ABIMS modules with the same enthusiasm. Finally, metric conversion is another hurdle for ABIMS. Much effort has already been expended within the Department on this topic, however, and no significant problems are anticipated in making ABIMS metric compatible.

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3. Chen, C. and David W. Johnston, *Bridge Management Under a Level of Service Concept Providing Optimum Improvement Action, Time and Budget Prediction*, Report No. FHWA-NC-88-004, Raleigh, NC, September 1987.
4. Turner, D.S., J.A. Richardson, and K.S. Wong, *Interim Report No. 1: Background Study and Preliminary Design of the Alabama Bridge Information Management System,* University of Alabama College of Engineering Report No. BER 523-39, March 1991.
5. Richardson, J.A. and D.S. Turner, *Interim Report No. 2: Development of Deficiency Point Algorithms for the Alabama Bridge Information Management System*, University of Alabama College of Engineering Report No. BER 547-39, December 1991.
6. Turner, D.S., J.A. Richardson, and K.S. Wong, *Interim Report No. 3: Development of Bridge Deterioration Models for the Alabama Bridge Information Management System,* University of Alabama College of Engineering Report No. BER 548-39, December 1991.
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CONNECTICUT'S BRIDGE MANAGEMENT INFORMATION SYSTEM

Robert G. Lauzon and James M. Sime,
Connecticut Department of Transportation

ABSTRACT

Procedures for the storage and retrieval of bridge-related information at the Connecticut Department of Transportation (ConnDOT) had remained virtually unchanged since the Department began keeping records. In 1985 the Department began utilizing advanced technologies to store and retrieve highway photolog images which provided an integral element in the development of the Department's Pavement Management System. In 1988 ConnDOT, in cooperation with the Federal Highway Administration, began investigating the use of the same technologies for the storage and retrieval of bridge-related information. The investigation brought to light inefficiencies in the storage and distribution of bridge-related data within the Department. With the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, six management systems were mandated, including one for bridges. This paper briefly describes the development of an information system dedicated to bridges and how it is being modified to provide input to the Connecticut Bridge Management Information System (CBMIS), to assist in the processing of data, and to support the results of a network analysis on a bridge-by-bridge basis.

BACKGROUND

The Connecticut Department of Transportation began using laser videodiscs in 1985 driven by a personal computer to store photolog images of the 7,700 bidirectional-mile highway network. The system used to access these images consists of a personal computer and videodisc player. It operates using software written by personnel in the Department's Division of Research and a private software firm. The system is referred to as the Photolog Laser Videodisc (PLV) System. It provides quick and easy access to any cumulative-mile location on any state-numbered route. The system is used in eleven application areas: network-level pavement management, safety analysis, project development and design, highway-sign inventory, legal evidence, public hearings, construction documentation, planning and inventory, and maintenance. It is used in the daily operation of the several units that work in these areas within the Department. Over $800,000 is saved each year in the elimination of field trips by pavement raters and others who use the system. There are 15 PLV stations located throughout the Department and in the Federal Highway Administration (FHWA). The number of PLV stations is anticipated to increase to meet the expansion in transportation applications, which is consistent with the philosophy on which it was initiated, to share existing information with as many potential users as possible.

Because of the large investment made in hardware and software expertise with the PLV system, in 1988, personnel in the Division of Research began investigating ways to expand the use of the underlying technologies. The Demonstration Bridge Information System (DBIS) project was initiated to develop an information system exclusively for the states' 5,000 bridges based on the PLV technology. The system would maintain an imagebase using the laser videodisc capability and a related database using a personal computer.

SYSTEM DEVELOPMENT

The purpose of the DBIS was to show the use of integrated computer and videodisc technology for the storage and retrieval of bridge information. The system was to be user-friendly and require no computer knowledge to operate. Although unforeseen at the time, the resultant system now provides the Department with the means for later development of a key element of its Bridge Management System (BMS).

Interviews

The first action in the development of the DBIS was to interview Department personnel who were familiar with the PLV system and whose duties were bridge-related. The question was posed that, given a system like the PLV, what type of information would you ideally want it to contain. It was determined that the internal flow of bridge-related database-type information was based on an archaic and inefficient system. Most of the bridge-related units did not share information with other units and conflicts did arise where the same work was scheduled to be done by two independent units. Several persons viewed the database capability of a DBIS as the solution to these conflicts and the investigators were quick to realize the importance of this type of information. The ability to query a common system or database made up from all pertinent sources was viewed as a timely development that would effectively address some difficult operational problems. It was with suggestions from these interviews, and the fundamental idea that the system would be used to query information only, that the database modules of the DBIS were designed. The imagebase portion was designed so it could be accessed through any of the database modules. Each of these modules is briefly described below.

Database

Bridge Log

This module was to replace the hard-copy binder used to maintain basic static information about bridges such as route, length, width, etc. Several suggestions were made to include other data and they were incorporated into this module. This module includes all National Bridge Inventory (NBI) data incorporated into the DBIS through an annual updating procedure. Representative screens from this module are shown in Figures 1 and 2. All data in the DBIS can be output in a printed report through a menu selection.

Chronology

This module was designed to provide a common database where all bridge-related units would share information. It is a chronological listing of all past, present and future activity on a bridge-by-bridge basis. This module tracks data necessary to analyze long-term performance of all construction, maintenance and inspection activity on a bridge with associated details. For example, through this module a user can access a copy of the Department's latest official bridge safety inspection report. This module also provides a cross-reference between a bridge identification number and associated project identification numbers. A representative screen for this module is shown in Figure 3.

Project

The design of this module was based on providing details about bridge-specific construction projects and, as the Chronology module does, provides a cross reference between a project identification number and associated bridge identification numbers. Often, there is a one-to-many relationship between projects and bridges. A representative screen for this module is shown in Figure 4.

Crisis

This module was based on the suggestion of a District Engineer who requested a source of information for off-hours use by an individual responding to an emergency. It lists recommended bypass routes for every route affected by closure of a bridge, and also utilities, local towns and DOT personnel to be notified. It is anticipated that an Incident Management System would derive benefit from ready access to this data. Representative screens for this module are shown in Figures 5 and 6.

Imagebase

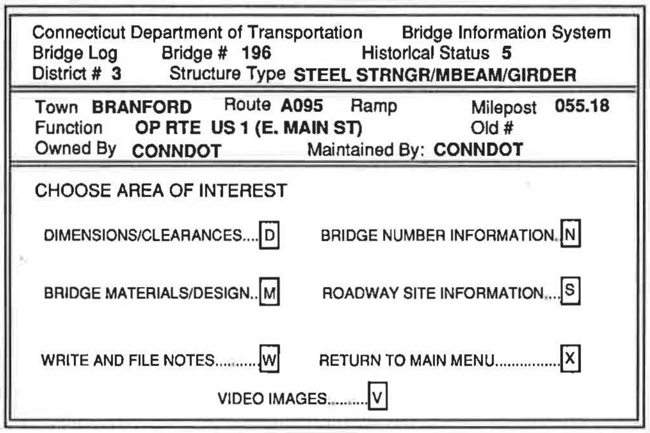
This pictorial module, accessible from all database modules other than "project," consists of a still-image photo album for each bridge. Images depict views of 1) each elevation of the bridge, 2) roadway approaches, 3) substructure details, 4) underside of deck, 5) superstructure details, 6) conditions photographed by Bridge Safety Inspectors, 7) special features such as mechanical systems on moveable bridges, 8) upstream and downstream, where appropriate, and 9) any special signing on or adjacent to the bridge.

For the DBIS, Research personnel gathered photo documentation of 43 bridges representing a broad cross-section of bridge designs found in Connecticut. The representative computer screen for choosing this module from the Bridge Log is shown in Figure 7. Note that the video images are displayed on the video monitor concurrently with the captions displayed on the computer monitor. Video prints of all images displayed are available as output using a color video printer.

IMPLEMENTATION

Based on the findings of the DBIS project, the FHWA approved a request for the implementation of a full-scale Bridge Information System (BIS) within ConnDOT. A fully implemented BIS is viewed as the means to improve communication, reduce duplicative efforts and facilitate later development of a BMS.

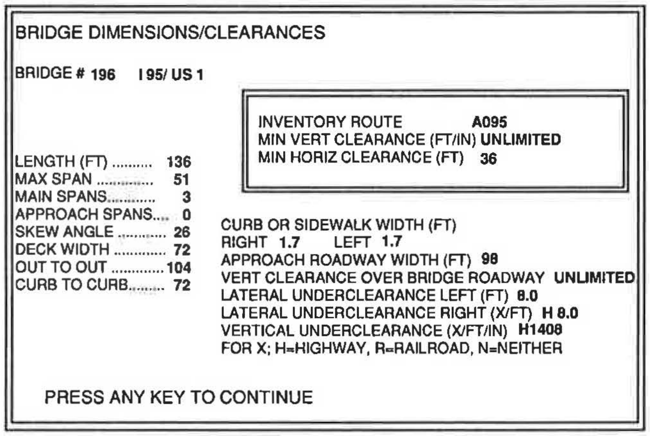
The largest task associated with implementation was the computerization or re-engineering of the operational processes of many bridge-related units. This involved purchase of hardware and development of software so information regarding the day-to-day operation of each unit would exist in an acceptable format. Once in this format, the data could then be provided to a full-scale BIS. To provide current information and ensure its validity, the task of generating and maintaining a computerized data source would have to be integrated


Connecticut Department of Transportation Bridge Information System
Bridge Log Bridge # **196** Historical Status **5**
District # **3** Structure Type **STEEL STRNGR/MBEAM/GIRDER**

Town **BRANFORD** Route **A095** Ramp Milepost **055.18**
Function **OP RTE US 1 (E. MAIN ST)** Old #
Owned By **CONNDOT** Maintained By: **CONNDOT**

CHOOSE AREA OF INTEREST

FIGURE 1 Bridge log module main menu.


BRIDGE DIMENSIONS/CLEARANCES

BRIDGE # **196** **I 95/ US 1**

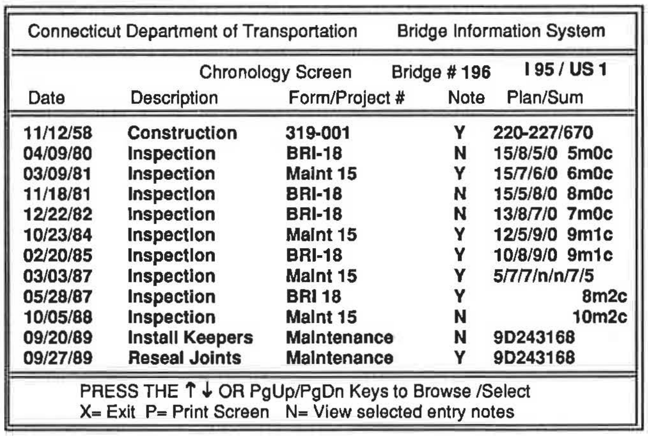
INVENTORY ROUTE **A095**
MIN VERT CLEARANCE (FT/IN) **UNLIMITED**
MIN HORIZ CLEARANCE (FT) **36**

LENGTH (FT) **136**
MAX SPAN **51**
MAIN SPANS........... **3**
APPROACH SPANS.... **0**
SKEW ANGLE **26**
DECK WIDTH **72**
OUT TO OUT **104**
CURB TO CURB........ **72**

CURB OR SIDEWALK WIDTH (FT)
RIGHT **1.7** LEFT **1.7**
APPROACH ROADWAY WIDTH (FT) **98**
VERT CLEARANCE OVER BRIDGE ROADWAY **UNLIMITED**
LATERAL UNDERCLEARANCE LEFT (FT) **8.0**
LATERAL UNDERCLEARANCE RIGHT (X/FT) **H 8.0**
VERTICAL UNDERCLEARANCE (X/FT/IN) **H1408**
FOR X; H=HIGHWAY, R=RAILROAD, N=NEITHER

PRESS ANY KEY TO CONTINUE

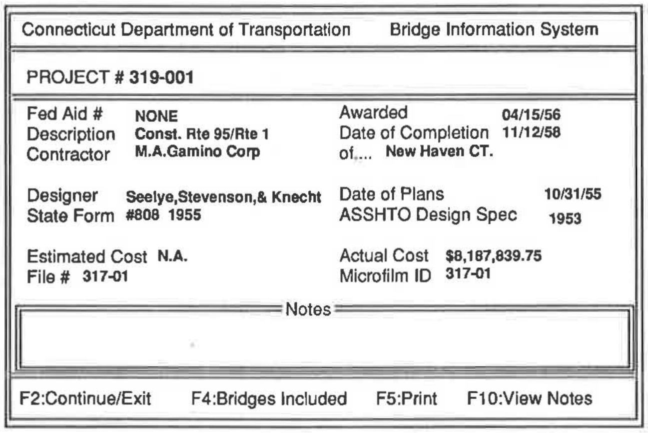
FIGURE 2 Bridge log module submenu.


Connecticut Department of Transportation Bridge Information System

Chronology Screen Bridge # **196** **I 95 / US 1**

Date	Description	Form/Project #	Note	Plan/Sum
11/12/58	**Construction**	**319-001**	**Y**	**220-227/670**
04/09/80	**Inspection**	**BRI-18**	**N**	**15/8/5/0 5m0c**
03/09/81	**Inspection**	**Maint 15**	**Y**	**15/7/6/0 6m0c**
11/18/81	**Inspection**	**BRI-18**	**N**	**15/5/8/0 8m0c**
12/22/82	**Inspection**	**BRI-18**	**N**	**13/8/7/0 7m0c**
10/23/84	**Inspection**	**Maint 15**	**Y**	**12/5/9/0 9m1c**
02/20/85	**Inspection**	**BRI-18**	**Y**	**10/8/9/0 9m1c**
03/03/87	**Inspection**	**Maint 15**	**Y**	**5/7/7/n/n/7/5**
05/28/87	**Inspection**	**BRI 18**	**Y**	**8m2c**
10/05/88	**Inspection**	**Maint 15**	**N**	**10m2c**
09/20/89	**Install Keepers**	**Maintenance**	**N**	**9D243168**
09/27/89	**Reseal Joints**	**Maintenance**	**Y**	**9D243168**

FIGURE 3 Chronology module main menu.



```
Connecticut Department of Transportation      Bridge Information System

PROJECT # 319-001

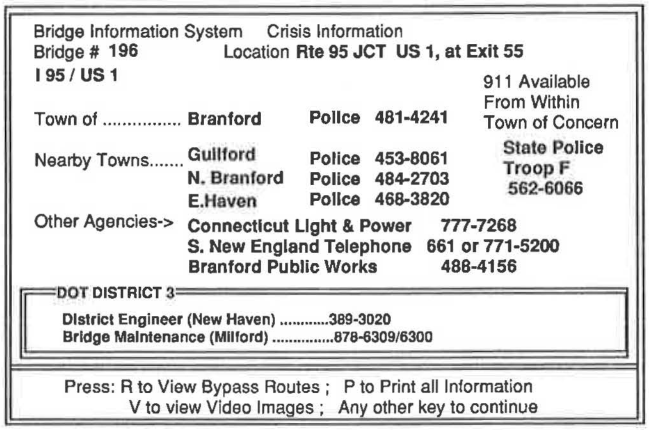
Fed Aid #     NONE                        Awarded                 04/15/56
Description   Const. Rte 95/Rte 1         Date of Completion  11/12/58
Contractor    M.A.Gamino Corp             of....  New Haven CT.

Designer     Seelye,Stevenson,& Knecht    Date of Plans           10/31/55
State Form   #808  1955                   ASSHTO Design Spec      1953

Estimated Cost  N.A.                      Actual Cost  $8,187,839.75
File #  317-01                            Microfilm ID  317-01
                                 Notes

F2:Continue/Exit     F4:Bridges Included     F5:Print     F10:View Notes
```

FIGURE 4 Project module main menu.

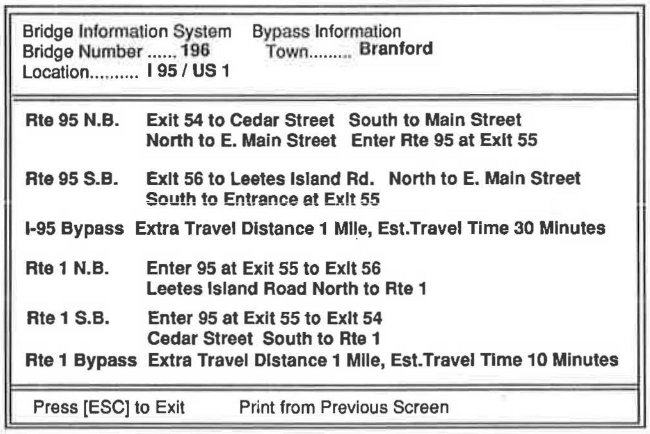


```
Bridge Information System    Crisis Information
Bridge #  196              Location Rte 95 JCT  US 1, at Exit 55
I 95 / US 1                                         911 Available
                                                    From Within
Town of ................ Branford     Police  481-4241   Town of Concern

Nearby Towns....... Guilford         Police  453-8061    State Police
                    N. Branford      Police  484-2703    Troop F
                    E.Haven          Police  468-3820     562-6066
Other Agencies->    Connecticut Light & Power      777-7268
                    S. New England Telephone   661 or 771-5200
                    Branford Public Works          488-4156
DOT DISTRICT 3
   District Engineer (New Haven) ............389-3020
   Bridge Maintenance (Milford) ..............878-6309/6300

     Press: R to View Bypass Routes ;  P to Print all Information
            V to view Video Images ;  Any other key to continue
```

FIGURE 5 Crisis module main screen.



```
Bridge Information System    Bypass Information
Bridge Number ...... 196        Town......... Branford
Location.......... I 95 / US 1

Rte 95 N.B.    Exit 54 to Cedar Street   South to Main Street
               North to E. Main Street   Enter Rte 95 at Exit 55

Rte 95 S.B.    Exit 56 to Leetes Island Rd.   North to E. Main Street
               South to Entrance at Exit 55

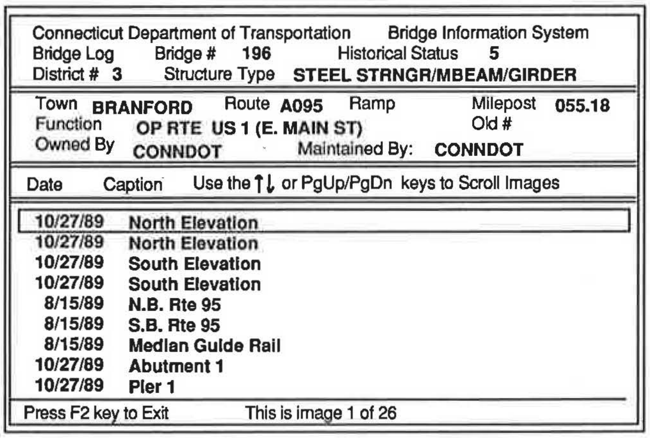
I-95 Bypass  Extra Travel Distance 1 Mile, Est.Travel Time 30 Minutes

Rte 1 N.B.     Enter 95 at Exit 55 to Exit 56
               Leetes Island Road North to Rte 1

Rte 1 S.B.     Enter 95 at Exit 55 to Exit 54
               Cedar Street  South to Rte 1
Rte 1 Bypass  Extra Travel Distance 1 Mile, Est.Travel Time 10 Minutes

  Press [ESC] to Exit        Print from Previous Screen
```

FIGURE 6 Crisis module bypass route screen.



```
Connecticut Department of Transportation      Bridge Information System
Bridge Log      Bridge #   196          Historical Status   5
District #  3      Structure Type  STEEL STRNGR/MBEAM/GIRDER

Town  BRANFORD      Route  A095    Ramp              Milepost  055.18
Function    OP RTE  US 1 (E. MAIN ST)                Old #
Owned By    CONNDOT           Maintained By:   CONNDOT

Date     Caption    Use the ↑↓ or PgUp/PgDn  keys to Scroll Images

10/27/89    North Elevation
10/27/89    North Elevation
10/27/89    South Elevation
10/27/89    South Elevation
 8/15/89    N.B. Rte 95
 8/15/89    S.B. Rte 95
 8/15/89    Median Guide Rail
10/27/89    Abutment 1
10/27/89    Pier 1

Press F2 key to Exit          This is image 1 of 26
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FIGURE 7 Bridge log module screen while viewing video images.

into the daily operation of each unit. Clearly this must be an improvement in their work process rather than an additional data-entry duty.

An example of this effort was the computerization of the bridge inspection process with the use of laptop computers. Inspectors within the Division of Bridge Safety began using the computers in the field to record information during the normal biennial safety inspections that was formerly recorded by hand on paper forms. This served to improve the recording of bridge inspection information and provide a source of information that is compatible with the BIS. This source can now be uploaded to the BIS and made available to users of the BIS without any extra effort in the inspection process. Future biennial inspections will be carried out by overwriting the BIS inspection report that will be downloaded to the laptop computer. The signed hardcopy of the previous year remains the official inspection report. Efforts are currently underway to computerize the permitting of oversize/overweight vehicles so this information can be made part of the BIS. Within the Office of Engineering, a program to track a project through the design process is also planned not only for interoffice use, but for interdepartment use through the BIS.

The imagebase is being filled with 35 mm images taken by bridge safety inspection personnel during their normal biennial inspections. Prints are returned to bridge-safety personnel while developed negatives are forwarded to the unit responsible for PLV production. Images are recorded on a recordable videodisc "master." When enough images have been accumulated, a Philips-format videodisc is produced and replicated. Copies are then distributed to the 27 BIS viewing systems as an imagebase update.

BIS COSTS

With the continual decline in the cost of personal computers, it is difficult to provide a valid cost for a BIS workstation. The essential components in a complete workstation are: a personal computer with a minimum hard disk capacity of 120 Megabytes; a laser videodisc player that can be controlled by the PC through a serial port; and, a NTSC compatible video monitor. The cost of other equipment such as a modem, video printer and laser or dot matrix printer, depends on the features specified.

The labor cost of implementing a full-scale BIS is directly related to the level of computerization that exists within bridge-related units. The cost of operating such a system is difficult to estimate given its current implementation stage. Optimistically, the cost of operation should be minimal since the information that the system uses will be provided through the normal operation of bridge-related units.

BRIDGE MANAGEMENT SYSTEM

As defined in the *Federal Register*,

> "The primary purpose of these management systems is to improve the efficiency of, and protect the investment in, the nations existing and future transportation infrastructure,"

wherein,

> "The management systems are envisioned as part of an integrated transportation information system that would: facilitate coordination of the

> management systems with related programs (e.g., HPMS, speed monitoring, air quality, etc.), facilitate the sharing of resources and data, improve communication among data users, and facilitate the coordination of the metropolitan and statewide plans and programs." (*1*)

While the BIS is not an "integrated transportation information system," it was designed as an integrated information system for bridges. Some problems discovered during the BIS project bring to light the importance of coordination, sharing and communication between data users. A common misconception is that a BMS is also a BIS. A major aspect of a BMS is a network analysis tool, such as Pontis or BRIDGIT. The validity of a network analysis is only as good as the data input to the program. The time spent actually doing a network analysis is insignificant when compared to the time and energy spent collecting and updating the required bridge-related data.

The data required for a BMS network analysis are essentially of two types: condition rating and inventory information. To collect Pontis condition ratings, a computer program was written for use on the laptop computers and augments safety inspection data collection. Inventory data will be gathered from many sources including several database files maintained on the Department's mainframe computer and other personal computer-based programs and data files. The BIS implementation project will provide an initial collection and updates of data for all bridges. The BIS data are available to a BMS analysis in the same way that mainframe data are. Further processing of some data, such as conversion of inspection-date format, to meet the requirements of a BMS analysis tool can be done within the BIS. The hardware used for the BIS meets the requirements of a BMS analysis tool such as Pontis and BRIDGET.

Operation

Operation of the BIS will address several issues related to an integrated transportation information system, such as, sharing data resources, improving communication among data users and coordinating the operation of bridge-related units within ConnDOT. This will be done through the distribution of computerized data files that are the products of the daily operation of the bridge-related units. These compatible data will then be processed and provided to a network analysis program as needed. The BIS will support the results of these analyses through the historical archive of information.

As with any system of this magnitude, several personnel will be responsible for ensuring that data are distributed and maintained. Software and hardware upgrades and maintenance also will be the responsibility of these personnel. These personnel also will be tasked with performing the network analyses.

Upgrades and Improvements

Several efforts are currently underway to expand and improve the use of laser videodiscs within ConnDOT. A "video windows capability" to view video images on the computer screen will eliminate the need for the video monitor and provide the full functionality of both the PLV and BIS. Future improvements will include the use of digital cameras during the inspection process. It is anticipated these images could be imported to upgraded laptop computers in the field and immediately integrated into the inspection report. Long-term storage and broad distribution of these digital images will then be efficiently provided using the laser-videodisc format currently used.

SUMMARY

Connecticut is fortunate to have been involved in a project of this type long before the mandated implementation of a BMS. A key element in the implementation of a full-scale BIS is the re-engineering of the information-process in affected units. The development of the BIS came at a good time, due to the availability of high performance personal computers and software. Many lessons learned during the project will aid in the implementation of Connecticut's BMS. The philosophy behind the Connecticut BIS is consistent with that of an "integrated information system," of which a BMS is a part. A true BMS should contain network analysis tools and BIS capabilities.

REFERENCE

1. "Management Systems; Proposed Rule," *Federal Register*, 23 CFR Chapter 1, 49 CFR Chapter VI, Volume 57, No. 107, pages 23460-23461.

INDIANA'S APPROACH TO A BRIDGE MANAGEMENT SYSTEM

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ABSTRACT

Indiana approached the development of a bridge management system with the requirement to utilize the current bridge inspection data collected under the guidelines of the National Bridge Inventory standards. There are four core modules of the system that run sequentially. The four modules are decision tree (*DTREE*), economic analysis (*COST*), ranking (*RANK*), and optimization (*OPT*). The objective of *DTREE* is to analyze condition and geometrical data selecting representative actions over a five-year time window, updating condition ratings dynamically by the Markovian process. The *COST* module uses recommended actions, costs and action years from *DTREE* to perform life-cycle cost analysis. The *RANK* module selects projects in priority order based on a weighted criteria to maximize effectiveness of investment, bridge condition preservation, bridge traffic safety, and minimize negative community impact. Utility curves were derived for these criteria to measure effectiveness (benefit) based on the difference in utility values from the projected bridge condition at the time of proposed construction, to the utility value of the proposed bridge improvement. Selection of projects can be made by selecting projects of the highest effectiveness until funds are expended. The *OPT* module uses the output from the *RANK* module to select bridges with the greatest total effectiveness. Thus, the effectiveness is the improvement in overall disutility of the bridge. The intent of the optimization process is to maximize the system effectiveness and minimize the cost while staying within the proposed budget.

INTRODUCTION

The management of any large group of items, as related to maintaining or improving their condition within a limited budget in the most economical manner, involves a complex decision-making process. The development of a bridge management system (BMS) fits this definition. A BMS is a planning tool that provides information to help in the selection of improvement projects, both by time and type, estimate costs and prioritize projects. The Indiana Department of Transportation (INDOT) through a Joint Highway Research Project at Purdue University initiated the development of such a BMS (*1,2,3*). There were six objectives established for the development of the system.

- Development of a method to better use the existing bridge inspection data as required by the National Bridge Inventory (NBI) requirements in the selection of bridges for maintenance, rehabilitation and replacement.
- Development of a method to provide consistent and statewide uniform measurements for rating bridges.
- Analysis of bridge maintenance, rehabilitation and replacement costs, and analysis of relationships between bridge attributes and costs.
- Development of a method to estimate remaining service life of bridges and effects of bridge activities on condition rating and service life.
- Development of a bridge traffic evaluation scheme that relates physical characteristics of a bridge structure to accident potential.
- Development of a project selection procedure using life-cycle cost analysis, ranking, and optimization.

These six objectives have been met and incorporated into a software package including a user's manual (*4*). We are presently in the implementation stage testing the complete system and completing the users manual. Indiana's BMS is a project level management system. As with any system, we have detected enhancements that we wish to incorporate, and we will begin that process in the near future.

PROGRAM REQUIREMENTS

The Indiana Bridge Management System (IBMS) runs on an IBM-compatible computer system. The IBMS package was developed using IBM FORTRAN/2, under the IBM Operating System/2 (OS/2), Standard Edition 2.0. Subprograms or tools used within the program to check data, formatting and sorting were written in Microsoft C. The following hardware equipment is the minimum to operate the system: a 386 IBM-compatible computer with a 20-megahertz processor, 4 megabytes (MB) of available memory (RAM), and 80 MB of hard drive space. The program only requires about 3 MB of hard drive space, but the commercial software packages (OS/2, Microsoft C, and IBM FORTRAN/2) require an additional 30 to 60 MB. To run the program, OS/2 must be installed. In addition, if one plans to modify the source code then IBM FORTRAN/2 and Microsoft C also must be installed. The capabilities of the IBMS can be expanded by installing a spreadsheet program such as Lotus 1-2-3 and a word processing program such as WordPerfect.

Input data are always required to run any software package. One objective in the development of the system was to use the bridge inspection data required under the guidelines of the NBI standards. The basis for this decision was to prevent the collection of additional inspection data than required. Our bridge inspectors were already operating under limited resources, both equipment and labor, to satisfy the Federal Highway Administration (FHWA) bridge inspection reporting requirements. With this objective established, there was no need to revise the inspection requirements, only a need to establish a method that would provide a consistent and uniform rating of bridge components on a statewide basis.

The required input data consist of twenty-seven (27) items collected under the NBI guidelines. These items for each bridge are down-loaded from our mainframe computer database to an input file for running the IBMS software. The data down-load for analysis can be selected by defining limits of the input parameter searches by road type, district, subdistrict, county, statewide, etc. This allows an analysis to be executed, for example, for the Interstate system, or maybe a selected district. The required input data items, some for analysis purposes, and others for housekeeping or information in the reporting mode, are listed in Table I.

As with planned details, the possibility exists of overlooking some items in the process. This held true in our case as well. There were two input data items that should have been collected to satisfy the software requirements that are not presently being collected. They will be collected in the future, and the software will be modified to accommodate this revision. The two data items are vertical clearance under (over water) and an estimated roadway improvement length. The vertical clearance is collected for bridges over any feature except water. To account for this, a default value of 18 feet was included in the program with the ability to revise this value for any specific bridge where the vertical clearance is different. Similarly, a default value of 100 feet was included for the roadway improvement length with the ability to revise for any specific bridge where the improvement length is different from the default value.

In addition, there are other input or program control items that must be included to operate the program. Two types of files have to be included as input to operate the system and a third file is an option for the user. These files control the program operation, provide a link between the user and the program, and control the use of the input data. The files are named *RUNFILE*, *PARAMETER FILE*, and *EXCEPTION FILE*.

TABLE I BRIDGE MANAGEMENT SYSTEM INPUT DATA

Highway Route Number
County Number
Bridge Number (last 5 digits)
Bridge Designation
District Code
Year Built
Year Last Reconstructed
Functional Class Code
Highway System of Inventory Route
Average Daily Traffic
Number of Traffic Lanes
Deck Width
Bridge Clear Roadway Width
Structure Length
Vertical Clearance-Feet
Vertical Clearance-Inches
Kind of Superstructure Material
Type of Superstructure Construction
Bypass Detour Length
Type of Loading
Inventory Rating (Gross Load in Tons)
Deck Condition Rating
Superstructure Condition Rating
Substructure Condition Rating
Deck Geometry Code
Type of Work Proposed
Last Inspection Date

RUNFILE is required and controls the program operation. The file sets all option settings and input/output file names used by the program. Instead of entering the option controls each time the program is executed the system uses this special file. There is a predefined *RUNFILE* included with the program and is named "DEFAULT." When the program asks for a *RUNFILE* name, entering "default" uses the internal file. However, if a name other than "default" is entered, the program will attempt to read a *RUNFILE* from a disk. The special *RUNFILE* may use completely different program controls from the default, or it may only have one change from the default. This option is at the discretion of the user. The file is divided into two sections. One section defines the option settings for running the *DTREE*, *COST*, *RANK*, and *OPT* program modules by a series of yes/no questions. The second section lists the names of the input/output and *PARAMETER FILE*s to be used by the program.

*PARAMETER FILE*s are required and provide another method of controlling the program operation by external means rather than hard coding into the source program. They are the primary link between the program and the user. There are six *PARAMETER FILE*s required to run the system. These files define input data, equations, and decision criteria for the parameter files of decision tree, cost estimates, life-cycle model, ranking weights for utility value computation, ranking utility factors, and dollar conversions to base year. These files are predefined in the program, but can be modified in whole or in part at the discretion of the user.

The reasoning for a *RUNFILE* and the *PARAMETER FILE*s was to provide flexibility to the user. By using these files, the user can utilize the predefined input data, equations, or decision criteria, or modify the data without having to recompile the source program. Therefore, the predetermined input data can be modified to the user's requirements, to run different scenarios for comparison of results, or to respond to inquiries.

The other input type file that can be used with the program is an *EXCEPTION FILE*. This file is not required for normal operation of the system; it merely provides additional control and flexibility. The *EXCEPTION FILE* allows the user to modify the input data that were down-loaded from the bridge NBI database. The data included in the *EXCEPTION FILE* allows an override of decisions made by the *DTREE*, *RANK* and *OPT* modules, and the physical features of each bridge. Data in this file can override the selected action, action year, and the bridge length, width, vertical clearance, and the road approach improvement length. A file record must be established for each bridge in which the user chooses to set these certain criteria. The *EXCEPTION FILE* is another means of entering data into the program that controls the output.

INTERRELATED SYSTEM CORE PROGRAMS

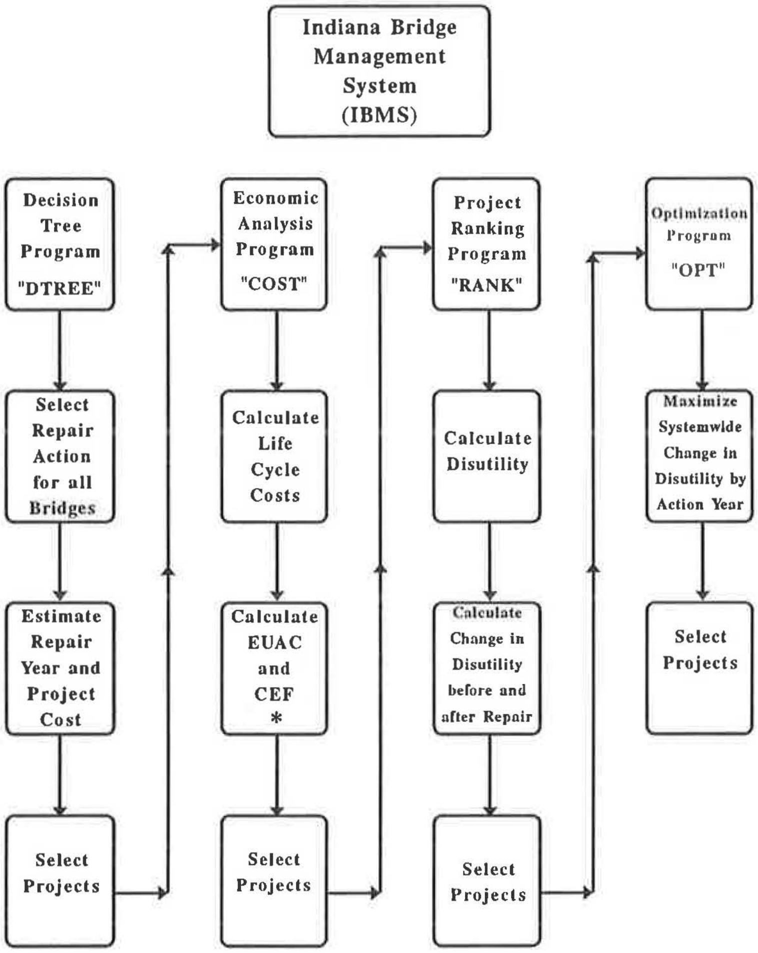
The core of the system for project selection is four interrelated modules that run sequentially. Output from one module is saved and passed on to the following module as input. The four modules are: *DTREE*, *COST*, *RANK*, and *OPT*. *DTREE* selects possible actions and passes the information on to the *COST* model that computes the life-cycle costs. The next module is the *RANK* program followed by the *OPT* program. A flow chart of the program operation is shown as Figure 1.

These programs were developed specifically for bridges under the jurisdiction of the INDOT. They also can be modified to serve other states and local units of government to satisfy the Intermodal Surface Transportation Efficiency Act (ISTEA) requirements by use of the *RUNFILE*, *PARAMETER FILE*s and *EXCEPTION FILE*s. Additional data are not required to be collected to run the program. Data collected under the requirements of the NBI guidelines satisfies the program requirements. Although the program was developed for INDOT it can serve other users with similar type bridges. The basic type bridges that can be analyzed for replacement and rehabilitation are RC slabs and box beams, concrete I-beams, steel beams, and steel girders. The program now will not handle trusses, frames or culverts because of the lack of cost data.

DECISION TREE

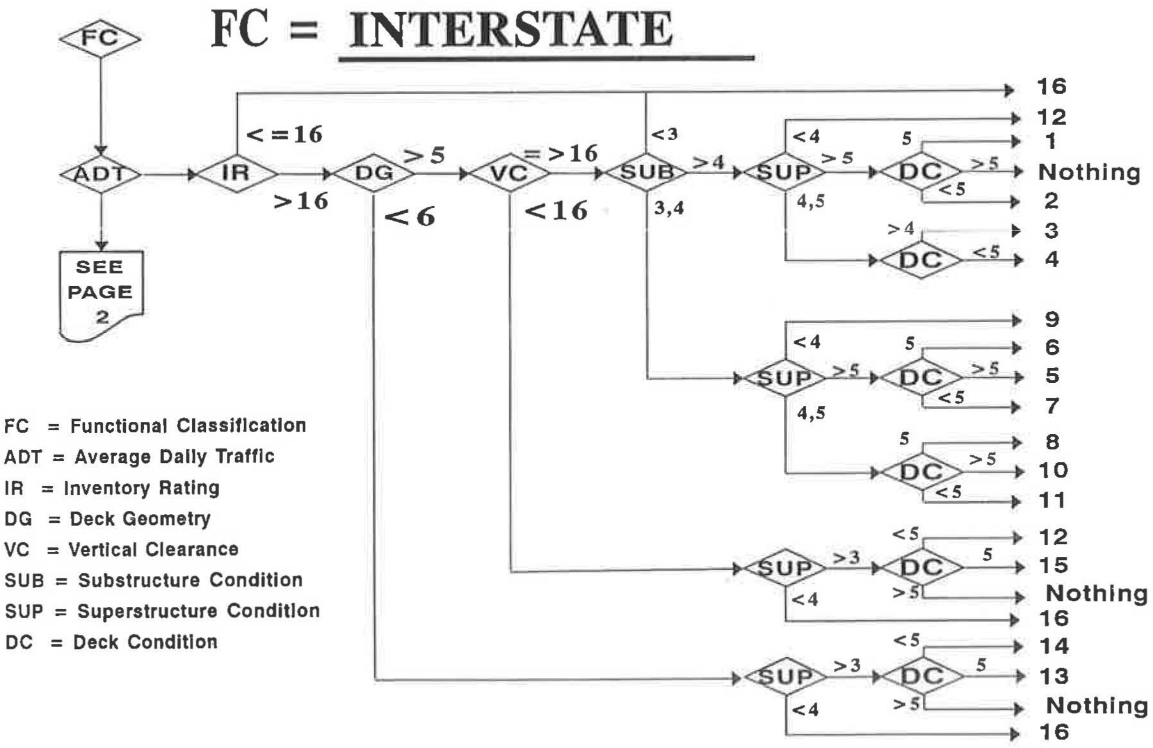
The *DTREE* program, the first module, analyzes the bridge input data and recommends an action for each bridge. The action is based on deck, superstructure and substructure element condition ratings, bridge geometric constraints, traffic, and road classification. The decision tree format is based on bridges of a given functional class. The program allows up to four sets of decision trees to be defined by *PARAMETER FILE*s. A decision tree for a major highway bridge is shown in Figure 2 and Table II. The action will be one of three alternatives: do nothing, rehabilitation, or replacement with the rehabilitation option selecting one of fourteen (14) different alternatives. These alternatives are the prevailing rehabilitation options with INDOT. The rehabilitation selections are either a reconstruction or improvement decision. The improvement alternatives are bridge widening, bridge replacement, raising the bridge, or lowering the pavement based on the geometrical, structural, and traffic characteristics of the bridge. If the bridge characteristics satisfy the geometrical and structural requirements for the respective classified road, any reconstruction actions selected will be based on the bridge condition ratings of the deck, superstructure, and/or substructure updated dynamically by the Markovian process.

The program analyzes the input set of bridges over a five-year period. Improvements are recommended two, three, four and five years in advance from the input year of analysis. The five-year analysis period is the typical time in Indiana for programming and preliminary engineering. An extended period can be analyzed by using a second run with a future input year of analysis.



* EUAC = equivalent uniform annual cost
CEF = cost effectiveness factor

FIGURE 1 IBMS operation.



FC = Functional Classification
ADT = Average Daily Traffic
IR = Inventory Rating
DG = Deck Geometry
VC = Vertical Clearance
SUB = Substructure Condition
SUP = Superstructure Condition
DC = Deck Condition

FIGURE 2 BMS - Condition rating default decision tree.

TABLE II BMS - MR&R ACTIONS

1 = Deck Rehabilitation
2 = Deck Replacement
3 = Superstructure Rehabilitation + Deck Rehabilitation
4 = Superstructure Rehabilitation + Deck Replacement
5 = Substructure Rehabilitation
6 = Substructure Rehabilitation + Deck Rehabilitation
7 = Substructure Rehabilitation + Deck Replacement
8 = Substructure, Superstructure and Deck Rehabilitation
9 = Substructure Rehabilitation + Superstructure Replacement
10 = Substructure Rehabilitation + Superstructure Rehabilitation
11 = Substructure and Superstructure Rehabilitation + Deck Replacement
12 = Superstructure Replacement
13 = Bridge Widening + Deck Rehabilitation
14 = Bridge Widening + Deck Replacement
15 = Raise Bridge/Lower Pavement
16 = Bridge Replacement

The program analyzes each bridge in each year in selecting an option action by updating the substructure, superstructure and deck condition ratings using the Markovian deterioration model. Transition probabilities were developed for the deck, superstructure, and substructure conditions for the Markov chain model in predicting future conditions of individual bridges. Probabilities were determined for different types of bridges of concrete or steel, and whether they are on the interstate or non-interstate system. The physical characteristics of the bridge remain constant, but the bridge element condition ratings can change during the analysis period resulting in different action options. Therefore, actions with costs are recommended in a four-year time window beginning two (2) years from the input year of analysis. The actions and costs for each bridge per year are saved and passed on to the next module that is named *COST*.

ECONOMIC ANALYSIS

Once a decision has been made to fund an improvement to a bridge, future funding needs also must be analyzed since a bridge represents a long term investment in the infrastructure. This is accomplished using the *COST* module. *COST* uses the recommended actions, costs and action year from *DTREE* to perform a life-cycle cost analysis for each bridge. A projected design life for steel and concrete bridges was determined from experience and preset in the software as shown in Table III.

The life-cycle analysis in *COST* module uses each recommended action from *DTREE* and selects future actions from Table III based on the present point in time of the bridge in its design life. For example, a steel bridge with a recommended action of deck replacement from *DTREE* would have a life-cycle analysis performed using costs of a deck rehabilitation 15 years and replacement of the bridge 30 years into the future. The projected bridge design life is used only for future strategies in the *COST* model. These projected design life actions are used in the life-cycle analysis per each recommended action resulting from the *DTREE* module. The various expenditures at different periods in the bridge activity profile are converted to a present value by multiplying appropriate interest formulas with a discount rate and the analysis period to compute an Equivalent Uniform Annual Cost (EUAC). The EUAC is then computed in perpetuity. This method is especially suitable for evaluating multiple alternatives with different analysis periods. A cost-effectiveness factor is determined by dividing the combination of the yearly traffic volume and deck area by the equivalent uniform annual cost. The cost-effectiveness factor is a value of annual vehicle deck area per expended dollar. This factor provides a mechanism to allow comparison of bridges with different attributes and service levels. Bridges can be prioritized at this point by using the cost-effectiveness factor.

RANK

The third core program is the project *RANK* module. This program is based on computing factors termed "utility" for several criteria. The definition of utility is the level of overall effectiveness that can be achieved by undertaking a project. Condition is not the only factor used to select bridges for improvement. There are many factors that should be considered in evaluating the overall condition and importance of a bridge when establishing a priority ranking method. The ranking method is a procedure to select projects in a priority order based on several weighted evaluation criteria. The projects are sorted by their priority ranking with the worst bridge listed first (highest utility value) and successive worst bridges listed in order. The selection

TABLE III BRIDGE DESIGN LIFE

Steel Bridge		Concrete Bridge	
Age	Activity	Age	Activity
0	New	0	New
20	Deck Rehabilitation	20	Deck Rehabilitation
35	Deck Replacement	35	Deck Rehabilitation
50	Deck Rehabilitation	50	Bridge Replacement
65	Bridge Replacement		

process is made by selecting from the top of the list until the available budget is expended. The ranking method must be a systematic procedure to set the relative importance of all projects, but also must show the importance of one project over another.

Four objectives were selected in determining the criteria for the IBMS: 1) maximize effectiveness of investment, 2) maximize bridge condition preservation, 3) maximize bridge traffic safety, and 4) minimize negative community impact. These four (4) objectives are the evaluation criteria on which the ranking system is based. The second criterion of bridge condition preservation is divided into two (2) factors of estimated remaining service life and structural condition rating. The third criterion of bridge traffic safety is divided into three components of clear deck width, vertical clearance, and inventory rating. This provides seven utility functions that can be weighted by the bridge management engineer's judgment, or by a group of individuals within the organization. The weighting values can be determined by one of two options; an eigenvector approach of determining relative importance by pairwise comparison, or by an expert opinion poll of agency decision makers. The value of each utility function can be added or used independently to obtain an overall priority ranking.

The utility function is an evaluation curve from zero (0) to one-hundred (100) with zero indicating the bridge is in perfect condition and 100 indicates immediate repair or replacement is required. The utility curve is a numerical measurement of the bridge condition, cost, safety or impact to the community. A utility curve must be constructed for each of the seven utility functions. These equations are soft coded into the system by *PARAMETER FILE*s. A simple utility curve for vertical clearance for the bridge traffic safety criteria is shown in Figure 3. This happens to be a straight line function, where, if the vertical clearance is 14 feet or less the bridge receives a utility value of 100; while a vertical clearance of 16'-3" or greater would receive a utility value of zero. Vertical Clearance between these two values will receive a utility value proportional to the differences between the two governing clearance values. The bridge manager can revise this criterion by changing the constants and line equations in the ranking utility *PARAMETER FILE*.

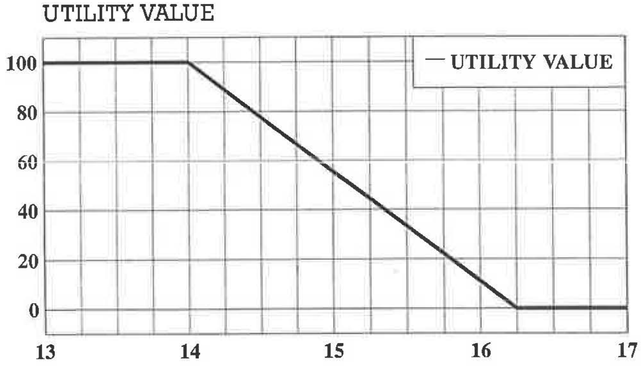


FIGURE 3 Vertical clearance utility curve.

The numeric difference in utility value for each evaluation criterion of before and after a proposed improvement activity is termed "disutility." The bridges can be ranked for any evaluation criterion using the disutility values with respect for that criterion only. This would not be the normal procedure as one would prefer to rank the bridges following all criteria. Therefore, weighted factors are assigned to each of the seven (7) evaluation criteria according to its importance. The four (4) functions of cost effectiveness, bridge condition, bridge safety, and community impact defining the ranking criteria are shown in Figure 4. The weighted values of each function are shown with its respective

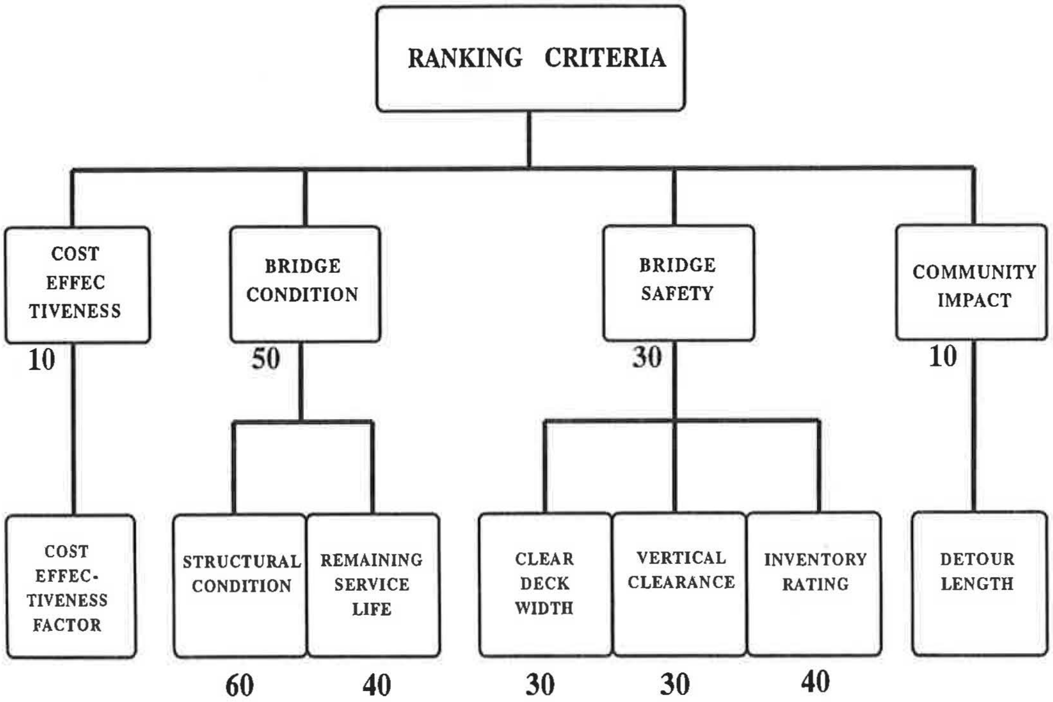


FIGURE 4 Ranking criteria basis.

function. The bottom group in the figure combines the utility values of structural condition and remaining service life into a utility value for bridge condition with their respective weighted values. Similarly, the utility values of clear deck width, vertical clearance, and inventory rating are combined into one utility value for bridge safety with their respective weighted values. A total ranking score is computed summing the individual criteria disutility values multiplied by their respective weight factors. This ranking method allows the comparison of different evaluation criteria measured in different units with different importance. The weighted values are soft coded into the program by *PARAMETER FILE*s and can be adjusted in time as more experience is gained within the system. Thus, the weighted values can be determined by an expert opinion poll within the organization and revised with ease any time. Furthermore, one can revise the weighted values to check the sensitivity of the results.

OPTIMIZATION

The ranking procedure selects projects from the worst to the best condition. It does not maximize benefits to produce an optimal solution for the BMS. The optimization procedure selects projects that add the most benefit or produce the highest network level of service to the bridge system based on the constraints, usually the budget. The *OPT* module uses the same factors determined in the *RANK* module, namely the utility values. The difference in the two systems is that the *RANK* module will select bridges with the highest overall disutility value (the worst bridges) until the allocated budget is depleted; whereas, the *OPT* module will select bridges with the greatest total benefit or effectiveness within the budget constraint. The bridge benefit or effectiveness is the difference in utility values from the present time, or projected bridge condition at the time of proposed construction, to the utility value of the proposed bridge improvement. Thus, the effectiveness is the improvement in overall disutility of the bridge. The intent of the optimization process is to maximize the system effectiveness and minimize the cost while staying within the proposed budget. The utility value of a bridge based on its condition at the projected time of improvement will always be larger than the utility value for the improved bridge based on our definition of the utility equations. Since there is a decrease in utility values, the difference is the benefit or effectiveness and is termed the disutility value. The disutility is the overall effectiveness gained by undertaking an action.

The *OPT* module was developed using dynamic programming in combination with integer linear programming and Markov chain. Markov chain transition probabilities were applied to predict or update bridge conditions at each stage of the dynamic

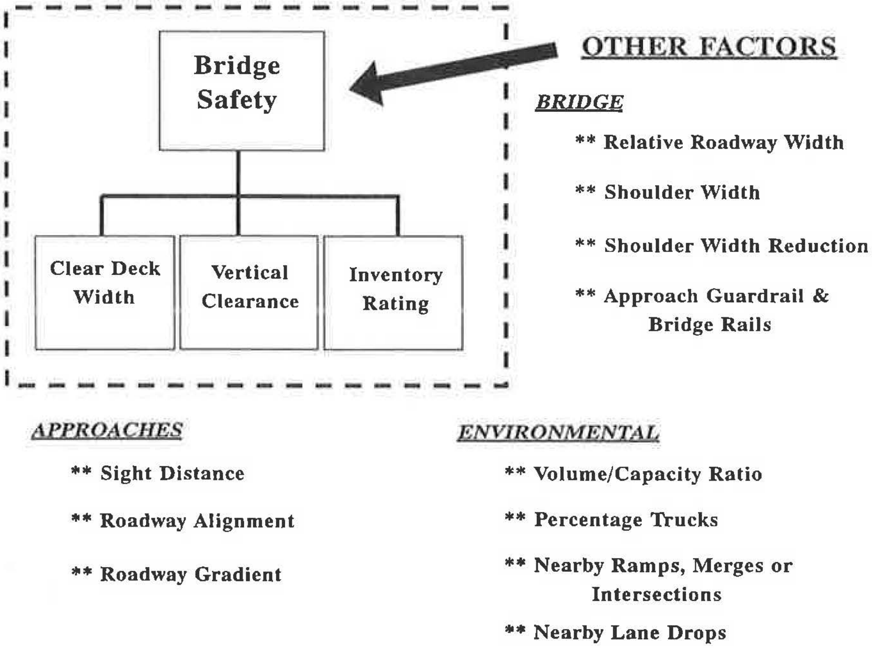


FIGURE 5 Bridge safety factors.

programming. The objective of developing performance curves was to find the relationship between condition rating and bridge age. A third order polynomial model was used to obtain the regression function of this relationship. The Markov chain as applied to bridge performance prediction is based on defining states in terms of bridge condition ratings and obtaining the probabilities of bridge condition changing from one state to another. These probabilities are represented in a matrix form called the transition probability matrix or simply, transition matrix, of the Markov chain. Knowing the present state of bridges, or the initial state, the future conditions can be predicted through multiplications of initial state vector and the transition probability matrix. The history of 1,000 bridges in Indiana was used to formulate the transition probabilities. This procedure projects the condition of each bridge rather than predict a condition based on the average deterioration rate of a group of similar type bridges. Therefore, the computed disutility values should be more accurate for each bridge.

Under a budget that is less than needed for the system, the *OPT* module provides a larger benefit to the system than the *RANK* module. As the budget increases, the two modules converge on benefit until the needed system is reached and the modules provide the same system benefit.

ENHANCEMENTS

We have an operating system with procedures determined, software written and tested, and a user's manual prepared. As with any system when completed, there are always improvements that can be made to refine the system operation. We have also found this to be true with our system. We have an enhancement proposal through our Joint Highway Research Project program with Purdue University to study and produce the proposed enhancements. These enhancements include updating the current cost algorithms, obtaining cost data and algorithms for rehabilitation scenarios that are not included, expanding the decision tree improvement options for each situation; and, adding other criteria to the utility process. Other items that we wish to have considered for inclusion into the utility routine are in the bridge safety area, i.e., approaches, environmental factors, and other bridge geometries as outlined in Figure 5, and community impact items as listed in Figure 6. These items may not be added to the system but we want to study the possibilities.

CONCLUSION

The BMS developed for Indiana is a project level management system. The analysis and results were

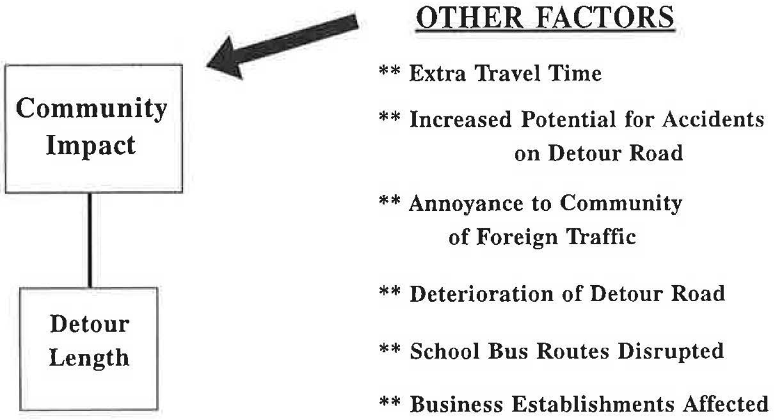


FIGURE 6 Community impact factors.

structured to develop a bridge improvement program and not a maintenance program. To refrain from misleading anyone that we are not concerned with a bridge maintenance program, there needs to be an explanation. The definition or terminology of maintenance in Indiana must be explained to understand our work program.

INDOT has two (2) methods of working on their bridges using maintenance personnel or contractors. The maintenance personnel manage five (5) identified work activities: hand cleaning bridges, bridge repair, flushing bridges, patching bridge decks, and other bridge maintenance activities. These work items are managed through our Maintenance Management System and are identified by our bridge inspectors during their biannual inspection or by notification from other sources. These work items are small as our maintenance forces do not have the equipment, labor, or allocated funding to handle larger repair projects. Bridge painting, a maintenance item, is accomplished through contract to paint the entire bridge. Our operating system is not set up to paint part of a bridge such as may be identified in another BMS. All other work is let to contract, whether it is a major repair, rehabilitation, or replacement.

It is not our intention to let the software dictate our program. The software will project future conditions based on current inspection results and analyze different rehabilitation options to formulate a proposed program. Once a proposed program is formulated, engineers will field check the bridges and prepare a complete scope of work. The scope will include all deck, structural, approach, and maintenance of traffic requirements with an updated cost estimate. Any revised data can be input into the software and executed again for a final program.

We need to leave the engineering judgment to engineers at the time of program development rather than a computer analysis based on inspection data of up to two (2) years old. The IBMS is a planning tool, not a final decision making mechanism. We want to avoid the black box syndrome. We believe the method of developing a complete analysis of the project condition including structural, approaches, environmental, and geometry conditions with proposed recommended actions is needed before starting the design phase. This procedure should provide a complete cost estimate and work scope of the entire project, rather than the bridge specific activities. Therefore, projects added to the annual program in this manner should not overload the system both in the funding requirements and preliminary engineering.

ACKNOWLEDGMENTS

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ANALYSIS OF BRIDGE MANAGEMENT DATA IN NORTH CAROLINA

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ABSTRACT

An overview is presented of the North Carolina Bridge Management System. The system is based on economic evaluation considering agency and user costs, and engineering evaluation considering minimum user and maintenance condition levels of service. The system seeks to reduce total costs to the ultimate owner, the user-taxpayer, while assuring essential minimum levels of condition and public service. Descriptions of databases, analyses conducted and samples of results are included.

BACKGROUND AND OBJECTIVES

In the 1970's, the public became increasingly aware of the serious bridge deficiencies in the United States. However, efforts by the responsible federal, state and local agencies to improve bridges have been hampered by a lack of funds. This lack of funds has been aggravated by agency inability to justify the needs on a defendable basis and legislative concerns about the absence of agency decision support systems to assist in determining best use of funds. Nationwide efforts to improve in-service inspection and accumulate at least minimal data on a uniform basis were in place by 1980. However, the North Carolina Department of Transportation (NCDOT) Bridge Maintenance Unit determined that data alone was not enough to solve the fundamental problems. Furthermore, the initial federally mandated method of determining eligibility for improvement, the Sufficiency Rating, was not an adequate measure of a bridge in meeting public needs, particularly across all roadway functional classifications.

North Carolina's highway system contains about 14,300 bridges and about 3,200 culverts and large pipes. Of the bridges, about 14,000 are state-owned and 300 city-owned. Of the pipes and culverts, about 3,000 are state-owned and 200 city-owned. There are no county-owned bridges or roadways in the state. Thus, the NCDOT has responsibility for allocation of bridge funds to essentially all the roadway functional classifications within the state, except city streets, and must adequately balance the relative needs.

Since 1982, NCDOT staff and North Carolina State University (NCSU) researchers have gradually developed (*1-9*) the elements of a Bridge Management System (BMS) for use by the NCDOT Bridge Maintenance Unit. Two objectives, set at the inception of the research and development, are met by the North Carolina BMS:

- The system has the capability to assess the optimum timing and selection among alternatives for maintenance, rehabilitation and replacement at the bridge level and to predict system-wide funding needs on an annual basis into the future; and
- The system has the capability to determine the optimum use of constrained budgets and to predict the resulting impact of inadequate budgets upon system-wide performance in terms of element condition deterioration, load capacity decline, and increasing user costs on an annual basis into the future.

Furthermore, the system is based on economic evaluation considering agency and user costs, and engineering evaluation considering minimum user and condition levels of service. By taking this approach, defendable methodologies result since they seek to reduce total costs to the ultimate owner, the user-taxpayer, while assuring essential minimum levels of condition and public service. In accomplishing these and other objectives, the system also meets the more recently developed American Association of State Highway and Transportation Officials (AASHTO) Guidelines for Bridge Management Systems and the expectations of Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA). This paper provides an overview of the system, the analyses conducted, and samples of the types of results. Additional details are available in the various referenced reports and papers (*1-9*).

DATABASES

The North Carolina BMS is designed as a mainframe system. Although this is partly because a centralized high speed mainframe is the primary hardware used within NCDOT, several other reasons have made this desirable for a large agency as follows:

- Widespread network of users for some data entry;
- Anticipated growth of network users seeking information from the system;
- BMS development decisions and database sizes less controlled by hardware limitations;
- Database and software security;
- Access to databases that serve multiple unit users within NCDOT, not just the Bridge Maintenance Unit; and
- Anticipated future directions toward interaction with other databases such as Accident Reports and GIS, and the BMS role in larger Management Information, Planning and Decision Systems.

Figure 1 illustrates the relationships between the BMS Databases, Application Programs, and Outputs. Currently, four databases are primarily utilized.

Bridge Inventory Records

The North Carolina Bridge Inventory (NCBI) contains the inspection data for all bridges, culverts and major pipes, about 17,500 records. Each record, with 273 items, is significantly expanded beyond the minimum National Bridge Inventory record requirement of 116 items. The added items include:

- Expanded descriptions of bridge components, materials, and features;
- Estimates of the quantities of maintenance needs under 40 work function codes with associated current unit costs;
- Condition ratings of about 40 elements of the bridge rather than three; and
- Expanded location, dimension and general information.

Maintenance Work Accomplished Records

As maintenance is accomplished by crews, it is reported to a centralized Fiscal Cost and Work Accomplished database. The database serves many units within NCDOT but certain function codes are assigned to activities within the Bridge Maintenance Unit. About 40 function codes are used to describe bridge maintenance field activities. Data entered, subdivided by function code on each bridge, include the number of hours worked by each worker, the quantities of work accomplished, the equipment hours, and the materials expended. These quantities are extended through appropriate unit cost rates to obtain total costs.

Historical Database Records

The bridge inventory is an active database in which many bridge records are updated every day. To preserve an understanding of how parameters change with time, it is important to retain a snapshot of the record periodically. Since the cycle for most inspections is two years, retaining a copy annually is adequate for most data. Similarly, data on work accomplished during each year should be saved for future analysis as needed. Therefore, record copies of each file are made at the end of each fiscal year. Although the record copies are critical historical resources for future data extraction, the volume of data stored on many tapes is inconvenient for frequent use. Thus, a separate History database of key parameters is extracted and updated annually. The extracted data focus on items that would be useful in analyzing long-term trends such as condition ratings, load capacity, average daily traffic (ADT), and maintenance needs.

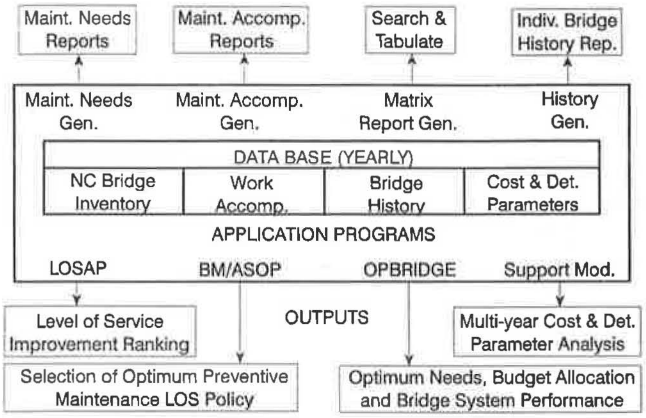


FIGURE 1 Elements of the North Carolina bridge management system.

Cost and Parameter Data File

The main optimization program in the BMS, OPBRIDGE, which will be described later, requires certain data for its analysis beyond the bridge records in the NCBI. These data, which are determined by various support modules and other sources, are stored in the Cost and Parameter Data file. Example cost data include unit costs for rehabilitation, widening and various other improvements, unit costs for maintenance at various condition levels, vehicle operating costs, and bridge-related accident costs. Parameter data examples include element material deterioration rates, load capacity deterioration rates, ADT growth rates, percentages of vehicles detoured due to load capacity and vertical clearance deficiencies, and level of service goals for lane and shoulder width, number of lanes, vertical clearance, and load capacity.

APPLICATION PROGRAMS AND EXAMPLE RESULTS

The BMS includes eight major application program and report generator groupings (Figure 1). Some are single, large (but modular) programs, such as OPBRIDGE, and others are a series of programs. Most act independently, while some produce outputs needed by other programs.

Report Generators

The databases are accessible for use by a broad range of users in NCDOT. In this process, portions of data may be downloaded by some users into other generic software such as spreadsheets or statistical analysis packages, particularly SAS. For more routine use within the Bridge Maintenance Unit, several application programs have the objectives of searching, tabulating and summarizing data from the databases. Among these are individual bridge printouts of the inventory record for staff reference and inspector updating. The primary report generators are described below.

History Generator

The History Report Generator assembles a one sheet summary for each bridge (Figure 2). One section of the data provided includes a listing of the current primary features of the bridge, materials, roadway information, etc. A second section tracks key inspection data on an annual basis since 1980. The data include condition ratings of the major components, appraisal ratings of various features, the operating rating (OP), posted load capacities (SV and TTST), ADT for the over and under routes (ADTO and ADTU), sufficiency rating and deficiency points. A third section tracks inspector estimated maintenance-need quantities and costs by function code as recorded annually since about 1983. The last section tracks the work-accomplished quantities and costs by function code on an annual basis since about 1983. This report allows the user to examine trends in maintenance needs, condition and strength deterioration, ADT, etc. and to determine the impact of maintenance efforts for individual bridges.

Matrix Manipulator & Report Generator

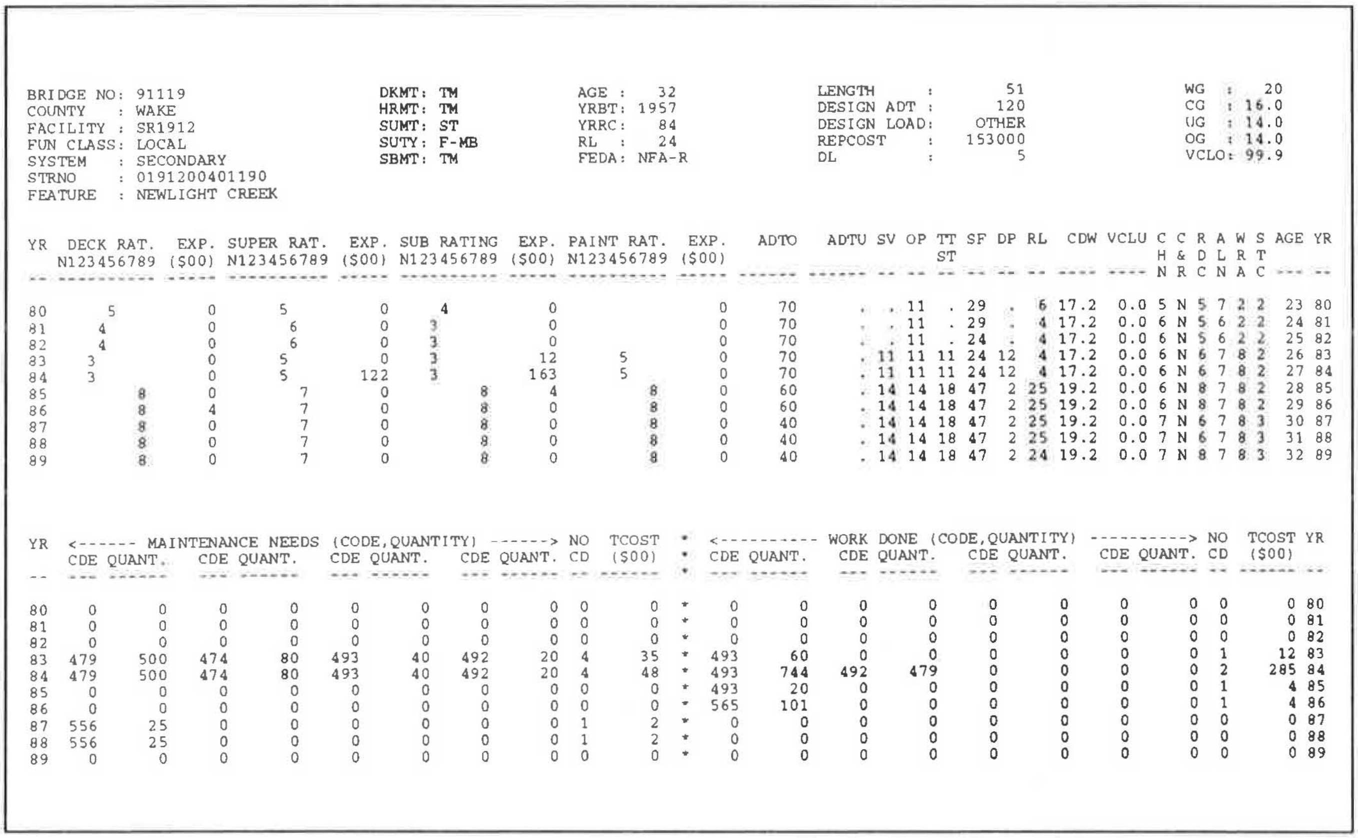
The Matrix/Report Generator program allows the user to search the NCBI database for particular data, to search for groups of bridges within selected parameter ranges, to tabulate the numbers of bridges categorized into various parameter features, etc. This program is a revised version of the Federally-provided Report Generator Program. The modifications by NCSU and NCDOT allow the software to operate on the NCBI, which is expanded beyond the normal Federal NBI database.

Maintenance Needs Generator

Maintenance needs for individual bridges are estimated under 40 work function codes during each inspection. The data, including the function code, the quantities and a unit cost based upon statewide averages, are part of each bridge record in the NCBI. The Maintenance Needs Report Generator program summarizes these data by function code under several options including bridge-by-bridge, county, maintenance area and statewide. The summaries allow the backlog of work to be monitored on both a quantity- and a cost-magnitude basis. The summary total, which always is greater than the available funds, and distribution by Maintenance Area have also traditionally been useful aids in apportioning available funds to the Maintenance Areas and in sizing the crews available in the Areas.

Maintenance Accomplished Generator

The Work Accomplished Report Generator summarizes the data by function code in monthly and cumulative year-to-date reports under several options including county (bridge-by-bridge), maintenance area and statewide. Resulting unit costs are summarized for each area and statewide for use in estimating costs associated with the maintenance needs backlog.



```
BRIDGE NO: 91119             DKMT: TM      AGE :   32      LENGTH      :       51     WG   :   20
COUNTY    : WAKE             HRMT: TM      YRBT: 1957      DESIGN ADT  :      120     CG   : 16.0
FACILITY  : SR1912           SUMT: ST      YRRC:   84      DESIGN LOAD:     OTHER     UG   : 14.0
FUN CLASS: LOCAL             SUTY: F-MB    RL  :   24      REPCOST     :   153000     OG   : 14.0
SYSTEM    : SECONDARY        SBMT: TM      FEDA: NFA-R     DL          :        5     VCLO: 99.9
STRNO     : 0191200401190
FEATURE   : NEWLIGHT CREEK

YR  DECK RAT.  EXP. SUPER RAT.  EXP. SUB RATING  EXP. PAINT RAT.  EXP.   ADTO   ADTU SV OP TT SF DP RL  CDW VCLU C C R A W S AGE YR
   N123456789 ($00) N123456789 ($00) N123456789 ($00) N123456789 ($00)                     ST                H & D L R T
-- ---------- ----- ---------- ----- ---------- ----- ---------- ----- ------ ------ -- -- -- -- -- -- ---- ---- N R C N A C --- --

80      5         0      5         0     4          0                0     70      .  . 11  . 29  .  6 17.2  0.0 5 N 5 7 2 2  23 80
81     4          0       6        0    3           0                0     70      .  . 11  . 29  .  4 17.2  0.0 6 N 5 6 2 2  24 81
82     4          0       6        0    3           0                0     70      .  . 11  . 24  .  4 17.2  0.0 6 N 5 6 2 2  25 82
83    3           0      5         0    3          12      5         0     70      . 11 11 11 24 12  4 17.2  0.0 6 N 6 7 8 2  26 83
84    3           0      5       122    3         163      5         0     70      . 11 11 11 24 12  4 17.2  0.0 6 N 6 7 8 2  27 84
85         8      0        7       0         8      4         8      0     60      . 14 14 18 47  2 25 19.2  0.0 6 N 8 7 8 2  28 85
86         8      4        7       0         8      0         8      0     60      . 14 14 18 47  2 25 19.2  0.0 6 N 8 7 8 2  29 86
87         8      0        7       0         8      0         8      0     40      . 14 14 18 47  2 25 19.2  0.0 7 N 6 7 8 3  30 87
88         8      0        7       0         8      0         8      0     40      . 14 14 18 47  2 25 19.2  0.0 7 N 6 7 8 3  31 88
89         8      0        7       0         8      0         8      0     40      . 14 14 18 47  2 24 19.2  0.0 7 N 8 7 8 3  32 89

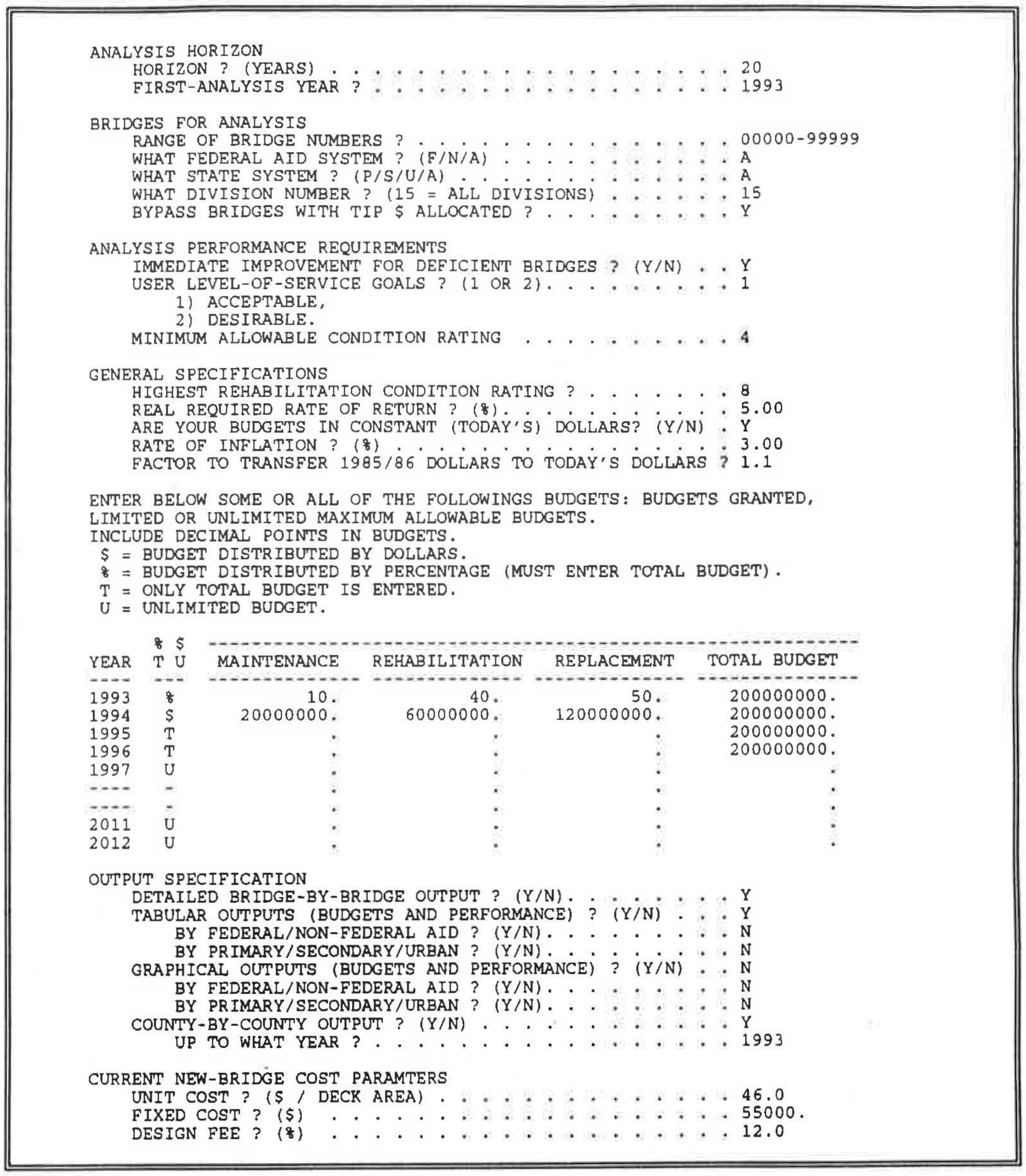

YR  <------ MAINTENANCE NEEDS (CODE,QUANTITY) ------> NO  TCOST  *  <---------- WORK DONE (CODE,QUANTITY) ----------> NO  TCOST YR
    CDE QUANT.   CDE QUANT.   CDE QUANT.   CDE QUANT. CD  ($00)  *  CDE QUANT.   CDE QUANT.   CDE QUANT.   CDE QUANT. CD  ($00)
--  --- ------   --- ------   --- ------   --- ------ -- ------  *  --- ------   --- ------   --- ------   --- ------ -- ------ --

80    0      0     0      0     0      0     0      0  0      0  *    0      0     0      0     0      0     0      0  0      0 80
81    0      0     0      0     0      0     0      0  0      0  *    0      0     0      0     0      0     0      0  0      0 81
82    0      0     0      0     0      0     0      0  0      0  *    0      0     0      0     0      0     0      0  0      0 82
83  479    500   474     80   493     40   492     20  4     35  *  493     60     0      0     0      0     0      0  1     12 83
84  479    500   474     80   493     40   492     20  4     48  *  493    744   492    479     0      0     0      0  2    285 84
85    0      0     0      0     0      0     0      0  0      0  *  493     20     0      0     0      0     0      0  1      4 85
86    0      0     0      0     0      0     0      0  0      0  *  565    101     0      0     0      0     0      0  1      4 86
87  556     25     0      0     0      0     0      0  1      2  *    0      0     0      0     0      0     0      0  0      0 87
88  556     25     0      0     0      0     0      0  1      2  *    0      0     0      0     0      0     0      0  0      0 88
89    0      0     0      0     0      0     0      0  0      0  *    0      0     0      0     0      0     0      0  0      0 89
```

FIGURE 2 Bridge history listing.

OPBRIDGE Program

The Optimum Bridge Budget Forecasting and Allocation System (OPBRIDGE) was developed (*3-7*) to determine the optimum improvement action and time for each bridge in the network under various level of service goals and funding constraints over an analysis horizon. Through input screens (Figure 3), a bridge manager enters the analysis horizon, minimum performance requirements, and policies as well as the granted budget, maximum allowable budget, or unlimited budget for each year in the horizon. A granted or limited budget can be entered either as a total available or as distributed by line item to maintenance, rehabilitation and replacement activities. Upon execution, OPBRIDGE extracts data from the bridge database, and the cost and parameter data file for analysis. The analysis determines the economic viability of various maintenance, rehabilitation and replacement alternatives. Life cycle costing is used, and comparisons are based upon the equivalent uniform annual costs of each alternative versus the analysis year annual maintenance and user costs as shown in Figure 4. User costs accumulate from detours due to load capacity deficiencies, detours due to vertical clearance deficiencies, and accidents induced by width, alignment and vertical clearance deficiencies. Under unlimited funding, decisions are made as indicated in Figure 5, and all of the most economic alternatives can be selected. However, in limited funding cases, sufficient funds are not available to select all of the most economic alternatives. Thus, OPBRIDGE then optimizes decisions for every year in the analysis horizon under the budget constraint using a zero-one (0-1) integer-linear programming formulation, as shown in Figure 6. At the end of every year in the analysis, OPBRIDGE ages bridges one year and predicts condition ratings, ADT, load capacity, etc. This allows the system to continue the analysis in the next year of the horizon. Finally, OPBRIDGE produces detailed bridge-by bridge output showing current and expected future status, county-by-county output showing bridge-by-bridge and summary costs, and tabular and graphical output showing statewide (or subset) agency costs, user costs and performance levels of the bridge system over the



```
ANALYSIS HORIZON
    HORIZON ? (YEARS) . . . . . . . . . . . . . . . . . . . 20
    FIRST-ANALYSIS YEAR ? . . . . . . . . . . . . . . . . . 1993

BRIDGES FOR ANALYSIS
    RANGE OF BRIDGE NUMBERS ? . . . . . . . . . . . . . . . 00000-99999
    WHAT FEDERAL AID SYSTEM ? (F/N/A) . . . . . . . . . . . A
    WHAT STATE SYSTEM ? (P/S/U/A) . . . . . . . . . . . . . A
    WHAT DIVISION NUMBER ? (15 = ALL DIVISIONS) . . . . . . 15
    BYPASS BRIDGES WITH TIP $ ALLOCATED ? . . . . . . . . . Y

ANALYSIS PERFORMANCE REQUIREMENTS
    IMMEDIATE IMPROVEMENT FOR DEFICIENT BRIDGES ? (Y/N) . . Y
    USER LEVEL-OF-SERVICE GOALS ? (1 OR 2). . . . . . . . . 1
        1) ACCEPTABLE,
        2) DESIRABLE.
    MINIMUM ALLOWABLE CONDITION RATING  . . . . . . . . . . 4

GENERAL SPECIFICATIONS
    HIGHEST REHABILITATION CONDITION RATING ? . . . . . . . 8
    REAL REQUIRED RATE OF RETURN ? (%). . . . . . . . . . . 5.00
    ARE YOUR BUDGETS IN CONSTANT (TODAY'S) DOLLARS? (Y/N) . Y
    RATE OF INFLATION ? (%) . . . . . . . . . . . . . . . . 3.00
    FACTOR TO TRANSFER 1985/86 DOLLARS TO TODAY'S DOLLARS ? 1.1

ENTER BELOW SOME OR ALL OF THE FOLLOWINGS BUDGETS: BUDGETS GRANTED,
LIMITED OR UNLIMITED MAXIMUM ALLOWABLE BUDGETS.
INCLUDE DECIMAL POINTS IN BUDGETS.
 $ = BUDGET DISTRIBUTED BY DOLLARS.
 % = BUDGET DISTRIBUTED BY PERCENTAGE (MUST ENTER TOTAL BUDGET).
 T = ONLY TOTAL BUDGET IS ENTERED.
 U = UNLIMITED BUDGET.

      % $  -------------------------------------------------------------
YEAR  T U   MAINTENANCE   REHABILITATION   REPLACEMENT    TOTAL BUDGET
----  ---  -------------- -------------- -------------- ---------------
1993   %              10.            40.            50.      200000000.
1994   $        20000000.      60000000.     120000000.      200000000.
1995   T                .              .              .      200000000.
1996   T                .              .              .      200000000.
1997   U                .              .              .               .
----   -                .              .              .               .
----   -                .              .              .               .
2011   U                .              .              .               .
2012   U                .              .              .               .

OUTPUT SPECIFICATION
    DETAILED BRIDGE-BY-BRIDGE OUTPUT ? (Y/N). . . . . . . . Y
    TABULAR OUTPUTS (BUDGETS AND PERFORMANCE) ? (Y/N) . . . Y
        BY FEDERAL/NON-FEDERAL AID ? (Y/N). . . . . . . . . N
        BY PRIMARY/SECONDARY/URBAN ? (Y/N). . . . . . . . . N
    GRAPHICAL OUTPUTS (BUDGETS AND PERFORMANCE) ? (Y/N) . . N
        BY FEDERAL/NON-FEDERAL AID ? (Y/N). . . . . . . . . N
        BY PRIMARY/SECONDARY/URBAN ? (Y/N). . . . . . . . . N
    COUNTY-BY-COUNTY OUTPUT ? (Y/N) . . . . . . . . . . . . Y
        UP TO WHAT YEAR ? . . . . . . . . . . . . . . . . . 1993

CURRENT NEW-BRIDGE COST PARAMTERS
    UNIT COST ? ($ / DECK AREA) . . . . . . . . . . . . . . 46.0
    FIXED COST ? ($)  . . . . . . . . . . . . . . . . . . . 55000.
    DESIGN FEE ? (%)  . . . . . . . . . . . . . . . . . . . 12.0
```

FIGURE 3 OPBRIDGE user input screen layout.

horizon. A variety of user options are incorporated to select sets of bridges for analysis and to summarize results. Examples of detailed bridge-by-bridge outputs are presented in Table I for several bridges—shown are the current and predicted conditions, and economic evaluations of alternatives leading to future actions and costs.

Example tabular statewide results for a $200 million annual budget over the next 20 years are shown in Table II. The full budget is needed each year and the summary totals determined as optimal for maintenance, repair, rehabilitation and replacement are indicated. Table III shows the statewide summary of the predicted effect of this spending. By analyzing at various levels of funding and other options available using a "what if" approach, the results of various strategies can be evaluated, as summarized in Figures 7, 8, and 9. If unlimited funds were somehow available, the economically justifiable backlog of almost $2 billion would be spent in the first year, resulting in an

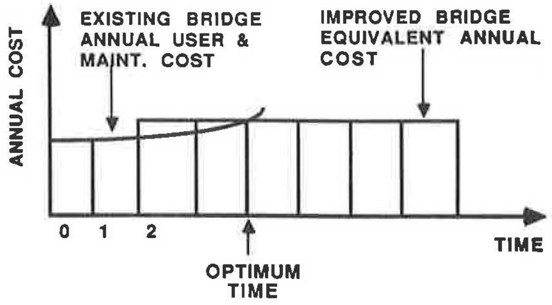


FIGURE 4 Optimum time to improve bridge.

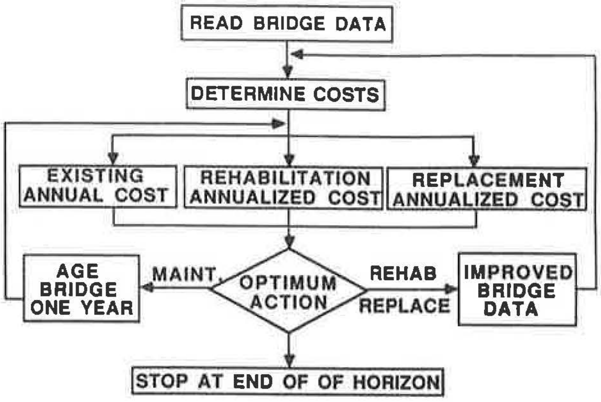


FIGURE 5 Selection of most economical individual action.

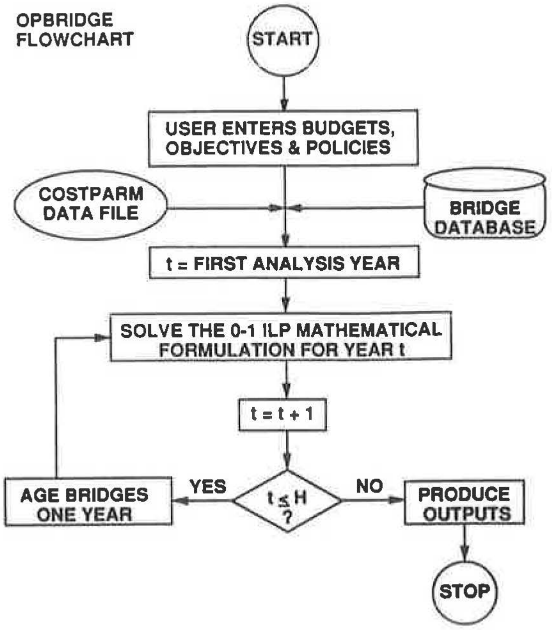


FIGURE 6 Optimum action selection under constraints.

immediate increase in the inventory state and virtual elimination of user costs. This would be followed by an annual need averaging $104 million in the 19 years thereafter. However, uniform budgeting is more realistic. At a budget level of $200 million per year, significant improvements can be made over the next 20 years. At $150 million, modest improvement can be expected. At $100 million, some parameters are in a state of decline.

It is significant to note that predictions made by OPBRIDGE have proved to be reliable considering the numerous parameters involved. Analyses made in late 1988 (*5,6*), included prediction of expected performance over a 20-year horizon at several budget levels. Funding since then has averaged about $80 million annually. Results predicted for 1993 at the $60 and $100 million budget levels are re-tabulated in Table IV with the actual current 1993 average condition, load posting and user cost states. The comparison, while not perfect, is very good considering that some prediction parameters are still being refined and many actions were programmed before availability of OPBRIDGE recommendations.

LOSAP Program

The Level of Service Analysis and Prioritization (LOSAP) program was one of the first programs put in place to assist the decision making process (*1*). Although the ultimate goal of the BMS was a system like OPBRIDGE, neither the agency or user cost data, nor an understanding of the methodologies appropriate for that goal, were available in 1982 when the study began. Thus, LOSAP was developed as an empirical system of weighting factors to parallel the concept of user costs in evaluating bridges. Acceptable and desirable level of service goals for load capacity and geometry were established as minimum measures of bridges to remain in place and as new bridge objectives respectively. To rank bridges for improvement, deficiency points were calculated as functions of the deficiency magnitude and traffic volume. Ranked listings provided one line comparisons of bridges in columnar format. LOSAP proved to be a useful and easily understood tool to assist bridge decision-making. However, it now serves only as a point of reference as OPBRIDGE is implemented for more rigorous decision-making.

MAINTBRG Program

MAINTBRG (*2,9*) is focused at the problem of allocating funds to routine and preventive maintenance

TABLE I SAMPLE DETAILED BRIDGE-BY-BRIDGE ANALYSIS PREDICTIONS OF STATES AND ACTIONS

```
                                                                  **** EQUIV. UNIFORM ANNUAL COST (EUAC) AND OPTIMUM ACTION *****
BRIDGE NO.  DK SPTY FC RL   CG     A                              USER  --- MN#1 --    * --- REP. --- *  --- MN#2 -- * --- REH. --- *
COUNTY      SP SUFF SY DL   UG     G                        D S S COST COST     PROVID *  COST   EUAC *  COST   EUAC *  COST   EUAC *
FACILITY    SB  DPA FA TT LENG YR  E    ADT SV WG  CDW VCLU K P B  $00    $          $ *  $000    $00 *   $00    $00 *  $00     $00 *


91070       ES M-BM LO  3 16.0 93 26   6600 21 26 28.0 99.9 5 6 3 1344  622          0 *  362     211 *   491   2977 *  690    2506 *
WAKE        ST  6.0 S   9 14.0 93 26   6600 34 26 54.0 99.9 9 9 9                         CONDITION RATINGS             ACTION-REP.
SR1615      TM  6.0 SR 25   76

91071       TM M-BM LO 15 16.0 93 31  13200 34 46 28.0 15.3 6 6 6  154 2487       2487 *  746     445 *     0      0 *  5003    445 *
WAKE        ST 71.0 P   4 14.0 93 31  13200 34 46 28.0 15.3 6 6 6                         ECONOMICAL COMPARISON         ACTION-MN#1
NC55        ST 12.0 FS 37  233
                              100 38  14808 34 46 28.0 15.3 4 5 5  172 7046          0 *  746     445 *     0      0 *  5468    611 *
                              100 38  14808 34 46 54.0 15.3 9 9 9                         CONDITION RATINGS             ACTION-REP.

91073       TM M-BM LO 21 16.0 93 24   3800 34 44 54.0 16.4 6 7 7    0 3649       3649 *  811     478 *     0      0 *  2167    388 *
WAKE        ST 77.0 P   3 14.0 93 24   3800 34 44 54.0 16.4 6 7 7                         ECONOMICAL COMPARISON         ACTION-MN#1
SR1002      RC  0.0 SR 37  262
                                2 33   4395 34 46 54.0 16.4 4 6 7    011627          0 *  811     484 *  1887    324 *  2774    344 *
                                2 33   4395 34 46 54.0 16.4 7 6 6                         CONDITION RATINGS             ACTION-MN#2

91074       TM M-BM LO 20 16.0 93 31   1200 34 22 24.0 14.2 5 5 7  133 1954       1954 *  381     219 *   922    367 *  1118    340 *
WAKE        PS 47.0 P   4 14.0 93 31   1200 34 22 24.0 14.2 5 5 7                         ECONOMICAL COMPARISON         ACTION-MN#1
SR1134      ST  0.0 SR 37  208
                               95 33   1242 34 22 24.0 14.2 4 5 7  137 3434          0 *  381     219 *   976    381 *  1173    354 *
                               95 33   1242 34 22 28.0 15.0 9 9 9                         CONDITION RATINGS             ACTION-REP.
```

TABLE II STATEWIDE ACTIONS AND DISTRIBUTIONS AT $200 MILLION ANNUAL BUDGET LEVEL

YEAR	ROUTINE MAINT. COST	MAJOR MAINT.		REHABILITATIONS		REPLACEMENTS		TOTAL YEARLY BUDGET
		COST	NO.	COST	NO.	COST	NO.	
1993	17675088.	31095104.	472	51170288.	596	100044064.	561	199984544.
1994	17928928.	14841812.	132	40421088.	228	126796096.	409	199987920.
1995	18488256.	19059200.	182	40025008.	276	122410832.	487	199983296.
1996	18684944.	25684048.	204	22444720.	211	133171872.	419	199985584.
1997	19043696.	15258803.	174	36156400.	209	129524080.	369	199982976.
1998	19122704.	13832032.	156	45771008.	151	121256224.	298	199981968.
1999	19249120.	14748202.	194	58056608.	260	107927056.	400	199980976.
2000	18741072.	23038128.	251	49990400.	232	108215840.	372	199985440.
2001	18410000.	24777472.	280	40327840.	233	116470320.	391	199985632.
2002	18210496.	18688288.	184	45478592.	316	117606896.	362	199984272.
2003	18258560.	15036579.	138	42772864.	250	123914560.	385	199982560.
2004	17651216.	15007082.	131	41806288.	216	125525920.	341	199990496.
2005	16937936.	15182900.	164	48059488.	221	119813808.	271	199994128.
2006	16014172.	25610160.	211	36675520.	264	121695872.	167	199995712.
2007	15555273.	26399968.	265	46203408.	215	111838336.	121	199996976.
2008	15029438.	27940464.	222	49929520.	207	107088496.	198	199987904.
2009	15249769.	20617680.	177	31451488.	184	132677952.	212	199996880.
2010	14803074.	18921888.	202	43018000.	173	123254576.	166	199997536.
2011	14620932.	15244430.	174	50392288.	194	119737760.	137	199995408.
2012	14165187.	20434048.	283	59880912.	309	105501344.	281	199981488.

of bridges. The objective is to determine the optimum maintenance levels-of-service (L-O-S) that can be sustained under various levels of funding. A maintenance level of service is a condition state or threshold that triggers an appropriate maintenance activity. The MAINTBRG program was adapted by NCSU from the Algorithm for Selection of Optimal Policy (ASOP) originally developed in *NCHRP Report 223* (*10*) and *NCHRP Report 273* (*11*) for roadway feature maintenance. The method provides a mechanism for combining alternative levels of service on multiple considerations (e.g., safety, preservation of investment) and for multiple elements (e.g., joints, rails, decks). In the system developed, bridge maintenance elements are evaluated using a zero to nine (0-to-9) rating, as in the Table V example. The rating also

TABLE III PREDICTIONS OF STATEWIDE AVERAGE PERFORMANCE AT $200 MILLION ANNUAL BUDGET LEVEL

END OF YEAR	AVERAGE CONDITION DECK	SUPER	SUB.	NMACR	AVG. SV POSTING	NSVA	NSVD	NLOSA	NLOSD	USER COST $MILLIONS
CURRENT	6.27	6.63	6.03	330	25.86	2185	6948	5606	10643	245.34
1993	6.49	6.79	6.31	274	26.64	1886	6424	4837	10014	229.39
1994	6.53	6.82	6.37	249	26.98	1748	6135	4440	9608	213.11
1995	6.60	6.88	6.48	224	27.54	1523	5733	4000	9110	201.12
1996	6.63	6.90	6.55	158	28.10	1326	5377	3603	8674	241.16
1997	6.65	6.91	6.59	135	28.46	1215	5152	3229	8297	252.72
1998	6.62	6.89	6.60	118	28.73	1144	4931	2971	7983	210.83
1999	6.66	6.91	6.66	93	29.13	1004	4632	2501	7547	200.29
2000	6.69	6.93	6.72	78	29.53	844	4362	2148	7175	183.18
2001	6.74	6.96	6.77	62	29.93	673	4107	1779	6807	169.01
2002	6.79	7.00	6.85	61	30.27	537	3860	1487	6452	163.23
2003	6.82	7.02	6.90	54	30.65	401	3558	1197	6060	154.66
2004	6.83	7.04	6.94	40	30.96	300	3338	964	5747	142.57
2005	6.84	7.04	6.95	28	31.17	221	3197	793	5493	112.28
2006	6.82	7.02	6.94	23	31.30	182	3110	607	5306	107.87
2007	6.79	6.99	6.92	11	31.38	146	3062	515	5188	59.08
2008	6.77	6.98	6.91	4	31.53	112	2924	414	4990	49.42
2009	6.75	6.96	6.90	2	31.71	92	2765	365	4793	41.61
2010	6.71	6.92	6.87	1	31.80	77	2664	319	4650	30.69
2011	6.66	6.89	6.84	0	31.89	88	2612	298	4542	24.17
2012	6.70	6.92	6.87	0	32.06	64	2467	202	4292	19.94

NMACR = NUMBER OF BRIDGES WITH A CONDITION RATING LESS THAN THE MINIMUM ALLOWABLE CONDITION RATING, "4"
NSVA = NUMBER OF BRIDGES POSTED AT LESS THAN ACCEPTABLE
NSVD = NUMBER OF BRIDGES POSTED AT LESS THAN DESIRABLE
NLOSA = NUMBER OF BRIDGES WITH A LESS-THAN-ACCEPTABLE USER LEVEL OF SERVICE
NLOSD = NUMBER OF BRIDGES WITH A LESS THAN DESIRABLE USER LEVEL OF SERVICE,

NOTE : USER COST IS IN FUTURE (THEN-CURRENT) DOLLARS.

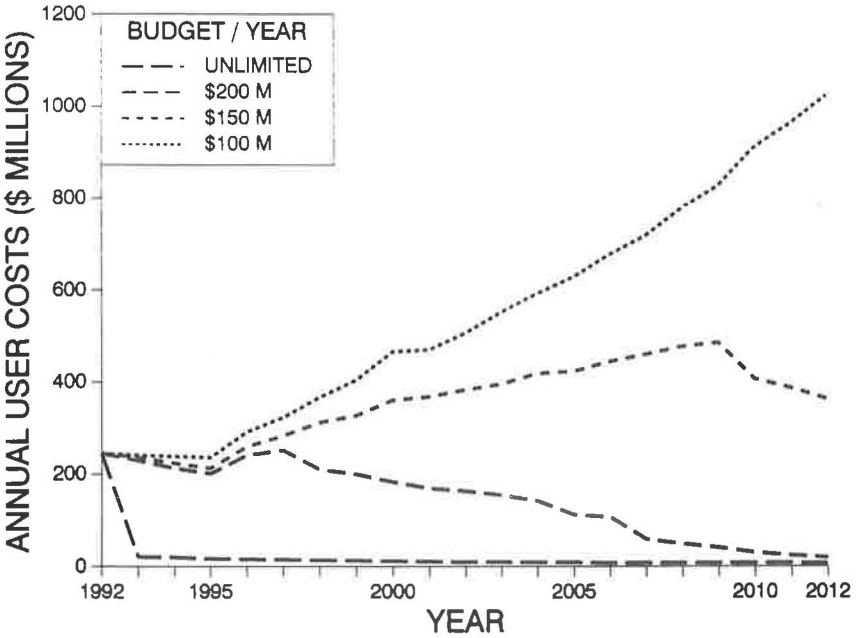


FIGURE 7 Predicted users Costs at various annual budgets.

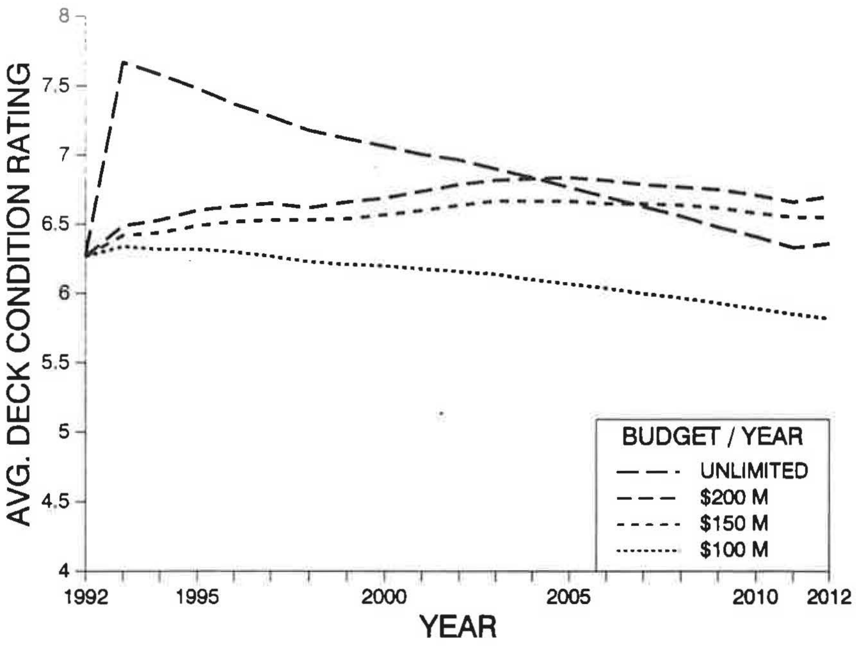


FIGURE 8 Predicted average deck condition rating at various annual budgets.

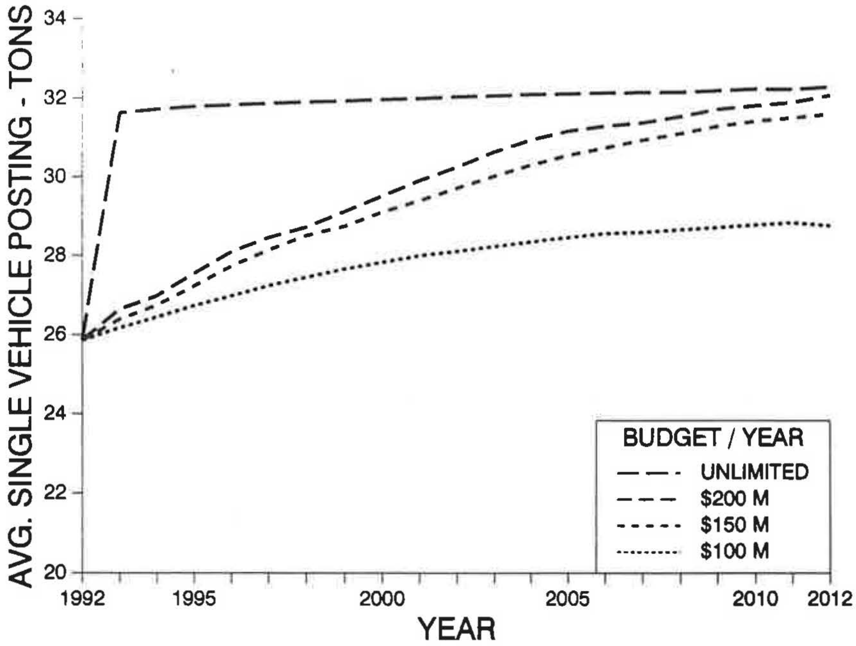


FIGURE 9 Predicted average single vehicle posting at various annual budgets.

corresponds to the maintenance levels-of-service where three to seven (3-to-7) are considered to be the normal range of the trigger options for maintenance activity and each has an expected normal improvement level (Table VI). The program allows an agency to establish the relative values of different considerations and elements based on collective inputs from inspectors, field supervisors, maintenance engineers, legislators, bridge system users, etc. The optimization algorithm then assesses the optimal policy considering the funding constraints (Table VII).

TABLE IV COMPARISON OF 1988 PREDICTIONS TO CURRENT STATE

	Annual Budget (Millions)	1988 Actual	1993 Predicted	1993 Actual
Average Deck Condition	$60	6.55	6.07	6.27
	$100		6.19	
Average Superstructure Condition	$60	6.86	6.48	6.63
	$100		6.60	
Average Substructure Condition	$60	6.36	5.98	6.03
	$100		6.11	
Average Single Vehicle Posting (Tons)	$60	24.97	25.52	25.86
	$100		26.08	
Annual User Cost ($ Millions)	$60	566.60	366.92	245.30
	$100		207.76	

TABLE V CONDITIONS AND LEVELS-OF-SERVICE FOR STANDARD DECK EXPANSION JOINTS

Condition L-O-S	Description	Consideration
9	Condition Rating 9 (Excellent Condition)	
8	Condition Rating 8 (Very Good Condition)	
7	Condition Rating 7 (Good Condition) - Presence of dirt and debris in the joints (>50% length affected).	Investment Preservation
6	Condition Rating 6 (Satisfactory Condition) - Presence of dirt and debris in the joints. Joint seal cracked and loose. Minor leakage.	Investment Preservation
5	Condition Rating 5 (Fair Condition) - Presence of dirt and debris. Joint seal cracked, loose, or partially missing. Joint seal leaking.	Investment Preservation
4	Condition Rating 4 (Poor Condition) - Presence of dirt and debris. Joint seal partially missing throughout the seal. Joint seal leaking to a large degree.	Investment Preservation
3	Condition Rating 3 (Serious Condition) - Joint seal is effectively missing.	Investment Preservation
2	Condition Rating 2	
1	Condition Rating 1	
0	Condition Rating 0	

TABLE VI EXAMPLE AVERAGE ELEMENT CONDITION RATING AFTER MAINTENANCE

Element	Condition Rating		Description of Typical Desirable Maintenance Work at Each Condition Rating
	Before	After	
Standard Deck Expansion Joints Function Code 576	7	7	No maintenance activity
	6	7	Reseal expansion joint
	5	7	Reseal expansion joint
	4	8	Complete expansion joint replacement
	3	8	Complete expansion joint replacement

TABLE VII EXAMPLE ELEMENT MAINTENANCE L-O-S RECOMMENDED BY MAINTBRG FOR VARIOUS ANNUAL BUDGET LEVELS

Bridge Maintenance Element (partial list)	Estimated Current L-O-S	Possible Selected Levels-of-Service at Each Budget Level (millions)				
		$A	$B	$C	$D	$E
Timber Deck	4	3	3	4	4	5
Steel Plank Deck	4	3	5	6	7	7
Concrete Rail	4	3	4	5	5	5
Timber Rail	5	3	4	4	5	5
Steel Rail	5	3	5	4	5	6
Compression Seal Expansion Joint	4	3	4	6	7	7
Standard Deck Expansion Joint	4	3	5	6	7	7
Steel Superstructure	4	3	4	6	7	6
P/S Concrete Superstructure	5	4	4	5	5	5
Timber Superstructure	4	3	5	6	7	7
Timber Substructure	4	3	3	4	4	4
Concrete Pile Substructure	4	4	6	6	7	7
Steel Pile Substructure	4	4	5	6	7	7
Paint System (Structural Steel)	3	3	4	5	6	6

Support Modules

The Support Modules (*8*) are a series of programs developed to generate data needed to periodically update the Cost and Parameter Data File used by OPBRIDGE or to develop cost data needed by MAINTBRG (*9*). Objectives of the modules are the following outputs:

- Estimates of the future Federal Highway Administration (FHWA) Structures Cost Index;
- Deterioration analysis of major bridge components;
- Relationships for estimating replacement bridge length and maximum span;
- Relationships for replacement costs;

- Unit costs of rehabilitation by component, material and condition;
- Maintenance unit costs for major components by material type and condition;
- Current and future unit costs of work by function code; and
- Annual costs to achieve L-O-S for routine and preventive maintenance.

The Support Module routines are based in SAS. Often standard statistical procedures are utilized such as various types of regression analysis. In other cases, particularly deterioration analysis, mathematical procedures have been derived. Most of these modules analyze data in the Historical Database, but some analyze data from the NCBI or other sources to produce the desired outputs.

SUMMARY

The North Carolina DOT Bridge Management System has been gradually developed in stages since 1982. The various parts have been implemented for use by the Bridge Maintenance Unit. The approaches employed have not only aided NCDOT but they have served as a model for other system and criteria developers. The analysis results produced assist NCDOT in the funding request and decision making process for bridge maintenance and improvement. Key features of the North Carolina DOT Bridge Management System include the following:

- A bridge inventory record significantly expanded beyond minimum FHWA requirements;
- Detailed bridge maintenance needs reporting during the in-service inspections;
- Detailed work-accomplished reporting during the maintenance process;
- Economic assessment of alternatives for maintenance, rehabilitation and replacement;
- Assessment based on both agency and user costs with optional minimum level of service criteria;
- Estimate of current backlog and prediction of optimum future needs for bridge maintenance and improvement; and
- Prediction of future system performance under various levels of constrained funding.

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The contents of this paper reflect the views of the authors, who are responsible for the accuracy of the data presented. The contents do not necessarily reflect the views or policies of the NCDOT. This paper does not constitute a standard, specification or regulation.

PennDOT's BRIDGE MANAGEMENT DECISION SUPPORT PROCESS

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ABSTRACT

The purpose of this paper is to describe the capabilities of Pennsylvania's Bridge Management System (BMS) and how these capabilities support decision making within the Department of Transportation. The Pennsylvania Department of Transportation (PennDOT) has developed and implemented a comprehensive BMS. This system has been operational since December 1986. Pennsylvania's BMS can store a wide range of bridge inspection data. BMS also can analyze this data using individual subsystems to provide decision support for Department managers. A Bridge Rehabilitation and Replacement Subsystem provides cost estimating and prioritization of bridge improvement projects to support long range planning and programming decisions. A Bridge Maintenance Subsystem provides cost estimating and prioritization of bridge maintenance activities for assistance in developing annual maintenance programs. A Modeling Subsystem that uses deterioration curves for bridge condition and bridge load capacity enables Department managers to predict future bridge improvement needs using different funding scenarios. An Automated Permit Rating and Routing Subsystem is being developed to provide decision support in the load rating, routing and issuance of permits for overweight and oversize vehicles. Finally, a Reports Subsystem is available to provide both standardized and customized report generation capabilities for any subset of data in BMS.

BACKGROUND ON PennDOT's BRIDGE MANAGEMENT SYSTEM

Pennsylvania maintains a proactive approach to bridge inspection and bridge management, often implementing new systems or procedures before Federal requirements to do so. The early development of a BMS illustrates this proactive posture.

PennDOTs BMS was implemented in December 1986. This BMS is a powerful management tool that not only records and stores bridge inspection data for Pennsylvania's bridges but also enables Department managers to make key decisions concerning bridge inspection, maintenance, rehabilitation and replacement. BMS operates in a main frame environment and includes 17 on-line data screens and up to 400 data elements for every bridge. The system also can produce a wide range of reports including standard monthly statistics reports, standard menu driven reports, and customized, user generated reports.

Besides storing and recording bridge inspection information, BMS can automatically generate improvement costs, by bridge, for maintenance, rehabilitation and replacement needs. BMS also can prioritize bridges for capital and maintenance improvements. A unique feature of BMS is its modeling capability that enables the user to predict future bridge needs by programmatically degrading bridge condition and load carrying capacity over time.

Although BMS has been in production since December 1986, improvements and enhancements have occurred continuously. Completed BMS enhancements include new screens for fracture critical and underwater bridge inspection, sign structure and retaining wall inspection, as well as system integration with our Roadway Management System and our Project Inventory and Project Management Systems.

DEVELOPMENT AND IMPLEMENTATION OF BMS

The Department first investigated the feasibility of establishing a BMS in 1983. A Task Group composed of seven prominent engineers from both inside and outside the Department was commissioned to determine if the development of a BMS was feasible for Pennsylvania and, if so, to provide guidance and direction for developing such a system.

The Task Group conducted four, 1-day meetings during the Fall of 1983. The Group unanimously agreed that development of a BMS was feasible and urgently needed to assist in the management of Pennsylvania's bridges with the finite resources that were available. (Table I provides a summary of Pennsylvania bridges, associated deficiencies, and the costs to eliminate these deficiencies through rehabilitation or replacement projects.) In March 1984, the Task Group published a report of its findings and recommendations (*1*). In October 1984, a ten-member BMS Work Group began development of the engineering concepts and requirements for Pennsylvania's BMS. With strong management support and frequent interaction with both users and managers within the Department, the Work Group developed the concepts and the initial technical

TABLE I PENNSYLVANIA BRIDGE STATISTICS FOR HIGHWAY BRIDGES GREATER THAN 6 METERS (20 FEET) IN LENGTH

Bridge Owner	Number of Bridges	Deficient Bridges	Cost to Remove, Billion $
State	16,200	6,000	4.8
Local	6,800	3,300	1.2
Total	23,000	9,300	6.0

requirements documented in a report entitled *Engineering Concepts and Requirements for a Bridge Management System* (*2*). This report then served as the basis for a "Request for Proposal" to develop and install computer software for BMS on the Department's mainframe computer. On August 20, 1985, a software consultant was hired to provide development, testing, implementation and training of the new BMS software. The BMS Work Group worked side by side with the consultant throughout this effort to further refine the engineering concepts and requirements, to ensure that all requirements were met, and to provide needed coordination. On December 24, 1986, BMS was placed in full operational status statewide.

The entire BMS development effort is documented in a report published by the Work Group entitled, *The Pennsylvania Bridge Management System - Final Report* (*3*). A separate *BMS Coding Guide* was also prepared. The *BMS Coding Guide* has been revised several times over the years to reflect BMS enhancements and revisions that have occurred continuously since 1987. The most recent version of the *BMS Coding Guide* was prepared in 1993 (*4*).

Data Requirements and Storage Capabilities of BMS

PennDOTs BMS contains 17 data information screens with provisions for up to 400 data elements for each bridge. All data required by the Federal Highway Administration (FHWA) are included plus additional data deemed necessary by the Department. Data are grouped by general data type and a coding manual provides detailed descriptions and codings for each data item. Table II provides a listing of all data screen names.

TABLE II SUMMARY OF BMS DATA SCREENS

Screen	Type of BMS Data
AA	General Data
AB	Features Intersected Data
AC	Structure Data
AD	Utility, Hydrology and Posting Data
AE	Inspection Data
AF	Proposed Improvement Data
AG	Repair and Painting Data
AH	Proposed Maintenance Data
AJ	Fracture Critical Data
AL	Narrative Data
AM	Condition Rating Data
AN	Completed Maintenance Data
AO	Planning, Programming and Budgeting Data
AR	State Roadway Data
AS	Sign Structure Data
AT	Retaining Wall Data
AW	Underwater Inspection Data

Data that resides in BMS can come from any of three sources: direct data entry via keyboard, such as bridge condition ratings; data generated through system calculations, such as improvement costs or priorities; and finally, data imported from other Department Management Systems, such as average daily traffic or program and budget status. BMS also exports bridge data to other Department Management Systems. The exchange of data between Department systems occurs automatically at either daily or weekly frequencies depending on data type. All Department Management Systems operate on a mainframe computer platform that simplifies the exchange of data between systems and offers instantaneous data access to all users via computer terminals in all of Pennsylvania's 67 counties. BMS currently exchanges data with the Project Inventory System, Project Management System and Roadway Management System. BMS also can store inspection data, on line, for the previous five inspections. Beyond that point, the oldest inspection data are archived on magnetic tape. All data are easily retrievable.

Data Analysis Capabilities and Decision Support

PennDOTs BMS includes the capability to analyze data in key areas and provide decision making tools to Department managers. The major data analysis capabilities of BMS are discussed in the following sections. A discussion of how these data analysis capabilities support decision making within the Department is also presented.

Bridge Rehabilitation and Replacement Subsystem of BMS

The Bridge Rehabilitation and Replacement Subsystem of BMS can prioritize bridges for capital improvements based on the degree to which each bridge is deficient in meeting public needs. Bridge deficiencies are evaluated in three general areas: level of service, bridge condition, and other related characteristics. A single deficiency rating is then computed for each bridge on a scale that ranges from 0 to 100.

Level of service deficiencies consider the bridge's load carrying capacity, bridge deck width, and vertical over and under clearances. Bridge data for each of these components are compared to established goals that vary depending on the functional classification of the bridge and traffic volumes. Deficiency points are assigned according to equations that relate actual data items to assigned goals for each bridge.

Deficiencies for bridge condition are based on an assessment of the individual condition ratings for the bridge deck, superstructure and substructure. For culverts, the overall culvert condition rating is used. Deficiency points are assigned based on table values that relate condition ratings to deficiencies. Other related characteristics that are also considered in determining deficiencies include: waterway adequacy, approach roadway alignment and remaining life of the bridge. Again, the appropriate data items are related to deficiency points using table comparisons.

Besides prioritizing bridge improvements, the Bridge Rehabilitation and Replacement Subsystem can automatically calculate bridge improvement costs. Costs are calculated by the system using the following data: proposed improvement code that is determined at the time of inspection, the deck area of the bridge, and unit cost tables stored and maintained in the system. Manual override of system generated costs is an available option for unique or unusual bridges.

Table III provides a summary of the general data required for the Bridge Rehabilitation and Replacement Subsystem of BMS. The Bridge Rehabilitation and Replacement Subsystem of BMS provides critical decision support for the development of the Department's Twelve Year Improvement Program. The Department maintains a rolling Twelve Year Improvement Program for highways and bridges that is updated every two years. BMS serves as the basis for selecting candidate bridge improvement projects by providing prioritized lists of needed improvements along with associated improvement costs.

TABLE III DATA USED FOR REHABILITATION AND REPLACEMENT SUBSYSTEM

Data Needed to Determine Deficiencies
Load Carrying Capacity
Clear Deck Width
Vertical Clearance on the Bridge
Vertical Clearance under the Bridge
Deck Condition Rating
Superstructure Condition Rating
Substructure Condition Rating
Culvert Condition Rating
Remaining Service Life
Approach Roadway Alignment Appraisal
Waterway Adequacy Appraisal
Average Daily Traffic
Detour Length
Data Needed to Estimate Costs
Proposed Improvement Type
Bridge Length
Bridge Width
Unit Costs for Improvements

Although BMS provides Department managers with an initial listing of candidate bridge projects, the ultimate selection of projects involves a rigorous planning and programming process that also includes extensive coordination with local and regional planning agencies, and public input solicited at several statewide public hearings. BMS also provides a means to help target fiscal resources to the various geographic areas of the state to ensure that all areas receive an equitable share of available funds. BMS simplifies the analysis of large amounts of data quickly and easily.

The Department's current Twelve Year Program for bridges includes more than 2,700 bridge rehabilitation and replacement projects. Since BMS was implemented in 1986, more than 1,000 bridge projects have been constructed or are now under construction. In addition, many more bridge rehabilitation projects are included as part of highway restoration projects each year. BMS data are utilized to help select these bridge projects and to determine the most appropriate improvement type.

Bridge Maintenance Subsystem

The Bridge Maintenance Subsystem of BMS can rank bridges based on needed maintenance activities. It also can estimate costs for these bridge maintenance activities. A prioritization procedure has been developed which considers the effect of the most structurally critical maintenance activity need on the bridge and the individual bridge's impact on the road system. A maintenance deficiency rating is calculated by the system for each bridge on a scale of 0 to 100 with higher values suggesting higher maintenance needs. A menu of 76 bridge maintenance activities has been developed and stored in the system. These activities cover the full range of maintenance that can be done on a bridge using either Department Forces or a contractor. Bridge inspectors select needed maintenance activities for each bridge, estimate an approximate quantity of repair, and assign a relative priority to each maintenance activity identified. This process occurs at the end of each safety inspection and does not require a significant amount of additional time. With this additional information, the system can prioritize bridges based on maintenance needs and estimate costs. A list of all data required for the Maintenance Subsystem is included in Table IV. After each maintenance activity is completed, maintenance information is transferred from the maintenance needs in BMS to the completed maintenance activities where it serves as a historical record of completed work.

TABLE IV DATA USED FOR MAINTENANCE SUBSYSTEM

Data Needed to Determine Deficiencies
Load Carrying Capacity
Deck Condition Rating
Superstructure Condition Rating
Substructure Condition Rating
Culvert Condition Rating
Remaining Service Life
Average Daily Traffic
Detour Length
Functional Classification
State Network
Priority of Maintenance Activity
Data Needed to Estimate Costs
Maintenance Activity
Bridge Length
Bridge Width
Estimated Quantity of Repair
Unit Costs for Maintenance Activity

The Bridge Maintenance Subsystem provides decision support in the development of the Department's Annual Maintenance and Betterment Programs. These programs provide for all non-capital highway and bridge work. The work is done by either Department Forces or contractors. Bridge work includes any of the 76 bridge maintenance activities mentioned above and also small bridge replacements. Programs are developed on an annual basis, and BMS provides support through its needs estimating, prioritization, costing and tracking capabilities. Besides the various maintenance activities completed each year, about 100 small bridge replacements are included each year in this program.

Bridge Modeling Subsystem

The Bridge Modeling Subsystem of BMS provides a means to predict future bridge rehabilitation and replacement needs for Pennsylvania's bridges. The Modeling Subsystem enables the user to develop future estimates for deficiency ratings, sufficiency ratings, condition ratings, load capacities, and improvement costs. From these estimates, prioritized listings and associated costs can be developed. The Modeling Subsystem also considers the effects of inflation, traffic increases, and current or proposed spending levels.

Two basic deterioration models drive the Modeling Subsystem. These models allow for the deterioration over time of bridge condition ratings and bridge load carrying capacity that are the primary components used in the prioritization of bridges for rehabilitation and replacement. A method has also been developed which establishes new improvement codes for deteriorated bridges. These new improvement codes are then used to estimate future improvement costs. Table V provides a summary of the data used in the Modeling Subsystem.

The Modeling Subsystem provides decision support capability by allowing Department managers the opportunity to predict future bridge needs under many scenarios. This capability is useful, for example, in

TABLE V DATA USED FOR MODELING SUBSYSTEM

Data Needed to Determine Deficiencies
Future Load Carrying Capacity
Clear Deck Width
Vertical Clearance on the Bridge
Vertical Clearance under the Bridge
Future Deck Condition Rating
Future Superstructure Condition Rating
Future Substructure Condition Rating
Future Culvert Condition Rating
Future Remaining Service Life
Approach Roadway Alignment Appraisal
Waterway Adequacy Appraisal
Future Average Daily Traffic
Detour Length
Functional Classification
Data Needed to Estimate Costs
Future Improvement Type
Bridge Length
Bridge Width
Unit Costs for Improvements

determining the minimum annual expenditures that must be made to stay even with continuing bridge deterioration, or the minimum annual expenditures that must be made to eliminate all bridge deficiencies over several years. The Modeling Subsystem enables managers to ask "what if?" questions concerning all or any subset of the bridges in BMS. Of course, predicting future bridge needs is not an exact science, and the degree of accuracy of these predictions must always be carefully scrutinized and, in time, checked against historical records. Historical records also should be used to refine the prediction capabilities of the model. BMS has been storing historical records since its implementation in 1986, in anticipation of using this data for fine tuning.

Bridge Automated Permit Routing and Analysis Subsystem

The Bridge Automated Permit Routing and Analysis Subsystem is a new subsystem of BMS that is currently under development and is anticipated to be implemented in about two years. This subsystem will replace the current permit system, which does only administrative functions. Permits are required for any oversize or overweight vehicles traveling through Pennsylvania. Each year the Department processes between 250,000 and 270,000 hauling permits, of which 12,000 are special hauling permits or superloads that require the review of a bridge engineer. The new subsystem will be completely automated. It will analyze individual bridges for load carrying capacity based on the actual axle weights and spacings of the permit vehicle. It also will check for vertical clearance and width restrictions based on vehicle size. Finally, it will evaluate and select travel routes, and issue the approved permit.

Three new data screens will be added to BMS to support the additional data requirements. Much of the new software will be installed on personal computers to simplify use by permit applicants, although data items will reside in BMS which is a mainframe system. Phone lines will connect the two. The primary benefits of this new subsystem will be rapid, consistent and responsive decision making by the Department in the review and issuance of hauling permits in Pennsylvania. This in turn will serve to increase productivity within the Department and within the trucking industry.

BMS Reporting Subsystem

A wide range of reporting capabilities has been included in BMS to access and use the extensive amount of data it contains. BMS can produce standard, menu driven reports; customized, user generated reports; and automatic monthly bridge statistics reports.

Standard menu driven reports are available in the Bridge Rehabilitation and Replacement Subsystem, the Maintenance Subsystem, the Modeling Subsystem, and they are anticipated to be available in the Automated Permit Rating and Routing Subsystem. These reports present the user with a menu of data and reporting options for each specific subsystem. The user selects from the menu of options and receives a report designed specifically for that subsystem. For example, the Bridge Rehabilitation and Replacement Subsystem will produce a report that displays candidate bridge projects in priority order with associated improvement costs. Other supporting data would be included as well. This reporting procedure is intended primarily for use by managers who have limited computer programming skills.

Customized, user generated reports require the user to be knowledgeable of computer programming languages; however, these reports offer the widest range of data reporting and manipulation for any subset of bridges in BMS. Some typical uses of this type of reporting that have been used to support decision making in the Department include: screening bridges for scour vulnerability, screening bridges for seismic vulnerability, selection of bridge painting candidates, and bridge inspection scheduling including underwater inspections and crane inspections.

Automatic monthly bridge statistics reports serve to report, document, and monitor the number, condition, type, ownership, improvement needs, and costs of all bridges in BMS. These reports also serve as a basis to track trends or patterns that may be developing over time. For example, a comparison of monthly reports could be used to detect whether bridge maintenance needs have increased or decreased over the last five years on a statewide basis or within specific areas of the state. Department managers would then have a basis to consider changes to bridge maintenance program funding levels.

Future Enhancements

Although PennDOTs BMS has been in operation since December 1986, enhancements and improvements have taken place continuously. Major BMS enhancements are also planned including the implementation of the Automated Permit Rating and Routing Subsystem. The Department is also considering the development of optimization capabilities in BMS. An optimization model would provide additional decision support to Department managers by determining bridge improvements using life cycle cost analysis. Besides bridge improvement costs, the optimization model also would consider user costs and benefits based on traffic and accident data. Additional system integration that would enable BMS to exchange more information with other Department Management Systems is also planned. BMS integration is proposed for the Maintenance Operations and Resources Information System, the Accident Records System, and the proposed Geographic Information System. New technologies are also being considered for implementation in BMS. The use of hand held, computer pen pads for field entry of bridge inspection data would replace the current pencil and paper method used in the field. This technology would provide faster, more accurate data entry, since computer disks would be uploaded into BMS rather than entered via keyboard from field notes and forms. This in turn would provide Department managers with the most current bridge inspection information in the shortest period. Other technologies being considered include the use of data imaging that would allow certain paper documents such as bridge plans, sketches and diagrams to be scanned and stored in BMS. Also available are photo and video storage capabilities that would allow pertinent bridge information to be viewable at BMS computer terminals. This would allow Department managers a close up look at bridge problems and conditions.

CLOSING

All BMS capabilities, both present and future, will serve to support management decision making within the Department. These support capabilities are driven by the Department's primary objective of providing a safe, reliable and efficient network of highways and bridges.

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WHAT A BRIDGE MANAGEMENT SYSTEM CAN DO FOR A LARGE CITY

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ABSTRACT

The benefits derived through the implementation of a Bridge Management System (BMS) at the state transportation agency level are well documented. Little attention has been given, however, to the use of a BMS at the local agency level. Local agencies face many of the same challenges as state agencies regarding allocation of scarce resources such as dollars, labor and equipment, to address the needs of an aging infrastructure. Local agencies also must deal with the reality of maintaining this infrastructure to meet the needs of the local population. BMSs, as they are currently envisioned, are principally planning and programming tools. Enhancements must be made to BMSs to allow bridge design and maintenance engineers at the local level to utilize all the capabilities of the database to effectively management and respond to the needs of the infrastructure.

INTRODUCTION

The City of Chicago's Department of Transportation (CDOT) is unique among local agencies responsible for the management and maintenance of bridge infrastructure. With fifty bridges, CDOT manages and maintains the largest movable bridge system in the world. It also has inspection, maintenance and capital planning responsibility for thirty-two (32) fixed spans over water, 107 highway overpasses and thirty-seven (37) pedestrian bridges and tunnels. The total replacement value of its bridge infrastructure is estimated at over $2.6 billion dollars. Eight of its structures are classified as fracture critical and half of its bridge inventory is over 50 years old. CDOT also is unique in that it directly establishes and manages its capital program for the State of Illinois. Between eight to ten million dollars for maintenance and 25 million dollars for capital rehabilitation and replacement are spent annually by CDOT on its bridge infrastructure. Annual funding needs, however, are between 60 and 80 million dollars.

Maintenance monies are derived principally from Motor Fuel Tax and City backed bonds. Capital rehabilitation and replacement monies come from the federal government through the state. Contracts for all design and construction work are managed, bid and awarded by the city with approval from state and federal agencies.

CDOT performs biannual inspections of its bridge infrastructure and yearly detailed inspections of all fracture critical structures. These inspections serve as the principal source of information regarding the current condition of the bridges. Inspections are performed following the provisions of the Federal Highway Administration's (FHWA) Bridge Training Manual 90. Standard Illinois Department of Transportation (IDOT) forms are completed for each bridge inspected. These forms comply with the FHWA's "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nations's Bridges" and provide data to support the requirements of the National Bridge Inventory (NBI). These inspections serve as the basis for the development of the City's Capital Program.

The size, age and complexity of this infrastructure pose particular problems in managing the data necessary to effectively prioritize maintenance repairs and capital rehabilitations and replacements. The standardized state and federal inspection forms do not capture all the information pertinent to CDOT's particular infrastructure. For example, no data are collected on the City's movable bridge electrical and mechanical systems. The inspection data collected also quickly looses its value due to the ongoing nature of maintenance repairs and capital projects. Since the data are not dynamic, limited by the frequency of inspections and the volume of this data is large, management's ability to quickly respond to changes in funding or assess the impact of capital deferrals is severely impaired.

Starting last year, CDOT began completing detailed assessment and defect inspection for each bridge rather than rely solely on the "free form" comment format used by the state inspection form to identify defects. A consistent identification and coding taxomony was developed which is used to locate critical defects and conditions for a structure on a span by span basis. This methodology allows the replication of the inspection for quality control and dispatch of repair crews to a given location. This detailed inspection forms the principal basis for the development of the City's bridge maintenance program.

A BRIDGE MANAGEMENT SYSTEM FOR A LOCAL AGENCY

For most local agencies, the small size of the bridge infrastructure means that decisions regarding planning and funding can be done without the aid of sophisticated analysis tools. Managing that infrastructure does not pose significant data management requirements. Immediate access to that data is of less important to a small local agency than it is to the state. Thus, information needs for a small local agency can be addressed on an "as needed" basis.

A large local agency, such as CDOT, that manages and implements its own capital program, shares many of the same information needs as a state agency. Due to its infrastructure's age, size, and complexity, the ready access to that information is of equal or greater importance than that of a state agency. Issues of resource allocation, current condition and future capital needs are as important to such local agencies as they are to state agencies. The challenges posed by limited and changed funding levels have even greater implications at the local level than they do at the state level. Managers at the local agency level require the same "what if" capabilities to effectively assess the impact of deferred capital investment.

To address this information need, the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, mandated that all state transportation agencies implement Infrastructure Management Systems (IMS) by the start of federal fiscal year 1995 (*1*). Failure to implement such systems by that date may result in withholding of up to ten (10) percent of federal funding apportioned through the ISTEA. Local agencies are generally exempt from the requirement to implement such systems. They are, however, required to provide input and data support to the IMS process through Metropolitan Planning Organizations (MPO). BMSs are one element of the IMS.

> "The (BMS) system itself consists of a database and an analysis capability that enable an agency to efficiently evaluate bridge needs, develop recommendations, and assess the near and long term impacts of bridge policies and alternative courses of action." (*1*)

As with the IMS, local agencies are not required to implement such systems, however participation in the state BMS is required and the data collected must be consistent with state BMS requirements.

The proposed federal requirements for a BMS reference the American Association of State Highway and Transportation Officials (AASHTO) Guidelines for Bridge Management Systems as the minimum standards for system design and implementation. The AASHTO Guidelines establish twelve minimum requirements for the BMS software (*2*). Central to this software is a database that serves as the repository for the inspection data used by the BMS. The remaining elements provide modeling capabilities that are principally used to forecast, plan and assess the impacts of funding on bridge capital programs.

BMS Applications at the Local Level

By virtue of its current design, the BMS has significantly greater application to needs of the City Planner and Program Administrator than the Chief Design or Maintenance Engineer. The optimization models used by the BMS seem to lend themselves to the occasional level of use demanded by the Planner and Administrator. The focus of the elements identified in the AASHTO Guidelines for a BMS support the programming aspects of bridge management over the engineering and maintenance aspects of the task. These current limitations should not, however, be construed as limiting the BMS's usefulness at the local agency level. The BMS can provide a context for the establishment or increase of local funding levels to support maintenance of the bridge infrastructure through enhanced justifications. The effects of deferred maintenance, such as for painting, can be easily seen through the modeling capability of the BMS. Based upon the optimization scenarios provided by the BMS, better justification can be developed to obtain an increased share of local level dollars for bridges.

For a local agency that plans and maintains its own capital program, the ability to evaluate changes in funding levels is essential. The BMS provides the data that are necessary for the planner and programmer to shift priorities to meet program changes. Adjustments in ongoing programs due to cost overruns or underruns could be quickly assessed with the BMS's cost models. The development of local programs for submittal to the state and federal level would also be expedited with the BMS.

The methodology required to establish the BMS impose certain disciplines on the local agency that might not otherwise be present. Engineers and planners must develop, evaluate and assess cost and deterioration data that are to be input into the BMS. This forces a conscience review by these decision makers of known factors that affect bridge life and life cycle costs. Previously assumed truths regarding pricing and durability can be tested against actual conditions using the models. The BMS database provides a convenient repository for the data collected on the biannual bridge inspections. These data can be used to prepare and transmit the information needed by state and federal agencies to update the NBI. The more rigid data collection methodology provides a means to insure the easier replication of inspections. Reproducibility of inspections is currently limited due to the reporting methodology allowed by the federal and state inspection forms. Follow-up inspections and quality assurance checks are of limited value since much of this data is in a form that is not easily retrieved or replicated in the field. The more detailed information required by the BMS allows the easy location of a particular defect in the field. Through its links with the IMS, the BMS forces local agencies to broaden their planning horizons. The need to interface between other infrastructure projects becomes a reality with the BMS. Greater efficiency can be gained through the "packaging" of like projects or adjacent projects. Greater coordination for construction would also minimize the impact on traffic.

Limitations of the BMS to Local Agencies

With 226 bridges, CDOT has a large bridge infrastructure compared with most local agencies. Within that infrastructure, there are a variety of bridge types and construction details. The probabilistic models used to forecast life expectancy, repair/rehabilitation costs and project types benefit from the large number of similar structure types and constructions typically found at the state and federal level. It is expected that the BMS models would have some limitations at the local level based upon the available population of data for a particular bridge type and construction details. Although these forecasting models may be adequate to establish funding for a particular type of repair or rehabilitation program at the state level, these predictions may not be readily transferred to specific projects at the local agency level.

To be a truly effective tool at the local level, the BMS should explore greater use of the database capabilities as a management tool for engineers. The BMS must provide more support to the local agency's Chief Bridge Maintenance or Design Engineer. Many potential enhancements identified as the short range goals in the AASHTO BMS Guidelines have immediate use to the local agency engineer (*2*). These enhancements include:

- Work order capability to dispatch repair crews. This system should be fully linked to database and note when capital programs are pending. This information can be used to tailor repairs to meet specific funding objectives and insure efficient use of limited resources. The system also should provide immediate update of the database. This capability presupposes a much more rigid taxonomy for the identification and location of bridge elements and components. The inspection system employed by CDOT has the rudimentary underpinning of such a system. Design and maintenance engineers must have the ability to accurately duplicate an inspection and quickly locate existing problems. More efficient inspections can be realized through the verification of existing conditions. With existing conditions quickly verified, the inspector can focus on the identification of new defects or conditions. A higher quality inspection is the result.
- Scheduling of inspections and monitoring of critical conditions. The system should produce summary level reports on current conditions that can be used to track critical bridge structures.
- Monitoring of permit loads to assess the effects of fatigue on structure and a means of identifying remaining life. For many local agencies, this poses one of the greatest challenges. Moving permit loads through a bridge system knowing the influence curve for a particular structure would greatly reduce the labor currently expended on such efforts. This capability also would benefit state agencies.
- The addition of other factors, not currently captured by the BMS, that may influence local agency project level decisions. Congestion mitigation, availability of alternate routes for detours, coordination with other projects and demographic considerations for allocation of programs, among other factors, must be evaluated in the preparation of local maintenance and capital programs particularly in large metropolitan areas. The BMS models should have the ability to be "tuned" to recognize these criteria.
- Expand the models to included movable bridge structures. The current NBI collects limited data on movable bridge structures. The electrical and mechanical systems of these bridges, in particular, represent potentially high capital investment requirements. More detailed information is required to effectively manage this infrastructure and assess the impacts of limited funding.

CONCLUSIONS

Local agencies need the ability to effectively allocate scarce resources of dollars, labor and equipment, to extend the useful life of its bridge infrastructure. Although capital plan forecasting is an element of CDOT's overall bridge program, the principal focus is in the day to day management of the bridge infrastructure to insure its continued serviceability. Local agencies must have the tools readily available to meet these needs. Large bridge infrastructure systems such as Chicago's could benefit directly from the implementation of a BMS outside the state agency level. Additional enhancements must be made to the proposed BMS format to insure its use by the widest number of users. The current BMS designs do not fully explore the potential uses of the database information as it applies to the needs of the Chief Bridge Design and Maintenance Engineer. The BMS models must also be sensitized to local needs and parameters, beyond those of cost and deterioration, to be truly effective management tools.

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COUNTY BRIDGE MANAGEMENT REQUIREMENTS

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ABSTRACT

This paper describes elements that will be important to counties as State Departments of Transportation develop and implement their Bridge Management Systems. Elements defined include:

- Ability to analyze, optimize, and prioritize by bridge ownership jurisdictions;
- Direct accesses by local governments to the state managed system, as "co-users;"
- Ability to accept several data input methods;
- Ability to perform optimization by several subsets such as type of jurisdiction, various geographic boundaries, and individual ownership jurisdiction;
- Need for states to work closely with their local governments as the system is developed; and
- Have early and meaningful dialogue with local governments related to both the development and use of the system is the most important element.

INTRODUCTION

This paper describes elements that will be important to counties as state departments of transportation (DOTs) develop the Bridge Management Systems (BMS) required by the Intermodel Surface Transportation and Efficiency Act (ISTEA). It is difficult to define specifics important to counties throughout the country because: the size and capabilities vary dramatically around the country; historical relationships with state DOTs vary greatly around the country; and responsibilities for bridges, bridge inspections and BMS vary around the country. I concluded that the most appropriate message I could give is to define the three most important elements. Like the old bromide in real estate, "Location, Location, Location," the most important element in the relationships of counties and departments of transportation is "Dialogue, Dialogue, Dialogue." The few specific elements I mention will be biased, based on my experience in a large urban county and a small rural developing county in Minnesota, the responsibilities for bridges that exist in Minnesota, and the emerging transportation programming processes that are being implemented due to ISTEA.

My remarks are organized on the three theme elements of this conference: data needs/data collection, data analysis, and decision support. However, I want to center on Decision Support because I believe that is where the issue will focus.

DATA NEEDS AND DATA COLLECTION PRACTICES

More data are needed because of element-level approach. Experience to date with Pontis suggests that it should not seriously increase data collection efforts. However, if it is a problem for some counties, it may be possible to use current National Bridge Inventory (NBI) System type of data with fuzzy logic to approximate results from element-level inspections.

DATA ANALYSIS PROCEDURES

Type and scope of analysis are the biggest changes from current NBIS and are what makes it a true management system. The outputs of this analysis can be valuable tools for counties in managing their bridge systems. I believe that in all but perhaps the largest jurisdictions, counties are comfortable with state DOTs establishing these analysis procedures because of their greater expertise and resources.

DECISION SUPPORT

Decision Support, which is the outcome of the Data Analysis and how it is used, is the area that requires the most attention and dialogue between State DOTs and local jurisdictions. In Minnesota, for example, 4,600 of the 19,500 bridges in the State are under Minnesota Department of Transportation (MnDOT) jurisdiction. If the BMS is not of practical use and value to local government, three-fourths of the bridges in Minnesota will not benefit from an effective BMS. Local governments will respond in one of two ways: larger units might develop their own systems to be of practical value, and smaller units will collect data (because it is required) but ignore the decision support of the system.

If a BMS is not of practical use to counties, I do not believe it would be because of technical disagreements, because counties generally look to their state DOT as the technical expert. I think it would be because the state DOT failed to adequately address "Service Support" and inter-jurisdictional issues. Examples:

- Some counties may wish to be interactive "co-users" of the system so they can develop various "what if" scenarios for their system;
- Many other counties may prefer to only receive a standard "update" of their system on a periodic basis;
- Probably all counties would want the state DOT to provide a consultative service for help in analyzing the various system outputs--almost a mentor role by the DOT; and
- Counties would look to the state DOT to provide adequate training to county personnel, not only for data collection but also for use of the system results.

In addition, counties would expect to play a role in establishing how the optimization models would be used in prioritizing bridges across jurisdictional lines in establishing State Transportation Improvement Programs (STIPS) under the ISTEA requirements. There must be satisfaction that the BMS provides a relatively level playing field among the various levels of government for competing for federal and state funds. To be of value for network-level decisions, particularly related to major rehabilitation or replacement, I believe it is essential that any BMS must provide decision support information for almost any subset of the total network. Examples are ownership jurisdiction, Metropolitan Planning Organization (MPO) boundaries, and any other geographic boundaries that might be used for program development purposes. Because of ISTEA, several other management systems also will play a role in development of a total capital program, particularly pavement management, congestion management, and safety management. While it is doubtful that these systems can or should be fully integrated, common items such as methodology for use cost estimating should be consistent across all systems, and common databases should be used to the maximum extent possible.

MINNESOTA CONSULTATIVE PROCESS

The MnDOT has been an active participant in the development and testing of the Pontis system. They have decided to use the Pontis system. I do not believe any county in Minnesota will argue with their doing so. The bulk of the technical development work is done. Now comes implementation. MnDOT has recently organized a task force to develop and resolve implementation issues that I hope will include many items I've described. This task force is both internal and external to MnDOT and involves representatives from programming, State Aid, information policy, traffic, Federal Highway Administration (FHWA), MPO and regional development commissions, urban and rural counties and cities. I am excited about this approach and believe it will result in a BMS that will be of value to all bridge jurisdictions in Minnesota. Paul Kivisto is the MnDOT Bridge Management Engineer and is in charge of this process.

SUMMARY

Timely and constant dialogue with counties and cities is required for a BMS to reach its intended potential in any state.

NBI CONDITION RATINGS FROM BMS DATA

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ABSTRACT

Methods to generate National Bridge Inventory (NBI) condition ratings for deck (NBI Field 58), superstructure (NBI Field 59), substructure (NBI Field 60) and culvert (NBI Field 62) from element-level condition data in a bridge management system (BMS) database have been developed. A translation of data from BMS coding to NBI coding is possible by linking BMS elements to corresponding NBI fields and mapping BMS condition states to the NBI rating scale. Methods for NBI generation are now available and have been calibrated against data gathered by nine state departments of transportation (DOTs) in testing of Pontis BMS in 1992. The performance of NBI generation is good and a uniform generation procedure for all state DOTs is feasible.

INTRODUCTION

The 1991 Intermodal Surface Transportation Efficiency Act (ISTEA) requires that state DOTs implement Bridge Management Systems to support planning of maintenance, repair and rehabilitation activities to promote an efficient use of resources. BMS is a new requirement; it does not supplant bridge condition reporting under the NBI structure.

A key feature needed to complete the implementation of BMS is an ability to serve NBI reporting requirements, specifically an ability to generate NBI rating fields from BMS data on bridge elements and conditions. The generation of NBI ratings from BMS condition reports promotes efficiency in inspections. NBI generation does not qualitatively alter the practice of bridge inspection; conditions are still assessed and reported by human inspectors. However where inspectors use a BMS format for recording conditions, NBI generation eliminates the need to record the same data again in the NBI scale.

One BMS that is being used or considered for use by many state DOTs is the Pontis BMS developed for the Federal Highway Administration (FHWA) (*1*). Pontis BMS operates with a unique format for coding bridge inspection data that differs from the NBI. In particular, Pontis employs new elements to model bridge structures, defines new condition states for elements, and requires a practice of reporting all conditions observed on an element along with the extent of each condition instead of reporting a single average rating value. These features are sources of incompatibility with NBI reporting.

NBI ratings are determined from the observed condition of the components of bridges. A BMS may use elements and condition states that differ from the NBI rating fields and rating scale, but both BMS condition reports and NBI ratings are derived from the same observations. There is a correspondence between the two reporting formats, and therefore it is possible to generate NBI rating fields from condition reports in a BMS database.

Procedures for the generation of NBI rating fields from the database of a BMS were developed in 1992 using data gathered by Colorado DOT in their β test of Pontis BMS. NBI generation procedures operate by combining BMS elements to form groups which contribute to common NBI fields, and by mapping BMS condition reports to the NBI rating scale. NBI generation procedures exist in two parts, a formal process for integrating BMS condition reports and a set of mapping constants that define the correspondence between rating scales. The 1992 study of Colorado data demonstrated the feasibility of the formal process and yielded mapping constants for many Pontis BMS elements.

In 1993, additional work using Pontis β test data from nine DOTs (California, Colorado, Iowa, Kansas, Michigan, Minnesota, Tennessee, Vermont & Washington) completed a general calibration of mapping constants and studied the overall performance of NBI generation procedures. With these data, mapping constants were calibrated for individual DOTs and for the union of all data (simulating a uniform, nationwide NBI generation). Overall performance of the NBI generation is good. Generated NBI rating values are within ±1 of assigned NBI values for 90% of all cases in calibrations for individual DOTs. Using a uniform generation, NBI ratings are within ±1 of assigned values for 88% of cases. Uniform NBI generation introduces only modest shifts in NBI ratings for individual DOTs, and it appears that a uniform NBI generation is feasible.

CONDITION REPORTS IN BRIDGE MANAGEMENT SYSTEMS

In their function as planning tools, Bridge Management Systems require a means of evaluating incidental costs of deferred maintenance and of selecting a workable order of repairs to bridges. BMS must forecast future condition of bridges and of bridge components. The means of forecasting and the data supporting forecasts may be referred to collectively as deterioration models. BMSs rely on deterioration models and actively refine deterioration models through calibration against a database of observed bridge conditions.

Deterioration rates and the impact of deterioration on the cost of repairs can be expected to vary for different bridge components, different structural materials, and different forms of members. It is necessary then to distinguish between deck components, superstructure components and substructure components, to distinguish among components constructed in steel, concrete and timber, and to distinguish among forms such as open sections, closed sections, slabs, columns, etc. Each use, material, and form implies a separate deterioration rate and a separate impact on repair costs. Each requires a separate deterioration model.

Separate deterioration models require separate data to constitute and refine them. Therefore, management systems require coding formats for condition data using many bridge elements. Coding formats are further adapted to the support of deterioration models through new condition states that are responsive to cost-significant changes in bridge elements. The proliferation of bridge elements and the creation of new condition states make BMS data incompatible with the existing NBI record and NBI rating scale.

BMS elements are recognizable bridge components such as steel stringers, steel box beams, prestressed concrete boxes, reinforced concrete abutments and reinforced concrete decks. Elements exist for each material (steel, reinforced concrete, prestressed concrete and timber), for each use (deck, superstructure, substructure, and culvert) and for each form (open stringer, closed box, column, wall, pile cap, slab, deck, etc.). BMS elements include all components that affect NBI rating fields along with other components such as railings that do not affect NBI ratings. In its β version, Pontis BMS included 120 defined elements. Recent work on Commonly Recognized (CoRe) elements has produced a set of 96 elements adapted from β elements (*3*).

The BMS model of a bridge consists of elements and quantities of elements. This is illustrated in Table I which shows the Pontis BMS model for a steel beam bridge. The model presents materials, member types and quantities. The condition report lists the quantities of an element in each condition state. The groupings *Deck, Superstructure, Substructure* and *Other* is the first step in NBI generation; specifically, the identification of contributing and non-contributing elements, and the grouping of contributing elements in specific NBI fields. Note that two BMS elements contribute to *Superstructure* and three contribute to *Substructure*. NBI generation must deliver the average rating for the set of elements grouped in a single NBI field.

NBI GENERATION FROM BMS DATA

BMS data on the condition of bridge elements differs from the NBI format in two ways: BMS uses many elements instead of the four NBI fields; and BMS reports all observed condition states instead of a single rating value. NBI generation therefore involves distinct operations of grouping BMS elements to form NBI fields and of combining BMS condition states. An ensemble of elements and condition states must become a single NBI rating.

BMS can support individual sets of condition states for each of its elements, and each set of condition states requires an individual map for translation to the NBI rating scale. In practice, similar materials and uses employ similar sets of condition states. For example, all painted steel superstructure elements have similar condition state definitions and can be treated with a single map for NBI generation. Prestressed concrete superstructure elements have a different set of condition states and require a different NBI generation map. In all, seventeen maps are needed (Table II).

Two approaches to NBI generation have been studied. The first is a weighted-average computation operating directly on condition state quantities for elements. The second is a table-driven procedure which compares quantities in condition states to requirements on quantities for NBI rating assignment. Weighted-average NBI ratings are generated as

$$NBI = \sum M_i F_i \qquad (1)$$

where:

NBI = NBI condition rating computed from BMS data,

M_i = Mapping Constant for BMS condition state *i*, and

F_i = Fractional quantity of a bridge element reported in condition state *i*.

TABLE I BMS BRIDGE MODEL AND CONDITION REPORT

Element	Quantity	Condition State				
		1	2	3	4	5
Deck						
124 Concrete Deck w/Rigid Overlay	20,600 SF	0	20600	0	0	-
Superstructure						
8 Steel Open Stringer, painted	2,840 LF	2,500	340	0	0	0
33 Steel Floor Beam, painted	936 LF	899	37	0	0	0
Substructure						
41 Concrete Cap, non-integral	6 Ea	4	2	0	0	-
47 Concrete Column	14 Ea	2	10	2	0	-
51 Concrete Expansion Joint	2 Ea	0	1	1	0	-
Other						
94 Open Expansion Joint	58 LF	8	42	8	0	0
96 Moveable Bearing	18 Ea	15	3	0	0	0
102 Metal Bridge Railing	1,422 LF	1,194	200	28	0	0

Weighted-average NBI generation for Pontis BMS can take the form

$$NBI = M_1F_1 + M_2F_2 + M_3F_3 + M_4F_4 + M_5F_5 \quad (2)$$

where the mapping constants and fractional quantities have the same meaning as in Equation (1). Equation (2) is explicitly for an element condition report of five condition states.

For table-driven NBI generation, quantities in condition states are compared to threshold quantities for assignment of an NBI rating. The form of the table is shown in Table III. Percentages of quantities are denoted as P_i. The four requirements for each NBI rating value are simultaneous requirements. The percentages in the BMS condition report must satisfy all four requirements to qualify for assignment of the corresponding NBI rating. The range of possible NBI ratings is determined by the form of the table. In this study, all tables allow ratings from zero to nine (0 to 9).

The mapping constants M_i for weighted average generation and $M_{i,j}$ for table-driven generation are chosen to yield a minimum error in NBI generation. Data from Pontis β test inspections (i.e., the NBI ratings and condition reports) were used as the basis of search procedures to arrive at optimal sets of mapping constants.

DATA IN THE STUDY OF NBI GENERATION

A search for optimal mapping constants M_i and $M_{i,j}$ examines many sets of mapping constants, computes the error in generated NBI ratings, and selects the set that delivers the minimum error. The mapping constants are said to be calibrated to the data used in the search. Data available from DOTs include copies of BMS bridge databases and current NBI condition ratings for bridges in the databases. The data set includes 3,300 bridges

TABLE II MAPS FOR NBI GENERATION

Map	Element Type
1	Unpainted Steel Superstructure
2	Painted Steel Superstructure
3	P/S Concrete Superstructure
4	Reinforced Concrete Superstructure
5	Timber Superstructure
6	Unpainted Steel Substructure
7	Painted Steel Substructure
8	P/S Concrete Substructure
9	Reinforced Concrete Substructure
10	Timber Substructure
11	Reinforced Concrete Deck
12	Steel Deck
13	Timber Deck
14	Reinforced Concrete Slab
15	Steel Culvert
16	Reinforced Concrete Culvert
17	Timber Culvert

TABLE III DECISION TABLE FOR NBI GENERATION

BMS Condition Report	NBI Rating
$P_1 \geq M_{1,9}$ $P_1 + P_2 \geq M_{2,9}$ $P_1 + P_2 + P_3 \geq M_{3,9}$ $P_1 + P_2 + P_3 + P_4 \geq M_{4,9}$	9
$P_1 \geq M_{1,8}$ $P_1 + P_2 \geq M_{2,8}$ $P_1 + P_2 + P_3 \geq M_{3,8}$ $P_1 + P_2 + P_3 + P_4 \geq M_{4,8}$	8

TABLE IV DISTRIBUTION OF BRIDGE CHARACTERISTICS IN THE NBI CALABRATION STUDY

Superstructure Type	Steel	Reinforced Concrete	P/S Concrete	Timber	Mixed	Culvert	Total
	400	1500	400	200	300	500	3,300
Year Built	To 1920	1921-1940	1941-1960	1961-1980	1981-1992		
	50	500	700	1700	350		3,300
Spans	To 100'	101-200'	201-300'	301-400'	> 400'		
	2830	400	30	30	10		3,300
NBI Ratings	0-3	4-6	7-9				
	1%	30%	69%				100%

TABLE V EXAMPLE OF NBI GENERATION

Element	Quantity	Condition State				
		1	2	3	4	5
107 Steel Open Girder, painted	2,840 LF	2,500	340	0	0	0

Weighted Average	**Decision Table**
NBI = 6.6(0.88) + 6.5(0.12)	**P_1 = 88**
NBI = 6.6	**$P_1 + P_2$ = 100**
	NBI = 7

and culverts (Table II). Most of these structures have current NBI rating values of six (6) and above, but there are several hundred occurrences of NBI ratings of three, four or five (3, 4 or 5). There are fewer than 10 occurrences of NBI ratings below three (3).

Mapping constants were calibrated for data from individual DOTs, and for the union of data from all nine DOTs (simulating a single, uniform NBI generation procedure). Constants M_i and $M_{i,j}$ were developed for both weighted-average and table-driven NBI generation. An example of the results is shown in Table V for the generation of NBI ratings for painted steel superstructure.

The two approaches to NBI generation respond differently to changes in a BMS condition report. Table VI shows an example in which four possible condition reports for a painted steel girder are considered. This first case, *a*, is a girder in good condition. Other cases, *b*, *c*, and *d* consider a small quantity of the girder in progressively poorer condition states. The results of both weighted-average generation and table-driven generation are shown. Note that the generated NBI rating decreases more rapidly for the table-driven approach. Generation using tables can be more responsive to poor condition states than a linear weighted-average.

Using mapping constants calibrated individually for DOTs, NBI generation is within ±1 of assigned NBI ratings for 90% of all cases. Using mapping constants calibrated for a unified data set of nine DOTs, NBI generation is within ±1 for 88% of all cases. Results are summarized in Tables VII and VIII.

There is little overall shift in NBI ratings when using a single set of mapping constants for all DOTs. Table VI shows the average differences in generated NBI ratings between the use of a single, uniform set of mapping constants for all DOTs, and mapping constants calibrated for each DOT individually. Positive values indicate that NBI ratings are increased on average using uniform generation; negative values indicate that NBI ratings are decreased. Differences in NBI ratings are often less than ±0.5. It appears that a uniform NBI generation process does not skew NBI ratings.

WORKSHOP ON NBI GENERATION

The data available from β tests have recently been enhanced by the addition of data from a workshop on NBI generation (*4*). Representatives from twenty-two DOTs were invited to review NBI generation procedures and to participate in an exercise of NBI rating and BMS condition reporting for example cases prepared by DOTs. Case histories were developed with real bridges which present specific concerns in NBI generation. There were six deck cases covering concrete, steel and timber decks and addressing concerns in deteriorated joints, deck cracking, spalling, AC overlays, and deck leakage. Seven superstructure cases covered reinforced concrete, P/S concrete, steel and timber bridges addressing concerns in bearing failure, impact damage, severe local loss of section and pack rust. Five substructure cases addressed concerns in substructure settlement, cracking and scour. Three culvert cases cover concrete, steel and timber culverts. These cases allow a

TABLE VI EXAMPLE OF NBI RESPONSE TO POOR CONDITION STATES FOR A STEEL OPEN GIRDER, 2840 LF

Case	Condition Report, LF					Weighted Average NBI	Table Driven NBI
	1	2	3	4	5		
a	2556	284	0	0	0	7(6.6)	7
b	2556	0	284	0	0	7(6.5)	6
c	2556	0	0	284	0	6(6.4)	6
d	2556	0	0	0	284	6(6.2)	4

TABLE VII PERFORMANCE OF NBI GENERATION CALIBRATED FOR INDIVIDUAL DOTs

State	Percentage of Bridges*					
	Weighted-Average Rating			Table-Driven Rating		
	Deck, %	Super, %	Sub, %	Deck, %	Super, %	Sub, %
California	91	85	84	94	88	85
Colorado	97	97	97	97	100	97
Iowa	93	88	98	89	80	99
Kansas	98	94	96	98	94	97
Michigan	88	77	100	94	86	97
Minnesota	94	98	79	94	94	80
Tennessee	82	79	87	83	91	88
Vermont	94	92	80	96	90	95
Washington	77	100	100	100	100	100
Overall	92	86	86	94	89	87

* Within ±1 of assigned NBI Rating

study of the sensitivity of NBI ratings to specific deterioration conditions. The NBI ratings and BMS condition reports obtained from participants are being used in additional calibrations of mapping constants. This calibration from workshop data is in progress. After this calibration is complete, NBI generation software will be made available to transportation departments.

SUMMARY

NBI generation from BMS element data allows inspectors to use BMS reporting formats without a duplication of effort and so aids in the implementation of management systems. Procedures for NBI generation have been calibrated using data from nine states and performance is good. A uniform generation for all

TABLE VIII PERFORMANCE OF NBI GENERATION CALIBRATED FOR ALL DATA

State	Percentage of Bridges[*]					
	Weighted-Average Rating			Table-Driven Rating		
	Deck, %	Super, %	Sub, %	Deck, %	Super, %	Sub, %
California	90	85	86	94	86	85
Colorado	91	88	85	91	88	79
Iowa	88	74	94	89	77	92
Kansas	97	93	97	98	92	96
Michigan	91	71	88	91	71	74
Minnesota	88	84	73	86	80	72
Tennessee	70	70	68	68	78	64
Vermont	81	89	80	82	89	90
Washington	85	83	85	85	92	100
Overall	90	85	86	93	86	85

[*] Within ±1 of Assigned NBI Rating

TABLE IX SHIFTS IN NBI RATINGS FOR UNIFORM GENERATION

State	Shift in NBI Ratings					
	Weighted-Average Rating			Table-Driven Rating		
	Deck	Super	Sub	Deck	Super	Sub
California	0.2	0.3	0.0	0.0	0.0	0.0
Colorado	0.2	0.5	0.9	0.2	0.4	0.9
Iowa	0.5	0.7	0.5	0.5	0.5	0.8
Kansas	-0.2	-0.4	-0.3	-0.3	-0.5	-0.1
Michigan	0.0	0.8	0.9	0.0	0.6	0.7
Minnesota	-0.4	-0.2	0.0	-0.4	-0.6	0.2
Tennessee	0.5	0.9	0.8	0.5	0.6	0.9
Vermont	0.4	0.0	0.6	0.3	0.0	0.6
Washington	0.5	0.7	1.2	0.0	0.3	1.0

DOTs is feasible. A recent workshop on NBI rating from BMS will allow a final calibration of NBI generation procedures before release of the software. Validation will continue as DOTs begin to use the NBI generation procedures.

ACKNOWLEDGMENTS

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USER COSTS IN A BRIDGE MANAGEMENT SYSTEM

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ABSTRACT

A fundamental task of bridge management is to optimize fund allocations for the reconstruction, maintenance, repair and inspection of a bridge network under existing constraints. The first step in this process is to assume that all existing bridges are beneficial to the community of users. Thus a bridge is rebuilt, repaired or maintained according to its condition. Since all bridge management decisions are optimized under certain constraints, a bridge management system (BMS) provides a method for prioritizing work on structures according to selected criteria. A simple approach would involve addressing the bridges in the worst condition first. An improved system evaluates bridges according to the cost of the work needed. Intervention in the bridge deterioration process at an earlier stage is cost effective by comparison to allowing the bridge to depreciate and then replacing it. A further refinement considers the importance of the bridge to the users. Several factors can be used to reflect this consideration, such as average daily traffic, peak daily traffic, alternate routes, traffic accident count, and level of serviceability. Some of these factors can be treated as deterministic variables, while others are of a random nature. A detailed evaluation would assign certain value to the time lost by the users due to partial or full bridge closure. The study of bridge deck repair strategies by Llanos and Yanev (*1*) for instance assumed that bridges rated below three (3) provide 75 percent and bridges rated below two (2) provide 50 percent of the full bridge service. An accurate evaluation of this assumption would be of considerable benefit. An estimate of the effect of bridge conditions on traffic accidents and their respective cost would have to be made as well. Considering the above factors as variables allows one to observe their influence on bridge management strategies. Thus, it becomes possible to demonstrate critical levels of service that determine the optimal strategy for a bridge, e.g., to rebuild under partial or full closure, to demolish without replacement, or to rehabilitate. In the current practice such decisions are based on experience and engineering judgement. It would be helpful to compare these decisions with a model addressing an entire network, consisting of bridges of different size, importance and level of deterioration, such as the ones in New York City or even individual cases such as the East River crossings.

INTRODUCTION

User costs or the benefits of a bridge to the community are hard to estimate. It is demonstrated that a bridge is needed when it is replaced. This is not always the case, for example when bridges are demolished and not replaced. In the general case when bridges are replaced, the cost of reconstruction is a lower estimate of their value over the useful life of the structure. The useful life, however is not uniquely defined for a bridge. Different designs can be expected to last over a variety of life-spans. In addition, the regular maintenance of the bridge can account for a variation in the life-span of a structure estimated at 30 to 120 years. Decisions related to bridge design and maintenance gain considerable significance when their implication to the life of the community is assessed. This is not easily quantified. The special case of a toll bridge provides a useful illustration of structural management with dedicated funding and, consequently, with a budget that lends itself to forecasting. In this instance it becomes possible to assess the benefits of the bridge to the users and to develop long range plans for maintenance and reconstruction such that these benefits are maximized. The George Washington Bridge in New York City is considered. The information about this structure was generously provided by the Port Authority of New York & New Jersey. A contrast with the above example is provided by the Williamsburg Bridge in New York City. This structure provides a similar service to the community but is owned by the City. Its maintenance is funded by the City expense budget while reconstruction is funded jointly with Federal and State funding. The bridge needs are well established by engineering studies, but the benefit to the community due to the bridge is not quantified. This has created significant drawbacks in the management of the structure over its 90 years existence.

METHOD OF ANALYSIS

A large investment in a capital construction project is commonly evaluated by the present worth method. Essential to this method is the assumption of a discount rate for future investments and benefits. The discount rate is an estimate of the rate at which the investor loses interest in future benefits instead of immediate ones.

This is an indicator of the investor's preference to postpone expenditures on activities, such as maintenance. Generally, the discount rate determines not only the rate of the investor's interest in the future but also the range of time that is significant to planning. The basic relationships of the method are shown below:

For $r>0$,

$$a \sum_{k=1}^{n} \frac{1}{(1+r)^k} = a\,(1+\frac{1}{r})\,[1-\frac{1}{(1+r)^n}]$$

For $n = \infty$,

$$a \sum_{k=1}^{n} \frac{1}{(1+r)^k} = a\,(1+\frac{1}{r})$$

where,

r equals the discount rate, $\frac{a}{(1+r)^n}$ equals the present worth of an amount a considered n years in the future,

and $a \sum_{k=1}^{n} \frac{1}{(1+r)^k}$ equals the present worth of a sum of annual increments a over n years. The period beyond which financial planning becomes insignificant can be determined by computing the sum of the convergent series of annual increments when the period tends to infinity. Here, the limit is defined by a sum of annual increments within x percent of the sum of the infinite series, which is determined by

$$\sum_{k=1}^{n} / \sum_{k=1}^{\infty} = [1-\frac{1}{(1+r)^n}] = 1-x$$

where, $n = -\frac{\ln(x)}{\ln(1+r)}$.

Table I lists the limits imposed on long-range planning for a variety of discount rates and values of the selected roundoff error x. Also listed are the factors by which a constant annual increment is multiplied for an infinite series. The assumed discount rate is extremely significant to the period over which planning can be extended. Lower discount rates indicate a confidence in the economy and allow for a long-range planning. High discount rates suggest that an investment should be recovered as soon as possible (Figure 1). The implication of the present worth method is that at high discount rates it is preferable to avoid annual expenditures such as maintenance in favor of maximizing annual profit. Since a civilian bridge is usually built on the assumption that the need for it will grow with time, the question arises if the present worth method applies to such an investment at all. An additional difficulty in applying the method is due to the lack of hard estimates showing the benefit from the bridge to society. If it is assumed that the benefits are known, it becomes possible to plan over a range defined by the discount rate. A general pattern of initial and annual investments and benefits is shown on Figure 2. Significant stages in the life of the bridge are:

TABLE I LIMITS OF LONG RANGE PLANNING DUE TO DISCOUNT RATES

r, %	$1 + 1/r$	n, years	
		$x = 5\%$	$x = 2\%$
3	34.33	101	132
4	26.00	76	100
6	17.67	51	67
8	13.50	39	51
10	11.00	31	41
12	9.33	26	35

T_1 = the recovery period for the original investment, and
T_2 = the period over which annual maintenance and annual benefits remain approximately constant.

The end of the latter stage is the one that should be anticipated, based on engineering knowledge, experience, etc. An intervention such as structural repair, rehabilitation or replacement should be planned to prevent the bridge level of service from declining. The two principal alternatives available to the bridge manager can be defined as follows:

A - Annual expenditures (such as maintenance) are minimized. It is assumed that this option will result in the shortest possible useful life for the bridge at full traffic capacity.

B - Annual expenditures are optimized to provide a maximum useful life of the structure at full traffic capacity. The life of the structure may easily extend

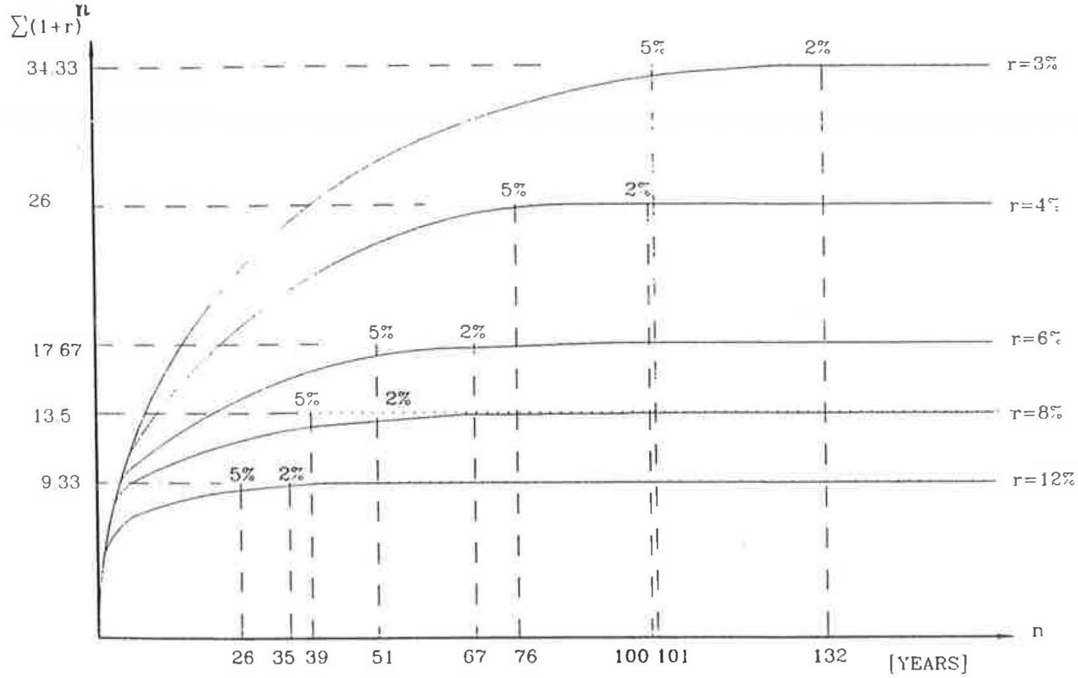

FIGURE 1 Effect of varying discount rates.

beyond the range defined as significant by the selected discount rate. It may be practical to divide the structural life-span into periods of 30 to 40 years and plan to arrive at the end of each period with the best capability to provide service, i.e., to maintain traffic at the least expense.

Two Present Worth methods for comparing the alternatives, *A* and *B*, are considered:

- A simple way to compare the two alternatives, *A* and *B*, is to consider both of them over the same number of years. The options can be compared as follows:

$$m\,(1+\frac{1}{r})\,[1-\frac{1}{(1+r)^n}] + \frac{C_m}{(1+r)^n} \ll\!\equiv\!\gg \frac{C_o}{(1+r)^n}$$

or

$$m\,(1+\frac{1}{r})\,[(1+r)^n-1] \ll\!\equiv\!\gg C_o - C_m$$

or

$$B \ll\!\equiv\!\gg A$$

where,

n = number of years under consideration,
m = annual maintenance expenditure,
C_m = reconstruction cost after n years at m maintenance,
C_o = reconstruction cost after n years at zero (0) maintenance, and
r = discount rate.

The equations can be construed as a relationship between alternatives *A* and *B*, such that if *B* is smaller, Option *B* is the more economical one and vice versa. In this simplified analysis additional costs due to the traffic constraints during construction are included in C_m and C_o respectively. Both traffic and maintenance are assumed constant over the period under consideration.

- The second approach distinguishes between structural life with and without maintenance, while the eventual reconstruction is assumed to have the same magnitude. Comparing the two alternatives *A* and *B* on those terms is expressed as follows:

$$m\,(1+\frac{1}{r})\,[1-\frac{1}{(1+r)}]^n + \frac{C}{(1+r)^n} \ll\!\equiv\!\gg \frac{C}{(1+r)^{no}} + \frac{C}{(1+r)^{2no}} + \dots + \frac{C}{(1+r)^n}$$

where,

n = number of years until reconstruction with maintenance m,

no = number of years until reconstruction without maintenance,

C = cost of reconstruction, and

$n > no$, since maintenance extends the life of the structure.

The inequality states that alternative A reconstructs the bridge every no years without maintenance, while alternative B maintains the bridge annually at an amount m and reconstructs it at the end of n years. Intermediate minor reconstruction also can be incorporated in alternative B, since this would better represent actual practice.

In the case when maintenance doubles the life of the structure ($n = 2no$) the above relationship obtains the form:

$$m\ (1+\frac{1}{r})\ [(1+r)^{no} - (1+r)^{-no}]\ \twoheadleftarrow\!\equiv\!\equiv\!\twoheadrightarrow\ C$$

Both methods show certain limitations. The case when $A = B$, the two alternatives are comparable. In reality however, alternative A is to entail full traffic closures for more comprehensive or frequent reconstructions. A partial closure may put a strain on the life of the community and reduce local business activities, while a complete closure may extinguish these activities permanently.

The Present Worth method becomes increasingly inaccurate with time, as shown on Figure 1. Consequently, public facilities or any other capital investment that runs to infinity should be analyzed by the Annual Rate of Return method instead. With these reservations, it is useful to apply the Present Worth method to actual bridges to discern patterns in their management history.

GEORGE WASHINGTON BRIDGE

Construction, reconstruction and maintenance historical data for the George Washington Bridge is listed in Tables II-IV. The historic data are a valuable source of information on the management of the World's longest bridge of its time that played a significant part in the life of the World's largest city.

The toll information can be used for several significant estimates as follows:

TABLE II CONSTRUCTION OF THE GEORGE WASHINGTON BRIDGE

Construction Activity	Year(s)	Cost, $ Million
Ordinal span and approaches (8 lanes)	1928-31	59.0
Lower level and approaches (6 lanes)	1957-62	76.0
Capital Rehabilitation	1992	20.7
Capital Rehabilitation	1993	15.5

TABLE III MAINTENANCE FOR THE GEORGE WASHINGTON BRIDGE

Maintenance Costs in $ Millions	Year	
	1992	1993 (Estimate)
Construction	5.4	6.0
Facility Maintenance	7.4	8.3
Total	12.8	14.3

TABLE IV ANNUAL TRAFFIC, TOLL COST, AND ANNUAL REVENUE FOR THE GEORGE WASHINGTON BRIDGE

Year	Annual Traffic (East Bound), Vehicles	Average Toll, $	Annual Revenue, $ Million
1932	10,500,000	0.50	5.25
1991	47,952,700	4.30	207.78
1992	47,764,900	4.70	223.76

- The worth of the bridge to the community is equal to or greater than the amount generated in tolls. This assumption may provide a lower limit of the actual worth of the bridge to the community, since it is not exactly known what traffic reduction results from a specific toll increase. The relationship between the number of users of a public facility of this kind and the toll they are willing to pay can be represented by a

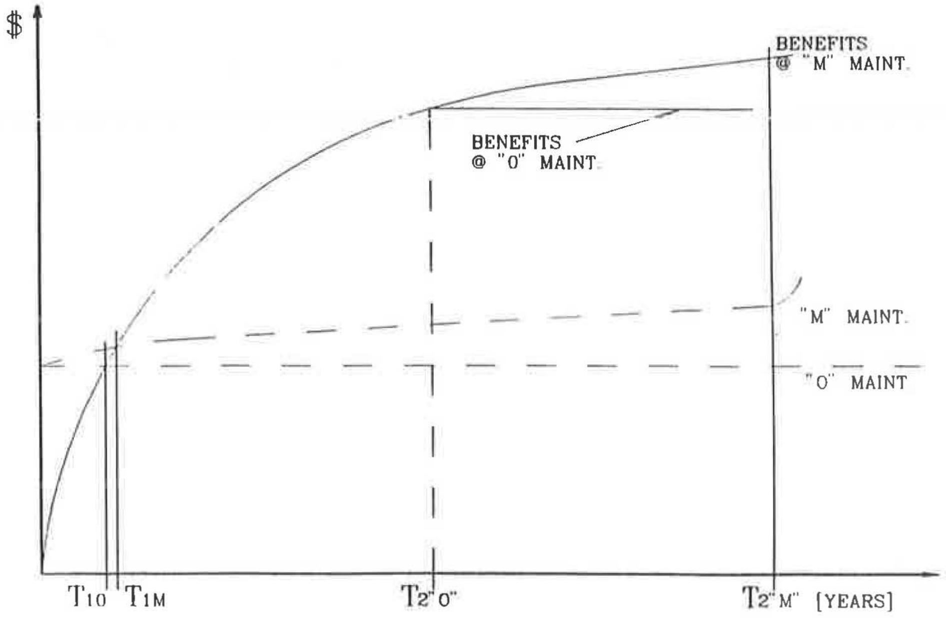

FIGURE 2 General pattern of initial and annual investments and benefits.

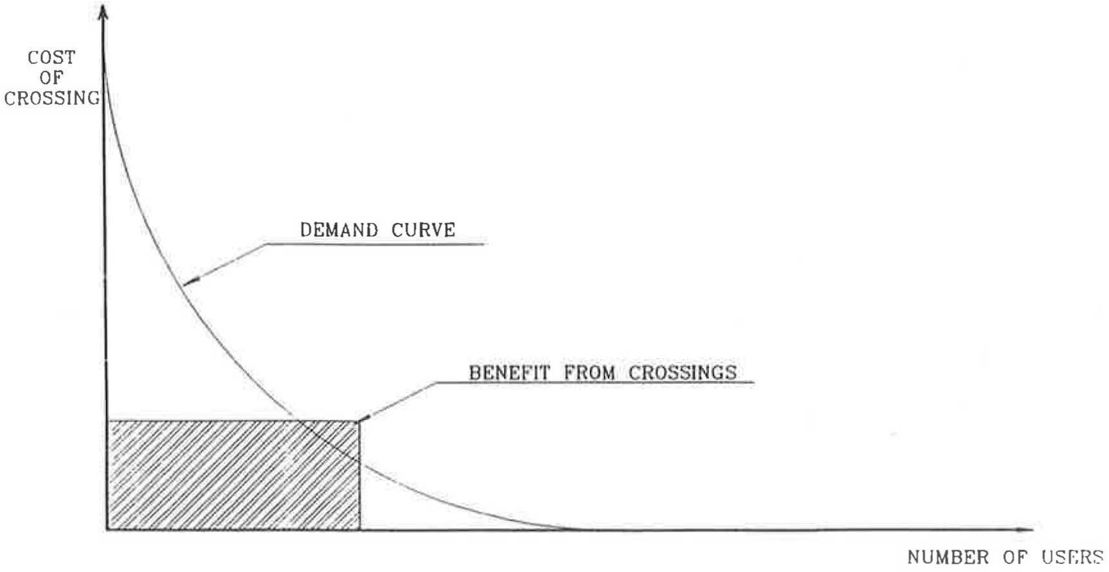

FIGURE 3 Relationship between users of a public facitlity and toll rate.

graph as shown on Figure 3 (*2*). The exact shape of the curve is not uniquely defined. Consequently, the optimal toll that would maximize the revenues (and the service rendered to the community according to the assumption above) is only tentatively established.

- The rate of inflation over the period under consideration can be estimated. If a period of 60 years (1932-92) is considered, assuming a uniform inflation rate and considering the average toll increase yields:

$$\$0.5\ (1 + i)^{60} = \$4.68$$

Hence, $i = 3.8\%$ is the average uniform inflation rate. At 3.8 percent the inflation rate over the 60 years of the bridge useful life to date is half of the discount rate of 8 percent, proposed for the present worth analysis. This is realistic, considering the usual difference between the expectations for future investments and actual record. This difference may be an important source of the well-known trend to neglect future investments in maintenance in favor of other activities, while also professing bewilderment at the reluctance of past managers to spend money on maintenance. The two strategies correspond to the curves for a discount rate of 4 percent and 8 percent of Figure 1. The future is usually assessed at 8 percent, while the past may be reviewed at 4 percent. As a result short range vision is proven faulty only in retrospect.

The data of Tables II-IV is used as follows. The capital expenditures for the bridge are brought back to the year of original completion at the inflation rate of 3.8 percent with the following result. For annual maintenance:

1932 @ 8 traffic lanes, 10.5M vehicles East bound: $\$(5.4 + 7.4) * (8/14) / (1.038)^{60} = \$(0.33 + 0.45)M$
1992 @ 14 traffic lanes, 47.8M vehicles East bound: $\$(5.4 + 7.4) = \$12.8M$.

The above equation assumes that maintenance expenditures have remained constant per traffic lane over the 60 years. If the relationship were corrected to reflect the traffic increase from 10.5M to 47.8M vehicles (East bound) annually, one obtains:

$\$(5.4 * (5.4 + 7.4) (10.5/ 47.8) / 1.038^{60} = \$(0.127 + 0.173)M = \$0.3M$

Forecasting the bridge revenues is based on a traffic forecast. The bridge capacity was increased by 75 percent in 1962 (from eight to 14 lanes). As shown the traffic during the life of the bridge has increased approximately 4.5 times. A linear traffic increase over the 60 years under consideration is assumed. Thus, the annual traffic increase per East bound lane is 0.035M vehicles per lane (1992 @ 47.8M vehicles/14 lanes = 3.4, 1932 @ 10.5M vehicles/8 lanes = 1.3). The ratio of annual revenue to annual maintenance expenditures remains near constant over the life of the structure to date as shown in Table V. The Preventive Maintenance Manual for the New York City Bridges (*3*) recommends a minimum of annual maintenance of 0.5 percent of the replacement value of the bridge. If $0.3M is assumed to have been the original maintenance amount, this results in 0.3 / 59 = 0.51 percent. The original construction cost of $59M and the reconstruction costs of 1957-62, 92, 93 corrected by an inflation rate of 3.8 percent for the present amount roughly to:

$59*1.038^{60} + 76*1.038^{30} + 20.7 + 15.5 = \$822M.$

TABLE V RATIO OF ANNUAL REVENUE TO ANNUAL MAINTENANCE EXPENDITURES

YEAR	MAINTENANCE, %
1932	(0.3 / 5.25)*100 = 5.7%
1992	(12.8 / 223.8)*100 = 5.7%

This suggests that a 3.8 percent inflation rate is below the true value. A bridge of this magnitude would cost over $1 Billion if built today. Depending on the replacement cost, the current total annual maintenance of $12.8M is near 1 percent. The annual structural maintenance amounts to approximately 0.5 percent of the replacement cost.

The reconstruction expenditures of 1957-62 and 1992-93 are discounted to 1932 at the inflation rate of 3.8 percent as shown in Table VI. With these expenditures expressed in 1932 currency, one can examine the future management of the bridge from the year it was opened. This is done at a discount rate of 8 percent, which is an average value common for such studies. Under the above conditions the management of

TABLE VI RECONSTRUCTION COSTS DISCOUNTED TO 1931 (INFLATION RATE = 3.8%)

Year	Construction Cost, $M	1931 Equivalent Cost, $M
1957	12.67	4.8
1958	12.67	4.6
1959	12.67	4.5
1960	12.67	4.3
1961	12.67	4.1
1962	12.67	4.0
Total	76.00	26.3
1992	20.7	2.1
1993	15.5	1.5

the bridge over the first 30 years appears to have followed a sound strategy of increasing service and revenue under growing demand. The second deck with additional traffic lanes (or possibly a rapid transit line) was anticipated and incorporated in the original design. The reconstruction was done when the demand had developed and the revenues had accumulated. Significantly, the assumed discount rate (8 percent) also suggests a 30-year span for long range planning. This coincides with the behavior of structural components, for instance decks, which exhibit a need for rehabilitations at a roughly 30-year cycle as demonstrated in many studies (*1*).

The comparison of the options *A* (no maintenance) and *B* (optimal maintenance) described above can be applied to the case of the George Washington bridge as follows:

$$0.127(1 + 1/0.08)(1.08^{30} - 1) + 26.3 <====> C_o$$

$$15.5 + 26.3 = \$41.8\text{M (1932 currency)}$$

This equation assumes that the facility maintenance that included toll collection at $0.173M annually could not have been eliminated but the construction maintenance of $0.127M could have been. In 1932 the construction of the bridge had recently been completed at $59M. It is therefore indicated that full maintenance and reconstruction cost in 30 years are preferable to a new construction of the above magnitude at the end of that period. If it is assumed that $n = 2no = 60$ years, the method yields the following relationship ($r = 8$ percent):

$$0.127(1 + 1/0.08)(1.08^{30} - 1.08^{-30}) + 26.3 + 2.1 + 1.5 = \$47\text{M}$$

Again the cost of maintenance and the added reconstruction fall below the $59M of constructing the new bridge. This analysis does not include the added benefit of expanding the bridge to 175 percent of its original capacity at the end of the 30-year period. This benefit is only possible if the structure has been designed accordingly and maintained in good condition. Furthermore, the good condition of the original structure makes it possible to add new lanes while maintaining traffic. The annual revenue of 1932 is $5.25M. Thirty years later, discounted at $r = 8$ percent, a traffic closure of a 6-year duration amounts to a $3.2M in 1932, to be added to C_o. The Present Worth premise fails over a period of $n = 2no = 120$, i.e., reconstruction in 120 years with maintenance and in 60 years without. In this case,

$$0.127(1 + 1/0.08)(1.08^{60} - 1.08^{60}) + 29.9 = \$203.5\text{M}$$

This amount relative to the year of construction would suggest a bridge that could provide service for 60 years without maintenance should be left well enough alone over that period and then replaced. This conclusion stems from the fact that a construction expenditure removed 60 years into the future loses most significance at a discount rate of 8 percent (Figure 1). It is for this reason that the Annual Rate of Return method is better suited for such analyses. The next case provides a clearer illustration of the same point since it deals with a bridge built 90 years ago and without a means for clearly showing its benefits.

WILLIAMSBURG BRIDGE

The Williamsburg Bridge was constructed in 1903. The bridge carries (8) eight vehicular traffic lanes, two subway tracks and pedestrian walkways. The number of people crossing daily has fluctuated over the years as shown in Table VII.

TABLE VII WILLIAMSBURG BRIDGE

Year	Number of People Crossing	
	Daily	Annually
1910	227,000	81,720,000
1924	505,000	181,800,000
1988*	240,000	86,760,000

* Closed for 2 months in Summer of 1988.

The deterioration of the bridge due to lack of maintenance led to its full closure for two months in 1988. Traffic was eventually resumed but serious consideration was given to the complete replacement of the bridge. Also considered was the option of partial replacement and/or rehabilitation, once it was determined that the structural condition allows for such an alternative. The value of the bridge to the community was aptly stressed by its closure. Yet, without tolls there is no quantified measure of the annual benefits due to the service of the bridge.

Assuming a toll equal to that of the George Washington Bridge, i.e., $4.7 (one way) and an average daily traffic of 150,000 vehicles (as opposed to the 260,000 on the George Washington Bridge) would result in an annual revenue of $128.6M. Applying this value to a full closure of the bridge for five years (deemed necessary for a full replacement) has the following present worth at 8 percent discount:

TABLE VIII CONSTRUCTION AND MAINTENANCE COSTS OVER THE BRIDGE USEFUL LIFE AT A 4.5% INTEREST RATE

Year	Construction, $	Maintenance, $, 0.5% of replacement cost
1903	$1{,}000 / 1.045^{90} = 19$M	0.1M
1993	1,000M	5.0M

TABLE IX WILLIAMSBURG BRIDGE REPLACEMENT VS. REHABILITATION (8% DISCOUNT RATE)

	Replacement, $M	Rehabilitation, $M	Percent
Construction, Lump Sum	1,000	400	40
Distributed Over 5 Years	863	-	
Distributed Over 10 Years	-	290	34
Traffic Interruption - 100% During 5 Years	555	-	
Traffic Interruption - 50% During 10 Years	-	466	
Total	1,418	756	53

$\$128.6\ (1 + 1/0.08)(1 - 1/1.08^{5}) = \$555\text{M}$

A 50 percent closure over 10 years costs:

$\$0.5 * 128.6\ (1 + 1/0.08)(1 - 1/1.08^{10}) = \$466\text{M}$

The cost of new construction was estimated at roughly $1 Billion. Uniformly distributed over a five-year period and discounted as above this yields the following present worth:

$\$200\text{M}\ (1 + 1/0.08)(1 - 1/1.08^{5}) = \$863\text{M}$

Rehabilitation with partial replacement was estimated at roughly $400M. Uniformly distributed over 10 years this has the following present worth:

$\$40\text{M}\ (1 + 1/0.08)(1 - 1/1.08^{10}) = \$290\text{M}$

Thus the total present worth of the new construction costs amounts to $1.418B, while the rehabilitation costs are estimated at $756M. The estimated costs are summarized in Table IX. Significantly, the rehabilitation cost considered as a lump sum represents 40 percent of the full replacement. If the same costs are distributed over 10 years for the rehabilitation and five years for the replacement, the former represents 34 percent of the latter, i.e., it becomes even more attractive. After adding the estimated costs to the community, however, the ratio changes to 53 percent. In this estimate, comparing quantitatively 50 percent and 100 percent closures is deceptive. A full closure may entirely extinguish certain activities while reduced traffic may cause hardship but no permanent consequences. This is an important limitation of the demonstrated analysis.

The alternative option of regularly maintaining the bridge at a level of expenditure comparable to that of the George Washington bridge is considered. A maintenance of 0.5 percent of full replacement cost of $1 Billion would amount to $5M annually. At a constant inflation rate of 4.5 percent over the bridge useful life one obtains the following values for the year of original completion as shown in Table VIII. The construction cost for the bridge is reported at $14.2M with an additional land cost of $9.1M. Consequently, the $19M appears to confirm the assumed 4.5 percent inflation rate. Within a period of 50 years the discounted sum of the annual maintenance accumulates to such amounts that new construction at no maintenance becomes attractive. This reasoning may have contributed to the neglect of the bridge, thus bringing it close to complete replacement. Neglected in the process are the benefits of the bridge to the community. If, as with the George Washington Bridge, the maintenance was to represent 5.7 percent of the annual revenues due to the structure, a different light is cast on the decision making process.

CONCLUSIONS

The parallel between a tolled and a publicly owned bridge is used to illustrate certain points, such as:

- User costs or benefits to the community from a public facility, such as a bridge, significantly influence the assessment of bridge management strategies.
- The Present Worth method is limited by the assumed discount rate to a period shorter than the life of a large structure, such as a suspension bridge. While the effect of the discount rate on the long-range planning for a bridge is obvious, it is less apparent how the overall condition of bridges affects the economy and, therefore, discount rates. It is generally agreed that the economy drives the bridge condition. The reverse effect however does exist within limits not clearly determined. A mechanical application of the Present Worth method to the bridge management problem may be partly responsible for the following two negative effects: 1) planning tends to ignore developments beyond the limit set by the discount rate, and 2) structural design seeks to accomplish a useful life, limited by the range provided by the discount rate and thus, shorter than the optimal.
- Any method for the assessment of bridge management alternatives must be modified to reflect the reduction of traffic due to structural deterioration and the added costs due to the corresponding increase in the probability of accidents.
- The annual rate of return method can be applied successfully to the bridge management problem if the means exist for quantifying the benefits due to the bridge. For a non-toll bridge, it is helpful to draw a parallel to a toll structure that provides comparable service. An established strategy in annual rate of return optimization is to opt for the higher initial investment when alternative projects have comparable rates of return. Under the fiscal constraints of capital reconstruction programs this strategy has yielded to the lowest first cost requirement for new bridge design. It is inevitable that structures built under such a requirement will not maximize the benefits they were designed.
- Most methods of economic analysis tacitly assume that any funding withheld from the structural annual maintenance is profitably invested elsewhere (at the discount rate) and available when optimally needed. This assumption is rarely true and the least so for a non-toll bridge.
- All quantitative methods of evaluating a bridge worth to the community suffer from limitations. An alternative approach is to consider the bridge as necessary and to minimize its costs while maximizing service. For a toll bridge, service is equivalent to revenue and the strategy is obvious. For a non-toll bridge the priorities are harder to discern, but should be recognized. A bridge is regarded as irreplaceable in the rare case when it happens to be a landmark. Here the replacement value of the bridge is infinite and any amount of annual maintenance always remains the economical alternative. It is not purely coincidental that the Brooklyn Bridge in New York City, a World famous landmark, is the oldest of the East River crossings and has the least traffic capacity but currently enjoys the best condition of the four bridges.

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DEVELOPING USER COSTS FOR BRIDGE MANAGEMENT SYSTEMS

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ABSTRACT

Evaluation of bridges for improvement in bridge management systems to meet expectations of ISTEA legislation and AASHTO guidelines depends on accurate estimates of various user and agency costs associated with both the existing structure and the improved or replaced structure. This paper summarizes methods developed for determining the user costs associated with deficiencies in load capacity, deck, approach and vertical clearance geometry.

BACKGROUND AND OBJECTIVES

Consideration of user costs is essential in Bridge Management Systems (BMSs) if functional deficiencies are to be eliminated. If agency costs alone are considered, the alternatives would tend to favor maintenance only to extend life until permanent closure. The objective of this paper is to outline an approach for estimating user costs generated by deficient bridges. This effort was initiated in 1983 when North Carolina began the development of methodologies for evaluating alternatives for bridge maintenance and improvement based upon economic analysis (*1,2*). These concepts are embodied in the OPBRIDGE analysis program (*3,4,5*), a major component of the North Carolina BMS. Due to length constraints, this paper will primarily reference summary reports of the authors (*1,6,7*). The reader is encouraged to refer to those reports for a more detailed development of each topic and a more thorough citation of other studies and sources of data. Some user costs involve parameters that must be periodically updated. One example is the operating costs of vehicles. In such cases, a priority was placed on identifying a source that could be easily referred to for an update. Usually, improvements in the methodology can be made by research that could provide more accurate data for individual parameters, or which could better define the parameters in a manner tailored to the user traffic of the individual states or other owning agencies. Nevertheless, the efforts summarized here have proved valuable in quantifying user costs for North Carolina and have provided a guide to others trying to conduct similar analyses.

TYPES OF USER COSTS

User costs can be generated by such bridge deficiencies as narrow width, low clearance, poor alignment and low load capacity. Bridges with narrow width, low clearance, or poor alignment induce vehicle accidents. Bridges with low clearance and low load capacity cause some vehicles to be detoured. The costs accumulate independently for both the over-route and the under-route roadway. If user costs incurred are assumed to be proportional to traffic volume and the level of service deficiency of the bridge, the user costs in any given year, *t*, can be derived as follows:

$$AURC(t) = 365\,ADT(t)\,[C_{WDA}U_{AC} + C_{ALA}U_{AC} + C_{CLA}U_{AC} + C_{CLD}U_{DC}DL + C_{LCD}(t)\,U_{DL}DL] \tag{1}$$

where:

AURC(t) = annual user cost of the bridge at year *t*, $;
ADT(t) = average daily traffic using the bridge at year *t*;
C_{WDA} = coefficient for proportion of vehicles incurring accidens due to width deficiency;
C_{ALA} = coefficient for proportion of vehicles incurring accidents due to poor alignment;
C_{CLA} = coefficient for proportion of vehicles incurring accidents due to a vertical clearance deficiency;

C_{CLD} = coefficient for proportion of vehicles detoured due to a vertical clearance deficiency;
$C_{LCD}(t)$ = coefficient for proportion of vehicles detoured due to a load capacity deficiency at year *t*;
U_{AC} = unit cost of vehicle accidents on bridges, \$/accident;
U_{DC} = unit cost for average vehicle detours due to a vertical clearance deficiency, \$/mile, (\$/km);
U_{DL} = unit cost for average vehicle detours due to a load capacity deficiency, \$/mile (\$/km); and
DL = detour length, miles (km).

For bridges with the same level-of-service deficiency, the one having greater ADT would generate, proportionally, higher user costs because of the higher probabilities of causing detours and accidents. For some user costs, the traffic affected is only the truck traffic. However, since average daily truck traffic, ADTT, is usually not in the bridge data file, the various coefficients are used to estimate the appropriate segment of traffic affected based on total ADT. The coefficients C_{WDA}, C_{ALA}, C_{CLA}, C_{CLD}, and C_{LCD}, of Equation 1 are assumed constant during the service life of a bridge unless action is taken to reduce the deficiencies. However, C_{LCD} may vary with time; if load capacity of the bridge deteriorates, the proportion of vehicles detoured increases. The coefficients, ADT and DL vary for the over-route and the under-route computations. C_{LCD} is zero (0) for the under-route. This paper describes the efforts to quantify the coefficients in Equation 1, the factors that influence the ADT increase rates for different functional classification routes, and the derivations of user costs due to the load capacity, deck width, alignment and vertical clearance deficiencies.

DETOUR LENGTH AND DETOUR UNIT COSTS

The route detour length listed in the National Bridge Inventory (NBI) is the bypass detour distance that a vehicle must travel for a closed and detour-posted bridge. However, the actual detour may be more for a load- or clearance-posted bridge. If the driver is not aware of the low capacity or clearance bridge, the detour would be longer since the posting is usually only placed at the bridge and not at the possible detour turnoff. If the detour route involves a posted bridge, the detour could increase even further. There are many possible permutations that would vary with drivers' knowledge of the route, destination, layout of the roadways, possibility of a posted bridge on the detour route, etc. For this analysis, the actual detour length, DL, is nevertheless assumed to be the detour length recorded in the inventory file. However, one could argue that this value is an underestimate.

Vehicle operating costs can vary due to vehicle characteristics and operator wage rates. Recognizing that the values would have to be updated periodically, easily referred to sources were desired. To estimate operating costs for all vehicles, two limiting extremes were established. The upper end vehicle was assumed to be a truck tractor semi-trailer (TTST) vehicle at the legal load limit of 36.7 tons (329 kN) and the lower end was assumed to be a vehicle weighing less than 3 tons (27 kN). Operating cost variations were then assumed linear with weight between these values since weight reflects both fixed costs and energy requirements and also need for operator skill.

Reliable data on operating costs for trucks in different weight ranges are limited (*1*). The trucking industry is regulated and truckers do not publish their actual costs since they are a part of the negotiations. The U.S. Department of Agriculture regularly compiles cost data on long distance haul fruit and vegetable trucks having a tractor-trailer configuration. The cost report for the fruit and vegetable trucks consists of fixed and variable costs and the total estimated operating cost per vehicle-mile. According to the cost report of May 1991, the estimated operating cost was \$1.28/mile (\$0.80/km), including the driver salary. The FHWA Office of Planning, Highway Performance Monitoring Branch, periodically publishes data on operating costs for various truck types and weights. A similar value for trucks at the legal weight limit can be deduced from this information, as shown by Abed-Al-Rahim and Johnston (*6,7*).

The average operating costs for passenger cars, small pickup trucks, and other vehicles weighing up to 3 tons (27 kN), were assumed to be equal. This lower end cost includes two components: vehicle and operator costs. The vehicle cost was assumed to be the same as the Federal IRS tax allowance for business use of passenger cars, currently \$0.28 per mile (\$0.17/km). The light truck operator cost was assumed to be the wage rate of a North Carolina State Government employee level one vehicle operator. Including fringe benefits and assuming a 48-week work year, 40 hours per week, and a speed of 40 mph (64 km/hr), this results in an operator cost of \$0.18 per mile (\$0.11/km) and a total average operating cost of \$0.46 per mile (\$0.28/km).

If the relationship between the vehicle operating cost and the vehicle weight is assumed to be linear, the following equation for vehicle operating cost could be deduced:

$$U_{DW} = U_{D3} + (U_{DNP} - U_{D3}) \frac{(W - 3tons)}{(NP - 3tons)} \quad (2)$$

where:

U_{DW} = operating cost for vehicle of weight W, \$/mile (\$/km);
U_{D3} = operating cost for vehicle weighing 3 tons (27 kN) or less, \$/mile (\$/km);
U_{DNP} = operating cost for vehicle weighing the maximum legal load, \$/mile (\$/km);
NP = maximum legal load or non-posted capacity of bridge, tons (kN); and
W = weight of vehicle, tons (kN).

One method for calculating the total cost of the vehicle detours due to load capacity deficiency is to multiply the average operating cost of the detoured vehicles by the detour length and the number of vehicles detoured, as indicated in Equation 1. If the distribution of vehicles above 3 tons (27 kN) is about uniform by weight, the average operating cost for the detoured vehicles could be calculated by averaging the smallest and the largest operating costs of the vehicles detoured. The average operating cost of the detoured vehicles is then given by:

$$U_{DL} = (U_{DP} + U_{DNP})/2 \quad (3)$$

where:

U_{DL} = average operating cost for the detoured vehicles; and
U_{DP} = operating cost for a vehicle weighing the posted bridge capacity (smallest operating cost among the detoured vehicles).

LOAD CAPACITY DETOURS

If a bridge is posted for load capacity, some proportion of the vehicles using the bridge must detour. The vehicles detoured are those that weigh more than the bridge posting. The number of vehicles detoured depends on the posted load capacity of the bridge, and the number and weight distributions of the vehicles encountering the bridge. Different functional classification routes have different patterns of vehicle weight distributions. Thus, the proportion of the vehicles detoured due to the bridge load capacity deficiency would be different for bridges on the different functional classifications. Current bridge policy requires that bridges with load capacities less than 3 tons (27 kN) be closed. Thus, if a bridge is open to the public, its load capacity is 3 tons (27 kN) or greater. Usually, passenger cars, pickup and panel trucks weigh less than 3 tons. Therefore, if a bridge is posted for load capacity, the vehicles detoured would be trucks and similar vehicles that weigh more than 3 tons (27 kN).

From Equation 1, the number of vehicles detoured in a given year for a posted bridge is calculated as follows:

$$N_{DET}(t) = 365ADT(t)C_{LCD}(t) \quad (4)$$

where:

$N_{DET}(t)$ = number of vehicles detoured in a given year for a posted bridge; and
$C_{LCD}(t)$ = coefficient for the proportion of vehicles detoured due to load capacity deficiency in year t.

The total number of trucks detoured includes single unit trucks (or single vehicle trucks, SV) and TTSTs. Thus,

$$C_{LCD}(t) = R_{SV}(t) + R_{TT}(t) \quad (5)$$

where:

$R_{SV}(t)$ = ratio of the number of single-unit trucks heavier than the bridge's single vehicle posting to the total vehicles using the bridge; and
$R_{TT}(t)$ = ratio of the number of trailer combinations heavier than the TTST posting to the total vehicles using the bridge.

Vehicle classification distribution, in terms of vehicle configurations, varies with route functional classification. Literature and data in this area were summarized and new data added from North Carolina and then synthesized (*1*). Since the North Carolina Department of Transportation (NCDOT) posts bridges for load limit considering SV and TTST configurations, the analysis was designed to estimate detours in these two categories. Some sources were categorized by number of axles, others by single-tired, dual-tired and TTST. Some sources separated buses and special vehicles, others did not. In the end, the goal became to define the percentage of major vehicle types on the different roadway functional classifications and to define the typical actual weight distributions of those vehicles. Since cars and light trucks typically weigh less than 3 tons (27 kN), they are not detoured by load posting. Thus, the vehicles of interest are the SV Duals and the TTSTs. Based on the analysis and synthesis of the data available, the values proposed for use as the vehicle

TABLE I VEHICLE DISTRIBUTIONS ON NORTH CAROLINA ROADWAYS BY FUNCTIONAL CLASSIFICATION

Functional Classification	Proportion of Total Vehicles (%)		
	Cars & Light Trucks	SV Duals	TTST
Interstate	83.1	4.4	12.5
Principal Arterial	87.3	6.0	6.6
Minor Arterial	92.1	4.6	3.3
Major Collector	96.3	2.6	1.1
Minor Collector	96.5	2.6	0.8
Local	97.0	2.4	0.6

classification distributions on the different functional classifications of North Carolina bridges are presented in Table I.

The actual truck weight distribution for each type of vehicle classification was needed for determining the number of vehicles detoured for a posted bridge. Weigh-In-Motion data (*8*) for bridges on Interstates, U. S. routes, and State routes were analyzed for this purpose. The truck configurations included 2-axle, 3-axle, and 4-axle single-unit trucks and most semi-trailer combinations. The trucks counted and weighed did not include pickup trucks, recreational vehicles, house trailers, or cars pulling trailers, but included buses. The single-unit trucks recorded in the study were about equivalent to the duals of North Carolina data. The loading distributions by truck type were then multiplied by the corresponding vehicle classification distributions in Table I to determine the percentage of each truck weight range out of the total vehicles encountering the bridge. Instead of showing the percentage for each weight range, Table II shows the cumulative percentage of trucks out of the total vehicles that are heavier than each weight listed. Thus, the values indicate the percentage of ADT detoured by the particular posting level.

On local routes with a low ADT, the detours calculated by this method may not adequately represent the need to provide essential access. If a bridge is posted for less than 16 tons (143 kN), most public service vehicles such as fire trucks, school buses, garbage trucks, heating oil trucks, etc., have to detour (*9*). For each school day, at least six trips may be generated by school buses (two for the elementary school, two for the middle school, and two for the high school). On average, there are about 180 school days in a year. Thus, the average is about three school bus trips every day of the year. For the rest of the public service vehicles, the trips are generated periodically and assumed to average one trip per day. Therefore, if a bridge on the local route is posted for less than 16 tons (143 kN), the number of detours (four per day) generated by the public service vehicles is compared with detours calculated from the results of Table II, and the larger is taken as the number of vehicles detoured by the local route bridge.

BRIDGE LOAD CAPACITY DETERIORATION

Bridge load capacity may deteriorate due to section loss or material degradation. Causes include spalling, cracking, scouring, rotting, infestation or corrosion of reinforcing steel or structural steel, sometimes aggravated by deicing chemicals. Load capacity deterioration is also influenced by the environment of the bridge. Bridges in different weather environments may have different load capacity deterioration rates. Bridges over water or in marine environments may have more severe substructure problems. High volumes of traffic may result in fatigue and overloads may cause damage. Materials and quality of construction are also factors influencing load capacity deterioration. However, such loss rates have not been quantified, and no helpful research results were found in the literature. When a bridge is maintained in good condition, there is virtually no reason to expect load capacity loss with increasing age. However, when deterioration is allowed to start, loss can occur. Experienced engineers note that load capacity decreases with severe deterioration, especially for timber superstructures and substructures. To determine the load capacity deterioration rate, a variety of analysis approaches were tried (*1*). North Carolina posts bridges for load capacity based on the operating rating. Regression analyses of bridge operating rating versus age were conducted using inspection data from

TABLE II PERCENTAGE OF ADT DETOURED BY BRIDGE LOAD POSTING LEVEL, FUNCTIONAL CLASSIFICATION AND VEHICLE TYPE

Bridge Posting (tons)	Interstate		Princ. Art.		Minor Art.		Major Coll.		Minor Coll.		Local	
	SV	TT ST	SV	TT ST	SV	TT ST	SV	TT ST	SV	TT ST	SV	TT ST
3	4.40	12.50	6.00	6.60	4.60	3.30	2.60	1.10	2.60	0.80	2.40	0.60
4	3.87	12.45	5.21	6.57	4.11	3.29	2.32	1.09	2.32	0.80	2.14	0.60
5	3.35	12.40	4.41	6.54	3.61	3.28	2.04	1.09	2.04	0.79	1.88	0.60
6	2.82	12.36	3.62	6.50	3.12	3.26	1.76	1.08	1.76	0.79	1.63	0.59
7	2.30	12.31	2.82	6.47	2.62	3.25	1.48	1.08	1.48	0.78	1.37	0.59
8	1.77	12.26	2.03	6.44	2.13	3.24	1.20	1.07	1.20	0.78	1.11	0.59
9	1.52	12.24	1.70	6.33	1.78	3.19	1.00	1.05	1.00	0.77	0.92	0.58
10	1.26	12.02	1.36	6.23	1.43	3.14	0.80	1.04	0.80	0.76	0.74	0.57
11	1.10	11.65	1.22	5.97	1.28	3.01	0.72	0.99	0.72	0.73	0.67	0.54
12	0.95	11.28	1.08	5.70	1.13	2.87	0.64	0.95	0.64	0.69	0.59	0.52
13	0.82	10.74	0.97	5.39	1.02	2.71	0.57	0.90	0.57	0.66	0.53	0.49
14	0.71	10.04	0.90	5.02	0.94	2.53	0.53	0.84	0.53	0.61	0.49	0.46
15	0.60	9.34	0.82	4.66	0.86	2.35	0.48	0.78	0.48	0.57	0.45	0.42
16	0.51	8.89	0.76	4.41	0.79	2.22	0.45	0.73	0.45	0.54	0.41	0.40
17	0.42	8.35	0.69	4.16	0.73	2.09	0.41	0.69	0.41	0.51	0.38	0.38
18	0.35	8.04	0.63	3.95	0.66	1.99	0.37	0.66	0.37	0.48	0.34	0.36
19	0.30	7.71	0.58	3.78	0.60	1.90	0.34	0.63	0.34	0.46	0.31	0.34
20	0.24	7.37	0.52	3.61	0.55	1.82	0.31	0.60	0.31	0.44	0.28	0.33
21	0.21	7.06	0.44	3.50	0.47	1.76	0.26	0.58	0.26	0.43	0.24	0.32
22	0.18	6.75	0.37	3.39	0.39	1.71	0.22	0.56	0.22	0.41	0.20	0.31
23	0.16	6.46	0.30	3.28	0.32	1.65	0.18	0.55	0.18	0.40	0.17	0.30
24	0.15	6.17	0.25	3.17	0.26	1.60	0.15	0.53	0.15	0.39	0.14	0.29
25	0.13	5.89	0.20	3.06	0.21	1.54	0.12	0.51	0.12	0.37	0.11	0.28
26	0.11	5.61	0.16	2.96	0.17	1.49	0.10	0.49	0.10	0.36	0.09	0.27
27	0.09	5.32	0.13	2.86	0.13	1.44	0.08	0.48	0.08	0.35	0.07	0.26
28	0.08	5.01	0.10	2.75	0.10	1.39	0.06	0.46	0.06	0.33	0.05	0.25
29	0.07	4.68	0.07	2.64	0.08	1.33	0.04	0.44	0.04	0.32	0.04	0.24
30	0.06	4.35	0.05	2.52	0.05	1.27	0.03	0.42	0.03	0.31	0.03	0.23
31	0.05	3.95	0.03	2.38	0.04	1.20	0.02	0.40	0.02	0.29	0.02	0.22
32	0.04	3.56	0.02	2.25	0.02	1.13	0.01	0.37	0.01	0.27	0.01	0.20
33	0.04	3.11	0.01	2.09	0.01	1.05	0.00	0.35	0.00	0.25	0.00	0.19
33.6	0.00	2.81	0.00	1.98	0.00	1.00	0.00	0.33	0.00	0.24	0.00	0.18
34		2.60		1.91		0.96		0.29		0.23		0.16
36		1.74		1.56		0.78		0.24		0.19		0.14
36.6		0.00		0.00		0.00		0.00		0.00		0.00

North Carolina bridges. These analyses excluded the bridges with known reconstruction in past years. The analyses were categorized based on original design loads as an indicator of original capacity. They were also categorized by the material combinations of bridge superstructures and substructures as variables possibly affecting deterioration. The results were found to have poor correlation due to severe scatter and other factors. Nevertheless, the loss rates shown in Table III, compiled with engineering judgement from the regression results and multi-year averaging results, have been used in absence of better information to represent the effect that occurs at low condition states.

When applied, the lowest of the substructure or superstructure condition ratings is assumed to control the deterioration. Analysis of the database shows that

TABLE III ESTIMATED BRIDGE LOAD CAPACITY DETERIORATION RATES

Lower Rating of Superstructure and Substructure	Deterioration Rate (Tons/Year)		
	Timber	Concrete	Steel
6 - 9	0.00	0.00	0.00
5	0.30	0.20	0.20
4	0.60	0.30	0.30
3 or less	1.00	0.50	0.50

1 ton = 8.964 kN

the deck rarely controls the load capacity. The load capacity loss is subtracted from the operating rating; however, the SV posting and TTST posting is similarly reduced only when the resulting operating rating is less than the legal load. Considering the rates of condition deterioration, the values estimated in Table III would result in a capacity loss of approximately 3 tons (27 kN) as the bridge passes through conditions five and four.

VERTICAL CLEARANCE DETOURS

At a bridge with a vertical restriction, some vehicles passing through or under the bridge must detour, i.e., those whose heights are higher than the vertical clearance. The proportion of vehicles detoured depends on the truck height distribution, which may vary with roadway functional classifications (*1*). User costs are generated due to accidents and vehicles that must be detoured at bridges with low vertical clearance. Most trucks on highways are less than 13.5 feet (4.11 m) in height, the legal height for many states. According to Kent and Stevens (*10*), about 0.067 percent of the duals and 0.444 percent of the trailer combinations are more than 13.5 feet (4.11 m) high. If the heights of duals are assumed to be well distributed between 8.0 and 13.5 feet (2.44 and 4.11 m) and if trailer combinations are well distributed between 10 and 13.5 feet (3.05 and 4.11 m), the truck height distributions would correspond to those listed in Table IV, using the vehicle classification distributions in Table I.

The detour length for the vertical clearance deficiency was also assumed to be the appropriate under- or over-route inventory detour length following the same approach used for load capacity detour. Although the operating cost may vary with height, no data were available indicating the variation. The number of bridges with a vertical clearance of less than 13.5 feet (4.11 m) in North Carolina is very small. Thus, it was assumed adequate to use the TTST legal load limit operating cost, U_{DNP}, as a reasonable estimate of the vertical clearance detour unit cost, U_{DC}

ACCIDENT UNIT COSTS

In a study of North Carolina accident data from 1984 to 1989, the annual number of all accidents and the annual number of bridge-related accidents was uniform, averaging 161,922 and 2,710 (1.7 percent) respectively (*6,7*). Although bridge-related accidents represent only 1.7 percent of all traffic accidents, it is important to evaluate these accidents to try to minimize them with appropriate bridge improvements. The severity of bridge-related accidents is usually higher than the severity of other roadway traffic accidents. However, the degree of severity will vary depending on the approach used for measuring the severity. In various published studies, the severity of bridge-related accidents has been estimated to be from 2-to-50 times the severity of general roadway traffic accidents (*6*).

The NCDOT classifies vehicular accidents as fatal, injury, and property-damage-only accidents. An A-B-C injury scale is used to describe the severity level of the injuries, where A is the most severe and C is the least severe. The pattern of bridge-related accident severity is summarized and is compared to other accidents in Table V. The average number of people killed in bridge-related accidents in North Carolina was determined to be 0.019 persons/accident. However, the average number of people killed for other traffic accidents was 0.009 persons/accident. Taking this as a measure of accident severity, it implies that bridge-related accidents are roughly twice as severe as general roadway traffic accidents. The ratio comparing the severity of bridge-related accidents to other traffic accidents decreased as the injury severity decreased. However, for all injury types except C, bridge-related

TABLE IV PERCENTAGE OF ADT DETOURED BY BRIDGE VERTICAL CLEARANCE POSTING LEVEL, FUNCTIONAL CLASSIFICATION AND VEHICLE TYPE

Vertical Clearance (feet)	Interstate		Princ. Art.		Minor Art.		Major Coll.		Minor Coll.		Local	
	SV	TT ST	SV	TT ST	SV	TT ST	SV	TT ST	SV	TT ST	SV	TT ST
8.0	4.40	12.50	6.00	6.60	4.60	3.30	2.60	1.10	2.60	0.80	2.40	0.60
8.5	4.00	12.50	5.45	6.60	4.18	3.30	2.36	1.10	2.36	0.80	2.18	0.60
9.0	3.60	12.50	4.91	6.60	3.76	3.30	2.13	1.10	2.13	0.80	1.96	0.60
9.5	3.20	12.50	4.36	6.60	3.35	3.30	1.89	1.10	1.89	0.80	1.75	0.60
10.0	2.80	12.50	3.82	6.60	2.93	3.30	1.66	1.10	1.66	0.80	1.53	0.60
10.5	2.40	10.72	3.27	5.66	2.51	2.83	1.42	0.94	1.42	0.69	1.31	0.51
11.0	2.00	8.94	2.73	4.72	2.09	2.36	1.18	0.79	1.18	0.57	1.09	0.43
11.5	1.60	7.17	2.18	3.78	1.67	1.89	0.95	0.63	0.95	0.46	0.87	0.34
12.0	1.20	5.39	1.64	2.85	1.26	1.42	0.71	0.47	0.71	0.34	0.66	0.26
12.5	0.80	3.61	1.09	1.91	0.84	0.95	0.47	0.32	0.47	0.23	0.44	0.17
13.0	0.40	1.83	0.55	0.97	0.42	0.48	0.24	0.16	0.24	0.12	0.22	0.09
13.5	0.00	0.06	0.00	0.03	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
14.0	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
14.5	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

1 ft = 0.3048 m

TABLE V AVERAGE NUMBER OF INJURIES BY TYPE (1984-1989)

Severity of Accident	Total Average Bridge-Related Accident Injuries per Year	Average Number of Injuries per Accident		
		Bridge-Related Accidents	Other Roadway Traffic Accidents	Ratio of Bridge-Related to Other Roadway Accidents
Fatal	52	0.02	0.01	2.00
Injury A	352	0.13	0.10	1.30
Injury B	555	0.20	0.19	1.05
Injury C	910	0.34	0.38	0.87

injuries were more severe than other traffic accident injuries. Furthermore, the number of injuries per accident was greater for bridge-related accidents.

Chen and Johnston (*1*) used similar data on relative severity of non-bridge to bridge-related accidents to determine the average cost of a bridge-related accident. In 1985 dollars, the estimated cost was $14,710 based upon a Human Capital Approach and $31,919 based upon a Willingness-to-Pay Approach. These amounts need annual updating due to inflation and changing relative costs in the economy. One method is to use the bridge-related accident injury data (Table V), which can be updated periodically by analysis of NCDOT accident data, and to combine it with injury costs published periodically by available sources. Injury costs based upon a Human Capital Approach are published annually (*Accident Facts*) by the National Safety Council (NSC). Injury costs based upon the Willingness-to-Pay Approach are published about every three to four years by the Federal Highway Administration (*11*). Table VI shows

TABLE VI BRIDGE-RELATED ACCIDENT AVERAGE COST

Injury Severity	Average Number of Injuries per Accident	Human Capital Approach (1990 Dollars)		Willingness-to-Pay Approach (1988 Dollars)	
		Average Cost per Injury, $	Cost per Bridge-Related Accident, $	Average Cost per Injury, $	Cost per Bridge-Related Accident, $
Fatal	0.02	410,000	8,200	1,500,000	30,000
Injury A	0.13	38,200	5,000	39,000	5,100
Injury B	0.20	8,900	1,800	12,000	2,400
Injury C	0.34	2,900	900	6,000	2,000
Property Damage			3,900		3,900
Total			19,800		43,400

the 1990 injury costs from NSC, the 1988 injury costs from FHWA, and the average property damage reported in bridge related accidents in 1990 in North Carolina. When extended, this results in an average bridge-related accident cost, U_{AC}, of $19,800 (1990 dollars) based on the Human Capital Approach and a cost, U_{AC}, of $43,400 (1988 dollars) based upon the Willingness-to-Pay Approach.

ACCIDENTS DUE TO DECK AND APPROACH ROADWAY GEOMETRY

One of the difficulties in developing prediction models for bridge related accidents has been that the accident data files cannot currently be linked directly to the bridge inventory file. This may be accomplished in the future either by complete mileposting or by GIS technique; however, for the present, alternate approaches were necessary. In one effort (*1*), average annual statewide bridge-related accidents were determined with accident data files. The accidents also could be tabulated by functional classification. However, since the individual accidents could not be linked to particular bridges, only an empirical approach could be used in developing a prediction equation. Assuming the accidents were primarily due to deck width and approach roadway alignment deficiencies, a trial-and-error approach was used evolve an equation that would predict about the same total accidents statewide and by functional classification. For the comparison, resulting accidents for each bridge were calculated and summed by the respective classifications. The resulting equation was:

$$ACCR_{CDW,ALI} = 6.28 x 10^{7.5} CDW^{-6.5} [1 + 0.5(9 - ALI)/7] \tag{6}$$

and

$$C_{WDA} + C_{ALA} = ACCR_{CDW,ALI} \text{ x } 10^{-6} \tag{7}$$

where:

$ACCR_{CDW,ALI}$ = Accident rate of bridge, accidents per million vehicles;
CDW = Clear deck width, feet (m/3.28); and
ALI = Alignment appraisal rating.

In a more recent effort (*6,7*), the accidents from 1983 to 1989 in five of the North Carolina's 100 counties were studied. Over 2,000 accident records indicating a bridge as a feature on the over-route were manually matched to the actual bridge. Various forms of regression analysis were conducted considering a variety of bridge data file parameters, such as deck width, alignment, ADT, bridge length, functional classification, etc. From this process, the annual number of accidents on a bridge was estimated to be

$$NOACC = 0.783 (ADT^{0.073})(LENGTH^{0.033})(WDIFACC + 1)^{0.05} - 1.33 \tag{8}$$

where:

ADT = Average daily traffic;
LENGTH = Bridge length, feet (m/3.28);
NOACC = Number of accidents per year; and

WDIFACC = Width difference between the goal clear deck width for an acceptable level of service and the actual bridge clear deck width, but not less than zero, feet (m/3.28).

Although developed from only five counties, Equation 8, when applied statewide, predicts the current average number of bridge-related accidents happening in North Carolina per year. The investigators noted with some surprise that the analysis did not find alignment significant for the accident data set studied. This may be because poor alignment is generally not associated with high ADT routes. When using this equation, the number of accidents for low ADT approaches zero. However, negative values for the number of accidents may be generated for very low values of the independent variables, particularly ADT. For example, the number of accidents at an ADT of less than 200 vehicles per day would be expected to be very low, when considering only bridge related factors. It is therefore reasonable to assume that at such low variable combinations the number of accidents would be zero. It is also important to interpret the results in combination with the width and lane goals that are simultaneously increasing with ADT (*4,9*). To date, Equation 6 has been the basis for predictions in OPBRIDGE; however, Equation 8 is being implemented simultaneous with other updates and improvements.

ACCIDENTS DUE TO VERTICAL CLEARANCE

Although low vertical clearance has been recognized as one of the contributing factors to accidents on bridges, neither definitive data nor studies relating accidents to vertical clearance deficiency could be found in the literature. Thus, data were obtained from NCDOT traffic accident records and analyzed. Vehicle accidents associated with underpasses of bridges in North Carolina consistently averaged approximately 440 per year. The data available for accidents involving bridge underclearance divided the accidents by roadway functional classification, but it did not show the actual bridge or clearance involved. Therefore, a direct analysis by regression or other means was not possible. Therefore, an empirical relationship was assumed, fitted and then tested to see if it could predict the accident trends. For analysis, the accidents were assumed to have occurred because of underclearance deficiency. Although some accidents may have involved under-route width problems, these could not be separated. Most of the underpass accidents reported to the NCDOT Bridge Maintenance Unit appear to involve vertical clearance. The accident rate was assumed to be linearly increasing with the amount of the vertical deficiency in relation to the desirable level of service goals (*9*) and the under-route ADT. Distributing the number of accidents to the bridges having vertical clearance deficiency in proportion to the deficiency, the accident rates for various functional classifications were calculated. From this approach, the accident rate generated due to a bridge vertical clearance deficiency, C_{CLA}, for a bridge can be estimated (*1*) as follows:

$$C_{CLA} = \frac{UG - UCL}{ACCRU} \tag{9}$$

where:

C_{CLA} = coefficient for proportion of vehicles incurring accidents due to a vertical clearance deficiency;
UG = underclearance desirable goal, feet (m);
UCL = bridge underclearance height, feet (m);
ACCRU = accident rate by functional classification due to vertical clearance deficiency;
= 7.4×10^6 veh./acc./ft. deficiency (2.25×10^6 veh./acc./m deficiency) for Interstates;
= 37.3×10^6 veh./acc./ft. deficiency (11.4×10^6 veh./acc./m deficiency) for Arterials;
= 8.0×10^6 veh./acc./ft. deficiency (2.44×10^6 veh./acc./m deficiency) for Collectors; and
= 1.1×10^6 veh./acc./ft. deficiency (0.34×10^6 veh./acc./m deficiency) for Locals.

Due to the insufficient data on the costs for vertical clearance accidents, the average vehicular bridge-related accident cost, U_{AC}, presented previously has been used as the average cost for bridge underpass accidents.

TRAFFIC GROWTH

Due to many factors, such as population growth, economic prosperity, the traffic volumes using most roadways increase year by year. Although there have been occasional drops, the national vehicle-miles have increased at an annual rate of about 3.7 percent while the population increase rate has averaged about 1.2 percent. The growth occurs partly on existing roadways and partly on newly added roadways. Different functional classification highways have different service purposes. The Interstate highways provide interstate traffic services. The arterial systems provide traffic services between major points within a state. The collector systems provide services for intracounty traffic. And the local systems usually provide the essential access to residences, farms, and other abutting properties. Since growth factors may affect these

TABLE VII EXAMPLE ANNUAL TRAFFIC GROWTH RATES FOR NORTH CAROLINA DIVISION 12 COUNTIES

NC Division 12 Counties (6 of 100 NC counties)	ADT Increase Rates (Percent per Year)			
	Local	Collector	Arterial	Interstate
Alexander	1.29	1.62	1.94 (Divisionwide)	4.06 (Statewide)
Catawba	0.92	1.43		
Cleveland	0.30	1.12		
Gaston	1.62	1.78		
Iredell	0.74	1.34		
Lincoln	1.13	1.53		

systems in different ways, the ADT increase rates of different functional classification routes may be different.

In North Carolina, there were 59 automatic traffic recording (ATR) stations in operation for continuous traffic counting at the time of the study. The locations of these ATR stations were spread over the state and distributed on most of the highway functional classifications. Of the 59 ATR stations, 20 were on arterial systems, including principal and minor arterials; 18 were on collector systems, including major and minor collectors; and seven were on the Interstate System. The remaining 14 stations were in urban areas. The ADT data collected at each ATR station over 10 years were used to analyze the ADT increase rates of North Carolina highways. Based on this data, the ADT increase rates of different functional classification highways were predicted.

The average yearly ADT increase rate of the 7 Interstate ATR stations was considered as the ADT increase rate of the North Carolina Interstate System. Although in some urban areas the interstate highways might serve as an expressway, the Interstate highways are mainly for long distance trips. Thus, a single number as the ADT increase rate was used for the entire Interstate System in a state. The yearly ADT increase rate of the 7 Interstate ATR stations was about 4.06 percent. Unlike the Interstate System, the arterial system connects several important towns located in several adjacent counties. The ADT increase rates of the arterial system would be influenced by regional factors. The state's 100 counties are divided into 14 highway divisions. Thus, the ADT increase rates of the arterial systems were predicted on a division basis. The arterial ADT increase rate of a particular division was found by calculating the average ADT increase rate of the ATR arterial stations in the division.

Due to the low volume of traffic, no ATR stations were located on local routes. Thus, the local route ADT increase rate was estimated on a different basis. Most of the traffic is locally initiated and is closely related to the local population. If the population of a local area increases, the number of local activities also would increase. Thus, the yearly ADT increase rate of the local route was assumed to be equal to the population growth of the local area or county. The North Carolina Office of State Budget and Management makes yearly estimates of the 20-year population growth in each county of the state. The county population growth rates were assumed as the local route traffic growth rate, except that a few negative growth rates were adjusted to zero.

The traffic volume of collectors in a region is between that of the arterial and the local systems. Similarly, the ADT increase rate of collectors might be between the increase rates of these two systems. Because of the nature of its traffic, the collector ADT increase rate also would be appropriately predicted by county. However, the data from the 18 collector ATR stations were not sufficient for predicting the ADT increase rates of the collector systems for each of the 100 North Carolina counties. Thus, the average ADT increase rates of the local system and the arterial system of each county were used as the ADT increase rate of its collectors. The resulting statewide collector ADT increase rate was about 1.92 percent percent compared to 2.03 from the 18 collector ATR stations. Table VII shows the ADT increase rate, calculated by these methods, for the roadway classifications in six of 100 NC counties constituting Highway Division 12. Similar data were developed for the other 94 counties (*1*).

SUMMARY

This paper has provided a summary of the efforts to estimate bridge generated user costs for North Carolina bridges. The methods developed were based on varying degrees of available data. Some parameters, such as accidents due to lateral underclearance, could not be defined due to a lack of data. Other parameters were defined for this stage of the state-of-the-art. With the newly expanding interest in economic assessment, it is hoped that more national and state efforts will be made in the future to collect data and allow improvement of such prediction methodologies. Nevertheless, the approaches and parameters developed should provide a starting point to those desiring to estimate bridge-related user costs.

Some have wondered if economic assessment of bridge improvement alternatives can be made sufficiently accurate. However, it is important to remember that although we engineers can calculate stresses to many insignificant figures, we only know the real loads, and thus the stresses, to one or sometimes two significant figures. Achieving the same level of accuracy in estimating costs may still be a goal, but it is probably attainable.

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BRIDGE MANAGEMENT TO THE YEAR 2000 AND BEYOND

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ABSTRACT

The momentum of Bridge Management System (BMS) development activities increased significantly during the 1980s. These activities have continued to accelerate with the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. This paper reviews the status of BMS development and the difficulties it faces. It also discusses the rapid advances taking place in automation and communications technologies and their beneficial impact on the developments in bridge management. The application of these technologies to bridge management data collection, data analysis and decision-support functions will provide dramatic improvements in BMS capabilities in terms of its comprehensiveness and cost-effectiveness. However, these developments must occur within the context of intermodalism and interface with other ISTEA mandated management systems.

INTRODUCTION

Efforts to develop comprehensive BMS were initiated in the 1980s and aroused the curiosity of many transportation-managers. However, strong interest developed only among a few of them. In fact by the late 1980s, only the state Departments of Transportation (DOTs) in Pennsylvania and North Carolina, and some transportation agencies abroad had major portions of their BMS in operation while a handful of other state DOTs and local agencies had minor development efforts underway. The American Association of State Highway and Transportation Officials through its National Cooperative Highway Research Program (NCHRP) started a project to develop a generic, network-level BMS in 1985. Completion of this comprehensive effort is expected shortly. During this period, the Federal Highway Administration (FHWA) provided active and visionary support for the concept and development of comprehensive bridge management. The passage of ISTEA provided a further boost to these development activities and added an even broader dimension by calling for BMS interface with the other mandated management systems. Besides these influences, continuing advances in automation and communications technologies have and will continue to provide dramatic improvements in the area of comprehensive bridge management. The decade of the nineties, therefore, promises to be a period of rapid BMS implementation activities throughout the nation. Consistent with the theme of this conference, this paper addresses the future of bridge management in the context of data and data collection, data analysis and bridge management decision-support.

DATA AND DATA COLLECTION

Current data and data collection activities have their origins in FHWA's National Bridge Inspection Standards (NBIS) that were implemented in the late 1960s following the 1967 catastrophic collapse of the Point Pleasant Bridge in West Virginia. While these NBIS data requirements were updated in 1990, their purpose continues to focus on Federal funding apportionments on a national level. Therefore, they are of little benefit to state DOTs trying to better manage their bridge network. Many transportation agencies have recognized the need for more detailed data. Data that would enable tracking of span-by-span bridge element condition and vulnerability to catastrophic failure have been accepted by many agencies as necessary to long-term bridge preservation and improvements. Physical deterioration of bridge structure components is a multi-variable function. The influence of most of these variables is quantitatively very difficult to define. Probabilistic approaches are often based upon some type of expert system. These systems are of questionable value since factors affecting rates of deterioration vary by region and have a complex relationship with environmental variables. Many agencies have recognized these limitations in predicting rates of deterioration and projecting future needs, and are now taking steps to ensure that appropriate data are being collected to provide historical information. Prediction of service-life expectancy of different improvement alternatives is also difficult and problematic. Nationwide research by NCHRP and the Strategic Highway Research Program (SHRP), and ongoing research at state agencies have been directed at solving these problems. Promising analytical techniques have been developed and sufficient quantities of necessary data should be available by the year 2000 to validate their accuracy. Transportation agencies can expect to have significant historical data available along with suitable analytical techniques by the end of this decade. Bridge managers will then be able to predict, with reasonable precision, future preservation needs and the service-life expectancy of the variety of bridge improvement actions.

Data Storage and Retrieval

Advancements in data storage and retrieval activities will be supported by the ongoing technological revolution in the automation and communications industries. If one extrapolates the past few years growth in microcomputer capabilities, by the year 2000, the extent of bridge management data storage capabilities can be expected to include:

- Ability to electronically store and retrieve all data (numeric, text, picture, video, CAD drawings, etc.) from a distributed database;
- Availability of all bridge related data from any location, via LAN, WAN, modem, cellular, satellite, etc.;
- Ability for geographically distributed users to interactively work together;
- High resolution screens;
- One gigabyte as typical desktop computer RAM memory;
- Multiple-optical drives using gigabyte-size replaceable cartridges as typical disc storage;
- Graphic User Interface (GUI) driven by pen and voice; and
- Application programs that automatically work together.

It is important to note that none of the capabilities listed need any new advances in automation or communications to become reality. As automation and communications technologies advance, the available technologies will be absorbed into day-to-day operational activities of the transportation agencies. By the year 2000 a bridge manager, using a BMS, can expect to:

- Access all bridge related information at any time, from any location, without having to be a computer expert;
- Analyze a selected bridge population easily for any chosen characteristic;
- Teleconference from a bridge site with bridge inspectors, bridge maintenance and design engineers, steel repair experts, etc.;
- Locate relevant drawings, design needed repairs, send modified drawings to fabricators, and include required checks for inspections of other similar bridges, etc.;
- Present video simulations ("virtual reality") of proposed project work and consequences of not doing it; and
- Use Geographic Information System (GIS) information to combine and analyze all relevant data (highway, bridge maintenance, accident, construction, topographic, weather, etc.).

It must be emphasized that, while technology makes possible these advances in bridge management capabilities, only organizational foresight and effective planning and action will turn them into reality.

Data Collection

Data collection activities will undergo advances similar to those in data storage and retrieval activities. Recent advances in pen-based and hand-held computers and in communications technology have improved the collection and reporting of bridge inspection data. The size of microcomputer memory, speed of operation, improved screen resolution and potential for pen and voice driven Graphic User Interface (GUI) can improve the efficiency and capabilities of the bridge inspector. The field inspector will have immediate access to prior inspection reports, photographs, video records and relevant parts of inspection manuals. Some state DOTs have pilot projects underway to determine how to most effectively use these technologies to electronically collect and store bridge inspection data. Since many of these technologies are available and efforts are underway to determine how best to use them, the expanded use of automation for bridge inspection is certain. Significant advances in remote sensing and communications technologies will provide decision-support capabilities in emergency situations. It is technically possible to have real-time audiovisual communications between bridge-sites and agency-main office. This will result in prompt assessment of problem areas and effective decision-making for remedial actions. These remote-sensing techniques also will enable agencies to have automated data collection and real-time monitoring of scour, behavior of fatigue-prone details, etc. This will support timely actions. By the year 2000 widespread use of automation technologies will facilitate field bridge inspection reporting, and data collection and storage systems that will include numeric data, text, photographs, videos and field sketches.

DATA ANALYSIS

Many analytical tools and techniques are available to manage the bridge infrastructure. Their effectiveness, however, has been limited by the absence of historic data on bridge-element condition deterioration, factors affecting rate of deterioration, total costs of improvement and maintenance actions, and service-life implications of improvement and maintenance alternatives. While reliable deterministic modeling has not been possible, the probabilistic approaches tried have had serious limitations. As historic databases build over the next few years, agencies will find the use of analytical tools and techniques to be more beneficial in providing appropriate and reliable decision-support. The analysis of a large body of historic data will either prove the worth of these analytic techniques or that they need to be revised or replaced with other methods. By the year 2000 the use of sophisticated analytical techniques such as linear programming, dynamic programming, fuzzy set theory, Markov chains, etc. are likely to become more prevalent. This will provide the bridge manager realistic life-cycle costs and improve the quality of bridge management decisions.

DECISION-SUPPORT

The goal of comprehensive bridge management is to determine and implement an infrastructure preservation and improvement strategy that best integrates capital and maintenance activities at the lowest possible life-cycle cost. So far, this has been only a dream for the bridge manager. Bridge managers have done a good job of managing individual bridges with available resources. However, they have experienced difficulties in trying to cost-effectively manage a large network of aging and deteriorating bridges. The challenging area in bridge management decision-support has been in determining the most cost-effective, long- and short-term capital improvement and maintenance program strategies in the face of severe fiscal constraints. There is a need for stronger decision-support capabilities in this area of bridge management.

There have been several major efforts to develop tools to support the bridge managers' assessment of network-level bridge conditions, vulnerability and serviceability based needs. Bridge failures in recent years have resulted in efforts to systematically assess and evaluate the vulnerability of bridges to catastrophic failures due to hydraulic, steel fatigue, seismic and other similar causes. Current research and relevant data collection activities can be expected to provide improved understanding and capabilities in dealing with these issues. Future bridge inventory and inspection reports will include detailed information of these types that in turn will help in risk assessment and identification of higher priority activities needed to assure public safety. The assessment of network-level condition needs has been possible for some time. However, the NBIS data does not have sufficient detail to indicate bridge element and span condition. Many agencies are supplementing the NBIS data with information on the extent and nature of element deterioration. With the collection of this information, the quality of the condition-based needs assessment can be expected to significantly improve.

Another hurdle in assuring maximum benefit from budgeted expenditures has been the bridge manager's difficulty to forecast, with reasonable accuracy, network and project-level bridge conditions when considering various capital or maintenance improvements. Current research and data collection activities should help in better prediction of deterioration rates with and without improvements, and also in better prediction of service-life expectancies of different improvement methods. The developments in these areas will improve the assessments of life-cycle cost effectiveness of options, thus facilitating the selection of options that assure maximum benefit from available resources.

As historical information and the additional data become available and improved algorithms emerge, analytical tools and techniques to analyze this information will also expand. Current analytical tools and techniques will have been tested in terms of their validity and utility. Advancements in automation will further increase processing capabilities, and these improvements will enable "what if studies" through improved algorithms. This will make sensitivity analyses possible thus enabling identification of cost-effective life-cycle strategies at the project and network levels.

With the improvements and advances in data collection and availability of additional data, there will be more historic information available at the initial scoping of capital improvement projects. Also available electronically will be photos and videos for better understanding of individual project needs. In addition, there will be easy access to information on what was done to similar bridges, and the service life and cost-effectiveness of different work alternatives. There may also be interstate linkages to share bridge data across jurisdictional boundaries. This type of linkage will lead to more common terminology between agencies and expose bridge managers to areas of commonality in the diverse bridge activities of different agencies.

Another advancement will occur through the linkage of engineering software to bridge management decision-support. A bridge management system cannot be considered comprehensive without having engineering components incorporated within its operational framework. This is especially important for project-level bridge management. The BMS of the future will have load rating, bridge design and drafting as essential components. The load rating capability will allow for prompt load capacity evaluations and will be helpful in accident damage assessments. It also can be used in comparing and selecting appropriate repair/retrofit work strategies and cost estimates, and to help in the efficient routing of overload vehicles.

Innovations in bridge designs and their implications in terms of construction sequencing will be beneficial in managing phased bridge construction. Realistic multi-year bridge maintenance programs and more cost-effective project mixes in the capital improvement program also will be possible. Detailed graphic displays of a variety of design alternatives can be prepared to visually display the implications of these alternatives in regard to their aesthetic appeal, changes in profile and effects on adjacent terrain or property. Developments in virtual reality will make it possible to visually depict to legislative bodies and the public the impact of different levels of public investment on the bridge deterioration process. Bridge engineers have come to realize the impacts of deferred remedial actions but have had limited success in convincing the policy makers. This will no longer be difficult to demonstrate. The multimedia techniques that exist today, when applied to bridges, will, through a sequence of compiled video clips, succinctly show the progression of bridge condition deterioration. No longer will the proponents of deferred maintenance be able to ignore the dire consequences of postponing maintenance activities.

IMPLICATIONS OF ISTEA

The ISTEA of 1991 mandated the development of management systems and emphasized intermodal transportation efficiency as the principal goal for surface transportation agencies. This clearly requires bridge managers to broaden their management perspective to ensure compatibility between BMSs and other ISTEA mandated systems. Pavement Management Systems (PMSs) and BMSs have been under development for some time and the need for compatibility and interface between them has been recognized by most agencies. Other management system developments are being initiated in response to rules recently promulgated by the FHWA. The BMS interface with these other management systems, therefore, will evolve. The emphasis on multimodalism will require coordinated transportation investment decisions to improve the safety and efficiency of the multimodal movement of people and goods. Future BMSs will be able to effectively show the comparative importance and long-term cost effectiveness of public investment in bridges within the context of multimodal transportation efficiency.

CONCLUSION

Starting in the 1980s, BMS development activities have increased in intensity and effectiveness. Advances in automation and communications technologies will support dramatic improvements in bridge management practices. Data collection, storage and retrieval activities will benefit from the rapid growth in microcomputer capabilities and multimedia techniques thereby dramatically improving bridge management practices. Current efforts to build comprehensive and historic bridge condition databases will enable validation of analytic techniques and/or evolution of improved techniques. The most significant improvements will be in the area of decision-support. These will enable the bridge manager to determine the most cost-effective, long/short term capital improvement/maintenance program strategies. The ISTEA legislation will support and shape the future of bridge management through interfaces with other management systems and the need to demonstrate public investment in bridges within the context of multimodalism.

APPENDIX A - WORKSHOP PROGRAM

7th Conference on Bridge Management

BRIDGE MANAGEMENT FOR TRANSPORTATION AGENCIES

Hyatt Regency Austin on Town Lake
Austin, Texas, September 15-17, 1993

Tuesday, September 14, 1993

7:00 - 9:00 p.m. REGISTRATION

Wednesday, September 15, 1993

7:00 - 8:00 a.m. CONTINENTAL BREAKFAST

7:00 a.m. - 5:00 p.m. REGISTRATION

8:30 - 9:00 a.m.

WELCOME AND CONFERENCE OVERVIEW

Luis Ybanez, *Texas Department of Transportation*, presiding

Welcoming Remarks, Arnold W. Oliver, Executive Director and Chief Administrative Officer, *Texas Department of Transportation*

Bridge Management Conference Overview, Arun M. Shirole, *New York State Department of Transportation*

9:00 - 10:00 a.m.

NATIONAL PERSPECTIVE ON BRIDGE MANAGEMENT

Arun M. Shirole, *New York State Department of Transportation*, presiding

Bridge Management: An Effective Tool for Transportation Agencies, James E. Siebels, Director of Central Engineering, *Colorado Department of Transportation*, and Chairman of AASHTO *Highway Subcommittee on Bridges and Structures*

FHWA Rules and Regulations for Bridge Management, David H. Densmore, Chief of the Bridge Management Branch, *Federal Highway Administration*

10:00 - 10:30 a.m. BREAK

10:30 a.m. - 5:00 p.m.

BRIDGE MANAGEMENT DECISION SUPPORT PROCESS

Daniel S. O'Connor, *Federal Highway Administration*, presiding

Bridge Management System Data Needs and Data Collection, Daniel S. Turner and James A. Richardson, *University of Alabama*

Case Study: Connecticut's Bridge Management Information System, Robert G. Lauzon and James M. Sime, *Connecticut Department of Transportation*

12:00 noon - 1:30 p.m. LUNCH

Tools for Bridge Management Data Analysis, Anton J. Kleywegt and Kumares C. Sinha, *Purdue University*

Case Study: Analysis of Bridge Management Data in North Carolina, David W. Johnston, *North Carolina State University*

3:00 - 3:30 p.m. BREAK

Bridge Management Decision Support, Arun M. Shirole, William J. Winkler and Michael W. Fitzpatrick, *New York State Department of Transportation*

Case Study: PennDOT's Bridge Management Decision Support Process, Jonathan D. Oravec, *Pennsylvania Department of Transportation*

6:30 - 8:00 p.m. RECEPTION

Thursday, September 16, 1993

7:00 - 8:00 a.m. CONTINENTAL BREAKFAST

8:00 - 12:00 noon REGISTRATION

8:30 - 12:00 noon

NATIONAL SYSTEMS TO SUPPORT BRIDGE MANAGEMENT

Ian M. Friedland, *State University of New York*, presiding

PONTIS, Paul D. Thompson, *Cambridge Systematics*, and Richard W. Shepard, *California Department of Transportation*

NBI Condition Ratings from BMS Data, George Hearn and Dan M. Frangopol, *University of Colorado*, and Brian L. Pinkerton, *Colorado Department of Transportation*

10:15 - 10:45 a.m. BREAK

BRIDGIT - NCHRP's Bridge Management System Software, Stephen E. Lipkus, *National Engineering Technology Corporation*

12:00 noon - 1:30 p.m. LUNCH

1:30 - 5:00 p.m.

AGENCY APPROACHES TO BRIDGE MANAGEMENT

Robert N. Kamp, *Consulting Engineer*, presiding

Project Bridge Management in Ontario, Ranjit S. Reel and Dan F. Conte, *Ontario Ministry of Transport*

Development of a Bridge Management System in Alabama, Sharon G. Green, *Alabama Highway Department*, and James A. Richardson, *University of Alabama*

3:00 - 3:30 p.m. BREAK

Unique Characteristics of Denmark's Bridge Management System, Niels H. Andersen and Jorn Lauridsen, *Danish Road Directorate*

Indiana's Approach to a Bridge Management System, Robert E. Woods, *Indiana Department of Transportation*

5:00 - 7:00 p.m. DINNER

7:00 - 10:00 p.m. DEMONSTRATION OF BRIDGE MANAGEMENT SUPPORT SYSTEMS

The following BM systems will be demonstrated concurrently starting at 7:00, 7:20, 7:40, 8:00 & 8:20 p.m. with opportunities for participants to ask detailed questions between 8:40 and 10:00 p.m.

Alabama, Sharon G. Green, *Alabama Highway Department*
Connecticut, Robert G. Lauzon and James M. Sime, *Connecticut Department of Transportation*
Denmark, Niels H. Andersen, *Danish Road Directorate*
Indiana, Robert E. Woods, *Indiana Department of Transportation*
New York, William J. Winkler, Michael W. Fitzpatrick and Donald E. Erickson, *New York State Department of Transportation*

The following BM systems will be demonstrated based on participant questions between 7:00 and 10:00 p.m.

California (PONTIS), Richard W. Shepard, *California Department of Transportation*
NCHRP (BRIDGIT), Stephen E. Lipkus, *National Engineering Technology Corporation*

Friday, September 17, 1993

7:00 - 8:00 a.m. CONTINENTAL BREAKFAST

8:30 - 11:45 a.m. DEVELOPMENT AND IMPLEMENTATION ISSUES WITH BRIDGE MANAGEMENT SYSTEMS

Jimmy D. Lee, *North Carolina Department of Transportation*, presiding

Panel Discussion

Developmental Issues and Data Collection, Larry H. Davis, *Florida Department of Transportation*
Bridge Management System Integration and Technical Difficulties, William A. Hyman, *The Urban Institute*
What a Bridge Management System Could Do for a Large City, Stan C. Kaderbeck, *Chicago Department of Transportation*
County Bridge Management Requirements, Patrick B. Murphy, *Hennepin County Minnesota*
Cooperation Between State and Local Government Bridge Management Efforts, Glenn Sprowls, *County Engineers Association of Ohio*
User Costs in a Bridge Management System, Bojidar S. Yanev, *New York City Department of Transportation*

10:00 - 10:30 a.m. BREAK

Developing User Costs for Bridge Management Systems, David W. Johnston, *North Carolina State University*, Chwen-jing Chen, *Taiwan Area National Expressway*, and Imad Abed-Al-Rahim, *California Department of Transportation*
Bridge Management to the Year 2000 and Beyond, Arun M. Shirole, *New York State Department of Transportation*

11:45 - 12:00 noon CLOSING REMARKS

Jimmy D. Lee, *North Carolina Department of Transportation*
Ralph K. Banks, *Texas Department of Transportation*

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