NATIONAL COOPERATIVE
HIGHWAY RESEARCH PROGRAM REPORT

300

BRIDGE MANAGEMENT SYSTEMS

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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AREAS OF INTEREST:

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(Highway Transportation, Public Transit, Rail Transportation)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to the National Research Council is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the National Research Council and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Research Council and the Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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NOTICE

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The members of the technical committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the technical committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the American Association of State Highway and Transportation officials, or the Federal Highway Administration, U.S. Department of Transportation.

Each report is reviewed and accepted for publication by the technical committee according to procedures established and monitored by the Transportation Research Board Executive Committee and the Governing Board of the National Research Council.

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FOREWORD

By Staff Transportation Research Board

This report contains the findings of a study that was undertaken to define the essential elements of a network-level bridge management system. The report defines the benefits from, and basic engineering concepts for, implementation of a bridge management system. The contents of this report will be of immediate interest and use to administrators, managers, and engineers with bridge responsibilities at all levels within a transportation agency.

About one-half of the approximately 600,000 highway bridges in the United States were built before 1940. Most of these bridges were designed for less traffic, smaller vehicles, slower speeds, and lighter loads than are presently found on the highway network. In addition, even in newer bridges, deterioration caused by service conditions and deferred maintenance is a growing problem. Nearly half of these bridges have been classified as structurally deficient or functionally obsolete by the Federal Highway Administration. The cost for rehabilitation and replacement of these bridges has been estimated at more than $50 billion. However, only $2 to $3 billion annually has been available to address this problem.

It is obvious that available funds will not permit total rehabilitation or replacement of all deficient bridges. Therefore, the limited funds available must be carefully allocated to bridges required by the public and transportation industries to provide the most cost-effective treatment.

This report contains the findings of the first phase of NCHRP Project 12-28(2), "Bridge Management Systems." The overall objective of this project is to develop a model bridge management system at the network level that can be implemented by small to medium size transportation agencies. The system is intended to ensure the effective use of available funds and identify the effects of various funding levels on the bridge network.

The specific objectives of the first phase of NCHRP Project 12-28(2) were to define the elements required for a model bridge management system (BMS) at the network level, and to initiate its development and programming. Six major modules were identified as the minimum required for an effective bridge management system. These are: the BMS data base module; the network level maintenance, rehabilitation, and replacement selection module; a maintenance module that will assign maintenance programs in a rational and continuing way within the system; the historical data analysis module; a project level interface module; and the reporting module. These modules can be customized according to the transportation agency's needs, and additional modules can be added and modified as needed.

A second phase of the project was initiated in late 1987 with the objective of further developing and refining the BMS model reported on here. The second phase will result in completion of the engineering concept development for a network level BMS, programming the system on a computer, and validation of the system and engineering concepts with actual bridge inventory data obtained from several transportation agencies. The second phase should be completed in late 1989.

Appendix C contains information on a BMS demonstration program that was developed as part of this project. The demonstrator shows the general concepts of what a computerized BMS can offer. The demonstration program is contained on one 5¼-in. IBM-PC compatible floppy disk formatted with IBM or MS DOS Version 3.0 or higher, double sided/double density (see Appendix C for requirements to run the program). A copy of the demonstration program may be obtained by sending one blank disk to the Transportation Research Board, National Cooperative Highway Research Program, 2101 Constitution Avenue, NW, Washington, D.C. 20418.

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Grateful acknowledgment is made to the members of the Technical Advisory Committee who participated in this study. The gratitude of the research team is also extended to the NCHRP Project Review Panel who helped guide the project.

Mr. Dan O'Conner (FHWA) and Mr. Fred Finn (ARE Inc) provided helpful discussions early in the project. Staff members of the DOT Bridge Design and Maintenance Divisions from Pennsylvania, Texas, California, Kansas, North Carolina, New York, and Arizona provided inputs during our state visits that resulted in a comprehensive state-of-the-art review memorandum.

BRIDGE MANAGEMENT SYSTEMS

SUMMARY About one-half of the inventoried and classified 574,000 highway bridges in the United States were built before 1940. Of these, according to the Federal Highway Administration, over 42 percent (244,000 bridges) are classified as structurally deficient or functionally obsolete and need rehabilitation or replacement, which is estimated at more than $50 billion. Each year, bridge inspections indicate that additional bridges are joining this growing list and, in spite of major expenditures, the problem is growing faster than it can be solved. Many states and the National Cooperative Highway Research Program have identified the need for effective bridge management techniques to help solve this problem. The objective of this project is to develop a form of effective bridge management at the network level (that is, dealing with a group of bridges rather than with a single bridge) that will ensure the effective use of available funds and identify the effects of various funding levels.

Basic Concept

Bridge management is not "business as usual." It requires a practical, objective, and systematic consideration of the problem with a set of economic and technical tools not previously combined to solve the problem. Specifically, a bridge management system (BMS) is a rational and systematic approach to organizing and carrying out the activities related to planning, designing, constructing, maintaining, rehabilitating, and replacing bridges vital to the transportation infrastructure. A BMS should assist decision-makers to select optimum cost-effective alternatives needed to achieve desired levels of service within the allocated funds and to identify future funding requirements. Bridge management is a relatively new concept that was adapted from successful application of systems concepts to pavement management functions.

A bridge management system provides benefits to administrators, engineers, and managers at all levels within a transportation agency. The basic concept can be developed in many ways, but the logical development presented in this report includes a minimum of six major modules. Others can be added or modified later, but these six are essential:

1. Data base module.
2. Network level major maintenance, rehabilitation, and replacement (MR&R) selection module.
3. Maintenance module.
4. Historical data analysis module.
5. Project level interface module.
6. Reporting module.

The Data Base Module contains information essential to the management of an individual bridge or a set of bridges. Without this information, good bridge management is not possible.

The Network MR&R Selection Module provides the analyses necessary for bridge managers to make more effective programming and budgeting decisions. This module includes four technical submodules which form a hierarchy of analysis:

1. Ranking.
2. Specific MR&R action selection.
3. Life-cycle costing.
4. Optimization.

At least the first three must be employed to truly have a BMS.

Because it is impossible to completely repair, rehabilitate, or replace all structures, it is necessary to have a Maintenance Module that can be used to assign maintenance programs in a rational and continuing way within the system. Maintenance programs include preventative maintenance as well as demand responsive maintenance.

The Historical Data Analysis Module is essential for tracking past and future actions and expenditures on the bridge network and for generating improved models for updating the bridge management system itself.

The Project Level Interface Module helps the bridge engineer move from programmed bridge management activities at the network level to the selection of individual and appropriate actions for a specific bridge under consideration.

The Reporting Module provides a capability for the transportation agency staff to generate a wide variety of technical and administrative reports and summaries of bridge conditions, bridge program budgets, and bridge MR&R programs. Additional modules and submodules are discussed in this report. They will be added as the bridge management system develops.

The model bridge management system developed in this report can assist in managing the bridge network by providing organized information for use in selecting and scheduling bridge maintenance, rehabilitation, and replacement (MR&R) projects. The decision criteria used by the BMS are selected by the users and, if a recommendation produced by the automated BMS is questionable, the user can override the system. The BMS can use retained historical data to develop better bridge deterioration and life prediction models. The entire process is cyclic because new data are collected periodically and the system is rerun. With each cycle, new information is obtained to make the output more accurate and to improve predictions and MR&R assignments. The BMS provides a useful and effective tool for managing a bridge network. Bridge managers, engineers, and administrators, however, exercise final control over the decisions.

Implementation

Continued design, enhancement, and implementation are essential for this model Bridge Management System to develop and reach its full potential. First an operational and generic BMS must be designed, programmed, and thoroughly tested. This is anticipated in a second phase of this NCHRP project. An implementation phase may then be possible in which one or more transportation agencies would be selected for trail implementation of the NCHRP program. The details of the modules and the concepts presented herein, in the form of the operational BMS, will be expanded and adapted directly to the specific characteristics of the selected agency(s). Although it is possible to demonstrate and apply all the concepts in cooperation with a single agency, it is desirable to use at least two agencies because the adaptation to two agencies provides more generality for future broader applications within AASHTO.

It is important now to apply the necessary work and resources to add details to the conceptual BMS in order to make it operational and then to implement it. There are no other reasonable alternatives because of the obvious need for good bridge management practices and the large effort that has been expended to develop the conceptual system presented in this report. Chapter Four of the report presents a long-term plan to fully design, develop, program, and implement an operational BMS. It takes full advantage of the momentum that has been gained in this study and allows for the most efficient and complete means of obtaining a working BMS.

Benefits

The specific benefits from implementation of a BMS are as follows:

1. Improved organized knowledge of the condition of bridges in a network.
2. Structured comparisons of bridge condition across the network.
3. Prioritized or optimized lists of bridges needing MR&R actions.
4. Life-cycle cost estimates associated with projected MR&R activities.
5. Mechanisms for improving historical predictions.
6. Projections of bridge performance and deterioration (improved models).
7. Data to quantify the effectiveness of MR&R strategies.
8. Better scheduling of minor bridge maintenance.
9. More rational programming of limited funds.

In summary, a bridge management system provides legislators, administrators, and technical personnel with improved information and methods for managing the critical bridge infrastructure of the transportation system. The consequences of not adopting some form of good bridge management could be catastrophic. Past methods of making decisions regarding the expenditure of available MR&R funds have left one with a large number of deficient bridges. It is logical to assume that to continue to operate as has been done in the past will only serve to worsen the problems. Effective bridge management, on the other hand, can begin to alleviate the problems by helping to make rational decisions regarding the most efficient ways to spend available funds.

This report details the results of a two-year project which formulates the detailed concepts of a model BMS and presents a plan for developing an operational BMS and for future implementation of the system in two transportation organizations. All phases of the bridge management process are covered, ranging from required data input to desirable outputs and improvements. Chapter One of the report provides a review of the background, objectives, and accomplishments of the project and is suggested as further reading for the executive or administrator.

CHAPTER ONE

INTRODUCTION

Federal, state, county, and city bridges are critical links in the national transportation system. The enormous public investment in these structures demands that they be properly managed and that they receive both timely and cost-effective maintenance, rehabilitation, and replacement. Bridges are essential for providing and maintaining the quality of life as it is known today. The historical significance and beauty of many of these structures is an invaluable part of one's heritage. The need for complete, consistent, and accurate bridge management practices becomes increasingly evident as the current status of these vital links in the transportation infrastructure is considered.

MAGNITUDE OF THE BRIDGE PROBLEM

Since 1978, the inventory and condition of the nation's bridges has been documented in reports to Congress and elsewhere (*1, 2, 3,*). Despite $13 billion in federal aid for bridge repair and replacement authorized by Congress since 1970, the average condition of bridges continues to decline.

In setting up this project, the National Cooperative Highway Research Program clearly cited the magnitude of bridge needs:

> About one-half of the approximately 600,000 highway bridges in the United States were built before 1940. Most were designed for less traffic, smaller vehicles, slower speeds, and lighter loads. In addition, even in newer bridges, deterioration caused by service conditions and deferred maintenance is a growing problem. Almost 40 percent of the nation's bridges are classified, according to the Federal Highway Administration's (FHWA) criteria, as deficient and in need of rehabilitation or replacement. More than 100,000 of these are judged to be structurally deficient because of deterioration or distress, and another 100,000 are considered functionally obsolete or inadequate for current requirements. In recent years, the Federal Highway Bridge Replacement and Rehabilitation Program has provided about $1 billion annually (scheduled to increase to $2 billion in FY '86) to cover the 80 percent federal aid share of the cost of work on deficient bridges. However, in 1983, the FHWA estimated the program's needs at almost $50 billion, and this estimate did not include future inflation or the cost of additional needs that will develop while the presently identified, deficient bridges are being eliminated from the list.
>
> It is obvious that available funds will not permit local rehabilitation or replacement of all deficient bridges, and the funds available must be carefully and correctly directed to bridges required by the public, industry, and emergency services to provide the most cost effective treatment in each case.

As summarized in the Annual Reports of the Secretary of Transportation to the Congress of the United States, this bridge problem is growing (see Table 1).

Table 1. Status of the nation's bridges (*1,2,4*).

	Annual HBRRP Reports to Congress		
	Fifth Annual Dec. 1983	Sixth Annual Dec. 1984	Seventh Annual Dec. 1985
Number of bridges inventoried & classified	571,246	574,045	574,729
Number of structurally deficient bridges* (includes closed bridges)	136,347	140,808	135,736
Number of functionally obsolete bridges*	123,959	119,367	108,181
Number of bridges that are load posted	90,028	98,356	112,522
Additional bridges that should be load posted	66,528	49,505	33,851
Total bridges that are or should be load posted	156,556	147,861	146,373
Number of bridges closed to all traffic (these bridges may be closed temporarily for repairs or closed permanently)	3,653	4,494	4,899
Total number of bridges funded under the bridge programs - SBRP	1,606	1,596	1,579
- HBRRP	13,577	18,246	21,398
TOTAL	15,183	19,842	22,977
Number of replaced or rehabilitated bridges now open to traffic (SBRP & HBRRP)	6,061	8,358	11,266
Bridges under construction and/or design (SBRP & HBRRP)	9,122	11,484	11,711

* A structurally deficient bridge, as defined by FHWA, is one that (1) has been restricted to light vehicles only, (2) is closed, or (3) requires immediate rehabilitation to remain open; a functionally obsolete bridge is one on which the deck geometry, load carrying capacity, clearance, or approach roadway alignment no longer meet the usual criteria for the overall system.

BACKGROUND

Project Objectives

Recognizing that a bridge management system (BMS) was a high priority of many states, the National Cooperative Highway Research Program (NCHRP) allocated research funds for the development of a model BMS. The specific objectives of NCHRP Project 12-28(2) were to develop a form of effective network level bridge management that included the following:

- Engineering methods to assess present and future needs of existing bridges (inventory, inspection, capacity, maintenance, rehabilitation, replacement, and funding).
- Guidelines for determining cost-effective alternatives both with and without financial constraints.
- Priority treatment of needs through the use of generalized work activities (from posting and preventive maintenance through replacement).
- Flexibility to accommodate a variety of policy approaches.
- Flexibility to accommodate future expansion to the project level.

- Methods to ascertain standards of data reliability.

The final model Bridge Management System must compare the agency and public costs of gradual structural deterioration and functional obsolescence against the costs and benefits of routine maintenance, interim repairs, partial rehabilitation, and/or major reconstruction for each structure. The BMS must evaluate all structures in the network for multiple years in order to:

- Compare different funding levels.
- Compare different spending policies (Capital Improvement versus Maintenance).
- Compare different maintenance, rehabilitation, and replacement (MR&R) actions.
- Compare different project options (Bridge A versus Bridge B).
- Compare different timing alternatives (MR&R action now or later).
- Predict the consequences of different scenarios.

Project Scope

The questions raised regarding bridges arose years ago in the pavement field, and the response was the development of pavement management systems. The overall scope of NCHRP Project 12-28(2) was to adapt similar technology, including economics, engineering, systems engineering, planning techniques, and optimization to the management of bridge resources.

The project scope was focused on developing a model BMS to meet the needs of medium to small size states, counties, and cities and to include the following:

- All structural types.
- All bridge sizes including culverts.
- Different bridge construction materials.
- Network level considerations.
- Life-cycle costing models.
- Prioritization/optimization procedures.
- Maintenance, rehabilitation, and replacement alternatives.
- Automation considerations.

Project Activities and Accomplishments

The model BMS modules, flow, and implementation plan presented in this report reflect multiple activities of Project 12-28(2) that include, among others, visits to six state DOT's, an extensive literature search and review, a survey of current bridge management practices, and coordination with other on-going bridge research activities. The information obtained from these sources was evaluated to produce a BMS framework. The framework (described in Appendix B) developed the intricacies of the flows of information related to managing a bridge network. The details of the framework provided an insight into the requirements for data collection, decision-making, and reporting to administration. The accomplishments of these project activities are described in detail throughout this report. In order to show the benefits of the BMS, a prototype demonstration program was developed for bridge managers and DOT administrators. The demonstrator is discussed in Appendix C.

DEVELOPMENT OF A BMS

Definition of a BMS

A bridge management system (BMS) is a rational and systematic approach to organizing and carrying out all the activities related to providing programs for bridges vital to the transportation infrastructure. The activities include: (1) predicting bridge needs, (2) defining bridge conditions, (3) allocating funds for construction, replacement, rehabilitation, and maintenance actions, (4) identifying and prioritizing bridges for MR&R actions, (5) identifying bridges for posting, (6) finding cost-effective alternatives for each bridge, (7) recommending MR&R actions, (8) accounting of MR&R actions, (9) scheduling and performing minor maintenance, (10) monitoring and rating bridges, and (11) maintaining an appropriate data base of information. A BMS should assist decision-makers at all bridge management levels to select optimum solutions from an array of cost-effective alternatives for every action needed to achieve the desired levels of service within the funds allocated and to identify future funding requirements.

Basic Modules

A BMS model must include, as a minimum, the following modules (described in Chapter Two): data base module, network level MR&R selection module, maintenance module, historical data analysis module, project level interface module, and reporting module.

Benefits

A BMS provides benefits to engineers and managers at all levels within an agency as follows:

Level	*BMS Benefits/Outputs*
Administrative	Summarizes bridge structural conditions Summarizes bridge functional conditions Addresses fund allocation questions Establishes needs Assists with statewide budget estimates Assists in developing annual work plans Reports NBIS data to the federal government
Executive	Prioritizes candidate projects Analyzes cost effectiveness of various programs Identifies bridges for posting Prioritizes bridge MR&R program Assists in bridge maintenance scheduling Tracks and schedules MR&R actions
Technical	Makes information readily available Allows easy input and editing of condition data Provides details for project level design Provides current costs Provides a history for each bridge Gives effectiveness data for particular MR&R actions Allows easy special sorting and reporting

Gives easy access to planning and programming data
Is overall source for NBIS data

Project Level versus Network Level

At the network level, the entire bridge population is dealt with globally. This level of management must consider such concerns as the number of deficient bridges on a particular route rather than the condition of a span in a specific location. The Network Level is concerned with obtaining the appropriate level of funding to maintain the performance of the bridge network to a desirable level. Once funds have been made available, it is then necessary to properly distribute resources to each bridge or district and ensure that they are used effectively at the proper level.

The Project Level treats each bridge on an individual basis for inspection, maintenance, repair, and/or rehabilitation needs. Once network level decisions are made on priorities and funding, then a detailed evaluation of each selected bridge must follow at the project level.

Detailed structural analysis must be used in selecting the most cost-effective rehabilitation or replacement action for a specific bridge. The option selected can be a function of several criteria, including:

- Detailed structural engineering analyses.
- Distress type, extent, and severity of critical component.
- Estimated remaining life.
- Rate of deterioration.
- Condition of the secondary components.
- Cost and design life of alternative MR&R treatments.
- Availability of funds.
- Essentiality of the bridge to the public.
- Impact of repairs on traffic flow.
- Related bridge or highway work nearby.
- Type and size of bridge.
- Load carrying capacity of the bridge.
- Projected future use of the bridge.
- Historical significance of the bridge.

The most traditional and important project level implementation activity is the detailed structural engineering analysis of various alternatives. The calculation of stresses, strains, and moments for each option is required to determine its structural feasibility. A survey of AASHTO software (*5*) revealed more than 250 software programs of different sizes and complexities for analyzing different structural components. These programs are readily available and can be used in conjunction with the BMS. The Bridge Analysis and Rating System (BARS) and Bridge Rating and Analysis Structural System (BRASS) (*6,7*), supported by AASHTO and used by many states, are principal candidates to link with the network level BMS, although it should be recognized that this is a complex and detailed task that would only be applied to a selected set of bridges.

Currently, the state of the art in network level bridge management lags project level developments.

The BMS presented in this report is a network level engineering tool with emphasis on the broader decisions. The activities associated with network level planning and programming include the following:

- Automate data entry, editing, storage, and management.
- Summarize global network structural and functional conditions.
- Establish candidate project lists.
- Prioritize and select among the various MR&R actions for all candidate bridges in the system and identify resource requirements.
- Develop life-cycle cost estimates.
- Optimize the various alternatives.
- Evaluate funds and resource allocation alternatives.
- Develop outputs specifically related to bridge posting and load permit routing.
- Develop MR&R action schedules and cost data.
- Ensure that standards of optimal safe maintenance levels are followed.
- Ensure uniform reporting of Inventory and Inspection information.
- Report historical expenditures for different types of work (dollars, manpower, materials).
- Report historical changes to condition of plant and inventory as well as predicting effectiveness of global maintenance strategies.

Existing Problems To Be Resolved by a BMS

State-of-the-Art Review

State visits and a comprehensive state-of-the-art review of bridge management practices (detailed in Appendix D and covering the following topics: inventory, inspection, and appraisal practices; definitions of bridge components, maintenance, rehabilitation, and replacement; bridge deck types and MR&R techniques; bridge substructure elements and MR&R techniques; bridge superstructure elements and MR&R techniques; other bridge components, such as sidewalks, curbs, railing, signs, and bridge approaches; timber bridges; prioritization methods; load rating and posting issues; and review of states' experiences) contributed much information to the BMS development and ideas for future direction. The results of interviews conducted in the six states visited and subsequent correspondence are summarized in Table 2.

A survey of bridge maintenance and rehabilitation work in 39 states, which was made by the Pennsylvania Transportation Institute in late 1982 (*8*), revealed that 26 of the 39 states had a statewide bridge maintenance policy. The survey indicated that, in general, maintenance and rehabilitation of bridges by state forces consisted of minor routine work on small projects that could be done quickly. Major work on large projects that required special equipment, materials, or manpower and long completion time was normally done by contract (*8*).

There are about 575,000 bridges on the nation's federal-aid and other highway systems, 75 percent of which were built before 1935. Paralleling the federal government's commitment to the bridge repair/replacement program has been an increased awareness among historians and preservationists that bridges are legitimate objects for preservation. NCHRP Synthesis 101 (*9*) examined possible decision-making criteria for historic bridges.

The survey of bridge-management-related activities showed that several states have refined or developed models for identifying bridges eligible for replacement or rehabilitation. Engi-

Table 2. Summary of state's responses.

Questions	PA	CA	TX	NC	KS	NY
How many years of data are available?	Since 1972	Up to 50 years	2 years	From 1980 forward	Since 1931	6 years
How are the data stored?	Computer	Computer/typed reports	Computer/ files	Computer	Computer (since 1971)	Computer
Construction history?	Yes, (for some bridges)	Yes, (in most cases)	Yes (in most cases)	Yes	Yes	Yes
Maintenance/rehabilitation history?	Yes, (for some bridges)	Yes (recent history)	Yes (in some cases)	Yes	Yes (contract work)	7 years (maintenance)
Design load data available?	Yes, (for specific bridges)	Yes	Yes (in most cases)	Yes (for primary system)	Yes	Yes (when known)
Fatigue considered in the design procedure?	Yes	Yes	Yes	Yes	Yes	Yes
Inventory rating (IR) used?	Yes	Yes	Yes	Yes	Yes	Yes
Operating rating (OR) used?	Yes	Yes	Yes	Yes	Yes	Yes
Load posting criterion?	IR/OR	OR	IR	OR	Between IR and OR	IR/OR
Construction/rehabilitation cost data available?	Yes	Yes (back to a reasonable date)	Yes	Yes	Yes	Yes
Maintenance/rehabilitation cost data available per year?	Maintenance	Maintenance cost (limited)	Yes (partially)	Yes	Maintenance cost	Yes
User delay costs considered?	Yes	No	Yes (in special cases)	No	No	Yes
Microcomputer used in field data collection?	No	No	No	No	No	No

neering judgment and empirical models form the basis of most procedures used in these states. A summary of BMS-related activities is included in Table 3. State responses concerning bridge management needs are summarized in Table 4 and reflect the deficiencies in the current bridge management practices.

Deficiencies with current bridge management activities that were identified during the state-of-the-art review are:

- Federal SI&A (structure inventory and appraisal) data deficiencies.
- Inability of most highway maintenance management systems (MMS) to provide good bridge maintenance data.
- Unavailable or poor expenditure and effectiveness records for bridge maintenance, replacement, and rehabilitation (MR&R), and construction activities for developing deterioration models.
- Little-to-no use of life cycle cost methods.
- Little attention to long-range network effects.
- Lack of consistent/systematic methods for prioritizing candidate bridges for MR&R activities.
- Unanswered network level policy questions.

Data Deficiencies

The Federal SI&A data are based on a few features and are of limited use relative to effective bridge maintenance management. Significant limitations of the SI&A data are:

- Lack of distress extent and type data.
- No flagging mechanism for urgent actions.
- Ratings do not reflect maintenance needs (type and quantity), for example, a deteriorated deck condition may be a costly major maintenance item, but it has little influence on the structural condition severity ratings.
- Low precision and reliability of the ratings and their associated definitions, especially in grey areas of intermediate condition ratings (it is difficult to differentiate between needs for minor maintenance, major maintenance, and minor rehabilitation).
- Lack of objective instrumentation that is reliable and measures valid parameters.
- Lack of maintenance items on SI&A forms (for example, painting is not considered in the inspection).
- Field inspection is geared to rehabilitation and replacement (structural, adequacy, safety considerations), and not to minor or preventive maintenance.

Inadequate Bridge Maintenance Data

A majority of the states have adopted highway maintenance

Table 3. BMS related activities in various states.

State	Activities
Pennsylvania	Data Base: 1) Enhanced SIRS data base 2) Structure cost data inventory file 3) Structural details data base (future enhancement) Outputs: 1) Prioritization for replacement/rehabilitation (present and future needs). It will use deficiency rating (based on the Federal Sufficiency Rating and Level-of-Service deficiency approach), cost information, and other factors. 2) Present and future needs for maintenance. 3) Bridge load capacity rating.(future enhancement)
N. Carolina	Priority ranking of bridges for replacement/rehabilitation based on level-of-service deficiency approach.
California	Priority ranking is mostly based on engineering judgement. 1) The Bridge Maintenance Engineer determines the priority need of work to be done by state maintenance force. 2) The Bridge Maintenance Engineer determines the fiscal year and urgency factor for contract work (including major rehabilitation and replacement). These are fed to a formula to determine the technical ranking.
Kansas	The current KDOT system selects the scope of work and makes a priority ranking for each bridge.
Texas	The Federal Sufficiency Rating is used for priority ranking on the federally aided bridge rehabilitation/replacement program.
New York	Priority ranking is based on a condition rating (7 to 1) scale.
New Mexico	A computer program analyzes SI&A data and picks out all the bridges which do not meet the equivalent load criteria.
Wisconsin	A computer model has been developed to determine a least cost mix of bridge repair and replacement work for up to 25,000 bridges. The results are used to formulate a six-year highway investment program and its biennial budget proposal for bridge repair and replacement.
Maryland	Priority ranking for replacement/rehabilitation projects is based on the Federal Sufficiency Rating and the Deck Sufficiency Rating.
Minnesota	Priority ranking for replacement/rehabilitation is based on the Federal Sufficiency Rating (FSR) and its own Replacement Priority Calculation (RPC). RPC is a modification of the FSR formula.

Table 4. Questions states want a BMS to answer.

CALIFORNIA

While still relying in large part on professional expertise and judgement, a BMS could remove some of the subjectivity from the Repair/Replace/Rehabilitation decisions.

NEW YORK

1) State of the bridge system at any time, current or future projection.
2) Evaluate program effects on bridge system.
3) Evaluate needs.
4) Cost-effectiveness of maintenance, rehabilitation, and replacement activities.
5) Identification of individual bridges for work.

NORTH CAROLINA

1) All of the following items:
   Life-cycle cost prediction
   Maintenance/rehabilitation effects on condition/performance
   Paint life
   Chloride concentration/penetration (FHWA Bridge evaluation procedures)
   Overall condition predictions
   Failure prediction
   Prediction of environmental effects
   Prediction of loading effects
   Level of Service System - Prioritization
2) Optimization of the use of bridge maintenance funds
3) Effects of less than optimal use of funds for maintenance, rehabilitation, and replacement.

TEXAS

1) Bridge Division's response:
   (a) What are the current overall field and obsolescent conditions of the bridges on the State Highway System?
   (b) What, where and how many bridges currently require routine and/or major maintenance/repair, and how much is this going to cost?
   (c) Priority listing for those structures in (b) above?
   (d) What, where and how many bridges should be posted for load limit?
   (e) Which of those structures in (d) above could be left unposted and instead frequently inspected?
   (f) What, where and how many bridges require rehabilitation or replacement and how much is this going to cost?
   (g) Priority listing for those structures in (f) above?
   (h) What and where are the bridges that should not carry any special permit loads?
2) Maintenance Division's response:
   (a) Which bridges are eligible for replacement?
   (b) When bridges are eligible for rehabilitation?
   (c) Which steel bridges are not weathering steel?
   (d) Which bridges contain fracture critical members?
   (e) Which bridges need underwater inspection?
   (f) Which bridges have serious problems?
   (g) Which bridges need emergency work?
   (h) Can a given overweight vehicle cross a given bridge?

management systems (MMS). Limitations of MMS programs identified relative to bridges include:

- An insufficient number of codes for bridge activities.
- Cost breakdowns are generally not available.
- Data are lumped and cannot be reported for individual bridges.
- Performance standards (how to do the work, required manpower, equipment, and material) and unit cost data for various bridge maintenance activities are generally not available.

Lack of Cost-Effectiveness Data and Life-Cycle Cost Analyses

In existing bridge practice, there is a lack of data on the effectiveness of maintenance treatments or replacement/rehabilitation alternatives and associated costs. There is almost no current use made of life-cycle cost models; thus, no information is available on cost effectiveness. Cost and effectiveness data for maintenance, rehabilitation, replacement, and construction activities are essential for the comprehensive deterioration models and life-cycle cost analyses of bridge strategies in a BMS.

Lack of Prioritization Methods

The literature review in this project revealed that there is poor or no established rationale for estimating the extent and priority ranking of overall bridge maintenance needs. In addition, there is inadequate knowledge of trade-offs and network priorities. Most states only have the standard Sufficiency Index for setting priorities. Most states would like to have the flexibility to develop alternative and more sensitive indices.

Unanswered Network Level Policy Questions

Bridge engineers have difficulty in assessing network level alternatives and policy questions, such as: What should the split be between maintenance and capital improvement budgets? What are the impacts of selecting different MR&R policies or procedures? What are the overall needs for bridge MR&R actions today and what will they be as a result of different funding levels?

REPORT ORGANIZATION

The findings and a proposed implementation plan are presented in five chapters. Background information is provided in four appendixes. Chapter One introduces the bridge management problem and outlines the report. Chapter Two defines model bridge management system components or modules and the different levels of analyses that can occur in the system. Chapter Three describes the details of each module of the model BMS and could be the basis for a useful operational BMS computer program. Chapter Four presents a development and implementation plan for establishing a working BMS. Chapter Five concludes the main text of the report with a summary of the findings of this research project and presents recommendations for the future. Appendix A describes the variables that may be considered for use in the model BMS. Appendix B provides graphical representation of the idealized bridge management system. Appendix C describes a prototype demonstrator BMS software package, which illustrates BMS activities. Appendix D presents a state-of-the-art review of BMS activities in several state DOT's. The final appendix (E) includes other useful publications that were not cited in the text of this report.

CHAPTER TWO

OVERVIEW OF THE MODEL BMS

This chapter presents a brief description of each module contained in the model BMS. More specific details of operation are provided in Chapter Three.

ESSENTIAL BMS MODULES

The BMS process can be divided into many types of modules and subsystems. Each person involved in the development of a BMS, however, seems to have a different viewpoint on the need for the specific modules and functions. Significant effort was spent in reviewing the proper division and selection of modules that must be included in a BMS. This effort consisted of state site visits, conferences, advisory committee and panel meetings, and numerous phone calls and letters. A consensus resulted that six minimum basic modules are essential to a functional BMS. These six modules and associated submodules are:

1. Data base module.
2. Network level MR&R selection module.
   a. Ranking submodule.
   b. Specific MR&R action selection submodule.
   c. Life-cycle costing submodule.
   d. Optimization submodule.
3. Maintenance module.
4. Historical data analysis module.
5. Project level interface module.
6. Reporting module.

The data base is the core module of the system. The other modules and submodules, which operate on the data to perform the functions of bridge management, all utilize the core, as shown in Figure 1.

Data Base Module

Information is essential to management; therefore, an essential module of a bridge management system involves the collection

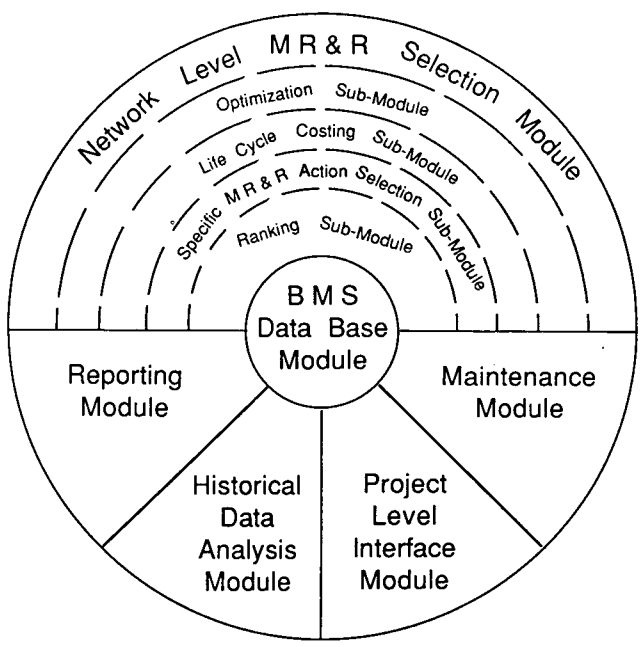


Figure 1. Modules and submodules comprising the model BMS.

and storage of bridge inventory, condition, and MR&R data. These data are the basis for all decisions and actions analyzed by the BMS. The quality of BMS results is directly affected by the quality of the data collected. In this regard, it is imperative to collect only data that contributes to accomplishing the defined objectives of bridge management. Excessive data collection only serves to make the system more cumbersome, inaccurate, and expensive. Appendix A suggests a list of BMS variables which an agency can use as a guideline in BMS data selection. Each data element included in a BMS must be justified by how it will help accomplish a defined BMS objective.

Bridge Inventory Data

Bridge inventory data describe each bridge in terms of location, type, functional classification, and importance within the network. The data also give specific details, such as dimensions.

The model BMS allows each bridge to be divided into "span groups." The span group can be the entire bridge; individual spans; or sets of spans having the same structural type, length, main member type, and deck type. A span group is assigned as best suits each bridge's characteristics and agency objectives. Condition data are collected, stored, and analyzed by span group. Consequently, MR&R actions may be specified differently for different span groups.

The model BMS will be able to locate bridges as they occur on the road. Because bridges usually are associated with more than one road (or other transport thoroughfare) a data structure accommodating and linking principal routes and secondary routes is a necessity in the model BMS. This is also required for meeting federal government reporting demands.

Bridge Condition Data

Bridge condition data include information produced during bridge inspections and appraisals. These data are used for choosing and prioritizing the appropriate bridge MR&R selections.

A significant aspect of the model BMS is the way bridge condition is rated, stored, and handled. Condition ratings available in the National Bridge Inspection Standards (NBIS) exist only in the form of a single severity rating for each of several major components of a bridge. The model BMS should contain bridge condition rating data which are based on the severity and extent of specific distresses. Chapter Three contains an example of a condition form based on this concept. Each of the major components of a bridge (deck, superstructure, substructure, and so on) consists of elements to be rated individually. The rating of each element consists of highly detailed information, rather than merely the severity of some general condition as is the current practice. The actual distresses present for each element and the severity and extent of these distresses are all input into the BMS data base. This allows a clearer understanding of the problems on each bridge and the prediction of specific selections for MR&R strategies.

Bridge MR&R Data

Bridge maintenance, rehabilitation, and replacement (MR&R) data are recorded and entered for all major actions that take place on a bridge. These data include action type, time of occurrence, quantity of work accomplished, work force identification, and expenditures incurred (labor, materials, and equipment). These data account for how and where MR&R funds are actually spent across the network.

A review of these data gives the bridge engineer information on how resources have been distributed throughout the bridge network on an MR&R action basis and a district-by-district basis. The data also show why resources were spent by recording bridge conditions prior to MR&R work and the bridge condition improvements due to the work.

Retaining MR&R data and bridge condition data allows the bridge engineer the capability to quantify the effectiveness of MR&R treatments.

Ascertaining Data Reliability

Data that are entered to the BMS data base must be verified for accuracy and reliability. Data checking procedures must be used to check that each data item meets certain acceptability criteria. A system of random reinspection of a number of bridges can also help determine data reliability. New data may be compared with previous data on the same bridge to identify major discrepancies that cannot be explained. Finally, good training programs for bridge inspectors will help reduce errors and produce high quality data.

Use of Data Base Management Software

The structure of the BMS data base together with BMS reporting objectives indicate that the BMS computer program should be coded in a 3rd and 4th generation computer language, such as dBASE III+. Computer language specifications for the model BMS include hierarchical data structuring; interactive data input, editing, and report generation; and a reporting capability that includes the selection and ordering of data to be reported, as well as a mechanism for producing rudimentary statistics summarizing each selected data subset.

Network MR&R Selection Module

In the model BMS, there are four submodules with which MR&R program selection can be made. These submodules, as shown in Figure 2, are the following:

Level	*Submodule*
1.	Ranking
2.	Specific MR&R action selection
3.	Life cycle costing
4.	Optimization

The model BMS may be implemented at any of these four levels, although use of the ranking submodule alone is not considered to be an effective or true BMS. The submodules are structured so that they build upon each other. Thus, ranking is a necessary step in BMS, but is not sufficient to be termed true management. Implementation of MR&R program selection at a higher level requires incorporation of all the lower level submodules. This staged implementation avoids duplication of ef-

fort while producing MR&R programs based on increasingly better decision criteria. This staged implementation provides flexibility based on needs or financial constraints of the user. A beginning BMS could include only the first two submodules, ranking and specific MR&R selection.

Ranking Submodule

Ranking is a simple prioritization of bridges or bridge projects based on a formula that considers, for example, a bridge condition, function, use, and importance. Using this ranking, a general screening of the network can be accomplished to identify bridges that need a closer examination.

The FHWA sufficiency index (SI) formula satisfies the specifications for a prioritization equation in the ranking submodule. In the model BMS, the concept of sufficiency will be used in the ranking submodule. Furthermore, the derivation of sufficiency will probably be agency-dependent. As documented in Appendix A and illustrated in the BMS demonstrator (Appendix C), the model BMS will accommodate user assignment of variables and their significance in the formulation of an agency-specific sufficiency index. In addition, the model BMS will also have the ability to calculate the FHWA standard SI. This dual sufficiency concept is recommended because it satisfies specific agency needs while providing the agency-to-agency standard for comparison that is needed and already used for distribution of federally allocated funds.

Specific MR&R Action Selection Submodule

In this submodule, the BMS assigns a user-specified and currently needed MR&R action to a bridge based on predefined criteria. These criteria consider bridge condition, function, use, and importance. Prioritization of these MR&R assignments for selection in the MR&R program is done using the ranking submodule. Once actual MR&R actions have been selected, the prioritization formula in the ranking submodule can be expanded to include chosen MR&R cost and effectiveness (benefit) estimates.

Implementation of the specific MR&R action selection submodule results in better MR&R program cost estimates and allows prioritization of MR&R selections on a cost/benefit basis.

In the model BMS, a decision tree approach will be used to create MR&R decision levels for which the user inputs costs and specific MR&R actions. Decision tree parameters can be input and modified by the user. These parameters include the decision variable, the number of levels of service, and their corresponding thresholds. In addition to the decision tree, the prioritization formula used by this submodule will be input through the ranking submodule and, as such, be user-specific.

Because specific MR&R selections are made in this submodule, effectiveness can now be defined. Effectiveness can constitute one part of the prioritization formula. The default effectiveness formula applied in the model BMS is based on the extended life concept.

Chapter Three describes the user-specified decision tree input methodology and shows the default decision tree and default effectiveness formula which can be used in the model BMS. The default prioritization equation is also given in Chapter Three.

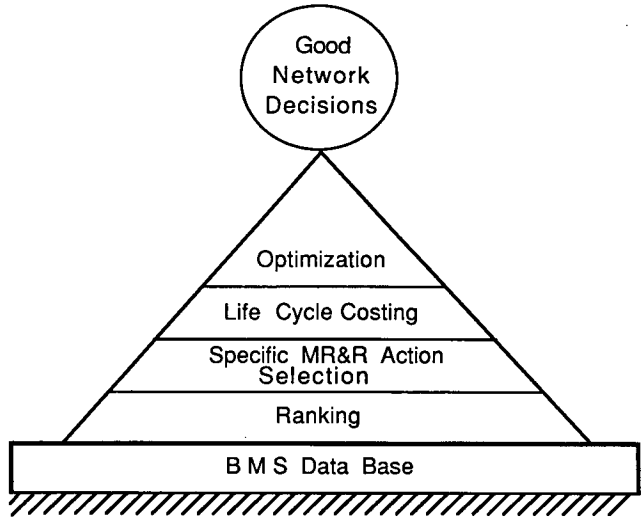


Figure 2. Illustration of the network MR&R selection submodules building to make good network MR&R decisions.

Life-Cycle Costing Submodule

The life-cycle costing submodule expands the MR&R action selection from one action based on current need to a set of MR&R actions to be taken on a bridge across a period of time. Cost and effectiveness (benefit) calculations can now be based on a cycle of future MR&R activities and their subsequent consequences on bridge condition and serviceability.

Implementation of this submodule improves the cost and effectiveness criteria used in MR&R program selection, because these parameters are based on expected resource allotment and consequences over the near future rather than just the next needed MR&R action.

To implement the life-cycle costing submodule; costing and effectiveness algorithms need to be defined that reduce the costs and effects of the entire set of life-cycle activities into one cost value and one effectiveness value. The model BMS will use the uniform annual cost method to produce the cost value. This method produces an annuity applicable for all life-cycle activities that occur during the analysis period. The advantage of this method is that these annuities are comparable even when analysis periods vary across different life-cycle activity profiles (LCAP). LCAP's are merely that set of MR&R actions and their associated timing which together form one alternative strategy of action for the bridge.

With respect to effectiveness, the model BMS employs the average sufficiency value over the analysis period as its default effectiveness measure. Chapter Three describes both the uniform annual costing method and the average sufficiency calculation used in this submodule.

Optimization Submodule

Optimization expands MR&R selection on each bridge from one choice to several alternative choices. Optimization tech-

niques are then incorporated into the BMS to decide the "best" set of MR&R actions to be selected across the entire bridge network. The determination of "best" is subject to budget constraints and other considerations. In this submodule, the optimization technique, the "best" criteria, and the constraints must be user-defined in order to produce an MR&R program.

The advantage of optimization is that the user need not try to determine the "best" MR&R choice on a case-by-case basis. Instead, several candidate MR&R actions and decision rules for MR&R selection are used to produce an MR&R program upon applying the optimization algorithm.

In this submodule, the model BMS will use a derivative of the Incremental Cost Benefit Analysis Method described in an FHWA publication (*10*). This method selects the optimum alternative under consideration using an incremental cost-benefit ratio. Availability of funds is a constraint on the optimization. For a severely restrained budget, this method chooses those MR&R actions that have the highest incremental benefit-to-cost ratio. As the budget gets larger, those MR&R actions that provide more net benefit, but at a smaller benefit-to-cost ratio, are selected.

In the model BMS, this methodology is used with the following modifications:

- Effectiveness is used in place of benefit (as expressed in dollars). Based on this methodology change, a minimally acceptable cost-effective threshold is a necessary user input.
- The budget constraint is expanded from one budget amount to several. In a system that employs life-cycle activities, there are many future budgets and thus the need for several budget constraints.

Maintenance Module

Bridges that are not selected for some type of major MR&R action during the period between inspections may be assigned to minor maintenance programs. The maintenance module assigns appropriate maintenance activities to each bridge based on user-observed estimates of required maintenance. Needs can also be estimated based on an analysis of historical actions and their frequencies. The maintenance activities are prioritized using a form of sufficiency index (SI).

The output of this module is a prioritized list of all bridges needing maintenance with the recommended maintenance activity. Budget levels are used to decide how many of the bridges will actually receive the assigned maintenance treatments. The maintenance module also schedules and prioritizes maintenance activities.

Historical Data Analysis Module

To get accurate estimates of effectiveness, either (1) extended life due to an MR&R action or (2) the average sufficiency over a life-cycle activity profile, bridge condition and MR&R action data should be collected, archived, and analyzed on a historical basis.

The model BMS will retain bridge MR&R action, cost, and condition data on a historical basis. It will have the ability to transfer appropriate subsets of this information in a format compatible with available statistical packages. From this information, condition improvement and subsequent condition deterioration rates, after various MR&R actions have been applied, can be estimated.

In addition, average MR&R cost estimates, region-to-region expenditure variations, and contractor-to-contractor expenditure comparisons can be calculated. Finally, typical life-cycle activity profiles (LCAP's) can be deduced from such historical data.

Project Level Interface Module

The model BMS data base contains information that is valuable to project level analysis packages. Conversely, there are project level results that can be used at the network level either strictly as inventory items or as components in costing and/or prioritization algorithms.

Because of this, the model BMS will have an interface module capable of transferring data between the BMS data base and project level applications. In addition, the model BMS will have the ability to synthesize information from the project level for use at the network level.

Structural analysis models for project level bridge evaluation should later be interfaced to the model BMS. BARS (Ref *6*) and BRASS (Ref *7*) are examples of such systems. It must be realized that these are detailed structural analysis programs and interfacing may require an extensive effort. Other project level applications can be considered on an agency-by-agency basis as implementation within that agency proceeds.

Reporting Module

The reporting module provides the communication link with the user by hardcopy output or computer screens. The model BMS will produce these general types of reports: data lists, summary reports, graphs and charts, and maps.

For each of the different reporting types, the following functions can be performed by the BMS or the user interactively: sorting of data, bridge subset selection, categorization of data, and format specification.

In the model BMS, format specifications will be fixed for most of the reports. Data sorting, subset selection and categorization will be user-defined, either as the report is produced or on a one-time basis.

Although the number and content of reports in the model BMS are not fixed, a list of some suggested reports and their brief description follows. Examples of most of these reports are shown in Chapter Three.

- Data lists.
- Summary table of network-wide MR&R actions taken over time showing the number of bridges and the associated cost for each type of MR&R alternative by bridge type.
- Bridge distribution reports and plots showing the number of bridges or percent of bridges in certain categories for any of a number of variables. This will include distributions and plots by age, condition, sufficiency index, rehabilitation type, type of bridge, maintenance dollars spent, and so forth.
- Listing of the number of bridges for each distress extent and severity combination. This allows the user to see which are the most prevalent distresses occurring on the bridge network

and to establish minor and major maintenance action plans.

- Print overall statistics summarizing current condition data, historical data, planned MR&R action, costs, and the like.
- Traffic report including current and forecasted volume and vehicle classification on bridges.
- Funding and budgeting reports including revenue forecasts, funding eligibility, and distribution of funds to districts.
- Administrative policy option reports showing current funding strategies, budget splits, "political projects," etc.
- Maintenance schedule showing all bridges which will receive only routine maintenance until the next rating period. This will include a description of the type of maintenance and timing.
- Bridge inspection schedule and inspectors routing report.
- Bridge posting and overweight permit routing reports.
- Bridge painting plan.

MODEL BMS OPERATIONAL FLOW

The modules constituting the model BMS are described above. These modules operate as a system to perform the functions of bridge management. Each module has several components that are used at various stages within the system. A description of the BMS operational flow serves to demonstrate when and how the components of each module are used to provide the complete system capabilities. Within this framework, the purpose of each function and the resulting benefits to the user are emphasized. The details of how the system performs its functions are presented in Chapter Three.

An operational flowchart of the system is shown in Figure 3 and is the basis for the following discussion. Each flowchart box represents a function that is accomplished relative to the BMS. The circles indicate activities performed outside the BMS. The flow begins with data collection and entry to the BMS data base. Analysis of the data produces measures of condition for each bridge in the network. Network overview reports are then generated for administrators and planners to analyze the general situation of their bridges and make administrative decisions. The BMS then chooses MR&R strategies for the highest priority bridges in the network. Bridges that are not selected for significant work are assigned some level of general maintenance. The BMS then predicts the impact of selected MR&R actions and available budget on the future condition of the network considering current and past condition, current backlog of bridge needs, and the most advanced bridge deterioration models available. All MR&R actions that take place on the bridge network are tracked by the BMS and the costs and resulting improvements of the actions are entered back into the system (feedback data) to be kept along with other information on a historical basis. After some time, the accurate bridge histories that are being accumulated are analyzed to produce better deterioration models and more accurate bridge life-cycle activity profiles, including the costs and effects of various MR&R strategies.

Update Data Base

At selected time intervals, new condition and inventory data are collected on the bridge network. The inventory data may be updated or errors in previous inventory information may be corrected. A new set of condition data, which reflects the current condition of the bridges, is collected. New bridges may have been added to the system because of new construction or changing jurisdictions. A complete set of inventory and condition data is required for these new bridges. A lot of new data may therefore be collected on a large network which must be entered into the BMS to begin a new analysis cycle.

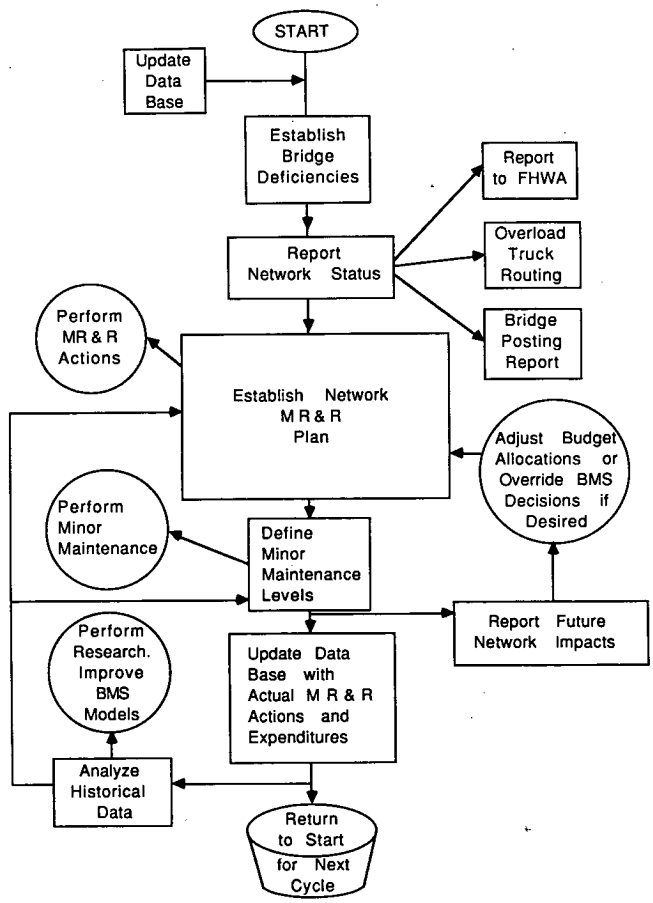


Figure 3. Illustration of model BMS operational flow.

Interactive data entry screens allow easy access to the data base to input the data with a minimum of errors. The data entry features of the BMS allow full screen review and editing of all data. An example of such a user friendly, interactive input screen is shown in Figure 4. This example illustrates major inventory items and a summary of major component condition. The condition ratings cannot be input or changed on this screen. Detailed condition data are input on separate screens and these summaries are made available for review only on this inventory data screen. The same screens are used to enter new data, to update the data base with new inspection information, and to modify existing data because of errors or changed circumstances. The data entered or modified on the screens are stored in the data base for use in the functions of BMS. The first function is to establish the overall deficiencies of bridges on the network.

Establish Bridge Deficiencies

Once the data required for the system are entered and stored

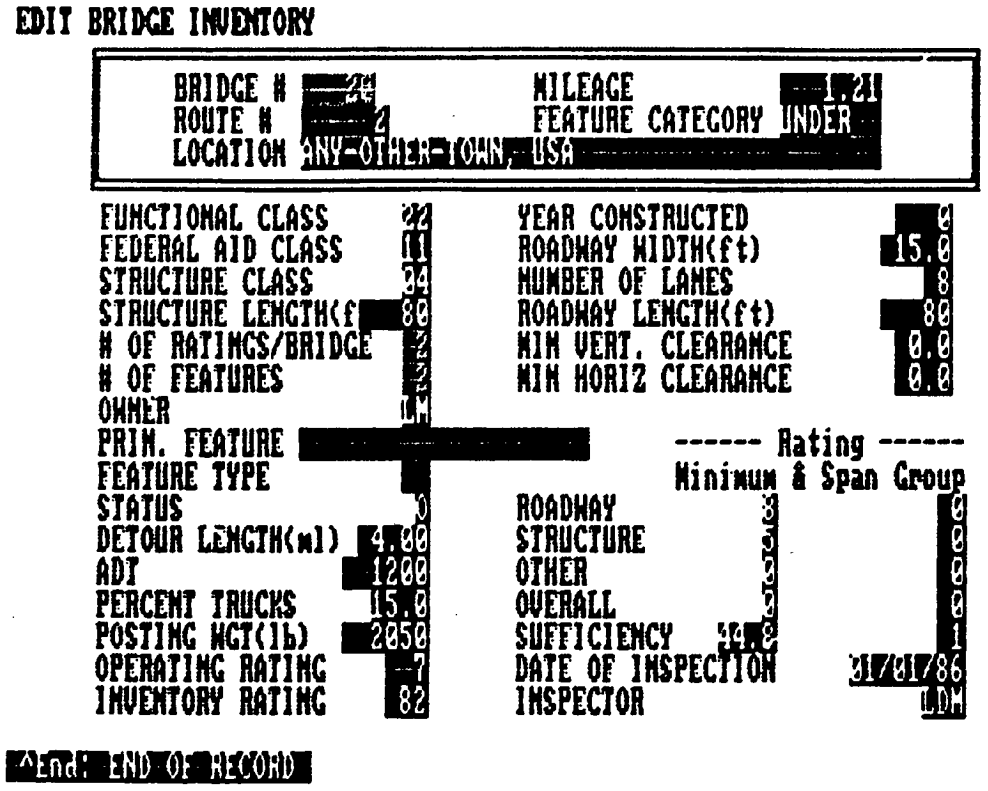


Figure 4. Example of interactive data input/edit screen.

in the data base, information useful for bridge engineers and managers can be obtained from the BMS. The data are first used to establish the deficiencies present (conditions) of each individual bridge. Condition and functional data on each bridge are manipulated to produce quantitative values representing how well the bridge performs its function and its current structural and physical condition.

Values such as the Federal Sufficiency Rating (FSR) (*3*) or a Sufficiency Index defined by the user agency for their particular conditions provide measures of overall bridge deficiency. Load capacity in terms of inventory rating (IR), operating rating (OR), or gross vehicle weight limit can be calculated and used as a measure of how well a bridge performs structurally. With a considerable effort, the BMS can be interfaced with the BARS or BRASS programs to perform the bridge rating and structural capacity calculations that some agencies currently use. Bridge deficiencies can also be defined in terms of how well a bridge performs its intended function. Bridge functional adequacy can be determined by individual measures or combinations of clear deck width, minimum vertical clearance approach width, lane widths, or volume-to-capacity ratios.

Bridge deficiency values are either input by the user or calculated by the BMS (or an interfaced project level subprogram) based on user input data. These values are then stored to the data base for later use in choosing MR&R alternatives for the bridges and reporting to the user. They can be used immediately by the BMS to produce results that will save the bridge agency time and money.

Report Network Status

A bridge network status overview is useful for administrative decisions regarding budget allocations and the division of available funds between maintenance, rehabilitation, and replacement activities. The overview consists of summary reports that indicate, for example, total number of bridges at various condition levels; distribution of bridges in the network by age and bridge type; summary of maintenance funds spent in the last several years divided by bridge type, age, and condition levels; total number of bridges that are deficient in width, vertical clearance, or load capacity; as well as other reports useful from an administrative planning standpoint. Bridge agencies may have several levels of organization, each of which controls a set of bridges. Each of these levels may be allocated a budget. The network status reports allow for educated administrative decisions regarding these budget allocations and the constraints to be placed at various levels.

One useful set of outputs of the BMS involves the federal reporting requirements. The task of reducing and summarizing the data required by the Federal Highway Administration for their budget allocation purposes and National Bridge Inspection Standards (NBIS) data base will automatically be produced by the BMS. This saves time and money for the user agency in meeting the federal requirements.

A routing report for overloaded permit vehicles can also be produced. The laborious task of locating a suitable route for trucks that have been granted overload permits is automatically

accomplished. The structural capacity of each bridge is calculated and combined with stored highway network location information to produce the reports. This saves a considerable amount of time currently required to perform the routings.

A bridge posting report can identify all posted bridges and bridges that urgently need attention because of an inadequate structural capacity. The urgent bridges are identified and an interim recommendation for posting is made until each bridge can receive the required MR&R action.

Another type of overview output which provides information to planners is a summary of the current backlog of rehabilitation or replacement projects. These are projects that have previously been chosen for major work that has not been accomplished. This type of report gives an immediate indication of known high priority projects with preliminary budget estimates.

Network overviews provide a basis to make important decisions regarding the bridge network. Policy goals which influence the BMS in terms of rehabilitation or replacement selections and routine maintenance levels are set using the network status reports. Decisions regarding the desired levels of service for different bridge classes can be made using traffic and bridge importance reports. These level-of-service goals are normally in terms of desired structural capacity, lane widths, and vertical clearances for the different bridge classes. Once the desired levels of service are defined they are entered into the BMS for use in the MR&R selection processes.

Establish the Network MR&R Plan

One of the primary functions of the BMS is selecting MR&R projects for the bridge network using the data base information with budget and political constraints input by the user. The network MR&R plan can be developed at any of the four selection levels described previously. Each successive level gives the user more resources to estimate MR&R needs. The model BMS, however, would use the highest level which includes selecting life-cycle activity profiles (LCAP's) for the MR&R strategy and optimizing the selections over the network to obtain the maximum effectiveness within the available budget. These concepts are discussed in more detail in Chapter Three.

The model BMS is flexible in that it gives the user the final word in all decisions. It is important for bridge engineers and managers to have full control over the final decisions regarding the bridge network for which they are responsible. Selecting MR&R projects can be accomplished automatically by the BMS. However, the user can override the system if desired. The override mechanism allows the user to disagree with the BMS selections in favor of his own or to choose special projects that the BMS is not programmed to consider. This is important because outside factors may affect priorities. This feature gives the user final control over decisions and recommendations. Therefore, the BMS is flexible and does not produce unrealistic decisions that cannot be changed.

Because it is useful to examine the effects of administrative decisions regarding budget allocations between maintenance, rehabilitation, and replacement, the model BMS has a mechanism for experimenting with various combinations to see how the resulting MR&R project selections and subsequently the entire network service levels will be affected. This capability gives administrators a powerful tool for making better decisions on funds allocation. Such decisions may involve, for example, how much money should go towards maintenance rather than rehabilitation, or whether rehabilitation or replacement is more effective in a given situation. Once the most effective budget split is determined, the BMS uses the information to make final MR&R selections for the network. This information is output to the user who coordinates the MR&R actions on the network.

The network MR&R plan developed by the BMS usually concerns major maintenance, rehabilitation, and replacement projects. A portion of the bridges will not be selected for any major MR&R actions. These bridges may, however, still receive maintenance attention depending on the policy goals of the agency. Therefore, a minor maintenance plan follows.

Define Preventive Maintenance Levels

It is generally believed that preventive maintenance slows or arrests deterioration, improves bridge condition, and generally prolongs bridge life. The model BMS will estimate a preventive maintenance level for each of the bridges not chosen for more substantial activity in the MR&R selection process. Bridges chosen for other MR&R work are also identified for preventive maintenance if conditions warrant. The BMS then schedules the work after considering the constraints of an agency's maintenance crews, equipment capabilities, and allocated maintenance budget. Condition level, bridge age, and needed maintenance actions input by the user are used to choose general maintenance plans. Administrative input for this function consists of budget levels, desired maintenance levels of service for the network, and maintenance crew production rates. The maintenance plans are output to the user who coordinates the maintenance activities.

Maintenance levels of service are administrative decisions regarding the level of deterioration that a bridge sustains before it triggers a reactive maintenance activity. Such levels of service are desirable constraints that the BMS is programmed to impose. However, there will normally be other overriding constraints, such as available maintenance budget, which will not allow the desired maintenance levels of service to be invoked. The decision made by the user regarding budget splits between maintenance, rehabilitation, and replacement will usually control the level of preventive and reactive maintenance provided.

Report Future Network Impacts

To show the impact of the MR&R assignments, the BMS predicts the future condition of the bridge network. This is accomplished in the life-cycle costing submodule. The current backlog of work, the scheduled MR&R work for the current year, and bridge deterioration rates are used to forecast conditions. Assumptions are made with respect to future activities to determine if, on the whole, the network will get better or worse with time. Such predictions can help to justify higher funding levels for the bridge program, if needed.

The network impact reports are used in the BMS process to adjust budget allocation percentages or to override the automated selections in some cases. Several alternative possibilities can be examined to see which one gives the best overall network condition. The MR&R plan finally selected is used to guide the actions on the bridge network.

The sensitivity of the BMS selections to various input assumptions is analyzed by examining these reports. The effects of variations in interest rates and estimated MR&R costs, effectiveness, and deterioration rates can be determined.

Update Data Base With Actual MR&R Actions and Expenditures

As scheduled MR&R work is performed on chosen bridges, the BMS tracks agency progress in terms of what is actually accomplished. The remedial actions performed, the costs, and the resulting improvements are recorded and entered to the BMS. This information is historically maintained for all bridges in the network. Other bridge data, such as individual component condition, sufficiency indexes, load ratings, and traffic levels, are also retained on a historical basis. Over time, an accurate life history will be available for each bridge. This allows more accurate deterioration models to be developed and provides information about the effectiveness of various MR&R strategies.

Analyze Historical Data

To obtain improved models, the historical information is analyzed by the BMS. The conditions (structural and functional) of the bridge before any action occurs are used as the starting point. The type of MR&R action and its cost are used as a basis for comparison with other types of actions on similar bridges. The amount of initial improvement that results is used as a measure of effectiveness of the action. Also, the resulting change in the deterioration rate of a bridge is analyzed after future inspections. These analyses produce more accurate bridge deterioration equations and effectiveness measures for the different MR&R actions. These improved models are then programmed back to the BMS for use in future predictions and analyses. This cyclic function of the BMS allows the system to be constantly improved. The entire BMS process can, in fact, be considered cyclic because new data are periodically gathered, entered into the system, analyzed, and used to predict network wide bridge needs. The system is thus able to analyze what actually occurs and adjust its models and predictive capabilities to make more cost effective MR&R choices.

CHAPTER THREE

DETAILS OF THE MODEL BMS

This chapter presents a detailed description of the BMS modules and submodules. Recommendations for specific models and equations to be used are also included as example problems for clarity.

Before proceeding with the discussion, it is worth reviewing the specific functions of each of these modules: (1) The data base module accepts and stores the data for use in a BMS. A large number of data items are presented with priorities assigned as to their necessity in bridge management. (2) The network MR&R selection module provides the data necessary for making more effective planning and budgeting decisions. This module is described in terms of the four levels available for making MR&R program selections for the network. (3) The maintenance module handles bridges selected for a preventive maintenance program. (4) The historical data analysis module analyzes bridge data to improve prediction models and upgrade the BMS. (5) The project level interface module provides a link to detailed analyses of individual bridges. (6) The reporting module provides the communication link to the user agency, including administrators, decision-makers, and engineers.

DATA BASE MODULE

The data base contains information relative to every bridge in the network. All functions and decisions of the BMS originate from the data base. The system output is only as good as the available data; high quality, detailed data yield the maximum effectiveness from the system. This does not mean the more data, the better. On the contrary, a limited number of significant data items is preferable to a large number of weak data items, some of which may never be used. Exact BMS variables depend on the needs and policy goals of the user agency. Some variables are required by all agencies. Others may be included by one agency and omitted by another.

This section describes the general categories of variables and lists the specific variables considered for the model bridge management system. These variables include inventory variables, condition and appraisal variables, and MR&R historical variables. A large number of variables are considered, prioritized in importance, and described in complete detail in Appendix A.

The variables list was assembled from several sources including the State of Texas BRINSAP data (Ref. *11*), the Pennsylvania Bridge Management System data (Ref. *12*), the Federal SI&A data (Ref. *3*), North Carolina's Bridge Management System data (Ref. *13*), numerous interviews with bridge and maintenance engineers, and an extensive documents search.

The success of a management system lies in its ability to generate improved performance and behavioral models based on historical data. Many states have the beginning of a historical data base in required federal inspection information. However, many of these data elements are subjective and therefore are

not suitable for model-building purposes. Historical data availability is an important factor and does deserve consideration in an initial BMS data base.

Table 5 presents the variables considered for inclusion in the model bridge management system. The table includes codes for the source of the variable, the priority of the variable, and the rationale for its use. The codes are defined in Table 6. Table 7 presents a summary of the number of variables at each of the five priority levels. Table 5 is divided into four categories: (1) inventory variables, (2) bridge condition variables, (3) bridge appraisal and proposed improvement ratings, and (4) MR&R historical variables. The four categories are subdivided into "records." Each record is a set of variables pertaining to a similar aspect of the bridge.

The variables included were common to most states and generally considered important. Omissions of important variables in current state BMS's were also identified and included. Each variable was assigned a priority ranking on a 1 to 5 scale. A useful BMS should include most of the priority 1, 2, and 3 variables. Priority 4 and 5 variables are optional or extraneous.

Each major record is identified by a letter. Each variable within a record is identified by a number. Therefore, each variable is uniquely described by a letter-and-number combination. For example, variable A2 names the county where the bridge is located. The numbers in parentheses correspond to numbered variables that are included in the current Federal SI&A rating form.

Inventory Variables

Inventory variables describe the bridge in terms of location, type, functional classification, etc. Once they are entered for a particular bridge, they are rarely changed. These variables provide information for locating the bridge and determining its relative importance within the network. In terms of the importance of the bridge, several inventory variables may be used in the prioritization and optimization techniques.

Bridge Condition Variables

The second type of variables includes condition, rating, or appraisal variables. The condition variables are obtained from field inspection of the bridge. They are entered into the BMS and are used in calculations. The results of these calculations produce output variables that are the appraisals of the bridge and are described in the next section. These condition and appraisal variables can be used for prioritizing and optimizing bridge rehabilitation and maintenance strategies. They can also be used in the decisions to determine feasible MR&R strategies for each bridge.

The input condition variables are divided into records and variables as with the inventory variables described previously. These major records correspond to a major component of the bridge such as roadway, superstructure, substructure, channel, or approaches. The subvariables correspond to the elements of the major components of the bridge, for example, deck and wearing surface are elements of the roadway; main members and floor system connections are elements of the superstructure.

Table 5. BMS variables.

Inventory Variables

	Source	Priority	Rationale of Use
A. Identification Information			
1. System Code	T	2	A
2. County (3)	F	3	G
3. City / Town code (4)	F	3	G
4. Structure number (8)	F	1	C
5. FIPS code for states and FHWA region (1)	F	5	H
6. Highway district (2)	F	3	B
7. Principal route (5)	F	2	B
8. Location (9)	F	1	C
9. Principal route milepoint (11)	F	1	C
10. Engineering project/drawing number	P	4	C
11. Bridge Name	WV	3	C
12. Principal route posiiton (over or under bridge)	A	2	C
13. Town Name	WV	3	G
B. Environment			
1. Freezing index	P	3	I
2. Saline environment	P	3	I
3. Rainfall	P	3	I
C. Defense Importance Ratings			
1. Defense road section number (12)	F	3	F
2. Defense bridge description (13)	F	4	F
3. Defense milepoint (14)	F	4	F
4. Defense section length (15)	F	4	F
5. Latitude (16)	F	4	F
6. Longitude (17)	F	4	F
7. Physical vulnerability (18)	F	4	F
D. Essentiality / Classification / Jurisdiction			
1. Essentiality to public transport	A	3	D
2. Detour length (19)	F	1	D
3. Toll road (20)	F	3	B
4. Custodian (21)	F	2	C
5. Owner (22)	F	2	C
6. Type of project (23 a)	F	3	H
7. Project Number - e.g. FAP No. (23 b)	F	3	H
8. Federal aid system code (24)	F	3	H
9. Principal Route Administrative jurisdiction (25)	F	4	B
10. Principal Route Functional classification (26)	F	3	A
11. Years of construction and major reconstruction (27)	F	1	B
12. Principal route ADT (29)	F	1	D
13. Year of traffic count (30)	F	2	B
14. Truck factor (% trucks with more than 2 axles)	A	1	E
15. Design truck loading (31)	F	1	B
16. Historical significance (37)	F	3	D
17. Political Unit number 1	A	3	A
18. Political Unit number 2	A	4	A
19. Walkway	WV	3	J
20. Speed limit		3	J
E. Navigation and Waterway			
1. Existence of navigation control (38)	F	4	A
2. Navigation vertical clearance (39)	F	4	E
3. Navigation horizontal clearance (40)	F	4	E
F. Posting Information			
1. Operational status (41) - (open or closed)	F	2	D
2. Operating rating (64) absolute maximum permissible	F	1	D
3. Inventory rating (66) highest load for long term use	F	1	D
4. Weight Limit			
4.1.Axle	A	3	D
4.2.Combination	A	3	D
G. Safety Inventory			
1. Approach roadway width in feet (32)	F	3	E
2. Bridge median code (33)	F	3	B
3. Skew (34)	F	3	E
4. Structure flared? (35)	F	3	B
5. Traffic safety features (36)			
5.1. type of bridge railing	T	3	B
5.2. type of approach guardrail transitions	T	3	B
5.3. type of approach guardrails	T	3	B
5.4. type ofapproach guardrail ends	T	3	B
6. Sight distance	T	3	B
7. Illumination	T	3	B
8. No. of accidents per 100,000 vehicles	A	3	
H. Secondary Features			
1. Name of secondary features	A	2	C
2. Type of feature (road, railroad, water)	A	2	C
3. Route (5)			
3.1.system classification	F	2	C
3.2.number	F	2	C
3.3.direction suffix	F	2	C
4. Route milepoint (11)	F	2	C

Table 5. Continued

	Source	Priority	Rationale of Use
5. Essentiality to public transport - School Bus, route, snowplow firelane, public transit route	A	3	B
6. Detour length (19)	F	2	D
7. Toll road (20)	F	4	B
8. Federal aid system code (24)	F	3	H
9. Route administrative jurisdiction (25)	F	4	G
10. Route Functional classification (26)	F	3	A
11. Route ADT (29)	F	2	D
12. Year of traffic count (30)	F	3	B
13. Truck factor (% trucks with more than 2 axle)	A	2	D
14. Design truck loading (31)	F	3	I
15. Route horizontal clearance (47)	F	3	J
15.1. right (55)	F	3	J
15.2. left (56)	F	3	J
16. Route minimum vertical clearance (10)	F	3	J
17. Number of lanes on the 'secondary' route (28)	F	3	J
18. Roadway width (51)	F	3	J
19. Existence of navigation control	A	3	B
20. Position (over or under the bridge)			
I. Structural Inventory			
1. Structure type	T	4	B
2. Principal route horizontal clearance (47)	F	1	J
3. Principal route minimum vertical clearance (10)	F	1	J
4. Widening code	T	3	E
5. Roadway width (51)	F	2	E
6. Length of structure (49)	F	1	E
7. Sidewalk width (50)	F	3	B
8. Number of lanes on the principal route (28)	F	2	J
9. Superstructure type (43)	F	1	E
9.1 number of span groups	A		
9.1.1. span type in group	T	1	E
9.1.2. main member type in group	T	1	E
9.1.3. number of spans in group	T	1	E
9.1.4. span length in group (48)	F	1	E
9.2 type of paint system	WV	2	E
9.3 date existing paint system placed	WV	2	E
10. Substructure type (44)	F	1	E
10.1. Cap Type	T	1	E
10.2. Pier Type	T	1	E
11. Deck type (57)	F	1	E
11.1. material type	T	1	E
11.2. design type	T	3	E
11.3. wearing surface	T	1	E
11.4. deck concrete air entrained	WV	2	E
11.5. membrane type	WV	2	E
11.6. stay-in-place forms used	WV	3	E
11.7. type of cathodic protection	WV	1	E
11.8. date wearing surface placed	WV	2	E
11.9 type of steel protection		3	E
12. Deck width (52)	F	2	E
13. Deck joint types	A	2	E
14. Fracture critical members	JA	2	E
(Bridge Condition Variables (Severity Rating=R, Extent=E, Distress=D)			
J. Roadway Condition Rating (58)	F	1	D&E
1. Deck R/E/D	T	1	D&E
2. Wearing surface R/E/D	T	1	D&E
3. Joints R/E	T	1	D&E
4. Drainage system R	T	2	D&E
5. Curbs, sidewalks, and parapets R/E	T	3	D&E
6. Median barrier R/E	T	3	D&E
7. Railings R/E	T	3	D&E
8. Delineation (striping and curve markers (R)	T	3	D&E
K. Superstructure Condition Rating (59)	F	1	D&E
1. Main members R/E/D	T	1	D&E
2. Main member connections R/E/D	T	1	D&E
3. Floor system members R/E/D	T	1	D&E
4. Floor system connections R/E/D	T	1	D&E
5. Secondary members R/E	T	1	D&E
6. Secondary member connections R/E	T	1	D&E
7. Expansion bearings R/E	T	2	D&E
8. Fixed bearings R/E	T	2	D&E
9. Steel protective coating R/E	T	1	D&E
L. Substructure Rating (60)	F	1	D&E
1. Abutments R/E/D	T	1	D&E
1.1. Caps	A	2	D&E
1.2. Above ground	A	2	D&E
1.3. Below ground	A	2	D&E
2. Intermediate supports R/E/D	T	1	D&E
2.1. Caps	A	2	D&E
2.2. Above ground	A	2	D&E
2.3. Below ground	A	2	D&E

Table 5. Continued

	Source	Priority	Rationale of Use
3. Collision protection system R	A	3	D&E
4. Steel protective coating R/E		1	D&E
5. Retaining walls (62) R/E/D	F	2	D&E
6. Culverts	T	3	D&E
6.1. Damage to pipe	A	3	D&E
6.2. Debris	A	3	D&E
6.3. Damage to walks	A	3	D&E
7. Concrete protective system R/E/D	WV	2	D&E
M. Channel and Channel Protection Rating (61)	F	3	D&E
1. Banks R	T	3	D&E
2. Bed R	T	3	D&E
3. Rip rap R/E	T	2	D&E
4. Dikes & Jetties R	T	3	D&E
5. Substructure foundation erosion R/E	T	1	D&E
N. Approaches Rating (65)			
1. Embankments R/E	F	3	D&E
2. Pavement R/E/D	T	3	D&E
3. Relief joints R/E	T	3	D&E
4. Drainage R/E	T	3	D&E
5. Guard Fence R/E	T	3	D&E
6. Delineation markers R	T	3	D&E
O. Estimated Remaining Life (63)	F	3	D&E
P. Inspection Information			
1. Date of last inspection (90)	F	2	A
2. Unusual inspection feature	WV	3	A
3. Frequency of unusual inspections	WV	4	A
4. Date of last unusual inspection	WV	4	A
5. Inspector	A	3	B
Bridge Appraisal and Proposed Improvement Ratings			
Q. Appraisal (Calculated values to be output in report)			
1. Traffic safety features (36)	F	3	D&E
2. Structural condition (67)	F	2	D&E
3. Roadway geometry (68)	F	3	D&E
4. Vertical and lateral clearance (69)	F	3	D&E
5. Safe loading capacity (70)	F	2	D&E
6. Waterway capacity (71)	F	3	D&E
7. Approach roadway (72)	F	3	D&E
R. Proposed Improvements			
1. Year needed (73)	F	3	A
2. Type of service (74) (same as 5 or 42)	F	3	A
3. Type of work (75)	F	2	E
4. Length of improvements (76)	F	2	E
5. Proposed design load (77)	F	3	E
6. Proposed roadway width (78)	F	3	E
7. Proposed number of lanes (79)	F	3	E
8. Design ADT (80)	F	3	A
9. Year of Estimated ADT (81)	F	3	A
10. Year of scheduled adjacent roadway improvements (82)	F	3	A
11. Type of adjacent roadway improvements(83)	F	3	A
12. Cost of all improvements (84)	F	2	E
13. Base year of improvement costs	JA	2	E
14. Preliminary engineering costs (85)	F	3	E
15. Demolition costs (86)	F	3	E
16. Substructure costs (87)	F	3	E
17. Superstructure costs (88)	F	3	E
18. Required maintenance activity 1	A	1	E
19. Level of maintenance activity 1	A	1	E
20. Urgency of maintenance activity 1	A	1	E
21. Required maintenance activity 2	A	1	E
22. Level of maintenance activity 2	A	1	E
23. Urgency of maintenance activity 2	A	1	E
24. Required maintenance activity 3	A	1	E
25. Level of maintenance activity 3	A	1	E
26. Urgency of maintenance activity 3	A	1	E
MR&R Historical Variables			
S. MR & R Record			
1. Structure number (8)	F	1	C
2. Year of MR & R Action	N	1	K
3. Type of action			
3.1. Major Category	N	2	K
3.2. Individual Activity	N	1	K
4. Scheduled, Completed, or In Progress	A	3	B
5. Quantity of units in type file	A	1	K
6. Costs			
5.1. Labor	N	2	K
5.2. Equipment	N	2	K
5.3. Materials	N	2	K
5.4. Other	N	2	K
5.5. Total	N	1	K

Table 6. Definitions of codes used in the overall list of Bridge Management System variables.

Source - Where the variable originated.

F - Federal S I & A
T - Texas
P - Pennsylvania
N - North Carolina
A - ARE Inc Project Staff
WV- Panel Member - Walter Verrill (Maine)
JA- Panel Member - John Ahlskog (FHWA)

Priority - Importance of including the variable in the BMS.

1. Highest Priority - Definitely required in BMS model.
2. High Priority - Very useful in BMS model.
3. Medium Priority - Nice to have in BMS for Input and Output or possible use.
4. Low Priority - Probably will not be in BMS.
5. No Priority - Definitely not to be included in any BMS.

Use - Use of the variable in the BMS and the rationale for choosing it.

A - Planning Information
B - Information Only
C - Identification
D - Ranking/Optimization
E - Estimate Corrective Action/Costs
F - Defense Planning - Emergencies
G - Budget Allocations
H - Federal Requirement or Need
I - Information on Possible Causes of Distress
J - Functional Adequacy
K - Predict Maintenance and Rehabilitation Effectiveness and Costs

Each bridge element should be surveyed and rated on one of three levels. The level is indicated next to the variable by various combinations of the letters R, E, and D. R stands for a severity rating of how bad the distress present is, E stands for an extent rating of how much of a particular distress is present, and D stands for a definition of the type of distress present. The lowest level of evaluation is only R, which indicates that the bridge element is merely rated on the standard 0 to 9 scale. The second level, R/E, indicates that the bridge element is rated on the 0 to 9 scale in terms of the severity of the distress that exists, and that the extent of the distress is also estimated in terms of being local or prevalent, the estimated area affected, or some other measure. The highest level of evaluation is indicated by the combination R/E/D. This indicates that the element is rated on the 0 to 9 scale, the extent of the distress is estimated and that the actual type of distress causing the problem is specified. It is not necessary to rate all elements of each bridge component to the same level of detail. For example, the elements Deck (Variable J1) and Railings (Variable J7), both affect the overall component roadway's rating, but information on the type of distress present is more important for the deck.

An example data form of the type needed for rating the condition of the elements is shown in Figure 5. The form allows the distresses to be identified by putting the extent rating next to the actual distress shown on the form. The condition or severity of each distress is also indicated on the form using the 0–9 scale. An example evaluation is shown on the form for all the elements of the superstructure, to illustrate how the system works. In the example, the main members are rated a 7 because they exhibited local cracks and local reinforcement corrosion. The floor system is rated 6 because of prevalent cracks, and the secondary system was rated 8 because of local corrosion. Other elements include expansion bearings rated 7, fixed bearings rated 7, and paint rated 6, but the distressess and extents associated with these ratings are not specified.

Table 7. Summary of variable priority for inclusion in BMS.

Priority Level for Inclusion in BMS	No. of Variables at Priority Level
1(2)	56
2	50
3	90
4	17
5	1
TOTAL	214

1. Highest Priority - Definitely required in BMS model.
2. High Priority - Very useful in BMS model.
3. Medium Priority - Nice to have in BMS for Input and Output or possible use.
4. Low Priority - Probably will not be in BMS.
5. No Priority - Definitely not to be included in any BMS.

Bridge Appraisal and Proposed Improvement Ratings

The appraisals are calculated values based on (1) the condition ratings of the bridge components and their elements as input to the BMS, and (2) inventory items, such as deck width, number of lanes, and vertical clearances. The method used by the BMS to calculate the appraisal ratings is the same method used in the Texas BRINSAP system (*11*).

The proposed improvements correspond to Federal variable numbers 73 through 88. These items, if included in the BMS, will be estimated after analysis of the bridge condition, the MR&R life-cycle activity options chosen by the BMS, and the local and network-wide budget constraints. These variables may be derived by the BMS or input directly by the user. The required maintenance activities are input by the user based on the observations made by the inspector. Estimates made by the BMS will improve with time.

MR&R Historical Variables

The last variables in the Data Base Module are historical records of the maintenance, rehabilitation, and replacement (MR&R) actions accomplished. These variables are input after an MR&R action takes place on a bridge and describe the actions undertaken. The variables are stored on a historical basis to develop a life profile for the bridge, to estimate maintenance and repair costs for bridges in general, to predict deterioration rates and deterioration retardant constants for bridges, and to estimate entire network MR&R budget levels.

These data are used to obtain better estimates of costs and improvements associated with MR&R actions such as shown in the MR&R code list of Table 8. Analysis of the data over time will produce more accurate bridge life-cycle profiles, better deterioration models, and better measures of effectiveness and benefits for various MR&R actions.

The MR&R data for use by the BMS could be incorporated through an agency's existing maintenance management system (MMS). The activities of most existing MMSs would need to be expanded to better define the bridge MR&R actions. Information should be provided on a bridge-by-bridge basis. The

ARE Inc BRIDGE CONDITION SURVEY FORM

9 - New condition
8 - Good condition - no repairs needed
7 - Generally good condition - potential exists for minor maintenance
6 - Fair condition - potential exists for major maintenance
5 - Generally fair condition - potential exists for minor rehabilitation
4 - Marginal condition - potential exists for major rehabilitation
3 - Poor condition - repair or rehabilitation required immediately
2 - Critical condition - bridge should be closed until repairs are complete
1 - Critical condition - bridge closed but repairable
0 - Critical condition - bridge closed and beyond repair
N - Not applicable

	Timber	Concrete	Steel
SUPERSTRUCTURE - PAGE 2 OF 4			
	EXTENT L/P	EXTENT L/P	EXTENT L/P
[7] Main Members	[ ] rotted timber [ ] cracked / broken [ ] connector probs. [ ] other	[L] cracks [L] reinf. corrosion [ ] spalling [ ] crushed [ ] broken / cracked [ ] other	[ ] failed connections [ ] corrosion [ ] buckle & kinks [ ] cracks [ ] other
[6] Floor System	[ ] rotted timber [ ] cracked / broken [ ] infested [ ] connector probs. [ ] other	[P] cracks [ ] reinf. corrosion [ ] scaling / spalling [ ] crushed [ ] broken / cracked [ ] other	[ ] failed connections [ ] corrosion [ ] buckles & kinks [ ] cracks [ ] other
[8] Secondary System			[ ] failed connections [L] corrosion [ ] buckles & kinks [ ] cracks [ ] other

[7] Expansion bearings
[7] Fixed bearings
[6] Painting
[ ] Other

Figure 5. Example bridge condition survey form including distresses.

MMS should summarize bridge actions by the eight major categories identified in Table 8. The MMS should be able to give the BMS the total cost of each activity by bridge for an entire year.

Data Structure Within the BMS

The variables to be included in a BMS are stored in several data files within the BMS data base. The structure of these files in terms of how they are connected and interact together is described in this section.

The following data files are required for the BMS:

- Bridge and principal feature inventory.
- Secondary feature inventory.
- Span group inventory, condition, and appraisal.
- Inventory and condition history.
- MR&R history.

Figure 6 shows how these data files are related. The variable that connects most of the files is a unique bridge number. Variables such as route number and mile point connect the principal feature with the secondary features to exactly locate each bridge. This helps with the "routed" reports that are created in the BMS, and lists bridges in order along the particular route where they exist.

There are several other files that are accessed by the BMS to obtain variables that are used in calculation and decision processes. These variables are primarily decision criteria and user inputs and include weighting values and ranges for variables to be used in the sufficiency calculation, the MR&R actions that

Table 8. MR&R action codes.

1 MINOR MAINTENANCE

01 painting
02 joint cleaning and sealing
03 bearing cleaning and lubrication
04 sealing concrete surfaces
05 drift removal
06 crack sealing
07 bolt tightening or replacement
08 deck washing
09 clean drainage system
10 moveable bridge mechanical or electrical equipment maintenance
11 approach leveling or repair
12 deck patching
13 touch up painting
14 minor repair or cleaning of culverts
15 handrail maintenance or repair
16 expansion joint maintenance
17 fender system maintenance
18 slope or shore protection system maintenance

2 MAJOR MAINTENANCE

01 replace drainage system elements
02 replace collision damaged structural members
03 correct scour condition
04 replace decayed timbers
05 bearing repair
06 deck injection with grout or resin
07 replace expansion devices
08 relevel abutments and piers
09 patch substructure members
10 strengthen of straighten steel members
11 curb repair
12 replace gaurdrails
13 repair fender system
14 sheath pier to add cross-sectional area
15 splice broken reinforcing steel and re-concrete
16 steel plating of timber decks
17 clean box culverts
18 repair steel deck grids
19 replace or upgrade bridge rails

3 REHABILITATE

01 deck replacement
02 increasing structure capacity
03 replace major superstructure main elements
04 replace major substructure main elements
05 deck overlay
06 cathodic protection
07 sheath pier to add cross sectional area
08 substructure strengthening
09 deck rehabilitation
10 bridge raising to gain vertical clearance
11 fatigue prone detail retrofit
12 seismic retrofit
13 replace wearing surface

4 RECONSTRUCT

01 new superstructure using existing substructure
02 bridge widening

5. REPLACE

6. POST

01 structural load capacity
02 speed
03 number of vehicles
04 height of vehicles

7. CLOSE

8. REMOVE

are selected by the decision process, life-cycle activity profiles for bridges, unit costs of MR&R actions, budget levels and allocation percentages, acceptable and desirable level-of-service goals, and maintenance activity codes. The variables needed for each of these functions are described in the section related to the function. Such variables are not individual bridge data per se and, therefore, are not discussed as part of the BMS data base. They are, however, stored in special data files that are accessed by the BMS when needed to perform specific functions. These are all user input variables (with defaults available) to make the BMS as flexible and adaptable as possible.

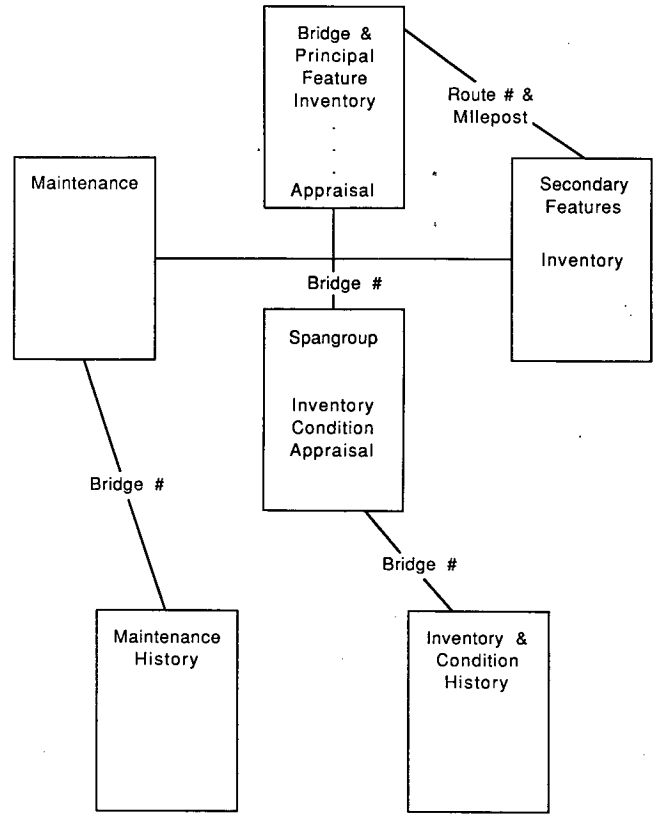


Figure 6. Illustration of data file relationships.

NETWORK MR&R SELECTION MODULE

There are four levels at which MR&R projects can be selected for the network. These four levels are accomplished by the BMS in submodules of the MR&R selection module. The four submodules are:

- Ranking submodule.
- Specific MR&R action selection submodule.
- Life cycle costing submodule.
- Optimization submodule.

Each submodule builds on the previous one, thus adding capability to make better selections. The lowest level can be used independently, but higher levels require the lower ones to support them. Each level is described separately in the following sections. The descriptions are in terms of specific methods to be used in each of the submodules.

The MR&R selections are made automatically by the BMS; however, a capability for the user to override the system is available. The user override allows special projects that may already be programmed or designed to be chosen. Also, the user may disagree with the MR&R strategy made by the BMS, and he may enter his own and rerun the system. The override mechanism operates by allowing the user to enter specific MR&R strategies for certain bridges. He may specify if the strategy is definitely to be selected for funding or whether it is to be compared and chosen in the same process as the other bridges.

It is important to be able to examine the effects of administrative decisions regarding budget splits between maintenance, rehabilitation, and replacement. The model BMS allows a mechanism for experimenting with various combinations to see how they change the resulting selections and subsequently how the entire network conditions will be affected. This gives decision-makers a powerful tool to assist in making better economic decisions as to how much money should go towards maintenance rather than rehabilitation or whether rehabilitation or replacement is more effective in certain situations. Once the most effective budget split is determined, the BMS uses the information to make final MR&R selections for the network.

Sufficiency Index for Ranking Submodule and General Project Screening

The sufficiency index (SI) provides a simple basis for ranking projects and screening the network to identify general MR&R needs. Projects are ranked by SI and general categories of maintenance, rehabilitation, or replacement (or some other categories) can be suggested based on threshold values of SI. This type of general MR&R category assignment based on simple ranking will produce only a rough estimate of needs and normally a "worst first" solution and as such it is not considered to be effective bridge management. MR&R costs may be roughly estimated by the size of the bridge and associated unit costs for the general type of work and bridge type. Therefore, at the lowest level, the network is screened, general work types are selected, and an estimate of total costs is given.

Sufficiency Indexes

A sufficiency index as it relates to BMS can be defined as an aggregate score which describes the ability of a bridge to serve its intended functions relative to the other bridges in the network. Such an index can include any of a number of bridge attributes, such as load capacity, horizontal clearance, vertical clearance, condition, or traffic level.

The Federal Highway Administration (FHWA) has defined a sufficiency index termed the Federal Sufficiency Rating (FSR) (*3*). This rating is used to determine if bridges are eligible for funding under the Federal Highway Bridge Replacement and Rehabilitation Program (HBRRP). Most states already use some form of the FSR. The current FSR should be included in the BMS. If a new version is adopted, it should be added to the BMS. FSR is important because it is a federally required statistic intended to be impartial with respect to funds distribution to states.

Other methods of calculating an SI can be defined to meet an agency's particular needs and level-of-service goals. Such a tailored index is more useful for internal agency decisions, including budget allocation, project prioritization, and network needs estimation.

The model BMS allows a flexible SI that is initially defined by the user then adjusted and compared over time. This allows the user agency to experiment with different combinations of variables and weights until it obtains the best mix for their particular conditions. For example, an agency may have many narrow bridges that are considered to be a safety hazard. The agency may give bridge horizontal clearance a high weighting and leave out variables that are not relevant to their system. Flexibility in the definition of SI allows an agency the freedom to manage its bridge network based on the most significant criteria.

Model BMS Sufficiency Formula

The sufficiency formula for the model BMS is based on a deduct point system. Bridge deficiencies score deduct points that are subtracted from a "perfect" score of 100. Weights can be assigned to the variables that describe bridge condition to give each a relative importance.

The formula recommended for the model BMS is shown in Figure 7. Major categories can be structural adequacy, functional obsolescence and serviceability, bridge importance or essentiality for public use, safety, or others encompassing a number of descriptive variables. The ith variable, V_{ij}, describes the condition level of an item in the jth category. For example, vertical clearance may be a variable used in the functional adequacy category. Table 9 gives the major categories and variables recommended for defaults in the model BMS. The two major categories are structural adequacy and functional obsolescence. These have weights of 60 percent and 40 percent respectively. Each variable in these categories has a maximum deduct value corresponding to a certain variable value, a variable value at zero deduct, a weighting factor, and the level of weight to apply. The user has the capability to change variables, deduct values, and weighting factors defined in the table.

Flexible Sufficiency Formula

$$S = \sum_{i=1}^{IMAJ} (100 - Di)$$

where,

$$0 \le S < 100$$

$Di \Rightarrow$ where, $0 \le Di \le di \le 100$

Bridge Deduct Value for Major Category i,

$di \Rightarrow$ Maximum Possible Deduct Value for Major Category i.

IMAJ = Number of Major Categories,

$$Di = \sum_{j}^{JMIN_i} W_{ij} \; MAX(O, MIN(MAXDEDUCT_{ij}, (a_{ij} V_{ij} + b_{ij})))$$

V_{ij} = The jth variable describing the condition of an element of the ith major category.

a_{ij}, b_{ij}, and $MAXDEDUCT_{ij}$ bound & define the influence of V_{ij}

W_{ij} = weighting factor to V_{ij} which is assigned by the user.

$JMIN_i$ = number of variables for the ith major category.

Figure 7. Flexible sufficiency formula for model BMS.

Table 9. Model BMS default sufficiency variable values.

MAJOR CATEGORIES		SUFFICIENCY VARIABLE VALUES							
Name	Worth 0 - 100%	Variable Name	Maximum Deduct	Value at Maximum Deduct	Value at No Deduct	Weight Name	Value at Normal Deduct Usage	Maximum Weighting Multiplicatioin effect ≥ 1.0	Value at Maximum Weighting Multiplication effect
Structural Adequacy	60%	Operating Rating	60	5 tons	25 tons	% Trucks	2%	1.25	8%
		Structure Condition	60	2	6	----	----	----	----
Functional Obsolescence	40%	Lane Width	15	9 ft.	12 ft.	ADT	500	2.00	5000
		Lane Diff.	10	2 ft.	0	----	----	----	----
		Vertical Clearance	15	14 ft.	17 ft.	% Trucks	2%	1.5	5%
		Roadway Condition Rating	10	3	6	ADT	500	2.00	5000
		Detour Length	10	50 mi.	5 mi.	ADT	100	2	1000

Example Using Sufficiency for Ranking and General MR&R Selection

The following example demonstrates the method of using SI for ranking and general MR&R selection. This method has been used by many agencies in the past to get a gross estimate of MR&R needs and required budget. It should be recognized that this method will produce only very rough estimates and, thus, may not be considered good bridge management if used by itself. For the example, suppose a small network consists of 15 bridges. A user-defined SI is calculated for each bridge. User input is required to tell the BMS what SI threshold levels divide the MR&R categories of maintenance, rehabilitation, and replacement. The user must also input total budget and percent budget allocation to each of the MR&R categories.

For this example, threshold levels are: bridges with SI greater than 80 are maintained, bridges with SI between 50 and 80 are rehabilitated, and bridges with SI less than 50 are replaced. The budget is $10 million. The budget split is designated as 10 percent for maintenance, 40 percent for rehabilitation, and 50 percent for replacement. Table 10 gives the bridges in the network ranked by SI. The initial division based on SI threshold is shown. The unit cost for replacement is used to estimate cost for replacement of the selected bridges. Two bridges are not selected because of budget limitations. These are transferred to the head of the group for rehabilitation along with the small remainder of budget not used for replacement. The unit cost for rehabilitation is then used to estimate cost for the highest priority rehabilitation projects. One bridge is not funded for rehabilitation and is transferred to the major maintenance category. The major maintenance projects are selected until the entire budget is exhausted. The two remaining bridges are designated to receive only cyclic preventive maintenance.

Table 10. Example project selections using sufficiency for ranking.

Bridge No.	SI	Threshold Required Action	Actual Cost ($1000)	Cumulative Cost ($1000)	Selected Action
462	37	Replace	1500		Replace
512	41	Replace	1300		Replace
118	42	Replace	1900	4700	Replace
227	45	Replace	700		Rehab
443	49	Replace	500		Rehab
495	57	Rehab	800		Rehab
189	61	Rehab	300		Rehab
238	63	Rehab	500		Rehab
342	70	Rehab	900		Rehab
365	76	Rehab	400	8800	Rehab
450	79	Rehab	400		Maint
528	82	Maint	400		Maint
164	85	Maint	300	9900	Maint
257	89	Maint			Minor Maint
390	92	Maint			Minor Maint

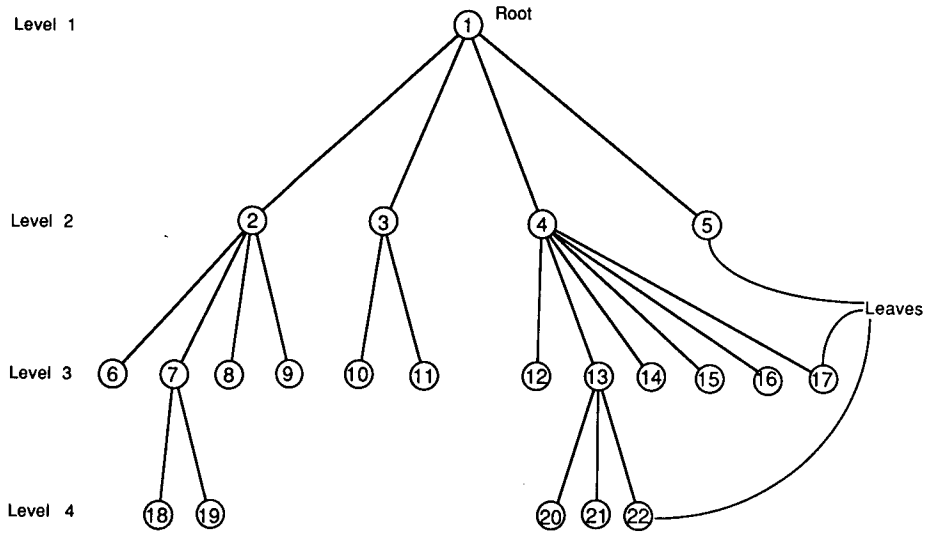


Figure 8. General representation of a decision tree (14).

Decision Tree for Specific MR&R Selection Submodule

The specific MR&R selection level provides better project selections than the ranking level because decision trees are used to choose the MR&R actions. Figure 8 shows a general decision tree (Ref. *14*). A decision tree is composed of a hierarchy of elements called nodes. The nodes are variables used as decision criteria. The uppermost level of the hierarchy has only one node called the root. Except for the root, every node has only one node connected above it, called the parent. Each node can have one or more nodes connected below it, called children. The children correspond to the levels applied to the decision variables. Elements at the end of the branches are called leaves. In the BMS decision tree, the leaves are MR&R selections based on the decision criteria in the nodes.

Using the decision criteria in the decision tree, specific MR&R actions are selected for each bridge. Better estimates of costs and effectiveness are available because each action is better defined than just the broad categories of Maintenance, Rehabilitation, or Replacement. The decision criteria are bridge condition variables and level-of-service variables, such as width, vertical clearance, and load capacity. Detailed decision trees allow more accurate assignments of MR&R projects and costs. The ranking submodel is then required to prioritize the projects by SI as described in the previous section.

User-Defined Decision Tree

The model BMS allows the user to define the decision tree in a format that most suits his needs. The user identifies the following items to define the tree:

- Number of decision variables.
- Variable names.
- Maximum number of children for each parent variable.
- The values separating the children for each variable.
- The structure of the tree.
- The MR&R action that is selected at the leaves.

With this method, the trees can be as simple or complicated as desired. A complete set of paths which totally define the decision process can be created. For example, the nonuniform decision tree presented in the next section, which is the default tree for the model BMS, can be constructed by user inputs using this method.

Model BMS Default Decision Tree

An example decision tree is presented to demonstrate the concept and to provide an initial default tree for the model BMS. The default decision tree has the following characteristics:

- Number of variables: 7
- Variable names:
  1. functional class (FC)
  2. average daily traffic (ADT)
  3. operating rating (OR)
  4. clear deck width (CDW)
  5. vertical clearance (VC)
  6. structure condition (SC)
  7. deck condition (DC)

The structure of the default tree is shown in Figure 9. The branches show the values of each decision variable that connect the children variables. The leaves are left as empty boxes. The user inputs the MR&R actions to be selected at the end of each decision path. The cost and effectiveness of each action also comes from the user input of alternatives (see discussion on data base).

A simple example of how the decision tree would make a decision is presented here to illustrate the method. Figure 9 shows one of the MR&R alternative boxes filled in with the number 3. This is a code for a user-defined MR&R activity. In this case the decision process is as follows. A bridge enters the routine and goes through a series of checks as shown on the figure. The bridge is on an interstate route, its operating rating (OR) is adequate, clear deck width is deficient, structural capacity is adequate, and deck condition is poor. User-defined MR&R activity number 3 might then be defined as deck replacement. Therefore, all bridges that meet these same criteria will be selected for deck replacement. As information and field measurements improve, chloride concentration could be another decision criterion for example.

Prioritizing Projects Selected by Decision Tree

The decision tree makes MR&R action selections for each bridge. These projects must then be prioritized to select the order to perform the actions. The SI is used at this point to perform this prioritization. The same index that was defined in the ranking level selection process could be used. However, more information is currently known about each bridge than in the ranking level. Specifically, costs and effectiveness of the proposed MR&R action are available. This information can be incorporated into a new SI to better prioritize the projects.

Equivalent Uniform Annual Cost Method for Life-Cycle Costing (LCC) Submodule

The life-cycle cost level builds on the network MR&R selection level by adding more capabilities and better economic criteria for choosing MR&R strategies. The decision tree is expanded by providing life-cycle activity profile's (LCAP's) for selection as MR&R strategies. LCAP's are a set of actions or activities that may be taken on a particular bridge over a period of time. This approach accounts for the effects of current actions on future costs and life of the bridge. For example, in choosing which LCAP to put at the end of a decision path, one option may be to provide a high level of maintenance for a period of time and then to replace the bridge. A second option may be to rehabilitate the bridge immediately and begin a program of low level routine maintenance. Analyzing the total life-cycle costs for each option would provide a better basis for choosing the most cost-effective alternative.

Defining LCAP's in the Model BMS

Each LCAP must be completely defined within the model BMS and have a unique identification code for assignment to the leaves of the decision tree. Some default LCAP's will be available for selection by the user or he may define his own. To define an LCAP, the following information is required:

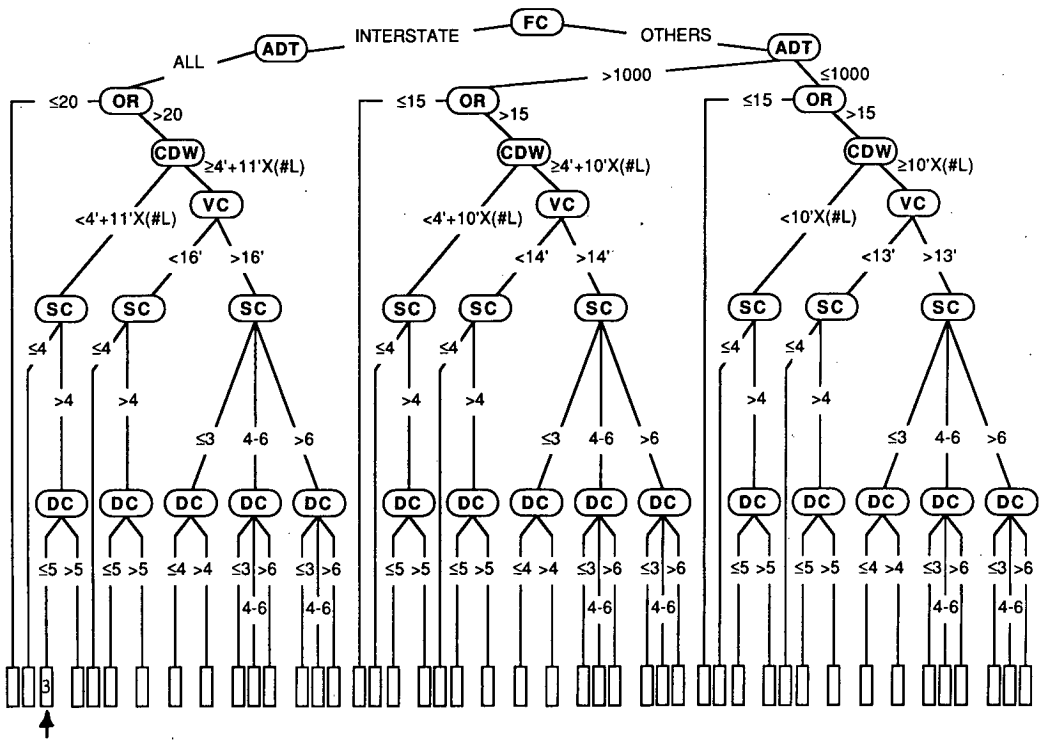


Figure 9. Structure of default decision tree for model BMS.

- Sequential MR&R actions.
- Time or condition at which each action is performed.
- Cost of each action.
- Effectiveness of each action.
- Deterioration rates between each action.
- Change in deterioration rate due to each action.

Some of these items may be defaulted values such as the deterioration rates and action costs. An effectiveness measure is desirable for including in a priority ranking formula, but is not absolutely necessary at this level. Effectiveness, however, is required in the next level to perform optimization.

The user will define each LCAP by entering the required information in a life-cycle table presented by the BMS. An example of such a table follows:

ACTION	TIME (YR)	UNIT COST	DETERIORATION RETARDANT	FINAL ELEMENT CONDITION
Reconstruct Deck	0	65 SF	—	9
Seal Deck	10	5 SF	10%	—
Repair Joints	15	2 LF	20%	—
Overlay Deck	15	35 SF	15%	7
Reconstruct Deck	25	85 SF	—	9

This example is specific for decks. However, LCAP's can be defined for any set of components or for an entire bridge. The user can define any number of these LCAP's to apply in various situations for the leaves of the decision tree.

Calculating Equivalent Uniform Annual Cost

To compare a nonuniform series of costs, it is necessary to express the costs in common terms. One way to do this is to express them in an equivalent uniform annual series of payments often referred to as annual costs. When the entire network is considered, this method provides an estimate of an agency's annual budget.

Equivalent uniform annual cost, EUAC, will give answers consistent with present worth analysis when the decision-making environment is not complex (such as differential inflation). When it is appropriate, it is an equally efficient means of conducting the calculations.

A case where EUAC can be used is that of a straight choice between alternatives in the absence of inflation. EUAC can also be used when anticipated information is uniform (meaning constant over time, across the alternative maintenance strategies and for all sources of cost). If exact answers are required with differential inflation rates, a present worth analysis is needed. If "good" approximations suffice, EUAC can be used where there are differential inflation rates (see below). A "good" approximation means 1 percent to 2 percent of the accuracy produced by more sophisticated methods.

Formulas. Several formulas are required to convert life-cycle costs to annualized costs. The first is the single payment present worth factor (PWF). This formula computes the present worth of future capital outlays such as rehabilitation or replacement of the bridge at an assumed discount rate. All life-cycle costs are converted to a present value with this formula. The second formula is the capital recovery factor (CRF). This formula computes a uniform annual payment for a period of years from a present amount based on some discount rate. The present value of all life-cycle costs is evenly distributed over the analysis period with this formula. Finally, any average annual costs such as maintenance and user costs are added to produce the total annual cost. A salvage value of the bridge can also be considered if desired.

The formulas for performing the life-cycle cost analysis are as follows:

$$PWF_{i,n} = \frac{1}{(1 + i)^n} \tag{1}$$

$$CRF_{i,n} = \frac{i(1 + i)^n}{(1 + i)^n - 1} \tag{2}$$

where: $PWF_{i,n}$ = the single payment present worth factor at discount rate (expressed as a decimal) i, over an analysis period of n years; $CRF_{i,n}$ = the capital recovery factor at discount rate i, over n years.

Calculation Procedure. The total annualized life-cycle cost (ALCC) is computed as follows:

- Convert each future MR&R expenditure and the total salvage value of the bridge to a present value by multiplying by the PWF at an accepted discount rate. The value of n is the number of years from the present until the MR&R action occurs.
- Convert the total present worth of all life-cycle MR&R costs to an equivalent uniform annual cost (EUAC) over the analysis period, n, by multiplying by the appropriate CRF at an accepted discount rate.
- Add average annual minor maintenance costs.
- Add average annual user costs.

The result is the total annualized life-cycle costs (ALCC) for a particular MR&R strategy.

Analysis Period. The analysis periods of the alternative MR&R strategies can be the same or different. This is not a factor in deciding the applicability of EUAC because the annualization part of EUAC makes the method equivalent to using a lowest common multiple horizon. Bridges commonly have lives of 70 years or more. This is extremely long for an economic analysis to produce meaningful results. An analysis period of 40 years is about the maximum recommended.

A fixed analysis period of 40 years is a fairly long horizon. According to Refs. *15* and *16*, a long fixed period corresponds to the Finite Horizon Method (FHM—a fixed cut-off date) with sensibly long horizon. This approach will favor the alternative with a relatively larger number of MR&R activities scheduled in the latter part of the analysis period. In such cases, the results will be even more favorable the longer the horizon is and the greater the discount rate is, so that distant events have less impact on PW and subsequently EUAC. For example, the 40-year discount factor (present worth factor) at 20 percent is 0.0007; whereas, at 3 percent it is over 400 times greater at

0.3066. While the use of FHM is not uncommon in public utilities, it can be improved upon significantly by the approaches discussed in Ref. *16*. In PW analysis, the analysis period should be the same for all design alternative strategies. However, the choice of varying analysis periods for design strategies in a life-cycle cost program provides flexibility to its users so the equivalent uniform annual cost (EUAC) method option should be provided to the user.

Discount Rate. In practice, the discount rate used will always contain judgmental elements and it is best to recognize this at the outset. The approach recommended below, like all others, is not without limitations. Sensitivity analyses often reveal that the discount rate is not a problem. For example, suppose that Alternative B is selected with a discount rate of 8 percent. Sensitivity analysis would then ask, "For what range of values of the discount rate is Alternative B the correct choice?" If the answer is a wide tolerance region (3 percent to 15 percent), then fretting over precise values for the discount rate is wasted energy. If the answer is a narrow range (7 percent to 9.5 percent), it may be appropriate to apply further resources to confirm or improve the accuracy of the 8 percent rate originally used. On the other hand, such precision may be superfluous in practice. It can be simply admitted that there is not much basis for selection between alternatives and that the financial consequences of a different choice of rate are slight. The analyst should, in any case, present the decision-maker with near optimal alternatives, as well as the best MR&R strategy on paper. The final decision could then include factors such as cash flow in the shorter term, and nonquantified factors, such as political implications or environmental effects.

Inflation. Conventionally, inflation is subtracted from the prevailing discount rate and cost inputs are used that are not normally affected by inflation. The costs for various inputs are regarded as increasing at similar rates so that cost differentials (which are the key factors) do not emerge. The model BMS offers the user the option of taking inflation into account. This is done by modifying the discount rate according to the following formula (*17*).

$$i^* = \frac{(1 + i)(1 + q)}{(1 + f)} \tag{3}$$

where: f = rate of inflation in maintenance activities; q = rate of increase in Department funding; i = prevailing discount rate; and i^* = "true" discount rate that incorporates the effect of inflation, where there is no inflation, $f = q$ and $i^* = i$.

Salvage Value. Salvage costs are unlikely to have a significant impact on the economic evaluation of bridge MR&R strategies; that is, they usually will not alter the ranking of competing projects. First, they will generally be similar in value (e.g., similar haulage, labor, and material costs) and this will tend to add a constant term to all projects. Second, the cost when discounted back to present value is likely to be small, even for modest discount rates.

User Costs. The user costs for a bridge are usually associated with user travel time, accidents, and vehicle operating costs. The detour to an alternate bridge is a cost incurred by the user if a bridge is closed. Accidents caused by a functionally inadequate bridge are other user costs. These are difficult to quantify. The final user cost is associated with poor bridge conditions that may cause damage to vehicles. If possible, these costs should be quantified and included in the LCC analysis.

Example Annualized Life-Cycle Cost (ALCC) Calculation. To demonstrate the calculation procedure, an example is presented to calculate ALCC using the LCAP from the section above on defining LCAP's. Assume the bridge is 1,000 sq ft with 100 linear ft of joints. The analysis period is taken as 25 years and the discount rate is assumed to be 5 percent. The calculations are given in Table 11. The PWF is calculated for each year an action takes place. The estimated cost of each action is multiplied by the PWF to calculate its present worth. The sum of the present worth values is multiplied by the CRF calculated for 25 years. The resulting annualized MR&R costs are added to estimated average annual maintenance and user costs to produce the total ALCC.

Effectiveness Algorithm For LCAPs

A measure of effectiveness is useful for each life-cycle strategy. Effectiveness can be used in the prioritization equation for ranking the selected projects. It is also required in the next level of MR&R strategy selection, optimization.

The model BMS allows the user to define his own measure

Table 11. Example calculation of Annual Life Cycle Cost.

Action	Time, yr.	Unit Cost	Total Cost	PWF	Present Worth
Reconstruct Deck	0	65 SF	65,000	1.0	$65,000
Seal Deck	10	5 SF	5,000	.61	3,050
Repair Joints	15	10 LF	1,000	.48	480
Overlay Deck	15	35 SF	35,000	.48	16,800
Reconstruct Deck	25	85 SF	85,000	.30	25,500
Salvage Value	50	-	<10,000>	.09	<900>
					$109,930

Example calculation of PWF for the 15 year case;

$$PWF_{i,n} = \frac{1}{(1+i)^n} = \frac{1}{(1+.05)^{15}} = .48$$

Calculation of CRF:

$$CRF_{i,n} = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{.05(1.05)^{50}}{(1.05)^{50} - 1} = .054$$

Annual Maintenance Cost = $2,000

Annual User Cost = $12,000

ALCC = .054 (109,930) + 2,000 + 12,000 = 19,936 $/yr.

of effectiveness. The objective function of the effectiveness algorithm may be the average (over the life-cycle analysis period) of a parameter that includes condition, structural capacity, and functionality variables. A very simple measure of effectiveness is average bridge condition over the analysis period.

In order to determine effectiveness over a life-cycle analysis period, an estimate of deterioration of the objective function is required. Deterioration estimates of a user-defined sufficiency index or a parameter containing condition, structural capacity, and functionality are not currently available. Only after the model BMS is implemented and has been functioning for some time will deterioration models of such functions be developed. There are, however, several deterioration models based on condition only, which may be used to estimate effectiveness as average condition over the analysis period. The following equations were developed by the Transportation Systems Center (TSC), U.S. Department of Transportation, Cambridge, Mass. (*18*) and are recommended for the current default deterioration models.

$$C_{deck} = 9 - 0.119\,(AGE) - 2.158 \times 10^{-6}\,(ADTAGE)$$
$$C_{super} = 9 - 0.103\,(AGE) - 1.982 \times 10^{-6}\,(ADT)$$
$$C_{sub} = 9 - 0.105\,(AGE) - 2.051 \times 10^{-6}\,(ADT)$$

where: C_{deck} = deck condition on 0–9 scale; C_{super} = superstructure condition on 0–9 scale; C_{sub} = substructure condition on 0–9 scale; AGE = bridge component age; ADT = average daily traffic of the route crossing the bridge; and ADTAGE = (ADT × AGE/10).

These equations were developed using more than 150,000 bridges, but at only one point in time. Because of this, and other factors, the accuracy may be somewhat limited. On average, as pointed out in the FHWA BMS Demonstration Project, bridges deteriorate at approximately 0.1 condition points per year.

Network Predictions

The LCC submodule also performs the function of estimating future network condition. The availability of bridge life-cycle activity profiles, deterioration rates, and effectiveness measures allows the estimation of future individual bridge and entire network condition.

This function allows the evaluation of the effects of various levels of inputs and sensitivity of a number of variables on the selected MR&R alternatives. The effects of budget allocation decisions and level of available funds can be examined with this feature. These can be adjusted as desired to determine the best combination to meet agency objectives. The sensitivity of variables such as MR&R costs, benefits, life expectancy, and the interest rate used in Life Cycle Cost Analysis can also be examined with this function.

Incremental Cost Effectiveness as Optimization Submodule

The optimization level is the highest level available for making decisions regarding MR&R strategies to be used on the network. In the optimization level, the decision tree is expanded by allowing multiple LCAP's to be chosen for each bridge. Besides the total life-cycle costs, a measure of effectiveness of total benefits are also available for each LCAP. An optimization routine is used in the BMS to compare all possible LCAP's for all bridges in the network and optimize the choices based on budget constraints to obtain maximum effectiveness or benefits over the network.

Optimization

A frequently encountered problem in bridge engineering and economic applications is to select a MR&R program from a wide range of candidate projects and MR&R alternatives so as to maximize the net benefit derived, subject to budget constraints. The benefits or returns from the MR&R alternatives selected can be expressed in dollars gained, time saved, or some type of effectiveness quantification. In this discussion, optimization is used to decide which decisions should be made in order to maximize net benefit, subject to the budget constraint.

All candidate bridges from which projects will be selected are subject to this optimization procedure. For each of these bridges, one or more appropriate MR&R alternatives are specified. The solution is the selection of bridges to be improved along with the best MR&R alternative (which may be to do nothing) for each bridge.

Incremental Cost-Benefit Method

In the course of ARE Inc's pavement management activities, the resolution of this same optimization question has been a major issue. After extensive review of optimization techniques, the incremental benefit-cost method of optimization was chosen because it is available and practical. The use of this technique in the research reported, herein, began after a review of FHWA documents from the "Testing of Improved Evaluation Techniques Using a Representative Set of Accident Countermeasures" Project produced by McFarland, Rollers and Dheri of the Texas Transportation Institute (TTI) (*10, 19*). Since then, ARE Inc has slightly modified this procedure, for both pavement and bridge management application.

The incremental benefit-cost procedure ranks all increments of expenditure on MR&R alternatives across all bridges. The unique aspect of this algorithm is its procedure for discarding some increments while averaging together increments of expenditure for a bridge if there are increasing ratios of incremental benefits to incremental costs. A set of expenditure increments in decreasing order of incremental benefit-cost ratios is produced, providing a prioritization of MR&R options across both bridges and MR&R alternatives.

For this application of the incremental benefit-cost optimization procedure, both benefits and costs must be defined. Costs are calculated as the equivalent uniform annual cost (EUAC) of all costs accrued during the bridge's life cycle due to MR&R activities. The equation for EUAC is described in the previous section on life-cycle costing.

Benefit is formulated in terms of the effectiveness of the MR&R strategy over an analysis period. Effectiveness may be calculated as discussed in the previous section on life-cycle costing.

Step 1. Input budget levels and several LCAP strategies (type

of MR&R action, costs, and timing) per bridge across all bridges for the entire analysis period.

Step 2. Calculate cost and effectiveness for each LCAP on each bridge (these will likely be several LCAP's per bridge).

Step 3. Order LCAP's across bridges by cost effectiveness to be rehabilitated.

Step 4. Choose bridges to be rehabilitated in order of cost effectiveness. As bridges are selected the associated LCAP is selected and the remaining total budget is diminished by the LCAP cost.

Step 5. At times, executing step 4 results in replacing the current (first) LCAP on a bridge with another (second) for the same bridge. The replacement is made only if the second LCAP gives substantially* more effectiveness for the extra cost to complete the rehabilitation. Diminish the remaining budget by the cost excess.

Step 6. If budget remains, go to step 4, else stop. When the total budget is expended, the bridges selected to fix and their associated LCAP's are near optimal.

This algorithm has many advantages over a simple needs assessment.

- The computer will decide the best rehabilitation alternative per bridge based on a user input budget level.
- Under the assumption that effectiveness is proportional to dollar benefit, the algorithm effect on maintenance strategy is to lean toward short, quick payoff solutions when budget levels are low and longer term large payoff solutions when budgets are higher.
- The algorithm can be run as a simple needs assessment based solely on the bridge engineer's specific choice of rehabilitation strategy.

Network MR&R Selection Module Summary

The model BMS, by definition, would contain all four levels for choosing projects because only with optimization level analyses involved would the best overall choices be possible. Upon implementing an initial BMS, however, a user agency may not want to pursue such a complex system. It is possible that the first two levels would be adequate until more experience is gained and better life-cycle cost information is obtained. No matter how MR&R projects are chosen in a BMS, there will always be a set of bridges that will not be chosen or scheduled for major work either because the bridges are in adequate condition or because there are inadequate MR&R funds available to handle all bridges. Such bridges will be designated to receive some level of preventive or minor maintenance. The BMS will then assist in suggesting and scheduling the preventive maintenance activities.

MAINTENANCE MODULE

Bridges which do not receive a major MR&R action are considered to require some demand responsive or preventive maintenance and are handled in the maintenance module. This module suggests maintenance levels for bridges that are not prioritized high for MR&R work. Maintenance activities are considered in the general categories of urgent demand responsive actions and programmed preventive maintenance.

Maintenance Actions

During bridge inspections, needed minor maintenance or urgent actions are observed and recorded using special maintenance item codes. These codes are input to the BMS data base for each bridge. Maintenance items were chosen and supplemented from North Carolina (*13*) and other sources. Table 12 gives the maintenance items and associated codes to be used by the model BMS. The inspector uses this list to choose the maintenance items needed on a particular bridge and enters the codes and levels of maintenance required on the inspection form. Urgently required actions are distinguished from programmed preventive maintenance needs during inspection.

Urgent actions include important work of a critical or emergency nature that must be performed to avoid serious consequences. Examples are: damaged railings or missing clearance signs for an underpass; girders damaged by an overheight vehicle traveling under a grade separation, and clogged drainage systems. This type of work can be classified as demand maintenance. The bridge inspector should flag urgently needed actions on the inspection sheet. A process for handling maintenance needs of this type is important, but such needs should not be stored in the computer data base. Frequently, road and bridge maintenance crews observe needs for urgent action on state-owned bridges during their routine inspections. Effective bridge management flags the need for urgent action and records the resulting repair treatment action taken in the BMS data base.

The programmed maintenance category includes preventive or minor maintenance treatments. Preventive maintenance is work performed to prevent future deterioration. These actions

Table 12. Maintenance action codes.

101	painting
102	joint cleaning and sealing
103	bearing cleaning and lubrication
104	sealing concrete surfaces
105	drift removal
106	crack sealing
107	bolt tightening or replacement
108	deck washing
109	clean drainage system
110	moveable bridge mechanical or electrical equipment maintenance
111	approach leveling or repair
112	deck patching
113	touch up painting
114	minor repair or cleaning of culverts
115	handrail maintenance or repair
116	expansion joint maintenance
117	fender system maintenance
118	slope or shore protection system maintenance

*substantially is defined as:

$$1 \geq (E_2 - E_1)/(C_2 - C_1) > k \geq 0$$

where: k is a user set value, E_{LCAP} is LCAP effectiveness, and C_{LCAP} is LCAP cost, LCAP = 1 for the LCAP for bridge X with higher cost effectiveness, and LCAP = 2 for the LCAP for bridge X with lower cost effectiveness.

can be divided into two subgroups: cyclic maintenance needs (those performed at specified intervals) and other minor maintenance performed as needed. For cyclic maintenance, the interval varies according to the type of work or activity. Examples of cyclic maintenance actions are: spot painting, cleaning drainage systems, cleaning and resealing deck joints, and cleaning expansion bearings and supports. Examples of other groups of programmed maintenance activities are: cleaning bridge decks and pier caps, improving surface drainage, and sealing concrete decks.

Maintenance Recommendations and Scheduling

The maintenance module prints a prioritized list of bridges needing maintenance with the recommended maintenance items included. Maintenance performance rates are input by the user describing how long specific maintenance activities take. The BMS uses these to estimate maintenance levels of service for the system for the available budget.

More detailed decision criteria regarding the type and timing of maintenance actions will be developed as the historical maintenance actions are analyzed with respect to detailed bridge condition data. The BMS will then be able to make maintenance program decisions that can be compared with the inspector's recommendations or replace them.

The maintenance programs selected by the BMS may be used in conjunction with the life-cycle costing and optimization submodules. Long-term maintenance levels and plans may be defined using the life-cycle costs level of analysis. The LCAP's can contain future major maintenance, rehabilitation, and replacement actions as well as the minor maintenance programs. This is required if they are to be compared on the optimization level with the major action selections made in the network MR&R module. If only the maintenance programs are to be optimized among themselves, the major work would not necessarily need to be included in the life-cycle cost analysis. Measures of effectiveness would be required for each of the maintenance programs on the various categories of bridges.

Scheduling of the selected maintenance activities may be accomplished if several items are available. The user must input maintenance performance rates, from the performance standards for each maintenance action, for the maintenance crews. Such rates describe the length of time, in man-hours, required to perform certain maintenance actions. This also includes general personnel requirements for each maintenance action. The availability of this personnel as well as required equipment and materials for each action is also required. Routing of the maintenance activities will be accomplished and output in the form of routing reports for the maintenance crews. This routing information can be input by the user or determined by the model BMS if a geographical data base capability is available.

HISTORICAL DATA ANALYSIS MODULE

Historical data are kept by the model BMS for analyses to improve predictive models. The purpose of the historical data analysis is to decrease errors in future predictions and increase reliability. Models which will be improved with the aid of this module include deterioration rates, bridge life cycle activities, MR&R costs and effectivenesses, and network impact of various strategies.

Variables Retained

Several types of variables should be retained for analysis by the historical data analysis module. The first type consists of MR&R actions, costs, and effectiveness which actually took place on each bridge. The next is condition data to get an accurate deterioration profile. Traffic and weight data are also kept to analyze the loading history of each bridge. Certain inventory data are retained to identify the bridge and changes that took place.

Enough detailed data are required to perform the required historical analysis. Extraneous data should not be kept in the accessible data base. Every year, the historical module transfers the applicable data elements to the data base historical files. Then, the entire old data base is stored on tape or other long-term storage device to be archived.

The variables for historical retention and their uses are given in Table 13. The variable numbers correspond to the variables described in the "Data Base Module" section. These variables, some more than others, would all be useful for analysis or identification purposes. Likewise, some variables, which may be considered useful by various agencies, are not included in this list. The model BMS allows the user to select a subset of the given default variables and to include additional variables if desired.

Statistical Analyses

To develop better predictive models, statistical analysis of the data is necessary. In particular, multiple linear and nonlinear regression analysis is required to find and develop relationships among the many bridge variables. Other forms of statistical analyses such as nonuniform distributions, analysis of variance, and statistical significance tests will also be required.

A statistically designed experiment may be used to obtain updated models. The variables considered to have the most significance in influencing a particular model will be selected in the analysis. A low and high value for each of the variables is chosen. A large number of variables would produce an extremely large factorial of combinations for the analysis. For example, if there were 15 variables to be considered with two levels each (low, high) there would be 2^{15} or 34,000 + combinations. It can be shown that a 1/128 replicate or $2^8 = 256$ combinations will find the main effects and all two factor interactions.

New models developed using the historical data analysis module are calibrated to observed conditions on an agency's bridge network. This occurs if an accepted form of a particular model has been developed, and the coefficients of the model are modified to better predict long-term behavior and deterioration. This calibration is extremely useful for agencies that are adapting an existing BMS with functioning models. The existing models may be calibrated to fit the adopting agencies situation.

There are currently several good statistical software packages, notably SAS and SPSS, that perform the mentioned analyses equally well. One of these packages should be interfaced with the model BMS historical analysis module to perform the required analyses. This would give the BMS the desired statistical capabilities with a minimum of programming effort.

The model BMS has the capability to automatically update its internal models when the statistical analyses develop im-

Table 13. List of BMS variables to be retained historically.

Inventory Variables

A. Identification Information
- 4. Structure number
- 7. Principal route
- 9. Principal route milepoint
- 11. Bridge Name
- 12. Town Name

D. Essentiality / Classification / Jurisdiction
- 2. Detour length
- 11. Years of construction and major reconstruction
- 12. Principal route ADT
- 13. Year of traffic count
- 14. Truck factor (% trucks with more than 2 axles)

F. Posting Information
- 1. Operational status - (open or closed)
- 2. Operating rating absolute maximum permissible
- 3. Inventory rating highest load for long term use
- 4. Weight Limit
  - 4.1.Axle
  - 4.2.Combination

G. Safety Inventory
- 1. Approach roadway width in feet
- 5. Traffic safety features
  - 5.1. type of bridge railing
  - 5.2. type of approach guardrail transitions
  - 5.3. type of approach guardrails
  - 5.4. type ofapproach guardrail ends
- 6. Sight distance
- 8. No. of accidents per 100,000 vehicles

H. Secondary Features
- 1. Name of secondary features
- 2. Type of feature (road, railroad, water)
- 3. Route
  - 3.1.system classification
  - 3.2.number
  - 3.3.direction suffix
- 4. Route milepoint
- 6. Detour length
- 11. Route ADT
- 12. Year of traffic count
- 13. Truck factor (% trucks with more than 3 axles
- 15. Route horizontal clearance
  - 15.1.right
  - 15.2.left
- 16. Route minimum vertical clearance
- 17. Number of lanes on the 'secondary 'route
- 18. Roadway width

I. Structural Inventory
- 1. Structure type
- 2. Principal route horizontal clearance
- 3. Principal route minimum vertical clearance (10)
- 5. Roadway width
- 6. Length of structure
- 8. Number of lanes on the principal route
- 9. Superstructure type
  - 9.1 number of span groups
    - 9.1.1. span type in group
    - 9.1.2. main member type in group
    - 9.1.3. number of spans in group
    - 9.1.4. span length in group (48)
  - 9.2 type of paint system
  - 9.3 date existing paint system placed
- 10. Substructure type
- 11. Deck type (57)
  - 11.1. material type
  - 11.3. wearing surface
  - 11.4. deck concrete air entrained
  - 11.7. type of cathodic protection
  - 11.8 date wearing surface placed
- 12. Deck width
- 13. Deck joint type

Bridge Condition Variables
(Severity Rating=R, Extent=E, Distress Type=D)

J. Roadway Condition Rating
- 1. Deck R/E/D
- 2. Wearing surface R/E/D
- 3. Joints R/E
- 4. Drainage system R
- 5. Curbs, sidewalks, and parapets R/E
- 6. Median barrier R/E
- 7. Railings R/E
- 8. Delineation (striping and curve markers (R)

K. Superstructure Condition Rating
- 1. Main members R/E/D
- 2. Main member connections R/E/D
- 3. Floor system members R/E/D
- 4. Floor system connections R/E/D
- 5. Secondary members R/E
- 6. Secondary member connections R/E
- 7. Expansion bearings R/E
- 8. Fixed bearings R/E
- 9. Steel protective coating R/E

L. Substructure Rating
- 1. Abutments R/E/D
  - 1.1.Caps
  - 1.2.Above ground
  - 1.3.Below ground
- 2. Intermediate supports R/E/D
  - 2.1.Caps
  - 2.2.Above ground
  - 2.3.Below ground
- 3. Collision protection system R
- 4. Steel protective coating R/E
- 5. Retaining walls R/E/D
- 6. Culverts
  - 6.1.Damage to pipe
  - 6.2.Debris
  - 6.3.Damage to walks
- 7. Concrete protective system R/E/D

M. Channel and Channel Protection Rating
- 1. Banks R
- 2. Bed R
- 3. Rip rap R/E
- 4. Dikes & Jetties R
- 5. Substructure foundation erosion R/E

N. Approaches Rating
- 1. Embankments R/E
- 2. Pavement R/E/D
- 3. Relief joints R/E
- 4. Drainage R/E
- 5. Guard Fence R/E
- 6. Delineation markers R

O. Estimated Remaining Life

P. Inspection Information
- 1. Date of last inspection

Bridge Appraisal and Proposed Improvement Ratings

Q. Appraisal (Calculated values to be output in report)
- 1. Traffic safety features
- 2. Structural condition
- 3. Roadway geometry
- 4. Vertical and lateral clearance
- 5. Safe loading capacity
- 6. Waterway capacity
- 7. Approach roadway

R. Proposed Improvements
- 1. Year needed
- 2. Type of service
- 3. Type of work
- 4. Length of improvements
- 5. Proposed design load
- 6. Proposed roadway width
- 7. Proposed number of lanes
- 8. Design ADT
- 9. Year of Estimated ADT
- 12. Cost of all improvements

Table 13. Continued

```
13.  Base year of improvement costs
18.  Required maintenance activity
19.  Level of maintenance activity
20.  Required maintenance activity
21.  Level of maintenance activity
22.  Required maintenance activity
23.  Level of maintenance activity
```

MR&R Historical Variables

```
S.  MR & R Record
    1.  Structure number
    2.  Year of MR & R Action
    3.  Type of action
        3.1.Major Category
        3.2.Individual Activity
    4.  Scheduled or Completed?
    5.  Quantity of units in type file
    6.  Costs
        5.1.Labor
        5.2.Equipment
        5.3.Materials
        5.4.Other
        5.5.Total
```

proved versions. This is done by statistical comparison tests between the new model and the old one. If the new model is considered statistically better than the old one, the submodule containing the old model is replaced with the update.

PROJECT LEVEL INTERFACE MODULE

This module provides an interface with project level data and project level BMS analyses. The details of this module are not yet well defined because the primary focus of this project was a network level BMS. One aspect of the network level BMS is the ability to communicate and exchange information with the project level BMS detailed analysis routines.

The project level interface module will allow communication with structural analyses programs such as BARS (*6*) or BRASS (*7*) or other programs which analyze the detailed structural components of a bridge. It must be recognized that such detailed structural analysis programs will require many detailed inputs such as load distributions, detailed dimensions, and material strength. Thus, the interface module will require extensive design and coding to implement the project level interface. It will also provide a link between the network BMS and the details of the MR&R actions performed on individual bridges if these are recorded in an MMS. This can assist in an automatic updating of the network BMS on actual MR&R activities.

REPORTING MODULE

The reporting module produces all of the reports of the model BMS. This includes lists, summaries, graphs, and maps. Reporting is the primary method for the BMS to communicate with bridge engineers and managers. Reports are normally in the form of paper output produced at various stages in the analysis.

BMS outputs have multiple objectives that are related to the level at which the system is being used. The general objectives of bridge management output and the general requirements of the BMS are to produce the following:

- Planning summarizes which give administrators overall network conditions and predicted needs and MR&R requirements for the network.
- Programming outputs bridge engineers responsible for various groups of bridges within the system to do the following:
  - Prioritize between various bridges to determine the best mix of major maintenance, rehabilitation, and replacement activities.
  - Prioritize between bridges within a specific action category to select those bridges with the highest priority for action.
  - Predict costs for various actions and for the subsystem group of bridges.
  - Output special reports regarding posting, load permitting, maintenance, rehabilitation, and construction unit cost information.
- Maintenance priorities to guide the maintenance division in its selection of maintenance projects for bridges.

A proposed initial design of some BMS outputs is presented in this section. It should be pointed out, however, that in a management system such as a BMS, data and output format designs must be flexible. They should be adaptable for the convenience of the user. It is important initially to have a fixed number of output formats that are specifically developed and give the user a wide range of information in different report types for different purposes. After using the BMS, the bridge engineer may determine that one or more of the following conditions exist requiring output changes:

- More variables or information is needed on a particular output.
- Some variables, which currently appear, are rarely used and are not required.
- Different ways of summarizing the information are needed.
- New reporting requests or requirements for the legislature and upper management require output modification.
- Bridge replacements, roadway realignments, and political boundary changes require some bridges to be moved into different reporting categories.

Therefore, in addition to having available the various general outputs described in this section, it is also important to develop the bridge management system around a data base management language so that engineers can introduce and develop new outputs for planning, programming, analysis, maintenance, and/or special output requirements.

Report Types

A large number of reports can be generated by the model BMS. Following is a description of specific reports which the user may initially desire.

Bridge Inventory Report

The BMS should produce an inventory report of all the structures in the system. This summary of all structures should include as a minimum, but not be limited to, the following types of information: bridge identification number, bridge location with respect to highway number, bridge type, bridge function and funding classification, bridge dimensions, bridge age and

construction details, bridge jurisdiction and responsibility designation for maintenance rehabilitation and replacement, current overall appraised condition, current priority for remedial action, and project under which bridge was constructed.

The inventory report will replace the requirement for many redundant manual files. The central office bridge division, district bridge engineers, and resident engineers receive inquiries from various users, legislators, contractors, and other engineers with respect to various bridges within their inventory. The inventory should be a great convenience for receivers of such inquiries and may be one of the most commonly used reports of the BMS system. It should be available for on-screen surveillance at a computer terminal and available for printing in various summary sort.

Sorted Listings

Listings of sorts on user-defined variables and subsets for any sorted variable can be produced to allow the user to review special aspects of the bridge network. For example, a listing of all bridges with vertical under clearance of less than 15 ft may be a useful output. Sorts can be done on any variables in the BMS data base such as inventory rating, clear deck width, conditions ratings, or others. An example of such a listing is shown in Figure 10.

Bridge ID Number	District Number	Name of Principal Feature Carried	Name of Other Related Feature	Bridge Location Milepost	Sufficiency Index FHWA Method	Component Ratings SP	RD	SB	AP	CH	Sufficiency Index by State Method	Principle Distress Types
10112	10	US 59	Brazos Riv.	57.35	45	7	4	7	3	6	20	Cracked and Spalled Deck and Inadequate Width.
10007	10	FM 76	Elm Creek	22.64	53	4	6	5	7	7	38	Rusted Steel Superstructure and Moving Abutments.

KEY:

SP - Superstructure
RD - Roadway
SB - Substructure
AP - Approach
CH - Channel

Figure 10. Sorted output of a system bridge from a given district by FHWA sufficiency index with condition ratings for each element.

Network MR&R Plan

Reports of this type will describe the selected MR&R strategies for the network in an optimized list. This report is used to schedule and plan the MR&R actions for the network. Each action in the model BMS is associated with an LCAP and has an estimated cost and effectiveness. An example of the Network MR&R Plan is presented in Figure 11.

The recommended MR&R selection report may also be sorted on the basis of the type of remedial actions specified. A listing of all bridges within the state or a subjurisdiction that requires a particular type of remedial action could be compared against one another to develop a final list for implementation.

					REHABILITATION SUMMARY			COSTS	
Bridge Number	Principal Feature Name	Other Feature Name	Milepost	Current Sufficiency Rating	Planned MR & R Action	Year	New Expected Sufficiency Rating	$/SF	Total 000's
12175	US 65	Elm Creek	56.75	20	Widen and Place New Superstructure	88	100	50	2,000
12046	IH 30	B&O RR	65.96	30	Widen and Repair Deck	88	100	65	3,000
12097	US 70	Yellow River	10.20	33	Repair Superstructure	89	100	35	2,000
12375	RM 1525	County Rd. 1746	12.84	42	Replace Culvert with New Bridge	89	100	40	1,000
12001	US 10	Walnut Creek	4.37	43	Replace Deck	89	100	25	4,000
12965	IH 45	IH 40	195.36	65	Replace Deck	90	100	60	5,000

Figure 11. Example of a network MR&R plan for a specific district including planned MR&R actions, timing, and costs.

Historical MR&R Summary

A summary of historical network MR&R actions is output by the model BMS. The number of bridges that received each type of MR&R alternative and the associated costs are printed. This allows the user to quickly know the quantities of MR&R actions that are most used and their average costs. This can aid in identifying problem areas in a bridge network. Also, MR&R strategies that are rarely used can be identified and evaluated for the possibility of increased use. An example of a historical MR&R summary report is shown in Figure 12.

Network Bridge Attribute Distributions

It is useful to examine the distribution of many bridge attributes throughout the network. These attributes may be variables such as age, condition, sufficiency index, rehabilitation type, type of bridge, or maintenance dollars spent. These distributions will give an overview of the condition or quality of the entire bridge network and will also be useful for distribution plots. They are useful for examining the impact of various alternative MR&R strategies on the network and for planning future bridge investments. An example bridge attribute distribution is shown in Figure 13.

Summary Distress Reports

The report includes the number of bridges in the network exhibiting each of the distresses at various levels of severity and extent. This allows the user to identify the most prevalent distresses occurring on the bridge network and to evaluate MR&R actions that will most effectively correct the distresses. This type of report will also allow planning of the MR&R actions and possible design changes and reviews. Scheduling of equipment and purchase of materials can be made based on the total number of each of the types of distresses present in the network. An example distress summary report is shown in Figure 14.

MR & R ACTIONS SUMMARY

Year:	88		89		90		91		92		93		94		95		96		97	
Number of Bridges and Expended Costs (000000)	#	$	#	$	#	$	#	$	#	$	#	$	#	$	#	$	#	$	#	$
MR & R Actions																				
A. Maintain																				
Painting	10	1.0																		
Joint Cleaning	50	1.1																		
Bearing Lubrication	150	.9																		
Subtotal	210	3																		
B. Repair																				
Replace Damaged Guardrail	15	.5																		
Correct Scour	6	1.5																		
Joint Repair	3	3.0																		
Subtotal	24	5																		
C. Rehabilitate																				
Deck Replacement	2	6																		
Increase Structural Capacity	1	5																		
Replace major Structural Element	2	4																		
Subtotal	5	15																		
D. Reconstruct																				
Widen	2	12																		
New Superstructure	1	8																		
Subtotal	3	20																		
E. Replace																				
Subtotal	1	15																		
All Actions																				
Total	243	58																		

Figure 12. Summary of actual MR&R actions and expenditures for all bridges in the network.

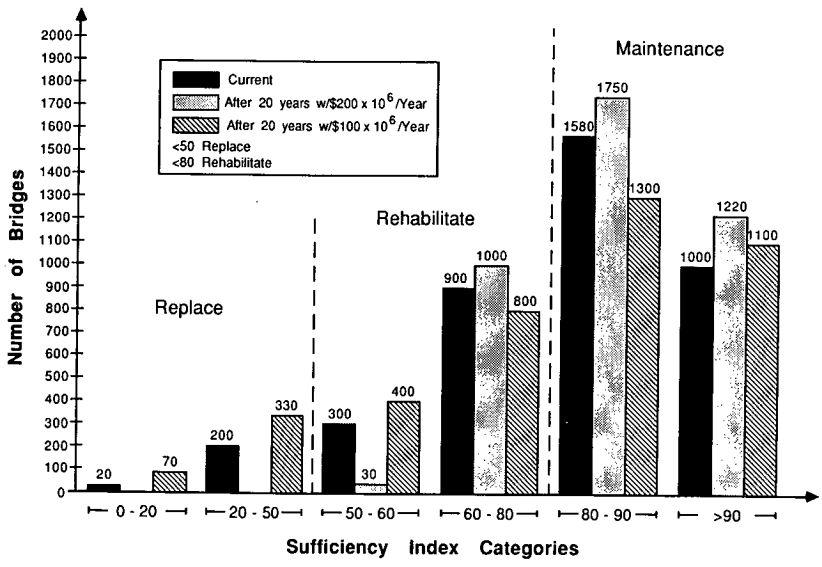


Figure 13. Distribution of bridge conditions currently and predicted for two levels of funding after 20 years for a 4,000 bridge network.

Network Summary Statistics

This report gives a concise overview of the overall condition of the network. Such a report can be based on a subset of the network or the entire network. Statistics such as average component conditions, sufficiency indexes, structural ratings, bridge widths or vertical clearances, or MR&R costs can be printed. The statistics can be divided by bridge type, age, functional class, level of ADT, or other such subsets of the entire network. An example of a network summary statistic report is shown in Figure 15.

Project Level Output

The project level output can present the details of a particular bridge. The details can consist of a number of bridge attributes. Any variable contained in the BMS data base can be output on the project level reports. An example of a project level report is shown in Figure 16.

Distress Type and Extent	DECK Severity				SUBSTRUCTURE Severity			
	987	654	321	0	987	654	321	0
1. Cracks								
L	28	15	6	2				
P	1	2	3	10				
2. Corrosion								
L								
P								
3. Spalling								
L								
P								
4. Polishing								
L								
P								
5. Leaking								
L								
P								
6. Roughness								
L								
P								

L = Localized area estimate or count
P = Prevalent area estimate

Figure 14. Summary distress report showing the distribution of bridges with respect to distress type, extent, and severity range for two of the principal bridge components.

ESTIMATED NEEDS, DOLLARS

Unit	System	SI < 50 Bridges Eligible for Replacement or Rehabilitation	Estimated Replacement Cost in Millions	SI 50 - 80 Bridges Eligible for Rehabilitation	Estimated Rehabilitation Cost in Millions	Total Cost in Millions
Statewide	IH:	2	2.0	6	1.5	3.5
	Primary:	25				
	Secondary:	15				
	Urban:	40				
Total Federal Aid:		82				15.0
	Off System:	50				12.0
	Total:	132				27.0

APPORTIONMENTS, DOLLARS

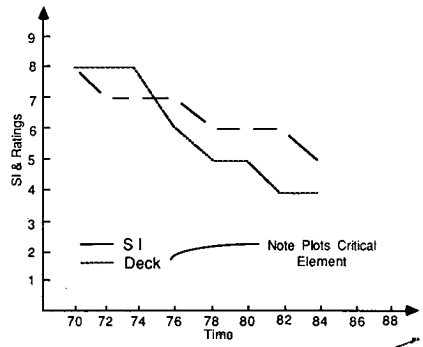
Source	Mandatory 65% on System	Mandatory 15% off System	Optional 20% on or off System	on System	Revenue Sharing off System	Total
FHWA	5.0×10^6	1.0×10^6	1.5×10^6			7.5×10^6
General Fund (Taxes)				1×10^6	2×10^6	3.0×10^6
Bonds		$.5 \times 10^6$		6×10^6		6.0×10^6
Totals		1.5×10^6				16.5×10^6

Figure 15. Network level summary report comparing predicted needs and apportionments.

Bridge I D: 20075
District: 20
Principal Feature Carried: U S 60
Other Feature: Brown River
Location Milepost: 53.65
Date of Construction: 1935 Age: 53 years

BRIDGE CONDITION

	1984	1982	1980 etc
Current Sufficiency Index:	5.0	6.0	6.0
Deck Rating:	4.0	4.0	5.0
Superstructure Rating:	6.0	6.0	6.0
Substructure Rating:	7.0	7.5	8.0
Approach Rating:	9.0	9.0	9.0
Channel Rating:	9.0	9.0	9.0
Maintenance Cost(000's):	20.0	10.0	10.0



Operating Rating: HS25
Inventory Rating: HS18

PROPOSED MR & R PLAN

YEAR	ACTION
1989	Deck Removal and Replacement with New Deck with Membrane and Coated Reinforcing Bars
COST:	$2,000,000

Figure 16. Project level BMS output for one bridge.

District : 12
Principal Feature : US 75

Bridge Number	Bridge Type	Other Feature Name	Milepost	OR	IR	Traffic Data ADT (000's)	% Growth	DDF	% Trucks %	% Growth	DDF
12100	SIB	A,T&SFRR	10.3	HS30	HS22	35	1.0	50	12.0	.01	50
12101	RC	Elm River	12.4	HS25	HS18	34	1.0	50	12.5	.01	50
12102	RC	Bear Creek	25.6	HS30	HS22	37	1.0	50	12.6	.01	50
12103	CC	Drainage Field	25.7	HS27	HS20	40	2.0	50	12.6	.01	50
12104	RC	Jones Creek	32.6	HS35	HS26	35	1.0	50	12.6	.01	50
12105	SC	Drainage Field	33.1	HS30	HS22	35	1.0	50	12.6	.01	50
12106	SC	Drainage Field	34.5	HS20	HS15	35	1.0	50	12.6	.01	50

SIB - Steel I Beam
RC - Reinforced Concrete
CC - Concrete Culvert
SC. - Steel Pipe Culvert

DDF : Directional Distribution Factor

Figure 17. Example traffic report for bridges on one route.

Bridge Traffic Reports

A report summarizing the current and forecasted traffic on individual bridges can include volume data, vehicle classification data, and truck weight data. This report is useful for identifying important bridges, bridges that carry many heavy loads, or bridges that may be inadequate for the volume or load that they carry. These reports may include functional data such as bridge widths or structural capacities to compare traffic levels and service adequacy of the bridge. An example of a bridge traffic report is shown in Figure 17.

Budget Reports

Reports that provide information about budgets are useful for planning purposes. These reports will give information such as individual funding eligibility of bridges, the summary of the distribution of funds to the various districts, distribution of funds between the maintenance, rehabilitation, and replacement alternatives, present and future budget estimates, estimated costs of various alternatives for MR&R, and other reports pertaining to budgeting. An example of a budget report is shown in Figure 18.

BRIDGE BUDGET FORECAST

Unit	Yr	Minor Maintenance	%	Major Maint.	%	Rehabilitation	%	Reconstruction	%	Bridge Construction or Replacement	%	Special Projects	%	Total
Statewide	88	5×10^6	9%	7×10^6	13%	12×10^6	21%	10×10^6	18%	20×10^6	%	2×10^6	%	56×10^6
	89													
	90													
	91													
	92													
Total														
District 1														
	88													
	89													
	90													
	91													
	92													
Total														
District 2														

Figure 18. Budget report showing distribution of planned bridge expenditures.

Administrative Policy Reports

These reports could show current funding strategies, budget splits, desired levels of service for the network, and the other policy goals used by the BMS to make decisions.

Maintenance Schedule Report

The maintenance report from the maintenance module summarizes bridges to receive preventive maintenance. These reports include a description of the type of maintenance and estimated timing of the actions on each bridge. These are bridges that were not selected for any major action in the MR&R selection module. An example of a maintenance report is shown in Figure 19. This maintenance listing is by no means the final decision on what maintenance and operations personnel should accomplish. It merely gives guidance for planning the use of maintenance funds.

Certain maintenance conditions, particularly those affecting safety, such as downed signs, damaged or missing guardrails, major potholes and abrupt grade changes that can cause vehicle loss of control, must be reported rapidly for special attention and care. Preventive maintenance patrols normally will pick up this type of information more rapidly and more specifically than the SI&A survey process. However, it would still be important to know those items observed by the SI&A data crew so they can be included as candidate maintenance projects. The maintenance report of the BMS should be provided to the appropriate maintenance authority; all the bridges under that authority's jurisdiction, and the prominent deficiencies requiring minor maintenance, should all be listed.

Bridge Inspection Routing Report

The model BMS should also schedule bridge inspections so that each bridge receives the periodic required inspections. The BMS can also produce a routing report to assist the inspectors in performing efficient inspections. It has been the experience of many persons involved in the collection of pavement management information that physical location in the field and the scheduling and routing of condition survey crews are important to the overall efficiency of the pavement management system. A survey routing schedule for the collection of bridge data will expedite this activity in the bridge management system. Rather than simply collecting all the bridges on one route and then working on another route, there may be organized flows of raters around loops in the systems where the largest number of bridges can be most effectively rated in the shortest amount of time. Whether the agency rates the bridges with its own personnel or hires consultant personnel, the routing report would save time in scheduling and planning. These reports should identify bridges that require more frequent inspection because they were recommended for posting but were not posted. An example of a bridge inspection routing report is shown in Figure 20.

Year	Maintenance Residency	Bridge ID. No.	Principal Feature Name	Milepost	Maintenance Action	Urgency
88	BROWN	12107	US 195	10.41	Grease Bearings	L
		12157	FM 1456	16.82	Sweep Deck and Clean Scuppers	L
		12965	IH 35	57.44	Clean Trash from Substructure	M
		12345	US 200	12.33	Clean and Reseal Joints	M
		12007	FM 1495	7.69	Replace Narrow Bridge Sign	H
		12143	FM 1245	12.45	Clean Culvert	M
		12144	FM 1245	14.00	Clean Culvert	M
		12145	FM 1245	17.00	Clean Culvert	M
88	GREEN	12007	FM 1495	15.45	Replace Several Floor Boards	L

L - Low, M - Medium, H - High

Figure 19. Bridge minor maintenance schedule for each maintenance subunit and district.

Bridge ID.	Principal Feature Name	Milepost	Last Rating	On / Off System	Special Needs	Critical Areas
12176	US 59	17.3*	86	ON	Underwater Needed	Foundation
12177	US 59	24.0*	86	ON	Bucket Truck	----
12178	US 59	29.0*	86	ON	----	----
12179	US 59	35.0*	86	ON	----	----
12201	FM 1602	6.9	86	ON	----	Deck
12202	FM 1602	7.9	86	ON	----	----
12203	FM 1602	15.4	86	ON	----	Piers
etc. ↓						

NOTE ; All structures are listed in order of occurrence along the route

Figure 20. Bridge inspection and data collection routing reports.

District	Level Posting	I R	O R	Bridge I D Name	Primary Feature Name	Milepost	System ON / OFF	Owner
12	H S 2	HS 5	H S 2	12765	Jackson Street	12.31	OFF	City of Clark
12	H S 2	HS 5	H S 2	12743	FM 1266	10.23	ON	
12	Unposted	HS 25	H S 20	12945	US 65	17.30*	ON	
12	Unposted	HS 25	H S 20	12946	US 65	25.40*	ON	

NOTE: In this output bridges are in routing order as they appear along Route 65.

Figure 21. Bridge posting summary status report.

Bridge Posting Reports

A summary bridge posting report identifies all posted bridges and bridges that are candidates for analysis to determine if they need posting. Unposted bridges are flagged and an interim recommendation for posting is made until each bridge can receive the required MR&R action or be analyzed by structural engineers. The posting report provides decision-makers with a tool to temporarily remedy unsafe situations. An example of a bridge posting report is shown in Figure 21.

Bridges that are functionally obsolete, structurally deficient, and for which there are no funds available in the current budget may or may not be posted. After prioritizing and selecting MR&R actions across the network, the BMS develops a list of those bridges that are currently posted and those bridges that require posting. The BMS reports the posting list in three general categories of (1) structurally deficient bridges, (2) functionally obsolete bridges, and (3) historically significant bridges.

Overweight Permit Routing Reports

Another useful model BMS output is a routing report for overloaded permit vehicles. Residency and district offices are regularly petitioned by truckers for load routing of special dimensioned and weighted vehicles. This type of decision is usually required rapidly. Ideally, the BMS output will list all bridges along a particular route in their order of occurrence and include the following information: permissible width of load, permissible height of load, operating load rating, inventory load rating, permissible speed, and other restrictions.

With this information, the number of axles, and the weight and dimensions of the requested load, department personnel should be able to determine how to route most vehicles. The system should be flexible enough to allow the load permit clerk to enter the specific mileage point on a particular route where a load would enter that route, specify its direction of travel and, then, searching through alternative routes, come up with an acceptable route for the vehicle. Extremely special loads or unique conditions may require further structural analysis in detail and would thus use a cadre of programs available at the project level interface in the BMS. In the absence of an automated system for calculating allowables, outputs, like Figure 21, could be available to all permit offices.

Bridge Painting Reports

The model BMS produces reports describing bridge paint characteristics and plans. An example of a bridge painting report is shown in Figure 22.

Year	District	Bridge ID	Principal Feature	Milepost	Painting Type	Cost	Action
88	12	12575	US 75	12.3	Lead Based	1×10^6	Removal & Repaint
	12	12374	US 40	14.4	Zinc	0.5×10^6	Spot Removal & Overcoat
	14	14333	FM 69	13.4	Zinc	0.2×10^6	Spot Removal & Overcoat
	14	14380	US 90	01.6	Zinc	0.3×10^6	Spot Removal & Overcoat
	16						
89	. . .						
	etc ↓						

Figure 22. Bridge painting report and type.

FHWA Reporting

The model BMS assists the user agency to meet federal reporting requirements with outputs that provide the data required by the Federal Highway Administration for their budget allocation purposes and National Bridge Inspection Standards System (NBIS) data base.

MR&R Backlog Reports

This report identifies the bridges that are scheduled to receive MR&R action which has not been accomplished. This type of report provides immediate information on the type of MR&R work which is currently required on the network. This also provides a general overview of the state of the network.

Flexibility of Data Base Languages for Reporting

The model BMS will be developed using data base management language software that is flexible in producing output formats. A large variety of reports and reporting formats will be available in the model BMS. The capability for the user to design and produce custom reports is possible with the model BMS.

An interface between the model BMS and a graphics package will allow graphs and charts. In many instances an illustration is the best way to communicate individual concepts. These packages are flexible in the type of graphical presentations they can make, so the user can design and produce figures meeting his special needs.

COMPUTER ENVIRONMENTS

In order for many states to be able to install and use such a BMS, it should be designed to be applicable across many state DOT computer environments. Within the various state DOT's there are several types of computer environments in which a BMS can reside. A description of the pros and cons associated with establishing a BMS for several types of data processing environments follows.

Environment 1—BMS Written in a Data Base Management (DBM) Language for Microcomputers

Pros

1. These higher level languages are easy to learn both for engineers and data processing professionals. They are also very flexible with respect to report creation and generation. As a result the engineer has a useful tool with which to manipulate bridge data.
2. These languages allow the user to easily sort and select information from the data base.
3. Many DBM languages support other language subroutines, whereas the opposite is less often true.
4. There is a prominent DBM language (DBASE III+) which is in use in the microcomputer market. DBASE III+ can easily be implemented across DOT agencies. It is in fact already used by many agencies.
5. The DBM language on a microcomputer can be conveniently used to demonstrate BMS to states in order to give them a basis to decide on implementation of BMS in their agency.

Cons

1. A microcomputer version could be implemented only by states that do not have an extremely large number of bridges. States with up to about 10,000 bridges would be candidates. These states, either in conjunction with their Information Management System (IMS) or independently, would be able to install this BMS version easily and efficiently. (An IMS consists of a data base, procedures, and computer programs which collectively provide for capturing, storing, manipulating, and retrieving information vital to management of all applications for which an agency is responsible.)
2. Within the agency, data processing professional support may not be available. For example, some state DOT data processing departments do not currently support microcomputers, although this is changing rapidly. On the other hand, engineers are quite capable of providing their own support.

Environment 2—BMS Written in a Data Base Management (DBM) and Report Generation Language for Mainframes or Minicomputers

Pros

1. These higher level languages are easy to learn both for engineers and data processing professionals. They are also very flexible with respect to report creation and generation. As a result, the engineer has a useful tool with which to manipulate bridge data.
2. These languages allow the user to easily sort and select information from the data base.
3. Many DBM languages support other language subroutines, whereas the opposite is less often true.

Cons

1. There is no predominant DBM language in use across state DOT agencies. As a result, one would have to convince agencies to adopt BMS as well as support a new DBM language. This may be difficult and delay the implementation of BMS.

Environment 3—BMS Written in COBOL for Mainframe and Microcomputer Application

Pros

1. Similar versions of COBOL are installable on computer machinery of all types: mainframe, minicomputer, and microcomputer.
2. State DOTs generally have COBOL software support.
3. There is precedent to distributing large COBOL systems across DOT agencies. As a result, the distribution and third party support have already been tested and proven.

Cons

1. Engineers are normally not familiar with COBOL and as a result will have a system which they cannot control or change.
2. User report generation and graphics capabilities will be restricted to a COBOL-based system that will be designed to be applicable to several agency computer environments.
3. In-house COBOL software support usually exists, but is often not readily accessible to the engineer.

Environment 4—BMS Framed Inside a Geographical Data Base or Information Management System (IMS)

Pros

1. Access to other types of DOT-related information such as traffic data or environmental information.
2. Access to mapping and graphics capabilities.
3. Software support is usually available specifically for applications on an IMS.

Cons

1. High cost of establishing and maintaining a coordinated geographical-informational data base.
2. Today, IMS does not exist in most states or is in the development stage. Waiting on IMS development would hinder BMS implementation.

Conclusions

After considerable review, it appears that a prototype model BMS could best be created on a microcomputer. Statewide implementations could later occur at both the microcomputer and mainframe level using a higher level data base management software as the dominant system language. COBOL applications are the least likely to be successful for BMS.

These hardware/software configurations can meet the following BMS needs: promoting the concept of bridge management, continued development of the concept, and implementing the concept across several states and other agencies.

For microcomputer application, the BMS should be developed on an advanced microcomputer that uses an 80386 microprocessor (or latest technology) which runs at a minimum of 16 megahertz and a math co-processor for extremely fast data access, processing, and output times. The microcomputer should have a large storage capacity in the form of at least a hard disk with at least 10 megabyte storage capacity for every 1,000 bridges expected in the data base.

CHAPTER FOUR

MODEL BMS DEVELOPMENT AND IMPLEMENTATION PLAN

With the completion of this project, the preliminary design of the model BMS has been completed. The next step in the development of the BMS is to perform a detailed system design with complete specifications for the software. The BMS would then be programmed on a suitable computer and thoroughly quality tested. This would produce an operational BMS that is generic in its applicability across user agencies.

Once a generic system is fully operational, it can be used in an implementation program to apply and use the BMS on an existing bridge network. This can be effectively accomplished while working cooperatively with state DOT's. This will greatly enhance the BMS by subjecting it to the close scrutiny and review of operating agencies. To make the current model BMS into a productive system, several objectives need to be accomplished as follows:

- Complete detailed BMS design and software programming.
- Implement and test the BMS with cooperative agencies.
- Disseminate BMS implementation guidelines to all agencies.
- Create a BMS support system.

Once these objectives are fulfilled, the model BMS will be a useful system which can be coordinated across agencies and will provide benefits to many public agencies at a relatively modest cost.

OBJECTIVE 1—SOFTWARE DEVELOPMENT[1]

The first objective in deploying the model BMS is complete development of working computer software. In this project, a good start has been made on this effort but much more needs to be done. Table 14 is a suggested list of those modules, coding activities, and options that could constitute the first operational BMS. This outline provides a framework from which (1) different system design options can be compared and chosen; (2) the final system design can be enhanced, checked, and improved; and (3) program coding can be scheduled.

Table 14. BMS software development—module and submodule coding units.

MODULE 1. DATA BASE MODULE
- A. Location data
- B. Inventory data
- C. Condition data
  - Option a. Severity rating only
  - Option b. Distress identified with severity and extent
- D. MR&R needs from bridge inspection
- E. MR&R expenditures/activities

MODULE 2. NETWORK MR&R SELECTION MODULE
- A. Rating submodule
  1. Sufficiency formulation unique to the agency
     - Option a. Fixed formula
     - Option b. User determined formula
  2. FHWA sufficiency formula
- B. MR&R selection submodule
  1. Decision tree algorithm
     - Option a. Fixed decision tree
     - Option b. User determined decision tree
  2. User override of MR&R choice
- C. Life cycle costing submodule
  1. LCAP data entry
  2. Deterioration model data entry
  3. Effectiveness variable calculation
  4. Life cycle costs calculation
  5. User override of LCAP choice
- D. Optimization submodule
  1. Incremental cost-effectiveness method
  2. User override of LCAP choice

MODULE 3. MAINTENANCE MODULE
- A. Needs estimation
  1. Direct data collection
  2. Algorithms based on distress
- B. User override

MODULE 4. HISTORICAL DATA ANALYSIS MODULE
- A. Archive data
- B. File creation for interfaced analysis packages
  1. User defined subset definition
  2. User defined variable needs
  3. User defined categories and summaries
- C. Self adjusting deterioration equations

MODULE 5. PROJECT LEVEL INTERFACE MODULE
- A. Flat file creation for data use by project level application
  1. User defined subset definition
  2. User defined variable needs
  3. User defined categories and summaries
- B. More data into BMS on bridge by bridge basis for a set of user selected BMS variables
- C. Data transfer into specific project level application format
  1. Data transfer to/from BARS
  2. Data transfer to/from BRASS

MODULE 6. REPORTING MODULE
- A. Data sorting
  1. Fixed
  2. Interactive user inputs
- B. Subset selection
  1. Fixed
  2. Interactive user input
- C. Data categorization
  1. Fixed
  2. Interactive user input
- D. Specific Reports
  1. Bridge Inventory
  2. Sorted Listings
  3. Network MR&R Plan

Table 14. Continued

4. Historical MR&R Summary
5. Network Bridge Attribute Distributions
6. Summary Distress
7. Network Summary Statistics
8. Project Level Results
9. Bridge Traffic and Loads
10. Budget
11. Administrative Policy
12. Maintenance Schedule
13. Bridge Inspection Schedule and Routing
14. Bridge Posting
15. Overweight Permit Routing
16. Bridge Painting
17. FHWA Report Requirements
18. MR&R Backlog

OBJECTIVE 2—BMS IMPLEMENTATION WITH COOPERATING AGENCIES

Agency involvement and contribution are essential to the implementation of the operational BMS. Further testing and implementation of the BMS in a state or local DOT is the principal mechanism by which these agencies can contribute to and influence the evolution of the BMS development. Table 15 contains recommendations regarding the subtasks for state DOT participation in the BMS implementation program. It is believed that such participation is an essential aspect in the development of a widely implementable BMS.

Implementing a working BMS in cooperation with medium-

Table 15. Subtasks for agency implementation of the BMS.

1. Set criteria for state selection
2. Screen candidate states and select a minimum of 2 states
3. Collect and review state BMS practices and data
4. Visit State DOTs
   - A. Explain BMS software
   - B. Show data list
   - C. Show decision criteria and data needed for each level of MR&R selection
   - D. Present user options
   - E. Present report options
5. Summarize State Decisions and suggestions
   - A. Data collection changes - variables in or out
   - B. Data analysis changes
   - C. Reporting changes - reports changed or added
6. Plan work and submit to states and NCHRP
7. Receive state comments and make software modifications
   - A. Data collection changes
   - B. Data analysis changes
   - C. Reporting changes
8. Make second visit to State DOTs
   - A. Submit data collection manual
   - B. Collect input data on the chose state's bridges
   - C. Collect existing network wide SI&A data
   - D. Install BMS
   - E. Train State DOT Data Processing Staff in software operation
9. Prepare network runs
10. Present results
11. Record agency feedback and report on malfunctions and enhancement needs
12. Correct malfunctions and add top priority enhancements
13. Work with State personnel and the bridge "network" results to plan additional enhancements
14. Report on any problems
15. Prepare Final Report to NCHRP on continued development/future of BMS
16. Prepare Final Documentation for Program

to small-sized agencies will lend additional credentials and proof to the value of the final product delivered on NCHRP Project 12-28(2). It will also highlight and determine any possible additional needs that should be included in the design of an overall BMS.

OBJECTIVE 3—BMS IMPLEMENTATION AIDS: CREATION AND DISSEMINATION

Widespread use of the model BMS will enhance familiarity, discussion, and acceptance of the BMS concept within the bridge community. Furthermore, for widespread use of BMS to occur, the acceptance of BMS precepts needs to be augmented with a road map illustrating BMS implementation.

To obtain support and implementation opportunities for the new BMS, it will be important to provide AASHTO member agencies a program that will familiarize state bridge engineers with the product of Project 12-28(2). A good format for such an activity could be a series of short-courses for introducing and training potential states on the availability of the product. An excellent example of this was the training activity undertaken to introduce the new AASHTO Pavement Design Guide to the states.

Tasks required to satisfy this objective are as follows:

- Prepare a 1½- to 2-day BMS short course.
- Establish contacts with interested state and local agencies and carry out a number of regional short courses/seminars.
- Summarize the results of these seminars and feedback provided by agency personnel.

The short-course seminar should include the following general elements among others:

- A general introductory session on the benefits of Bridge Management.
- A general overview of BMS activities including those of the larger states and the FHWA.
- A hands-on working period for state bridge engineers to use the operational microcomputer program.
- An informal discussion and workshop period for feedback on the review of the BMS by those attending.

A series of short-courses provided in this manner will rapidly make known to potential users of the BMS system the capabilities and availability of the system. This will provide state of the art in both concepts and applications.

These short courses will establish a referendum of potential users as to the most preferable computer environment. This will assist with a decision of whether to continue to support and enhance a microcomputer version of the system or to develop and support an appropriate mainframe version and to determine which would have the most widespread acceptance, use, and support.

OBJECTIVE 4—ESTABLISH A BMS SUPPORT GROUP

The viability of a cooperative BMS effort is contingent on the creation of a central BMS support group. Such a group provides a valuable service to the use and development of the model BMS. Among those services provided by such a support group are:

- Aid to users.
- System malfunction correction.
- System distribution.
- Implementation of system enhancements.
- Coordination of system versions, releases, and associated documentation.

Experience with other programs suggests that AASHTO is an appropriate agency under which this type of service can be accommodated.

It will be important that the BMS support group select a technical user's group committee. For example, the bridge analysis and rating system (BARS) has a user's group that meets on a biannual basis to provide information and direction to the software support group relative to user's desires for the system they are supporting. System malfunctions can be listed and provided by members to the technical user's group which then can prioritize those malfunctions for correction by the central software supporting group.

These four general objectives and their related tasks comprise the level of effort that is required for complete BMS development and widespread implementation. This will produce a system which can, from that point forward, be self-sustaining for its enhancement. It can also provide for future linking to other infrastructure management systems like pavement management systems, roadway maintenance management systems, equipment maintenance management systems, and so on.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

This report recounts the findings of an intensive 24-month study of bridge management in the United States, a search of worldwide literature describing related efforts, and the development of a model BMS. The research highlights a working network-level bridge management system. The findings disclose the desire of numerous agencies to use a BMS at levels ranging from structural analysis and recordkeeping on a single bridge or project to programming and planning activities on a whole network of bridges within a state highway agency. The emphasis, however, is on the network level.

Significant interaction underlies this report, including meetings with the NCHRP advisory panel, representatives of several states, and individual visits by the project staff to six state DOT's. This interaction and detailed staff work produced a conceptual modular bridge management system for network level bridge management, which contains six basic modules (data base module, network level MR&R selection module, maintenance module, historical data analysis module, project level interface module, and reporting module). Each module has a number of important functions which have been described in this report. The functions that can be considered most important are: (1) the selection of an MR&R program for the network with the use of life-cycle costing methods and optimization, (2) assignment of a preventive maintenance program on the network, and (3) handling the large amount of data from bridges on the network.

In addition to the concepts, a demonstrator BMS was produced for use on a personal computer. The available project funding did not permit the completion of the demonstrator. Nevertheless, a simple computer program is available along with a short user's manual. The program demonstrates the benefits and potential output of a BMS to potential sponsors.

It is clear from the project work that a network level bridge management system is within the reach of today's technology. The development and implementation plan presented in Chapter Four will make it possible to develop and test a working BMS. The BMS will then be implemented in some state DOT's as a significantly improved tool for bridge management. It will also provide the mechanism for self-improvement through use of the historical data base in any given state and related sources. States with similar backgrounds can combine their historical data in some cases to improve the quality of performance prediction and life prediction models. Regional models may result from such cooperation.

A number of technological improvements will enhance the practice of bridge management and the model BMS. The first needed improvement is a method to obtain more objective measures of bridge condition. Automated survey and condition rating devices and procedures would facilitate obtaining rapid, reliable measurements of bridge condition and structural capacity. Aspects such as width and length measurement, vertical clearance, roughness, and rutting can already be easily measured by high technology automated devices. Techniques using photography and laser technology are currently used in the measurement of pavement distresses. These techniques could be adapted to the condition rating of bridge decks. Other automated techniques such as monitoring steel corrosion and measuring the chloride content of decks would also be useful. Ultimately, a geographical mapping capability interfaced with the data base would be extremely useful. A map of the bridge network would be digitized and stored in the data base and could be printed with routing information, inspector's schedules, network MR&R plan, minor maintenance plan, and the bridge posting report. This type of technological improvement would greatly enhance the capabilities of the BMS. One final improvement that would assist the field engineer would be the use of small hand-held computers to collect and immediately store the bridge rating data. This technology is already available; it only needs to be adapted and applied to bridge survey activities.

Improvements are also needed in the prediction of distress and rehabilitation effectiveness models used in the BMS. These include deterioration rates, bridge life cycle cost models, and effectiveness of various MR&R actions. A significant amount of research is necessary to produce better models. Over time, the implementation of the suggested BMS will provide a great deal of the information necessary to develop new and better predictive equations. The model BMS itself will have the capability to develop improved equations as adequate data are collected over time.

Presentations at a national bridge management workshop held in conjunction with the Transportation Research Board Annual Meeting in Washington, D.C., January 1987, strongly underscored the several basic needs found in this project.

There is inadequate information available from any data source within the United States to provide significant life prediction models for bridges in a variety of conditions. Additional efforts in a later phase will be needed to collect what information is available to develop preliminary life prediction models for use in an improved BMS. More importantly, it will be necessary for many states to begin to collect and store bridge condition information in a format that can be used to make life cycle and performance predictions. Various theoretical and analytical models can potentially be used to initially fill the gaps in these life prediction models. Additional information is also needed to estimate the relationship between various maintenance activities and bridge life and performance. These include for example: painting of steel structures, inspection of pins and weldment, riveted connections, and cathodic protection of decks.

This project suggests the value of implementing the first BMS on a microcomputer. Ultimately, the software can be adapted for use on microcomputers, minicomputers, or mainframe computers, depending on the needs and availability of equipment in the agency involved.

A significant need exists for improved bridge management and a bridge management system for use in state DOT's in the United States and the world, at large. Most agencies contacted showed enthusiastic interest in the potential of bridge management and a number of agencies have specifically requested inclusion for implementation in a subsequent research phase. The study suggests that it will be possible to implement a working BMS in a small or moderate-size agency within the next 2 to 5 years if adequate support and funding are provided.

In developing an operational BMS it is important to keep the modules of the system general enough for application in any agency. While additional data and improved models will be helpful in later phases, it is clear that there now exists adequate technology and information for BMS development. The immediate benefits that will arise from such development will undoubtedly lead to the additional data and research support necessary for subsequent implementation and improvement of BMS. Multistate support of a common system would pay exponential dividends for the expenditures.

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APPENDIX A

DESCRIPTION OF MODEL BMS VARIABLES

A set of variables to be considered for use in a BMS is presented in this appendix. The variables are listed according to major record types. Each variable is described separately. The description is for programming purposes and includes the variable's name, number, class, description, number of characters of disk storage space required, and type (i.e., alphanumeric, integer, real, or logical). Many of the variables were originally defined by the FHWA for its National Bridge Inspection Standards (*3*).

The variables are divided into four categories: (1) inventory variables, (2) bridge condition variables, (3) bridge appraisal and proposed improvement ratings, and (4) MR&R historical variables. The four categories are subdivided into "records". Each record is a set of variables pertaining to a similar aspect of the bridge.

Each major record is identified by a letter. Each variable within a record is identified by a number. Therefore, each variable is uniquely described by a letter-and-number combination. For example, variable A2 names the county where the bridge is located. The corresponding Federal SI&A rating form variable numbers are included in the description.

INVENTORY VARIABLES

Inventory variables describe the bridge in terms of location, type, functional classification, and so on. Once they are entered for a particular bridge, they are rarely changed. These variables provide information for locating the bridge and determining its relative importance within the network. In terms of the importance of the bridge, several inventory variables may be used in the prioritization and optimization techniques. A description of each of the inventory variables follows:

A. Identification Information Record

A1. System Code - a variable to describe the bridge system or network that the bridge belongs to or whether the bridge is on or off the federal aid system.
Number of characters - 2
Type - integer

A2. County - the FIPS code identifying the county in which the bridge is located.
Number of characters - 3
Type - integer

A3. City/town code - the FIPS code identifying the city or town in which the bridge is located. All zeros are coded if the bridge is not in a city or town.
Number of characters - 4
Type - integer

A4. Structure number - a number which uniquely identifies the structure or bridge. This may be a numbering system unique to the agency involved.
Number of characters - 15
Type - alphanumeric

A5. FIPS code for states and FHWA region - code identifying the state and FHWA region in which the bridge is located. This is the same as the federal form's current standard.
Number of characters - 3
Type - integer

A6. Highway district - same as federal variable number 2.

A7. Principle route - same as federal variable number 5.

A8. Location - same as federal variable number 9.

A9. Principle route mile point - same as federal variable number 11.

A10. Engineering project/drawing number - This is an internal agency identification number to allow project drawings, specifications and designs to be quickly located in the agency's filing system.
Number of characters - 15
Type - alphanumeric

A11. Bridge name - common name which a bridge is known by in the community
Number of Characters - 15
Type - alphanumeric

A12. Principal Route Position - Whether the principal route is over or under the bridge.
Number of Characters - 1
Type - integer

A13. Town name - The name of the town the bridge in nearest to.
Number of Characters - 15
Type - alphanumeric

B. Environmental Record

B1. Freezing index - a variable to describe the propensity toward freezing of the area in which the bridge is located.
Number of characters - 1
Type - integer

B2. Saline environment - a variable to describe the degree of salt to which the bridge is exposed. Various levels or codes may be assigned.
Number of characters - 2
Type - integer

B3. Rainfall - a variable which describes the average amount of rainfall received in the area in which the bridge is located.
Number of characters - 2
Type - integer

C. Defense Importance Record

C1. Defense road section number - same as federal variable number 12.

C2. Defense bridge description - same as federal variable number 13.

C3. Defense mile point - same as federal variable number 14.

C4. Defense section length - same as federal variable number 15.

C5. Latitude - same as federal variable number 16.

C6. Longitude - same as federal variable number 17.

C7. Physical vulnerability - same as federal variable number 18.

D. Essentiality/classification/jurisdiction record

D1. Essentiality to public transport - this variable describes whether the route that the bridge serves is used by public transport such as for school buses, as a fire lane, for snow plows, or as a public transit route.
Number of characters - 1
Type - logical

D2. Detour length - same as federal variable number 19.

D3. Toll road - same as federal variable number 20.

D4. Custodian - same as federal variable number 21.

D5. Owner - same as federal variable number 22.

D6. Type of project - this variable explains how the bridge was funded. It is coded as follows:
1 - federal aid
2 - nonfederal aid with all state funds
3 - nonfederal aid with other public nonstate funds
4 - nonfederal aid with private funds
5 - other or unknown
Number of characters - 1
Type - integer

D7. Project number - same as federal variable number 23.

D8. Federal aid system code - same as federal variable number 24.

D9. Principle route administrative jurisdiction - same as federal variable number 25.

D10. Principle route functional classification - same as federal variable number 26.

D11. Year of construction and major reconstruction - same as federal variable number 27 except multiple years can be handled to account for all major construction work.

D12. Principle route ADT - same as federal variable number 29.

D13. Year of traffic count - same as federal variable number 30.

D14. Truck factor - this variable describes the amount of truck traffic which crosses the bridge. It is expressed in terms of % trucks with more than two axles.
Number of characters - 4
Type - real

D15. Design truck loading - same as federal variable number 31.

D16. Historical significance - same as federal variable number 37.

D17. Political unit number 1 - this variable describes the primary political unit in which the bridge is located.
Number of characters - 3
Type - alphanumeric

D18. Political unit number 2 - this variable describes the secondary political unit in which the bridge is located.
Number of characters - 3
Type - alphanumeric

D19. Walkway - indicates if walkway space is provided for pedestrians.
Number of characters - 1
Type - logical

D20. Speed limit - the posted speed limit on the principal route
Number of Characters - 2
Type - Intéger

E. Navigation and Waterway Record

E1. Existence of navigation control - same as federal variable number 38.

E2. Navigation vertical clearance - same as federal variable number 39.

E3. Navigation horizontal clearance - same as federal variable number 40.

F. Posting Record

F1. Operational status - same as federal variable number 41 to indicate whether bridge is open or closed.

F2. Operating rating - same as federal variable number 64 indicating the absolute maximum permissible load on the bridge.

F3. Inventory rating - same as federal variable number 66 which indicates the highest load for the bridge for long-term use.

F4. Weight limit - this includes two subvariables (the axle load limit and the gross load limit) for which the bridge may be posted.
Number of characters - 5
Type - integer

G. Safety Inventory Record

G1. Approach roadway width - same as federal variable number 32.

G2. Bridge median code - same as federal variable number 33.

G3. Skew - same as federal variable number 34.

G4. Structure flare - same as federal variable number 35.

G5. Traffic safety features - this is the same as federal variable number 36 and consists of four subvariables which indicate the type and acceptability of (1) bridge railings, (2) approach guard rail transitions, (3) approach guard rails, and (4) approach guard rail ends.

G6. Sight distance - this variable indicates the distance from the bridge at which it can first be sighted.
Number of characters - 3
Type - integer

G7. Illumination - this variable indicates how well the bridge is lighted for pedestrians and vehicular traffic to see obstacles on the bridge.
Number of characters - 1
Type - integer

G8. Number of accidents per 100,000 vehicles - gives information and accident data for the bridge.

H. Secondary Features Record

H1. Name of secondary features - this is the name which the agency recognizes for the secondary feature which may pass under or over the bridge. The secondary feature is not the principle route. For example, if the principle route passes under the bridge, then the secondary feature would be whatever is on top of the bridge and vice versa.
Number of characters - 12
Type - alphanumeric

H2. Type of feature - this is whether the feature is a road, railroad, or waterway, etc.
Number of characters - 1
Type - integer

H3. Route number - this is the same as federal variable number 5 for the principle route except that it is for the other route if the secondary feature is a roadway. It is left blank or zeros are entered if the secondary feature is not a roadway.

H4. Route mile point - same as federal variable number 11 except for the secondary feature if a roadway.

H5. Essentiality to public transport - this indicates how essential the secondary feature is to public transport, such as school buses, snow plows, fire trucks, or public transit. Number of characters and type are the same as the principle route essentiality to public transport.

H6. Detour lengths - this is the same as federal variable 19 except applied to the secondary feature.

H7. Toll road - this is the same as federal variable number 20 except applied to the secondary feature.

H8. Federal aid system code - same as federal variable number 24 except applied to the secondary feature.

H9. Route administrative jurisdiction - same as federal variable number 25 except applied to the secondary feature.

H10. Route functional classification - same as federal variable number 26 except applied to the secondary feature.

H11. Route ADT - same as federal variable number 29 except applied to the secondary feature.

H12. Year of traffic count - same as federal variable number 30 except on the secondary feature.

H13. Truck factor - same as truck factor (variable D14) described for principle route except applied to the secondary feature.

H14. Design truck loading - same as federal variable number 31 except for secondary feature.

H15. Route horizontal clearance - this is the horizontal clearance on the secondary feature. It is divided into two subvariables: H15.1 - right clearance and H15.2 - left clearance.

H16. Route minimum vertical clearance - this is the same as federal variable number 10 except applied to the secondary feature.

H17. Number of lanes on the other feature if roadway - same as federal variable number 28 except applied to the secondary feature.

H18. Roadway width - same as federal variable number 51 except applied to the secondary feature.

H19. Existence of navigation control - this variable will be added in case all variables under category E are not included. If so, then this variable will be the same as federal variable number 38.

H20. Position - whether the secondary feature is under or over the bridge.

I. Structural Inventory Record

I1. Structure category - this is the category that the structure is in: steel bridge, concrete bridge, timber bridge, composite bridge, culvert, or tunnel.

Number of characters - 1
Type - integer

I2. Principle route horizontal clearance - this is the same as federal variable number 47. It includes two subvariables: I2.1 - right hand clearance and I2.2 - left hand clearance. These are the same as federal variables numbers 55 and 56, except that 55 and 56 refer to the under clearance on the right and on the left for divided highways and one-way streets. See Reference 3 for more details.

I3. Principle route minimum vertical clearance - this is the same as federal variable number 10.

I4. Widening code - this tells whether the bridge can be widened or not.
Number of characters - 1
Type - logical

I5. Roadway width - this is the same as federal variable number 51.

I6. Length of structure - this is the same as federal variable number 49.

I7. Sidewalk width - this is the same as federal variable number 50.

I8. Number of lanes on the principle route - this is the same as federal variable number 28.

I9. Superstructure type - this is similar to federal variable number 43 but has subvariables to further define how the bridge is divided. The method used is to divide the bridge into "span groups" for the purpose of rating the bridge and storing the data. A span group can be defined as sections of equal span length, span type, and main member type. A span group can also consist of individual spans or an entire bridge if the user does not wish to distinguish a difference or if a bridge is of like construction throughout.

I9.1. Number of span groups - for each span group the following variables are defined in a separate span group data file.

I9.1.1. Span type in span group
I9.1.2. Main member type in span group
I9.1.3. Number of spans in span group
I9.1.4. Span length in span group
I9.1.5. Span group number
I9.1.6. Name of span group

I9.2 Type of paint system
I9.3 Date existing paint system placed

I10. Substructure type - this is similar to federal variable number 44 but is further divided into two subvariables as follows:

I10.1. Cap type
I10.2. Pier type

I11. Deck type - this is similar to federal variable number 57 and is further divided into subvariables as follows:

I11.1. Material type
I11.2. Design type
I11.3. Wearing surface type
I11.4. Deck concrete air entrained
I11.5. Membrane type
I11.6. Stay-in-place forms used
I11.7. Type of cathodic protection
I11.8. Date wearing surface placed
I11.9. Type of reinforcing steel protection

I12. Deck width - this is the same as federal variable number 52.

I13. Deck joint types - this variable indicates the types of joints that are present on the deck. Three integer codes are used for changing joint types.
Number of characters - 3
Type - integer

I14. Fracture critical members - indicates if the bridge contains fracture critical numbers.
Number of characters - 1
Type - logical

BRIDGE CONDITION VARIABLES

Condition variables are obtained from field inspection of the bridge. They are entered into the BMS and are used in calculations. The input condition variables are divided into records and variables as with the inventory variables described previously. The major records correspond to federal sufficiency rating variables as indicated by the number. These records correspond to a major component of the bridge such as roadway, superstructure, substructure, channel, or approaches. The subvariables correspond to the elements of the major components of the bridge, for example, deck and wearing surface are elements of the roadway; main members and floor system connections are elements of the superstructure.

Each bridge element may be evaluated on one of three levels. The level is indicated next to the variable by various combinations of the letters R, E, and D. The lowest level of evaluation is only R, which indicates that the element corresponding to the variable is merely rated on the standard 0 to 9 scale. The second level, R/E, indicates that the element corresponding to the variable is rated on the 0 to 9 scale in terms of the problem that exists, and the extent of the problem is estimated in terms of being local or prevalent, the estimated area affected, or some other measure. The highest level of evaluation is indicated by the combination R/E/D. This indicates that the element is rated on the 0 to 9 scale, the extent of the problem is estimated, and the actual distress causing the problem is specified.

The bridge condition variables with their recommended level for being rated are as follows. The variable numbers in parentheses correspond to the variable numbers in the Federal SI&A rating form.

J. Roadway Condition Rating (58)
- J1. Deck R/E/D/
- J2. Wearing surface R/E/D
- J3. Joints R/E
- J4. Drainage system R
- J5. Curbs, sidewalks, and parapets R/E
- J6. Median barrier R/E
- J7. Railings R/E
- J8. Delineation (striping and curve markers) R

K. Superstructure Condition Rating (59)
- K1. Main members R/E/D
- K2. Main member connections R/E/D
- K3. Floor system members R/E/D
- K4. Floor system connections R/E/D
- K5. Secondary members R/E
- K6. Secondary member connections R/E
- K7. Expansion bearings R/E
- K8. Fixed bearings R/E
- K9. Steel protective coating R/E

L. Substructure Rating (67)
- L1. Abutments R/E/D
  - L1.1. Caps
  - L1.2. Above ground
  - L1.3. Below ground
- L2. Intermediate supports R/E/D
  - L2.1 Caps
  - L2.2. Above ground
  - L2.3. Below ground
- L3. Collision protection system R
- L4. Steel protective coating R/E
- L5. Retaining walls (62) R/E/D
- L6. Culverts
  - L6.1. Damage to pipe
  - L6.2. Debris
  - L6.3. Damage to walks
- L7. Concrete protective system R/E/D

M. Channel and Channel Protection Rating (61)
- M1. Banks R
- M2. Bed R
- M3. Rip rap R/E
- M4. Dikes & Jetties R
- M5. Substructure foundation erosion (scour) R/E

N. Approaches Rating (65)
- N1. Embankments R/E
- N2. Pavement R/E
- N3. Relief joints R/E
- N4. Drainage R/E
- N5. Guard Fence R/E
- N6. Delineation markers R

O. Estimated Remaining Life (63)

P. Inspection Information
- P1. Date of last inspection (90)
- P2. Unusual inspection features
- P3. Frequency of unusual inspections
- P4. Date of last unusual inspection
- P5. Inspector

BRIDGE APPRAISAL PROPOSED IMPROVEMENT RATINGS

Appraisals are calculated values based on the condition ratings of the bridge components and their elements, and on inventory items, such as deck width, number of lanes, and vertical clearances. The method used by the BMS to calculate the appraisal ratings is the same method used in the Texas BRINSAP system (*11*).

The proposed improvements correspond to federal variable numbers 73 through 88. These items, if included in the BMS, will be estimated after analysis of the bridge condition, the MR&R life-cycle activity options chosen by the BMS, and the local and network-wide budget constraints. These variables may be derived by the BMS or input directly by the user. The required maintenance activities are input by the user based on the observations made by the inspector. Estimates made by the BMS will improve with time.

The following is a list of the variables for appraisals and proposed improvements. Detailed explanations, number of characters, and type of variable may be obtained in the Federal SI&A coding procedures (*3*).

Q. Appraisal (Calculated values to be output in report)
- Q1. Traffic safety features (36)
- Q2. Structural condition (67)
- Q3. Roadway geometry (68)
- Q4. Vertical and lateral clearance (69)
- Q5. Safe loading capacity (70)
- Q6. Waterway capacity (71)
- Q7. Approach roadway (72)

MR&R HISTORICAL VARIABLES

Historical records of maintenance, rehabilitation, and replacement (MR&R) actions accomplished are maintained in the BMS data base. These variables are input after an MR&R action takes place on a bridge and describe the actions undertaken. The variables are stored on a historical basis to develop a life profile for the bridge, to estimate maintenance and repair costs for bridges in general, to predict deterioration rates and deterioration retardant constants for bridges, and to estimate entire network MR&R budget levels. The following is a list of the variables associated with the historical MR&R record.

R. Proposed Improvements
(Items as specified in federal form have federal number in parentheses)

- R1. Year needed (73)
- R2. Type of service (74) (same as 5 or 42)
- R3. Type of work (75)
- R4. Length of improvements (76)
- R5. Proposed design load (77)
- R6. Proposed roadway width (78)
- R7. Proposed number of lanes (79)
- R8. Design ADT (80)
- R9. Year of Estimated ADT (81)
- R10. Year of scheduled adjacent roadway improvements (82)
- R11. Type of adjacent roadway improvements (83)
- R12. Cost of all improvements (84)
- R13. Base year for estimated improvement costs
- R14. Preliminary engineering costs (85)
- R15. Demolition costs (86)
- R16. Substructure costs (87)
- R17. Superstructure costs (88)
- R18. Required maintenance activity 1
- R19. Level of maintenance activity 1
- R20. Urgency of maintenance activity 1
- R21. Required maintenance activity 2
- R22. Level of maintenance activity 2
- R23. Urgency of maintenance activity 2
- R24. Required maintenance activity 3
- R25. Level of maintenance activity 3
- R26. Urgency of maintenance activity 3

S. Historical MR&R Record

S1. Bridge Number - this is the unique number which identifies the bridge or structure under consideration. It is the same as our variable number A4 which is the same as federal variable number 8. It is used for cross-referencing the BMS files with the maintenance files from the MMS for bridges.

S2. Year - this is the year that the MR & R action takes place. It is coded such that 1986 would be 986.
Number of characters - 3
Type - integer

S3. Type of action - this is divided into two subvariables:

S3.1. Major category of action - these are the five major categories: maintain, repair, rehabilitate, reconstruct and replace. These are coded 1 through 5 respectively.
Number of characters - 1
Type - integer

S3.2. Action item - this is the individual activity which is a subitem of one of the major categories listed above. It consists of detailed MR&R actions which take place on a bridge. It is coded with a number which corresponds to the specific item as listed in Table A.1.
Number of characters - 2
Type - integer

Table A.1. MR&R action codes.

1 MINOR MAINTENANCE

01 painting
02 joint cleaning and sealing
03 bearing cleaning and lubrication
04 sealing concrete surfaces
05 drift removal
06 crack sealing
07 bolt tightening or replacement
08 deck washing
09 clean drainage system
10 moveable bridge mechanical or electrical equipment maintenance
11 approach leveling or repair
12 deck patching
13 touch up painting
14 minor repair or cleaning of culverts
15 handrail maintenance or repair
16 expansion joint maintenance
17 fender system maintenance
18 slope or shore protection system maintenance

2 MAJOR MAINTENANCE

01 replace drainage system elements
02 replace collision damaged structural members
03 correct scour condition
04 replace decayed timbers
05 bearing repair
06 deck injection with grout or resin
07 replace expansion devices
08 relevel abutments and piers
09 patch substructure members
10 strengthen of straighten steel members
11 curb repair
12 replace gaurdrails
13 repair fender system
14 sheath pier to add cross-sectional area
15 splice broken reinforcing steel and re-concrete
16 steel plating of timber decks
17 clean box culverts
18 repair steel deck grids
19 replace or upgrade bridge rails

3 REHABILITATE

01 deck replacement
02 increasing structure capacity
03 replace major superstructure main elements
04 replace major substructure main elements
05 deck overlay
06 cathodic protection
07 sheath pier to add cross sectional area
08 substructure strengthening
09 deck rehabilitation
10 bridge raising to gain vertical clearance
11 fatigue prone detail retrofit
12 seismic retrofit
13 replace wearing surface

4 RECONSTRUCT

01 new superstructure using existing substructure
02 bridge widening

5. REPLACE

6. POST

01 structural capacity
02 vehicle speed
03 vehicle height
04 number of vehicles

7. CLOSE

8. REMOVE

S4. Scheduled, completed, or in progress - indicates whether the maintenance action described by variable 3 is scheduled for the bridge or has been completed.
Number of characters - 1
Type - logical

S5. Quantity of the units specified in the type file - this is the quantity of the action taken on the bridge. The units for the quantity are specified in the type file as described under variable S3 above. For example, action 1.01 is painting. The units in the type file are specified for painting to be square feet of paint, for example. Therefore, this variable (S5) will specify the number of sq. ft. of surface which requires paint on this particular bridge.
Number of characters - 6
Type - real

S6. Costs - these are the costs associated with the MR&R action taken on the bridge. It is divided into five subvariables: individual labor cost, equipment cost, materials cost, the total cost, and miscellaneous costs. It is anticipated that such a breakdown of costs may not always be possible, and values should be given to each variable as applicable.
Number of characters - 7
Type - integer

APPENDIX B

GRAPHICAL REPRESENTATION OF THE IDEALIZED BRIDGE MANAGEMENT SYSTEM

The idealized Bridge Management System is a complex framework composed of numerous interrelated functions. During the development of this BMS, the individual functions were grouped into a series of modules. Each module is described in detail in Chapter Three of the main text.

In order to better understand the relationships between these operational modules in the idealized system, a series of BMS framework flow charts has been developed. The flow charts are shown in Figures B-1 through B-5. These figures indicate the intricacies inherent in the flow of information related to man-

FUNCTIONAL FRAMEWORK OF BRIDGE MANAGEMENT SYSTEM

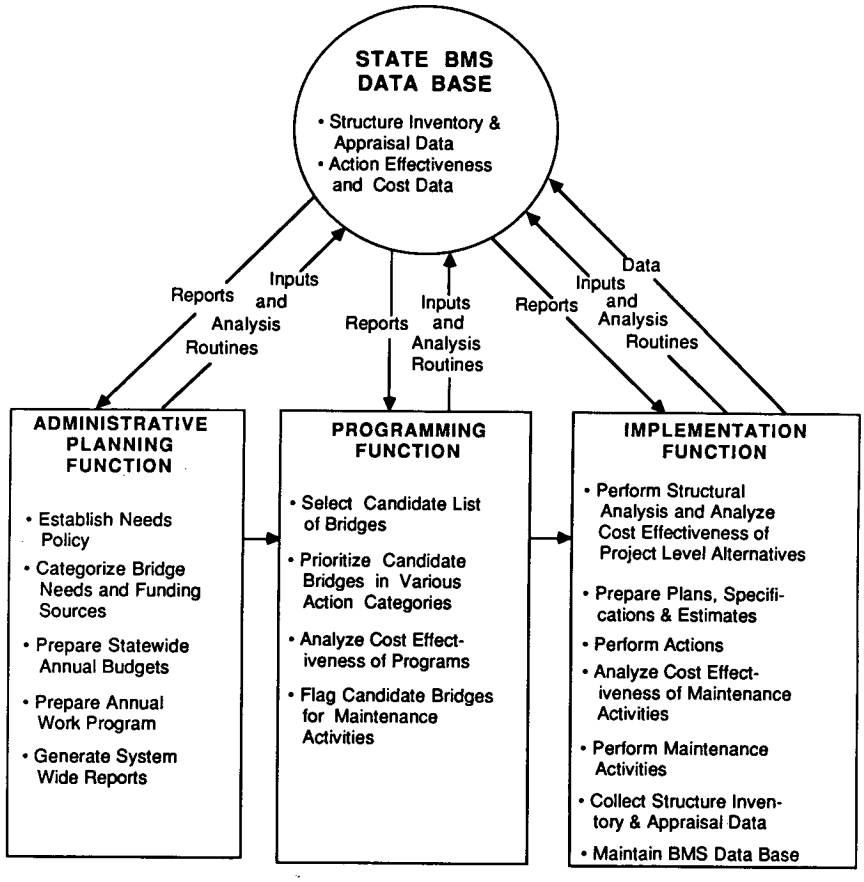

Figure B-1. A conceptual framework of BMS.

aging a bridge network. The details of the framework provide insight into the data collection requirements, decision-making processes, and reporting requirements.

Figure B-1 shows the functional framework of the complete idealized Bridge Management System. Figures B-2 through B-5 detail the activities that should be included in the administrative planning, programming, implementation, and bridge maintenance activities, respectively.

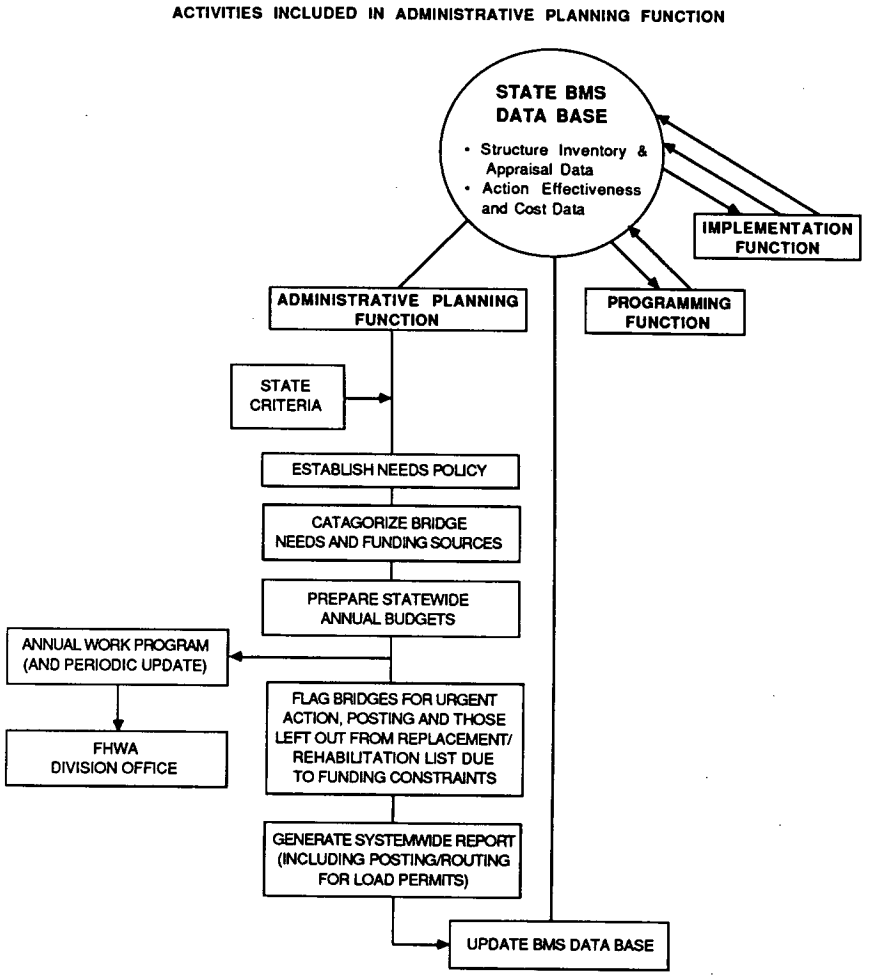

Figure B-2. A conceptual illustration of the administrative planning function.

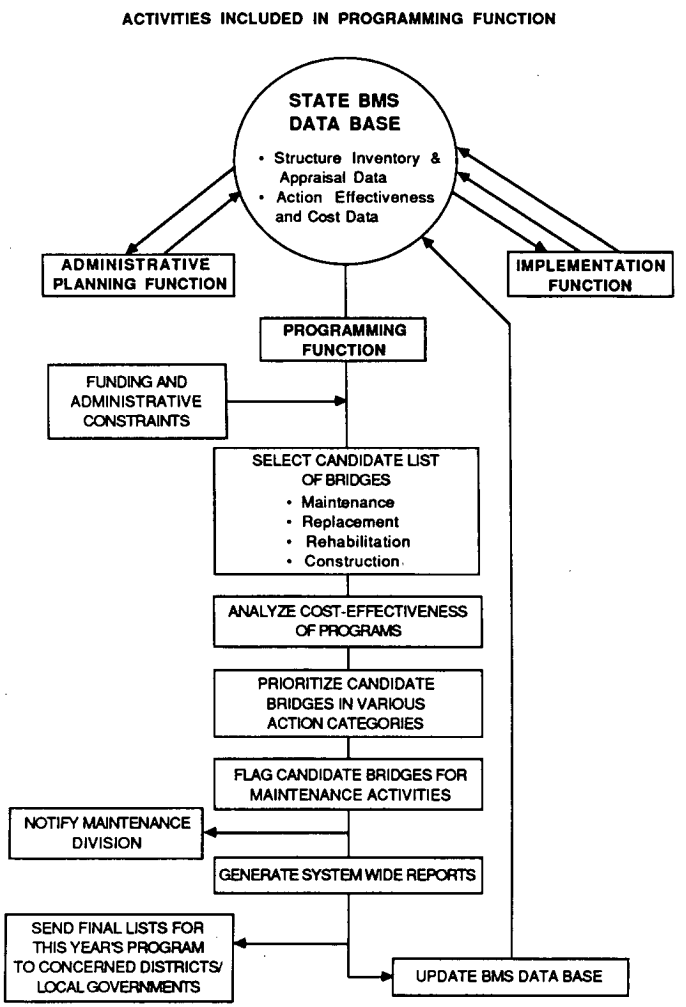

Figure B-3. A conceptual illustration of the programming function.

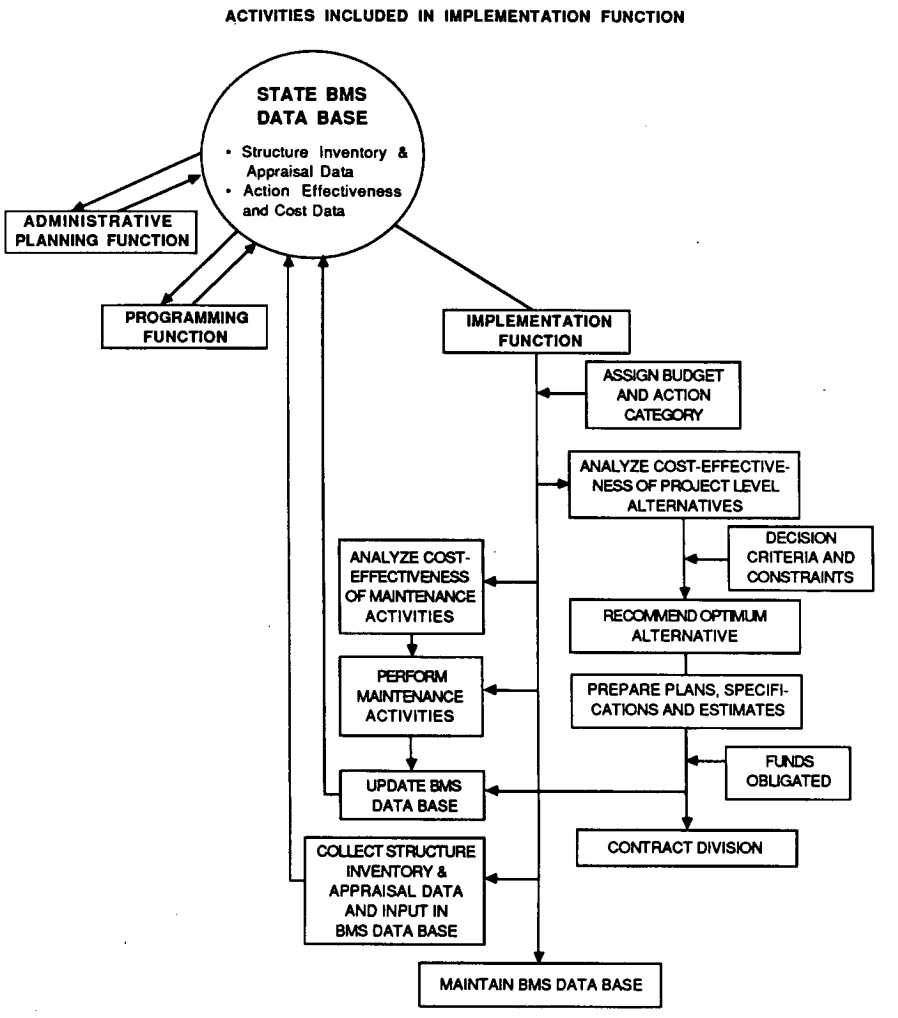

Figure B-4. A conceptual illustration of the implementation function.

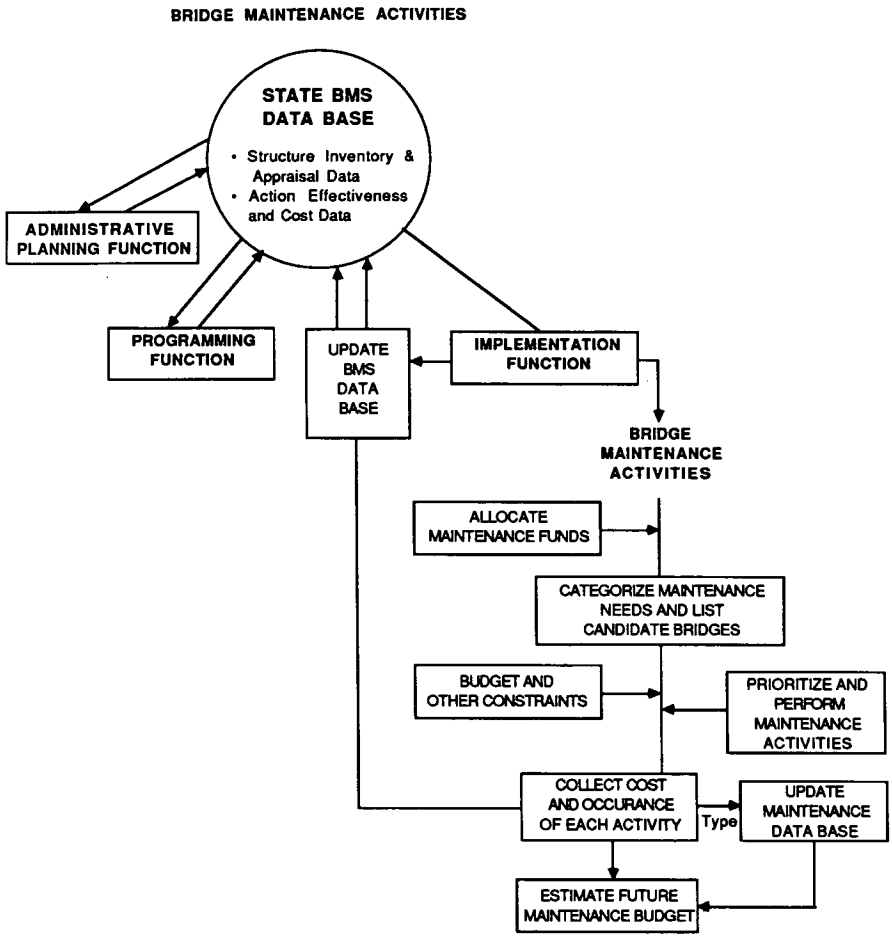

Figure B-5. A conceptual illustration of bridge maintenance activities.

APPENDIX C

BMS DEMONSTRATOR

INTRODUCTION

As a part of this project, a BMS demonstration software program was developed and written in the DBASE III+ (registered trademark of Ashton-Tate) computer language on an IBM PC compatible microcomputer. DBASE III+ is a data base management software package designed for easy data handling. It facilitates data input and reporting.

The BMS demonstrator is useful to show the concepts of bridge management to interested agencies and generate interest in other agencies. A working program, even though it only performs basic functions, presents the concepts and develops interest in BMS. The demonstrator is also useful as a starting point for further software development. The existing code can be enhanced and expanded when programming the model BMS described in this report.

An input guide for the demonstrator BMS is presented in the following section. The user-friendly and interactive screens available with the program and the outputs produced by the demonstrator are also presented.

RUNNING THE BMS DEMONSTRATOR

The BMS demonstration disk contains all of the programs necessary to operate the demonstrator. Some small example data base files are also included. To operate the demonstrator, the user must:

1. Own an IBM-PC compatible microcomputer with a hard disk.
2. Own the DBASE III+ software package.
3. Have DBASE III+ installed on the hard disk.
4. Make sure that the CONFIG.SYS file located in the main directory of the hard disk (or boot disk if you boot from a floppy) contains:

FILES = 20
BUFFERS = 24

If it does not contain this information, change it and reboot.

Two sequences are described to load and run the demonstrator.

Sequence One

1. Put demonstration disk in Drive A.
2. Get into the (sub)directory where DBASE III+ is located.
3. Type "A:BMSA".

This starts the BMS demonstrator located in Drive A.

Sequence Two

1. Copy all files from the demonstrator disk to the hard disk in the same (sub)directory as the DBASE III+ program.
2. Get into the (sub)directory where DBASE III+ is located.
3. Type "BMS".

This starts the BMS demonstrator which is located on the hard disk.

For both sequences, a printer must be connected and turned on to produce reports. If the printer is not properly connected, the program will terminate operation.

INPUT GUIDE

An input guide for the demonstrator BMS is presented in this section. The demonstrator contains fully interactive and user-friendly data input screens for all data entry. Use of the program is easy because all functions are described with simple keystrokes directly on the screen. The program prompts the user for all input data in a full screen editing format. Examples of the user-friendly data input screens are given in the next section.

This input guide consists of an abridged version of the complete data list presented in Appendix A. Only some of the most important data are included in the demonstrator. Table C-1 presents a list of all of the input data. Appendix A includes a brief description of each variable, the number of characters, and type of variable. The variables in Table C-1 are numbered for easy cross-referencing with Appendix A.

These variables, once entered to the BMS demonstrator, are stored in the data base for use by analysis modules. The modules that are currently functioning consist of: (1) sufficiency index calculation, (2) sorting of the data base by several variables, (3) MR&R project assignment based on sufficiency, (4) data base module, and (5) reporting module which provides several basic reports.

EXAMPLE SCREENS

The demonstrator BMS interacts with the user through user-friendly screens. These screens communicate with the user and allow the user to communicate with the BMS. The BMS consists of screens for data entry, function setting, sufficiency index calculation definition, output selection, function selection, data base sorting, record location, and others. Examples of all of the screens provided by the demonstrator BMS are shown in Figures C-1 through C-23.

DEMONSTRATOR OUTPUTS

The demonstrator produces some of the many reports defined for the model BMS. The demonstrator produces reports showing data lists and sorts of the data base, and a listing of the data base by sufficiency with general MR&R selections. Examples of all of the outputs produced by the demonstrator are shown in Figures C-24 through C-28.

Table C-1. Variable included in BMS demonstration program.

```
Inventory Variables

A.  Identification Information
    4.  Structure number
    7.  Principal route
    8.  Location
    9.  Principal route milepoint
   12.  Position of principle feature
        (over or under)

D.  Essentiality / Classification / Jurisdiction
    2.  Detour length
    5.  Owner
    8.  Federal aid system code
   10.  Principal Route Functional
          classification
   11.  Year of construction or major
          reconstruction
   12.  Principal route ADT
   14.  Truck factor (% trucks with
          more than 2 axles)

E. Navigation and Waterway
   1.   Existence of navigation control

F. Posting Information
   1.   Operational status
          (open or closed)
   2.   Operating rating absolute
          maximum permissible
```

Table C-1. Continued

3. Inventory rating highest load for long term use
4. Weight Limit
   4.1.Axle
   4.2.Combination

H. Secondary Features
1. Name of secondary features
2. Type of feature (road, railroad, water)
3. Route number
4. Route milepoint
6. Detour length
8. Federal aid system code
10. Route Functional classification
11. Route ADT
13. Truck factor (% trucks with more than 3 axles
15. Route horizontal clearance
16. Route minimum vertical clearance
17. Number of lanes on the "other" route
18. Roadway width
19. Existence of navigation control
20. Position of secondary feature (over or under)

I. Structural Inventory
1. Structure type
2. Principal route horizontal clearance
3. Principal route minimum vertical clearance
5. Roadway width
6. Length of structure
8. Number of lanes on the principal route
9. Superstructure type
   9.1 number of span groups
      9.1.1. span type in group
      9.1.4. span length in group
      9.1.5 span group number
      9.1.6 name of span group
10. Substructure type
   10.1. Cap Type
   10.2. Pier Type
11. Deck type

<u>Bridge Condition Variables</u>

J. Roadway Condition Rating
1. Deck
2. Wearing surface
3. Joints
4. Drainage system
5. Curbs, sidewalks, and parapets
6. Median barrier
7. Railings
8. Delineation (striping and curve markers)

K. Superstructure Condition Rating
1. Main members
3. Floor system members
5. Secondary members
7. Expansion bearings
8. Fixed bearings
9. Steel protective coating

L. Substructure Rating
1. Abutments
   1.1.Caps
   1.2.Above ground
   1.3.Below ground
2. Intermediate supports
   2.1.Caps
   2.2.Above ground
   2.3.Below ground
3. Collision protection system
4. Steel protective coating
5. Retaining walls
6. Culverts
   6.1.Damage to pipe
   6.2.Debris
   6.3.Damage to walks
8. Miscellaneous structure rating

M. Channel and Channel Protection Rating
1. Banks
2. Bed
3. Rip rap
4. Dikes & Jetties
5. Substructure foundation erosion

N. Approaches Rating
1. Embankments
2. Pavement
4. Drainage

P. Inspection Information
1. Date of last inspection
5. Inspector

```
N C H R P   P R O J E C T   1 2 - 2 8 ( 2 )
   BRIDGE MANAGEMENT SYSTEM DEMONSTRATOR
                ARE Inc
```

```
BMS Modules

(1) Data Base Module
(2) Network MR&R Selection Module
(3) Maintenance Module
(4) Historical Data Analysis Module
(5) Reporting Module
(6) Project Level Interfacing Module

(X) Exit Bridge Management System

[Enter Selection (1 - 6, or X to exit) : :]
```

Figure C-1. BMS demonstrator main menu.

```
BRIDGE MANAGEMENT SYSTEM DEMONSTRATOR
Data Base Module

SELECT OPTION

(1) Structure Inventory
(2) Structure Feature Information
(3) Component Inventory & Apprsl.
(4) Distress Ratings
(5) Bridges by Route Number

(F) Find Bridge by Bridge Number

(X) Exit to Previous Menu

BRIDGE#   ROUTE#   MILEPOINT
-------------------------------
▶ 20        2       1.21
        ANY-OTHER-TOWN, USA
  25     480030     0.00
        WILL BSSUFF.PRG CATCH
  30     409999     1.22
        ANY-OTHER-TOWN, USA
  40        30      1.22
        ANY-OTHER-TOWN, USA
  50        22      1.22
        AUSTIN, TEXAS

[Enter (1 - 5, F or X to exit) : :]
```

Figure C-2. First screen of "Data Base" module to allow option selection.

```
MODE (A,D,R,X)
ADD/DELETE/REVIEW BRIDGE INVENTORY DATA

BRIDGE MANAGEMENT SYSTEM DEMONSTRATOR
Data Base Module

(1) Structure Inventory
(2) Structure Feature Information
(3) Component Inventory & Apprsl.
(4) Distress Ratings
(5) Bridges by Route Number

(F) Find Bridge by Bridge Number

(X) Exit to Previous Menu

BRIDGE#   ROUTE#   MILEPOINT
-------------------------------
▶ 20        2       1.21
        ANY-OTHER-TOWN, USA
  25     480030     0.00
        WILL BSSUFF.PRG CATCH
  30     409999     1.22
        ANY-OTHER-TOWN, USA
  40        30      1.22
        ANY-OTHER-TOWN, USA
  50        22      1.22
        AUSTIN, TEXAS

MODE: A Add D Delete R Review X Exit
```

Figure C-3. Screen to designate the function (add, delete, or review) to apply to the selected option.

```
BRIDGE MANAGEMENT SYSTEM DEMONSTRATOR
Data Base Module

(1) Structure Inventory
(2) Structure Feature Information
(3) Component Inventory & Apprsl.
(4) Distress Ratings
(5) Bridges by Route Number

(F) Find Bridge by Bridge Number

(X) Exit to Previous Menu

FIND BRIDGE

BRIDGE#   ROUTE#   MILEPOINT
-------------------------------
  50        22      1.22
        AUSTIN, TEXAS
  55        95     10.00
        TEXAS
▶ 60     480030     1.22
        LONGHORN CITY, TEXAS
  65        94     10.00
        ARIZONA
  66       100      5.00
        MMMMMMMMMMM

ACTION: ↑ Home End
        $ PgUp PgDn
```

Figure C-4. Screen to locate the bridge for deletion or review.

```
EDIT BRIDGE INVENTORY

BRIDGE # 20          MILEAGE          1.21
ROUTE # 2            FEATURE CATEGORY UNDER
LOCATION ANY-OTHER-TOWN, USA

FUNCTIONAL CLASS      22     YEAR CONSTRUCTED          0
FEDERAL AID CLASS     11     ROADWAY WIDTH(ft)        15.0
STRUCTURE CLASS       24     NUMBER OF LANES           8
STRUCTURE LENGTH(f    80     ROADWAY LENGTH(ft)       80
# OF RATINGS/BRIDGE   2      MIN VERT. CLEARANCE       0.0
# OF FEATURES         2      MIN HORIZ CLEARANCE       0.0
OWNER                LM
PRIM. FEATURE
FEATURE TYPE                        ------ Rating ------
STATUS                0                Minimum & Span Group
DETOUR LENGTH(mi)     4.00   ROADWAY        3          0
ADT                   1200   STRUCTURE      5          0
PERCENT TRUCKS        15.0   OTHER          2          0
POSTING WGT(lb)       2050   OVERALL        2          0
OPERATING RATING      7      SUFFICIENCY    44.8       1
INVENTORY RATING      82     DATE OF INSPECTION     01/01/86
                             INSPECTOR              LDM

^End: END OF RECORD
```

Figure C-5. Screen for editing bridge inventory data.

```
ACTION:

BRIDGE # 20          MILEAGE          1.21
ROUTE # 2            FEATURE CATEGORY UNDER
LOCATION ANY-OTHER-TOWN, USA

FUNCTIONAL CLASS      22     YEAR CONSTRUCTED          0
FEDERAL AID CLASS     11     ROADWAY WIDTH(ft)        15.0
STRUCTURE CLASS       24     NUMBER OF LANES           8
STRUCTURE LENGTH(f    80     ROADWAY LENGTH(ft)       80
# OF RATINGS/BRIDGE   2      MIN VERT. CLEARANCE       0.0
# OF FEATURES         2      MIN HORIZ CLEARANCE       0.0
OWNER                LM
PRIM. FEATURE                       ------ Rating ------
FEATURE TYPE                         Minimum & Span Group
STATUS                0      ROADWAY        3          0
DETOUR LENGTH(mi)     4.00   STRUCTURE      5          0
ADT                   1200   OTHER          2          0
PERCENT TRUCKS        15.0   OVERALL        2          0
POSTING WGT(lb)       2050   SUFFICIENCY    44.8       1
OPERATING RATING      7      DATE OF INSPECTION     01/01/86
INVENTORY RATING      82     INSPECTOR              LDM

ACTION: N Next Record P Previous Record R Reedit Record X Exit
```

Figure C-6. Screen requesting next action once data editing is complete.

```
                                                Caps
EDIT FEATURE INVENTORY

        BRIDGE #                                MILEAGE
        ROUTE #                                 NUMBER

   FEATURE CATEGORY                 UNDER      FUNCTIONAL CLASS
   FEATURE TYPE                                FEDERAL AID CLASS
   FEATURE NAME                                NAVIG?

   ADT                                            Minimum Clearance
   NUMBER OF LANES                             VERTICAL
   DETOUR LENGTH(ft)                           HORIZONTAL
   TRUCK ADT %
   ROADWAY LENGTH(ft)
   ROADWAY WIDTH(ft)

^End: END OF RECORD
```

Figure C-7. Screen for editing feature inventory data.

```
                                                Caps
EDIT SPAN GROUP INVENTORY

        BRIDGE #                SPAN #
        TYPE                    NAME  first span group

                    RATED? RATING                          TYPE
   ROADWAY                                SUPER-STRUCTURE
   SUPER-STRUCTURE                        SUB-STRUCTURE
   SUB-STRUCTURE                          DECK
   CULVERT                                ROADWAY
   CHANNEL                                CAP
   APPROACH                               PIER

   (SPAN) LENGTH (ft)                     SUFFICIENCY

^End: END OF RECORD
```

Figure C-8. Screen for editing span inventory and condition summary data.

```
EDIT SPAN GROUP CONDITION

        BRIDGE #                SPAN #
        TYPE                    NAME  first span group

   ROADWAY RATED?          SUPERSTRUCTURE?         SUBSTRUCTURE?
      SURFACE                 MAIN MEMBERS            ABUT-CAPS
      DECK                    FLOOR SYSTEM            ABUT-GR-ABOVE
      JOINT                   SECOND SYSTEM           ABUT-GR-BELOW
      DRAINAGE                BEARING-EXPAND          INT-SPRT-CAPS
      CG&P                    BEARING-FIXED           INT-SPRT-GR-AB
      BARRIER                 PAINTING                INT-SPRT-GR-BL
      RAILING                                         COLLISION
      DELINEATING          CHANNELS RATED?            CORROSION
      PAINTING                BANKS                   WALLS
                              BEDS
                              RIP - RAP
                              DIKES
                              SCOUR
   CULVERTS RATED?                                 APPROACH RATED?
      PIPES                                           PAVEMENT
      DEBRIS                                          EMBANKMENT
      WALLS                                           DRAINAGE
^End: END OF RECORD
```

Figure C-9. Screen for editing detailed span condition data.

```
                                  FIND BRIDGE BY ROUTE #

                          BRIDGE NUMBER IDENTIFICATION
                              INDEX BY ROUTE #

BRIDGE #  ROUTE #    MILEAGE   SUFFICIENCY   LOCATION
   0                 234.00
  20        2          1.21      44.8
  55        5         23.00       0.0        ////////
  55        6         24.00       0.0        FFFFFFF
  50       22          1.22     100
  40       30          1.22      98.2
  65       94         10.00       0.0        HWY 183
  55       95         10.00       0.0        XXXXXXX
  66      100          5.00       0.0        GGGGG

ACTION: ↑ Cursor-Up  ↓ Cursor-Dn  Home  First Item   End   Last Item
        X Exit                    PgUp  Page Up      PgDn  Page Down
```

Figure C-10. Screen to locate bridge by route number.

```
BRIDGE MANAGEMENT SYSTEM DEMONSTRATOR

Network MR&R Selection Module

(1) Sufficiency
(2) Specific MR&R Action Selection
(3) Life Cycle Costing
(4) Optimization

(X) Exit to Previous Menu

[Enter Selection (1 - 4, or X to exit) : :]
```

Figure C-11. First screen of "Network MR&R Selection" module to allow option selection.

```
BRIDGE MANAGEMENT SYSTEM DEMONSTRATOR

Determine Sufficiency

(1) Edit Sufficiency Determinants
(2) Print Bridge Sufficiency by Bridge
(3) Print Bridge/Span Sufficiency by Bridge
(4) Print Bridge Sufficiency by Sufficiency
(5) Print Bridge/Span Sufficiency by Suff.
(6) Print Rehab Needs Report
(7) Recalculate Sufficiency

(X) Exit to Previous Menu

[Enter Selection (1 - 7, or X to exit) : :]
```

Figure C-12. First screen of "Sufficiency" submodule to allow option selection.

Caps

MAJOR SUFFICIENCY ITEMS

ITEM #	MAXIMUM PERCENT	DESCRIPTION
2	40	FUNCTIONAL ADEQUACY
3	0	
4	0	
5	0	
6	0	
7	0	
8	0	
9	0	

ACTION: ↑ Cursor Up ↓ Cursor Dn Home First Item End Last Item
U Update X Exit PgUp Page Up PgDn Page Down

Figure C-13. First screen of "Edit Sufficiency Determinants" option of sufficiency submodule to define the major sufficiency categories.

REVIEW SUFFICIENCY ITEMS

Caps

MINOR SUFFICIENCY COMPONENT

ITEM #	COMP #	MAX DED	VALUE AT MAX DED	VALUE AT ZERO DED	VARIABLE NAME	WEIGHT VARIABLE NAME	VALUE AT WEIGHT OF 1.0	MAX WGT	VALUE AT MAX WGT	MIN WGT
1	15	70	2.00	6.00	DR	TRUCK PCNT	2.00	1.25	8.00	0.00
1	2	70	2.00	6.00	R_MIN_RY	ADT	2.00	1.25	8.00	0.00

STRUCTURAL ADEQUACY

ACTION: ↑ Cursor Up ↓ Cursor Dn Home First Item End Last Item
R Review X Exit PgUp Page Up PgDn Page Down
^End: END OF RECORD

Figure C-14. Second screen of "Edit Sufficiency Determinants" option of sufficiency submodule to define the sufficiency variables.

MR&R COSTING WHEN USING RANKING FOR MR&R PROJECT SELECTION

The sufficiency index (SI) provides a simple basis for ranking projects and for choosing and costing the most fundamental level of MR&R action. Projects are ranked by SI and the work is specified in general categories of maintenance, rehabilitation, or replacement based on threshold values of SI. MR&R costs are roughly estimated by the size of the bridge and unit costs are based on the general type of work and bridge type.

This subsystem is currently not operational.

PRESS ANY KEY TO CONTINUE

Figure C-15. Substitute screen for the nonoperational "Print Rehab Needs" option of the sufficiency submodule.

DECISION TREE FOR SPECIFIC NETWORK MR&R SELECTION

The specific MR&R selection submodule provides more capability for better selections because a decision tree is used to choose the MR&R actions. A decision tree is composed of a hierarchy of variables used as decision criteria. Elements at the end of the branches are MR&R selections based on the decision criteria variables. Using the decision criteria in the decision tree, specific MR&R actions are selected for each bridge. Better estimates of costs and effectivenesses are available because each action is better defined than just the broad categories of Maintenance, Rehabilitation, or Replacement. Detailed decision trees allow more accurate assignments of MR&R projects and costs.

This submodule is currently not operational.

PRESS ANY KEY TO CONTINUE

Figure C-16. Substitute screen for the nonoperational "Specific MR&R Action Selection" submodule.

LIFE CYCLE COSTING

The life cycle cost submodule builds on the network MR&R selection submodule calculations by adding more capabilities and better economic criteria for choosing MR&R strategies. The decision tree is expanded by providing life cycle activity profile's (LCAP's) for selection as MR&R strategies. LCAP's are a set of actions or activities which may be taken on a particular bridge over an analysis period. This approach accounts for the effects of current actions on future costs and life of the bridge. Analyzing the total life cycle costs for each MR&R strategy option provides a better basis for choosing the most cost effective alternative.

This submodule is currently not operational.

PRESS ANY KEY TO CONTINUE

Figure C-17. Substitute screen for the nonoperational "Life Cycle Costing" submodule.

OPTIMIZATION

The optimization submodule is the highest level available for making the best possible decisions regarding the projects and actual MR&R strategies to be used on the network. In this submodule the decision tree is expanded by allowing multiple LCAP's to be chosen for each bridge. Besides the total life cycle costs, a measure of effectiveness or total benefits is also available for each LCAP. An optimization routine compares all possible LCAP's for all network bridges and optimizes the choices based on budget constraints to obtain maximum effectiveness or benefits over the network.

This submodule is currently not operational.

PRESS ANY KEY TO CONTINUE

Figure C-18. Substitute screen for the nonoperational "Optimization" submodule.

MAINTENANCE MODULE

Bridges which are not selected for any major MR&R action in any year are handled in the maintenance module, which assigns individual minor maintenance programs to each bridge. Maintenance actions are also prioritized using a sufficiency index. Minor maintenance activities are considered in the general categories of urgent actions and programmed maintenance.

This module is currently not operational.

PRESS ANY KEY TO CONTINUE

Figure C-19. Substitute screen for the nonoperational "Maintenance" module.

HISTORICAL DATA ANALYSIS MODULE

Historical data is kept by the model BMS for analysis to improve predictive models. The purpose of the historical data analysis module is to decrease errors in future predictions and increase prediction reliability. Models which will be improved with the aid of this module include deterioration rates, bridge life cycle activities, MR&R costs and effectivenesses, and network impact of various strategies.

This module is currently not operational.

PRESS ANY KEY TO CONTINUE

Figure C-20. Substitute screen for the nonoperational "Historical Data Analysis" module.

BRIDGE MANAGEMENT SYSTEM DEMONSTRATOR
Generate Reports/Listings

(1) Structure Inventory	(C) Bridge Traffic Reports
(2) Bridge Condition Summary Data	(D) Budget Reports
(3) Detailed Distress Data	(E) Administrative Policy Reports
(4) Span Group Summary Data	(F) Maintenance Schedule Report
(5) Other Feature Inventory	(G) Inspection Schedule & Routing
(6) Network MR&R Plan	(H) Bridge Posting Report
(7) Historical MR&R Summary	(I) Overweight Truck Routing
(8) Network Distress Summary	(J) Bridge Painting Report
(9) Summary Distress Reports	(K) FHWA Reporting
(A) Network Summary Statistics	(L) MR&R Backlog Reports
(B) Project Level Output	(M) User Defined Reports
(X) Exit to Previous Menu	

[Enter Selection (1 - M, or X to exit) : :]

Figure C-21. First screen of the "Reporting" module.

REPORTING MODULE

The selected report is currently not operational.

The reporting module produces all of the reports in the BMS. This includes lists, summaries, graphs, and maps. Reporting is the primary method for the BMS to communicate with bridge engineers and managers. Reports are normally in the form of paper output. They are produced at various stages in the operation of the BMS. Screen outputs are also needed for many reporting options. Reporting flexibility and user defined reports are important features of the BMS.

PRESS ANY KEY TO CONTINUE

Figure C-22. Substitute screen if a nonoperational report (options 6–M) is selected.

PROJECT LEVEL INTERFACE MODULE

This module provides an interface with project level data and project level analyses. One aspect of the network level BMS is the ability to communicate and exchange detailed bridge information with the project level. The project level interface module allows communicatiot with structural analysis programs such as BARS or BRASS or other programs which analyze the detailed structural components of a bridge.

This module is currently not operational.

PRESS ANY KEY TO CONTINUE

Figure C-23. Substitute screen for the nonoperational "Project Level Interface" module.

STRUCTURE INVENTORY LISTING PAGE: 1

BRIDGE #	ROUTE #	MILEAGE POSITION	-- ROADWAY -- LENGTH	WIDTH	# OF LANES	CLASSES FUNC	FED AID	STRUC	OWNER	STRUCT LENGTH	# OF RATINGS	# OF FEATURES	LOCATION
0		0.00	0.0	0	0					0	0	0	
0		0.00	0.0	0	0					0	0	0	
0		0.00	0.0	0	0					0	0	0	
1031	103	20.00	24.0	47	2	06	11	15	3	47	1	0	1 MILE JCT IH-35
1032	103	3.50	18.0	106	2	06	11	15	3	126	1	0	JUNCTION WITH IH-35
1033	103	30.00	19.0	23	2	06	11	15	3	23	1	0	30 miles from JCT IH 35
1071	107	65.00	17.7	55	1	06	11	15	3	55	1	0	.65 MILES WEST OF COUNTY ROAD 103
2981	298	5.00	26.0	540	2	06	11	15	3	540	1	0	5.5 FROM BEGINNING OF ROAD
3051	661	11.80	15.8	101	1	06	11	15	3	100	1	0	4.4 MI EAST OF FM 963 IN BURNET
8001	80	1.00	12.0	27	1	06	11	15	3	27	1	0	FARM ST
8141	814	3.00	16.0	39	1	06	11	15	3	39	1	0	3.0 miles from JCT RM & HWY 1431
8201	82	2.20	10.5	31	1	05	11	11	3	31	2	0	2.2 W. OF CO RD 201
9601	96	30.00	40.0	44	4	06	11	15	3	44	1	0	1.3 MI E OF BALCONES DR
15641	1564	1.05	19.0	53	1	06	11	15	3	53	1	0	BITTINGS SCHOOL ROAD
15681	1568	1.85	15.0	30	1	06	11	15	3	30	1	0	JONES ROAD

Figure C-24. Structure inventory listing obtained using option 1 of the "Reporting" module.

BRIDGE CONDITION SUMMARY DATA LISTING PAGE: 1

BRIDGE #	ROUTE #	MILEAGE POSITION	DETOUR LENGTH	ADT	TRUCK %	RATING OPER	RATING INVN	STATUS	POST WGT.	INSPECTION DATE	INSP. NAME	SUFFICIENCY MINIMUM	SPAN	MINIMUM RATINGS ROADWAY RTNG	ROADWAY SPAN	STRUCTURE RTNG	STRUCTURE SPAN	OTHER RTNG	OTHER SPAN	OVERALL RTNG	OVERALL SPAN
0		0.00	0.00	0	0.0	0	0		0	/ /		10.0	0	0	0	0	0	0	0	0	0
0		0.00	0.00	0	0.0	0	0		0	/ /		0.0	0	0	0	0	0	0	0	0	0
0		0.00	0.00	0	0.0	0	0		0	/ /		0.0	0	0	0	0	0	0	0	0	0
1031	103	20.00	2.00	660	1.0	20	15	A	0	01/23/87	MD	20.0	1	0	0	0	0	0	0	0	0
1032	103	3.50	4.00	630	1.0	48	36	D	0	01/23/87	MD	20.0	1	0	0	0	0	0	0	0	0
1033	103	30.00	4.00	350	0.0	48	36	A	0	01/26/87	MD	20.0	1	0	0	0	0	0	0	0	0
1071	107	65.00	4.00	1200	0.0	09	07	A	12500	01/26/87	MD	19.4	1	0	0	0	0	0	0	0	0
2981	298	5.00	6.25	700	1.0	20	15	P	80000	01/26/87	MD	19.5	1	0	0	0	0	0	0	0	0
3051	661	11.80	1.00	40	5.0	03	02	A	0	01/26/87	MD	20.0	1	0	0	0	0	0	0	0	0
8001	80	1.00	3.00	600	15.0	20	15	A	0	01/26/87	MD	20.0	1	0	0	0	0	0	0	0	0
8141	814	3.00	2.00	120	1.0	08	06	A	0	01/27/87	MD	20.0	1	0	0	0	0	0	0	0	0
8201	82	2.20	5.00	200	0.1	13	09	P	16000	01/26/87	MD	15.0	1	0	0	0	0	0	0	0	0
9601	96	30.00	1.00	12860	10.0	48	36	A	0	01/26/87	MD	0.0	1	0	0	0	0	0	0	0	0
15641	1564	1.05	3.50	350	0.5	15	09	P	15000	01/26/87	MD	20.0	1	0	0	0	0	0	0	0	0
15681	1568	1.85	2.20	40	2.5	13	09	P	15000	01/26/87	MD	20.0	1	0	0	0	0	0	0	0	0

Figure C-25. Bridge condition summary data listing obtained using option 2 of the "Reporting" module.

DETAILED SPAN GROUP CONDITION DATA LISTING PAGE:

BRG #	SPAN #	RATED? 123456	ROADWAY: SURFACE	DECK	JOINTS	CURB & GUTTER	BRIDGE RAILING	ABUTMENT	DECK EXPANSION	SUPER: MAIN COLUMN	FOUNDATION	SUPER COLUMN	SUPER SUPPORT	SUPER EXPANSION	BEARING	SUB: ABUTMENT	GRND BEAM	ABUTMENT COLUMN	INTER SUPRT	GRND BEAM	SUB COLUMN	CULVERT: PIPE	DECK	WALL	CHN: BRIDGE	BRIDGE RAILING	DECK	JOINTS	SUPERSTRUCTURE	APR: PIER	EXPANSION	DECK	WALL	APPROACH
0	0																																	
0	0																																	
0	0																																	
98	0																																	
1031	1	YY NYY	7	7	7	8				8	8					8	8	8	8	8	8				8	8				7	8	8		
1032	1	YY NYY	7	8	8	8	8			8	8		8	8		8	8	8	8	8	8		8		8	8	8		8	8	8	8		
1033	1	YY YYY	8	8	8	8				8	8	8	8	8			8			8			8			8	8			8	8	8		
1071	1	YY YYY	6	5	6					6							8			8			8			8	8			7	8	8		
1987	1																																	
2981	1	YY NYY	N	5	6	7	8	N	7	N	N	4	N	N	6	6	N	6	8	8	5	6	8	N	N	7	N	N	N	8	7	8	N	N	6	8	8
3051	1	YY NYY	8	8	N	N	8	N	6	N	6	7	7	7	N	N	6	N	8	8	N	N	N	N	N	8	N	N	N	8	8	N	N	N	8	8	8
8001	1	YY NYY	8	8	8	7	8	N	8	N	N	8	N	N	8	8	N	8	8	8	N	N	N	N	N	N	N	N	N	7	7	N	N	N	7	8	7
8141	1	YY NYY	8	8	8	8	8	N	N	N	N	7	N	N	7	7	N	N	N	N	7	7	7	N	N	N	N	N	N	7	8	N	N	N	8	8	8
8141	2	YY NYY	8	8	8	8	8	N	N	N	N	7	N	N	7	7	N	8	7	7	7	7	8	N	N	8	N	N	N	7	8	N	N	N	8	8	8
8201	1	YY NYY	8	6	N	N	6	N	N	N	N	7	N	N	N	N	N	7	7	7	7	3	3	N	N	6	N	N	N	8	8	N	N	N	8	8	8
8201	1																																	
8201	2	YY NYY	8	6	N	N	6	N	N	N	N	7	N	N	N	N	N	7	7	7	7	3	3	N	N	6	N	N	N	8	8	N	N	N	8	8	8
8309	2																																	
9601	1	YY NYY	8	8	8	8	8	N	N	N	N	8	N	N	8	8	N	8	8	8	N	N	N	N	N	8	N	N	N	8	8	N	N	N	8	8	N
9867	1																																	
15641	1	YY NYY	N	6	6	8	8	N	N	N	N	7	N	7	7	7	7	7	8	8	7	4	4	N	N	8	N	N	N	4	4	5	N	N	7	N	8
15681	1																																	

Figure C-26. Detailed condition data listing obtained using option 3 of the "Reporting" module.

SPAN GROUP SUMMARY DATA LISTING PAGE: 1

BRG #	SPAN #	SPAN NAME	LENGTH	BR	SUP	SRF	DCK	SUB	CAP	PIER	MINIMUM RATINGS: ROADWAY	SUPERSTRUCTURE	SUBSTRUCTURE	CULVERT	CHANNEL	APPROACH	SUFFICIENCY
0	0		0														10.0
0	0		0														0.0
0	0		0														0.0
98	0		0														0.0
1031	1	SLAUGHTER CRE	47	15	126	2	12	651									20.0
1032	1	ONION CREEK	106	15	101	2	12	651									20.0
1033	1	BRANCH ONION	23	15	23												20.0
1071	1	ONION CREEK	55	15	23	1	12										19.4
1987	1		0														0.0
2981	1	N. FORK BRAZO	0	15													19.5
3051	1	RUSSELL FORK	100	15	219	5	61	621									20.0
8001	1	GILLS BRANCH	27	15	125	1	11	754									20.0
8141	1	COW CREEK	18	15	111	1	11	651									20.0
8141	2	COW CREEK	21	15	126	1	12	651									20.0
8201	1	BRANCH OF CED	19	15	141	5	61	133									15.0
8201	1	BRANCH OF CED	0	15													15.0
8201	2	BRANCH OF CED	12	15	141	5	61	133									15.0
8309	2		0														0.0
9601	1	WALLER CREEK	44	15	122	2	12	341									0.0
9867	1		0														0.0
15641	1	WILBARGER CRK	73	15	111	1	11	621									20.0
15681	1		0	15													20.0

Figure C-27. Span group summary data listing obtained using option 4 of the "Reporting" module.

OTHER FEATURE INVENTORY LISTING PAGE: 1

BRG. #	FEAT. #	ROUTE #	TYPE	NAME	MILEAGE POSITION	DETOUR LENGTH	ADT	CLASS FED AID	FUNCT	LANES	MINIMUM CLEARANCE VERT	HORIZ	NAVIG ?	LOCATION
0	0				0.00	0.00	0			0	0.0	0.0		
0	0				0.00	0.00	0			0	0.0	0.0		
0	0	0			0.00	0.00	0			0	0.0	0.0		
0	0	0			0.00	0.00	0			0	0.0	0.0		
0	0	0			0.00	0.00	0			0	0.0	0.0		
1031	0	103			20.00	2.00	660	11	06	2	0.0	0.0		1 MILE JCT IH-35
1032	0	103			3.50	4.00	630	11	06	2	0.0	0.0		JUNCTION WITH IH-35
1032	1	103			3.50	0.00	0			0	0.0	0.0		JUNCTION WITH IH-35
1033	0	103			30.00	4.00	350	11	06	2	0.0	0.0		30 miles from JCT IH 35
1071	0	107			65.00	4.00	1200	11	06	1	0.0	0.0		.65 MILES WEST OF COUNTY ROAD 1
2981	0	298			5.00	6.25	700	11	06	2	0.0	0.0		5.5 FROM BEGINNING OF ROAD
3051	0	661			11.80	1.00	40	11	06	1	0.0	0.0		4.4 MI EAST OF FM 963 IN BURNET
8001	0	80			1.00	3.00	600	11	06	1	0.0	0.0		FARM ST
8141	0	814			3.00	2.00	120	11	06	1	0.0	0.0		3.0 miles from JCT RM & HWY 143
8201	0	82			2.20	5.00	200	11	05	1	0.0	0.0		2.2 W. OF CO RD 201
9601	0	96			30.00	1.00	12860	11	06	4	0.0	0.0		1.3 MI E OF BALCONES DR
15641	0	1564			1.05	3.50	350	11	06	1	0.0	0.0		BITTINGS SCHOOL ROAD
15681	0	1568			1.85	2.20	40	11	06	1	0.0	0.0		JONES ROAD

Figure C-28. Other feature inventory listing obtained using option 5 of the "Reporting" module.

APPENDIX D

CURRENT BMS PRACTICES

This appendix presents an overview of bridge management practices in various states. The information concerning Pennsylvania, California, Texas, North Carolina, Kansas, and New York is based on Technical Advisory Committee meetings and surveys of these states with questionnaires and visits. A more detailed write-up concerning state bridge management practices is contained in a project technical memorandum entitled "A Summary of Current Bridge Management Practices" available for loan upon request through NCHRP.

PENNSYLVANIA

The Pennsylvania Department of Transportation Structure Inventory Record System (SIRS) contains 22,500 highway bridges 20 ft and greater in length. An estimated 32 percent of these bridges are either structurally deficient or functionally obsolete (having Federal Sufficiency Ratings less than 80). PennDOT has recently completed an operational BMS that will enhance current data bases and provide priority ranking for rehabilitation/replacement and for maintenance needs.

Current Status

A bridge management work group of nine persons, five department employees, and four outside consultants has been established by PennDOT to develop and implement its BMS. The skeleton of the existing organization for bridge activities is as follows.

Four Bureau Chiefs work under the Deputy Secretary for Highway Administration. The Division of Bridge Management Systems reports to the Bureau of Bridge and Roadway Technology and is responsible for bridge inspection and records. The Bureau of Maintenance and Operations is responsible for bridge maintenance. Fifteen people work in the BMS group (one in each of the 11 districts and four in the Harrisburg headquarters). There are 50 to 60 inspectors working year-round.

Many Pennsylvania bridges were built more than 40 years ago and are due for either major rehabilitation or replacement. The following table shows the number of bridges classified as eligible for replacement and/or rehabilitation by Federal criteria:

	NO. BRIDGES IN SIRS (AS OF JUL. 1985)	NO. STRUCTURALLY DEFICIENT OR FUNCTIONALLY OBSOLETE BRIDGES	EST. COST OF IMPROVEMENT (BILLION DOLLARS)
State	16,700	4,463	1.9
Local (non-State)	5,800	2,771	0.6
Total	22,500	7,234	$ 2.5 billion

From the foregoing table, it is evident that about $2.5 billion for replacement/rehabilitation are required to provide a satisfactory set of highway bridges in Pennsylvania (*22*).

Approximately 17 percent of bridge expenditures are devoted to preventive and routine maintenance. About 83 percent are spent on replacement/rehabilitation and new bridge construction.

Inventory, Inspection, and Appraisal

Rating and inventory forms are based on the standard FHWA guidelines. Data collection with SI&A began in 1972. PennDOT has already implemented the "Structural Inventory Record System (SIRS): Coding Manual" (*12*). Existing data have been coded in computer files.

Load Posting Criteria

Inventory and operating ratings are used and, if necessary, actual traffic lanes are loaded for evaluating safe load capacity and posting.

Priority Ranking

In the proposed Pennsylvania system, priority ranking of bridges is based on the degree to which each bridge is deficient in meeting public needs (*22*). Deficiencies are evaluated in two categories: (1) level-of-service evaluation considering load capacity, clear bridge deck width, and vertical clearance; and (2) bridge condition evaluation using the Federal Sufficiency Rating System (FSRS). The total deficiency of each bridge is determined by combining the scores from both categories using appropriate weighting factors. This procedure will be used to generate priority rankings for rehabilitation/replacement and the associated costs for each alternative.

Maintenance/Rehabilitation Practices

PennDot's BMS group (*22*) points out: (1) the need for a priority ranking procedure to allocate maintenance funds between bridge-related and nonbridge activities, and (2) the inadequacy of the SI&A sheets to define maintenance needs for bridges. The BMS being developed by PennDOT proposes to enhance the SIRS information by including a list of maintenance activities to be identified and priority ranked by the raters. According to the available "Highway Maintenance Foreman Manual" issued by the PennDOT Bureau of Maintenance and Operations (*23*), bridge maintenance activities are divided into seven categories, as given in Table D-1. Performance standards for these activities were not established in this manual. A larger number of maintenance activities are being proposed for inclusion in PennDOT's BMS (*22*). The results of a survey (*8*) on various types of bridge maintenance and rehabilitation work performed in Pennsylvania are presented in Table D-2.

Cyclic needs of some preventive maintenance treatments and a method for annual funding have been identified by the PennDOT (*22*) using the following information:

Table D-1. PennDOT's codes for bridge maintenance and repair activities.

Activity No.	Description
711-412-01	Maintenance and Repair-Deck Repairs.
711-413-01	Maintenance and Repairs-Structures (pier, abutments, wing walls, etc.).
711-414-01	Preventive Maintenance - Annual cleaning.
711-415-01	Preventive Maintenance-Joint Sealing
711-416-01	Preventive Maintenance-Spot Painting (contract bridge painting program is to be considered if painting is required on more than 10% of the structure).
711-417-01	Preventive Maintenance-Minor Repairs (minor amount of maintenance works required to preserve the serviceability of a bridge).
711-419-01	Maintenance/Repair-Other (for all other routine activities).

ACTIVITY	FREQUENCY
Bridge Painting	12 years
Deck Rehabilitation (unprotected decks or reinforcement)	Bridge 20 years old or deck condition rating ≤ 5
Clean & Reseal Deck Joints	5 years
Clean Scuppers	1 year
Clean Deck (bridges wider than 24 ft)	1 year
Breakdown Maintenance (bridges in poor condition) until rehabilitation or replaced	2 years
Replace Timber Deck	15 years

Available Data

In addition to the SIRS data, construction and maintenance cost data are also available in scattered locations. The maintenance cost data are presently available (in the seven categories, given in Table D-1) in the annual expenditure summary prepared by the PennDOT Bureau of Maintenance. In the PennDOT BMS, a "Structure Cost Data Inventory File" will be created to store unit costs of new construction and rehabilitation work (*22*).

Models/Computer Programs

Traditionally, initial costs are used to compare alternatives for construction, rehabilitation, and maintenance. A life-cycle cost model has been developed to evaluate rehabilitation and replacement alternatives (*24*). A microcomputer program, based on this model, determines a least cost solution to bridge work considering the service life of the bridge, the time value of money, and inflation. User delay costs are also considered in rehabilitation design.

The BAR4 rating program, written by PennDOT, analyzes individual bridges to determine their live load capacities for various truck configurations, using Working Stress Rating methodology.

Future/Planned Activities

PennDOT is developing a comprehensive bridge management system (BMS) which: (1) integrates and utilizes data from the SIRS and other sources, (2) enhances and expands the SIRS data and other data bases, (3) systematically evaluates deficiencies and associated costs, (4) records maintenance and construction cost histories, (5) stores physical attributes of bridges to evaluate their load ratings, and (6) enables cost-effective management of Pennsylvania bridges included in the BMS. The overall goal of this BMS is to provide a management tool that will allow a systematic determination of present and future maintenance, rehabilitation, and replacement needs along with a priority ranking for effective use of designated funds. The PennDOT BMS is expected to be operational in early 1987 (*22*).

CALIFORNIA

California's Bridge Division dates back to 1936 when 2,000 bridges were inventoried. The division was centralized and located in Sacramento, but now is decentralized. The 1983 bridge statistics (*25*) list 24,116 bridges, including 14,000 state bridges. California does have a working BMS with respect to data collection, priority ranking for rehabilitation or replacement, and effective maintenance. The system relies on professional expertise and judgment.

Current Status

The Bridge Division is responsible for design and construction. Minor maintenance is performed by a maintenance division, and major repairs are carried out by contract through the central office. The districts make most decisions. Fifteen people work at the state headquarters. Inspectors are responsible for all inspection and recommendations. Fifty people work for the data collection. A system of colors is used to develop a maximum load and routing map. Posting is done by the Bridge Division. No load-posted state bridges exist in California now on the state system. An approximate breakdown of current bridge expenditure is given below.

ACTIVITY	PERCENT OF 1984 DOLLARS SPENT ON BRIDGES
Minor Maintenance	7
Repair/Rehabilitation	15
Replacement	14
New Bridge Construction	64

In 1978 the data base was computerized. There are 59 counties, and bridge numbers are designated by county number. The bridge records (generated by computer) contain all the information including structural evaluation, damage history, and

Table D-2. Types of bridge maintenance and rehabilitation work performed in Pennsylvania (*8*).

SUBSTRUCTURE

1. Foundation Protection
   - A. Underpinning
   - B. Stream bed paving
   - C. Encase arch footing
2. Piers, Abutments, and Wing Walls
   - A. Repoint masonry
   - B. Dri-Pak masonry
   - C. Gabion wing walls
   - D. Replace concrete wing walls
   - E. Concrete abutment and wing walls placed in front of loose masonry abutments and wing walls
   - F. Jacketing
   - G. Masonry wing walls capped
   - H. Temporary abutments and wing walls made of steel soldier piles with timber cribbing
   - I. Rebuild head walls and wing walls for concrete arch
   - J. Tie head walls of masonry arch together with steel rods and turnbuckles
3. Additional Support
   - A. Place timber or steel bents at midspan of girders or trusses
   - B. Place timber supports under end of arches on a timber covered bridge
   - C. Place steel bents and beams under covered bridge

SUPERSTRUCTURE

1. Railing Treatment
   - A. New Jersey type concrete curb and parapet
   - B. Structure mounted guard rail (including wheel guard)
     - (1) Attached to top of concrete curb
     - (2) Attached to side of concrete curb
     - (3) Attached to steel stringers
     - (4) Attached to metal grid deck
   - C. 8-in. concrete curb and parapet
2. Deck Replacement
   - A. Reinforced concrete (conventional or stay-in-place forms)
   - B. Metal grid
   - C. Timber (laminated or planking)
   - D. Structural planking with bituminous surface
3. Drainage
   - A. Add deck drains
   - B. Drain extensions below bottom of structure
   - C. Replace watertable (concrete slab and drains)
4. Expansion Joints (or Dams)
   - A. Plate dam (steel)
   - B. Angle dam (steel)
   - C. Elastomeric joints
   - D. Reseal joints
   - E. Dams replaced with open joints
5. Bearings
   - A. Make bearings functional
6. Truss Repair
   - A. Lower pin connection repair
   - B. Strengthening members
   - C. Floor beam strengthening
   - D. Increase vertical clearance
7. Widening
   - A. Concrete slab bridge
   - B. Concrete T-beam bridge
   - C. Steel I-beam bridge
     - (1) Concrete deck
     - (2) Metal grid deck
     - (3) Timber deck
8. Main Structural Members
   - A. Replace stringers or add more stringers
   - B. Repair holes in stringer webs
   - C. New R/C slab superstructure
     - (1) Cast-in-place
     - (2) Precast
   - D. Encase (jacket) R/C T-beams
   - E. Dri-Pak work on masonry arch
9. Sidewalks
   - A. Concrete slab
   - B. Steel stringer with timber deck
10. Bridge Replacement with Pipe
   - A. Steel plate arch with head walls
   - B. Steel pipe arch with head walls
   - C. Multi-pipe with head walls
   - D. Reinforced concrete box culvert

Table D-3. Priority ranking for maintenance levels of service.

Priority Ranking Code	Meaning	Definitions
U	Urgent	An immediate response is authorized including the use of overtime and after hours call back if necessary.
Q	Quick	This work requires early attention and should be undertaken within two weeks. Some work may require a response with one or two days.
R	Routine	This work should be underway within two months.
S	Seasonal	This work should be accomplished during the appropriate season of the year.
D	Delayed	This work needs to be done but may be deferred for a reasonable period of time to accumulate a sufficient quantity of work, or allow for work load leveling.

Table D-4. Urgency factors used by California in preparing reports for structures replacement and improvement.

Factors	Definition
1	The work is essential and should not be deferred beyond the year shown.
2	The work is important. It should be done in the year shown but may be deferred for one year with only minor consequence to the structure.
3	The work is required. It should be done in the year shown but may be deferred up to two years without serious consequence to the structure.
4	The need for work is identifiable. It could be done in the year shown but may be deferred five years or more without major consequence to the maintenance of the structure.
8	Program is administered and priorities are established by others.
-	Permit upgrade jobs are to be nominated and prioritized by districts.

Table D-5. Technical prioritization procedure used by California.

Technical Rank = $[\ UF^{.7} + (.9)\ (FY)]\ (K_1)\ (K_2)\ (K_3)\ (K_4)$

UF = Urgency Factor *

FY = Fiscal Year **

K_1 = Type of Work

= 1.0 when work = Misc. Major Work or Replacement. Permit Upgrade.

= 1.2 when not as above

K_2 = If on SHELL Route = 0.85
K_3 = If not on SHELL Route = 1.00

K_3 = Square root of the Sufficiency Rating

$K_4 = 2.0722\ (ADTT)^{-0.113}$

Note: 1. ADTT = ADT of trucks with 5 or more axles
2. K_4 ranges from about 0.72 minimum to absolute maximum of 1.25.

*If "UF" = 1, write "UF" = 1.00
If "UF" = 2, write "UF" = 2.00
If "UF" = 3, write "UF" = 3.00
If "UF" = 4, write "UF" = 10.00
If "UF" = 0, write "N" = blank
If "UF" = 9, write "N" = 999.9

**If "FY" = 1st input year, write "FY" = 1.0
If "FY" = 2nd input year, write "FY" = 2.0
If "FY" = 3rd input year, write "FY" = 3.0
If "FY" = 4th input year, write "FY" = 4.0
If "FY" = 5th input year, write "FY" = 5.0

priority rating. The bridge records are kept in 8½ × 11 in. size books. There are 1,800 books, at present, which contain all summarized information including maintenance/repair/cost records (445,000 pages of information). The summary data of each bridge are also kept on a 4 × 6 card file.

Inventory, Inspection, and Appraisal

From the standard forms used in California the following additional data are collected for state bridges only: (1) paint data, (2) damage history, (3) recommended maintenance work, (4) recommended contract work, (5) additional structure type data, (6) substructure and foundation data, and (7) overload capacity rating.

Bridge performance is described in much more detail than that available on the standard SI&A system.

Load Posting Criteria

Structural capacity is rated using both inventory and operating ratings criteria. Inventory rating is based on normal design load (working stress); operating rating is based on 30 percent overstressed condition. Bridges are posted at the operating rating level.

Priority Ranking

The Bridge Maintenance Engineer recommends in his bridge report the priority ranking (Table D-3) of work to be done by state maintenance forces. The Bridge Maintenance Engineer determines the fiscal year and urgency factors (Table D-4) for work to be done on contract. These data along with other data are fed to a prioritization formula to determine the technical ranking (Table D-5).

Maintenance/Rehabilitation Practices

California considers the standard SI&A forms to be an inadequate descriptor of maintenance activities. Bridge reports usually include a narrative and sketches to detail recommended work. The following items are arranged in order of the decreasing dollar values of work done by the maintenance forces.

1. Painting
2. Bridge deck joints
3. Concrete superstructure
4. Miscellaneous
5. Substructure
6. Bridge railings
7. Steel superstructure

Maintenance is defined as the preservation and repair of a bridge to its designed or accepted configuration in a safe and usable condition. Maintenance programs are developed to offset the effects of weather, aging, material failure, design or construction defects, traffic wear, damage or vandalism. Rehabilitation is defined as the extension of the life and/or capacity or subsequently improvement of the bridge from its original condition.

Available Data

Records are available for all contract work. Unit costs for various coating operations are available, as are maintenance costs, for the painting of steel bridges. Inventory inspection records kept for the last 50 years are in typed reports filed in books and on the computer for later years. Maintenance cost data by year are available to some extent, and cost data for replacement structures are available to a reasonable date.

Models/Computer Programs

Only initial costs are used to compare various alternatives for construction, rehabilitation, and maintenance. User delay costs are not considered in economic evaluation. California does not use computerized evaluation models such as BARS or BRASS.

Data are available which consider the effectiveness of cathodic protection on seven bridge decks. Life expectancy is available for coatings on structural steel bridges. The state is divided into four environmental zones. The expected paint service life for steel bridges is given in the following for each zone.

ZONE	DEFINITION	EXPECTED SERVICE LIFE OF PAINT (YEARS)
1	Coastal area to ½-mile inland	3–5
2	Inland and bay areas	5–10
3	Mountain and coastal valley	10–15
4	Central valley and desert	15–25

Future/Planned Activities

The published work on cost-effective decision models (*24*) is currently being studied by the Department.

TEXAS

In the Texas State Department of Highways and Public Transportation (SDHPT) no single organization is responsible for bridge management. The State has a large number of bridges on its road network. A summary of 1983 bridge posting statistics (*25*) is presented here:

SYSTEM	NUMBER OF BRIDGES	NUMBER POSTED
Interstate	6,898	0
Other Federal-Aid	19,471	4
Off System	19,493	2,516 (Est.)
TOTAL	45,862	2,520 (Est.)

Current Status

In the Texas SDHPT three divisions are primarily concerned with bridges. These are: (1) D5—Bridge Division, (2) D18—Maintenance Division, and (3) D8—Roadway Design Division. The District Engineer is the most important person in the priority process. The Divisions provide services and advice to district engineers, but district engineers determine their own priorities.

This organization is characterized by an informal exchange of information. The University of Texas Center for Transportation Research and The Texas Transportation Institute of Texas A & M University provide research services. Periodic research conferences provide a forum for them to meet. Some districts, like the Houston Urban District, have their own integrated bridge design and management sections.

The breakdown of bridge expenditure, as provided by the Bridge Division of the Texas SDHPT, is approximately as follows:

ACTIVITY	PERCENT OF TOTAL BRIDGE EXPENDITURE
Minor Maintenance	3.6
Repair/Rehabilitation	8.3
Replacement	19.8
New Bridge Construction	68.3

Large amounts of new bridge expenditures are the result of a need to increase capacity. Both the Bridge and Maintenance Divisions were contacted to determine the overall status of bridge management. Their responses are used in the following sections.

Inventory, Inspection, and Appraisal

Texas uses it own forms for the inventory, inspection, and appraisal of bridges which provide information required by the FHWA. These are collected on a contract basis. Bridge inspection is the responsibility of D5. Inventory data forms are based on standard FHWA guidelines. With the exception of federally mandated bridges, the management of other bridges is mixed in with the management of other roadway items, primarily the responsibility of district engineers. The Texas SDHPT uses the BRINSAP (*11*) system for these inspections. The following components are included in the SI&A forms.

1. Approaches
2. Waterway
3. Substructure
4. Superstructure
5. Roadway
6. Culvert and retaining walls

Several elements are included in each of these components. A provision for coding the posted load limit is also provided in these forms.

Load-Posting Criteria

Both inventory and operating ratings are used to evaluate structural capacity. Inventory rating is the usual practice. For bridges with operating ratings less than H20, the bridge is usually load posted at the inventory rating level.

Priority Ranking

The Federal Sufficiency Rating scheme is used on the federally aided bridge rehabilitation/replacement program. There is no optimization model at the network level, although 20-year planning is done with priority assignment.

Maintenance/Rehabilitation Practices

Maintenance is defined as repair work done to keep the bridge functioning at about the same level. Rehabilitation is defined as the improvement necessary to bring all components of the bridge up to acceptable standards. Maintenance of bridges is the responsibility of district engineers and their maintenance engineers. Most bridge money is used in new construction and replacement. Other frequently addressed items are: bridge deck repair, cleaning and painting steel structures, rail repair, emergency repair of overheight-load damage (grade separation bridges), and joint cleaning resealing.

Available Data

The SI&A data are available for 2 years and are stored on computer by the Bridge Division. About 4 years of data are available in file cabinets of the Maintenance Division. Histories of bridge performance, maintenance, and rehabilitation are generally not available. Cost information is available in very broad categories. Maintenance expenditures are reported for fixed bridges and movable bridges. Bid prices can be found only for rehabilitation/replacement and new construction projects.

Models/Computer Programs

User delay costs are considered only in special cases: usually where some aspect of design has to be justified. Trade-offs between initial construction cost and periodic maintenance costs (especially steel painting, joint cleaning, rail repair, and deck patching) are generally considered when comparing alternatives. More and more consideration is being given during initial design to minimize future maintenance costs. BARS computer program for ratings of load capacity is available but rarely used.

Future/Planned Activities

The Center for Transportation Research of the University of Texas at Austin has been awarded a research study to develop a priority ranking procedure for project selection (bridge projects).

NORTH CAROLINA

In the past, the Bridge Division was responsible for all bridge operations. Responsibility is now decentralized. Bridge designers no longer control construction and this may cause communications gaps. There are 17,300 bridges in North Carolina; 97 percent of these are State-maintained bridges. About 65 percent of these bridges qualify for replacement (structurally deficient or functionally obsolete).

Current Status

Bridge maintenance is still an autonomous division. It has two sections: (1) operation (inspection/rating), and (2) maintenance. State force labor is used for a majority of maintenance jobs. Forty-five people perform inspections in 2-year rotations. The central office has more than 30 people in its staff for appraisals.

Inventory, Inspection, and Appraisal

The forms used by North Carolina have expanded codes (*13*) in addition to the kind of information available in standard SI&A forms.

Load-Posting Criteria

Both inventory and operating ratings are calculated for evaluating bridge structural capacity. Load posting is based on operating rating. Operating rating is associated with 75 percent of yield strength.

Priority Ranking

The North Carolina Department of Transportation (NCDOT) has taken a significant lead in developing a rational priority ranking method for replacement/rehabilitation. Realizing that the Federal Sufficiency Rating does not place adequate emphasis on level of service provided to the public, a procedure for evaluating bridges and producing priority ranking has been developed on the basis of level-of-service deficiency (*26*). This procedure utilizes data from the NCDOT Structure Inventory and Appraisal Expanded File. Priority ranking for replacement/rehabilitation is based on the extent of bridge deficiency calculated in a manner that parallels the magnitude of user costs incurred (*26*).

Maintenance/Rehabilitation Practices

Following is a list of items on which most of the bridge maintenance/rehabilitation funds are spent.

1. Deterioration of bridge timbers—superstructure.
2. Deterioration of concrete decks.
3. Failure of deck-joint system.
4. Bearing systems (both concrete and steel spans).
5. Machinery and electrical systems of movable bridges.

6. Timber substructure.
7. Handrails (mostly timber, but sometimes metal).

Available Data

Inventory/inspection data have been available on computer since 1980. Construction, maintenance, rehabilitation, and posting histories are also available on computer. Bridges on all systems (primary, secondary) have been designed for HS20 loading since 1976/1977. Cost information is readily retrievable in general categories. Examples are: initial costs, force account and contract maintenance/rehabilitation cost, and bridge removal cost (by contract only). Maintenance/rehabilitation cost data are also available by year.

Models/Computer Programs

User costs are generally not considered in economic evaluation. A computer program, Level of Service and Prioritization (LOSAP), has been developed for priority ranking of bridge replacement projects (*26*).

Future/Planned Activities

North Carolina has a very active research program on various aspects of a BMS: a procedure of priority ranking for replacement, economic evaluation of competing alternatives, and generation of cost summaries from inspection and maintenance data.

KANSAS

Kansas reported 24,915 bridges (*25*). Most of these bridges are owned by the Kansas Department of Transportation (KDOT), Kansas Turnpike Authority, and counties. Kansas Turnpike Authority itself performs all bridge operations including inspection and reporting. Cities are responsible for bridges in the urban system. Counties and cities hire consultants for inspection, but KDOT performs in-house inspections and ratings.

Current Status

A bridge inspection team is part of the bridge design section. They go out to each of the six districts, bring data back to the design section, and use the data to load rate the bridges. Plans are prepared in the office. The inspection is carried out year-round. A history of each structure is maintained on computer sheets. Maintenance is handled in the field. Major work is carried out through contracts by the construction division. The programs are developed on a 5-year basis.

The funds allocation (obtained from the KDOT) for various work items related to bridges is given below:

ACTIVITY	EXPENDITURES
Minor Maintenance	$1,000,000
Repair/Rehabilitation	$2–$8,000,000
Replacement/Rehabilitation	$27,000,000
New Bridge Construction	Unknown

It is apparent that the KDOT spends a major part of bridge money on replacement/rehabilitation.

Load-Posting Criteria

Inventory rating is used to evaluate structural capacity. Bridges are posted when Kansas legal loads exceed the operating rating. The posted limit is set between the inventory and operating ratings based on 5-ton increments.

Priority Ranking

The current KDOT system selects the scope of work and makes a priority ranking for each bridge. In some respects Kansas is a step ahead of several other states, since optimization software is being prepared to parallel its PMS system and thereby provide consistency in network trade-off comparisons.

Maintenance/Rehabilitation Practices

The KDOT uses the term preservation to define maintenance. Rehabilitation includes widening and strengthening. Following is a list of bridge work items most frequently done by the KDOT.

1. Roadway width improvements.
2. Strengthening due to raised load limit.
3. Deck deterioration.
4. Concrete girder cracking.
5. Bridge painting.
6. Concrete deterioration (superstructures and substructures).
7. Backwall and expansion joint failure.
8. Channel alignment.
9. Wing wall failure.

Available Data

Inventory/inspection data have been collected since 1931. The data are being stored on computer files from 1971. Histories for maintenance/rehabilitation (contract work) can be retrieved. A wide variety of cost information is available. These are: initial costs (including replacement costs), contract work costs, bridge removal costs, and yearly maintenance costs.

Models/Computer Programs

Trade-offs between initial construction costs and periodic maintenance costs are considered when comparing alternatives. User delay costs are not considered in economic evaluation. A model is currently in use for bridge evaluation/replacement programs. In-house computer programs are used for structural evaluation and ratings of bridges.

NEW YORK

The New York Department of Transportation (NYDOT) is making a major effort to develop and implement a Bridge Management System. The 1983 bridge statistics (*25*) are given below.

SYSTEM	NUMBER OF BRIDGES	NUMBER POSTED
Interstate	1,690	0
Other Federal-Aid	7,177	169
Off System	8,831	1,675
TOTAL	17,248	1,844

Current Status

Both the Bridge Division and Maintenance Division are involved in bridge management activity. A scale of 7 to 1 is used to rate bridge elements in the State of New York. These ratings are given below.

RATING	MEANING
7	New Condition
6	Used to shade between 7 and 5
5	Minor deterioration and functioning as originally designed
4	Used to shade between 5 and 3
3	Serious deterioration, or not functioning as originally designed
2	Used to shade between 3 and 1
1	Potentially hazardous

Each element of every bridge component (Table D-6) is rated on this scale every 2 years: bridges in poor condition are rated yearly, however.

Following is an estimate of bridge expenditures:

ACTIVITY	PERCENT OF BRIDGE DOLLARS
Minor Maintenance	4
Repair/Rehabilitation	43
Replacement	35
New Bridge Construction	18

The NYDOT has devoted significant resources to develop and implement a comprehensive BMS. Twenty new positions have been authorized for this activity.

Inventory, Inspection, Appraisal

The NYDOT Special Report 70 (*27*) concluded that the Bridge Inspection reports made after 1977 were very good. Because of training and organizational difficulties, inspections before that date were variable and inconsistent.

Table D-6. Bridge components and their elements as defined by the NYDOT (*29*).

BRIDGE COMPONENT	ELEMENT
ABUTMENTS (Beginning & Ending)	Joint with deck Bearings, Anchor bolts, Pads Seat & Pedestals Backwall Stem (Breastwall) Erosion or Scour Footings & Piles
WINGWALLS (Beginnings & Ending)	Walls Footing Erosion or Scour Piles
STREAM CHANNEL	Adequate opening Erosion & Scour Channel siltation Bank protection
APPROACHES	Drainage Embankment Settlement Erosion Pavement Guide railing
DECK	Wearing surface Monolithic deck surface Curbs Sidewalks & facias Railings & parapets Railings paint Scuppers Gratings Medians
SUPERSTRUCTURE	Deck, structural Primary members Secondary members Paint Joints
PIER	Bearings, Anchor bolts, Pads Pedestals Top of pier cap or beam Stem (solid pier) Cap beam Pier columns Footings Erosion or scour Piles
UTILITIES	Lighting standards Lighting fixtures Sign structure Utilities Utilities support

The NYDOT performs inventory and inspection of bridges on a *per span* basis, and many more structural components are taken into account in the compilation of the bridge rating. These components and their elements are described in Table D-6.

Load-Posting Criteria

Both inventory and operating ratings, as per AASHTO's "Manual for Maintenance Inspection of Bridges" (*28*), are used to evaluate bridge structural capacity. Both ratings are used for posting in appropriate cases. Posting value will be based on Inventory rating for certain complex and/or nonredundant structures—somewhere in between inventory and operating rating for other bridges.

Priority Ranking

New York State does not use the FHWA SI&A information

as a bridge management tool. Many more structural components are considered in establishing the bridge condition rate scale. When the 7 to 1 scale (described earlier) is applied to whole bridges, the cost to repair appears to increase exponentially with decreasing rating, as shown by the following data.

RATING	AVERAGE COST PER STRUCTURE ($)
7	670
6	3,400
5	11,200
4	27,500
3	62,000
2	122,000
1	250,000

Based on these data, it is proposed that the most cost-effective work for a BMS is the necessary preventive maintenance before a structure starts deteriorating, rather than waiting until the structure deteriorates more rapidly.

Maintenance/Rehabilitation Practices

The NYDOT relates the difference between bridge maintenance and rehabilitation to the extent of the work done. Maintenance restores one or several elements of a bridge to a serviceable condition (*30*). Rehabilitation is intended to restore the entire bridge to full operational condition, correcting as many deficiencies and substandard features as feasible. The following items are frequently responded by the NYDOT:

1. Concrete bridge decks.
2. Superstructure steel deterioration.
3. Substructure deterioration or distress.
4. Geometric deficiencies.
5. Waterway deficiencies, scour.
6. Painting.
7. Joints and bearings (cleaning and replacement).

Available Data

Six years of bridge inventory/inspection data are available as a computerized data base. The state SI&A system allows tracking of bridge, or bridge type, and performance over a period of years. The Maintenance Division keeps records of maintenance tasks, by bridge and by date. Cost information is kept by various divisions to suit individual needs. The Structures Division keeps a cost per square feet for new, replacement, and rehabilitated bridges. The Maintenance Division keeps records for bridge repair costs by task. These data are retrievable from both sources.

Models/Computer Programs

Trade-offs between initial design cost and periodic maintenance costs are considered to a minor extent in design alternatives. The following models are available for possible use in a BMS:

1. Life-cycle cost prediction.
2. Paint life.
3. Chloride concentration/penetration.
4. Overall condition prediction.
5. Prediction of loading effects.

Models have been used for: (1) life-cycle costing, (2) bridge evaluation/replacement, (3) research, and (4) planning/bridge management.

Future/Planned Activities

A comprehensive BMS is being developed by the NYDOT. Research is currently underway to determine the most cost-effective strategies for maintenance and rehabilitation/replacement.

OTHER STATE BMS

The following section contains state bridge management system information collected from the literature review.

The New Mexico Bridge Inspection Program

New Mexico has 3,000 bridges on the federal-aid system. All these bridges have received their initial inspection and inventory by July 1973. Annual training sessions and field work with the staff of the Civil Engineering Department of New Mexico State University have kept the program very viable and have led to the use of bridge capacity data developed within the program into a statewide overload routing and permit system. All bridge data are stored in numerical order by bridge number on a magnetic tape and disk. The computer program OVLOAD has the ability to pick out all bridges that do not meet the equivalent load criteria along a proposed route and to generate a printout of the pertinent data (*31*).

Wisconsin's Computer Model

The Wisconsin Department of Transportation (WISDOT) has developed a computer simulation model that uses life-cycle cost analysis, in addition to the information on the structural adequacy and functional obsolescence of bridges, to determine the least cost mix bridge repair and replacement work for up to 25,000 bridges and up to 20 program periods (*32*).

Wisconsin has about 12,000 bridges. Steel deck girders, prestressed concrete, and concrete slabs represent 77 percent of all bridges and 85 percent of the total deck area. The average age of all bridges is 25.6 years. However, more than 500 bridges are at least 50 years old. In all, 12 percent of the bridges, for which the State is responsible, have a sufficiency rating below 50 percent, the threshold to be eligible for federal bridge replacement funds. WISDOT is using the results of the computer model in its State Highway Plan to provide guidance in formulating its

Table D-7. Minnesota condition point values (*33*).

Excellent	9.	Condition superior to present desirable criteria
	8.	Condition equal to present desirable criteria
	7.	Condition better than present minimum criteria
	6.	Condition equal to present minimum criteria
Fair	5.	Condition somewhat better than minimum adequacy to tolerate being left in place as is
	4.	Condition meeting minimum tolerable limits to be left in place as is
Poor	3.	Basically intolerable condition requiring high priority or repair
	2.	Basically intolerable condition requiring high priority or replacement
	1.	Immediate repair necessary to put back in service
	0.	Immediate replacement necessary to put back in service
	N.	Does not apply

Table D-8. Summary of the Replacement Priority Calculation (RPC) used by Minnesota (*33*).

Category 1	Structural Adequacy and Safety	
	Safe Load Appraisal Rating Point	X
	X Average Daily Traffic Point	X
	Product Category 1	XX 50% to RPC
Category 2	Serviceability and Functional Obsolescence	
	Deck Geometry Appraisal Rating Point	X
	+ Average Daily Traffic Point	X
	+ Underclearance Appraisal Rating Point	X
	+ Waterway Adequacy Appraisal Rating Point	X
	+ Approach Roadway Alignment Appraisal Rating	X
	+ Structural Condition Appraisal Rating Point	X
	+ Type of Bridge Point	X
	Sum	X
	X Age Point	X
	Product Category 2	XX 25% to RPC
Category 3	Essentiality for Public Use	
	Detour Length Point	X
	+ Average Daily Traffic Point	X
	+ Road System Designation Point	X
	+ Functional Classification Point	X
	+ Bridge Record for Defense Point	X
	Product Sum Category 3	XX 25% to RPC

6-year highway investment program, and its biennial budget proposal for bridge repair and replacement (*32*).

Maryland

Maryland uses the Federal Sufficiency Rating in conjunction with its own Deck Sufficiency Rating to generate priority ranking of bridge replacement/rehabilitation projects. The Deck Sufficiency Rating is evaluated from ten factors that are: average daily traffic volumes, detour lengths, functional class of highway, structure location, potential area development, deck chloride content, deck core recovery, percentage of deck corrosion, life of deck if not repaired, and condition of the bridge structure. This method is computerized (*33*).

Minnesota

Minnesota prioritizes its bridges by both the Federal Bridge Sufficiency Rating formula and its own Replacement Priority Calculation (RPC). The RPC procedure maintains the three basic categories found in the Federal Sufficiency Rating formula:

1. Structural Adequacy and Safety
2. Serviceability and Functional Obsolescence
3. Essentiality for Public Use

Instead of the FHWA-weighted percentages of 55 percent, 30 percent, and 15 percent, however, Minnesota has modified these to 50 percent, 25 percent, and 25 percent, respectively. Also, instead of using formulas, point values are assigned according to the conditions described in Table D-7. The RPC procedure is summarized in Table D-8 (*33*).

Illinois

Illinois has developed a project priority ranking system based on bridge inventory data to determine backlog categories related to required levels of service. The system relies on computer output of inventory data, which is then used by a panel of field district representatives and headquarters specialists from the Bridge, Maintenance, and Planning and Programming offices.

SUMMARY

This appendix has presented state-of-the-art information on bridge management practices and ongoing research. It includes bridge maintenance, rehabilitation, replacement, rating, posting, inspection and prioritization. A comprehensive review of state bridge management practices has shown that several states have devoted considerable efforts to the development of bridge management systems at various levels. Pennsylvania currently has the most advanced BMS model. However, other states, namely, North Carolina and Kansas, have made significant developments.

APPENDIX E

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