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# Bridge Management Systems
# Literature Review and Search

The first section of this report contains a literature review of bridge management systems. The objective of the literature review is to provide a general description of a bridge management system and briefly outline those systems in development. The first section of the review discusses the history of legislation concerning bridge management systems. Next, the various components of a bridge management system are described. An overview of the major systems in use or development follows. The final section briefly discusses how data from non-destructive inspections could provide additional information to be used by a bridge management system.

The second section of this report contains a literature search related to bridge management systems. All of the references listed can be found in the collection at the Transportation Library at Northwestern University. The search is divided into four sections. The first section lists references that provide a general overview of a bridge management system. The second section provides a listing of references that discuss various models that are used in bridge management system. References that pertain to the data required by bridge management systems are included in the third section. The final section outlines references for individual bridge management systems that are in use or development.

This report was funded by the Infrastructure Technology Institute at Northwestern University under the project *Improved Condition Monitoring for Bridge Management*. The author would like to thank Renee McHenry, the Infrastructure Librarian at Northwestern University for her assistance throughtout the course of this and other projects.

# Bridge Management Systems
# Literature Review

## Introduction

The impending implementation of bridge management systems (BMSs) by all state Departments of Transportation (DOTs) and Metropolitan Planning Organizations (MPOs) as mandated by the Intermodal Transportation Efficiency Act (ISTEA) of 1991, is resulting in a change in maintenance planning for bridge repair. The increasing age of the infrastructure and reduced maintenance budgets have resulted in project funding for bridges in crisis taking precedence over routine maintenance. The deferral of routine maintenance perpetuates the "siege mentality" presently being experienced by transportation planning agencies. However, systematic maintenance planning can result through implementation of a bridge management system. The bridge management system assists in determining the optimal time for an agency to execute improvement actions on a bridge, given the funds available. The objective of adopting such a system is to improve the overall condition of an agency's network of bridges, emphasizing the need to maintain the condition of a bridge before lapsing into an unsafe state.

This literature review will describe the framework under which a BMS operates and to identify research efforts in the area of BMS. The first section details the legislation requiring adoption of a BMS. The second section provides an overview of the minimum standards of a BMS that are required by ISTEA and those suggested by the American Association of State Highway and Transportation Officials (AASHTO). The third section details research in the area of BMSs. These efforts have resulted both in the creation and implementation of a BMS and the tailoring of existing BMSs to an agency's unique needs. Finally, the significance of BMSs in the context of the nondestructive evaluation (NDE) projects being undertaken at Northwestern is discussed.

## History of Legislation Concerning Bridge Maintenance

The need to carefully monitor the condition of bridges became apparent after the collapse of the Silver Bridge between Point Pleasant WV and Gallipolis OH in 1968. The loss of 47 lives due to the instantaneous fracture of an eye-bar caused great concern about the safety of bridges. At the time, there was no systematic maintenance program in place to monitor the condition of the bridge population. In fact, the exact number of bridges that were standing in the United States was not even known at this time.

To address this problem, the Federal Highway Act of 1968 created the National Bridge Inspection Program (NBIP) which ordered state agencies to catalogue and track the condition of bridges on principal highways. Specifically, the program set standards for state highway departments to conduct safety inspections, establish the maximum time lapses between inspections and determine the qualifications of those responsible for carrying out the inspections. The data collected as part of the NBIP is submitted after every inspection period and maintained by the Federal Highway Administration (FHWA) in the National Bridge Inventory (NBI) database.

The Federal Highway Act of 1970 used the information contained in the NBI as the basis for funding for the Special Bridge Replacement Program (SBRP). This program provided federal funding to states in order to replace bridges that were in the most danger of failure. Under this program, bridges are classified under two different schemes. First, the condition of the bridge is rated according to one of three categories: nondeficient, structurally deficient, or obsolete. A bridge that is classified as nondeficient is in satisfactory condition and adequately serves the specifications for which it was designed. A structurally deficient bridge has either been closed because of structural inadequacy or in immediate need of rehabilitation in order to remain open. A functionally obsolete bridge is inadequate due to its geometry or the traffic on the road it serves, although the bridge may be structurally sound. Second, a sufficiency rating is calculated based upon the NBI data items related to its structural condition, functional obsolescence and essentiality for public use. If the sufficiency rating for a bridge was less than 50, then the bridge was eligible for SBRP funds.

To provide further guidance with the NBIP, the FHWA published the *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*. Specifically, the Coding Guide outlined the specific elements that are required to be inspected on each bridge and guidelines regarding the inspection procedures. The Coding Guide has been revised in 1972, 1979 and most recently in 1988.

Later, the Surface Transportation Assistance Act of 1978 changed the basis for eligibility of bridges for federal funding. Under this act, the NBIP was expanded to include bridges on all public roads, not just principal highways. The SBRP was replaced by the Highway Bridge Replacement and Rehabilitation Program (HBRRP) which provided funding for bridge rehabilitation in addition to replacement projects. The intent of this change was to begin repairing bridges before they deteriorated into a critical state. If the sufficiency rating for a bridge was less than 80, but more than 50, then the bridge is eligible for rehabilitation funding.

The Intermodal Surface Transportation Efficiency Act of 1991 further recognized the need for the preventative maintenance of infrastructure to minimize problems before they occur. This legislation mandated that every state department of transportation and metropolitan planning organization implement six different management systems that maximize resource allocation for maintenance planning. Specifically, the objective of the BMS is to establish the most cost effective maintenance schedule for a network of bridges.

ISTEA originally established a deadline in 1995 that all states must implement a BMS. However, due to delays in the rulemaking process, the notice of proposed rulemaking (NPRM) was not issued until March 1993 and the interim final rule until December 1993. Now, under the interim final rule, states must have a work plan to implement a BMS in place by October 1, 1994, with the system fully operational by October 1, 1998. The FHWA is responsible for monitoring the compliance of the schedule.

## Components of a Bridge Management System

The mandated requirements for a bridge management system are outlined in the interim final rule which was distributed December 1, 1993. The rule also refers to the American Association of State Highway and Transportation Official's (AASHTO) *Guidelines for Bridge Management Systems* as representing "good practice." Both of these references suggest that a bridge management system include four basic components: data storage, cost and deterioration models, optimization models for analysis and updating functions.

The database connected to the bridge management system stores data from periodic field inspections. Traditionally, states have been required to monitor the condition of bridges to support the National Bridge Inventory (NBI) which is maintained by the Federal Highway Administration. The NBI format attaches a subjective rating from 0-9 to each portion of the bridge which represents its physical condition. However, most BMSs measure the deterioration of a bridge in more specific terms. The bridge is divided into individual elements, or sections of the bridge which are comprised of the same material and can be expected to deteriorate in the same manner. The condition of each element is reported according to a condition state, which is a quantitative measure of deterioration. The condition states are defined in engineering terms and are on a scale from 1 to 5 for most elements. For example, if 12 ft. of a 24 ft. unpainted steel open girder is in excellent condition with little or no corrosion, then 50% of the girder is in condition state 1.

Information stored in the database is used as input into the modeling. The models are used to predict future conditions for each element and to perform a "what if" analysis under different budget constraints to determine the impacts of carrying out different projects. The three primary types of models are deterioration, cost and optimization models.

Deterioration models predict the condition of bridge elements at any given point in the future and may be deterministic or probabilistic in nature. A deterministic model predicts that a bridge will deteriorate at a known, given rate. A probabilistic model takes into consideration that the actual deterioration rate is unknown, and includes a probability that the bridge will actually deteriorate at a certain rate. In addition, most deterioration models are patterned as a Markov process. This type of model predicts deterioration in a probabilistic fashion and on the basis of the current, not historical condition of the element.

A bridge management system typically estimates two types of costs: improvement and agency. Improvement costs are estimated to determine the cost of a maintenance action to improve the condition of an element. The expected user cost savings for safety and serviceability improvements should also be estimated.

From the results of the cost and deterioration models, the optimization models determine the least-cost maintenance, repair and rehabilitation strategies for bridge elements using life-cycle cost analysis or some comparable procedure. Life cycle costing takes into account the maintenance performed on a bridge throughout its entire service life. When this approach is taken, a small improvement action may be initiated before further degradation of condition occurs since in the long-run it would cost more to wait and improve the bridge after its condition has worsened. The BMS also performs multi-year, network analysis. This capability allows analysis over all bridges in an agency's inventory to determine impacts of implementing or deferring repairs in the future. Likewise, the BMS should also be able to analyze feasible options over any subset of bridges.

The optimization routine also accounts for the desired level of service a bridge should accommodate. The level of service pertains to the amount and type of traffic a bridge serves.

For example, it would prove more beneficial to upgrade the condition of a bridge on an interstate highway, rather than a culvert of a rural, dirt road, to handle heavy trucks on account of the traffic volume and mix on each bridge.

A BMS may take either a top-down or bottom-up approach to optimization. The top-down approach first determines the desired goals for the entire network then selects the individual bridge projects based on those goals. The bottom-up approach determines the optimal action for each bridge then selects which projects will be completed based upon the network optimization. The top-down approach works quicker, since the individual projects are determined after the network goals are set. However, this optimization routine requires a large population to provide meaningful results. The bottom-up approach uses more computer time optimizing the individual bridge projects thus the process often proves cumbersome for large bridge populations.

Finally, the BMS generates summaries and reports for planning and programming processes and use the information from actions taken the update the prediction and cost models. Since most of the transition rates used in the deterioration models and improvement costs are based on initial estimates, the models need to be updated to make the more reflective of actual conditions.

## Bridge Management Systems in Development

Most BMS projects began development prior to ISTEA. Two nationwide projects, Pontis and BRIDGIT, have a generic design that can be adapted to accommodate the individual needs of an agency. Only a handful of states have opted to develop and implement their own BMSs. A review of the BMS systems in development and their unique features follows.

### Pontis

Pontis is a bridge management system developed by the FHWA in conjunction with six state DOTs and the consultant joint venture of Optima, Inc. and Cambridge Systematics. Soon after the HBRRP was passed, the FHWA determined that the gap between the funding needed to make the necessary repairs to bridges and the available budgets for many agencies was widening. In 1986, a demonstration project was initiated that supported workshops in almost every state which sought to develop sound bridge management practices. This demonstration project provided the foundation for the development of a generic bridge management system, later named Pontis, that could be adapted for use by any state. In 1989, the state of California administered the development of Pontis with the assistance of technical advisory committee including the FHWA, NCHRP, and five other states, representing a wide range of bridge environments and size.

Pontis includes many innovative features. The condition data included in the system are more detailed than the requirements of the NBI. The bridge is divided into individual elements, or sections of the bridge which are comprised of the same material and can be expected to deteriorate in the same manner. The condition of each element is reported according to a condition state, which is a quantitative measure of deterioration. The condition states are defined in engineering terms and are on a scale from 1 to 5 for most elements.

Pontis also views bridge deterioration as probabilistic, recognizing the uncertainty in predicting deterioration rates. The system models deterioration of the bridge elements as a Markov process. Pontis automatically updates the deterioration rates after historical inspection data are gathered.

Cost models have been adapted from research performed by North Carolina. Pontis has the ability to estimate accident costs, user costs resulting from detours and travel time costs. This information is used in the optimization models to examine trade-offs between options.

In the optimization routine, maintenance, repair and rehabilitation actions are separated from improvement actions. Pontis also employs a top-down analytical approach by optimizing over the network before determining individual bridge projects. The speed of the optimization model allows for the investigation of impacts on the network with the variation of certain parameters such as the budget or delaying a certain action.

CALTRANS is in the process of implementing Pontis state-wide. Currently, 42 states are participating in an AASHTOWare project to enhance Pontis. About 2/3rds of these states currently have plans to officially implement Pontis. In an effort to standardize the reporting of elements among the different users of Pontis, the technical advisory committee recently completed the Commonly Recognized Elements (CoRE) Report which defines bridge elements and corresponding condition states.

### BRIDGIT

BRIDGIT is a bridge management system developed jointly by NCHRP and National Engineering Technology Corporation. This project grew out of an NCHRP project in 1985, similar to that of the FHWA demonstration project in 1986, to develop a model form of effective bridge management at the network level. The software that was developed in conjunction with this project was deemed inadequate without major revisions, and was not compatible with any of the minimum requirements outlined in the final interim rule.

BRIDGIT is the result of the second effort of NCHRP to develop a system. BRIDGIT is very similar to Pontis in terms of its modeling and capabilities. The system requires data at an element level and reports the condition of the elements in terms of condition states. Deterioration is modeled as a Markov process. Cost models are addressed in a similar fashion.

The primary difference between Pontis and BRIDGIT lies in the optimization model. BRIDGIT bases its optimization model on North Carolina's OPBRIDGE routine. Both of these systems adopted the bottom-up approach to optimization. The advantage of this approach is that BRIDGIT can perform multi-year analysis and consider delaying actions on a particular bridge to a later date. Pontis only has this capability at a network level. Bottom-up programming provides better results for smaller bridge populations than top-down programming. The disadvantage is that the system is slower than Pontis for larger bridge populations.

Another difference between the two systems is the ability of BRIDGIT to define and distinguish between specific protection systems for elements when determining feasible options. Some agencies have also commented that BRIDGIT's menus and screens are easier to negotiate. The BRIDGIT software is based upon the relational database FoxPro, which is accessible in the system.

BRIDGIT completed its initial testing in Fall 1993. The beta test is currently underway with a total of 8-10 states.

### North Carolina

North Carolina was the first state to undertake BMS related research. In 1982, NCDOT began developing individual components in conjunction with North Carolina State University to be used by the bridge maintenance unit after determining that the federal eligibility requirements of data and the sufficiency rating were not adequate for maintenance bridges. Eventually, these individual components were synthesized together to create a BMS.

The data in North Carolina's BMS only includes deck, substructure and superstructure elements, rated on a scale used in the NBI. Deterioration is deterministically modeled. The deterioration rates are revised based on historical data. North Carolina has performed extensive research to devise the user cost models included in the system. The cost models included in the system determine the annual user cost for a bridge, detour length and detour unit costs, load capacity detours, bridge load capacity deterioration, vertical clearance detour and accident unit costs. The Pontis system has adopted many of these models for calculating its user costs.

The optimization model, the Optimum Bridge Budget Forecasting and Allocation System (OPBRIDGE), was developed in 1989, and was the first analysis method developed to determine the optimum improvement action and time for each individual bridge in a network, using a bottom-up approach. The model prioritizes bridge maintenance activities based on the level of service desired and the available budget. Life cycle and user costs are also considered. Results from this model can be reported on the network, county or individual bridge level. OPBRIDGE is included as the optimization model in BRIDGIT and other state BMSs.

### Pennsylvania

Pennsylvania is another state which began early development of a bridge management system after realizing in 1983 that it would cost six billion dollars to remove the deficiencies from its bridge population. A working group of engineers, both inside and outside the Pennsylvania Department of Transportation (PennDOT), developed a bridge management system with McDonnell Douglas Professional Services creating the software. By 1986, the system was operational statewide.

PennDOT's BMS is project-based and is geared towards supporting the department's 12 year improvement program. Each bridge receives a rating, ranging from 0-100 based primarily upon the level of service and condition. The system prioritizes bridges for maintenance, rehabilitation and repair based on a benefit-cost analysis and also provides a module which to predict future bridge needs. There are no optimization capabilities to suggest allocation of available budgets based on a life-cycle cost analysis, though PennDOT is considering developing such a module.

Currently, PennDOT is adding a module which will assist in administering permits for oversized and overweight vehicles. This module will track the capacity and clearances for all bridges and select the appropriate routes for any vehicle requiring a permit. PennDOT also prepares and continually revises its own coding guide which provides detailed descriptions and codings for each data item required by the BMS.

### Alabama

Alabama began developing a BMS in conjunction with the University of Alabama in 1989. The project progressed with the guidance of several committees comprised of state, local, county, federal and University representatives. The system primarily uses NBI data and rates each bridge on a deficiency scale which compares bridge characteristics with the appropriate level of service goals. While most of the specifications for the system have been identified, only a few of the 22 modules are currently operational.

The scour module was the first module to be implemented statewide. This module detects changes in the stream bottom which may lead to the undermining of the bridge foundation. A graphical depiction of is displayed along with historical stream bed sounding data. The module can also calculate and plot the anticipated scour profile for a given flood frequency. The optimization model is based upon North Carolina's OPBRIDGE program and is currently being customized for use in Alabama.

### Indiana

Indiana's BMS is a project level system, recently developed in conjunction with research performed at Purdue University. The data requirements for the system are the same as for the NBI. The Indiana DOT decided it was more important to retain the current inspection method which yielded consistent and uniform rating of bridge components. The system is comprised of four interrelated models.

The first model is a decision tree which selects the best improvement action for a bridge each year over a five year period based upon the condition ratings of each element. The deterioration rate of each element is modeled as a Markov process. A utility rating, based upon the bridge condition, life cycle cost, safety and impact to the community, is calculated for each bridge.

Based on the utility rating, the bridges are prioritized by two different models. The *Rank* model prioritizes the bridges to overall condition. Under this system, the projects for the bridges in the worst condition are ranked first. The *Optimization* model selects the projects which will provide the highest network level of service with the given budget. The Indiana DOT uses these recommendations as decision support in determining its maintenance planning.

The system is currently in implementation stage testing. Proposed enhancements to the system include expanding the decision tree improvement options, obtaining cost data and improving upon the utility function.

## Other Research Related to Bridge Management

Other current research efforts that pertain to BMSs focus on the feasibility of an agency either adopting one of the generic bridge management systems or developing their own system.

### Washington

The Washington Department of Transportation developed a program to manage its maintenance of bridge decks. The state implemented the system in 1988 to determine if the deck of a bridge required an overlay protection system. The deck of each bridge is surveyed and assigned a condition rating similar to that required by the NBI. No protection system is required due to the type of the bridge or if the bridge is scheduled to be replaced. If the bridge is in an environment where deterioration is not likely to occur, or the bridge has already received an overlay, no action is performed on the bridge. The remaining bridges are prioritized based on their condition and level of service considerations. The results of the system are then forwarded to each district at which level the projects are decided upon.

Washington state was included in the original Pontis testing on account of their experience in developing this system. The system could easily be expanded into a full-scale BMS since it includes all the minimum requirements outlined in the final rule.

### Connecticut

The Connecticut Department of Transportation (ConnDOT) began development of a "bridge information system" in 1988 in an effort to improve the storage and retrieval of related bridge data. The project grew out of ConnDOT's successful program of storing information about highways on computer and images on laserdisc. The bridge information system stores inspection and maintenance reports, details on construction projects and "crisis" information such as detour routes and basic information about each bridge in a database. An "imagebase" stores laserdisc images of the bridge and its approaches and elevations. The bridge information system allows a bridge engineer to view the site instantly without having to travel to the actual location.

ConnDOT's bridge information system works in conjunction with Pontis. ConnDOT uses a custom program to record condition ratings for Pontis, along with the safety inspection reports, on a laptop computer. Other inventory related information is translated directly from the database.

### Texas

The Texas Department of Transportation is currently deciding whether to implement Pontis or pursue the proposed BMS specifications developed by the Texas Transportation Institute at Texas A&M University. The Texas DOT already has a database on-line that could be integrated to form a BMS. Most of the inspection data for bridges is coded and stored in the Bridge Inventory, Inspection and Appraisal (BRINSAP) Database. However, BRINSAP currently only identifies serious defects in the bridge inventory. Texas A&M has already developed the appropriate deterioration and cost modeling as well as an optimization model to complete the system.

### Iowa

Iowa State University initially embarked on a project to develop a bridge management system for the state of Iowa. During the initial stage of the research, it was deemed better to focus on adapting Pontis for use in Iowa. The research effort then became to develop tables of minimum acceptable and desirable goals for level of service characteristics, develop bridge component deterioration modeling that uses a Markov chain process, develop a comprehensive list of feasible repair and rehabilitation alternatives presently used by the Iowa DOT and to investigate agency and user costs.

### South Carolina

Clemson University is engaged in a research agreement with the South Carolina Department of Transportation to evaluate Pontis for their use. The Phase I report of this study recommends the adoption of Pontis. However, several modules in Pontis need to be customized for SCDHPT use. A number of elements and respective conditions are not part of the software and need to be incorporated into the software. NBI data needs to be converted from the format that SCHDPT uses to a format that can be read into Pontis. The primary focus of continuing study is on capturing cost data, a critical part of the Pontis modeling for which South Carolina has little data.

## Integrating NDE into Bridge Management Systems

A key point in the implementation of a BMS is that the analysis the system provides is only as good as the information that is input into the system. If the information about a bridge is inaccurate, the resulting analysis will not be optimal. Most bridge management system research has focused on the implementation of the system as well as improving the modeling. Much of the input required for these models includes information that is not currently collected or reported in a different format. Very little work has been published on improving the quality of the information that is required for these models or how to narrow the gap between the data required for the models and current inspection processes.

Currently, visual inspection is the primary means of data collection. While the condition rating of an element is defined in quantitative, engineering terms, the system only records the overall ratings, not a description of the condition that caused the rating. There is no mechanism currently in place to record any other inspection information other than the condition rating in the bridge management system. Thus, data resulting from NDE testing is not formally incorporated into the bridge management system. Using this NDE data as input into a BMS will result in a more accurate description of the actual condition of the individual elements of the bridge.

# Bridge Management Systems
# Literature Search

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