Bridge Management and Inspection Data: Leveraging the Data and Identifying the Gaps

KRISTEN L. SANFORD
University of Missouri–Columbia
PANNAPA HERABAT
Mahanakorn University of Technology, Thailand
SUE MCNEIL
Carnegie Mellon University

ABSTRACT

Data used to support bridge management vary from agency to agency. Collection of these data is time consuming and expensive. Therefore, as bridges continue to age and agencies are under increasing pressure due to limited resources, there is a great need to ensure that data collection is rational. This paper reviews the gaps between what data are actually collected and what is required, and the opportunities to leverage existing data collection efforts. The gaps and opportunities are explored in three areas. First, the role of bridge management data as inputs to analysis tools such as rating programs is explored. Second, detailed safety inspection data are rarely included in bridge management programs, but again they are a critical input for rating and analysis tools. Finally, the inclusion of results from rating and analysis tools in bridge management systems is the exception rather than the rule. The paper also describes the need for a new approach to data collection in terms of these gaps and the existing data. To decide what information should be included in the bridge management system, the paper then describes some tools that are used to evaluate the data needs of an organization and the value derived from additional information. These tools are applied to the case of load rating data.

INTRODUCTION

Three decades of experience with bridge inspection and data collection and analysis means that many agencies routinely use bridge management for setting preservation and improvement priorities and budgets. Catastrophic failures, improved understanding of the behavior of bridges, changing technology, and increased public awareness of environmental and safety issues have all shaped the data collection process for bridges. The result is a set of procedures and software to support data collection, recording and reporting that have evolved rather than been designed. As a result, the data collection effort results in duplication, redundancy, and poor quality and missing data (*1*). As new types of data are generated, and the relationships among specific key structural conditions, vulnerability to natural hazards, and decisions over the life of the bridge are better understood, management systems need to take advantage of these changes. Similarly, the data collected vary from agency to agency. Even within a single agency, the relationship among bridge management data, safety inspection data, and rating and analysis of bridges has not been well developed. Data collection is expensive and time consuming. Therefore, as organizations move toward the next generation of bridge management systems and increase their use of analysis tools, it is important that the data to collect are selected in a rational manner.

Some specific events can be tied to changes in data collection procedures and practice. The collapse of the Silver Bridge in 1968 precipitated the initiation of the National Bridge Inventory (NBI) and the mandatory biennial inspection of all bridges on the federal aid system (*2*). The failure of the Mianus River Bridge in 1983 escalated concern over fracture critical bridges (*3, 4*). The collapse of the Schoharie Creek bridge in 1987 placed new emphasis on scour critical bridges (*3*). With each of these events, state departments of transportation responded in different ways, often by collecting more data.

Effective decision making requires not just inspection and inventory data, but also traffic data, costs, and predicted future condition. These data are often collected and used by other parts of the organization (*5*). Using existing data is important because the cost of data collection is staggering. For example, in 1986, it was estimated that the NBI costs approximately $150–180 million (*6*) to maintain and update, representing around 6,000 person years of inspection and approximately 3 gigabytes of data every two years (*7*).

Agencies are increasingly concerned with making the best use of their limited resources. Currently, many of these agencies are re-engineering their business practices. They are also looking for ways to incorporate their bridge management systems and pavement management systems, which are reasonably mature, into a larger asset management system (*8*). As a result, analyzing data needs and leveraging data to obtain the most information possible are becoming more important. This paper provides some direction for organizations in planning their data collection efforts and in clearly identifying the role of data in decision making.

STATE-OF-THE-ART—STATE-OF-THE-PRACTICE

The need to improve the state of U.S. bridges has been well documented (*9*). Significant research and development has focused on data, new technologies, and computer-based tools to support activities related to the improvement of these bridges. These activities include the development of bridge management systems (BMS) (*10*), inspection and inventory data (*11, 12, 13, 14*), and analysis tools (*15*). However, the state-of-the-practice not only varies from agency to agency but also reflects individual state interpretations of federal requirements and guidelines.

In practice, inspection is conducted to ensure the safety of the structure and to provide information about the current condition. This information is the basis for preservation and improvement decisions. Since the Federal Aid Highway Act of 1968, all states have been required to establish a database of bridges and complete biennial safety inspections on all federal aid bridges, and since the Surface Transportation Assistance Act of 1978 on all bridges on public roads. In addition, the data collection has changed over time as reflected in the "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges," which was revised in 1972, 1979 and 1988 (*2*). As the "Bridge Inspector's Training Manual/90" states, "It is important to note that the Structure Inventory and Appraisal (SI&A) Sheet is not an inspection form. Rather it is a summary sheet of bridge data required by the FHWA to effectively monitor and manage the National Bridge Inspection Program and the Highway Bridge Rehabilitation and Replacement Program." While the resultant database (the NBI) and the inspection program have provided an excellent foundation from which bridge management systems have been developed, much of the detailed information collected during safety inspections is not recorded.

The Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA) focused interest on bridge management, as it required all states to develop and implement bridge management systems as one of six transportation management systems. Although the National Highway System Designation Act of 1995 made these management systems optional, many states have realized the benefits to be gained from a bridge management system and proceeded with implementation. As of September 1996, forty-eight states, as well as Puerto Rico and the District of Columbia, were implementing a bridge management system (*16*). Kentucky and Idaho have chosen not to implement one. Of the agencies implementing systems, forty-one states, Puerto Rico, and the District of Columbia have chosen Pontis, a management system developed by the Federal Highway Administration (FHWA), the American Association of State Highway and Transportation Officials (AASHTO), and six states (*16, 17*). Other states, such as Pennsylvania and North Carolina, have developed or are developing their own bridge management systems. More detailed descriptions may be found in (*16, 18*).

A major role of a bridge management system (BMS) is to manage and organize bridge inspection reports and keep track of inventory records to facilitate better decisions for both maintenance and rehabilitation (*11*). In addition, the most important role of a BMS is to provide a systematic procedure for anticipating bridge maintenance, repair, and rehabilitation activities and the prioritization of these activities. A BMS includes many components such as bridge inspection reports, data analysis tools, and tools for identifying and selecting activities to maintain the system of bridges in the state or jurisdiction (*11*).

The NBI and BMS are designed for "routine" inspections of bridges. For specialized inspections, such as those of fracture critical or scour critical bridges, FHWA provides guidelines but not requirements for inspection (*19, 20*). In general, the results of these inspections, like much of the data collected during the safety inspections, are not recorded in the bridge management system. Although many bridge management systems have been built on the NBI data, there are serious discrepancies between bridge management systems, such as Pontis, and the federal reporting requirements for the NBI (*21*). Other challenges in bridge management include deterioration modeling and the assessment of accurate cost estimates from historical cost data (*22*).

A critical activity to ensure bridge safety is the analysis of bridge performance using load rating programs. Load rating is undertaken when an inspector encounters a defect or deficiency, except in Connecticut where load rating is undertaken as a routine part of every bridge inspection (*23*). A load rating analysis may determine that immediate repairs are required, the loading should be restricted, or that the bridge should be closed immediately.

GAPS AND OPPORTUNITIES

Every bridge is required by law to be inspected at least every two years. This results in the National Bridge Inventory (NBI). Bridge inspection and reporting is mandated in

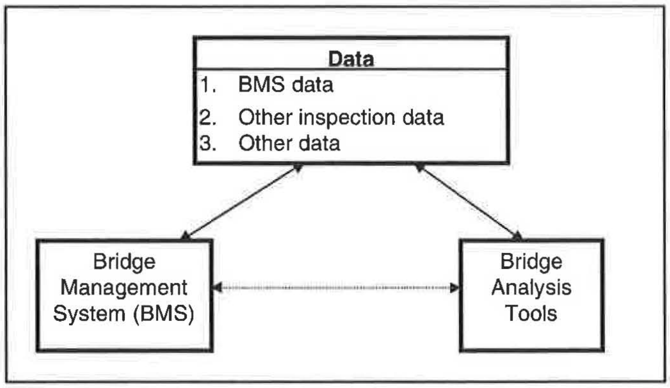

Figure 1: The relationship between BMS, data, and analysis tools.

order to ensure the safety of the structures for every state. Different states have developed their own bridge management systems to manage and keep track of all the inspection records. However, many states collect additional data beyond that required by the NBI, some of which is included in the BMS, along with other data related to special inspections and bridge-related activities. These data are not necessarily assembled in a systematic manner.

The lines shown in Figure 1 represent the relationships between BMS, data, and analysis tools. None of these relationships are obvious, but the least obvious link is between BMS and analysis tools since a BMS does not provide any systematic procedures for tool selection. The need for a formal link between BMS and analysis tools has been suggested in the literature (*11*).

As inspection data collection and recording practices have evolved rather than been designed, there are significant gaps between the actual data collected and the data required. There are also opportunities to leverage resources by using existing data. The remainder of this paper explores the gaps and opportunities in three areas. First, the role of bridge management data as inputs to analysis tools such as rating programs is explored. These data are a critical input to the selection of a particular tool and include some of the basic parameters that describe a particular bridge. Second, detailed safety inspection data are rarely included in bridge management programs, but again they are a critical input for rating and analysis tools. Finally, the inclusion of the results of rating and analysis in bridge management systems is the exception rather than the rule, but these results determine the use of the bridge (for example, when a bridge load limit is posted) and the need for improvement.

BMS Data as Input to Analysis Tools

Bridge management systems record basic inventory data such as the bridge type and material, orientation, and continuity. This information forms the basic input for determining the type of analysis tool to be used to determine the bridge rating. The following list describes the structure information, which is commonly available in the BMS, that is required to select a rating program and is then used by the rating programs (*24*):

- **orientation:** straight, curved and skew
- **continuity:** simple, continuous and cantilever spans
- **type:** slab, beam, girder, truss, frame and arch
- **material:** reinforced concrete, prestressed concrete, steel and composite steel.

This list does not cover special bridge types such as cable-stayed bridges. However, the list presents the most common bridge types.

Detailed data required to use the analysis tool may or may not be included in the BMS. These data include design details (member, shape, size, material, and connectivity), AASHTO standard loads, usage, section loss and cracking, and environment. In addition, analysis tools require information on analysis methods as input data.

Safety Inspection Data as Input to the BMS

Although reporting and recording of safety inspections vary from state to state, detailed safety inspection data are rarely recorded in the bridge management system. The concept of including detailed data has been proposed. For example, Itoh et al. (*5*) argue that information is not used efficiently in managing each stage of the bridge life cycle. With the goal of using resources more effectively, they propose a bridge life cycle management system that includes a geographic information system (GIS), design data, inspection and maintenance data, and images. Photographs are common records for safety inspections but are not used in a BMS. Similarly, non-destructive evaluation (NDE) data are not included, and valuable information is lost (*25*).

Rating and Analysis Results as Input to the BMS

Rating and analysis tools provide critical information on load carrying capacity and in some cases expected life. Connecticut is the only state that requires load rating information to be included in the bridge management system on a regular basis. Ng (*23*) showed that these data can be valuable for modeling deterioration of bridges. Load rating information is also important because it may generate actions such as posting of weight limits or closure of the bridge. While user costs are also not included in current bridge management systems, the user costs associated with these activities are often significant and should be documented.

Filling the Gaps and Leveraging the Opportunities to Use Existing Data

The following sections describe three approaches that address these issues. The first explores the data needed to select a load rating tool and presents a prototype decision support system. The second addresses the role of safety inspection data, specifically NDE data, in bridge management. The third focuses on tools for redesigning the data collection process.

DATA NEEDED FOR SELECTING ANALYSIS TOOLS

There are many types of analysis tools used in practice, such as load rating programs, finite element analysis programs, and design and analysis programs. Each analysis program requires different types of inputs and provides different types of results. This paper focuses on rating programs. Analysis tools have a variety of strengths and limitations. Table 1 highlights the main capabilities of some widely used rating programs and their functions.

Researchers have been attempting to improve the link between BMS data and analysis tools because the current generation of BMS does not provide any systematic procedures for analysis tool selection (*30*). However, in order to understand what data are needed for analysis tools, some commonalties between BMS data and inputs of analysis should be identified. Most load rating programs require the configuration, layout, and geometry of a structure as input, and the resultant output is the load rating (*24*). A BMS keeps track of the structure inventory data, which includes general information about the structure, such as configuration and layout. Therefore, the structure information, configuration, layout, and geometry can be treated as a common ground between BMS and inputs to rating programs.

The structure information described above is the data needed for the analysis tools. However, the selection of an appropriate analysis tool requires additional input about analysis methods. Analysis methods can be specified by bridge engineers or by agency policy. There are three types of analysis methods used for rating—Working Stress Rating (WSR), Load Factor Rating (LFR) and Load and Resistance Factor Rating (LRFD). To summarize the above discussion, rating programs requires the basic structure information, which is commonly available in the BMS, and the rating analysis methods described above.

Not only should all the data required for analysis tools be identified, these data should be organized and assembled in a systematic manner. Possible approaches to structure and organize the required data include theory of classification and knowledge structuring. Theory of classification is a data structuring technique in which the data can be classified into main classes and subclasses (*31*). For example, if bridge type is classified by material, then bridge types will be divided into concrete, steel, and other combinations. The concept of knowledge structuring uses the knowledge in the related domain to structure the problem and the solution, then to try to arrive at a solution (*32, 33*). Herabat (*24*) presents the prototype of a decision support system to select bridge analysis tools based on the structure information that already exists in the BMS or NBI

Table 1: Examples of Analysis Tools

Bridge Analysis Tools	Functions
1. BAR 7 (*26*)	• Calculate load rating for different types of bridges. This includes the inventory and operating rating.
2. BDS (*27*)	• Design and analyze concrete bridges and pre-stressed concrete bridges.
3. BRASS (*28*)	• Calculate load rating for girder bridges.
4. PS program (*29*)	• Calculate load rating for pre-stressed concrete bridges.

and the analysis methods. The prototype provides an example of the link between BMS and the data needed to select an appropriate analysis tool.

SAFETY INSPECTION AND RATING DATA IN BMS

The main purpose of inspection is to ensure the safety of the structure. Following inspection, the structure is given a "condition rating" which quantifies the overall condition of the structure. The condition rating is defined as "sets of visual indicators for use in routine inspection" (*12*). For the NBI, FHWA provides a rating system which ranges from 0 to 9 (a rating of 9 describes a structure in good condition) (*2*). In addition, the inspectors can collect additional data on each structure, such as condition of specific components. Some of the collected data will be stored in the BMS. However, not all collected data get stored in the BMS. The data that do not get stored in the BMS may be stored in a local database or in archival files, depending on each state's procedures. An example of data not commonly stored in the BMS is NDE data.

Given that bridge management systems rely on condition ratings to develop optimal decisions for repair, maintenance, and rehabilitation, two strategies are possible for including NDE data in BMS. The first is to modify the BMS to account for the additional data from NDE. The second is to use the NDE to either determine or modify the condition rating before it is input into the BMS. Using either strategy requires careful consideration of the quality and reliability of the data obtained using NDE, and the different types of information NDE and visual ratings provide. In general, raw NDE data requires interpretation before inclusion in a BMS, or integration with condition ratings. That is, it needs to become information rather than data, as information can be used to make decisions (*34*).

Hearn and Shim (*12*) have developed a strategy for integrating NDE data into or with condition ratings. They propose that, as condition ratings represent mechanisms for including both qualitative and quantitative data, have common definitions, and an ordinal scale, they can be adapted to account for NDE data as opposed to modifying the BMS to account for additional data. Their proposed redefinition of condition states as integrated condition states reduces the reliance on visual data. The integrated condition states reflect the presence of aggressive agents, the stage in the deterioration process, and the existence of damage. This proposed definition is intended to provide condition states that are mutually exclusive, are detectable, are defined by multiple attributes, correspond to maintenance repair actions, and indicate severity but not extent of damage. Tables 2 and 3 show examples of integrated condition states for reinforced concrete elements and painted steel elements under fatigue, respectively. Using this approach, NDE detects and measures attributes of states such as loss of section or loss of structural integrity. For example, as shown in Table 3, it is obvious that if the element is in Condition State 5 (possessing damage cracks), its condition is considered critical. The level of criticality of the structure or structural element determines when the structure needs to be analyzed. Analysis tools are used to perform analysis in order to ensure the safety of the structure. This renders the concepts of safety inspection and rating data in BMS essential to the need of performing analysis.

Similarly, Hadavi (*35*) suggests the use of NDE to quantitatively measure condition. Quantitative measures can then be compared with a limit state standard that uniquely determines the repair or maintenance strategy.

Table 2: Integrated Condition States for Reinforced Concrete Elements [Modified from (12)]

		1 Protected	2 Exposed	3 Vulnerable	4 Attacked	5 Damaged
Attributes	**Exposure**	No ingress of Cl ions	Cl ion ingress, concentration below threshold	Cl ion ingress, Concentration at threshold		
	Corrosion Mechanism		No corrosion activity	Possible corrosion activity	Corrosion activity	
	Rebar Damage				No loss in rebar area	Loss of rebar section
	Concrete Damage				Delaminations and minor spalls	Large spalls
NDE Measure	**Electrical Resistance**	High	Low			
	Specific Ion Probe		Low Cl	High Cl		
	Corrosion Current			Low	High	
	Radar, Sounding				No Damage	Damage

While there is clearly a role for improving and enhancing the status of the nation's bridges through the integration of additional data from safety-related inspections and better non-destructive evaluation with bridge management systems, there are several issues that will need to be addressed:

- There are many nondestructive evaluation methods appropriate for bridges. How valuable is any one method? Answering this question requires consideration of the cost and reliability of NDE (35).

Table 3: Integrated Condition States of the Steel Elements Under Fatigue [Modified from (12)]

		1 Protected	2 Exposed	3 Vulnerable	4 Attacked	5 Damaged
Attributes	**Exposure Endurance**	No exhaustion within service life	No exhaustion within planning period	No exhaustion before next inspection	—	—
	Damage Cracks	—	—	Cracks or flaws detected. No apparent growth	Small cracks or slow growth of cracks. Repair may be delayed.	Significant cracks and/or significant growth rates. Repair needed.
NDE Measure	**Paint Condition**	Adequate	Thin	Exposed		
	Section Loss				Minor	Significant
	Cracks				Initiated	Progressing

- As BMS currently include only visual condition data, the value of multiple sources of data needs to be explored. It should be understood that NDE data may not be a substitute for visual condition ratings but may complement, reinforce, or support visual condition rating data.
- Many NDE methods for bridge evaluation search for a specific type of defect. There have been no systematic attempts to analyze this type of data in terms of the impacts on the life cycle costs of the bridge, the opportunities to reduce the probability of such defects in similar bridges, and the effectiveness of the remediation strategy (*1*).
- The impact of low probability, high impact catastrophic events on life cycle costs should be considered. Bridge engineers have been very successful at avoiding catastrophic failure, but the cost must be accounted for (*36*).
- The burdens of data collection and analysis should also be explored (*7*).
- The role of NDE data in the decision making process must be understood. For example:
  - BMS correlate actions—repair, maintenance, or rehabilitation—with condition ratings.
  - BMS in general do not address project level activities. Therefore, they do not address the issue of what to do if the data collected suggests imminent failure of the need to close or post the bridge.
  - BMS are likely to evolve to reflect level of service criteria (37). The relationships among condition, performance, and level of service must be explored.

REDESIGNING THE DATA COLLECTION PROCESS

Data collection procedures and guidelines have evolved over time as regulations have been issued and management practices have emerged. While most agencies have a bridge management system, there are a variety of systems in use, which often differ in structure and data needs. Even agencies using the same management system may use different quantities and types of data in running the system. The NBI was developed to determine the status of the nation's bridges and the magnitude of the funding needs, and it requires that a total of three ratings be reported—one each for the superstructure, deck, and substructure. The NBI does not provide information about the severity and extent of deterioration of a particular bridge or a strategy for meeting future needs (*38*). Pontis, on the other hand, requires that condition states be reported for each element of the bridge. That is, a condition rating is reported for each beam, column, girder, etc. While Pontis is the most widely used of the bridge management systems, there are many others at both the national level (e.g. Bridgit) and the state level (e.g. Pennsylvania's in-house BMS). States are now faced with collecting data for the NBI and for their chosen BMS as well as any additional data used, and researchers have been working to provide a translation between the various rating scales to reduce the data collection effort required (*39, 40*) .

Sanford developed a process for assessing the data collection practices of an agency (*1*). The example in this work was applied to condition rating of bridge decks. The process uses a combination of data flow diagrams and influence diagrams to structure the data needed to make the decisions agencies want to make, as shown in Figure 2. The

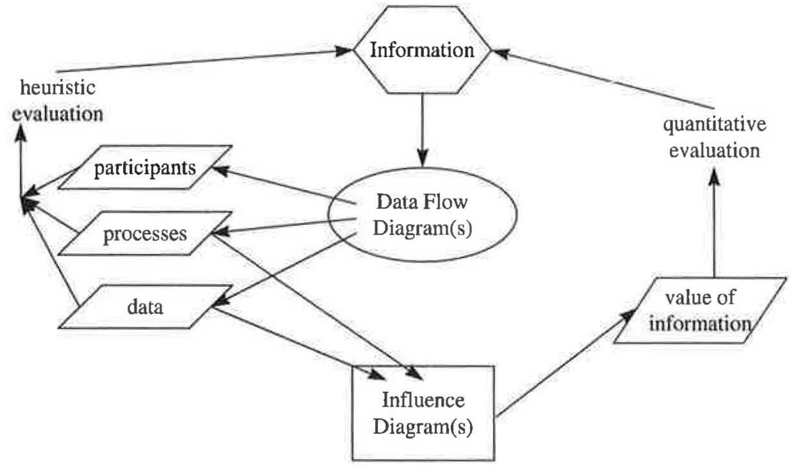

Figure 2: Data requirements approach.

tools are used in a complementary manner to allow both qualitative and quantitative analysis of the process.

Data flow diagrams allow the decision-making process to be structured in terms of the person or people making the decisions, the decisions themselves, and the information inputs and outputs for those decisions. Figure 3 shows a schematic of the partitions of a data flow diagram. The data flow diagrams allow layered structuring. In other words, the nodes of a diagram representing a high-level process can be exploded to sub-diagrams, each of which describes the process in greater detail.

Influence diagrams represent a decision at a point in time. The three most common types of nodes in an influence diagram are:

- chance nodes, which represent events over which the decision-maker has no control, such as the number of freeze-thaw cycles in a location;
- decision nodes, which represent choices the decision-maker must make, such as whether to overlay a bridge deck; and
- outcome nodes, which represent the result of the interaction between the chance nodes and decision nodes. Outcome nodes often represent monetary values, and therefore

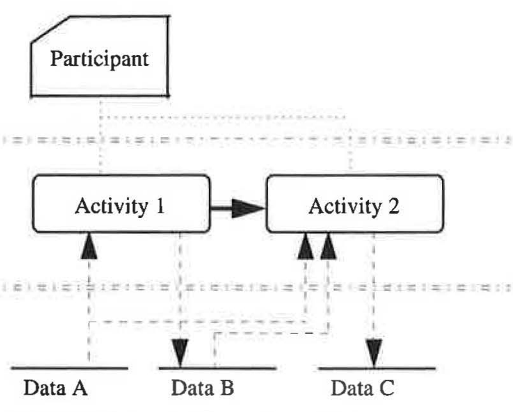

Figure 3: Data flow diagram.

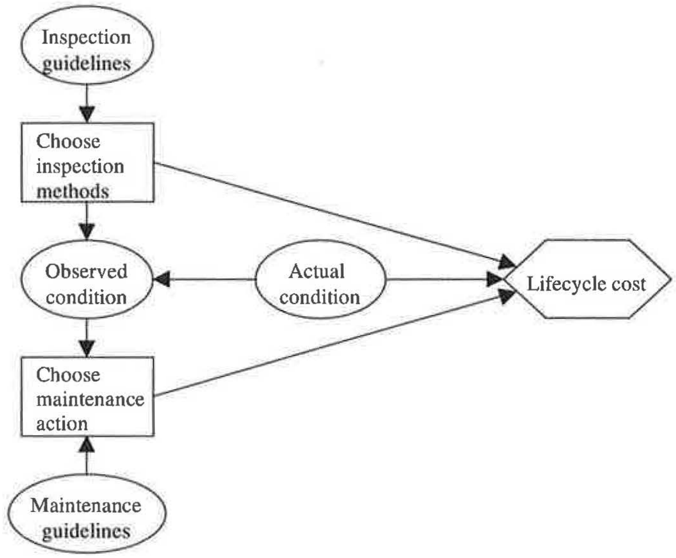

Figure 4: Influence diagram.

they can be used to represent the cost of maintaining a bridge or to determine the value of a particular type of data or data collection technology.

Figure 4 provides a simple example of an influence diagram for a bridge deck.

AN EXAMPLE

Bridge analysis tools are one application that requires significant amounts of data from an agency. As detailed by Herabat (*24*), both the data required for selecting an analysis tool

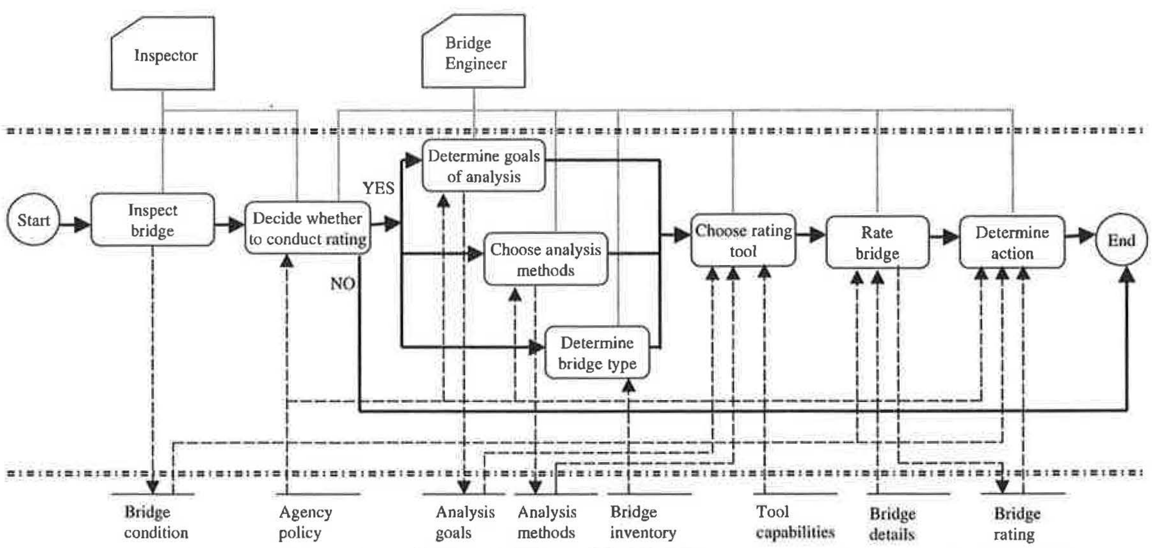

Figure 5: Data flow diagram—Determine rehabilitation action for a bridge.

and the data required for applying an analysis tool are drawn from a variety of sources. The procedure developed by Sanford (*1*) can be applied to the case of data required for bridge analysis tools as well as selection of bridge analysis tools. In Herabat's work (*24*), the bridge analysis tools were classified using data structuring, but they were classified based on their capabilities, rather than on the basis of the data required. Figure 5 shows one way to structure the people, decisions, and data involved in integrating rating and inspection data for bridge management. The inspector and/or the bridge engineer decide whether to conduct a rating analysis based on agency policy and bridge condition. If a rating is conducted, a number of actions, such as closing or load posting the bridge, may be considered, or the rating results may be considered in determining appropriate rehabilitation options.

The Need for Rating Data

There are multiple uses for rating data in the bridge management process, although the data are not necessarily collected and stored in the bridge management system. One of the issues in using a particular bridge analysis tool is whether the user has access to the data needed. Other issues, as described by Herabat (*24*), include the access of the user to the tool and the familiarity with the tool. As discussed previously, rating data are important because of the implications for bridge usage and the potential for preventing catastrophic failure.

The Value of Rating Data

Rating data have the potential to provide tremendous value to the bridge management process by minimizing life cycle costs. For example, rating data may allow an agency to prevent overloading, thereby extending the life of the facility. Figure 6 is an influence

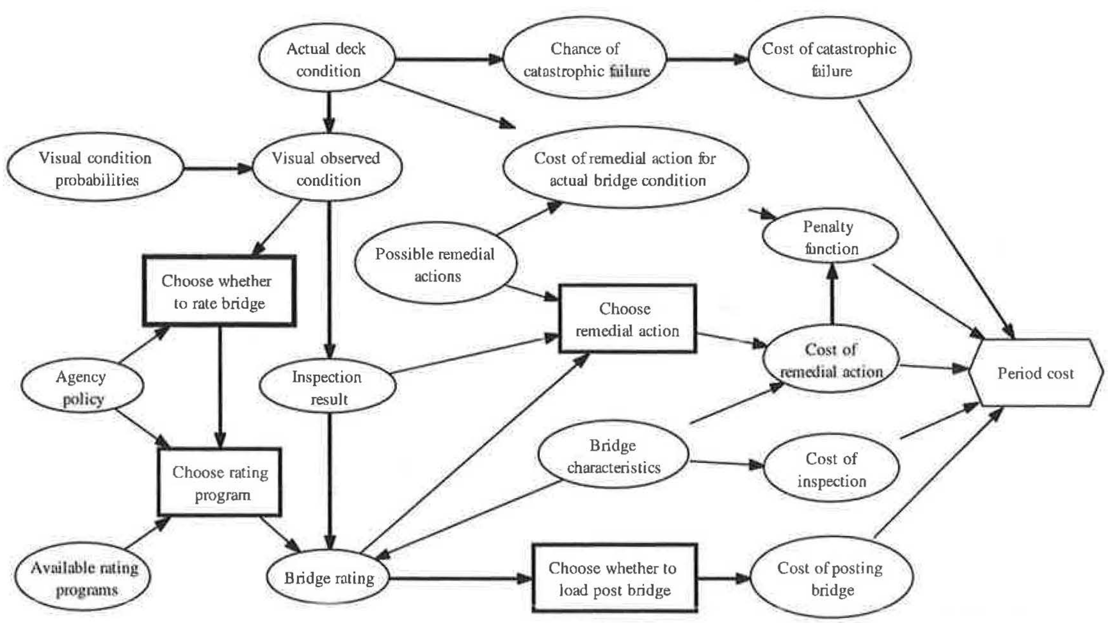

Figure 6: Influence diagram for rating data.

diagram, which allows the user to evaluate the value of rating data over the life of the bridge. The *penalty function* and *period cost* are used as proxies for determining the life cycle cost. In other words, the penalty function is meant to account for costs related to errors in perceived condition and the resulting action. As pointed out in (*41*), this requires both good probability data and good cost data, which may or may not be available.

CONCLUSIONS AND RECOMMENDATIONS

Effective and efficient data collection, storage, and access are critical for managing bridges under constrained resources. As data collection practices have evolved in response to regulations, new technologies, and management practices, there are gaps in the data collection efforts, data that are collected but not recorded, and data collection efforts that are duplicated.

Several tools are available to improve the data collection process. These include structuring the data collection process using data flow models and using influence diagrams to explore the value of additional information. The use of data from BMS to select a load rating tool demonstrated that it is possible to develop a link between BMS and analysis tools. It is surprising to find that the proposed link required a minimum amount of already existing BMS data to be useful in identifying the data necessary to provide a link between BMS and rating programs.

This paper is a starting point in understanding the gaps between BMS and analysis tools. Based on the discussion above, there is some common ground between the two. However, practice varies from state to state. Not all states use the same types of analysis tools. The concepts presented in this paper can be easily adapted to each state's specific practice.

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