BRIDGE MANAGEMENT SYSTEM DATA NEEDS AND DATA COLLECTION

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ABSTRACT

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

INTRODUCTION

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

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

BRIEF HISTORY OF BRIDGE INSPECTION

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

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

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

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

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

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

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

EXPANSION OF BRIDGE DATA COLLECTION

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

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

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

TABLE I EVOLUTION OF FHWA CODING GUIDE

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

* Twenty-five items were deleted in 1988 Edition.

AASHTO BMS Guidelines

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

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

Proposed FHWA Rules for Bridge Management Systems

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

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

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

STATE HIGHWAY AGENCY DATA COLLECTION PRACTICES

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

Number of Bridges

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

TABLE II STATE BRIDGE COMPARISON

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

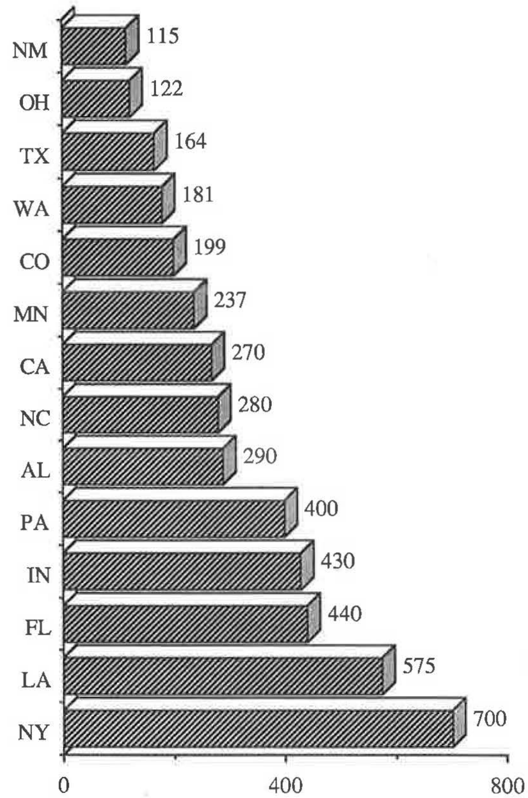

FIGURE 1 Number of data items per bridge.

Number of Data Items

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

Labor Requirements

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

Data Cost Effectiveness

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

Frequency of Data Collection

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

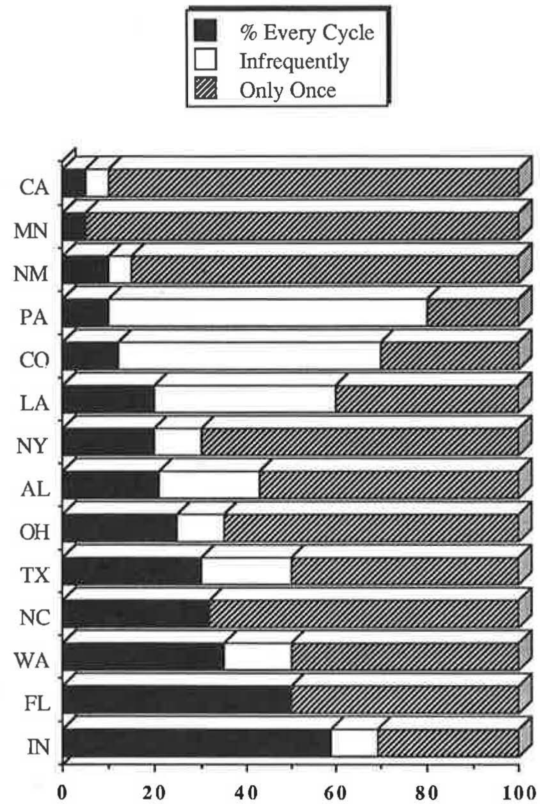

FIGURE 2 Percentage of BMS data items.

Data Collection Methods

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

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

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

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

BRIDGE DATA NEEDS

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

Decisions on Immediate Needs

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

Prevent Bridge Failures

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

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

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

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

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

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

Determine Functional Obsolescence

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

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

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

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

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

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

Determine Maintenance Needs

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

TABLE III MAINTENANCE ACTION ITEMS

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

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

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

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

Decisions on Future Needs

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

Predict Bridge Deterioration

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

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

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

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

Predict Bridge-Related Costs

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

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

DECISION CRITICAL DATA

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

SUMMARY

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

TABLE IV SURVEY OF DECISION CRITICAL DATA ITEMS

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

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

REFERENCES

1. "National Bridge Inspection Standards," Section 23, *Code of Federal Regulations*, Part 650.3, Washington, D.C.
2. "Defense Bridges and Critical Highway Facilities Reports," *Federal-aid Highway Program Manual*, Volume 6, Chapter 10, Section 2, Washington, D.C.
3. *Recording and Coding Guide for the Structure Inventory of the Nation's Bridges*, Transmittal 123, Volume 20, Appendix 54, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., July 1972.
4. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., January 1979.
5. *Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges*, Report No. FHWA-ED-89-044, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., December 1988.
6. *Bridge Inspectors Training Manual 70*, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1970.
7. *Manual for Maintenance Inspection of Bridges*, American Association of State Highway and Transportation Officials, Washington, D.C., 1983.
8. *Guidelines for Bridge Management Systems*, American Association of State Highway and Transportation Officials, Washington, D.C., 1992.
9. "Management and Monitoring Systems, Notice of Proposed Rulemaking," FHWA/FTA Docket No. 92-14, *Federal Register*, Vol. 58, pages 12096-12125, March 2, 1993.
10. Johnston, D.W. and P. Zia, "A Level of Service System for Bridge Evaluation," *Transportation Research Record 899*, Transportation Research Board, Washington, D.C., 1988.
11. Thompson, P.D. and R.W. Shepard, *Pontis*, paper presented at the *Bridge Management for Transportation Agencies Conference*, Transportation Research Board, Austin, Texas, September 1993.
12. O'Connor, D.S., Personal Communication, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., May, 1993.