PONTIS

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ABSTRACT

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

BACKGROUND

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

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

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

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

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

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

DATA NEEDS

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

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

TABLE I DISTRIBUTION OF PONTIS ELEMENTS IN CALIFORNIA BRIDGES

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

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

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

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

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

DATA ANALYSIS PROCEDURES

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

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

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

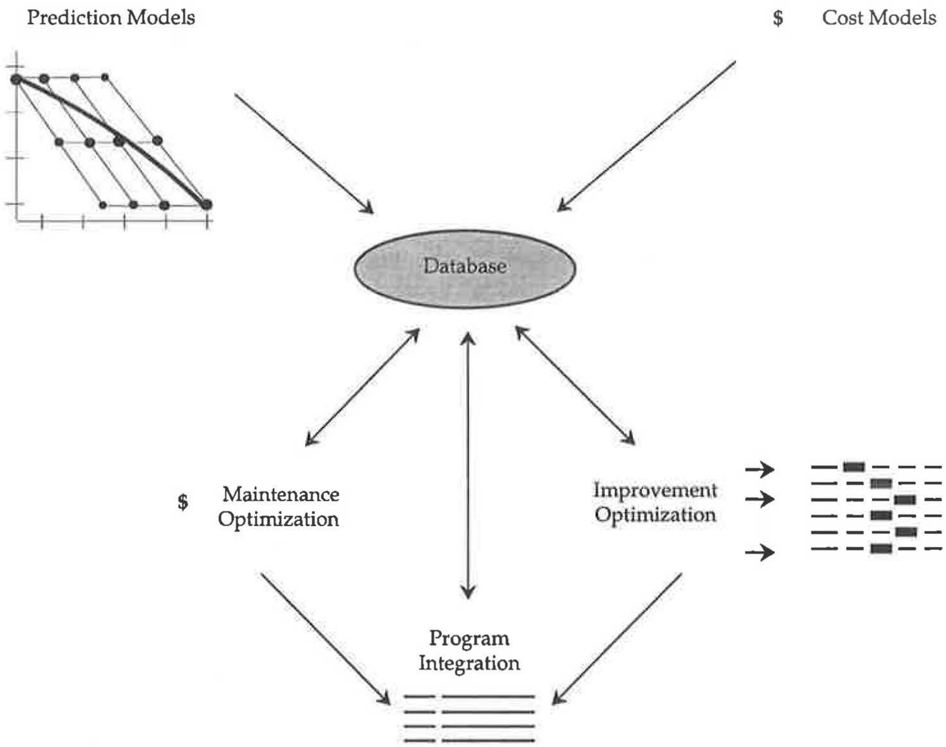

FIGURE 1 Overall structure.

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

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

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

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

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

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

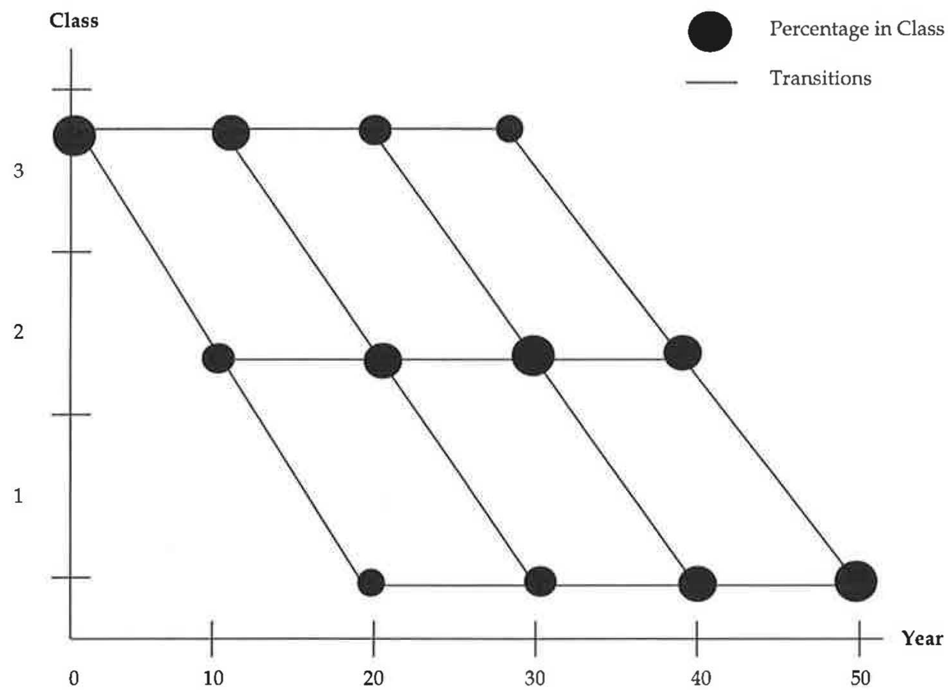

FIGURE 2 Prediction models.

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

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

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

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

DECISION SUPPORT

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

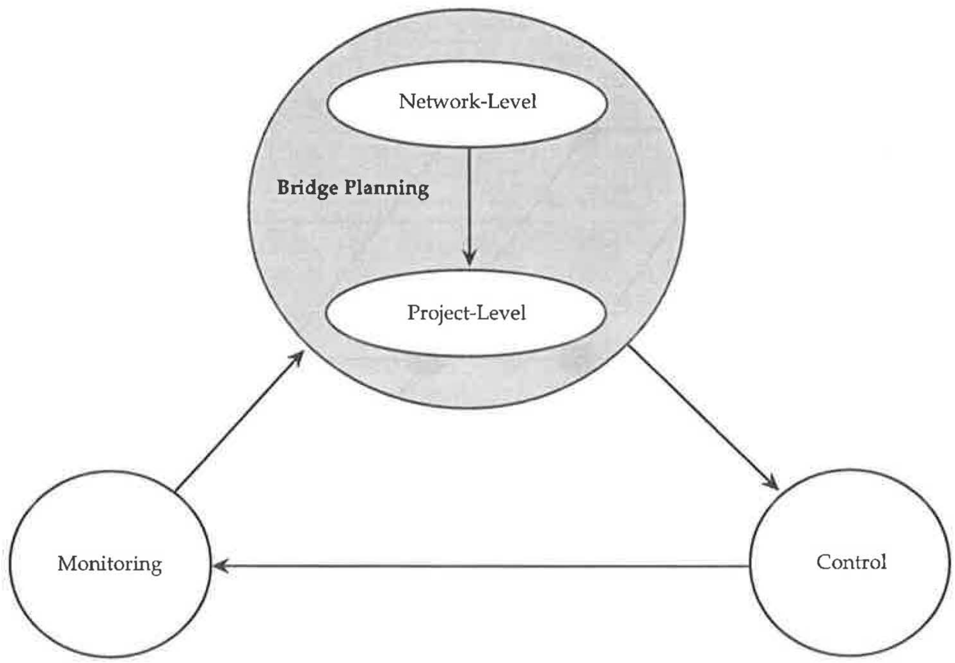

FIGURE 3 Bridge management cycle.

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

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

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

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

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

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

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

IMPLEMENTATION STATUS

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

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

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

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

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

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

FUTURE DIRECTIONS

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

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