BRIDGIT Deterioration Models

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Accurate prediction of the future condition of bridge elements is one of the cornerstones of any bridge management system's (BMS's) optimization model. The BRIDGIT BMS software uses condition state quantities to represent the conditions of the various elements that make up a bridge. The use of condition states does not allow for an easy application of classical deterministic deterioration curves. It is necessary to model the transition of element quantities through their various condition states. Predicting the deterioration of an element through time is essential for estimating the timing of future repair and improvement actions and calculating their associated costs. Deterioration of a bridge element can be represented by a Markov chain process. By this approach transitional rates are calculated to project the quantities of a bridge element that will move to lower condition states in a defined time interval. BRIDGIT uses derivatives of Markov chain processes to model unprotected elements, protection systems (such as paint systems or deck overlays), and protected elements in which the protection system modulates the deterioration of the base element. In addition, BRIDGIT considers the effects of environment, traffic volumes, and previous repairs that may accelerate the deterioration of decks, slabs, and overlays.

The principal objective of NCHRP Project 12-28(2)A (*1,2*), which began in January 1992, was to develop, validate, and document a fully operational microcomputer-based bridge management system (BMS) software package that could readily be used by transportation agencies. The system is based on the conceptual design presented in NCHRP Report 300 as well as the recommendations identified in "Guidelines for Bridge Management Systems" that resulted from NCHRP Project 20-7, Task 46.

This paper is restricted to a discussion of the deterioration models used.

BRIDGIT ELEMENT AND PROTECTION SYSTEM MODELS

BRIDGIT uses condition state quantities to identify the nature, severity, and extent of deterioration of bridge elements and protection systems. Up to five condition states may be defined for an element or protection system model. Condition states for an element or protection system are associated with different levels of physical defects as well as functional performance deficiencies.

As part of the inspection process inspectors must record the quantity or percentage of an element in each condition state. Each condition state can be associated with specific repair actions and unit costs. BRIDGIT automatically considers the replacement and do-nothing alternatives for the element as well.

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PREDICTION OF FUTURE CONDITION

The information defined for each element deterioration model in BRIDGIT is used to calculate the quantity of element that transitions from a particular condition state to the next lower one in any year. This is accomplished by assuming a Markov chain process (*3*) and calculating the transitional rates for each condition state of an element.

In the Markov chain process the probability that an element transitions from condition state i to another condition state j does not depend on how the element arrived at the ith state. That is, the probability of a quantity of an element moving to a future state always considers its current state as if it were a starting point.

The probability that the process moves to state j from state i in 1 year (i.e., in one step) is called the *transition probability* and is generally denoted p_{ij}. In the case of bridge element deterioration it can be assumed that the probability of transitioning from one state to the next is the same from year to year. This assumption makes it possible to define an n-step matrix of the transitioning process, which is simply the one-step transition matrix raised to the nth power.

Development of Equations for Predicting Future Condition State Quantities

The following assumptions are used by BRIDGIT in applying the Markovian chain process to a practical modeling of bridge element deterioration:

1. Elements cannot improve their condition unless some action has been effected.
2. An element quantity can transition to a lower condition by, at most, one state in 1 year. Thus, it is not possible to deteriorate from Condition State 2 to Condition State 4 in 1 year.
3. For a total quantity of element, *TOTQUAN*, the sum of the normalized quantities in each condition state must be equal to unity.

$$\sum_{i=1}^{5} X_i = 1.0 \qquad (1)$$

where X_i is equal to $QUAN_i/TOTQUAN$ and $QUAN_i$ is the quantity of element in state i at the beginning of the current year of the analysis.

4. The sum of the normalized quantities in each condition state in Y years must be equal to unity.

$$\sum_{i=1}^{5} NEWX_i = 1.0 \qquad (2)$$

where $NEWX_i$ is equal to $NEWQUAN_i/TOTQUAN$ and $NEWQUAN_i$ is the quantity of element in state i in Y years.

These assumptions lead to a Markovian transition probability matrix in which all matrix elements are zero except for the diagonal and one line below the diagonal. Thus:

$$[NEWX] = [P]^{y}[X]$$

$$\begin{bmatrix} NEWX_1 \\ NEWX_2 \\ NEWX_3 \\ NEWX_4 \\ NEWX_5 \end{bmatrix} = \begin{bmatrix} P_{11} & 0 & 0 & 0 & 0 \\ (1-P_{11}) & P_{22} & 0 & 0 & 0 \\ 0 & (1-P_{22}) & P_{33} & 0 & 0 \\ 0 & 0 & (1-P_{33}) & P_{44} & 0 \\ 0 & 0 & 0 & (1-P_{44}) & 1.0 \end{bmatrix}^{Y} \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \end{bmatrix} \quad (3)$$

where P_{ii} is the probability of a state i quantity staying in state i after 1 year.

Note that the transition matrix in Equation 3 is raised to the Yth power to reflect Y years of deterioration.

This matrix equation can be solved by standard mathematical procedures involving eigenvalues and eigenvectors. Equation 3 permits BRIDGIT to determine the future quantities in each state after Y years, [$NEWX$], based on knowing the initial mix of condition state quantities, [X].

Developing Transition Probabilities

In fully implementing the Markovian model it is necessary to determine the transition probabilities P_{11}, P_{22}, P_{33}, and P_{44} used in Equation 3 to predict the future quantities of an element in each condition state. Initially, BRIDGIT is supplied with default deterioration model data that can be altered by each agency if desired. When sufficient historical condition information is available from annual inspections, BRIDGIT can automatically update these model parameters.

For each element deterioration model the following information must be provided by the user for each condition state of the element, as well as for the four possible environments:

1. The average number of years that it takes for a specific percentage of an *unprotected* element quantity to deteriorate from new condition to another condition state *or worse.*
2. The corresponding fractional element quantity.

BRIDGIT requires that the agency determine this information through research, statistical analysis, or field observation.

Using this information BRIDGIT can calculate the transition probabilities for each condition state.

Table 1 shows a sample deterioration model for a concrete deck element. For a moderate environment it shows 25 percent of the total quantity of element in an average bridge to be in Condition State 3 or worse after 20 years.

DETERIORATION OF PROTECTED AND UNPROTECTED ELEMENTS

The following sections describe the application of the Markov process as well as the models used by BRIDGIT to predict the future conditions of elements and protection systems.

Deterioration of Unprotected Elements and Protection Systems

To predict the future conditions of unprotected bridge elements, BRIDGIT directly applies Equation 3 for different years (Y) over the life of the element. The values used for Y are determined during the development of the life-cycle activity profiles produced by BRIDGIT for each bridge in a network. In addition, Y is adjusted to account for the effect of average daily traffic on the rate of deterioration of the element.

This methodology is used for any elements which that do not have an associated protection system and that include elements such as bare decks, unpainted steel girders, joints, and bearings and is also used for protection systems themselves.

Deterioration of Protected Elements

The deterioration of protected elements is more complex. In general terms BRIDGIT assumes that the protection system modulates the deterioration of the protected element. For example, a concrete deck protected by an asphalt overlay may deteriorate at half the rate of a bare deck if the asphalt is in good condition, at 80 percent of the rate of a bare deck if the asphalt is in fair to poor condition, and perhaps even faster than a bare deck if the overlay is in bad condition.

TABLE 1 Element Deterioration Model for Concrete Decks

Condition State	% of Element in this State or Worse	Time in Years to Deteriorate Specified % of Element by Environment			
		Benign	Low	Moderate	Severe
2	35.00	10	10	8	6
3	25.00	30	25	20	11
4	20.00	50	40	25	15

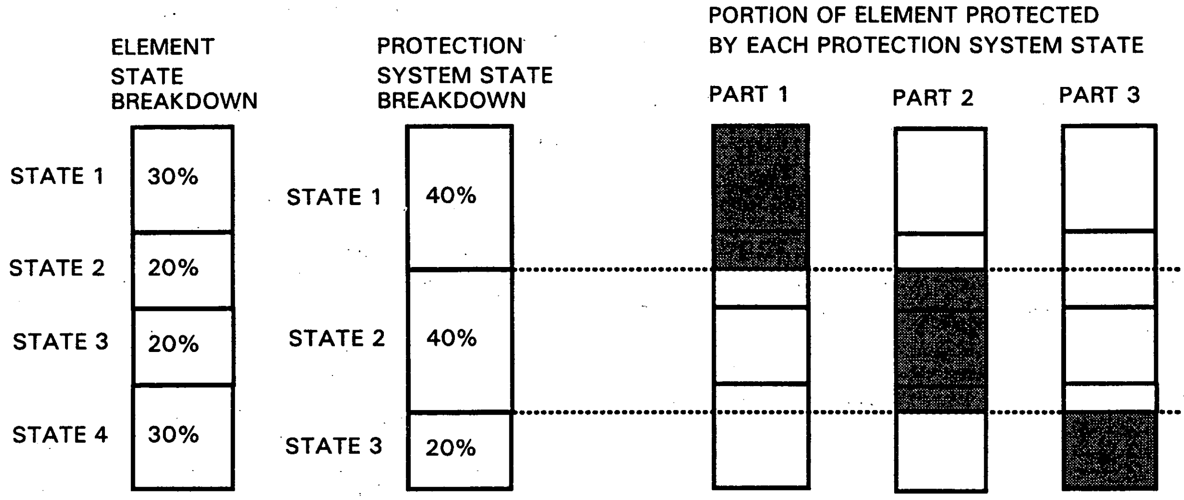

FIGURE 1 Portion of element protected by each protection system state.

BRIDGIT also assumes that element condition and protection system condition are linked (i.e., the locations where the element is in its worst condition are the same as the locations where the protection system is also in its worst condition). For example, steel girder deterioration due to corrosion is assumed to occur where the paint has failed.

As part of the information used to define protection system models, a protection modifier must be specified for each condition state. This represents a factor by which the rate of deterioration of a protected element is decreased. In other words, if the protection modifier for a paint protection system in Condition State 2 is 4 then the rate of deterioration of quantities of element protected by paint in State 2 is one-fourth the rate of deterioration for the unprotected element quantity.

The most difficult part of modeling the deterioration of protected elements is in determining the quantities of base elements that are protected by each associated protection system quantity. BRIDGIT performs the following steps to obtain results for any year of an element's life:

1. Deteriorate the protection system by Y years to calculate the predicted future state quantities $NEWXP_j$ of the protection system.
2. Determine the average protection to the element provided over the Y-year interval. For bridge deterioration modeling averaging is sufficiently accurate provided that the time interval is small compared with the life span of the protection system (i.e., deterioration from state to state is generally linear in the short term).
3. Determine the condition state quantities of the element that are protected by each of the protection system states. Figure 1 illustrates this for an element with four condition states and a protection system with three states. Figure 1 shows, for example, that State 2 of the protection system protects half of State 2 of the base element, all of State 3, and one-third of State 4.
4. BRIDGIT then separates the base element into a series of unprotected elements, one for each condition state of the protection system. These "separated" elements are then deteriorated individually, accounting for the effects of the protection system modifier. This is accomplished by modifying the time interval Y as follows:

$$Y'_j = Y / SUBMOD_j$$

where $SUBMOD_j$ is the protection system modifier for State j of the protection system. Using the transition probabilities already known for the unprotected base element, Equation 3 is used to determine the $[NEWX]$ quantities of the separated elements and for each Y'_j. The final predicted element quantities are then determined by combining the results obtained for the separated elements.

OTHER FACTORS AFFECTING ELEMENT DETERIORATION

Effect of Previous Repairs on Deterioration

For some elements it is appropriate to account for previous repairs in the deterioration rates since repaired elements tend to deteriorate more quickly. This is especially true for concrete decks. This increase in deterioration rate could be due to two factors:

1. Repairs are not of the same quality.
2. Past repairs are indicative of defects that are not detectable by visual inspections. Engineers involved in planning deck repairs always inflate repair quantities in the contract above those indicated by even instrumented inspections because they know that more problems show up during the actual repairs.

BRIDGIT attempts to reflect the effects of these hidden defects by moving a percentage of the State 1 quantity into State 2. This effectively accelerates the deterioration process.

Effects of Average Daily Traffic

It is well understood that the amount of traffic, especially the amount of truck traffic, can influence the deterioration rates of decks, joints, and other elements directly affected by wheel loads. In general, average daily traffic and percent truck traffic are related to the functional classification of the roadway. BRIDGIT makes use of an average daily traffic modifier that is associated with each functional route classification.

BRIDGIT incorporates the effects of the average daily traffic modifier by adjusting the value of Y used in Equation 3. For example, if it is determined that bridge decks on local roads tend to deteriorate at only 70 percent of the rate for the entire bridge population because of low traffic volumes, BRIDGIT uses a value of $Y' = 0.70 \cdot Y$ instead of Y in the equation.

CONCLUSIONS

Markov chain processes are ideally suited to the prediction of future element condition in which each element's condition is defined by a set of condition state quantities.

The deterioration models used in BRIDGIT model elements and protection systems separately and also account for the interplay between the two.

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