Bridge Element Deterioration Rates

IMAD J. ABED-AL-RAHIM AND DAVID W. JOHNSTON

Predicting the deterioration rates of bridge elements is an important component of any bridge management system. This is because the prediction of future bridge funding needs is based in part on the existing and future conditions of the bridge element. A methodology for predicting the deterioration rates of bridge elements was developed on the basis of an analysis of historical data from bridge inspections. The methodology is applied to the bridge deck, superstructure, and substructure as example elements. General deterioration curves were developed for the three major bridge elements by material type. More detailed deterioration curves for the bridge elements were also developed for various subgroupings of these elements divided by material and environmental factors.

Deterioration is the process of decline in bridge element condition. It is caused by the environment, traffic, and other spontaneous factors. The prediction of future bridge funding needs is made in part on the basis of the existing and future conditions of the bridge element. It is thus important for the success of any bridge management system to accurately predict the bridge element deterioration rates.

Under current FHWA inspection procedures elements (such as the deck, superstructure, and substructure) are evaluated on a scale of 9 to 0 indicating the degree of deterioration. Unless maintenance or rehabilitation work is performed on the bridge, the element condition rating would be expected either to remain unchanged or to drop in any inspection period. The inspection of bridges is conducted by trained technicians under engineering supervision every 2 years. Bridge-owning agencies keep records of the conditions of the various bridge elements in the Bridge Inventory data file along with other bridge data.

According to the FHWA's *Bridge Management Systems* report (*1*) all studies to date on bridge deterioration rates tend to predict slower declines in bridge condition ratings after 15 years or so. The report also included results from a regression analysis of National Bridge Inventory (NBI) data for deterioration of deck condition and overall structural condition. The results suggest that the national average deck condition rating declines at the rate of 0.104 points per year for approximately the first 10 years and 0.025 points per year for the remaining years. For overall structural condition the values were 0.094 per year for 10 years and 0.025 per year thereafter. This implies that the average conditions never fall below a condition rating of 6 until after 60 years.

However, these results do not fit with the experience encountered in practice, which suggests a much faster decline in condition. The primary difficulty encountered by researchers in developing a reasonable representation of the actual deterioration curves is that the models used to analyze aggregate inventory conditions at a point in time did not take into account the effects of any improvement work done to the bridge elements in the past.

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OBJECTIVE

The objectives of the study were to develop analytical methods for estimating the deterioration rates of the three major bridge elements (deck, superstructure, and substructure) as a function of material types and various environmental factors. The mathematical method developed was to allow periodic reanalysis by using existing (but then current) North Carolina Department of Transportation (NCDOT) bridge data bases.

LITERATURE REVIEW

Several efforts have been made to estimate the deterioration rates of bridge elements. A study conducted at the Transportation Systems Center (TSC) (*2*) used NBI data and regression techniques to develop equations that related the three major bridge element condition ratings to other bridge characteristics found in the NBI. The study included only bridges that were 25 years or younger. Age was found to be the most highly correlated factor, with average daily traffic (ADT) being the next highest. The equations developed were used to predict the change in bridge condition over time. It was suggested on the basis of the equations that were developed that the deck deteriorates slightly faster with age than the superstructure or substructure. The study estimated the average deterioration of decks to be about 1 point in 8 years and that of both the superstructure and substructure to be about 1 point in 10 years.

The FHWA's *Bridge Management Systems* report (*1*) indicated three weaknesses in the TSC study. The first was that the analysis was performed on bridges that were no more than 25 years of age. The second was that the equations developed assumed linear relationships between the bridge element condition ratings and the parameters included in the equations. The third weakness was that the intercept coefficient in the equations was constrained to 9.

In a study by Hyman et al. (*3*) for the Wisconsin Department of Transportation piecewise linear regression was used on numerical condition appraisal data to develop deterioration curves. The study estimated a composite deterioration curve for all bridge types. In addition, deterioration curves were developed for six different bridge types: steel deck girders, other steel structures, reinforced concrete deck girders, concrete slabs, prestressed concrete structures, and culverts.

Chen and Johnston (*4*) conducted a survey of bridge inspectors and maintenance supervisors to determine age to the various levels of condition on the basis of accumulated expert experience by a Delphi approach. A series of trilinear deterioration relationships was developed, largely on the basis of survey results, for major bridge elements and material types.

Jiang and Sinha (*5*) used two approaches for developing deterioration curves. These were (a) regression analysis of condition versus age and (b) Markov chain model techniques.

The Markov chain model technique was used for two kinds of predictions: the condition rating of a bridge at a given age and the service life of a bridge. This technique was based on defining states in terms of a bridge element condition transiting from one condition to another. The zoning technique was used to obtain transition matrices, since the rate of deterioration of bridge conditions varies at different ages, thus making it a nonhomogeneous process. "Bridge age was divided into groups and within each group the Markov chain was assumed to be homogeneous" (*5*). A transition probability matrix was therefore developed for each group.

The Markov chain approach produced unusually slow predictions of element deterioration in comparison with those produced by Chen and Johnston's (*4*) surveys and in comparison with the subjective experience. However, the curve shapes, a flat S curve, were similar to the trilinear shapes developed by Chen and Johnston (*4*).

Saito and Sinha (*6*) also used the Delphi approach to develop deterioration curves for the different bridge elements. This was based on a survey of 14 Indiana Department of Highway employees in charge of bridge inspection and design.

FHWA's *Bridge Management Systems* report (*1*) stated that "All the studies on bridge deterioration to date imply that the rate of deterioration tends to slow down markedly after 15 years or so. In fact, data from many studies—when taken at face value—suggest that the average bridge condition actually improves or heals with age at some point."

This is due to the fact that in most of the studies mentioned earlier no consideration was given to the effect of the work performed on the bridge condition rating. Such effects will mask the actual relationship between the bridge's age and the element's condition rating.

DATA ON BRIDGE ELEMENT CONDITION RATINGS

FHWA requires bridge-owning agencies to keep records of numerous characteristics for every bridge under their jurisdiction. Element condition ratings of the deck, superstructure, and substructure are part of these records. NCDOT has been keeping such records since 1980. These data, which are updated as new inspections occur, are kept in the North Carolina Bridge Inventory (NCBI) data file. A status record of the total file is retained at the end of each fiscal year. Selected fields of these records, including bridge element condition ratings, are stored in the Bridge History files. These files are appended annually to include records of the latest fiscal year.

Unless it is recorded as an *N*, for nonapplicable, the bridge element condition rating can only be an integer from 0 to 9. Thus, when a bridge element changes from one condition rating to another it can only change in integer values such as 1 and 2. Hence, the data for condition rating versus time do not yield a curve when they are plotted (Figure 1).

Bridge elements almost never receive condition ratings 0, 1, or 2 because they are either rehabilitated or replaced before they reach such conditions. Of more than 14,000 bridges in North Carolina, each with three primary elements, only one bridge element had a condition rating of 2 and none had a condition rating of 0 or 1 in 1989. A bridge element only rarely receives a condition rating of 3 since, once again, they are generally either rehabilitated or replaced before reaching this level. Only 185 bridge elements in North Carolina were rated at a condition of 3 in 1989, and the majority of these were timber bridge elements.

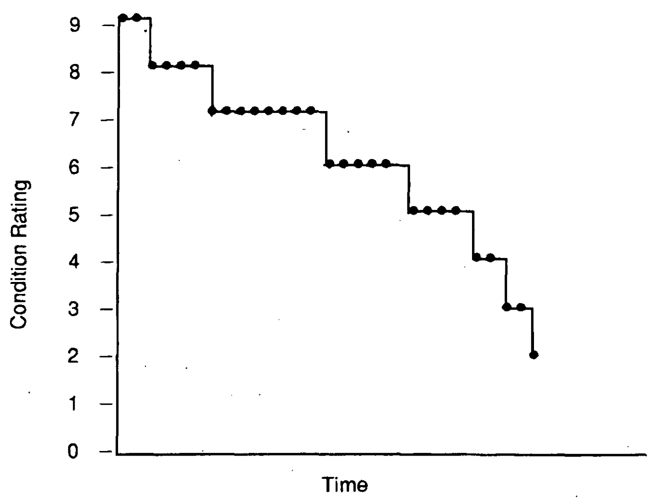

FIGURE 1 Condition rating versus time.

PROBLEMS RELATED TO BRIDGE CONDITION RATINGS

FHWA provided a coding guide (*7*) for evaluating the condition ratings of the various bridge elements. However, it did not provide a detailed reference guide that would explicitly describe the relationship between the deterioration levels of the bridge elements and numeric condition ratings (*6*). Thus, what might be recorded by one inspector as a 6 might be recorded by another inspector as a 5. An actual measure of the effect of this phenomenon on the consistency of the data stored is hard to measure. The states and FHWA have, however, attempted to promote consistency through inspection training.

When work improvement is performed on the bridge, it will increase the condition of the bridge but it will not affect the age, thus distorting the actual relationship between age and condition rating. Although NCDOT keeps records of all of the work performed on the bridges, it is difficult to measure the contributions of various improvement activities toward the condition of the bridge elements. This is caused by the fact that members of a crew performing one type of repair work might go ahead and perform some other minor repairs to other components of the bridge while they are at the site. The condition rating of the other components might thus improve, although the work might incorrectly be recorded only under the primary work item code.

Work improvements performed on bridges will in general either improve the condition rating of the element or increase the stay of the element in its current condition rating. Such work will thus disrupt the actual relationship between the bridge age and condition rating. This is evident in Figure 2, in which the average age of bridges with condition ratings of 4, 5, and 6 are almost equal, whereas the average age of bridges with a condition rating of 3 is less than the average age of the bridges with the previous three ratings. It can also be seen from Figure 2 that there is typically a lot of variation in the data for bridges with the different condition ratings.

These problems are caused by looking at data from only 1 year for bridges with no previous work, bridges with some previous work, and bridges that may have been substantially rehabilitated in the past. Unfortunately, since records only extend back to 1980 for some data and even less for other data, these groups of bridges can-

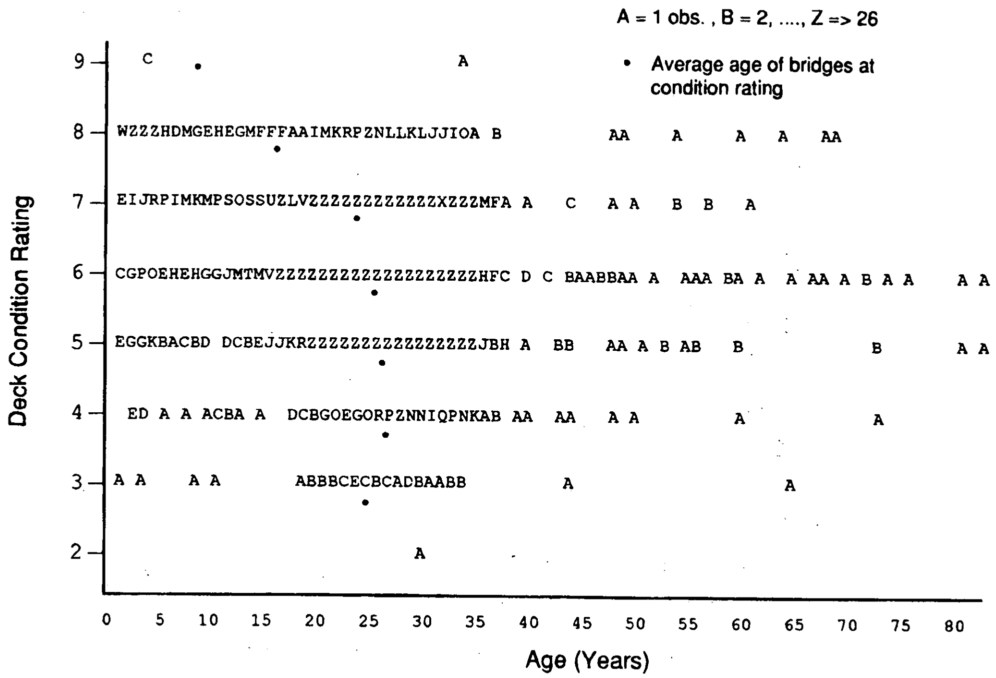

FIGURE 2 North Carolina timber deck condition ratings versus age.

not be separated. A method other than regression on data from a single year must be found.

CHARACTERISTICS OF BRIDGE CONDITION RATING DATA

The actual relationship between a material condition and time should yield a continuous curve when plotted. However, the shape of the "curve" will be affected among many things by the definition of the condition ratings. Take for example a case with two different scales. The definition of a 9 rating might be the same in both scales, but the definition of an 8 rating is very good condition in one scale and average in the other. The time that it takes for a bridge element to drop from a 9 to an 8 will therefore be different for the two scales. Furthermore, the "curve" representing the relationship between the condition rating and time for the two scales will be different. The curves will also be different in the case in which two scales have different ranges. An example of this would be the scale used by FHWA, which has ratings from 0 to 9, versus the one used by Saudi Arabia, which has a range of 0 to 7 (*8*).

As mentioned earlier, according to the FHWA definition of condition ratings, the data will not yield a "curve" when plotted against time (Figure 1). However, a curve can be plotted if the slope of various condition ratings increments can be estimated. A more realistic curve would be one that has a series of linear segments between the successive condition ratings (Figure 3).

The only time measurement related to the condition rating that can be directly used in such analysis is the age of the bridge. However, for traditional techniques such as regression and the Markov chain model, this relationship is usually distorted by previous work improvements performed on the bridge elements. It was therefore necessary to develop a methodology by which the relationship between the bridge element condition rating versus time could be analyzed.

PROPOSED DETERIORATION ANALYSIS METHOD

The approach proposed for finding a solution is to consider each condition rating separately. Once a condition rating (r) is chosen,

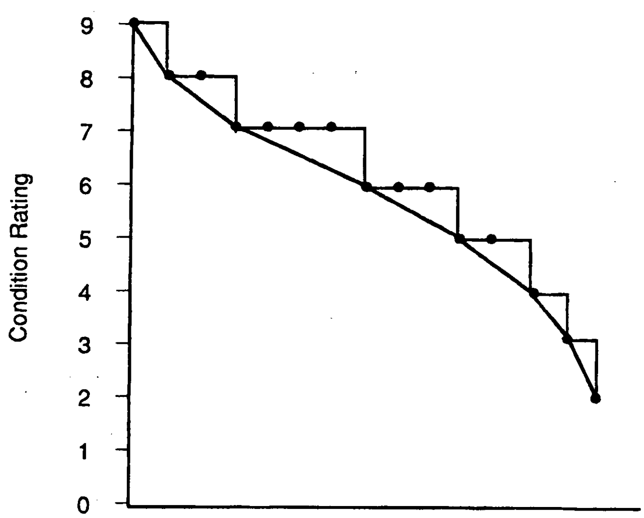

FIGURE 3 Linear segments connecting successive condition ratings.

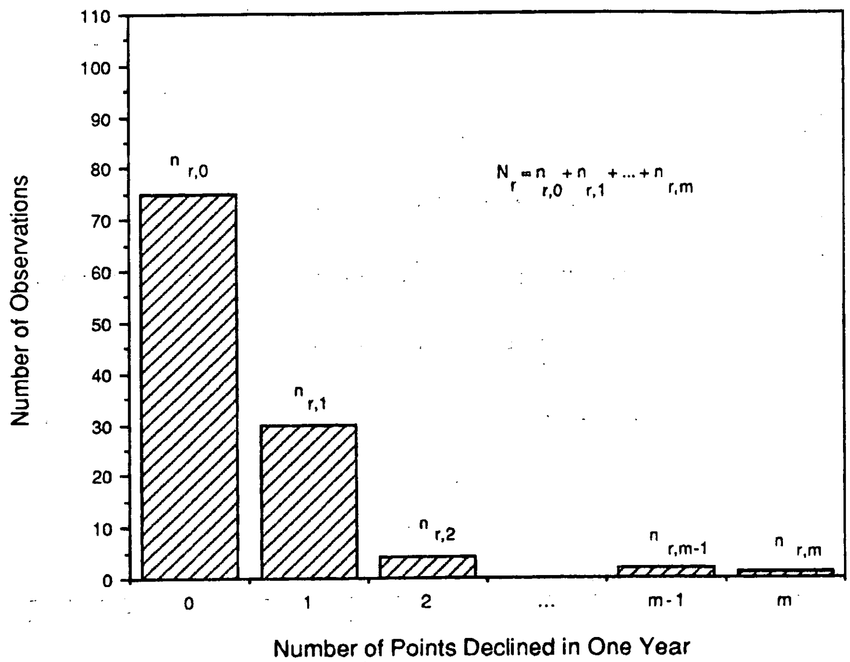

FIGURE 4 Number of observations of condition rating decline.

bridges with that condition rating are identified from the Bridge History file for a selected year, plan t. Records of the element condition rating of the identified bridges for the following year, $t + 1$, are then compared with r. Initially, bridges were considered if the condition rating in the following year, $t + 1$, either did not change or declined to a lower rating. This was to eliminate improved bridges from the study.

The total number of bridges, N_r, having a condition rating of r in year t can be tabulated. For example, Figure 4 shows a distribution of the number of bridges from a particular subset that either changed by 0 points (i.e., did not decline) or declined to a lower condition rating by 1 year later, $t + 1$. The number of bridges for which the condition rating changed by j points from the original r is represented by $n_{r,j}$ with m being the maximum decline possible for r. The summation of $n_{r,j}$ for all possible j's will thus be equal to N_r. The average weighted change within that 1-year period selected will be equal to

$$AVGCHN_r = \frac{\sum_{j=0}^{m} n_{r,j} \times j}{N_r} \qquad (1)$$

where

$AVGCHN_r$ = average change from condition rating r within the 1-year period selected $(t, t + 1)$;
$n_{r,j}$ = number of bridges changing by j points from condition rating r;
j = r_t − (element condition rating of the same bridge in the following year);
m = maximum number of points the bridge element can drop from r; and
N_r = total number of bridges at r in year t.

The time that it takes to drop by 1 point from r to $r - 1$ can thus be calculated once $AVGCHN_r$ is determined by using similar triangles (Figure 5):

$$\frac{\text{TIME}_r}{(t + 1) - t} = \frac{r - (r - 1)}{AVGCHN_r} \qquad (2)$$

where TIME_r is the time that it takes to drop by 1 point from condition level r.

Equation 2 can be reduced to

$$\text{TIME}_r = \frac{1}{AVGCHN_r} \qquad (3)$$

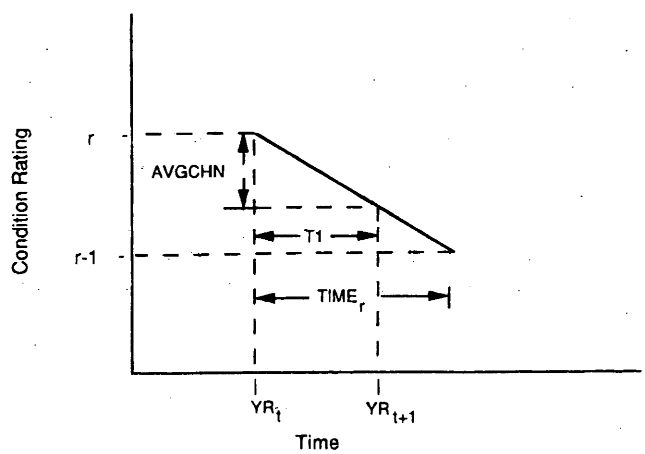

FIGURE 5 Condition rating versus time for selected *r*.

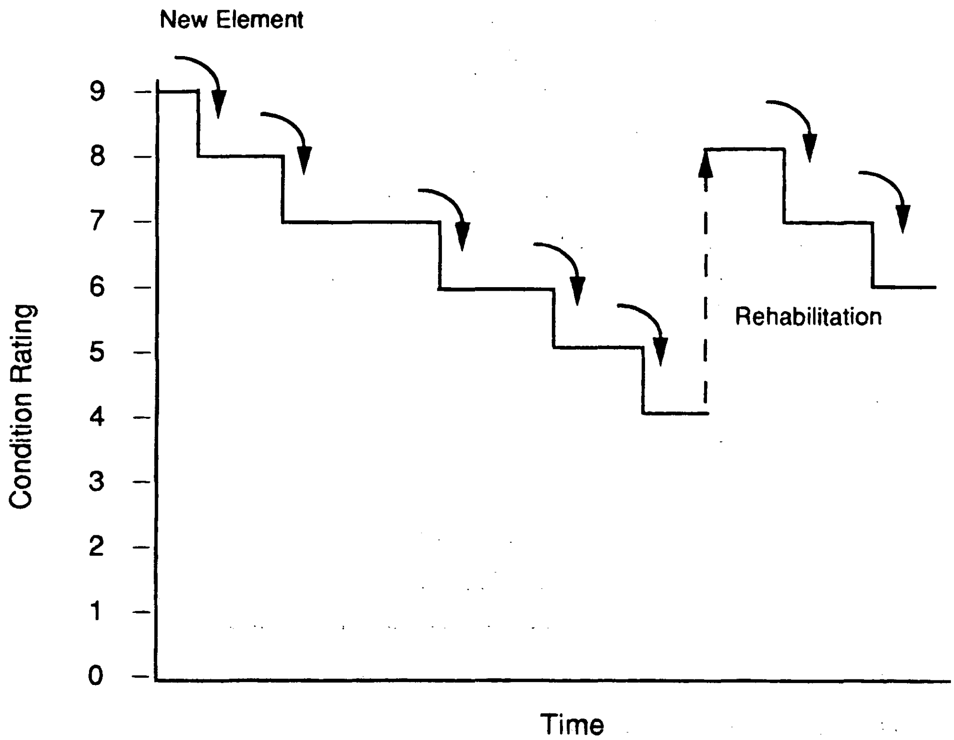

FIGURE 6 Effect of work improvement on bridge element condition rating.

Equation 1 can be modified to the following form for use when data exist for multiple 1-year intervals:

$$AVGCHN_r = \frac{\sum_{t=YR1}^{YRL-1} \sum_{j=1}^{m} n_{(r,t,j)} \times j}{\sum_{t=YR1}^{YRL-1} \sum_{j=0}^{m} n_{(r,t,j)}} \tag{4}$$

where

$YR1$ = first year selected,
YRL = last year selected, and
t = year being considered.

The equation can be applied for each value of condition rating r, calculating the slopes for the linear segments connecting successive condition ratings. Plotting the linear segments for the various condition ratings end-to-end, as in Figure 3, will produce a deterioration curve indicating the relationship between the condition rating and time.

However, two problems are associated with the data and adjustments must be made. First, it was recognized that many bridges are either rehabilitated or replaced as the element condition rating declines to lower levels. Thus, the number of bridges dropping to a lower condition rating becomes small compared with the number improving or remaining unchanged. This can make the numerator of Equation 4 very small compared with the denominator. As a result, the average change calculated would be very small. Hence, the time calculated to decline to a lower condition rating would be overestimated.

The second problem was a significant number of 1-point increases in condition that were not clearly linked to rehabilitation. After consultation with bridge maintenance experts from NCDOT, it was concluded that the improvement of 1 point is sometimes the result of a different conclusion by a subsequent inspector. This upgrading of condition can occur in borderline cases because of the general nature of the condition rating definitions. Another cause for the 1-point improvements was attributed to the effects of very minor work or preventive maintenance.

As a result of the first problem it was determined that considering the observations for improved bridges in the analysis was essential for finding a reasonable solution. A rational method of accounting for the decline before improvement was needed. The bridge element condition rating at r (Figure 6) would have declined to a lower condition rating if the work had not been performed. However, it was not possible to determine how soon this would have occurred. As illustrated in Figure 7, the improvement might occur immediately after a decline to r such as I_0 or at any later time up to just before the time that it would have declined to $r - 1$. Assuming a normal distribution of the improvement timing, a reasonable approximation would be to assume a timing as shown by $I_{0.5}$. This is equivalent to assuming that the rehabilitation is coincident with a decline of one-half point to $r - 0.5$. In reality, a condition rating cannot drop by half of a point. However, the number of observations that had improvement indicated from condition rating r were assumed to decline by $j = 0.5$.

As for problem two, it was determined on the basis of the advice of experts from NCDOT to exclude the data for which there was a

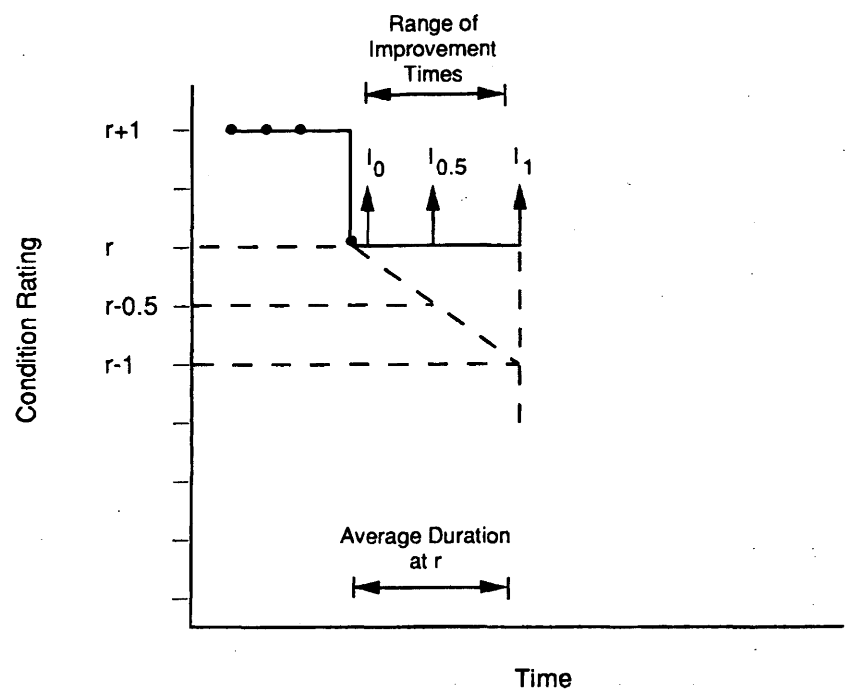

FIGURE 7 Timing of improvements.

1-point improvement. Thus, the number of observations that had an improvement of 1 point was set equal to zero.

Based on this, Equation 4 was reformulated to account for these changes. The general equation can be summarized as

$$AVGCHN_r = \frac{\text{weighted no. of declines} + 1/2 \text{ no. of improving by} > 1 \text{ point}}{\text{total no. of bridges} - \text{no. of bridges improving by 1 point}} \quad (5)$$

The new equation was thus

$$AVGCHN_r = \frac{\sum_{t=YR1}^{YRL-1} \sum_{j=1}^{m} n_{(r,t,j)} \times j + \sum_{t=YR1}^{YRL-1} \sum_{j=-2}^{z} (n_{(r,t,j)} \times 0.5)}{\sum_{t=YR1}^{YRL-1} \sum_{j=z}^{m} n_{(r,t,j)} - \sum_{t=YR1}^{YRL-1} n_{(r,t,-1)}} \quad (6)$$

where z is the maximum number of points the bridge element can improve from r (i.e., $9 - r$).

This methodology was used to develop deterioration curves for the three major bridge elements. Data on bridge condition ratings for the deck, superstructure, and substructure and other bridge characteristics were extracted from the Bridge History file for the years 1980 through 1989. Each bridge element was also initially subdivided by the element material type. The results generated are illustrated elsewhere (*9*). Further subgroupings were then considered for each element.

Deck Groupings for Deterioration Analysis

One of the main causes of deck deterioration is reinforcement corrosion induced by deicing salt. It was therefore desired to include the effects of deicing salts on the deterioration rates of the deck bridge element. However, bridges on which salt is used are not specifically defined in the NCBI. An alternate approach was used on the basis of input received from NCDOT engineers indicating that salt use is roughly limited to federal aid bridges in NCDOT geographic Divisions 5 and 7 through 14 [Table 1 (*a*)]. These divisions are located in the Piedmont and western parts of the state (Figure 8), where ice and snow are more frequent than in the eastern region. All other bridges were defined as nonsalted bridges.

A second variation of this grouping was based on dividing the salt region into two parts, the far west part of the state, which included Divisions 11, 13, and 14, as Salt Region 1, and Divisions 5, 12, and 7 through 10 as Salt Region 2. Salt Region 1 was thus located in the coldest part of the state. Both salt regions included only federal aid bridges. All other bridges in these divisions and all bridges in Divisions 1 through 4 and 6 were categorized as nonsalt bridges. The results indicated that the differences between Salt Regions 1 and 2 were not very significant. However, the effect of the combined salt regions was very obvious compared with that of the nonsalt regions. The grouping with one salt region of federal aid bridges versus all other bridges as nonsalt was therefore selected.

The effect of ADT on bridge deterioration was then considered. This was done by dividing the ADT ranges into six subgroups as shown in Table 1 (*a*). Although some of the results generated for some of the subgroupings were reasonable, the overall pattern did not fit the experience encountered in practice. The majority of those that did not fit the pattern were based on a very limited number of observations, in particular for the upper and lower ranges of ADT.

Bridges on different highway classifications are sometimes built to different standards. Therefore, the effect of highway functional classification on the deterioration rates of bridge decks was also investigated. Another advantage of using the highway functional classification as a way of subgrouping the bridges is that in general

TABLE 1 Deck Groupings for Deterioration Analysis

(a) Preliminary

Trial Groupings	Categories within Group
Salt Region Classification	I. Define Federal Aid bridges in Divisions 5 and 7-14 as salted bridges, vs other bridges and divisions as non salted; or II. Divide Bridges into 3 subgroupings: a) Divisions 11, 13, 14 (Federal Aid salted vs. others non-salted) b) Divisions 5, 7, 8, 9, 10, 12 (Federal Aid salted vs. others non-salted) c) Divisions 1, 2, 3, 4, 6 (all non-salted)
Deck Material Type	a) Reinforced concrete b) Cored slab and precast concrete c) Timber and laminated timber d) Steel plank
Functional Classification	a) Interstate, Principal Arterial, and Minor Arterial b) Major Collector c) Minor Collector d) Local
Average Daily Traffic (ADT)	0 - 200 201 - 800 801 - 2000 2001 - 4000 4001 - 8000 ADT => 8001

(b) Final

Final Groupings	Categories within Group
Salt Region Classification	Define Federal Aid bridges in Divisions 5 and 7-14 as salted bridges, vs other bridges and divisions as non salted.
Deck Material Type	a) Reinforced concrete b) Cored slab and precast concrete c) Timber and laminated timber d) Steel plank
Functional Classification	a) Interstate, Principal Arterial, Minor Arterial, and Major Collector b) Minor Collector and Local

there is an approximate relationship between the traffic volume and the type of highway. Thus, the effect of ADT on deterioration rates would be roughly accounted for by considering the type of highway classification.

Bridges were divided into four subgroups of highway classifications as indicated in Table 1 (*a*). The results generated were promising. However, certain subgroupings still suffered from the lack of a sufficient number of data points. There were almost no observations for the minor collector and local routes in the salt regions. In addition, very limited data existed for the timber and steel decks on Interstates and arterials.

The data for the nonsalt region were further analyzed by combining the Interstate and arterials subgroup with the major collectors. The minor collector and local routes were also combined into one subgroup. Data in the salt region were analyzed as one group. Table 1 (*b*) shows the final groupings for the deck deterioration analysis.

Superstructure Groupings for Deterioration Analysis

The effect of salt on the bridge superstructure condition rating was considered from two perspectives. The first was deicing salt, similar to the earlier approach for bridge decks. The other was to study the effect of seawater since corrosion-related deterioration can occur in any area that is exposed and within the reach of the seawater spray (*10*).

The effect of the deicing salts was first studied. The superstructure elements in the salt region, especially prestressed and reinforced concrete, tended to deteriorate at a faster rate than those in the nonsalt region. However, the effect was not significant for the steel and timber superstructures.

The effect of the seawater on the superstructure deterioration rates was then studied. Bridges were divided into two groups: those bridges in coastal counties (Figure 8) and over a waterway were classified as marine environment; all other bridges were classified

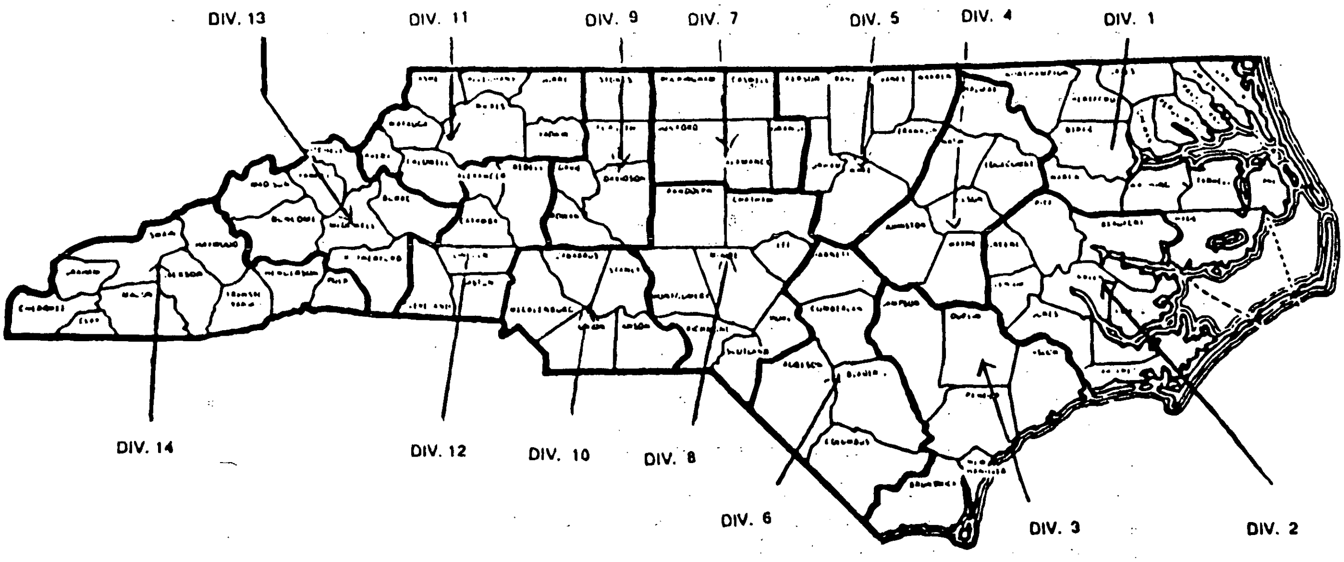

FIGURE 8 Divisions in North Carolina.

as nonmarine environment. The deterioration rates for the marine environment were greater than those for the nonmarine environment. It was also evident that the effect of the seawater was more significant than the effect of the deicing salts. Thus, the effect of the seawater was selected for further analysis.

Bridges were then subgrouped by functional classification, similar to the approach used for bridge decks. The superstructure type was another parameter thought to influence the deterioration rates of the bridge superstructure. Reinforced concrete and steel structures were therefore divided into two subgroups each, as shown in Table 2 (*a*). The steel truss subgroup did not contain sufficient numbers of observations when it was subdivided by highway classification and marine versus nonmarine environment. Thus, all steel trusses were analyzed as one group. The difference in the deterioration rates for the concrete structure types was very small. The subgroups were therefore combined together under reinforced concrete. However, steel trusses tended to deteriorate at a faster rate than the other types of steel structures. The final groupings for the superstructure deterioration analysis are given in Table 2 (*b*).

Substructure Groupings for Deterioration Analysis

The effect of seawater on the deterioration rates of substructure elements was first studied. Bridges were thus divided into groups of marine and nonmarine environments similar to the approach used for the superstructure analysis. However, the nonmarine environment group was further divided into waterway and grade separation. This was done so that the effect of freshwater on the bridge substructure could be evaluated. Bridges were also subgrouped by material type.

DETAILED DETERIORATION RESULTS

Detailed deterioration curves for bridge decks are plotted in Figure 9. From these curves it is apparent that the deicing salt accelerates the deterioration of bridge decks. The effect of the deicing salt was most significant on the prestressed concrete decks; this was followed by the reinforced concrete. The effect of the deicing salt on the steel (asphalt-filled steel pan) and timber decks was very small, as might be expected. It can be noted that the prestressed concrete generally has higher condition ratings at early ages, but once problems occur the condition ratings decline rapidly. This is probably due to recognition by inspectors that evidence of a problem in prestressed members can be a major concern since the small area of steel is sensitive to corrosion or other forms of deterioration. Bridge decks located on minor collector and local routes tended to deteriorate at a slower rate than those located on Interstate, arterial, and major collector routes. This could be attributed to the higher volume of traffic and the higher percentage of trucks that use the latter types of highways. Prestressed concrete was the only exception to this trend, possibly because of variations in the design of prestressed concrete decks.

As for the deterioration rates of the bridge superstructure element, it was evident that the salt from the sea air or water splash increased the deterioration rates of the element. It was also evident that bridges on Interstate, arterial, and major collector routes deteriorated at a faster rate than those on minor collector and local routes. However, the difference in the deterioration rates of the superstructure rates between the two types of highway groupings was not as significant as the difference in the deterioration rates of bridge decks. This could be attributed to the fact that the impact of traffic on the superstructure is not as severe as that on decks. The deterioration curves generated for superstructure elements, subdivided by material and other groupings, can be found elsewhere (*9*).

Bridge substructures located in a marine environment were found to deteriorate at a much faster rate than those located in a nonmarine environment. In addition, those bridges that were over a waterway tended to deteriorate at a faster rate than bridges at a grade separation but at a slower rate than the bridges in a marine environment. The deterioration curves generated for substructure elements, subdivided by material and other groupings, can be found in elsewhere (*9*).

TABLE 2 Superstructure Groupings for Deterioration Analysis

(a) Preliminary

Trial Groupings		Categories within Group
Marine Environment Classification	a) b)	Marine Environment: In a coastal county shown in Figure 8 and over a waterway Non-marine Environment: All other bridges not included in the marine environment category
Salt Region Classification		Define Federal Aid bridges in Divisions 5 and 7-14 as salted bridges, vs other bridges and divisions as non salted.
Material and Structure Type	a) b) c) d)	Prestressed Concrete Reinforced Concrete i) Slab and M-beam ii) T-beam, Girder Floor Beam, Box Beam (Multiple and Single) Steel i) Truss (Thru and Deck) ii) All other Types Timber
Functional Classification	a) b) c) d)	Interstate, Principal Arterial, and Minor Arterial Major Collector Minor Collector Local

(b) Final

Final Groupings		Categories within Group
Marine Environment Classification	a) b)	Marine Environment: In a coastal county shown in Figure 8 and over a waterway Non-marine Environment: All other bridges not included in the marine environment category
Material and Structure Type	a) b) c) d)	Prestressed Concrete Reinforced Concrete Steel i) Truss (Thru and Deck) ii) All other Types Timber
Functional Classification	a) b)	Interstate, Principal Arterial, Minor Arterial, and Major Collector Minor Collector and Local

Overall, the analysis produced a set of results that is consistent with a rational comparative consideration of the material, environment, and other factors.

SUMMARY AND CONCLUSIONS

A methodology was developed for predicting the deterioration rates of the bridge deck, superstructure, and substructure elements as measured by FHWA bridge inspection condition ratings. A set of deterioration curves was developed for the three major bridge elements by material type. Another set of deterioration curves was developed for various subgroupings of the bridge elements on the basis of environment and functional classifications.

1. For decks deicing salts were found to cause the deterioration rates to increase, in particular for prestressed and reinforced concrete decks. The effect of the deicing salts on the timber decks was not very significant. The highway classification was significant in relation to the deterioration rates of the bridge decks. Bridge decks on minor collector and local routes tended to deteriorate at a slower rate than those on Interstate, arterial, and major collector routes. This was attributed to the higher traffic volumes and the higher percentage of trucks that use the latter type of highways.

2. Deterioration rates for the superstructure tended to be higher for those bridges exposed to the splashing of saltwater than those that are not exposed to saltwater. Bridge superstructures on Interstate, arterial, and major collector routes were found to deteriorate at a faster rate than those on minor collector and local routes.

3. The effect of saltwater was found to cause a rapid increase in the deterioration of the bridge substructure. Although freshwater was also found to increase the deterioration rate of the substructure, the impact was not as significant as that of saltwater. Substructure deterioration rates at grade separation were comparatively low.

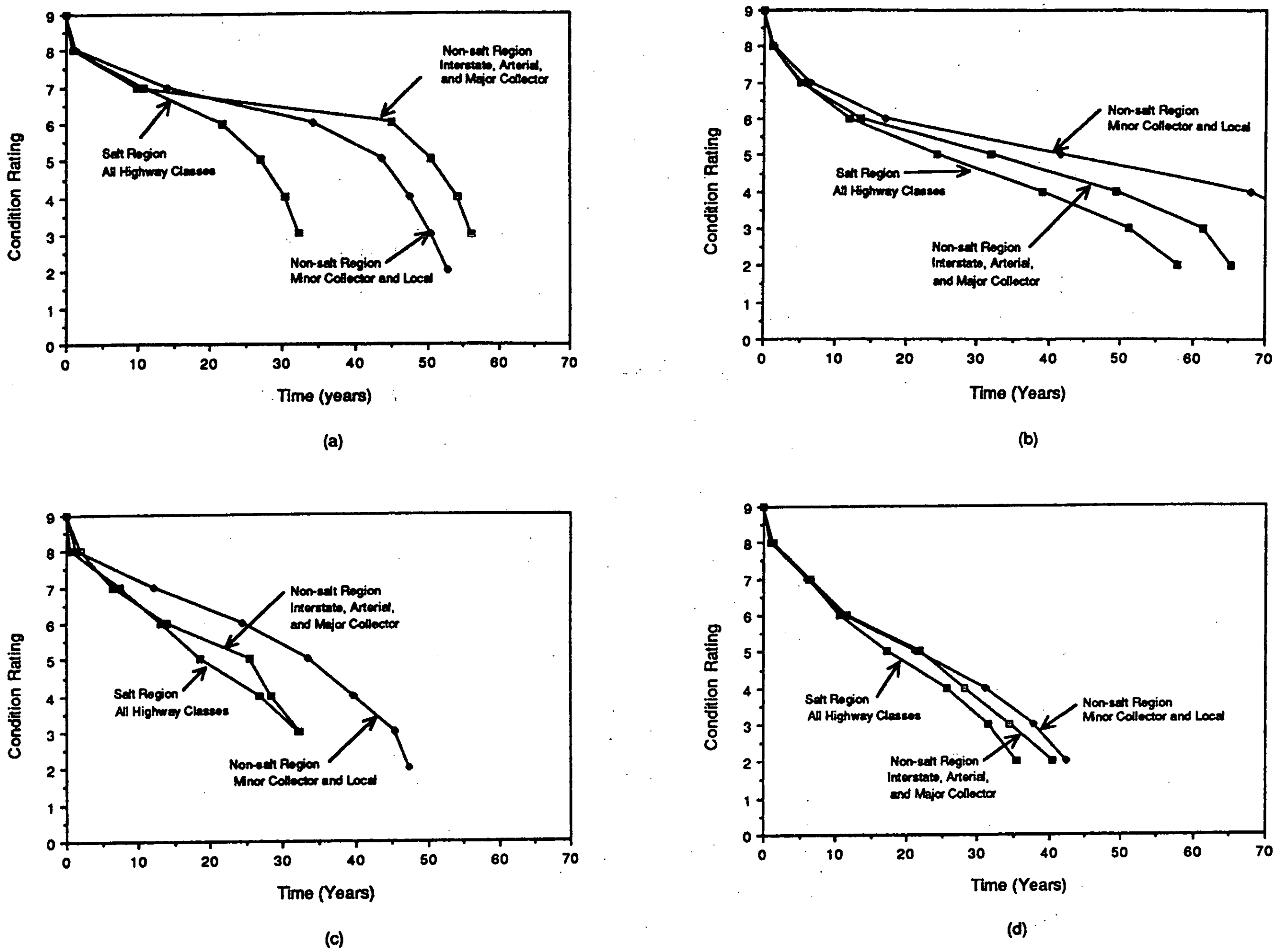

FIGURE 9 Deck condition rating versus time: (*a*) prestressed concrete, (*b*) reinforced concrete, (*c*) steel, and (*d*) timber.

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