Bridge Deterioration Models for States with Small Bridge Inventories

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In a bridge management system the estimation of bridge performance is a key tool for devising the optimal strategies for the maintenance, rehabilitation, and replacement of bridges. Therefore it is essential that deterioration models that accurately estimate the remaining performance of bridges be developed. This is a difficult task for states that have a limited number of bridge structures. Deterioration models and modifications to data bases that produced reasonable projections for bridge deterioration are described. Four different levels of modeling are described. The models are different because of the number of parameters included. Therefore the amount of data used to develop each model also changes. In the project 277 data sets were obtained from the four levels of modeling. The models were nonlinear with exponential decay functions and spikes for rehabilitation. The equations incorporate the following parameters: average daily traffic, bridge age, time of rehabilitation, environmental factors, type of structure, and bridge component. Examples of the deterioration models developed are given, as are two examples showing the application of the models. The results of the models indicated some basic trends in bridge deterioration and also pointed to the need for the regionalization of deterioration models. The regionalization of deterioration models would permit states with similar bridges and environmental conditions to combine their data bases. This would provide a larger data base from which to produce more accurate bridge deterioration models.

All states are required to have initiated a bridge management system by October 1, 1994. To do so they must be able to predict the deterioration of their bridges so that they can plan for their maintenance, rehabilitation, and reconstruction. This requires an analysis of the state's past inspection records and an inventory of the existing bridges to establish patterns, types, and rates of deterioration under the specific conditions in that state.

Several individual states are developing their own bridge management systems, whereas others are examining PONTIS or are waiting for the results of NCHRP-12-28. One common thread in all of the work that has been done or that is under way is that it is geared to be used on an individual-state basis. Therefore they are geared toward states that have large bridge inventories. The state of Nevada is 285,000 km^2 (110,000 mi^2), yet it has only 887 bridges [structures over 6 m (20-ft) long excluding culverts]. Of these 887 bridges, 587 are reinforced concrete, 159 are prestressed concrete, 137 are steel, and 4 are timber bridges. Nevada has fewer bridges than many other states, and the bridges in its inventory are very young. Most of the bridges in Nevada have been built since the early 1960s. This is a result of the construction of the Interstate highway system and the rapid growth in Nevada since the early 1960s. Inspection data that are consistent with current inspection data are available back to 1979. Therefore there is not a substantial amount of data for establishing deterioration models.

This paper describes the challenges in establishing the deterioration models for small bridge inventories. The model variables that were included and the modifications done to the data base to develop reasonable results are also discussed (*1*). One conclusion from the paper is that even though effective models for small bridge inventories can be developed, the regionalization of deterioration models would be an effective means of improving deterioration predictions.

FACTORS AFFECTING BRIDGE DETERIORATION AND EXISTING MODELS

The deterioration models developed in the past included linear (*2*), piecewise linear (*3*), linear regression coupled with a spike reflecting a single rehabilitation (*4*), nonlinear with exponential decay functions coupled with spikes to reflect the effects of rehabilitations (*5*), and methods that incorporate the Markov chain (*6*). For an initial examination of deterioration trends and an investigation of the data base, it was decided that nonlinear deterioration models that included spikes for rehabilitations would be used. The linear curves do not provide sufficient accuracy, and the effort to develop the Markov chain was not justified until an initial examination and a model of the data base were completed.

Several factors influence deterioration. Those that were considered in the model included the bridge's age, structural component, structure type, rehabilitation history, average daily traffic (ADT), and environmental conditions. Bridge maintenance was not included in the models. A specific study would need to be undertaken to determine the impacts of different maintenance procedures. The bridge's age is the most pertinent factor for establishing deterioration. Modeling of the structural component can be done in two ways: (a) generally (substructure, superstructure, and deck) and (b) specifically (stringers, bearings, parapets, expansion joints, abutment wings, abutment backwalls, etc.). The more general approach was selected for the Nevada models. The bridges were divided into three categories: reinforced concrete, steel, and prestressed concrete. These general categories include 99 percent of the bridges in Nevada.

Rehabilitation plays a major role in bridge deterioration. An early minor rehabilitation has less of an effect on a bridge than a later major rehabilitation. The data base does not retain all of the rehabilitation dates for a bridge nor a record regarding the nature of the rehabilitation. The work that has been done can be found by examining the original contract documents. This requires significant effort even for only 900 bridges. Therefore if a bridge

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rehabilitation was recorded in the data base it was assumed that all of the major components of a bridge were rehabilitated. The Nevada Department of Transportation's definition of a rehabilitation is an event that corrects most or all of the structural deficiencies. Major maintenance (e.g., resurfacing of a bridge deck) is not considered a rehabilitation.

Environmental factors also play a significant role. Exposure of bridges to certain environmental conditions, both natural and artificial, can drastically shorten a bridge's service life. It is very difficult to include all of the environmental effects directly in a model. Therefore environmental factors are included indirectly in the model through geographical location. According to the National Oceanic and Atmospheric Administration, Nevada is divided into four regions (Figure 1). Upon further review the northwestern and northeastern regions are very similar both in climate and geography. The extreme southern region is warmer and on average has significantly less precipitation than the northern regions. The south-central region combines features of the northern and southern regions and has only a few bridges. Therefore the state was divided into two geographical regions for modeling the environmental effects. Bridges above 38 degrees north latitude were considered to be in the northern region; those below that latitude were considered to be in the southern region.

DETERIORATION MODEL DEVELOPMENT

Once the variables affecting bridge deterioration were identified, the researchers could then incorporate them into a deterioration analysis. Independent variables are either discrete (constant) or continuous (changing) in nature. The discrete variables include the bridge components, structure type, rehabilitation history, and geographical location, whereas age and ADT are continuous variables. However the ADT can be translated from a continuous to a discrete variable by grouping it into three ranges, such as 0 to 1,000, 1,001 to 10,000, and more than 10,000 vehicles per day. When the bridges are divided into ADT groups, age remains the only continuous variable.

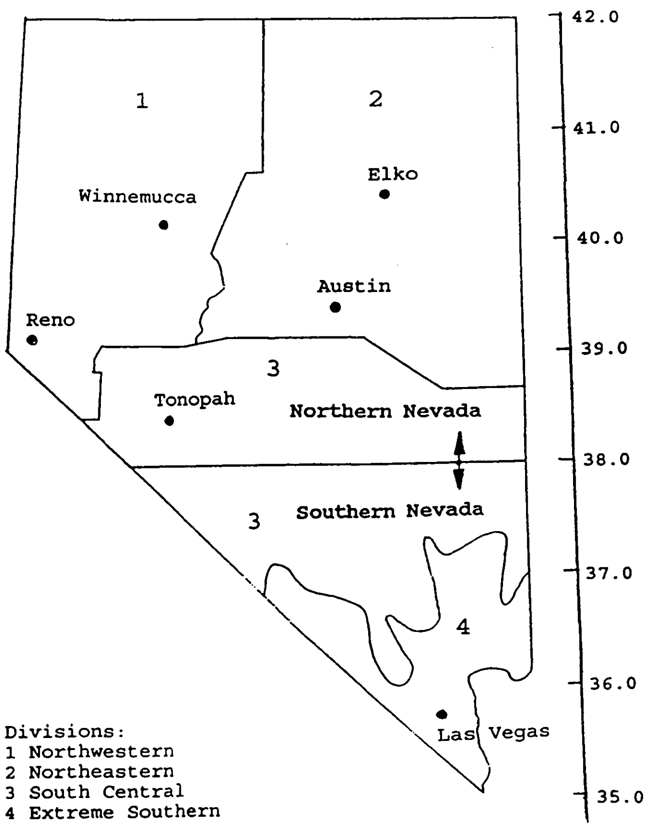

FIGURE 1 Geographical division of Nevada.

To include all of the variables, separate deterioration models were developed for each combination of the five discrete variables. Therefore the records that have the same bridge component, structure type, rehabilitation history, ADT range, and geographical location were combined. A group is the result of each combination of these five discrete variables. Once the bridge deterioration models (bridge performance curve of condition rating versus age) were developed, the effects that the six variables have on bridge deterioration could be evaluated. The initial model version (version 1) included all five discrete variables (Table 1): (a) three bridge components, (b) three structure types, (c) four rehabilitation statuses, (d) three ADT levels, and (e) two geographical locations. If all of the possible combinations had been used there would have been a total of 216 groups.

The data base was obtained from the Nevada National Bridge Inventory (1991) and from FHWA (1979 to 1990). The total data base contained 16,760 inspection records of all of the bridges in Nevada for the years 1979 to 1991. The inspection years before 1979 were not used because of inconsistencies in condition rating descriptions. Each inspection record consists of one inspection report that includes more than 90 coded variables describing the features and characteristics of a structure. The 10 variables selected from each record because of their impact on the bridge deterioration analysis were structure number; geographical location; structure type; ADT; numerical condition ratings for the bridge deck, superstructure, and substructure; construction date; last reconstruction year; and inspection year.

There were four procedures for data filtering. Initial filtering deleted records for structures other than bridges (e.g., culverts) and limited bridges to reinforced concrete, steel, and prestressed concrete. The initial filtering reduced the data base from the original 16,760 records to 11,536 records. The data were then screened for duplicate records caused by bridges located over highways; this decreased the data base from 11,536 to 8,601 records. Duplicate records from 2 or more consecutive years existed for almost every bridge since each structure was typically inspected every 2 years. Repeat records from the bridge's noninspection years were deleted. The removal of these duplicate records left 4,237 records for reinforced concrete, steel, and prestressed concrete bridges inspected from 1979 to 1991. The final filter eliminated records containing missing or miscoded information and excluded records containing condition rating increases of two or more between inspections without corresponding histories of rehabilitation. This was done because, most likely, a bridge received a rehabilitation that was not recorded. If these records were not removed these types of data would encourage an upward trend in the deterioration curves. After the final filter, 4,180 records were available for use in the bridge deterioration models. Of the 4,180 records, 2,457 were for reinforced concrete bridges (59 percent), 1,038 were for steel bridges (25 percent), and 687 were for prestressed concrete bridges (16 percent). Once

TABLE 1 Model Parameters

	Model Version			
Parameter	1	2	3	4
Component	1) Deck 2) Superstructure 3) Substructure	1) Deck 2) Superstructure 3) Substructure	1) Deck 2) Superstructure 3) Substructure	1) Deck 2) Superstructure 3) Substructure
Bridge Type	1) Reinforced Conc. 2) Steel 3) Prestressed Conc.	1) Reinforced Conc. 2) Steel 3) Prestressed Conc.	1) Reinforced Conc. 2) Steel 3) Prestressed Conc.	1) Reinforced Conc. 2) Steel 3) Prestressed Conc.
Rehabilitation	1) Non-or Rehab. before 10 yrs. 2) 10 to 24 yrs. 3) 25 to 39 yrs. 4) ≥ 40 yrs.	1) Non-or Rehab. before 10 yrs. 2) 10 to 24 yrs. 3) ≥ 25 yrs.	1) Non-or Rehab. before 10 yrs. 2) ≥ 10 yrs.	Not a Variable
ADT	1) 0 to 1,000 2) 1,001 to 10,000 3) >10,000	1) 0 to 1,000 2) >1,000	Not a Variable	Not a Variable
Location	1) Northern NV 2) Southern NV	Not a Variable	Not a Variable	Not a Variable
Groups- Max.	216	54	18	9
Groups- Actual	120	42	15	9

the data base was filtered the data were placed into 216 modeling groups.

Of the original 216 groups, many of them had no data or very few data (fewer than 10 inspection reports). Seventy-five groups had no data, and 21 groups had fewer than 10 inspection reports. Those that had fewer than 10 inspection reports were combined with the next closest group. This reduced the actual number of groups to 120. This shows the difficulty in dividing the data into precise groups. As the number of groups increased the amount of data per group was reduced; this can significantly affect the accuracy of the models. The philosophy of including as many variables as possible works well when there is a significant amount of data. The inclusion of many variables can adversely affect the reliability and applicability of the models when there are limited data. By using a few variables the amount of data in each group increases and the reliability also increases. This gives rise to a trade-off between providing groups with the greatest amount of detail or fewer groups with sufficient data for each group. The problem was solved by establishing three more versions of the variable combinations (Table 1). In versions 2, 3, and 4 there were 42, 15, and 9 data sets, respectively. The purpose of these other versions was to increase the amount of data per group and to provide a secondary model for cases in which the results from version 1 were not correct (e.g., increasing condition rating with time and condition ratings greater than 9). The four models created a total of 186 data sets. Since the number of bridges was limited, all of the data were used to develop the model. Therefore there were no data available for a verification set.

The basic model used was an eight-parameter model (Equation 1).

$$Y(t) = (1 - A)(1 - B)(1 - C)\alpha_1 e^{-t/\beta_1} + A\alpha_2 e^{-t-t_{r1}/\beta_2} + B\alpha_3 e^{-t-t_{r2}/\beta_3} + C\alpha_4 e^{-t-t_{r3}/\beta_4} \quad (1)$$

where

$Y(t)$ = projected bridge condition rating;

t = bridge age (years);

t_{r1}, t_{r2}, and t_{r3} = bridge ages in the years when a major rehabilitation was conducted on a bridge (for the Nevada model these years were set at t_{r1} = 10 years, t_{r2} = 25 years, and t_{r3} = 40 years);

α_1 = condition rating intercept at age zero;

β_1 = exponential decay coefficient for bridges that have not been rehabilitated or have rehabilitation ages of less than 10 years;

α_2, α_3, and α_4 = condition ratings at the ages of 10, 25, and 40 years for bridges that have been rehabilitated between the ages of 10 and 24, 25 and 39, and 40 years and older, respectively; and

β_2, β_3, and β_4 = exponential decay coefficients after rehabilitations for the same respective intervals.

If a bridge has not been rehabilitated or has been rehabilitated at an age of less than 10 years, *A*, *B*, and *C* are 0. If a bridge has been rehabilitated between the ages of 10 and 24 years, then *A* equals 1 and *B* and *C* stay 0. If a bridge has been rehabilitated between the ages of 25 and 39 years, then *B* equals 1 and *A* and *C* are 0. If the rehabilitation occurs after the age of 40 years, then *C* equals 1 and *A* and *B* are 0. The coefficients for the model were determined statistically by using the Statistical Analysis System (*7*). Figure 2 shows the basic eight-parameter model.

As the number of variables is reduced, including the number of rehabilitation intervals, the model becomes simpler. Equations 2, 3, and 4 are the general equations for the six-, four-, and two-parameter models, respectively (*5*).

$$Y(t) = (1 - A)(1 - B)\alpha_1 e^{-t/\beta_1} + A\alpha_2 e^{-(t-t_{r1})/\beta_2} + B\alpha_3 e^{-(t-t_{r2})/\beta_3} \quad (2)$$

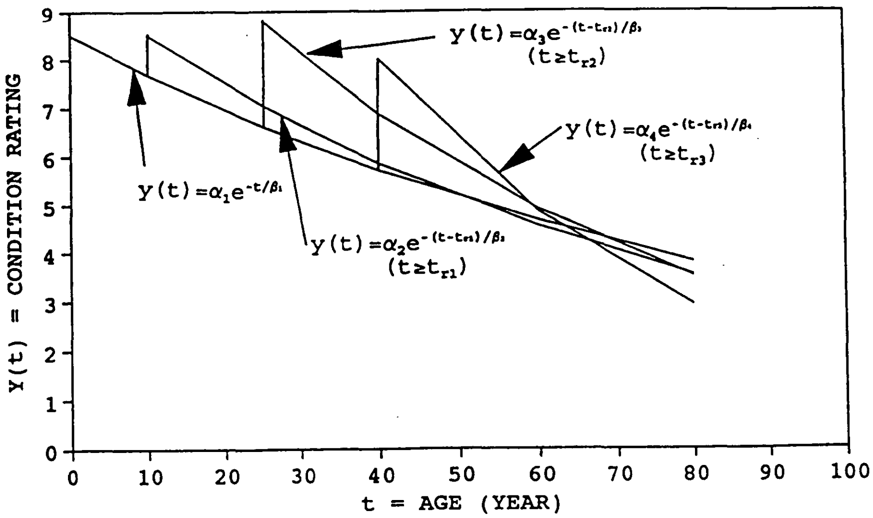

FIGURE 2 Eight-parameter deterioration model.

$$Y(t) = (1 - A)\alpha_1 e^{-t/\beta_1} + A\alpha_2 e^{-(t-t_{r1})/\beta_2} \quad (3)$$

$$Y(t) = \alpha_1 e^{-t/\beta_1} \quad (4)$$

Figures 3, 4, and 5 show examples of the deterioration curves that were developed by using the eight-parameter model. It is possible to obtain curves over a wide range of years since the bridge ages during the years from which data were collected (1979 to 1991) varied widely. Problems with the models that were developed included unrealistically high condition ratings at the ages of 10, 25, and 40 years because of rehabilitations, flat deterioration curves, and curves with increasing condition ratings with increasing age. To combat these problems the data were examined to see if these problems were caused by poor data, insufficient data, or improper use of the data.

MODEL DIFFICULTIES AND MODIFICATION

Two primary problems with the data and with the models developed from those data were identified:

1. The spike for the model was at discrete points in time (10, 25, and 40 years), and
2. Few data existed near the time of rehabilitation.

The result of the first problem is that if there are rehabilitation data along the entire interval the curve will be very flat (Figure 6). If the bridge data within the interval show that most of the rehabilitations were done toward the end of the interval, a high spike for the effect of the rehabilitation can occur (Figure 7). For

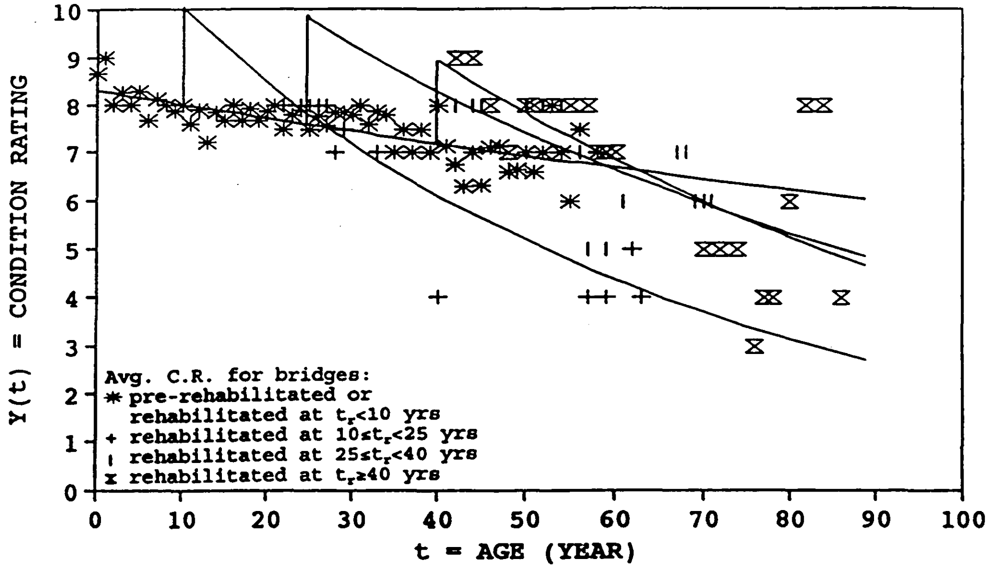

FIGURE 3 Deck deterioration, reinforced concrete bridges in northern Nevada with ADT ≤ 1,000 (unmodified data).

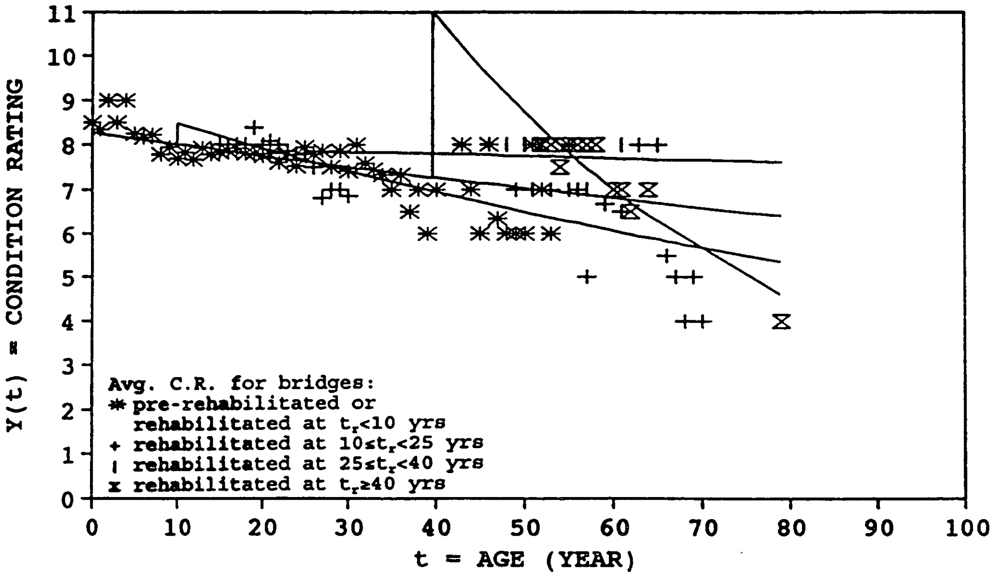

FIGURE 4 Deck deterioration, reinforced concrete bridges in northern Nevada with 1,000 < ADT ≤ 10,000 (unmodified data).

instance in Figure 3 there are no datum points (plus signs) between the ages of 10 and 20 years for the development of the second curve (rehabilitated between the ages of 10 and 24 years). The plus signs were concentrated between the ages of 20 and 24 years. Since the regression line is the best-fit line through the data, a high spike occurs.

If it is assumed that the deterioration rate after a rehabilitation is approximately the same within each interval (10 to 24, 25 to 39, and 40 or more years), the data can be shifted to the one year chosen as the rehabilitation year for each interval. Figure 6 shows several different inspection data sets for bridges rehabilitated between the ages of 10 and 24 years. Figure 8 shows the new curve that results from the shifting of the individual curves so that all of the rehabilitations occur at 10 years. For example to develop a deterioration curve for a bridge that was rehabilitated at 18 years of age, the rehabilitation year would be shifted to 10 years and all the inspection dates after rehabilitation would be shifted back 8 years. This concentrates the data and starts the deterioration from the same point in time.

The second problem was caused by too few data being available immediately after the rehabilitations. Therefore the regression analysis frequently predicted rehabilitation spikes that were much

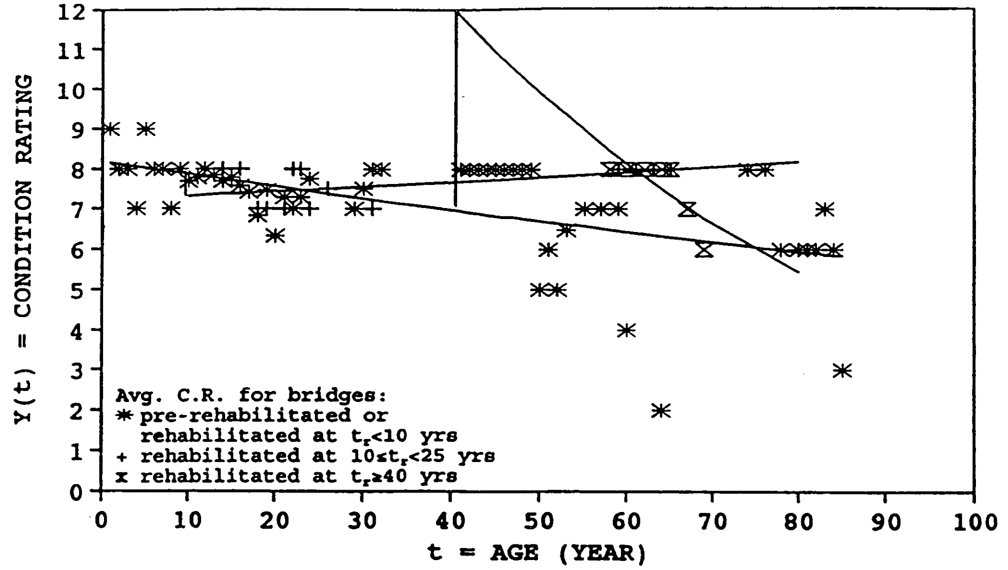

FIGURE 5 Deck deterioration, reinforced concrete bridges in northern Nevada with ADT > 10,000 (unmodified data).

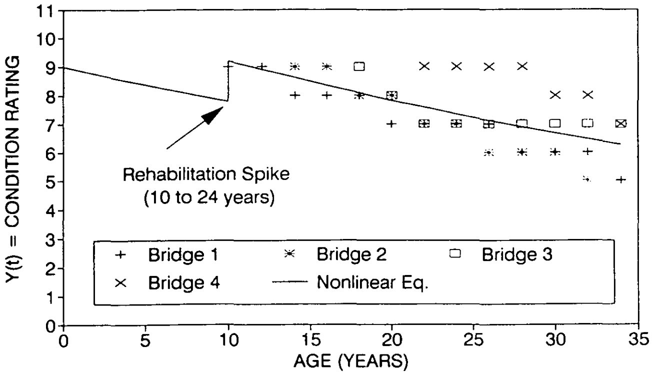

FIGURE 6 Rehabilitation spread along entire interval.

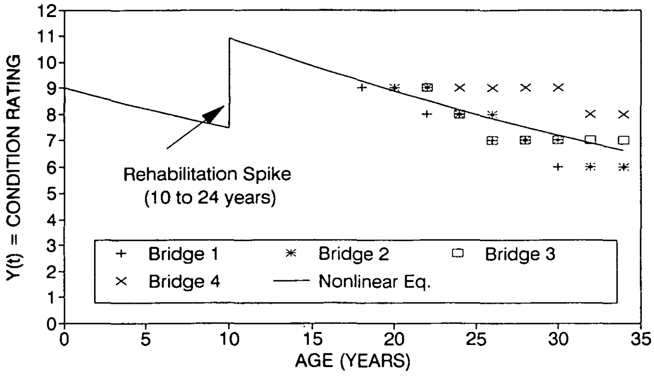

FIGURE 7 Rehabilitation concentrated near end of interval.

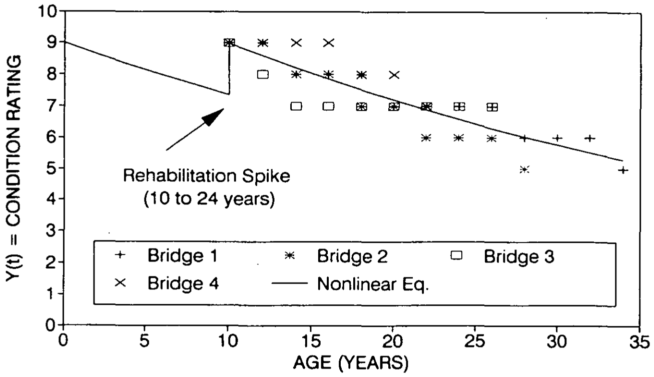

FIGURE 8 Effect of rehabilitation shifting.

too high: inspection rating scores of 10 and 11 on a scale of 1 to 9. Figure 9 shows what can happen. With no data near the rehabilitation year, the best-fit curve is dominated by the later inspection data and the curve is above 9 at the rehabilitation time.

In almost all cases a component of a bridge that has been rehabilitated will receive a rating of 8 or 9 for the first inspection score after a rehabilitation occurs. These data were not available for many of the bridges since they were rehabilitated before 1979. To overcome this shortcoming data were added for the rehabilitation inspection year for bridges for which data were not available. The number of datum points added was equal to the number of bridges within a rehabilitation interval for which inspection data were not available for the years immediately after rehabilitation. The magnitude of the inspection condition rating that was added was 8. A score of 8 is a conservative estimate of the post-rehabilitation inspection score. An example would be a bridge rehabilitated at 18 years of age for which an inspection record for that year was not available. This bridge would first have its inspection data shifted back 8 years, and then a datum point of 8 would be added at 10 years. Figure 9 shows an example of the data after they have been modified to include the inspection year data. The modified curve (W/Rehab Insp. Data) has a more realistic rehabilitation spike at 10 years.

Figures 10, 11, and 12 are the deterioration curves for the same categories in Figures 3, 4, and 5, respectively, except that the curves are based on the modified data set. For all of the deterioration curves there is a drop in the maximum inspection rating at the spike. In comparing Figures 3 and 10, the most significant change is in the deterioration curve for bridges rehabilitated after the age of 40 years. The modified data predict a much higher deterioration rate. This is due to the shifting of the rehabilitation to the same year (40 years). Figure 11 shows all three of the deterioration curves with decreasing condition ratings, whereas Figure 4 shows the deterioration curve for 10 to 25 years going upward. Figure 4 also shows a very large spike for the deterioration curve for age 40 years and older. Figure 12 is an example of how a small data set may still cause problems even with modifications. The deterioration curve for rehabilitations done at between 10 and 25 years of age is increasing with time. In this case the version 2 curve would be used to predict deterioration.

APPLICATION

The deterioration curves that were developed can be used as a predictive tool for an individual bridge as well as a group of bridges. In most cases the more detailed curves should be used (version 1). As seen in Figure 12, for cases in which version 1 gives unreasonable results, a more general model (version 2, 3, or 4) should be used. The following examples show how the deterioration curves are used effectively.

Example 1

A reinforced concrete substructure in northern Nevada has an ADT of less than 1,000. The substructure was rehabilitated at the age of 15 years. It is currently 20 years old and has a condition rating of 7. Two curves are shown in Figure 13 (*top*). The solid line is the average curve developed from the data base. The dotted curve is the average curve shifted to match the current data from the reinforced concrete bridge. By using a bridge-specific deterioration curve a more accurate model is possible for the individual bridge.

Example 2

A reinforced concrete superstructure in northern Nevada has an ADT of between 1,000 and 10,000. The superstructure was rehabilitated at the age of 30 years. It is currently 36 years old and

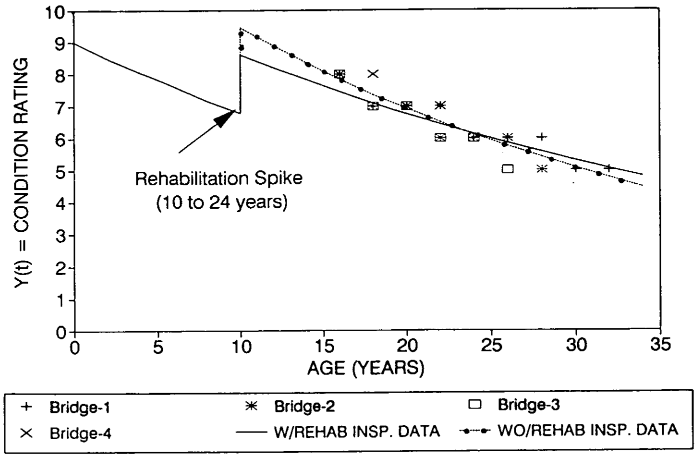

FIGURE 9 Inspection year data addition.

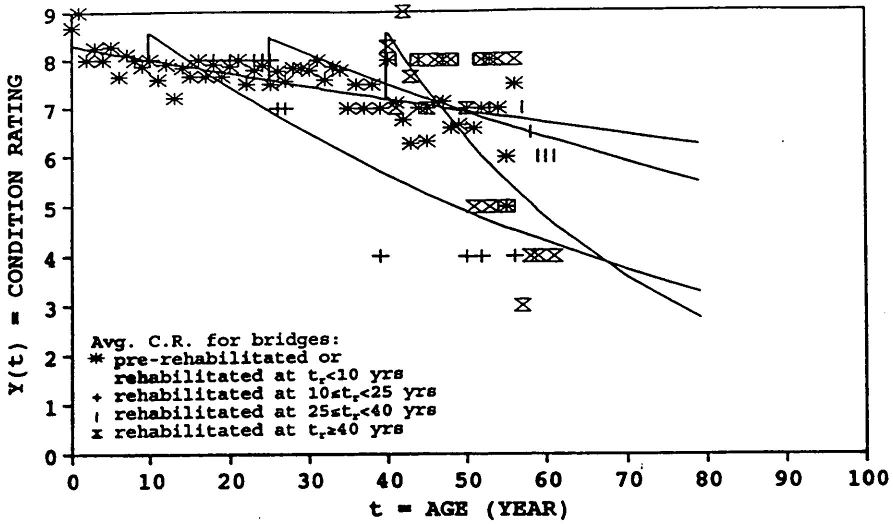

FIGURE 10 Deck deterioration, reinforced concrete bridges in northern Nevada with ADT ≤ 1,000 (modified data).

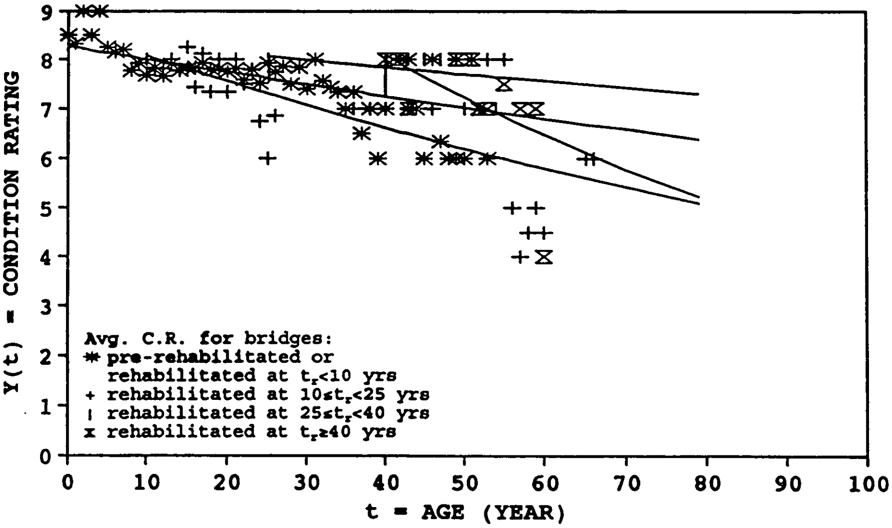

FIGURE 11 Deck deterioration, reinforced concrete bridges in northern Nevada with 1,000 < ADT ≤ 10,000 (modified data).

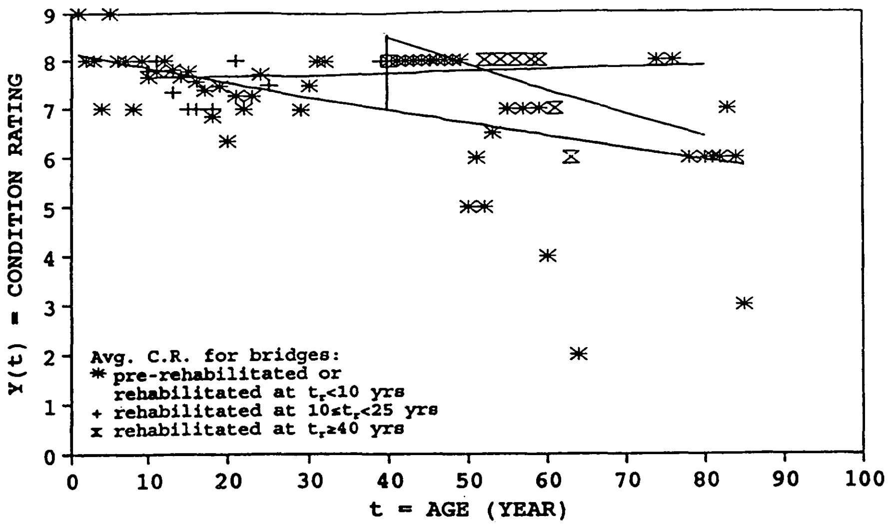

FIGURE 12 Deck deterioration, reinforced concrete bridges in northern Nevada with ADT > 10,000 (modified data).

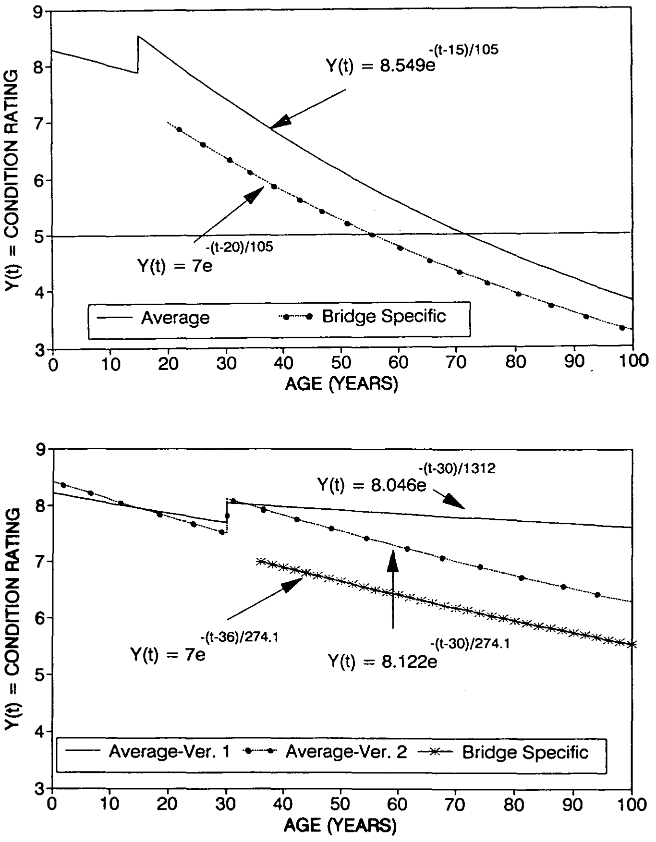

FIGURE 13 Deterioration curve: *top*, example 1; *bottom*, example 2.

has a condition rating of 7. Even after the modification of the data the deterioration curve (version 1) is still invalid because of the small data set [Figure 13 (*bottom*)]. It is necessary to use the second version of the deterioration curve to have a valid curve. The second version eliminates the environmental parameter (geographical location) and has two ADT intervals (≤1,000 and >1,000). The second version of the curve is then shifted to correspond to the current bridge data.

SUMMARY AND RECOMMENDATIONS

The ability to estimate bridge performance is a key aspect of a bridge management system and is necessary for devising optimal strategies for the maintenance, rehabilitation, and replacement of bridges. Therefore it is essential that models of bridge deterioration that accurately estimate remaining performance be developed. This is a difficult task for states that have just a few bridges of each type.

This paper provided a description of deterioration models and modifications to the data base that produced deterioration models that resulted in reasonable projections for deterioration. Occasionally (example 2) coarser models (e.g., version 2) must be used to establish reasonable trends. Such strategies are necessary for states like Nevada that have small bridge inspection data bases.

A conclusion from the study is that the data base could be enlarged by cooperating with other states. Some states have sufficiently large bridge inventories to easily establish accurate bridge deterioration models. Other states have small inventories but have much in common with their surrounding states. For example the bridge environment in northern Nevada is very similar to those in eastern Oregon, southern Idaho, and western Utah. The bridge environment in southern Nevada is similar to those in northern New Mexico and Arizona. It would be very easy to exchange the bridge inventory data, since they are stored in approximately the same format, and to develop common deterioration models. Cooperative agreements would be a great asset to all of the states involved. This would allow enough data to permit a verification data set and more confidence in the deterioration curves. This technique for increasing the size of small data bases would work in many parts of the country.

The deterioration models that were developed established some basic trends in bridge deterioration. They are as follows.

1. Postrehabilitation decay is greater than decay of a new bridge. This implies that although it is possible to increase the bridge condition rating through rehabilitation, the rehabilitated bridge is not new and will experience an accelerated rate of deterioration compared with that for a new bridge. The bridges with rehabilitations at a bridge age of more than 40 years had the greatest postrehabilitation decay rates. Therefore the earlier that rehabilitations are done the better the postrehabilitation performance. The result and the comparison that may be made are affected by unrecorded rehabilitations. These unrecorded rehabilitations cause a reduction in the projected decay of unrehabilitated bridges and cause a perception that a rehabilitated bridge will have a shorter life than a unrehabilitated bridge. The unrecorded bridge rehabilitations are a big problem. The only way to solve this problem is to go back through the contract data. This would be a very large task.
2. The prestressed concrete bridges are especially sensitive to ADT.
3. Bridges in northern Nevada deteriorate faster than those in southern Nevada. Northern Nevada has a significantly harsher winter environment (freezing, thawing, and salt application) than southern Nevada.
4. Decks deteriorate faster than the superstructure and the substructure.

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