FINAL REPORT

DEVELOPMENT OF PERFORMANCE AND DETERIORATION CURVES AS A RATIONAL BASIS FOR A MAINTENANCE MANAGEMENT SYSTEM FOR STRUCTURES

K. K. McGHEE
Research Scientist

G. R. ALLEN, Ph.D.
Director of Research

W. T. McKEEL, Jr.
Research Manager

Virginia Department of Transportation
VDOT
Research Council

VIRGINIA TRANSPORTATION RESEARCH COUNCIL

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/VA-94-R1		

4. Title and Subtitle	5. Report Date
Development Of Performance And Deterioration Curves As A Rational Basis For A Maintenance Management System For Structures	July 1993
	6. Performing Organization Code
7. Author(s) K. K. McGhee, G. R. Allen, & W. T. McKeel, Jr.	8. Performing Organization Report No. VTRC 94-R1
9. Performing Organization Name and Address Virginia Transportation Research Council Box 3817, University Station Charlottesville, Virginia 22903-0817	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. HPR 2859
12. Sponsoring Agency Name and Address Virginia Department of Transportation 1401 E. Broad Street Richmond, Virginia 23219	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

In cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. Abstract

The Virginia Department of Transportation is deeply committed to the development and implementation of an efficient, cost-effective maintenance management system for its bridges. Much effort is being applied towards the development of a management system that will ensure that appropriate maintenance takes place at the optimum times. Within such systems, the ability to anticipate with reasonable accuracy how rapidly and in what fashion bridges will deteriorate is essential in optimizing expenditures of limited maintenance funds. The research described in this report was undertaken to provide this predictive capability. Specifically, the objective was to use existing bridge inspection data in conjunction with multiple regression analyses to develop models relating the rate of deterioration of structural components with variables such as age, loadings, and environmental factors and to evaluate the relative importance of these variables. In addition, these efforts include a discussion of current bridge management activities and recommendations on needed modifications to the VDOT record-keeping system.

17. Key Words	18. Distribution Statement
bridges, bridge management, maintenance, bridge deterioration, bridge performance, management systems, bridge inspection, multiple	No restrictions. This document is available to the public through NTIS, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	30	

FINAL REPORT

DEVELOPMENT OF PERFORMANCE AND DETERIORATION CURVES AS A RATIONAL BASIS FOR A MAINTENANCE MANAGEMENT SYSTEM FOR STRUCTURES

K. K. McGhee
Research Scientist

G. R. Allen, Ph.D.
Director of Research

W. T. McKeel, Jr.
Research Manager

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Transportation and the University of Virginia)

In Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

July 1993
VTRC 94-R1

ABSTRACT

The Virginia Department of Transportation is deeply committed to the development and implementation of an efficient, cost-effective maintenance management system for its bridges. Much effort is being applied towards the development of a management system that will ensure that appropriate maintenance takes place at the optimum times. Within such systems, the ability to anticipate with reasonable accuracy how rapidly and in what fashion bridges will deteriorate is essential in optimizing expenditures of limited maintenance funds. The research described in this report was undertaken to provide this predictive capability. Specifically, the objective was to use existing bridge inspection data in conjunction with multiple regression analyses to develop models relating the rate of deterioration of structural components with variables such as age, loadings, and environmental factors and to evaluate the relative importance of these variables. In addition, these efforts include a discussion of current bridge management activities and recommendations on needed modifications to the VDOT record-keeping system.

FINAL REPORT

DEVELOPMENT OF PERFORMANCE AND DETERIORATION CURVES AS A RATIONAL BASIS FOR A MAINTENANCE MANAGEMENT SYSTEM FOR STRUCTURES

K. K. McGhee
Research Scientist

G. R. Allen, Ph.D.
Director of Research

W. T. McKeel, Jr.
Research Manager

INTRODUCTION

The Virginia Department of Transportation (VDOT) is responsible for the maintenance of all roads and bridges in the Commonwealth. Inspection of its bridges in accordance with standards set by the Federal Highway Administration (FHWA) is generally supervised by the Central Structure and Bridge Division and administered through bridge engineers in nine district offices located around the state. The districts also have the responsibility for maintaining these bridges. The required activities utilize federal bridge replacement or rehabilitation (BR/BH) funds for work done to FHWA standards and state maintenance replacement funds for replacement-in-kind or rehabilitation to lesser standards. Routine maintenance—generally small jobs—utilizes ordinary maintenance funds, which are state funds administered by resident engineers.

Funds from all of these sources are limited, and considerable effort has been devoted to ensuring that the proper action is taken on each structure. Initiatives to date have focused on the prioritizing of deficient bridges for available funding and the use of levels of service as a basis for field-generated maintenance budgets.

Deficiency Points

In the deficiency point system, priorities for replacement funding are based on a program developed for the North Carolina Department of Transportation by Dr. David Johnston and his colleagues at North Carolina State University.[1] The procedure, which uses data on file in the computerized bridge inventory, establishes level-of-service goals for load capacity, clear deck width, and vertical under- or over-clearance for bridges on each of the functional classifications of roads. A fourth factor used in Virginia's computations is the bridge sufficiency rating used as a measure of the structure's overall condition. Virginia's adoption of the North Carolina procedure differs mainly from the original in the relative importance assigned to the factors and in the use of the sufficiency rating rather than the estimated remaining life as a measure of the structure's condition.[2]

For the past several years, the deficiency point ratings have been used to prioritize on a statewide basis those bridges scheduled for replacement in Virginia's 6-year improvement program. Because of the nature of the bridge characteristics (capacity, roadway width, and clearance) included in the deficiency computations, the procedure is mainly applicable to bridges in need of replacement. One criticism of the procedure, therefore, has been that it does not lend itself to cost-effective rehabilitation and maintenance strategies before the condition of a bridge becomes critical. This shortcoming has been addressed to some degree through the application of a condition-based level-of-service approach to state-funded maintenance.

Level of Service

Federal regulations require that bridges replaced or rehabilitated using BR/BH funds meet the standards for new structures. Replacement-in-kind, which means rebuilding what was there, must be paid for through state maintenance replacement funds administered by VDOT's Maintenance Division. Because the use of state funds allows for a much wider latitude in the selection of alternative maintenance strategies than does the use of BR/BH funds, the choice of structures and the corrective actions to be applied to them become more complex. In order to help overcome this complexity and to properly administer its funds, the Maintenance Division in cooperation with the Bridge Division adopted a level-of-service approach to maintenance. These levels of service relate to a structure's condition rather than its physical characteristics, which was the case in the deficiency point computations.

Under this policy, certain inspection ratings flag a structure for maintenance action intended to preserve or restore it as near as possible to its condition as constructed. The system does not address the cure: field engineers must assess the situation and choose the appropriate corrective action. The level of service, shown below, addresses the scheduling of both ordinary maintenance and maintenance replacement activities depending on the severity of the condition. [Note: The condition ratings referred to here are numerical assessments of a component's condition for which a value of 9 represents a new structure, and a 0 indicates a critical condition level for which a facility is closed and beyond repair.]

- Maintenance replacement is used whenever a deck, superstructure, or substructure receives a generally fair condition rating (potential exists for minor rehabilitation); that is, when the numeric code is 5 or below. Also, whenever all structural steel must be painted; that is, when paint is rated poor.

- Ordinary maintenance is used whenever a deck, superstructure, or substructure receives a fair condition rating (numeric code 6) or a poor or critical sub-component rating with a generally good condition rating (numeric code 7). Also, whenever spot painting is needed; that is, when the paint is rated fair.

A prioritizing procedure, such as the use of deficiency points, does not constitute a management system. The level-of-service approach just described is a positive step towards indicating needed rehabilitation, but it does not allow for the necessary planning of future maintenance expenditures. A predictive capability is required, and the desire to develop this capability provided the impetus of this research.

PURPOSE AND SCOPE

The primary objective of this project was to investigate the deterioration of bridge components resulting from age, traffic, and exposure to deicing salts. The modeling efforts were undertaken to provide curves that could be used as guides for anticipating the needs of VDOT's bridges that might be candidates for inclusion in a bridge management system.

The study also allowed an evaluation of the bridge inspection program and provided some recommendations pertaining to its improvement and maximizing its effectiveness as part of a comprehensive management system.

This study began with visits with the district bridge engineers who were directing structural inspection and maintenance operations across Virginia. The purpose was not only to acquaint them with the project, but also to gain practical insights into maintenance problems.

After discussions with the district bridge engineers and an advisory panel composed of engineers involved in bridge maintenance, it was decided to evaluate records for 725 bridges in the 4 categories shown below. The number of bridges of each type is shown in parentheses:

1. steel beam bridges with timber decks(256)

2. steel beam bridges with concrete decks(142)
3. concrete beam bridges with concrete decks(182)
4. concrete box beam bridges(145).

The following types of structures were excluded from the sample:

1. municipal bridges not under VDOT jurisdiction
2. railroad overpasses
3. foot bridges
4. major bridge-tunnels
5. timber beam bridges
6. truss bridges
7. concrete slab spans.

METHODS

Bridge inventory forms were requested for the 725 bridges, which were selected randomly by structure number from all of the structures in the above 4 categories. All available inspection data on the conditions of the deck, superstructure, and substructure, the estimates of remaining service life, posted load limits, and traffic count data were manually collected for each bridge at the district bridge offices. The records of the work done, the condition of the structure, and the recommendations shown on the supplementary bridge reports for each inspection were also summarized. Traffic safety and channel and alignment ratings, which were also included on the inspection forms, were not recorded.

Field Evaluation

At the time of this study, inspections of Virginia's bridges were conducted by 18 teams located in 8 district offices. An important aspect of this study was a field evaluation to verify the accuracy and consistency of safety inspections. A total of 64 bridges in 7 of the districts were selected from the final study population and evaluated by the central bridge office engineer charged with the general administration of the inspection program accompanied by a member of the research team. Occasionally, the assistant state bridge engineer in charge of maintenance participated in the evaluations, as did the FHWA's division bridge engineer in one instance.

The field evaluation was of those structures having ratings in the range indicating a need for rehabilitation (generally values from 6 to 3) or to older structures that had unusually high ratings (values of 7 or 8). Information available to the evaluation team included the structural inventory form and the summary of inspection data gathered at the district offices used in the statistical portion of the study. Inspections made later in the research project after the statistical study were also made available.

Theoretical Model Design

Three major questions guided the design of the theoretical models. These were as follow: (1) Which variables, if any, reflect structural deterioration?; (2) Can their magnitude be measured?; (3) Do the suggested relationships make sense?

Modeling Technique

The decisions regarding testing methods were based upon discussions with bridge engineers and the project advisory team, the published research from MIT and the Transportation Systems Center, research conducted at Wisconsin's and New York State's Departments of Transportation, and other published research reports.[3-6] A review of this literature showed that there are several common approaches to estimating bridge deterioration rates. Case studies of individual structures have frequently been used. However, they tend to provide a poor basis for programmatic decisions because such case studies often lack generalizable results. Probabilistic studies, such as those employing Markov chains, are only recently widely understood and are only amenable to treating age as a factor on bridge deterioration. Multiple regression models, on the other hand, provide great flexibility in the variables tested and allow one to test variables other than age as a major influence on the condition of a structure.

Once multiple regression analysis was settled upon, three equation forms were considered. The initial tests assumed that primarily linear relationships would predominate between bridge component conditions and the factors influencing them. Based on theory and work in the pavement management field, the next phase looked at logarithmic relationships between condition ratings and the age and cumulative traffic of a bridge. Lastly, in order to account for the ratings on the lower end of the scale, models were investigated that incorporated polynomial behavior.

Choosing Variables

In the simplest sense, multiple regression analysis is a statistical technique that identifies whether one variable brings about change in another variable; it also allows one to test for the magnitude of the influence of one variable on another. Among the variables considered important by the district bridge engineers were geographical location, type of superstructure (i.e., steel beams versus concrete beams), and age. The age of the structure is important not only for length of exposure but because it also provides a monitoring variable for changes in design trends. For example, the depth of cover in deck concrete has been increased in recent years, and epoxy-coated reinforcing steel has been used only since the mid 1970s. Additional variables considered by researchers included cumulative vehicle and truck traffic, number of spans in a bridge, degree of skew, roadway system (i.e. interstate, primary, or secondary), and the amount of deicing chloride use.

Prior to running regressions, correlation matrices that included all potentially useful independent and dependent variables were examined. The correlation matrix provides mathematical reinforcement to the graphical breakdown. It allows the analyst to identify relative degrees of influence that variables may have on a given dependent variable, and it signals the existence of intercorrelations among those variables assumed to be independent of one another.

Following this procedure, regressions on the dependent variables of interest (current condition ratings) were performed including those explanatory variables identified as most highly related by the correlation matrices. To ensure that all possible influences were investigated, the most theoretically appealing independent variables were included in the first trials whether their correlation coefficient was significant or not. Statistical output produced during each regression analysis aided in refining models to incorporate only those variables that explained an appreciable portion of one condition rating's deviation from another.

Data Preparation

The majority of the information assimilated for this project was transcribed directly from structural inventory and inspection records. Cumulative traffic data and chloride usage, however, required additional research and processing in order for it to be meaningfully implemented into the modeling program.

Cumulative traffic volumes were obtained using growth rate and extrapolation and interpolation formulas borrowed from the pavement management field. Using average daily traffic (ADT) counts for a given bridge, one set from the latest available traffic tables and one from the earliest available records, an estimate of the traffic rate for the year the bridge was built was made. With these volumes, a cumulative traffic volume can be estimated including all traffic from the opening of the bridge to present. The formulas used were as follows:

$$g = \left[10^{\frac{1}{85-y_1}\log\frac{ADT_2}{ADT_1}} \right] - 1 \ ,$$

$$ADT_0 = \frac{ADT_1}{(1+g)^m} \ ,$$

$$ADT_{cum} = \frac{365ADT_0\frac{(1+g)^n - 1}{g}}{2} \ ,$$

where: g = growth rate from earliest ADT to 1985

y_1 = year of earliest available ADT

ADT_0 = estimated ADT for year bridge was built

ADT_1 = ADT for year of earliest available ADT

ADT_2 = ADT from latest tables (1985)

m = number of years between the year the bridge was built and the year of earliest available ADT

n = bridge age

ADT_{cum} = cumulative traffic from opening of bridge to present (for a 4-lane divided highway).

Calculation of chloride application rates was more straightforward but still involved a rigorous records search and some minor modifications. Chloride applications are recorded by county and were available fairly consistently for the past 10 to 15 years. The records include the total weight of calcium chloride, sodium chloride, and abrasives (with approximately 10 percent calcium or sodium chloride content) used yearly on each highway system within a residency. To facilitate comparison of the use of chlorides among other counties and on other bridges, this rate is calculated as a chloride per lane mile of roadway. The final average county chloride rate per system was calculated using the total volume of CaCl plus NaCl used per lane mile in addition to 10 percent of the abrasives volume. The relatively simple equation forms were:

$$R_{CACL} = \frac{weight_{CACL}}{lanemiles_{roadway}},$$

$$R_{NACL} = \frac{weight_{NACL}}{lanemiles_{roadway}},$$

$$R_{ABR} = \frac{weight_{ABR}}{lanemiles_{roadway}},$$

$$CL_{TOT} = R_{CACL} + R_{NACL} + 0.10 \times R_{ABR},$$

where: R_{CACL} = calcium chloride application per lane mile

R_{NACL} = sodium chloride application per lane mile

R_{ABR} = abrasives application per lane mile

CL_{TOT} = total chloride application per lane mile.

RESULTS

File and Record Examination

At the initiation of the project prior to the employment attrition prompted by early retirement incentives of 1991, the district safety inspection teams had had relatively little turnover in personnel. Inspection records maintained in Virginia for structures and culverts having waterway openings of 36 ft^2 or greater have been available in most of the districts since the National Bridge Inspection Standard (NBIS) was issued in 1971. Because of the comprehensive nature of the Virginia inspection form and the extensive experience and stability of the inspection force, data on the current conditions of the structures was reasonably complete and of good quality. The data on maintenance performed, however, was found to be much more sketchy and less reliable. In fact, an evaluation of the improvement in performance gained by various corrective actions, which was one of the original objectives of the study, could not be met because of a lack of usable data. Among the inspection documents available were the following:

Bridge Inspection Report (Form B7)—Virginia's inspection report, like that of many states, allows the recording of information beyond that required for the federal SI & A. In addition to the general condition ratings for the deck, superstructure, substructure, etc., subcomponents such as the wearing surface, railings, expansion joints, and bearings are also rated. Space is provided for a description of the nature of any distress encountered, and at times, lengthy descriptions with photographs are included with the reports. The inspection reports are filed in each district bridge office, and copies are sent to the central bridge division. No microfilm or computer files are made of the report.

Supplementary Bridge Report (Form B6)—The supplementary report is a single sheet that is generally used to summarize the inspection report, indicate any change in load carrying capacity, and recommend needed repairs or rehabilitation. There is space to report any work done since the last inspection, but since no formal communication channels exist, the information may not be complete. The supplementary bridge report is filed with the inspection report.

Structure Inventory (Form B79)—This is the master record that includes a complete description of the structure, location data, condition and appraisal rating summaries, and other data required for the federal SI & A system or desired by the Department. The data is contained in a computer file, and those items required for any report can be retrieved as needed.

The original pool of 725 bridges was later trimmed to 571 bridges as a result of incomplete records and questionable data for structures older than 50 years on primary routes and 30 years on secondary roads. Nevertheless, the sample represents nearly 5 percent of the total number of bridges in the inventory. Figure 1 shows the relative condition of the major bridge components for the investigated data set.

The structures were assigned to 3 groups of districts, each group having common geographical features:

1. the eastern coastal area to the fall line (districts 4-Richmond, 5-Fredericksburg, and 6-Suffolk),

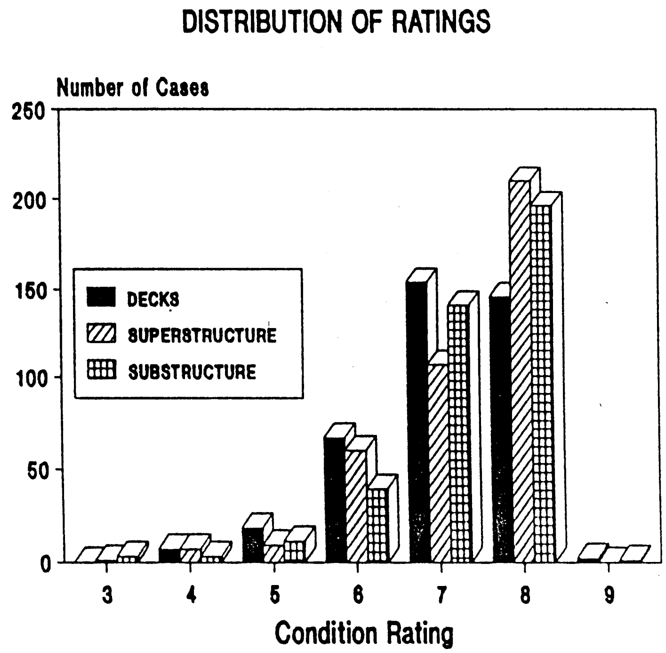

Figure 1. Data set condition histogram.

2. the piedmont plateau (districts 3-Lynchburg, 7- Culpeper, and 9-Northern Virginia), and

3. the western mountains and valleys (districts 1-Bristol, 2-Salem, and 8-Staunton).

At least 40 structures of each type were included in each geographical area.

Review of Previous and Current Research

Deterioration Studies.

Much of the work carried out through this project has emulated ongoing federal- and state-funded efforts in the bridge management area. Related bridge performance studies include those mentioned earlier, which are described in FHWA's Demonstration Project Number 71, "Bridge Management Systems."[4] The TSC and the MIT projects used a national bridge database and provided deterioration functions relating major component ratings with the state within which the bridge is located, structure type, skew, number of spans, custodian type (i.e. city, county, state), age, and traffic. New York and Wisconsin both developed relatively generalized deterioration models using piece-wise linear regression techniques and an in-state data base.

Along with discussing data-fitting techniques, this related research notes common rating trends and similar experiences in finding and interpreting inaccurate or inconsistent data sets. A common observation was the tendency of the deterioration rate to decrease approximately 10 to 15 years after a bridge is built. In general, it was determined that bridges can be expected to decline in overall rating at about 0.1 points per year and can be expected to have a useful life of about 65 to 70 years.

System Studies

Over the duration of this study, including the lapse between completion of research and the reporting of results, a number of bridge management system projects have been launched. FHWA's DP No. 71 has prompted several research efforts both with overall system development and with optimum fund allocation programs incorporating specific numerical techniques. The National Cooperative Highway Research Program administered a project that identified and developed the necessary elements of a comprehensive BMS, including the earliest attempts at providing a universally applicable software package. Most recently, under the funding of FHWA, Cambridge Systematics has produced a powerful and flexible adaptation of a national bridge management system software package (PONTIS).

The FHWA demonstration project was based on and done in conjunction with the work done at N.C. State under the direction of Dr. David W. Johnston. Its primary purpose was to encourage state and other local agencies to adopt a systematic procedure for allocating bridge MR&R funds. The priority ranking formulas for several states and the level-of-service methods adopted by North Carolina DOT are presented and discussed. The latest efforts have studied the feasibility of automated fund distribution systems using an incremental benefit-cost-analysis algorithm.

NCHRP Project 12-28, "Bridge Management Systems," was conducted by ARE, Inc. engineering consultants of Austin, Texas.[7] The first phase of research identified six essential elements of a bridge management system:

1. database
2. network-level major maintenance, rehabilitation, and replacement selection
3. maintenance
4. historical data analysis
5. project level interface
6. reporting.

The second and third phases of the project investigated development, testing and implementation of a standardized microcomputer software package based on the elements identified in the first phase. The six major modules of the program corresponded to those components identified earlier and interact to perform the basic functions of bridge management. The third phase, now underway and scheduled for completion sometime in mid 1993, will include a review of the software package produced in the second phase. At this stage, it would appear that it is a system better suited to smaller networks with fewer structures (such as a municipality). In light of this, the review of this package by the Department has taken on a somewhat secondary priority ranking.The latest research effort, an additional FHWA-sponsored venture, is being conducted by Cambridge Systematics and Optima, Inc.[8] The objective of this study is to provide a universally applicable network optimization system for bridge improvements and maintenance. It incorporates the Markov Chain methodologies to enable a network to make historical adaptations to locally specific deterioration and costs using a probabilistic approach. The system design goals, as presented in the "PONTIS - Executive Summary," are as follows:

— to provide a systematic procedure for finding MR&R budget requirements

— to incorporate level-of-service goals in assessing bridge improvement needs and budget requirements

— to provide a capability to consider the entire bridge network simultaneously in arriving at optimal policies and recommendations for MR&R

— to retain the flexibility to address any subset of bridges

— to provide priority orders and sequencing for bridges in need of MR&R and improvement

— to coordinate MR&R planning decisions with future improvement decisions

— to consider the differing inspection and repair needs of the major structural components of bridges as well as the differing needs of the various types of bridges

— to allow for updating of predictive probabilities as the necessary data becomes available over time

— to consider the immediate and future costs and benefits of the various courses of action and their effect on future conditions (In particular, the model would weigh the benefits of preventive maintenance versus costlier but less frequent corrective actions)

— to allow sensitivity analyses of the recommended policies in terms of future conditions of the bridge network and cost requirements

— to be flexible to accommodate different state-specific improvement, MR&R, and fiscal policy issues

— to provide a basis for short-term and long-term MR&R and improvement budget planning and resource allocation

— to provide a rigorous procedure and an analytical framework for incorporating expert engineering judgment in the model.

Recently, the Department and the departments of transportation of 12 other states and the city of San Jose completed a beta test (secondary assessment conducted outside the developing institution) of the PONTIS software package. The results have been extremely promising. Of the modifications recommended by the testing agencies, much of the emphasis was placed on the establishment of Commonly Recognized (CoRe) elements. The flexibility allowed to the participants in the creation and maintenance of non-CoRe elements was of equal concern. Overall, the PONTIS testers agreed that the program is a powerful and flexible software package that can be implemented in part or as a whole to fulfill bridge MR&R planning needs of most agencies.[9]

Descriptive Statistics of Database

The appendix includes most of the original database. In its raw form, however, it is difficult to identify distributions and trends that may be statistically important. The following figures provide better descriptive illustrations of data trends. To avoid confusion resulting from plot clutter, the actual data points have been replaced with linear "best fit" approximations developed through single-variable regression analysis.

The breakdown of the database began at the most aggregate level with an observation of the trends in condition ratings of the major components of the bridge: the deck, the superstructure, and the substructure. Figure 2 summarizes the relative performances of these components and demonstrates that the rating of the deck, which is usually the most "exposed" component of a bridge, is a leading indicator in the deterioration process. The superstructure rating tends to parallel the deck at slightly higher values. The substructure rating drops more quickly initially but stabilizes and maintains a higher level of service over the bridge life span.

Best Fit of Data

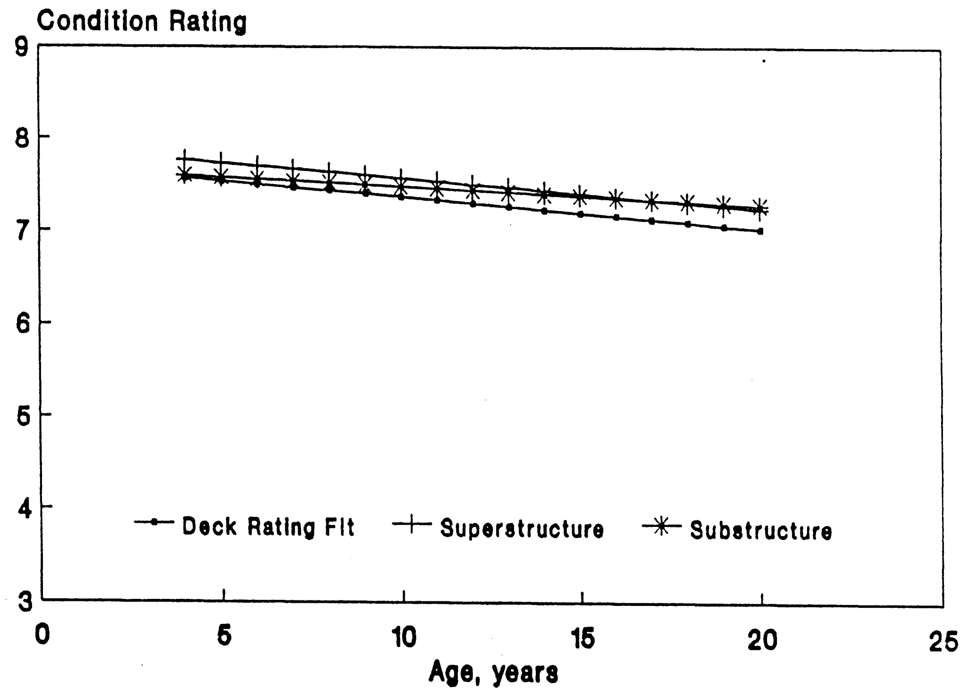

Figure 2. All major components.

In general, bridges tend to deteriorate in response to deck performance. Since this was anticipated, most of the effort expended for this project addressed the performance of the decks.

Figures 3 through 5 illustrate the deck condition ratings versus time for each of the nine districts in the state. Figure 6 approximates their performances with respect to the geographical regions discussed earlier.

From the standpoint of functional classification, Figure 7 suggests that secondary system bridge decks typically outperform those in the primary and interstate systems.

Two variables that are likely strongly correlated with both geographics and system classification are cumulative traffic loadings and chloride application rates. Figure 8 demonstrates that both total vehicle traffic and truck traffic adversely affect the decks of bridges. An obvious trend can be identified for total vehicle traffic for most bridges. However, when the counts are parsed (as for interstate and primary systems), the effects of cumulative truck volumes are amplified significantly. Likewise, with the aid of a regressional best fit, damage associated with chlorides may be inferred from Figure 9.

Figures 10 and 11 show potential influences on deck performance that might stem from the general configuration of a structure. Consistent with our

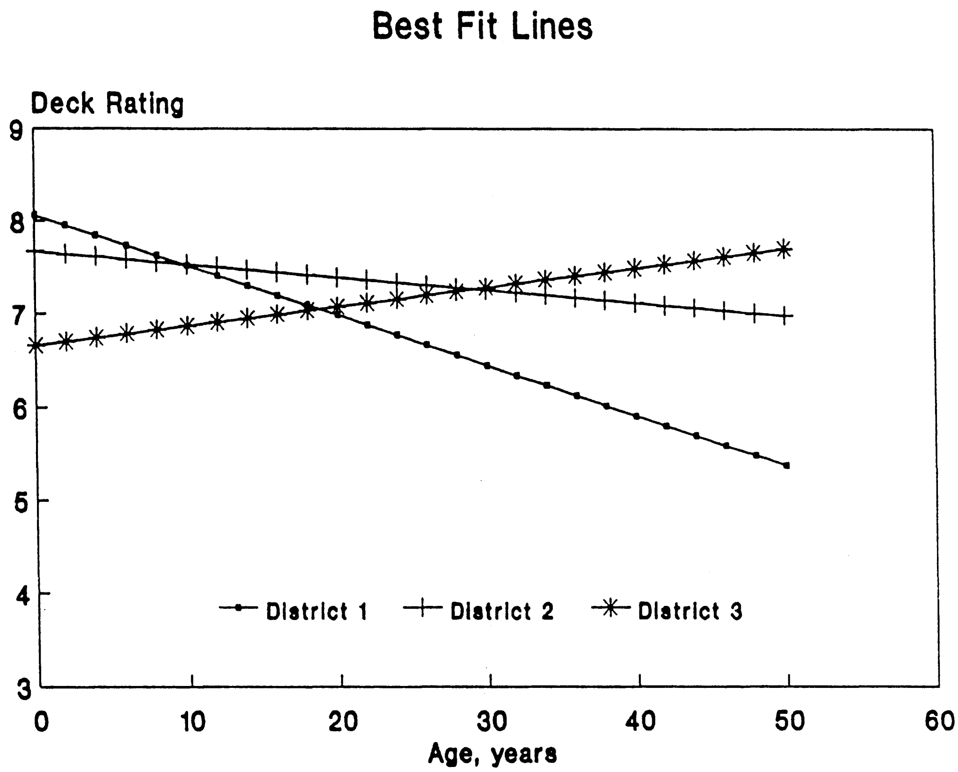

Figure 3. Districts 1, 2, and 3.

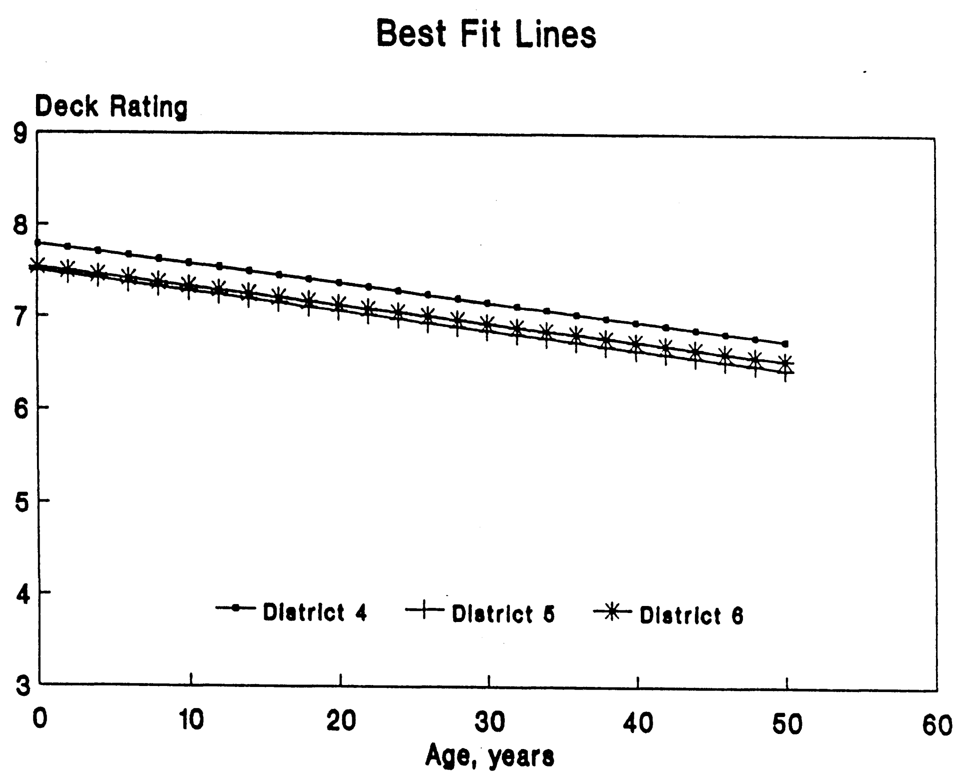

Figure 4. Districts 4, 5, and 6.

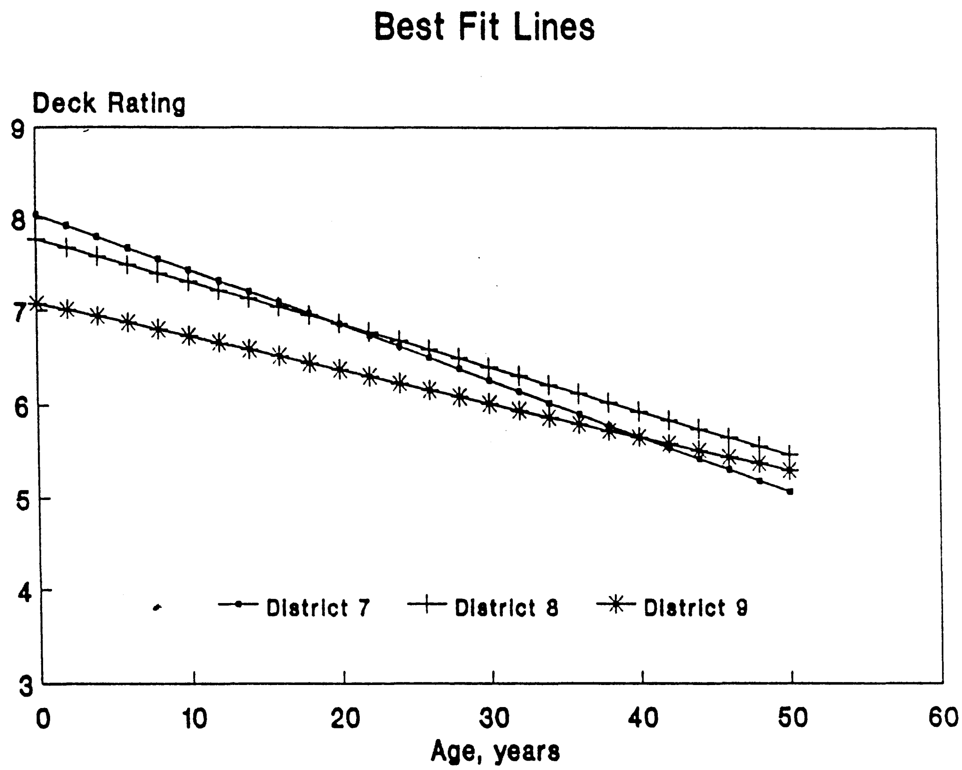

Figure 5. Districts 7, 8, and 9.

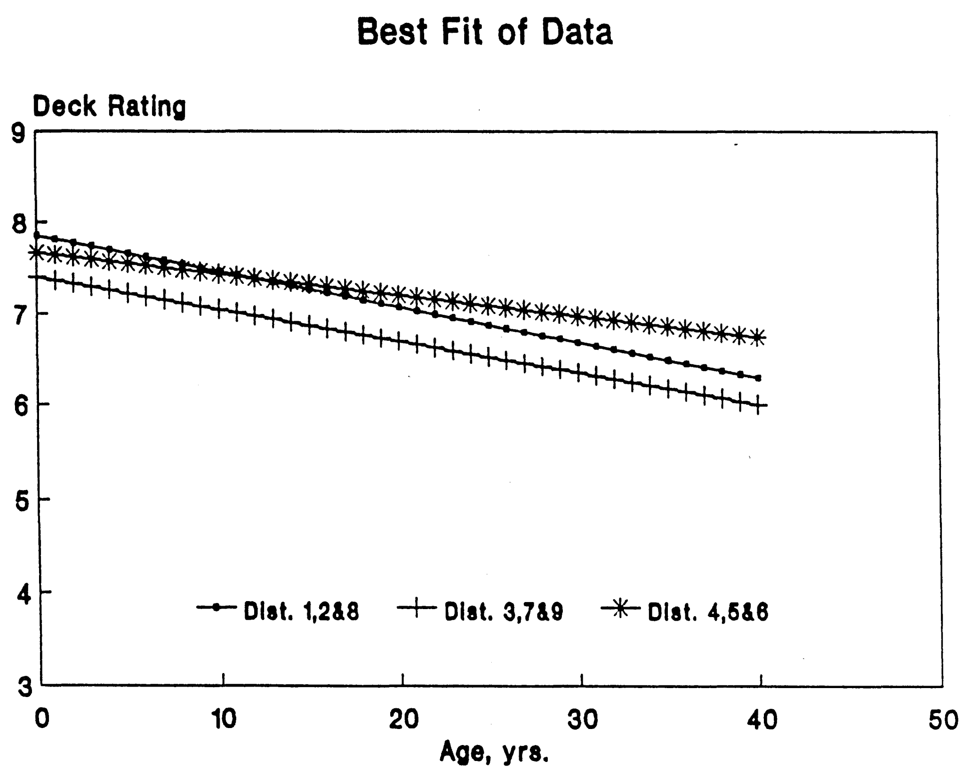

Figure 6. Regional influences.

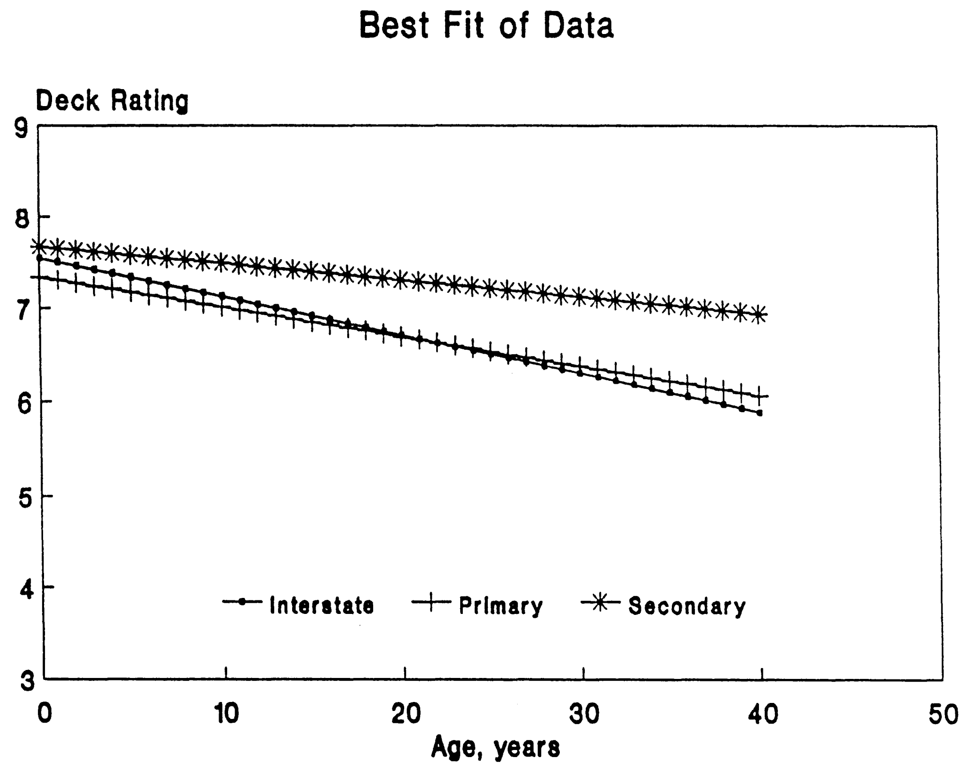

Figure 7. System influences.

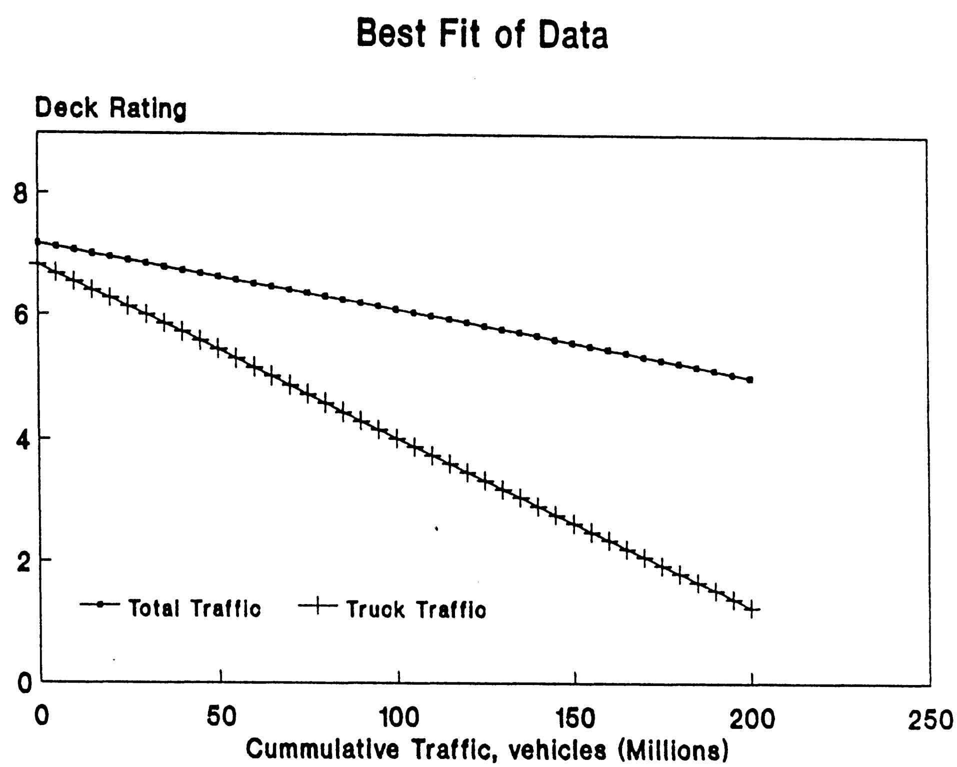

Figure 8. Traffic influences.

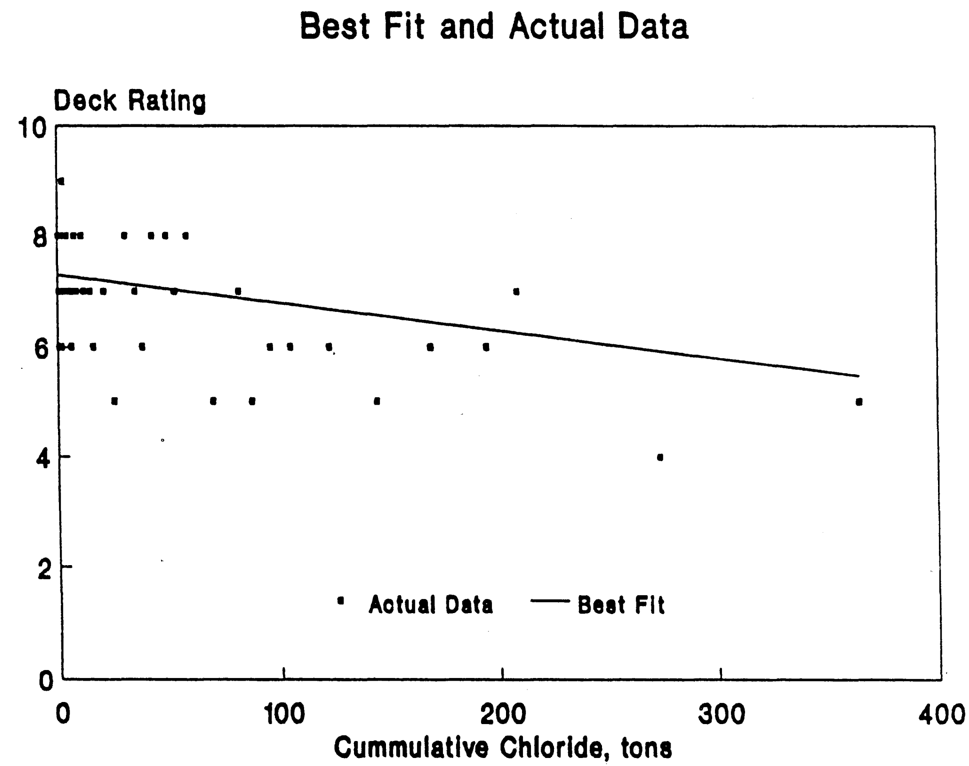

Figure 9. Chloride usage influence.

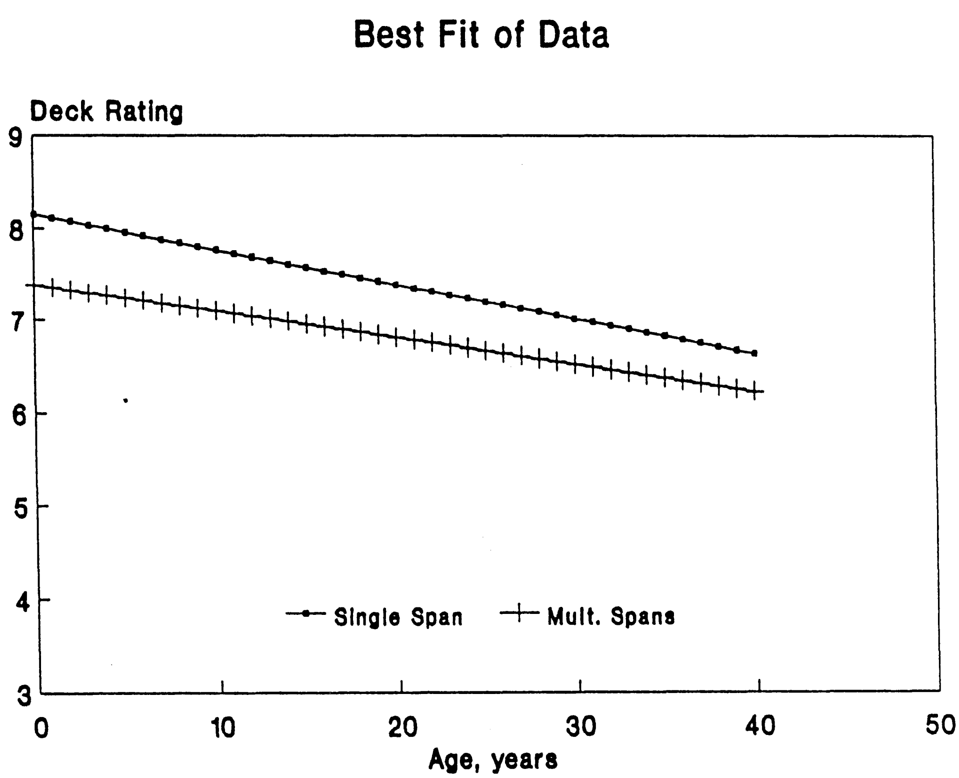

Figure 10. Single- or multiple-span influence.

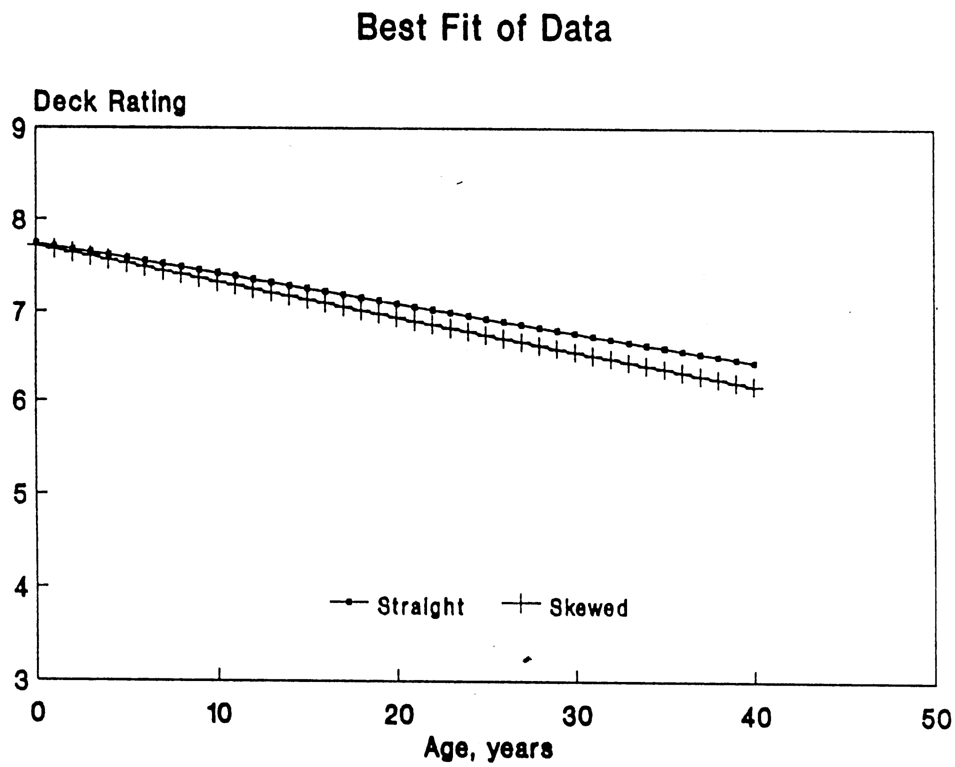

Figure 11. Straight or skewed effects.

expectations, Figure 10 shows that single-span bridges will generally fair better than multiple-span structures. Figure 11 shows that ratings will drop off faster on skewed decks than on perpendicular alignments.

Empirical Test Results

The modeling phase involved running and evaluating a variety of predictive equations. The relative accuracy of the models was measured by the coefficient of determination (which is frequently called the R-squared value). Other tests of model suitability included comparisons of predicted versus actual conditions and the standard error of the estimated variable.

A battery of regression models were tested using each of the mathematical formats discussed earlier and an assortment of variables. The values of the statistical significance indicators were acceptable for linear models, but actual versus predicted plots illustrated a larger-than-desirable scatter at extreme values. The full logarithmic models proved to be overly reactive, but semi-log models produced significant results. The last experiments were with polynomially equipped equations. Their performance was not, however, an improvement; it was not even as accurate as the original models.

This section presents the best models developed for several of the stratifications that were investigated. All the models that will be discussed were based on linear or semi-log functions. Since the most functionally important component of the bridge is its deck, the majority of regression analyses were dedicated to modeling its performance.

Each of the models tested had the following general form:

$$A = f(a, b, c, \ldots x) \quad ,$$

where: A = the condition rating of the component, such as the deck, the superstructure, or the substructure

f = a mathematical relation between condition and influences on condition

x = those variables hypothesized to explain variations in the condition of a structure (such as age, log(age), bridge type, traffic volume, chloride application, etc.).

Wooden Decks

Two of the best equations for explaining variations in wooden deck ratings are shown below:

$$A = 9 - 0.29\,(SPANS) - 0.64\,(CL) - 1.01\,(LOGAGE)\,, \qquad [1]$$

where: R-squared = 0.861
Standard Error = 0.6
Weight = 8 percent Spans, 20 percent Chloride, 72 percent Age
t-statistics significant at 0.95.

$$A = 9 - 0.57\,(CL) - 0.22\,(LOGCTV)\,, \qquad [2]$$

when: R-squared = 0.862
Standard Error = 0.6
Weight = 19 percent Chloride, 81 percent Traffic
t-statistic significant at 0.95.

The first equation shows that a timber bridge rating is inversely related to the number of spans, chloride applications, and age. The R-squared is 0.86. More specifically, the rating can be estimated by subtracting from 9 (the rating of a new component) the log of the age of the bridge, by subtracting 0.64 times the average annual chloride application in tons per lane mile by county, and by subtracting 0.29 if the wooden bridge has multiple spans rather than a single span. The weights that are shown indicate the relative importance of the influence of each of the variables. In addition, each of the variables were statistically significant at the 95 percent level of confidence.

Results shown in equation 2 are quite similar. This equation relates the deck rating to the log of cumulative traffic volume (which has a very high explanatory value in the equation) and to chloride application.

Wooden Decks Rated 7 and Below

Because bridges with deck ratings of 7 and below are frequently of the greatest concern to those who have responsibility for maintenance and rehabilitation, the authors also tested deck equation models for this stratification of the bridge sample. The results were quite interesting and are shown in Equation 3.

$$A = 9 - 0.29\,(CL) - 0.34\,(LOGCTV)\ , \qquad [3]$$

where: R-squared = 0.973
Standard Error = 0.38
Weight = 8 percent Chloride, 92 percent Traffic
t-statistics significant at 0.95.

R-square now goes to 0.973. In other words, 97 percent of the variation in wooden bridge deck ratings can be explained by an equation that includes chloride application rates and the log of cumulative traffic volume. These results suggest that such an equation can estimate the rating within about 0.4 points of the actual rating for wooden deck bridges. The log of cumulative traffic volume simply indicates that the relationship between wooden deck ratings and traffic volume is not linear. The reader should also note that cumulative traffic is the major explanatory variable.

Concrete Decks

The next subset of evaluations includes all types of bridges with concrete decks. The most interesting modeling results are shown in Equations 4 and 5. Equation 4 estimates that a deck rating is equal to 9 minus 0.42 if the bridge is a multi-span rather than a single-span bridge and that the deck rating declines by 1.23 times the log of the age of the bridge.

> NOTE: As has been the case throughout, the SYSTEM and SPANS variables are what is referred to as regression dummies. In other words, they test the influence of a particular categorical variable. The system variable takes on a value equal to one for primary sys-

tem bridges or interstate bridges and a value of zero for the secondary system. Multi-span bridges are assigned a value of one; single-span bridges a value of zero.

Equation 5 shows roughly the same ability to explain variations in deck rating. That is, the R-squared in both Equations 4 and 5 is 0.85. Equation 5 is an alternative model for predicting concrete deck ratings, and it also demonstrates that decks on multi-span bridges have a tendency to rate lower than single spans of the same age, the same traffic volume, and other similar characteristics. It also shows that the log of the age of the bridge and the log of cumulative traffic volume have significant negative influences on deck ratings. Either of the equations predicts ratings within 0.9 of the actual rating.

$$A = 9 - 0.41\,(SYSTEM) - 0.42\,(SPANS) - 1.23\,(LOGAGE)\ , \qquad [4]$$

where: R-squared = 0.85
Standard Error = 0.9
Weight = 15 percent SYSTEM, 17 percent SPANS, 68 percent LOGAGE
t-statistics significant at 0.95.

$$A = 9 - 0.36\,(SPANS) - 0.96\,(LOGAGE) - 0.11\,(LOGCTV)\ , \qquad [5]$$

when: R-squared = 0.85
Standard Error = 0.9
Weight = 15 percent SPANS, 48 percent LOGAGE, 37 percent LOGCTV
t-statistics significant at 0.95.

Concrete Decks Rated 7 and Below

Turning to concrete decks rated 7 and below, equation 6 performs very well since it suggests that system type, the span layout (single versus multi-span), the log of age, and the log of cumulative traffic volume are the significant explanatory variables.

$$A = 9 - 0.32\,(SYSTEM) - 0.31\,(SPANS) - 0.96\,(LOGAGE) - 0.12\,(LOGCTV), \qquad [6]$$

where: R-squared = 0.93
Standard Error = 0.73
Weight = 10 percent SYSTEM, 11 percent SPANS, 47 percent LOGAGE, 32 percent LOGCTV
t-statistics significant at 0.95.

Age and traffic volume have the greatest proportionate influence on the ratings, but it should be noted that among two bridges of the same age and traffic volume, a multi-span bridge will be rated slightly lower on average than a single-span bridge (as indicated by the minus 0.31 coefficient on the SPANS variable).

Other Deck Models

Concrete deck modeling results on the secondary system, the primary system, and the interstate system stratifications were very similar to those for the entire data set. Significant variables include the number of spans, the age, the traffic volume, truck traffic volume, and the ratings 4 years prior. As one might suspect, previous deck ratings tend to be excellent predictors of short-run critical rating levels. Bridge type and skew proved to be insignificant. R-squared values ranged from 0.87 for long-run models to 0.98 for those models that were short-run and based on ratings four years previously. The accuracy of the models generally is within 0.75 of the actual rating.

Superstructure and Substructure Models

Numerous tests were run on superstructure and substructure models. These models incorporated the same general form as the deck models described in this report. Bridge type, age, spans, and the joint and deck rating four years previously proved to be the most significant influences on superstructure and substructure ratings. Steel beam, concrete deck, and multi-span structures tend to deteriorate more rapidly than concrete beam or concrete box-beam structures. In all modeling tests, care was exercised to ensure that problems of multi-colinearity were avoided or corrected for. In addition, model results reflect only variables that are statistically significant influences on ratings at or above the 95 percent confidence level.

DISCUSSION

Appraisal of Inspection Records

During the early stages of the project, an assessment of the inspection records began to indicate some distinct strengths and weaknesses in the current recording system. Perhaps the most significant of the deficiencies was the lack of reliable historical maintenance records. There are at least two reasons for this inadequacy. First, there apparently was incomplete communication between the inspection teams, the district bridge offices, and those maintenance forces assigned to the residency offices. The recommendations on work to be done formulated by the district offices on the basis of the inspection reports consist of general tasks, i.e., "the expansion joint should be cut out and recast; all areas of spalled concrete should be patched with pneumatically applied mortar." The provision of specific details on quantities of the work required or its urgency, such as used by states such as Pennsylvania, might be a useful addition to Virginia's system. Similarly, the communication back to the district offices of work done is often vague and, occasionally, omitted. There is also some concern about the activity codes used to describe maintenance activities. Either the limited number of available codes or an incomplete use of existing codes may be preventing the development of usable task and cost data.

Accuracy and Consistency of Inspections

An initial goal of this project was to provide an assessment of the accuracy and consistency of the field safety inspection teams. The field evaluation was, necessarily, a comparison of informed opinions: those of the inspectors for each bridge versus those of the office engineer. This methodology did not yield quantifiable results, but certain trends were indicated.

In general, there was a tendency towards a stricter interpretation of the standards on the part of the office engineer. Of the seven districts checked, four often tended to rate the components of a given bridge higher than did the office engineer, whereas three generally assigned equivalent ratings. Many instances of overrating by the districts occurred in the range from 8 to 6. The distinctions between values in this range, which encompass conditions from good to fair, are not always clear in the field. Overrating is serious primarily in the case of a structure in the range of 5 to 6, for which a high value would not alert the level-of-service system to needed rehabilitation. Differentiation of rating levels in this range is easier, however, and overrating of the structure as a whole was not as prevalent.

The examination of structures in the field also indicated the importance of subcomponent ratings. There was an apparent acceptance of lower standards of railing adequacy and a toleration for absolutely poor performance or complete failure of expansion joint seals. Subcomponent ratings of "poor" or "critical" activate the level-of-service system call for the scheduling of needed repairs. Unfortunately, prompt corrective action has not always been taken, especially in the case of joint seals. There were many instances of deterioration of bridge seats, pier caps, beam ends, and diaphragms that resulted from failed joint seals. Lastly, the districts often displayed a tendency to overrate older bridges (those 40 years and older) particularly on low-volume secondaries. Also, characteristic of these bridges was a healing phenomenon that may occur periodically throughout its life-span. More relaxed records systems generally fail to account for maintenance or improvements to many of these structures, and preconceived budget allocations may sway inspection ratings.

For several reasons, it was impossible to assign corrective factors to the ratings of individual teams or districts. Within the relatively small sample, no district overrated all of its bridges. In most cases, only certain components of the structure were overrated. Later inspection data indicated that performance in terms of the grouping of values improved after the training course in 1986. The course concentrated on minimizing the subjectiveness of ratings through the application of rules, with the aim that graduates would rate any given component within a one-point range. An evaluation of actual inspections in two districts by a team of engineers from the FHWA confirmed the adequacy of the procedures observed. Many of the later cases of overrating were within this tolerance, and there were only a few instances of overrating in which serious distress was ignored. Therefore, it appears doubtful that the application of a corrective factor is necessary.

Assessment of Experimental Database

An overview of the data set, from a deck condition standpoint, indicates that the worst performing decks are found in the Bristol, Culpeper, and Staunton Districts. A common factor that may bear some responsibility may involve the increased number of yearly freeze-thaw cycles of these regions. The inconsistency in this hypothesis is the conspicuous absence of Salem and, to some extent, Northern Virginia, where the yearly temperature fluctuations are comparable. Obviously, factors other than geographic/climatic conditions affect the data significantly.

The apparent bridge performances in the Lynchburg district could elicit some reservations concerning the database. According to the best data fit of these ratings, the decks in District 3 tend to improve slightly with age. The domination of secondary bridges and a complete lack of interstate bridges in this district may contribute to this unusual outcome. The absence of the interstate system, alone, allows officials in Lynchburg to prioritize maintenance activities differently and could result in a more evenly maintained network. In addition, none of the Lynchburg bridges over 30 years of age appeared in the final database, resulting in an unusually young representation.

The consistency of the present conditions and deterioration trends in districts 4, 5, and 6 indicate that the researchers' decision to group the Richmond, Fredericksburg, and Suffolk districts together in a regional stratification was valid. The observed rating decline in this region may be indicative of the influence of climate on performance. Despite some localized high traffic volumes and scattered tidal conditions, widespread rapid deck deterioration did not appear to predominate in these milder climates.

The best estimate plots in Figure 6 indicate that the worst deck performances are in region 2 (districts 3, 7, and 9) in which the large number of deteriorated structures in the Culpeper district negate the moderate to good performances in the other two districts of the region. Again, these results are most likely attributable to climatic fluctuation in addition to the fact that the network is older and more heavily travel.

An unexpected phenomenon noted during the modeling study was the tendency for wooden deck deterioration to accelerate with increased salt applications. Possibly the chloride variable reflects the effects of a related factor such as higher truck volumes on certain more heavily traveled (and hence more often salted) secondary roads, or perhaps the deleterious effect of chlorides on timber is more significant than originally envisioned. Except for this aberration, the timber deck models were intuitively sound, and each of the variables portrayed influences that are consistent with the theoretical relationship one would normally expect. For example, one would expect deck ratings to be reduced by increased cumulative traffic volumes and age; hence, the negative coefficient on the traffic and log-age variables.

Another pertinent observation was made during exercises with concrete deck performance modeling. In this case, a concrete deck on the interstate or primary system was hypothesized to deteriorate more rapidly than a comparable concrete deck on the secondary system largely as a result of the potential influence of chloride application on major thoroughfares. Engineering design and structural relationships further suggested to the authors that multi-span bridges would most likely deteriorate more rapidly than a comparable single-span concrete deck. The negative values on the SYSTEM and SPANS coefficients in Equation 4 serve to confirm these hypotheses.

CONCLUSIONS AND RECOMMENDATIONS

The condition ratings and the rating process in Virginia has provided an adequate basis for management system development. Results of the field evaluations reinforced the findings of the earlier records search. In general, comparisons of ratings from an independent team of rating engineers were reasonable, and there were no major inconsistencies among regions of rating teams throughout the state.

In anticipation of a new optimization and planning system (specifically one incorporating PONTIS), this rating process will evolve to encompass a more network level perspective. Although the existing methodologies will provide a sound foundation upon which this new system can build, an evaluation of it does suggest some areas of concern. Among those, perhaps the most critical pertain to the accuracy and detail typically furnished in regard to needed maintenance activities. If accurate planning is expected, a mechanism must also be provided to better track corrective actions, costs, and corresponding performance responses.

The modeling effort conducted during this study has been successful. The results are logical, and they are consistent with reasonable structural and theoretical relationships. The multiple regression technique employed allows for variables other than age to be tested as influences on bridge deterioration and performance, and the forecasting accuracy is sufficient for program planning.

Of the numerous positive aspects of these modeling research efforts, perhaps the greatest potential application lies in the ability to ask "What if?" questions. For example, the modeling effort now provides VDOT with the ability to predict with a reasonable degree of accuracy what might happen to a bridge rating if general traffic or truck traffic volume were to increase substantially or if chloride application rates were to be altered. It also provides the ability to forecast how comparable bridges on the primary or the interstate system might deteriorate as compared to a bridge on the secondary system of equal age.

The predictive capabilities developed under this project involved purely deterministic methods. An interim study conducted through the Mid-Atlantic Universities Transportation Center[11] incorporated the identical database to investigate the use of a probabilistic approach to deterioration modeling. It provides a particularly timely function in that it documents a test of VDOT's network bridge deterioration for compliance with the Markovian Decision Process, which is the modeling technique used in PONTIS. The conclusions suggest that VDOT's bridges demonstrate the Markovian Property (transition properties only a function of current state - no memory). However, an upcoming research project that will investigate the penalty exacted if the network is not 100 percent applicable is expected in the near future.

The facility to monitor and predict structural performance given regional financial and environmental influences is imperative if MR&R needs are to be accurately anticipated and the allocation of funds optimized. The learning capacity of the Markov Chain methodologies incorporated into PONTIS allows for this sort of historical adaptation to locally specific deterioration and cost probabilities. The quantity and accuracy of the historical database continue, therefore, to be critical issues. The reliability of MR&R planning will be directly related to the quality of information on which it is based.

FURTHER RESEARCH

The results presented here have reflected a portion of a larger effort underway to implement a structures maintenance management system for the Virginia Department of Transportation. As referred to earlier, the Department recently participated in a very favorable beta-testing of the Cambridge Systematics system. The impending federal mandate for bridge management, administered under the Intermodal Surface Transportation Efficiency Act (ISTEA), also serves as an element of motivation. In response, VDOT has elected to dedicate its BMS development efforts towards the implementation of PONTIS. To accomplish this, a considerable effort will be needed to manage the incorporation of the beta-test suggestions and the adaptation of many of the methods and means unique to VDOT to those of PONTIS. Future research should provide support to the Department's Bridge and Maintenance Divisions as they works to satisfy the requirements set forth under ISTEA while providing Virginia with a cost-effective maintenance management system for its bridges.

The scope of this work will be driven by the needs that surface as the system is put into place. Typical areas of concern that will likely require the technical expertise available at The Research Council include the following:

1. *The identification of the MR&R alternatives for bridges in Virginia and the corresponding cost strategies necessary for their incorporation into PONTIS.* This would include a survey of the current MR&R activities implemented by VDOT and the development of strategies for tracking costs and converting them into units compatible with a network-level management system (specifically PONTIS).

2. *The evaluation of developing bridge inspection technology.* For example, the feasibility of bar coding, digital/video logging, and other multi-media recording and storage techniques should be included. This research may seek to build upon emerging technologies of PC-based multimedia, optical storage, and network computing to streamline the process of gathering and distributing structural inspection information. Finally, some attention may be directed to permanent instrumentation as a means to monitoring a structure's health (i.e. fiber optic strain gages).

3. *The investigation of the role of a bridge inventory and management system in a comprehensive geographic information system (GIS) for VDOT.* A significant effort will be necessary to coordinate the relevant database material of each of the management networks slated for incorporation into a state-side GIS. The most immediate benefits would include better access to information regarding structure location, classification, history, and current conditions. It is expected that much of this work will also incorporate the products of developing inspection technology, such as digital video and optical storage.

These subject areas represent a preliminary cross-section of concerns that will likely be investigated. The scope, however, should by no means be limited to these areas because many phases of the process have yet to mature much beyond the conceptual.

REFERENCES

1. Johnston, David W., Svendsen, Eric K. and Zia, Paul 1983. *An analysis of bridge inspection data—progress report on a level of service system for bridge evaluation.* Research Project 23241-050 Interim Report. Raleigh: North Carolina State University, Center for Transportation Engineering Studies.

2. McKeel, W.T., Jr., and Andrews, J.E. 1985. *Establishing the priority of funding for deficient bridges* (Unpublished VTRC Report). Charlottesville, VA: Virginia Transportation Research Council.

3. Busa, G., Cassella, M., Gazda, W., and Horn, R. 1985. *A national bridge deterioration model.* Report No. SS-42-U5-26. Cambridge, MA: U.S. Department of Transportation, Transportation Systems Center.

4. Busa, G., Ben-Akiva, M., and Buyukozturk, O. 1985. *Modeling concrete deck deterioration.* Cambridge, MA: Massachusetts Institute of Technology, Department of Civil Engineering.

5. Hyman, W., Hughes, D., and Dobson, T. 1983. *The least cost mix of bridge replacement and repair work on Wisconsin's state highways over time—a computer simulation.* Draft Technical Report. Madison, WI: Wisconsin Department of Transportation.

6. O'Connor, D.S., and Hyman, W.A. 1989. *Bridge management systems.* Report No. FHWA-DP-71-01R. Washington, D.C.: Federal Highway Administration, Demonstration Projects Division.

7. Hudson, S.W., R.F. Carmichael III, L.O. Moser and W.R. Hudson. 1987. *Bridge management systems.* NCHRP Report 300. Washington, D.C.: Transportation Research Board.

8. Golabi, Kamal, and Paul Thompson. 1991. *Pontis executive summary - a network optimization system for bridge improvements and maintenance.* Prepared for the Federal Highway Administration. Cambridge, MA: Cambridge Systematics and Optima, Inc.

9. *PONTIS beta test report.* 1992. California, Colorado, Florida, Iowa, Kansas, Michigan, Minnesota, Oregon, Tennessee, Vermont, Virginia, and Washington: Pontis beta test participants.

10. Federal Highway Administration. 1986. *The Pennsylvania bridge management system - executive summary.* FHWA/PA Report No. 85-045+84-28A. Washington, D.C.: U.S. Department of Transportation.

11. Glagola, D. M., and W. T. Scherer. 1992. *The development of a bridge performance prediction model as a rational basis for a structures management system.* Charlottesville: University of Virginia.