Impact of Environmental Classification on Steel Girder Bridge Elements Using Bridge Inspection Data

Daniel K. Dadson

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Dr. Jesus M. de la Garza, Co-Chair
Dr. Richard E. Weyers, Co-Chair
Dr. Klaus H. Hinkelmann
Dr. Richard M. Barker
Dr. Imad L. Al-Qadi
Mr. James Lefter

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(ABSTRACT)

State Departments of Transportation (DOT's) have established Bridge Management Systems (BMS) with procedures to aid in estimating service lives of bridge components and elements. Service life estimates, together with cost information, are used to develop life-cycle costs of bridges. These estimates are necessary to prioritize and optimize bridge improvement programs within budgetary constraints. Several factors, including age, traffic, and environment have been identified in current BMS literature as being directly responsible for the deterioration of bridge components or elements. However, no formal methodology exists to determine the effects of the environment. Estimating bridge elements service lives, without considering the effect of environmental factors, could potentially lead to biased estimates. A methodology is proposed using statistical analysis to determine the effects of environmental regions on service life estimates of steel girder bridge component (concrete deck) and element/protective system (girder paint) using bridge inspection field data collected by bridge inspectors. Further, existing deterioration models are incapable of using the non-numeric element level inspection data, which most state DOT's have been collecting for nearly thirty years per Federal Highway Administration guidelines. The data format used were the numerical condition appraisal scale (9 through 0) for concrete deck component, and the letter condition appraisal (G-F-P-C) for steel girder paint element. The methodology proposed an environmental classification system for use in BMS programs. In addition, least squares mean and corresponding standard errors and also means and corresponding standard deviations of service lives at the component and element/protective system levels were estimated. The steel girder paint estimated service lives can be used in scheduling maintenance, repair and rehabilitation operations, and also in life-cycle costs analysis at the project and network levels. Because of limitations in the concrete deck data sets, the estimated concrete deck service lives are not true estimates of their service lives but do reflect the influence of environmental exposure characteristics on their performance.

Dedication

This report is dedicated to the living memory of papa,
Emmanuel K. Dadson,
who instilled in me the importance of education and supported me in every way.

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Finally, views and opinions expressed in this report do not necessarily reflect those of the Virginia Department of Transportation (VDOT).

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Chapter 1: INTRODUCTION

1.1 Background

Bridges in the United States are monitored by the states with technical and financial support from the federal government. In 1967, the Silver Bridge between Point Pleasant, West Virginia, and Gallipolis, Ohio, collapsed during rush hour traffic resulting in the deaths of 46 people. The tragedy ushered in the federally mandated inspection programs. The Federal-Aid Highway Act of 1968 required the states to inventory, inspect, and report the condition of the bridges to the Federal Highway Administration (FHWA). The inventory database subsequently named National Bridge Inventory (NBI), contains inspection data on bridges over 20 feet in total length on public roads, forwarded at least once every two years. In 1994, the total number of bridges in the U.S. was estimated to be nearly 600,000 of which 40 percent were functionally obsolete and/or structurally deficient requiring over $90 billion to eliminate the deficiencies (Dunker and Rabbat 1995, Turner and Richardson 1994). Recent analysis of FHWA records found that as of August 31, 2000, 167,993 of 587,755 bridges (or 29 percent) of the nation's bridges remain functionally obsolete and/or structurally deficient (Associated Press, 2001). The current percentage is said to be a slight improvement from four years earlier when the percentage of functionally obsolete and/or structurally deficient bridges was estimated at 31 percent (Associated Press, 2001). For the state of Virginia as of August 2000, NBI records show that of the total 12,710 bridges, 1,237 (or 10 percent) were classified structurally deficient and 2,287 (or 18 percent) were classified functionally obsolete (*FHWA 2001*).

The need to have a comprehensive management system to identify deficiencies, prioritize and optimize bridge improvement programs within budgetary constraints has resulted in states developing management systems referred to as Bridge Management Systems (BMS), (Turner and Richardson 1994). The various sectors of a comprehensive BMS are discussed in Appendix A. BMS incorporates all the engineering and management functions that are necessary to carry out bridge operations. It also includes formal tools for coordinating these functions and analytical tools or models to help identify bridge needs and establish priorities. One essential input into evaluating and subsequently selecting and programming projects is life-cycle cost analysis. Life-cycle cost (LCC) analysis is defined as the economic evaluation of all current and future costs associated with investment alternatives (*NCHRP* 1995). Knowledge of bridge element service life or rate of deterioration is essential for determining element life-cycle profiles needed for life-cycle cost analysis.

Bridge life-cycle cost analysis (BLCCA) is an important technique that can assist transportation officials in making investment decisions affecting bridges and their users. Several legislative and regulatory requirements recognize the potential benefits of life-cycle cost analysis and call for consideration of such analyses for infrastructure investments, including investments in highway bridge programs (*NCHRP* 1995). However, a commonly accepted comprehensive methodology for BLCCA currently does not exist according to the same report. Further, according to Frangopol (1999), there is no accepted methodology for developing criteria for life-cycle cost design and analysis of new and old bridges.

Transportation officials are continually dealing with intricate decisions involving whether to perform maintenance, rehabilitation, replacement, or a combination amid budgetary, political and other resource constraints. In addition, officials have to consider short-term and long-term solutions and their interrelationships to achieve overall cost-effective solutions. Therefore, it is imperative that a methodology be developed to aid bridge management officials especially at the project level in selecting the most appropriate bridge improvement alternatives. One essential requirement in this endeavor is service life estimates, which are required for life-cycle profiles, and in combination with cost estimates, yield life-cycle costs.

Although, state departments of transportation (DOT's) have been collecting federally mandated bridge inspection data for about thirty years, a review of the research literature for the purpose of this research showed that a model capable of using the existing data at the state level to estimate service lives at the element level has not yet been developed (Hearn et al. 1996, Abed-Al-Rahim and Johnston 1995, and McGhee et al. 1989). Probability-based models for estimating element deterioration rates use recently developed and collected data based on the American Association of Highway and Transportation Officials (AASHTO) Commonly Recognized (CoRe) structural elements. "CoRe" data format is a detailed condition assessment of bridge elements for use in

BMS. However, these new data formats are not adequate during these initial stages to generate reliable deterioration rates. According to Small et al. (2000), only two states have element level data of the new format covering more than six years.

The current study provides a methodology for estimating bridge component and element service lives using bridge inspection data and also determines the impact of environmental regions on the estimated service lives. NBI data have been collected by all states since the early1970's and the portion of the NBI database covering the state of Virginia was used in this study.

1.2 Definitions

Bridge component, as used in this research study, refers to bridge deck, superstructure or substructure. Bridge element (or subcomponent) refers to the sub-units of the components of the bridge. A protective system is evaluated similar to an element. Service life of a bridge component or element is defined as the duration of time (years) between the component or element construction to the first year of its functioning below a minimum expected performance. The physical condition of a newly constructed bridge component or element is typically appraised with a number or letter on a scale corresponding to new construction and therefore does not require any maintenance. When the bridge component or element deteriorates through the years and reaches the end of its service life, its physical condition is typically appraised with a number or letter on a scale corresponding to a recommendation for major repairs, rehabilitation, or complete replacement.

Bridge component or element/protective system "condition appraisal code" is synonymous with "condition appraisal rating". Numeric condition appraisal code is from 9 through 0, i.e., best to worst. Non-numeric condition appraisal code is G- Good, F-Fair, P-Poor, and C-Critical.

A structurally deficient bridge is one that has been restricted to light loads only, is closed, or requires immediate rehabilitation to remain open. A functionally obsolete bridge is one in which the deck geometry, load-carrying capacity, clearance, or approach roadway alignment no longer meets the usual criteria for the system of which it is an integral part.

1.3 Objectives

One of the objectives of this research study was to develop a model for estimating existing bridge element service lives using statistical methods. The model had to be capable of using both component and element level bridge inspection data. Consequently, the model used the two basic condition data formats mandated by FHWA. Of significant interest was element level data, which the condition of the vast majority of bridge elements have been coded with. The model was evaluated using steel girder superstructure bridge data in which the concrete deck component or the paint protective system (uses element level data format) had deteriorated and received a condition rating code equivalent to end of service life, and therefore required either major repairs or rehabilitation.

The second objective of the research study was the analyses of the effects of environmental regions on the estimated mean service lives of the selected bridge elements. The Virginia State Climatology Office had identified six regions within the state as having different topography and climate, including snowfall, rain, temperature, relative humidity, and by deduction severity of freezing and thawing cycles. Consequently, the research study was designed to determine the effects of environmental regions on the mean service lives of bridge components, elements and protective system located within the environmental regions. After mean service life estimates were determined, environmental region pairwise comparisons were necessary to determine which pairs were statistically different or equal. The ranking of mean service life estimates in conjunction with pairwise comparisons of the regions provided a methodology for assigning environmental classification to the bridge components and elements. Environmental classification is a measure of the relative rate of deterioration of similar bridge elements in the different regions. In the absence of any formal methodology for assigning environmental classification to bridge elements based on field inspection records, a methodology for assigning the environmental classification for use in BMS was developed.

The objective of the research study was not to determine the precise point in time for certain levels of deterioration of elements to occur, which is an elusive estimate considering the variability involved in element deterioration rate due to the effect of the environment, traffic, and material composition of the element. Rather, the objective was to derive a statistical expected duration of time between when an element is installed or constructed to the end of its service life.

A developed methodology for the determination of bridge element service lives from bridge inspection records is applicable to most bridge elements inspected. An effective BMS requires reliable element service lives in order to develop accurate life-cycle profiles. Until recently, only non-numeric inspection data type (G-good, F-fair, P-poor, and C-critical) was used by bridge inspectors to code elements, which newly developed discrete models, notably those based on Markov chains, are incapable of using. Consequently, models that use NBI data primarily focus on the major components comprising deck, superstructure and substructure because of the discrete data format.

Knowledge of element age and service life estimate of that element provide a means for estimating the remaining service life needed to develop the life-cycle profile of the bridge element. Bridge element life-cycle profiles are developed by constructing end of element service life profiles which define the most likely sequence and timing of bridge maintenance, repair, or rehabilitation (MR&R). By applying costs of repairs or replacements to the life cycle profiles of the individual bridge elements and summing for all elements of the bridge, an estimate of the bridge life-cycle cost is obtained.

Information based on the sequencing, timing, and level of MR&R performed was not used to derive the mean service lives since the MR&R may not have been done exactly at the time they were needed usually due to resource constraints especially funding. Actual field inspection reports of bridge element conditions are better predictors of element behavior than data from the type, timing and sequencing of MR&R operations, and therefore used in the current study.

1.4 Benefits

By developing service lives for bridge elements, the sequencing and type of maintenance or repair operations by agencies will simply be to review the service lives of the bridge elements, compare with age, and aggregate the needed operations. This will aid project level scheduling operations and ensure that the required manpower is allocated according to predetermined schedules. State bridge agencies will be able to evaluate the performance of similar bridge elements in different parts of the state. The comparison of service lives of similar bridge elements in different regions of the state provides valuable information that may be used to answer questions about the need to review structural designs, construction methods or even local practices that impact bridge component and element service lives. The answers could potentially lead to different design and construction specifications for different regions to replace the current uniform specifications.

By combining unit costs for bridge elements repair with the maintenance and repair schedules, life-cycle cost profiles can be developed. The aggregate costs for maintenance and repair for bridges obtained from the LCC profiles will provide decision-makers at the network level with critical information necessary for making sound investment decisions during budget allocations.

The estimated service lives are applicable for use in life-cycle cost programs such as BridgeLCC ("BridgeLCC" 1999). BridgeLCC is a BLCCA computer program developed by National Institute of Standards and Technology (NIST). BridgeLCC is ideally setup to benefit from the results of this research study. In the program, each individual element requires an input of the recurrent service life over the project duration. The developed model can be used to provide the required element service life input into BridgeLCC to obtain the life-cycle cost of a bridge.

The results of the environmental classification are applicable as input into BMS programs such as Pontis (Thompson and Shepard 1994) and BRIDGIT (Lipkus 1994). Both BMS programs assign different rates of deterioration of elements based on the agency providing an environmental classification for the elements in the region.

1.5 Scope and Limitations of the Research

The research study was based on steel girder superstructure bridges with concrete decks and girder paint that were routinely inspected. All the bridges were simply-supported. The concrete decks had concrete wearing surfaces with approximately two inches of cover. Further, the decks had non-epoxy bars and no membrane protection. The bridge selection period, based on year-built for the selected bridges, was from 1960 through 1979. However, the extent of data collected was based on availability. NBI and VDOT data were used in the study.

The focus of this research study was statistical estimation of the mean service lives of a selected component and element/protective system of steel girder superstructure bridges built over a twenty year period and the impact of environmental regions on the estimated mean service lives. Any conclusions drawn from the current study may not be applicable to bridges built before 1960 and also bridges built after 1979 due to changes in the governing design and construction specifications in the different periods. However, the methodology developed is applicable to any period with uniform design and construction specifications. Also, the estimated service lives may not be applicable to continuous span steel girder superstructure bridges built during the same time period as the bridges used in the study. Studies have shown that continuous span steel girder bridges tend to have different deterioration rates from simple span bridges ("Bridge Management" 1987, Scherer and Glagola 1994).

VDOT bridge inspection condition data on steel girder paint does not distinguish between the exterior girder paint condition and the interior girder paint condition. The assigned condition rating is for the entire superstructure girders' paint condition. Hence, the estimated steel girder paint service lives in the current study, which was based on the paint inspection data, was for the entire superstructure girders. However, a study on steel girders performed by Estes and Frangopol (1999), demonstrated that there are differences in the corrosion deterioration rates between the exterior and interior girders which could impact the paint condition. VDOT bridge inspectors recommend painting the entire bridge superstructure girders when the paint deteriorates to the end of its service life, which is an indication that the paint on both the interior and the exterior girders has reached the end of its service life.

The model developed in the study is not applicable to bridge components or elements without identifiable end of service lives. Such components and elements would include wingwalls and abutments that typically are capable of being in service throughout the existence of the bridge, without requiring major repair or replacement.

The lack of comprehensive bridge inspection data covering the concrete decks used in the study from the year-built to the end of their service lives limited the applicability of the estimated concrete deck service lives. Extrapolation was used to determine if any major repairs had been performed on the decks during the earlier years without data and some bridges were subsequently excluded from the final analyses. If any of the bridges that were excluded did not have any major repairs or rehabilitation of their decks as assumed, then potentially a bias was introduced in the data sorting. However, the number of such bridges were small compared with the overall concrete deck data size used in the study and the impact of the elimination was expected to be limited. The consistency of the elimination of the questionable bridges in the concrete deck analyses ensured that the environmental regions analyses were not impacted.

Bridge inspection data used in the study were collected by trained bridge inspectors who inspected the bridges and based on their judgment assigned numerical or letter appraisal codes to classify the existing physical conditions of the bridge elements and components. Hence, there is some subjectivity in the data collected. However, the subjectivity is minimized when the inspectors are trained to be cognizant of the implications of their judgment and ratings are applied in a consistent manner. VDOT recognizes this drawback and has a program to periodically train inspectors and sometimes invites FHWA personnel to evaluate the quality of its bridge inspectors (Coleman 2000).

Construction methods used by the different bridge contractors in the state of Virginia impacts the service lives of bridge components and elements. Although, VDOT provides contractors with construction standards and specifications which should translate into uniform bridge construction methods across the state, that is not the case. The lack of a formal methodology for documenting the impact of construction methods on bridge components and elements makes it harder to account for their effects. Considering the resources available to VDOT, it is reasonable to assume that such variations in construction methods will be taken seriously and carefully controlled if identified.

1.6 Contributions to the Body of Knowledge

The research study outlined a methodology with the capability to use existing element level data collected by all state DOT's for nearly thirty years under guidelines from the FHWA. The element level data are non-numeric and use letters to record condition appraisal ratings. Currently developed models, based on probability, are incapable of using the existing non-numeric element level data. The existing models have been developed to use component level data that are numeric. Data to support these new models at the element level are presently being collected. In addition, the models have not been tested and evaluated for their level of accuracy and effectiveness at this time.

The study converted bridge component level data, e.g., concrete deck, to element level data by identifying the component's constituent elements. By identifying the specific elements of a bridge component, a single service life estimate can be assigned to that component. This is in contrast to analyzing a bridge component such as concrete deck without identifying its material composition beyond the initial concrete identification. Estimating the service life of a bridge component without identifying its material composition would yield an average service life of the constituent elements. The constituent elements of a component also have different service lives. The study provided service life estimates of a bridge component (concrete deck converted to an element) and element/protective system (girder paint) for use in various aspects of a BMS such as scheduling MR&R operations.

The study also developed a methodology for determining the impact of previously established environmental regions of the state of Virginia on the service lives of the concrete decks and steel girder paint. Further, the study provided a methodology for classifying the regions in terms of benign, low, moderate or severe effect on the service lives of the bridge components and elements. This classification is a required input into Pontis and BRIDGIT BMS softwares.

Figure 1.1 shows the contributions of this research study to the broader framework of a BMS.

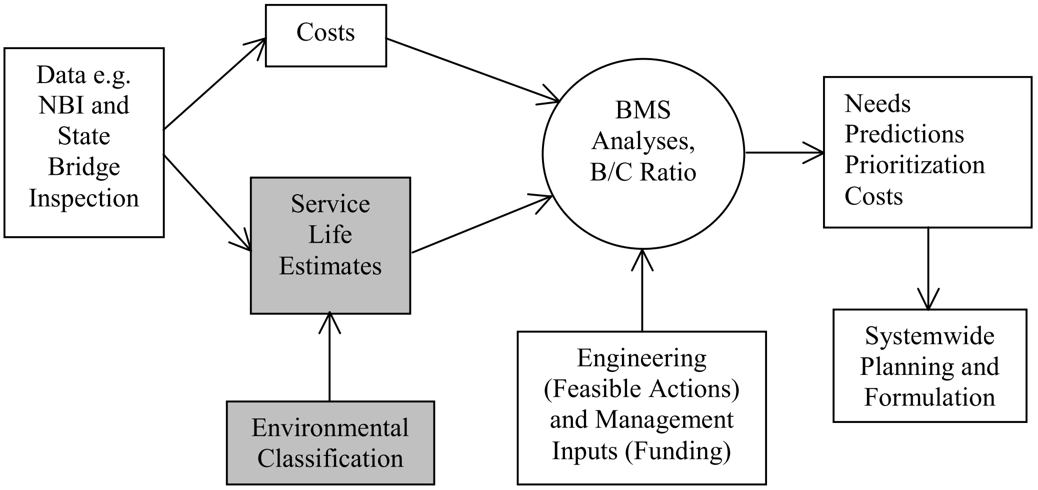


Figure 1.1: Components of a BMS

Note: Shaded boxes show contributions of the current study to the broader framework of a BMS.

1.7 Level of Bridge Management Systems -VDOT

According to Coleman (2000), a senior bridge personnel at VDOT, VDOT has always maintained a BMS program. The use of Pontis software and its data collection started in 1995. However, the use of Pontis is limited to collection of element condition data and NBI general condition ratings. Currently, no management decisions are based directly on recommendations from Pontis. On a scale of 1 to 10, with 1 being not at all and 10 being only software used, Pontis is ranked 3 according to Coleman (2000).

The main issues limiting VDOT in the use of a fully effective BMS are the limitations of the general condition ratings, the lack of long-term deterioration modeling by a computer program, and life-cycle cost analysis programs, according to the VDOT personnel. In spite of these shortcomings, VDOT is fully committed to maintaining a BMS program.

1.8 Summary

Service life estimates for the various components and elements of bridges in the inventory of any DOT are essential for providing quantitative estimates of the length of time the elements and components are performing at an acceptable level of service. Lack of service life estimates hampers the bridge agency's ability to determine elements or components that are underperforming due to high deterioration rates and to take subsequent corrective actions such as design, material or construction changes. All state DOT's have thousands of bridges to manage, and therefore it becomes imperative that service life estimates be made available for informed decisions on MR&R operations. An additional important information is the agency's ability to determine the effects of the various regions under its jurisdiction on the service lives of bridge elements and components. Different regions in the state may have different effects on the service lives of similar bridge elements. The present study develops a methodology for estimating service life at the component and element levels and determines the impact of the environment on the estimated service lives.

Chapter 2: LITERATURE REVIEW

2.1 Introduction

Literature review for the research study started with the review of the recommendations for establishing a BMS by FHWA and AASHTO. It progressed with the review of published articles in engineering journals and books relating to bridge element service life and deterioration rate estimation. Interviews were also conducted via telephone, emails and face-to-face with bridge engineers and others knowledgeable in this field including VDOT engineers, FHWA personnel, and senior engineers from consulting companies. These contacts were excellent sources of unpublished experiences which enhanced the quality of this study. References used have been quoted and referenced throughout this report.

2.2 Current Research

Currently, all states have a BMS and are increasingly collecting data including cost information as required by FHWA under the Intermodal Surface Transportation Efficiency Act of 1991 (ISTEA), (Turner and Richardson 1994). BMS relies on condition ratings assigned during field inspections as indicators of the needs, the actions, and the quantities of repairs (Hearn et al. 1996). For these management systems, condition ratings are linked to repair actions. Interpretation of these condition ratings is essential for scheduling MR&R operations. Bridge condition ratings collected during biennial inspections provide essential information required by state DOT's regarding the health of their bridge inventory. Of all the information derived from condition ratings, the most important are the service life estimates or deterioration rates of the elements or components. Currently, several methods have been proposed to aid in the determination of the deterioration rates including regression analysis, analytical methods, and probabilistic methods.

The two nationally known BMS computer programs are Pontis and BRIDGIT. A number of the states are trying Pontis (Thompson and Shepard 1994) and BRIDGIT (Lipkus 1994). According to Roberts and Shepard (2000), as of the year 2000, there were 40 states using Pontis. Pontis is a network-level BMS software with features for the optimization of budgets and programs for the maintenance and improvement of each state's inventory of bridge structures. It was developed under FHWA with input from AASHTO. It performs life-cycle cost analysis at both the element and component levels. However, it requires an entirely new set of bridge inspection data format currently in the rudimentary stages. Thus, bridge inspection records in the NBI cannot be used directly by Pontis. A number of states, including Virginia, that are experimenting with Pontis, collect bridge data both for the NBI and Pontis. Collecting bridge element data for use with Pontis requires a little more effort than collecting data for the NBI (Thompson and Shepard 1994). Consequently, AASHTO has endorsed the "CoRe" group of structural elements as a means of providing a uniform basis for translation of data between a state's BMS and NBI data (Recording and Coding Guide, 1995). This is intended to encourage state DOT's to adopt the "CoRe" elements in their BMS and also allow the states to meet the FHWA requirements of forwarding their bridge inspection data for inclusion in the NBI. To this end, the FHWA has provided bridge agencies with a computer program for translating bridge condition data in the "CoRe" element format to NBI condition ratings for the purpose of NBI data submittal to FHWA ("Recording and Coding Guide" 1995). Incidentally, there are only two states that have collected element level data suitable for Pontis covering more than six years (Small et al. 2000).

BRIDGIT is also a BMS software with modules to perform optimization and prioritization of bridge improvement needs. It was developed under the National Cooperative Highway Research Program (NCHRP) to meet state and local bridge agency needs. BRIDGIT also performs analysis at the element level, using the same type of condition rating system as Pontis. Elements used by Pontis can also be identified in BRIDGIT through a combination of basic elements, paint protection systems and overlays embedded in the BRIDGIT program.

The basic philosophical difference between Pontis and BRIDGIT is that Pontis uses a top down approach while BRIDGIT uses a bottom up approach (Small et al. 2000). For Pontis, budgets and standards are used to develop optimal policies, which are then used to plan projects. The models are refined through feedback. What-if analysis is performed by modifying budgets and standards. On the other hand, BRIDGIT uses standards to assist in planning projects. Planned projects are totaled to generate costs which are then compared to budgets. The budgets are then used to adjust standards and modify plans.

Abed-Al-Rahim and Johnston (1995) developed an analytical method for estimating deterioration rates of the three major bridge components (deck, superstructure, and substructure) as a function of material type and various environmental factors in the state of North Carolina. The methodology used bridge inspection data and computed the average change in condition rating from a selected year to the following year, for a selected group of bridges. By multiplying the change in condition rating by the corresponding number of bridges, summing over the different rate change groups and dividing by the total number of bridges involved, the average change in condition rating for one year was computed. The time it took for the bridges to decrease by one condition rating point was the inverse of the average change. The equation was modified for multiple 1-year intervals. The equation was applied at each value of condition rating, and then the slopes for the linear segments connecting successive condition ratings were calculated. By plotting the various linear segments for the various condition ratings end-to end, a deterioration curve for the relationship between the condition rating and time was obtained.

The final form of the equation was as shown:

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

where:

$AVGCHN_r$ = average change from condition rating r within the 1-year period selected (t, t+1)

m = maximum number of points the bridge element can decrease from r

$n(r,t,j)$ = number of bridges changing by j points from condition rating r for year t

$j = r_t$ – (element condition rating of the same bridge in the following year)

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

Environmental factor considered was salt-use, which was linked to Federal-Aid bridges in certain regions where ice and snow were more frequent according to North Carolina DOT engineers. All other bridges were classified non-salt bridges. Average Daily Traffic (ADT) was initially considered in six separate groups but due to data limitations and unreasonable patterns, the groups were reduced to two. These were interstate, principal arterial, minor arterial, and major collector as one group and then minor collector and local in the other group. Types of bridge deck material considered included reinforced concrete, precast, timber and steel plank.

Results showed accelerated deterioration rates in salt regions especially for precast concrete decks followed by reinforced concrete decks. Salt effect on steel (asphalt-filled steel pan) deck was very small relative to precast and reinforced concrete decks. Bridge decks on minor collector and local routes had slower deterioration rates. For superstructure analysis, prestressed and reinforced concrete in the salt region had faster deterioration rates while steel and timber superstructures were non-significant. Also, bridges in coastal counties and over waterway were grouped as marine environment and those that were not, classified as non-marine. Superstructure deterioration was faster in marine environment.

In the Abed-Al-Rahim and Johnston (1995) study, the climate of the state of North Carolina was not considered directly in obtaining the environmental regions but rather the environmental regions were assigned according to the locations of Federal-Aid bridges. Consequently, salt-use, which was considered an environmental factor, was limited to Federal-Aid bridges. The locations of the Federal-Aid bridges may not have been determined with considerations given to climatic factors. Bridges in coastal counties were considered as one class and bridges in the interior over waterway were also added to this group. However, the effect of the ocean on bridge components may be quite different even though a bridge may be over water in the interior. Service lives of bridge components were not estimated in the study. However, the deterioration rates that were estimated in the study were measures of service lives. The relationship between deterioration rate and service life is shown in Figure 2.1 assuming a linear relationship. Deterioration rate is measured as the change in condition rating per year, which may not be constant. In contrast, service life is measured as the period of time (years) from the construction of the bridge component to the year the component reaches the end of its service life. Service life estimate is a more applicable quantity than deterioration rate especially when deterioration rates is non-linear. Unless the deterioration rate is determined for the entire service life, it usually cannot be extrapolated to obtain service life.

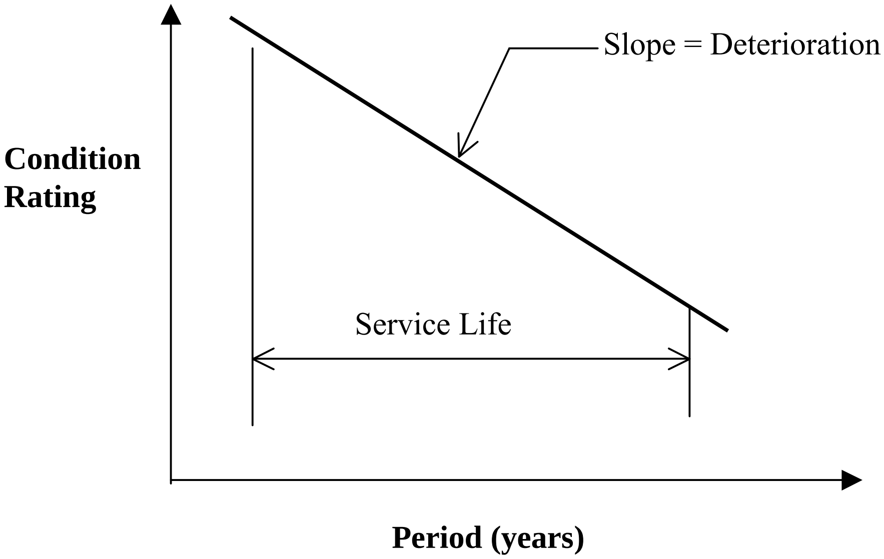


Figure 2.1: Relationship Between Deterioration Rate and Service Life

Abed-Al-Rahim and Johnston (1995) study used an analytical method quite different from statistical analytical methods that employs least squares in estimating the mean service lives of bridge components or elements. Bridge elements or protective systems with condition rating format G-F-P-C, which account for most of the element condition ratings, were not considered.

A number of studies have also been conducted regarding bridge deterioration. Busa et al. (1985) employed linear regression to relate bridge condition ratings to age, traffic volume, structure type and others. Jiang and Sinha (1987) used Markov chains to model bridge deterioration as a function of age. West et al. (1989) developed a nonlinear deterioration model that expressed condition rating as a function of age using an exponential decay function. One shortcoming of these models according to OECD (1992) is that, they all lump bridge elements into the three major categories (deck, superstructure and substructure) which lack the necessary details to support a maintenance management program. Each major component such as bridge deck needs to be identified in terms of its elements that exhibit distinct and different deterioration patterns. This may be accomplished by identifying the different material compositions, life expectancies and rates of deterioration under different environmental conditions. The methodology employed in this current study used bridge deck data similar to the studies discussed above. However, the current study can be distinguished from the other studies above for its initial identification of the material composition of the concrete deck and its protective system before the performance of any analysis. The initial identification was necessary for the selection of a specific type of deck material and its protective system which ultimately resulted in a single estimated service life applicable to that specific deck group. Failing to perform the initial identification of the bridge component or element potentially results in the analysis of a bridge component with different material compositions, strengths, and protective systems which may have different service lives (OECD 1992). The collection of concrete deck component data through identification of the material composition and protective system reduces the bridge component to an element status because a specific service life can be associated with that component.

Hearn et al. (1996), in a discussion of data interpretation in BMS, stated that for deterioration models that use condition ratings, age is the single dominant variable. Secondary variables include traffic level and service environment, with separate models established for separate environments. The condition ratings used by Hearn et al. (1996) were the numeric condition rating (9-0) assigned to the major components. Data format G-F-P-C, which most element conditions are rated by, was not discussed. In contrast, the research study in this report considered age, traffic and environment in developing the methodology. In addition, the research study in this report used the two basic forms of coding the conditions of bridge elements and components, i.e., G-F-P-C and 9-0, respectively. The main focus of Hearn et al. (1996), however, was the development of condition coding to account for damage in bridge elements by using the AASHTO “CoRe” elements. Hearn et al. (1996) suggested that damage to bridge elements can be measured using NDE methods such as linear polarization which is used for corrosion current. In addition, condition coding can be assigned according to quantity of element that is damaged which is then correlated to the amount of current flowing.

Hyman and Hughes (1982) developed a computer model for life-cycle cost analysis for bridge repair and replacement needs for the state of Wisconsin. This was one of the earliest models that recognized the importance of life-cycle cost analysis in BMS. In their model, life-cycle activity profiles of bridge repair and replacement were obtained based on the judgment of bridge maintenance and construction engineers regarding past and future bridge maintenance trends and practices. Additional data was obtained from the bridge section (WisDOT) computer data file, which contained information on the construction year of bridges and high-type repair work (e.g. concrete overlays and new decks), and from bridge maintenance records. Hyman and Hughes (1982) then identified the sequence of repair work on each state-owned bridge. Using rough random samples (>100 bridges) for each combination of repair and bridge type, samples were taken to determine the frequency, timing and costs of repairs. Piecewise linear regression analysis was then employed to forecast future conditions. Limitation of this model lies in the apparent lumping of a considerable number of bridge elements into major categories such as superstructure and substructure. Again, this lumping results in a lack of detail necessary to support maintenance and repair management programs (OECD 1992). Each major category consisted of several elements which were themselves maintenance entities. These bridge elements differed significantly in material composition, life expectancy, and rates of deterioration. Therefore, lumping them together may not provide the necessary information on their conditions, repair, and maintenance requirements. In addition, the data used for the regression analysis was based on responses from interviews with bridge engineers and actual maintenance schedules rather than field condition rating of bridge elements. With agencies responsible for monitoring and inspecting thousands of bridges, responses from bridge engineers may not be able to capture the actual history and behavior of the bridge elements without a formal investigation. Also, maintenance and repair schedules do not necessarily occur exactly when they were needed typically due to lack of funding. Consequently, maintenance and repair schedules may not be reliable predictors of bridge element deterioration profiles, especially in areas that continually defer MR&R activities. Finally, the possible effect of the environment was not accounted for.

McGhee et al. (1993) investigated bridge component deterioration due to age, traffic, and exposure to deicing salts. The research was sponsored by VDOT and the objective was to develop performance and deterioration curves for Maintenance Management Systems (MMS). They used regression and lines of best fit to show the relationship between the deck, superstructure and substructure deterioration rates. The research lumped bridge elements that exhibited different deterioration rates under the major components, and then developed curves for the deck, superstructure and substructure deterioration. This approach, as well as those discussed above, do not capture the true deterioration of the different bridge elements but rather provide average values for the three main components of the bridge, which may not present a true picture. In addition, the three geographic regions of the state used in the report may be inadequate to capture the true effects of the environmental regions of the state. In contrast, the present research study used six environment regions. Regions used in McGhee et al. (1993) study were assigned according to the nine VDOT districts with entire districts located inside the regions. However, the climatic regions of the state of Virginia developed by the State Climatology Office, based on decades of climatic records, do not follow VDOT district borders. For example, sections of VDOT Salem district are located in the Southwestern, Western Piedmont and Central Mountain regions. Also, a larger section of VDOT Richmond district is located in the Eastern Piedmont region but a significant section is located in the Tidewater region. Further discussion of environmental regions and VDOT districts maps can be found in Section 3.3 entitled “Methodology”. Consequently, McGhee et al. (1993) study may have grouped together some bridge data that were essentially in different environmental regions and possibly had different service lives or deterioration rates.

Wells (1994) developed a methodology for assigning concrete bridge decks to one of four environments used in Pontis. The four environments were benign, low moderate and severe. The study recognized the potential differences in deterioration rates of bridge elements due to differences in climatic exposure and operating practices such as ADT and annual chloride application. Survey questionnaires were sent to bridge engineers in the nine VDOT districts to elicit their expert judgment on what level combinations of three variables they would consider slow, medium slow, medium rapid, and rapid deterioration. The three variables were Average Daily Truck Traffic (ADTT), annual freeze/thaw (F/T) cycles, and annual chloride applications. The range of values used for ADTT was 0-800, F/T was 0-60, and annual chloride application was 0-75. The survey questionnaires showed different levels of the three variables and based on that the respondent was required to specify whether in their opinion they would classify that specific combination slow, medium slow, medium rapid, or rapid deterioration. Each survey questionnaire had 27 graphs to cover every possible combination of high, medium, and low range of each of the three variables.

In the Wells (1994) study, one person responded from Culpeper, Fredericksburg, Northern Virginia, Richmond, Salem, Staunton, Hampton Roads (formerly Suffolk) and the central office districts of VDOT. Three responses were received from the Lynchburg district. The data collected was used in a knowledge-based approach involving classification trees and multiple regression. The knowledge-based approach uses rules that are developed from training data to classify future data. A set of descriptive characteristics then maps directly to one of the four environmental classes. Classification and Regression Trees (CART) software package was used in the data analyses. The second approach used statistical analysis, which involved fitting a function to the data to produce a function that characterizes future data. In this approach the four environments were treated as numerical values. By specifying applicable ranges, the values are massaged to depict the four environmental classes. Multiple regression was used to determine the intercept and coefficients of the variables, ADTT, F/T, and chloride application. The value obtained in the multiple regression analysis was rounded off to the nearest integer, which corresponded to the four environments benign, low, moderate, and severe.

In the Wells (1994) study, the data was not divided into training and testing sets, the approach typically used in expert systems. Actual bridge inspection data was not used in the data analysis. Climatic factors and topographical features of the state of Virginia were not considered in the study. The environmental assignments were subjective opinions of experts. The experts may have had different frames of reference, experience and exposure. In addition, the number of survey respondents was limited.

Research performed by Purdue University for Indiana Department of Transportation (Kleywegt and Sinha 1994) outlined methods of BMS data analyses including prediction tools. This paper identified regression analysis, Markov chains and Bayesian estimates as the three main tools for making bridge component deterioration predictions. Markov chains and Bayesian estimates are probability based analyses suitable for network analysis. Current literature on the application of Markov chains in bridge element deterioration prediction include DeStefano and Grivas 1998, Scherer and Glagola 1994, Madanat and Ibrahim 1995, and Madanat et al. 1995. Pontis and BRIDGIT employ Markov chains in predicting bridge element deterioration. However, Chase (1995), in a discussion about research needs for BMS, stated that although stochastic methods such as Markov chains are adequate for network level predictions, deterministic models are needed for project level analysis. The present research study used statistical analysis to determine element service lives suitable for project and network level analysis.

Estes and Frangopol (1999) proposed using a systems approach to life-cycle cost analysis of bridges. Reliability, as used in the paper, was a measure of how consistently a bridge system will perform based on a set level of performance or goal. The paper identified the relevant failure modes of a bridge, selected random variables from a list of design variables and then estimated their mean and standard deviation. Limit state equations in terms of the random variables were developed for each failure mode. The reliability for each failure mode was computed. The system reliability of the bridge was then computed using a combination of the individual failure modes. The system reliability was again computed for the effect of live loads and deterioration. In this system, whenever the system reliability falls below a specified value, repair or replacement would be triggered. Two separate environments were used for the interior and exterior girders which was a recognition of the impact of the environment on the deterioration rates of bridge elements. Non-Destructive Evaluation (NDE) methods were used to collect the data. Unfortunately, the data used in the report is currently unavailable at most DOT’s. The deterioration models used were regression analysis which were based on data collected on corrosion of the concrete deck and girders.

Other deterministic models of note include a methods application manual by Weyers et al. (1993), which provided information on the mechanism of chloride-ion-induced corrosion of concrete decks. Chloride-ion-induced corrosion was said to be responsible for nearly 40% of the current backlog in bridge MR&R. They provided a model to estimate the service lives of new and old concrete decks.

Roberts and Shepard (2000) discussed the methodology for a new performance measure known as the health index (HI) used in California which measures the structural condition of a bridge by using quantitative condition data collected as part of the bridge inspection data. Weighting factors are assigned to each of the condition states of an element based on the AASHTO "CoRe" system. By using the fractions of an element in various states, multiplied by their corresponding weighting factors and unit failure costs, dividing the result by the product of the original element size and unit failure cost, a health index fraction or percentage is obtained. The health index can be considered a measure of the remaining asset value of the bridge element. This is one of the current methods being used to assess the condition of the nation's highway bridges.

2.3 Summary

A review of the BMS literature indicated an exclusive concentration on discrete probability methods using Markov chains to determine element deterioration rates and service lives. However, as noted above, data to support these new models are just recently being collected by newly trained bridge inspectors. It would not be known for some time how effective these new models are, or whether they are even applicable at the project level. Meanwhile, non-numeric element data have been collected for over thirty years under guidance from the FHWA. There is a general consensus about the inadequacy of the original numeric condition rating system provided by FHWA (Hachem et al. 1991, Abed-Al-Rahim and Johnston 1995, Atkan et al. 1996, and Roberts and Shepard 2000). This lack of detail prompted AASHTO to endorse the "CoRe" system of identifying bridge elements which a number of BMS programs have adopted including Pontis and BRIDGIT.

There is substantial bridge data in the NBI and at state DOT's. An appropriate use of these existing condition data should be based on the field assigned condition rating codes and guidelines identifying the end of the component or element service life. When a bridge component or element is new, there is little subjectivity in the condition rating code assuming uniform construction standards by the bridge agency. Subsequent condition rating codes can be subjective. However, when the end of service life is interpreted from bridge inspectors' field notes as recommendations for major repair or rehabilitation, the subjectivity of the condition rating code is minimized. The reduction in the subjectivity of the condition rating data used in the current study was achieved by limiting the data used to new elements and when the elements deteriorated to their end of service lives. Current regression-based models (e.g. McGhee et al. 1989) and probability-based models (e.g. Scherer and Glagola 1994) use condition rating data taken throughout the service life of the bridge component or element, thereby increasing the subjectivity of the data used. There is the need for models that can utilize existing data to generate service lives necessary for MR&R activities. As other models that rely on currently unavailable element data formats are developed, models that use existing data would provide a basis to test the reliability and accuracy of the other new models. The model in this study utilized existing bridge inspection data which state DOT's are still required to collect and send to FHWA for inclusion in the NBI.

Chapter 3: RESEARCH PLAN

3.1 Introduction

The research study used bridge concrete deck and steel girder paint inspection data collected since the inception of the NBI to determine the impact of environmental regions on the service lives of the bridge elements. The study provided a methodology for estimating service life at the bridge element/protective system level (paint) and also at the major component level (deck). Service life estimate is also a measure of the rate of deterioration, since a low service life is a reflection of a high deterioration rate and a high service life is a measure of low deterioration rate. Currently, most deterioration rate estimates are based on inspection data on the three major components namely deck, superstructure, and substructure using the discrete numerical rating format (9-0). As previously discussed in Chapter 2 entitled “Literature Review”, such estimates are inadequate to support management operations. The study used existing data at the component and element level. The deck data at the component level were collected after identifying the material composition, the type of protective system, and type of wearing surface.

Newly developed BMS systems employ new element recording systems which collect significantly more element information to support newly developed probabilistic deterioration models. Until such time that adequate element data has been collected to support these new models, critical element information will be unavailable. However, there is adequate element data recorded by state DOT’s in a non-numeric format (G-good, F-fair, P-poor, and C-critical) and also in numeric format (9-0). Then, using statistical analysis, the model estimated element service lives. As the newly developed probabilistic models gather adequate data and provide element service life estimates, the service lives from the model developed from this study can be used for comparisons.

The study employed Analysis of Variance (ANOVA), a statistical analysis procedure, to test for the effect of environmental regions of the state on estimated mean service lives of bridge elements selected for the study. The environmental regions were based on climatic regions established by the Virginia State Climatology Office. The bridge selection period for the study was established to ensure consistent design, construction and maintenance practices. A detailed discussion of the selection period is covered in the next section entitled “Bridge Selection Period”. Comparisons between regions were also performed to make inferences about the equality or non-equality of mean service lives of similar bridge elements in different environmental regions of the state. Finally, the comparisons yielded statistically-based results significantly different from the analysis performed by Wells (1994), which was based entirely on responses of interviews with bridge engineers in the state of Virginia, and not on actual bridge data collected in the field.

3.2 Bridge Selection Period

3.2.1 Introduction

Changes in VDOT design and construction specifications for bridges are presented below. As was discussed under “Literature Review”, material composition of a bridge component or element is a significant determinant in the service life or deterioration rate of that component or element. To ensure consistent material compositions of selected bridges within selected periods, VDOT design and construction specifications changes were used as guidance for establishing the divisions within the analysis period for this research.

3.2.2 VDOT Specification Changes

Concrete Strength

Until 1962, concrete 28-day strength (f’c) used in concrete decks was 3,000 psi with 4%+/- 2% air content and a maximum water cement ratio of 5.5 gallons per sack of cement (0.49 by mass) with a minimum of 6.25 sacks of concrete (588) per cubic yard.

In 1962, the specification was changed to 4000 psi concrete with 6.5 % air +/- 1.5%, and a maximum water cement ratio of 5.25 gallons per sack of cement (0.47), with a cement content of 6.75 bags per cubic yard (635 pounds).

In 1982, 4,500 psi concrete was specified with the same cement content but a lower w/c of 0.45.

In 1988, the strength was changed back to 4,000 psi with 635 pounds of cement per cubic yard and 6.5 % air and a maximum 0.45 w/c.

Clear Cover to concrete

The clear concrete cover to reinforcement in bridge decks changed from a minimum of 2 inch to 2 ½ inch in December 1975.

Epoxy Coated Reinforcing Steel

Epoxy coated reinforcing steel (ECR) was included in concrete decks as top bars only in 1976 and then later as top and bottom bars.

Girder Paint

Until 1981, lead-based oil/alkyd paint system was used. By 1985, it had been eliminated and primarily inorganic zinc-based paint was used and is presently in use.

The time-line for the specification changes and year-built for bridges used in the study is shown in Figure 3.1. In discussions with VDOT personnel, Volgyi (2000) and Steele (2000), they emphasized that the dates shown in Figure 3.1 were dates when the proposed changes appeared in the specifications book. Typically, VDOT proposes changes through special provisions that are issued a few years prior to the next edition of the VDOT specifications book Even when specification are issued, some projects that were let soon after the issue date may or may not implement the various changes in the specifications.

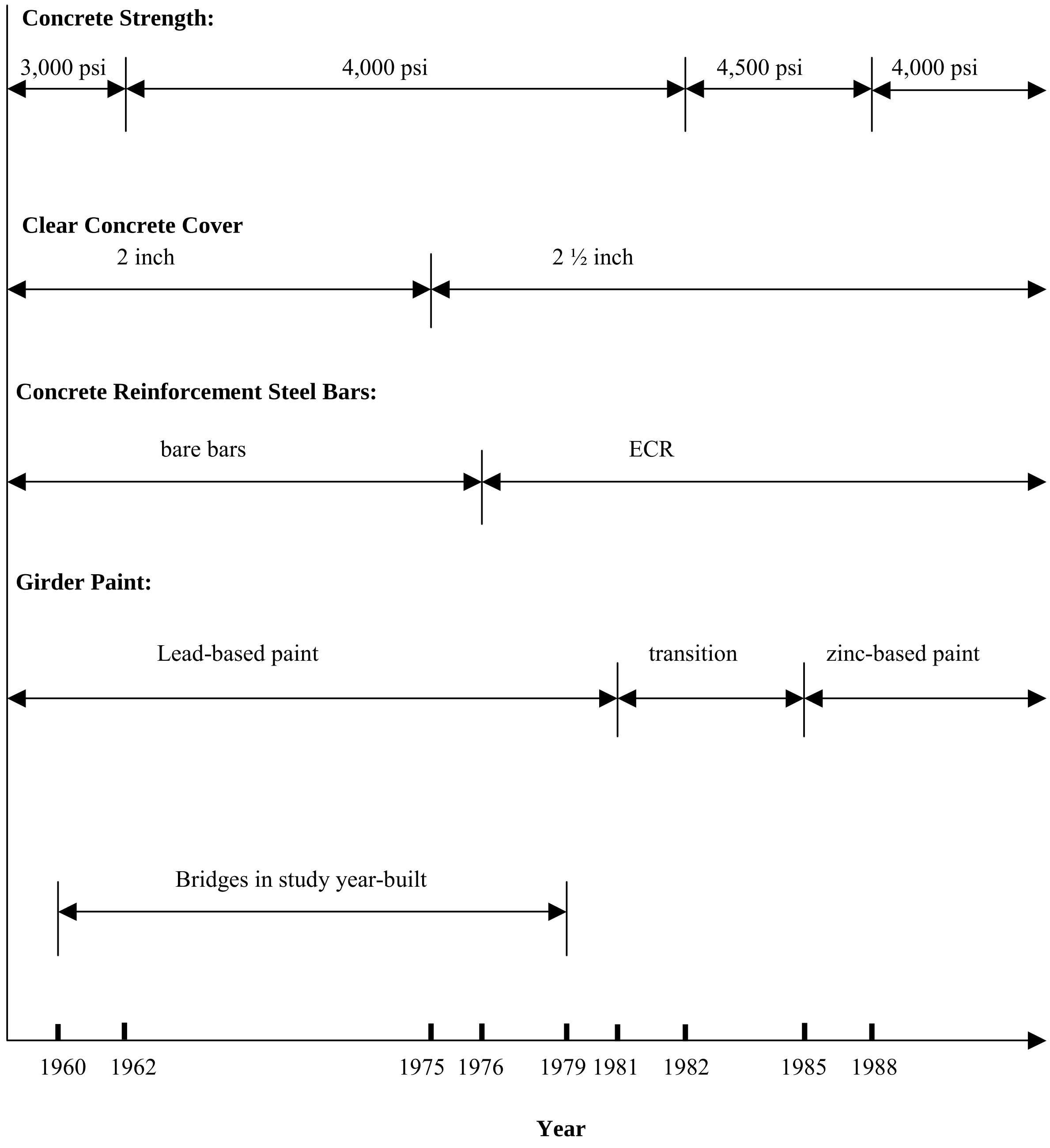


Figure 3.1: Time-Line for VDOT Specification Changes

3.2.3 Selection of Bridges

The initial bridge year-built selection periods were 1959 and earlier, 1960-1979, and 1980-2001. Subsequent data sorting and review limited a viable selection period to bridges built from 1960 through 1979. The selected bridge year-built period was prior to the change in paint type from lead-based to zinc-based in 1981. However, the vast majority of the data on girder paint used in the study was after the health hazards of lead paint was discovered. Incidentally, lead-based paint on bridge girders were subsequently removed and replaced with zinc-based paint from 1981 through 1985 (Sprissler 2000). VDOT bridge inspection records do not specify the type of paint on the girder but only the year the paint was first applied and the current paint condition. Therefore the research study assumed that all paint data collected after 1985 were zinc-based and classified all girder paint in the study as zinc-based.

The compressive strength of the deck concrete prior to 1962 was 3,000 psi and after that was 4,000 psi until 1982. The strength of concrete during the selection period 1960-1979 was assumed to be 4,000 psi with water-cement ratio of 0.47 based on the prevailing strength used by VDOT. There was a change in concrete cover in 1975. A review of the bridge data for the study showed that the majority were built before 1975 and based on the delayed implementation noted by some VDOT personnel, it would be reasonable to assume that bridges used in this study were built with a minimum of 2 inches of cover.

Although, ECR usage and changes to concrete strength occurred in 1975-76, discussions with VDOT personnel suggested that actual usage on some projects was delayed as long as three years. VDOT bridge inspection records specify the type of reinforcement bar used in the deck. Due to lack of data, bridge decks with ECR were subsequently removed from the current study, as discussed in Section 3.3.3.4.3 entitled “Data Sorting Issues – VDOT Electronic Data“.

3.2.4 Summary

Bridges used in the study were built from 1960 through 1979 and had decks with bare bars, 2 inches of concrete cover, and strength of 4,000 psi with w/c ratio of 0.47. The steel girders with paint were assumed to be inorganic zinc-based. The material compositions associated with the year-built of bridges in the study were based on the existing VDOT design and construction specifications. Due to the noted delays in actual implementation of specification changes, it is possible that bridges built during transition periods may or may not have incorporated the changes. However, based on the time-line shown, the number of such bridges was expected to be minimal compared to the total bridge data set used in the study.

3.3 Methodology

The following outlines the various steps in the methodology for the study.

3.3.1 Identification of Environmental Regions

This was achieved by identifying and grouping together districts that have similar topography and climatic conditions, including rainfall, snowfall, humidity, temperature, and by deduction severity of freezing and thawing cycles. After a review of climatic data and literature on the state of Virginia (Appendix B), the state was divided into six such environmental regions as shown in Figure 3.2. This followed the regional divisions used by the Virginia State Climatology Office. All the counties of the state have been listed under their respective environmental regions in Table 3.1. All the counties are completely embedded in their respective environmental regions except a small southern portion of Prince William county in Northern Virginia, which falls into the Tidewater region with most of the county in the Northern region.

VDOT divides the state into nine (9) districts namely; Bristol, Salem, Lynchburg, Richmond, Hampton Roads, Fredericksburg, Culpeper, Staunton, and Northern Virginia districts as shown in Figure 3.3. Each of the districts oversees the maintenance and construction on the state-maintained highways, bridges and tunnels in the region. VDOT districts and their respective counties have been grouped under the six environmental regions in Table 3.1. Figure 3.4 shows a map of VDOT districts superimposed on the six environmental regions. In a discussion with Thomas Lester, a senior VDOT bridge management personnel, it was suggested that other factors to consider would include operational procedures such as heaviest to lightest use of salt compounds for de-icing in the winter months. Typically, interstate routes get first priority, then primary and urban, and down to local routes. Further, the western part of the state gets heavier application than the eastern part of state. Eastern part typically has brackish to salty water. Although VDOT does not collect data on salt usage, it has been pointed out that all these considerations may be self-evident from the data segregation by environmental regions (Lester, 1999).

Legend

TW – Tidewater
EP – Eastern Piedmont
WP – Western Piedmont
N – Northern
CM – Central Mountain
SM – Southwestern Mountain

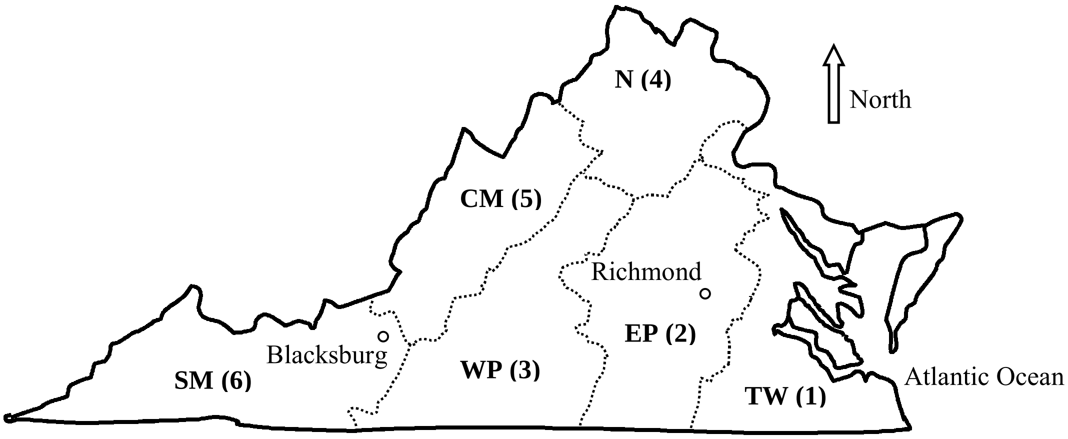


Figure 3.2: Virginia Environmental Regions

Table 3.1: Environmental Regions and Respective Counties

TW **(Tidewater):**	**Hampton Roads** and **Fredericksburg districts** minus Caroline and Spotsylvania counties (both in **Fredericksburg district**); plus Charles City, New Kent and Prince George counties (all in **Richmond district**); plus a portion of Prince William county (in **Northern Virginia district**)
EP **(Eastern Piedmont):**	**Richmond district** minus Charles City, New Kent and Prince George counties; plus Caroline and Spotsylvania counties (both in **Fredericksburg district**); plus Fluvanna and Louisa counties (both in **Culpeper district**); plus Buckingham, Cumberland and Prince Edward counties (all in **Lynchburg district**)
WP **(Western Piedmont):**	Lynchburg district minus Buckingham, Cumberland and Prince Edward counties; plus Albemarle county (in **Culpeper district**) plus Bedford, Franklin, Henry and Patrick counties (all in **Salem district**)
N **(Northern):**	**Culpeper and Northern Virginia districts** minus Albemarle, Fluvanna and Louisa Counties (all in **Culpeper district**); minus a portion of Prince William county (in **Northern Virginia district**); plus Clarke, Frederick, Page, Shenandoah and Warren counties (all in **Staunton district**)
CM **(Central Mountain):**	**Staunton district** minus Clarke, Frederick, Page, Shenandoah and Warren counties (all in **Staunton district**); plus Botetourt, Craig and Roanoke counties (both in **Salem district**)
SM **(Southwestern Mountain):**	**Bristol district** plus Carroll, Floyd, Giles, Montgomery and Pulaski counties (all in **Salem district**)

Legend

1 - Bristol District
2 - Salem District
3 - Lynchburg District
4 - Richmond District
5 - Hampton Roads District
6 - Fredericksburg District
7 - Culpeper District
8 - Staunton District
9 - Northern Virginia District

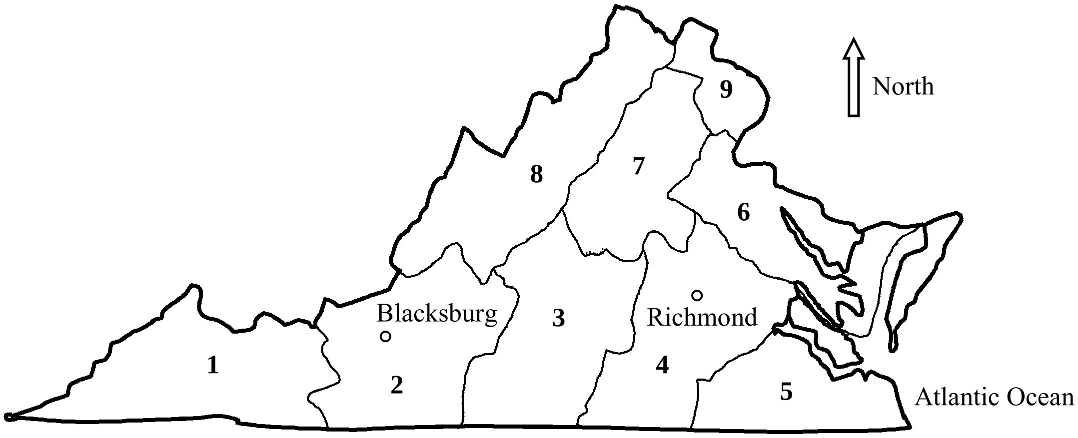


Figure 3.3: Virginia Department of Transportation Districts

Legend

—— Solid line denotes borders for VDOT districts.

⋯⋯ Dashed line denotes borders for Environmental regions.

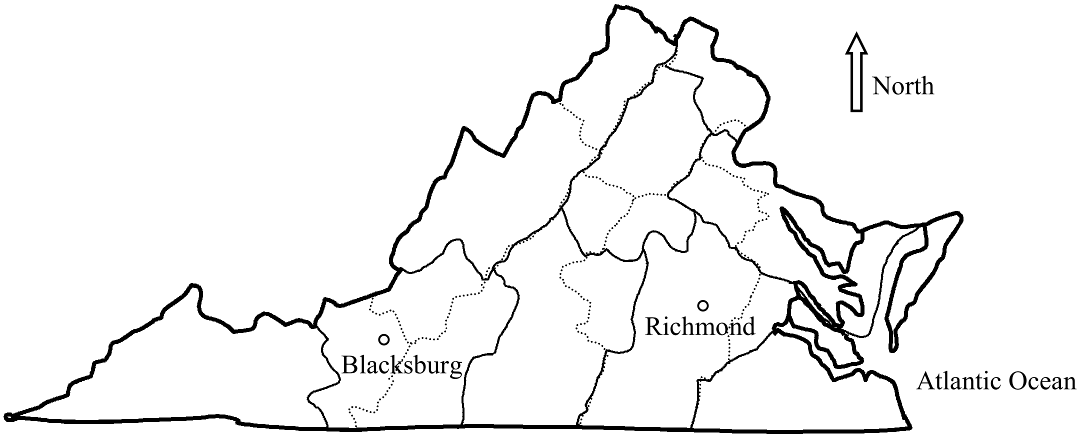


Figure 3.4: Virginia Department of Transportation Districts and Environmental Regions

3.3.2 Selection of Component and Element/Protective System

Bridge concrete deck and steel girder paint were selected for the study. The deck and paint are considered significant to MR&R budgets by VDOT and they are inspected during every inspection cycle. In addition, the deck and paint are more likely to have gone through at least one life-cycle during the availability period of the bridge inspection data used in the study. The deck and paint system have relatively higher levels of exposure to the effects of the environment than other elements of the bridge. Therefore, they are considered excellent candidates for analyses capable of capturing the environmental effects. In contrast, bridge elements such as abutment walls and wingwalls are capable of functioning effectively throughout the bridge design life without requiring any major rehabilitation and therefore they are not suitable candidates for this study.

3.3.3 Availability of State Bridge Inspection Reports

3.3.3.1 Introduction

Field inspection records documenting the physical conditions of concrete decks and steel girders paint during each inspection cycle were obtained and used as data sets in subsequent statistical analyses. The physical conditions of the concrete decks and steel girders paint have been reported based on visual assessment. The condition of a bridge component or element is assigned either a numeric or letter rating describing its physical condition during that specific inspection period, according to stipulated guidelines (Coleman 2000). The concrete deck physical condition have been evaluated using numerical coding 9 to 0, i.e., best to worst. Similarly, the condition of the girder paint has been reported based on visual assessment of the paint as good (G), fair (F), poor (P) or critical (C).

3.3.3.2 Data Source

Data for the study were obtained from VDOT and FHWA. Figure 3.5 shows the data sources and the data applications in the study. Section 3.3.3.3.5 entitled “Measured Service Life Validation” further discusses the procedures followed to ensure that the data available provided adequate information to measure the service lives of all the bridge components and elements/protective systems used in the current study. Bridge inspection records for the state of Virginia, dating back to 1992 in spreadsheet electronic format, was made available by Mr. John Coleman, a senior bridge personnel with VDOT. Additional bridge data prior to 1992 on hard copies had to be obtained from the districts. The additional data was necessary because measured service lives of bridge elements selected for the study were longer than eight years, which was the duration of the VDOT electronic data. Due to the limited duration of the VDOT electronic data, it was only used to sort out the bridges that qualified for the study. Appendix E is a sample bridge inspection data from the VDOT electronic data showing applicable columns used in this study. The sample is taken from the Southwestern Mountain region which includes Blacksburg.

At least once every two years, VDOT forwards the inspection records for every bridge in the state to FHWA, where they are compiled into the NBI. NBI data for the state of Virginia in electronic format was obtained from FHWA (Shemaka 2000). Appendix F is a sample NBI data of Virginia bridges for 1983. The entire data consisted of numerical ratings for the deck, superstructure and substructure of Virginia bridges from 1983 through 1999.

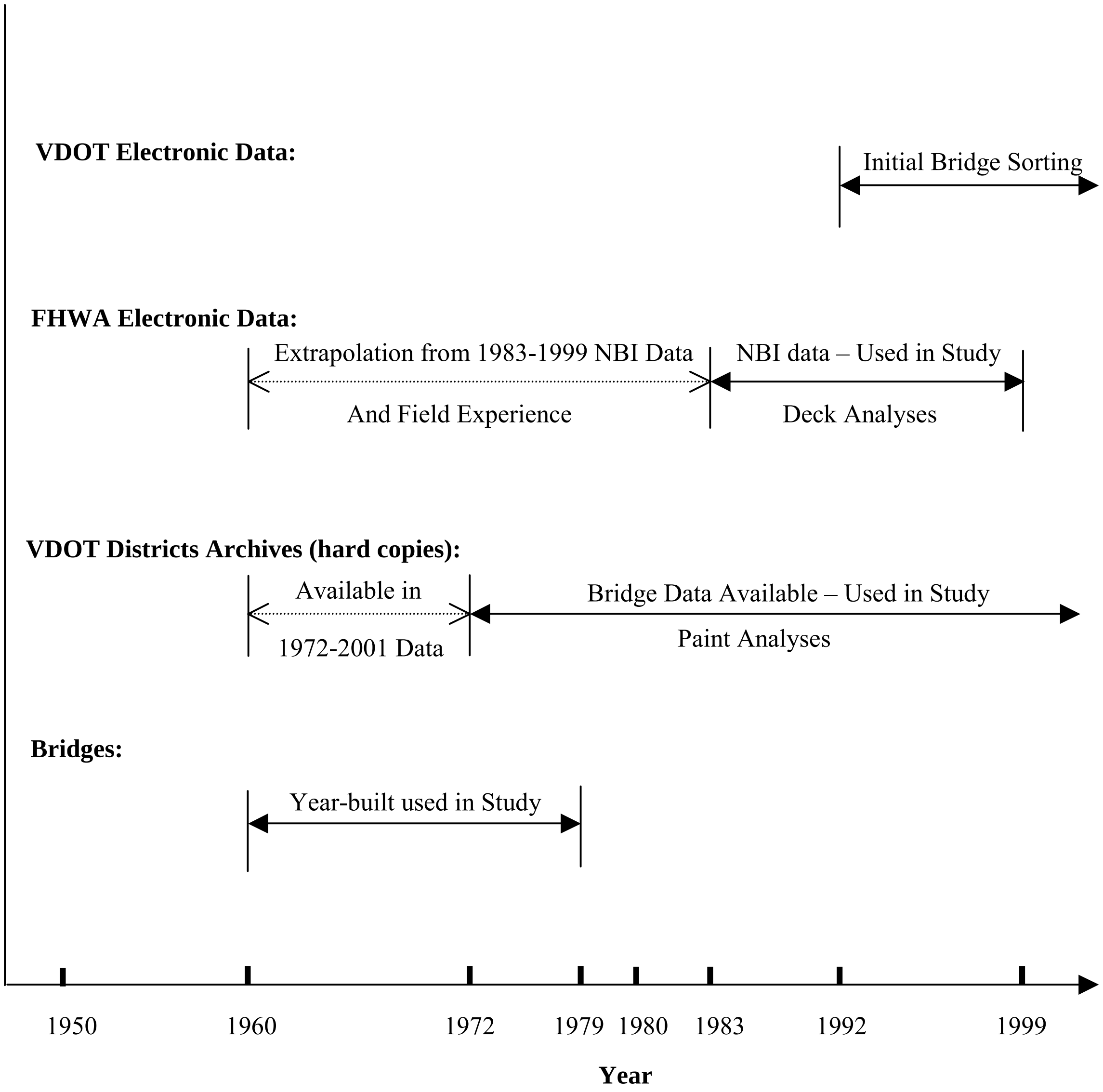


Figure 3.5: Time-Line for Data Availability

The data was a 432 character ASCII Flat file. The data had to be converted to spreadsheet format for sorting based on column descriptors provided by FHWA. The FHWA data was used for the concrete deck analysis. The bridge identification numbers were previously selected from the VDOT electronic data before collecting the condition ratings from the FHWA data. The paint data used in the study was obtained from the individual districts after the bridge identification numbers were sorted out using the VDOT electronic data. Personal trips were made to the Northern Virginia, Fredericksburg, Culpeper, Staunton, and Salem districts to collect the paint data. Paint data for Hampton Roads, Richmond, Lynchburg and Bristol districts were obtained from the bridge inspection records in the respective districts by VDOT personnel after the list of qualified bridges in those districts were sent to Mr. Coleman of VDOT.

3.3.3.3 Data Format and Service Life Measure

The methodology outlined required a data set to evaluate its effectiveness. Access to the state of Virginia bridge data from VDOT was critical to the successful completion of this study. The NBI format, which is the single digit numbers 9 through 0, is a composite number assigned to the condition of the deck, superstructure or substructure. According to VDOT guidelines for assigning condition appraisal codes to bridge elements, condition codes are used to describe the existing, in-place bridge as compared to the as-built condition (Coleman 2000). Evaluation is based on the materials-related, physical condition of the deck, superstructure and substructure components of the bridge. Condition codes are properly used by bridge inspectors when they provide an overall characterization of the general condition of the entire component being rated. Further, VDOT considers improper, the use of condition codes to describe localized or normally occurring instances of deterioration or disrepair. Thus, the correct assignment of a condition code considers both the severity of the deterioration or disrepair, and the extent to which it is widespread throughout the component being rated. Load carrying capacity of bridge elements is not used in evaluating condition items. The above VDOT guidelines regarding the collection of bridge inspection data are covered in the FHWA issued “Recording and Coding Guide” (1988) and “Recording and Coding Guide” (1995).

The service life of a bridge component or element, as previously defined, is the number of years from when the bridge was built to the first year the element was assigned a condition rating triggering recommendation for major repairs or rehabilitation of that bridge component or element. The bridge component or element may continue to function minimally under this definition, and therefore, the period after the end of service life may be considered deferred maintenance. Research performed by Chasey (1995), discusses the impact of deferred highway maintenance and/or construction on user and non-user benefits.

3.3.3.3.1 Concrete Deck Data Format

Since 1972, VDOT has been using the following codes and descriptions for evaluating the physical condition of the deck, which are also used for superstructure and substructure general condition rating.

Code	*Description*
“N”	Not Applicable.
“9”	Excellent Condition.
“8”	Very Good Condition No problems noted.
“7”	Good Condition Some minor problems.
“6”	Satisfactory Condition Structural elements show minor deterioration.
“5”	Fair condition All primary structural elements are sound but may have some minor section loss, cracking, spalling or scour.
“4”	Poor Condition Advanced section loss, deterioration, spalling, or scour.
“3”	Serious Condition

Loss of section, deterioration, spalling, or scour has seriously affected primary structural components. Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present.

"2" Critical Condition

Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present or scour may have removed substructure support. Unless closely monitored, it may be necessary to close the bridge until corrective action is taken.

"1" "Imminent" Failure Condition

Major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.

"0" Failed Condition

Out of service – beyond corrective action.

The item "DECK GEN COND" in the VDOT inspection data describes the overall condition rating of the deck. In the FHWA NBI data, the condition of the deck which VDOT forwards, is identified as Item 58 ("Recording and Coding Guide" 1995, 1988, and 1972). The deck condition is rated based on the above descriptions. According to VDOT, concrete decks are inspected for cracking, scaling, spalling, leaching, chloride contamination, potholes, delamination, and full or partial depth failures. More importantly, the condition of the wearing surface/protective system, joints, expansion device, curbs, sidewalks, parapets, fascias, bridge rail, and scuppers are not considered in the overall deck evaluation.

3.3.3.3.2 Measured Service Life - Concrete Deck

For the deck analyses, the measure of deck service life was the number in years from when its physical condition was appraised equal to 9 to when it deteriorated to the first condition appraisal rating of 5. The difference in years between the two numerical codes was the measured service life for that specific deck. Figure 3.6 is a schematic illustration of the measured service life for concrete decks. The year selected for the condition rating of 9 was the year the bridge was built.

Based on the codes and descriptions, the period from 9 through 4 would have been the expected service life measure. However, upon reviewing the actual bridge data, it became apparent that bridge decks in the state were seldom assigned a rating of 4. Rehabilitation in the form of deck replacement or major repairs occurred after they were assigned a rating of 5, and thus the rating rarely reached 4. This was manifested in the sudden increase in rating after deck condition rating reached 5. There were sudden increases in deck rating for a few bridges after they were assigned a rating of 6. Those bridges were excluded from the study.

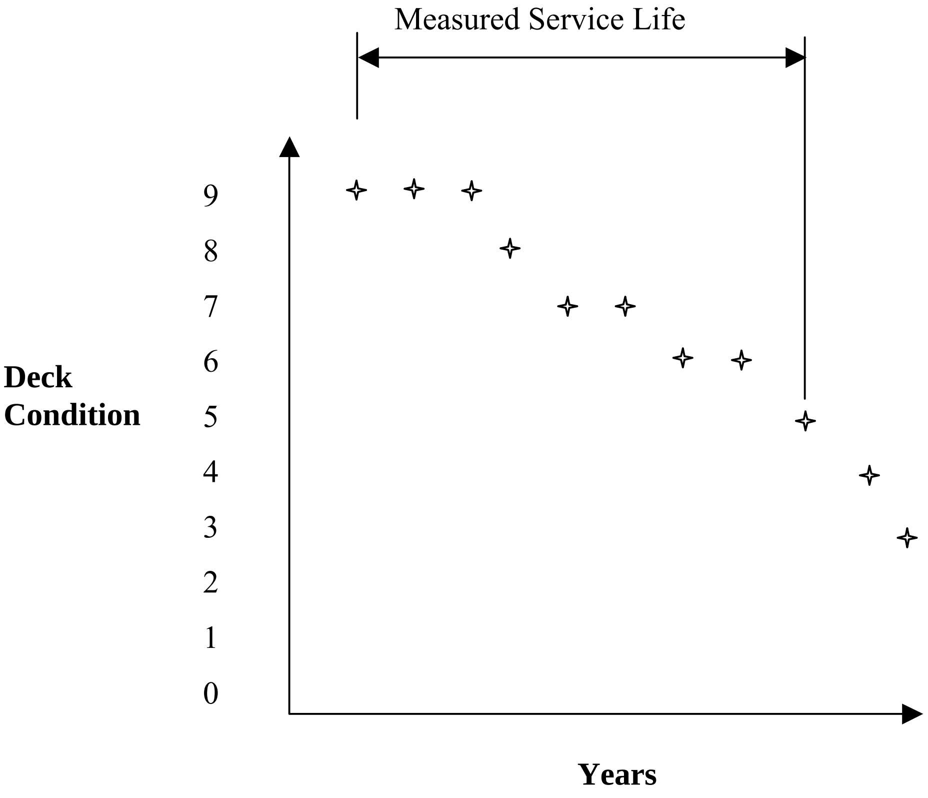


Figure 3.6: Measured Service Life for Concrete Deck

The original bridge data sets were further sorted by deck condition ratings. The number of bridges assigned a rating of 4 were extremely small with most of the affected bridges built in the

40’s and 50’s. Therefore, it was evident that rehabilitation or major repairs were occurring between deck condition rating of 5 and 4.

There was additional explanation to the observation that bridge elements were being repaired or rehabilitated after a condition rating of 5. According to FHWA “Recording and Coding Guide” (1972), a deck condition rating of 5 was interpreted as “major repair contract needs to be let”. Most of the bridges used in this study were built in the 60’s and 70’ and their inspections were based on the 1972 FHWA coding guide. Therefore, assigning condition rating code of 5 as equivalent to end of service life was the appropriate code.

3.3.3.3.3 Steel Girder Paint Data Format

Since 1972, VDOT has been using the following guidelines for establishing a bridge element or protective system condition ratings. This is the format used to evaluate the condition of the girder paint used in the study.

G – Good	The item is in new or good condition. All portions of the component are functioning as intended. There may be some very minor problems present, however, it does not affect the functioning of the component and no repairs are necessary.
F – Fair	The item is still performing the function for which it was intended. There may be some minor deterioration, section loss, cracking, spalling, or scour present; however, it does not affect the functioning of the component. There is no need for repair.
P – Poor	The item is still performing the function for which it was intended, but at a minimum level. There may be advanced section loss, deterioration, spalling or scour present. This item is in need of major repair.
C – Critical	The item is no longer performing the function for which it was intended. There may be major deterioration, section loss, cracking, spalling or scour present. Immediate replacement or repair is required.

3.3.3.3.4 Measured Service Life - Steel Girder Paint

The item “PAINT COND” in the VDOT bridge inspection report describes the overall condition rating of the steel girder paint. The item “PAINT YEAR” in the inspection report shows the year the paint was applied and it may not be the same as the year the bridge was built. The period in years from a rating of G-Good through F-Fair, and to P-Poor was used as the service life measure. Figure 3.7 is a schematic illustration of the measured service life for steel girder paint. The G-Good was the year the paint was first applied, i.e., “PAINT YEAR”. The field notes of bridge inspectors for P-Poor rating was paint failure and was always followed with the recommendation to paint the entire superstructure steel. The field notes for F-Fair was the recommendation for spot painting the steel girder. In the current study, the measure of a bridge girder paint service life (L) was the period (years) from when it was first assigned a “G” rating to when it was first assigned a “P” rating.

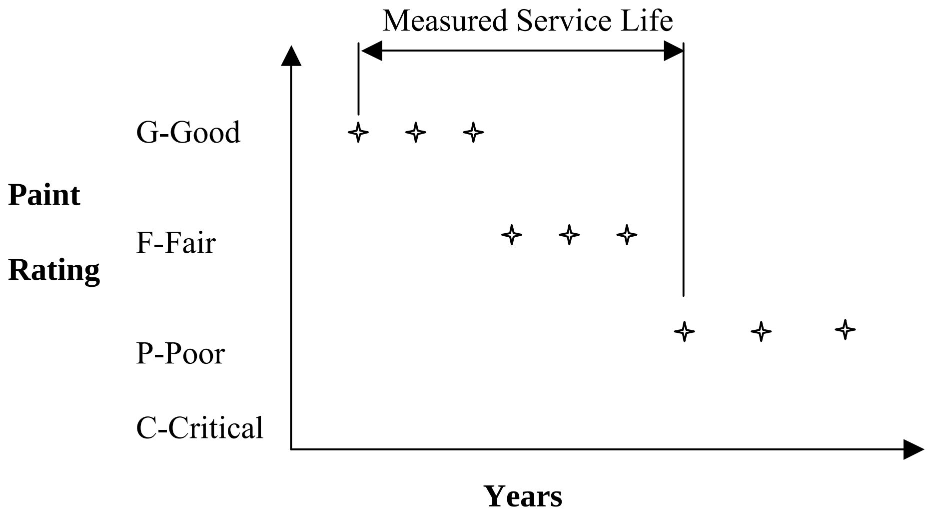


Figure 3.7: Measured Service Life for Steel Girder Paint

It needs to be pointed out that each bridge agency has the flexibility to select its own measured service life range. Thus, the range could be the first “G” to the second or third “P”, or for the concrete deck analysis, numerical rating 9 to 4.

3.3.3.3.5 Measured Service Life Validation

A single year bridge inspection record can have the relevant information to establish the measured service life of a bridge element as defined in this study. An inspection record of a bridge for any inspection year contains the year-built and the prevailing condition appraisal number or letter code for that element or component. Hence, a single record that establishes the end of service life would have the end of service life condition appraisal code. The difference between the year built and the year corresponding to the end of service life condition appraisal rating is defined as the measured service life. To ensure that a single inspection record contains the end of service life information for an element or component, a review of the inspection record just prior to the current one is required. This is important to establish the condition of the element or component just prior to the element reaching the end of its service life. For the deck analyses, since the first assignment of condition appraisal rating of 5 was established as the end of service life, the inspection record just prior to the current inspection record must be a condition appraisal rating of 6. Any other condition appraisal rating before a rating of 5 would not validate the end of service life as defined in this study. By the same analogy, the end of service life for the steel girder paint was established as the first condition appraisal rating of "P". The inspection record just prior to the current one must be a condition appraisal rating of "F". Any other condition appraisal rating would not validate the end of steel girder paint service life.

In addition, it is necessary to extrapolate and determine if any major repair or rehabilitation had been performed on the bridge element or component between when it was first built or applied and the end of its service life. A major repair or rehabilitation activity on an element would distort the measured service life by increasing the value measured, potentially skewing any statistical analysis by introducing outliers. For example, if a bridge was built in 1960 and the condition appraisal rating for the concrete deck in 1983 was 9, 8 or 7, it most likely underwent repairs of some sort. It would be reasonable to assume that after 23 years in service with no major repair or rehabilitation, the condition appraisal rating would be a 6 or lower. In discussions with various VDOT personnel, this assumption was considered reasonable. In addition, during the initial collection of the measured service life data, bridges that had questionably high condition rating, in spite of their ages, tended to have very long service lives compared with the rest of the data. Though the number of bridges that fell in this category were small, they were excluded from the data set used in the final analyses. As a cautionary note, some of the bridges that were subsequently excluded from the final concrete deck analyses may not have undergone any major repairs or rehabilitation and therefore eliminating them potentially introduces data bias. However, due to the limited number of such bridges encountered and the consistency of the elimination process, the overall effect on the final results should be minimal.

The steel girder paint data did not have the same end of service life identification issue as the concrete deck. A single inspection record contains the year the paint was applied and the prevailing condition appraisal rating. Any intermediate work performed would be spot painting not at the level of major repair or rehabilitation which would be equivalent to painting entire superstructure girders. Should the entire steel girder system be repainted, this would require a change in the inspection record to show a new paint year. A number of girders were repainted especially those that previously had lead-based paint. The year the paint was applied in a number of data collected was not the same as the year the bridge was built. Hence, data to establish the end of service life does not have to begin from when the element or component was initially built or applied. Intermediate data is only necessary to ensure no major repair or rehabilitation occurred in the interim to distort the measured service life. Data used for the deck analyses begun in 1983 but the year-built for the bridges used in the concrete deck analysis were from 1960 through 1979.

3.3.3.4 Data Sorting

3.3.3.4.1 Introduction

The following outlines the steps used in sorting and assigning the bridges used for the research study. Electronic data from VDOT was used to group the bridges according to predefined classes. VDOT electronic data had descriptive expressions making them more amenable to grouping. VDOT grouped the electronic data into districts for every year the data covered. Most of the descriptive expressions in the VDOT electronic data had subsequent numerical codes identifying specific sub-descriptions.

3.3.3.4.2 Outline of Data Sorting Procedures - VDOT Electronic Data

Columns with applicable codes and descriptions follow the column identification.

A) Inspection data from one of the nine VDOT districts was selected.

B) The following columns were identified in the data:

i) DIS district column A
ii) CO/CTY county column B
iii) ROUTE column C
iv) CROSSING column D
v) VA STR. NUMB Virginia Structure Number Column E
vi) LOCATION column F
vii) YEAR BLT Year Built column G
viii) ADT Average Daily Traffic column H
ix) ADTT PRCNT Average Daily Truck Traffic Percentage Column I
x) DECK TYPE Column K

Table 3.2: Codes for "DECK TYPE"

Code	Description
1	Concrete cast-in-place
2	Concrete precast panels
3	Open grating
4	Close grating
5	Steel plate
6	Corrugated steel
7	Aluminum
8	Timber
9	Other

xi) MAIN SPAN MAT Main Span Material and/or Design Column L

Table 3.3: Codes for "MAIN SPAN MAT"

Code	Description
1	Concrete
2	Concrete continuous
3	Steel
4	Steel continuous
5	Prestressed concrete
6	Prestressed concrete continuous
7	Timber
8	Masonry
9	Aluminum

xii) MAIN SPAN TYPE Main Span Design and/or Construction Column M

Table 3.4: Codes for "MAIN SPAN TYPE"

Code	Description
01	Slab
02	Stringer/multi beam or girder
03	Girder and floor beam system
04	Tee beam
05	Box beam or girders – multiple
06	Box beam or girders – single or spread
07	Frame
08	Orthothropic
09	Truss – deck
10	Truss – thru

xiii) PROT WEAR SURF Wearing Surface of the Bridge Deck Column Q

Table 3.5: Codes for “PROT WEAR SURF”

Code	Description
1	Concrete – not the monolithic wearing surface applied for design
2	Integral concrete – separate layer of concrete added but not LMC, Low Slump, etc.
3	LMC
4	Low slump concrete
5	Epoxy overlay
6	Bituminous
7	Timber
8	Gravel
9	Other
0	None
N	Not Applicable
A	Silica Fume

xiv) PROT WEAR MEMB Protective Membrane System of Bridge Deck Column R

Table 3.6: Codes for “PROT WEAR MEMB”

Code	Description
1	Built-up
2	Preformed fabric
3	Epoxy
8	Unknown
9	Other
0	None
N	Not applicable

xv) PROT WEAR DECK Protective System of the Bridge Deck Column S

Table 3.7: Codes for "PROT WEAR DECK"

Code	Description
1	Epoxy-coated reinforcing
2	Galvanized
3	Other coated reinforcing steel
4	Cathodic protection
6	Polymer impregnated
7	Internally sealed
8	Unknown
9	Other
0	None
N	Not applicable

xvi) PAINT COND Paint Condition of the Superstructure only Column T

xvii) PAINT YEAR Superstructure Year Painted Column U

C) Sorted by "MAIN SPAN TYPE":

i) Identified stringer/multi-beam or girder bridges using the numerical code 2. All other rows were eliminated.

D) Sorted by "DECK TYPE":

i) Selected rows using the numerical code 1 corresponding to concrete cast-in-place, deleted all other rows in the column.

E) Sorted by "PROT WEAR SURF":

i) Identified decks with concrete wearing surface by using code 1 and 2, deleted all other rows in that column. Deleted rows were bridges with latex concrete, low slump, epoxy overlay, bituminous, timber, silica fume or gravel wearing surface.

F) Sorted by “PROT WEAR MEMB”:

i) Identified bridge decks with no membrane protection, which constituted the vast majority in the database using numerical code 0. Deleted all other bridges.

G) Sorted by “YEAR BLT”:

i) Identified bridges in terms of age in ascending order.

ii) Made two additional worksheet copies in the same file.

iii) Inside 1st worksheet, deleted bridges built in 1979 and before, leaving bridges 21 years and younger.

iv) Inside 2nd worksheet, deleted bridges built in 1980 and later, and also bridges built in 1959 and before, leaving bridges older than 21 years but younger than 41 years old.

v) Inside 3rd worksheet, deleted bridges built in 1960 and later, leaving bridges 41 years and older.

H) Sorted by “PROT WEAR DECK”:

i) Identified protective systems such as ECR or none using numerical codes 1 and 0 respectively.

ii) Bridges ages 21 years and younger were built with ECR. This was accomplished by using numerical code 1 in the 1st worksheet and deleting all other bridges. Subsequent data collection issues rendered the ECR excluded from the final analysis for lack of data. Most of the bridges with ECR in decks had not deteriorated to their end of service lives (refer Section 3.3.3.4.3 entitled “Data Sorting Issues – VDOT Electronic Data”).

iii) Bridges older than 21years but younger than 41 years old typically had no protective systems. The 2nd worksheet was sorted out using numerical code 0 and then deleted all other bridges.

iv) Similarly, bridges 41 years and older were sorted out using numerical code 0 in the 3rd worksheet and deleted all other bridges. Subsequent data collection issues rendered this section excluded from the final analysis for lack of reliable data. Based on data availability, bridges 41 years and older may have undergone major repair or rehabilitation. This which would have inflated their measured service lives, thereby skewing service lives estimated in this study (refer Section 3.3.3.3.5 entitled

"Measured Service Life Validation" and Section 3.3.3.4.3 entitled "Data Sorting Issues – VDOT Electronic Data").

I) Sorted by "ADT":

i) Duplicated each of the 3 worksheets from (H) above.
ii) For each of the 6 worksheets sorted "ADT" in ascending order.
iii) Inside the 1st worksheet of bridges 21 years and younger, deleted bridges with "ADT" greater than 5000.
iv) Inside the 2nd worksheet of bridges 21 years and younger, deleted bridges with "ADT" 5000 and less.
v) Repeated (iii) and (iv) for the bridges older than 21 but younger than 41 years old and also bridges 41 years and older.

J) Sorted by "MAIN SPAN MAT":

i) Duplicated each of the 6 worksheets in (I) to a total of 12 worksheets.
ii) Inside the 1st of each pair, sorted using the numerical code 3 for simply supported bridge and deleted all other rows.
iii) Inside the 2nd worksheet, sorted using the numerical code 4 for continuous and deleted all other rows.
iv) Repeated (ii) and (iii) 5 more times.
v) Obtained various combinations of age (3 groups: 00-21-41), ADT (2 groups: lt-ht) and simple/continuous (2 groups: s-c), yielding a total of 12 worksheets as shown in Table 3.8.

Table 3.8: Interim Data Classes

s-00-lt	s-00-ht	c-00-lt	c-00-ht
s-21-lt	**s-21-ht**	c-21-lt	c-21-ht
s-41-lt	s-41-ht	c-41-lt	c-41-ht

Legend: s: simply supported bridge
c: continuous span bridge

lt: low traffic (ADT<= 5000)
ht: high traffic (ADT > 5000)
00: bridge age <= 21
21: 21 < bridge age < 41
41: bridge age >= 41

Data availability rendered the data classes reduced to s-21-lt and s-21-ht. These were simply-supported steel girder bridges with bare bars, ages older than 21 but younger than 41, with either low traffic volume or high traffic volume. Section 3.3.3.4.3 entitled "Data Sorting Issues – VDOT Electronic Data" discusses some of the issues encountered that contributed to the final selection regarding the final classes employed in the study.

K) Repeated steps C through J for the remaining eight (8) VDOT districts.

L) All the VDOT counties and cities/municipalities were grouped within the selected six (6) regions. The next important step was the grouping into regions. By identifying the county numbers within specific regions, all counties within the same region were combined into one file. This involved combining same class of factors from different counties within the same region. For example, southwestern mountain region included the entire Bristol district plus Carroll, Floyd, Giles, Montgomery, and Pulaski counties in Salem district. The five (5) counties in Salem district had to be sorted out, class by class, and added to their corresponding classes in the Bristol district to make the southwestern region data set complete. There would have been twelve (12) classes in each district as outlined in (J) above but due to lack of data two (2) classes were finally used.

M) Repeated the procedure outlined in (L) to obtain the data sets for the remaining five (5) regions.

N) Finally, there were six (6) regions each with two (2) worksheets yielding a total of twelve (12) data sets.

O) One bridge component (concrete deck) and one element/protective system (steel girder paint) were selected for the study. Since data can only be taken once from a bridge, the data sets were not separated at this stage to ensure that multiple data were not collected from the same bridge. This was done to ensure independent analyses of the concrete deck and steel girder paint.

3.3.3.4.3 Data Sorting Issues – VDOT Electronic Data

During the sorting process decisions were made to include or exclude certain classes based on the results of the data sizes obtained. The classes have been listed previously in Table 3.8. It was important to obtain the data sizes in each class to determine if the sizes were significant to run any statistical analysis. As subsequently discussed in Section 3.3.7.2.10 entitled “Bridge Element Data Size”, the minimum data size per environmental region was greater than 30. The minimum data size ensured that any analysis of a single region would have data size greater than 30.

Table 3.9 shows the classes and data sizes for continuous steel bridges after sorting through the VDOT electronic data and assembling the data into the six environmental regions. Based on the inadequate data sizes shown in Table 3.9, continuous steel girder bridges were excluded from the study for lack of data. This decision rendered Table 3.8 reduced to 6 possible classes, after eliminating all the classes with the letter “c”, which denotes continuous.

Table 3.9: Data Sizes for Continuous Steel Bridges

Region	Class	Data Size
Northern	c-41-lt c-41-ht	9 9
Tidewater	c-21-lt c-41-lt	5 7
Eastern Piedmont	c-41-ht	9
Western Piedmont	c-21-lt c-41-ht	11 11
Central Mountain	c-00-ht	12
Southwestern Mountain	c-41-ht	9

In an attempt to account for truck traffic, actual ADTT values using the percentages provided in the bridge inspection data was added to the columns to create a separate truck category. Total truck traffic would have been divided into low and high truck traffic. However, when actual ADTT was used, some of the classes with either low or high traffic volumes did not have adequate number of high ADTT category. Also, in some regions with low ADT, even with high percentage ADTT, the regions still had inadequate ADTT count. Table 3.10 shows the affected regions with their bridge classes and the corresponding data sizes for high ADTT. The data sizes in Table 3.10 indicated that creating a separate category for ADTT as a way of separating trucks from ADT was not feasible. In some cases the resulting data was not adequate for statistical analysis as seen with data sizes 0, 1 and 2. Consequently, a separate ADTT category was excluded. However, the data review indicated that high ADTT's were associated with high ADT's. The group with high ADT provided the desired effect of high ADTT and the group with low ADT provided the desired effect of low ADTT. Thus, a separate category for ADTT within an ADT group would not have resulted in a separate grouping significantly different from the final grouping used in the analyses. The study performed in North Carolina by Abed-Al-Rahim and Johnston (1995) encountered similar issues and eventually settled on two classes of ADT after starting with six separate classes.

Table 3.10: Data Sizes for Select Regions with Class, Size, and High ADTT

Region	Class	Data Size	Size with ADTT>500
Northern	s-21-lt	88	1
	c-21-lt	16	0
	s-21-ht	118	70
	c-21-ht	43	33
Eastern Piedmont	s-41-lt	65	1
	c-41-lt	16	0
	c-41-ht	77	58
	c-00-ht	9	7
Southwestern Mountain	s-00-lt	93	0
	c-00-lt	39	2
	s-00-ht	29	19
	c-00-ht	17	14

Bridges built before 1960 would have had data starting in 1972 in the VDOT archives in the districts and 1983 for the NBI data. However, bridges built before 1960 were excluded from the study due to the high probability that a significant number of the bridge components and elements would have had major repairs or rehabilitation before bridge inspection data collection formally begun in 1972. Such component or element condition improvements would not have been recorded on the inspection records rendering the service life estimates inflated because of the improvements performed.

Bridge concrete decks built in 1980 and after, were typically constructed with epoxy-bars and a review of their inspection data showed that the vast majority have not reached their end of service lives as defined in this study. The current study analyzed bridge components and elements/protective system that have deteriorated and reached their end of service lives. Thus, concrete decks with ECR were not included in this study for lack of data.

3.3.3.4.4 Outline of Data Collection Procedures - FHWA Electronic Data

As discussed under "Data Source," the FHWA NBI data on Virginia was used to provide data for the deck analyses. After the qualifying bridges were selected from the VDOT electronic data, the condition rating codes were obtained from the FHWA electronic data. For each year, the FHWA ASCII file was converted into spreadsheet format by identifying the columns corresponding to bridge identification number, bridge route number, bridge crossing, year-built, and deck condition rating. The identification of the columns were based on "Recording and Coding Guide" 1995, 1988 and 1972. The concrete deck condition appraisal rating was Item 58 in the Structure Inventory and Appraisal Form in the coding guides. There were multiple bridges with the same bridge identification numbers and therefore other descriptors, such as year-built and bridge crossing, were particularly important to ensure that the data was being recorded from the correct bridge. Using bridge information gathered from the VDOT electronic data, the condition rating code for the concrete deck for each qualifying bridge was followed from the beginning of the FHWA data in 1983 to the first year the condition code was recorded as 5. This was done for all qualifying bridges.

3.3.4 Identification of Factors Affecting Bridge Element Service Lives

Based on a review of current research previously covered under "Literature Review" and also discussions with VDOT bridge personnel, a list of factors responsible for the deterioration of bridge elements was identified. Factors that were considered in the study have been listed in Table 3.11.

Table 3.11: Factors and Levels

Factors	**Levels**	**Explanation**
Simple Span	1	Self – explanatory
Age	1	>21 and <41
Average Daily Traffic (ADT)	2	0-5000, >5000
Average Daily Truck Traffic (ADTT)	1	Inherent in ADT, high ADT =>high ADTT
Functional Classification	1	Inherent in ADT
Chloride Application	1	Inherent in Environmental Classification
Freezing and Thawing cycles	1	Inherent in Environmental Classification
	2	**Total Combination Levels**

3.3.5 Formation of Deterioration Levels

Based on factors listed in Table 3.11, different degrees of each deterioration factor were established. It was initially intended to have three levels of age and two levels of span and in combination with the two levels of ADT, a total combination of 12 would have been used. As explained in Section 3.3.3.4 entitled "Data Sorting Issues – VDOT Electronic Data", this was later found to be not feasible. Consequently, two overall levels of deterioration based on the factors listed in Table 3.11 were used. The distinguishing characteristic between the two deterioration levels used in the current study was the number of ADT involved. Level 1 had ADT less than or equal to 5,000 and level 2 had ADT more than 5,000. The highway system in Virginia has been functionally classified as Principal Arterial, Minor Arterial, Collector and Local Services. VDOT Road Design Manual (1998) classified Minor Arterial, Collector and

Local Services highway system, for the purpose of geometric design criteria, as having ADT ranging from 1 to over 4,000. Based on this classification, low traffic volume with ADT less than or equal to 5,000 was used in this research study and included bridges located on Minor Arterial, Collector and Local roads. Bridges with high traffic volumes with ADT more than 5,000 included bridges located on Principal Arterial. The interstate highways and freeways were considered part of the Principal Arterial system.

The two deterioration levels combined with the 6 environmental regions to provide 12 cells (2 x 6 = 12). Each cell had a minimum data size of more than 15 bridges in the subsequent data analyses.

It is worthwhile to note that any number of combinations are possible depending on the number of levels selected in each factor. However, more levels yield more deterioration levels, requiring more divisions within the same data set, and increasing the potential for combinations which do not have adequate number of bridges for statistical analyses.

3.3.6 Description of Bridge Data Set

A total of 476 bridges was used in the study, with 228 for the concrete deck analyses and 248 for the steel girder paint analyses. None of the bridges involved in the study were used for both concrete deck and steel girder paint analyses. This was necessary to ensure that conclusion drawn on concrete deck analyses were not influenced by the effect of actions performed on the steel girders of the same bridge and vice versa. In addition, the statistical model developed for the study may not be applicable in cases where multiple data is collected from the same sample. Tables 3.12 and 3.13 show a breakdown of the data sets used in the study. A total of 476 bridges were used in the study. As of August 2000, there were 5,976 simply supported steel bridges in Virginia (*FHWA* 2001) and approximately 4,000 have concrete decks (Coleman 2001). The percentages of the total used in the current study were 5.7 % for concrete decks and 4.1 % for steel girder paint.

Table 3.12: Data Set – Concrete Deck

Environmental Region	Deterioration Level 1	Deterioration Level 2	Total
Tidewater (1)	17	23	40
Eastern Piedmont (2)	18	22	40
Western Piedmont (3)	16	17	33
Northern (4)	16	23	39
Central Mountain (5)	17	16	33
Southwestern Mountain (6)	16	27	43
Total	100	128	**228**

Table 3.13: Data Set – Steel Girder Paint

Environmental Region	Deterioration Level 1	Deterioration Level 2	Total
Tidewater (1)	16	32	48
Eastern Piedmont (2)	23	18	41
Western Piedmont (3)	16	16	32
Northern (4)	16	27	43
Central Mountain (5)	17	16	33
Southwestern Mountain (6)	20	31	51
Total	108	140	**248**

3.3.7 Organization of Data and Statistical Analyses

3.3.7.1 Introduction

After the data was organized, the general linear model (GLM) procedure of Statistical Analysis System (SAS 2000) was used to run the ANOVA analysis. The impact of the six environmental regions, identified in Section 3.3.1 entitled “Identification of Environmental Regions”, on both the concrete deck and steel girder paint exposed to deterioration levels identified in Section 3.3.5 entitled “Formation of Deterioration Levels” were analyzed. A total of ten (10) statistical analyses were run, five for the concrete deck and five for the steel girder paint.

3.3.7.2 Statistical Model

3.3.7.2.1 Introduction

The study involved the analyses of bridge component and element/protective system data collected based on factors such as their locations within the state of Virginia, their material compositions, age, span, and the level of ADT on the bridges. Bridge components hereafter will also be referred to as elements, having converted the component to element status by the identification of its material composition. The analyses were performed to determine the effects of the identified factors on the mean service lives of the bridge elements. The state of Virginia had previously been divided into six environmental regions based on climatic and geographical features. For each bridge element included in the analyses, the measured service life constituted a data point in the statistical analyses. Each bridge element was identified by its environmental region and by exposure to a level of a deterioration factor.

According to numerous studies in BMS discussed in Chapter 2 entitled “Literature Review”, deterioration factors and the environment are directly responsible for bridge element deterioration. To assist in making sound inferences and predictions about the effects of the environmental regions and the different levels of deterioration factors on the service lives of bridge elements, a statistical model was developed. The separate and combined effects of the environmental regions and deterioration levels on estimated mean service lives of bridge elements was one of the objectives of the study. Each environmental region of the state had the same number of deterioration levels. Each deterioration level was made up of a set of deterioration factors identified in Table 3.11. Similar bridge elements were analyzed and compared with overall regions for the same deterioration level. This type of comparison results in a matrix format as shown in Tables 3.12 and 3.13. Conclusions were then drawn from the results of the statistical analyses regarding the equality or non-equality of the effects of the environmental regions, deterioration levels or both. The statistical analysis employed was the Analysis of Variance (ANOVA). Multiple-comparison procedure was then used to determine the relative differences between the effects of the regions on similar elements. Least squares mean service lives and standard errors of the bridge element per region were also estimated.

3.3.7.2.2 Analysis of Variance (ANOVA)

This is a statistical method used in deciding whether the differences in sample means for sets of data from different populations are statistically significant to imply that the corresponding population means are different. This is accomplished by comparing variations within-sample with variations between-samples. All differences in sample means are judged statistically significant (or not) by comparing them with variations within samples. This analysis allows the mean service lives of similar elements in different regions of the state to be compared with each other to determine if the deterioration levels or the environmental regions have different effects on the service lives of the bridge elements.

To perform ANOVA, a hypothesis is made about the equality of the population means called the null hypothesis and then an alternative hypothesis is made to dispute the first.

One-way analysis of variance with *t* population means has the following null and alternative hypothesis respectively:

H_o: $\mu_1 = \mu_2 = \mu_3 = \ldots = \mu_t$ (i.e., the *t* population means are equal)
H_a: Not all equal

Defining:

$$S_B^2 = \frac{\text{SSB}}{t-1}$$ mean squares between samples with degrees of freedom t-1

$$S_W^2 = \frac{\text{SSW}}{n_T-t}$$ mean squares within samples with degrees of freedom n_T-t

The null hypothesis of equality of the t population means is rejected if

$$F = \frac{S_B^2}{S_W^2} \qquad \text{(F-test)}$$

exceeds the value of F for a given α (usually 0.05, the probability of falsely rejecting the null hypothesis), degrees of freedom $df_1 = t$-1, and $df_2 = n_T$-t, where n_T is the total sample size.

The results can be put in the form of an ANOVA table shown in Table 3.14.

Table 3.14: One-way ANOVA

Source	**Sum of Squares**	**Degrees of Freedom**	**Mean Squares**	**F-test**
Between samples	SSB	t - 1	S_B^2 = SSB/(t-1)	S_B^2 / S_W^2
Within samples	SSW	n_T - t	S_W^2 = SSW/(n_T -t)	
Totals	TSS	n_T - 1		

The following assumptions are made concerning the sample measurements and the populations from which they are drawn:

i) the samples are independent random samples
ii) each sample is selected from a normal population
iii) the mean and variance for population i are, respectively, μ_i and σ_ε^2 (i=1,2,...,t)

There are commercial software programs for ANOVA that also print out the table. The software used for this study was SAS (2000). It has capabilities to perform this procedure and other desirable features including means and standard errors of data sets.

The model can be written in equation form as follows:

$$y_{ij} = \mu + \alpha_i + \varepsilon_{ij}$$

y_{ij} : the jth sample measurement selected from population i
μ : the overall mean and is an unknown constant

α_i : denotes an effect due to population i with mean μ_i, $\alpha_i = (\mu_i - \mu)$ also an unknown constant

ε_{ij} : denotes a random error associated with the jth observation from population i; the random error is normally distributed with mean 0 and a variance σ_ε^2, and the errors are independent of each other

Consequently, the null hypothesis for a one-way ANOVA as written above can also be written as follows:

H_o: $\alpha_1 = \alpha_2 = ... = \alpha_t = 0$

H_a: At least one of the α_i's differs from 0

The model above is referred to as *One-way Classification* and it probably is the most common of all the linear models. The model above has only one independent variable. However, there are more complicated designs and ANOVA tables involving two or more independent variables and their interactions. In the current study, there were two main effects (independent treatment variables) on the bridge elements namely the environmental regions and the levels of deterioration.

Classifying the regions as factor A (Tidewater, East and West Piedmont, Northern, Central Mountain, and Southwestern Mountain) and the levels of deterioration as factor B (ADT, age and span type, etc.), the model can be considered as a *Two-Way Cross-Classification.* The model allows the comparison of every level of the independent variables, i.e., it allows the study of the effect of the two independent variables and their interaction. The effect of the regions and deterioration levels may be analyzed with respect to their interaction or, where appropriate, separately.

Within the regions of the state (factor A), bridge elements are subjected to two levels of deterioration (factor B). In general, the model may be classified as either a fixed, random or mixed model depending on whether the variables are fixed or random. The state is completely divided into six regions making the effects due to the regions (factor A) fixed. The deterioration levels (factor B) are also considered to have fixed effects, having been specifically selected from a group of field deterioration conditions. Consequently, the model was classified as a *fixed-effects model.*

The general model for a Two-way Cross Classification with fixed-effects (n observations per cell) can be written as:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk}$$

where :

μ is an overall unknown mean.

α_i is an effect due to region $A_i = \mu_{Ai} - \mu$

β_j is an effect due to deterioration factor $B_j = \mu_{Bi} - \mu$

$\alpha\beta_{ij}$ is an effect due to the interaction of region A_i and deterioration factor B_j

$= \mu - \mu_{Ai} - \mu_{Bi} + \mu$

ε_{ijk} is a random error associated with the *k*th element exposed to deterioration factor B_j in region A_i. It has a distribution with mean 0 and variance σ_ε^2.

i = 1,2,...,a (the number of regions)

j = 1,2,...,b (the number of deterioration factors)

k = 1,2,...,n (sample size)

The ANOVA table is shown in Table 3.15.

Table 3.15: Two-way ANOVA

Source	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**Expected MS**
A (region)	SSA	a-1	MSA	$\sigma_\varepsilon^2 + bn\Sigma\alpha_i^2/(a-1)$
B (deterioration)	SSB	b-1	MSB	$\sigma_\varepsilon^2 + an\Sigma\beta_j^2/(b-1)$
AB	SSAB	(a-1)(b-1)	MSAB	$\sigma_\varepsilon^2 + n\Sigma(\alpha\beta_{ij})^2/[(a-1)(b-1)]$
Error	SSE	ab(n-1)	MSE	σ_ε^2
Total	TSS	abn-1		

3.3.7.2.3 Test for Interaction

The first test involves testing for the effect of the interaction between regions (factor A) and the deterioration levels (factor B).

Null Hypothesis

H_o: $\alpha\beta_{11} = \alpha\beta_{12} = \ldots = \alpha\beta_{ij} = \ldots = \alpha\beta_{ab} = 0$ (i.e., the *ab* population service life means are equal)

Alternative Hypothesis

H_a: At least one of the $\alpha\beta_{ij}$ differs from the rest

The test statistic

$F = MS(AB) / MSE$ F-test

A decision is made when this value is compared with the value of F in the rejection region α = (usually 0.05), degrees of freedom $df_1 = (a-1)(b-1)$, and $df_2 = ab(n-1)$. If this test is non-significant, then the null hypothesis is accepted. Then a test for the main effects (regions (A) and deterioration factor (B)) is appropriate. However, in the event that this test is significant, that is, the null hypothesis is rejected, the alternative hypothesis is accepted. A test for the main effect is not considered appropriate in the presence of significant interaction effect except where a profile plot indicates that the interaction is "orderly" (Ott 1993, p. 888). A profile plot is one where one variable is plotted for each level of the second variable with the y-axis being the response. In some studies the interaction may be the most significant aspect. Under a case such as this, the main effects do not have to be tested for. However, in this study, the main effects were important to the study and when significant interaction was encountered, additional statistical procedures were explored to assist in explaining the data. These additional statistical procedures are subsequently explained.

3.3.7.2.4 Test for Main Effect A (Regions)

In the event of a non-significant interaction test, a test for the main effect is appropriate. A test for the regions (factor A) to determine if there are differences in the mean service lives of similar bridge elements due to regional effects is written as follows:

Null Hypothesis

H_o: $\alpha_1 = \alpha_2 = \alpha_3 = \ldots = \alpha_a = 0$ (i.e., the *a* population service life means are equal)

Alternative Hypothesis

H_a: Not all equal

The test statistic

$F = MSA / MSE$ F-test

A decision is made when this value is compared with the value of F in the rejection region α = (usually 0.05), degrees of freedom $df_1 = a-1$, and $df_2 = ab(n-1)$. If by this test the null hypothesis is rejected, then there is strong evidence that the mean service lives for similar elements in different regions of the state are not the same, indicating a strong regional or environmental effect. If on the other hand, the null hypothesis is not rejected, it will indicate that there are non-significant differences between the mean service lives of similar bridge elements from region to region.

3.3.7.2.5 Test for Main Effect B (Deterioration Levels)

Following a non-significant test for interaction, a second test is performed on the deterioration levels (factor B), to determine the impact of the deterioration levels on the service lives of similar bridge elements. The ANOVA test of factor B to determine if there are differences in the mean service lives of similar bridge elements due to the deterioration levels is similar to the test on factor A. The test statistic is written as follows:

The test statistic:

$F = MSB / MSE$ F-test

A decision is made when this value is compared with the value of F in the rejection region α = (usually 0.05), degrees of freedom $df_1 = b-1$, and $df_2 = ab(n-1)$. If by this test the null hypothesis is rejected, then there is strong evidence that the mean service lives for similar elements subjected to different deterioration factor levels are not the same. If on the other hand, the null hypothesis is not rejected, it will indicate that there are not significant differences between the mean service lives of similar bridge elements across levels of deterioration factor.

In the event that a test for the interaction effect is significant, a profile plot will be necessary to give an insight to the nature of the data. It may be necessary to separate one or more levels of a variable to achieve a non-significant interaction upon running the remainder of the data. The level of the variable to be separated from the data set would potentially be the one that contributes the most to the "disorderly" appearance of the profile plot. Upon obtaining a non-significant interaction test, a separate analysis is performed on the level of the variable that was separated. For example, if one of the regions is removed to achieve a non-significant interaction for the remainder of the data set, one such test is the two-sample t-Test if the levels within of the deterioration factor is two.

3.3.7.2.6 Two-sample t-Test

It is used to test the hypothesis about the difference between two population means. The underlying assumptions are:

i) the two samples are independent
ii) the samples are drawn from a normal population
iii) the two population variances are equal (a different test for unequal variance exists).

Defining:

Null Hypothesis

$H_o: \mu_1 - \mu_2 = 0$ (i.e., the two population service life means are equal)

Alternative Hypothesis

H_a: $\mu_1 - \mu_2 \neq 0$

The test statistic

$t = (\hat{y}_1 - \hat{y}_2) / [s_p \sqrt{(1/n_1 + 1/n_2)}]$ t-Test

where:

$s_p = \sqrt{[(n_1-1)s_1^2 + (n_2-1)s_2^2]/(n_1+n_2-2)}$

and:

$\hat{y}_1$, $\hat{y}_2$ are the sample means with sizes n_1 and n_2 respectively, and

s_p^2 is the weighted average of the sample variances s_1^2 and s_2^2.

Specifying an α = (usually 0.05), degrees of freedom $df = n_1+n_2-2$, a decision is made to reject H_o if $|t| > t_{\alpha/2}$. The value of $t_{\alpha/2}$ is obtained from a t-table.

The above analysis assumes that the two samples were drawn from two populations with equal variances. In the case of unequal variances, the test statistic and degrees of freedom are revised for use in an alternative t-Test.

3.3.7.2.7 Unequal Variances

The test statistic

$t = (\hat{y}_1 - \hat{y}_2)/\sqrt{(s^2{}_1/n_1 + s^2{}_2/n_2)}$ t-Test

where:

$df = (n_1-1)(n_2-1)/[(n_2-1)c^2+(1-c)^2(n_1-1)]$

and $c = (s^2{}_1/n_1) / (s^2{}_1/n_1 + s^2{}_2/n_2)$

Similarly, by specifying an α = (usually 0.05), a decision is made to reject H_o if $|t| > t_{\alpha/2}$. The value of $t_{\alpha/2}$ is obtained from a t-table.

3.3.7.2.8 Multiple-Comparison Procedure

The analyses above constitute the initial steps in determining the existence of any differences in t population means. However, they do not tell which means differ from each other and by how much after the null hypothesis of equality of the means is rejected. Multiple-comparison procedures have been developed to answer these questions. There are a number of multiple-comparison procedures with different features depending on the design and the data to be analyzed. These include Fisher's LSD, Tukey's, and Duncan's procedures (Ott 1993, p. 807).

The procedure adopted for this research was Tukey's procedure (Ott 1993, p. 807). This was applied after the ANOVA procedure, to determine the nature of the differences between the means. It involves more than two sample means. The procedure is as follows:

To rank t sample means, two population means μ_i and μ_j are declared different if:

$$|\hat{y}_i - \hat{y}_j| \geq W$$

where:

$\hat{y}_i$, $\hat{y}_j$ are the sample means from populations i and j respectively,

$W = q_{\alpha}(t,v) \sqrt{[MS(E)/2*(1/n_i+1/n_j)]}$ - (Kramer 1956)

$MS(E)$ is the mean square error of the effects A and B with degrees of freedom $v = ab(n-1)$, and $q_{\alpha}(t,v)$ is the upper-tail critical value of the studentized range for comparing t different populations. The symbols n_i, and n_j are the number of observations in samples i and j respectively and may not be equal. The error rate that is controlled is an experimentwise error rate. Thus, the probability of observing an experiment with one or more pairwise comparisons falsely declared significant is specified at α.

Ranking of LSM from the highest to the lowest and using Tukey pairwise comparisons provide a methodology for classifying environmental regions. In certain cases a pair (or set) of regions may not be significantly different from each other, however, the regions need to be classified into groups and using Tukey pairwise comparisons alone may not accomplish that. What is needed is a procedure that uses, in combination with hypothesis testing, ideas of cluster analysis

(Hinkelmann and Kempthorne 1994). One such method was developed by Calinski and Corsten (1985), which is based on an extension of the studentized range procedure. The procedure is a stepwise procedure referred to as a hierarchical agglomerative procedure which uses ordinary distance as a working criterion. In the procedure, once a treatment is included in a hierarchy, it will not be deleted in a subsequent step. In each step, two adjacent clusters (each or both consisting possibly of one element only) are combined to form a new cluster.

The algorithm starts with t clusters (or regions), represented by service life means, $\hat{y}_{i.}$(i = 1,2,…,t), arranged in increasing (or decreasing) order. At the first step the two closest regions means, as measured by the smallest $|\hat{y}_{i.} - \hat{y}_{i'.}|$, are combined to form one cluster and the range $R_1 = |\hat{y}_{i.} - \hat{y}_{i'.}|$ is compared with the critical value $C_\alpha = Q_{\alpha,t,t(r-1)}\sqrt{(MS(E)/r)}$ for a given α. $Q_{\alpha,t,t(r-1)}$ is the upper α 100% point of the studentized range distribution for t independent random variables with sample size r and $t(r-1)$ degrees of freedom. With unequal sample sizes r is the harmonic mean.

At each following step a new cluster is formed by combining two adjacent clusters with the smallest range. The range R_s at step s ($1 \leq s \leq t-1$) is then compared with the critical value C_α. If $R_s > C_\alpha$ then the process stops and the clustering obtained at step s-1 will be the accepted grouping of the treatments. The groups thus formed are considered to be internally homogeneous with the studentized range test at the significance level α (Hinkelmann and Kempthorne 1994). The groups established may not necessarily have significantly different means, however, cluster analysis procedure provides a methodology to establish groups without violating any multiple comparison procedure results. By using a fixed α, the probability of terminating too early, and hence accepting too many homogeneous groups is bounded by α. The choice of α is important and a value of 0.10 may not be unreasonable (Hinkelmann and Kempthorne 1994).

3.3.7.2.9 Service Life Determination

The procedure in Section 3.3.7.2.8 was used to determine which regions of the state have higher deterioration rates (or shorter service lives) for similar elements subjected to the same deterioration levels. After the effect of the regions were analyzed, the least square mean service lives and standard errors for the selected bridge elements in each region of the state were determined. The least squares mean is one for which the sum of the squared deviations of each data point from the mean is minimum (Howell 1992, p.34). It represents the predicted value for a particular factor level combination (SAS 2000). The standard error is the standard deviation of the predicted means. The mean bridge element service lives are improved estimates having initially determined factors that potentially could impact their magnitudes and ensuring the validity of the regions used. The estimated service lives are region-specific and may not be applicable in another region which may have different environmental effects. Means and standard deviations of the elements were also estimated.

3.3.7.2.10 Bridge Element Data Size

In order to make the correct inferences from the statistical analyses outlined above, it was necessary to determine the minimum statistically significant sample sizes. There are approximately 13,000 bridges in Virginia based on the data provided by VDOT. As discussed in Section 3.3.1 entitled “Identification of Environmental Regions”, there are six (6) climatic (environmental) regions. Two (2) levels of deterioration condition factors were previously identified in Table 3.11. The number of data cells is (6x2=12). Each cell requires a minimum sample size. A cell data size of more than 15 was used for each combination of deterioration level and a specific region resulting in more than 30 data points in each region. Numerous statistical studies conducted over the years suggest that the Central Limit Theorem (CLT) holds when the sample size is greater than 30 (Ott 1993, p.181). CLT states that the distribution of sample means from a population with mean μ and standard deviation σ, is approximately normal with mean μ and standard deviation $\sigma/\sqrt{n}$. One of the assumptions in ANOVA is that the samples are taken from a normal population. CLT still holds for symmetric populations when the sample size is less than 30 (Ott 1993, p.182). In addition, the assumptions of ANOVA hold for a t-test of two populations with a combined data size greater than 30 (Ott 1993, p.268).

Therefore:
Number of deterioration levels = 2
Number of environmental regions = 6
Number of data set cells = 2 x 6 = 12
Minimum sample size per cell > 15
Minimum total number of observations > 2 x 6 x 15 = 180 for either concrete deck or steel girder paint analysis.

Appendix C and Appendix D contain the complete results of the SAS (2000) analyses. A detailed discussion of the results can be found in Chapter 4.

3.3.7.2.11 Summary

An outline of the procedures for identifying qualifying bridges and the data formats have been discussed. Some of the bridges built in the same time frame with the same material composition as the final group of bridges were subsequently excluded from the study due to lack of reliable data and inadequate data sizes suitable for statistical analyses. A specific group of bridges from a specific time period were selected for this study to ensure consistent design and construction specifications and provide a basis for comparing their performances due to their locations within the environmental regions of the state of Virginia. The statistical methods used in the study were also outlined. The procedures for determining the effects of the six environmental regions and deterioration levels on estimated mean service lives of concrete deck and steel girder paint were also outlined. The least squares mean (LSM) service lives of concrete deck and steel girder paint with their standard errors for each region with either deterioration level 1 or 2 are part of the expected results of the analyses. Ranking the LSM and using the results of pairwise comparisons allows the environmental regions to be classified as benign, low, moderate, or severe. In some instances it may be necessary to apply the Calinski-Corsten procedure to establish environmental classifications.

Chapter 4: ANALYSES AND DISCUSSION OF RESULTS

4.1 Introduction

A total of 476 steel girder bridges were included in this study with 228 bridges for deck analysis and 248 bridges for girder paint analysis. None of the selected bridges in the study was used for both deck and paint service life analysis. Figure 4.1 shows a flowchart detailing the various steps employed in the total analyses of either the concrete deck or steel girder paint data sets. Appendix C and Appendix D contain the SAS output of the analyses of the bridge data for concrete deck and steel girder paint respectively. A total of 10 analyses were performed, with five analyses each on the bridge concrete deck and the girder paint service life data. Means and standard deviations for both the concrete deck and steel girder paint were also computed. Relevant portions of the SAS results are tabulated within the various sections of the following discussions. There were two independent variables for both the deck and the paint analyses: the environmental factor and the deterioration factor. The environmental factor had six (6) divisions or regions and the deterioration factor had two (2) levels.

The environmental factor regions were assigned as follows:

- Tidewater (TW) – region 1
- Eastern Piedmont (EP) – region 2
- Western Piedmont (WP) - region 3
- Northern (N) – region 4
- Central Mountain (CM) – region 5
- Southwestern Mountain (SM) – region 6

The deterioration factor had two levels and were assigned as follows:

- Deterioration Level 1
- Deterioration Level 2

The common characteristics of the deterioration levels were simple span steel bridges, built between the year 1960 through 1979, bare bars in deck, no protective membrane, and deck wearing surface made of concrete with approximately two inches of clear cover.

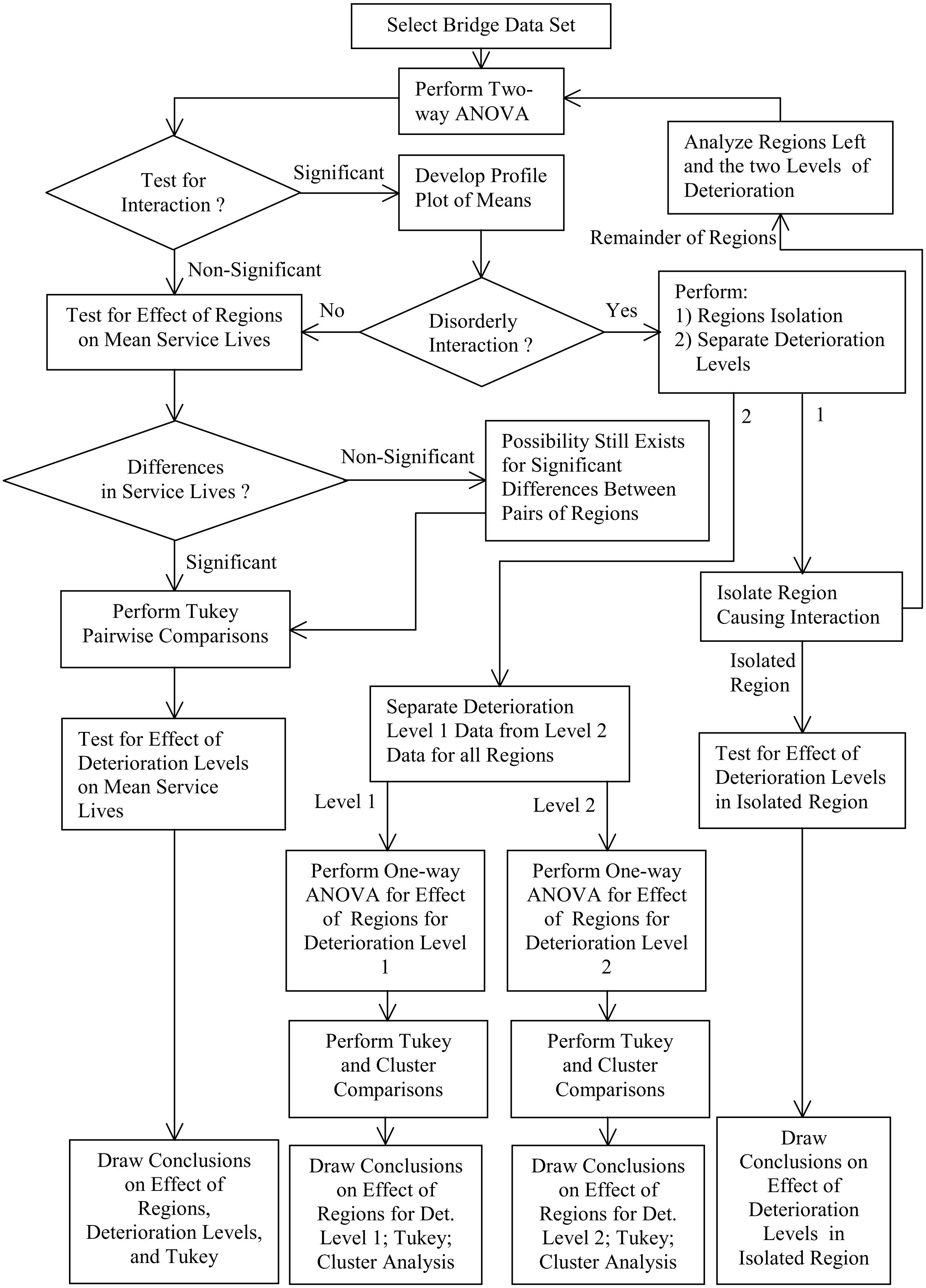


Figure 4.1: Flow Chart for Statistical Analyses of Concrete Deck and Girder Paint

The distinguishing characteristic was that deterioration level 1 had ADT less than or equal to 5,000 and deterioration level 2 had ADT above 5,000.

Based on the statistical model outlined in Section 3.3.7.2 entitled "Statistical Model", three effects of significance were explored. They were the effect due to the environmental regions, the effect due to the deterioration levels, and the effect due to interactions between the regions and the levels of deterioration. The data sets for both the deck and the paint were unbalanced, i.e., number of observations per cell were not equal for all combinations of regions and deterioration levels. Consequently, the Type III sums of squares in SAS ANOVA was used in making decision about the tests for effects. All ANOVA tests were based on an $\alpha = 0.05$, which is the probability of falsely rejecting the null hypothesis, typically a hypothesis of equality of means. The value of $\alpha = 0.05$ is a commonly acceptable risk level.

4.2 Deck Analyses Results

Analysis #1:

The first test of significance was the test for interaction between environmental regions and deterioration levels.

ANOVA (6x2) Cross-Classification for Deck

Results:

> Test for interaction indicated a significant interaction with $p = 0.0002$ which was less than a given $\alpha = 0.05$ (refer Table 4.1). Given the significant interaction, test for effect of main effect (regions, deterioration levels) may not be appropriate.

Table 4.1: Deck – Two-way ANOVA for Six Regions with Two Deterioration Levels

Source	**DF**	**SS**	**Mean Square**	**F Value**	**Pr > F**
Model	11	652.9888	59.3626	3.88	<.0001
Error	216	3302.6383	15.2899		
Corrected Total	227	3955.6272			
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
region	5	182.2106	36.4421	2.38	0.0394
det_factor	1	45.2864	45.2864	2.96	0.0867
region*det_factor	5	384.3385	76.8677	5.03	**0.0002**

A profile plot of the least square means versus regions for each deterioration level was constructed to determine whether a test for main effect was appropriate (refer Figure 4.2). The least square mean deck service lives and their corresponding standard errors for each environmental region with either deterioration level 1 or level 2 are tabulated in Table 4.2. The profile plot showed a "disorderly" interaction and therefore a test for main effect was not appropriate. This was important because in the presence of "disorderly" interaction, the effects of main effects may not be detected when they are present (Ott 1993, p. 888). After observing the profile plot, the decision was made to analyze the data for region 4 (Northern) separate from the rest. This resulted in a 5x2 ANOVA Cross-Classification and a 1x2 or a two-sample t-test. These were analyzed and discussed in the next section.

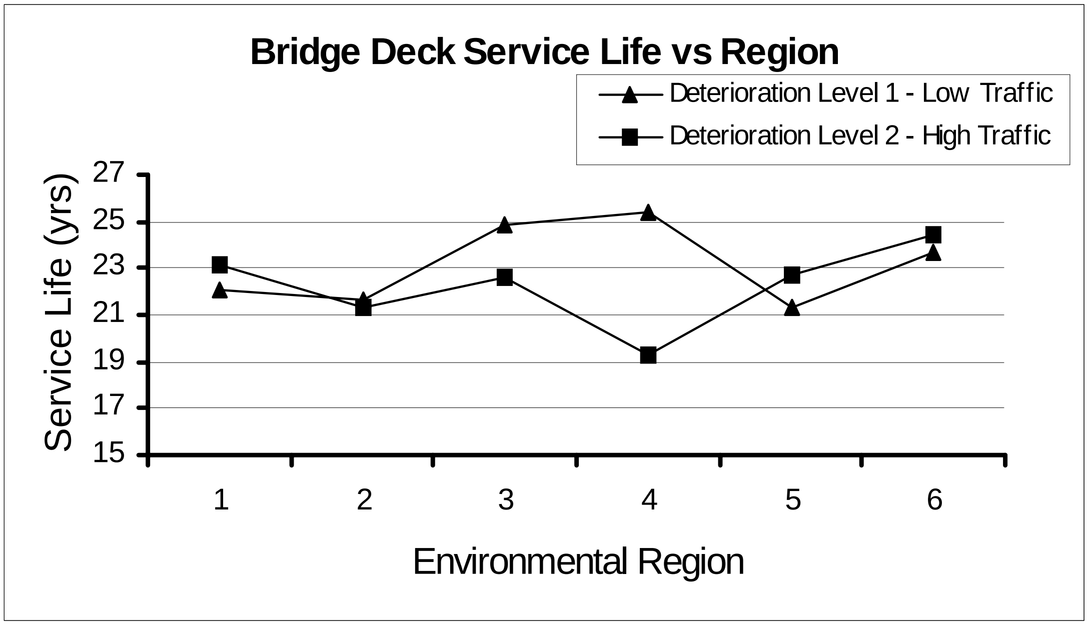


Figure 4.2: Profile Plot of Deck Service Life Means

Table 4.2: Deck LSM Service Lives and Standard Errors per Region

Region	Environmental Region Number	Deterioration Level	Least Square Mean (yrs)	Standard Error (yrs)
Tidewater	1	1	22.1	0.9
	1	2	23.2	0.8
Eastern Piedmont	2	1	21.6	0.9
	2	2	21.4	0.8
Western Piedmont	3	1	24.8	1.0
	3	2	22.6	0.9
Northern	4	1	25.4	1.0
	4	2	19.3	0.8
Central Mountain	5	1	21.4	0.9
	5	2	22.8	1.0
Southwestern Mountain	6	1	23.7	1.0
	6	2	24.4	0.8

The least square mean deck service lives and their corresponding standard errors for either deterioration level 1 or level 2 are tabulated in Table 4.3.

Table 4.3: Deck LSM Service Life and Standard Error per Deterioration Level

Deterioration Level	Least Square Mean (yrs)	Standard Error (yrs)
1	23.2	0.4
2	22.3	0.4

The mean deck service lives and their corresponding standard deviations for either deterioration level 1 or level 2 are tabulated in Table 4.4.

Table 4.4: Deck Mean Service Lives and Standard Deviations per Region

Region	Environmental Region Number	Deterioration Level	Mean (yrs)	Standard Deviation (yrs)
Tidewater	1	1	22.1	4.4
	1	2	23.2	3.1
Eastern Piedmont	2	1	21.6	4.8
	2	2	21.4	2.5
Western Piedmont	3	1	24.8	4.6
	3	2	22.6	4.2
Northern	4	1	25.4	5.5
	4	2	19.3	3.1
Central Mountain	5	1	21.4	3.7
	5	2	22.8	2.9
Southwestern Mountain	6	1	23.7	5.2
	6	2	24.4	3.1

The mean deck service life and the corresponding standard deviation for either deterioration level 1 or level 2 are tabulated in Table 4.5.

Table 4.5: Deck Mean Service Life and Standard Deviation per Deterioration Level

Deterioration Level	Mean (yrs)	Standard Deviation (yrs)
1	23.1	4.9
2	22.3	3.5

Analysis #2:

ANOVA (5x2) Cross-Classification for Deck

Results:

Test for interaction indicated no significant interaction between the remaining regions and the deterioration levels with p = 0.3007 which was greater than a given α = 0.05 (refer Table 4.6). Test for effect of region or deterioration level was appropriate.

Table 4.6: Deck – Two-way ANOVA for Five Regions with Two Deterioration Levels

Source	**DF**	**SS**	**Mean Square**	**F Value**	**Pr > F**
Model	9	265.4068	29.4896	2.01	0.0407
Error	179	2627.8313	14.6806		
Corrected Total	188	2893.2381			
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
region	4	176.8508	44.2127	3.01	**0.0195**
det_factor	1	0.9021	0.9021	0.06	**0.8045**
region*det_factor	4	72.0975	18.0244	1.23	**0.3007**

Test for effect of region on service lives for deck was significant with p = 0.0195 which was less than a given α = 0.05 (refer Table 4.6). The null hypothesis of equal means was rejected. This implied significant differences in the mean service lives of bridge decks in the five regions due to environmental region effects.

Test for effect of deterioration levels on mean service lives for deck was not significant with p = 0.8045 which was more than a given $\alpha = 0.05$ (refer Table 4.6). The null hypothesis of equal means was not rejected. This implied no significant differences in the mean service lives of bridge decks due to the effect of the two levels of deterioration.

Tukey pairwise comparison of regions was significant for one (1) pair 2-6 (EP–SM) (refer Table 4.7).

Table 4.7: Deck - Tukey Comparisons of Five Regions with Deterioration Levels 1 and 2

Least Squares Means for effect region
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: serv_life

Region	**1**	**2**	**3**	**5**	**6**
1		0.6660	0.7718	0.9653	0.4812
2	0.6660		0.1071	0.9710	**0.0265**
3	0.7718	0.1071		0.4079	0.9953
5	0.9653	0.9710	0.4079		0.1782
6	0.4812	0.0265	0.9953	0.1782	

Regions 2 and 6 were mainly responsible for the differences in the mean service lives due to environmental region effects. This was represented as follows after ranking the means from the highest to the lowest:

Region 6 3 1 5 2

Expressing in terms of the actual region names:

Region SM WP TW CM EP

All regions not underlined by a common line had service life means that were significantly different from each other. Therefore, region 2 (EP) LSM service life was significantly less than region 6 (SM) LSM service life.

Analysis #3:

Two-sample t-test for Region 4 (Northern)

Data from region 4 was tested for the effect of the deterioration levels after performing the 5x2 ANOVA Cross-Classification above.

Results:

The first step was a test for the equality of variance which yielded a significant value of p = 0.0137 which was less than a given $\alpha = 0.05$ (refer Table 4.8). The null hypothesis was rejected and the decision made to use unequal variances in the t-Test for the effect of the deterioration levels.

Using unequal variance assumption, test for effect of deterioration levels on region 4 deck yielded p-value of 0.0006 which was less than a given $\alpha = 0.05$ (refer Table 4.8). This implied significant differences in the mean service lives of the bridge decks due to effect of levels of deterioration.

Table 4.8: Deck - t-Test for Northern Region

Variable	**Method**	**Variances**	**DF**	**T Value**	**Pr > |t|**
serv_life	Pooled	Equal	37	4.41	<.0001
serv_life	Satterthwaite	Unequal	21.6	4.00	**0.0006**
serv_life	Cochran	Unequal	.	4.00	0.0010
Equality of Variances					
Variable	**Method**	**Num DF**	**Den DF**	**F Value**	**Pr > F**
serv_life	Folded F	15	22	3.18	**0.0137**

Analyses #4 and #5:

Two independent one-way ANOVAs

For each level of deterioration combined with the six environmental regions, a one-way ANOVA was performed.

Results:

For regions and deterioration level 1, test for effect of regions on mean service lives yielded a p-value is 0.0585 which was more than a given α of 0.05 (refer Table 4.9). The null hypothesis of equal means was not rejected. This implied no significant difference in the mean service lives of the deck due to effect of the environmental regions for deterioration level 1.

Table 4.9: Deck – One-way ANOVA for Deterioration Level 1

Source	DF	SS	Mean Square	F Value	Pr > F
Model	5	248.0527	49.6105	2.22	0.0585
Error	94	2099.7373	22.3376		
Corrected Total	99	2347.7900			
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
region	5	248.0527	49.6105	2.22	**0.0585**

Tukey pairwise comparison showed no significant pairwise comparison between the regions (refer Table 4.10). The p-values in the table all exceed α of 0.05.

Table 4.10: Deck – Tukey Comparisons for Six Regions with Deterioration Level 1

Least Squares Means for effect region
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: serv_life

Region	1	2	3	4	5	6
1		0.9996	0.5765	0.3409	0.9970	0.9311
2	0.9996		0.3665	0.1826	1.0000	0.7959
3	0.5765	0.3665		0.9990	0.2955	0.9845
4	0.3409	0.1826	0.9990		0.1403	0.9005
5	0.9970	1.0000	0.2955	0.1403		0.7160
6	0.9311	0.7959	0.9845	0.9005	0.7160	

For regions and deterioration level 2, test for effect of regions on mean service lives yielded a significant p-value of 0.0001 which was less than a given α of 0.05 (refer Table 4.11). The null hypothesis of equal means was rejected. This implied significant differences in the mean service lives of the deck due to effect of the environmental regions for deterioration level 2.

Table 4.11: Deck – One-way ANOVA for Deterioration Level 2

Source	DF	SS	Mean Square	F Value	Pr > F
Model	5	367.8177	73.5635	7.46	<.0001
Error	122	1202.9009	9.8598		
Corrected Total	127	1570.7187			
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
region	5	367.8178	73.5635	7.46	**<.0001**

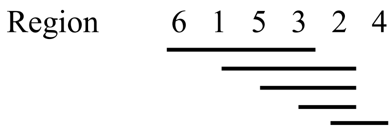
Tukey pairwise comparison showed significant pairwise comparison for five (5) pairs of regions (refer Table 4.12)

Table 4.12: Deck – Tukey Comparisons of Six Regions with Deterioration Level 2

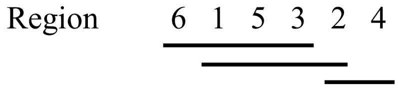
Least Squares Means for effect region
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: serv_life

Region	1	2	3	4	5	6
1		0.3872	0.9920	**0.0008**	0.9984	0.7363
2	0.3872		0.8324	0.2458	0.7600	**0.0124**
3	0.9920	0.8324		**0.0172**	1.0000	0.4248
4	0.0008	0.2458	0.0172		**0.0126**	**<.0001**
5	0.9984	0.7600	1.0000	0.0126		0.5522
6	0.7363	0.0124	0.4248	<.0001	0.5522	

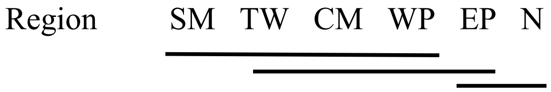
The pairs of regions were 6-4; 6-2; 5-4; 4-3; and 4-1 (SM-N, SM-EP, CM-N, N-WP, and N-TW). All regions were responsible for the differences in the mean service lives of the decks in the regions. This was represented as follows after ranking the means from the highest to the lowest:



This can be simplified to:



Expressing in terms of actual region names:



All regions not underlined by a common line have mean service lives that were significantly different from each other. Therefore, the LSM service of region 2 (EP) and region 4 (Northern) were not significantly different. Also, the LSM service life of region 4 (N) and region 2 (EP) were significantly less than the mean service lives of regions 6, 1, 5, and 3 (SM, TW, CM, and WP respectively). In addition, the LSM service life of region 2 (EP) was significantly less than the mean service life of region 6 (SM).

Table 4.13 is a summary of the results of analyses #1 through #5 for the concrete deck discussed above.

Table 4.13: Summary of Deck Analyses Results

Analysis Type	ANOVA Results	Tukey Pairwise Comparisons of Regions	Comments
Analysis #1: 6x2 Cross-Classification Between Regions and Deterioration Levels.	Significant Interaction Between Regions and Deterioration Levels. Hence Main Effects not Tested.	Not Recommended.	Region 4 (N) Lowest LSM in State for Deterioration Level 2.
Analysis #2: 5x2 Cross-Classification Between Regions (TW, EP, WP, CM, SM) and Deterioration Levels.	No Significant Interaction. Significant Regional Effect. Non-Significant Deterioration Effect.	Significant for 1 pair : Regions 2-6 (EP-SM).	Service Lives Affected by Regional but not Deterioration Effects.
Analysis #3: 2-Sample t-Test for Effect of Deterioration Levels in Region 4 (N).	Significant Effect due to Deterioration Levels.	Not Applicable.	Service Lives Affected Differently by Deterioration Levels.
Analysis #4: One-way ANOVA for Regions with Deterioration Level 1.	Non-significant Effect due to Regions.	No Significant Comparisons.	Service Lives not Affected by Regional Effects.
Analysis #5: One-way ANOVA for Regions with Deterioration Level 2.	Significant Effect due to Regions.	Significant for 5 pairs: 6-4, 6-2, 5-4, 4-3, 4-1 (SM-N, SM-EP, CM-N, N-WP, N-TW).	Service Lives Affected by Regional Effects.

4.3 Paint Analyses Results

The first test of significance was the test for interaction between environmental regions and deterioration levels.

Analysis #1:

ANOVA (6x2) Cross-Classification for Paint

Results:

> Test for interaction indicated significant interaction with a p-value of 0.0002 which was less than a given value α of 0.05 (refer Table 4.14). Test for effect of main effect (regions or deterioration levels) may not be appropriate. A profile plot of the least square means versus regions for each deterioration level was developed to determine whether a test for main effect was appropriate (refer Figure 4.3). Similar to the profile plot for the deck, the profile plot for the paint showed a "disorderly" interaction and therefore a test for main effect was not appropriate. By observing the profile plot, the decision was made to analyze the data for region 1 (Tidewater) separate from the rest. This resulted in a 5x2 ANOVA Cross-Classification and a 1x2 or a two-sample t-Test. These were analyzed and discussed in the next section.

Table 4.14: Paint – Two-way ANOVA for Six Regions with Two Deterioration Levels

Source	DF	SS	Mean Square	F Value	Pr > F
Model	11	1796.9431	163.3585	6.31	<.0001
Error	236	6105.0408	25.8688		
Corrected Total	247	7901.9838			
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
region	5	846.1591859	169.2318372	6.54	<.0001
det_factor	1	325.0894406	325.0894406	12.57	0.0005
region*det_factor	5	643.9295114	128.7859023	4.98	**0.0002**

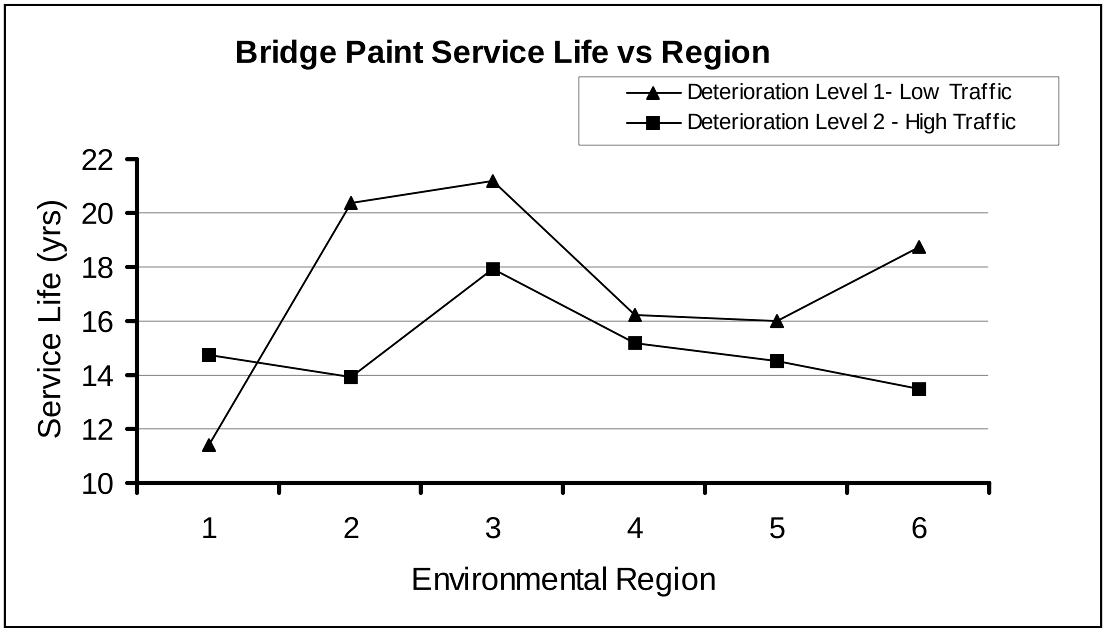


Figure 4.3: Profile Plot of Paint Service Life Means

Table 4.15: Paint LSM Service Lives and Standard Errors per Region

Region	Environmental Region Number	Deterioration Level	Least Square Mean (yrs)	Standard Error (yrs)
Tidewater	1	1	11.4	1.3
	1	2	14.7	0.9
Eastern Piedmont	2	1	20.4	1.1
	2	2	13.9	1.2
Western Piedmont	3	1	21.2	1.3
	3	2	17.9	1.3
Northern	4	1	16.2	1.3
	4	2	15.2	1.0
Central Mountain	5	1	16.0	1.2
	5	2	14.5	1.3
Southwestern Mountain	6	1	18.8	1.1
	6	2	13.5	0.9

Another observation from the cell profile plot was that region 1 (Tidewater region) had the lowest least square mean girder paint service life for deterioration level 1 (11.4 years). This service life was also the lowest in the state across both deterioration levels.

The least square mean steel girder paint service lives and their corresponding standard errors for each environmental region with either deterioration level 1 or level 2 are tabulated in Table 4.15. The least square mean steel girder paint service lives and their corresponding standard errors for both deterioration level 1 and level 2 are tabulated in Table 4.16.

Table 4.16: Paint LSM Service Life and Standard Error per Deterioration Level

Deterioration Level	Least Square Mean (yrs)	Standard Error (yrs)
1	17.3	0.5
2	15.0	0.4

The mean steel girder paint service lives and their corresponding standard deviations for each environmental region with either deterioration level 1 or level 2 are tabulated in Table 4.17.

Table 4.17: Paint Mean Service Lives and Standard Deviations per Region

Region	Environmental Region Number	Deterioration Level	Mean (yrs)	Standard Deviation (yrs)
Tidewater	1	1	11.4	3.8
	1	2	14.7	4.9
Eastern Piedmont	2	1	20.4	4.3
	2	2	13.9	4.2
Western Piedmont	3	1	21.2	5.1
	3	2	17.9	5.3
Northern	4	1	16.2	6.9
	4	2	15.2	3.6
Central Mountain	5	1	16.0	3.6
	5	2	14.5	3.4
Southwestern Mountain	6	1	18.8	8.4
	6	2	13.5	5.3

The mean steel girder paint service life and the corresponding standard deviation for either deterioration level 1 or 2 is tabulated in Table 4.18.

Table 4.18: Paint Mean Service Life and Standard Deviation per Deterioration Level

Deterioration Level	Mean (yrs)	Standard Deviation (yrs)
1	17.6	6.4
2	14.8	4.7

Analysis #2:
ANOVA (5x2) Cross-Classification for Paint

Results:

Test for interaction indicated no significant interaction between the remaining regions and the deterioration levels with a p-value of 0.0874 which was greater than a given α of 0.05 (refer Table 4.19). Test for effect of regions or deterioration levels (main effect) was appropriate.

Test for effect of region on service lives for paint was significant with a p-value of 0.0066 which was less than a given α of 0.05 (refer Table 4.19). The null hypothesis of equal means was rejected. This implied significant differences in the mean service lives of girder paint in the five regions due to environmental region effects.

Test for effect of deterioration levels on mean service lives for girder paint was significant with a p-value of 0.0001 which was less than a given α of 0.05 (refer Table 4.19). The null hypothesis of equal means was rejected. This implied significant differences in the mean service lives of girder paint due to the effect of the two levels of deterioration.

Table 4.19: Paint – Two-way ANOVA for Five Regions with Two Deterioration Levels

Source	DF	SS	Mean Square	F Value	Pr > F
Model	9	1348.6454	149.8495	5.56	<.0001
Error	190	5124.6345	26.9717		
Corrected Total	199	6473.2800			
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
region	4	396.0341	99.0085	3.67	**0.0066**
det_factor	1	580.1949	580.1949	21.51	**<.0001**
region*det_factor	4	222.4569	55.6143	2.06	**0.0874**

Tukey pairwise comparison of regions was significant for three (3) pairs 4-3, 5-3, and 6-3 (refer Table 4.20).

Table 4.20: Paint - Tukey Comparisons of Five Regions with Deterioration Levels 1 and 2

Least Squares Means for effect region
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: serv_life

Region	2	3	4	5	6
2		0.2843	0.7182	0.5310	0.8925
3	0.2843		**0.0161**	**0.0087**	**0.0335**
4	0.7182	0.0161		0.9965	0.9944
5	0.5310	0.0087	0.9965		0.9433
6	0.8925	0.0335	0.9944	0.9433	

The pairs of regions are 4-3, 5-3, and 6-3 (N-WP, CM-WP, and SM-WP). Regions 3, 4, 5 and 6 were mainly responsible for the differences in the mean service lives due to environmental region effects. This was represented as follows after ranking the means from the highest to the lowest:

Region 3 2 6 4 5

Expressing in terms of actual region names:

Region WP EP SM N CM

All regions not underlined by a common line had service life means that were significantly different from each other. Therefore, regions 6, 4, and 5 (SM, N and CM respectively) mean paint service lives were significantly less than region 3 (WP) mean paint service life due to environmental region effects.

Analysis #3:

Two-sample t-Test for Region 1 (Tidewater Region)

Data from region 1 was tested for the effect of the deterioration levels after performing the 5x2 ANOVA Cross-classification above.

Results:

The first step was a test for the equality of variance which yielded a non-significant p-value of 0.3031 which was more than a given α = 0.05 (refer Table 4.21). The null hypothesis was not rejected and the conclusion made to use equal variances in the t-Test for the effect of the deterioration levels.

Using equal variance assumption, test for effect of deterioration levels on region 1 paint yielded p-value of 0.0248 which was less than a given α of 0.05 (refer Table 4.21). This implied significant differences in the mean service lives of the girder paint due to effect of the two levels of deterioration.

Table 4.21: Paint - t-Test for Tidewater Region

Variable	**Method**	**Variances**	**DF**	**t Value**	**Pr > |t|**
serv_life	Pooled	Equal	46	-2.32	**0.0248**
serv_life	Satterthwaite	Unequal	37.6	-2.52	0.0159
serv_life	Cochran	Unequal	.	-2.52	0.0204
Equality of Variances					
Variable	**Method**	**Num DF**	**Den DF**	**F Value**	**Pr > F**
serv_life	Folded F	31	15	1.65	**0.3031**

Analyses #4 and #5:

Two independent one-way ANOVAs

For each level of deterioration combined with the six environmental regions, a one-way ANOVA was performed.

Results:

For regions and deterioration level 1, test for effect of regions on mean paint service lives yielded a p-value is 0.0001 which was less than a given α of 0.05 (refer Table 4.22). The null hypothesis of equal means was rejected. This implied significant differences in the mean service lives of the girder paint due to effect of the environmental regions for deterioration level 1.

Table 4.22: Paint - One-way ANOVA for Deterioration Level 1

Source	DF	SS	Mean Square	F Value	Pr > F
Model	5	1094.5055	218.9011	6.81	<.0001
Error	102	3278.0407	32.1376		
Corrected Total	107	4372.5463			
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
region	5	1094.5055	218.9011	6.81	**<.0001**

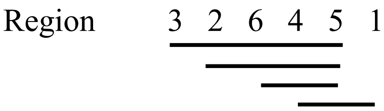
Tukey pairwise comparisons showed significant pairwise comparisons between three (3) pairs of regions (refer Table 4.23).

Table 4.23: Paint – Tukey Comparisons of Six Regions with Deterioration Level 1

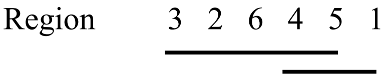
Least Squares Means for effect region
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: serv_life

Region	1	2	3	4	5	6
1		**<.0001**	**<.0001**	0.1768	0.1994	**0.0028**
2	<.0001		0.9981	0.2127	0.1585	0.9331
3	<.0001	0.9981		0.1354	0.1001	0.7942
4	0.1768	0.2127	0.1354		1.0000	0.7577
5	0.1994	0.1585	0.1001	1.0000		0.6837
6	0.0028	0.9331	0.7942	0.7577	0.6837	

The regions were 2-1, 3-1, and 6-1 (EP-TW, WP-TW, and SM-TW). This was represented as follows after ranking the least square mean service lives of paint from the highest to the lowest:



This can be simplified to:



Expressing in terms of actual region names:

Region 1 (TW) mean steel paint service life was significantly less than regions 3, 2 and 6 (WP, EP and SM respectively) for deterioration level 1.

For regions and deterioration level 2, test for effect of regions on mean service lives yielded a non-significant p-value of 0.0609 which was more than a given α of 0.05 (refer Table 4.24). The null hypothesis of equal means was not rejected. This implied no significant differences in the mean service lives of the girder paint in the six regions for deterioration level 2.

Table 4.24: Paint – One-way ANOVA for Deterioration Level 2

Source	**DF**	**SS**	**Mean Square**	**F Value**	**Pr > F**
Model	5	229.1357	45.8271	2.17	0.0609
Error	134	2827.0000	21.0970		
Corrected Total	139	3056.1357			
Source	**DF**	**Type III SS**	**Mean Square**	**F Value**	**Pr > F**
region	5	229.1357	45.8271	2.17	**0.0609**

Tukey pairwise comparison showed significant pairwise comparison for one (1) pair (refer Table 4.25). The pair of regions was 6-3 (SM-WP).

Table 4.25: Paint - Tukey Comparisons of Six Regions with Deterioration Level 2

Least Squares Means for effect region
Pr > |t| for H0: LSMean(i)=LSMean(j)
Dependent Variable: serv_life

Region	1	2	3	4	5	6
1		0.9899	0.2060	0.9988	1.0000	0.9039
2	0.9899		0.1132	0.9388	0.9988	0.9998
3	0.2060	0.1132		0.4071	0.2850	**0.0258**
4	0.9988	0.9388	0.4071		0.9970	0.7387
5	1.0000	0.9988	0.2850	0.9970		0.9821
6	0.9039	0.9998	0.0258	0.7387	0.9821	

It should be noted that the overall comparison showed no significant differences, however, the pairwise comparison showed a significant difference between regions 6 and 3. This was represented as follows after ranking the means from the highest to the lowest:

Region 3 4 1 5 2 6

Expressing in terms of actual region names:

Region WP N TW CM EP SM

Therefore, the mean girder paint service life of region 6 (SM) was significantly less than the mean girder paint service life of region 3 (WP) for deterioration level 2.

Table 4.26 is a summary of the results of analyses #1 through #5 for the steel girder paint discussed above.

Table 4.26: Summary of Paint Analyses Results

Analysis Type	ANOVA Results	Tukey Pairwise Comparisons of Regions	Comments
Analysis #1: 6x2 Cross-Classification Between Regions and Deterioration Levels.	Significant Interaction Between Regions and Deterioration Levels. Hence Main Effects not Tested.	Not Recommended.	Region 1 (TW) Lowest LSM in State for Deterioration Level 1.
Analysis #2: 5x2 Cross-Classification Between Regions (EP, WP, N, CM, SM) and Deterioration Levels.	No significant Interaction. Significant Regional Effect. Significant Deterioration Effect.	Significant for 3 pairs : Regions 4-3, 5-3, 6-3 (N-WP, CM-WP, SM-WP).	Service Lives Affected by Regional and Deterioration Effects.
Analysis #3: 2-Sample t-Test for Effect of Deterioration Levels in Region 1 (TW).	Significant Effect due to Deterioration Levels.	Not Applicable.	Service Lives Affected Differently by Deterioration Levels.
Analysis #4: One-way ANOVA for Regions with Deterioration Level 1.	Significant Effect due to Regions.	Significant for 3 pairs : Regions 2-1, 3-1, 6-1 (EP-TW, WP-TW, SM-TW).	Service Lives Affected by Regional Effects.
Analysis #5: One-way ANOVA for Regions with Deterioration Level 2.	No Significant Effect due to Regions (Overall Comparisons).	Significant for 1 pair – Regions 6-3 (SM-WP).	Service Lives Affected by Regional Effects - (Trending).

4.4 Assignment of Environmental Classification

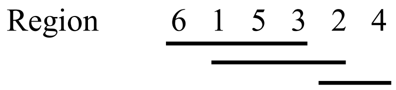
The results from the ranking of the LSM and Tukey pairwise comparisons, and the subsequent application of the Calinski-Corsten procedure, provided a methodology for assigning environmental classification using the terminologies benign (B), low (L), moderate (M) or severe (S). Specifying the bridge element environment in such terms are required inputs for both BMS software programs Pontis and BRIDGIT. A bridge element located in an environmental region classified as low typically will have a longer service life or lower deterioration rate. In contrast, a similar bridge element located in an environmental region classified either as moderate or severe typically will have a shorter service life or a higher deterioration rate, all other deterioration factors being equal. Due to the physical location of the state of Virginia, its topographical features and climatic conditions, a decision was made to only consider low, moderate or severe environments in its environmental classification.

The concrete deck analyses and steel girder paint analyses that showed significant effects due to environmental regions were used to demonstrate the environmental classification system. Deterioration level 1 had ADT less than or equal to 5,000 and was distinguished from deterioration level 2 which had ADT greater than 5,000.

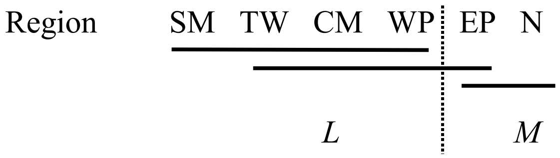
4.4.1 Environmental Classification of Concrete Deck

The one-way ANOVA and Tukey pairwise comparisons for deck analysis with deterioration level 1 had no significant pairwise comparisons. However, the deck analysis with deterioration level 2 had significant comparisons.

Using the one-way ANOVA and Tukey pairwise comparisons for deck analysis with deterioration level 2, the environmental classification was assigned using the following steps:



Or in terms of region names:



Regions 4 (N) and 2 (EP) were assigned moderate environment, and regions 6, 1, 5 and 3 (SM, TW, CM, and WP respectively) were assigned low environment. Regions 1, 5, 3, and 2 (TW, CM, WP, and EP respectively) have LSM that were not significantly different from each other, and regions 6, 1, 5, and 3 (SM, TW, CM, and WP respectively) LSM were not significantly different. Also, regions 2 and 4 (EP and N respectively) LSM service life were not significantly different. The environmental classification assignment was based primarily on the LSM ranking and then Tukey comparisons was used to established clear distinctions. Some regions with non-significant differences have been assigned different environments, e.g. regions 2 (EP) and 3 (WP). It should be emphasized that none of the regions with significant difference were assigned the same classification region. Not adhering to Tukey pairwise comparisons would be a violation of the model developed. However, using this approach in some instances to establish groups of similar effects may not be easily accomplished. The use of cluster analysis in combination with hypothesis testing is recommended.

4.4.1.1 Cluster Analysis of Concrete Deck

Using the ranked LSM for concrete deck for deterioration level 2, the Calinski-Corsten procedure was applied using an α of 0.10 (refer Section 3.3.7.2.8 entitled "Multiple Comparison Procedure"). The Calinski-Corsten procedure is shown in Figure 4.4.

Harmonic mean = $6/(1/23+1/22+1/17+1/23+1/16+1/27) = 20.63$
$MS(E) = 9.86$
$df_{error} = 122$
$Q_{0.1,6,122} = 3.71$ (Pearson and Hartley 1958)
Critical value $C_{0.1} = 3.71*\sqrt{(9.86/20.6)} = 2.57$
Expressing the ranked LSM in their actual values:

Region SM TW CM WP EP N

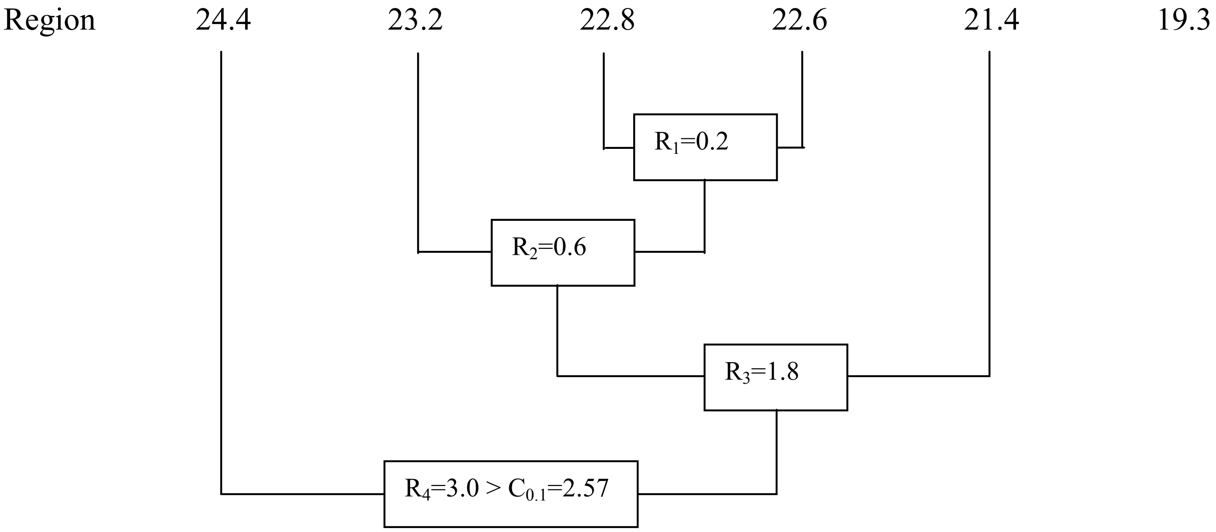


Figure 4.4: Concrete Deck with Deterioration Level 2 - Calinski-Corsten Procedure

Based on Figure 4.4 cluster analysis, three (3) groups can be classified as different. Thus, the environmental classification can be assigned as follows:

Region SM ⋮ TW CM WP EP ⋮ N
L ⋮ *M* ⋮ *S*

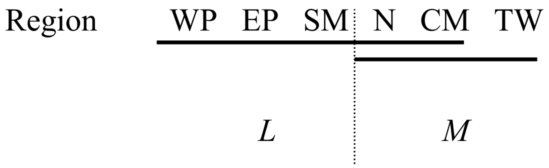
SM was classified low environment; TW, CM, WP and EP were classified moderate environment; and N was classified severe environment.

4.4.2 Environmental Classification of Girder Paint

The environmental region assignment using the results of the steel girder paint for deterioration level 1 can be assigned as follows:

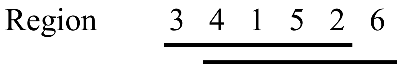
Region $\underline{3\ 2\ 6\ 4\ 5}\ 1$
$\underline{4\ 5\ 1}$

Or in terms of region names:

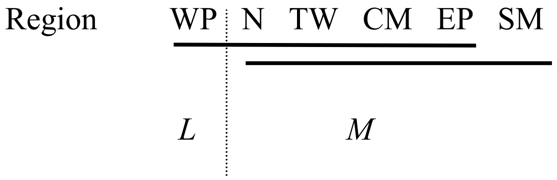


Regions 1, 5 and 4 (TW, CM and N) were assigned moderate environment, and regions 6, 2, and 3 (SM, EP, and WP respectively) were assigned a low environment. Again, the LSM service lives of steel girder paint in regions 3, 2, 6, 4, and 5 (WP, EP, SM, N and CM respectively) were not significantly different but were separated based on the order of the LSM rankings.

Similarly, the environmental region assignment using the results of the steel girder paint for deterioration level 2 can be assigned as follows:



Expressing in terms of actual region names:



WP was assigned low environment and N, TW, CM, EP and SM were assigned moderate environment.

4.4.2.1 Cluster Analyses of Girder Paint

Using the ranked LSM for girder paint for deterioration level 1, the Calinski-Corsten procedure was applied using an α of 0.10 (refer Section 3.3.7.2.8 entitled "Multiple Comparison Procedure"). The Calinski-Corsten procedure is shown in Figure 4.5.

Harmonic mean = 6/(1/16+1/23+1/16+1/16+1/17+1/20) = 17.66

MS(E) = 32.14

$df_{error} = 102$

$Q_{0.1,6,102} = 3.72$ (Pearson and Hartley 1958)

Critical value $C_{0.1} = 3.72*\sqrt{(32.14/17.66)} = 5.02$

Expressing the ranked LSM in their actual values:

Region WP EP SM N CM TW

Region 21.2 20.4 18.8 16.2 16.0 11.4

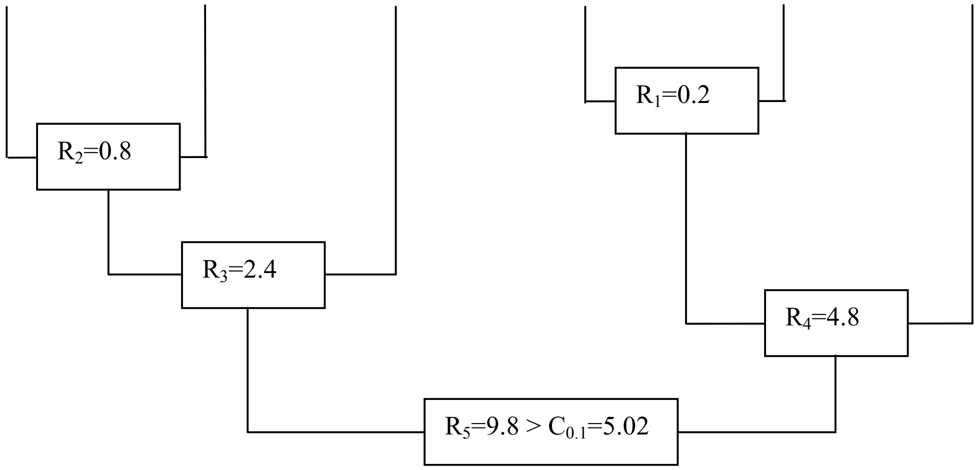


Figure 4.5: Girder Paint with Deterioration Level 1 - Calinski-Corsten Procedure

Based on Figure 4.5 cluster analysis, two (2) groups can be classified as different. Thus, the environmental classification was assigned as follows:

Region WP EP SM ⋮ N CM TW
L ⋮ *M*

WP, EP and SM were classified as low environment and N, CM and TW were classified as moderate environment.

Similarly, using the ranked LSM for girder paint for deterioration level 2, the cluster analysis procedure was applied using an α of 0.10. The Calinski-Corsten procedure is shown in Figure 4.6.

Harmonic mean = 6/(1/32+1/18+1/16+1/27+1/16+1/31) = 21.34
MS(E) = 21.10
df_{error} = 134
$Q_{0.1,6,134}$ = 3.71 (Pearson and Hartley 1958)
Critical value $C_{0.1} = 3.71 * \sqrt{(21.10/21.34)} = 3.69$

Expressing the ranked LSM in their actual values:

Region	WP	N	TW	CM	EP	SM
Region	17.9	15.2	14.7	14.5	13.9	13.5

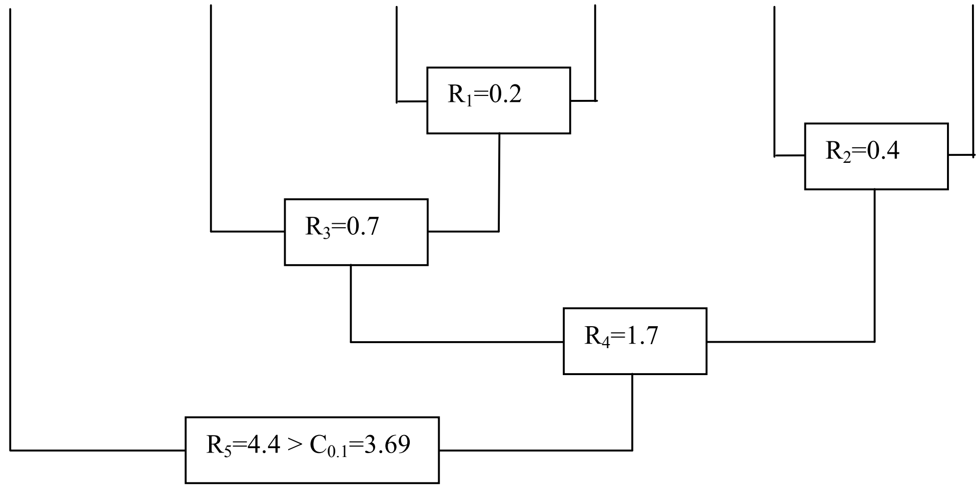


Figure 4.6: Girder Paint with Deterioration Level 2 - Calinski-Corsten Procedure

Based on Figure 4.6 cluster analysis, two (2) groups can be classified as different. Thus, the environmental classification was assigned as follows:

Region	WP	N TW CM EP SM
	L	*M*

WP was classified as low environment and N, TW, CM, EP, and SM were classified as moderate environment.

4.5 Summary

The methodology developed in the study was evaluated using bridge inspection data for the state of Virginia. Five analyses were performed for both the concrete deck and the steel girder paint. SAS (2000) was used to run all 10 analyses. Service life estimates were determined for the concrete deck and the steel girder paint. Using one-way and two-way ANOVAs, the effects of the environmental regions on the estimated mean service lives were analyzed. The one-way ANOVAs were necessary because of significant interaction effects between the regions and deterioration levels for both concrete deck and steel girder paint. More importantly, the results of the one-way ANOVAs were applicable statewide. Tukey pairwise comparisons of regions were performed to determine which pairs were significantly different from each other.

Ranking of LSM service lives and Tukey pairwise comparisons were employed to develop the environmental classification scheme. In this classification procedure, some regions with non-significant differences were assigned different environmental regions solely based on LSM ranking and subjective assignments. Therefore, the Calinski-Corsten procedure was employed to establish a more consistent procedure for classifying the regions into groups of similar effects. The established groups do not necessarily indicate significant differences between the regions in the different groups but the cluster analysis procedure provided a formal methodology for classifying the regions into groups.

Chapter 5: SUMMARY AND CONCLUSIONS

5.1 Introduction

Several factors have been identified as being directly responsible for bridge component or element deterioration. However, the effects of the environment have largely been overlooked or assigned randomly, which may have resulted in biased estimates of bridge component or element service lives. In models where the effect of the environment was recognized, there was no acceptable methodology to assign environmental classifications to the different regions under the bridge agency's jurisdiction. The importance of standardizing the environmental classification system cannot be overlooked. Classifying one region as moderate and another as benign, causes an element in the moderate region to potentially have a higher deterioration rate than a similar element in the benign region, all other factors being equal. High deterioration rates typically result in low service lives.

Most of the current studies on service lives or deterioration rates in BMS deal with the major bridge components such as the deck, superstructure and substructure largely due to the fact that the models being used require discrete data that are currently only available for these three major components. The major components are themselves made up of several elements which because of their different physical and chemical composition exhibit different deterioration rates. One encompassing deterioration rate which in turn determines the service life of the major component may not provide a reliable service life estimate. Therefore, a model based on the three major components may not be able to support effective management systems.

5.2 Summary of Research

The current study developed a methodology for using the existing six regions of the state established by the Virginia State Climatology Office to determine their effects on the mean service lives of selected bridge elements using data from biennial inspection of bridges by state bridge inspectors. The six regions of the state had been established as having different characteristics in terms of topography and climate, including snowfall, rainfall, relative humidity, temperature, and by deduction severity of freezing and thawing cycles. In addition, existing research using regression analysis, Markovian deterioration models and Bayesian estimates had established certain factors such as age, traffic (ADT, ADTT), span, skew, and chloride application as being responsible for the deterioration of major bridge components such as deck, superstructure and substructure.

The methodology used in the research study incorporated the six environmental regions and a group of deterioration levels to determine their effects on the mean service lives of selected bridge elements using statistical analyses. The statistical methods used were Analysis of Variance and Multiple Comparison Procedures. The statistical methods used were capable of detecting the effects of the environmental regions and levels of deterioration on selected bridge concrete decks and steel girder paint. The bridge component and protective system/element (deck and paint respectively), were selected based on their significant share of MR&R budgets. The deck and paint physical conditions were recorded by bridge inspectors using the two basic forms of recording bridge element or component physical conditions mandated by FHWA. The numerical condition coding format is used in classifying major components such as the deck, and the letter condition coding format is used in classifying element/protective system. The year-built for the bridges used in the study ensured that design and construction practices were for the most part consistent. Most of the bridges in the state are under the jurisdiction of VDOT and as such have been designed and built based on the prevailing uniform design and construction specifications. Bridges under the jurisdiction of counties and cities are also designed and built using VDOT standards. Therefore, all bridges used in the current study can be considered as having had the same uniform design, construction standards and specifications. However, due to the fact that different bridge contractors constructed the bridges used in the study, and each potentially impacted the construction process with its unique methods in spite of VDOT prevailing specifications, their impacts on the results of this study cannot be overemphasized.

The distinguishing characteristics of the steel girder bridges used in the research were their locations within the environmental regions and the deterioration factors to which they were subjected. Deterioration factors used in the study included simple span bridges and bridges older than 21 years but less than 41 years old. Sets of deterioration factors formed the deterioration levels. Deterioration level 1 had low traffic volume corresponding to ADT less than or equal to 5,000. Bridges carrying low traffic volumes were classified as being located on Minor Arterial, Collector, and Local roads. In contrast, deterioration level 2 included high traffic volume corresponding to ADT higher than 5,000. Bridges carrying high traffic volumes were classified as being located on Principal Arterial highways, which included the interstates and freeways.

The results of the analyses showed significant interactions between the regions and the deterioration levels for both the concrete deck and steel girder paint. In light of the significant interaction effect, the single effect of regions or deterioration levels was not easily discernible. The profile plots of LSM service life for both the concrete deck and steel girder paint affirmed the interaction effect. Two approaches were subsequently pursued to shed more light on the data collected. One approach was to separate out the region that appeared to contribute significantly to the interaction effect. For the deck data, region 4 (Northern) was separated from the other five regions and analyzed separately (Figure 4.2). For the steel girder paint, region 1 (Tidewater) was separated from the other five regions and analyzed separately (Figure 4.3). The second approach involved separating the data for deterioration level 1 (low traffic) from level 2 (high traffic) for both the concrete deck data and steel girder paint data across all six regions. The separate data were then analyzed independently. Separating one region from the rest and analyzing them independently renders the results inapplicable statewide, except to provide information on those specific regions. This was the case with the first approach. However, the second approach which involved separating deterioration level 1 (low traffic) data from deterioration level 2 (high traffic) data and analyzing them separately is applicable statewide.

The profile plot of the mean service lives for the deck showed that the Northern region, which included Northern Virginia, had the lowest service life in the state for high traffic volume (Figure 4.2). Northern Virginia is the most urban part of the state with very high traffic volumes and consequently relatively heavier de-icing salt use on the highways, which may have contributed significantly to the low deck service life. The profile plot for the steel girder paint showed that the Tidewater region, which is adjacent to the Atlantic Ocean, had the lowest mean paint service life in the state when both low and high traffic volumes are combined (Table 4.15). The impact of the ocean in the Tidewater region with its chloride-laden environment on steel girder paint service lives may have contributed to the low paint service life.

Pairwise comparisons between regions, excluding the Northern region, showed that the Eastern Piedmont and Southwestern Mountain regions had significantly different effects on the service lives of their concrete decks (Table 4.7). The effect of the deterioration levels on the concrete deck was not significant for the five regions tested. With respect to the Northern region, there were significant differences in the mean deck service lives for low and high traffic volumes (Table 4.8). This was expected as high traffic volumes tend to cause more deterioration than low traffic volume in the same region. This is supported by existing research that have used traffic volume as one of the independent variables as discussed in the section entitled "Literature Review".

For decks with low traffic volumes, it was observed that across all six regions, the environmental regional effect was not significant (Table 4.9). In contrast, there were significant differences in the effect due to the environmental regions for decks with high traffic volumes (Table 4.11). Given that all the concrete decks had been exposed to high traffic volumes, differences in the service lives due to the regions were attributed to the characteristics of the individual regions as it relates to climate, topography and possibly de-icing salt usage. Thus, environmental effect was more pronounced for bridges with concrete decks located on high traffic volume highways than low traffic volume highways and this result is applicable statewide.

When the regions were ranked from the highest to the lowest mean for decks with high traffic volumes, Northern region which includes Northern Virginia had the lowest deck mean service life (Table 4.2). Eastern Piedmont which includes the Richmond urban metropolitan area, followed as the next lowest mean deck service life which was not significantly different from the Northern region. The highest mean deck service life was Southwestern Mountain which includes the Bristol district (Table 4.2). There are no major urban areas in this region and therefore among other climatic and topographical factors, salt usage was probably less than in other parts of the state. Tidewater region had the second highest mean deck service life but it was not significantly different from the Eastern Piedmont which had the second lowest mean deck service life.

For the steel girder paint analysis, excluding the Tidewater region, pairwise comparisons between Northern, Western Piedmont, Central Mountain, and Southwestern Mountain regions showed significant differences in steel girder paint mean service lives (Table 4.20). With respect to the Tidewater region alone, there were significant differences in the steel girder mean paint service lives due to low and high traffic volumes (Table 4.21). This was an interesting result since the assumption is that level of traffic may not directly impact steel girder paint.

For low traffic volume, it was observed that there were significant differences in the mean paint service lives due to effect of regions using pairwise comparisons (Table 4.22). However, total analysis showed non-significant differences in the means due to effect of regions for high traffic volume (Table 4.24). Ranking the steel girder mean paint service lives from the highest to the lowest for low traffic volume, the Tidewater region had the lowest mean which was significantly less than three other regions (Table 4.15). The Tidewater region by virtue of its proximity to the Atlantic Ocean with its chloride-laden environment, was expected to be influenced by the ocean and may have contributed to the low paint service life. Western Piedmont region had the highest mean paint service life which was not significantly different from the Central Mountain region which came in second lowest (Table 4.15). For high traffic volume, again Western Piedmont had the highest mean paint service life which was not significantly different from Eastern Piedmont which came in second lowest. Although the Tidewater region was ranked fourth lowest, it was not significantly different from Southwestern Mountain which had the lowest mean paint service life for high traffic volume.

The environmental classification methodology provides bridge agencies with the ability to identify which regions of the state may be classified as having benign, low, moderate or severe environment with respect to a specific bridge element and also provide environmental classification inputs for BMS software programs such as Pontis and BRIDGIT. The environment of the state of Virginia was classified using low, moderate or severe due to its location, topography, and climatic factors. By ranking the LSM and using Tukey pairwise comparison, regions with non-significant differences can be combined using connecting lines and those with significant differences separated. None of the regions with significant difference were assigned the same classification region. Not adhering to Tukey pairwise comparisons would violate the model developed. Using LSM and Tukey comparisons present a classification issue when there are no significant differences between regions that need to be classified. The regions would have been classified into different environmental regions arbitrarily. However, the Calinski-Corsten procedure presented a more formal and consistent approach for classifying the regions with non-significant differences. Using the Calinski-Corsten procedure after the LSM rankings, the environmental regions of the state of Virginia were classified as either low, moderate or severe. The environmental effects on concrete decks with low traffic volumes was not significant and therefore no classification was performed.

Using the Calinski-Corsten procedure for concrete decks with high traffic volumes, the analysis resulted in Southwestern Mountain region being classified as low environment; Tidewater, Central Mountain, Western Piedmont, and Eastern Piedmont regions classified moderate environment; and Northern region classified severe environment (Figure 4.4). For girder paint with low traffic, the Calinski-Corsten procedure classified Western Piedmont, Eastern Piedmont, and Southwestern Mountain regions as low environment and classified Northern, Central Mountain and Tidewater regions as moderate environment (Figure 4.5). For girder paint with high traffic, the Calinski-Corsten procedure classified Western Piedmont as low environment and classified Northern, Tidewater, Central Mountain, Eastern Piedmont, and Southwestern Mountain regions as moderate environment (Figure 4.6).

5.3 Implications of Results

The above observations underscore the importance of accounting for the effect of the environment in service life estimates or deterioration rates for bridge components or elements using bridge inspection data. Such accounting may not be critical if all data is collected within a specific region. However, when such data is derived from multiple regions in the state, as seen from the study results, the effect of the regions may be significant. The environmental classification scheme for the state can be established for most bridge components and elements/protective systems with similar condition data formats. The classification may not be the same for all elements since environmental regions, as seen from the current study, have different effects on different elements given the same deterioration levels.

The estimated mean and standard deviations of element service lives have numerous applications. They can be used as inputs for the bridge software "BridgeLCC" to compute bridge life-cycle cost. Service lives of bridge elements will also aid project level and district level scheduling operations. By reviewing the mean service lives of bridge elements in its jurisdiction and comparing with current age, the remaining service lives can be estimated. This will allow life-cycle profiles of bridge elements to be determined. MR&R operations can subsequently be scheduled based on the life-cycle profiles. In addition, by combining unit costs of repairs to the life-cycle profiles and aggregating the total for a bridge, the life-cycle cost can be estimated. Aggregating the total for a region or district provides scheduling and cost information necessary for entire network management. Currently, there are a number of prediction models that are probability-based (e.g. Markov chains) but do not have extensive data to fully support the models. The statistical model employed in the research study provides valuable estimates for these probability-based models until such time that enough data is collected to support these models.

The service life estimates are expected to be important to transportation officials and legislators involved in making decisions at the network level regarding funding for bridges. States will be able to quickly understand each other's element service lives estimates and make comparisons especially between adjacent states.

The methodology developed for sorting, collecting and analyzing bridge element data from bridge inspection records at the component and element levels is applicable to other bridge elements with similar data collection formats. This provides VDOT (and other state DOT's), with a statistical methodology for comparing the performance (service lives) of bridge elements in different parts of the state using bridge inspection data. Estimated service lives are useful in scheduling major repairs or rehabilitation of the bridge element or protective system.

In conclusion, the initial goal of the research study was to determine the impact and the extent of the effects of the environmental regions on estimated mean service lives of selected bridge elements in the state of Virginia. The data used were both at the component and element levels. The model developed was capable of determining the effects of the environmental regions on the service lives of the selected concrete deck and steel girder paint. The results showed that statewide, the effect of the environment was not significant on concrete decks of bridges located on low traffic volume roads but the effect was significant on concrete decks of bridges located on high traffic volume roads. The results also showed that statewide, the effect of the environment on steel girder paint was significant for bridges located on both low and high traffic volume roads. It also confirmed the different effects of deterioration levels on bridge component and element/protective system service life.

5.4 Recommendations for Future Research

The methodology developed in this research study was based on the two basic data collection formats recommended by FHWA; the numerical condition rating 9-0 and the letter condition rating G-F-P-C. Many state DOT's, like VDOT, use this format for recording the bridge element physical conditions. Many states also collect additional data with different formats for use in programs such as Pontis or BRIDGIT. Although, the present research study was limited to concrete deck and steel girder paint, the methodology is applicable to all other bridge elements that are inspected with similar condition inspection data format.

Other significant bridge elements that could be investigated using this methodology are deck joints, bearing systems, concrete decks with ECR (if the end of service life can be obtained from the inspection records), concrete superstructures, and wearing surface.

Field performance of similar bridge elements in different parts of the state could also be compared by establishing an intermediate rating point of comparison before the anticipated end of service life. It could be set at condition rating 6 or 7 especially when the selected elements in the inventory have not yet reached their end of service life. Such a comparison would not yield service life estimates but a measure of the deterioration rate since a higher mean can be interpreted as slower deterioration rate and a lower mean interpreted as a faster deterioration rate. Investigating field performance of bridge elements using the methodology developed in the study is important in that it eliminates the subjectivity involved in identifying the rating code associated with end of service life which was an issue in the concrete deck data used in the current study.

Finally, there are numerous deterioration factors such as span continuity, ADTT, skew, and span length, which were not considered in the current study. Provided data is available, the deterioration factors and levels may be expanded to include such factors.

APPENDIX A

Bridge Management Systems (BMS)

Definition

Bridge management addresses all bridge-related activities from the construction stage through maintenance and repair to the replacement of the bridge. According to OECD (1992), a Bridge Management System (BMS) encompasses all engineering and management functions that are necessary to efficiently carry out bridge operations. These include data collection and management, inspection, planning, programming , construction and maintenance. To augment these, a BMS also includes formal procedures for coordinating these functions and analytical tools and models to help identify bridge needs and establish priorities. "Bridge Management" (1987), defines a BMS as any system or series of engineering and management functions which, when taken together, result in the actions necessary to manage a bridge program. These necessary actions include inventorying and inspecting bridges; evaluating priorities; selecting and programming projects; and improving bridges.

According to "Guidelines" (1993), a BMS facilitates budget and program formulation by providing a structured process based upon sound economic and engineering analysis. In addition, the process helps to mediate among all the parties that interact in bridge funding and spending decisions: professional staff, administrators, elected officials, and the general public.

Classification of BMS

Management systems for highway infrastructure have been in existence for 30 years. Since the establishment of the National Bridge Inspection Standard (NBIS) in 1968 by the U.S. Congress, which requires all highway agencies to collect bridge data, all states have developed some form of a BMS. OECD (1992) is a report by Organization for Economic Cooperation and Development (OECD) which indicates that all member countries have some level of a BMS.

The member countries include the US, Canada, Mexico, Australia, most of the western European countries, Japan, Korea, and Czech republic.

A classification system can be applied to cover the wide range of spectrum within which all BMS fall. They may be classified as:
-informal to formal
-loosely coordinated to closely coordinated, and
-subjective and intuitive to objective and analytical.

"Bridge Management" (1987) indicates that a comprehensive BMS tends toward the formal, closely coordinated, objective, and analytical end of the spectrum.

Elements of a BMS

One of the primary purposes of a BMS is to assist highway and bridge agencies in making sound and cost-effective decisions resulting in optimal improvements to the bridge network. A comprehensive BMS considers the conditions of the entire bridge inventory (network) when allocating resources and establishing maintenance policies. This is in contrast to previous practices in which bridge engineers rely heavily on field inspections and judgment to set priorities for bridge programming. Reliance on systematized procedure for making bridge programming decisions, which is at the core of a BMS, is different from applying engineering expertise on a case-by-case basis (project). Analytical tools of a BMS should be able to:
-reasonably predict deterioration rates of structural bridge components;
-assess a broad array of optional corrective strategies;
-optimize a selection of projects, recognizing either specifically constrained or unconstrained budgets; and
-forecast both short-term (budget cycle) and long-term (planning cycle) bridge needs.

A BMS Prototype

Depending on the classification of the structure of a BMS, there may be variations from agency to agency due to specific requirements and preferences. Factors that tend to affect the structure of a BMS include availability of data and mode of collection, centralized or decentralized agency, the size, type, and condition of the bridge population and level of funding. However, the basic components and functions of a comprehensive BMS are essentially the same. A prototype BMS is shown in Figure A.1.

The operational activities common to all BMS include: routine activities for inventorying, inspecting, constructing, and maintaining bridges; special data collection activities such as traffic surveys, accident reporting, and cost accounting; and regulatory activities such as signing. The information and data obtained from the results of these activities represent the system's operational characteristics.

The BMS model contains systematic procedures for incorporating data, engineering judgment and managerial considerations into the decision-making process. Cost estimating, deterioration prediction and evaluation of feasible alternative improvement actions are also incorporated. At the core of the system is the analytical process that, through mathematical programming or other methods, converts the raw data, engineering and managerial inputs, deterioration predictions and cost estimates into information useful to decision-makers.

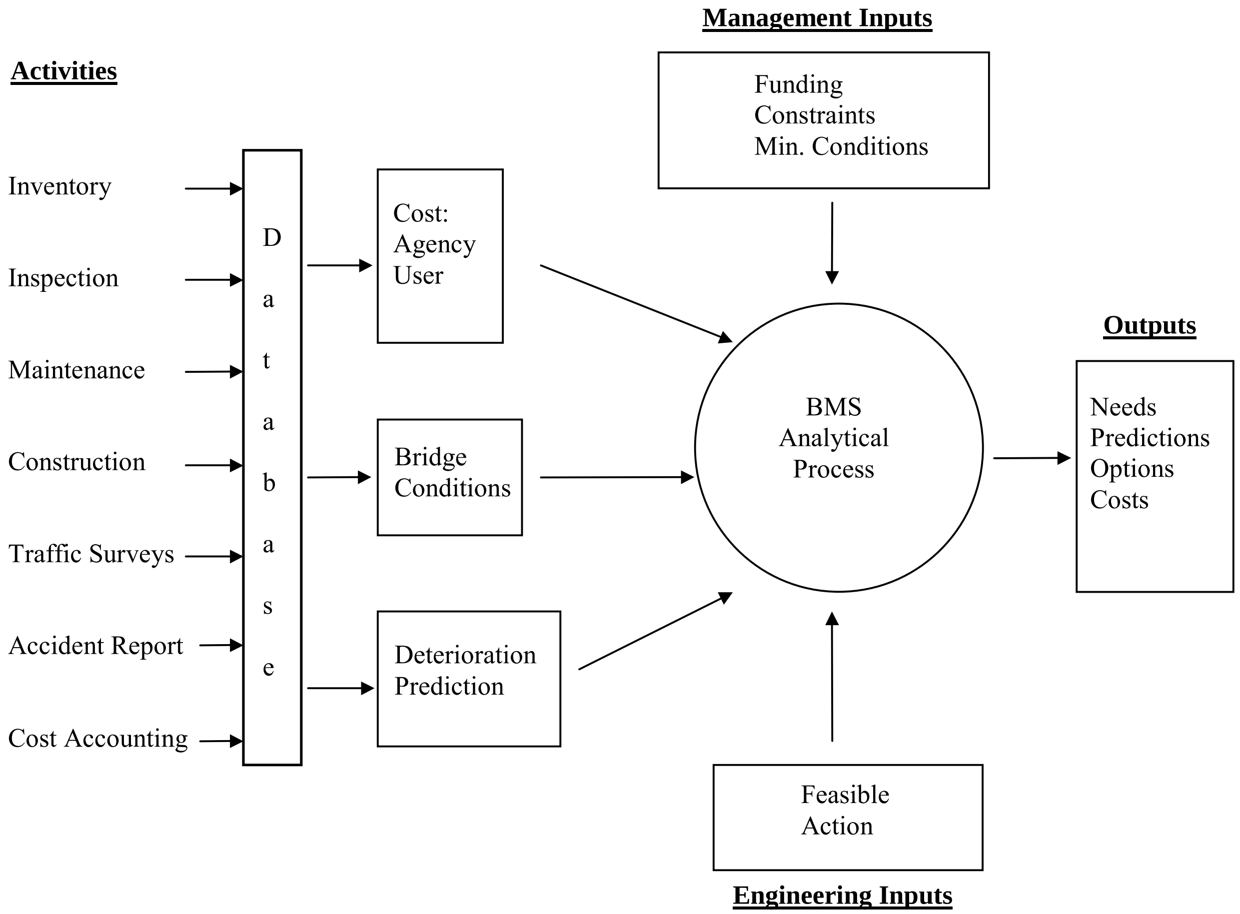


Figure A.1: Structure of a BMS prototype, OECD (1992)

Road Transport and Intermodal Linkages Research Programme

Bridge Management

Copyright OECD, 1992

Activities

Inventory

All states in the U.S. are required to forward at least once every two years inspection reports on all bridges on public roads of over 20 feet in total length to the National Bridge Inventory (NBI). This was initiated in 1968 and the total number of bridges in the U.S. was estimated at 577,000 ("Guidelines" 1993). About 40% of the bridges were deficient. The U.S. Department of Transportation uses this inventory to report to the Congress and the President the status and condition of the nation's bridges. The states individually maintain their own inventory of bridges which in certain cases are more detailed than those required for the NBI. Typically the states keep records of inspection and appraisal data of bridges covering items such as identification of location, structure type, age, geometry, and classification (Dunker and Rabbat 1995).

The definition of bridge is similar in member countries of OECD except the Netherlands where the definition is based on the type of bridge. Most of the bridges are relatively young and about 70% were built over the last three decades (OECD 1992). Japan and France are the two other countries in addition to the United States that have the most bridges in the OECD member countries. Most of the countries have developed computerized data collection, storage and utilization capabilities called data banks. The contents of these data banks include identification, technical description, construction, inspection, repair work and traffic.

Inspection

Inspection is an essential component of any BMS, providing the necessary data which ultimately is used to schedule maintenance and repair. Inspection types can generally be grouped in three main categories.

i) superficial inspection - this is considered routine or cursory inspection carried out by highway maintenance personnel who are not necessarily trained bridge inspection but have a good practical knowledge of bridges. It is normally done once a year or when the opportunity arises. Any adverse defects are reported.

ii) principal inspection - this is usually carried out by a trained inspector under the supervision of a bridge engineer. There are two types namely general and major inspections. General inspection is carried out every 1-2 years as required by the FHWA to the NBI. Other OECD countries have up to 3 years in this category. Principal inspection involves visual inspection and supplemented by standard instruments and tools. A standard report is usually prepared for inventory. Major inspection is carried out between 3-6 years or even up to 10 years for newer bridges. This is more in-depth involving all structural members and special access equipment and instruments.

iii) special inspection - this is usually made in connection with unusual circumstances, the eminence of failure or reassessment of a structure against revised specifications and regulations. This is usually accompanied by extensive testing and structural analysis performed by bridge engineers.

The classification system may vary from country to country but they tend to follow the pattern above. Considerable amount of investment is involved in manpower costs including training for personnel, consultancy work and special inspection in connection with bridge inspections.

Maintenance

Activities performed to preserve the structural and functional integrity of a bridge are considered maintenance. There are two distinct levels of bridge maintenance which are undertaken at different times and for different results. These are:

i) routine maintenance - this is usually done at local levels involving minor repairs sometimes as a response to routine inspection by agency services at that local level . The maintenance involves low budgets and limited engineering analysis.

ii) major maintenance - this is carried out at the national, state and regional levels depending on the country. This type of maintenance is scheduled and undertaken based on comprehensive engineering and management analysis incorporating several techniques, tools and models. The dollar amount of investment is usually large and run in the billions in the U.S. Almost all BMS operate under constrained budgets and therefore resort to some kind of priority ranking to schedule maintenance. The major factors of importance tend to be safety, traffic flow and cost. The constrained budgets has led to emphasis being placed on benefit/cost and life-cycle cost analyses especially in the U.S. Recent attempts to develop a comprehensive bridge life-cycle cost analysis model to aid transportation officials in making investment decisions is being undertaken by the National Cooperative Highway Research Program (NCHRP) in a report about bridge life-cycle cost (*NCHRP* 1995).

Construction

This is carried out as a direct response to the results of the analysis of bridge needs, priorities and availability of funds. Construction usually involves replacement of bridge decks, superstructure or substructure of existing bridges. In very few cases it involves an entirely new bridge when repairing an existing bridge is considered more costly. The budget amount is generally higher than those used for maintenance and usually involves bridge construction companies.

Traffic Surveys

Traffic surveys are done to evaluate the impact of detours, partial and complete shutdowns of bridges on traffic flow. It is also done to estimate the change in traffic flow pattern, weight and volume. Special equipment is involved in data collection and storing. Interpretation of such data is done by transportation engineers with the aid of special tools and techniques.

Accident Reports

These reports are collected to determine if the original design was safe and whether certain members have rendered the bridge unsafe. The first priority of a BMS is safety and such data collection could lead to certain policy or regulatory changes.

Cost Accounting

This is an essential input in the database of a BMS. Typically, unit costs are gathered for components of different bridge types. The unit costs may be based on volume, area, length or number. Unit costs constitute the basis of assessing the cost of any bridge improvement alternative. Most states are now beginning to include such information in their databases as inputs into life-cycle cost models.

Costs

An essential component of any BMS is the cost associated with any bridge improvement or replacement alternative to facilitate decision-making. The cost associated with a bridge is a long-term multi-year investment. The various cost factors include:

Agency Costs

This is the cost that the highway agency in charge of the bridge incurs in the form of cost of maintenance, repair, rehabilitation, strengthening, widening and replacement. Agency spending for bridge improvements lowers future costs. Any expenditure that lowers discounted future costs by a greater amount than the expenditure itself is considered to be net beneficial ("Bridge Management" 1987). Bridge agencies are continually facing reduced funding and therefore resort to intricate analysis to find the best combination of bridge improvement projects that maximizes net benefits for the available funds. The goal is, for a given level of funding in any given year, operations that result in net benefits being maximized at every bridge location in the system.

Associated with agency costs is agency benefits which result from actions that conserve agency resources. For example, preventive maintenance and some types of rehabilitation effectively extend the service life of a bridge and defer replacement to the future.

User Cost

Functional deficiencies attributable to restricted loads and limited lane widths are transformed as higher vehicle operating costs. These higher costs result from increased travel time because of detours, vehicle operation and higher accident rates. Also associated with user costs is user benefits resulting from actions that reduce user costs. User cost or benefits of a bridge to the community are hard to estimate and a number of models have been proposed to estimate them (Yanev 1994; Johnston et al. 1994).

Potential failures due to floods, earthquakes, vehicle or ship collisions impact cost of bridge operation. Certain components of these may be incorporated in the two costs above. However, some OECD countries have a separate category for these risks. Long-term agency expenditures and users costs equal the total cost of a bridge to society. The type, amount, sequence, and timing of agency expenditures determine the magnitude of total costs as well as the split between agency and user costs ("Bridge Management" 1987). Bridge expenditures are sometimes deferred by highway agencies for a number of reasons notably limited funds but the shifted costs usually resurface in future at a higher rate.

One essential input into evaluating and subsequently selecting and programming projects is life-cycle cost analysis. Bridge life-cycle cost analysis (BLCCA) is defined as the economic evaluation of all current and future costs associated with bridge investment alternatives. Transportation officials apply BLCCA but a comprehensive methodology currently does not exist (*NCHRP* 1995).

Bridge Condition

Data on bridge condition is obtained through bridge inspections that is done annually or every other year by all states through their various highway agencies. Bridge inspection data comprise information on element condition ratings which reflect physical deterioration due to environmental effects and traffic. They are a measure of deterioration, section loss, excessive cracking, scour and other characteristics. The ratings are per guidelines set out by the FHWA but many states use their own inspection and ratings systems but eventually convert to FHWA reporting system in order to qualify for federal aid (Dunker and Rabbat 1995). According to Dunker and Rabbat 1995, ratings are subjective and dependent on the bridge inspector's judgment and experience as numerical ratings are used to categorized varied structural conditions.

The National Bridge Inventory (NBI) coding guide (1988) establish deficiencies based on numerical coding ranging from 9 (excellent) to 0 (failed condition), otherwise it is coded N (not applicable). Bridge condition ratings of main components; deck, superstructure and substructure are subjected to the condition ratings based on its overall integrity. Bridge main component appraisal rating uses 9 for "superior to present desirable criteria," or 0 for "bridge closed" (Dunker and Rabbat 1995). There are intermediate rating numbers that describe the component conditions between superior and bridge closed. Some states have further applied this rating system to subcomponents of the main components. This allows them to ascertain the condition of individual bridge subcomponents but eventually obtain the overall rating which is the information forwarded to the NBI.

To qualify for federal funding a bridge has to be classified as structurally deficient or functionally obsolete. A structurally deficient bridge is one that has been restricted to light loads only, is closed, or requires immediate rehabilitation to remain open. A functionally obsolete bridge is one which the deck geometry, load-carrying capacity, clearance, or approach roadway alignment no longer meets the usual criteria for the system of which it is an integral part. There is an additional deficiency qualification introduced by FHWA called the 10-year rule which stipulates that a deficient bridge must have a construction or reconstruction date at least 10 years prior to the present date. About 16,000 bridges presently are in the 10-year holding pattern.

According to a FHWA report of the 1992 NBI, the counts for structurally deficient and functionally obsolete bridges were 20.6 % and 14.0 %, respectively (Dunker and Rabbat 1995). The total number of bridges in the NBI in 1992 was 575,000 ("The Status of the Nation's" 1993) and another estimate put this number at 577,000 with a cost of about $90 billion to eliminate existing deficiencies (Dunker and Rabbat 1993).

OECD member countries collect technical data on bridges similar to the United States. They collect rating data with regards to safety and functionality using numerical codes (OECD 1992).

Deterioration Prediction

An essential requirement of an effective BMS is the ability to predict changes in bridge condition over its service life based on site conditions. Deterioration rates are required for economic comparisons of alternatives and for estimates of present and future needs of bridges. To obtain deterioration rates complex models are developed and utilized. Factors that are considered in these models include the different types of bridges, materials, environment, maintenance and repair history of the bridge and also its initial state. Deterioration prediction is employed in the assessment of bridge needs based on its service life if newly constructed, the remaining service life if existing, and the extension of service life due to MR&R. Factors that affect service life may be technical, functional or economic. The classification currently used by the FHWA incorporates all three factors namely structural deficiency, functional deficiency, sufficiency rating and also the newly introduced 10-year rule. In the OECD countries various forms of consideration and definition of the three factors are utilized.

Definitions

Service life: the period of time between the opening of bridge to traffic and its closure.
Useful life: the number of years a bridge can serve traffic before it becomes structurally unsafe.
Functional life: the number of years before a bridge becomes functionally obsolete.
Economic life: the number of years before replacement becomes more cost effective than continued rehabilitation and maintenance considering life cycle and user costs.

Prediction of deterioration rates for bridges that have been in service for some time is mostly based on historical information. Historical information may be partly experienced-based derived from the knowledge and experience involved in bridge design, construction, and maintenance. Historical information may also be derived from bridge agency databases containing bridge condition, costs, maintenance activities. For new types of bridges or those that have been in service for a relatively short period of time, there is little historical basis for estimating service life (“Bridge Management” 1987). Examples include cable-stayed bridges, prestressed concrete, and segmental constructed bridges. In these cases only mechanistic modeling of bridge fatigue and engineering judgment can be used to estimate the remaining service life (“Bridge Management” 1987).

Most deterioration prediction models are statistically-based or probability-based since they provide an objective analysis of historical data. In cases when historical data is not sufficiently refined, is incomplete, or contains questionable data, the expertise of engineers is utilized. Use of a formal group process to document the experience of experts is desirable.

Prediction Models

There have been significant research to estimate deterioration rates of bridges. A study by the Transportation System Center (TSC) in Cambridge Massachusetts, used a simple linear regression model to develop empirical equations which relate deck, superstructure and substructure condition ratings to age, traffic volume, structure type, and other factors (Busa et al. 1985). The Wisconsin Department of Transportation conducted studies that were similar to the TSC report except they used piecewise linear regression techniques (Hyman et al. 1983). Purdue University used Markov chains to model bridge deterioration as a function of age (Jiang and Sinha 1987). The states of the Markov chain are the condition ratings for deck, superstructure and substructure.

The deterioration curves produced in these studies have been useful in long-range planning and budget estimation studies. However, since they lump all bridge elements into three major categories namely; deck, superstructure and substructure, they lack the detail necessary to support maintenance management programs (OECD 1992).

The Markov chain as applied to bridge service life prediction is based on the concept of defining states in terms of bridge condition ratings and obtaining the probabilities of bridge condition transiting from one state to another. The basic unit is transition probability, which is the probability that an element or a bridge in some condition state will transit to some other state, presumably the next lower, in some fixed period of time. These probabilities are represented in a matrix form called the transition probability matrix.

The Markovian bridge deterioration model is currently being applied in the U.S. and Finland. In this country it has been used in the BMS softwares called Pontis and BRIDGIT. Pontis has 160 different elements. Each of these elements has a specified unit of measure, and up to five unique condition states described in engineering terms, three MR&R actions for each condition state, and four environments (Thompson and Shepard 1994). It is currently being tested by a number of state bridge agencies.

In Finland’s model, bridges are divided into sub-systems which are essentially bridge components. Sub-systems are further divided according to material construction method. In all, 25 bridge sub-systems are modeled on main roads and 25 on other roads. These 25 sub-systems consist of 116 bridge elements. The condition of these elements is described by damages having ratings from 0 to 4. The condition state of a model is then expressed in terms of several different damages. Prediction of behavior of these damages and bridge service life, and thus, transition probabilities, are based on the study of material behavior under different circumstances (“Bridge Management” 1987).

Engineering Inputs

Expert judgment of bridge engineers are incorporated as engineering inputs into feasible strategies for maintenance and repair. These engineering inputs are in the form of rules which take into account the type of design, material characteristics, traffic volume and composition, current structural condition, current load-carrying capacity, the feature crossed, geometrics and other factors. Variations in environmental conditions and situations encountered in practice often result in the development of feasible rules becoming complex analysis. Most present systems deal with this problem inadequately, using simple decision tree-logic to aid in the application of rules (OECD 1992).

Managerial Inputs

Managerial inputs reflects the agency's policies and goals, external constraints such as laws and regulations and other social, political or economic considerations. The agency's standards, engineering preferences and transportation related goals are reflected in the policies. The constraints may include budgetary, environmental such as wetland protection or endangered species, political or social constraints due to local opposition or ordinances, administrative imposed by design policies or project dependencies, and regulatory arising out of clearance requirements or requirement to preserve historically significant bridges.

An important aspect of management input is the minimum condition that will be allowed in the system from an operational or safety standpoint. Any condition below the minimum threshold triggers an immediate response.

Analytical Process

The overriding analytical approach to bridge management is benefit-cost analysis ("Guidelines for Bridge Management" 1993). The main principle underlying benefit-cost analysis is the following: if one must choose whether to do A or not, always do A if the benefits exceed its costs; otherwise don't do A. If the benefits of A is expressed as the avoided costs of the next best option, and apply this principle to all possible choices within funding constraints, the largest possible net benefits will result, and the selection among alternatives will be optimal.

The engineer's perspective needs to be incorporated into the economic analysis and broaden the management perspective. Upper management is often concerned with the effectiveness of bridge management from the perspective of the motoring public and commerce. A BMS is designed as a strategic planning tool for upper management and an engineering tool for technical decision-makers ("Guidelines for Bridge Management" 1993).

Analytical processes for determining optimal bridge strategies can be applied at basically two levels: network or project. Network level analysis deals with system-wide implications. Project level analysis views each bridge separately or in isolation. Decisions on bridge improvements at this level would consider only project alternatives. At the network level bridges are viewed as part of a larger system and improvements to bridges are evaluated in terms of their effect on the system rather than on the individual bridges. Network level analysis is appropriate for evaluating bridge conditions, quantifying system-wide needs, setting bridge improvement priorities, and establishing maintenance policies. Project level analysis is appropriate for close examination of individual bridge improvement alternatives. Commonly used project level analysis tools include life-cycle analysis and benefit-cost analysis. Life-cycle analysis can be used to compare expected costs of alternative strategies involving a series of improvement actions (e.g. maintenance, repair and replacement). Benefit-cost analysis can be used to determine net benefits of alternative strategies with consideration for both agency and user costs.

Key philosophical approaches in BMS is either deterministic or probabilistic. Deterministic models attempt to predict with certainty how bridges will deteriorate over time, while probabilistic models predict the likelihood of each possible condition level over time. In other words, deterministic models are approximation of the "average" behavior of bridges while probabilistic models recognize the uncertainty in predicting actual behavior and the potential errors in assuming all bridges behave "on the average" ("Guidelines for Bridge Management" 1993).

Outputs

The core of the BMS is the analytical process that, through mathematical programming or other methods, converts the raw data, managerial inputs, engineering inputs, deterioration predictions, and cost estimates into information that is useful to the decision-makers. BMS helps engineers and decision-makers determine when and where to spend bridge funds so as to enhance safety, preserve existing infrastructure, and serve commerce and the monitoring public.

The output of a BMS helps agencies assess current and future conditions and needs, predict future bridge conditions and allocate limited funds among competing projects in order to produce justifiable and defensible bridge programs and budgets, and examine the implications of various weight and clearance restrictions on traffic.

Formal and analytical tools employed in BMS foster good agency decision-making. In the broad sense, the organization can serve as an analytical engine for making bridge management decisions: decisions of large number of engineers and managers congeal into bridge programs and budgets, and ultimately projects. The output of BMS such as needs determination, predictions, options and costs are the most critical components that decision-makers require to make cost-effective and sound judgment on bridges at both the network and project levels.

Conclusion

A BMS, if properly designed and implemented, can greatly simplify the process of developing programs and budgets for bridges. It enables decision-makers to grasp the essential trade-offs concerning large numbers of bridges. It helps to use the limited funding in the best possible manner. It also provides essential information to help transportation agencies enhance safety and extend the service life of bridges.

A comprehensive BMS provides managers with an effective tool for forecasting system-wide needs and developing work programs. Multi-year models allow agencies to analyze bridge conditions, traffic characteristics and budgets over a planning period, for example twenty years, rather than at a single point. Such models allow comparison of bridge costs over the short-term and long-term for various courses of action and their effect on future conditions. This type of information is essential for developing well-substantiated estimates of needs in support budget requests for top management and legislatures (OECD 1992).

Recent attempts by NCHRP to develop a comprehensive bridge life-cycle analysis model for bridge agencies in making investment decisions underscores the importance of having a comprehensive, efficient and effective BMS. All states are already managing their own bridge programs that have evolved over the years which are not all well planned. However, according to “Bridge Management Systems” 1987, most of them are now recognizing the desirability and need for more systematic procedures to ensure the most cost-effective use of bridge funds. Therefore, BMS combines management, engineering, and economic inputs in order to determine the best actions to take on all bridges on a network over time.

APPENDIX B

Environmental Regions of Virginia

Topographic Features

Virginia is located on the eastern coast of the United States between latitudes 36.5° and 39.5 ° north. The state is triangular in shape with the longest north-south distance about 200 miles and the longest east-west distance more than 400 miles. There are 40,815 square miles of area within the state, of which 1,200 square miles are inland waters.

The state is composed of three major topographic regions; the Tidewater or coastal plains area, the Piedmont plateau or middle Virginia, and the mountain regions. Other natural regions of lesser extent include the "Fall Line," located between Tidewater Virginia and the Piedmont region; the Blue Ridge Mountains that serve as the eastern boundary of the great Shenandoah Valley; the Shenandoah Valley; and the Appalachian plateau, in the southwestern Virginia. Together these additional lesser regions allow the state of Virginia to be divided into six geographical regions (refer Figure 3.2).

Tidewater Virginia extends westward from the Atlantic Coast and west shore of the Chesapeake Bay to the "Fall Line". The "Fall Line" extends from Great Falls in the north, southward through Richmond to Emporia. It is divided into necks or peninsulas by four principal rivers and by numerous estuaries that open into the Chesapeake. There are numerous peninsulas, wide estuaries, and many swamp areas. The principal rivers include the Potomac, Rappahannock, York, and the James. Tidewater extends up these rivers to near the "Fall Line."

The Piedmont region is more than 200 miles wide in the southern Virginia, but the Virginia section is quite narrower in the north. This region from east to west becomes more rolling and hilly with a few isolated mountains and ridges appearing a few miles east of the Blue Ridge. The elevations in this region generally range from about 300 feet above sea level in the east to about 1,000 feet in the west. The James, the largest river crossing in this region, divides it into two parts. The two parts are the eastern Piedmont and the western Piedmont with the western section generally having a higher elevation than the eastern section.

The third region, west of the Piedmont, is the Blue Ridge Mountains traversing the state from southwest to northeast. They range from narrow ridges in the north to a high, wide plateau southwest from Roanoke. Elevations range generally from 1,500 to 3,500 feet. Mt. Rogers, in western Grayson County, towers to 5,719 feet, the highest point in the State. The western mountains can be divided into three parts namely: the northern , the central mountain and the southwestern mountain.

A great valley west of the Blue Ridge extends from Tennessee through Scott and Washington Counties in the south, northeastward to the northernmost point in the state. It includes six separate valleys of which the largest is the Shenandoah. Elevations range mostly from 1,000 feet to 2,000 feet. The Appalachian Plateau in the southwestern Virginia is divided into many sharp ridges and deep valleys.

Climatic Features

The climate of Virginia is determined by its proximity to the Atlantic Ocean, latitude, and topography. The State is in the zone of prevailing westerly movement of the earth's atmosphere, in or near the mean path of winter storm tracks, and in the mean path of tropical, moist air from the southwest Atlantic and Gulf of Mexico much of the summer and early fall seasons. The mountains provide the usual elevation effects on temperatures, which are distinctly lower in this section, and there are wide variations over short distances as elevations change. Summers in the mountains are comparatively cool, and the winters are more severe. The mountains also cause various steering, blocking, and modifying effects on storms and general air movements in their vicinity (Climate 1982).

Temperature variations in the state due to latitude alone are very small; yearly averages are only 2° to 3 °F higher in the south than in the north. On the other hand, longitudinal variations are significant, showing sharper contrast from the mountain extremes in the west toward an ocean influence in the east.

Temperature

Annual temperature averages, by division, range from 54 °F in the Southwestern Mountain Division to nearly 59 °F in the Tidewater Virginia. The highest temperature of record in the State occurred in the Piedmont Plateau and the lowest in the higher mountains of the central and southwest. The average dates of the last freeze in spring and the first in fall ranges from about 140 days in part of Tazewell County to a little over 250 days in the Norfolk area.

The state of Virginia lies in the zone of the prevailing westerlies with a general direction from west to east. Southerly and northerly winds are about equally frequent, reflecting the progression of weather systems over the state. The Appalachian Mountains, however, act to deflect these winds to some extent, with northeasterly and southwesterly directions occurring frequently. Local winds are also created by other factors such as differential heating, air drainage, local terrain, and proximity to bodies of water. A more intense circulation exists during cold seasons with frequent storms and outbreaks of cold polar air. Northerly winds are most common during the cold season. The storm track is well north of the state during the warm season, and southerly winds with light speeds prevail.

Relative Humidity

Summers in the state are usually warm and humid, and there can be several days like that during the year. The Gulf of Mexico and the Atlantic Ocean are the principal sources of moisture. Relative humidity, the usual measure of moisture, varies inversely with temperature. This means it is high in the morning and low in the afternoon. Average values are not significantly different across the state, but Tidewater locations have a much higher frequency of humidity and temperature values. Norfolk has about 228 hours each year of temperature greater than 80 °F and relative humidity greater than 70 percent while Roanoke has only 23 hours.

Precipitation

Annual precipitation based on the period 1931-60 ranges from about 35 to 50 inches. The heaviest amounts occur in the extreme southwest, the southeast, and the south-central areas. Minimum amounts are found in the sheltered valleys west of the Blue Ridge Mountains. Precipitation are well distributed throughout the year without distinct wet and dry periods. Maximum rainfall occurs in the summer months and minimum in the fall months. Precipitation during cold season is associated with migratory low-pressure storms. The amounts are quite evenly distributed during this season in comparison to the warm season when showers and thunderstorms account for most of the rainfall. Excessive rainfall usually occurs in the fall season with the passage of hurricanes (Hayden 1982).

Snow

Average seasonal snowfall ranges from less than 10 inches in the Tidewater Virginia to about 20 inches west of the Blue Ridge, and up to 30 inches only on the mountains. Snow for individual seasons range from none to the record amount of 98 inches observed at Mountain Lake in 1913-14. A month with snow of 10 inches or more has occurred about once every four years in the Tidewater area, about once every two years in the Piedmont areas, and almost yearly in the mountain locations. Occasionally, a major snowstorm will occur with snow depths up to, but usually much less than, the record 42 inches which fell at Big Meadows in March 1962.

APPENDIX C

DECK ANALYSES

Analysis #1

Virginia Bridge Deck Service Life Analysis
Six Environmental Regions and Two Deterioration Levels

```
          The SAS System

                       det_      serv_
   Obs    region     factor      life

     1       1          1         20
     2       1          1         21
     3       1          1         14
     4       1          1         24
     5       1          1         21
     6       1          1         15
     7       1          1         30
     8       1          1         28
     9       1          1         19
    10       1          1         24
    11       1          1         28
    12       1          1         17
    13       1          1         22
    14       1          1         24
    15       1          1         24
    16       1          1         24
    17       1          1         21
    18       1          2         21
    19       1          2         27
    20       1          2         27
    21       1          2         25
    22       1          2         27
    23       1          2         23
    24       1          2         27
    25       1          2         27
    26       1          2         20
    27       1          2         19
    28       1          2         18
    29       1          2         21
    30       1          2         18
    31       1          2         21
    32       1          2         21
    33       1          2         23
    34       1          2         24
    35       1          2         28
    36       1          2         24
    37       1          2         24
    38       1          2         22
    39       1          2         24
    40       1          2         22
    41       2          1         19
    42       2          1         26
    43       2          1         20
    44       2          1         25
    45       2          1         22
    46       2          1         25
    47       2          1         23
    48       2          1         20
    49       2          1         14
                The SAS System

                       det_      serv_
   Obs    region     factor      life
```

```
 50       2         1        23
 51       2         1        32
 52       2         1        14
 53       2         1        14
 54       2         1        20
 55       2         1        20
 56       2         1        20
 57       2         1        26
 58       2         1        26
 59       2         2        23
 60       2         2        23
 61       2         2        18
 62       2         2        19
 63       2         2        18
 64       2         2        19
 65       2         2        24
 66       2         2        21
 67       2         2        21
 68       2         2        21
 69       2         2        21
 70       2         2        26
 71       2         2        20
 72       2         2        20
 73       2         2        20
 74       2         2        20
 75       2         2        23
 76       2         2        25
 77       2         2        25
 78       2         2        17
 79       2         2        23
 80       2         2        23
 81       3         1        30
 82       3         1        26
 83       3         1        21
 84       3         1        28
 85       3         1        18
 86       3         1        29
 87       3         1        28
 88       3         1        28
 89       3         1        28
 90       3         1        22
 91       3         1        18
 92       3         1        29
 93       3         1        25
 94       3         1        26
 95       3         1        26
 96       3         1        15
 97       3         2        24
 98       3         2        22
         The SAS System

                  det_     serv_
Obs    region    factor     life

 99       3         2        26
100       3         2        21
101       3         2        26
102       3         2        24
103       3         2        22
104       3         2        21
105       3         2        22
106       3         2        22
107       3         2        18
108       3         2        28
109       3         2        12
110       3         2        17
111       3         2        23
112       3         2        29
113       3         2        27
114       4         1        33
115       4         1        24
```

```
116       4         1         31
117       4         1         27
118       4         1         19
119       4         1         27
120       4         1         35
121       4         1         24
122       4         1         24
123       4         1         21
124       4         1         21
125       4         1         23
126       4         1         15
127       4         1         25
128       4         1         34
129       4         1         24
130       4         2         24
131       4         2         23
132       4         2         19
133       4         2         19
134       4         2         20
135       4         2         17
136       4         2         17
137       4         2         17
138       4         2         20
139       4         2         17
140       4         2         15
141       4         2         17
142       4         2         19
143       4         2         17
144       4         2         17
145       4         2         20
146       4         2         17
147       4         2         17
         The SAS System

                  det_      serv_
Obs    region    factor      life

148       4         2         17
149       4         2         24
150       4         2         20
151       4         2         24
152       4         2         27
153       5         1         17
154       5         1         19
155       5         1         25
156       5         1         18
157       5         1         18
158       5         1         17
159       5         1         21
160       5         1         18
161       5         1         18
162       5         1         23
163       5         1         22
164       5         1         23
165       5         1         28
166       5         1         19
167       5         1         26
168       5         1         27
169       5         1         24
170       5         2         21
171       5         2         21
172       5         2         21
173       5         2         29
174       5         2         19
175       5         2         26
176       5         2         24
177       5         2         21
178       5         2         25
179       5         2         26
180       5         2         24
181       5         2         21
```

```
     182         5         2        22
     183         5         2        19
     184         5         2        20
     185         5         2        25
     186         6         1        26
     187         6         1        29
     188         6         1        28
     189         6         1        18
     190         6         1        20
     191         6         1        33
     192         6         1        31
     193         6         1        15
     194         6         1        15
     195         6         1        24
     196         6         1        24
              The SAS System

                       det_     serv_
     Obs    region    factor     life

     197         6         1        24
     198         6         1        20
     199         6         1        24
     200         6         1        25
     201         6         1        23
     202         6         2        21
     203         6         2        23
     204         6         2        23
     205         6         2        23
     206         6         2        25
     207         6         2        25
     208         6         2        25
     209         6         2        25
     210         6         2        25
     211         6         2        25
     212         6         2        29
     213         6         2        24
     214         6         2        21
     215         6         2        20
     216         6         2        19
     217         6         2        25
     218         6         2        25
     219         6         2        24
     220         6         2        20
     221         6         2        20
     222         6         2        22
     223         6         2        28
     224         6         2        28
     225         6         2        28
     226         6         2        28
     227         6         2        28
     228         6         2        30
Virginia Bridge Deck Service Life Analysis

            The GLM Procedure

         Class Level Information

  Class           Levels    Values

  region               6    1 2 3 4 5 6

  det_factor           2    1 2


      Number of observations    228
Virginia Bridge Deck Service Life Analysis
```

```
                                    The GLM Procedure

Dependent Variable: serv_life

                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                       11      652.988869       59.362624       3.88    <.0001

      Error                      216     3302.638324       15.289992

      Corrected Total            227     3955.627193


                     R-Square     Coeff Var      Root MSE    serv_life Mean

                     0.165078      17.26109      3.910242          22.65351


      Source                      DF       Type I SS     Mean Square    F Value    Pr > F

      region                       5     224.4677822      44.8935564       2.94    0.0138
      det_factor                   1      44.1825393      44.1825393       2.89    0.0906
      region*det_factor            5     384.3385472      76.8677094       5.03    0.0002


      Source                      DF     Type III SS     Mean Square    F Value    Pr > F

      region                       5     182.2106132      36.4421226       2.38    0.0394
      det_factor                   1      45.2864009      45.2864009       2.96    0.0867
      region*det_factor            5     384.3385472      76.8677094       5.03    0.0002
                              Virginia Bridge Deck Service Life Analysis

                                      The GLM Procedure
                                     Least Squares Means
                         Adjustment for Multiple Comparisons: Tukey-Kramer

                                    serv_life        Standard                    LSMEAN
                        region         LSMEAN           Error    Pr > |t|      Number

                        1          22.6457801       0.6253386      <.0001           1
                        2          21.4873737       0.6213782      <.0001           2
                        3          23.7003676       0.6809985      <.0001           3
                        4          22.3709239       0.6364760      <.0001           4
                        5          22.0514706       0.6809985      <.0001           5
                        6          24.0474537       0.6168307      <.0001           6


                                Least Squares Means for effect region
                                 Pr > |t| for H0: LSMean(i)=LSMean(j)

                                    Dependent Variable: serv_life

    i/j              1             2             3             4             5             6

       1                      0.7771        0.8638        0.9996        0.9876        0.6022
       2        0.7771                      0.1606        0.9197        0.9901        0.0437
       3        0.8638        0.1606                      0.7110        0.5253        0.9990
       4        0.9996        0.9197        0.7110                      0.9994        0.4102
       5        0.9876        0.9901        0.5253        0.9994                      0.2551
       6        0.6022        0.0437        0.9990        0.4102        0.2551
                              Virginia Bridge Deck Service Life Analysis
```

```
                               The GLM Procedure
                              Least Squares Means
                 Adjustment for Multiple Comparisons: Tukey-Kramer

                                                                H0:LSMean1=
              det_         serv_life        Standard    H0:LSMEAN=0      LSMean2
              factor           LSMEAN           Error       Pr > |t|       Pr > |t|

              1            23.1698666       0.3914056         <.0001         0.0867
              2            22.2645900       0.3514216         <.0001
                    Virginia Bridge Deck Service Life Analysis

                               The GLM Procedure
                              Least Squares Means
                 Adjustment for Multiple Comparisons: Tukey-Kramer

                       det_         serv_life        Standard                  LSMEAN
             region    factor           LSMEAN           Error    Pr > |t|      Number

             1         1            22.1176471       0.9483730      <.0001           1
             1         2            23.1739130       0.8153418      <.0001           2
             2         1            21.6111111       0.9216529      <.0001           3
             2         2            21.3636364       0.8336664      <.0001           4
             3         1            24.8125000       0.9775605      <.0001           5
             3         2            22.5882353       0.9483730      <.0001           6
             4         1            25.4375000       0.9775605      <.0001           7
             4         2            19.3043478       0.8153418      <.0001           8
             5         1            21.3529412       0.9483730      <.0001           9
             5         2            22.7500000       0.9775605      <.0001          10
             6         1            23.6875000       0.9775605      <.0001          11
             6         2            24.4074074       0.7525264      <.0001          12


                   Least Squares Means for effect region*det_factor
                         Pr > |t| for H0: LSMean(i)=LSMean(j)

                           Dependent Variable: serv_life

   i/j              1             2             3             4             5             6

      1                      0.9995        1.0000        1.0000        0.7074        1.0000
      2        0.9995                      0.9820        0.9237        0.9800        1.0000
      3        1.0000        0.9820                      1.0000        0.4223        0.9999
      4        1.0000        0.9237        1.0000                      0.2413        0.9982
      5        0.7074        0.9800        0.4223        0.2413                      0.8949
      6        1.0000        1.0000        0.9999        0.9982        0.8949
      7        0.3857        0.8281        0.1679        0.0733        1.0000        0.6290
      8        0.5159        0.0429        0.7736        0.8344        0.0014        0.2721
      9        1.0000        0.9505        1.0000        1.0000        0.3212        0.9989
     10        1.0000        1.0000        0.9995        0.9953        0.9414        1.0000
     11        0.9917        1.0000        0.9259        0.8116        0.9996        0.9997
     12        0.7634        0.9939        0.4447        0.2285        1.0000        0.9385

                   Least Squares Means for effect region*det_factor
                         Pr > |t| for H0: LSMean(i)=LSMean(j)

                           Dependent Variable: serv_life

   i/j              7             8             9            10            11            12

      1        0.3857        0.5159        1.0000        1.0000        0.9917        0.7634
      2        0.8281        0.0429        0.9505        1.0000        1.0000        0.9939
      3        0.1679        0.7736        1.0000        0.9995        0.9259        0.4447
      4        0.0733        0.8344        1.0000        0.9953        0.8116        0.2285
                    Virginia Bridge Deck Service Life Analysis
```

```
                                   The GLM Procedure
                                  Least Squares Means
                   Adjustment for Multiple Comparisons: Tukey-Kramer

                    Least Squares Means for effect region*det_factor
                          Pr > |t| for H0: LSMean(i)=LSMean(j)

                             Dependent Variable: serv_life

i/j              7             8             9            10            11            12

   5        1.0000        0.0014        0.3212        0.9414        0.9996        1.0000
   6        0.6290        0.2721        0.9989        1.0000        0.9997        0.9385
   7                      0.0002        0.1160        0.7301        0.9824        0.9995
   8        0.0002                      0.8930        0.2301        0.0328        0.0004
   9        0.1160        0.8930                      0.9970        0.8600        0.3315
  10        0.7301        0.2301        0.9970                      0.9999        0.9723
  11        0.9824        0.0328        0.8600        0.9999                      1.0000
  12        0.9995        0.0004        0.3315        0.9723        1.0000
```

Analysis #2

```
          Virginia Bridge Deck Service Life Analysis
     Five Environmental Regions and Two Deterioration Levels
                        The SAS System

                                det_     serv_
               Obs    region    factor     life

                 1       1         1        20
                 2       1         1        21
                 3       1         1        14
                 4       1         1        24
                 5       1         1        21
                 6       1         1        15
                 7       1         1        30
                 8       1         1        28
                 9       1         1        19
                10       1         1        24
                11       1         1        28
                12       1         1        17
                13       1         1        22
                14       1         1        24
                15       1         1        24
                16       1         1        24
                17       1         1        21
                18       1         2        21
                19       1         2        27
                20       1         2        27
                21       1         2        25
                22       1         2        27
                23       1         2        23
                24       1         2        27
                25       1         2        27
                26       1         2        20
                27       1         2        19
                28       1         2        18
                29       1         2        21
                30       1         2        18
                31       1         2        21
                32       1         2        21
                33       1         2        23
                34       1         2        24
                35       1         2        28
                36       1         2        24
                37       1         2        24
                38       1         2        22
                39       1         2        24
                40       1         2        22
                41       2         1        19
                42       2         1        26
                43       2         1        20
                44       2         1        25
                45       2         1        22
                46       2         1        25
                47       2         1        23
                48       2         1        20
                49       2         1        14
                        The SAS System

                                det_     serv_
               Obs    region    factor     life

                50       2         1        23
                51       2         1        32
                52       2         1        14
                53       2         1        14
                54       2         1        20
                55       2         1        20
                56       2         1        20
```

```
 57       2         1         26
 58       2         1         26
 59       2         2         23
 60       2         2         23
 61       2         2         18
 62       2         2         19
 63       2         2         18
 64       2         2         19
 65       2         2         24
 66       2         2         21
 67       2         2         21
 68       2         2         21
 69       2         2         21
 70       2         2         26
 71       2         2         20
 72       2         2         20
 73       2         2         20
 74       2         2         20
 75       2         2         23
 76       2         2         25
 77       2         2         25
 78       2         2         17
 79       2         2         23
 80       2         2         23
 81       3         1         30
 82       3         1         26
 83       3         1         21
 84       3         1         28
 85       3         1         18
 86       3         1         29
 87       3         1         28
 88       3         1         28
 89       3         1         28
 90       3         1         22
 91       3         1         18
 92       3         1         29
 93       3         1         25
 94       3         1         26
 95       3         1         26
 96       3         1         15
 97       3         2         24
 98       3         2         22
         The SAS System

                  det_     serv_
Obs    region    factor     life

 99       3         2         26
100       3         2         21
101       3         2         26
102       3         2         24
103       3         2         22
104       3         2         21
105       3         2         22
106       3         2         22
107       3         2         18
108       3         2         28
109       3         2         12
110       3         2         17
111       3         2         23
112       3         2         29
113       3         2         27
114       5         1         17
115       5         1         19
116       5         1         25
117       5         1         18
118       5         1         18
119       5         1         17
120       5         1         21
121       5         1         18
122       5         1         18
```

```
123       5         1        23
124       5         1        22
125       5         1        23
126       5         1        28
127       5         1        19
128       5         1        26
129       5         1        27
130       5         1        24
131       5         2        21
132       5         2        21
133       5         2        21
134       5         2        29
135       5         2        19
136       5         2        26
137       5         2        24
138       5         2        21
139       5         2        25
140       5         2        26
141       5         2        24
142       5         2        21
143       5         2        22
144       5         2        19
145       5         2        20
146       5         2        25
147       6         1        26
         The SAS System

                  det_     serv_
Obs    region    factor     life

148       6         1        29
149       6         1        28
150       6         1        18
151       6         1        20
152       6         1        33
153       6         1        31
154       6         1        15
155       6         1        15
156       6         1        24
157       6         1        24
158       6         1        24
159       6         1        20
160       6         1        24
161       6         1        25
162       6         1        23
163       6         2        21
164       6         2        23
165       6         2        23
166       6         2        23
167       6         2        25
168       6         2        25
169       6         2        25
170       6         2        25
171       6         2        25
172       6         2        25
173       6         2        29
174       6         2        24
175       6         2        21
176       6         2        20
177       6         2        19
178       6         2        25
179       6         2        25
180       6         2        24
181       6         2        20
182       6         2        20
183       6         2        22
184       6         2        28
185       6         2        28
186       6         2        28
187       6         2        28
188       6         2        28
```

```
                     189       6         2        30
        Virginia Bridge Deck Service Life Analysis w/o Region 4

                          The GLM Procedure

                       Class Level Information

                    Class           Levels    Values

                    region               5    1 2 3 5 6

                    det_factor           2    1 2


                      Number of observations    189
        Virginia Bridge Deck Service Life Analysis w/o Region 4

                          The GLM Procedure

Dependent Variable: serv_life

                                        Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                        9      265.406836       29.489648       2.01    0.0407

      Error                      179     2627.831259       14.680622

      Corrected Total            188     2893.238095


                     R-Square     Coeff Var      Root MSE    serv_life Mean

                     0.091733      16.78626      3.831530          22.82540


      Source                      DF       Type I SS     Mean Square    F Value    Pr > F

      region                       4     191.8222742      47.9555686       3.27    0.0129
      det_factor                   1       1.4871061       1.4871061       0.10    0.7506
      region*det_factor            4      72.0974558      18.0243640       1.23    0.3007


      Source                      DF     Type III SS     Mean Square    F Value    Pr > F

      region                       4     176.8507984      44.2126996       3.01    0.0195
      det_factor                   1       0.9021003       0.9021003       0.06    0.8045
      region*det_factor            4      72.0974558      18.0243640       1.23    0.3007
        Virginia Bridge Deck Service Life Analysis w/o Region 4

                          The GLM Procedure
                         Least Squares Means
           Adjustment for Multiple Comparisons: Tukey-Kramer

                         serv_life        Standard                   LSMEAN
                region      LSMEAN           Error    Pr > |t|      Number

                1       22.6457801       0.6127507      <.0001           1
                2       21.4873737       0.6088701      <.0001           2
                3       23.7003676       0.6672902      <.0001           3
                5       22.0514706       0.6672902      <.0001           4
                6       24.0474537       0.6044141      <.0001           5
```

```
                  Least Squares Means for effect region
                   Pr > |t| for H0: LSMean(i)=LSMean(j)

                      Dependent Variable: serv_life

i/j              1             2             3             4             5

   1                      0.6660        0.7718        0.9653        0.4812
   2        0.6660                      0.1071        0.9710        0.0265
   3        0.7718        0.1071                      0.4079        0.9953
   4        0.9653        0.9710        0.4079                      0.1782
   5        0.4812        0.0265        0.9953        0.1782
         Virginia Bridge Deck Service Life Analysis w/o Region 4

                            The GLM Procedure
                           Least Squares Means
            Adjustment for Multiple Comparisons: Tukey-Kramer

                                                            H0:LSMean1=
   det_         serv_life         Standard    H0:LSMEAN=0      LSMean2
   factor          LSMEAN            Error       Pr > |t|       Pr > |t|

   1           22.7163399        0.4184638         <.0001         0.8045
   2           22.8566384        0.3810732         <.0001
```

Analysis #3

Virginia Bridge Deck Service Life Analysis for Region 4
One Environmental Region and Two Deterioration Levels

```
                    The SAS System

                    det_     serv_
             Obs    factor    life

               1       1        33
               2       1        24
               3       1        31
               4       1        27
               5       1        19
               6       1        27
               7       1        35
               8       1        24
               9       1        24
              10       1        21
              11       1        21
              12       1        23
              13       1        15
              14       1        25
              15       1        34
              16       1        24
              17       2        24
              18       2        23
              19       2        19
              20       2        19
              21       2        20
              22       2        17
              23       2        17
              24       2        17
              25       2        20
              26       2        17
              27       2        15
              28       2        17
              29       2        19
              30       2        17
              31       2        17
              32       2        20
              33       2        17
              34       2        17
              35       2        17
              36       2        24
              37       2        20
              38       2        24
              39       2        27
  Virginia Bridge Deck Service Life Analysis for R4
```

```
                                  The TTEST Procedure

                                      Statistics

                                   Lower CL          Upper CL  Lower CL           Upper CL
Variable  det_factor      N        Mean    Mean        Mean   Std Dev  Std Dev   Std Dev  Std Err

serv_                    16       22.48  25.438      28.395    4.0994   5.5494    8.5888   1.3873
life       1
serv_                    23      17.959  19.304      20.649    2.4057   3.1106    4.4026   0.6486
life       2
serv_     Diff (1-2)             3.3162  6.1332      8.9501    3.4817   4.2706    5.5251   1.3903
life


                                        T-Tests

             Variable     Method           Variances      DF    t Value    Pr > |t|

             serv_life    Pooled           Equal          37       4.41      <.0001
             serv_life    Satterthwaite    Unequal      21.6       4.00      0.0006
             serv_life    Cochran          Unequal         .       4.00      0.0010


                                 Equality of Variances

                 Variable     Method      Num DF    Den DF    F Value    Pr > F

                 serv_life    Folded F        15        22       3.18    0.0137
```

Analysis #4

Virginia Bridge Deck Service Life Analysis
Six Environmental Regions and Deterioration Level 1

```
                         The SAS System

                                          serv_
                     Obs    region     life

                       1       1        20
                       2       1        21
                       3       1        14
                       4       1        24
                       5       1        21
                       6       1        15
                       7       1        30
                       8       1        28
                       9       1        19
                      10       1        24
                      11       1        28
                      12       1        17
                      13       1        22
                      14       1        24
                      15       1        24
                      16       1        24
                      17       1        21
                      18       2        19
                      19       2        26
                      20       2        20
                      21       2        25
                      22       2        22
                      23       2        25
                      24       2        23
                      25       2        20
                      26       2        14
                      27       2        23
                      28       2        32
                      29       2        14
                      30       2        14
                      31       2        20
                      32       2        20
                      33       2        20
                      34       2        26
                      35       2        26
                      36       3        30
                      37       3        26
                      38       3        21
                      39       3        28
                      40       3        18
                      41       3        29
                      42       3        28
                      43       3        28
                      44       3        28
                      45       3        22
                      46       3        18
                      47       3        29
                      48       3        25
                      49       3        26
                         The SAS System

                                          serv_
                     Obs    region     life

                      50       3        26
                      51       3        15
                      52       4        33
                      53       4        24
                      54       4        31
```

```
               55       4        27
               56       4        19
               57       4        27
               58       4        35
               59       4        24
               60       4        24
               61       4        21
               62       4        21
               63       4        23
               64       4        15
               65       4        25
               66       4        34
               67       4        24
               68       5        17
               69       5        19
               70       5        25
               71       5        18
               72       5        18
               73       5        17
               74       5        21
               75       5        18
               76       5        18
               77       5        23
               78       5        22
               79       5        23
               80       5        28
               81       5        19
               82       5        26
               83       5        27
               84       5        24
               85       6        26
               86       6        29
               87       6        28
               88       6        18
               89       6        20
               90       6        33
               91       6        31
               92       6        15
               93       6        15
               94       6        24
               95       6        24
               96       6        24
               97       6        20
               98       6        24
                  The SAS System

                                serv_
              Obs    region     life

               99       6        25
              100       6        23
Virginia Bridge Deck Service Life Analysis w/ D1

                The GLM Procedure

             Class Level Information

      Class         Levels    Values

      region             6    1 2 3 4 5 6


         Number of observations    100
Virginia Bridge Deck Service Life Analysis w/ D1
```

```
                                       The GLM Procedure

Dependent Variable: serv_life

                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        5      248.052663       49.610533       2.22    0.0585

      Error                       94     2099.737337       22.337631

      Corrected Total             99     2347.790000


                     R-Square     Coeff Var      Root MSE    serv_life Mean

                     0.105654      20.45119      4.726270          23.11000


      Source                      DF       Type I SS     Mean Square    F Value    Pr > F

      region                       5     248.0526634      49.6105327       2.22    0.0585


      Source                      DF     Type III SS     Mean Square    F Value    Pr > F

      region                       5     248.0526634      49.6105327       2.22    0.0585
                        Virginia Bridge Deck Service Life Analysis w/ D1

                                       The GLM Procedure
                                      Least Squares Means
                       Adjustment for Multiple Comparisons: Tukey-Kramer

                              serv_life        Standard                  LSMEAN
                 region          LSMEAN           Error    Pr > |t|      Number

                 1           22.1176471       1.1462889      <.0001           1
                 2           21.6111111       1.1139926      <.0001           2
                 3           24.8125000       1.1815676      <.0001           3
                 4           25.4375000       1.1815676      <.0001           4
                 5           21.3529412       1.1462889      <.0001           5
                 6           23.6875000       1.1815676      <.0001           6


                             Least Squares Means for effect region
                              Pr > |t| for H0: LSMean(i)=LSMean(j)

                                 Dependent Variable: serv_life

    i/j              1             2             3             4             5             6

       1                      0.9996        0.5765        0.3409        0.9970        0.9311
       2        0.9996                      0.3665        0.1826        1.0000        0.7959
       3        0.5765        0.3665                      0.9990        0.2955        0.9845
       4        0.3409        0.1826        0.9990                      0.1403        0.9005
       5        0.9970        1.0000        0.2955        0.1403                      0.7160
       6        0.9311        0.7959        0.9845        0.9005        0.7160
```

Analysis #5

```
                  Virginia Bridge Deck Service Life Analysis
            Six Environmental Regions and Deterioration Level 2

                               The SAS System

                                          serv_
                           Obs    region     life

                             1       1        21
                             2       1        27
                             3       1        27
                             4       1        25
                             5       1        27
                             6       1        23
                             7       1        27
                             8       1        27
                             9       1        20
                            10       1        19
                            11       1        18
                            12       1        21
                            13       1        18
                            14       1        21
                            15       1        21
                            16       1        23
                            17       1        24
                            18       1        28
                            19       1        24
                            20       1        24
                            21       1        22
                            22       1        24
                            23       1        22
                            24       2        23
                            25       2        23
                            26       2        18
                            27       2        19
                            28       2        18
                            29       2        19
                            30       2        24
                            31       2        21
                            32       2        21
                            33       2        21
                            34       2        21
                            35       2        26
                            36       2        20
                            37       2        20
                            38       2        20
                            39       2        20
                            40       2        23
                            41       2        25
                            42       2        25
                            43       2        17
                            44       2        23
                            45       2        23
                            46       3        24
                            47       3        22
                            48       3        26
                            49       3        21
                               The SAS System

                                          serv_
                           Obs    region     life

                            50       3        26
                            51       3        24
                            52       3        22
                            53       3        21
                            54       3        22
                            55       3        22
```

```
 56       3        18
 57       3        28
 58       3        12
 59       3        17
 60       3        23
 61       3        29
 62       3        27
 63       4        24
 64       4        23
 65       4        19
 66       4        19
 67       4        20
 68       4        17
 69       4        17
 70       4        17
 71       4        20
 72       4        17
 73       4        15
 74       4        17
 75       4        19
 76       4        17
 77       4        17
 78       4        20
 79       4        17
 80       4        17
 81       4        17
 82       4        24
 83       4        20
 84       4        24
 85       4        27
 86       5        21
 87       5        21
 88       5        21
 89       5        29
 90       5        19
 91       5        26
 92       5        24
 93       5        21
 94       5        25
 95       5        26
 96       5        24
 97       5        21
 98       5        22
    The SAS System

                   serv_
Obs    region      life

 99       5        19
100       5        20
101       5        25
102       6        21
103       6        23
104       6        23
105       6        23
106       6        25
107       6        25
108       6        25
109       6        25
110       6        25
111       6        25
112       6        29
113       6        24
114       6        21
115       6        20
116       6        19
117       6        25
118       6        25
119       6        24
120       6        20
121       6        20
```

```
                                     122       6        22
                                     123       6        28
                                     124       6        28
                                     125       6        28
                                     126       6        28
                                     127       6        28
                                     128       6        30
                        Virginia Bridge Deck Service Life Analysis w/ D2

                                       The GLM Procedure

                                    Class Level Information

                              Class         Levels    Values

                              region             6    1 2 3 4 5 6


                                 Number of observations    128
                        Virginia Bridge Deck Service Life Analysis w/ D2
                                       The GLM Procedure

Dependent Variable: serv_life

                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        5      367.817762       73.563552       7.46    <.0001

      Error                      122     1202.900988        9.859844

      Corrected Total            127     1570.718750


                     R-Square     Coeff Var      Root MSE    serv_life Mean

                     0.234172      14.08287      3.140039          22.29688


      Source                      DF       Type I SS     Mean Square    F Value    Pr > F

      region                       5     367.8177623      73.5635525       7.46    <.0001


      Source                      DF     Type III SS     Mean Square    F Value    Pr > F

      region                       5     367.8177623      73.5635525       7.46    <.0001
                        Virginia Bridge Deck Service Life Analysis w/ D2

                                       The GLM Procedure
                                      Least Squares Means
                       Adjustment for Multiple Comparisons: Tukey-Kramer

                              serv_life        Standard                   LSMEAN
                 region          LSMEAN           Error    Pr > |t|      Number

                 1           23.1739130       0.6547434      <.0001           1
                 2           21.3636364       0.6694585      <.0001           2
                 3           22.5882353       0.7615713      <.0001           3
                 4           19.3043478       0.6547434      <.0001           4
                 5           22.7500000       0.7850097      <.0001           5
                 6           24.4074074       0.6043008      <.0001           6
```

```
                     Least Squares Means for effect region
                      Pr > |t| for H0: LSMean(i)=LSMean(j)

                         Dependent Variable: serv_life

i/j              1             2             3             4             5             6

   1                      0.3872        0.9920        0.0008        0.9984        0.7363
   2        0.3872                      0.8324        0.2458        0.7600        0.0124
   3        0.9920        0.8324                      0.0172        1.0000        0.4248
   4        0.0008        0.2458        0.0172                      0.0126        <.0001
   5        0.9984        0.7600        1.0000        0.0126                      0.5522
   6        0.7363        0.0124        0.4248        <.0001        0.5522
```

Concrete Deck Service Life Means and Standard Deviations

```
          The SAS System

                  det_     serv_
Obs    region    factor     life

  1       1         1        20
  2       1         1        21
  3       1         1        14
  4       1         1        24
  5       1         1        21
  6       1         1        15
  7       1         1        30
  8       1         1        28
  9       1         1        19
 10       1         1        24
 11       1         1        28
 12       1         1        17
 13       1         1        22
 14       1         1        24
 15       1         1        24
 16       1         1        24
 17       1         1        21
 18       1         2        21
 19       1         2        27
 20       1         2        27
 21       1         2        25
 22       1         2        27
 23       1         2        23
 24       1         2        27
 25       1         2        27
 26       1         2        20
 27       1         2        19
 28       1         2        18
 29       1         2        21
 30       1         2        18
 31       1         2        21
 32       1         2        21
 33       1         2        23
 34       1         2        24
 35       1         2        28
 36       1         2        24
 37       1         2        24
 38       1         2        22
 39       1         2        24
 40       1         2        22
 41       2         1        19
 42       2         1        26
 43       2         1        20
 44       2         1        25
 45       2         1        22
 46       2         1        25
 47       2         1        23
 48       2         1        20
 49       2         1        14
         The SAS System

                  det_     serv_
Obs    region    factor     life

 50       2         1        23
 51       2         1        32
 52       2         1        14
 53       2         1        14
 54       2         1        20
 55       2         1        20
 56       2         1        20
 57       2         1        26
```

```
 58       2         1        26
 59       2         2        23
 60       2         2        23
 61       2         2        18
 62       2         2        19
 63       2         2        18
 64       2         2        19
 65       2         2        24
 66       2         2        21
 67       2         2        21
 68       2         2        21
 69       2         2        21
 70       2         2        26
 71       2         2        20
 72       2         2        20
 73       2         2        20
 74       2         2        20
 75       2         2        23
 76       2         2        25
 77       2         2        25
 78       2         2        17
 79       2         2        23
 80       2         2        23
 81       3         1        30
 82       3         1        26
 83       3         1        21
 84       3         1        28
 85       3         1        18
 86       3         1        29
 87       3         1        28
 88       3         1        28
 89       3         1        28
 90       3         1        22
 91       3         1        18
 92       3         1        29
 93       3         1        25
 94       3         1        26
 95       3         1        26
 96       3         1        15
 97       3         2        24
 98       3         2        22
         The SAS System

                  det_     serv_
Obs    region    factor     life

 99       3         2        26
100       3         2        21
101       3         2        26
102       3         2        24
103       3         2        22
104       3         2        21
105       3         2        22
106       3         2        22
107       3         2        18
108       3         2        28
109       3         2        12
110       3         2        17
111       3         2        23
112       3         2        29
113       3         2        27
114       4         1        33
115       4         1        24
116       4         1        31
117       4         1        27
118       4         1        19
119       4         1        27
120       4         1        35
121       4         1        24
122       4         1        24
123       4         1        21
```

```
124       4         1        21
125       4         1        23
126       4         1        15
127       4         1        25
128       4         1        34
129       4         1        24
130       4         2        24
131       4         2        23
132       4         2        19
133       4         2        19
134       4         2        20
135       4         2        17
136       4         2        17
137       4         2        17
138       4         2        20
139       4         2        17
140       4         2        15
141       4         2        17
142       4         2        19
143       4         2        17
144       4         2        17
145       4         2        20
146       4         2        17
147       4         2        17
         The SAS System

                  det_     serv_
Obs    region    factor     life

148       4         2        17
149       4         2        24
150       4         2        20
151       4         2        24
152       4         2        27
153       5         1        17
154       5         1        19
155       5         1        25
156       5         1        18
157       5         1        18
158       5         1        17
159       5         1        21
160       5         1        18
161       5         1        18
162       5         1        23
163       5         1        22
164       5         1        23
165       5         1        28
166       5         1        19
167       5         1        26
168       5         1        27
169       5         1        24
170       5         2        21
171       5         2        21
172       5         2        21
173       5         2        29
174       5         2        19
175       5         2        26
176       5         2        24
177       5         2        21
178       5         2        25
179       5         2        26
180       5         2        24
181       5         2        21
182       5         2        22
183       5         2        19
184       5         2        20
185       5         2        25
186       6         1        26
187       6         1        29
188       6         1        28
189       6         1        18
```

```
               190       6         1        20
               191       6         1        33
               192       6         1        31
               193       6         1        15
               194       6         1        15
               195       6         1        24
               196       6         1        24
                        The SAS System

                                 det_     serv_
               Obs    region    factor     life

               197       6         1        24
               198       6         1        20
               199       6         1        24
               200       6         1        25
               201       6         1        23
               202       6         2        21
               203       6         2        23
               204       6         2        23
               205       6         2        23
               206       6         2        25
               207       6         2        25
               208       6         2        25
               209       6         2        25
               210       6         2        25
               211       6         2        25
               212       6         2        29
               213       6         2        24
               214       6         2        21
               215       6         2        20
               216       6         2        19
               217       6         2        25
               218       6         2        25
               219       6         2        24
               220       6         2        20
               221       6         2        20
               222       6         2        22
               223       6         2        28
               224       6         2        28
               225       6         2        28
               226       6         2        28
               227       6         2        28
               228       6         2        30
          Virginia Bridge Deck Service Life Analysis

                      The GLM Procedure

                   Class Level Information

           Class           Levels    Values

           region               6    1 2 3 4 5 6

           det_factor           2    1 2


                Number of observations    228
          Virginia Bridge Deck Service Life Analysis


                      The GLM Procedure


Level of     Level of             ----------serv_life----------
region       det_factor      N            Mean          Std Dev

1            1              17      22.1176471       4.40003342
1            2              23      23.1739130       3.05483483
2            1              18      21.6111111       4.76678322
2            2              22      21.3636364       2.47935196
```

```
3            1              16       24.8125000       4.60751198
3            2              17       22.5882353       4.24350715
4            1              16       25.4375000       5.54939937
4            2              23       19.3043478       3.11060916
5            1              17       21.3529412       3.69020962
5            2              16       22.7500000       2.88675135
6            1              16       23.6875000       5.19895823
6            2              27       24.4074074       3.05411777
           Virginia Bridge Deck Service Life Analysis

                       The GLM Procedure


       Level of            ----------serv_life----------
       region        N             Mean          Std Dev

       1            40       22.7250000       3.67240227
       2            40       21.4750000       3.63732432
       3            33       23.6666667       4.49768459
       4            39       21.8205128       5.20562345
       5            33       22.0303030       3.34929889
       6            43       24.1395349       3.94353839


      Level of               ----------serv_life----------
      det_factor       N             Mean          Std Dev

      1              100       23.1100000       4.86981011
      2              128       22.2968750       3.51679743
```

APPENDIX D

PAINT ANALYSES

Analysis #1

```
             Virginia Bridge Paint Service Life Analysis
        Six Environmental Regions and Two Deterioration Levels

                            The SAS System

                                  det_      serv_
              Obs    region    factor      life

                1       1          1         15
                2       1          1         12
                3       1          1         12
                4       1          1          5
                5       1          1         15
                6       1          1          6
                7       1          1         17
                8       1          1         11
                9       1          1         18
               10       1          1          9
               11       1          1         12
               12       1          1         12
               13       1          1          6
               14       1          1          8
               15       1          1         13
               16       1          1         12
               17       1          2         12
               18       1          2         12
               19       1          2         19
               20       1          2         25
               21       1          2         25
               22       1          2         14
               23       1          2         11
               24       1          2         15
               25       1          2         12
               26       1          2         10
               27       1          2         18
               28       1          2         18
               29       1          2          5
               30       1          2          9
               31       1          2         10
               32       1          2         26
               33       1          2         13
               34       1          2         10
               35       1          2         10
               36       1          2         14
               37       1          2         13
               38       1          2         10
               39       1          2         13
               40       1          2         14
               41       1          2         14
               42       1          2         20
               43       1          2         11
               44       1          2         19
               45       1          2         15
               46       1          2         18
               47       1          2         19
               48       1          2         17
               49       2          1         21
                            The SAS System

                                  det_      serv_
              Obs    region    factor      life
```

```
 50       2         1        23
 51       2         1        19
 52       2         1        19
 53       2         1        13
 54       2         1        23
 55       2         1        27
 56       2         1        27
 57       2         1        18
 58       2         1        18
 59       2         1        16
 60       2         1        25
 61       2         1        23
 62       2         1        23
 63       2         1        20
 64       2         1        21
 65       2         1        23
 66       2         1        19
 67       2         1        13
 68       2         1        11
 69       2         1        25
 70       2         1        21
 71       2         1        21
 72       2         2        15
 73       2         2        15
 74       2         2        13
 75       2         2        19
 76       2         2         6
 77       2         2        10
 78       2         2        14
 79       2         2        20
 80       2         2        18
 81       2         2        15
 82       2         2        15
 83       2         2         7
 84       2         2        15
 85       2         2        15
 86       2         2        15
 87       2         2        20
 88       2         2         9
 89       2         2         9
 90       3         1        15
 91       3         1        28
 92       3         1        23
 93       3         1        19
 94       3         1        14
 95       3         1        25
 96       3         1        23
 97       3         1        18
 98       3         1        18
         The SAS System

                  det_     serv_
Obs    region    factor     life

 99       3         1        19
100       3         1        14
101       3         1        29
102       3         1        23
103       3         1        18
104       3         1        23
105       3         1        30
106       3         2        18
107       3         2        31
108       3         2        15
109       3         2        14
110       3         2        21
111       3         2        20
112       3         2        22
113       3         2        15
114       3         2        15
```

```
115       3         2        15
116       3         2        11
117       3         2        11
118       3         2        18
119       3         2        27
120       3         2        17
121       3         2        17
122       4         1        21
123       4         1        31
124       4         1        18
125       4         1        15
126       4         1        15
127       4         1        12
128       4         1        22
129       4         1        25
130       4         1        14
131       4         1        12
132       4         1         8
133       4         1         8
134       4         1        25
135       4         1         7
136       4         1        12
137       4         1        14
138       4         2        16
139       4         2        13
140       4         2        16
141       4         2        13
142       4         2        16
143       4         2        15
144       4         2        14
145       4         2        14
146       4         2        13
147       4         2        15
         The SAS System

                  det_     serv_
Obs    region    factor     life

148       4         2        13
149       4         2        22
150       4         2        13
151       4         2        25
152       4         2        19
153       4         2        15
154       4         2        13
155       4         2        14
156       4         2        14
157       4         2         9
158       4         2        10
159       4         2        18
160       4         2        14
161       4         2        14
162       4         2        12
163       4         2        21
164       4         2        19
165       5         1        16
166       5         1        14
167       5         1        16
168       5         1        12
169       5         1        17
170       5         1        14
171       5         1        22
172       5         1        22
173       5         1        13
174       5         1        21
175       5         1        18
176       5         1        17
177       5         1        20
178       5         1        14
179       5         1        12
180       5         1        11
```

```
181       5         1        13
182       5         2        13
183       5         2        13
184       5         2        16
185       5         2        16
186       5         2        17
187       5         2        12
188       5         2        12
189       5         2        15
190       5         2        13
191       5         2        13
192       5         2        15
193       5         2        10
194       5         2        10
195       5         2        21
196       5         2        14
         The SAS System

                  det_     serv_
Obs    region    factor     life

197       5         2        22
198       6         1        32
199       6         1        24
200       6         1        10
201       6         1        23
202       6         1        31
203       6         1        11
204       6         1        25
205       6         1        22
206       6         1        11
207       6         1        20
208       6         1        11
209       6         1        23
210       6         1        19
211       6         1        11
212       6         1        11
213       6         1         7
214       6         1         5
215       6         1        30
216       6         1        25
217       6         1        24
218       6         2        18
219       6         2         7
220       6         2         7
221       6         2        18
222       6         2        21
223       6         2        20
224       6         2         9
225       6         2        12
226       6         2        16
227       6         2         9
228       6         2         9
229       6         2         7
230       6         2         8
231       6         2        25
232       6         2        20
233       6         2        11
234       6         2        13
235       6         2        15
236       6         2        15
237       6         2        12
238       6         2         9
239       6         2        14
240       6         2        14
241       6         2         5
242       6         2         9
243       6         2         9
244       6         2        21
245       6         2        22
         The SAS System
```

```
                                                  det_     serv_
                                Obs    region    factor     life

                                246       6         2        18
                                247       6         2        12
                                248       6         2        14
                          Virginia Bridge Paint Service Life Analysis


                                       The GLM Procedure

                                    Class Level Information

                             Class           Levels    Values

                             region               6    1 2 3 4 5 6

                             det_factor           2    1 2


                                 Number of observations    248
                          Virginia Bridge Paint Service Life Analysis

                                       The GLM Procedure

Dependent Variable: serv_life

                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                       11     1796.943073      163.358461       6.31    <.0001

      Error                      236     6105.040798       25.868817

      Corrected Total            247     7901.983871


                     R-Square     Coeff Var      Root MSE    serv_life Mean

                     0.227404      31.80440      5.086140          15.99194


      Source                      DF       Type I SS     Mean Square    F Value    Pr > F

      region                       5     809.0038394     161.8007679       6.25    <.0001
      det_factor                   1     344.0097220     344.0097220      13.30    0.0003
      region*det_factor            5     643.9295114     128.7859023       4.98    0.0002


      Source                      DF     Type III SS     Mean Square    F Value    Pr > F

      region                       5     846.1591859     169.2318372       6.54    <.0001
      det_factor                   1     325.0894406     325.0894406      12.57    0.0005
      region*det_factor            5     643.9295114     128.7859023       4.98    0.0002
                          Virginia Bridge Paint Service Life Analysis

                                       The GLM Procedure
                                      Least Squares Means
                       Adjustment for Multiple Comparisons: Tukey-Kramer

                              serv_life        Standard                  LSMEAN
                 region          LSMEAN           Error    Pr > |t|      Number

                 1           13.0781250       0.7786529      <.0001           1
                 2           17.1400966       0.8002949      <.0001           2
                 3           19.5625000       0.8991110      <.0001           3
                 4           15.6863426       0.8023256      <.0001           4
                 5           15.2500000       0.8857901      <.0001           5
                 6           16.1330645       0.7293694      <.0001           6
```

```
                         Least Squares Means for effect region
                          Pr > |t| for H0: LSMean(i)=LSMean(j)

                             Dependent Variable: serv_life

i/j             1             2             3             4             5             6

   1                     0.0045        <.0001        0.1851        0.4412        0.0514
   2       0.0045                      0.3383        0.7942        0.6104        0.9384
   3       <.0001        0.3383                      0.0183        0.0096        0.0390
   4       0.1851        0.7942        0.0183                      0.9991        0.9985
   5       0.4412        0.6104        0.0096        0.9991                      0.9723
   6       0.0514        0.9384        0.0390        0.9985        0.9723
                      Virginia Bridge Paint Service Life Analysis

                                 The GLM Procedure
                                Least Squares Means
                     Adjustment for Multiple Comparisons: Tukey-Kramer

                                                                H0:LSMean1=
          det_          serv_life        Standard    H0:LSMEAN=0       LSMean2
          factor           LSMEAN           Error       Pr > |t|       Pr > |t|

          1            17.3256341       0.4941398         <.0001         0.0005
          2            14.9577422       0.4494361         <.0001
                      Virginia Bridge Paint Service Life Analysis

                                 The GLM Procedure
                                Least Squares Means
                     Adjustment for Multiple Comparisons: Tukey-Kramer

                  det_         serv_life        Standard                      LSMEAN
        region    factor          LSMEAN           Error    Pr > |t|          Number

        1         1           11.4375000       1.2715349      <.0001               1
        1         2           14.7187500       0.8991110      <.0001               2
        2         1           20.3913043       1.0605334      <.0001               3
        2         2           13.8888889       1.1988146      <.0001               4
        3         1           21.1875000       1.2715349      <.0001               5
        3         2           17.9375000       1.2715349      <.0001               6
        4         1           16.1875000       1.2715349      <.0001               7
        4         2           15.1851852       0.9788280      <.0001               8
        5         1           16.0000000       1.2335701      <.0001               9
        5         2           14.5000000       1.2715349      <.0001              10
        6         1           18.7500000       1.1372954      <.0001              11
        6         2           13.5161290       0.9134977      <.0001              12


                    Least Squares Means for effect region*det_factor
                          Pr > |t| for H0: LSMean(i)=LSMean(j)

                             Dependent Variable: serv_life

i/j             1             2             3             4             5             6

   1                     0.6183        <.0001        0.9621        <.0001        0.0186
   2       0.6183                      0.0035        1.0000        0.0026        0.6468
   3       <.0001        0.0035                      0.0037        1.0000        0.9442
   4       0.9621        1.0000        0.0037                      0.0024        0.4677
   5       <.0001        0.0026        1.0000        0.0024                      0.8126
   6       0.0186        0.6468        0.9442        0.4677        0.8126
   7       0.2630        0.9986        0.3213        0.9765        0.1953        0.9981
   8       0.4546        1.0000        0.0191        0.9995        0.0121        0.8596
   9       0.2998        0.9995        0.2332        0.9863        0.1379        0.9947
  10       0.8653        1.0000        0.0224        1.0000        0.0131        0.7509
  11       0.0016        0.1952        0.9961        0.1333        0.9567        1.0000
  12       0.9747        0.9986        0.0001        1.0000        0.0001        0.1769
```

```
              Least Squares Means for effect region*det_factor
                     Pr > |t| for H0: LSMean(i)=LSMean(j)

                        Dependent Variable: serv_life

i/j             7             8             9            10            11            12

   1       0.2630        0.4546        0.2998        0.8653        0.0016        0.9747
   2       0.9986        1.0000        0.9995        1.0000        0.1952        0.9986
   3       0.3213        0.0191        0.2332        0.0224        0.9961        0.0001
   4       0.9765        0.9995        0.9863        1.0000        0.1333        1.0000
                  Virginia Bridge Paint Service Life Analysis

                             The GLM Procedure
                            Least Squares Means
                Adjustment for Multiple Comparisons: Tukey-Kramer

                 Least Squares Means for effect region*det_factor
                     Pr > |t| for H0: LSMean(i)=LSMean(j)

                        Dependent Variable: serv_life

i/j             7             8             9            10            11            12

   5       0.1953        0.0121        0.1379        0.0131        0.9567        0.0001
   6       0.9981        0.8596        0.9947        0.7509        1.0000        0.1769
   7                     1.0000        1.0000        0.9986        0.9388        0.8638
   8       1.0000                      1.0000        1.0000        0.4267        0.9845
   9       1.0000        1.0000                      0.9995        0.8928        0.9009
  10       0.9986        1.0000        0.9995                      0.3506        1.0000
  11       0.9388        0.4267        0.8928        0.3506                      0.0203
  12       0.8638        0.9845        0.9009        1.0000        0.0203
```

Analysis #2

```
               Virginia Bridge Paint Service Life Analysis
          Five Environmental Regions and Two Deterioration Levels

                              The SAS System

                                       det_      serv_
                      Obs    region    factor     life

                        1       2         1        21
                        2       2         1        23
                        3       2         1        19
                        4       2         1        19
                        5       2         1        13
                        6       2         1        23
                        7       2         1        27
                        8       2         1        27
                        9       2         1        18
                       10       2         1        18
                       11       2         1        16
                       12       2         1        25
                       13       2         1        23
                       14       2         1        23
                       15       2         1        20
                       16       2         1        21
                       17       2         1        23
                       18       2         1        19
                       19       2         1        13
                       20       2         1        11
                       21       2         1        25
                       22       2         1        21
                       23       2         1        21
                       24       2         2        15
                       25       2         2        15
                       26       2         2        13
                       27       2         2        19
                       28       2         2         6
                       29       2         2        10
                       30       2         2        14
                       31       2         2        20
                       32       2         2        18
                       33       2         2        15
                       34       2         2        15
                       35       2         2         7
                       36       2         2        15
                       37       2         2        15
                       38       2         2        15
                       39       2         2        20
                       40       2         2         9
                       41       2         2         9
                       42       3         1        15
                       43       3         1        28
                       44       3         1        23
                       45       3         1        19
                       46       3         1        14
                       47       3         1        25
                       48       3         1        23
                       49       3         1        18
                              The SAS System

                                       det_      serv_
                      Obs    region    factor     life

                       50       3         1        18
                       51       3         1        19
                       52       3         1        14
                       53       3         1        29
                       54       3         1        23
                       55       3         1        18
```

```
 56       3         1        23
 57       3         1        30
 58       3         2        18
 59       3         2        31
 60       3         2        15
 61       3         2        14
 62       3         2        21
 63       3         2        20
 64       3         2        22
 65       3         2        15
 66       3         2        15
 67       3         2        15
 68       3         2        11
 69       3         2        11
 70       3         2        18
 71       3         2        27
 72       3         2        17
 73       3         2        17
 74       4         1        21
 75       4         1        31
 76       4         1        18
 77       4         1        15
 78       4         1        15
 79       4         1        12
 80       4         1        22
 81       4         1        25
 82       4         1        14
 83       4         1        12
 84       4         1         8
 85       4         1         8
 86       4         1        25
 87       4         1         7
 88       4         1        12
 89       4         1        14
 90       4         2        16
 91       4         2        13
 92       4         2        16
 93       4         2        13
 94       4         2        16
 95       4         2        15
 96       4         2        14
 97       4         2        14
 98       4         2        13
         The SAS System

                  det_     serv_
Obs    region    factor     life

 99       4         2        15
100       4         2        13
101       4         2        22
102       4         2        13
103       4         2        25
104       4         2        19
105       4         2        15
106       4         2        13
107       4         2        14
108       4         2        14
109       4         2         9
110       4         2        10
111       4         2        18
112       4         2        14
113       4         2        14
114       4         2        12
115       4         2        21
116       4         2        19
117       5         1        16
118       5         1        14
119       5         1        16
120       5         1        12
121       5         1        17
```

```
122       5         1        14
123       5         1        22
124       5         1        22
125       5         1        13
126       5         1        21
127       5         1        18
128       5         1        17
129       5         1        20
130       5         1        14
131       5         1        12
132       5         1        11
133       5         1        13
134       5         2        13
135       5         2        13
136       5         2        16
137       5         2        16
138       5         2        17
139       5         2        12
140       5         2        12
141       5         2        15
142       5         2        13
143       5         2        13
144       5         2        15
145       5         2        10
146       5         2        10
147       5         2        21
         The SAS System

                  det_     serv_
Obs    region    factor     life

148       5         2        14
149       5         2        22
150       6         1        32
151       6         1        24
152       6         1        10
153       6         1        23
154       6         1        31
155       6         1        11
156       6         1        25
157       6         1        22
158       6         1        11
159       6         1        20
160       6         1        11
161       6         1        23
162       6         1        19
163       6         1        11
164       6         1        11
165       6         1         7
166       6         1         5
167       6         1        30
168       6         1        25
169       6         1        24
170       6         2        18
171       6         2         7
172       6         2         7
173       6         2        18
174       6         2        21
175       6         2        20
176       6         2         9
177       6         2        12
178       6         2        16
179       6         2         9
180       6         2         9
181       6         2         7
182       6         2         8
183       6         2        25
184       6         2        20
185       6         2        11
186       6         2        13
187       6         2        15
```

```
                              188       6         2        15
                              189       6         2        12
                              190       6         2         9
                              191       6         2        14
                              192       6         2        14
                              193       6         2         5
                              194       6         2         9
                              195       6         2         9
                              196       6         2        21
                                       The SAS System

                                                det_     serv_
                              Obs    region    factor     life

                              197       6         2        22
                              198       6         2        18
                              199       6         2        12
                              200       6         2        14
                 Virginia Bridge Paint Service Life Analysis w/o Region 1

                                     The GLM Procedure

                                  Class Level Information

                            Class           Levels    Values

                            region               5    2 3 4 5 6

                            det_factor           2    1 2


                               Number of observations    200
                 Virginia Bridge Paint Service Life Analysis w/o Region 1

                                     The GLM Procedure

Dependent Variable: serv_life

                                                Sum of
      Source                      DF          Squares     Mean Square    F Value    Pr > F

      Model                        9      1348.645452      149.849495       5.56    <.0001

      Error                      190      5124.634548       26.971761

      Corrected Total            199      6473.280000


                     R-Square     Coeff Var      Root MSE    serv_life Mean

                     0.208340      31.36132      5.193434          16.56000


      Source                      DF        Type I SS     Mean Square    F Value    Pr > F

      region                       4      475.5499684     118.8874921       4.41    0.0020
      det_factor                   1      650.6385700     650.6385700      24.12    <.0001
      region*det_factor            4      222.4569133      55.6142283       2.06    0.0874


      Source                      DF      Type III SS     Mean Square    F Value    Pr > F

      region                       4      396.0340886      99.0085222       3.67    0.0066
      det_factor                   1      580.1949225     580.1949225      21.51    <.0001
      region*det_factor            4      222.4569133      55.6142283       2.06    0.0874
                 Virginia Bridge Paint Service Life Analysis w/o Region 1
```

```
                            The GLM Procedure
                           Least Squares Means
            Adjustment for Multiple Comparisons: Tukey-Kramer

                   serv_life        Standard                   LSMEAN
      region          LSMEAN           Error    Pr > |t|       Number

      2           17.1400966       0.8171775      <.0001            1
      3           19.5625000       0.9180782      <.0001            2
      4           15.6863426       0.8192511      <.0001            3
      5           15.2500000       0.9044763      <.0001            4
      6           16.1330645       0.7447558      <.0001            5


                  Least Squares Means for effect region
                   Pr > |t| for H0: LSMean(i)=LSMean(j)

                      Dependent Variable: serv_life

i/j              1             2             3             4             5

   1                      0.2843        0.7182        0.5310        0.8925
   2        0.2843                      0.0161        0.0087        0.0335
   3        0.7182        0.0161                      0.9965        0.9944
   4        0.5310        0.0087        0.9965                      0.9433
   5        0.8925        0.0335        0.9944        0.9433
         Virginia Bridge Paint Service Life Analysis w/o Region 1

                            The GLM Procedure
                           Least Squares Means
            Adjustment for Multiple Comparisons: Tukey-Kramer

                                                            H0:LSMean1=
   det_         serv_life        Standard    H0:LSMEAN=0      LSMean2
   factor          LSMEAN           Error       Pr > |t|       Pr > |t|

   1           18.5032609       0.5469668         <.0001         <.0001
   2           15.0055406       0.5191883         <.0001
```

Analysis #3

Virginia Bridge Paint Service Life Analysis for Region 1
One Environmental Region and Two Deterioration Levels

```
                The SAS System

                  det_      serv_
        Obs    factor      life

          1       1         15
          2       1         12
          3       1         12
          4       1          5
          5       1         15
          6       1          6
          7       1         17
          8       1         11
          9       1         18
         10       1          9
         11       1         12
         12       1         12
         13       1          6
         14       1          8
         15       1         13
         16       1         12
         17       2         12
         18       2         12
         19       2         19
         20       2         25
         21       2         25
         22       2         14
         23       2         11
         24       2         15
         25       2         12
         26       2         10
         27       2         18
         28       2         18
         29       2          5
         30       2          9
         31       2         10
         32       2         26
         33       2         13
         34       2         10
         35       2         10
         36       2         14
         37       2         13
         38       2         10
         39       2         13
         40       2         14
         41       2         14
         42       2         20
         43       2         11
         44       2         19
         45       2         15
         46       2         18
         47       2         19
         48       2         17
 Virginia Bridge Paint Service Life Analysis for R1
```

```
                                   The TTEST Procedure

                                          Statistics

                             Lower CL          Upper CL  Lower CL          Upper CL
Variable  det_factor      N      Mean    Mean      Mean   Std Dev  Std Dev  Std Dev  Std Err

serv_                    16    9.3878  11.438    13.487    2.8415   3.8465    5.9532   0.9616
life       1
serv_                    32    12.935  14.719    16.502    3.9655   4.9464    6.5761   0.8744
life       2
serv_     Diff (1-2)           -6.127  -3.281    -0.436    3.8363   4.6166    5.7984   1.4135
life


                                            T-Tests

             Variable     Method           Variances      DF    t Value    Pr > |t|

             serv_life    Pooled           Equal          46      -2.32      0.0248
             serv_life    Satterthwaite    Unequal      37.6      -2.52      0.0159
             serv_life    Cochran          Unequal         .      -2.52      0.0204


                                     Equality of Variances

                 Variable     Method      Num DF    Den DF    F Value    Pr > F

                 serv_life    Folded F        31        15       1.65    0.3031
```

Analysis #4

```
          Virginia Bridge Paint Service Life Analysis
        Six Environmental Regions and Deterioration Level 1

                         The SAS System

                                   serv_
                     Obs    region     life

                       1       1        15
                       2       1        12
                       3       1        12
                       4       1         5
                       5       1        15
                       6       1         6
                       7       1        17
                       8       1        11
                       9       1        18
                      10       1         9
                      11       1        12
                      12       1        12
                      13       1         6
                      14       1         8
                      15       1        13
                      16       1        12
                      17       2        21
                      18       2        23
                      19       2        19
                      20       2        19
                      21       2        13
                      22       2        23
                      23       2        27
                      24       2        27
                      25       2        18
                      26       2        18
                      27       2        16
                      28       2        25
                      29       2        23
                      30       2        23
                      31       2        20
                      32       2        21
                      33       2        23
                      34       2        19
                      35       2        13
                      36       2        11
                      37       2        25
                      38       2        21
                      39       2        21
                      40       3        15
                      41       3        28
                      42       3        23
                      43       3        19
                      44       3        14
                      45       3        25
                      46       3        23
                      47       3        18
                      48       3        18
                      49       3        19
                         The SAS System

                                   serv_
                     Obs    region     life

                      50       3        14
                      51       3        29
                      52       3        23
                      53       3        18
                      54       3        23
                      55       3        30
```

```
               56       4        21
               57       4        31
               58       4        18
               59       4        15
               60       4        15
               61       4        12
               62       4        22
               63       4        25
               64       4        14
               65       4        12
               66       4         8
               67       4         8
               68       4        25
               69       4         7
               70       4        12
               71       4        14
               72       5        16
               73       5        14
               74       5        16
               75       5        12
               76       5        17
               77       5        14
               78       5        22
               79       5        22
               80       5        13
               81       5        21
               82       5        18
               83       5        17
               84       5        20
               85       5        14
               86       5        12
               87       5        11
               88       5        13
               89       6        32
               90       6        24
               91       6        10
               92       6        23
               93       6        31
               94       6        11
               95       6        25
               96       6        22
               97       6        11
               98       6        20
                  The SAS System

                               serv_
              Obs    region     life

               99       6        11
              100       6        23
              101       6        19
              102       6        11
              103       6        11
              104       6         7
              105       6         5
              106       6        30
              107       6        25
              108       6        24
Virginia Bridge Paint Service Life Analysis w/ D1

                The GLM Procedure

             Class Level Information

       Class         Levels    Values

       region             6    1 2 3 4 5 6


          Number of observations    108
Virginia Bridge Paint Service Life Analysis w/ D1
```

```
                                    The GLM Procedure

Dependent Variable: serv_life

                                              Sum of
      Source                      DF         Squares     Mean Square    F Value    Pr > F

      Model                        5     1094.505535      218.901107       6.81    <.0001

      Error                      102     3278.040761       32.137655

      Corrected Total            107     4372.546296


                     R-Square     Coeff Var      Root MSE    serv_life Mean

                     0.250313      32.27480      5.669008          17.56481


      Source                      DF       Type I SS     Mean Square    F Value    Pr > F

      region                       5     1094.505535      218.901107       6.81    <.0001


      Source                      DF     Type III SS     Mean Square    F Value    Pr > F

      region                       5     1094.505535      218.901107       6.81    <.0001
                       Virginia Bridge Paint Service Life Analysis w/ D1

                                       The GLM Procedure
                                      Least Squares Means
                       Adjustment for Multiple Comparisons: Tukey-Kramer

                              serv_life        Standard                  LSMEAN
                 region          LSMEAN           Error    Pr > |t|      Number

                 1           11.4375000       1.4172521      <.0001           1
                 2           20.3913043       1.1820699      <.0001           2
                 3           21.1875000       1.4172521      <.0001           3
                 4           16.1875000       1.4172521      <.0001           4
                 5           16.0000000       1.3749365      <.0001           5
                 6           18.7500000       1.2676288      <.0001           6


                             Least Squares Means for effect region
                              Pr > |t| for H0: LSMean(i)=LSMean(j)

                                 Dependent Variable: serv_life

    i/j               1             2             3             4             5             6

       1                      <.0001        <.0001        0.1768        0.1994        0.0028
       2        <.0001                      0.9981        0.2127        0.1585        0.9331
       3        <.0001        0.9981                      0.1354        0.1001        0.7942
       4        0.1768        0.2127        0.1354                      1.0000        0.7577
       5        0.1994        0.1585        0.1001        1.0000                      0.6837
       6        0.0028        0.9331        0.7942        0.7577        0.6837
```

Analysis #5

Virginia Bridge Paint Service Life Analysis
Six Environmental Regions and Deterioration Level 2

```
              The SAS System

                              serv_
          Obs    region      life

            1       1         12
            2       1         12
            3       1         19
            4       1         25
            5       1         25
            6       1         14
            7       1         11
            8       1         15
            9       1         12
           10       1         10
           11       1         18
           12       1         18
           13       1          5
           14       1          9
           15       1         10
           16       1         26
           17       1         13
           18       1         10
           19       1         10
           20       1         14
           21       1         13
           22       1         10
           23       1         13
           24       1         14
           25       1         14
           26       1         20
           27       1         11
           28       1         19
           29       1         15
           30       1         18
           31       1         19
           32       1         17
           33       2         15
           34       2         15
           35       2         13
           36       2         19
           37       2          6
           38       2         10
           39       2         14
           40       2         20
           41       2         18
           42       2         15
           43       2         15
           44       2          7
           45       2         15
           46       2         15
           47       2         15
           48       2         20
           49       2          9
              The SAS System

                              serv_
          Obs    region      life

           50       2          9
           51       3         18
           52       3         31
           53       3         15
           54       3         14
           55       3         21
```

```
 56       3        20
 57       3        22
 58       3        15
 59       3        15
 60       3        15
 61       3        11
 62       3        11
 63       3        18
 64       3        27
 65       3        17
 66       3        17
 67       4        16
 68       4        13
 69       4        16
 70       4        13
 71       4        16
 72       4        15
 73       4        14
 74       4        14
 75       4        13
 76       4        15
 77       4        13
 78       4        22
 79       4        13
 80       4        25
 81       4        19
 82       4        15
 83       4        13
 84       4        14
 85       4        14
 86       4         9
 87       4        10
 88       4        18
 89       4        14
 90       4        14
 91       4        12
 92       4        21
 93       4        19
 94       5        13
 95       5        13
 96       5        16
 97       5        16
 98       5        17
    The SAS System

                 serv_
Obs    region     life

 99       5        12
100       5        12
101       5        15
102       5        13
103       5        13
104       5        15
105       5        10
106       5        10
107       5        21
108       5        14
109       5        22
110       6        18
111       6         7
112       6         7
113       6        18
114       6        21
115       6        20
116       6         9
117       6        12
118       6        16
119       6         9
120       6         9
121       6         7
```

```
                      122       6         8
                      123       6        25
                      124       6        20
                      125       6        11
                      126       6        13
                      127       6        15
                      128       6        15
                      129       6        12
                      130       6         9
                      131       6        14
                      132       6        14
                      133       6         5
                      134       6         9
                      135       6         9
                      136       6        21
                      137       6        22
                      138       6        18
                      139       6        12
                      140       6        14
        Virginia Bridge Paint Service Life Analysis w/ D2

                        The GLM Procedure

                     Class Level Information

               Class         Levels    Values

               region             6    1 2 3 4 5 6


                  Number of observations    140
        Virginia Bridge Paint Service Life Analysis w/ D2
```

```
                                       The GLM Procedure

Dependent Variable: serv_life

                                              Sum of
      Source                       DF        Squares     Mean Square    F Value    Pr > F

      Model                         5     229.135677       45.827135       2.17    0.0609

      Error                       134    2827.000037       21.097015

      Corrected Total             139    3056.135714


                     R-Square     Coeff Var      Root MSE    serv_life Mean

                     0.074976      31.07979      4.593149          14.77857


      Source                       DF      Type I SS     Mean Square    F Value    Pr > F

      region                        5    229.1356769      45.8271354       2.17    0.0609


      Source                       DF    Type III SS     Mean Square    F Value    Pr > F

      region                        5    229.1356769      45.8271354       2.17    0.0609
                       Virginia Bridge Paint Service Life Analysis w/ D2

                                       The GLM Procedure
                                      Least Squares Means
                       Adjustment for Multiple Comparisons: Tukey-Kramer

                              serv_life        Standard                  LSMEAN
                 region          LSMEAN           Error   Pr > |t|      Number

                 1           14.7187500        0.8119617     <.0001            1
                 2           13.8888889        1.0826155     <.0001            2
                 3           17.9375000        1.1482872     <.0001            3
                 4           15.1851852        0.8839519     <.0001            4
                 5           14.5000000        1.1482872     <.0001            5
                 6           13.5161290        0.8249539     <.0001            6


                             Least Squares Means for effect region
                              Pr > |t| for H0: LSMean(i)=LSMean(j)

                                 Dependent Variable: serv_life

    i/j               1             2             3             4             5             6

       1                       0.9899        0.2060        0.9988        1.0000        0.9039
       2         0.9899                      0.1132        0.9388        0.9988        0.9998
       3         0.2060        0.1132                      0.4071        0.2850        0.0258
       4         0.9988        0.9388        0.4071                      0.9970        0.7387
       5         1.0000        0.9988        0.2850        0.9970                      0.9821
       6         0.9039        0.9998        0.0258        0.7387        0.9821
```

Steel Girder Paint Service Life Means and Standard Deviations

```
          The SAS System

                  det_     serv_
Obs    region    factor     life

  1       1         1        15
  2       1         1        12
  3       1         1        12
  4       1         1         5
  5       1         1        15
  6       1         1         6
  7       1         1        17
  8       1         1        11
  9       1         1        18
 10       1         1         9
 11       1         1        12
 12       1         1        12
 13       1         1         6
 14       1         1         8
 15       1         1        13
 16       1         1        12
 17       1         2        12
 18       1         2        12
 19       1         2        19
 20       1         2        25
 21       1         2        25
 22       1         2        14
 23       1         2        11
 24       1         2        15
 25       1         2        12
 26       1         2        10
 27       1         2        18
 28       1         2        18
 29       1         2         5
 30       1         2         9
 31       1         2        10
 32       1         2        26
 33       1         2        13
 34       1         2        10
 35       1         2        10
 36       1         2        14
 37       1         2        13
 38       1         2        10
 39       1         2        13
 40       1         2        14
 41       1         2        14
 42       1         2        20
 43       1         2        11
 44       1         2        19
 45       1         2        15
 46       1         2        18
 47       1         2        19
 48       1         2        17
 49       2         1        21
         The SAS System

                  det_     serv_
Obs    region    factor     life

 50       2         1        23
 51       2         1        19
 52       2         1        19
 53       2         1        13
 54       2         1        23
 55       2         1        27
```

```
 56       2         1        27
 57       2         1        18
 58       2         1        18
 59       2         1        16
 60       2         1        25
 61       2         1        23
 62       2         1        23
 63       2         1        20
 64       2         1        21
 65       2         1        23
 66       2         1        19
 67       2         1        13
 68       2         1        11
 69       2         1        25
 70       2         1        21
 71       2         1        21
 72       2         2        15
 73       2         2        15
 74       2         2        13
 75       2         2        19
 76       2         2         6
 77       2         2        10
 78       2         2        14
 79       2         2        20
 80       2         2        18
 81       2         2        15
 82       2         2        15
 83       2         2         7
 84       2         2        15
 85       2         2        15
 86       2         2        15
 87       2         2        20
 88       2         2         9
 89       2         2         9
 90       3         1        15
 91       3         1        28
 92       3         1        23
 93       3         1        19
 94       3         1        14
 95       3         1        25
 96       3         1        23
 97       3         1        18
 98       3         1        18
         The SAS System

                  det_     serv_
Obs    region    factor     life

 99       3         1        19
100       3         1        14
101       3         1        29
102       3         1        23
103       3         1        18
104       3         1        23
105       3         1        30
106       3         2        18
107       3         2        31
108       3         2        15
109       3         2        14
110       3         2        21
111       3         2        20
112       3         2        22
113       3         2        15
114       3         2        15
115       3         2        15
116       3         2        11
117       3         2        11
118       3         2        18
119       3         2        27
120       3         2        17
121       3         2        17
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```
122       4         1        21
123       4         1        31
124       4         1        18
125       4         1        15
126       4         1        15
127       4         1        12
128       4         1        22
129       4         1        25
130       4         1        14
131       4         1        12
132       4         1         8
133       4         1         8
134       4         1        25
135       4         1         7
136       4         1        12
137       4         1        14
138       4         2        16
139       4         2        13
140       4         2        16
141       4         2        13
142       4         2        16
143       4         2        15
144       4         2        14
145       4         2        14
146       4         2        13
147       4         2        15
         The SAS System

                  det_     serv_
Obs    region    factor     life

148       4         2        13
149       4         2        22
150       4         2        13
151       4         2        25
152       4         2        19
153       4         2        15
154       4         2        13
155       4         2        14
156       4         2        14
157       4         2         9
158       4         2        10
159       4         2        18
160       4         2        14
161       4         2        14
162       4         2        12
163       4         2        21
164       4         2        19
165       5         1        16
166       5         1        14
167       5         1        16
168       5         1        12
169       5         1        17
170       5         1        14
171       5         1        22
172       5         1        22
173       5         1        13
174       5         1        21
175       5         1        18
176       5         1        17
177       5         1        20
178       5         1        14
179       5         1        12
180       5         1        11
181       5         1        13
182       5         2        13
183       5         2        13
184       5         2        16
185       5         2        16
186       5         2        17
187       5         2        12
```

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188       5         2        12
189       5         2        15
190       5         2        13
191       5         2        13
192       5         2        15
193       5         2        10
194       5         2        10
195       5         2        21
196       5         2        14
         The SAS System

                     det_     serv_
Obs    region    factor     life

197       5         2        22
198       6         1        32
199       6         1        24
200       6         1        10
201       6         1        23
202       6         1        31
203       6         1        11
204       6         1        25
205       6         1        22
206       6         1        11
207       6         1        20
208       6         1        11
209       6         1        23
210       6         1        19
211       6         1        11
212       6         1        11
213       6         1         7
214       6         1         5
215       6         1        30
216       6         1        25
217       6         1        24
218       6         2        18
219       6         2         7
220       6         2         7
221       6         2        18
222       6         2        21
223       6         2        20
224       6         2         9
225       6         2        12
226       6         2        16
227       6         2         9
228       6         2         9
229       6         2         7
230       6         2         8
231       6         2        25
232       6         2        20
233       6         2        11
234       6         2        13
235       6         2        15
236       6         2        15
237       6         2        12
238       6         2         9
239       6         2        14
240       6         2        14
241       6         2         5
242       6         2         9
243       6         2         9
244       6         2        21
245       6         2        22
         The SAS System

                     det_     serv_
Obs    region    factor     life

246       6         2        18
247       6         2        12
248       6         2        14
```

```
          Virginia Bridge Paint Service Life Analysis

                       The GLM Procedure

                    Class Level Information

             Class           Levels    Values

             region               6    1 2 3 4 5 6

             det_factor           2    1 2


                 Number of observations    248

          Virginia Bridge Paint Service Life Analysis

                       The GLM Procedure


Level of     Level of              ----------serv_life----------
region       det_factor      N             Mean          Std Dev

1            1              16       11.4375000       3.84653524
1            2              32       14.7187500       4.94638594
2            1              23       20.3913043       4.26123254
2            2              18       13.8888889       4.19928410
3            1              16       21.1875000       5.12794631
3            2              16       17.9375000       5.35995958
4            1              16       16.1875000       6.92068157
4            2              27       15.1851852       3.55221531
5            1              17       16.0000000       3.58817502
5            2              16       14.5000000       3.38624669
6            1              20       18.7500000       8.39094123
6            2              31       13.5161290       5.28438560
          Virginia Bridge Paint Service Life Analysis

                       The GLM Procedure


       Level of            ----------serv_life----------
       region        N             Mean          Std Dev

       1            48       13.6250000       4.82733793
       2            41       17.5365854       5.30611704
       3            32       19.5625000       5.41763846
       4            43       15.5581395       5.01570071
       5            33       15.2727273       3.52023372
       6            51       15.5686275       7.08309227


      Level of              ----------serv_life----------
      det_factor       N             Mean          Std Dev

      1              108       17.5648148       6.39256745
      2              140       14.7785714       4.68898580
```

APPENDIX E

SAMPLE – VDOT ELECTRONIC BRIDGE INSPECTION DATA (1999)

D	CO/	ROUTE	CROSSING	VA	YEAR	ADT	ADTT	DECK	MAIN	MAIN	FUNC
I	CTY			STR	BLT	CNT	PRCNT	TYPE	SPAN	SPAN	CLASS
S				NUMB					MAT	TYPE	
1	13	609	LEVISA RIVER	6259	1967	3426	5	1	3	2	7
1	13	635	DISMAL RIVER	6054	1972	697	0	1	3	2	9
1	13	604	LEVISA RIVER	6119	1974	1290	0	1	3	2	9
1	13	624	GARDEN CREEK	6041	1960	2469	5	1	3	2	7
2	17	607	CHESTNUT CREEK	6004	1973	417	0	1	3	2	9
2	17	749	LITTLE REED ISLAND CRK.	6149	1970	447	0	1	3	2	8
2	17	721	CHESTNUT CREEK	6439	1964	3081	5	1	3	2	7
1	25	652	MCCLURE RIVER	6122	1962	316	0	1	3	2	9
1	25	631	POUND RIVER	6139	1967	1436	1	1	3	2	7
1	25	773	MCCLURE RIVER	6071	1978	576	0	1	3	2	9
1	25	63	RUSSELL F R @ HAYSI	1042	1960	1594	5	1	3	2	7
2	31	705	LITTLE RIVER	6379	1968	131	0	1	3	2	9
2	31	615	LITTLE RIVER	6354	1966	1155	5	1	3	2	7
2	31	8	DODDS CREEK	1002	1976	4115	6	1	3	2	6
2	31	8	W FORK LITTLE RIVER	1003	1976	4115	6	1	3	2	6
2	35	61	WOLF CREEK	1080	1969	823	5	1	3	2	7
2	35	61	WOLF CREEK @ NARROWS	1078	1963	1132	5	1	3	2	7
2	35	460	SINKING CREEK	1075	1977	4739	10	1	3	2	2
2	35	460	SINKING CREEK	1077	1961	4739	10	1	3	2	2
1	52	606	N FORK POWELL RIVER	6466	1964	1198	5	1	3	2	7
1	52	23	NORFORK&SOUTHERN	1008	1975	4629	10	1	3	2	2
1	52	23	NORFORK&SOUTHERN	1009	1975	4629	10	1	3	2	2
1	52	654	POWELL RIVER @ HR FORD	6044	1978	458	4	1	3	2	8
1	52	661	HARDYS CREEK	6054	1979	435	5	1	3	2	7
2	60	637	S FORK ROANOKE RIVER	6047	1975	1620	5	1	3	2	7
2	60	603	N FORK ROANOKE RIVER	6008	1970	2109	5	1	3	2	7
2	60	605	LITTLE RIVER	6901	1969	2277	0	1	3	2	9
2	60	177	RTE I 81	1062	1965	3086	6	1	3	2	6
2	77	601	LITTLE WALKER CREEK	6004	1978	210	0	1	3	2	9
2	77	611	RTE I 81	6166	1965	1543	5	1	3	2	7
2	77	100	BACK CREEK	1018	1974	1800	6	1	3	2	6
2	77	660	RTE I 81	6165	1965	3033	5	1	3	2	7
1	92	643	BLUESTONE RIVER	6243	1961	2612	5	1	3	2	7

SAMPLE DATA - CONTINUATION

VA	PROT	PROT	PROT	PAINT	PAINT	DECK	SUPR	SUB	W.S.	STRUC.	STRUCTURE
STR	WEAR	WEAR	WEAR	COND	YEAR	GEN	GEN	GEN	COMP	COMP	LENGTH
NUMB	SURF	MEMB	DECK			COND	COND	COND	COND	COND	
6259	0	0	0	F	1985	6	6	6	F	G	242
6054	1	8	0	F	1971	4	6	4	-	P	102
6119	0	0	0	F	1974	6	6	6	-	F	219
6041	1	8	0	G	1987	6	8	6	G	F	51
6004	1	0	0	F	1972	5	6	6	-	F	66
6149	0	0	0	F	1970	7	8	8	-	G	223
6439	3	0	0	P	1964	6	6	6	-	F	176
6122	0	0	0	F	1987	5	5	7	-	F	64
6139	0	0	0	P	1987	4	5	6	-	P	175
6071	1	8	0	P	1978	5	5	5	-	F	143
1042	3	1	9	P	1987	5	5	5	F	F	284
6379	0	0	0	F	1986	5	5	5	-	F	194
6354	0	0	0	F	1985	8	8	7	-	G	493
1002	0	0	0	P	1975	6	7	7	-	F	190
1003	0	0	0	F	1975	5	4	6	P	F	210
1080	0	0	0	G	1998	5	5	5	-	-	202
1078	6	0	0	F	1986	7	7	7	F	F	213
1075	0	0	0	F	1977	5	7	7	-	F	220
1077	6	0	0	F	1991	7	6	7	F	G	199
6466	0	0	0	P	1988	5	6	6	-	F	154
1008	0	0	0	P	1974	5	5	5	-	F	152
1009	0	0	0	P	1974	5	5	5	-	F	147
6044	0	8	0	G	1978	6	7	7	-	F	242
6054	0	0	0	F	1979	6	7	6	-	F	224
6047	0	0	0	F	1975	5	6	6	-	F	1600
6008	0	0	0	F	1970	7	7	6	-	G	248
6901	0	0	0	P	1984	7	5	6	G	G	160
1062	3	0	0	G	1995	5	7	5	-	F	268
6004	0	0	0	F	1978	5	6	5		G	408
6166	0	0	0	P	1979	7	8	7	-	F	304
1018	0	0	0	P	1974	6	7	6	-	G	80
6165	3	0	0	P	1979	6	7	7	G	G	187
6243	1	8	1	G	1988	7	6	7	-	G	175

APPENDIX F

SAMPLE - FHWA NBI DATA FOR VIRGINIA (1983)

```
51300000001016829818100000007013     G WASH PKWY O RTE 120          ROUTE  0000                    9999
385542000770706000163606019193202020923001979001460000
5N000000000A5130200000400001760045700162501501501460183999H0609H999000      304 225  35NN
0000                     000000      000000                     0   8 0000 100                              A              2*0781
51300000001016829823100120007013     ROUTE  0000            ROUTE  0000      0243309      0006123     0609
385542000770706000263      19320202011090               5N         51302          15200457001625                H    H
1   3 0000                                   Z              0
51300000001046760013300000007013     MILITARY RD O RTE 120          ROUTE  00000201309      0038123
9999
00000000000000000106327271619640206012000198160104000010005N004200024A513020000300000920031
40006520150050073009999999H0464H024999586NN 441 3244555N5351      0583                        002520
000280                       0   3 0000 100                          Z              0 0610
51300000005000790818700000007013     ABING ST O 395 & RMP D&F        ROUTE  00000016NCL
ALEXA0116120     9999
38500600077054200002301011919700410008300198160183002010105N000000000A613020000500001760025
00011060150150146018399999H0762H058020888NN 477 3247785N6         0583                   000000      000000
0   8 0000 100                           Z              0 0832
51300000005000790821700395007013     ROUTE  0000            ROUTE  0000      0016NCL ALEXA0116125
0762                  38500600077054200   3      19700410127650               5N         61302          22700250001106
H    H                                                                                   1   1 0000                               Z
0
51300000005001973018100000007013     CT H RD O WB RT 50(A BLV        ROUTE  0000000613THST
000150EBL   9999
3853120007705000000230202191954020200967219810013700001115N000000000A513020000100001000018
300018301400800790107999H0439H030030476NN 338 2483755N6351      0782                   000087
000090                       0   8 1954 100                          A              1 0754
51300000005001973022100050007013     ROUTE  0000            ROUTE  0000      0122AR MEM BR0016237
0485                  385312000770500000023      19540202047675               5N         51302          17000183000183
H    H                                                                                   2   3 1954                               Z
0
51300000005002776218700000007013     MEADE ST O RTE 50& RMP C        ROUTE  0000001017TH ST
ATN MEAD S9999
38532400077044200003302021419660407043520198160229210010005N000000000A5140230200200012370026
2000640015015020702449999H0454H013020678NN 441 3245555N7         0782                   000000      000000
0   3 0000 100                           Z              0 0828
51300000005004776318100000007013     N RHODES ST O RTE 50           ROUTE  00000001RAMP
000314TH ST 9999
38532400077044200003302021919660209010161198150152013010005N000000000A513020000400001400025
30006640150150110014699999H0474H013023677NN 441 3245755N7         0782                   000000      000000
0   8 0000 100                           Z              0 0893
51300000005004776322100050007013     ROUTE  0000            ROUTE  0000      0082D C LINE 0047237
0520                  385324000770442000023      19660209047675               5N         51302          15000253000664
H    H                                                                                   1   3 0000                               Z
0
51300000005007937814100000007013     WILSON BLVD O FOUR MI RN        ROUTE  00000075MCKIN RD
0070N GEO MA9999
```

NBI FOR VIRGINIA - CONTINUATION

```
0000000000000000000530202141950040002280019710015820001011500000000000A55302000001000018800140
0001400150150158019599999N0000N0000005777N 304 22556N567         0480                   000000      000000
0   3 1959 600                            Z               0 0734
51300000005008938814100000007013     WALTER REED DR O FOUR MI        ROUTE  000000707
00104MI RU D9999
0000000000000000000530202161975050000820019746022301301111500000000000A15302000002000024300244
0004880200200204025299999N0000N0000008888N 441 32488N588         0480                   000000      000000
0   3 0000 100                            Z               0 0930
51300000005009938914100000007013     CARLYN SPG RD O FOUR M R        ROUTE  00000130GLEBE RD
0010ARL BLVD9999
0000000000000000000230202161932020001610419810009800001000500000000000A55102000001000009400098
0000980150060073010199999N0000N0000004444N 304 22533N532311      0482                   000270      000290
0   3 1954 600                            A               1 0405
51300000005010939014100000007013     CARLYN SPS RD OG MASN DR        ROUTE  0000008550
0045GLEBE RD9999
000000000000000000023020216196004040153001979501682000111115N000000000A51502000001000019800021
0000210015015016802049999H0487H012000756NN 441 3248885N8         0480                   000000      000000
0   3 0000 600                            Z               0 0734
51300000005011941914100000007013     GEO MASON DR O FOUR MI R        ROUTE  000000757
0015FOUR MI 9999
0000000000000000000230202161966020000410019715011000001111150000000000A55302000003000010800210
0006310050210082011499999N0000N0000008687N 441 32488N588         0480                   000000      000000
0   3 0000 100                            Z               0 0846
51300000005012941114100000007013     GEO MASON DR O FOUR MI R        ROUTE  000000757
0015FOUR MI 9999
0000000000000000000230202161966020000410019715011000001NNN50000000000A553020000030000108002
1000063102100500820114 9999N0000N0000008687N 441 32478N588         0480                   000000      000000
0   3 0000 100                            Z               0 0846
51300000005013940614100000007013     17ST N O FORT MYER DRIVE        ROUTE  00000010N LYNN
ST0010N NASH S9999
000000000000000000023020214196803020030001979501430001111115N000000000A51302000001000019100037
5000375030030013101989999H0474H030000787NN 441 3248885N8         0480                   000000      000000
0   3 0000 600                            Z               0 0885
51300000005014940314100000007013     N SYCAMORE ST OFOUR MI R        ROUTE  00000075WILS
BLVD0025WASH BLV9999
0000000000000000000230202161971020000300019715011000001NNN50000000000A553020000010000105001
9500019501800500820111 9999N0000N0000007878N 441 32489N589         0480                   000000      000000
0   3 0000 600                            Z               0 0847
51300000005015939514100000007013     N SYCAMORE ST OFOUR MI R        ROUTE  00000075WILS
BLVD0025WASH BLV9999
000000000000000000023020216197102000030001971501100000NNNN50000000000A153020000010000105001
9500019500501800820111 9999N0000N0000007878N 441 32488N589         0480                   000000      000000
0   3 0000 600                            Z               0 0847
51300000005020587216100000007013     MEMORIAL AVE O RTE 110          ROUTE  0000                         9999
000000000000000000063606014193204050372001979 00271
```

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VITA

Daniel K. Dadson

Daniel was born on October 20, 1962 in Kumasi, Ghana, in the western part of Africa. He had his elementary and high school education in Ghana. He obtained his bachelor of science in Civil Engineering with honors in 1987 from the University of Science and Technology, also in Ghana. After graduation, he taught for two years at the same university as a teaching aid. In 1989, Daniel enrolled in a structural engineering graduate program at Tufts University in Medford, Massachusetts. He graduated with his masters in structural engineering in 1991.

After his masters, Daniel worked for nearly four years for two consulting companies in Boston doing civil/structural engineering with emphasis on bridges. In 1995, Daniel enrolled in the construction engineering and management graduate program at Virginia Tech to pursue a doctoral degree. After two years of full-time status at Virginia Tech, Daniel took full-time employment with structural/bridge consulting companies while completing his graduate program.

Daniel is a member of Chi Epsilon, National Civil Engineering Honor Society Virginia Tech Chapter and Tau Beta Pi, National Engineering Honor Society Massachusetts Chapter.

Daniel is a registered professional engineer in the states of Virginia, Massachusetts and Florida.

Daniel currently resides in Northern Virginia with his family.