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16. Abstract

The objectives of the research were to identify and quantify the factors that affect the life of South Dakota's bridges, and to evaluate the rehabilitation procedures being used by SDDOT. Furthermore, this work was intended to aid in the implementation of a Bridge Management System (BMS).

An extensive literature review was performed that included efforts by other states related to BMS. The capabilities of the Pontis BMS software and the information required to utilize this program were reviewed. Elements essential to a BMS such as level of service goals, user and agency costs for the state of South Dakota were defined. Finally, deterioration curves for bridge decks, bridge superstructure and bridge substructure considering the effects of ADT, bridge type, geographic location, bridge length, and degree of skewness were developed. The Markov chain statistical approach was the basis in developing these curves.

The research demonstrated that the South Dakota's present bridge maintenance policy is adequate. In addition, the developed deterioration curves verified that an expected bridge design life of 50 years if applicable.

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TABLE OF CONTENTS

ACKNOWLEDGMENT iv

1. INTRODUCTION 1
   1.1. Background 1
   1.2. Objective 3
   1.3. Research Plan 3
      1.3.1. Task 1 3
      1.3.2. Task 2 3
      1.3.3. Task 3 3
      1.3.4. Task 4 4
      1.3.5. Task 5 4
      1.3.6. Task 6 4

2. LITERATURE REVIEW 5
   2.1. South Dakota's Bridge Management Processes 5
      2.1.1. Division of Planning, Office of Data Inventory 6
      2.1.2. Division of Operation 7
      2.1.3. Division of Engineering 7
      2.1.4. Prioritization Criteria 8
      2.1.5. Division of Planning, Office of Planning and Programming 9
      2.1.6. South Dakota's Bridge Deck Maintenance Policies 9
      2.1.7. Comments on South Dakota's Bridge Maintenance Policies 11
   2.2. Iowa Department of Transportation 12
   2.3. North Carolina Department of Transportation Bridge Management Research . . 13
   2.4. Pennsylvania Department of Transportation Bridge Management System 16
   2.5. National Cooperative Highway Bridge Management Systems 19
   2.6. Washington State Department of Transportation Bridge Deck Management Systems 20
   2.7. Minnesota Department of Transportation Priority System 21
   2.8. Michigan Department of Transportation - Critical Bridge Rating 21
   2.9. Illinois Department of Transportation 22
   2.10. New York Department of Transportation 24
   2.11. North Dakota Department of Transportation 24
   2.12. Kansas Department of Transportation 25
   2.13. Virginia Department of Transportation 26
   2.14. Maryland Department of Transportation 26
   2.15. Wisconsin Department of Transportation 27
   2.16. Nebraska Department of Roads 27
   2.17. Florida Department of Transportation 28
   2.18. FHWA Bridge Management System Phase I 29
   2.19. Summary of Existing Bridge Management System Procedures 29
3. PONTIS - BRIDGE MANAGEMENT SYSTEM 31
   3.1 Background 31
   3.2. Major Elements in the Pontis Program 32
      3.2.1. Database 32

3.2.2. Maintenance, Repair and Rehabilitation (MR & R) Optimization Model ... 32
3.2.2.1. Prediction model ... 33
3.2.2.2. MR & R action costs ... 35
3.2.2.3. User costs ... 36
3.2.2.3.1. Accident costs ... 36
3.2.2.3.2. Vehicle operating costs ... 37
3.2.3. Improvement Model ... 42
3.2.4. Integration Model ... 42
3.3. Pontis Output ... 42
3.3.1. MR & R Network Recommendation ... 42
3.3.2. Scheduled Needs and Backlog ... 43
3.3.3. First-Year Project List ... 43
3.3.4. Thirty Years Simulation ... 43
3.4. Evaluation of the Pontis BMS by Iowa DOT ... 43

4. LEVEL-OF-SERVICE GOALS ... 47
4.1. Load Capacity ... 47
4.2. Vertical Clearance ... 48
4.3. Clear Deck Width ... 49
4.4. Other Measures for Bridge Performance ... 51

5. AGENCY AND USER COSTS ... 53
5.1. Agency Costs ... 53
5.1.1. South Dakota's Improvement Action Costs Associated with New Bridges ... 54
5.1.2. South Dakota's MR&R Costs Associated with Contract Maintenance ... 55
5.1.2.1. Cost for deck overlay ... 55
5.1.2.2. Painting cost ... 55
5.1.2.3. Cost of repairing damaged bridge beams ... 55
5.1.3. Cost Associated with In-House Bridge Maintenance ... 56
5.1.3.1. Cost for deck overlay ... 56
5.1.3.2. Cost for bridge deck epoxy injection ... 56
5.1.3.3. Cost for bridge deck patching ... 57
5.1.3.4. Cost for repairing damaged bridge beams ... 57
5.1.3.5. Cost for erosion control ... 57
5.2. User Costs ... 58
5.2.1. South Dakota Vehicle Operating Costs ... 58
5.2.2. South Dakota Accident Costs ... 60
5.2.3. South Dakota ADT Growth Rate ... 60
5.3. Summary ... 61

6. BRIDGE PERFORMANCE PREDICTION MODEL ... 63
6.1. Transition Matrices ... 63
6.2. State Vector ... 69
6.3. Prediction of Future Conditions by Markov Chain ... 71
6.4. Approximate Prediction Model ... 71

6.5. Integration of the Markov Chain and the Approximate Model 75

7. CONDITION RATING - AGE RELATIONSHIP FOR THE SOUTH DAKOTA BRIDGES 83
7.1. Factors Affecting Bridge Deterioration 86
7.2. Development of Condition Rating-Age Relationships 87
7.2.1. Data File Preparation 88
7.2.2. Preparation of the Transition Matrices File 88
7.2.3. Calculation of Condition Ratings.............................. 88
7.3. Computer Software Availability 89
7.4. South Dakota's Bridge Components Deterioration--Age Relationships 89
7.4.1. Effect of Bridge Length 91
7.4.2. Effects of Average Daily Traffic 91
7.4.3. Effect of Geographic Location 104
7.4.4. Effect of Bridge Type 108
7.4.5. Effect of Degree of Skewness 112
7.5. Actual Bridge Life vs. Design Life 116

8. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS 117
8.1. Summary 117
8.2. Conclusions 119
8.3. Recommendation 120

9. REFERENCES 123

APPENDIX A 127
A.1. AGENCY COST 127
A.1.1. Cost Associated with New Bridges 127
A.1.2. Cost Associated with Contract Maintenance 128
A.1.3. Cost Associated with In-House Bridge Maintenance 130
A.1.4. Cost Associated with Administration Expenses 132
A.2. USER'S COST 133
A.2.1. Vehicle Cost Per Mile 133
A.2.2 Accident Cost 133
A.2.3 Accident Rates 134
A.2.3 Average Daily Traffic (ADT) Growth Rates 134

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1. INTRODUCTION

1.1. Background

The congressional hearing that followed the collapse of the Silver Bridge over the Ohio River at Point Pleasant clearly supported the need for a national bridge inspection program. As a result of that hearing, the National Bridge Inspection Standard (NBIS) was established with the aim of assuring proper safety of the nation's principal highways [1]. Initially, the standard was to be applied only to the federal-aid system. In 1978 Congress expanded the NBIS to include highway bridges on all public roads. The standards require by law that all bridges on public roads be inspected and rated on a regular schedule--at least every two years, unless an exception is approved. In addition, all public and private agencies that own bridges are required to report on an annual basis the updated bridge inventory and inspection data to be included in the National Bridge Inventory (NBI). The bridge inspection data must also include condition rating for the bridge deck superstructure and the bridge substructure. The rating condition of these three components is based on a scale from zero to nine with a rating of nine representing an excellent condition.

Today, all states have an ongoing bridge inspection program that conforms to the minimum requirements of the NBIS. In addition, all states have an established database consisting of bridge inventory and inspection data that meet the requirements of the NBI. These data, gathered from all states, are compiled to provide a complete picture to the Congress of the condition and status of the nation's bridges. These data are also used to manage a federally-aided bridge replacement and rehabilitation program.

Statistical analysis of the NBI data showed that of the nation's 578,000 bridges, 41% are structurally deficient or functionally obsolete [2]. Also, the 1990 analysis showed that of the 6659 bridges in the state of South Dakota, about 24% were classified as structurally deficient and 23% are functionally obsolete [2]. The states of New York and Arizona were reported to have the highest and lowest number of deficient bridges, respectively. To prevent an increase in the number of deficient bridges, either bridge funds must be dramatically increased or present bridge management techniques must be improved.

Concern for the deterioration of highway bridges and the desire to stretch available funds as far as possible has prompted the FHWA [3,4,5,6], the National Cooperative Highway Research Program [NCHRP] [7,8], and individual states to develop comprehensive bridge management systems (BMS). Although methods such as utilizing the opinion of several engineers or a priority ranking or project level optimization are used for bridge management, a comprehensive BMS with an overall bridge maintenance rehabilitation and replacement program could help states to make the best use of available funds to maintain the entire bridge network. In this approach, the decision-making is based on three main elements: 1) bridge condition at the present and in the future; 2) costs incurred by the highway agencies; and 3) the costs of the roadway users.

The costs incurred by the highway agency and the roadway users vary with different maintenance strategies. For example, a strategy that requires high levels of maintenance implies higher agency costs. On the other hand, if low levels of maintenance are performed on deteriorated bridges, higher user costs and lower agency costs would result. Although the latter would be preferred by the bridge owners, that lower cost may be offset by the increase in user costs. Therefore, the optimum maintenance strategy should be based upon the total of the agency and user costs.

The arguments summarized above were used in the recently developed "Pontis" Bridge Management System (BMS) under the sponsorship of the FHWA [5,6]. Pontis was designed to develop annual long-range maintenance and improvement programs and budgets, incorporating flexibility to allow all states to customize the program for their own use.

1.2. Objective

The objectives of the work presented were not to develop a BMS but rather to

1) Compare actual bridge life to design life.

2) Identify and quantify the factors that affect bridge life.

3) Evaluate rehabilitation procedures presently used by the South Dakota Department of Transportation (DOT).

4) Identify state-specific items, essential to a bridge management system.

5) Develop deterioration curves for a bridge deck, bridge superstructure, and bridge substructure utilizing the Markov Chain statistical approach.

1.3. Research Plan

The objectives listed above were attained by completing the following tasks.

1.3.1. Task 1

An extensive review of published literature relevant to bridge management was conducted. Information for completion of this task resulted from collected literature or personal contact with other states' Department of Transportation.

1.3.2. Task 2

Task 2 included a survey that was conducted to evaluate currently available bridge management system (BMS) programs. A detailed summary regarding the capabilities of the Pontis BMS was given.

1.3.3. Task 3

This task was devoted to evaluate and determine the effects of different factors that affect bridge performance. Among the factors considered were the average daily traffic, bridge type, bridge length, degree of skewness and geographic locations. All available inspection records were utilized to accomplish the objectives of this task.

1.3.4. Task 4

The purpose of this task was to utilize the South Dakota's bridge inspection data to develop bridge deterioration models taking into account the factors defined in Task 3. Deterioration models relating age to the condition of a bridge deck, superstructure and substructure were developed utilizing the Markov Chain statistical method. Information such as the statistical distribution around the predicted mean was also estimated. Results of this task were presented in several graphical relationships. Two PC computer codes were developed to accomplish the objectives of this task.

1.3.5. Task 5

In this task, essential elements for a bridge management system were identified. These are level-of-service goals (LOS), user costs and agency costs. The LOS included bridge deck width, vertical clearance, load capacity and the condition ratings of bridge deck, bridge superstructure and bridge substructure. Information regarding agency and user costs associated with a bridge level-of-service deficiency were identified. These costs represent vital elements needed in a BMS to determine various rehabilitation, repair, or replacement activities.

1.3.6. Task 6

The objective of this task was to prepare a final report documenting the research undertaken in this study. Findings of the research were documented along with the research methodology, data collection, conclusions and recommendations. In addition to the final report, quarterly progress reports were submitted. These reports summarized the accomplished work during each quarter and laid out the planned research activities for the quarter to follow.

2. LITERATURE REVIEW

Currently, each bridge-controlling agency (a bridge-controlling agency owns and maintains bridges) has its own policy on bridge programming for repairs, rehabilitation, and replacement. These policies on levels of management vary from a do-nothing approach, to a priority ranking system, project level optimization, and network level optimization. The last two represent important elements in developing a bridge management system (BMS). The priority system has been the most common approach, used by many DOTs. It starts with bridge inspection and operating load ratings to prepare a report of needed maintenance activities. The report is then used by engineers along with other personnel at higher levels of management to decide which bridges need to be repaired. However, this approach does not ensure efficient use of available limited resources.

Unlike the priority ranking method, a complete bridge management system should include analytical models that are capable of assessing the trade-offs and implications of present actions and policies on long-term needs. This would allow management to formulate maintenance and rehabilitation policies not only on a project level but also statewide. This chapter summarizes some of the bridge management system research that has been completed or is under development by other states; however, it is not an all-inclusive list of states that have performed BMS research. The summary resulted from collected literature or personal contact with other states' Departments of Transportation. In addition, part of the literature review was included in similar work performed previously by the authors for the Iowa DOT and the Midwest Transportation Center and is included herein to provide the reader a complete picture of the efforts being devoted by other states to develop or implement a BMS. South Dakota's existing bridge management practices are presented first, followed by a brief summary of related work in other states.

2.1. South Dakota's Bridge Management Processes

Since 1976, the South Dakota DOT has been following and utilizing the FHWA bridge inspection rules [9]. This effort involves collecting comprehensive data regarding all bridges on the state's public highway systems. Data collection, structure inventory, and appraisal data are performed following the South Dakota Bridge Inventory Coding Manual. This manual, developed through a joint effort among several divisions within the SDDOT, is updated when necessary to address the state's need or to add data required by the FHWA.

The collected bridge data are utilized by the state of South Dakota to make both long- and short-term decisions regarding which of the state's bridges need to be replaced, rehabilitated, maintained or eliminated. Making such decisions integrates data from various state and local entities. The following section summarizes the process of bridge management that was outlined in [9] and has been used in the state of South Dakota.

2.1.1. Division of Planning, Office of Data Inventory

The Office of Data Inventory is responsible for maintaining the computer files containing the physical characteristics of each bridge structure within the state. The office also is responsible for preparing the computer tape to be transferred to FHWA with the required data to be added to the NBI data.

One of the main responsibilities of the Office of Data Inventory is to review non-state bridge inspection files for inconsistencies and prepare quarterly reports for all bridges to the FHWA. This office also prepares an annual report for the FHWA summarizing bridge posting problems and bridge inspection within the state.

2.1.2. Division of Operations

The Division of Operations is responsible for maintaining South Dakota's highway bridges in a condition that assures safety and convenience to the traveling public. A quality assurance program has been developed by Operations Support to confirm consistency and identify training needs. To attain such a goal, the SDDOT requires that all bridges be inspected every two years or less, as structure condition dictates. Bridges that fall under the authority of the SDDOT are inspected through the regional office. Local governing authority is responsible for inspecting and maintaining bridges on the local system (county and city).

To insure uniform bridge inspection, periodic training sessions are conducted for bridge maintenance supervisors and bridge inspectors. In addition, the inspection crew is required to use a standardized inspection form on all state and local inspections. The crew leader is responsible for preparing the inspection data sheet summarizing the condition rating and other data related to the bridge structure and for summarizing and recommending repair activities.

On the basis of the inspection reports, repair recommendations are budgeted in one of the following categories: (1) routine maintenance and/or minor repairs that can be performed by in-house crews; (2) minor repairs that must be done under informal contract due to lack of manpower within SDDOT; and (3) major rehabilitation where formal plans and specifications prior to letting of bids are needed. The latter is entered into the five-year construction program and may involve the use of federal funding.

2.1.3. Division of Engineering

The Office of Bridge Design of the Division of Engineering within the SDDOT is responsible for updating the Structural Inventory and Appraisal (SI & A) data, appraisal ratings, bridge analysis data, bridge plans and repair as well as rehabilitation plans. This is required whenever new bridge inspection data are provided by the Division of Operations. The SDDOT bridge design office utilizes the Bridge Analysis and Rating System (BARS) software package to perform the structural analysis in conjunction with the HS20 design vehicle to determine the inventory and operating rating of bridge structures. Operating ratings are also performed for the three South Dakota legal trucks. The results are then used along with the South Dakota bridge inventory coding manual to assign an appraisal rating for each bridge structure. Based on the inspection data and appraisals, the Office of Bridge Design prepares a priority list showing repair recommendations and cost estimates for all major bridge projects.

2.1.4. Prioritization Criteria

The priority list prepared by the Bridge Design Office is based on needs. These needs are categorized as follows:

I. Interstate 3R Structure Needs: This category contains only bridges that are eligible for Interstate 3R funding. Selection is based on:

a. Deficiencies based on condition

b. Deficiencies based on functonal obsolescence.

Prioritization is based on the following:

a. Urgency of the work required

b. Structures on the interstate traveled way

c. Interchange structures

d. Separation structures

In general, the Department tries to get the maximum use of an existing deck before deck replacement or bridge replacement is required. Programs such as deck overlays, waterproofing open joints and replacing bridge rails to current standards are used.

II. Bridge Replacement Needs: This category contains bridges eligible for funding under the FHWA guidelines for Bridge Replacement Funds. Structures are analyzed on an individual basis with such things as Sufficiency Rating, Type of Deficiency, Safety, Route and Load Rating all taken into account. Sometimes a long grading project involving a structure within the limits of the project will take priority based on urgency of need for the grading project.

III. State 3R Bridge Needs: This category involves non-interstate structures that are not eligible for Bridge Replacement Funding but are in need of repair work or general maintenance. As with the Interstate Structures, deck deterioration is the main concern. Programs to extend the deck life are the major considerations along with safety and load carrying capacity. Program types such as deck overlays, waterproofing joints, rail retrofits along with repair work of an urgent need are the main focal points.

2.1.5. Division of Planning, Office of Planning and Programming

The Office of Planning and Programming receives bridge design's prioritized list of bridge projects and the estimates of bridge construction and rehabilitation costs. After review and approval by the division directors and region managers, the Office of Planning and Programming places these replacement and rehabilitation projects in the five-year construction program in the order designated by the Office of Bridge Design. After the annual public involvement process is completed, the final recommendations are assembled and presented to the SDDOT Commission for approval.

2.1.6. South Dakota's Bridge Deck Maintenance Policies

To attack the rapidly accelerating deck deterioration problems, the SDDOT developed in 1978 a policy on bridge deck repair priorities [10]. The developed priority list was as follows:

a. Continuous concrete bridges with observed deterioration.

b. Continuous concrete bridges in high chloride areas. These include all interstate bridges.

c. Relatively new bridges of any type in high chloride areas and lacking a protection system such as epoxy-coated bars, dense concrete, or latex modified concrete overlays.

d. All other bridges starting with newer bridges and working toward older ones.

The 1978 policy suggested using overlayment to repair bridge decks. In addition, the policy recommended that bridge decks on girder bridges with deck thickness less than 6 inches can be maintained to service conditions by epoxy injection and/or concrete surface repair with membranes and asphalt concrete overlays.

After four years of experience under the deck repair policy suggested above, the problems experienced with continuous concrete bridges were examined and evaluated [11]. Various solutions for these problems were also identified. This re-evaluation recommended that a deck protection system that allows replacing deteriorating concrete should be used. The system should be cost effective and should be capable of extending the life of bridge decks. Re-examination of the 1978 policy also revealed that using rigid concrete overlay is the best way to repair continuous concrete bridges.

In 1985, the Division of Operations conducted a survey to gather information and views of SDDOT bridge experts regarding protection of bridge components [12]. The survey revealed that the major cause of bridge deterioration in South Dakota is the de-icing chemicals such as chlorides used on bridge decks. Other causes include

- the lack of adequate retarders for use with South Dakota cement leads to transverse cracks in decks of continuous steel girder bridges and thus to premature deterioration of the decks,
- poor concrete quality,
- the use of thin decks with an inadequate concrete cover and inadequate distribution of reinforcing steel, especially in bridge decks built prior to 1962.

The 1985 survey summarized the methods that can be used to rehabilitate bridges as follows: 1) a rigid concrete overlay will rehabilitate decks for a continuous concrete slab or a concrete box girder bridge. This reinforces the findings of the study reported in [11]; 2) rigid overlay or rubberized asphalt chip seals can be utilized to repair slabs on girder bridges built after 1962; 3) bridges built prior to 1962 should be modified to eliminate leakage and to retard chloride intrusion into the bridge deck; and 4) high-grade concrete and epoxy-coated reinforcing bars should be used when replacing bridge decks.

Reference [12] also documented that on the average, a 50-year life span for a bridge is reasonable. Prediction of bridge life or the remaining life of a bridge structure represents an important element of life cycle cost analysis. The survey documented that no reliable method to predict the life expectancy of a bridge existed at that time. The authors of this report agree with that conclusion.

To address the 1985 survey concerning the prediction of bridge life, the authors of this report utilized the South Dakota's bridge inspection records in conjunction with the Markov Chain statistical approach to develop deterioration curves for different bridge components; the results are summarized in Chapter 7.

2.1.7. Comments on South Dakota's Bridge Maintenance Policies

As can be seen, the repair recommendations used by SDDOT as contained in the bridge inspection report are the basis of bridge maintenance activities and bridge-related budget recommendations. In the author's opinion, the prioritization and selection of bridges for maintenance require a careful and thorough understanding of bridge needs to assure adequate safety. However, to the author's knowledge, the SDDOT selection processes did not include any analytical model that is capable of assessing the trade-offs and implications of present actions and policies on long-term needs. In addition, South Dakota's current bridge management policies do not take into account user costs although this vital element must be considered along with the agency cost to achieve the optimum solutions for bridge needs in the context of overall network and budget constraints. These are among the reasons that have motivated researchers and others interested in bridge maintenance to develop management tools that can derive the most return for the dollar spent. Among these tools is the newly developed Pontis BMS which was sponsored by the FHWA [3,4,5]. Since the Pontis software was developed to be generic, it can be customized for use by any state DOT. More details regarding the Pontis capabilities and the program's structure are given in Chapter 3.

2.2. Iowa Department of Transportation

The Iowa Department of Transportation (IADOT) has a process rather than a formal policy for choosing bridges for repair, replacement, and rehabilitation [13]. In this process, all the state-controlled bridges within each of the state's six districts are inspected biennially. In the case of bridges classified in critical condition, inspections are increased to once per year. The state requires that all bridge inspection reports must include any degree of deterioration and note specific areas where immediate attention is required.

All inspection reports are reviewed by the staff of the Office of Maintenance in IADOT headquarters. In addition, the bridge inspection reports are submitted to the Bridge Rating section of the Office of Bridge Design to be used in preparing an inventory and operating-load rating. Then the State Bridge Maintenance Engineer reviews the inspection reports and makes recommendations for potential repair work.

A summary of each inspection report is then sent to the District Maintenance Engineer (DME) and Resident Maintenance Engineer (RME). The DME and RME review the reports and determine if a bridge should receive maintenance that can be performed by an in-house crew or if the project should contract repair or a complete replacement. In the latter situation, the DME submits a recommendation to the IADOT Program Management Department for entry into the five-year program of repair and replacement.

The Office of Program Management combines all lists provided by the six districts and prepares a priority list for these bridges. Recently, the IADOT Office of Program Management developed a bridge-ranking system to prioritize bridges according to maintenance needs. However, this ranking system was not developed to replace the current bridge management process.

After bridges are prioritized and a list of bridges is entered into the five-year program, the Iowa Transportation Commission reviews the list for final acceptance. This review is accomplished annually.

One can see from the above brief summary that the IADOT and the SDDOT bridge maintenance processes are similar and are subject to the opinions of the personnel involved. However, the state of Iowa has already taken steps toward implementing a more comprehensive bridge management system (BMS). In addition, level of service goals, user and agency costs, and bridge deterioration curves have been established for Iowa bridges [13]. The IADOT has also tested the recently developed Pontis BMS and recommended implementing this BMS in the near future. To the author's knowledge, the SDDOT will be investigating the use of the same BMS as a tool to manage the bridges within the state of South Dakota.

2.3. North Carolina Department of Transportation Bridge Management Research

Much research accomplished at North Carolina State University (NCSU) for the North Carolina DOT has helped develop many of the general BMS concepts presently in use. Some of the concepts initially developed at NCSU include level-of-service criteria and goals, level-of-service priority ranking systems, level-of-service concept applied to maintenance activities, agency and user costs applied to project selection, and incremental benefit-cost analysis applied to project optimization [14,15,16,17].

The first research project performed at NCSU investigated the concept of level-of-service goals for use in a priority ranking system [14]. This system uses formulas to calculate deficiency points in four separate categories. Each category is weighted according to its relative importance: 70% for load capacity; 12% for deck width; 12% for vertical over/underclearance; and 6% for the estimated remaining life.

NCSU established desirable and minimum acceptable level-of-service goals for load capacity, deck width and vertical over/underclearance. The priority ranking system formulas compare the actual bridge characteristic values to either the desirable or minimum acceptable goals. These formulas also include the roadway functional classification, the average daily traffic, and detour length in the calculation of deficiency points. The deficiency points from each category are summed to give the total rating on a scale of 0 to 100.

The second NCSU research project applied the level-of-service concept to the optimization of maintenance activities [15]. The bridge structure was subdivided into the ten areas that account for a majority of the existing maintenance budget (i.e., main members, structural deck, substructure, railings, and expansion joints). Because of the large number of bridge maintenance activities possible, every maintenance activity could not be considered. Next, specific levels-of-service were identified for each maintenance activity.

For the selection of the optimal policy, the study used a modified version of a nonlinear programming algorithm that was originally developed in NCHRP Reports 223 and 273 [18,19]. This program was applied to the various bridge maintenance activities to identify the optimal levels of service under limited resources. This program can vary the available maintenance budget to determine the sensitivity of the optimal levels of service. This type of analysis can be used to predict future maintenance budgets by comparing the results to desirable levels of service maintenance.

The third research project performed at NCSU developed a computer program to determine the optimum improvement action and time for a single bridge [16]. This project established some of the initial work underlying general BMS concepts such as project level optimization, bridge condition deterioration rates, agency costs associated with maintenance, rehabilitation and replacement, and user costs associated with level-of-service deficiencies.

Agency costs and user costs were developed for inclusion in the analysis of project alternatives. Agency costs were developed in terms of their associated unit measurement (i.e., sq. ft., lin. ft., etc.) for maintenance activities, rehabilitation, and replacement projects. Annual maintenance costs were related to the current condition rating for each major bridge component. Rehabilitation costs were established for each major bridge component in terms of the incremental increase from initial to final component condition ratings. For example, if the initial deck condition rating was 5, rehabilitation costs were established that were associated with increasing the deck condition to 6, 7, 8, and 9. User costs were developed for level-of-service deficiencies. These included the cost per mile to detour a bridge with a deficient load capacity and the accident costs associated with bridges with poor roadway approach alignment or narrow deck width.

The computer program used to optimize project alternatives was developed using the Statistical Analysis System (SAS) software. The program analyzes project alternatives on the basis of standard annual equivalent cost procedures and includes the costs of the agency (i.e., North Carolina DOT) as well as the costs incurred by the roadway user. The analysis optimizes the improvement action and time for individual bridges (project level). A summary of system-wide bridge improvements developed by the program can estimate future needs. However, this summary does not optimize project selections over the entire bridge system (network level).

The most recent research completed at NCSU applied the concept of incremental benefit-cost analysis to determine the optimum bridge improvement strategy [17]. A computer algorithm called the Incremental Benefit-Cost Program (INCBEN), which was originally developed by the Texas Transportation Institute [20], was used to perform the incremental benefit-cost analysis. The main objective of the research was to determine the applicability of the INCBEN program in allocating limited budgets to bridge improvement alternatives at the network level.

Because an economic analysis of all system bridges was determined to be too extensive, only deficient bridges in need of immediate improvement were considered in the analysis. The INCBEN program first discards improvement alternatives with undesirable benefit-cost ratios then lists the desirable alternatives in order of decreasing benefit-cost ratio. This list is used to allocate limited funds to the deficient bridges.

A sample of 25 in-service bridges was analyzed for several budget levels; the results were compared with the results of sufficiency-rated methods using the procedure developed in Reference [16] for estimating the costs and benefits of improvement alternatives. This analysis determined that the INCBEN program is feasible for small groups of bridges (less than 85) over a one-year analysis period. If a larger sample size or multi-year analysis is desired, modifications must be made to the original INCBEN program.

The North Carolina DOT is presently using the procedures developed in the first three NCSU research projects [21]. The last research project using the INCBEN program has not been implemented because of the program's limited capabilities. This combined research effort of NCSU and the North Carolina DOT has established North Carolina as a leader in the field of BMS technology.

2.4. Pennsylvania Department of Transportation Bridge Management System

The Pennsylvania DOT (PennDOT), in conjunction with four outside consultants, developed a BMS for in-house use that modified and expanded their existing computer database for bridges [22]. The Pennsylvania BMS, initially installed on the PennDOT mainframe computer in January 1987, extensively developed many of the accepted general BMS concepts. The central BMS database expanded the department's existing bridge information database and was integrated with other information databases such as roadway, planning, and maintenance. An extensive priority ranking system was developed for the evaluation of bridge replacement and rehabilitation projects, and a substantial amount of agency cost data (i.e., replacement, rehabilitation, and maintenance costs) were collected and compiled on the system database.

The priority ranking system was based on a deficiency point system using criteria in three major categories to calculate the deficiency rating: 1) level-of-service capabilities, 2) bridge condition, and 3) miscellaneous related characteristics. Level-of-service capabilities included the load capacity, deck width, and the vertical clearance above and below the structure. Deficiency points for these criteria are calculated using formulas that compare existing values with desirable or minimum acceptable level-of-service goals. These formulas also include the roadway's ADT, detour length, and functional classification as adjustment factors in the calculation of deficiency points. The second category of deficiencies was based on the FHWA condition ratings for each of the three major bridge components (deck, superstructure, and substructure). Deficiency points in this category are assigned on the basis of the present condition for each of the components. Criteria included in the miscellaneous related characteristics category are the estimated remaining life, the FHWA roadway approach alignment appraisal rating, and the FHWA waterway adequacy appraisal rating. The deficiency points for both appraisal ratings are based on their respective current appraisal values. However, deficiency points for the estimated remaining life are determined using a formula.

The total deficiency rating (TDR) for a bridge is comprised of each of the criteria deficiency points with several modification factors, including four limiting conditions for combinations of criteria deficiency point values and an overall adjustment factor that accounts for the functional classification of the roadway. The maximum deficiency points associated with each criteria and the four limiting conditions are shown in Table 2.1. The TDR for each of Pennsylvania's bridges provides the basis for ranking replacement and rehabilitation projects.

Table 2.1. Pennsylvania priority ranking system categories, criteria and limiting conditions

Deficiency Point Criteria	Maximum Deficiency Points
Level of Service Capabilities	
Load Capacity (LC)	70
Deck Width (DW)	15
Vertical Overclearance (VO)	15
Vertical Underclearance (VU)	10
Bridge Condition	
Deck Condition Rating (DCR)	50
Superstructure Condition Rating (SPCR)	50
Substructure Condition Rating (SBCR)	50
Miscellaneous Related Characteristics	
Remaining Life (RL)	5
Approach Roadway Alignment (ARA)	10
Waterway Adequacy (WA)	10
Limiting Conditions	
Bridge Condition Rating (BCR) = DCR + SPCR + SBCR $BCR \leq 50$ $LC + BCR \leq 80$ $VU + WA \leq 15$ Total Deficiency Rating (TDR) ≤ 100	

The comparison of projects at the project and network levels, after prioritization by the TDR, is performed using a modified cost-benefit ratio. These ratios are calculated for a bridge's replacement or rehabilitation cost versus various nonmonetary benefits. Nonmonetary benefits considered include items such as the ADT of the roadway and the incremental increase in the TDR caused by replacement or rehabilitation. The cost-benefit ratios can be used at the project level to compare total bridge replacement versus several rehabilitation alternatives and at the network level to compare potential projects.

Since 1987 when it was put into use, several modifications to the Pennsylvania BMS have been suggested, although because of insufficient funding, additional modifications have not been completed [23]. Some of the suggested modifications include: 1) develop and implement an automated load capacity rating system; 2) incorporate economic evaluation concepts; and 3) expand the future needs modeling to include maintenance activities.

2.5. National Cooperative Highway Bridge Management Systems

The National Cooperative Highway Research Program (NCHRP) has been sponsoring an extensive BMS research project, two phases of which are completed. Findings of Phase I, which was completed in 1987, were published in NCHRP Report #300 [7]; Phase II was completed in 1990, but the results were released only to a very few states.

The objective of Phase I was to define the elements required for developing a network level BMS and organize and computerize them for use when developing Phase II of that project. In Phase I, six basic BMS concepts were defined to form the overall structure of a complete BMS: 1) central database; 2) network level major maintenance, rehabilitation, and replacement selection; minor maintenance; 4) historic data analysis; 5) project level interface; and 6) reporting modules.

The objective of Phase II of the NCHRP project [8] was to implement the findings and computer models of Phase I to develop a BMS. Specific tasks of Phase II included validation of the developed BMS utilizing actual bridge inventory data from several cooperating states. Four states and one city installed the NCHRP BMS system on their computers and performed primarily evaluations. Based on the findings and additional testing, these agencies concluded that the software required further debugging and coding.

In October of 1992, the NCHRP awarded a contract to Delcan Corporation of Canada to develop, validate, and document a fully operational microcomputer-based BMS. Completion date of this project is expected to be July of 1993. The system will be based on the conceptual design noted in NCHRP Report #300 [7] and will be modified as necessary to incorporate other elements and strategies.

2.6. Washington State Department of Transportation Bridge Deck Management Systems

In 1984 the Washington State Department of Transportation (WSDOT) initiated a bridge deck information program to gather information regarding bridge deck maintenance policies within the state [24,25]. The WSDOT effort concentrated only on problems associated with bridge decks and gave no consideration to bridge superstructure or substructure.

The WSDOT bridge deck information program included 1) the severity and extent of spalling and delamination; 2) stripping and debonding of overlays; 3) concrete cover of reinforcing rebars; 4) extent of cracking; 5) existing patches on bridge decks; 6) scaling; and 7) rutting in wheel paths. All information gathered about conditions of bridge decks is used to prepare a priority list. This list is then used to categorize bridge deck projects into five rehabilitation priority groups based on the condition rating and the average daily traffic.

In 1988, the University of Washington completed a research project, the objective of which was to use the WSDOT's deck inspection information to develop a bridge deck management system [26]. The principal investigators of that project used a sufficiency rating system that was based on the severity and extent of the deterioration in conjunction with nonlinear regression to develop a priority list for deck maintenance. A present worth analysis of available alternatives was performed to determine the project level optimization. Network level analysis was based on a similar approach that is used by the Pennsylvania DOT. To the authors' knowledge, the concepts developed in the University of Washington research have not been implemented by the WSDOT [25].

2.7. Minnesota Department of Transportation Priority System

For the past several years, the Minnesota DOT has used a priority ranking system to establish bridge priorities [27,28]. This ranking system utilizes deficiency points to identify bridges with the greatest maintenance needs. Rather than using a set of maximum or minimum point values, e.g., 0 to 100, that qualify a bridge for immediate repair, the Minnesota DOT estimated the total deficiency as the sum of three major categories: 1) 50% for the structural adequacy and safety, including bridge posting and average daily traffic ADT; 2) 25% for the serviceability and functional obselesence, incorporating the factors of deck geometry appraisal rating, ADT, underclearance appraisal rating, age of structure, type of bridge structure, approach roadway alignment, waterway appraisal rating and structural evaluation appraisal rating; 3) 25% for public use, including detour length, ADT, road system designation, functional classification.

After using that priority rating system for several years, the Minnesota DOT determined that it was not providing any better priority information than the Federal Sufficiency Rating (FSR) and reverted back to using the FSR as the sole criterion for evaluating potential bridge projects.

In the summer of 1992, the Minnesota DOT began implementing the recently developed Pontis bridge management system [5,6].

2.8. Michigan Department of Transportation - Critical Bridge Rating

The Michigan Department of Transportation (MDOT) uses a priority rating system to establish bridge project priorities [27,29]. This system, called "Critical Bridge Rating," was developed inhouse using a deficiency point scale from 0 to 98 points and the categories are shown in Table 2.2. During August of every year, a technical committee of nine members rates all potential projects. The subjective judgment of the committee members accounts for 27 of the 98 possible deficiency points. This critical bridge rating is used in conjunction with the federal sufficiency rating in the selection of bridge projects.

Table 2.2. Michigan priority ranking system categories and criteria

Deficiency Point Criteria	Maximum Deficiency Points
Physical Condition and Traffic Safety	
Operating load capacity	25 (9 by committee)
Bridge and approach features	12.5 (4.5 by committee)
Deck geometry	2
Financial Capability of the Highway Authority	
Total needs versus funds ratio	15
Total funds versus structure cost ratio	15
Importance of Structure	
Detour evaluation	4.5 (by committee)
Traffic volume	15
Functional classification performance evaluation	9 (by committee)

2.9. Illinois Department of Transportation

The Illinois DOT developed a procedure to group state-owned bridges into four priority categories: critical backlog, other backlog, short- and long-term accuracy. The critical background and other backlog categories are automatically considered in Illinois' five-year program. The procedure uses the 16 criteria listed in Table 2.3 [30,31]. These criteria are based on the federal requirements for structural deficiency and functional obsolescence.

Table 2.3. Illinois priority ranking system categories and criteria

Category	Criteria
Critical Backlog	Superstructure, substructure or culvert condition rating ≤ 3 Deck condition rating ≤ 3 Structural condition appraisal rating ≤ 2 Any posted load limits
Other Backlog	Superstructure, substructure or culvert condition rating = 4 Operating rating < 27 tons Deck geometry appraisal rating ≤ 3 (ADT $\geq$ 1000 and accident experience) Underclearance appraisal rating ≤ 3 Approach roadway alignment appraisal rating ≤ 3 (ADT $\geq$ 1000 and accident experience)
Short-term Accruing	Deck condition rating = 4 Structural condition appraisal rating = 3 Superstructure, substructure or culvert condition rating = 5 Operating rating = 27 to 35 tons FSR < 50
Long-term Accruing	Deck geometry appraisal rating ≤ 3 and ADT < 1000 or Deck width < 24 ft. and ADT $\geq$ 1000 FSR = 50 to 80

2.10. New York Department of Transportation

The New York Department of Transportation (NYDOT) presently uses a weighted condition rating to establish priorities for selecting bridges for rehabilitation and replacement [27,32,33]. This rating system is derived from ratings of the physical conditions of the thirteen structural elements listed in Table 2.4 and does not consider geometric characteristics such as vertical clearance and deck width. These structural elements are evaluated on a subjective scale from 1 (worst) to 7 (best). The selection of replacement and rehabilitation projects is based on the weighted condition rating and the ADT using the established minimum acceptable weighted condition rating for a different ADT.

The New York DOT is in the process of developing a comprehensive BMS [33] with both network level and project level systems that will consider evaluations of physical conditions, vulnerability, necessity of use, and serviceability when selecting bridges for projects.

When completed, probably in 1997, the new system is expected to provide significant assistance in project selection and budget requirement area. It is of interest that, at the end of 1991, the NYDOT had spent approximately $.75 million in staff time and microcomputer and software costs in the process of developing their BMS.

2.11. North Dakota Department of Transportation

The North Dakota DOT follows the FHWA guidelines for bridge inspection, rating, and codification of bridge data. Selection of bridge projects is based on a subjective evaluation of each bridge by several department engineers. To the authors' knowledge, the North Dakota DOT does not have immediate future plans to expand their procedure into any type of BMS [34].

The North Dakota DOT developed an inspection manual to assist inspectors within the state in the inspection process. This manual identifies areas of distress associated with various bridge components and relates the level of distress to the FHWA condition ratings. The manual is intended to increase consistency of the condition ratings assigned by different inspectors.

Table 2.4. New York condition rating criteria

Structural Element	Weighting Factor
Primary members	10
Abutments	8
Piers	8
Structural decks	8
Bridge seats	6
Bearings	6
Wingwalls	5
Backwalls	5
Secondary members	5
Joints--superstructure	4
Wearing surface and joints	4
Sidewalks and fascias	2
Curbs	1

2.12. Kansas Department of Transportation

The Kansas DOT (KDOT) uses a priority ranking system to establish priority for bridge replacement and rehabilitation projects [35]. This ranking system is based on calculations of weighted deficiency points in five major categories: 1) 19.6% for deck width; 2) 8.8% for bridge roadway restriction; 3) 23.2% for deck condition; 4) 31.4% for structural condition; and 5) 17% for load capacity. Formulas based on upper and lower limits similar to level-of-service goals are used to calculate the deficiency points in each category. The points are then adjusted according to the roadway functional classification and ADT. Reference [3] gives more detailed information pertaining to KDOT priority system.

2.13. Virginia Department of Transportation

The Virginia DOT developed a priority ranking system based on the North Carolina level-of-service goals approach. The ranking system is being used to prioritze bridges that meet FSR criteria for rehabilitation and replacement [36]. The priority listing is then used as a guideline for the selection of future projects.

Virginia's priority ranking system is a modified version of North Carolina's level-of-service ranking system. The Virginia system includes categories for the load capacity, deck width, vertical clearance, and the FSR and several modifications made to the North Carolina system: 1) level-of-service goals were developed for Virginia; 2) inventory rating (rather than operating rating) is used for load capacity; and 3) the FSR is used in place of estimated remaining life. In addition, the weighting of categories was changed to 30% for load capacity, 12% for deck width, 12% for vertical clearance, and 46% for the FSR. The Virginia system then calculates deficiency points for each category using the formulas developed previously in North Carolina.

2.14. Maryland Department of Transportation

The Maryland DOT presently uses a priority ranking system as a guideline for establishing bridge replacement and rehabilitation project priorities [37]. The system was developed by Maryland DOT personnel and to the authors' knowledge has been in use since 1989.

Maryland's ranking system evaluates and assigns one to five deficiency points to six criteria for each bridge: 1) federal sufficiency rating; 2) structural condition; 3) load posting; 4) age; 5) ADT; and 5) detour length. Maryland DOT engineers also establish a structural condition rating based on a subjective rating scale from 1 (worst) to 10 (best). The weighted average of the criteria represent the total bridge priority rating. The weights assigned to each of the criteria are 0.375 for structural condition and 0.125 for the remaining criteria.

2.15. Wisconsin Department of Transportation

The Wisconsin DOT (WisDOT) developed a computer simulation model to perform life-cycle cost analysis on bridge replacement and repair alternatives [3]. The cost analysis is performed yearly for project level repair and replacement alternatives. Optimum project level alternatives are generated to assist decision makers in programming project selections.

The computer program bridge replacement decision rule is based on the future component condition ratings, age, and life expectancy of each bridge. Future component condition ratings are estimated using a piecewise linear regression deterioration model [3]. Standard life-cycle activity profiles are used to project future costs. A life-cycle activity profile is an established, time-dependent series of repair and rehabilitation alternatives expected to occur over the life of a structure. The computer model applies life-cycle cost analysis to replacement and repair life-cycle activity profiles in order to determine when a bridge should be replaced.

The WisDOT has never implemented the computer simulation model to assist in the selection of bridge replacement projects [40]. When tested, the computer model determined that it is nearly always more economical to repair, rather than replace, a bridge. The WisDOT presently relies on the judgment of engineers involved in the decision-making process to select bridge replacement and rehabilitation projects [40]. The primary bridge characteristics considered in making the decision include the FHWA structural condition appraisal rating, the FHWA substructure condition rating, and the level of load posting. Additional bridge characteristics considered include the FHWA deck geometry appraisal rating, the FHWA approach roadway alignment appraisal rating, and the roadway ADT.

2.16. Nebraska Department of Roads

In 1984, the Nebraska Department of Roads formed a departmental committee to investigate bridge management concepts. The committee developed a priority ranking system that was detailed in a 1986 Interim Report [39]. The Nebraska system uses level-of-service concepts similar to those used in North Carolina.

Nebraska's ranking system is based on the deficiency points calculated in four categories with associated maximum deficiency point values: 1) 50 points for load capacity; 2) 12 points for deck width; 3) 33 points for vertical over/underclearance; and 4) 10 points for the estimated remaining life. The deficiency points in each category are calculated using a linear relationship between minimum acceptable and desirable level-of-service goals developed for Nebraska. Depending on the average daily truck traffic, up to 12 additional deficiency points may be added to the deck width category. If a bridge is over a waterway, 9 additional deficiency points are added to the vertical clearance category.

This ranking system has not been used by the Nebraska Department of Roads to set project priorities. To the authors' knowledge, project priorities are currently established using the FSR and the evaluation of the engineers involved. The Nebraska Department of Roads is waiting for the development of the Pontis BMS [40].

2.17. Florida Department of Transportation

The Florida Department of Transportation (FDOT) is in the process of developing a BMS. However, because of the need to gather new and additional data, it will take the FDOT at least four years to fully develop a BMS [41].

Since many of the bridges within Florida are built near salt water, the environment has a major impact on the rate of deterioration. Four elements of corrosion are measured to determine the rate of deterioration: chloride, sulfate, electrical resistivity, and pH. Data for an additional thirty variables, including environmental variables, must be collected to develop representative deterioration curves. The FDOT expects to have developed reliable deterioration curves by 1995 [42]; however, other aspects of a BMS are expected to be in operation before then [14].

2.18. FHWA Bridge Management System Phase I

The FHWA conducted a research project to investigate the following general BMS concepts that are being used in existing BMSs [4,5,6]: 1) computer database structure; 2) level-of-service characteristics and goals; 3) priority ranking formulas; 4) level of service for maintenance activities; 5) deterioration rates and estimating service life; and 6) project and network level cost analysis procedures. The FHWA Phase I research concluded that a comprehensive BMS is needed at the state level to strengthen the states' bridge maintenance programs.

In response to this conclusion, the FHWA and the California Department of Transportation awarded a research grant to Cambridge Systematics, Inc. and Optima, Inc., in 1989 to develop a generic, flexible BMS for implementation by any state [4]. This project resulted in a Pontis computer-based network level BMS. More details regarding the capabilities and the structure of this system are given in the following chapter.

2.19. Summary of Existing Bridge Management System Procedures

As can be seen from the literature review presented above, some states' highway agencies in the United States have procedures or systems for selecting bridges for maintenance, rehabilitation, or replacement. The level of the selecting methods ranges from a priority ranking system to project level optimization and network level optimization. Other states still rely on FHWA guidelines for the inspection and rating of bridges and the expert opinion of the engineers involved in the decision-making process.

Recently legislation requires states to have a BMS in use by September of 1996 in order to qualify for federal funds. This was one reason for the FHWA and the NCHRP taking leading roles to formalize the management of the nation's bridges. One result from the FHWA effort is the newly developed Pontis BMS software which was recently tested by the states of California, Colorado, Florida, Iowa, Kansas, Michigan, Minnesota, Oregon, Tennessee, Vermont, Virginia and

Washington. The authors of this report expect the system will be used nationwide. Efforts by the NCHRP to develop a similar system are still under way. Undoubtedly, these efforts will help the states to make the best use of available funds in overall bridge maintenance, rehabilitation, or replacement.

3. PONTIS - BRIDGE MANAGEMENT SYSTEM

3.1 Background

Recognizing the magnitude of the problems our nation's bridges face, the Federal Highway Administration (FHWA) awarded a research contract in August of 1989 to Optima Inc., and Cambridge Systematic, Inc. to develop a generic, comprehensive bridge management system (BMS) [4]. This was an outgrowth of the first phase of FHWA demonstration project 71 [3], funded by the FHWA and administrated by the California Department of Transportation (CALTRNS).

The FHWA required that this system be a flexible network optimization and planning system that can be customized by each state for its own use. To ensure the flexibility of the system, a Technical Advisory Committee (TAC) consisting of representatives from the FHWA, the Transportation Research Board, and the states of California, Minnesota, North Carolina, Tennessee, Vermont and Washington was formed. The purpose of this committee was to oversee and guide development of the system. In addition, the TAC was responsible for defining a list of bridge elements, conditions that each element can be in, and a set of appropriate maintenance actions that can be taken to improve the condition of these elements.

In the summer of 1992, Optima and Cambridge Systematic, Inc. released the first version of their BMS, called Pontis which is derived from the Latin word for bridges [5]. The Pontis program was made available to some states for testing and commentary on its performance. The ultimate objective of the Pontis program is to provide users with the most efficient maintenance, repair and rehabilitation (MR & R), and improvement policies that would derive the maximum benefits from the use of available limited funds. To attain this objective, several inter-related submodels were includede in Pontis to handle different parts of a capital and maintenance programming analysis [5,6]. All of the submodels draw data from a centralized database. In addition all communication among these submodels is through the database.

3.2. Major Elements in the Pontis Program

The Pontis program consists of four major components which are: 1) database; 2) Maintenance, Repair, and Rehabilitation (MR & R) optimization model; 3) Improvement model; and 4) Integration model.

3.2.1. Database

The backbone of the Pontis BMS is a database that includes some of the inventory and condition data from the NBI as well as data for maintenance cost, improvement cost, and user cost. In addition, feasible improvement actions, maintenance actions, and prediction models that use statistical methods to reflect future conditions of bridge components are also included along with a model that is necessary to update the database whenever new data are gathered.

Flexibility, speed, and transportability are among the factors that govern the database feature of the software. Transportability is essential to allow any of the states to transfer data from the NBI database to the Pontis database. The current database in Pontis was structured to handle inventories of up to 50,000 bridges. A complete list of the data required for each bridge to be included in the Pontis database is given in Appendix 1 of Ref. [5].

3.2.2. Maintenance, Repair, and Rehabilitation (MR & R) Optimization Model

Bridge maintenance problems have many similarities with pavement maintenance but are more complex. The complexity arises from the critical nature of the bridges; the greater cost associated with bridge replacement; public safety in case of a bridge failure; type of bridge, e.g., prestressed, steel girder, slab, etc.; deterioration rates associated with different bridge elements, e.g., bridge deck, bridge superstructure and bridge substructure; and environmental factors. Furthermore, the lack of historical data that can be used to describe the structural performance of bridges represents a great obstacle in developing accurate models of bridge element deterioration.

The Pontis program clearly distinguishes between bridge management problems and most other maintenance problems. For example, the program refers to improvement actions for bridges by using two specific sets of activities. One activity is related to maintenance, repair, and rehabilitation (MR & R) in which actions are performed to repair or replace a wearing element to improve its condition which may deteriorate again with time. The Pontis MR & R model uses prediction models and maintenance costs to choose minimum-cost maintenance strategies for up to 160 elements per bridge. The other activity is related to improvement actions and is discussed later in this chapter. Pontis addresses these two activities separately and then combines the recommendations for each bridge in the overall network requirements.

3.2.2.1. Prediction model Although the current 0 to 9 condition rating numbers in the NBI are easy to communicate, the TAC and the Pontis developers agreed that fundamental shortcomings exist with the current bridge rating system. They felt that it cannot be directly used to build a decision model for the following reasons:

1. Bridge deck, superstructure, and substructure consist of many elements that are built using different materials. Each of these elements behaves differently over time and may be affected differently by the surrounding environment. These factors are not reflected in the current rating system.
2. Two elements with the same rating can have totally different conditions, and totally different maintenance actions may be suitable for them. Therefore, just knowing the rating number is not sufficient to specify the action required.
3. The current rating system only shows the relative condition of components and cannot be directly used to investigate the tradeoffs of cost and benefits of various actions.
4. Despite the detailed guidelines that are being used in conjunction with the current rating system, considerable uncertainties are associated with these ratings.

The above arguments were the reasons behind the development of a new rating system that can adequately define the condition of bridge elements. In this system, the condition of each of the 160 elements can be classified in one of four categories referred to as condition states. Feasible actions associated with each of these states are listed in Appendix 1 of Ref. [3] along with the unit measures of each action.

Concerns arose regarding the difficulties associated with understanding the new system and with the time and effort required by bridge inspectors to implement the system. These concerns were resolved after the states of California, Minnesota, and Vermont reported that the new system is not difficult to follow when compared to the current NBI inspection and rating program.

One should realize that for the first few years when using Pontis, no historical data would be available to utilize the prediction model in the Pontis system. Hence, the judgment of experts working in the field of bridge inspection should be used to develop what is referred to as transition probabilities. These are defined as the probability that a bridge element will deteriorate from one condition state to another.

Until enough historical data become available, the transition probabilities for the Pontis prediction model can be estimated by asking bridge experts the following two questions:

1. Suppose there is an element in 100 bridges at state i, "If no maintenance action is taken, how many years will 50 of them deteriorate to state j and 50 of them will remain at state i?" where i = 1,2,3 and 4 and j = 2,3 and 4.
2. "Suppose there are 100 bridges having the same element at state k and some maintenance action was taken. How many are now in condition k-m?" where k = 4,3,2 and m = k-1, k-2....1.

Answers to these questions can then be converted to transition probabilities. For example, the transition probability from state 1 to state 2, P_{12}, can be estimated as:

$$P_{12} = 1 - 0.5^{2/T1} \tag{3.1}$$

where T^1 is the answer to question number 1 above. Utilizing Eq. 3.1, one can estimate a 4 by 4 transition matrix in which each element represents the transition probabilities from one condition state to another.

Over the years, the transition probabilities in the Pontis BMS will place more weight on the historical data. This will add more confidence and reliability to predicting future state conditions of the various bridge elements. Having formulated the transition probabilities matrix, the Markov chain statistical approach is used to estimate future condition states.

Despite the fact that the Pontis program utilizes a new rating system, the authors of this report proceeded to develop deterioration models for the bridges in the state of South Dakota using the NBI ratings for the following reasons:

1. No one knows whether the new system will be adopted to replace the current 0 to 9 rating system.
2. Condition-age relationships developed herein (see Chapter 7) can be used as a rough guide for estimating bridge life or forecasting to some extent future bridge conditions.
3. The condition rating relationships presented herein can be employed to compare performances of different bridge types.

<u>3.2.2.2. MR & R action costs</u> The Pontis BMS lists the feasible actions that can be used to improve the performance of bridge elements. A complete list of these actions and their units of measure is given in Appendix 1 of Ref. [5]. Information related to the unit MR & R costs can be gathered from many sources including state maintenance engineers, county engineers, city engineers and historical data.

The authors of this report prepared a questionnaire (see Appendix A) to establish the South Dakota costs associated with the MR & R activities; unfortunately, because this was prepared prior to receiving any information regarding the MR & R costs required by the Pontis BMS, costs for few MR & R activities for the SDDOT were gathered; they are summarized in Chapter 5. In the future, more extensive effort should be devoted to collecting the required MR & R activity costs prior to implementing the Pontis BMS, if desired.

3.2.2.3. User costs User costs are those incurred by the roadway users based upon various levels-of-service characteristics. The costs can be related to two primary sources: 1) deficiencies that require certain (or all) vehicles to detour a bridge; and 2) deficiencies that are associated with an increased accident rate. Level-of-service deficiencies that cause vehicle detours include bridges with a reduced load capacity or insufficient vertical clearance, while increased accident rates are primarily associated with narrow bridge deck widths.

In the Pontis BMS [5], the user cost per year, U_c, is computed as the sum of the accident costs, A, vehicle operating costs, Q, and the travel time costs, T. thus,

$$U_c = A + Q + T \tag{3.2}$$

3.2.2.3.1. Accident costs The accident costs, A, may be calculated by the sum of the accident cost on the structure A_o and the accident cost under the structure A_u, where

$$A_o = \frac{365}{10^6} V_o \sum_i r_{o,i} * C_i \tag{3.3}$$

and

$$A_u = \frac{365}{10^6} V_u \sum_i r_{u,i} * C_i \tag{3.4}$$

in which

V_o and V_u	=	ADT on and under the structure, respectively,
$r_{o,i}$ and $r_{u,i}$	=	Accident rate for type i accident on and under the bridge; respectively, per 10^6 vehicles,

c_i = cost for a type i accident
i = fatality, injury, or damage only.

Accident costs, C_i, for different accident types, i.e., for fatality, injury, and damage were given in Ref. [5] for the state of California as \$574,000, \$11,800 and \$2,500, respectively. It is important to mention here that each state should utilize its own accident costs using collect data or to utilize the costs defined by the FHWA. The developers of the Pontis BMS suggested that these should be adjusted using consumer price indices for future years.

3.2.2.3.2. Vehicle operating costs Vehicle operating costs include the increase in fuel consumption and depreciation of a vehicle, maintenance, and parts resulting from detouring around a bridge restricted for weight or height. In Pontis, the number of trucks, R, routed per year due to these restrictions is calculated as:

$$R = 365\ VF\ [P(L)+(1-P(L))G(L)D(H)] \qquad (3.5)$$

where

V = ADT
F = proportion of trucks in the traffic stream
P(L) = proportion of trucks affected by weight limit
L = posted weight limit (ton)
I-P(L) = proportion of trucks not detoured due to weight limit
G(L) = proportion of trucks not detoured due to weight that are of dual axle/TTST (truck-tractor semi-trailer) or,

$$= P\frac{(1-P(L))_{dual} + TTST}{(1-P(L))_{ALL}\ trucks}$$

D(H) = proportion of G that will be detoured due to height limit.
H = posted height limit (ft)

For CALTRANS, the functions for P(L), 1-P(L), and G(L) are shown in Figs. 3.1, 3.2, and 3.3, respectively. These two functions were approximated as piecewise linear relations. Also, Ref.[6] gives the percentage of trucks detoured due to height restriction within the state of California as 10.81%, 0.18%, 0.051% and 0.027% for height of 13.0, 13.5, 14.0, 14.5, respectively. Motor vehicle

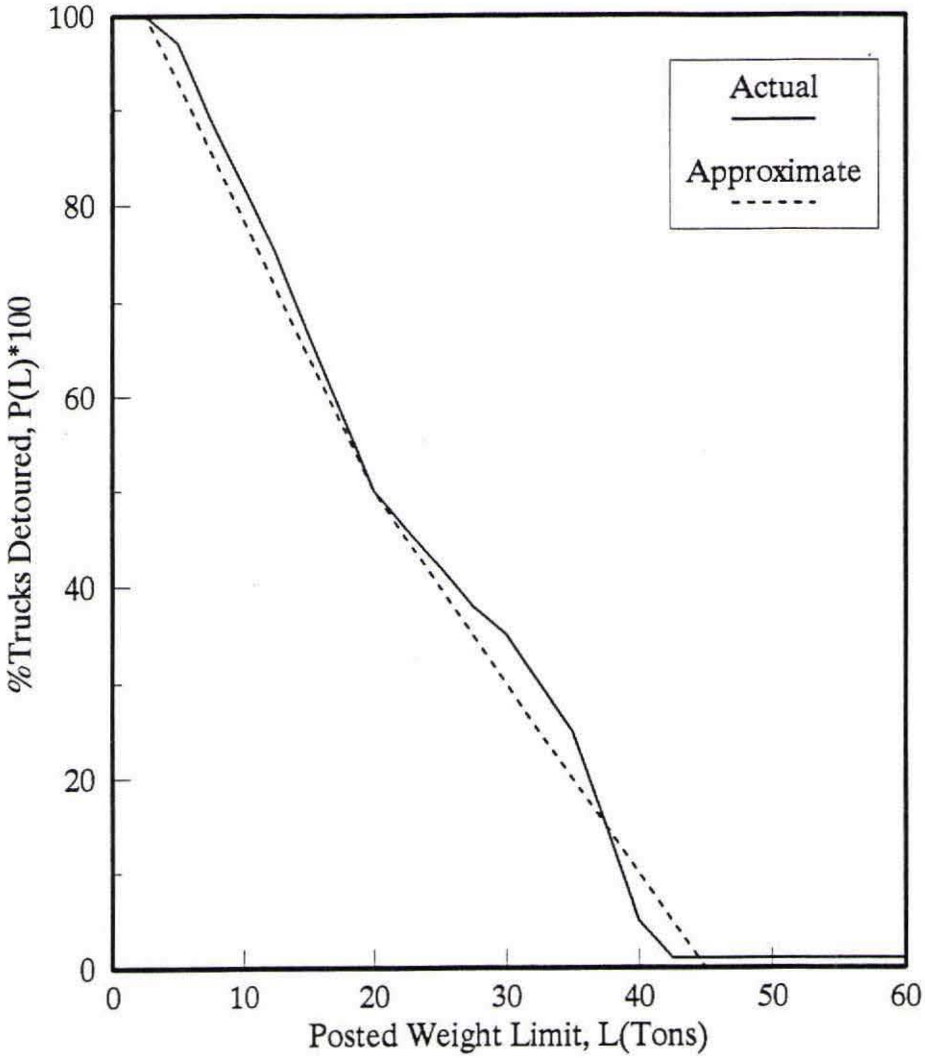


Figure 3.1. Truck weight distribution (posted weight limit)

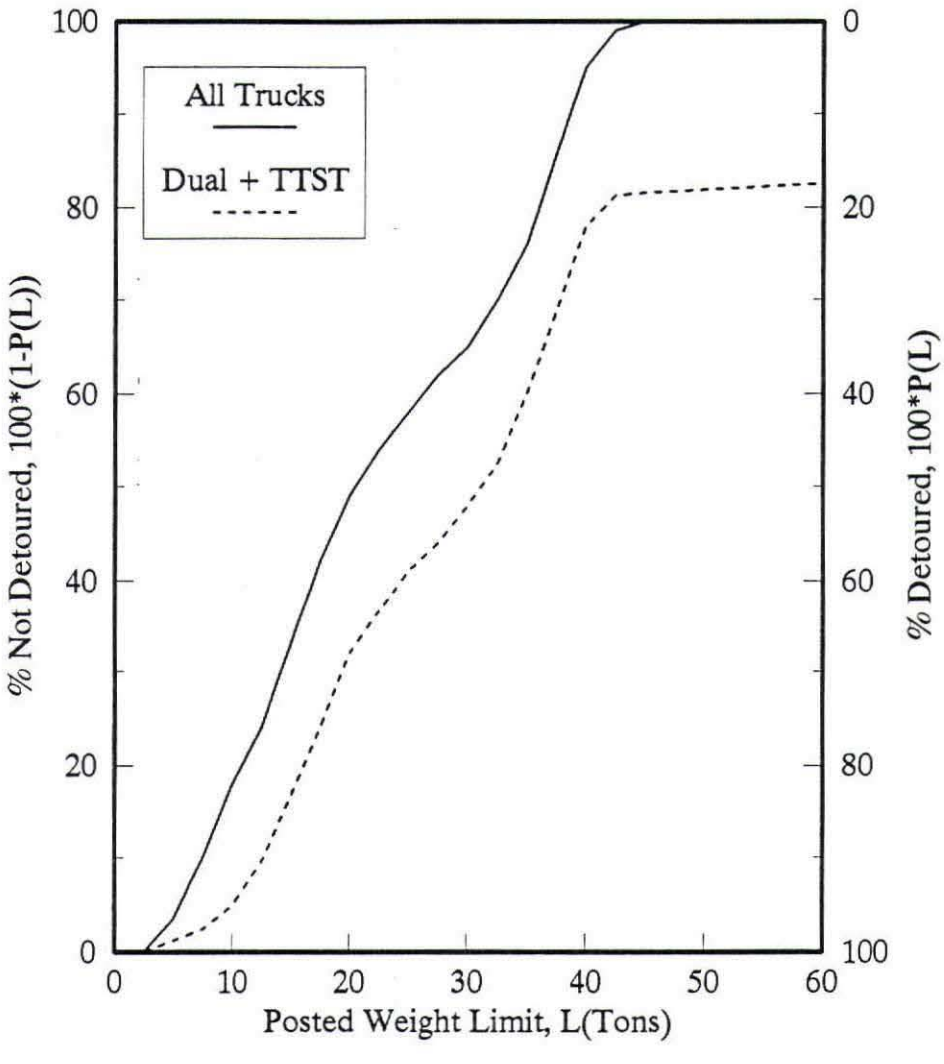


Figure 3.2. Cumulative truck distribution (dual + TTST vs. all trucks)

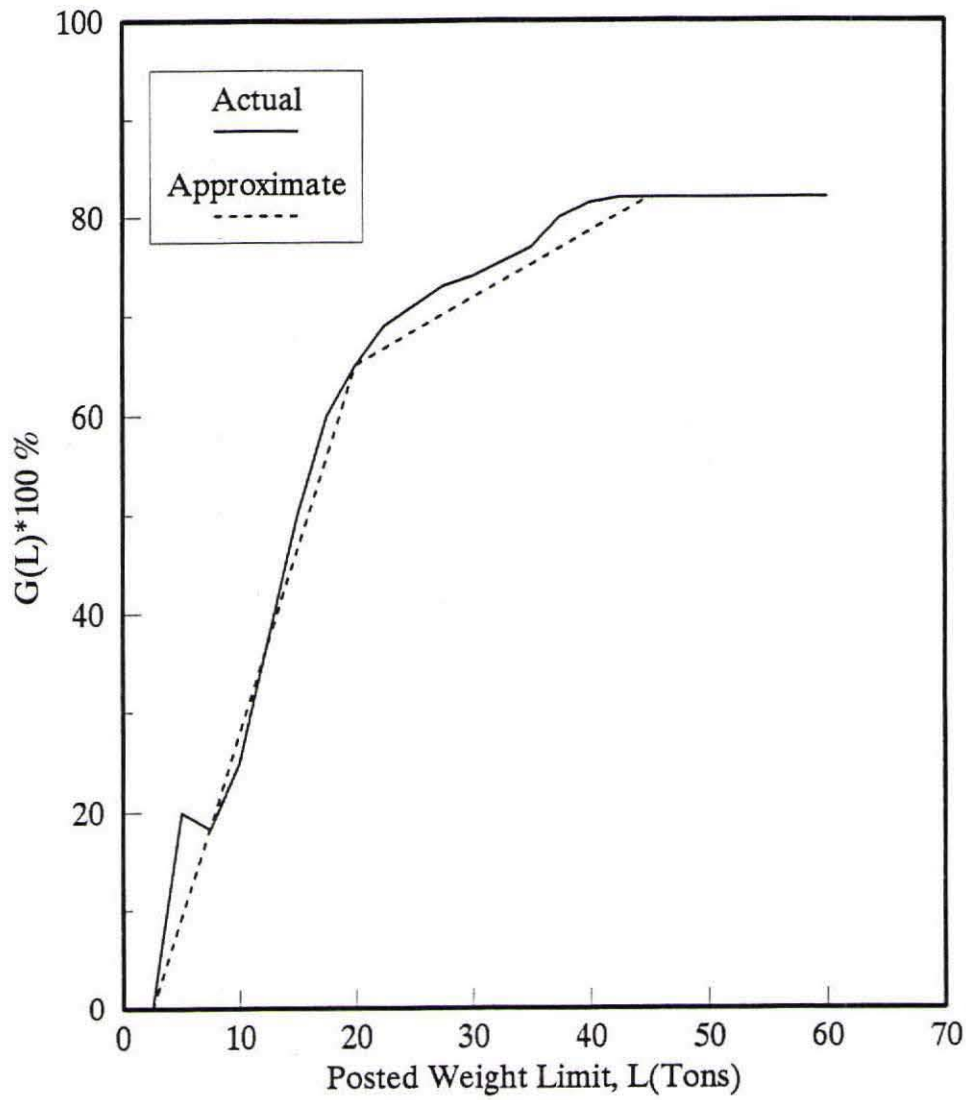


Figure 3.3. Truck weight distribution (dual + TTST)

operating costs, 0_t, due to combined weight and height restrictions are expressed in Ref. [6] as

$$0_t = RUS \tag{3.6}$$

where R is the number of trucks calculated by Eq. (3.5), U is the average truck operating cost per mile, and S is the detour distance.

Utilizing these relations in conjunction with CALTRANS data, Ref. [5] reported that the average truck operating cost for 1989 was $0.59 for owner operators and $0.52 for flat operators (excludes driver costs, fuel, tax, insurance, and other overhead).

Another factor that must be considered when estimating total user cost is the yearly percentage increase or decrease in traffic volume for a specific roadway. This is referred to as ADT growth rate and represents an important element in estimating user cost over the life of a bridge structure. The ADT growth rate can be estimated utilizing inventory data. Additional travel time cost imposed on users due to weight and height restrictions posted on a bridge is another factor needed to be considered in estimating users costs. Pontis BMS estimates such costs using the following relationship:

$$Y = R \frac{S}{K} C \tag{3.7}$$

where

Y = yearly travel time cost
R = number of trucks detoured per year
S = detour distance in miles
K = average speed on detour road - mile/hr
C = value of travel time in $/hr

The Pontis technical manual [6] recommends a speed on the detour road about 80% of the average speed on the main road.

3.2.3. Improvement Model

Improvement actions are those associated with deficiencies in various level-of-service characteristics including load capacity, clear deck width, and vertical clearance above and below a bridge. To eliminate these deficiencies, improvement actions typically involve major rehabilitation such as widening, raising, straightening, or replacing. The unit costs associated with each improvement action is state specific. Costs for some of these actions are given in Chapter 5.

3.2.4. Integration Model

The integration model combines the bridge element maintenance results and the improvement projects into a single recommended bridge-level program. This model uses a benefit/cost ranking system to set priorities based on funding program eligibility requirements and budgets.

3.3. Pontis Output

The Pontis program provides two types of outputs. Reports summarizing users' input can be obtained and used to check or retrieve information for selected items for a group of bridges or for a specific bridge. In addition, data related to MR & R costs can be printed out or transferred into a file for inclusion in a word processing document.

Results from executing the Pontis BMS are summarized in the following four reports.

3.3.1. MR & R Network Recommendation

The MR&R network report summarizes the recommendations of the maintenance, repair, and rehabilitation optimization model for all the elements and environments at the network level. It also provides information related to unit cost for the recommended actions as well as to the benefits of taking a recommended action immediately as opposed to delaying it.

3.3.2. Scheduled Needs and Backlog

In the scheduled needs and backlog report, scheduled actions illustrating the total MR & R, improvement, replacement and pre-programming needs, along with the number of these projects that have been scheduled within budget constraints are printed out. This report consists of three major sections: (1) total unconstrained needs calculated without regard to any budget constraints, (2) work programmed for MR & R, improvement, replacement, pre-programmed and total programmed costs, and (3) backlog of actions that were recommended but could not be programmed. In addition, information related to MR & R, improvement, and replacement backlog is provided.

3.3.3. First-Year Project List

A detailed list of priority projects is included in the first-year project list covering all MR & R actions for all elements. In addition, elements and actions that are likely to need work during the next ten years are outlined along with information on element state condition, total cost of recommended actions, and quality and units for each element.

3.3.4. Thirty Years Simulation

The thirty-years simulation report summarizes the results of analyzing long-term MR & R policy, which is accomplished by simulating element deterioration and actions over a thirty-year period given a fixed annual budget constraint. Because the simulation covers the entire network, the results may differ from these obtained in the scheduled needs and backlog report.

3.4. Evaluation of the Pontis BMS by Iowa DOT

Early in the summer of 1992, a version of the Pontis BMS software was distributed to the states that showed interest in adapting the program as a bridge management tool. The state of Iowa was among the early states to evaluate the capabilities of the Pontis BMS. Iowa's evaluation was conducted using a small set of data for 102 bridges from two counties in the state. Elements for each of these bridges were established and their conditions were identified. Pontis NBI and other available data were uploaded into the Pontis database, and Pontis field inspection was conducted on some of the bridges.

The Pontis program contains transition matrices and MR & R and improvement costs based on information gathered via CALTRANS. However, because of differences in the environment surrounding the bridges and differences in maintenance costs between the states of California and Iowa, these data were not used. Instead, the evaluation team utilized similar data provided by the Minnesota DOT.

Having provided the data required to execute the Pontis BMS, the MR & R and the improvement models were applied. The results were tabulated in the four main reports printed by Pontis (see Sec. 3.3) and compared by the evaluation team using four different funding levels.

The IADOT evaluation study reported that Pontis is a user friendly, comprehensive BMS, but suggested several minor changes to suit users' needs. For example, Pontis requires painting costs to be estimated by linear foot/ but in the opinion of one member of the evaluation team, this unit measure should be changed to square feet. Furthermore, some customization to the software must be performed to meet any specific need, policy, or management requirements. For efficiency, it would be appreciated if such modification, which might involve redefining bridge elements, adding new items to the database, and adjusting descriptions of element condition and feasible actions, were performed by the developers of the Pontis program.

Based on the results achieved during testing the Pontis BMS, the evaluation team recommended its implementation as a tool for the state of Iowa. The team believes that with the appropriate customization, this software would be a very useful tool to develop effective and consistent bridge maintenance and improvement programs.

Evaluation of the Pontis software BMS was not among the tasks of this report. However, the authors agree with the conclusions reached by the IADOT evaluation team and recommend that this software to be used by the state of South Dakota. Unlike other available BMS programs, the Pontis program was developed under the direction of bridge experts who are aware of the problems and the need to keep the nation's bridges safe. However, one must recognize that some customization to the program and MR & R and improvement costs besides those listed in Chapter 5 are needed. This should be the next step toward the implementation of a comprehensive BMS for the SDDOT.

4. LEVEL-OF-SERVICE GOALS

Level-of-service (LOS) goals are a set of selected bridge characteristics that are used to assess bridge adequacy. These are measurable variables that change according to each state's needs and goals. LOS goals are measured in terms of minimum acceptable and desirable levels.

In existing BMSs, LOS goals are used in developing a priority ranking by comparing the value of a bridge characteristic to target values to determine a bridge level of deficiency which identifies potential rehabilitation improvement projects. The bridge characteristics selected by the state of South Dakota as LOS goals include load capacity, deck width, and operational status.

4.1. Load Capacity

LOS goals for load capacity are measured in terms of the operating rating for South Dakota's Type 3S2 legal truck because it was selected by the SDDOT since this loading is used by the SDDOT Bridge Design in generating the South Dakota bridge weight limit map [43]. Most other states use HS-type loading.

LOS goals for load capacity for South Dakota's interstate and noninterstate bridges are listed in Table 4.1 along with the number of bridges in each of the six ranges of load capacity defined by the SDDOT. These numbers were obtained utilizing the South Dakota 1990 NBI data. The goals listed in Table 4.1 do not apply to box culverts. Unlike the SDDOT, some other states allow reduction in the acceptable load capacity as the ADT decreases.

Table 4.1. Load capacity level-of-service goals

(Interstate, primary, and secondary bridges)		
Load Capacity (tons)	Status	No. of Bridges
greater than 60	desirable	974
55 - 59	acceptable	154
50 - 54	acceptable	155
45 - 49	acceptable	32
40 - 44	acceptable	18
less than 40	unacceptable	21

4.2. Vertical Clearance

Vertical clearance level-of-service goals are defined for the clearance above the bridge deck and for the clearance below the structure. The vertical overclearance is measured from the bridge deck to either the truss or the structure above it. The vertical underclearance depends on whether the structure is over a waterway, railroad, or another roadway. The level-of-service goals for vertical clearance are listed in Table 4.2.

Table 4.2. Vertical underclearance level-of-service goals

Interstate Bridges		
Height (ft)	Status	No. of Bridges
less than 16	unacceptable	152
16 - 16.5	acceptable	69
greater than 16.5	desirable	26
Primary and Secondary Bridges		
Height (ft)	Status	No. of Bridges
less than 14	unacceptable	2
14 - 16.5	acceptable	93
greater than 16.5	desirable	69

Table 4.2 illustrates that there are only two bridges on the primary and secondary system that do not satisfy the minimum acceptable height of 14 feet. This is a negligible number compared to the number of the unacceptable bridges on the interstate system.

4.3. Clear Deck Width

The clear deck width of a bridge structure is the most restrictive distance between the curbs or rails on the structure's roadway. The SDDOT clear deck width LOS goals are grouped by type of roadway, ADT, bridge length, and the number of lanes on a bridge. Shown in Table 4.3 are the desirable and acceptable deck width LOS goals for two-lane bridges.

Analyzing the 1990 bridge inspection data provided by the SDDOT showed that only 13 bridges on the principal artieral highways do not meet the minimum acceptable bridge width of 27 ft., and 162 bridges do not meet the desirable bridge width of 36 ft. This is a relatively low number of unacceptable bridges compared to the high number of unacceptable bridges on the high traffic volume interstate bridges.

On the minor arterial highways, 27 bridges do not satisfy the minimum acceptable LOS goals, and 274 bridges do not meet the desirable bridge width of 32 ft. This classification has 14 more unacceptable bridges than the higher traffic volume principal arterial highways.

The analysis of the inspection data also showed that 7 bridges on the collector routes are classified below the minimum acceptable bridge width of 22 ft., and 30 bridges do not meet the desirable bridge width of 28 ft.

Table 4.3. Clear deck width level-of-service goals

Interstate and other divided highways		
Bridge Length	Acceptable (ft.)	Desirable (ft.)
less than 200 ft.	38	40
greater than 200 ft.	31	40
Principal Arterials		
ADT	Acceptable (ft.)	Desirable (ft.)
0 - 1000	27	36
1001 - 1500	27	40
1501 - 2000	27	44
2001 - 5000	28	44
greater than 5001	32(a)	44
Minor Arterials		
ADT	Acceptable (ft.)	Desirable (ft.)
0 - 500	25	32
501 - 1000	27	36
1001 - 2000	27	40
2001 - 5000	28	40
greater than 5001	32(a)	40
Collectors		
ADT	Acceptable (ft.)	Desirable (ft.)
0 - 250	22	28
251 - 500	22	32
501 - 1000	24	36
1001 - 2000	27	36
2001 - 5000	28	36
greater than 5001	32(a)	36

(a) use 28 ft. for bridges with lengths greater than 200 ft.

In summary, 153 bridges do not meet the minimum acceptable bridge width goal, and 776 bridges do not have desirable bridge widths. This large number could represent safety concerns. However, just because a bridge does not meet the desirable deck width LOS goals does not necessarily mean that it is in poor condition.

4.4. Other Measures for Bridge Performance

The SDDOT uses the federal sufficiency and the 0-9 condition rating scale for rating bridges, deck, superstructure, and substructure as other measures for bridge performance. Once again this is not the condition rating system that is used in the Pontis BMS program (see Chapter 3). In addition the Pontis program does not utilize either the sufficiency rating or the 0 to 9 rating system to develop the required MR&R activities. However, for the reader's interest, the SDDOT goals regarding the condition and the sufficiency ratings as well as the number of bridges in each category are listed in Tables 4.4, 4.5, and 4.6.

Table 4.4. Sufficiency rating goals

Rating (a)	Status	No. of Bridges
less than 49	unacceptable	66
50 - 79	acceptable	366
greater than 80	desirable	893

(a) Rating ranges from 1 to 100

Table 4.5. Deck superstructure and substructure goals condition

Bridge Component	Rating (a)	Status	No. of Bridges
Deck	less than 5	unacceptable	82
	5 to 7	acceptable	229
	greater than 7	desirable	1014
Superstructure	less than 5	unacceptable	42
	5 to 7	acceptable	278
	greater than 7	desirable	1005
Substructure	less than 5	unacceptable	33
	5 to 7	acceptable	305
	greater than 7	desirable	987

(a) Ranges from 0 to 9

The SDDOT defines bridges with deck or substructure or superstructure condition rating of 4 or less to be in poor condition and classifies them as structurally deficient. This criterion is used in this report to estimate the life of these three components as described in Chapter 7.

5. AGENCY AND USER COSTS

A bridge management system must be based on agency and user costs (see Chapters 1 and 3). The controlling agency must be able to calculate the cost of bridge repair, rehabilitation, or replacement to optimize the annual bridge funds. User costs associated with such items as detour lengths, accident rates, and bridge widths must also be considered. The reduction of user and agency cost is a benefit to both the controlling agency and the general public

5.1. Agency Costs

As previously mentioned, agency costs can be divided into MR&R and improvement costs. The first are those associated with distressed or deteriorated conditions; they can be fixed but will deteriorate again with time. The improvement costs are those related to deficiencies in the various LOS characteristics.

MR&R and improvement costs for the state of South Dakota were collected via a questionnaire prepared by the authors and completed by SDDOT personnel. This questionnaire, given in Appendix A, was prepared prior to receiving information regarding the Pontis MR&R and improvement models (see Chapter 3). The following sections summarize the response of the SDDOT which included the costs for both in-house and contract maintenance activities. Costs associated with new bridges were also given.

Currently, the accounting department in most controlling agencies administers the bid items and stores cost data for construction or maintenance contracts. However, cost information in this form is not suitable for use in conjunction with the Pontis BMS; as summarized in Chapter 3, cost information for 160 elements per bridge needs to be provided to utilize the Pontis BMS. Therefore, most controlling agencies will have to restructure their ways of storing cost information to meet this need.

5.1.1. South Dakota's Improvement Action Costs Associated with New Bridges

The SDDOT supplied only costs associated with new bridges, not costs associated with bridge widening. The costs for bridge replacement are estimated from the backwall to the backwall of a bridge and do not include the cost for the approach pavement (see Table 5.1). The costs related to replacement contracts are the contractor's labor, materials, overhead, and contract administration cost but not SDDOT administration costs.

Table 5.1. Cost Associated with New Bridges.

Bridge Type	Bridge Length	Cost ($/ft^2)
Slab	60 to 145	40
Prestressed concrete	200 to 350	42
Steel or girder	> 200	45

The SDDOT was asked if construction cost varied by geographical region or bridge length. It was conceivable to the authors that costs associated with labor and transportation of materials to different locations around the state might differ among the four geographical regions. However, the SDDOT reported no significant difference in the cost per square foot among the different regions. Further investigation regarding these costs is deemed necessary prior to adopting a network level BMS.

The typical detour cost associated with a new bridge is $9,000 for non-interstate and $100,000 for interstate highway bridges. This cost includes expenses paid to local agencies, expenses paid to maintain the detour road, expenses paid to sign the detour, expenses paid to inspect the detour, and expenses paid to administration of the detour. State agencies are usually required to pay a local agency for the use and maintenance of the local highways used on a detour.

The SDDOT estimates that a typical agency cost for a new bridge is 16.5 percent of the contract. This cost includes design cost, letting cost, construction inspection cost, supervisor/manager cost, overhead cost, and administration cost.

5.1.2. South Dakota's MR&R Costs Associated with Contract Maintenance

In the questionnaire submitted to the SDDOT (see Appendix A), only three items were listed for contract maintenance: 1) bridge deck overlay; 2) bridge painting; and 3) bridge beam damage. As with the agency cost of a new bridge, the SDDOT estimates that this cost is approximately 16.5 percent of the contract.

5.1.2.1. Cost for deck overlay Currently, the SDDOT is using only low slump concrete bridge deck overlays at an average cost of $4.25/ft.[2] In the past, latex modified concrete overlays have been used, but their performance has not been as expected [11]. The cost for low slump concrete bridge deck overlays includes the cost of contractor's labor, the cost of the materials, overhead cost, and contractor's administration cost.

5.1.2.2. Painting cost The SDDOT uses one painting system for new bridges and another for existing structures (see Table 5.2). The cost per square ft. includes all of the contractor's cost. Unfortunately, painting costs in the Pontis are defined as the cost per linear ft. These units of measurement need to be consistent.

5.1.2.3. Cost of repairing damaged bridge beams The estimated cost to heat straighten a steel beam or girder bridge is $15,000 to $20,000 per bridge (see Appendix A). The SDDOT also estimated the typical cost to repair a prestressed concrete beam bridge at $10,000 per bridge. It has been known that controlling agencies usually find it is more economical to replace a damaged prestressed beam than to heat straighten a steel beam.

Table 5.2. Contract bridge painting

Coating New Bridges		
Thickness (mls)	Coating	Cost ($/ft^2)
3 - 6	inorganic zinc primer coat	1.00
3 - 5	high build polyurethane finish coat	
Recoating Existing Bridges		
Thickness (mls)	Coating	Cost ($/ft^2)
5	aluminum filled epoxy mastic primer coat	1.15
3 - 5	high build aliphatic polyurethane finish coat	

5.1.3. Cost Associated with In-House Bridge Maintenance

Because contractors' charges for their administration, set up, and overhead costs can, on small bridges, be a substantial part of the contract costs, small maintenance projects are usually performed by the controlling agency. The SDDOT listed only five activities that are performed by in-house maintenance forces: bridge deck overlays, bridge deck epoxy injection, bridge deck patching, collision damage, and erosion control.

5.1.3.1. Cost for deck overlay The SDDOT has installed rubberized asphaltic chip seals on bridge decks at a cost of $2.25 per square foot and is presently studying the performance of this deck overlay. The SDDOT is using this type of overlay only to extend the life of the bridge deck prior to using a low slump concrete overlay or replacing the deck.

5.1.3.2. Cost for bridge deck epoxy injection Epoxy bridge deck injection is a time-consuming maintenance activity performed by in-house forces at a cost of $70.00 per square foot. Some controlling agencies have let this activity out to contract; however, this alternative costs about four times more than in-house maintenance.

5.1.3.3. Cost for bridge deck patching The SDDOT estimates that concrete bridge deck patching costs about $10.00 per square foot. Controlling agencies usually patch bridge decks when they start to spall out to add a few years to service life of the deck before using a low slump bridge deck overlay.

5.1.3.4. Cost for repairing damaged bridge beams Bridges that experience minor damage due to a hit by traffic are repaired by local maintenance crews. The costs associated with this type of repair are listed in Table 5.3. The estimated cost for repairing barrier rails and guard rails ranges from $500 to $750.

Table 5.3. Cost for repairing damaged bridge beams by in-house maintenance

Bridge Beams	
Beam Type	Cost ($/bridge)
steel beam or girder	3,000 to 5,000
prestressed concrete	2,000 to 3,000

5.1.3.5. Cost for erosion control Occasionally, during floods, bridges are scoured out around the piers and the foreslopes. Flood damage usually requires earth work as well as the placement of rip-rap as listed in Table 5.4. Bridges that have scour problems are usually repaired by the local maintenance force as soon as possible to minimize erosion problems.

Table 5.4. Erosion control by in-house maintenance

Erosion Control	
Type of Work	Cost ($/bridge)
Earth work	15,000
Rip-rap	20,000

As can be seen, the agency costs summarized here represent a small portion of the MR & R or improvement cost required to implement the Pontis BMS. In Pontis, costs can be provided for different maintenance activities on the 160 bridge elements listed in Appendix A of Ref. [5]. However, the Pontis user need not provide costs for all of these elements; only costs for the specific elements in each bridge type being investigated are required. Preparing maintenance, rehabilitation, replacement and improvement costs for the state of South Dakota should be the next step toward implementing the Pontis BMS.

5.2. User Costs

User costs are those incurred by the owner of a vehicle being operated on a highway. Detouring around structurally deficient or functionally obsolete bridges increases the user's costs. Functionally obsolete bridges also may have increased accident rates.

5.2.1. South Dakota Vehicle Operating Costs

As outlined in Chapter 3, the vehicle operating costs in the Pontis BMS are estimated utilizing Eq. (3.6). Variables required to implement this equation are defined in Chapter 3, and the information related to these variables can be obtained from the NBI data.

For the development of South Dakota's vehicle operating cost, a minimum vehicle weight of 3.0 tons and maximum of 40.0 tons were employed. The minimum corresponds to allowable load before a bridge must be closed and the maximum represents allowable operating load for a standard HS-type truck load. Vehicle operating cost for each vehicle weight classification was established through the questionnaire that was submitted to the SDDOT (see Appendix A). The questionnaire specified that vehicle operating cost per mile should include costs associated with vehicle depreciation, repair, and other miscellaneous expenses. The results of the questionnaire are summarized in Table 5.5, which for comparison also lists vehicle operating costs for the states of Iowa and North Carolina.

Driver's cost for the states of South Dakota, Iowa and North Carolina is listed in Table 5.5. The state of Iowa cost was estimated using data collected in 1990 as \$12.00/hr and \$18.10/hr for light and heavy weight vehicles, respectively and assuming a vehicle speed of 40 miles/hr. Driver's cost for the state of North Carolina was based on the data collected in 1987. The Information gathered from the questionnaire given in Appendix a was used to estimate the direr's cost for the SDDOT. However, the table illustrates that these costs are small compared to those associated with the state of Iowa and North Carolina. Therefore, it is recommended to further study these values prior to using them in a BMS.

Table 5.5. Vehicle operating cost, \$/mile

	SDDOT	IADOT	North Carolina DOT
Light Weight Vehicles			
Vehicle Cost	0.14	0.35	0.20
Driver Cost	0.07	0.30	0.15
Total Cost	0.21	0.65	0.35
Heavy Weight Vehicles			
Vehicle Cost	0.50	0.78	0.87
Driver Cost	0.14	0.45	0.34
Total Cost	0.64	1.23	1.15

If an assumption is made that a light weight vehicle weighs approximately 3 tons and a heavy weight vehicle weighs approximately 40 tons (HS-20), an equation that relates the vehicle operating cost to the vehicle weight for the state of South Dakota is

$$VOC = 0.21 + [0.011622 \times (VW - 3.0)] \quad (5.1)$$

where

VOC = vehicle operating cost, \$ per mile
VW = vehicle weight, HS-type loading, tons

5.2.2. South Dakota Accident Costs

Section 3.2.2.3.1 of this report summarizes the relationship used to estimate accident costs. In these equations, information regarding the ADT, the accident rates, and the cost associated with the type of the accident is needed.

In 1989, the costs associated with various types of accidents for the state of South Dakota were established (see Appendix A - Sec. A.2.2) as follows: $290,000 per fatality; $32,000 per major injury; $8,300 to $2,600 per minor injury; and $1,600 to $1,800 per property damage.

The Pontis BMS requires information related to the accident rates (number of accidents per 10^6 vehicles). To date, four studies completed by others relate the accident rate to bridge width [42]. Figure 5.1 summarizes the results of these studies. It shows that the accident rates estimated by Colorado and Jorgenson reach a minimum value when the bridge width equals approximately 32 ft. and that the accident rates estimated by Chen and Johnson and by Mak and Brinkman reach a minimum when the bridge width is greater than 24.0 ft.

The SDDOT's recorded inspection data showed 158 bridges with unacceptable bridge deck widths (see level-of-service goals in Chapter 4). Seventy percent of the unacceptable bridges with narrow bridge deck widths are on high traffic volume interstate highways. These bridge deficiencies in the deck width may result in high accident rates although no information regarding accident rates could be obtained from the SDDOT. Before making a recommendation regarding which of the four relations in Fig. 5.1 can be utilized for the SDDOT, one needs to perform several spot checks, i.e., collect information regarding accident rates and impose the results on Fig. 5.1. This will help establish a definite trend toward one of these relations that can be used by the SDDOT.

5.2.3. South Dakota ADT Growth Rate

The ADT growth rate represents the yearly percentage growth or decline in traffic volume for a specific roadway. This percentage is required when conducting an economic study to adjust the current traffic value to future values after performing any improvement or maintenance activities to a deficient bridge structure. Accurate traffic projection will yield an accurate evaluation of the economic worth of the various improvement and replacement options.

The ADT growth rate for the SDDOT is given in Table 5.6 for two roadway functional classifications--rural and urban highways (see Appendix A). These rates are listed for interstate highways, federal aid highways, and other highways.

Table 5.6. South Dakota ADT growth rates

Rural Highways					
Class	1986	1987	1988	1989	1990
Interstate	+4.1	+7.7	+6.4	+4.8	+7.3
Federal Aid	+8.3	+4.0	+1.9	+2.2	+5.3
Other	+1.7	+7.4	-3.3	+1.7	-0.6
Urban Highways					
Class	1986	1987	1988	1989	1990
Interstate	+1.8	+15.5	+5.4	-0.2	+1.5
Federal Aid	+4.3	+4.7	-2.0	-0.4	+3.4
Others	+5.4	+3.8	-2.3	+0.9	+0.5
State Wide	+1.9	+6.1	+0.6	+2.1	+3.5

5.3. Summary

The information presented in this chapter represents two vital elements in implementing the Pontis BMS. However, the authors recognize the need to gather more information regarding user and agency costs prior to implementing the Pontis BMS by the SDDOT. Until complete user and agency cost data are developed for the state of South Dakota, the authors suggest using similar data from surrounding states, e.g., from the Iowa or Minnesota Departments of Transportation.

6. BRIDGE PERFORMANCE PREDICTION MODEL

The rate of bridge deterioration is an important aspect of a complete maintenance system. In the United States, a few studies have been conducted to predict bridge deterioration. Studies performed by the Transportation System Center in Cambridge, Massachusetts, the Massachusetts Institute of Technology, the Wisconsin DOT, the Pennsylvania DOT, and the New York DOT have related bridge age to its numerical ratings condition [3]. These studies yielded simple linear or piecewise linear deterioration curves for all bridge types or for different bridge structures. Recently, Purdue University developed a deterioration model for the Indiana DOT based on the Markov Chain probabilistic approach [42,43]. All deterioration curves presented in Refs. [3,42,43] are unique and cannot be used nationwide to predict bridge performance. For example, the curves resulting from the Wisconsin DOT study were obtained using data related to bridges within the state of Wisconsin.

In this work the deterioration models for bridge deck, bridge superstructure, and substructure will be predicted utilizing a Markov chain statistical method [44] that has been successfully used in pavement management [45]. This model simulates the nonlinear nature of the deterioration rates and also estimates information such as the probability distribution around the predicted mean.

According to the FHWA rating system, bridge components are rated every 2 years using a scale of 0 to 9 (with 9 being the rating number for a near perfect condition). In fact, the SDDOT follows the FHWA requirements to classify bridges with a rating of 4 or less as structurally deficient [41]. Thus, the service life of a bridge can be defined as the number of years a bridge at condition 9 takes to reach condition 4.

6.1. Transition Matrices

The key elements in the Markov Chain are referred to as transition matrices (see Chapter 3). In this work, these matrices are established utilizing the bridge inspection data from every two-year inspection period.

As an example, the general form of a two-year transition matrix and its condition ratings are listed in Table 6.1. A typical element $p_{i,j}$ in the matrix is called a transition probability, which is defined as the probability that a bridge at state i deteriorates to state j in two years. For example, the probability that a bridge currently at state 2 will go to state 4 in a two-year interval is $p_{2,4}$ in the transition matrix.

Table 6.1 Transition matrix showing the correspondence of condition ratings and states

CR[a]		9	8	7	6	5	4	3
9		$P_{1,1}$	$P_{1,2}$	$P_{1,3}$	$P_{1,4}$	$P_{1,5}$	$P_{1,6}$	$P_{1,7}$
8		$P_{2,1}$	$P_{2,2}$	$P_{2,3}$	$P_{2,4}$	$P_{2,5}$	$P_{2,6}$	$P_{2,7}$
7		$P_{3,1}$	$P_{3,2}$	$P_{3,3}$	$P_{3,4}$	$P_{3,5}$	$P_{3,6}$	$P_{3,7}$
6	[P] =	$P_{4,1}$	$P_{4,2}$	$P_{4,3}$	$P_{4,4}$	$P_{4,5}$	$P_{4,6}$	$P_{4,7}$
5		$P_{5,1}$	$P_{5,2}$	$P_{5,3}$	$P_{5,4}$	$P_{5,5}$	$P_{5,6}$	$P_{5,7}$
4		$P_{6,1}$	$P_{6,2}$	$P_{6,3}$	$P_{6,4}$	$P_{6,5}$	$P_{6,6}$	$P_{6,7}$
3		$P_{7,1}$	$P_{7,2}$	$P_{7,3}$	$P_{7,4}$	$P_{7,5}$	$P_{7,6}$	$P_{7,7}$

[a]CR = FHWA component condition rating.

Without repair or rehabilitation, the bridge condition decreases as the bridge age increases. In this work an assumption is made that a bridge condition rating would not drop more than two ratings in any two-year transition interval. In other words, the bridge condition either stays at its current condition or deteriorates to one of the next two lower conditions. As a result, the general form of the transition matrix in Table 6.1 is simplified as shown in Table 6.2. Transition matrices similar to Table 6.2 are employed throughout this work.

Table 6.2 Transition matrix for a two-year transition interval

	$P_{1,1}$	$P_{1,2}$	$P_{1,3}$	0	0	0	0
	0	$P_{2,2}$	$P_{2,3}$	$P_{2,4}$	0	0	0
	0	0	$P_{3,3}$	$P_{3,4}$	$P_{3,5}$	0	0
[P] =	0	0	0	$P_{4,4}$	$P_{4,5}$	$P_{4,6}$	0
	0	0	0	0	$P_{5,5}$	$P_{5,6}$	$P_{5,7}$
	0	0	0	0	0	$P_{6,6}$	$P_{6,7}$
	0	0	0	0	0	0	1

Elements in transition matrices differ from one interval to another. For illustration, assume that a transition matrix is to be established for an interval between time t and time t+2. Hence, one must use only the inspection records for bridges that satisfy the following: (1) bridges that have been inspected at both age t and age t+2 (to reflect the real bridge deterioration transition behavior); and (2) bridges where condition ratings have not increased over the two-year interval (to eliminate effects of repairs and rehabilitations).

Using these assumptions, the transition probabilities within a given interval can be estimated as

$$P_{ij} = \frac{n_{ij}}{N_i} \tag{6.1}$$

where

P_{ij} = transition probability from state i to state j

n_{ij} = number of bridges that deteriorate from state i to state j within the interval

N_i = number of bridges at state i at the beginning of the interval

and i,j = 1,2...7

Tables 6.3 and 6.4 summarize the data and the transition matrix for an interval between age 4 and age 6. The column vector $\{N_i\}_4$ in Table 6.3 gives the number of the 4-year old bridges at state i as 4, 13, and 4 bridges at conditions 9, 8, and 7, respectively. As illustrated in the matrix $[n_{i,j}]_{4,6}$, two of the bridges rated at condition 9 remained at condition 9, one deteriorated to condition 8, while the other one was rated at condition 7 at the end of the interval. Similar explanations can be stated for the bridges that were at conditions 8 and 9 at the beginning of the interval. Using this information in conjunction with Eq. (6.1), the transition probability for this interval $[P]_{4,6}$ was estimated as given in Table 6.4.

One must realize that the accuracy of $P_{i,j}$ in Eq. (6.1) depends on the size of the available data, i.e., on the size N_i. Unfortunately, since mandatory inspection has been in effect for only about 17 years, problems may be encountered when using Eq. (6.1). First, insufficient data may exist for a specific condition within a specific interval. In this case, one can interpolate or extrapolate transition probabilities of the same condition at an earlier or later age to approximate the transition probabilities within this interval. For example, assume that the results given in Table 6.5a are those obtained using Eq. (6.1). However, upon examining this table, one notices some zero rows in the intervals from ages 6 to 8 and ages 8 to 10 (these are shown as bold numbers in the table). To approximate these zero probabilities, the average of the transition probabilities (shown as underlined rows in the table) of the adjacent transition intervals was used to estimate the zero transition probabilities. Table 6.5b illustrates the transition probabilities after this interpolation was performed. Notice that Table 6.5b illustrates constant transition probabilities associated with the intervals for ages 6 to 8 and 8 to 10. These are equal to the average of the corresponding probabilities of intervals 4 to 6 and 10 to 12. In this work, this procedure was used regardless of the number of unknown transition intervals.

Table 6.3. Data for establishment of the transition matrix over transition interval [4,6] for decks on steel bridges on primary highways in South Dakota.

$\{n_4\}$				$[n_{4,6}]$				$\{n_6\}$
4	2	1	1	0	0	0	0	2
13	0	5	8	0	0	0	0	6
4	0	0	4	0	0	0	0	13
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0

Table 6.4. Transition matrix established directly using Eq. (6.1) over transition interval [4,6] for decks of steel bridges on primary highways in South Dakota.

			$[p_{4,6}]$			
0.50	0.25	0.25	0.00	0.00	0.00	0.00
0.00	0.38	0.63	0.00	0.00	0.00	0.00
0.00	0.00	1.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	1.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 6.5 An interpolation example

(a) Preliminary Transition Matrices before Interpolation

[4, 6]

.60	.40	.00	.00	.00	.00	.00
.00	.95	.05	.00	.00	.00	.00
.00	.00	.80	.20	.00	.00	.00
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---

[6, 8]

.54	.46	.00	.00	.00	.00	.00
.00	.29	.57	.14	.00	.00	.00
.00	**.00**	**.00**	**.00**	**.00**	**.00**	**.00**
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---

[8, 10]

.00	**.00**	**.00**	**.00**	**.00**	**.00**	**.00**
.00	.67	.33	.00	.00	.00	.00
.00	**.00**	**.00**	**.00**	**.00**	**.00**	**.00**
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---

[10, 12]

.14	.86	.00	.00	.00	.00	.00
.00	.38	.62	.00	.00	.00	.00
.00	.00	.90	.10	.00	.00	.00
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---

b - The Transition Matrices after Performing Interpolation

.60	.40	.00	.00	.00	.00	.00
.00	.95	.05	.00	.00	.00	.00
.00	.00	.80	.20	.00	.00	.00
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---

.54	.46	.00	.00	.00	.00	.00
.00	.29	.57	.14	.00	.00	.00
.00	**.00**	**.85**	**.15**	**.00**	**.00**	**.00**
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---

.34	.66	.00	.00	.00	.00	.00
.00	.67	.33	.00	.00	.00	.00
.00	**.00**	**.85**	**.15**	**.00**	**.00**	**.00**
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---

.14	.86	.00	.00	.00	.00	.00
.00	.38	.62	.00	.00	.00	.00
.00	.00	.90	.10	.00	.00	.00
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---
---	---	---	---	---	---	---

The extrapolation procedure utilized herein varies depending upon the direction of extrapolation, i.e., prior to or beyond the known transition interval. In order to determine the transition interval probabilities prior to a known transition interval, the probabilities associated with the first known interval were used for all preceding intervals. Table 6.6 illustrates how extrapolation was performed to estimate the null rows. For example, the transition probabilities in row two of interval 2 to 4 was used in row 2 of interval 0 to 2.

In order to establish the transition probability beyond a known transition interval, the probabilities associated with the two fastest deteriorating intervals are averaged. The fastest deteriorating transition intervals are those defined as the two intervals with the smallest P_{ij} values. The average of the fastest deteriorating intervals was used in order to eliminate the effect of possible erroneous data associated with using only the fastest deterioration of one interval.

6.2. State Vector

The seven conditions from 9 to 3 can be expressed in a vector {C} as

$$\{C\} = \{9\ 8\ 7\ 6\ 5\ 4\ 3\}^T \qquad (6.3)$$

The probabilities associated with these seven conditions can also be expressed in a vector {Q}. For example, the vector

$$\{Q\} = \{0\quad 0.5\quad 0.3\quad 0.2\quad 0\quad 0\quad 0\}^T$$

illustrates that there are 50%, 30%, and 20% probabilities that this bridge component will be at condition 8, 7, and 6, respectively. Knowing the vectors {C} and {Q}, one can estimate the mean condition of these components as

Table 6.6 Example illustrating extrapolation of transition matrices

a - Transition Matrices Before Extrapolation

[0, 2]

.45	.32	.23	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00

[2, 4]

.38	.46	.16	.00	.00	.00	.00
.00	.89	.11	.00	.00	.00	.00
.00	.00	.30	.50	.20	.00	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00

[4, 6]

.60	.40	.00	.00	.00	.00	.00
.00	.83	.17	.00	.00	.00	.00
.00	.00	.40	.40	.20	.00	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00

[6, 8]

.00	1.0	.00	.00	.00	.00	.00
.00	.29	.57	.14	.00	.00	.00
.00	.00	.20	.40	.40	.00	.00
.00	.00	.00	.85	.10	.05	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00

b - Transition Matrices After Extrapolation

[0, 2]

.45	.32	.23	.00	.00	.00	.00
.00	.89	.11	.00	.00	.00	.00
.00	.00	.30	.50	.20	.00	.00
.00	.00	.00	.85	.10	.05	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00

[2, 4]

.38	.46	.16	.00	.00	.00	.00
.00	.89	.11	.00	.00	.00	.00
.00	.00	.30	.50	.20	.00	.00
.00	.00	.00	.85	.10	.05	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00

[4, 6]

.60	.40	.00	.00	.00	.00	.00
.00	.83	.17	.00	.00	.00	.00
.00	.00	.40	.40	.20	.00	.00
.00	.00	.00	.85	.10	.05	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00

[6, 8]

.83	.17	.00	.00	.00	.00	.00
.00	.29	.57	.14	.00	.00	.00
.00	.00	.20	.40	.40	.00	.00
.00	.00	.00	.85	.10	.05	.00
.00	.00	.00	.00	.00	.00	.00
.00	.00	.00	.00	.00	.00	.00

$$Mean\ Condition = \{Q\}^T \{C\} \tag{6.4}$$

6.3. Prediction of Future Conditions by Markov Chain

The Markov Chain states that future probabilities associated with specific states can be estimated if the transition probabilities for these transition periods are known. For example, if $\{Q_t\}$ is the probability vector at time t, then the probability vector $\{Q_{t+m}\}$ after m years is estimated as

$$\{Q_{t+m}\} = \{Q\}_t^T [P_{i,j}]_{(t,t+2)} \cdot\cdot [P_{i,j}]_{(t+m-4,t+m-2)} [P_{i,j}]_{(t+m-2,t+m)} \tag{6.5}$$

where the $[P_{ij}]$ matrices are the transition matrices associated with the two-year intervals between time t and t+m.

In summary, the Markov chain approach can be used whenever the transition interval probabilities can be determined. However, if the transition probabilities associated with a particular condition cannot be established for some transition interval, then a different approach must be employed. One alternative approach to constructing transition matrices is to use expert opinions such as those in the Pontis program; questionnaires to bridge inspection experts collect probabilities of bridge deterioration from one condition to another (see Chapter 3). Another technique to establish transition matrices where insufficient inspection data exist is the approximate model developed in [13] and described below.

6.4. Approximate Prediction Model

Since all bridges on primary highways in the state of South Dakota receive high levels of maintenance, very few interstate bridge components will be given low ratings. As a result, there will be no recorded data that can be directly used to establish the transition probabilities below this condition. Let i be the condition below which no inspection data are available. In a region with conditions greater than or equal to i, one can directly employ Eq. (6.5) to establish the probability vector, Q, to be used to predict mean condition of a bridge component. On the other hand, a different approach must be used in the region below condition i where no inspection data are available.

The approximate model assumes that the deterioration rates are defined by the user who has approximated them from linear regression on the bridge inspection data or expert opinions. This model also assumes that the probabilities in the state vector change rather than the transition matrices.

To illustrate how the approximate model and Markov chain approach are integrated to predict future component condition at time t, recall that such value is estimated using Eq. (6.4):

$$\text{Average Condition} = \{Q_t\}^T \{C\}$$

where $\{Q\}_t$ is the probability vector estimated using Eq. (6.5), and $\{C\}$ is the condition vector. Let t and i be the time and condition at which it becomes necessary to use the approximate model. At this time, the vector $\{Q_t\}$ obtained by the Markov Chain approach is separated into two vectors. The first vector, $\{Q^m{}_t\}$ contains the state probabilities obtained utilizing the Markov Chain for the conditions up to and including condition i. The probabilities in the second vector $\{Q^a{}_t\}$ are those obtained utilizing the approximate model. For example, let condition 5 at time t be the condition where one must switch from using the Markov Chain to the deterministic model. Then

$$\{Q_t^m\} = \{P_1 P_2 P_3 P_4 P_5 0 0\}^T \qquad (6.6)$$

$$\{Q_t^a\} = \{0\ 0\ 0\ 0\ 0\ P_6 P_7\}^T \qquad (6.7)$$

where P_j is the probability that a bridge component be at a state j, and j=1,2,...7. In the vectors, $\{Q^m_t\}$ and $\{Q^a_t\}$, zeros are used for the probabilities corresponding to conditions greater than 5 and less than or equal to condition 5, respectively.

To proceed with the prediction beyond time t, one continues to use Eq. (6.5) to estimate the probabilities in the state vectors {Q} until all probabilities above and up to condition i become zeros. Each of these vectors is then decomposed into the approximate $\{Q_t^a\}$ and Markov Chain $\{Q_t^m\}$ vectors as listed above. The approximate state vectors $\{Q^a_{t+L}\}$ and the associated vectors $\{C^a_{t+L}\}$ at time t+L are then estimated as follows: let t be the current time and L be the number of years at which one wishes to predict the condition; then the condition vector $\{C^a_{t+L}\}$ utilizing the approximate model is expressed as

$$\{C^a_{t+L}\} = \{C_t^a\} - sL\ \{I\} \qquad (6.8)$$

where

{I} = the identity vector with the same length as the vector $\{C_{ta}\}$ and contains zero for the element above condition i and ones in the entries below condition C.

s = the deterioration rate defined by the user.

One should notice that since the lowest condition that a bridge component may reach is 3, then the lowest entry in the vector $\{C^a_{t+L}\}$ must be equal to 3. It is important to notice that depending on the slope s in Eq. (6.8), the entry in the vector $\{C^a_{t+L}\}$ may not be an integer. Hence, to avoid this problem, the slope s should be approximated to fraction like 0.5, 0.25, or 0.125 that yields a multiplier of even integer numbers. Even numbers indicate that the condition of the bridge component under consideration will drop one rating condition after

2 years, 4 years, and 8 years. This assumption was made since bridge inspection is performed every two years.

The probabilities in the vector $\{Q^a_{t+L}\}$ are assumed equal to the probabilities in the vector $\{Q^a_t\}$ but with conditions estimated using Eq. (6.8). For example, if the deterioration rate s is 0.25, the vector $\{Q^a_t\}$ i

$$\{Q_t^a\}^T = \{0\ 0\ 0\ 0\ .4\ .1\ .0\}$$

and

$$\{Q_{t+2}^a\}^T = \{0\ 0\ 0\ 0\ .4\ .1\ 0\}$$

and

$$\{Q_{t+4}^a\}^T = \{0\ 0\ 0\ 0\ 0\ .4\ .1\}$$

Notice that this example illustrates that it will take four years for conditions 5 and 4 to drop to 4 and 3 with no change in the probabilities associated with these conditions at time t. Having estimated the vectors $\{Q^m_{t+L}\}$ and $\{Q^a_{t+L}\}$, the future probability vector $\{Q_{t+L}\}$ is estimated as

$$\{Q_{t+L}\} = \{Q_{t+L}^m\} + \{Q_{t+L}^a\} \tag{6.9}$$

This vector can then be used in Eq. (6.4) to estimate the future mean condition of a bridge component.

One may criticize the method outlined above since the deterioration rates used in the approximate model were assumed. An alternative to formulating the transition matrices when no data are available is to use linear programming [46], nonlinear programming [42,43], or expert opinion. The expert opinion alternative was not pursued here since the objective of the work was to utilize the inspection data to formulate more accurate transition probabilities. In addition, the linear and nonlinear programming were not employed as requested by the project technical committee since these require the use of a mainframe computer and several commercial software packages. Future addition of inspection data will eliminate the assumption used in the approximate model.

6.5. Integration of the Markov Chain and the Approximate Model

To illustrate how to use the prediction models summarized in the previous sections, a simple example is provided. In this example, it was assumed that a bridge deck has reached condition 6 after 10 years, and one wishes to predict the deck condition 14 years later. Therefore, the probability vector $\{Q_{10}\}$ associated with this assumption is expressed as

$$\{Q_{10}\} = \{0\ 0\ 0\ 1\ 0\ 0\ 0\}^T \tag{6.10}$$

The transition matrices for the intervals 10 to 12 years, 12 to 14 years, and 14 to 16 years used in this example are given in Table 6.7. (<u>These are imaginary transition matrices and are not related to any of SDDOT bridges.</u>) Notice that no transition probabilities are listed in the rows corresponding to conditions 9, 8, or 7, since the initial vector $\{Q_{10}\}$ indicated that the deck is at condition 6. In the development of this example's transition matrices, it was also assumed that all transition probabilities for conditions below 6 are zeros (see Table 6.7). Therefore, the approximate model must be employed in conjunction with the Markov chain to continue the prediction below this condition.

Table 6.7 An example illustrating decomposition of state vector

The state vectors {Q} predcited by Markov chain before utilizing the approximate model

$$
\{Q_{10}\}\;\; P_{10,12} \;\; \{Q_{12}\}\;\; P_{12,14} \;\; \{Q_{14}\}\;\; P_{14,16} \;\; \{Q_{16}\}
$$

$$
\begin{bmatrix} .0 \\ .0 \\ .0 \\ 1. \\ .0 \\ .0 \\ .0 \end{bmatrix} \cdot
\begin{bmatrix} \hline \\ \hline \\ \hline \\ .00 & .00 & .00 & .50 & .40 & .10 & .00 \\ .00 & .00 & .00 & .00 & .00 & .00 & .00 \\ .00 & .00 & .00 & .00 & .00 & .00 & .00 \\ .00 & .00 & .00 & .00 & .00 & .00 & .00 \end{bmatrix} =
\begin{bmatrix} .0 \\ .0 \\ .0 \\ .5 \\ .4 \\ .1 \\ .0 \end{bmatrix} \cdot
\begin{bmatrix} \hline \\ \hline \\ \hline \\ 00 & .00 & .00 & .40 & .40 & .20 & .00 \\ .00 & .00 & .00 & .00 & .00 & .00 & .00 \\ .00 & .00 & .00 & .00 & .00 & .00 & .00 \\ .00 & .00 & .00 & .00 & .00 & .00 & .00 \end{bmatrix} =
\begin{bmatrix} .0 \\ .0 \\ .0 \\ .2 \\ .2 \\ .1 \\ .0 \end{bmatrix} \cdot
\begin{bmatrix} \hline \\ \hline \\ \hline \\ 00 & .00 & .00 & .00 & 1.0 & .00 & .0 \\ .00 & .00 & .00 & .00 & .00 & .00 & .0 \\ .00 & .00 & .00 & .00 & .00 & .00 & .0 \\ .00 & .00 & .00 & .00 & .00 & .00 & .0 \end{bmatrix} =
\begin{bmatrix} .0 \\ .0 \\ .0 \\ .0 \\ .2 \\ .0 \\ .0 \end{bmatrix}
$$

The Decomposed Sub-vectors {Q^m}

$$
\{Q^m_{10}\} = \begin{bmatrix} .0 \\ .0 \\ .0 \\ 1. \\ .0 \\ .0 \\ .0 \end{bmatrix} \quad
\{Q^m_{12}\} = \begin{bmatrix} .0 \\ .0 \\ .0 \\ .5 \\ .0 \\ .0 \\ .0 \end{bmatrix} \quad
\{Q^m_{14}\} = \begin{bmatrix} .0 \\ .0 \\ .0 \\ .2 \\ .0 \\ .0 \\ .0 \end{bmatrix} \quad
\{Q^m_{16}\} = \begin{bmatrix} .0 \\ .0 \\ .0 \\ .0 \\ .0 \\ .0 \\ .0 \end{bmatrix}
$$

$$+ \qquad\qquad + \qquad\qquad + \qquad\qquad +$$

The Decomposed Sub-vectors {Q^a} to be Transited by the approximate method

$$
\{Q^a_{10}\} = \begin{bmatrix} .0 \\ .0 \\ .0 \\ .0 \\ .0 \\ .0 \\ .0 \end{bmatrix} \quad
\{Q^a_{12}\} = \begin{bmatrix} .0 \\ .0 \\ .0 \\ .0 \\ .4 \\ .1 \\ .0 \end{bmatrix} \quad
\{Q^a_{14}\} = \begin{bmatrix} .0 \\ .0 \\ .0 \\ .0 \\ .2 \\ .1 \\ .0 \end{bmatrix} \quad
\{Q^a_{16}\} = \begin{bmatrix} .0 \\ .0 \\ .0 \\ .0 \\ .2 \\ .0 \\ .0 \end{bmatrix}
$$

To use the approximate model, a deterioration rate, s, of 0.25 was assumed. The probability vectors $\{Q_t\}$, where t = 12, 14,...24 were calculated as follows:

1. Utilize Eq. (6.5) to predict the probability vector $\{Q_t\}$. Continue this procedure for all probabilities above and up to the condition at which the switch to the approximate model becomes zero. In this example, this occurred at age 16 years (see Table 6.7).

2. Decompose the vectors $\{Q_{12}\}$, $\{Q_{14}\}$, and $\{Q_{16}\}$ into Markov Chain and approximate vectors using Eqs. (6.6) and (6.7). For example, the vector

   $\{Q_{12}\}^T = \{0 \;\; 0 \;\; 0 \;\; .5 \;\; .4 \;\; .1 \;\; 0\}$

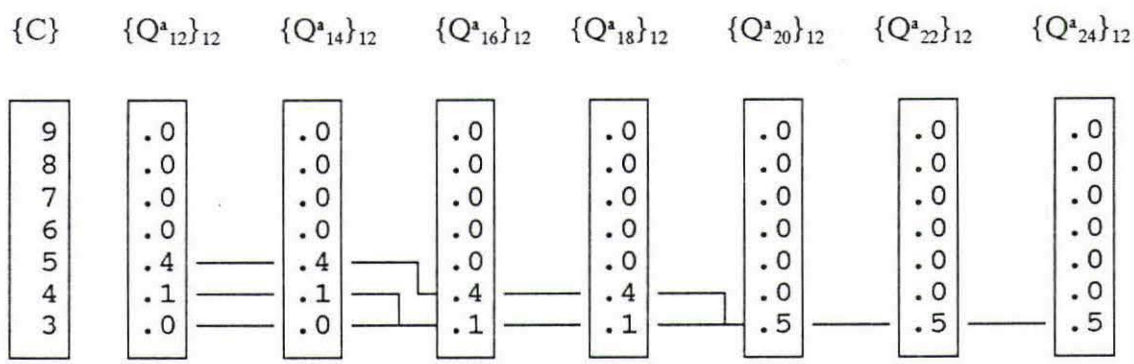
   is decomposed into

   $\{Q^m{}_{12}\}^T = \{0 \;\; 0 \;\; 0 \;\; .5 \;\; 0 \;\; 0 \;\; 0\}$ and

   $\{Q^a{}_{12}\}^T = \{0 \;\; 0 \;\; 0 \;\; 0 \;\; .4 \;\; .1 \;\; 0\}$.

The decomposed vectors $\{Q^m{}_{10}\}$, $\{Q^m{}_{12}\}$, $\{Q^m{}_{14}\}$, and $\{Q^m{}_{16}\}$ are listed in Table 6.7.

3. Use Eq. (6.8) to transfer the probabilities in the approximate vectors $\{Q^a{}_{12}\}$, $\{Q^a{}_{14}\}$, and $\{Q^a{}_{16}\}$. This is performed to approximate the deterioration probabilities. For example, the probabilities in the vector $\{Q^a{}_{12}\}$ are transferred to the next inspection, i.e., 14, 16, 18...24, until the predicted future condition reaches 3 as follows:



A subscript 12 is used above to designate that the estimated probability vectors are associated with the approximate vector $\{Q^a_{12}\}$. Notice that the conditions corresponding to the probabilities in this vector drop one condition rating every 4 years. This is based on the assumed deterioration rate of 0.25. Repeat this step to approximate the probabilities associated with the vectors $\{Q^a_{14}\}$ and $\{Q^a_{16}\}$. The results are listed in Table 6.8.

4. Estimate the final state vector $\{Q_t\}$ at future time t by superimposing the vectors $\{Q^m_t\}$ and $\{Q^a_t\}$ evaluated in steps 2 and 3, respectively. This can be accomplished as follows:

$$\{Q_t\} = \{Q_t^m\} + \{Q_t^a\}_{10} + \{Q_t^a\}_{t0+2} \ldots \{Q_t^a\}_{t-2} + \{Q_t^a\} \quad (6.11)$$

where t0 represents the current age of the bridge component being investigated.

For example, the state vector $\{Q_{16}\}$ for this particular bridge deck can be predicted as

$$\{Q_{16}\} = \{Q_{16}^m\} + \{Q_{16}^a\}_{10} + \{Q_{16}^a\}_{12} + \{Q_{16}^a\}_{14} + \{Q_{16}^a\}_{16} \quad (6.12)$$

Substituting the vectors listed in Tables 6.7 and 6.8 corresponding to the vectors on the right-hand side of Eq. (6.12) yields

$$\{Q_{16}\} = \{0\ 0\ 0\ 0\ .4\ .5\ .1\}^T$$

This vector illustrates that there are 40%, 50%, and 10% probabilities that the bridge deck used in this example will deteriorate over six years from condition 6 to conditions 5, 4, and 3, respectively. The mean condition of this deck after 6 years can conditions 5, 4, and 3, respectively. The mean condition of this deck after 6 years can then be estimated utilizing Eq. (6.4) as

$$\text{Deck Mean Condition} = \{Q_{16}\}^T\{C\} = 4.3 \text{ (say 4)}$$

The other state vectors $\{Q_t\}$ for t = 10, 12,...24 are listed in Table 6.9. This table illustrates that the bridge deck studied in this example will deteriorate from condition 6 at age 10 to condition 3 after 14 years.

The approach outlined above was computerized to estimate future conditions and the associated probabilities for bridge decks, superstructures, and substructures for South Dakota bridges. The results are summarized in the following chapter.

Table 6.8 An example illustrating transition of state probabilities utilizing approximate model

$\{Q^*_{12}\}$	$\{Q^*_{14}\}_{12}$	$\{Q^*_{16}\}_{12}$	$\{Q^*_{18}\}_{12}$	$\{Q^*_{20}\}_{12}$	$\{Q^*_{22}\}_{12}$	$\{Q^*_{24}\}_{12}$
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.4	.4	.0	.0	.0	.0	.0
.1	.1	.4	.4	.0	.0	.0
.0	.0	.1	.1	.5	.5	.5

$\{Q^*_{14}\}$	$\{Q^*_{16}\}_{14}$	$\{Q^*_{18}\}_{14}$	$\{Q^*_{20}\}_{14}$	$\{Q^*_{22}\}_{14}$	$\{Q^*_{24}\}_{14}$
.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0
.2	.2	.0	.0	.0	.0
.1	.1	.2	.2	.0	.0
.0	.0	.1	.1	.3	.3

$\{Q^*_{16}\}$	$\{Q^*_{18}\}_{16}$	$\{Q^*_{20}\}_{16}$	$\{Q^*_{22}\}_{16}$	$\{Q^*_{24}\}_{16}$
.0	.0	.0	.0	.0
.0	.0	.0	.0	.0
.0	.0	.0	.0	.0
.0	.0	.0	.0	.0
.2	.2	.0	.0	.0
.0	.0	.2	.2	.0
.0	.0	.0	.0	.2

$\{Q^*_{12}\}$	$\{Q^*_{14}\}$	$\{Q^*_{16}\}$	$\{Q^*_{18}\}$	$\{Q^*_{20}\}$	$\{Q^*_{22}\}$	$\{Q^*_{24}\}$
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.4	.6	.4	.2	.0	.0	.0
.1	.2	.5	.6	.4	.2	.0
.0	.0	.1	.2	.6	.8	1.

Table 6.9 An example illustrating prediction of total state vectors utilizing Markov chain in conjunction with approximate model

$\{Q^m_{12}\}$	$\{Q^m_{14}\}$	$\{Q^m_{16}\}$	$\{Q^m_{18}\}$	$\{Q^m_{20}\}$	$\{Q^m_{22}\}$	$\{Q^m_{24}\}$
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.5	.2	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0

+	+	+	+	+	+	+

$\{Q^*_{12}\}$	$\{Q^*_{14}\}$	$\{Q^*_{16}\}$	$\{Q^*_{18}\}$	$\{Q^*_{20}\}$	$\{Q^*_{22}\}$	$\{Q^*_{24}\}$
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.5	.2	.0	.0	.0	.0	.0
.4	.6	.4	.2	.0	.0	.0
.1	.2	.5	.6	.4	.2	.0
.0	.0	.1	.2	.6	.8	1.

The total state vectors predicted using Markov chain and the approximate approach

$\{Q_{12}\}$	$\{Q_{14}\}$	$\{Q_{16}\}$	$\{Q_{18}\}$	$\{Q_{20}\}$	$\{Q_{22}\}$	$\{Q_{24}\}$
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.0	.0	.0	.0	.0	.0	.0
.4	.6	.4	.2	.0	.0	.0
.1	.2	.5	.6	.4	.2	.0
.0	.0	.1	.2	.6	.8	1.

7. CONDITION RATING - AGE RELATIONSHIP FOR THE SOUTH DAKOTA BRIDGES

As previously mentioned, the state of South Dakota has been following guidelines outlined by the FHWA in collecting and recording inspection data for the bridges within the state. Inspection data from 1980 to date were provided by the SDDOT and was used herein to identify the factors that affect the performance of the bridges. In addition, these data were employed to develop relationships between the age and the condition rating of bridge decks, superstructures, substructures, and bridge age.

Figure 7.1, which categorizes the bridges in the state of South Dakota by type, shows that most of these bridges are prestressed girder, concrete slabs, steel beams, and culverts and that not enough concrete beams, tee beams, box beams, rigid frames, arches, and timber beam bridges exist to perform reliable statistical analyses on them. Also, since culverts cannot be categorized as bridges, no deterioration curves were developed for this type of structure. Hence, the study presented here concentrates on concrete slab bridges (673 bridges), steel beam bridges (553 bridges), and prestressed girders (95 bridges).

Figure 7.2 plots the number of bridges built versus the construction year. The figure indicates that the oldest existing bridge in the state of South Dakota was built in 1920 and 96.5% of its bridges were built after 1935. This graph illustrates also that the SDDOT bridges are not as old as most bridges in the United States where 72% of the total bridges were built after 1935.

According to Ref. [9], the SDDOT suggests that a bridge life of 50 years can be expected. This means that bridges built prior to 1940 should have been or will within the next few years be replaced. Factors such as geographic location, average daily traffic, bridge type, functional classification, material type, degree of skewness, and deicing and maintenance policies may affect the rate of deterioration and life span of a bridge deck, superstructure, and substructure.

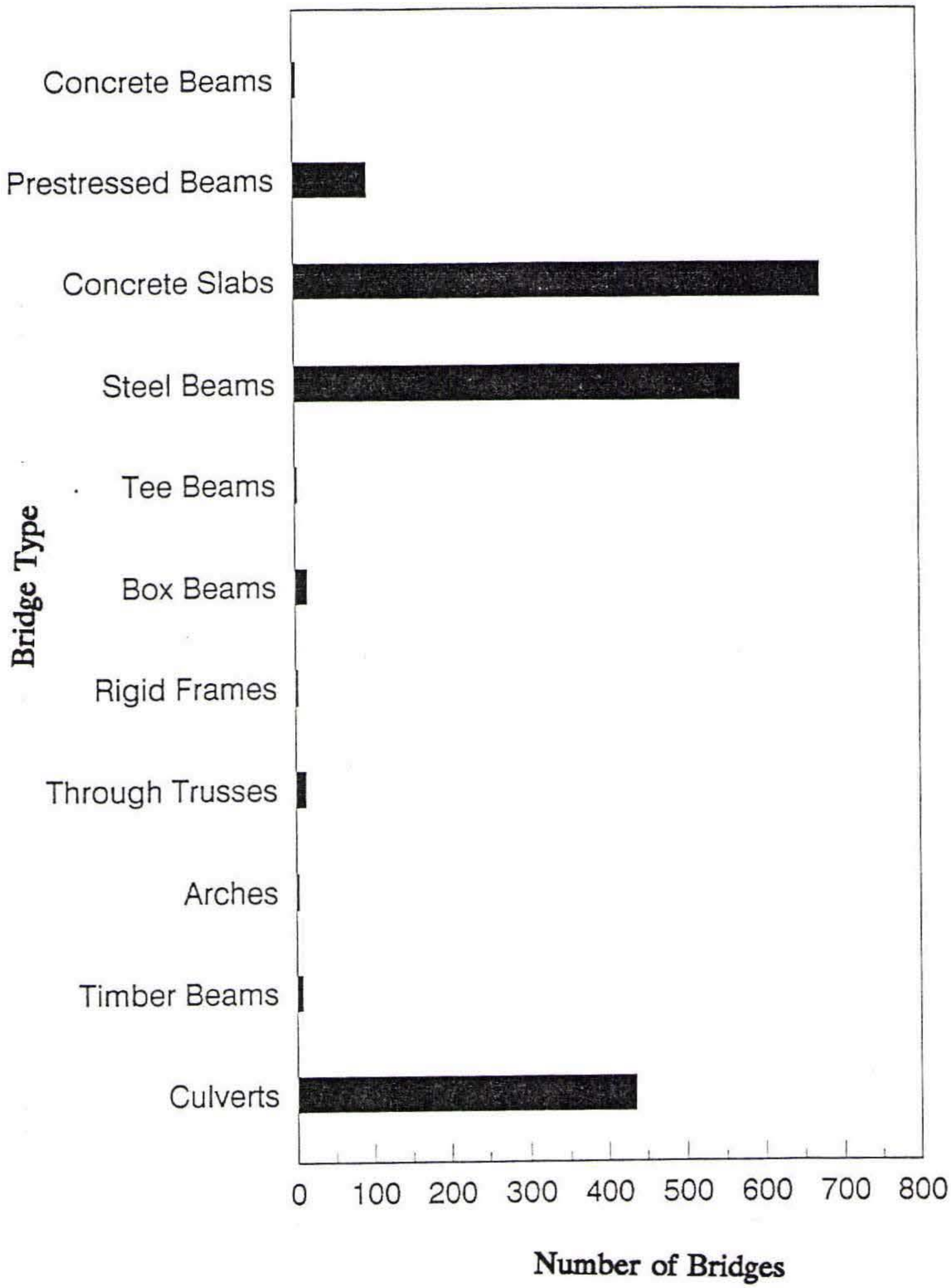


Figure 7.1. Types of bridges in the state of South Dakota

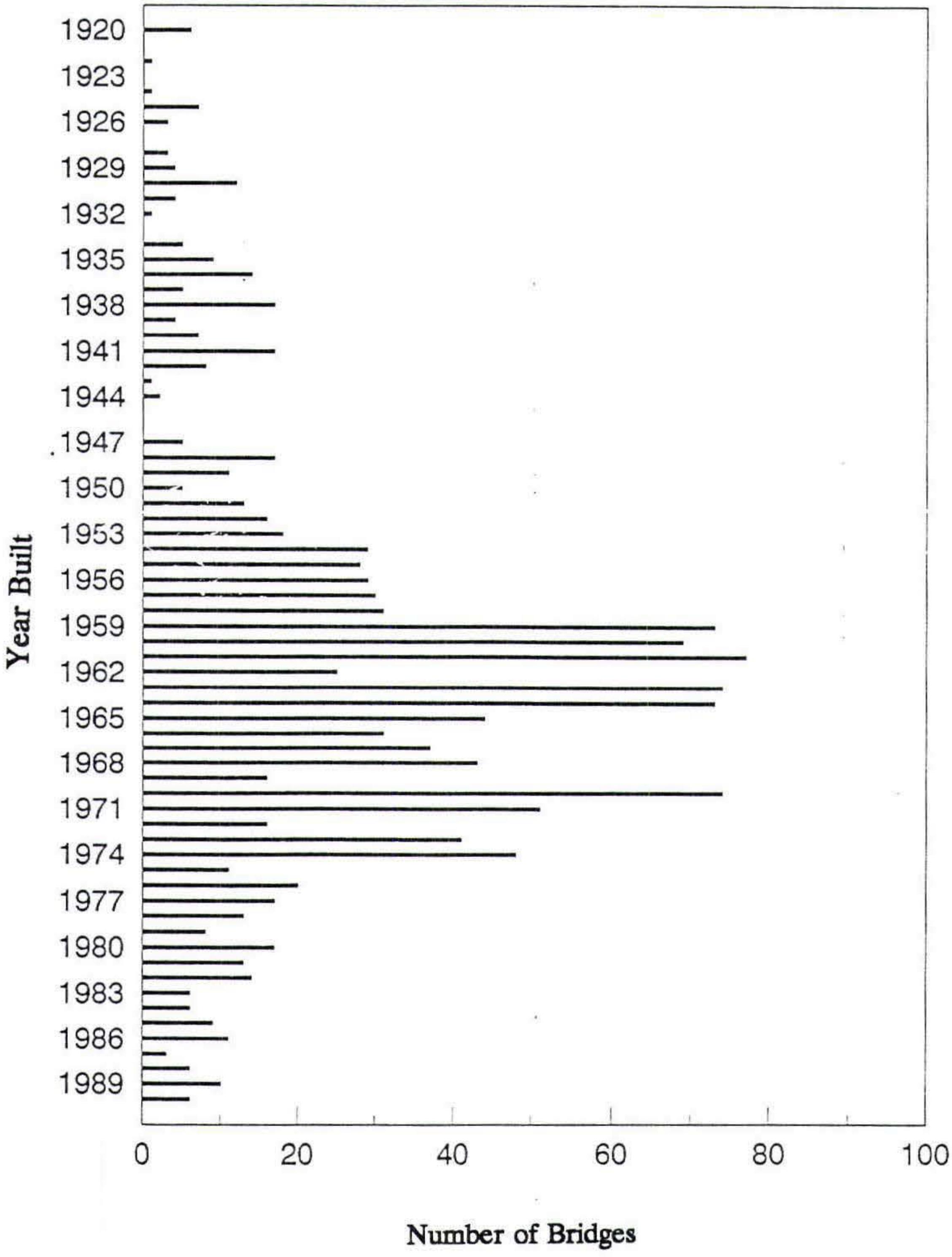


Figure 7.2. Year built vs the number of bridges in the state of South Dakota

In addition, a bridge structure may exhibit faster or slower deterioration rates that can be related to design details and/or construction quality. For example, poorly designed expansion joints and deck drains may allow salt water to leak until it reaches critical locations and affects the performance of the bridge structure. Such factors were not considered in this work. However, it is recommended to refer to recorded information gathered during constructing a bridge when a severe deterioration is noticed. These records should describe the daily activities and actions that may explain fast or slow deterioration. Another source of information is the Office of Materials. The quality of construction material and its effect on deterioration rates was not considered in this research.

7.1. Factors Affecting Bridge Deterioration

The following factors were defined by the authors and the project technical panel to be ones that might affect the rate of deterioration of a bridge structure: 1) bridge length ; 2) average daily traffic (ADT); 3) geographic location; 4) structure type; and 5) degree of skewness. At the suggestion of members of the project technical committee, a statistical analysis was performed using the SAS statistical package [47] to determine the correlation among these factors. However, the analysis did not show high correlation among these factors. Therefore it was concluded to develop deterioration curves considering the factors listed above.

Deterioration curves were developed herein for three different ADT: 1) low ADT (less than 640 vehicles/day); 2) medium ADT (between 641 and 2100 vehicles); and 3) high ADT (greater than 2100 vehicle/day). These ADT categories were determined utilizing the SAS program [47]. First all ADT data was arranged into an ascending order and the frequency of occurrence of different ADT was estimated. This was then used to calculate the occurrence percentage of each frequency by dividing the frequency of each ADT by the total number of frequency occurrence. In the next step, the accumulated percentage was estimated and was used to determine the limits for each of the three ADT groups listed above. The accumulated percentage used for the low, medium and high ADT were less than 33%, from 34% to 66%, and from 67% to 100%, respectively.

Deterioration rates for bridges with lengths less than 120 ft, bridges with ranges from 121 to 185 ft, and for bridges longer than 185 ft were also developed. Furthermore, the recorded inspection data showed that there are several skewed bridges in the state of South Dakota. The effect of the degree of skewness on bridge deterioration was investigated by developing deterioration curves for bridge with degree of skewness less than 15 degrees, greater than 15 and less than 30 degrees and greater than 30 degrees.

During the progress of this project the project technical committee requested that the geographical location should be considered as one of the main factors that affect bridge deterioration rates. In addition, it was also recommended by the committee to develop separate deterioration curves for steel, pre-stressed and slab bridges.

7.2. Development of Condition Rating-Age Relationships

The procedure outlined in Chapter 6 was utilized to develop deterioration curves for the bridge groups listed above. The following steps were followed to attain this objective:

- Data file preparation
- Formulation of transition matrices
- Development of condition rating--age relationship

No formal software was developed for data preparation. Instead the Statistical Analysis System (SAS) [47] commercial package was used to accomplish this task. The two computer software packages previously developed for the state of Iowa [13] to formulate the transition matrices and to predict the condition rating were modified for use in conjunction with the South Dakota bridge inspection data.

7.2.1. Data File Preparation

All available inspecyopn data were used in estimating the deterioration rates for the bridge groups listed in section 7.1. Each file for each of the categories listed above contains a standard set of records stored in a specific format. The information and format are as follows: 1) FHWA bridge identification number (10 characters); 2) year the bridge was built (4 characters); 3) year the bridge was inspected (4 characters); 4) month the bridge was inspected (2 character); 5) deck condition rating (1 character); 6) substructure condition rating (1 character); 7) superstructure condition rating (1 character). The name of the file consists of 6 characters with an extension of .dat, i.e., xxxxxx.DAT. A sample of this input file is shown in Table 7.2.

7.2.2. Preparation of the Transition Matrices File

An interactive and easy to use PC program referred to hereafter as Matmak was developed using a Fortran programming language. To execute this program the user needs to issue the command "matmak." Matmak prompts the user with questions, requesting the drive name and the name of the data file containing inspection data as prepared in the previous step. Also, the user is asked to input the deterioration rates to be used in conjunction with the approximate approach outlined in Chapter 6. This information is optional. If no rate is given, the program assumes a deterioration rate of 0.5 for the deck, superstructure, and substructure.

The program utilizes this data file to formulate the transition matrices using Eq. (6.1). In addition, Matmak determines the state at which the formulation of the transition matrices switches from using Eq. (6.1) to using the approximate approach outlined in Section 6.3. Output of this program is stored in a file with the same name as the input file but with an extension of .MAT.

7.2.3. Calculation of Condition Ratings

PRED, the program that performs the steps to relate condition ratings to age, was also developed on IBM-compatible PCs utilizing the Fortran programming language. To execute this program the user needs to issue the command "pred." The program uses the output from the transition matrices developed in Section 7.2.2 and a user-specified state vector $\{Q_t\}$ at time t to forecast the rating conditions for the bridges analyzed in this step. For example, the probability vector $\{Q_o\}$ for a new bridge component, i.e., deck, superstructure, or substructure, is {1 0 0 0 0 0 0}; and $\{Q_{10}\}$, the state vector for a bridge component that has been in service for 10 years and is rated at condition 6 is, $\{Q_{10}\}$ = {0 0 0 1 0 0 0}. Output from this step includes component mean condition rating (see Chapter 6) versus age and the probability vectors for each year in the prediction period. A sample of this output is given in Table 7.3.

7.3. Computer Software Availability

Although hard copies of the two Fortran programs described above are not part of this report, the computer source files and executable versions are included on a 5.25 in. diskette. Separate diskette containing input data pertaining to the bridge categories listed in Section 7.1 is also provided. These data files were prepared using the South Dakota bridge inspection data. The user needs to update these files whenever new inspection records are collected and added to the data base. This latter step can be accomplished utilizing the SAS software (see section 7.2.1).

The authors strongly recommend that the users not make any changes to the enclosed software. Changes made without involving the authors relieves them from any responsibility.

7.4. South Dakota's Bridge Components Deterioration--Age Relationships

The deterioration curves illustrate the average (or mean) condition for a bridge deck, superstructure, and substructure with respect to age. In developing these curves, a rating of 9 was assumed at the beginning of the life of each component. All developed relationships showed faster decay rate in the first few years, clearly reflecting the inspectors judgment and reinforcing the fact that no component would remain in a perfect condition when subjected to daily traffic.

Bridge I.D.	Year Built	Year Inspected	Month Inspected	Deck Condition	Substructure Condition	Superstructure Condition
05187180	1900	1985	1	6	6	7
05187180	1900	1987	1	6	6	7
05187180	1900	1989	1	6	6	7
06320181	1920	1980	1	7	6	6
06320181	1920	1982	3	7	6	6
06320181	1920	1990	6	7	6	6
17395043	1920	1978	11	6	6	6
17395043	1920	1980	9	6	6	6
17395043	1920	1982	10	6	6	6
23330165	1920	1979	12	5	7	7
23330165	1920	1982	5	5	7	7
25270014	1920	1979	12	5	7	7
25270014	1920	1982	2	5	7	7

Table 7.3 Prediction program sample output file

Component number = 1
Current age = 0
Current condition = 9

The mean predicted remaining life = 43

Age	Mean condition	Probability Vector						
0	9.00	1.00	.00	.00	.00	.00	.00	.00
1	8.73	.79	.15	.06	.00	.00	.00	.00
2	8.46	.58	.29	.13	.00	.00	.00	.00
3	8.20	.40	.40	.20	.00	.00	.00	.00
4	7.95	.22	.51	.27	.00	.00	.00	.00
5	7.78	.14	.50	.36	.00	.00	.00	.00
6	7.61	.06	.49	.45	.00	.00	.00	.00
7	7.54	.06	.45	.45	.04	.00	.00	.00
8	7.46	.06	.41	.45	.08	.00	.00	.00
9	7.36	.03	.37	.53	.08	.00	.00	.00
10	7.25	.00	.33	.60	.08	.00	.00	.00

7.4.1. Effect of Bridge Length

Figures 7.3, 7.4, and 7.5 compare the performance of the deck, superstructures, and substructures for bridges of long, medium, and short length. The figures demonstrate that in long-span bridges these three components exhibit faster deterioration rates than in short- or medium-span bridges. Figures 7.4 and 7.5 show the particularly fast deterioration in the superstructures and the substructures of bridges with long and medium lengths. Fast deterioration rates associated with long-span bridges may be related to several factors among which are the number of expansion joints, frequent maintenance activities, and ADT.

Examining these figures show that bridge decks deteriorate faster than the other two components. For example, the deterioration curves demonstrate that, on average, for bridges with long lengths, it will take the deck approximately 34 years to reach a condition rating of 5. On the other hand, the prediction model developed herein illustrates that bridge substructures and superstructures will reach condition 5 after approximately 52 and 56 years, respectively.

7.4.2. Effects of Average Daily Traffic

Deterioration rates for bridges in the state of South Dakota were developed for the three different traffic volumes (see sec. 7.1) on the state highways (see Figs. 7.6, 7.7 and 7.8). These figures illustrate that the decks, superstructures, and substructures for bridges with high ADT patterns exhibit faster deterioration rates. This was expected since heavily travelled bridges are deiced more frequently. Figure 7.6 demonstrates that the mean condition of decks on bridges with high ADT will reach condition 5 in about 50 years. On the other hand, bridge decks with medium or low ADT will reach the same condition after 52 and 56 years of service, respectively.

The effect of the ADT on the performance of steel girder and concrete slab bridges was also investigated. These effects are summarized in Figs. 7.9 through 7.14. Notice that only low ADT (less than 1700 vehicles/day) and high ADT (more than 1700 vehicles/day) were used. The data

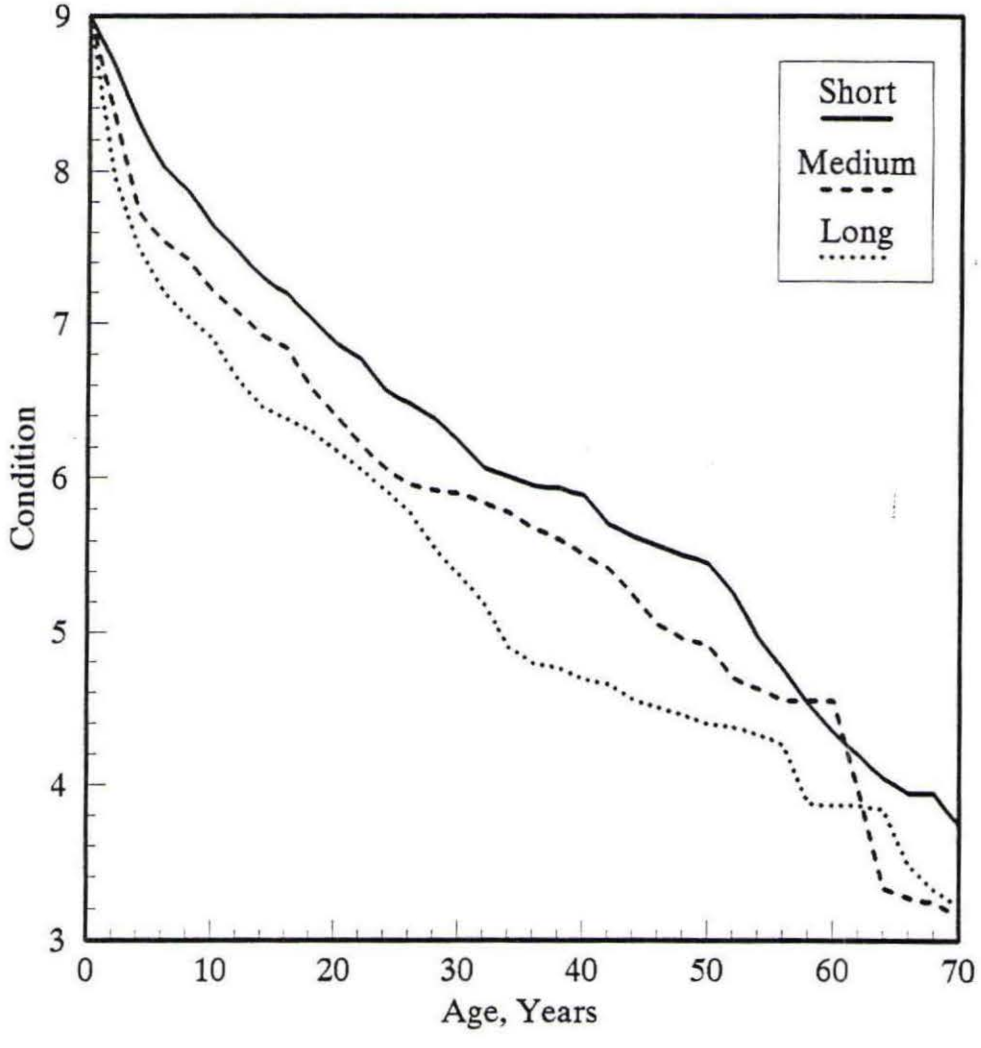


Figure 7.3. Deck condition for different bridge lengths

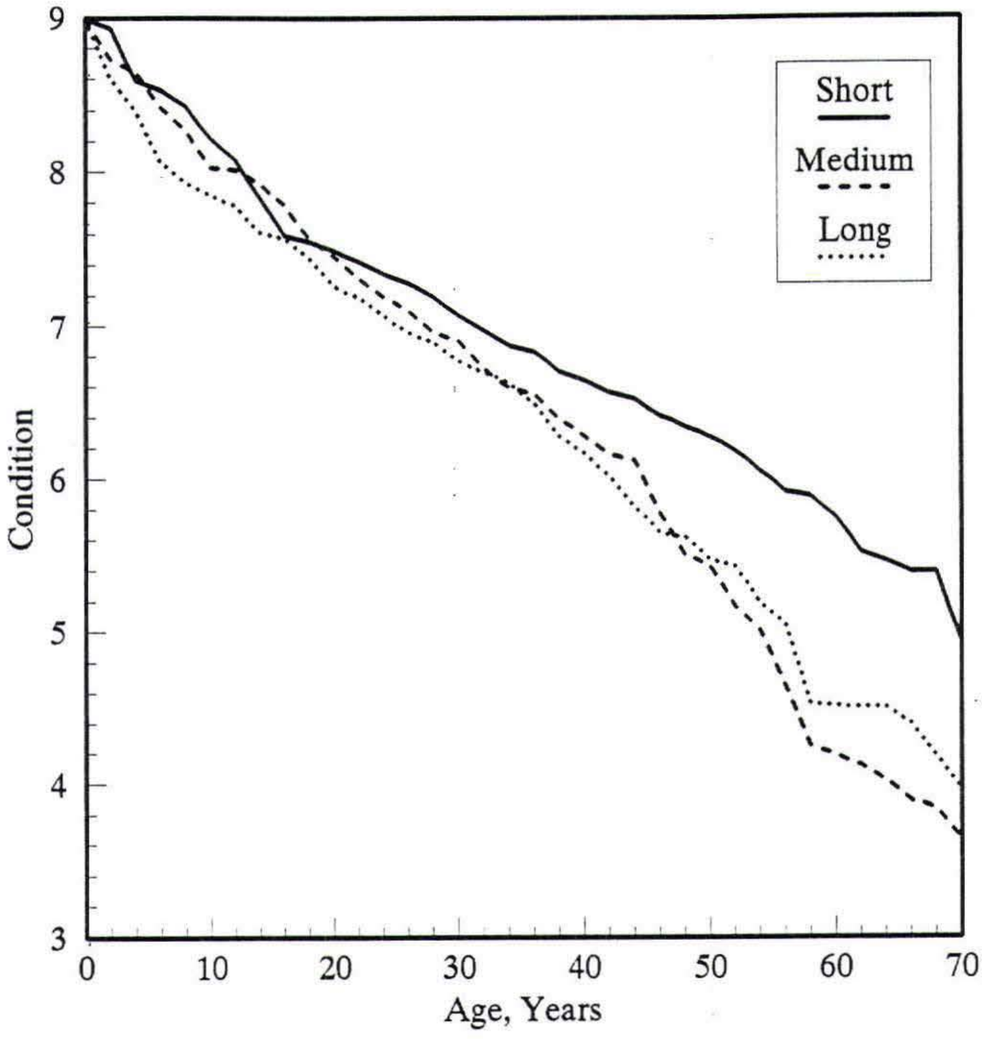


Figure 7.4. Superstructure condition for different bridge lengths

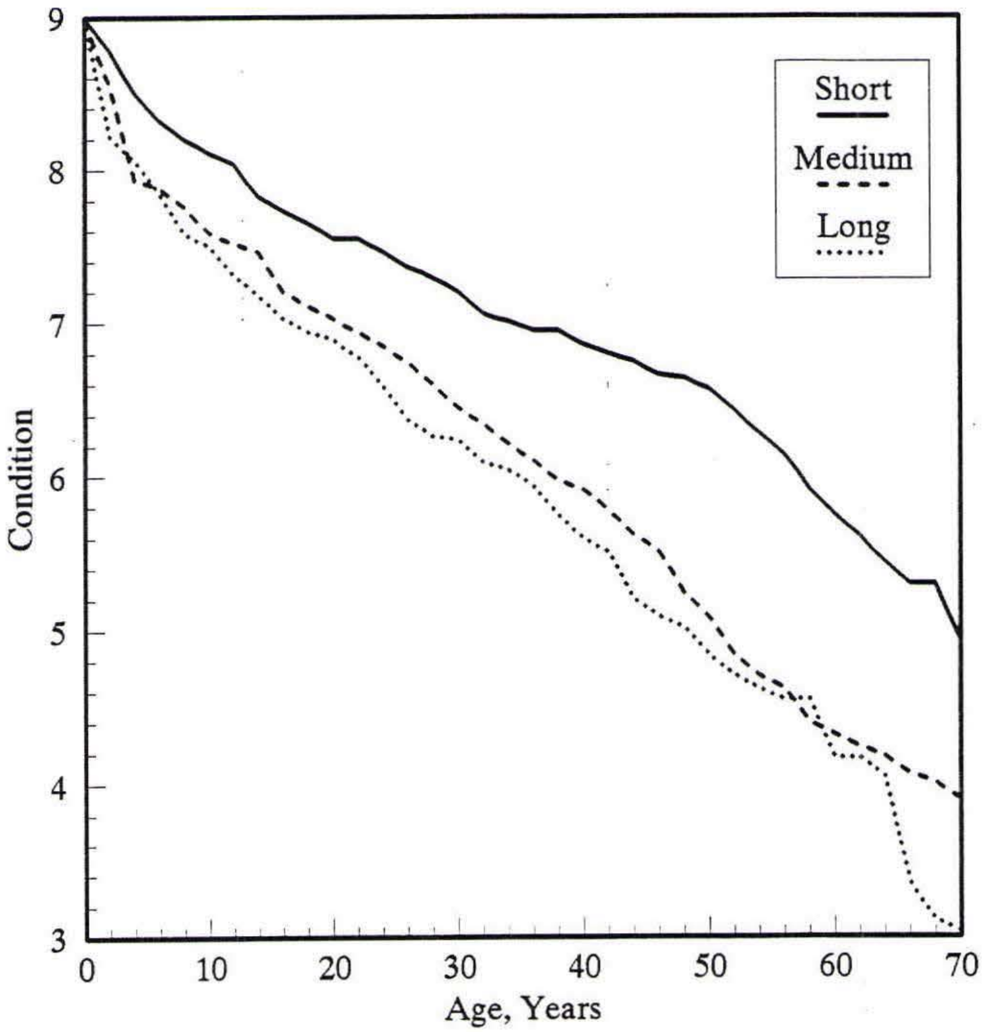


Figure 7.5. Substructure condition for different bridge lengths

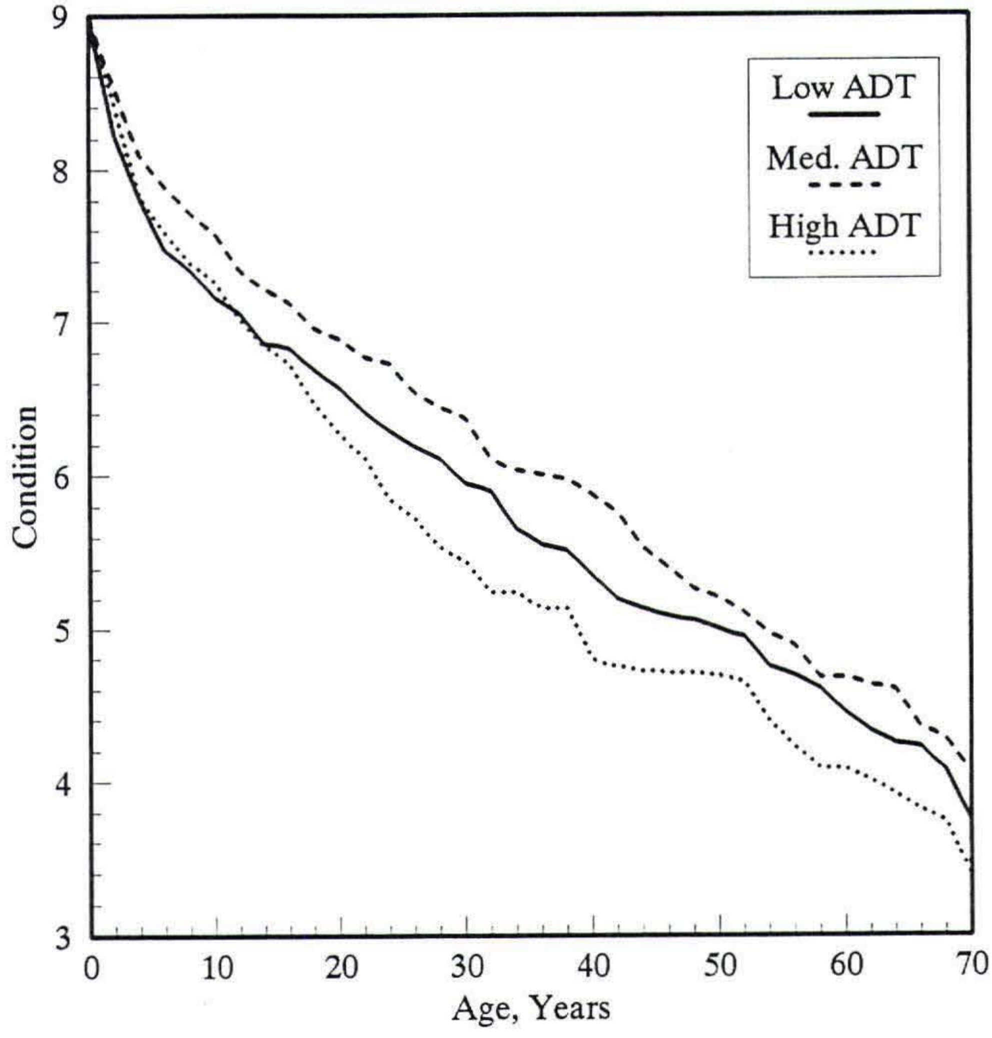


Figure 7.6. Deck conditions for different average daily traffic--all bridges

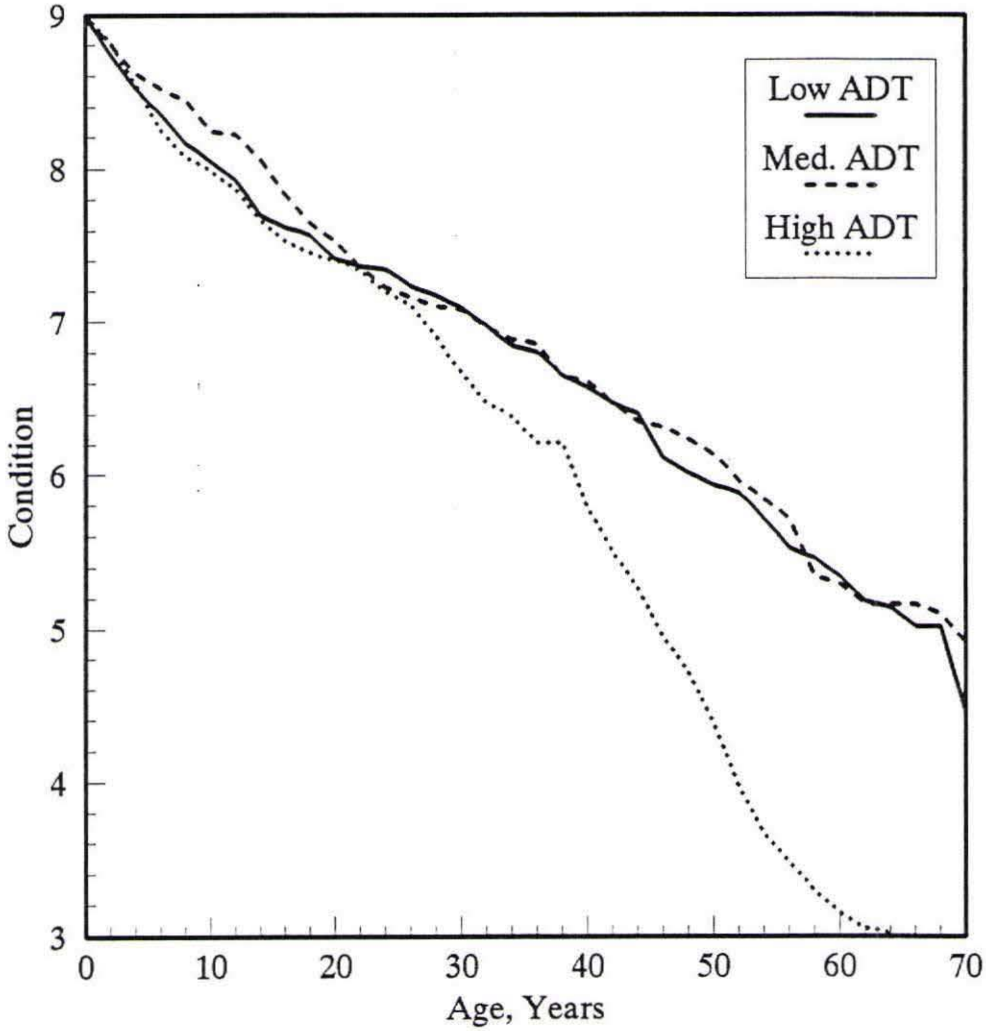


Figure 7.7. Superstructure condition for different average daily traffic--all bridges

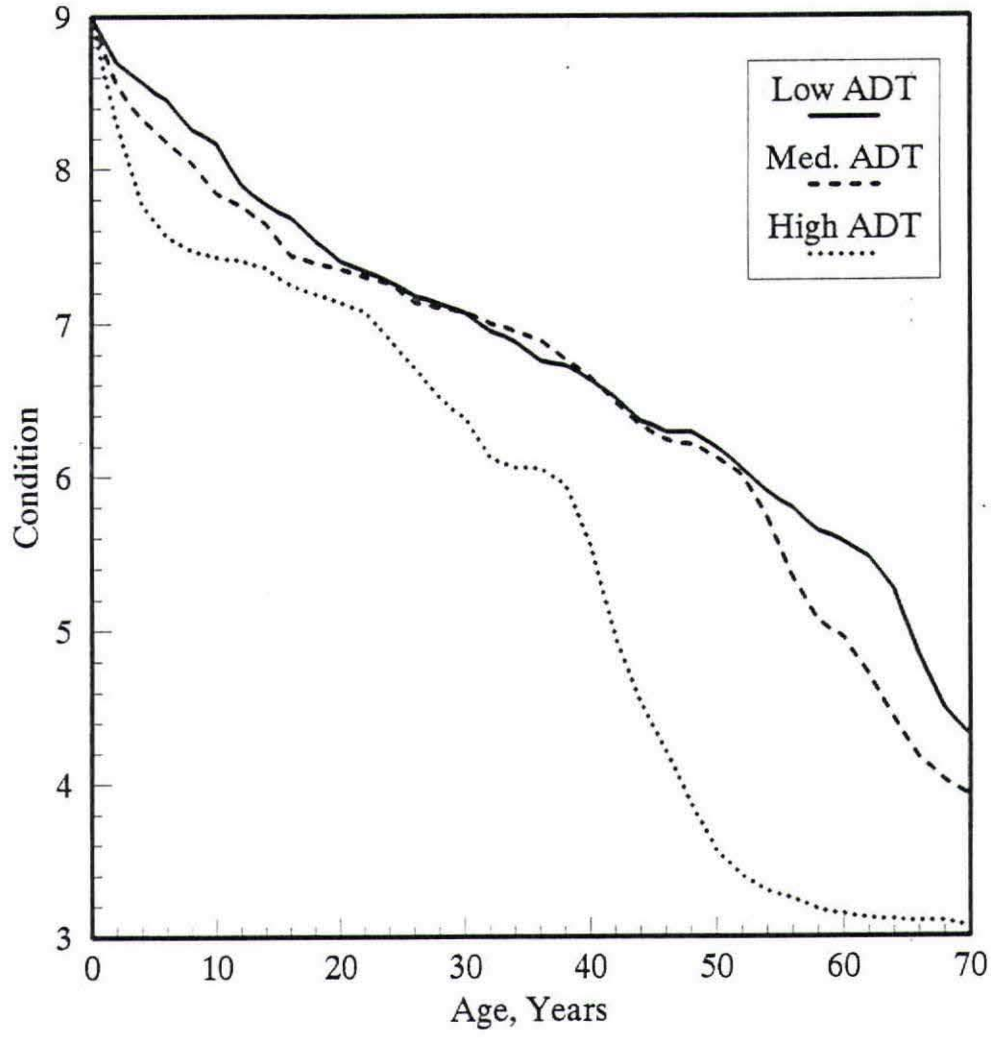


Figure 7.8. Substructure condition for different average daily traffic--all bridges

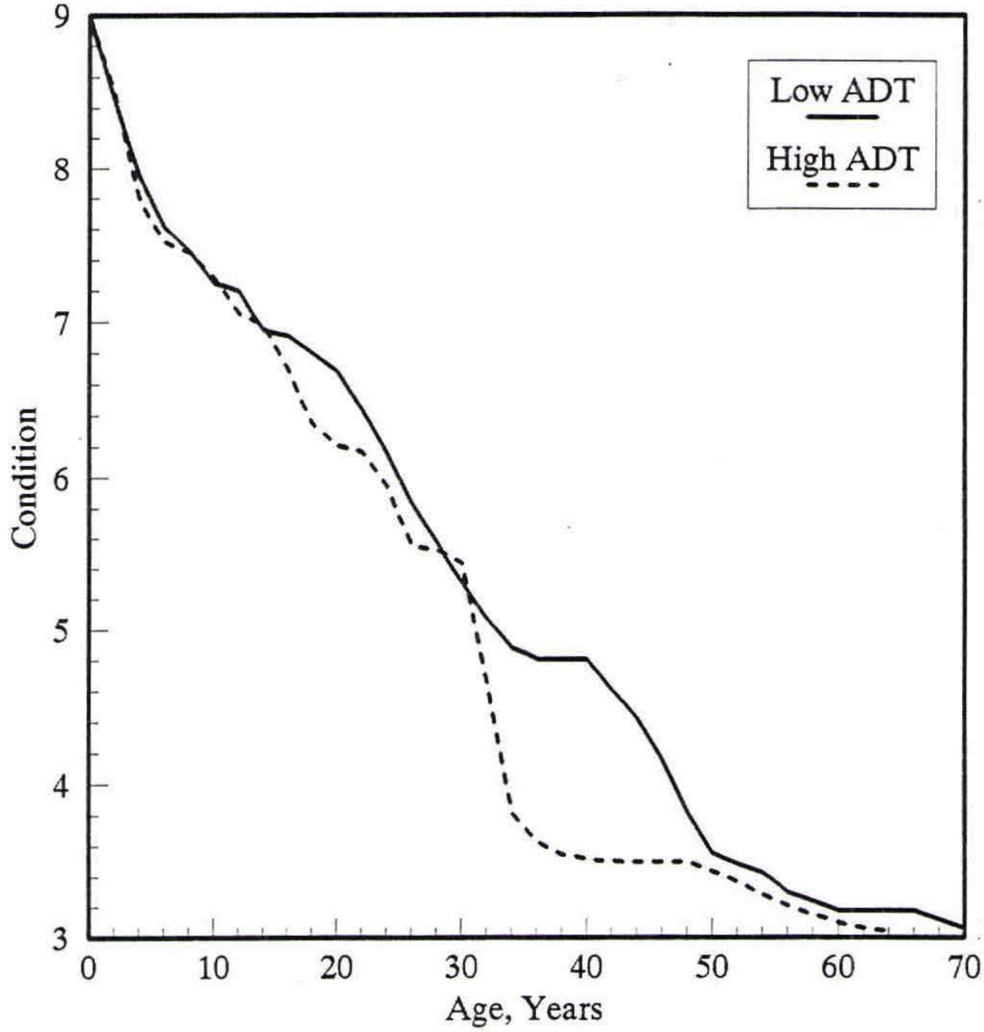


Figure 7.9. Deck condition for concrete slab bridges and different average daily traffic

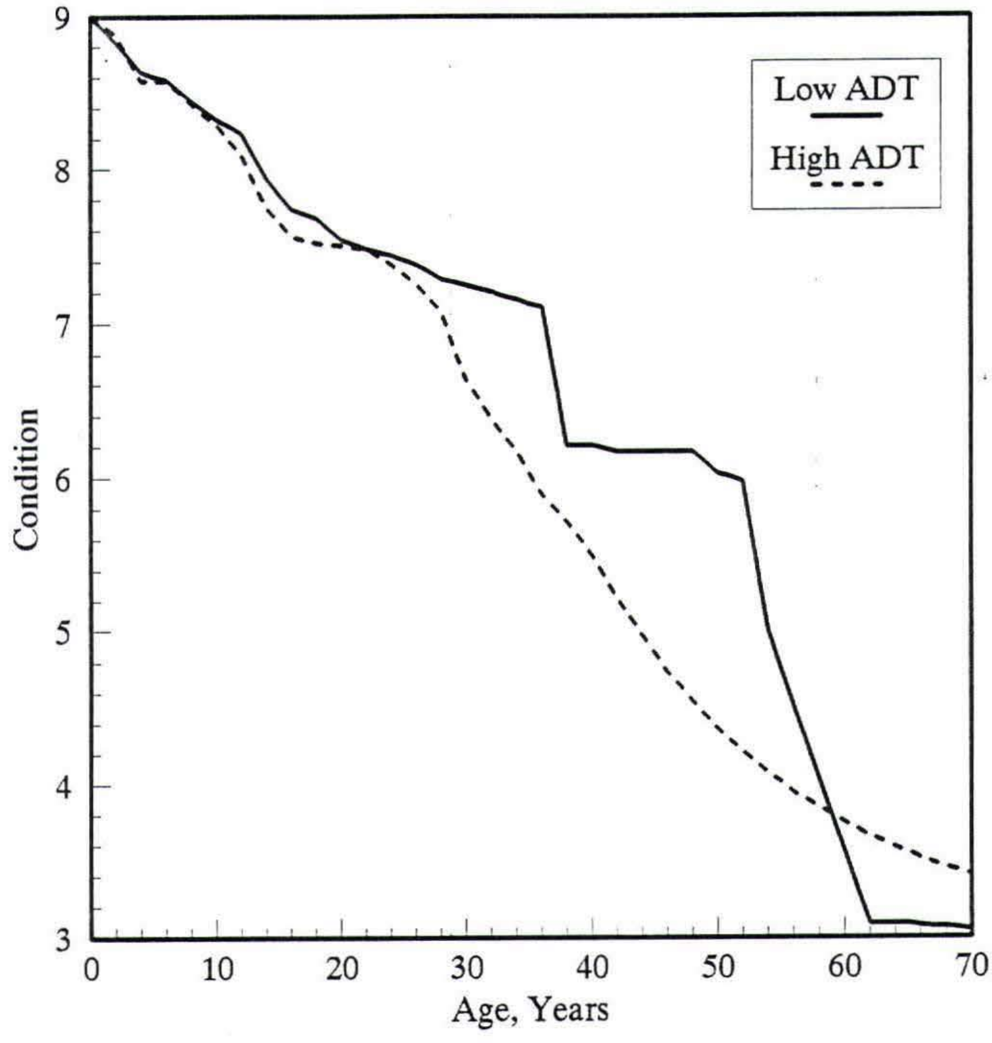


Figure 7.10. Superstructure condition for concrete slab bridges and different average daily traffic

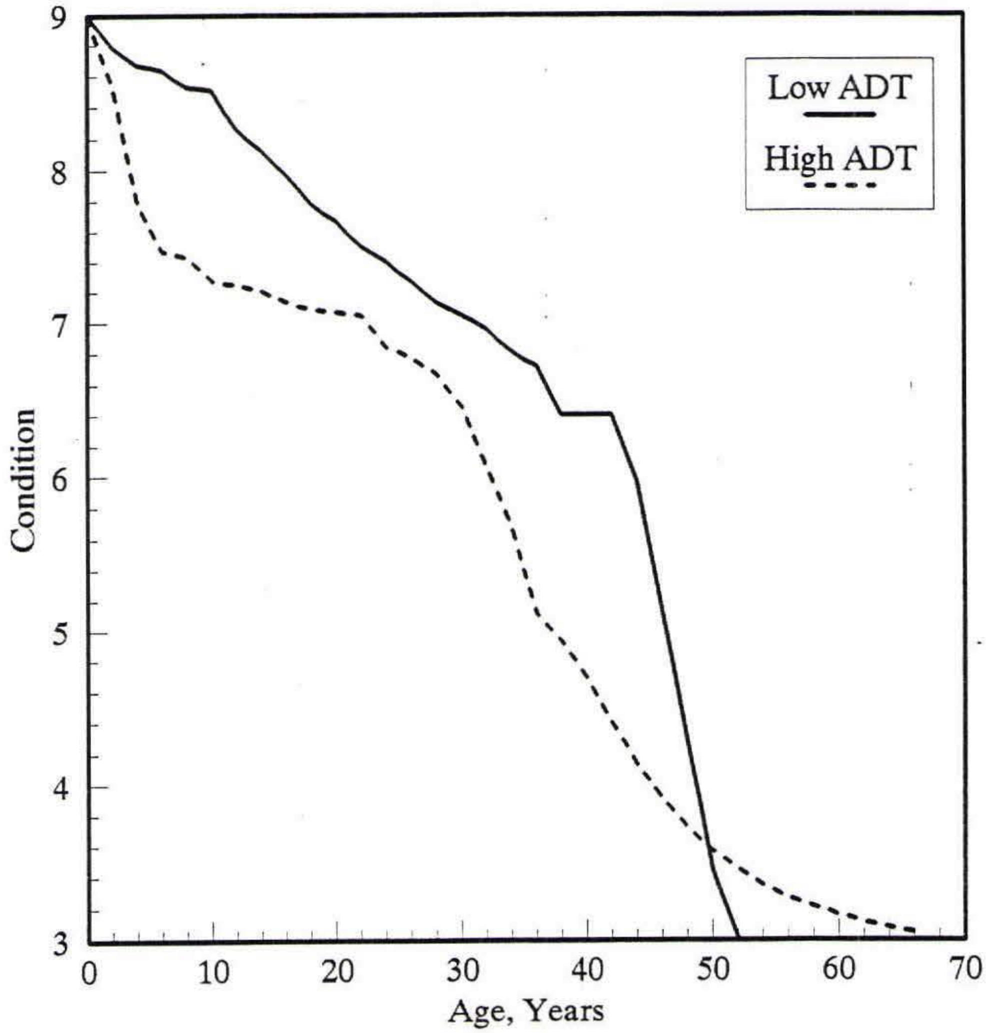


Figure 7.11. Substructure condition for concrete slab bridges and different average daily traffic

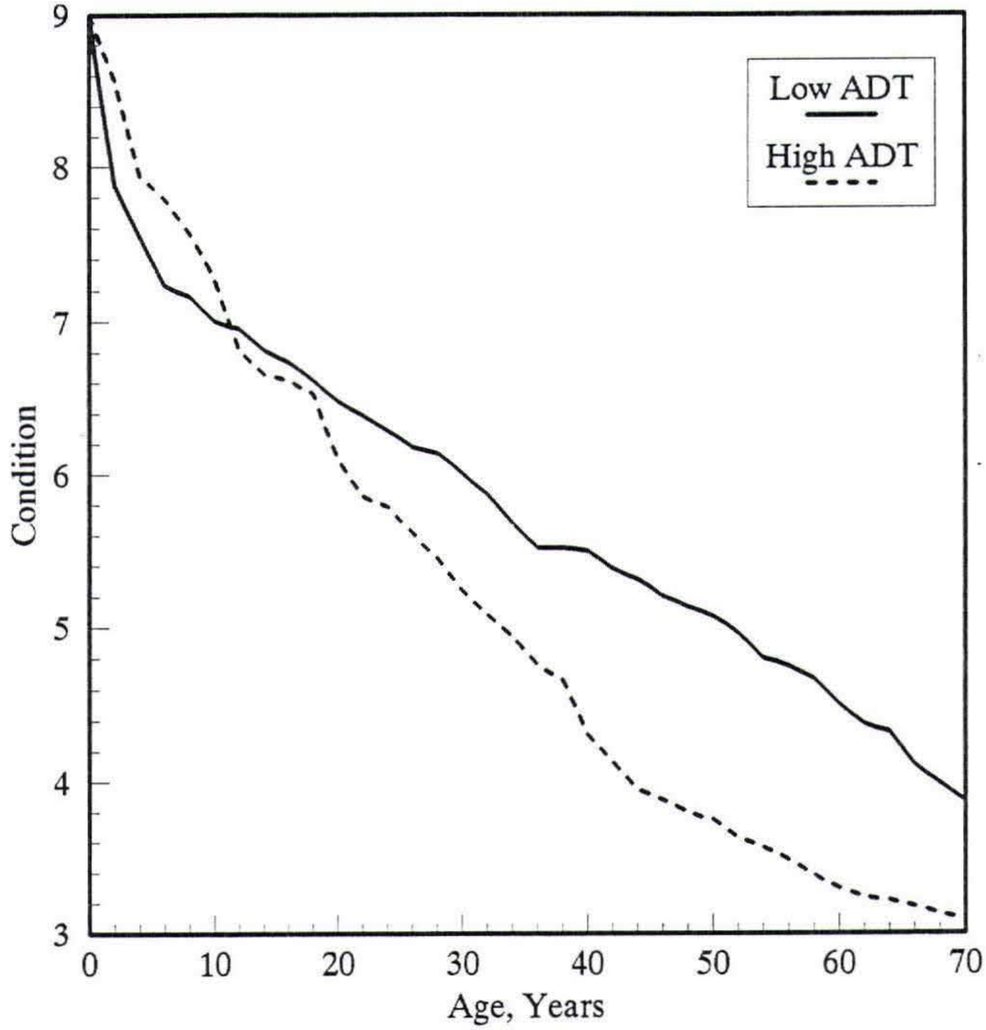


Figure 7.12. Deck condition for steel bridges and different average daily traffic

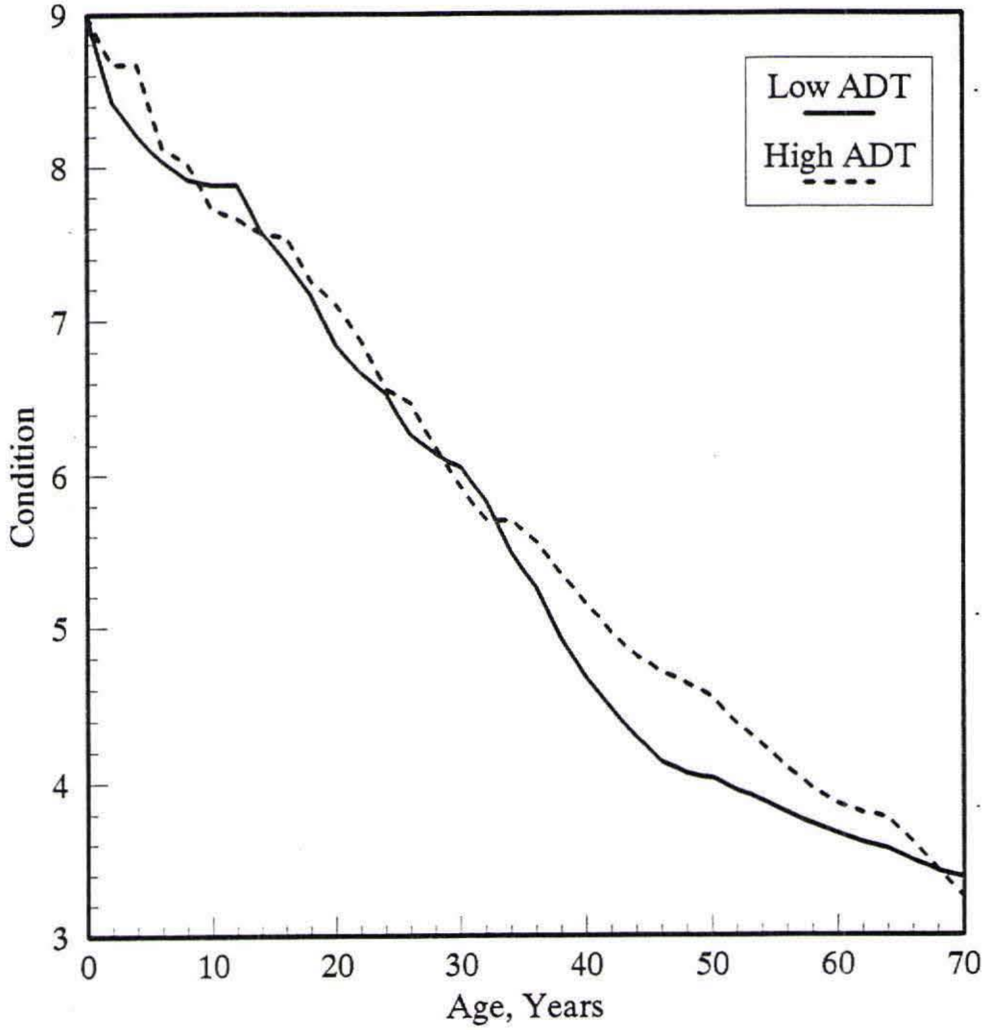


Figure 7.13. Superstructure condition for steel bridges and different average daily traffic

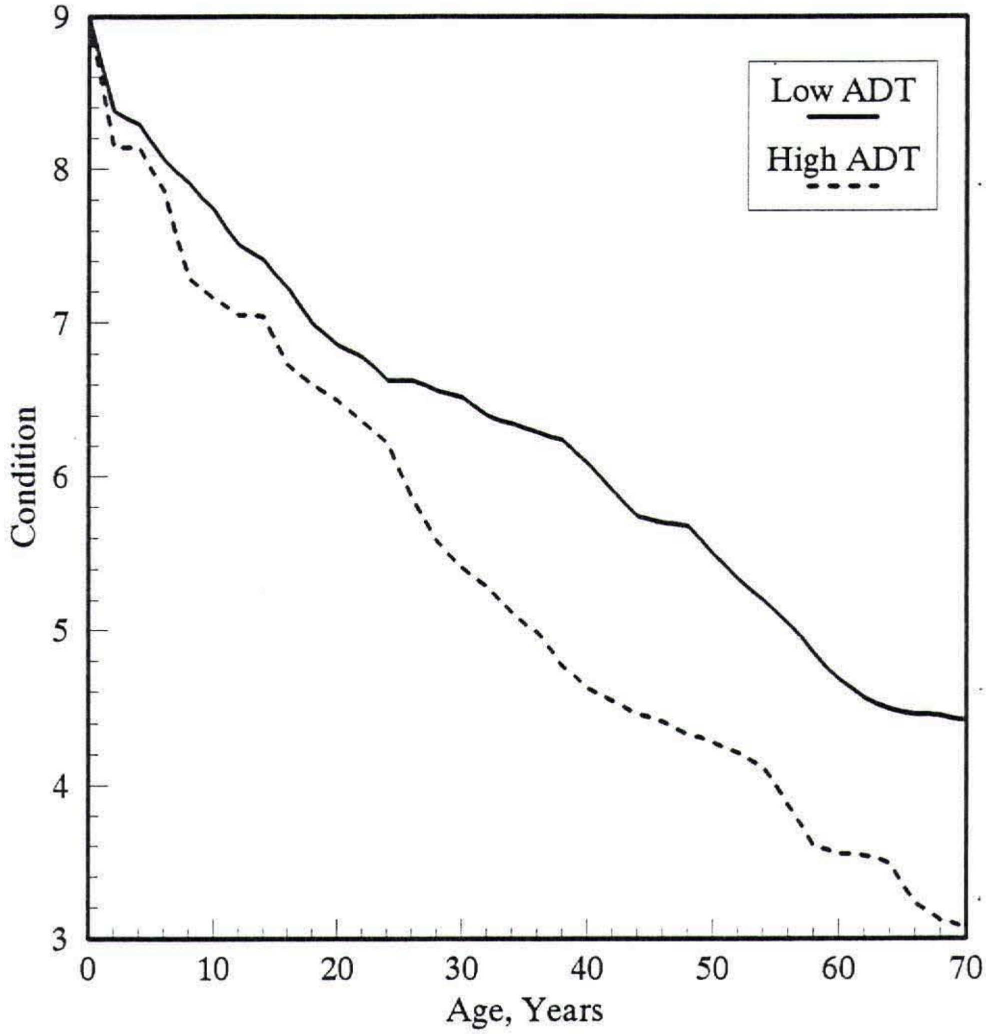


Figure 7.14. Substructure condition for steel bridges and different average daily traffic

available for medium ADT on these two types of bridges were insufficient to construct a reliable deterioration curve. In addition, no deterioration curves for different ADT patterns or prestressed concrete bridges are given, again because adequate inspection data for this type of bridge were unavailable.

These figures illustrated that the highly traveled concrete bridges exhibit faster deterioration rates. The salt used for frequent deicing of these bridges may have contributed to the faster deterioration rates. Similar behavior for steel bridges was noticed (see Figs. 7.12, 7.13, and 7.14).

7.4.3. Effect of Geographic Location

Figures 7.15, 7.16, and 7.17 show the deterioration curves that compare the performance of bridge decks, bridge superstructures, and bridge substructures in each of the four South Dakota geographical regions. The plots demonstrate that the decks in Region 1 exhibit slower deterioration rates than in the other three regions. However, this was not true when comparing the performance of the superstructures and substructures. In this case, bridges in Region 3 showed slower deterioration rates than those in Regions 2 and 4.

Discussion of these differences with the project technical panel identified the following factors that could cause the different deterioration rates among the four regions: 1) The weather in Region 1 is colder than in the other regions, so bridges there do not go through as many freeze- thaw cycles; 2) Region 2 uses the most deicing chemicals because of its high population density, and this region experiences more freeze-thaw cycles. Areas of Region 4 also use a large amount of deicing chemicals; 3) Areas of Region 3 have highly expansive soils and high alkali content runoff. Region 4 also has areas of high alkali content runoff; 4) The bridges in Region 4 are built using a high-quality aggregates. A specification change approximately 8 to 10 years ago requires that all course

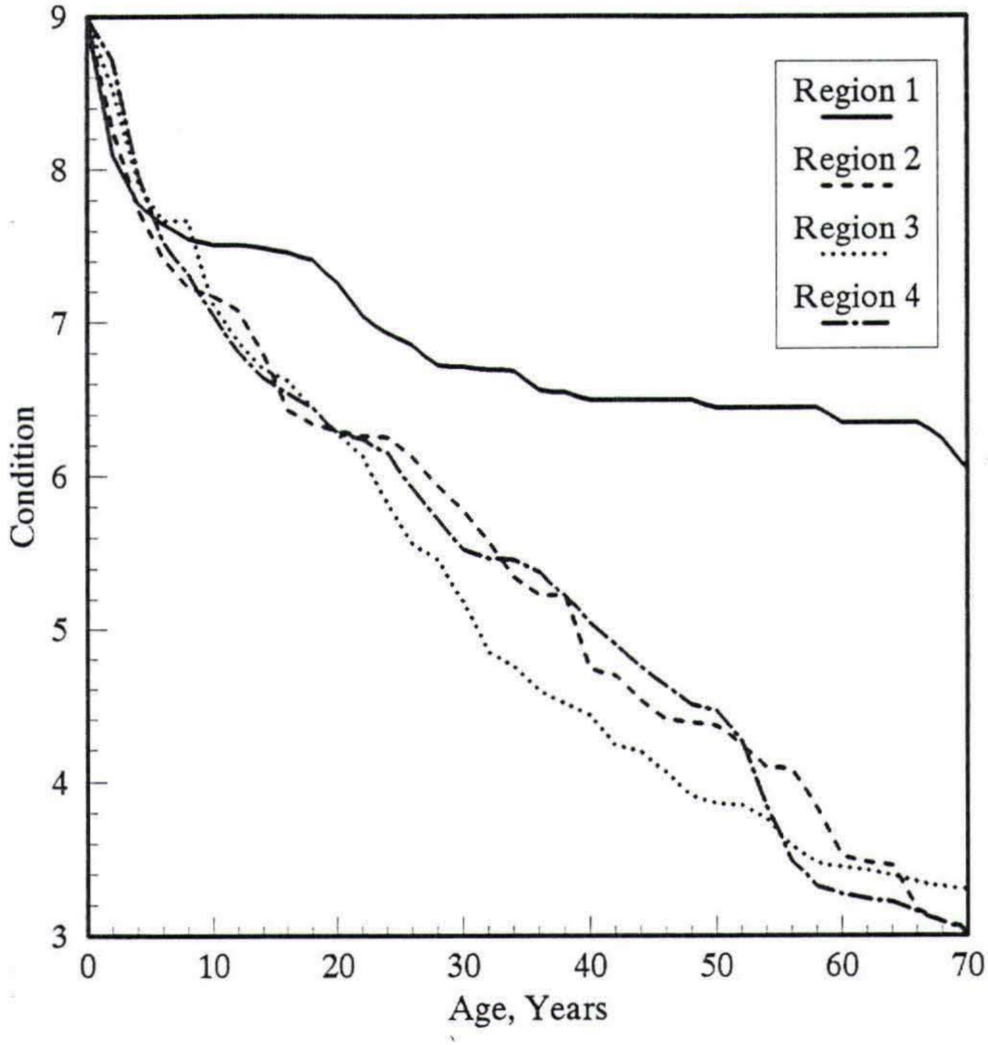


Figure 7.15. Deck condition for the four South Dakota geographical regions

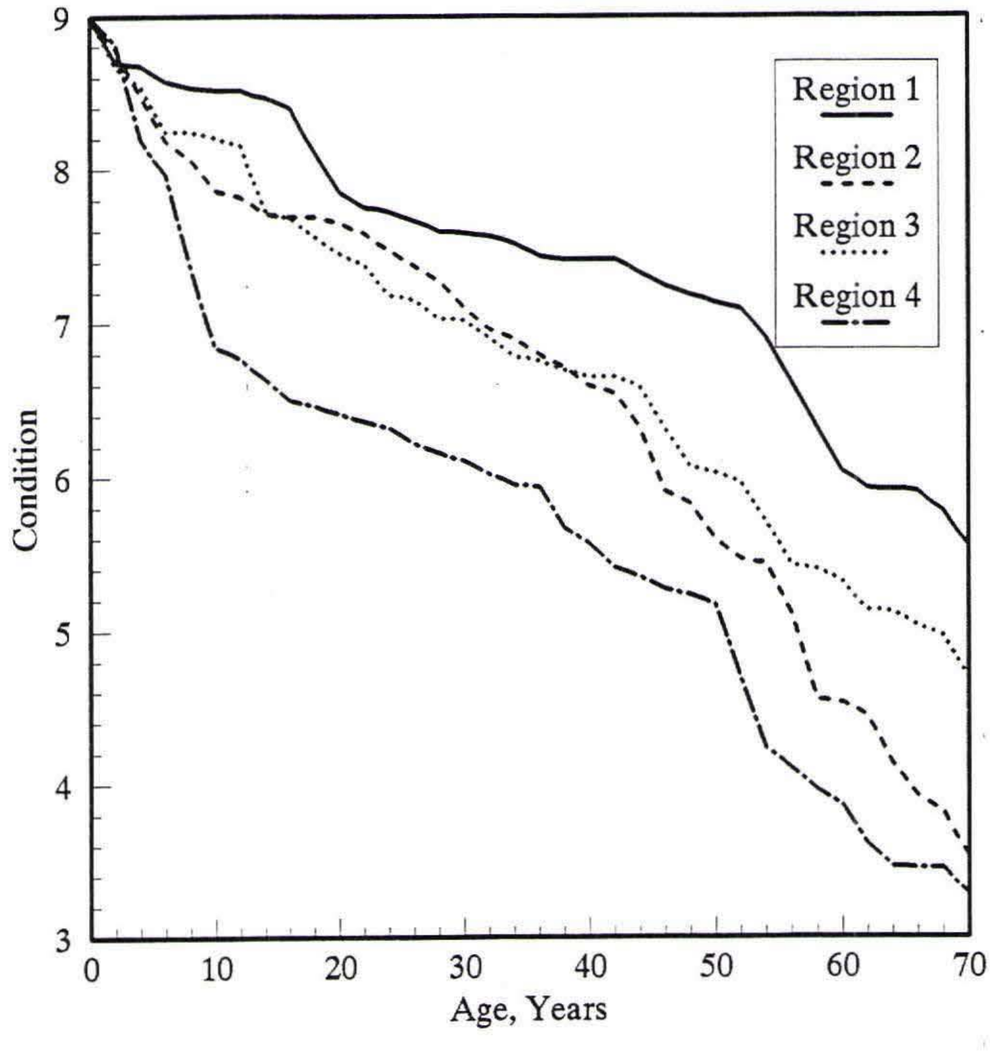


Figure 7.16. Superstructure condition for the four South Dakota geographical regions

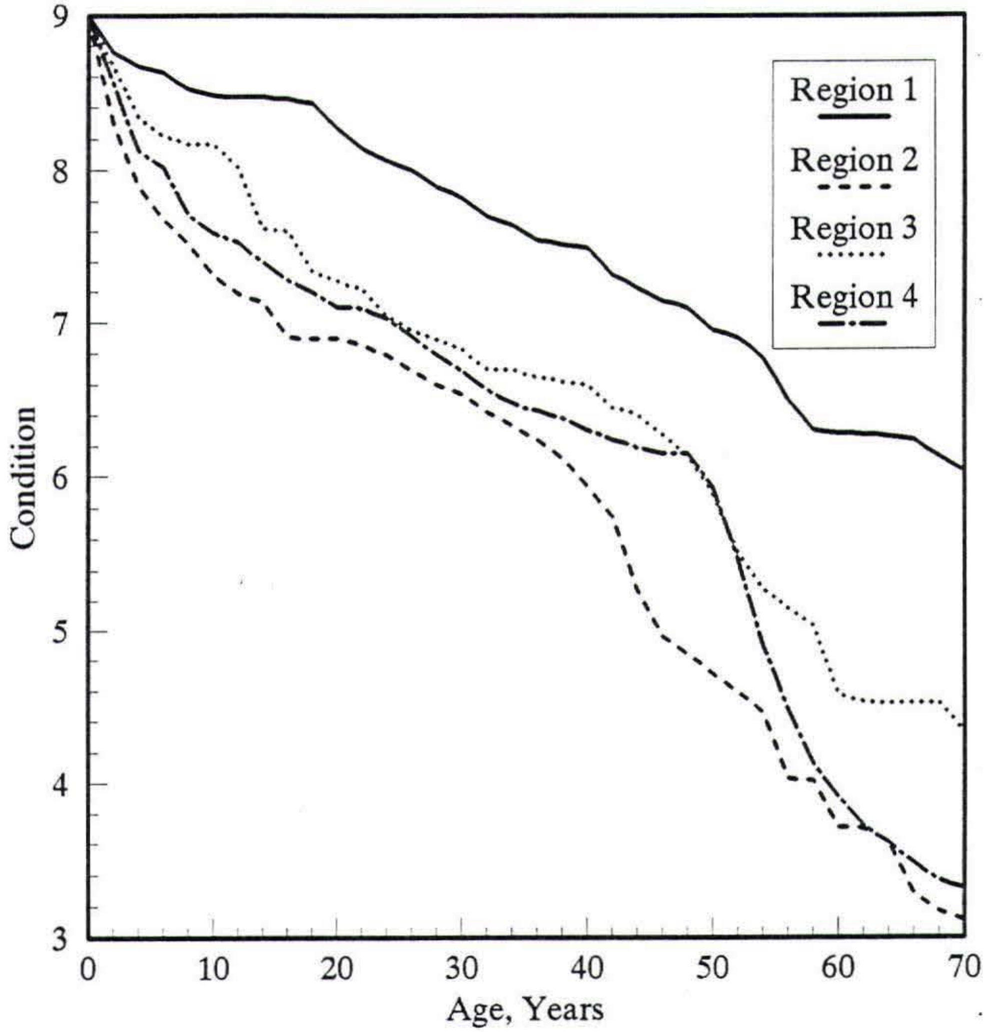


Figure 7.17. Substructure condition for the four South Dakota geographical regions

aggregate be derived from crushed ledge rock; 5) Region 1 contains some of the newest interstate and therefore use of the latest design improvements. Regions 2 and 4 contain some of the first interstates built in the state; 6) Region 2 has the highest population density and ADT over the entire region. Region 4 has areas of high and very low population densities. Overall, Region 1 has the second highest population density and Region 3 has the lowest population density.

In summary, the climatic conditions, ADT, use of deicing chemicals, and soil types were the major factors that could affect the deterioration rates.

7.4.4. Effect of Bridge Type

Figures 7.18, 7.19, and 7.20 show the relation of condition ratings to age for concrete slab, steel girder, and prestressed girder bridges. Because the first prestressed concrete bridge in the state of South Dakota was built in 1959, careful interpretation of the deterioration rates for this type of bridge beyond 30 years of age must be exercised. Remember that the approximate deterioration model explained in the previous chapter takes over the Markov Chain whenever inspection data become unavailable, and the prediction condition depends on the user's specified deterioration rates (see Section 6.4).

Figure 7.19 shows that over 24 years, the concrete decks on steel girder bridges deteriorate at faster rates than those on concrete slab or prestressed girder bridges. Similar behavior can also be noticed when examining the deterioration rates of the substructure in concrete slab, prestressed, and steel girder bridges.

The better performance of the concrete slab bridges can be related to the span length used in conjunction with this type of bridge. The shorter the span, the less the stress induced in the structure elements, and lower stress reduces the possibilities of crack formation that may yield faster deterioration rates. On the other hand, steel girders are used in longer span bridges and hence there

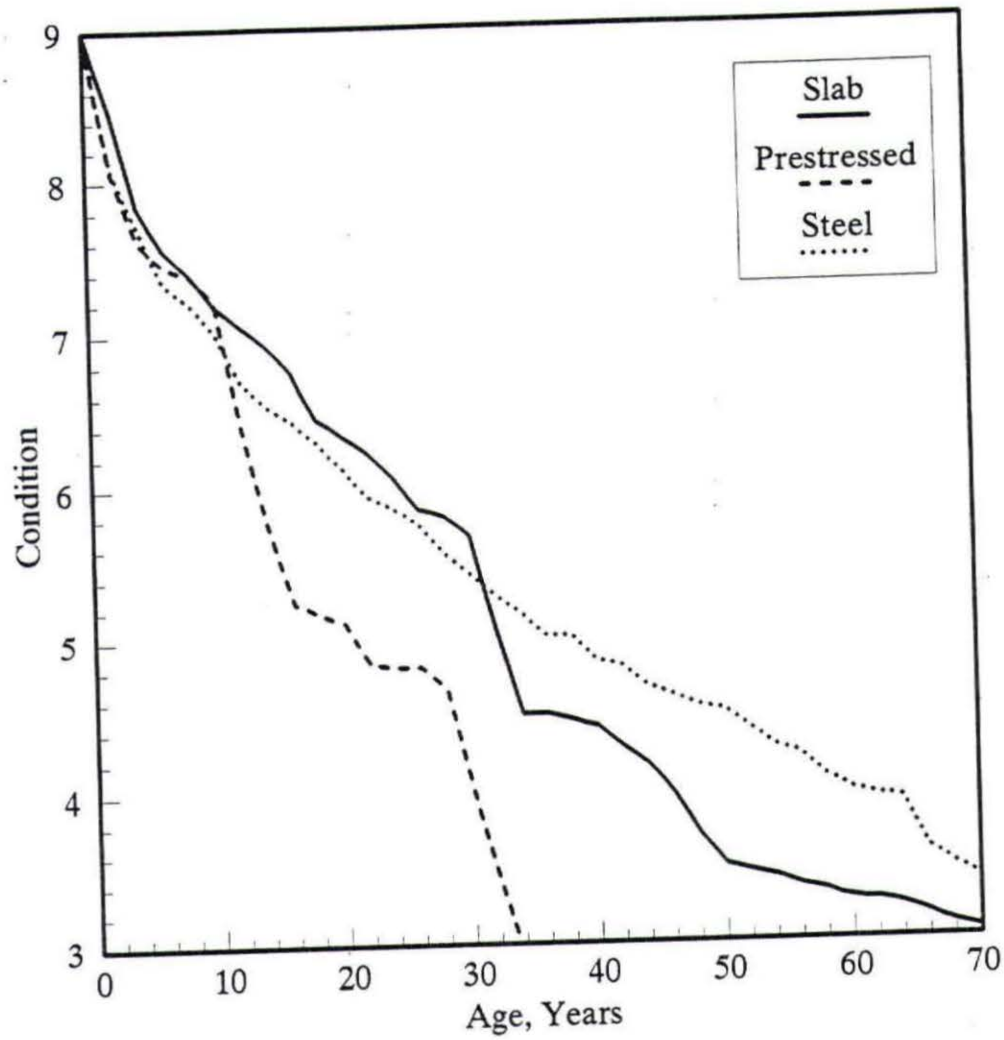


Figure 7.18. Deck condition for different structure types

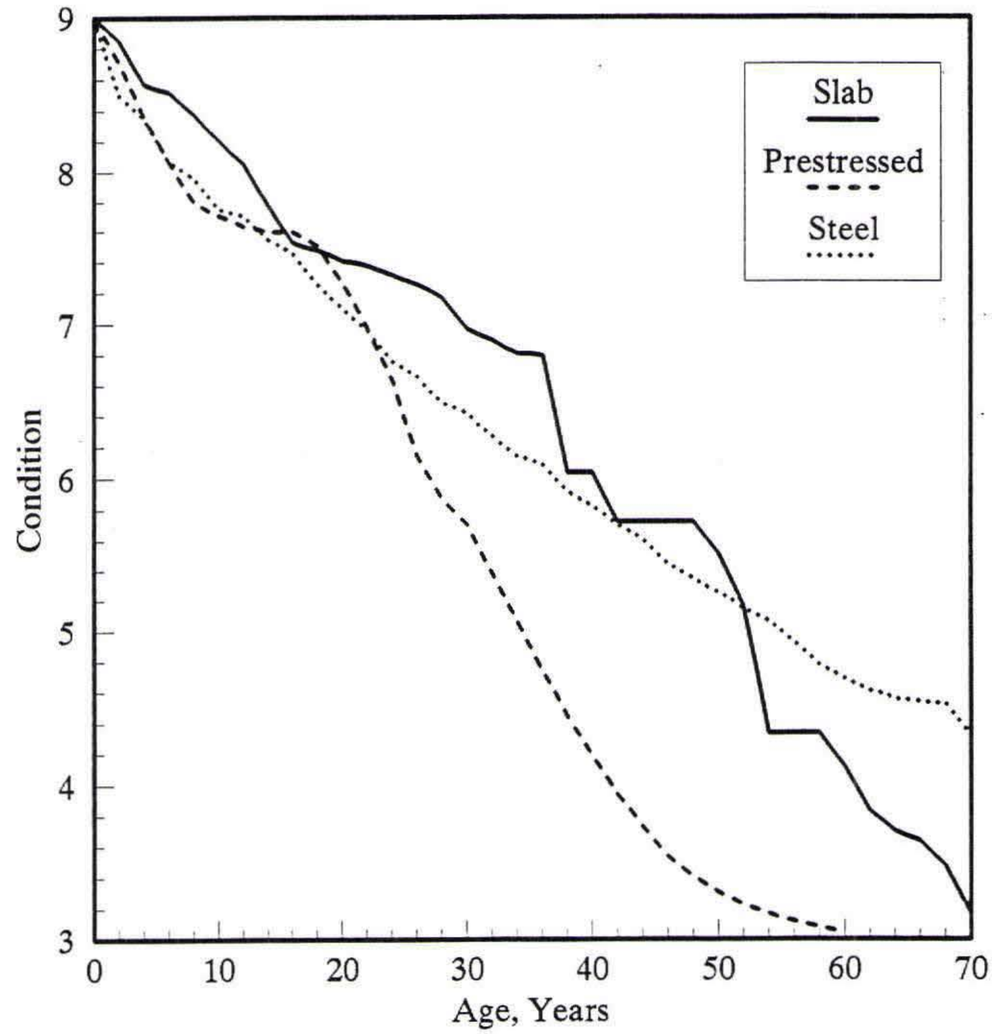


Figure 7.19. Superstructure for different structure types

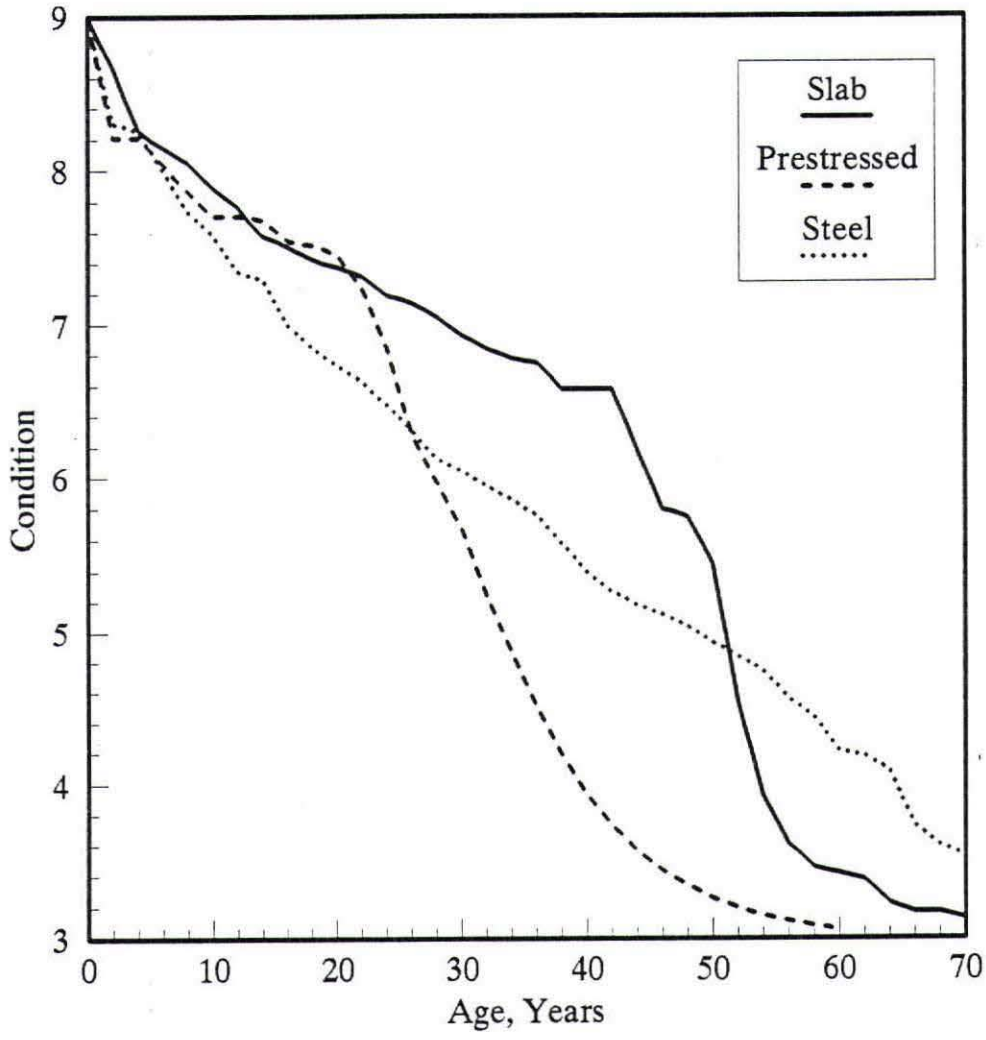


Figure 7.20. Substructure condition for different structure types

will be a tendency for more deflection and high stresses that may increase crack formation and crack propagation and thus result in faster deterioration rates. In long span bridges, the additional expansion joints required along the bridge deck may result in leakage of deicing salt to the bridge superstructure and substructure which may also expedite the deterioration rates of these two components unless continuous maintenance is performed.

7.4.5. Effect of Bridge Degree of Skewness

Deterioration rates for bridges with different degree of skewness are shown in Figs. 7.21 through 7.23. These figures compare the performance of bridge decks, bridge substructure and bridge superstructure for bridges with degree of skewness less than 15°, between 15° and 30° and larger than 30°. Examining these figures demonstrates that up to the age of 20 years, there is an insignificant difference in the deteriorate rates due to the difference in the degree of skewness. In addition, up to 50 years of age, no significant difference in the deterioration rates for bridges with degree of skewness up to 30° was noticed. On the other hand, Figs. 7.21, 7.22 and 7.23 illustrated that the rate of deterioration is faster for bridges with degree of skewness larger than 30°. The number of bridges used in this study with degree of skewness larger than 30° is 113 bridges. Apparently, these bridges were constructed within the past twenty or thirty years and hence there is not enough historical data to construct a reliable condition rating--age relationship for these bridges. This is noticeable in Figs. 7.21 through 7.23 where the approximate model (see Sec. 6.4) was used instead of the Markov chain method to continue constructing the deterioration curves for bridges with degree of skewness larger than 30°. It is important to mention here that the default deterioration rate (see Sec. 6.4) was used in conjunction with the approximate model to continue constructing these curves when inspection data becomes unavailable.

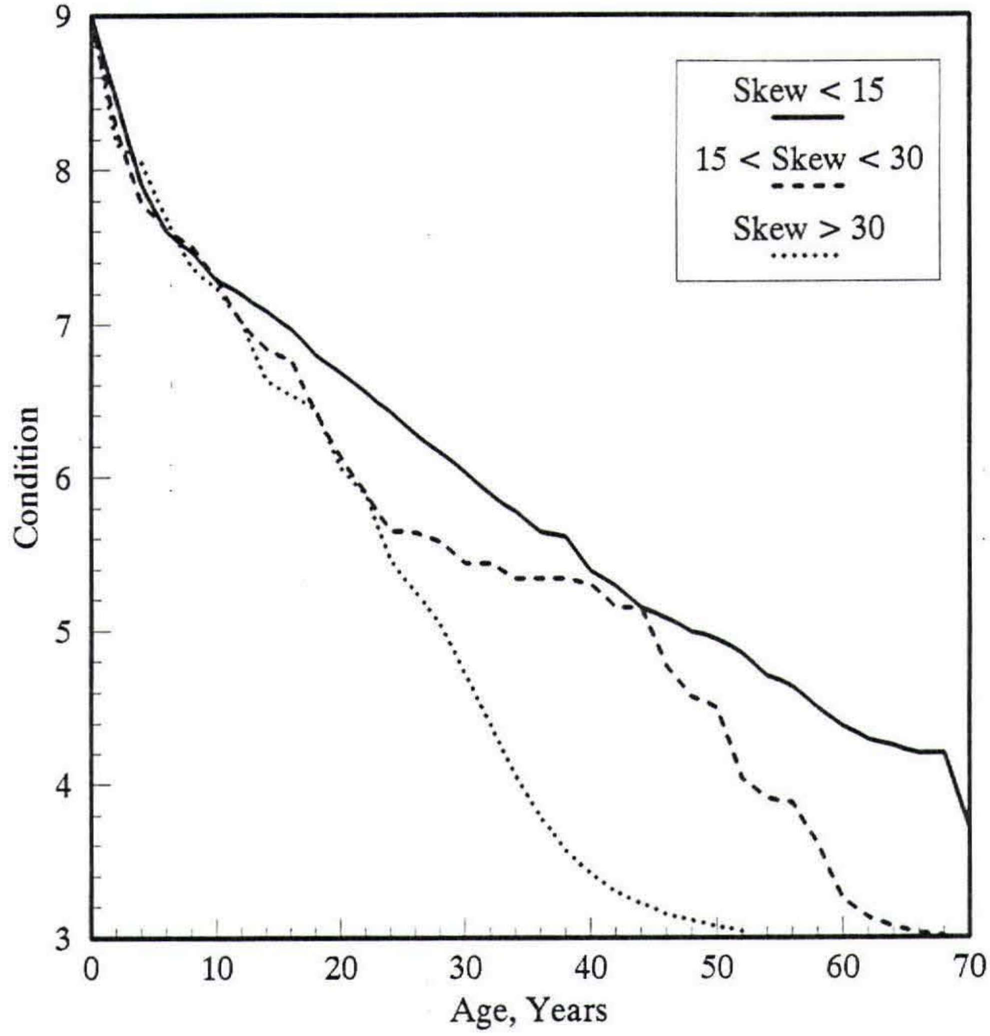


Figure 7.21. Deck condition for different skew angles-- all bridges

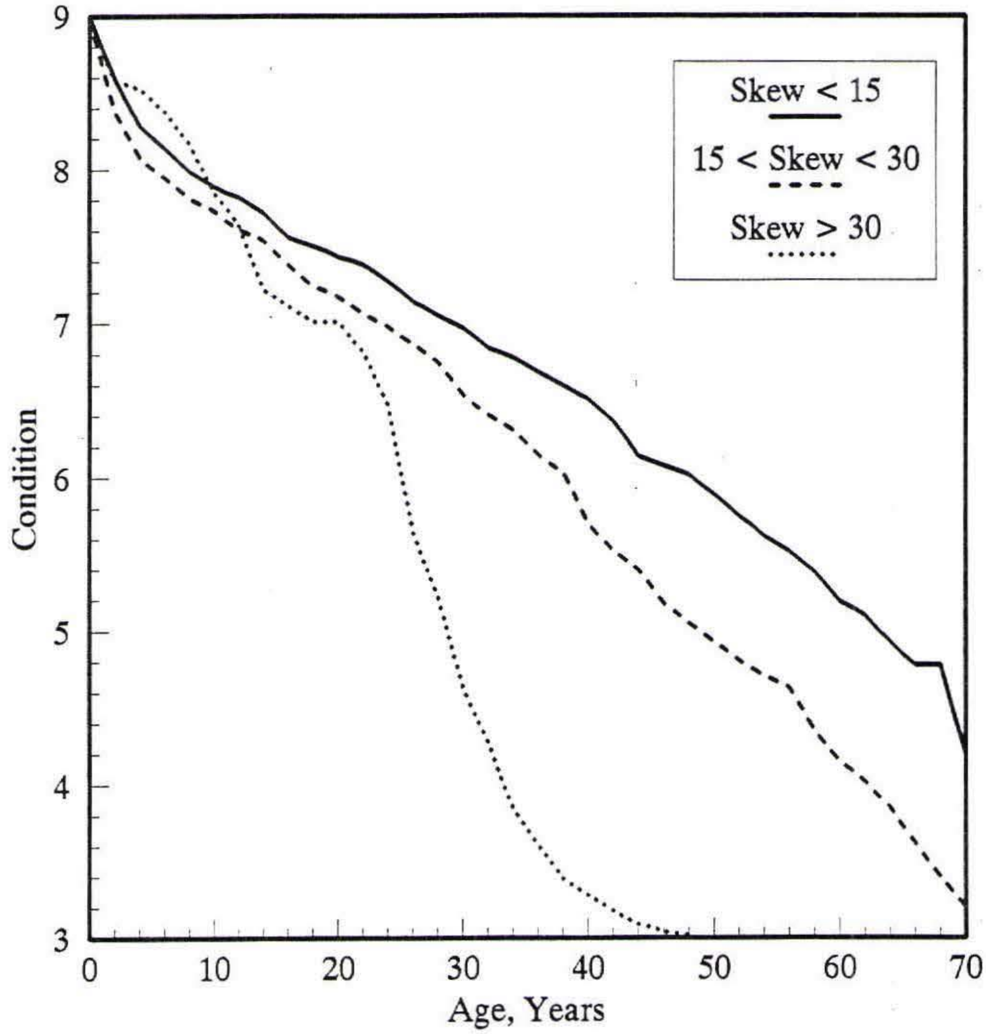


Figure 7.22. Superstructure condition for different skew angles-- all bridges

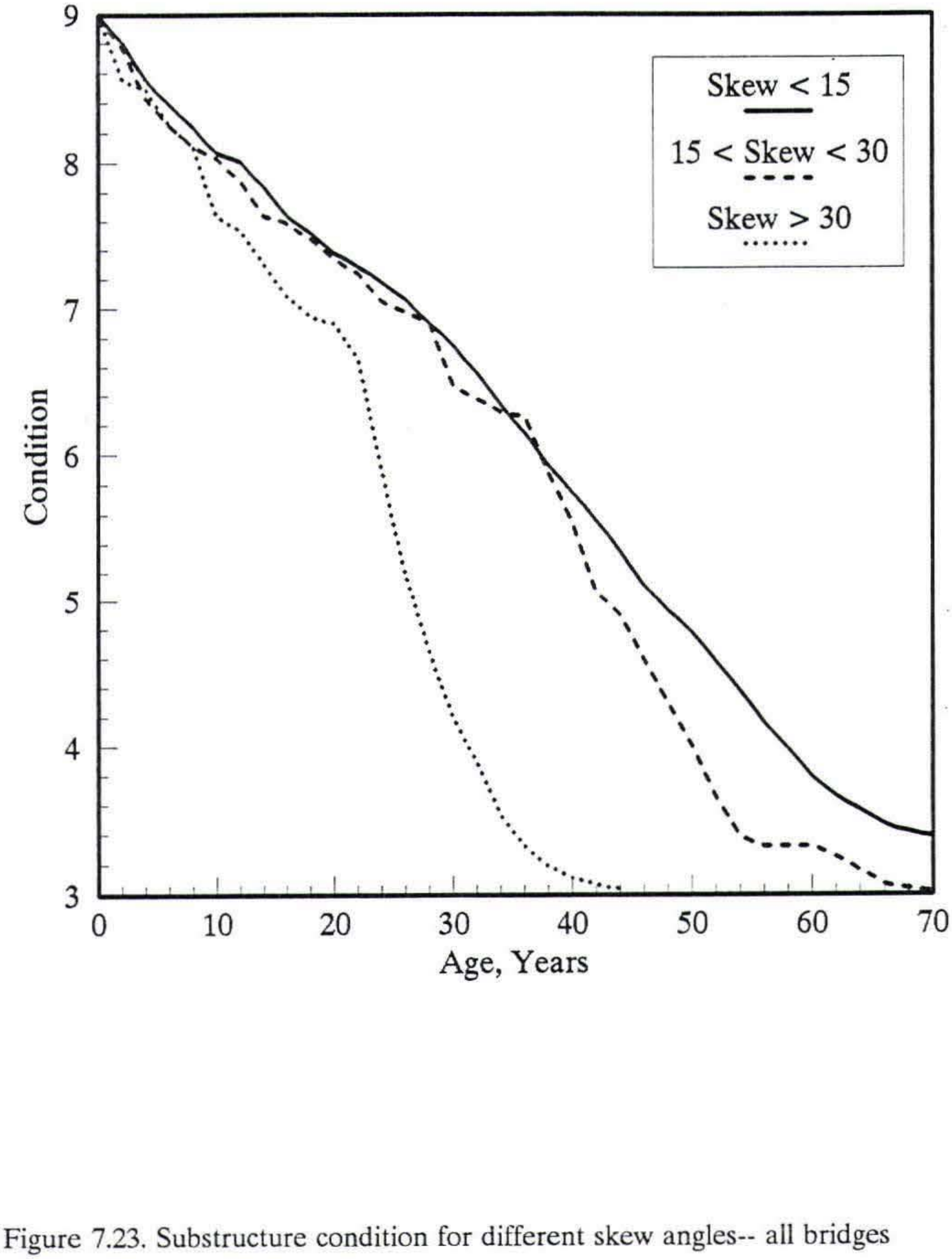


Figure 7.23. Substructure condition for different skew angles-- all bridges

In summary, the degree of skewness may accelerate the deterioration rates of a bridge deck, bridge substructure and bridge superstructure. This could be confirmed when additional historical data becomes available to utilize the Markov chain procedure outlined in Chapter 6.

7.5. Actual Bridge Life vs. Bridge Design Life

As mentioned earlier in this report, the SDDOT expects a bridge life of 50 years [9]. The deterioration rates presented herein considering factors such as the ADT, geographic location, structure type and degree of skewness illustrated that such an assumption is applicable. In the authors opinion and based on the deterioration figures shown in Chapter 7 of this report, the 50 years of expected bridge life span is reasonable. However, one must realize that the effect of each of these factors was examined separately and the effect of combining more factors on the deteriorate rates was not studied. This was not visible to investigate since combining more factors would reduce the number of bridges in the sample to be used in conjunction with the Markov chain method. In addition, factors such as life cycle cost, and maintenance, rehabilitation and replacement activities were not considered in the study presented herein. In addition, constraints imposed by federal regulations were not included in this work. These factors and bridge conditions are the vital elements that a BMS must be considered. The Pontis BMS was developed to account for most if not all of these factors. This reinforces the recommendation proposed by the authors (see Sec. 8.3) to use the Pontis program by the SDDOT.

8. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

8.1. Summary

Collectively, the operative efficiency of a ground transportation system depends upon the structural performance and the condition of the bridges connecting the highway system together. Recent statistics reported that approximately 41% of the bridges in the United States are deficient The statistics also showed that there are 22% and 24% of the state of South Dakota bridges are functionally obsolete and structurally deficient, respectively. To prevent an increase in the number of deficient bridges, either bridge funds must be dramatically increased or present bridge management techniques must be improved.

The objectives of this report were to identify and quantify the factors that affect the life of South Dakota's bridges and to evaluate the rehabilitation procedures presently used by the SDDOT. Furthermore, this work was intended to aid in the implementation of the Pontis bridge management system software developed under the sponsorship of the FHWA and CALTRAN.

An extensive literature review included most current and previous related efforts by other states. Elements essential to bridge management or priority ranking systems used by other states were identified, but these are state specific and may vary depending on geographic location, economic climate, and specific needs. A brief summary regarding the capabilities of and the information required to utilize the Pontis BMS was given.

Level-of-service goals for the state of South Dakota were identified to describe the performance of existing bridges and to establish design goals for new bridges. Goals for load capacity, vertical clearance, and clear deck width for the state of South Dakota were also established taking into account the roadway functional classification and the average daily traffic volume.

A questionnaire to gather costs associated with maintenance, repair, and replacement was prepared and submitted to the SDDOT for response (see Appendix A). The collected information was tabulated in different sections of this report.

Costs that are incurred by roadway users because of various level-of-service deficiencies were also collected from the questionnaire (see Appendix A) that was submitted to the SDDOT. These costs are the result of detours around a bridge structure and increases in accident rates due to some level-of-service deficiencies. The users costs identified for the SDDOT are those defined in the Pontis BMS; they included vehicle operating costs, ADT growth rates, accident costs and accident rates.

The Markov Chain statistical method was used to estimate deterioration rates for bridge deck, superstructure, and substructure. South Dakota bridge inspection data were used to set up the transition matrices that are essential to utilize this statistical technique. Transition matrices were developed for every two years and inspection intervals; and approximate transition matrices, whenever data were insufficient, were established utilizing either extrapolation or interpolation techniques. To continue the development of the deterioration rates when no data were available, an approximate method was also employed. Two computer programs were developed to accomplish this purpose and the procedures to execute these programs are given in Sections 7.2.2 and 7.2.3 of this report. The first program calculates the transition matrices that are used as input for the second program to predict bridge components rating conditions and the probabilities that a component will reach these ratings.

8.2. Conclusions

Conclusions reached from this study can be summarized as follows:

1. South Dakota's present policy for bridge maintenance is adequate. The current policy follows all the guidelines outlined in the NBIS and the FHWA. However, this policy does not account for user costs.
2. Statistical analysis of the inspection data revealed the following mean condition values tabulated for the three bridge types. The tabulated numbers are rounded to the nearest integer value.

Component	Bridge Type		
	Concrete slab	Steel	Prestressed
Deck	7	6	7
Superstructure	7	7	7
Substructure	7	6	7

3. The Markov Chain procedure in conjunction with available inspection data can be used to predict bridge performance. The only limitation with this approach occurs when insufficient data exist.
4. The Markov Chain approach is capable of predicting deterioration rates of bridge decks, superstructures, and substructures that are at a particular condition at a given time. This method also estimates the probabilities associated with this prediction (see sec. 6.3)
5. Bridges with high ADT exhibit faster deterioration rates than those with medium or low ADT.
6. Long span bridges tend to deteriorate faster than those with medium or short spans.
7. Bridges in region 1 exhibit slower deterioration rates than those in regions 2, 3, and 4.

8. Differences in the rate of deterioration of decks and substructures in Regions 2, 3, and 4 are insignificant. However, bridge superstructure in region 4 showed faster deterioration rates than in regions 2 and 3.
9. Level-of-service goals and agency and user costs developed herein provide the basis for implementing the Pontis bridge management system.

8.3. Recommendation

To comply with the regulation that will require all states to have implemented a BMS by september of 1996, the South Dakota DOT needs to select a comprehensive system that is capable of making the best use of available funds to maintain the bridges within the state. The authors of this report recommends the Pontis BMS for the use by the state of South Dakota to accomplish this purpose. To utilize this program, the following actions are needed:

1. The SDDOT needs to gather more information regarding MR&R and improvement costs. Notice that not all information related to the 160 bridge elements listed in Pontis is required; only the data pertaining to the elements of the SDDOT bridges is needed.
2. The SDDOT needs to train inspectors to use the new Pontis inspection procedure. Inquiries to states involved in testing the Pontis program about their training programs will be useful.
3. Customization of some of the Pontis user costs, MR&R costs, improvement costs and deterioration , bridge elements submodels (see chapters 4 and 5 for more details) is required prior to using the program. This work could be performed by inhouse engineers. Contact with the state that have been experiencing with the software or the developers of the Pontis software is storngely recommended.
4. Additional data regarding accident rates is needed. This will help to develop a relationship between accident rates and bridge deck width level-of-service goals.

5. The SDDOT needs to prepare questionnaires to gather information related to the transition matrices used in the Pontis program (see Chapter 3). Another alternative is to investigate the possibilities of utilizing the NBI data to formulate these matrices. This step represents the most important element in the Pontis BMS.

In addition to the above listed recommendations regarding using the Pontis BMS software, it is also recommended to use the current 0 to 9 NBI rating procedure in conjunction with the software presented herein to develop condition-age relationships for a bridge deck, substructure and superstructure. Despite that this rating system differed from the rating system used in the Pontis BMS (see sec. 3.2), one can uses the 0 to 9 rating system to compare performances of different bridge types and to roughly estimates a bridge life or forecasting to some extent the bridge deck, superstructure and substructure future conditions .

Finally, to reduce deterioration rates and to increase the life of bridge structures factors such as: 1) reducing bridge's angle of skewness; 2) improve material quality; 3) reduce span length should be considered. However, the tradeoff using additional supports to reduce the length of the spans and the change in the deterioration rate should carefully be investigated.

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APPENDIX A

This appendix contains a complete list of the questions that were submitted to the South Dakota DOT to prepare the state's agency and user costs. The responses received are designated by the shaded areas.

A.1. AGENCY COST

A.1.1. Cost Associated with New Bridges

The cost of new bridges should be reported in cost per foot squared over the length of the bridge, from backwall to backwall. If the cost of a new bridge is different for the length or the regional location of the bridge, then please subdivide the cost accordingly, otherwise, give the cost per square foot. The cost is to include the barrier rail and guard rail but not the concrete approach slab.

a. SLAB BRIDGE

Please give an estimate for the different bridge lengths for the regional locations listed below. Give one estimate if length and regional location do not have an effect on the cost.

	Short Length	Medium Length	Long Length
(approx. range)	(____-____)	(____-____)	(____-____)
Region 1	$________	$________	$________
Region 2	$________	$________	$________
Region 3	$________	$________	$________
Region 4	$________	$________	$________

Other Regional Location $40.00/ft^2 (60′ to 145′ lengths)

b. PRESTRESSED CONCRETE BRIDGES

Please give an estimate for the different bridge lengths for the regional locations listed below. Give one estimate if length and regional location do not have an effect on the cost.

	Short Length	Medium Length	Long Length
(approx. range)	(____-____)	(____-____)	(____-____)
Region 1	$________	$________	$________
Region 2	$________	$________	$________
Region 3	$________	$________	$________
Region 4	$________	$________	$________

Other Regional Locations, please specify $42.00/ft² (200' to 350' lengths)

c. STEEL BEAM OR GIRDER

Please give an estimate for the different bridge lengths for the regional locations listed below. Give one estimate if length and regional location do not have an effect on the cost.

	Short Length	Medium Length	Long Length
(approx. range)	(____-____)	(____-____)	(____-____)
Region 1	$________	$________	$________
Region 2	$________	$________	$________
Region 3	$________	$________	$________
Region 4	$________	$________	$________

Other Regional Locations, please specify $45.00/ft² (200'+ lengths)

d. DETOUR COST

Please include the agency cost per bridge associated with an average detour for a new bridge. The cost should include all expenses paid to local agencies, cost for maintaining the detour road, the signing cost for the detour route, and the extra cost needed for a highway supervisor to inspect the detour route during the project. We are only interested in estimated cost.

Project Detour Cost $ 9000 non-interstate

Interstate crossovers for a pair of bridges = $100,000.00

e. OTHER COSTS

Please include other costs you consider necessary in order to develop a better estimate for costs associated with new bridges.

A.1.2. Cost Associated with Contract Maintenance

Contract maintenance costs are to be calculated in square feet over the length of the bridge, from backwall to backwall, unless otherwise specified.

a. BRIDGE DECK OVERLAYS

Please indicate from the listing below the types of bridge deck overlays that you use on a "regular" basis and give an estimate. If you do not use any of the following, please mark "No." If you use any other type of bridge deck overlays, then please add them to the list and give your estimated cost.

1. Low Slump Concrete	(Yes) (No)	$ 4.25 /sq. ft.
2. Latex Concrete	(Yes) (No)	$__________/sq. ft.
3. Epoxy	(Yes) (No)	$__________/sq. ft.
4. Bituminous	(Yes) (No)	$__________/sq. ft.
5. Asphalt Membrane	(Yes) (No)	$__________/sq. ft.
6. Other Types, please specify		

b. BRIDGE PAINTING

Please indicate the types of bridge painting that you use on a "regular" basis and give an estimate. If you do not use any of the listed types of bridge painting, please mark "No." If you use a different type of bridge painting, please add it to the list and give your estimated cost.

1. Inorganic Zinc Silicate	(Yes) (No)	$__________/sq. ft.
2. Aluminum Epoxy	(Yes) (No)	$__________/sq. ft.
3. Other Types, please specify		

Coating New Structures	Recoating Existing Structures
3-6 mils inorganic zinc prime coat	5 mils prime coat of aluminum filled epoxy mastic
3-5 mils high build polyeurethane finish coat	3-5 mils high build aliphatic polyurethane finish coat
$1.00/ft^2 or $0.10/lb structural steel	$1.15 ft^2

c. BRIDGE DECK PATCHING

Include this item only if you perform bridge deck patching by contract on a "regular" basis, if not, then please mark "No." If you use any other types of bridge deck patching, please add it to the list and give the cost.

1. Concrete	(Yes) (No)	$__________/sq. ft.
2. Asphalt	(Yes) (No)	$__________/sq. ft.
3. Other Types, please specify		

d. BRIDGE DAMAGE

Please include any bridge damage that is repaired by contract. Please feel free to add any additional bridge damage items that you also repair on a "regular" basis by contract, such as heat straightening of damaged steel beams, etc.

1. Prestressed Concrete Beam Repair — $ 10,000 per bridge
2. Heat Straightening of Steel Beams — $15,000-20,000 per bridge
3. Other Costs, please specify

_______________ Please indicate any other contract maintenance items that your office performs on a "regular" basis; you may subgroup them if necessary. Do not include small maintenance items that you do every few years.

1. ____________________ $__________/sq. ft.
2. ____________________ $__________/sq. ft.
3. ____________________ $__________/sq. ft.

A.1.3. Cost Associated with In-House Bridge Maintenance

In house bridge maintenance is to be estimated by the square foot over the length of the bridge, from backwall to backwall, unless otherwise indicated.

a. BRIDGE DECK OVERLAYS

Include this item only if you are installing bridge deck overlays on a "regular" basis. If you are installing other types, please add them to the list and give the cost.

1. Rubberized Asphalt Chip Seal (Yes) (No) $ 2.25 /sq. ft.
2. Other Types, please specify

b. BRIDGE EPOXY DECK INJECTION

Please indicate the average cost for epoxy injection for a "typical" bridge deck.

Epoxy Injection $ $70.00 /sq. ft.

c. BRIDGE DECK PATCHING

Please give an estimate for the types of bridge deck patching listed below. If you use other products for patching, please add them to the list and give your estimated cost.

1. Asphalt (Yes) (No) $__________/sq. ft.
2. Concrete (Yes) (No) $ 10.00 /sq. ft.
3. Other Types

d. COLLISION DAMAGE

Please give an average cost to repair each item listed below. If there are any other items that you repair, please add them to the list.

1. Bridge Beams
   i. Steel — $ 3000-5000 per bridge
   ii. Prestressed Concrete — $ 2000-3000 per bridge
   iii. ________________ — $______ per bridge
2. Barrier Rails — $ 500-750 per bridge
3. Guard Rails — $ 500-750 per bridge
4. Other Items, please specify
   a. ________________ — $__________ per bridge
   b. ________________ — $__________ per bridge

e. EROSION CONTROL

Please give an average cost for erosion control per bridge. Also, indicate the average cost per year spent on erosion control. If there are other items that need to be added to the list, please do so.

1. Earth work — $ 15,000 per bridge
2. Rip-Rap — $ 20,000 per bridge
3. Others, please specify
   i. ______________ — $__________ per bridge
   ii. ______________
4. Average Total Annual Cost — $__________ *per year

*Varies greatly depending on flooding conditions. Can be $0, can be $1 million.

If there is another in-house maintenance item that you perform, please add it in the space provided below. You may use additional sheets if necessary. Do not include small maintenance items that you do every few years.

1. ____________________ — $_______/sq. ft.
2. ____________________ — $_______/sq. ft.

A.1.4. Cost Associated with Administration Expenses

Please indicate your agency's cost for a typical bridge project.

New Bridge

Design Cost	$__________
Letting Cost	$__________
Construction Inspection Cost	$__________
Supervisor/Manager Cost	$__________
Overhead	$__________

SDDOT uses 16.5% of the project cost

Contract Maintenance

Design Cost	$__________
Letting Cost	$__________
Construction Inspection Cost	$__________
Supervisor/Manager Cost	$__________
Overhead	$__________

can use 16.5% of project costs

In-House Maintenance

Supervisor/Manager Cost	$__________
Overhead	$__________

absorbed into other costs

A.2. USER'S COST

A.2.1. Vehicle Cost Per Mile

For the maximum vehicle weight, you may want to include the weights for the different axle loadings.

Light Vehicle Weight	____	Tons	Cars, Pickups and Panels
Heavy Vehicle Weight	____	Tons	All trucks together

All costs are to be calculated per mile.

Light Weight Vehicle = cars, pickup and panels			
Weight	____	tons	personnel
Depreciation	____	cost	cost/min = $.07,
Finance Charge	____	cost	cost/mile = $.14
Taxes and Registration	____	cost	equipment
Fuel	____	cost	
Repairs and Maintenance	____	cost	
Insurance	____	cost	
Miscellaneous Expenses	____	cost	
Driver	____	cost	
Heavy Weight Vehicle = average all trucks			
Weight	____	tons	cost/min = $.14,
Depreciation	____	cost	
Finance Charge	____	cost	cost/mile = $.50
Taxes and Registration	____	cost	
Fuel	____	cost	
Repairs and Maintenance	____	cost	
Insurance	____	cost	
Miscellaneous Expenses	____	cost	
Driver	____	cost	

A.2.2 Accident Cost

The cost for each item is to be calculated for each accident.

use Sheet 4 council figures		'89	
Fatality	____	cost	290,000
Major Injury	____	cost	32,000
Minor Injury	____	cost	8,300 non-cap.
Property Damage	____	cost	2,600 possible inj.
Miscellaneous Expenses	____	cost	1,600-1,800

A.2.3 Accident Rates

We do not normally calculate these numbers in this form, normally we calculate onsite by site situation by situation basis--if information is needed in this form, we can calculate that way.

Accident rates are to be calculated per 100 million vehicles.

Interstate and Principal Arterials	_____	accidents
Minor Arterials	_____	accidents
Major & Minor Collectors	_____	accidents
Local Routes (Optional)	_____	accidents

A.2.3 Average Daily Traffic (ADT) Growth Rates

The growth rate is to be calculated in percent for the last five years.

		86	87	88	89	90
Rural						
	Interstate	+4.1	+7.7	+6.4	+4.8	+7.3
	FA Rural	+8.3	+4.0	+1.9	+2.2	+5.3
	Other	+1.7	+7.4	-3.3	+1.7	-0.6
	Total	—	—	—	—	—
Urban						
	Interstate	+1.8	+15.5	+5.4	-0.2	+1.5
	FA Urban	+4.3	+4.7	-2.0	-0.4	+3.4
	Local Urban	+5.4	+3.8	-2.3	+0.9	+0.5
	City Streets	—	—	—	—	—
	Statewide	+4.9	+6.1	+0.6	+2.1	+3.5

1,748,009
1,718,479 = +1.7

2,145,659
1,997,633 = +7.4

2,110,632
2,074,879 = +1.7

*other = Local City streets
Local rural roads

2,074,879
2,145,659 = -3.3

2,097,864
2,110,632 =

*FA rural = Federal-Aid Primary and Federal Aid Secondary