Essential parameters for an Iowa bridge management system

by

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PREFACE

This study was cosponsored by the U.S. Department of Transportation's Midwest Transportation Center and the Iowa Department of Transportation in the research project, "Bridge Management System For the States of Iowa, Nebraska, Kansas and Missouri". The research team for this project consisted of: Dr. Fouad Fanous, principal investigator; Dr. Lowell Greimann, co-principal investigator; and David Petermeier, research assistant. Additional work for this project was performed by Zhongsheng Yuan and David Schoeller.

The material presented in this Master of Science thesis is essentially the same as that contained in the final report submitted to the Midwest Transportation Center. All of the work presented in Chapters 1 through 5 and Appendix A were developed and written by the author. The work presented in Chapter 6 was initiated by Yuan and completed by the author, and the work presented in Appendix B was performed by Schoeller.

The computer programs and files described in section 6.4.1 and Appendix B have not been included as a part of this thesis.

1. INTRODUCTION

Bridges are one of the vital segments in a surface transportation system. According to 1990 statistics [1], there are over 578,000 bridges on our nation's highways. Almost 40% of these bridges are classified as substandard according to federal guidelines. Unfortunately, the state of Iowa contains a disproportionate share of these substandard bridges. There are over 26,000 bridges in the state of Iowa, almost 4,000 of which are state-owned. Over 20% of the state-owned bridges and over 50% of the remaining Iowa bridges are classified as substandard. This group of over 12,000 substandard bridges annually competes for a share of Iowa's limited transportation budget.

In order to reduce the large number of deficient bridges, a more cost effective procedure for allocating bridge funds must be established. Bridge management systems (BMS) are one means of accomplishing this goal. The principal objective of a BMS is to make the best use of available funds in an overall bridge maintenance, rehabilitation and replacement program. The decision making, either at the level of the entire highway system (network level) or for an individual bridge (project level), is based on bridge conditions at the present and in the future. Without regular maintenance, the overall condition of a bridge deteriorates over time. Therefore, a BMS should determine the optimal level of maintenance for a bridge (or bridges) which minimizes the required funds.

The costs incurred by the highway agency and the roadway user vary with different maintenance strategies, as illustrated in Figure 1.1. Strategy 1, which represents a high level of maintenance, implies higher agency costs resulting from maintenance, rehabilitation or replacement policies, but lower costs for users of the bridges. On the other hand, strategy 2 represents a low level of maintenance. From an agency view, strategy 2 is the lower agency cost alternative and perhaps would be preferred. The benefits of moving from strategy 1 to strategy 2, however, may be offset by the increase in user costs. The optimum maintenance strategy must be based upon the total of agency and user costs for all available options, as illustrated in Figure 1.2.

1.1 Federal Bridge Legislation

The federal government has taken a leading role in attempting to formalize the management of the nation's bridges. In fact, legislation is currently being considered which would require states to have a BMS in order to qualify for federal bridge funds [2]. In the past, the Federal-Aid Highway Acts of 1968 and 1970 and the Surface Transportation Assistance Act of 1978 established the federal requirements

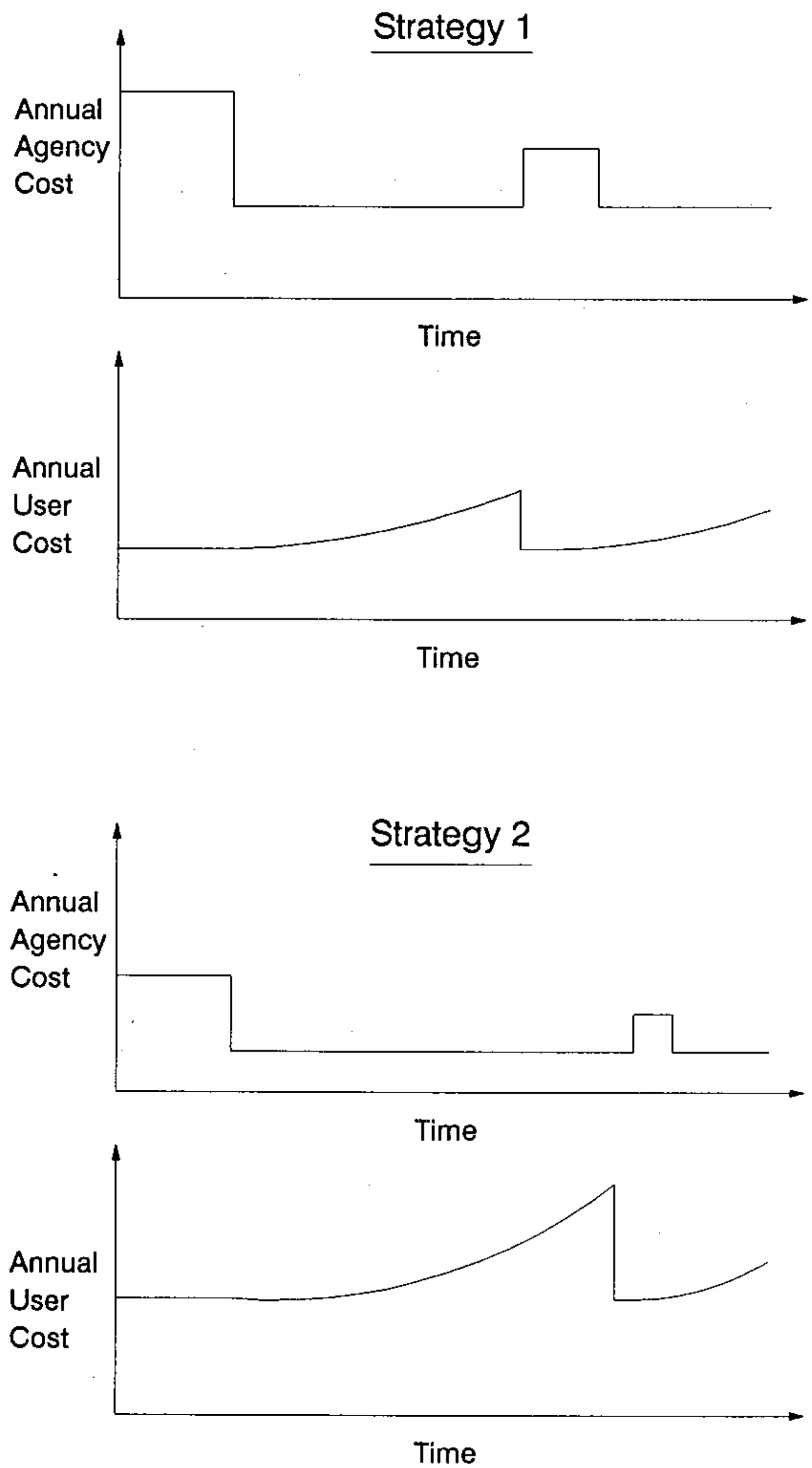

Figure 1.1 Schematic cost for two maintenance policies

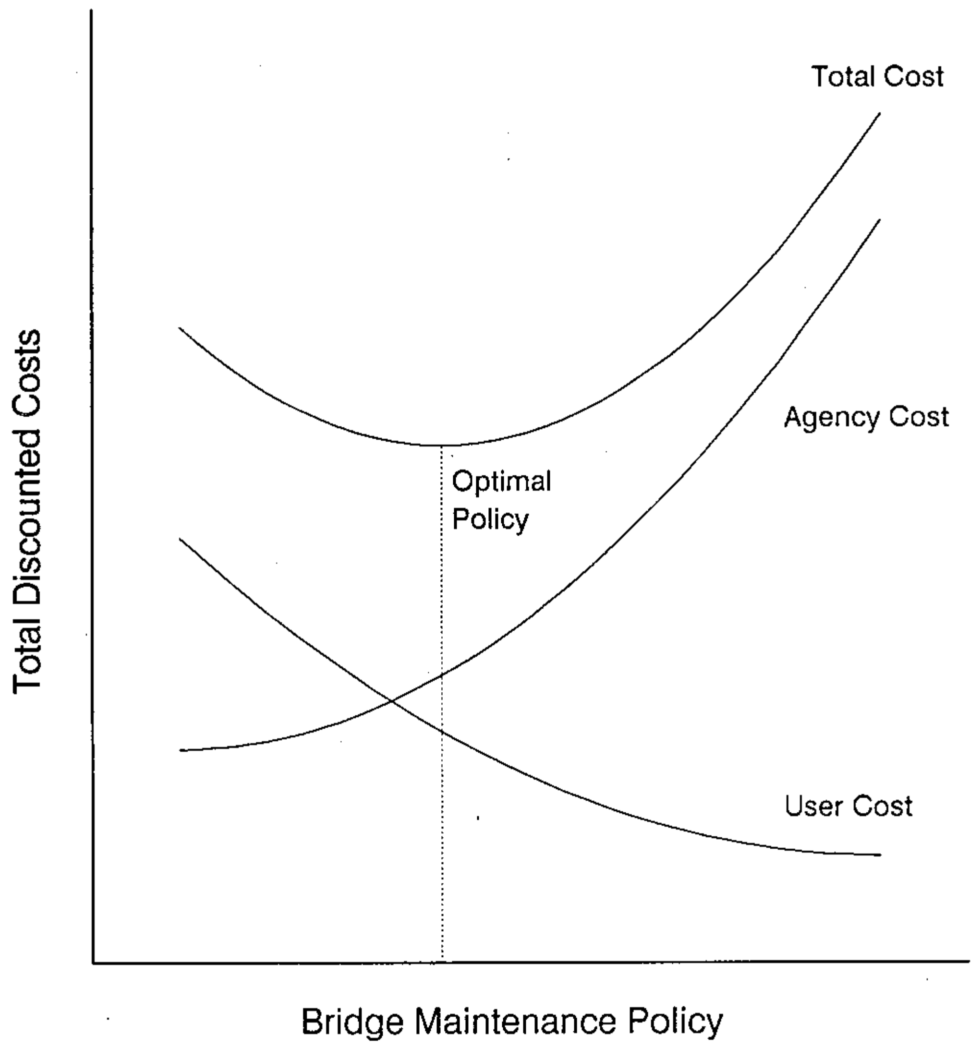

Figure 1.2 Determination of the optimal maintenance policy

governing the inspection and funding of bridges [3]. The Federal Highway Administration (FHWA) is in charge of the National Bridge Inventory (NBI) which collects and stores inventory data for all U.S. bridges. The National Bridge Inspection Standards (NBIS) set various rules governing the inspection and evaluation of bridges such as: (1) all bridges must be inspected biennially, (2) all inspection personnel must meet certain qualifications, and (3) specific data items are designated which must be submitted to the NBI.

In order to insure comprehensive and consistent inspection data, the FHWA developed the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges [4]. The recording and coding guide dictates what inspection data are to be recorded on the Structure Inventory and Appraisal (SI&A) sheets for submittal to the NBI. Several of these data items are combined to calculate the Federal Sufficiency Rating (FSR). The FSR is a rating from 0 to 100 which is used to determine qualification for federal funding; bridges with a FSR less than 50 qualify for replacement or rehabilitation bridge funds, while bridges with a FSR from 50 to 80 qualify only for rehabilitation funds. The FSR does provide an adequate means of establishing broad limits on funding requirements, however, the ranking of projects according to FSR will not always insure the optimum order of project selection.

The recording and coding guide presents guidelines used to establish condition ratings for the three main bridge components (deck, superstructure and substructure) and appraisal ratings for several additional bridge characteristics. The component condition ratings are used to describe the existing bridge component's condition as compared to it's original as-built condition. Appraisal ratings are used to evaluate various bridge characteristics to determine the level-of-service provided versus the desired level-of-service for the roadway of which it is a part. The condition and appraisal ratings are evaluated numerically on a scale of 9 to 0. A rating of 9 represents a bridge condition or appraisal in near-perfect condition, while a rating of 0 indicates complete component failure and warrants closure of the bridge. In reality, condition and appraisal ratings are rarely allowed to fall below a rating of 3.

The FHWA classifies bridges as deficient according to two distinct categories, bridges that are structurally deficient and bridges that are functionally obsolete. A structurally deficient bridge is one that is restricted to light vehicles only, closed, or requires immediate rehabilitation to remain open. A functionally obsolete bridge is one which has deficiencies associated with the deck geometry, vertical clearances, load carrying capacity, approach roadway alignment, or waterway. The condition and appraisal ratings are the criteria used to determine when a bridge is classified as deficient. The specific requirements for classification in each category are listed in Table 1.1 [5]. The classification of a bridge as structurally deficient or functionally obsolete does not qualify a bridge for federal funding. As stated previously, funding requirements are based solely on the FSR. These classifications are simply used to provide a general overview on the status of a bridge system.

1.2 Levels of BMS Development

The concept of providing the optimal maintenance strategy for the management of a bridge network is nothing new to experienced bridge maintenance engineers. Experienced engineers may argue that the development of sophisticated BMS will not provide any revelations regarding the management of bridges. However, the purpose of a BMS is to provide a means of comparing viable alternative maintenance strategies to assist in the decision making process. The level of BMS development among various governmental agencies and current research efforts varies widely due to this general attitude.

Table 1.1 FHWA structurally deficient and functionally obsolete requirements

Structurally deficient	
Condition rating ≤ 4	deck, or superstructure, or substructure
OR	
Appraisal rating ≤ 2	structural condition, or waterway adequacy
Functionally obsolete	
Appraisal rating ≤ 3	deck geometry, or underclearances, or approach roadway
OR	
Appraisal rating = 3	structural condition, or waterway adequacy

In general, there are four levels of BMS development that are presently being utilized among various governmental agencies. A brief description for each of the four general BMS levels follows; and the current status of national BMS research and the existing bridge management policies used in several individual states will be described in detail in Chapter 2.

The lowest level of BMS development can be termed the do-nothing policy (do-nothing simply implies the lack of BMS techniques). This type of bridge management relies on the existing federal guidelines of inspection and evaluation using the FSR. The decision regarding the maintenance, rehabilitation and replacement of bridges is based on the subjective opinion of several engineers. This type of management policy relies heavily on the experience of the engineers involved in the decision making process.

The next level of BMS development involves the use of priority ranking systems to identify bridges with the greatest need. Priority ranking systems are similar to the FSR; several quantifiable bridge characteristics are combined to calculate a sufficiency or deficiency rating which describes the performance of a bridge. Priority ranking systems are typically used to generate a priority listing of existing system bridges. The primary advantage of using priority ranking systems (versus the FSR) to establish bridge project priorities is that states may customize priority ranking systems to meet their specific needs.

The analysis and optimization of several project alternatives (project level optimization) is the next level of BMS development. Life-cycle cost analysis is typically used to compare replacement, rehabilitation and maintenance alternatives. Project level optimization techniques have been used in conjunction with priority ranking systems in order to estimate future funds required.

The highest level of BMS development involves the optimization of project selections over the entire bridge network (network level optimization). Network level optimization expands on the concepts utilized in project level optimization. In general, the procedure utilized in network level optimization involves the analysis and optimization of several alternatives for each potential bridge project.

1.3 Revised Project Objectives/State-specific Elements

The initial proposal, as it was accepted in November 1988 and modified April 7, 1989, was divided into six tasks [6]. The first four tasks deal with the development of a bridge component deterioration model that utilizes the Markov Chain statistical method. Task 5 detailed the development of a project level life cycle cost analysis for the determination of the optimum policy of bridge maintenance, rehabilitation, or replacement. The proposed life cycle cost analysis was to include agency costs, user costs, and use the deterioration model to determine the expected remaining life. Task 6 involved the development of a user-friendly interactive computer program for use on the Iowa DOT computer system.

During the course of this research project, the proposed project objectives were changed at the request of the Iowa Department of Transportation (DOT) project advisory committee [7]. Original members of the project advisory committee include: Mr. Gus Anderson, Iowa DOT; Mr. Bruce Brakke, FHWA; Dr. Carl Kurt, University of Kansas; Mr. John Risch, Iowa DOT; Mr. Lee Smithson, Iowa DOT; and Mr. Jerry Solbeck, Iowa DOT. Additional advisory committee members that were informally included during the course of this research include the following: Mr. Steve Belzung, Iowa DOT; Mr. Bill McCall, Iowa DOT; Mr. Larry Jesse, Iowa DOT; and Mr. Roger Walton, Iowa DOT. The subsequent changes, suggested by the advisory committee, regarding project tasks were made in order to expand the proposal from the project level to a network level analysis. It was expressed that the project should attempt to parallel and complement the research developments achieved in FHWA Demonstration Project

No. 71, Phase II (FHWA DP 71/II). The primary objective of FHWA DP 71/II is the development of a computer based network level BMS with sufficient flexibility for implementation in various states upon completion (this project will be described in further detail in section 2.3).

Changes were made so that research would not duplicate work to be performed in FHWA DP 71/II. Therefore, only BMS elements which are specific to the state of Iowa (state-specific) were to be developed. These state-specific items include the component deterioration model, level-of-service goals, agency costs, and user costs. The development of items such as project prioritization, cost analysis techniques, and network level optimization should be performed by FHWA DP 71/II.

In September 1989, the project tasks were officially changed to meet the requests of the project advisory committee [8]. The first four original tasks, which deal with the development of the component deterioration model, have remained essentially the same. The remaining two tasks were changed in order to concentrate solely on the development of additional state-specific BMS elements. These additional elements include the following: development of tables of minimum acceptable and desirable goals for level-of-service characteristics, development of a comprehensive list of feasible repair and rehabilitation alternatives presently used by the Iowa DOT, and investigation of agency and user costs.

2. LITERATURE REVIEW

The level of development for BMS range from no established procedures to sophisticated systems. As described in Chapter 1, there are four general levels of BMS development. These levels include the do-nothing policy, priority ranking systems, project level optimization, and network level optimization. This chapter describes some of the BMS research projects that have been completed or are presently under development. Iowa's existing bridge management practices are presented first in order to compare with other existing systems and procedures. This is followed by summaries of existing and current BMS research and other state's bridge management practices. A detailed review of existing bridge component deterioration models is presented in section 6.1.

2.1 Iowa's Current Bridge Management Policy [9]

The process begins with the biennial inspection of all state-owned bridges. In the case of bridges classified in special (i.e., critical) condition, inspections are normally increased to once a year. The inspections include photographs and engineering drawings of the various bridge components to illustrate the degree of deterioration. Finally, the inspector notes specific problem areas that require immediate attention.

Each inspection report is then reviewed by the Office of Maintenance at the Iowa DOT headquarters. An inventory and operating load rating is prepared by the Office of Bridge Design. Recommendations for any potential repair work are made by the State Bridge Maintenance Engineer.

A summary of each inspection report is sent to the District Maintenance Engineers (DME) and Resident Maintenance Engineers (RME) for their review. The DME and RME decide which bridges will be repaired based on their evaluation of the inspection report and the recommendation made by the State Bridge Maintenance Engineer. The DME and RME determine if a bridge should receive maintenance performed by in-house crews or if the project should be recommended for contract repair or total bridge replacement.

When a bridge reaches the point that a contract repair or complete replacement is required, the DME submits a recommendation to the Iowa DOT Program Management Department for entry into the five-year program of repair and replacement. The Iowa Transportation Commission annually reviews the five-year program.

During the course of this project, a priority ranking system was proposed by Belzung [10]. The proposed system would not replace the preceding procedures, although it would assist in the decision making process. The ranking system assigns points according to the following categories:

Federal Sufficiency Rating (FSR), average daily traffic (ADT), weight restriction, deck width, detour length, remaining life and service level. An Iowa DOT technical committee is presently considering implementation of this priority ranking system [9].

2.2 FHWA Bridge Management Systems - Phase I

The FHWA conducted research to investigate the general BMS concepts that are being used in existing BMS [11]. Reference [11] primarily contains a collection of existing concepts that have been utilized to some extent in the past.

The report investigated several different topics associated with BMS. Concepts that were investigated include: (1) computer database structure, (2) level of service characteristics and goals, (3) priority ranking formulas, (4) levels of service for maintenance activities, (5) deterioration rates and estimating service life, and (6) project and network level cost analysis procedures. The report also proposed how these various concepts could be combined to develop a comprehensive BMS.

The report concluded that a comprehensive BMS is required at the state level. A comprehensive BMS at the state level would build and strengthen their current bridge inspection, priority ranking, and programming processes.

2.3 FHWA Bridge Management Systems - Phase II

In response to the conclusions reached in FHWA Bridge Management Systems - Phase I, a follow-up project was initiated in August 1989 [12, 13]. Phase II research is a two-year project cosponsored by the FHWA and the state of California. Research is being conducted jointly by Cambridge Systematics, Inc. and Optima, Inc. The primary objective of this research is to develop a computer-based network level BMS with sufficient flexibility for implementation in several states over the next few years. As stated in Chapter 1, this research project forms the basis of the state-specific concepts developed for the state of Iowa.

The conceptual approach to the problem is being supervised by a technical advisory committee which includes members from the FHWA, California, and five additional states. The computer-based BMS model is being developed in a modular format. The individual modules will perform specific functions associated with network level BMS analysis. The functions, or tasks, initially proposed for computer module development include: the input data base, selection of feasible actions for maintenance and improvement activities, calculation of agency and user costs, deterioration rate prediction, optimization of maintenance, rehabilitation and corrective actions, optimization of improvements and replacement, and integration of both optimization programs to develop long-term and short-term capitol programs. As mentioned previously, the preceding concepts were those originally proposed at the start of the research project. Therefore, these concepts may change slightly as the project develops.

During the development of the network level BMS, data from the state of California are being utilized to test the various elements of the computer program. Upon completion, the program will be implemented for testing in several state agencies.

2.4 NCHRP Bridge Management Systems

The National Cooperative Highway Research Program (NCHRP), a division of the Transportation Research Board, recently sponsored an extensive BMS research project. This research was conducted by Austin Research Engineers Inc. and Figg & Muller Engineers Inc. [14]. The research consisted of two distinct phases. Phase I was completed in 1987 and the findings were published in NCHRP Report #300 [14]. Phase II was completed in 1990; however, the results have not been formally released to the public.

The objective of Phase I was similar to that of FHWA Bridge Management Systems - Phase I. Specifically, the main objective was to define the various elements required for the development of a network level BMS. In addition, these elements were then organized and input into a computer database for the future development of a network level BMS.

Six basic BMS concepts were identified as essential to the development of any BMS. The concepts were chosen for the development of the following computer modules: (1) central database, (2) network level major maintenance, rehabilitation and replacement selection, (3) minor maintenance, (4) historic data analysis, (5) project level interface, and (6) the reporting module. These modules were utilized to form the overall structure of the BMS computer model. For additional information pertaining to the six computer modules, the reader is referred to Reference [14].

During Phase I, a preliminary, partially completed computer program for use on personal computers was developed. This computer program was written using the DBASE III+ programming language. This program illustrated how the various computer modules fit together and served as a base for future software development.

The objective of Phase II was to further develop the BMS model previously established. Specific tasks to be completed include: refinement of the concepts involved in a network level analysis, completion of the programming of the Phase I computer program, and validation of the computer program with actual bridge inventory data from cooperating agencies.

As stated previously, the findings of Phase II research have not been officially published. However, a recently released request for proposal for NCHRP Project 12-28(2)A briefly describes some of the results achieved in Phase II [15]. The Phase I computer program was completed using the FoxBase database programming language. However, only minimal validation and testing were performed on the software. Therefore, additional testing was requested by NCHRP [15]. The transportation departments from four states and one city installed and evaluated the system. Based on this additional testing, it was found that the software requires further debugging, optimizing, and recoding.

NCHRP recently initiated Project 12-28(2)A to refine the work completed previously in NCHRP Project 12-28(2), Phases I and II. The contract starting date of this project has been tentatively set for June 1, 1991, and the total contract time is limited to eighteen months. The objective of the project is to develop a fully operational microcomputer-based BMS software package. A NCHRP advisory committee and the selected contractor will determine the specific tasks to be accomplished. These tasks may include providing modifications to the existing FoxBase source code developed in Phase II or completely rewriting the BMS software in another PC-based programming language.

2.5 North Carolina

A considerable amount of BMS research has been accomplished at North Carolina State University (NCSU) for the North Carolina DOT. Research at NCSU 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 applied to maintenance activities, agency and user costs applied to project selection, and incremental benefit-cost analysis applied to project optimization [16, 17, 18, 19].

The first research project performed at NCSU investigated the concept of level of service goals for use in priority ranking systems [16]. This system utilizes formulas to calculate deficiency points in four separate categories. Each category is weighted according to it's relative importance: 70% for lqad 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, 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 [17]. 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). Naturally, due to the large amount of all possible bridge maintenance activities, every maintenance activity could not be considered. Next, specific levels of service were identified for each maintenance activity.

The study used a modified version of a non-linear programming algorithm for the selection of the optimal policy that was originally developed in NCHRP Reports 223 and 273 [20, 21]. This program was applied to the various bridge maintenance activities to identify the optimal levels of service under limited resources. This program has the capability to vary the available maintenance budget to determine the sensitivity of the optimal levels of service. This type of an analysis can be used to predict future maintenance budgets by comparing the results to desirable maintenance levels of service.

The third research project performed at NCSU developed a computer program to determine the optimum improvement action and time for a single bridge [18]. This project established some of the initial work concerning general BMS concepts such as project level optimization, bridge condition deterioration rates (see section 6.1.5), 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 established 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 of initial and final component condition ratings. For example, if the initial deck condition rating was 5, rehabilitation costs were established which were associated with increasing the deck condition to 6, 7, 8, and 9. The preceding maintenance and rehabilitation costs, as well as bridge replacement costs, were developed in terms of their associated unit measurement (i.e., sq. ft., lin. ft., etc.). User costs were developed for level of service deficiencies. User costs included the cost per mile to detour a bridge with a deficient load capacity and the accident costs associated with bridges with a poor approach roadway alignments and/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 based on standard annual equivalent cost procedures. This program includes the costs of the agency (i.e., NC 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 systemwide 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 [19]. A computer algorithm called the Incremental Benefit-Cost Program (INCBEN), which was originally developed by the Texas Transportation Institute [22], 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.

An economic analysis of all system bridges was determined to be too extensive. Therefore, only deficient bridges in need of immediate improvement were considered in the analysis. First, the INCBEN program discards improvement alternatives with undesirable benefit-cost ratios. Then, the desirable alternatives are listed in order of decreasing benefit-cost ratio. This list is used to allocate limited funds to the listing of deficient bridges.

A sample of 25 in-service bridges were analyzed for several budget levels and compared with the results of sufficiency-rated methods. The procedure developed in Reference [18] for estimating the costs and benefits of improvement alternatives was used. This analysis determined that the INCBEN program is feasible for small groups (less than 85) of bridges over a one-year analysis period. On the other hand, if a larger sample size or multi-year analysis is desired, then modifications must be made to the original INCBEN program.

The North Carolina DOT is presently making use of the first three NCSU research projects [23]. The last research project utilizing the INCBEN program has not been utilized due to some of the limited capabilities of the program.

This combined research effort of NCSU and the North Carolina DOT has established them as leaders in the field of developing BMS technology.

2.6 Pennsylvania

The Pennsylvania DOT (PennDOT), in conjunction with four outside consultants, developed a BMS for in-house use [24]. The resulting BMS modified and expanded on their existing computer database for bridges. The BMS computer program was initially installed on the PennDOT mainframe computer in January 1987.

The Pennsylvania BMS extensively developed many of the accepted general BMS concepts. The central BMS database expanded on 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. 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 developed was based on a deficiency point system. The criteria used to calculate the deficiency rating was divided into three major categories: level-of-service capabilities, bridge condition, and 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 which compare existing values with desirable or minimum acceptable level-of-service goals. These formulas also include the roadway's associated 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 based on the present condition for each of the components. Criteria included in the miscellaneous related characteristics category consist of the estimated remaining life, the FHWA approach roadway 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. Modifications made to the total deficiency rating include four limiting conditions for combinations of criteria deficiency point values and an overall adjustment factor which accounts for the functional classification of the roadway carried by the bridge. 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 the prioritization of replacement and rehabilitation projects.

The comparison of projects at the project and network level, 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 due to 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.

As stated previously, the Pennsylvania BMS has been in use since 1987. Since that time, several modifications to the existing system have been suggested. However, due to insufficient funding, additional modifications have not been completed [25]. Some of the suggested modifications include: an automated load capacity rating system should be

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) $\leq$ 100	

developed and implemented, economic evaluation concepts should be incorporated, and the future needs modeling should be expanded to include maintenance activities.

2.7 Washington

In 1984, the Washington DOT (WSDOT) initiated a bridge deck program intended to provide comprehensive information regarding their current bridge deck maintenance policy [26, 27]. The system concentrates on problems associated with the deck and does not directly consider superstructure or substructure elements; inspection procedures for these elements correspond with current FHWA guidelines.

The WSDOT bridge deck program makes use of extensive inspection information to establish priorities for bridge deck maintenance and rehabilitation. Information collected for each bridge include the following: the extent and severity of spalling and delaminations, stripping and debonding of overlays, concrete cover over reinforcing steel, cracking, scaling, existing deck patches, and rutting of the wheel paths. In addition, laboratory tests are performed on field samples to determine the amount of chloride contamination. The condition of the bridge decks are rated based on this inspection data and a modified version of the FHWA deck condition rating scale. Bridge deck projects are then categorized into five rehabilitation priority groups based on the condition rating and ADT.

The University of Washington (UW) completed research which was intended to build on WSDOT's inspection information and develop a Bridge Deck Management System (BDMS) [28]. Priorities were established using a sufficiency rating system based on the extent and severity of the various deterioration categories. Deterioration rates associated with the sufficiency rating condition index were established using nonlinear regression analysis. A present worth analysis of available alternatives was performed to determine project level optimization. Network level programming was based on a system similar to that used by the Pennsylvania DOT (i.e., reconstruction cost versus ADT, bridge deck area, remaining life, and deficiency points eliminated by reconstruction). The concepts developed in this research project have not been utilized by the WSDOT [27].

2.8 Minnesota

In the past, the Minnesota DOT utilized a priority ranking system to establish bridge priorities [29, 30]. The ranking system was developed by Minnesota DOT personnel and was based on deficiency points accrued in several categories. This type of system identifies bridges with the greatest need with a high rating value. In addition, the Minnesota system does not have any set maximum or minimum point values (i.e., 0 - 100) which qualify a bridge for immediate repair.

The total deficiency rating is the sum of three major categories: 50% structural adequacy and safety, 25% serviceability and functional obsolescence, and 25% essentiality for public use. The criteria included in each of the major categories are shown in Table 2.2. One might note that these categories are identical to those utilized in the FSR. However, the percent weighting of each category has been changed slightly. In addition, the criteria used to evaluate each category are similar to that of the FSR. The criteria that establish the point total for each of the major categories are all available on the current Federal Structure Inventory and Appraisal forms.

After using the priority ranking system for several years, the Minnesota DOT determined that their in-house system was not providing any better priority information than the FSR. Therefore, they have recently reverted back to using the FSR as the sole criteria for evaluating potential bridge projects [30].

Table 2.2 Minnesota priority ranking system categories and criteria

Structural Adequacy and Safety: 50%
Bridge posting Average daily traffic
Serviceability and Functional Obsolescence: 25%
Deck geometry appraisal rating Average daily traffic Underclearance appraisal rating Waterway adequacy appraisal rating Approach roadway alignment appraisal rating Structural evaluation appraisal rating Type of bridge structure Age of structure
Essentiality for Public Use: 25%
Detour length Average daily traffic Road system designation Functional classification Bridge record for defense

2.9 Michigan

The State of Michigan utilizes a priority ranking system to establish bridge project priorities [29, 31]. Their system, termed the "Critical Bridge Rating", was developed by Michigan DOT personnel and is based on a deficiency point scale from 0 to 98 points. The Critical Bridge Rating includes deficiency points for specific quantifiable bridge characteristics and for various subjective categories.

Each year, the rating of potential projects is performed by a nine member technical committee. The technical committee includes three permanent members from the Michigan DOT and six elected members divided equally between county and city government personnel. The subjective judgement of the nine committee members accounts for 27 of the 98 possible deficiency points for each potential bridge project. Each committee member evaluates four subjective criteria and assigns deficiency points accordingly. The four subjective criteria and their associated deficiency point totals include: 9.0 points for operating rating/load capacity, 4.5 points for bridge and approach features, 4.5 points for detour evaluation, and 9.0 points for functional classification performance.

Michigan's Critical Bridge Rating is comprised of three major categories. A bridge's physical condition and traffic safety account for 39.5 of the 98 deficiency points, the financial capability of the highway authority accounts for 30 points, and the overall importance of the structure accounts for the final 28.5 points. The specific criteria and associated maximum point values included in each of the major categories are shown in Table 2.3.

The Critical Bridge Rating is used in conjunction with the FSR in the selection of bridge projects. However, failure to meet federal requirements for funding does not necessarily exempt a bridge from acceptance into the critical bridge program [31].

2.10 Illinois

In order to identify bridges in critical condition, the Illinois DOT developed a procedure to group state-owned bridges into priority categories [32, 33]. This system develops lists according to sixteen separate criteria, which classify bridges into four priority needs categories. The sixteen criteria used to establish bridge priority needs are based on the federal requirements for structural deficiency and functional obsolescence. Structural deficiency requirements are based on the condition ratings of the deck, superstructure, substructure, and/or culvert, and the appraisal ratings of the structural condition and waterway adequacy. Functional deficiency requirements are based on

Table 2.3 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)

the appraisal ratings of the deck geometry, underclearances, approach roadway alignment, structural condition and waterway adequacy. The criteria priority lists are mutually exclusive. Therefore, once a bridge appears on a priority list, it is excluded from all subsequent lower priority lists.

Bridges are classified into four categories according to their priority level. The four categories of priority needs include: critical backlog, other backlog, short-term accruing, and long-term accruing. The critical backlog and other backlog categories automatically qualify bridges for inclusion in Illinois' five-year program. Bridges classified in the short-term accruing category are expected to qualify for the five-year program within the next five years. The long-term accruing category represents bridges expected to qualify in the next five to ten years. The criteria associated with each of the four categories are shown in Table 2.4.

2.11 Kansas

The Kansas DOT (KDOT) utilizes a priority ranking system to establish priorities for bridge replacement and rehabilitation projects [11, 34]. The ranking system was developed by Woodward-Clyde Consultants in conjunction with a panel of KDOT engineers. Woodward-Clyde also developed a

Table 2.4 Illinois priority ranking system categories and 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 ≥ 1000 and accident experience)
Underclearance appraisal rating ≤ 3
Approach roadway alignment appraisal rating ≤ 3 (ADT ≥ 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 ≥ 1000
FSR = 50 to 80

system to perform network level optimization of the projects selected. However, when tested, the optimization system subdivided the timing of repair projects much too extensively. Therefore, the optimization system has not been utilized by KDOT [34].

The Kansas ranking system is based on the calculation of deficiency points in five major categories. The categories and their respective weights include: 19.6% for deck width, 8.8% for bridge roadway restriction, 23.2% for deck condition, 31.4% for structural condition, and 17.0% for load capacity (operating rating). Formulas, based on upper and lower limits similar to level-of-service goals, are used to calculate the deficiency points in each category. Adjustment factors are utilized to modify the deficiency points calculated in each category. Deficiency points for the deck width and bridge roadway restriction are adjusted according to the associated prior accident rate and the posted speed limit. The deficiency points in all categories are adjusted according to the roadway functional classification and ADT. See Reference [11] for additional information pertaining to Kansas' priority ranking system.

In order to help Kansas bridge inspectors make uniform evaluations of the various subjective condition ratings, the Kansas DOT developed a bridge inspection manual [35]. This manual is similar to the "Bridge Inspector's Training Manual

70" developed by the U.S. Department of Transportation/FHWA [36]. The Kansas inspection manual lists the types of deterioration/distress typically encountered on the various bridge elements.

Additional research was conducted by the University of Kansas (KU) to develop a priority ranking system for bridges owned by local governments [37]. The research performed by KU is not associated with the previous research sponsored by KDOT. The KU system was modeled after the level-of-service priority ranking system developed by North Carolina State University (NCSU). KU research utilized the NCSU formulas with level-of-service goals developed for Kansas. The ranking system was programmed on a microcomputer using the DBASE 3+ database management system, and testing was performed on a sample of county-owned bridges. Evaluation of the test data confirmed that this type of priority ranking system is feasible for use on microcomputers at the local level.

2.12 Virginia

The Virginia DOT developed a priority ranking system based on the North Carolina level of service approach [11]. The ranking system is presently being used to prioritize bridges that meet FSR criteria for rehabilitation and replacement [38]. 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. Modifications made to the North Carolina system include: level-of-service goals were developed for Virginia, inventory rating (rather than operating rating) is used for load capacity, and the FSR is used in place of estimated remaining life. In addition, the weighting of categories were 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.

2.13 Maryland

The Maryland DOT presently use a priority ranking system as a guideline for establishing bridge replacement and rehabilitation project priorities [39]. The system was developed by Maryland DOT personnel and has been in use since 1989.

Maryland's ranking system evaluates and assigns one to five deficiency points to six criteria for each bridge. The criteria evaluated for each bridge include the following: FSR, structural condition, load posting, age, ADT, and detour length. The structural condition is based on a subjective rating scale from one (worst) to ten (best). The subjective structural condition rating is established by Maryland DOT engineers. The criteria for bridge age is different for timber and non-timber bridges.

The weighted average of the criteria represent the total bridge priority rating. The weight assigned to each of the criteria are 0.375 for structural condition and 0.125 for the remaining criteria. At the present time, the Maryland DOT is satisfied with the performance of their ranking system and do not intend to make any further developments toward a total BMS [39].

2.14 Wisconsin

The Wisconsin DOT (WisDOT) developed a computer simulation model to perform life-cycle cost analysis on bridge replacement and repair alternatives [11]. 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; the deterioration model is described in further detail in section 6.1.3. 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 have 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 subjective opinion of the 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 also considered include: the FHWA deck geometry appraisal rating, the FHWA approach roadway alignment appraisal rating, and the ADT of the roadway.

2.15 Nebraska

In 1984, the Nebraska DOT formed a departmental committee to investigate bridge management concepts. The committee developed a priority ranking system which was detailed in a 1986 Interim Report [41]. The Nebraska system uses level of service concepts similar to that used in North Carolina and Virginia.

Nebraska's ranking system is based on the deficiency points calculated in four categories. The categories considered and their associated maximum deficiency point values are as follows: 50 points for load capacity, 12 points for deck width, 33 points for vertical over/underclearance, and 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. The additional 9 deficiency points are calculated based on the FHWA waterway adequacy appraisal rating.

The ranking system developed has not been utilized by the Nebraska DOT to set project priorities. Project priorities are currently established using the FSR and the subjective evaluation of the engineers involved. The Nebraska DOT do not have plans for the further development of BMS concepts until FHWA Demonstration Project 71, Phase II has been completed [42].

2.16 New York

The New York DOT presently use a weighted condition rating to establish priorities for bridge replacement and rehabilitation projects [29, 43]. The rating system only considers the physical condition of various structural elements. Geometric characteristics, such as vertical clearance and deck width, are not considered.

The weighted condition rating is calculated using the individual condition ratings of thirteen structural elements. These elements are evaluated on a subjective scale, from seven (best) to one (worst), similar to the FHWA condition rating scale. Each of the thirteen structural elements accounts for a portion of 72 total points used in the weighting process. The structural elements considered, and their respective weights, are as shown in Table 2.5.

Table 2.5 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

The selection of replacement and rehabilitation projects is based on the weighted condition rating and ADT [43]. Minimum acceptable weighted condition ratings have been established for several ranges of ADT. In order to be considered for replacement or rehabilitation, a bridge must have a weighted condition rating less than the limiting value which corresponds to the current ADT.

The New York DOT is presently in the process of developing a comprehensive BMS [43]. The weighted condition rating procedure previously described will be replaced by a ranking system which includes evaluations of a bridge's physical condition, vulnerability, essentiality of use, and serviceability. Eventually, the new ranking system will be expanded to include the identification of remedial actions, the assignment of costs to the remedial actions, and optimization of project and network levels.

2.17 Missouri

The Missouri DOT developed a priority ranking system which divides state-owned bridges into groups according to their priority level [44]. Four priority levels are used which range from (1) bridges which require immediate replacement or rehabilitation (and should be scheduled for remedial action) to (4) bridges which do not meet any of the priority criteria.

The procedure used to establish a bridge's priority level is similar to the level-of-service concept utilized in other priority ranking systems. Priority levels, from (1) to (3), were associated with various quantifiable ranges of deck width, load capacity, and the FHWA component condition ratings (i.e., deck, superstructure and substructure). The priority level is established by comparing existing bridge values with goal values in each of the three categories. The priority level within a category varies according to the ADT and the average daily truck traffic (ADTT). For example, if an existing bridge has a deck condition rating of four, ADT of 2000 and ADTT of 500; the priority level is two. However, if the same bridge only had an ADTT of 499, then the priority level would be three. Priority levels have been established for all three categories over eight traffic volume ranges.

The priority level bridge groups established by the Missouri ranking system are mutually exclusive. The highest priority level achieved in the three categories controls for each bridge. The Missouri system is presently being used as a guideline for the selection of replacement and rehabilitation projects [45].

2.18 North Dakota

The North Dakota DOT does not presently utilize any form of structured BMS, including priority ranking systems, to establish bridge project priorities [46]. Current procedures follow FHWA guidelines for the inspection, rating, and codification of bridge data. The selection of bridge projects is based on a subjective evaluation of each bridge by several department engineers. The North Dakota DOT do not have future plans for expanding current procedures into any type of BMS.

The North Dakota DOT has developed an inspection manual to assist their inspectors in the inspection process. The 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 the consistency of the condition ratings given by different inspectors.

2.19 South Dakota

The South Dakota DOT presently relies on the subjective opinion of several department engineers in establishing bridge project priorities. However, they recently sponsored a research project which will develop initial concepts associated with BMS [47]. Specific objectives include an extensive literature review and the development of several state specific elements associated with network level BMS. The research is being conducted by Iowa State University and is scheduled for completion in the Fall of 1992.

2.20 Commercially Developed BMS Software

Several private companies are currently marketing commercial BMS software packages. These privately developed systems are advertised as either bridge information systems or comprehensive network level BMS's. The general concepts associated with these systems are similar to the concepts reported in public research (i.e., expanded database, priority ranking, project and/or network level analysis). However, it is difficult to assess the capabilities of these systems since specific details regarding their development are not available to the public.

Several commercial systems are presently in use. The Delcon Corporation and National Engineering Technology Corporation are the developers of the most well-known commercial system. Their system is known as "Bridge Rehabilitation, Inventory and Maintenance Management System (BRIMMS)" [48] and is capable of analyzing highway or railway system bridges. This system is currently being used by Canadian National Railways, Jamaica, and the city of Toronto. COWIconsult are the developers of the commercial system "Bridge Management and Maintenance System (BMMS)"

[49]. This system is also capable of analyzing highway or railway systems and is presently being used by Thailand and the Danish Railway Organization. Cambridge Systematics, Inc., the researchers presently involved in FHWA DP 71 Phase II, have developed a system presently being utilized by the Roads and Waterways Administration in Finland and the Massachusetts Bay Transportation Authority in Boston [13]. Finally, Austin Research Engineers, the researchers involved in the NCHRP research projects, are marketing an extension of the BMS developed in NCHRP Project 12-28(2) [50].

2.21 Summary of Existing BMS Procedures

The status of BMS policies, or procedures, presently in use encompass all previously mentioned BMS levels. In general, network level BMS research is being accomplished in research projects sponsored by the FHWA and NCHRP or by private commercial firms, while lower levels of BMS research are being accomplished by various state agencies.

The level of BMS development utilized in various state agencies varies widely. Several states have performed, or sponsored, significant amounts of BMS research and are presently using priority ranking systems and/or project level BMS in the selection of bridge replacement and rehabilitation projects. However, many 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.

Table 2.6 illustrates the level of BMS development presently, or formerly, used by the states reviewed. The four general levels of BMS previously defined are used to describe each state's level of development (some states may be using more than one level). It should be noted that several states developed priority ranking systems, but have recently returned to using FHWA guidelines and subjective judgement for project selection. In addition, the states reviewed are not an all-inclusive list of states that have performed BMS research, but do represent a large portion of state performed, or sponsored, research.

Table 2.6 illustrates that priority ranking systems are the most widely used level of BMS development utilized by state agencies. This is probably due to the simplistic nature of priority ranking systems and the desire to simply highlight bridges with the greatest need and allow engineers to make the final decision regarding project selection. Tables 2.7a and 2.7b detail the variables included in priority ranking systems presently in use, or previously developed, by state agencies.

Table 2.6 Comparison of state's BMS development

State	Level of Development			
	1[a]	2[b]	3[c]	4[d]
Iowa	X[e]	O[f]		
North Carolina		X	X	O
Pennsylvania		X	X	O
Washington		X	O	O
Minnesota	X	O		
Michigan		X		
Illinois		X		
Kansas		X		O
Virginia		X		
Maryland		X		
Wisconsin	X		O	
Nebraska	X	O		
New York		X		
Missouri		X		
North Dakota	X			
South Dakota	X			

[a]1 = do-nothing / subjective judgement.

[b]2 = priority ranking system.

[c]3 = project level optimization.

[d]4 = network level optimization.

[e]X = presently in use.

[f]O = developed, but not being used.

Table 2.7 Comparison of priority ranking formula variables

State	Variable Type					
	1[a]	2[b]	3[c]	4[d]	5[e]	6[f]
Iowa	X	X				
North Carolina	X	X	X			
Pennsylvania	X	X	X	X	X	X
Washington						
Minnesota	X	X	X	X	X	
Michigan	X	X				
Illinois	X	X	X		X	X
Kansas (KDOT)	X	X			X	X
Kansas (KU)	X	X	X			
Virginia	X	X	X			
Maryland	X					
Nebraska	X	X	X	X		
New York						
Missouri	X	X				X

[a]1 = load capacity, structural evaluation appraisal rating, weight restriction or bridge posting appraisal rating.

[b]2 = deck width or deck geometry appraisal rating.

[c]3 = vertical clearance or underclearances appraisal rating.

[d]4 = waterway adequacy appraisal rating.

[e]5 = roadway restriction or approach roadway alignment appraisal rating.

[f]6 = component condition ratings.

Table 2.7 (continued)

State	Variable Type					
	7[g]	8[h]	9[i]	10[j]	11[k]	12[l]
Iowa	X	X	X	X	X	
North Carolina	X	X	X	X		
Pennsylvania	X	X	X	X		
Washington		X				X
Minnesota	X	X	X			X
Michigan	X	X	X			X
Illinois		X			X	X
Kansas (KDOT)	X	X				X
Kansas (KU)	X	X	X	X		
Virginia	X	X	X		X	
Maryland		X	X		X	X
Nebraska	X	X	X	X		X
New York		X				X
Missouri		X				X

[g]7 = functional classification or service level.

[h]8 = ADT.

[i]9 = detour length.

[j]10 = remaining life.

[k]11 = FSR.

[l]12 = other miscellaneous variables.

3. LEVEL-OF-SERVICE GOALS

Level-of-service goals are target values for selected bridge characteristics that are used to assess bridge adequacy. These characteristics are measurable quantities that are used to describe the performance of a bridge. The goals are measured in terms of minimum acceptable and desirable levels which vary according to each state's individualized needs.

Level-of-service goals indicate the level of performance for existing bridges and establish design goals for new bridge construction. In existing BMS, level-of-service goals are primarily used in priority ranking systems (see Chapter 2). Priority ranking formulas compare existing bridge characteristic values with the goal values to determine the level of deficiency associated with each characteristic. In addition, these bridge characteristic deficiencies identify potential rehabilitation improvement projects.

The bridge characteristics selected for the development of Iowa's level of service goals include: load capacity, vertical clearance, clear deck width, and lateral clearance below the structure. These characteristics are the most commonly used criteria in existing BMS. Level-of-service goals could also be established for additional bridge characteristics such as the condition ratings for the deck, superstructure and substructure and the approach roadway alignment or waterway adequacy appraisal ratings.

Tables of minimum acceptable and desirable level-of-service goals were developed for the selected Iowa bridge characteristics. These goals vary according to roadway functional classification and average daily traffic (ADT). Iowa's goals were established using the January 1987 version of Iowa's Quadrennial Needs Study [51] as a guideline. The goals developed were subject to review and verification by the Iowa DOT. To eliminate discrepancies in measurement procedures, the definitions of Iowa's bridge characteristics correspond with those in the FHWA Recording and Coding Guide [4]. This allows numerical values to be taken directly from the Federal Structure Inventory and Appraisal (SIA) Sheets for comparison with Iowa level-of-service goals.

3.1 Load Capacity

The level-of-service goals for the load capacity are measured in terms of the operating rating for standard HS type loading. The operating rating indicates the absolute maximum permissible load level to which the structure may be subjected. The HS type load operating rating is coded as Item #64 on the Federal SIA form [4]. The level-of-service goals for load capacity are listed in Table 3.1.

3.2 Vertical Clearance

Vertical clearance level-of-service goals apply to both over the structure on high trusses and below the structure when the inventory route is over another roadway. In either case, the functional classification of the traveled route is used to enter the table.

For the vertical clearance over a structure, Federal SIA Item #53 is used [4]. This is the minimum vertical clearance over the bridge roadway, including shoulders, to any superstructure restriction. For the vertical clearance under a structure, Federal SIA Item #54 is used [4]. This is the minimum vertical clearance from the roadway (no shoulders) to the underside of the superstructure. The level-of-service goals for vertical clearance are listed in Table 3.2.

3.3 Clear Deck Width

The clear deck width of a structure is the most restrictive minimum distance between the curbs or rails on the structure roadway. The clear deck width is coded as Item #51 on the Federal SIA sheet [4]. The level-of-service goals for clear deck width are listed in Tables 3.3a, 3.3b and 3.3c.

Table 3.1 Load capacity level-of-service goals (tons)

Rural or Urban Structures			
Functional Classification	ADT	Minimum Acceptable	Desirable
Interstates	All	36	40
Principal Arterials	≥ 5000	36	40
	< 5000	30	40
Minor Arterials	≥ 5000	28	40
	500 - 4999	26	40
	< 500	24	40
Collector Routes	≥ 5000	26	40
	500 - 4999	22	40
	< 500	20	40
Local Routes	≥ 500	20	40
	< 500	18	40

Table 3.2 Vertical clearance level-of-service goals (feet)

Rural or Urban Structures		
Functional Classification	Minimum Acceptable	Desirable
Interstates	14.5	16.5
Principal Arterials	14.5	16.5
Minor Arterials	14.0	14.5
Collector Routes	14.0	14.5
Local Routes	14.0	14.5

Table 3.3a Clear deck width level-of-service goals (feet)

Rural Structures, Two-lane Routes			
Functional Classification	ADT	Minimum Acceptable	Desirable
Interstates	All	30	40
Principal Arterials	All	26	44
Minor Arterials and Collector Routes	≥ 1000	24	40
	< 1000	20	30
Local Routes	≥ 1000	24	40
	50 - 999	20	30
	< 50	18	30

Table 3.3b Clear deck width level-of-service goals (feet)

Urban Structures, Two-lane Routes			
Functional Classification	ADT	Minimum Acceptable	Desirable
Interstates	All	30	40
Principal Arterials	All	26	44
Minor Arterials and Collector Routes	≥ 5000	24	40
	1000 - 4999	22	40
	< 1000	20	36
Local Routes	≥ 1000	22	40
	100 - 999	20	36
	< 100	20	30

Table 3.3c Clear deck width level-of-service goals (feet)

Rural or Urban Structures, Number of Lanes > 2			
Functional Classification	ADT	Minimum Acceptable	Desirable
Interstates and One-Way[a] Principal Arterials	All	11n+6+2	12n+10+6
Two-Way[b] Principal Arterials	All	11n+2+2	12n+10+10
Two-Way Minor Arterials, Collector Routes, and Local Routes	≥ 1000 < 1000	11n+1+1 10n	12n+8+8 11n+4+4

[a] one-way routes, width = (LW * n) + RS + LS.

[b] two-way routes, width = (LW * n) + RS + RS.

where: LW = lane width

n = number of lanes

RS = right shoulder

LS = left shoulder

3.4 Lateral Clearance Under the Bridge

The lateral clearance under a bridge normally has only one value recorded, the minimum lateral underclearance on the right, which is Federal SIA Item #55 [4]. This is the lateral clearance as measured from the right edge of the roadway (excluding shoulders) to the nearest substructure unit (piers, abutments, etc.), to a rigid barrier, or to the toe of slope steeper than 3:1. The distance to be recorded is the minimum after measuring the clearance in both directions of travel.

Under special circumstances, such as on divided highways or one-way streets, the minimum lateral underclearance on the left is also recorded. This item is recorded as #56 on the Federal SIA [4], and the measurement procedure is the same. The level-of-service goals for right and left lateral underclearances are listed in Tables 3.4 and 3.5.

Table 3.4 Lateral underclearance on the right level-of-service goals (feet)

Rural or Urban Structures		
Functional Classification	Minimum Acceptable	Desirable
Interstates	10	20
Principal Arterials	8	20
Minor Arterials	6	20
Collector Routes	6	20
Local Routes	2	10

Table 3.5 Lateral underclearance on the left level-of-service goals (feet)

Rural or Urban Structures		
Functional Classification	Minimum Acceptable	Desirable
Interstates	6	10
Principal Arterials	4	10
Minor Arterials	4	10
Collector Routes	2	8
Local Routes	2	8

4. AGENCY COSTS

Agency costs are the costs incurred by the governing agency (i.e., state, county, municipal, etc.) due to the maintenance, repair, rehabilitation or replacement of their bridges. As mentioned previously, agency costs are one of the elements considered specific to each state. Agency costs can be divided into two major categories: maintenance, repair and rehabilitation activities (MRR) and improvement activities. MRR activities are associated with distress or deterioration conditions, whereas improvement actions are associated with various level-of-service characteristic deficiencies. Therefore, MRR activities improve the condition of a bridge, but it will deteriorate again with time. On the other hand, improvement activities are actions that, once performed, do not change with time. Both agency cost categories are explained in further detail later in this chapter.

4.1 Iowa's Agency Cost Development

Agency costs for the state of Iowa were developed using a four-step process. First, potential deterioration and distress conditions were identified in five major bridge component categories (deck, superstructure, substructure, waterway and approach roadway). Second, feasible MRR activities were assigned to the deterioration or distress conditions of each component; and, improvement activities were identified which improve deficient level-of-service characteristics. Next, unit measurement procedures were established for each MRR or improvement activity. The unit measurement procedure depends on the type of activity performed. The most common unit measurement procedures used in previous research [11, 18, 24] include the following: $ per square feet, $ per square yard, $ per linear foot, $ per ton, $ per man-hour, and $ each. The final step involved the investigation of the unit cost for each MRR and improvement activity. The first three steps of this process were performed under the guidance of the project advisory committee in order to insure a suitable format for use at the Iowa DOT.

4.1.1 Iowa MRR action costs

Several sources were used in order to establish the agency costs associated with the MRR activities identified for Iowa. The sources utilized in establishing these costs include: a questionnaire completed by Iowa DOT personnel, a questionnaire completed by Iowa county engineers, and historical data compiled by the Iowa DOT.

4.1.1.1 Iowa DOT questionnaire The first procedure used to collect unit MRR costs was a short questionnaire that was mailed to the six Iowa DOT District Maintenance

Engineers (DME). The format for this questionnaire was developed with the assistance of Risch, Iowa DOT State Bridge Maintenance Engineer. The initial list of feasible MRR alternatives was reviewed by Risch. Then, he recommended nine activities that, in his opinion, are performed frequently enough by in-house personnel in order to establish unit costs. These activities were then sent to the six DMEs for their evaluation. Three responses were received: District 3, District 4 (Residency 42), and District 6. The response from District 3 included a detailed estimate (i.e., cost breakdown according to materials, labor and equipment) for each activity, while Districts 4 and 6 submitted only final unit repair costs.

The three responses were compiled to evaluate the variation for each activity. Some of the costs correlated very well, while others had a wide range in their values. The unit cost for each MRR activity was determined by Risch after an evaluation of the responses. See Table 4.1 for a list of the nine MRR activities and a summary of the unit cost information.

4.1.1.2 County level questionnaire   The second procedure used to collect unit MRR costs was a questionnaire developed for mailing to Iowa county engineers. Twenty-seven of the ninety-nine Iowa counties were randomly selected to take part in the survey. These counties were

Table 4.1 Unit MRR costs collected from the Iowa DOT questionnaire

MRR Activity	District 3	District 4	District 6	Average	Final Unit Cost
1[a]	3.29	3.02	2.70	3.00	3.00
2[b]	5.63	7.10	6.67	6.47	6.47
3[c]	73.08	None	155.00	114.04	100.00
4[d]	5.11	12.75	13.00	10.29	10.00
5[e]	6.55	1.65	1.50	3.23	6.55
6[f]	0.011	0.040	0.025	0.025	0.020
7[g]	23.12	37.50	30.00	30.21	23.12
8[h]	59.68	17.25	15.00	30.64	59.68
9[i]	223.30	177.60	230.00	210.30	225.00

[a]1 = spall patching with bituminous material, $ per sq.ft.

[b]2 = spall patching with PC concrete, $ per sq.ft.

[c]3 = epoxy injection of delaminated overlays, $ per gallon (Note: $100.00 per gallon = $10.00 per sq.ft.).

[d]4 = painting steel guardrails, $ per lin.ft.

[e]5 = spot painting structural steel, $ per sq.ft.

[f]6 = cleaning deck surfaces, $ per sq.ft.

[g]7 = cleaning bridge seats, $ each.

[h]8 = cleaning and painting bearing devices, $ each.

[i]9 = cutting/filling pressure relief joints, $ each.

assumed to be a representative sample for Iowa in terms of county size and geographical location.

The initial questionnaire was mailed on February 15, 1990. However, due to a low response rate a follow-up questionnaire was prepared and mailed on May 4, 1990. Prior to the second mailing, a total of twelve responses had been received. The second questionnaire managed to bring in an additional four responses. Thirteen of the sixteen responses were either fully or partially completed, while the remaining three responses returned the questionnaire uncompleted.

The questionnaire consisted of twenty-four MRR activities which are typically performed by county maintenance crews. Fourteen of the procedures were associated with timber bridge components. Due to the very general nature of many of the MRR procedures, several assumptions were required to arrive at a unit cost. The responses varied from a simple unit cost showing no assumptions to a detailed estimate which included all assumptions regarding materials, labor and equipment. This wide range in detail resulted in a large variation in the unit MRR costs. In order to arrive at a representative cost for each MRR procedure, an individual estimate was prepared utilizing portions of various responses.

The estimates listed all required assumptions. These assumptions include: travel distance to the site, labor costs, equipment, materials, and brief procedural descriptions for selected items. The cost per hour or mile for the preceding labor and equipment costs, as well as the material costs, were taken from the questionnaire responses.

Many of the MRR procedures are highly dependent on specific assumptions which may cause the unit cost to fluctuate very widely. These assumptions include: the quantity of work to be performed, the labor cost per hour to be used, the distance traveled to the site, and the combination of two or more MRR procedures. An example of the last assumption would be the inclusion of timber deck replacement costs in the cost for timber superstructure replacement. In this case, the labor and equipment costs to remove and replace the deck should be included. However, the deck and guardrail materials are assumed to be in a salvageable condition. In the estimates prepared, these assumptions were all made based on the author's opinion.

A summary of the MRR procedures and unit costs established from the Iowa county engineer's questionnaire is presented in Tables 4.2a and 4.2b. These tables list the number of responses received, the average unit cost of the responses, and the unit cost to used (based on the prepared estimate) for each MRR procedure.

Table 4.2 Unit MRR costs collected from the Iowa county engineer's questionnaire

MRR Activity	Number of Responses	Average	Final Unit Cost
Renail individual timber deck planks, $ each	11	16.54	12.00
Replace individual timber deck planks, $ each	10	77.87	65.00
Replace entire timber deck with a plank deck, $ / sq.ft.	10	4.70	3.80
Replace entire timber deck and superstructure with a laminated deck, $ / sq.ft.	4	10.20	11.20
Repair/replace timber guardrail, $ / lin.ft.	4	3.97	4.70
Repair/replace steel guardrail, $ / lin.ft.	4	12.42	13.80
Add/replace individual timber stringers, $ / lin.ft. of stringer	4	14.04	17.50[a]
Replace entire timber superstructure, $ / lin.ft. of stringer	6	11.23	11.50[b]
Add/replace timber abutment pile, $ each	7	546.43	575.00
Add/replace timber wing pile, $ each	1	----	340.00

[a]$17.50 / lin.ft. of stringer = $105.00 / lin.ft. bridge = $350.00 / stringer.

[b]$11.50 / lin.ft. of stringer = $184.00 / lin.ft. bridge = $230.00 / stringer.

Table 4.2 (continued)

MRR Activity	Number of Responses	Average	Final Unit Cost
Replace timber abutment/ wing planks, $ each	7	213.71	160.00
Clean abutment seats, $ each	7	41.71	37.00
Replace entire timber abutment, $ / sq.ft. surface area	6	11.58	8.20[c]
Add/replace timber pier piles, $ each pile	5	453.10	780.00
Replace all timber pier piles, $ each pile	6	544.25	560.00[d]
Add/replace X-bracing on timber pier piles, $ / pier	6	249.15	370.00
Install riprap to pier or abutment footings, $ / footing	6	854.17	800.00
Remove flood debris from piers or abutments, $ each	10	273.13	270.00
Clearing and grubbing in the channel, $ / sq.yd.	7	2.46	2.25
Tighten loose bolts, $ each	6	5.00	10.20
Replace missing bolts, $ each	4	11.50	12.20
Clean concrete deck surfaces, $ / sq.ft.	7	0.065	0.050
Clean gravel-covered deck surfaces, $ / sq.ft.	6	0.081	0.080
Add gravel fill to approach roadway, $ each	6	161.33	170.00

[c]$8.20 / sq.ft. surface area = $5756.40 / abutment.

[d]$560.00 each pile = $3360.00 / pier.

4.1.1.3 Iowa DOT historical data   The next procedure used to establish unit MRR costs involved summarizing historical data collected by the Iowa DOT Contracts Department. The Contracts Department stores data for all contracted projects let each year. Information collected for each project includes a summary of all contractor's bid proposals in terms of each bid item (i.e., structural concrete, reinforcing steel, etc.). Each year, the Contracts Department summarizes the awarded contracts and compiles data pertaining to each bid item. The information compiled yearly for each bid item include: the total quantity of work performed, the total cost, and the low, high and average unit bid prices.

A total of sixteen MRR procedures were established using the Contracts Department historical data. Considerably more bid items are collected by the Contracts Department. However, the majority of the MRR procedures are a combination of several different bid items which prohibits the use of this information. The range of most unit bid prices was very large. However, this should be expected due to various contractors assigning a subjective value to each bid item (i.e., each contractor uses different labor rates, production rates, etc.). In order to account for the large variation, the average unit bid prices were utilized to establish the MRR costs.

The sixteen unit MRR procedure costs were developed from the 1988 and 1989 contract bid summaries [52, 53]. The total quantity of work and the average unit bid prices for each year were used to calculate the weighted average unit cost for the two year period. The recommended unit cost was then established based on a subjective evaluation of the weighted average and the two yearly averages. For four of the MRR procedures, two separate (but similar) unit bid categories were combined to calculate the weighted average unit cost. See Tables 4.3a and 4.3b for a list of the sixteen MRR activities and a summary of the unit cost information.

The final source used to establish unit MRR costs was historical data collected by the Iowa DOT Bridge Maintenance Department. The Bridge Maintenance Department collects data pertaining to painting contracts awarded for complete steel bridge and/or handrail painting. Information recorded include: painting contractor, total contract cost, surface area painted (sq.ft.), and type of paint system used.

Summary statistics are compiled yearly to evaluate painting costs in terms of unit costs ($ / sq.ft.). Unit painting costs are categorized according to the existing versus future paint type utilized, type of bridge, and the bridge size. Existing versus future paint categories include: red lead to zinc silicate, red lead to epoxy

Table 4.3 Unit MRR costs collected from the Iowa DOT Contracts Department

MRR Activity	1988 Average	1989 Average	Weighted Average	Final Unit Cost
Bridge floor overlay, \$ / sq.yd.	25.37	25.70	25.46	25.46
Bridge floor repair, Class A, \$ / sq.yd.	37.66	39.78	38.42	38.42
Bridge floor repair, Class B, \$ / sq.yd.	108.11	147.93	119.44	145.00
Epoxy deck injection, \$ / sq.ft.	9.60	30.00	10.14	10.14
Joints, steel extrusion with neoprene, \$ / lin.ft.	82.09	88.68	85.60	85.60
Joints, pressure relief, \$ / lin.ft.	18.86	12.50	18.54	18.54
Concrete barrier rail, \$ / lin.ft.	21.76	20.87	21.19	24.68
Concrete barrier rail, cast-in-place, \$ / lin.ft.	25.77	23.53	24.68	
Class A crushed stone, on road, \$ / ton	8.63	8.63	8.63	8.63
Riprap, \$ / ton	12.50	19.72	19.69	19.69
Deck drain extensions, \$ each	150.00	---	150.00	150.00

Table 4.3 (continued)

<table>
<tr><th>MRR Activity</th><th>1988 Average</th><th>1989 Average</th><th>Weighted Average</th><th>Final Unit Cost</th></tr>
<tr><td>Bridge approach section, reinforced, as per plan, $ / sq.yd.</td><td>56.96</td><td>60.21</td><td>57.79</td><td rowspan="2">60.00</td></tr>
<tr><td>Bridge approach section, $ / sq.yd.</td><td>52.42</td><td>52.00</td><td>52.07</td></tr>
<tr><td>Cracks, routing and sealing, Class 1, ACC surfaces, $ / lin.ft.</td><td>0.38</td><td>0.92</td><td>0.39</td><td rowspan="2">0.43</td></tr>
<tr><td>Cracks, cleaning and sealing, Class 2, ACC surfaces, $ / lin.ft.</td><td>0.43</td><td>---</td><td>0.43</td></tr>
<tr><td>Cracks, routing and sealing, Class 1, PCC surfaces, $ / lin.ft.</td><td>0.68</td><td>0.95</td><td>0.70</td><td rowspan="2">0.73</td></tr>
<tr><td>Cracks, cleaning and sealing, Class 2, PCC surfaces, $ / lin.ft.</td><td>0.71</td><td>1.13</td><td>0.73</td></tr>
<tr><td>Patches, ACC, partial-depth, $ / sq.yd.</td><td>25.82</td><td>40.32</td><td>33.76</td><td>40.00</td></tr>
<tr><td>Patches, PCC, partial-depth, $ / sq.ft.</td><td>14.51</td><td>19.61</td><td>15.04</td><td>19.50</td></tr>
</table>

aluminum, and cycled zinc silicate. Type of bridge categories include: steel beam bridges - structural steel only, steel beam bridges - structural steel and handrails, truss bridges, and handrails only. Subdivision according to bridge size is only considered for the steel beam bridge categories. Bridge size is based on the amount of surface area requiring paint. Bridge size categories include: large ($\geq$ 100,000 sq.ft.), medium (10,000 to 99,999 sq.ft.), and small (< 10,000 sq.ft.).

A summary of the painting cost data collected for 1988 and 1989 is presented in Table 4.4. This table lists the average unit painting cost in each category for both years. In order to reduce the amount of information for painting costs, recommendations were made to combine several of the painting classification categories. Combining several of the categories would allow this information to be used more easily in a BMS. The recommended categories and their associated suggested unit painting costs are presented in Table 4.5.

As stated previously, feasible MRR actions were identified for all potential deterioration/distress conditions associated with five major bridge component categories (deck, superstructure, substructure, waterway, and approach roadway). A total of 100 MRR actions were identified in these categories (several MRR actions were

Table 4.4 Unit painting costs collected from the Iowa DOT Bridge Maintenance Department, $ / sq.ft.

Red Lead to Zinc Silicate		1988 Average	1989 Average
Steel Beam Bridges, Structural Steel Only	Large	0.83	1.01
	Medium	0.81	0.96
	Small	1.21	1.03
Steel Beam Bridges, Structural Steel and Handrails	Large	----	----
	Medium	0.93	1.53
	Small	1.12	1.42
Truss Bridges		----	----
Handrails Only		3.61	----
Red Lead to Epoxy Aluminum			
Steel Beam Bridges, Structural Steel Only	Large	----	----
	Medium	----	1.16
	Small	----	1.35
Steel Beam Bridges, Structural Steel and Handrails	Large	----	----
	Medium	----	----
	Small	----	----
Truss Bridges		----	1.39
Handrails Only		----	----
Cycled Zinc Silicate			
Steel Beam Bridges, Structural Steel Only	Large	----	----
	Medium	0.35	0.54
	Small	0.48	0.78
Steel Beam Bridges, Structural Steel and Handrails	Large	----	----
	Medium	0.43	0.53
	Small	0.64	0.77
Truss Bridges		0.56	----
Handrails Only		1.64	1.47

Table 4.5 Recommended unit painting costs, $ / sq.ft.

Red Lead to Zinc Silicate or Red Lead to Epoxy Aluminum	Recommended Unit Cost
Steel Beam Bridges, Structural Steel Only	1.10
Truss Bridges and Steel Beam Bridges, Structural Steel and Handrails	1.50
Handrails Only	3.60
Cycled Zinc Silicate	
Steel Beam Bridges, Structural Steel Only	0.75
Truss Bridges and Steel Beam Bridges, Structural Steel and Handrails	0.75
Handrails Only	1.50

used more than once for similar deterioration/distress conditions on different bridge elements). Unfortunately, unit MRR costs could not be established for all of the MRR actions identified. The four sources used to establish unit MRR costs accounted for 63 of the 100 MRR actions. At the request of the project advisory committee, the remaining 30 unidentified unit MRR costs (includes 7 duplicate MRR actions) are to be left blank until more historical data can be gathered at the Iowa DOT. A complete listing of the deterioration/distress conditions for each category, associated unit measurement procedures, and associated unit cost (if available) is presented in Appendix A.

4.1.2 Iowa improvement action costs

As stated previously, improvement actions are associated with various level-of-service characteristic deficiencies. The level-of-service characteristics identified for Iowa include: load capacity, clear deck width, vertical clearance above and below the bridge, and the horizontal underclearance (see Chapter 3). In order to eliminate deficiencies associated with these characteristics, improvement actions typically involve major rehabilitation or the complete replacement of a bridge. Due to the complex nature of improvement actions, the evaluation of their costs are much more difficult to assess than the costs associated with MRR activities (i.e., improvement actions are much more case-specific).

Feasible improvement alternatives were established for each of the level-of-service characteristic deficiencies. Bridges with insufficient load capacity can either be strengthened or replaced. Bridges with narrow deck widths can either be widened or replaced. Bridges with insufficient vertical clearance above the structure (i.e., high trusses) should be replaced, rehabilitation is not a feasible alternative. Bridges with insufficient vertical clearance below the structure can be raised or replaced. Finally, bridges with narrow horizontal underclearances should be replaced, rehabilitation is not a feasible alternative.

The unit costs associated with each of the improvement actions were investigated using several sources of information [18, 24, 52, 54, 55]. As stated previously, there are no feasible rehabilitation alternatives to increase the horizontal underclearance or the vertical clearance above a bridge. Therefore, the costs related to these improvement actions were not investigated. In addition, bridge rehabilitation projects which are designed to increase load capacity are extremely case-specific (i.e., highly dependent on the specific strengthening procedure) [54]. Therefore, the costs associated with bridge strengthening were not investigated. The three remaining improvement actions (widening, raising and total replacement) are also case-specific procedures, however, unit costs for these actions have been approximated.

An extensive review of bridge widening costs was performed in Reference [24] (Pennsylvania BMS Final Report); unit costs for bridge widening in 10 states were reported. The unit costs were based on data for 61 projects during the years from 1977 to 1985. The costs reported varied from $60 to $280 / sq.ft.; these costs are based on the square feet of deck area added (i.e., existing bridge length times additional width). A more descriptive, and perhaps useful, quantity included in Reference [24] was the ratio of bridge widening unit cost versus total bridge replacement unit cost; these ratios varied from 0.92 to 2.80 with an average of 1.82.

The bridge widening unit cost recommended for use in Iowa was based on the ratio of widening versus replacement cost. This procedure was used in order to eliminate the effects of using old data and data from states other than Iowa. A ratio of 2.0 was used to establish the bridge widening cost for Iowa. Therefore, based on a total bridge replacement cost of $50.00 / sq.ft. (developed later), a bridge widening cost of $100 / sq.ft. is suggested for use in Iowa.

Due to the complex nature of bridge raising, this activity is seldom performed, and the associated unit cost is extremely case-specific. However, data collected by the Iowa DOT Contracts Department indicate that five bridge raising projects were performed in 1988 [52]. The cost of these projects range from $8,240 to $25,000 / project with an average cost of $15,508 / project. Based on this limited data, a bridge raising cost of $15,500 / project is suggested for use in Iowa.

The costs associated with total bridge replacement projects have been investigated much more thoroughly than the two previous improvement procedures. Three sources of information were used to establish total bridge replacement costs for Iowa. An existing formula for the calculation of bridge replacement costs used by the Iowa DOT Office of Program Management and bridge replacement cost procedures used in North Carolina and Pennsylvania were evaluated [18, 24, 55].

The existing formula used by the Iowa DOT Office of Program Management considers a unit cost of either $40 or $50 / sq.ft. for deck surface area and three additional fixed costs [55]. The deck surface area of a proposed replacement bridge is based on a constant value of 44 ft. for the width. However, the proposed bridge length is a function of the existing bridge length. The criteria used to estimate bridge length are as follows:

Existing Length ≤ 75 ft.	New Length = 2.0 x Existing
Existing Length = 76-250 ft.	New Length = 1.5 x Existing
Existing Length > 250 ft.	New Length = 1.0 x Existing

This criteria is used to account for either an increase in hydraulic capacity or an increased horizontal underclearance. The unit cost used in the formula depends upon the proposed bridge length. If the proposed length is ≤ 250 ft., then a unit cost of $40.00 / sq.ft. is used. Whereas, if the proposed bridge length is > 250 ft., then a unit cost of $50.00 / sq.ft. is used. The unit cost used is intended to account for the difference in bridge type construction as related to bridge length (i.e., short spans versus long spans). Finally, fixed costs, which include $5,000 for right-of-way (ROW) acquisition, $20,000 for grading and $25,000 for paving, are included to account for these expenditures.

The procedures used to calculate bridge replacement cost in North Carolina and Pennsylvania [18, 24] are similar to the Iowa system. A unit cost is used to calculate the cost related to bridge size, and various fixed costs are included to account for additional expenses. The unit costs used in North Carolina and Pennsylvania are $43 and $82 / sq.ft. respectively. These unit costs vary widely, however, both values should be considered specific to their respective states. Fixed costs considered by North Carolina and Pennsylvania include: ROW costs, approach roadway costs (i.e., grading and paving), and a cost associated with the design and construction engineering expenses. Therefore, the only difference between these procedures and the existing Iowa procedure is the inclusion of a cost to account for design and construction engineering.

Upon comparison of the procedures used in North Carolina and Pennsylvania, the existing Iowa procedure is a sufficient approximation. However, it would seem that the inclusion of a cost to account for design and construction engineering fees should be included. In North Carolina, this cost is calculated as 12% of the replacement base cost (i.e., unit cost times deck surface area). Whereas, in Pennsylvania, this cost is considered as 20% of the base cost plus approach roadway cost. Therefore, based on these two procedures, a design/construction engineering fee of 15% of the base cost is suggested for inclusion in the calculation of Iowa total bridge replacement cost.

As stated previously, the costs associated with improvement actions are highly variable due to their inherent case-specific nature. Therefore, these costs should be regarded strictly as approximations of the required costs. A summary of the level-of-service characteristics, feasible improvement alternatives, and associated unit cost (if available) for Iowa is presented in Table 4.6.

4.2 Agency Costs Software

A computer software program was developed which prepares a cost estimate for any combination of the agency costs previously described. The menu-driven program is based on a unit measurement/cost format for the MRR and improvement activities identified for Iowa. Additional details pertaining to the program's development are presented in Appendix B.

Table 4.6 Iowa improvement costs

Level of Service Characteristic	Improvement Alternative	Improvement Cost
Load Capacity	Strengthening	Case Specific
	Replacement	$40-50 / sq.ft. plus fixed costs
Clear Deck Width	Widening	$100 / sq.ft.
	Replacement	$40-50 / sq.ft. plus fixed costs
Vertical Above Clearance	Replacement	$40-50 / sq.ft. plus fixed costs
Vertical Below Clearance	Bridge Raising	$15,500 each
	Replacement	$40-50 / sq.ft. plus fixed costs
Horizontal Underclearance	Replacement	$40-50 / sq.ft. plus fixed costs

5. USER COSTS

User costs are the costs incurred by the roadway user due to various level-of-service characteristic deficiencies. As stated in Chapter 1, user costs are an important variable that must be included in the economic analysis of project alternatives. User costs can be attributed 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 which cause vehicle detours include bridges with a reduced load capacity and/or insufficient vertical clearance, while increased accident rates are primarily associated with bridges which have a deficient deck width.

In order to include a bridge's user costs in an economic analysis, user costs must be established on an annual basis. The annual user cost associated with vehicle detours is calculated using the following equation:

$$\begin{aligned} AUCD = {} & (ADT \times 365\ \frac{days}{year}) \times (\%\ Vehicles\ Detoured) \\ & \times (Vehicle\ Operating\ Cost,\ \frac{\$}{vehicle\ mile}) \\ & \times (Detour\ Length,\ miles) \end{aligned}$$

where: AUCD = annual user cost due to detours

In order to establish the percentage of vehicles that must detour a given bridge, the distribution of ADT as related to vehicle weight and vehicle height must be known. The annual user cost associated with accidents is calculated using the following equation:

$$AUCA = (ADT \times 365\ \frac{days}{year}) \times (\Delta\ Accident\ Rate,\ \frac{accidents}{vehicle}) \times (Accident\ Cost,\ \frac{\$}{accident})$$

where: AUCA = annual user cost due to accidents

Δ Accident Rate = incremental change in accident rates

The incremental change in accident rates is associated with an increase in deck width from the present deficient value to the desirable level-of-service goal value. Furthermore, accident rates are typically reported in terms of accidents per 100 million vehicles.

Three of the variables used in the preceding annual user cost equations were investigated: vehicle operating costs, accident costs, and accident rates. In addition, ADT growth rates were also investigated (which are used to predict user costs in the future). However, ADT distributions with regard to vehicle weight and height were not investigated, see Reference [18] for additional information.

5.1 Vehicle Operating Costs

Most recent BMS research projects recognize that user costs due to vehicle detours should be included in the economic analysis of project alternatives. However, only Reference [18] defines a procedure for the calculation of these costs. Therefore, this procedure was used as a model for the development of Iowa's vehicle operating costs.

In Reference [18], vehicle operating costs were established as a function of the vehicle weight. This type of format (i.e., cost versus weight) was used to facilitate the calculation of total vehicle operating costs for a bridge with a known posted load limit. The procedure involved the calculation of vehicle operating costs for a minimum weight vehicle and a maximum weight vehicle, then, a linear relationship was assumed to exist between these values.

For the development of Iowa's vehicle operating costs, a minimum vehicle weight of 3.0 tons, which corresponds to the minimum allowable load before a bridge must be closed, was utilized. A maximum vehicle weight of 40.0 tons was used, which represents the maximum allowable load (operating rating) for a standard HS type truck load. Vehicle operating costs were established for each vehicle weight classification and a linear relationship was assumed to exist between the two values.

The vehicle operating costs for Iowa were based on a report published by the Iowa DOT Division of Planning and Research [56]. The report established the cost per mile to operate nine types of vehicles. Vehicle expenses included in this study were depreciation, finance charges, taxes and registration, fuel, tires, repairs and maintenance, insurance, and miscellaneous expenses. The cost established for the 3.0 ton vehicle was based on an average of the costs for a cargo van and a standard size pickup. The cost established for the 40.0 ton vehicle was taken as the cost for a 5-axle truck-tractor semi-trailer (TTST) combination.

An additional expense that should be accounted for in the calculation of vehicle operating costs is the cost of the driver. The driver cost for the 3.0 ton vehicle was assumed to be $12.00 per hour. This corresponds to the average wage rate for a county-employed laborer (as determined from the county-level questionnaire described in section 4.1.1.2). The driver cost for the 40.0 ton vehicle was assumed to be $18.10 per hour. This was based on the national average for heavy truck drivers [57]. These values were converted to $ per mile using a vehicle speed of 40 miles per hour [18].

The total vehicle operating costs established for Iowa were $0.65 per mile for the 3.0 ton vehicle and $1.23 per mile for the 40.0 ton vehicle. These values correspond rather well with the values calculated in Reference [18], a comparison of the two sets of vehicle operating costs are shown in Table 5.1. The linear relationship that was assumed for the Iowa data can be represented by either of the following equations:

$$VOC = 0.65 + [\frac{(1.23 - 0.65)}{(40.0 - 3.0)} \times (VW - 3.0)]$$

or

$$VOC = 0.65 + [0.015676 \times (VW - 3.0)]$$

where: VOC = Vehicle Operating Cost, $ per mile

VW = Vehicle Weight, HS type loading, tons

A graphical representation of the vehicle operating cost versus vehicle weight relationship for Iowa is shown in Figure 5.1.

5.2 Accident Costs

The user costs due to accidents may have a profound influence on the economic analysis of project alternatives; the extent of their influence depends upon the value associated with each accident and the reduction in accidents at a particular bridge. An average accident cost for use in Iowa is presented in this section, while accident rates will be detailed in the following section.

Table 5.1 Vehicle operating costs, $ / mile

	Iowa (1990 data)	Reference [18] (1987 data)
Minimum Weight Vehicles:		
Vehicle Cost	0.35	0.20
Driver Cost	0.30	0.15
Total Cost	0.65	0.35
Maximum Weight Vehicles:		
Vehicle Cost	0.78	0.81
Driver Cost	0.45	0.34
Total Cost	1.23	1.15

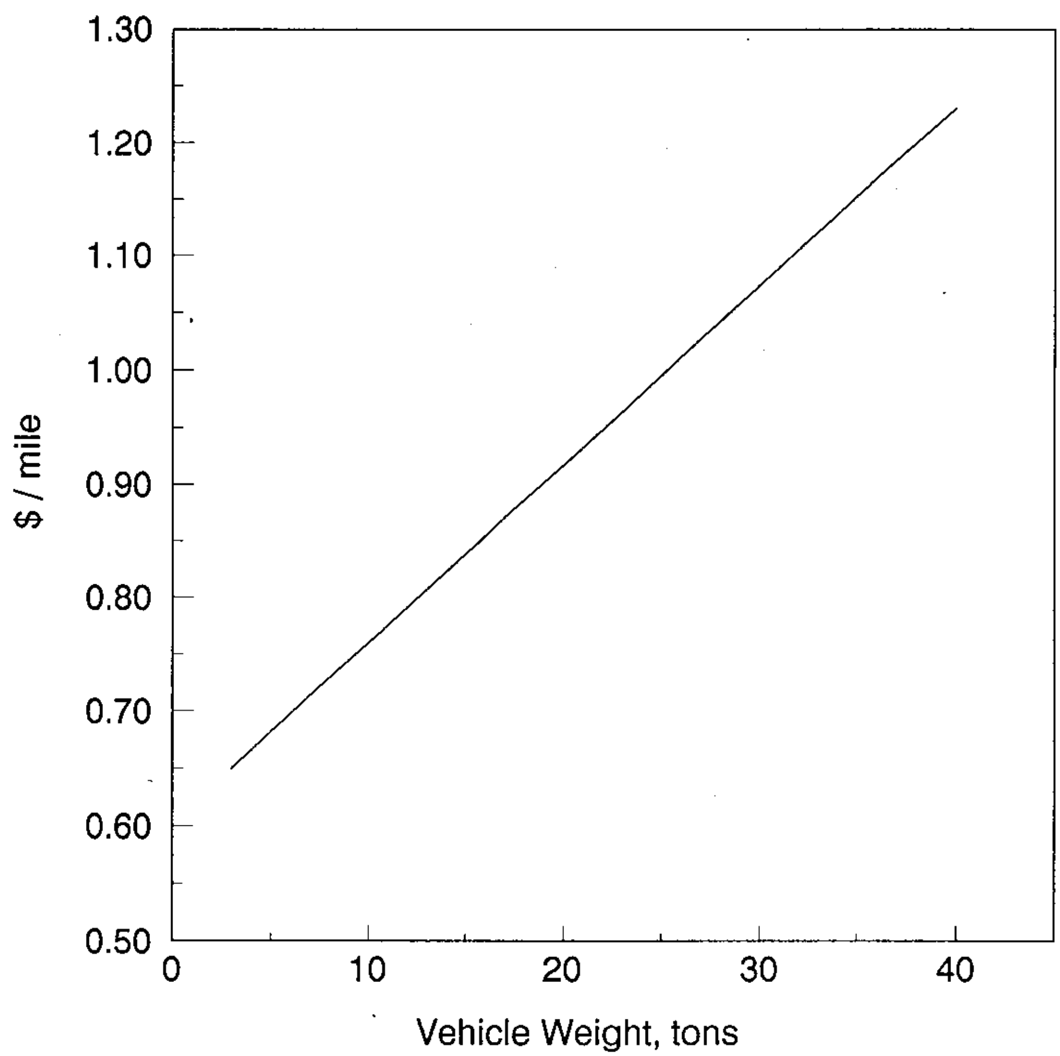

Figure 5.1 Iowa vehicle operating costs

Accident costs are typically defined in terms of the severity of accident (i.e., fatality, major injury, etc.). However, when predicting the number of future accidents or the reduction in accidents at a specific location, the distribution of accidents according to severity is unknown. Therefore, in order to include accident costs in an economic analysis, an average accident cost value must be determined.

Accident cost data for Iowa was obtained from the Iowa DOT Bureau of Transportation Safety. The costs associated with five accident severity categories, as well as a weighted average accident cost, were established. The accident costs presently used by the Iowa DOT Bureau of Transportation Safety are as follows: $500,000 per fatality, $100,000 per major injury, $6,000 per minor injury, $1,500 per possible injury, $1,000 for property damage only, and a weighted average of $16,500 per accident. The weighted average accident cost of $16,500 per accident should be used in the determination of user costs for economic analysis.

5.3 Accident Rates

As stated previously, the accident rate associated with a bridge is primarily a function of deck width. Several studies have been completed which investigate the relationship between accident rate versus bridge width. Four previous studies were evaluated in order to determine if existing information could be utilized to establish accident rates for Iowa.

The first study was performed in Colorado over a four year time period, during which 94 accidents occurred [58]. Two hundred nineteen bridges located on rural two-lane primary roads were used in the analysis. The results were presented in the form of the following quadratic equation which relates the number of accidents per 100 million vehicles to bridge width:

$$ACC = 100 \times [0.387 - (0.10)(BW - 25) + (0.009)(BW - 25)^2]$$

where: ACC = accidents per 100 million vehicles

BW = bridge width, feet

A second study performed by Jorgenson and Westat investigated accident rates in terms of the relative bridge width [58]. The relative bridge width was defined as the curb to curb bridge width minus the approach roadway width. Details concerning the type and amount of data used in the analysis were not included in Reference [58]. Accident rates were provided for relative bridge widths over a range of -6.0 ft. to +12.0 ft. The relative bridge widths were converted to actual bridge widths (for comparison purposes) by using a standard approach roadway width of 24.0 ft. The accident rates determined in the Jorgenson/Westat study are shown in Table 5.2.

Table 5.2 Jorgenson/Westat study accident rates

Relative Bridge Width[a], ft.	Actual Bridge Width, ft.	Accidents per 100 Million Vehicles
-6	18	120
-4	20	103
-2	22	87
0	24	72
2	26	58
4	28	44
6	30	31
8	32	20
10	34	12
12	36	7

[a]relative bridge width = (actual bridge width) - (approach roadway width = 24 ft.).

Table 5.3 Mak/Brinkman study accident rates

Bridge Width, ft.	Accidents per 100 Million Vehicles
< 18	188
18 - 20	104
20 - 22	119
22 - 24	82
> 24[a]	75
> 24[b]	66
> 24[c]	59

[a]shoulder reduction > 50%.

[b]shoulder reduction ≤ 50%.

[c]no shoulder reduction.

The third accident rate study that was evaluated was performed by Mak and Brinkman [59]. This study included data from Arizona, Michigan, Montana, Texas and Washington. A three-year study period was utilized during which 24,809 accidents occurred on 11,880 bridges. The large quantity of data permitted the subdivision of the data according to single versus twin structures, divided versus undivided traffic, number of lanes, and bridge width. The data set utilized for comparison with other studies was for single, undivided, 2-lane structures. Accident rates were reported in 2 ft. width ranges; for widths greater than 24 ft., bridges were subdivided according to the percent shoulder reduction. A summary of the accident rates for single, undivided, 2-lane structures is presented in Table 5.3.

The final accident rate study evaluated was performed by Chen and Johnston [18]. Details concerning the amount and type of data used in the analysis were not included in Reference [18]. Accident rates were reported in 2 ft. width ranges (similar to the Mak and Brinkman study). In addition, accident rates were determined for four ADT ranges: 201-800, 801-2000, 2001-4000, and >4000. In general, the accident rates determined in Reference [18] were substantially lower than those determined in the other three studies. A summary of the accident rates for each ADT range, as well as the maximum value for each width range, is presented in Table 5.4.

A spot check of Iowa accident rates versus bridge width was conducted to determine if one of the existing studies could be utilized in Iowa. A random sample of 24.0 ft. bridges were investigated. The bridge sample was divided among four roadway functional classification categories. The sample consisted of eight bridges on interstates and/or principal arterial routes, eight bridges on minor arterial routes, seventeen bridges on major and/or minor collector routes, and fifteen bridges on local routes. General data for each bridge (i.e., maintenance number, roadway functional classification, and ADT) were obtained from the Iowa DOT bridge data file, whereas accident data for each bridge were collected by the Iowa DOT Bureau of Transportation Safety. Accident data were available for a five-year period from 1985 to 1989. This data was used to establish the accident rates for each of the functional classification categories, as well as a total accident rate for all data. The accident rates per 100 million vehicles determined for Iowa data are as follows:

Interstates and Principal Arterials = 29.42

Minor Arterials = 26.62

Major and Minor Collectors = 48.09

Local Routes = 33.93 Total = 29.93

Table 5.4 Chen/Johnston study accident rates

Bridge Width, ft.	Accidents per 100 Million Vehicles				
ADT	201 to 800	801 to 2000	2001 to 4000	>4000	Max. Value
≤ 16	22.6	112.2	71.3	0.3	112.2
16 - 18	22.5	66.5	76.5	46.0	76.5
18 - 20	17.3	30.9	27.7	19.4	30.9
20 - 22	12.5	19.5	19.5	32.4	32.4
22 - 24	15.3	16.7	12.1	12.2	16.7
24 - 26	0	8.6	2.3	10.3	10.3
26 - 28	0	0	1.8	10.5	10.5
28 - 30	0	8.8	2.7	8.0	8.8
30 - 32	0	0	0	4.0	4.0
32 - 34	0	0	0	9.4	9.4
34 - 36	0	11.1	6.9	1.8	11.1
36 - 38	0	0	5.2	6.8	6.8
38 - 40	0	5.2	5.9	2.2	5.9

In order to compare the Iowa spot check value with the four existing studies, the accident rates for each study and the Iowa spot check value were plotted (see Figure 5.2). The equation developed for use with the Colorado data reaches a minimum value at 30.5 ft.; therefore, in Figure 5.2 the accident rate was assumed to remain constant for bridge widths greater than 30.5 ft. In addition, for bridge widths greater than 24.0 ft., the Mak/Brinkman study values are for bridges with no roadway restriction. Finally, the values shown for the Chen/Johnston data are the maximum accident rates for the four ADT ranges.

The spot check of 24 ft. Iowa bridges establishes that Iowa accident rates are of the same magnitude as determined in previous studies. The Iowa spot check falls between the Colorado and Chen/Johnston data; thus, a preliminary recommendation would be to utilize one of these data sets. The Colorado data curve represents the more conservative approach (i.e., a higher level of predicted accidents), therefore, this curve is recommended for use in Iowa. However, the best recommendation for the given information would be to collect more Iowa data before making a final recommendation. A spot check of two or three additional bridge widths would likely establish a definite trend toward one of the existing studies.

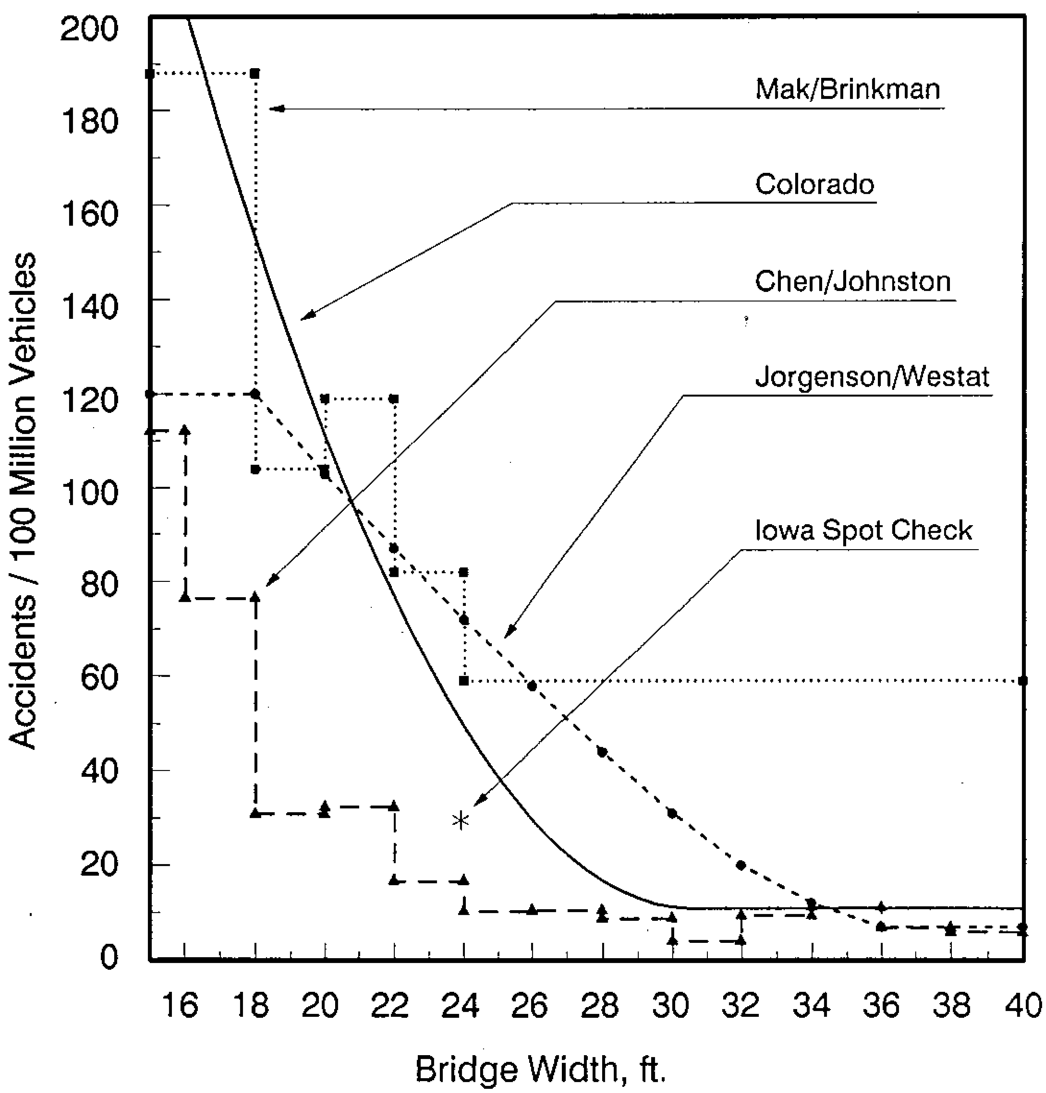

Figure 5.2 Comparison of accident rate studies

5.4 ADT Growth Rates

ADT growth rates represent the yearly percentage increase or decrease in traffic volume for a specific roadway. ADT growth rates are used to adjust current traffic volumes to future values. Future traffic volumes are important in the calculation of user costs over the life of a structure.

ADT growth rates vary according to the primary function of the roadway (i.e., long distance travel vs. local trips), as well as the mixture of vehicle types that utilize the roadway. Therefore, ADT growth rates should be determined for various roadway functional classifications.

ADT growth rates for Iowa roadways are currently calculated by the Iowa DOT Transportation Inventory Department. Data are collected by continuous automatic traffic recorders located throughout the State. The data are used to calculate the ADT growth rate for six roadway functional classifications: rural and municipal Interstates, primary routes and secondary routes. Data were provided by the Iowa DOT Transportation Inventory Department for the years of 1984-85 through 1988-89; a summary of this information is provided in Table 5.5.

Table 5.5 Iowa ADT growth rates

	Yearly % Change in Traffic Volume					
	84/85	85/86	86/87	87/88	88/89	Average
Rural Interstates	+2	+3	+5	+8	+6	+4.8
Rural Primary	0	+4	+4	+3	+4	+3.0
Rural Secondary	+1	0	+5	-2	+1	+1.0
Rural Total	+1	+2	+4	+3	+3	+2.6
Municipal Interstates	+2	+1	+5	+7	+3	+3.6
Municipal Primary	+1	+1	0	+4	+3	+1.8
Municipal Streets	+1	+1	+2	+4	+4	+2.4
Municipal Total	+1	+1	+2	+4	+3	+2.2
State Total	+1	+2	+3	+3	+3	+2.4

6. DETERIORATION MODELS

The prediction of bridge performance is an important aspect of a complete BMS. Bridge performance can be measured in several ways; however, the most common measure of bridge performance is the FHWA bridge component condition ratings (see chapter 1). Hence, previous bridge deterioration studies have primarily used the FHWA condition ratings as a measure of bridge performance (see section 6.2). The prediction of component condition ratings can be used to determine the service life of a new bridge, the remaining life of an existing bridge, or the time when future rehabilitation will be required.

In the United States, a few studies have been conducted to predict bridge deterioration (see section 6.2). However, these studies yielded simple linear or piece-wise linear deterioration curves. These deterioration curves are unique to the states studied and cannot be used nationwide to predict bridge performance. Thus, there is an urgent need to predict the future condition of bridges within the state of Iowa. Such a deterioration model should be reliable and should reflect the effect of any maintenance, repair or rehabilitation on the bridge condition ratings.

6.1 Review of Existing Deterioration Models

This section briefly summarizes some of the existing bridge deterioration prediction models that have been developed.

6.1.1 Transportation Systems Center

The Transportation Systems Center (TSC) used data from the NBI to develop bridge deterioration curves utilizing a multiple linear regression technique [11]. In the model, data were first screened to filter out any duplication, records with missing or miscoded data, and data recorded for bridges more than 25 years old. The effects of bridge age, ADT, structure type, number of spans, and skew angle on the bridge component condition ratings were considered. A constraint was imposed to insure that the model yielded a condition of 9 at year 0 (i.e., perfect condition for a new bridge).

The TSC study concluded that age and ADT were the most significant factors that influence the rate of bridge deterioration. The multiple linear regression equations which were developed for the component condition ratings are:

$$DCR = 9.0 - (0.119)(AGE) - (2.158\times10^{-6})(ADTAGE)$$

$$SUBCR = 9.0 - (0.105)(AGE) - (2.051\times10^{-6})(ADT)$$

$$SUPCR = 9.0 - (0.103)(AGE) - (1.982\times10^{-6})(ADT)$$

where: DCR = deck condition rating

SUBCR = substructure condition rating

SUPCR = superstructure condition rating

AGE = bridge age

ADT = average daily traffic

$$ADTAGE = \frac{(ADT)(AGE)}{10}$$

The TSC deterioration curves indicate that decks deteriorate slightly faster than the substructure or superstructure. In general, deck deterioration is approximately 1 condition rating point in 8 years, while substructure and superstructure deterioration is approximately 1 condition rating point in 10 years.

6.1.2 Massachusetts Institute of Technology

The Massachusetts Institute of Technology (MIT) study of bridge deterioration was somewhat similar to TSC's [11]. In their study, the researchers at MIT used statistical techniques such as binary linear probability estimation, ordered binary linear probability estimation, and logit estimation to overcome the discreteness of the condition scales. The model accounted for the nonlinear behavior of the deterioration conditions of a bridge. In this model, the dependent variable was not a condition (a value from 9 to 0), but rather a probability from 0 to 1. The slope of the curve within some regions was positive indicating the effect of maintenance, repair or rehabilitation on the bridge condition.

6.1.3 Wisconsin Department of Transportation

The Wisconsin Department of Transportation's (WisDOT) prediction model used a 3-step piece-wise linear regression technique to develop bridge deterioration curves [11]. This model only considered the effects of bridge age and structure design type on the FHWA structural condition appraisal rating. Deterioration curves were developed for the following bridge types: steel deck girders, all other steel design types, prestressed concrete, reinforced concrete deck girders, concrete slabs, and culverts. In addition, a single deterioration curve was developed which considered all Wisconsin bridges (see Figure 6.1). Some of the regression curves have slightly positive slopes in the middle portions indicating the effect of maintenance, repair or rehabilitation on the bridge condition. In addition, no constraints were imposed to insure that the model yielded a condition of 9 at year 0; therefore, the predicted condition

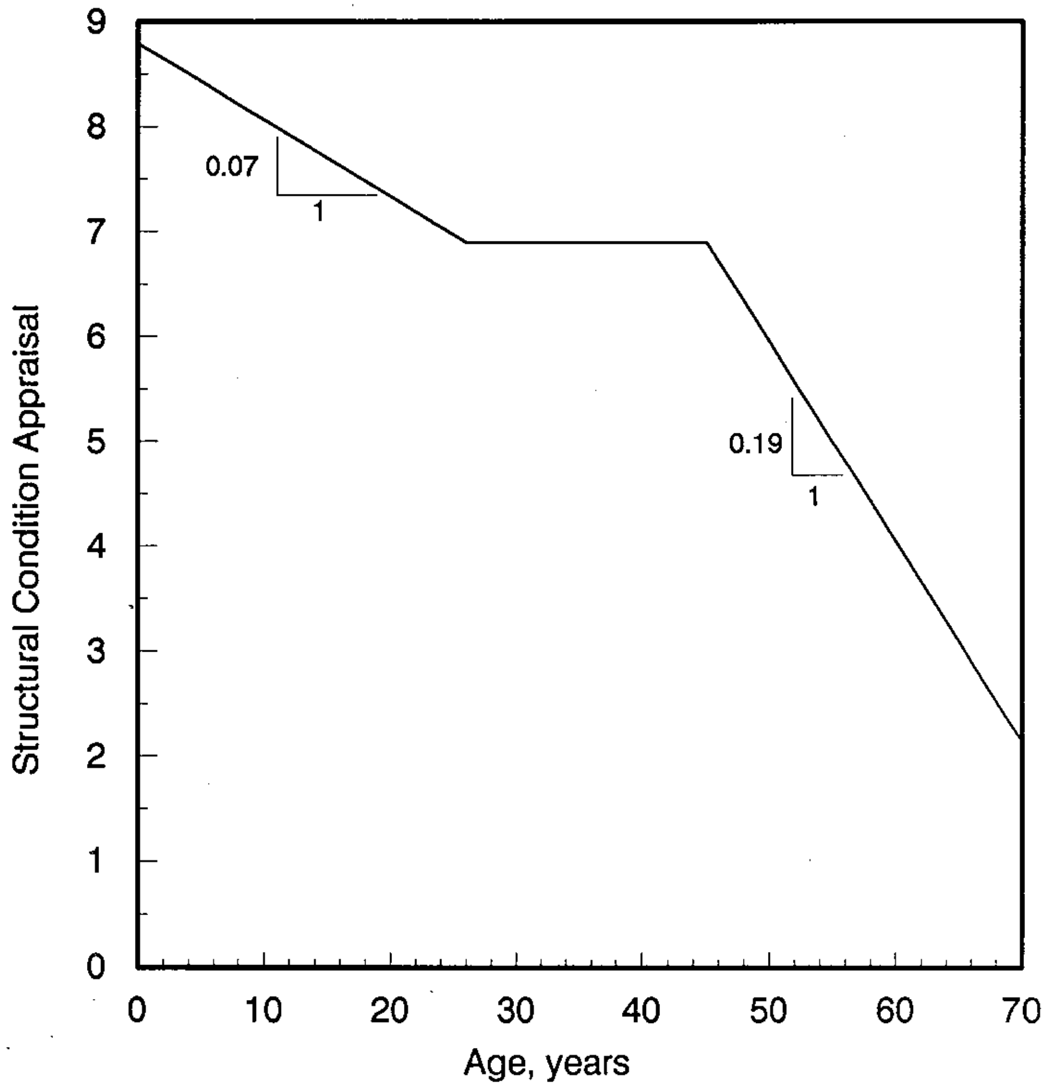

Figure 6.1 Wisconsin DOT deterioration curve

at year 0 was between 6.5 and 8.5. The average service life of bridges predicted by the WisDOT model was about 60 years.

6.1.4 New York Department of Transportation

The New York Department of Transportation's (NYDOT) deterioration model was developed using a two-step piece-wise linear regression technique [11]. The overall bridge condition rating used by the NYDOT is based on a scale of 7 to 1, rather than 9 to 0. The NYDOT developed two curves using data from the years 1977/78 and 1979/80. The results gave two distinct parallel curves as shown in Figure 6.2. Once again, the lack of initial constraints resulted in the prediction of an initial condition of approximately 6.8, rather than the NYDOT new bridge condition rating of 7.

6.1.5 North Carolina State University

In a project for the North Carolina DOT (see section 2.5), North Carolina State University (NCSU) developed a 3-step piece-wise linear bridge deterioration model [18]. The NCSU model was established using an expert opinion survey of North Carolina bridge inspectors and maintenance supervisors. Deterioration rates were established for the component condition ratings with respect to various combinations of the following variables: material type, ADT, structure type, type of roadway system, and geographical

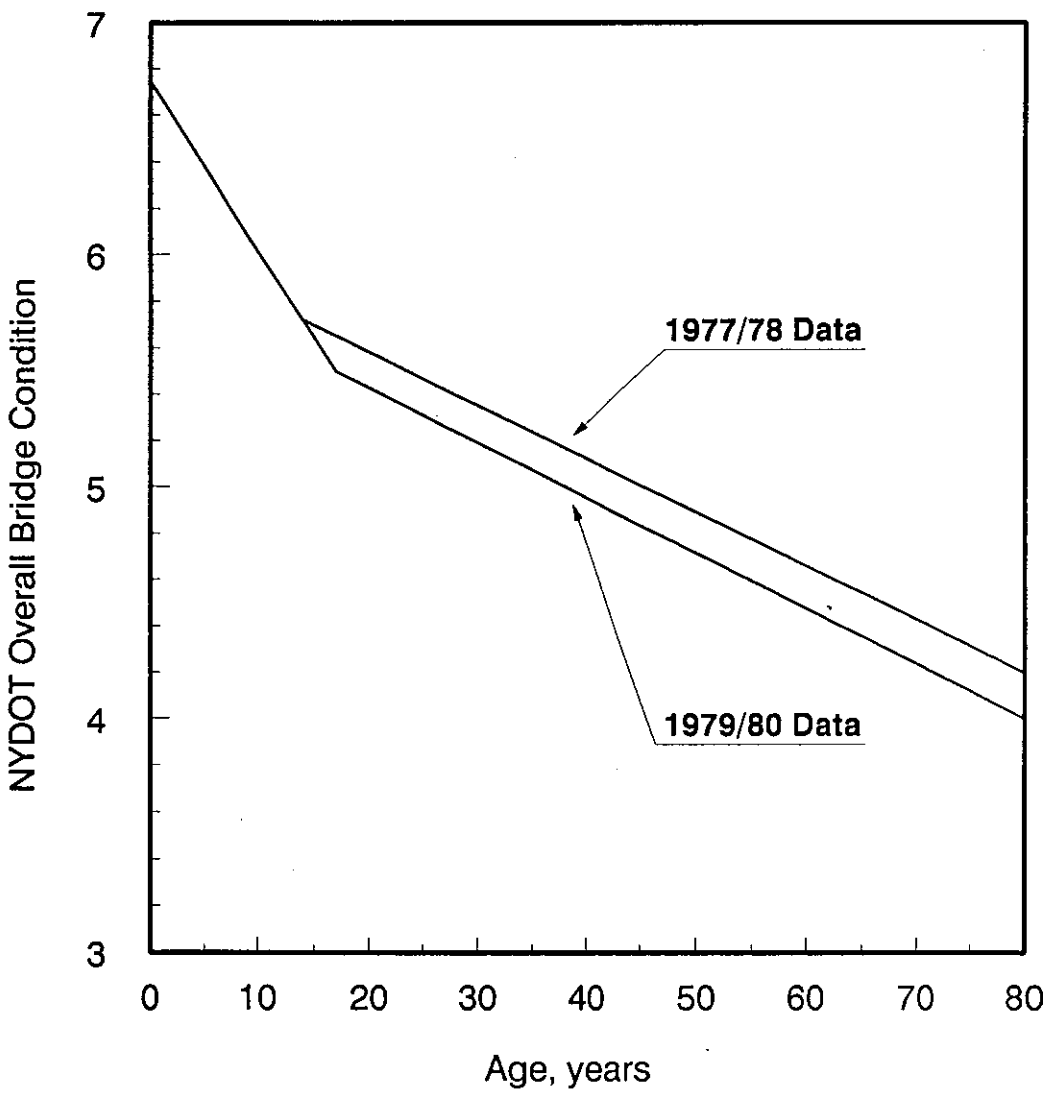

Figure 6.2 New York DOT deterioration curve

region. Table 6.1 illustrates the deterioration rates which were established for timber and reinforced concrete decks. In Table 6.1, the deterioration rates represent the time required for the deck condition to deteriorate 1 condition rating point. For example, for timber decks with ADT less than 200 it takes 5 years to deteriorate from condition 9 to condition 8, 5.7 years to deteriorate from condition 8 to condition 7, etcetera. Similar tables were developed for the superstructure and substructure condition ratings.

6.1.6 FHWA Bridge Management Systems - Phase I

The bridge performance prediction model developed by the FHWA utilized the NBI database to establish deterioration rates [11]. A two-step piece-wise linear regression technique was employed to establish the deterioration rates associated with the deck condition rating and the structural condition appraisal rating. The results from this study suggest that the deck condition declines at a rate of 0.104 per year for approximately the first 10 years and 0.025 per year for the remaining years, while the structural condition declines at a rate of 0.094 per year for approximately the first 20 years and 0.025 per year for the remaining years. The deterioration rates determined in this study indicate that the deck and structural condition ratings would only be slightly less

Table 6.1 North Carolina State University deck deterioration rates

Material	ADT	Deterioration Rate (Years/Point)		
		Rating 9 - 8	Ratings 8 - 5	Ratings 5 - 3
Timber	≤ 200	5.0	5.7	3.6
	201-800	5.0	4.9	3.6
	801-2000	5.0	3.9	3.2
	2001-4000	5.0	3.0	3.0
	> 4000	5.0	2.6	2.6
Reinforced Concrete	≤ 200	5.0	9.7	6.5
	201-800	5.0	9.0	6.3
	801-2000	5.0	8.0	5.6
	2001-4000	5.0	7.4	5.5
	> 4000	5.0	6.4	5.2

than 6 after 60 years. The slow rate of deterioration is due to the inclusion of all bridges from the NBI database in the analysis. Therefore, the effects of maintenance, repair and rehabilitation have not been filtered out.

6.1.7 Virginia Transportation Research Council

The Virginia Transportation Research Council (VTRC) study used a multiple linear regression technique to develop bridge deterioration equations for the component condition ratings [60]. Based on suggestions from bridge engineers within VTRC, bridges were classified according to steel beam bridges with timber or concrete decks, concrete beam bridges with concrete decks, and concrete box girder bridges. These four types of bridges were investigated with respect to various combinations of the following variables: age, traffic volume, rate of chloride application, number of spans (single versus multispan), and type of roadway system (primary versus secondary). For example, two of the equations developed to predict concrete deck deterioration are as follows:

$$DCR = 9.0 - (0.41)(SYSTEM) - (0.42)(SPANS) - (1.23)(LOGAGE)$$

or

$$DCR = 9.0 - (0.36)(SPANS) - (0.86)(LOGAGE) - (0.11)(LOGCTV)$$

where: DCR = deck condition rating

SYSTEM = type of roadway system
(primary = 1, secondary = 0)

SPANS = number of spans
(multispan = 1, single span = 0)

LOGAGE = log of the bridge age in years

LOGCTV = log of the cumulative traffic volume

The authors did not recommend which of the two previous equations should be used to predict deck condition. Several similar equations were developed for the superstructure and substructure component condition ratings. The results of this study suggest that bridge age is the most significant bridge deterioration variable. However, a multiple linear regression approach allows for variables other than age to be tested for their influence on bridge deterioration.

6.1.8 Purdue University

In a project for the Indiana Department of Highways (IDH), Purdue University developed a deterioration model based upon the Markov chain probabilistic approach (see section 6.2 for details concerning Markov chain analysis) [61, 62, 63]. A zoning technique was used to approximate the nonhomogeneous nature of the Markov chain problem by using a six-year step-wise homogeneous Markov chain model. Polynomial regression and nonlinear programming techniques were employed to establish the transition probabilities which are essential for the Markov chain model. The transition probabilities were determined by minimizing the differences between the predicted mean from the Markov chain analysis and the polynomial regression function.

Factors that affect bridge condition, such as roadway functional classification, structure type (concrete versus steel), traffic volume, and climatic region, were considered. The last two factors were found to statistically insignificant. The deterioration rates associated with the component condition ratings were studied with respect to the preceding factors.

The study compared the average future conditions predicted by the Markov chain model and those of the polynomial regression model. The comparison yielded close results, however, the study did not provide a statistical distribution of future bridge conditions or a prediction of the remaining life for an existing (rather than new) bridge.

6.1.9 Evaluation of existing deterioration models

All of the regression models previously discussed are easy to understand and easy to use. However, except for the IDH model which used Markov chain analysis, all of the models neglect the variabilities in performance among individual bridges and may yield inaccurate results when used beyond the available data region. Also, these models may underestimate or overestimate the future condition of bridges whose current condition is not on the prediction curve [61, 62, 63]. In addition, a condition rating other than 9 at age 0 may be obtained unless a constraint is imposed during the formulation of these models. On the other hand, a constrained linear regression model may yield inaccurate prediction results.

The deterioration model developed for Iowa was based on the probabilistic Markov chain approach. A probabilistic approach such as the Markov chain concept has certain advantages over regression techniques. A Markov model can simulate the nonlinear nature of the deterioration rates of bridges [61, 62, 63]. Furthermore, information such as the statistical distribution, range and predicted mean can be estimated using the Markov chain method (this information was not included in the IDH model). The Markov model for Iowa has been formulated to predict the future conditions of bridges that have conditions which deviate from the average Markov curve and to provide the statistical distribution of future conditions.

6.2 Introduction to Markov Chain

Markov chain analysis is a probabilistic approach that has been successfully used in pavement management [64] and other prediction models for condition ratings [61, 62, 63].

Markov chain, as applied to bridge performance prediction, is based on the concept of defining states in terms of bridge condition ratings and obtaining the probabilities that a bridge condition will change from one state to another over a given time interval. When these probabilities are represented in matrix form they are referred to as a transition probability matrix. Knowing the initial or current state vector of a bridge, the future conditions can be predicted by multiplying the current state vector and the transition matrix [65, 66].

The FHWA component condition rating scale was used to define the state vector for the Markov chain analysis. Since a bridge condition is rarely allowed to fall below a value of 3, the service life of a bridge was defined as the number of years that it takes a bridge to deteriorate from condition 9 to condition 3. As a result, only condition ratings from 9 to 3 are of interest in bridge performance prediction. As mentioned above, the Markov chain process uses terminology such as states instead of condition rating to describe bridge deterioration. Hence, the seven bridge conditions (9 to 3) are defined as seven states, each of which corresponds to one of these seven conditions. For example, condition rating 9 is defined as state 1, rating 8 as state 2, and so on (see Table 6.2).

Since all federally supported bridges are inspected on a biennial basis, one can establish transition matrices for each bridge component in two-year intervals. Table 6.2 represents a transition matrix, [P], and the correspondence of condition ratings, states and transition probabilities. In this table, $P_{i,j}$, represents the transition probability from state i to state j within a transition period. In other words, it is the probability that a bridge will deteriorate from condition i to condition j in two years. For example, a $P_{2,3}$ of 0.25 means that there is a 25% probability that a bridge currently with condition 8 will deteriorate to condition 7 in 2 years.

Without maintenance, repair or rehabilitation, the bridge condition rating should decrease as the bridge age increases. In this study, it is assumed that a bridge condition will not drop more than two ratings over a two-year interval. This assumption was used by others to predict bridge and pavement deterioration [62, 64]. With this assumption, a bridge condition will maintain its current state or transit to one of the next two lower conditions. As a result, the transition matrix, [P] given in Table 6.2, takes the form shown in Table 6.3. It should be noted that the lowest state in Tables 6.2 and 6.3 is state 7 (condition 3), indicating that bridges are usually

Table 6.2 Transition matrix showing the correspondence of condition ratings and states

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

[a]CR = FHWA component condition rating.

[b]CS = condition state used in Markov chain notation.

Table 6.3 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

repaired or replaced at this stage and as a result $P_{7,7}$ should always be equal to unity in Table 6.3.

Using the transition probability matrices in conjunction with a given state vector one can predict the future state vector [65, 66]. Let, $\{Q_t\}$, be the current state vector for a given bridge component; hence, the state vector, $\{Q_T\}$, at a future time T is estimated as [61, 62, 63, 65, 66]:

$$\{Q_T\} = \{Q_t\} * [P]_{(t,t+2)} * [P]_{(t+2,t+4)} * \cdots * [P]_{(T-2,T)} \qquad \textbf{(6.1)}$$

where:

$\{Q_t\}$ = current state vector

$\{Q_T\}$ = future state vector

$[P]_{(K,L)}$ = transition matrix from time K to time L

The current state vector, $\{Q_t\}$, is a 1x7 row vector which represents the current state at time t. Therefore, the current state vector contains a value of one in the column that corresponds to the current state (i.e., condition), and the remaining entries are all zero. For example, if a four-year old bridge has a component which is rated an 8 (state 2), then the state vector takes the form of:

$$\{Q_4\} = \{0 \quad 1 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0\}$$

The future state vector, $\{Q_T\}$, is also a 1x7 row vector and contains the probabilities that the bridge component will be in a specific state at time T. To continue the previous example, if the future state vector of the previous component at time T (due to the subsequent matrix multiplications) is:

$$\{Q_T\} = \{0 \quad 0.1 \quad 0.3 \quad 0.3 \quad 0.3 \quad 0 \quad 0\}$$

The resultant probabilities at time T are: 0.1 for state 2, 0.3 for states 3, 4 and 5, and 0 for states 1, 6 and 7. It should be noted that the summation of the probabilities in any state vector must equal 1.0.

The average condition of a component at time T is determined by:

$$\text{Average Condition} = \{Q_T\} * \{C\} \tag{6.2}$$

in which $\{C\}$ is the condition vector (a column vector that contains the condition ratings associated with each state):

$$\{C\}^T = \{9 \quad 8 \quad 7 \quad 6 \quad 5 \quad 4 \quad 3\}$$

For example, for the preceding final state vector the average condition is 6.20. For practical purposes, the average condition should be rounded to the nearest integer.

Due to the formulation of the transition matrices in two-year intervals, the future condition of a bridge can only be predicted in two-year increments. However, these conditions can then be interpolated to estimate conditions at any intermediate time.

In summary, the Markov chain process is completely defined when all of the transition matrices [P] and the current state vector $\{Q_t\}$ are known. Since the state vector is usually known, the main task in the Markov chain process is to determine the transition probability matrices.

6.3 Problem Approach

The bridge performance prediction model consists of two submodels. The first is referred to as the permanent, or Markov chain, submodel and is developed utilizing the Markov chain probabilistic approach (see section 6.3.1). This submodel is used where adequate data are available to determine the transition probabilities. The second submodel is referred to as the temporary, or deterministic, submodel (see section 6.3.2) and is used where currently available data are insufficient to establish any of the transition probabilities associated with a particular state. The second submodel was established using a deterministic approach that is based on a linear regression technique. However, formulation of the entire bridge prediction model is developed to allow users to automatically replace the deterministic submodel with the Markov chain submodel when enough data become available.

6.3.1 Markov chain model

The data used to establish the transition matrix for each transition interval are different. For illustration, assume that a transition matrix is to be established for an interval between time k to time k+2. Hence, one must use only the inspection records for bridges that satisfy the following: (1) bridges that have been inspected at both age k and age k+2 (to reflect the real bridge deterioration transition behavior); and (2) data for bridges that have non-increasing condition ratings over the two-year interval to eliminate the upgrading effects due to repairs and rehabilitations. To reflect the effects of repair and rehabilitation, one needs to formulate different transition matrices that include increasing condition ratings. In this work, these transition matrices were not developed.

Using these assumptions, the transition probabilities within a given interval are:

$$P_{i,j} = \frac{n_{i,j}}{n_i} \tag{6.3}$$

where: $n_{i,j}$ = 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

In order to increase the accuracy of the transition probabilities, a requirement was imposed such that $n_i \geq 3$. If this requirement is not met, the transition probability must be determined by other means (i.e., the deterministic submodel).

In order to illustrate the use of the direct Markov chain approach, a sample data set for the interval from 2 to 4 years was created. Tables 6.4 and 6.5 summarize the data and the resulting transition matrix for the interval between age 2 to age 4. The column vector $\{N_i\}_2$ in Table 6.4 illustrates the number of 2 year old bridges in each state i. In this column, there are 12, 9 and 8 bridges at states 1, 2 and 3, respectively. As illustrated in the matrix $[N_{i,j}]$, four of the bridges rated at state 1 remained at state 1, six deteriorated to state 2, and two deteriorated to state 3 at the end of the interval. Similar explanations apply to the bridges that were at states 2 and 3 at the beginning of the interval. Using the information summarized in Table 6.4 in conjunction with Equation 6.3, the transition matrix for this interval, $[P]_{2,4}$, was estimated as shown in Table 6.5.

There are two types of problems that may occur which prohibits the use of the direct Markov chain approach. First, there may be insufficient data to establish the transition probabilities for some transition intervals

Table 6.4 Markov state transitions for the sample data set

State	$\{N_i\}_2$[a]	$[N_{i,j}]_{2,4}$[b]						
1	12	4	6	2	0	0	0	0
2	9	0	7	1	1	0	0	0
3	8	0	0	8	0	0	0	0
4	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0

[a] $\{N_i\}_2$ = number of bridges at state i at age 2.

[b] $[N_{i,j}]_{2,4}$ = number of bridges that deteriorate from state i to state j between ages 2 and 4.

Table 6.5 Transition matrix for the sample data set

$$[P]_{2,4} = \begin{matrix} 4/12 & 6/12 & 2/12 & 0 & 0 & 0 & 0 \\ 0 & 7/9 & 1/9 & 1/9 & 0 & 0 & 0 \\ 0 & 0 & 8/8 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1.0 \end{matrix}$$

associated with a particular state; and second, there may be insufficient data to establish the transition probabilities for all transition intervals in a particular state. The first situation can be corrected by extrapolating or interpolating the known transition probabilities of different transition intervals which are associated with the particular state. However, as stated previously, the second situation prohibits the use of the Markov chain approach and requires that the deterministic approach (see section 6.3.2) be used.

In order to illustrate the extrapolation and interpolation techniques used to establish unknown transition probabilities, a sample data set was created. Table 6.6 shows the data set prior to modifications, Table 6.7 summarizes the interpolation procedure, and Tables 6.8 and 6.9 summarize the extrapolation procedures. The values shown in the tables represent the three transition probabilities associated with state i (i.e., $P_{i,i}$, $P_{i,i-1}$, and $P_{i,i-2}$) for 10 consecutive transition intervals.

Table 6.6 illustrates the transition probabilities determined by Equation 6.3. This table illustrates that the transition probabilities are known for the following transition intervals: 4 to 6, 10 to 12, 12 to 14, and 14 to 16. Hence, the remaining transition probabilities must be established by interpolation or extrapolation.

Table 6.6 Transition probabilities determined by Equation 6.3

Transition Interval	$P_{i,i}$	$P_{i,i-1}$	$P_{i,i-2}$
0 - 2	*	*	*
2 - 4	*	*	*
4 - 6	0.9	0.1	0.0
6 - 8	*	*	*
8 - 10	*	*	*
10 - 12	0.3	0.5	0.2
12 - 14	0.4	0.4	0.2
14 - 16	0.1	0.5	0.4
16 - 18	*	*	*
18 - 20	*	*	*

Table 6.7 Transition probabilities after interpolation

Transition Interval	$P_{i,i}$	$P_{i,i-1}$	$P_{i,i-2}$
0 - 2	*	*	*
2 - 4	*	*	*
4 - 6	0.9	0.1	0.0
6 - 8	0.6	0.3	0.1
8 - 10	0.6	0.3	0.1
10 - 12	0.3	0.5	0.2
12 - 14	0.4	0.4	0.2
14 - 16	0.1	0.5	0.4
16 - 18	*	*	*
18 - 20	*	*	*

Table 6.8 Transition probabilities after extrapolation prior to interval 4 - 6

Transition Interval	$P_{i,i}$	$P_{i,i-1}$	$P_{i,i-2}$
0 - 2	0.9	0.1	0.0
2 - 4	0.9	0.1	0.0
4 - 6	0.9	0.1	0.0
6 - 8	0.6	0.3	0.1
8 - 10	0.6	0.3	0.1
10 - 12	0.3	0.5	0.2
12 - 14	0.4	0.4	0.2
14 - 16	0.1	0.5	0.4
16 - 18	*	*	*
18 - 20	*	*	*

Table 6.9 Transition probabilities after extrapolation beyond interval 14 - 16

Transition Interval	$P_{i,i}$	$P_{i,i-1}$	$P_{i,i-2}$
0 - 2	0.9	0.1	0.0
2 - 4	0.9	0.1	0.0
4 - 6	0.9	0.1	0.0
6 - 8	0.6	0.3	0.1
8 - 10	0.6	0.3	0.1
10 - 12	0.3	0.5	0.2
12 - 14	0.4	0.4	0.2
14 - 16	0.1	0.5	0.4
16 - 18	0.2	0.5	0.3
18 - 20	0.2	0.5	0.3

The interpolation procedure determines the average of the transition probabilities of the adjacent transition intervals and uses these values for all unknown transition interval probabilities. Table 6.7 shows the transition probabilities after the interpolation has been performed on the sample data set (interpolated values are shaded). The average of the transition probabilities associated with the transition intervals of age 4 to 6 and age 10 to 12 have been used to establish the transition probabilities for intervals of age 6 to 8 and age 8 to 10. This procedure is used regardless of how many unknown transition intervals must be determined (e.g., two unknown transition intervals for the example). This procedure was assumed to be a reasonable approximation since unknown transition probabilities for interior transition intervals rarely occur.

The extrapolation procedure varies depending upon the direction of extrapolation (i.e., prior to or beyond known transition interval probabilities). For the transition interval probabilities prior to a known transition interval, the probabilities associated with the first known interval are used for all preceding intervals. Table 6.8 illustrates this procedure with regard to the sample data set (extrapolated values are shaded). As shown in Table 6.8, the transition probabilities associated with the interval from age 4 to 6 have been used to establish the transition probabilities for the intervals of age 0 to 2 and age 2 to 4. This simple procedure was used since the probabilities associated with the preceding transition matrices have little to no effect on the prediction process. This conclusion was reached due to the fact that if no data are available for the preceding transition intervals, then few bridges have reached the particular state at that time. For example, in the transition interval for age 4 to 6, one would not expect to have data for states 6, 7 or 8 (i.e., conditions 5, 4 or 3) because bridges do not typically deteriorate that quickly.

In order to establish the transition probabilities beyond a known transition interval, the probabilities associated with the two most rapidly deteriorating intervals are averaged. The most rapidly deteriorating transition intervals have been defined as the two intervals with the lowest $P_{i,i}$ values. These are the two intervals which are most likely to deteriorate to a lower condition. Table 6.9 illustrates this procedure with regard to the sample data set (extrapolated values are shaded). The average of the transition probabilities associated with the intervals of age 10 to 12 and age 14 to 16 (i.e., most rapidly deteriorating intervals) have been used for all subsequent intervals. This procedure was selected to represent the maximum rate of deterioration for the particular state. The most rapidly deteriorating interval could also have been used for all subsequent intervals. However, the average of the two most rapidly deteriorating intervals was used in order to reduce the effect of possible erroneous data in one transition interval.

6.3.2 Deterministic model

Since interstate highway bridges in the state of Iowa receive a high level of maintenance, very few of their components have been rated below a condition of 5. As a result, bridge data does not exist for component conditions of 4 and 3. In general, the research performed herein has shown that there is always a condition, i, that divides bridge conditions into two regions. In the region with conditions greater than or equal to i, the Markov chain approach can be used to predict future bridge conditions. However, in the region with conditions less than i, the transition probabilities for these conditions cannot be determined and an alternative approach is needed to predict future bridge conditions. In this work, a deterministic model was employed to predict conditions below state i. It should be noted that sufficient data were available for non-interstate bridges. Therefore, the deterministic model was not required for non-interstate bridges.

The deterministic model assumes that the deterioration rates are constant and equal to those from linear regression. The deterministic deterioration rates take the place of the Markov chain transition matrices. In order to illustrate how the Markov chain approach and the deterministic approach are integrated, recall that the average condition at any time can be calculated using Equation 6.2. When using the deterministic model in conjunction with the Markov chain model the state vector {Q} must be separated into two vectors for use in each model. If, for example, state 5 is the state in which the switch between the Markov approach and the deterministic approach occurs, then the state vector at time t should be separated as follows:

$\{Q^m{}_t\}$ = Markov state vector

$= \{P_1 \quad P_2 \quad P_3 \quad P_4 \quad P_5 \quad 0 \quad 0\}$

$\{Q^d{}_t\}$ = deterministic state vector

$= \{P_6 \quad P_7\}$

The Markov state vector is a 1x7 row vector which contains the probabilities associated with states less than or equal to the state at which the switch occurs (zeros are input for states greater than this state). The deterministic state vector is a variable size row vector which contains only the probabilities associated with states greater than the state at which the switch occurs.

The prediction of the subsequent condition at time t+L is determined using both state vectors. The final condition in the year t+L is the sum of the two preceding contributions. The contribution due to the Markov approach is determined using the Markov state vector and the associated transition matrix:

$$\{Q^m_{t+L}\} = \{Q^m_t\} * [P]_{t,t+L} \quad (6.4)$$

and

$$\text{Average Condition}^m = \{Q^m_{t+L}\} * \{C^m\} \quad (6.5)$$

where:

$$\{C^m\}^T = \{9 \quad 8 \quad 7 \quad 6 \quad 5 \quad 4 \quad 3\}$$

The contribution due to the deterministic approach differs from the Markov approach in that the conditions change, rather than the probabilities. For the preceding example, the deterministic contribution is as follows:

$$\text{Average Condition}^d = \{Q^d_{t+L}\} * \{C^d\}_{t+L} \quad (6.6)$$

where:

$\{Q^d_{t+L}\} = \{Q^d_t\} = \{P_6 \quad P_7\}$ for this example

$$\{C^d\}_{t+L} = \{C^d\}_t - (s*L)*\{1\} \quad (6.7)$$

$\{C^d\}_t$ = the current conditions associated with $\{Q^d_t\} = \{4 \quad 3\}^T$ for this example

s = deterioration rate from linear regression

$\{1\}$ = a unit column vector with the same order as $\{C^d\}_t = \{1 \quad 1\}^T$ for this example

It should be noted that since the minimum allowable condition is equal to 3, then a limitation must be placed such that $\{C^d_i\}_{t+L}$ is greater than or equal to 3. It should also be noted that $\{C^d_i\}_{t+L}$ may not be an integer value.

The average condition in the year t+L is the sum of the two preceding contributions. In order to continue the prediction process past time t+L, the state vectors and condition vectors at time t+L must be combined, separated as previously described, and the entire process repeated.

6.3.3 Markov chain and deterministic approach example

In order to illustrate how to use the prediction models in the previous sections, a simple example is provided. In this example, assume that a bridge component was given a condition rating of 6 when it was 30 years old and one wishes to predict the condition after 4 years.

The transition matrices used in the problem, for the intervals of age 30 to 32 and 32 to 34, are shown in Tables 6.10 and 6.11. In the development of the example transition matrices it was assumed that sufficient data were available only for conditions greater than or equal to 6. Therefore, when the conditions are less than 6 the deterministic approach must be used. It should be noted that in Tables 6.10 and 6.11 the first three rows of each transition matrix are not required for this example since the initial

Table 6.10 Transition matrix (age 30 - 32) for the example problem

	0.0	0.1	0.9	0	0	0	0
	0	0.1	0.1	0.8	0	0	0
	0	0	0.2	0.2	0.6	0	0
$[P]_{30,32} =$	0	0	0	0.5	0.4	0.1	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0

Table 6.11 Transition matrix (age 32 - 34) for the example problem

	0.0	0.1	0.9	0	0	0	0
	0	0.1	0.1	0.8	0	0	0
	0	0	0.2	0.2	0.6	0	0
$[P]_{32,34} =$	0	0	0	0.4	0.4	0.2	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0
	0	0	0	0	0	0	0

condition is equal to 6 (i.e., the first three rows correspond to initial conditions of 9, 8 and 7 respectively). In addition, the last three rows contain all zeros to represent the unavailability of sufficient data.

When the deterministic model is applied, a deterioration rate of 0.1 points (i.e., condition rating) per year was assumed. Therefore, the deterioration rate for a two-year interval is equal to 0.2 condition rating points.

The deterioration of the component condition over the first interval of 30 to 32 was accomplished using only the Markov chain approach since the initial condition of 6 is equal to the condition at which the switch from the Markov approach to the deterministic approach occurs. In other words, the state vector for an age of 32 is determined using Equation 6.1:

$$\{Q\}_{32} = \{Q\}_{30} * [P]_{30,32}$$

where:

$\{Q\}_{30} = \{0 \quad 0 \quad 0 \quad 1 \quad 0 \quad 0 \quad 0\}$

$[P]_{30,32}$ = see Table 6.10

$\{Q\}_{32} = \{0 \quad 0 \quad 0 \quad 0.5 \quad 0.4 \quad 0.1 \quad 0\}$

The deterioration of the component condition over the second interval of 32 to 34 must be accomplished using the Markov and deterministic approaches since the state vector at age 32 contains probabilities for conditions less than 6.

Therefore, the state vector, $\{Q\}_{32}$, was first separated into the Markov state vector and the deterministic state vector:

$$\{Q^m\}_{32} = \{0 \quad 0 \quad 0 \quad 0.5 \quad 0 \quad 0 \quad 0\}$$

$$\{Q^d\}_{32} = \{0.4 \quad 0.1 \quad 0\}$$

The contribution due to the Markov approach at age 34 was then accomplished using Equations 6.4 and 6.5:

$$\{Q^m\}_{34} = \{Q^m\}_{32} * [P]_{32,34}$$

where:

$$\{Q^m\}_{34} = \{0 \quad 0 \quad 0 \quad 0.2 \quad 0.2 \quad 0.1 \quad 0\}$$

and:

$$\text{Average Condition}^m_{34} = \{Q^m\}_{34} * \{C^m\} = 2.6$$

The contribution due to the deterministic approach at age 34 was accomplished using Equations 6.6 and 6.7:

$$\text{Average Condition}^d_{34} = \{Q^d\}_{34} * \{C^d\}_{34}$$

where:

$$\{Q^d\}_{34} = \{Q^d\}_{32} = \{0.4 \quad 0.1 \quad 0\}$$

$$\{C^d\}_{34} = \{C^d\}_{32} - (s*L)*\{1\}$$

$$\{C^d\}_{32} = \{5 \quad 4 \quad 3\}^T$$

$$(s*L) = 0.2$$

$$\{C^d\}_{34} = \{4.8 \quad 3.8 \quad 2.8\}^T$$

$$= \{4.8 \quad 3.8 \quad 3\}^T, \text{ from } \{C^d_i\} \geq 3 \text{ requirement}$$

$$\text{Average Condition}^d_{34} = 2.3$$

The total average condition at age 34 is the sum of the contributions of the Markov and deterministic approaches:

Total Average Condition$_{34}$ = 2.6 + 2.3 = 4.9

If the prediction process were to continue past the age of 34, the state vectors and condition vectors at age 34 must be combined. These vectors are combined by simply summing the $\{Q\}_{34}$ terms which have the same $\{C\}_{34}$ values:

$$\{Q^m\}_{34} = \{0 \quad 0 \quad 0 \quad 0.2 \quad 0.2 \quad 0.1 \quad 0\}$$

$$\{C^m\}_{34} = \{9 \quad 8 \quad 7 \quad 6 \quad 5 \quad 4 \quad 3\}^T$$

$$\{Q^d\}_{34} = \{0.4 \quad 0.1 \quad 0\}$$

$$\{C^d\}_{34} = \{4.8 \quad 3.8 \quad 3\}^T$$

$$\{Q\}_{34} = \{0 \quad 0 \quad 0 \quad 0.2 \quad 0.2 \quad 0.4 \quad 0.1 \quad 0.1 \quad 0\}$$

$$\{C\}_{34} = \{9 \quad 8 \quad 7 \quad 6 \quad 5 \quad 4.8 \quad 4 \quad 3.8 \quad 3\}^T$$

These matrices would be used to continue the prediction process.

6.4 Application to Iowa Bridges

In order to apply the Markov chain and deterministic approach deterioration models to bridges in Iowa, several procedures were required. First, the development of several computer programs were required to: sort the bridge data, determine the linear regression deterioration rates, establish the required Markov chain transition matrices, and perform the actual bridge performance predictions. Second, Iowa bridges were classified into homogeneous groups, and their associated data were sorted and filtered. Finally, the data for each group were used in conjunction with the prediction program to determine the deterioration curve for each bridge component.

6.4.1 Deterioration model computer programs

The computer programs which were developed can be classified into three groups: data file preparation, Markov transition matrice development, and bridge performance prediction. No formal computer programs were developed for the first category involving the preparation of the required data files. However, two formal programs were developed in order to perform the two remaining tasks.

The data used in the prediction process were obtained from the Iowa DOT Bridge Maintenance Department. Inspection data were supplied for all state-owned bridges for the years from 1974 through 1988. The computer data files were prepared from the master computer file using the Statistical Analysis System (SAS) software package. Data were filtered to eliminate duplicate bridge records and bridge records which contained component condition ratings which increased between inspection periods. The latter procedure was performed in order to suppress the effects of major repairs and rehabilitation.

Each data file contains a standard set of information which must be stored in a specific format for use in the transition matrice program. The information and format required for each bridge record are as follows: FHWA bridge identification number (5 characters), year built (4 characters), year inspected (4 characters), month inspected (4 characters), deck condition rating (1 character), substructure condition rating (1 character), superstructure condition rating (1 character), and the structural condition appraisal rating (1 character). The preceding information and format must be used for each data file, however, data files may be grouped according to bridge characteristics such as bridge type, superstructure material type or traffic volume.

The computer program which establishes the Markov transition matrices was developed using the Fortran computer programming language. This program reads a user-specified data file and creates the Markov transition matrices in two-year intervals for the deck, substructure and superstructure component condition ratings, and the structural condition appraisal rating. In addition, this program determines the state at which the prediction program must switch from the Markov chain approach to the deterministic approach.

The computer program which performs the bridge performance predictions was also created using the Fortran computer programming language. Execution of this program requires the prior development of the Markov transition matrices and the determination of the linear regression deterioration rates. The linear regression deterioration rates for each group's components were determined using the SAS statistical software program; then, they were input to the bridge performance prediction program by means of a Fortran DATA statement. In the prediction process, the program automatically determines when (or if) the deterministic approach should be used.

The execution of this program relies on user input for the following information: group type (available groups described later), component type, current age, and the current condition. Therefore, the program can predict the service life of a new bridge (i.e., condition 9 in year 0) or the remaining life of a bridge in service. Output from this program include the component's mean condition and state vector for each year in the prediction.

A hardcopy of the two Fortran computer programs has not been included in this report; however, the computer files containing the source code and executable versions have been included on a 5.25 in. diskette. In addition, the data file and file containing the transition matrices for each of the

6 groups analyzed (to be described later) have been included on the diskette. The following computer files have been stored on the diskette in the subdirectory DETER:

MATMAK6.FOR = source code for the Markov transition matrice development program

MATMAK6.EXE = executable version of the Markov transition matrice development program

PRED6.FOR = source code for the bridge performance prediction program

PRED6.EXE = executable version of the bridge performance prediction program

GROUP*.DAT = data file for group number * (* = 1 - 6)

GROUP*.MAT = file containing the Markov transition matrices for group number * (* = 1 - 6)

It should also be noted that execution of the bridge performance prediction program creates a file called GROUP*.PRD (where * denotes the user-specified group number) which contains only the prediction information for the user-specified component. The files associated with the bridge performance predictions included in this report (to be described later) have not been included on the diskette.

6.4.2 Classification of Iowa bridges

Bridges in the state of Iowa were sorted into 6 groups according to their superstructure material type, interstate versus noninterstate classification, and skewed versus nonskewed classification. These three variables were determined to be significant based upon previous research (see section 6.1) and suggestions received from the Iowa DOT advisory committee. The six groups which were individually analyzed are as follows:

(1) steel bridges on interstate highways

(2) nonskewed steel bridges on noninterstate highways

(3) skewed steel bridges on noninterstate highways

(4) concrete bridges on interstate highways

(5) nonskewed concrete bridges on noninterstate highways

(6) skewed concrete bridges on noninterstate highways

It should be noted that the computer programs which were developed can analyze any data file containing the required information given in section 6.4.1. Therefore, the six groups listed above could be further subdivided according to additional criteria. However, additional classification reduces the size of the data set used in the analysis, which in turn reduces the accuracy of the final prediction. Hence, it was determined that the groups used should not be subdivided any further.

6.4.3 Iowa's bridge component deterioration curves

The deterioration curves established for Iowa are shown in Figures 6.3 through 6.26. Four deterioration curves were developed for each of the six Iowa bridge groups previously defined. The curves established for each bridge group include the following: FHWA deck component condition rating (Figures 6.3 through 6.8), FHWA superstructure component condition rating (Figures 6.9 through 6.14), FHWA substructure component condition rating (Figures 6.15 through 6.20), and the FHWA structural condition appraisal rating (Figures 6.21 through 6.26). The deterioration curves illustrate the average (or mean) condition with respect to time and are based on an initial rating of 9 in year 0. In addition to the average condition, the statistical distribution of condition rating probabilities has been included for years 10, 20, and 40.

As stated previously, the deterioration curves illustrate the average bridge component condition. However, for practical purposes, the component conditions should be rounded to the nearest integer value. Therefore, the service life of each component should be based on the age in which the average component condition is less than 3.5. A summary of the service lives associated with each group's bridge components is presented in Table 6.12.

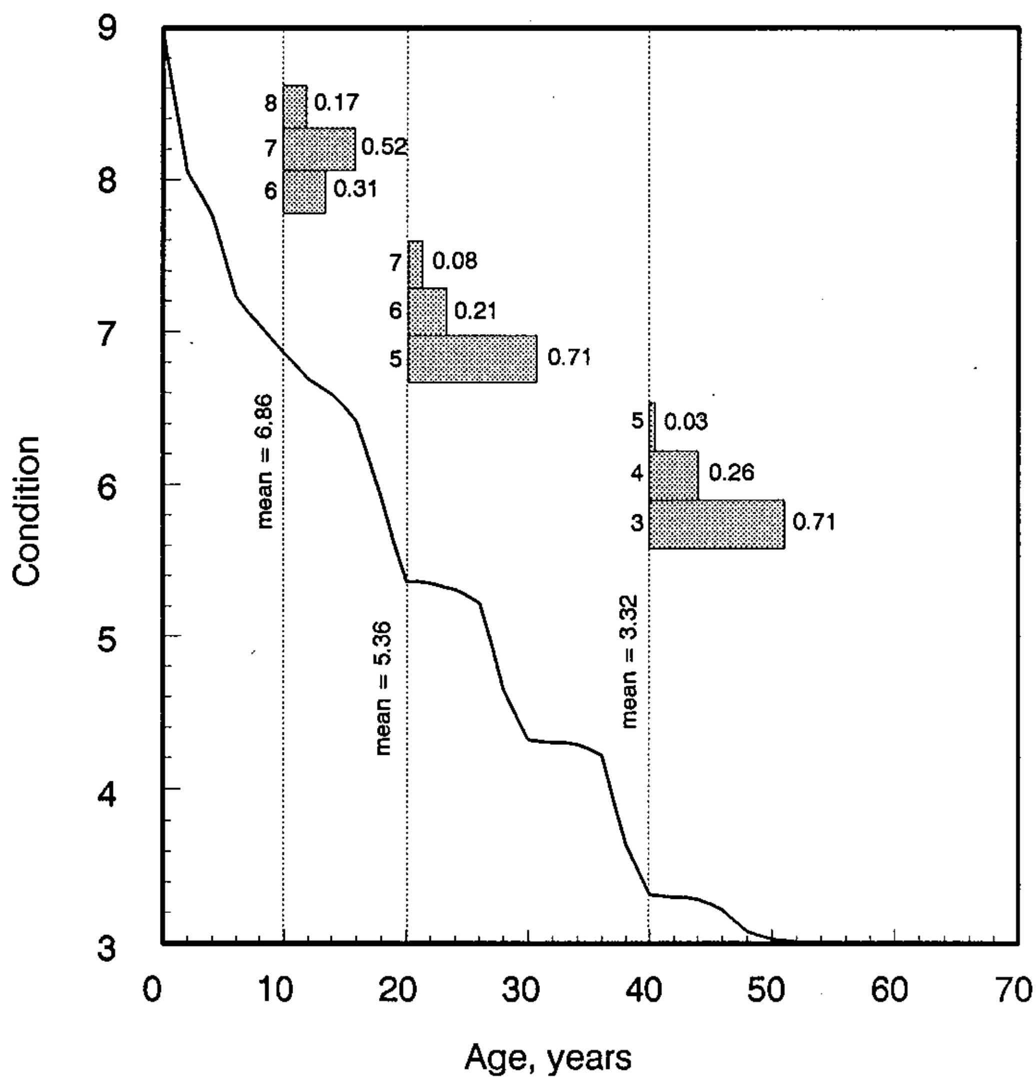

Figure 6.3 Deck condition - steel bridges on interstate highways

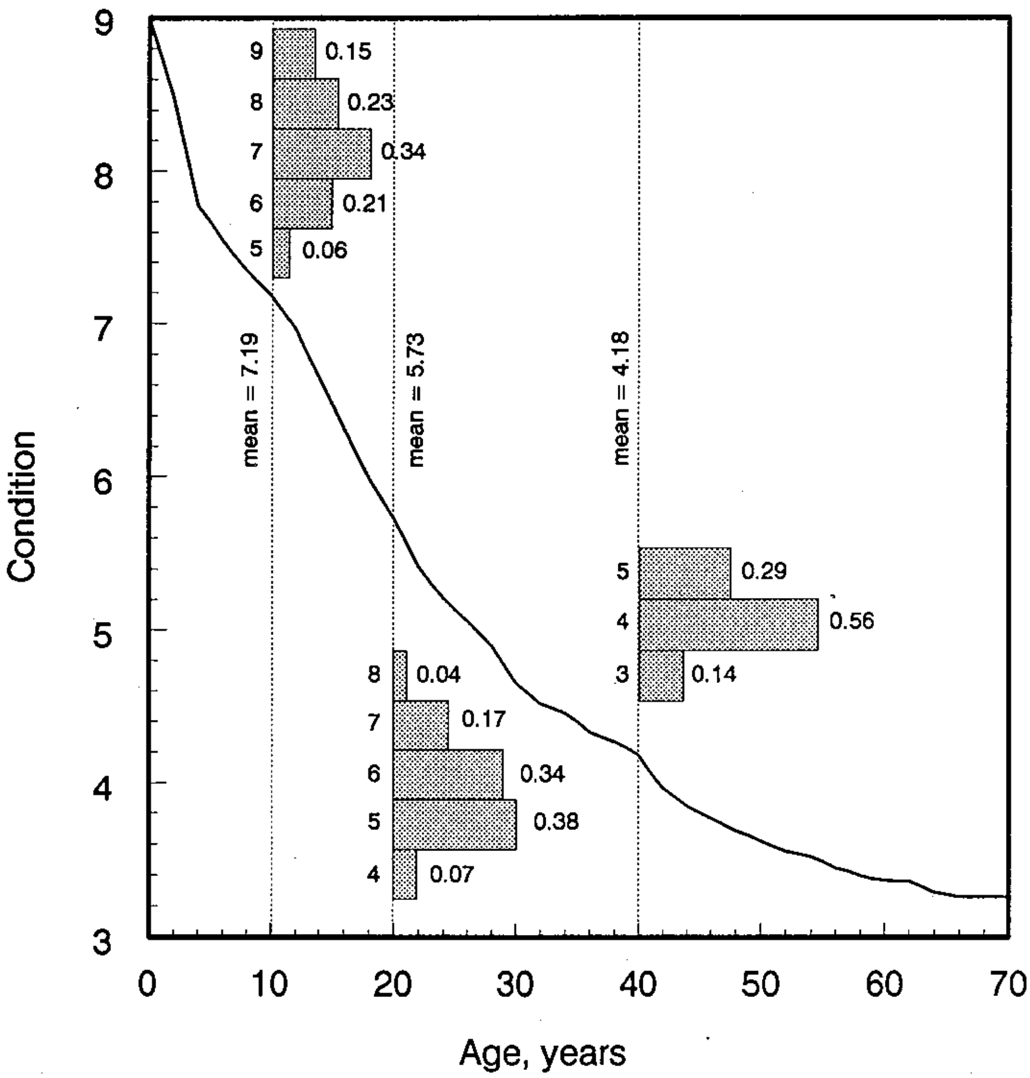

Figure 6.4 Deck condition - nonskewed steel bridges on noninterstate highways

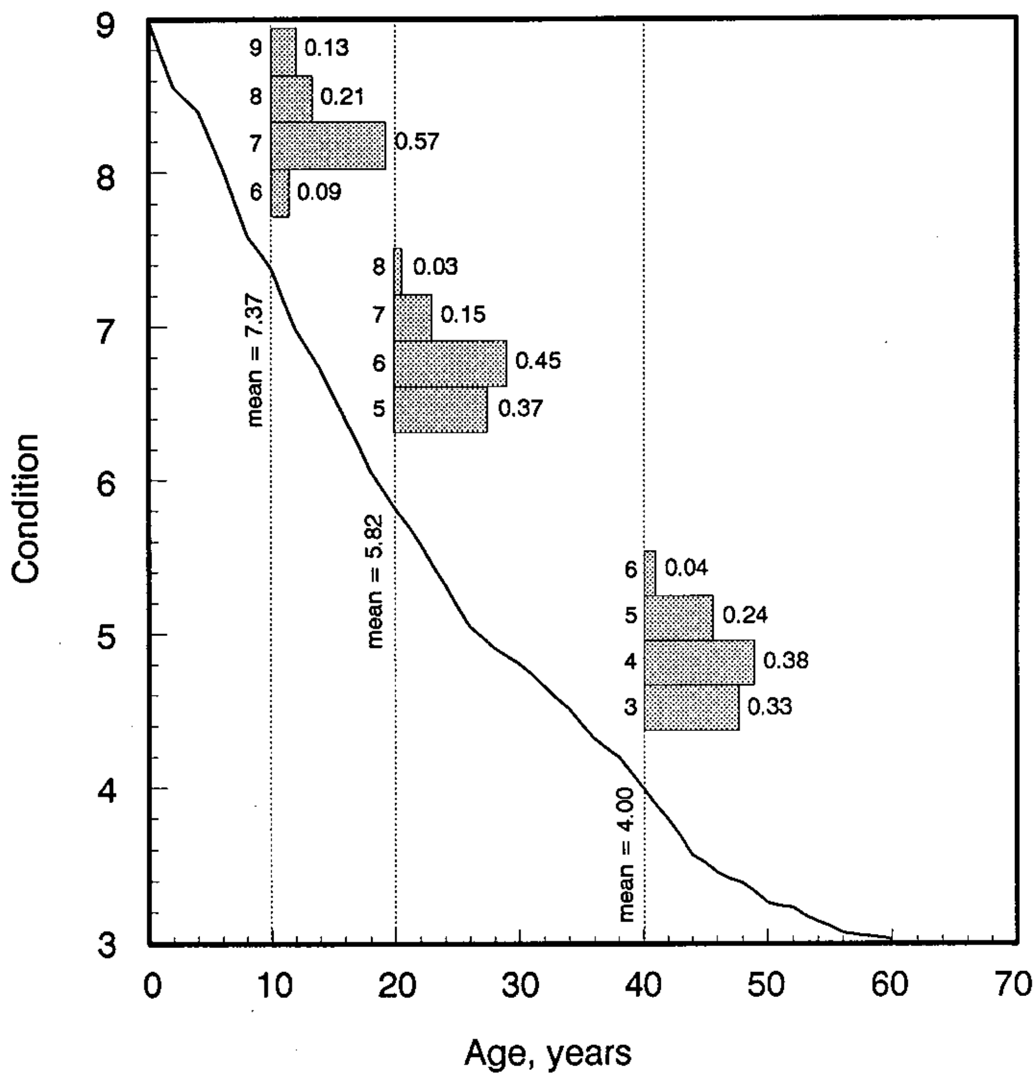

Figure 6.5 Deck condition - skewed steel bridges on noninterstate highways

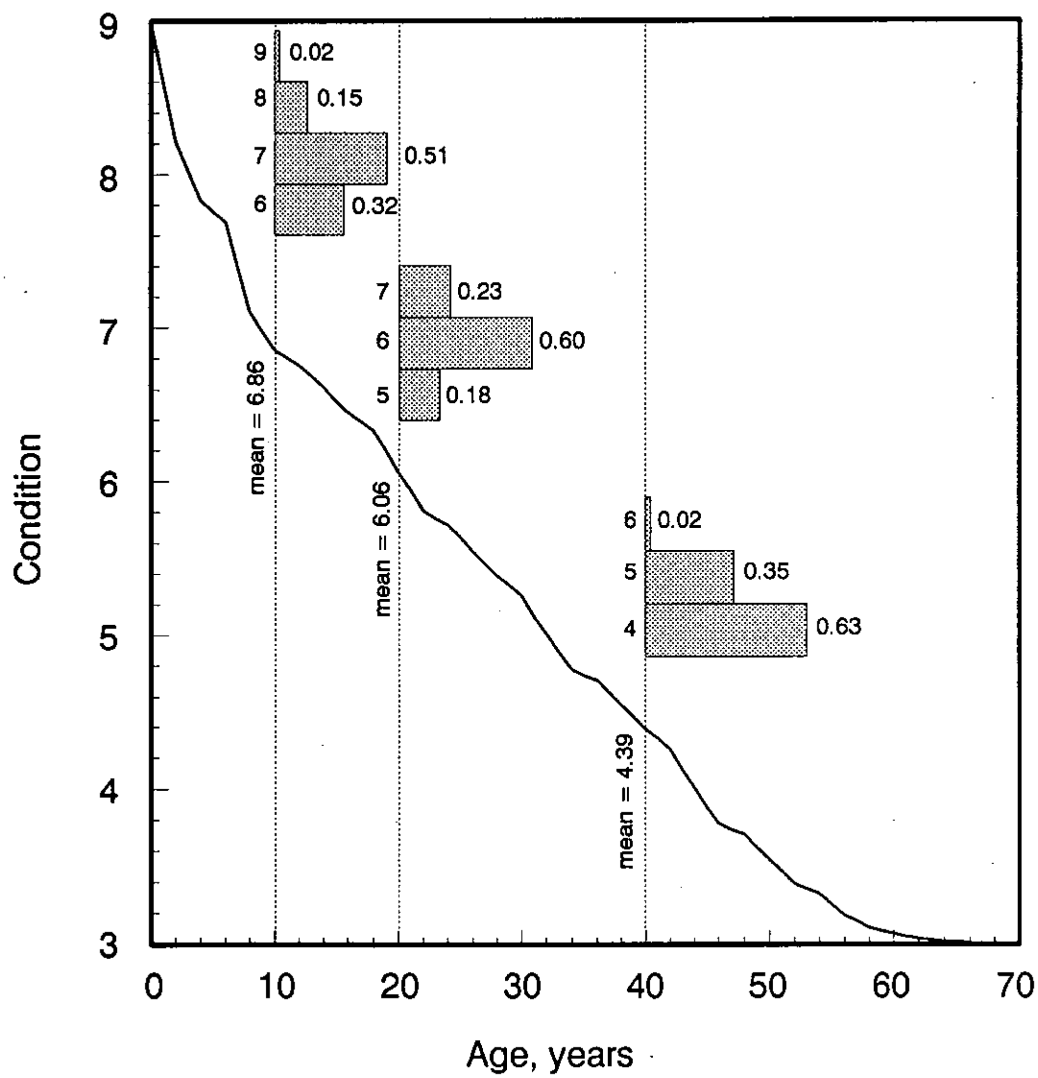

Figure 6.6 Deck condition - concrete bridges on interstate highways

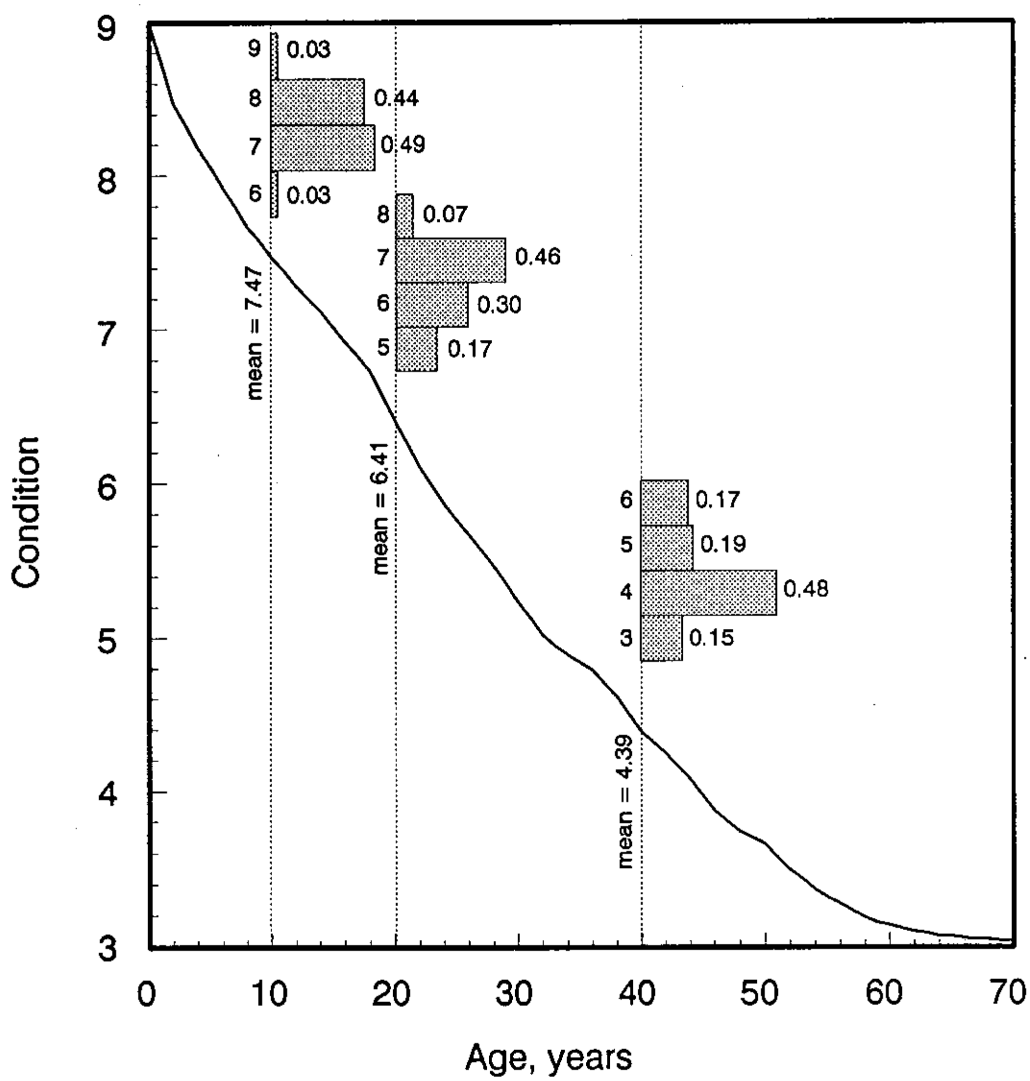

Figure 6.7 Deck condition - nonskewed concrete bridges on noninterstate highways

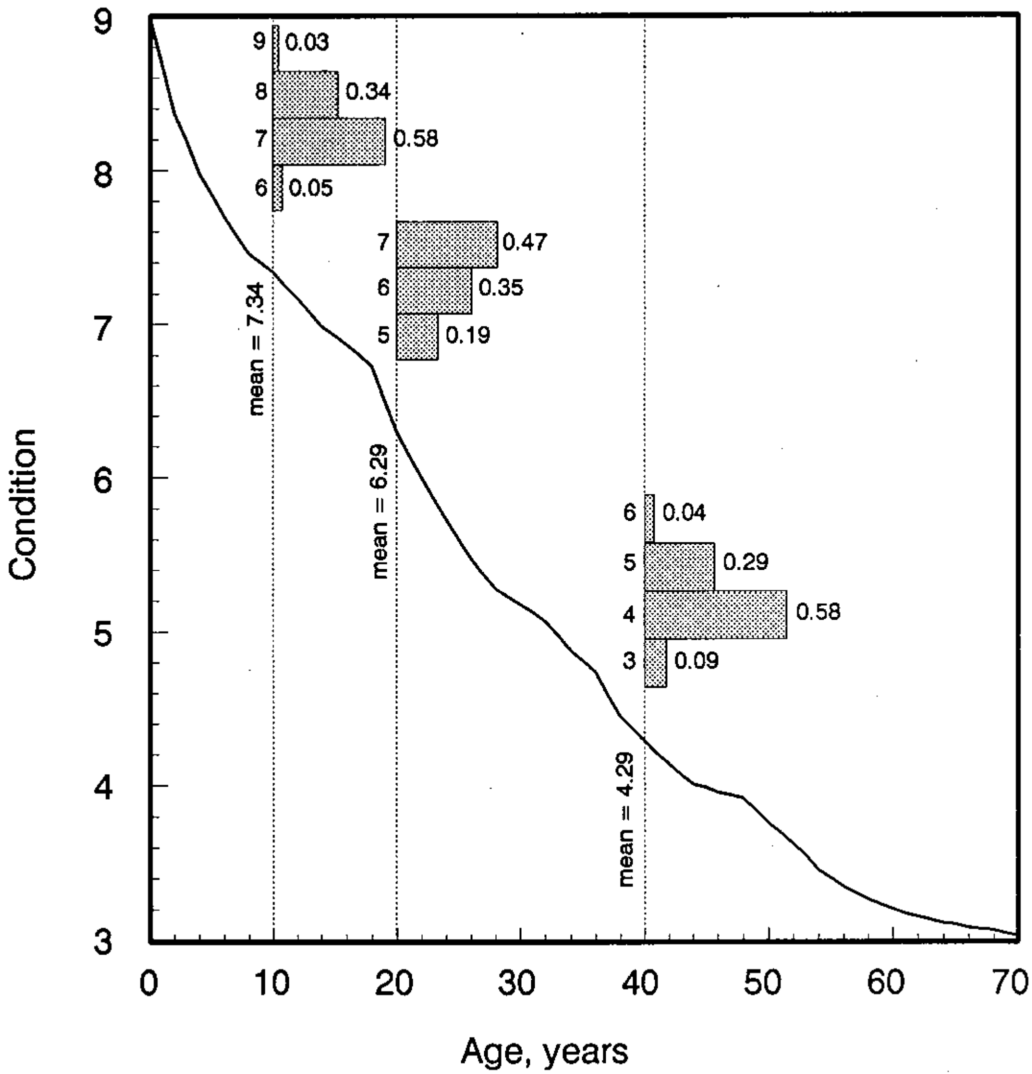

Figure 6.8 Deck condition - skewed concrete bridges on noninterstate highways

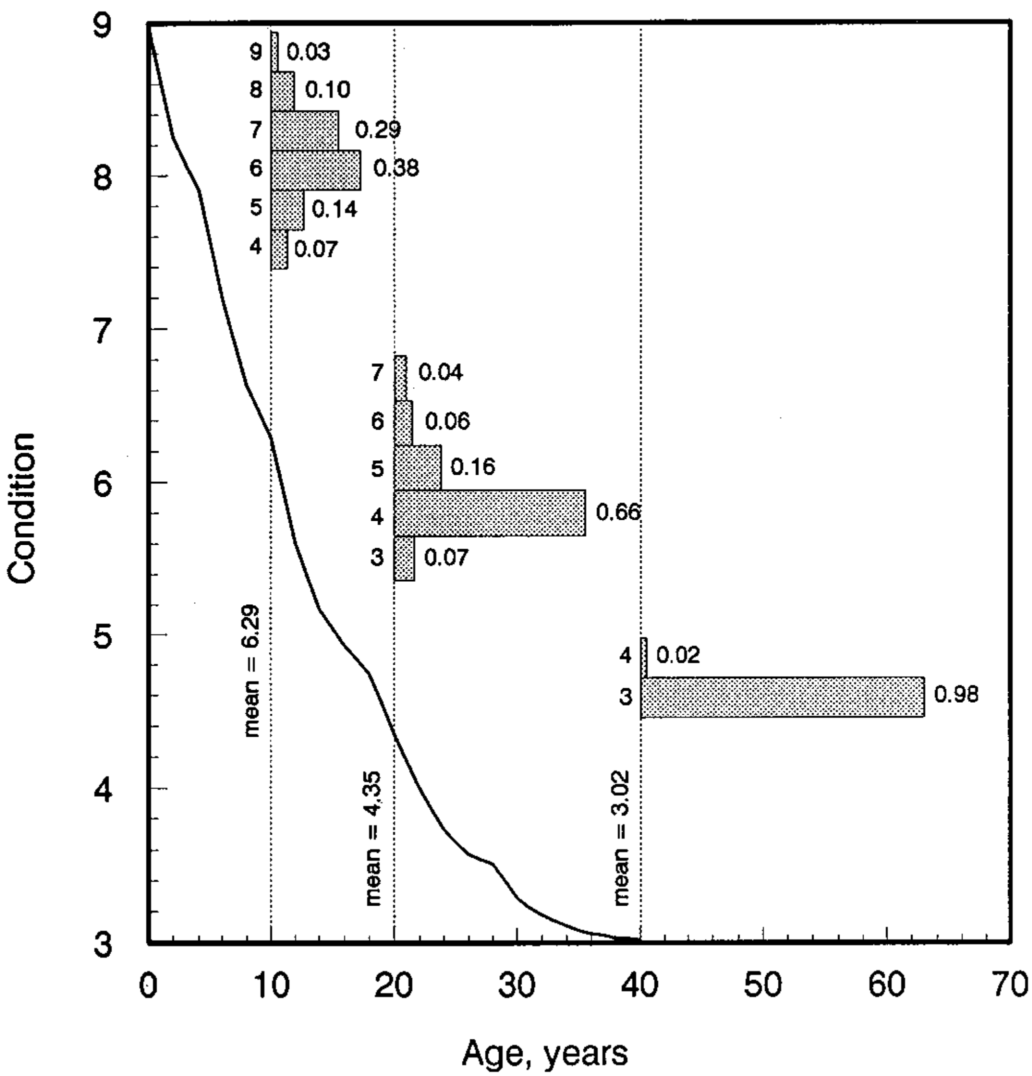

Figure 6.9 Superstructure condition - steel bridges on interstate highways

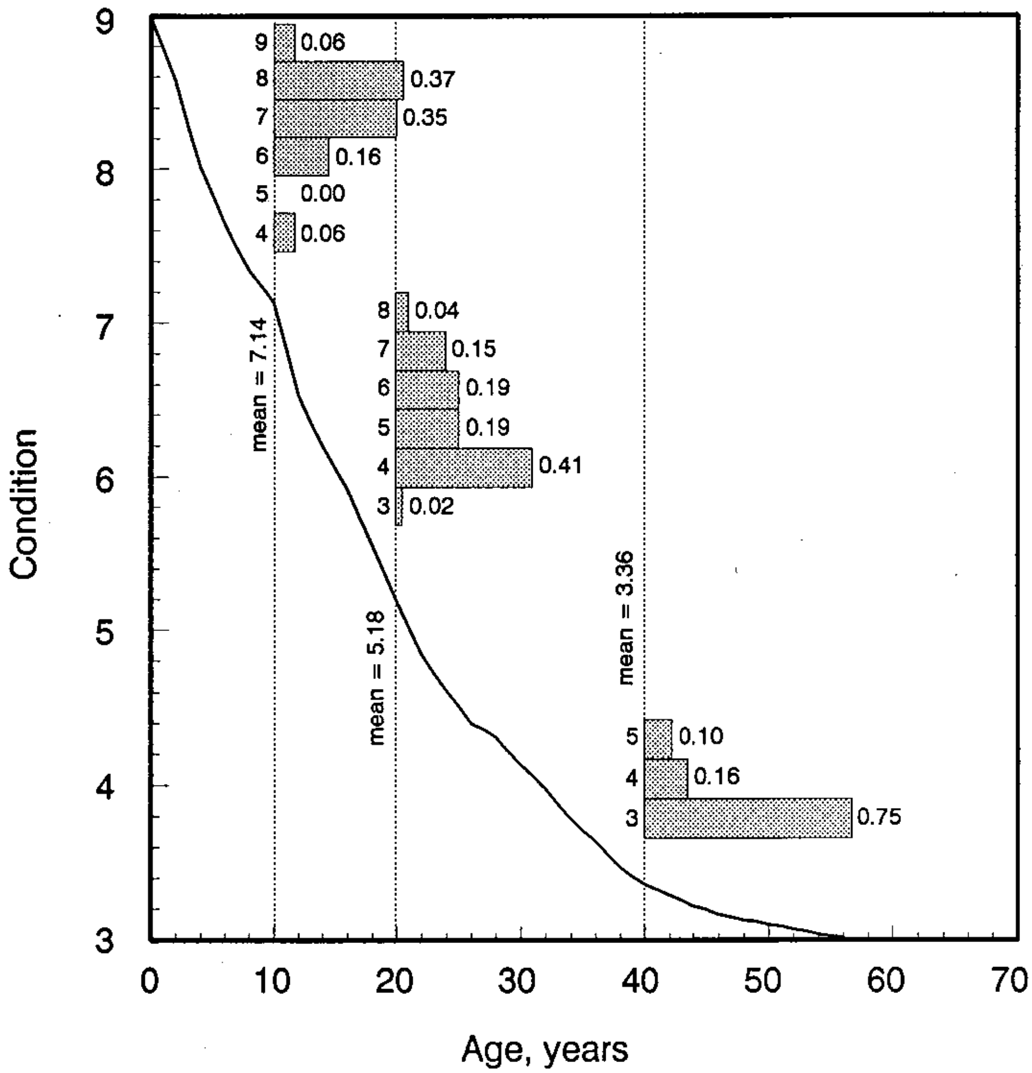

Figure 6.10 Superstructure condition - nonskewed steel bridges on noninterstate highways

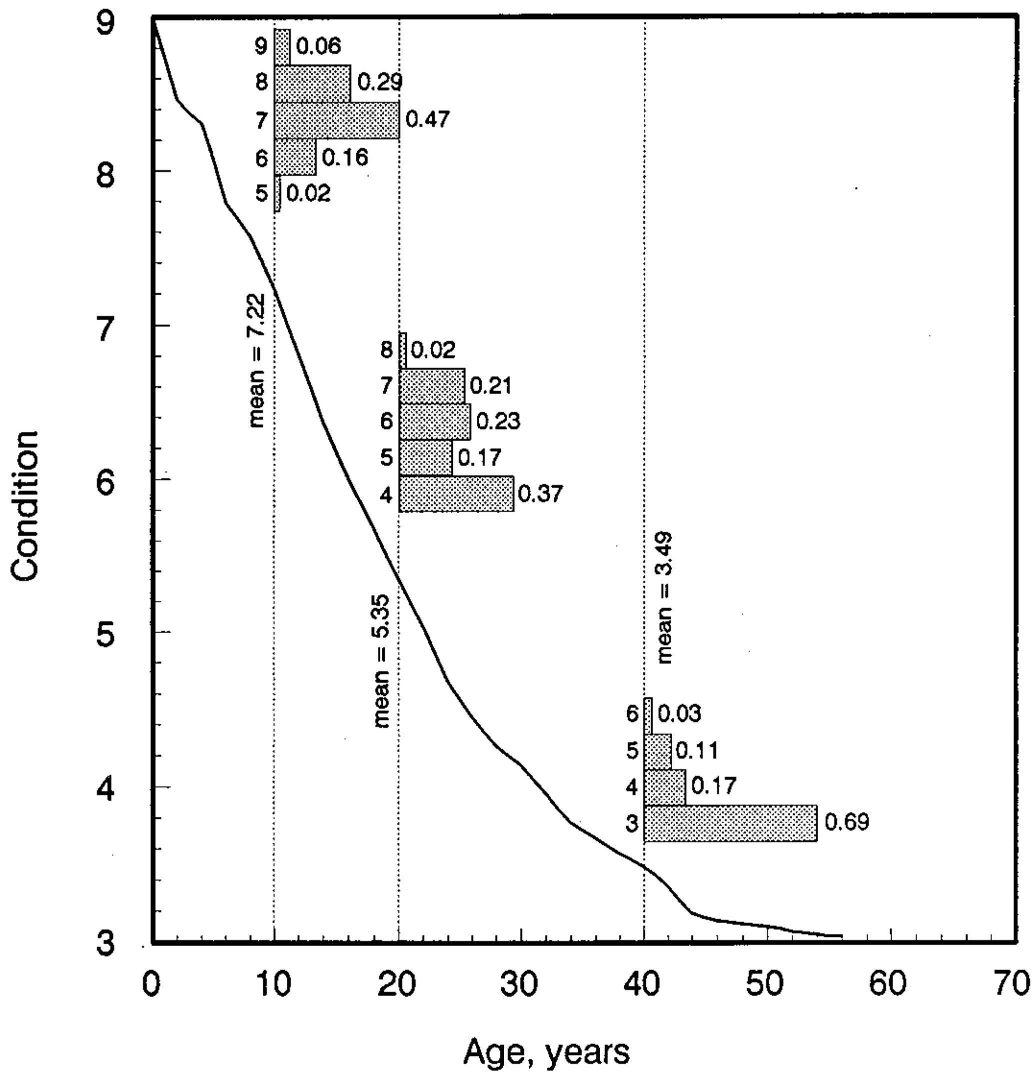

Figure 6.11 Superstructure condition - skewed steel bridges on noninterstate highways

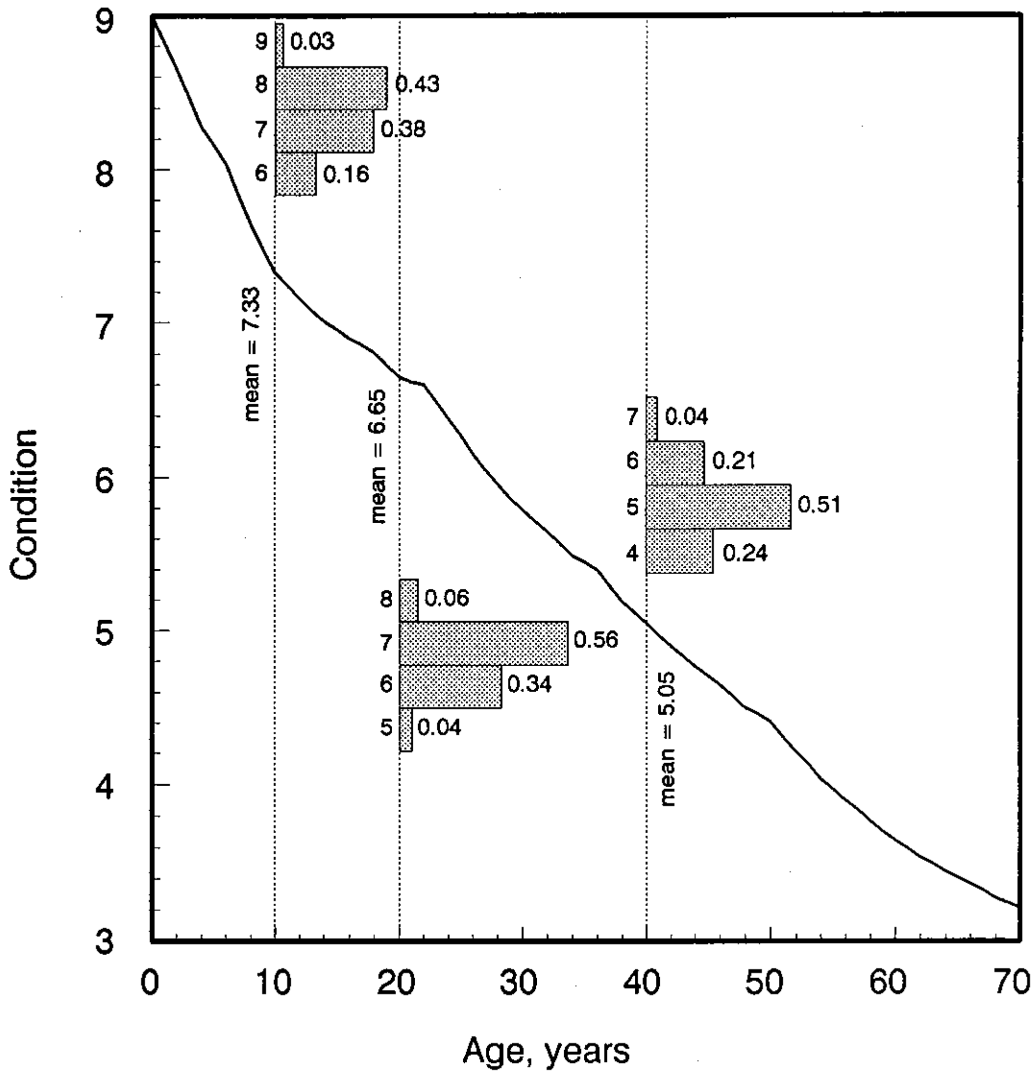

Figure 6.12 Superstructure condition - concrete bridges on interstate highways

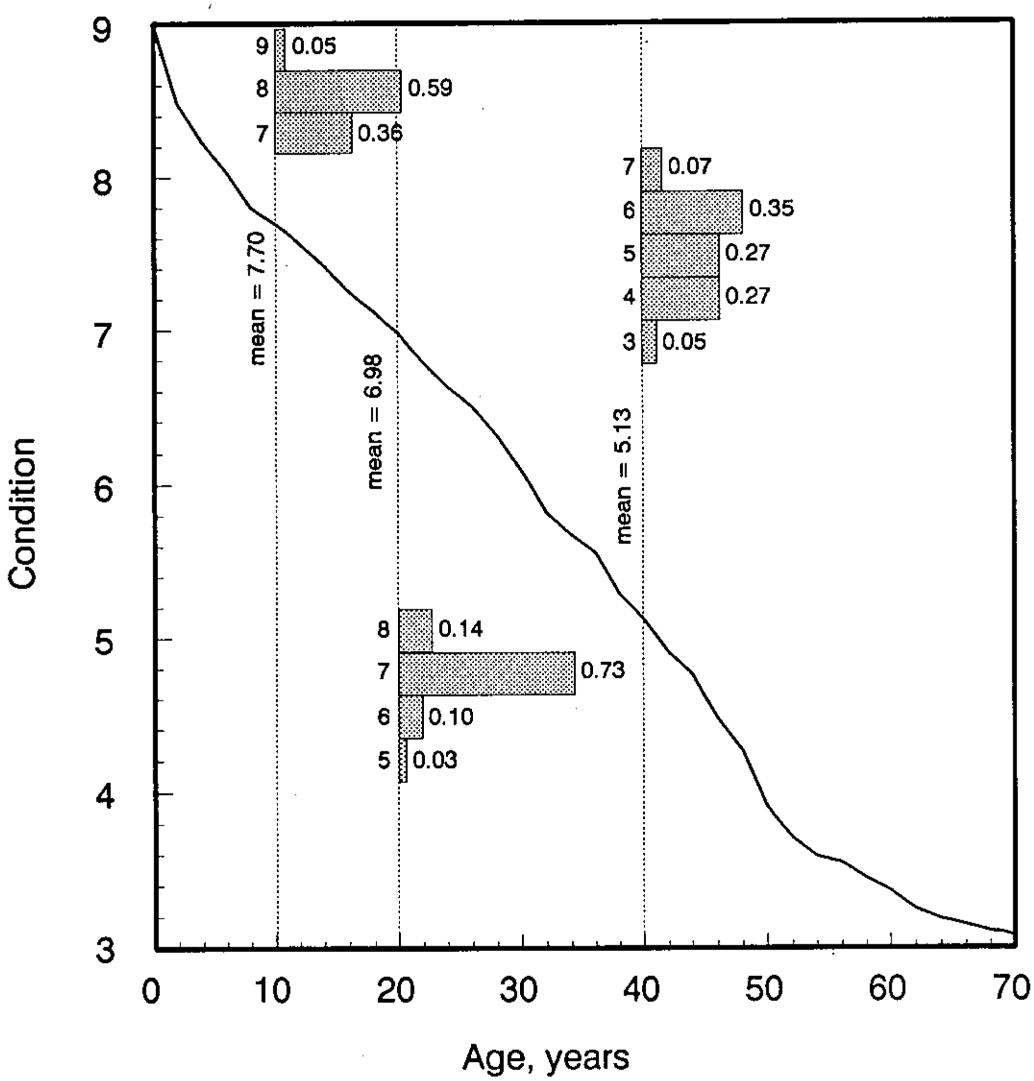

Figure 6.13 Superstructure condition - nonskewed concrete bridges on noninterstate highways

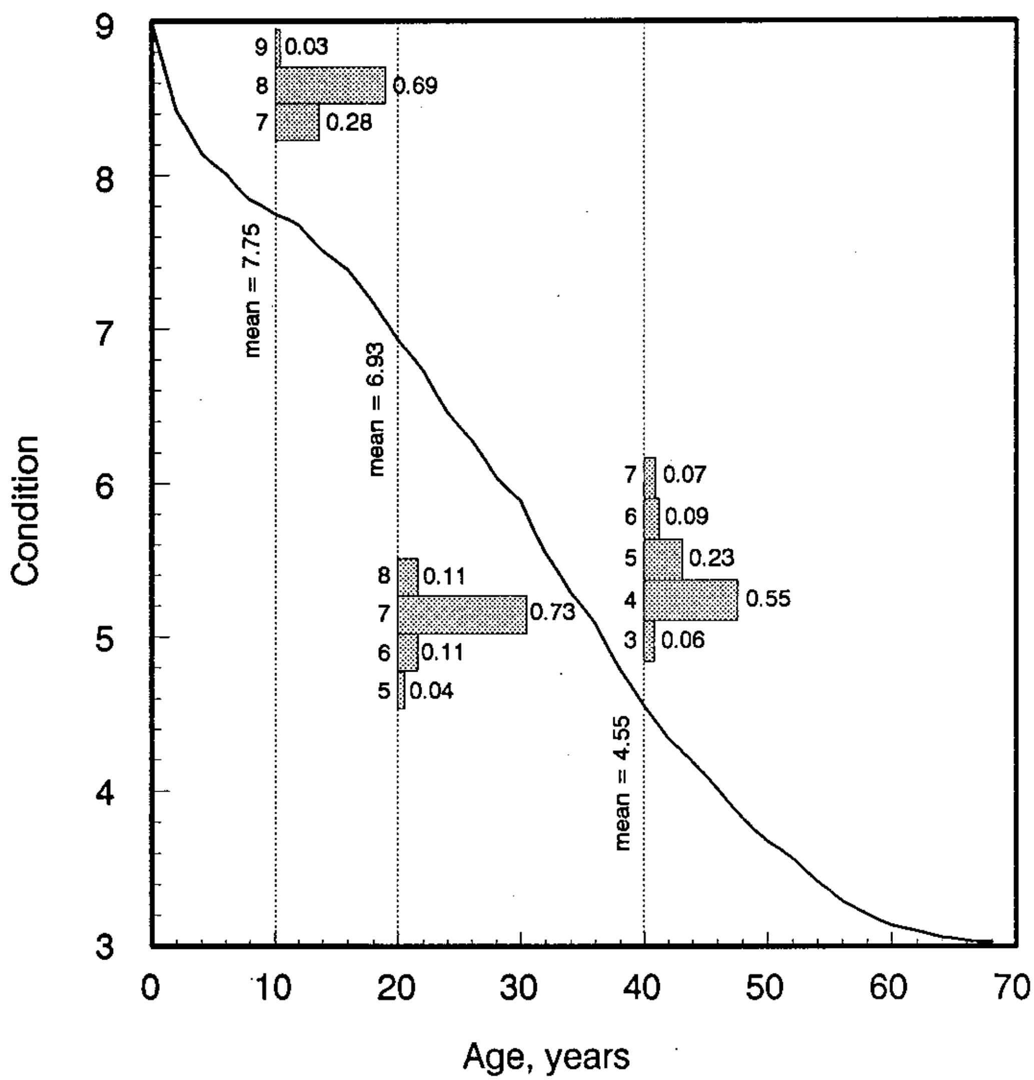

Figure 6.14 Superstructure condition - skewed concrete bridges on noninterstate highways

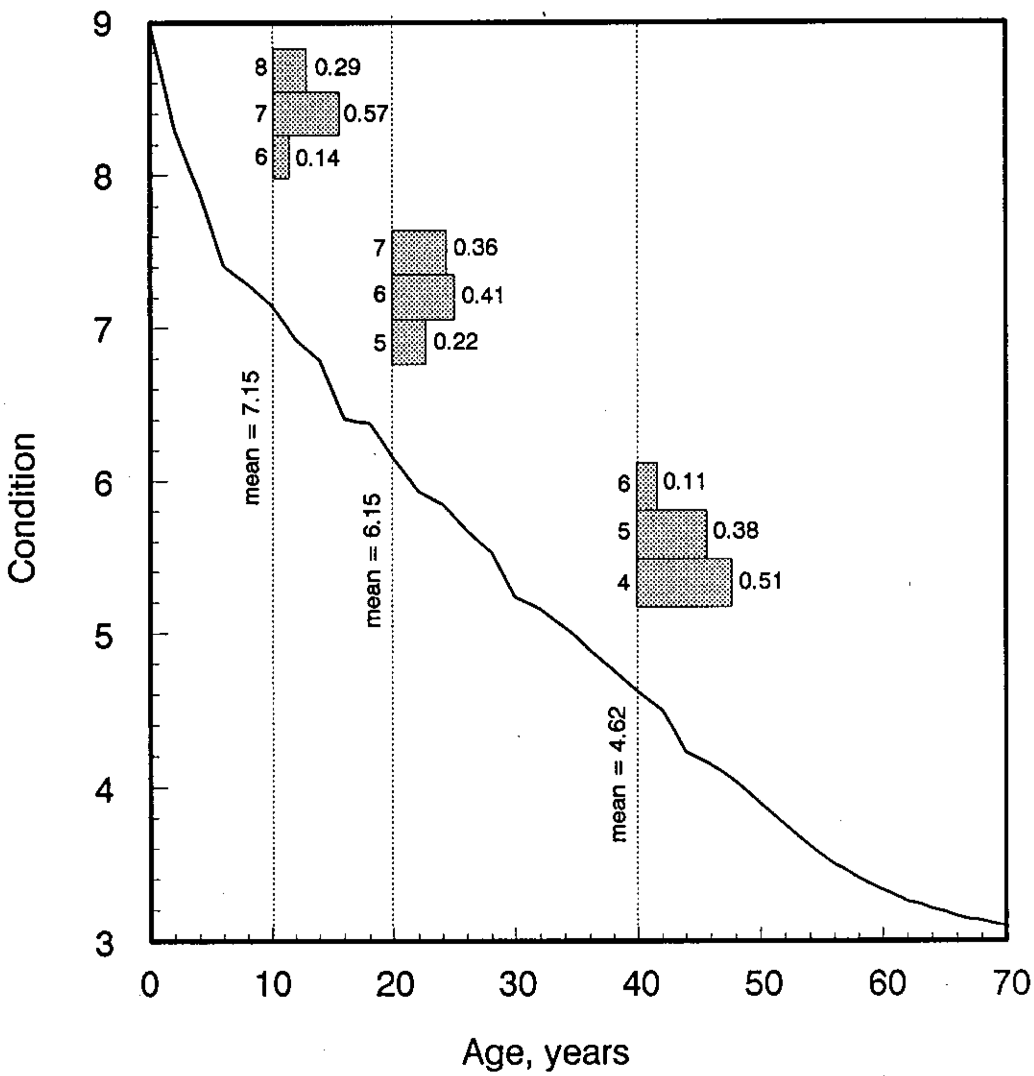

Figure 6.15 Substructure condition - steel bridges on interstate highways

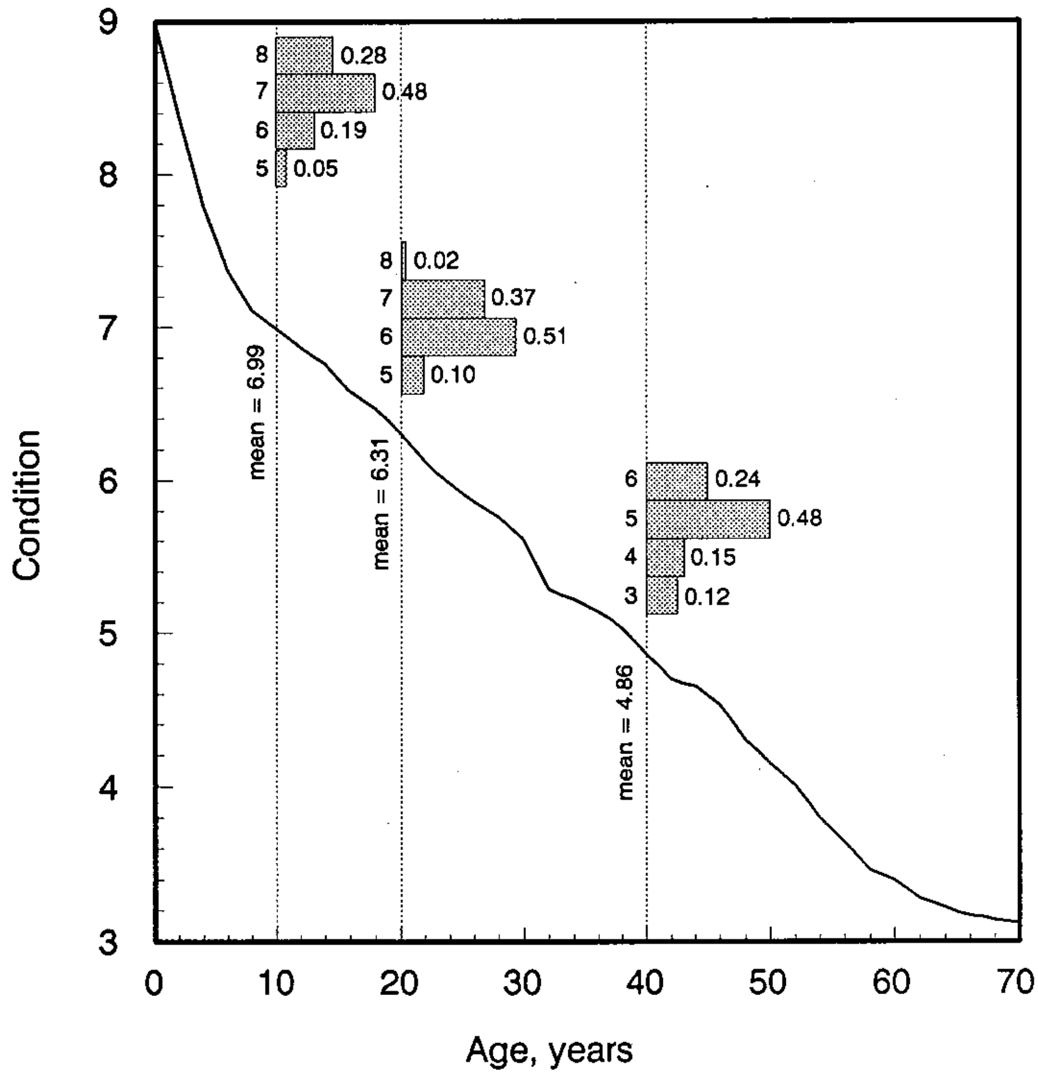

Figure 6.16 Substructure condition - nonskewed steel bridges on noninterstate highways

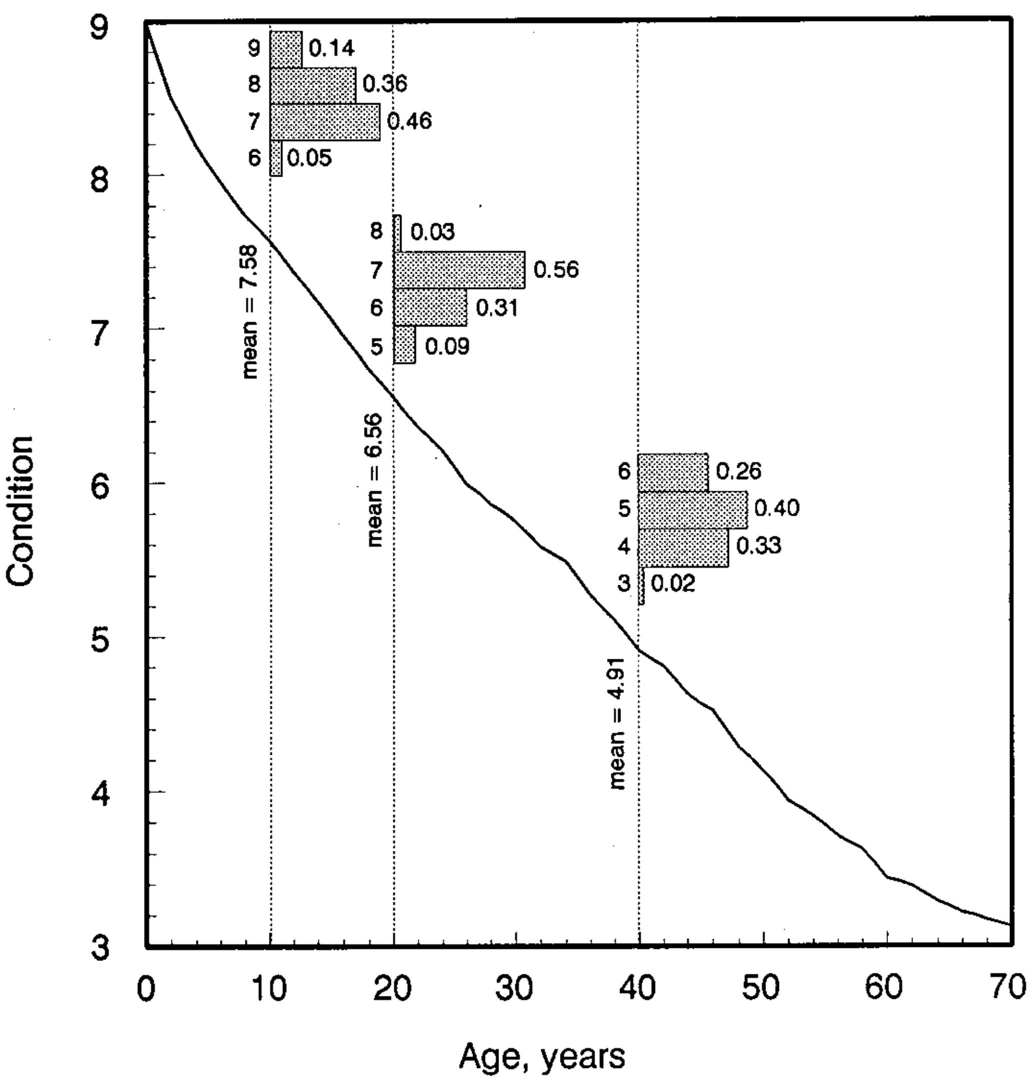

Figure 6.17 Substructure condition - skewed steel bridges on noninterstate highways

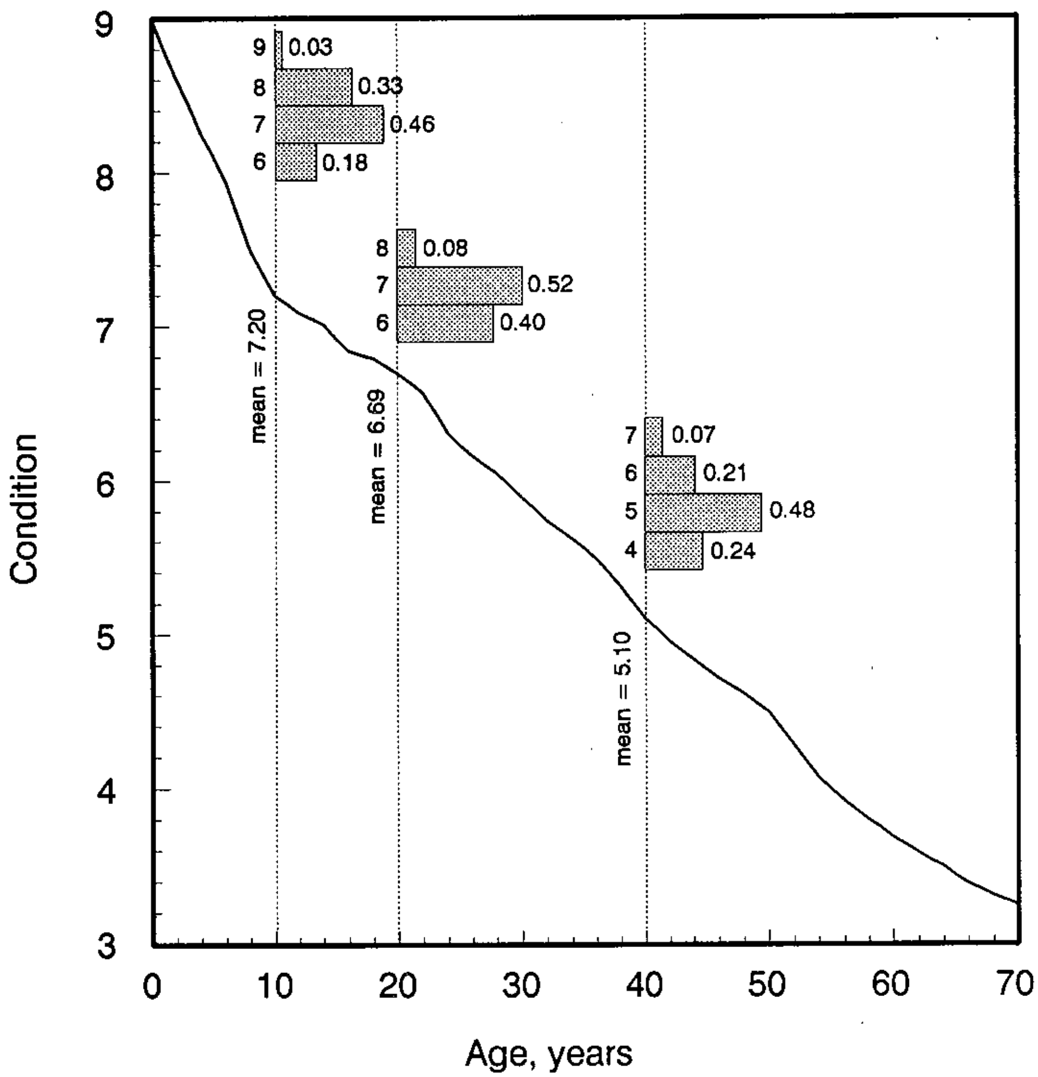

Figure 6.18 Substructure condition - concrete bridges on interstate highways

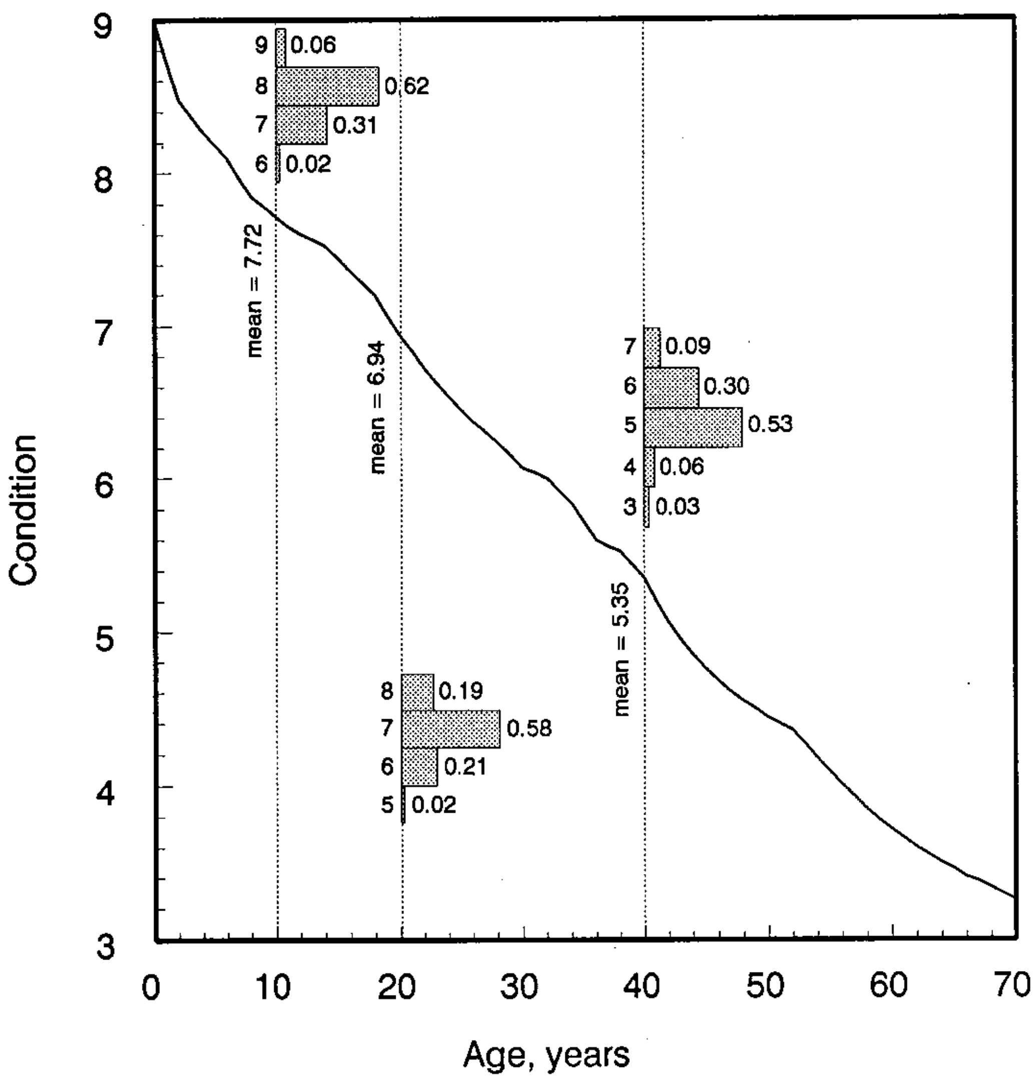

Figure 6.19 Substructure condition - nonskewed concrete bridges on noninterstate highways

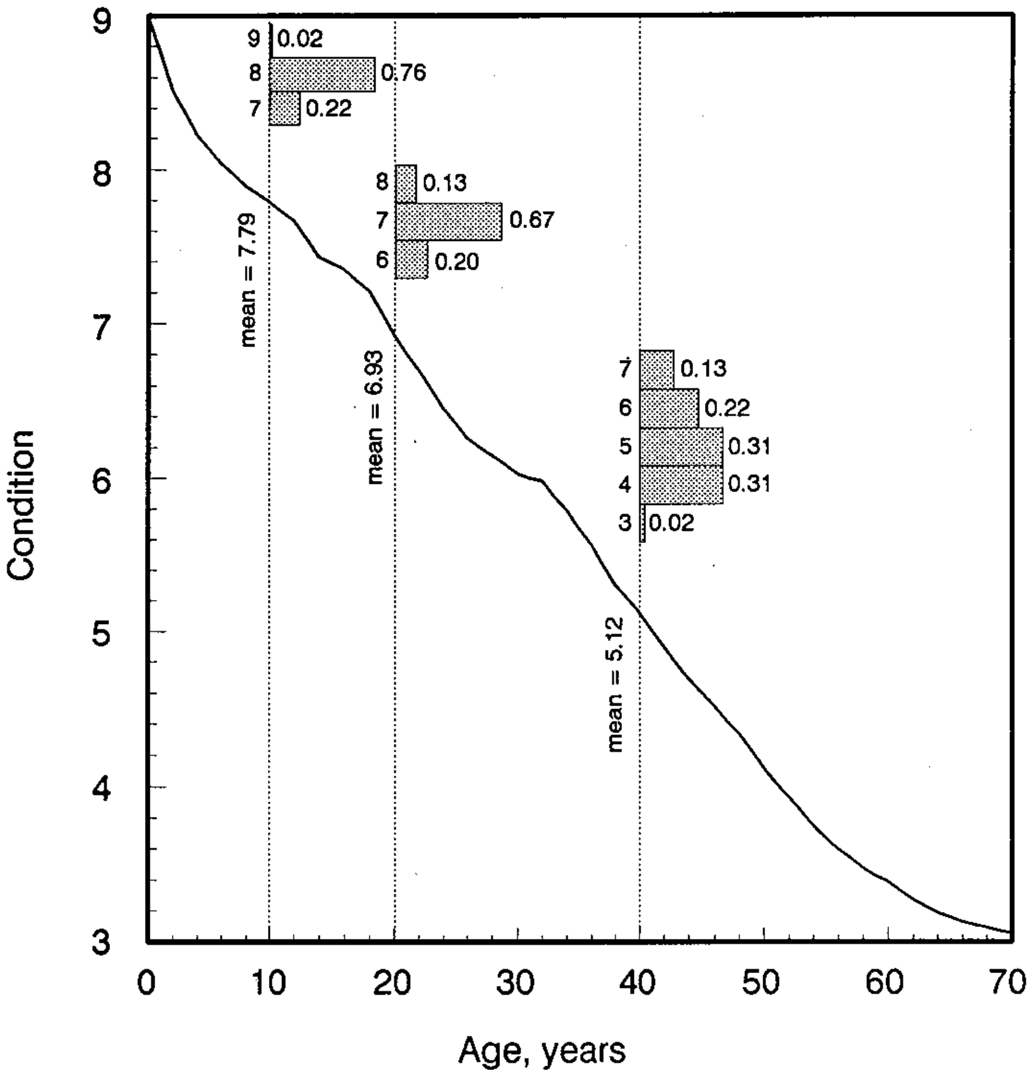

Figure 6.20 Substructure condition - skewed concrete bridges on noninterstate highways

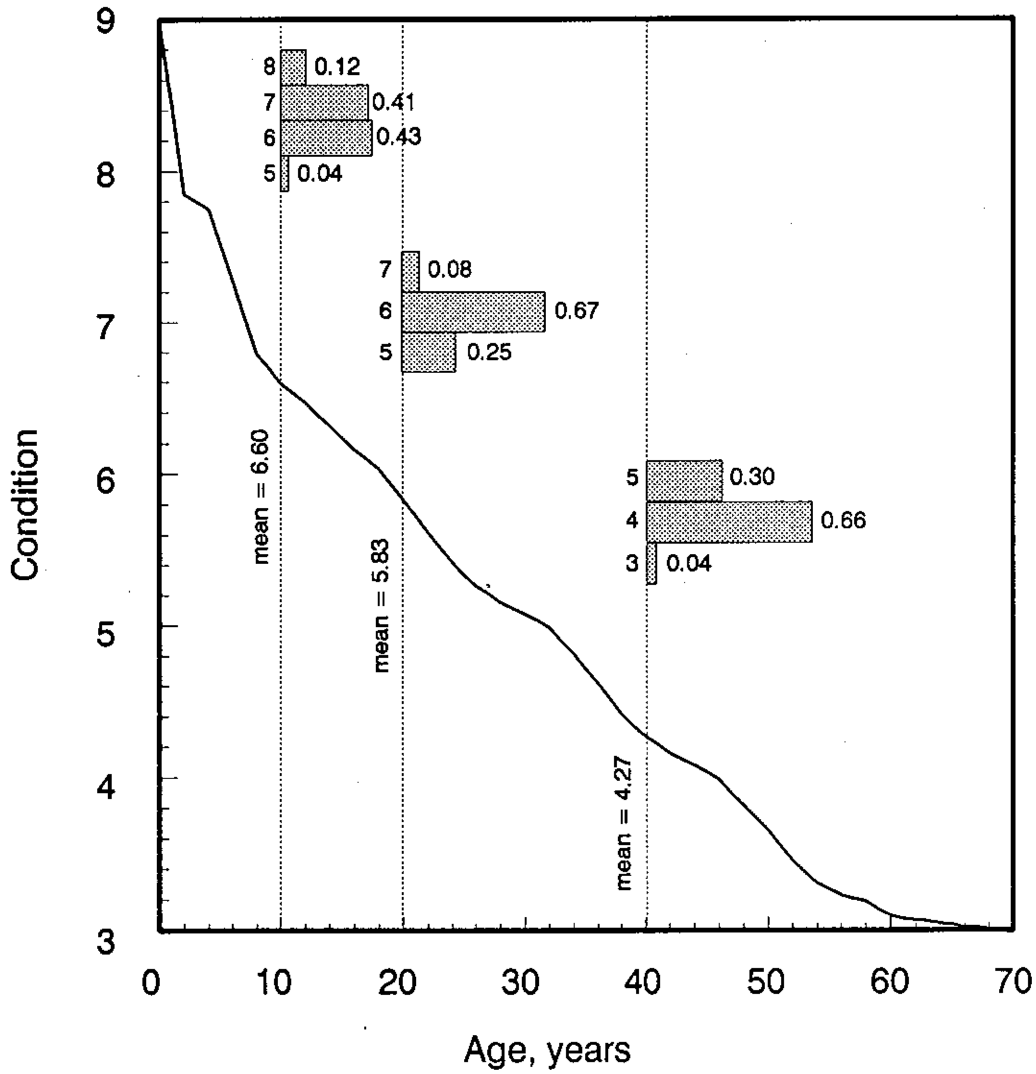

Figure 6.21 Structural appraisal - steel bridges on interstate highways

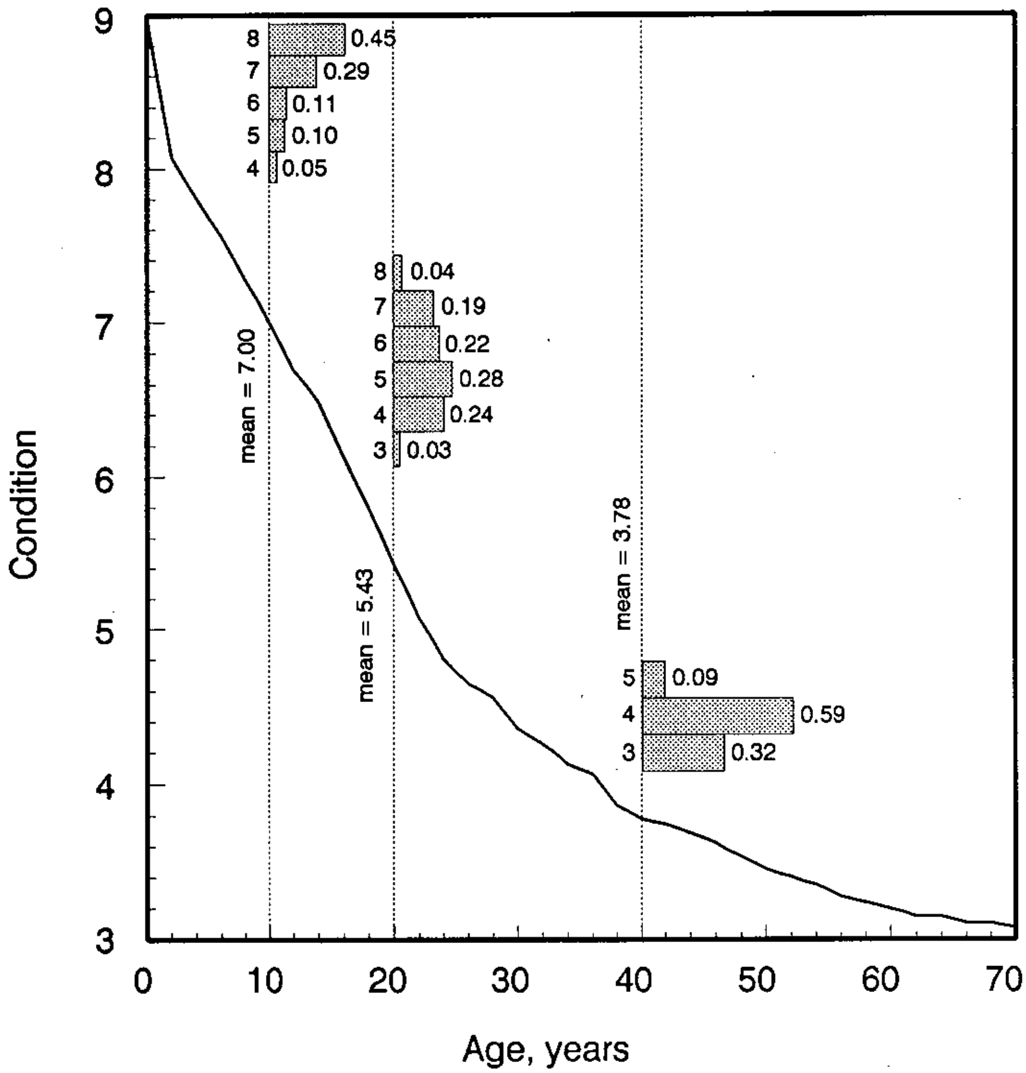

Figure 6.22 Structural appraisal - nonskewed steel bridges on noninterstate highways

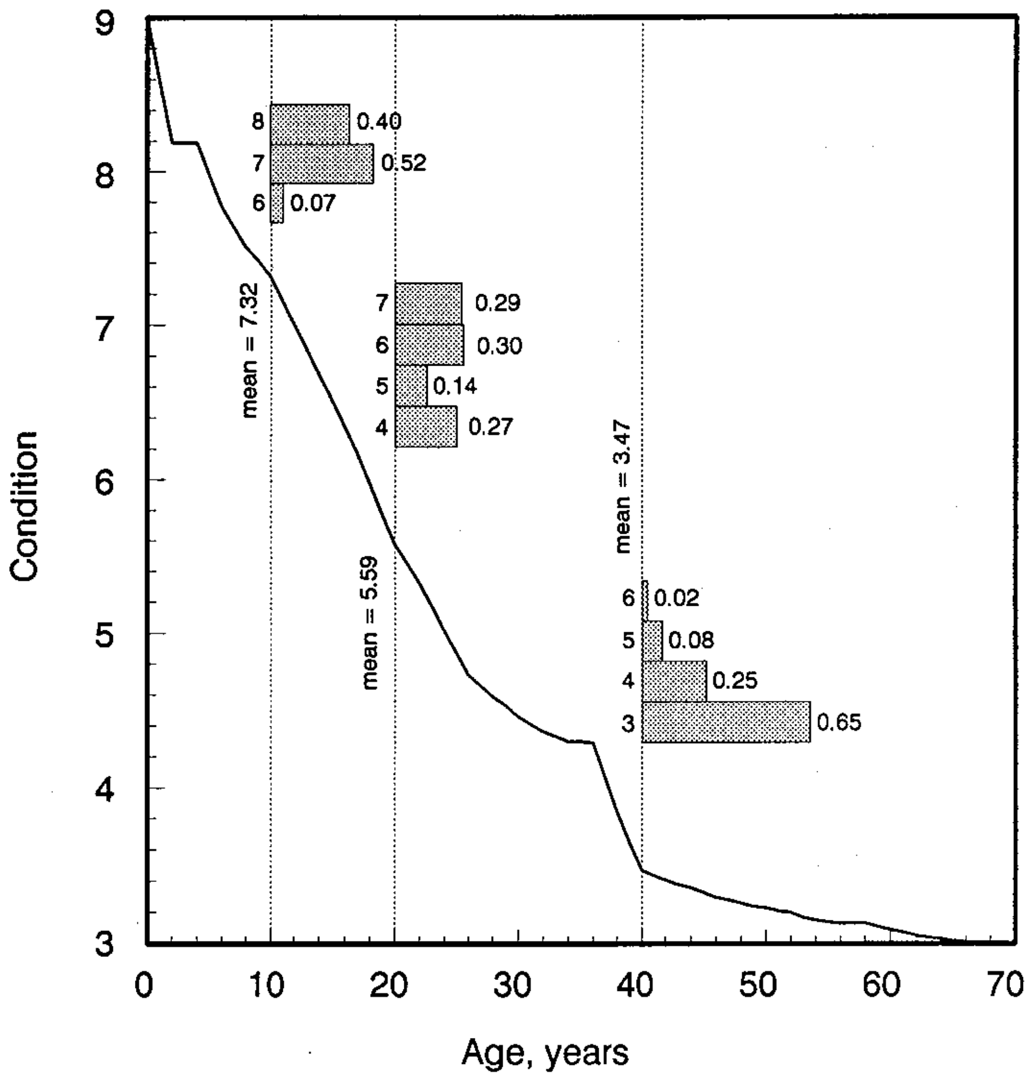

Figure 6.23 Structural appraisal - skewed steel bridges on noninterstate highways

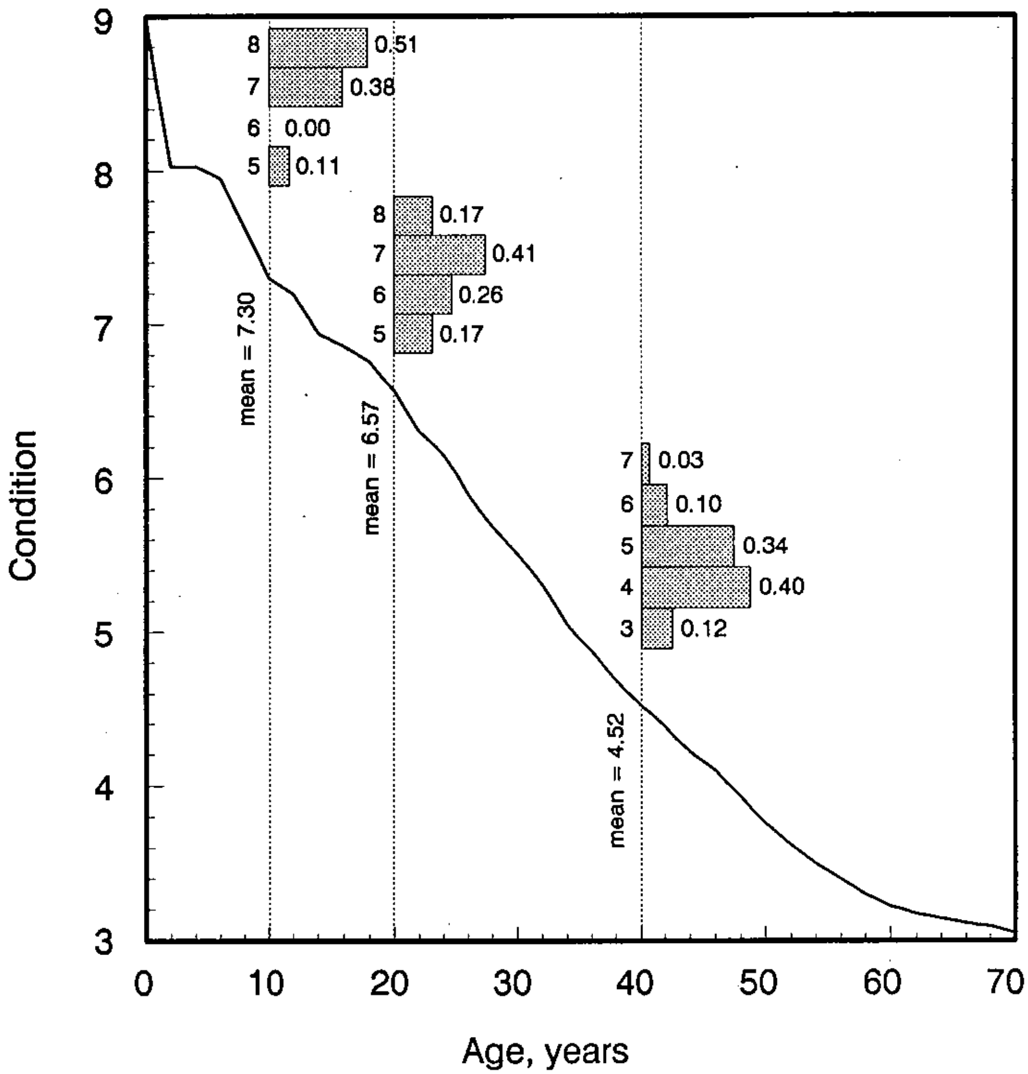

Figure 6.24 Structural appraisal - concrete bridges on interstate highways

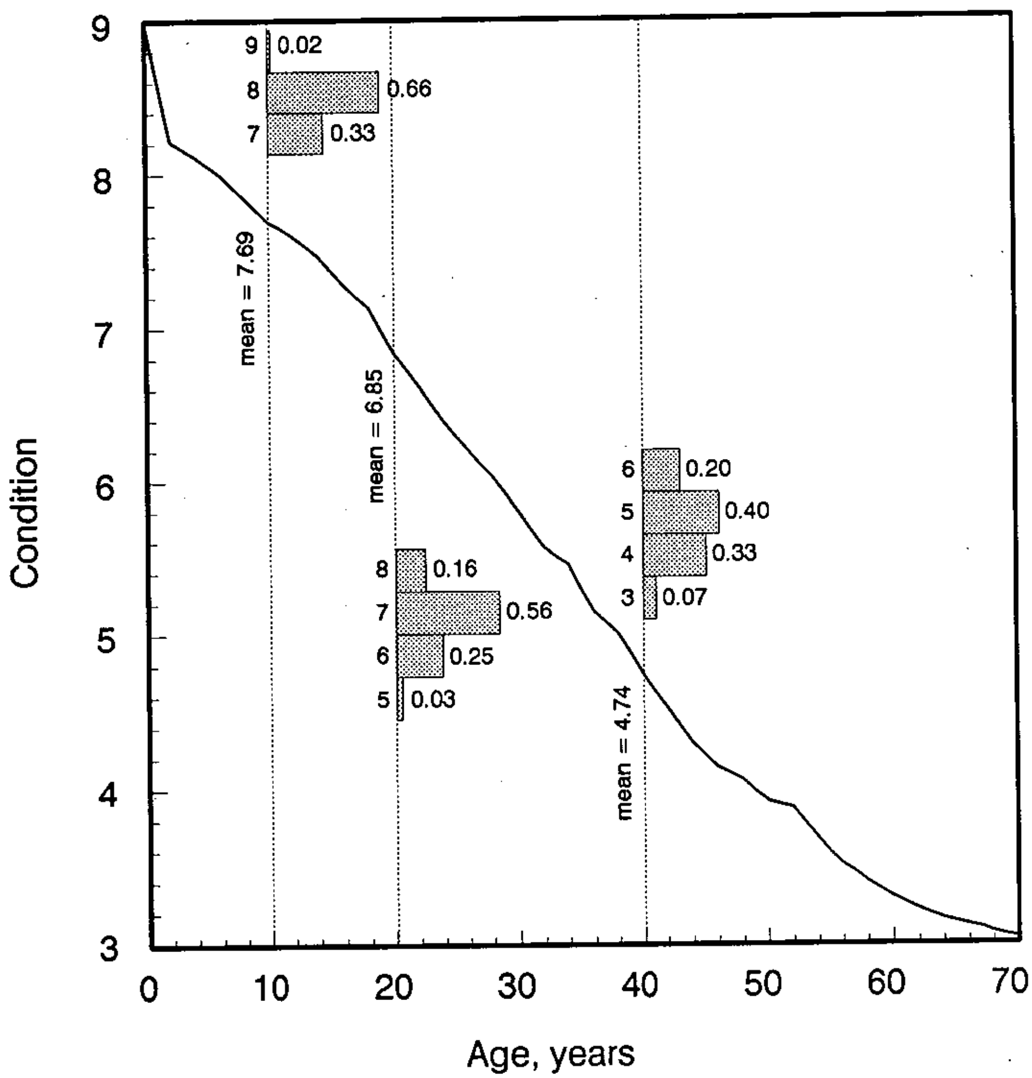

Figure 6.25 Structural appraisal - nonskewed concrete bridges on noninterstate highways

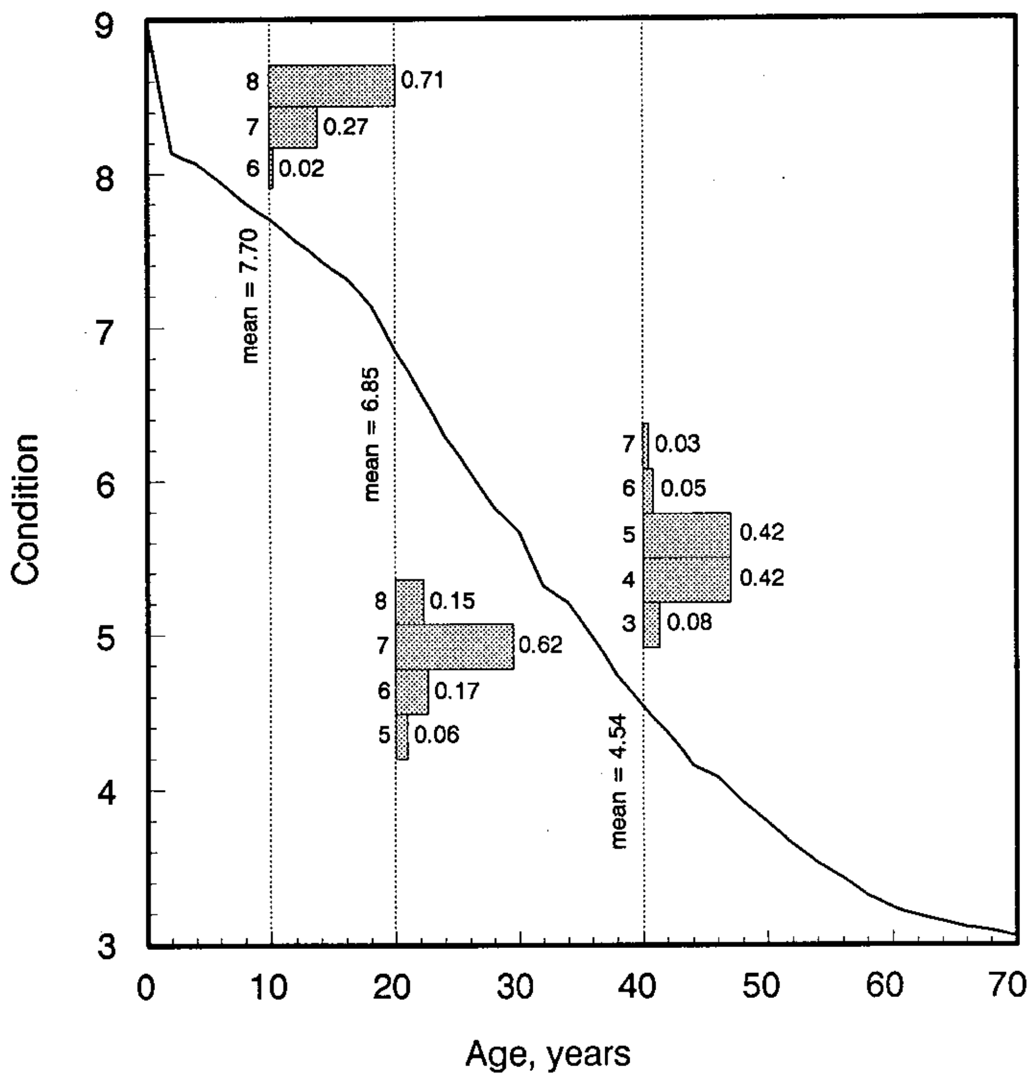

Figure 6.26 Structural appraisal - skewed concrete bridges on noninterstate highways

Table 6.12 Iowa bridge component service lives, years

	Group Number					
	1[a]	2[b]	3[c]	4[d]	5[e]	6[f]
Deck Condition	38	54	43	50	51	53
Superstructure Condition	26	35	34	60	51	52
Substructure Condition	54	55	58	61	60	56
Structural Appraisal	51	48	39	52	56	52

[a]1 = steel bridges on interstate highways.

[b]2 = nonskewed steel bridges on noninterstate highways.

[c]3 = skewed steel bridges on noninterstate highways.

[d]4 = concrete bridges on interstate highways.

[e]5 = nonskewed concrete bridges on noninterstate highways.

[f]6 = skewed concrete bridges on noninterstate highways.

Table 6.12 illustrates that Iowa bridges do not require extensive categorization in order to establish their respective bridge component deterioration curves. The subdivision of bridges according to superstructure material type is only significant for the deterioration associated with the deck and superstructure condition ratings, as well as the structural condition appraisal rating. Substructure deterioration varies very little between all six categories.

The subdivision of bridges according to interstate versus noninterstate classification is not significant for any of the concrete bridge categories. However, the service life associated with steel bridge components does vary depending on this criteria. For example, the service life for the deck and superstructure of interstate steel bridges is considerably less than that of noninterstate steel bridges. The service life for the structural condition appraisal rating is actually higher for interstate steel bridges than that for noninterstate steel bridges; this is probably due to higher initial design standards for interstate bridges.

The subdivision of noninterstate bridges according to skewed versus nonskewed classification is only significant for the deck condition and structural condition appraisal ratings associated with steel bridges. For the remaining bridge categories and components, bridge skew has little effect on the rate of their deterioration.

7. SUMMARY AND CONCLUSIONS

7.1 Summary

According to 1990 statistics [1], there are over 578,000 bridges on our nation's highways. Almost 40% of these bridges are classified as substandard according to federal guidelines. In order to reduce the large number of deficient bridges, a more cost effective procedure for allocating bridge funds must be established. BMS are one means of accomplishing this goal. The principal objective of a BMS is to make the best use of available funds in an overall bridge maintenance, rehabilitation and replacement program.

The objective of this research was to investigate the current status of BMS development and develop various BMS elements which are specific to the state of Iowa. This research is intended to aid in the development of a BMS for the Iowa DOT by complementing research presently being performed in FHWA Demonstration Project No. 71, Phase II.

An extensive literature review was performed which included all current BMS research, numerous state's bridge management practices, and several commercial BMS packages. The literature review identified the BMS elements which were considered to be specific to each state. The BMS elements which were investigated for the state of Iowa include:

level-of-service goals, agency costs, user costs, and bridge component deterioration rates.

Level-of-service goals are target values for selected bridge characteristics that are used to assess bridge adequacy. Minimum acceptable and desirable level-of-service goals were established for load capacity, vertical clearance, clear deck width, and the lateral clearance under the bridge.

Agency costs are the costs incurred by the governing agency due to the maintenance, repair, rehabilitation or replacement of their bridges. Agency costs were collected for maintenance, repair and rehabilitation (MRR) activities and improvement activities. A computer software program was also developed which prepares a cost estimate for user-specified repairs.

User costs are the costs incurred by the roadway user due to various level-of-service characteristic deficiencies. The elements associated with user costs which were investigated include: vehicle operating costs, accident costs, accident rates, and ADT growth rates.

Deterioration curves were developed (for the FHWA deck, superstructure and substructure component condition ratings and the structural condition appraisal rating) for six categories of Iowa bridges. A computer program based on the Markov chain statistical approach and a deterministic approach was written to perform the deterioration predictions.

7.2 Conclusions and Recommendations

The literature review illustrated that there are four levels of BMS development: the do-nothing policy, priority ranking systems, project level optimization, and network level optimization. In general, network level BMS research is being accomplished in research projects sponsored by the FHWA and NCHRP or by private commercial firms, while lower levels of BMS research are being accomplished by various state agencies. FHWA Demonstration Project No. 71, Phase II research should provide a comprehensive network level BMS which can be utilized in several states. The Iowa DOT should continue to coordinate with the FHWA project if the FHWA BMS is intended for future implementation.

The level-of-service goals which were developed for load capacity, vertical clearance, clear deck width and lateral underclearance provide an excellent means of evaluating the adequacy of existing bridges. These level-of-service goals could eventually be incorporated into a priority ranking system. In the future, the level-of-service goals should be reevaluated to determine if they still represent adequate goals.

The computer software program based on the MRR and improvement activity agency costs can be used to quickly evaluate several project level maintenance, repair, rehabilitation or total replacement alternatives. Additional agency cost data should be collected or an expert opinion poll of Iowa DOT personnel should be used to establish the costs associated with the unknown MRR procedures. In the future, a definitive procedure to collect annual unit agency costs should be established at the Iowa DOT.

All of the data collected pertaining to user costs should be directly transferrable to a future BMS. The information associated with accident costs and ADT growth rates were collected from existing Iowa DOT procedures; therefore, no procedural changes are required in order to continue collecting future updated accident costs and ADT growth rates. Further refinements could be made to the data collected for vehicle operating costs and accident rates. The linear relationship developed for vehicle operating costs versus vehicle weight could be refined to a multi-linear relationship if additional cost data were collected for one or more intermediate vehicle weights. Additional Iowa accident rate spot checks should be made in order to better define which of the existing accident rate studies should be used, or an entire study of Iowa accident rates versus bridge width could be performed to develop a curve based solely on Iowa data. Finally, the distribution of vehicles according to weight and height should be established in order to determine the number of vehicles which must detour a given bridge.

The investigation of bridge component deterioration illustrated that actual bridge inspection data and the Markov chain statistical procedure can be used to predict bridge performance. The only limitation associated with the Markov chain approach occurs when insufficient data exist to establish the transition probabilities. As an alternative to the interpolation, extrapolation and deterministic procedures used in this study, the Markov chain transition matrices could be established utilizing a nonlinear programming technique similar to Reference [62].

The work performed in this project provides a basis for establishing a BMS for the Iowa DOT. In order to ensure the future implementation of a BMS in the state of Iowa, the Iowa DOT is encouraged to continue close coordination with the FHWA research project and to keep abreast of new BMS concepts.

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APPENDIX A. MRR ACTIVITY COSTS

This appendix contains a complete listing of the deterioration/distress conditions, associated unit measurement procedure, and associated unit cost (if available) for the MRR activities described in Chapter 4. The MRR activities are organized according to five major bridge component categories: deck, superstructure, substructure, waterway, and approach roadway. The source of information for the unit cost has also been included:

S.Q. = state level questionnaire

C.Q. = county level questionnaire

C.B. = Iowa DOT contract bids summary

P.D. = Iowa DOT painting cost data

None = case specific or no apparent source

A1. Deck MRR Activities

Concrete Decks

Spalling and Scaling

ACC patching	S.Q.	$ 3.00	sq.ft.
PCC patching	S.Q.	6.47	sq.ft.
Class A repair (partial depth)	C.B.	38.42	sq.yd.
Class B repair (full depth)	C.B.	145.00	sq.yd.
PCC overlay	C.B.	25.46	sq.yd.

Concrete Decks - continued

Spalling and Scaling - continued

New deck	None	$	sq.ft.

Delamination

Epoxy injection	S.Q.	10.00	sq.ft.
	C.B.	10.14	sq.ft.

Cracking

No specific repair policy

Steel Grid Decks

Corrosion/Section Loss

New deck panel	None		sq.ft.

Unsound Welds

Reweld	None		each

Timber Decks

Misc. Decay and Weathering

Replace planks	C.Q.	65.00	each
New plank deck	C.Q.	3.80	sq.ft.
New laminated deck	C.Q.	11.20	sq.ft.

Loose Planks

Renail	C.Q.	12.00	each

Joints, Steel Plate or Finger			
Functional Failure			
Replace	None	$	lin.ft.
Joints, Steel Extrusion with Neoprene			
Leaking			
Seal	None		lin.ft.
Functional Failure			
Replace	C.B.	85.60	lin.ft.
Concrete Barrier Rails			
Collision Damage			
Repair	None		lin.ft.
Replace	C.B.	24.68	lin.ft.
Delamination or Spalling			
Repair (patching)	None		sq.ft.
Replace	C.B.	24.68	lin.ft.
Cracking			
No specific repair policy			
Steel Guardrails			
Collision Damage			
Repair/replace	C.Q.	13.80	lin.ft.

Steel Guardrails - continued

Corrosion/Section Loss

Spot paint	S.Q.	$ 10.00	lin.ft.
Complete paint	P.D.	See paint summary	
Replace	C.Q.	13.80	lin.ft.

Timber Guardrails

Collision Damage

Repair/replace	C.Q.	4.70	lin.ft.

Misc. Decay and Weathering

Replace	C.Q.	4.70	lin.ft.

Miscellaneous Items

Install Drain Extensions

	C.B.	150.00	each

Clean Concrete Deck Surface

	S.Q.	0.02	sq.ft.
	C.Q.	0.05	sq.ft.

Clean Gravel Covered Deck Surface

	C.Q.	0.08	sq.ft.

A2. Superstructure MRR Activities

Steel Girders, Floor Beams, Truss Members and Diaphragms

Note: In the future, this subcategory may require subdivision by member type.

Collision Damage			
Repair/strengthen	None	$	lin.ft.
Replace	None		lin.ft.
Corrosion/Section Loss			
Spot paint	S.Q.	6.55	sq.ft.
Complete paint	P.D.	See paint summary	
Replace	None		lin.ft.
Fatigue Cracking			
Retro-fit	None		each
Replace	None		lin.ft.

Steel Joints and Splices

Loose or Missing Rivets			
Replace with bolts	C.Q.	12.20	each
Loose Bolts			
Tighten	C.Q.	10.20	each
Missing, Cracked, or Corroded Bolts			
Replace	C.Q.	12.20	each

Prestressed Concrete Girders

Collision Damage

Repair/strengthen	None	$	lin.ft.
Replace	None		lin.ft.

Delamination or Spalling

Repair (patching)	None		sq.ft.
Replace	None		lin.ft.

Cracking

No specific repair policy

Monolithic Concrete Girders and Beams

Collision Damage

Repair/strengthen	None		lin.ft.
Replace	None		lin.ft.

Delamination or Spalling

Repair (patching)	None		sq.ft.
Replace	None		lin.ft.

Cracking

No specific repair policy

Concrete Diaphragms

Collision Damage

Repair/strengthen	None		lin.ft.
Replace	None		lin.ft.

Concrete Diaphragms - continued

Cracking, Delamination or Spalling

Block up from bridge seat			
	None	$	each
Repair (patching)	None		sq.ft.
Replace	None		lin.ft.

Timber Members

Collision Damage

Add/replace individual stringers			
	C.Q.	17.50	lin.ft.
Replace all stringers			
	C.Q.	11.50	lin.ft.

Misc. Decay and Weathering

Add/replace individual stringers			
	C.Q.	17.50	lin.ft.
Replace all stringers			
	C.Q.	11.50	lin.ft.

A3. Substructure MRR Activities

Concrete Piers and Abutments

Delamination or Spalling

Repair (patching)	None		sq.ft.
Replace	None		sq.ft.

Concrete Piers and Abutments - continued

Cracking

No specific repair policy

Timber Abutments

Misc. Decay and Weathering

Add/replace abutment piles			
	C.Q.	$575.00	each
Add/replace wing piles			
	C.Q.	340.00	each
Replace abutment or wing planks			
	C.Q.	160.00	each
Replace abutment	C.Q.	8.20	sq.ft. (surface area)

Timber Piers

Misc. Decay and Weathering

Add/replace X-bracing			
	C.Q.	370.00	each pier
Add/replace pier piles			
	C.Q.	780.00	each pile
Replace all pier piles			
	C.Q.	560.00	each pile

Bridge Seats			
Dirt and Debris			
Clean	S.Q.	$ 23.12	each
	C.Q.	37.00	each
Bearings			
Corrosion			
Paint	S.Q.	59.68	each
Piers and Abutments, General			
Settlement			
Block up from bridge seat			
	None		each

A4. Waterway MRR Activities

Degradation or Undermining of Piers			
Protect footing with riprap			
	C.B.	19.69	ton
	C.Q.	800.00	footing
Protect footing with steel sheet pile			
	None		each
Install downstream weir or dam			
	None		each

Meander Near Abutment

Protect footing with riprap

	C.B.	$ 19.69	ton
	C.Q.	800.00	footing

Center and align upstream channel

	None		each

Install jetties or spur dikes

	None		each

Berm Erosion Near Abutment

Protect berm with riprap

	C.B.	19.69	ton
	C.Q.	800.00	berm

Control runoff and rebuild berm

	None		each

Silt Accumulation

Clean and deepen the channel

	None		each

Flood Debris Accumulation

Clean off the upstream noses of piers

	C.Q.	270.00	each

Trees and Brush

Clearing and grubbing	C.Q.	2.25	sq.yd.

A5. Approach Roadway MRR Activities

Pavement Pressure Relief Joints			
Closed or Lacking			
Recut and fill	S.Q.	$225.00	each
	C.B.	18.54	lin.ft.
Concrete Pavement			
Differential Settlement			
Mud jacking	None		each
ACC overlay	None		sq.ft.
Replace slab	C.B.	60.00	sq.yd.
Spalling and Scaling			
ACC patching	S.Q.	3.00	sq.ft.
	C.B.	40.00	sq.yd.
PCC patching	C.B.	19.50	sq.ft.
ACC overlay	None		sq.ft.
Replace slab	C.B.	60.00	sq.yd.
Cracking			
Clean and seal, ACC pavement			
	C.B.	0.43	lin.ft.
Clean and seal, PCC pavement			
	C.B.	0.73	lin.ft.
Replace slab	C.B.	60.00	sq.yd.

Gravel or Dirt Roads

Low Approach

Fill as required	C.B.	$ 8.63	ton
	C.Q.	170.00	bridge

APPENDIX B. BRIDGE REPAIR COST ESTIMATOR SOFTWARE

This appendix describes the computer software which was developed to prepare cost estimates for various bridge maintenance, repair, and rehabilitation activities. In addition, the cost associated with total bridge replacement can also be determined. The format for this program was based upon the agency costs detailed in Chapter 4 and Appendix A.

The bridge repair cost estimation software consists of the following files:

BRIDGE.EXE = the executable version of the program used to perform the cost estimate

EDIT.EXE = the executable version of the program used to edit the item cost file

DEFAULT.RPR = the default repair cost estimate file

DEFAULT.CST = the default item cost file

The software is supplied on two 5.25 in. diskettes. The diskette labeled BRIDGE contains the files: BRIDGE.EXE, DEFAULT.RPR, and DEFAULT.CST. In order to use the repair cost estimator software all three of these files must be on the same diskette or be transferred to a subdirectory on a hard disk. The diskette labeled EDIT contains the files EDIT.EXE and DEFAULT.CST. Once again, in order to use the item cost file editor both of these files must be on the same diskette or be transferred to a subdirectory on a hard disk. It should be noted that the source code for the two executable programs has not been included.

B1. Features of the Bridge Repair Cost Estimator

The bridge repair cost estimator (BRIDGE.EXE) is run by making the directory which contains the files BRIDGE.EXE, DEFAULT.RPR, and DEFAULT.CST the current working directory. The program is started by typing "bridge" at the dos prompt and then pressing the enter key. A title screen will appear after a few seconds to indicate that the repair estimator is running. The title page will be replaced by the main menu which has the following options:

(1) Analyze a new repair option: This choice allows you to create a new repair option. The file created will always end with .RPR. This newly created repair option will use the currently loaded item cost file as it's basis for each item's repair cost. The currently loaded item cost file name is listed on the line directly below menu choice number 5, "Load a different item cost file". If you wish to create a new repair option using a different item cost file, then the item cost file must be loaded by selecting menu option number 5 before creating the new repair option.

(2) Modify an existing repair option: This choice allows you to modify an existing repair option. The file must be in the same directory as the repair cost estimator program (BRIDGE.EXE). The name of the currently loaded repair option file is printed on the line directly below this menu option.

(3) Delete an existing repair option: This choice allows you to delete any existing repair option. The file must be in the same directory as the repair cost estimator program (BRIDGE.EXE). The name of the currently loaded repair option file is printed on the line directly below this menu option.

(4) Print repair summary: This choice allows you to print a summary of any repair option either to a printer connected to LPT1 or to a text file on disk. The repair option file must be in the same directory as the repair cost estimator program (BRIDGE.EXE). If the summary is printed to a disk file, the name of the summary will be the same as the repair option file, but the suffix will be .PRT instead of .RPR.

(5) Load a different item cost file: This choice will allow you to use a different item cost file for the basis of calculating repair costs. The name of the item cost file

that is loaded when the repair estimate is saved will be the item cost file used when that repair file is calculated, printed or recalled from disk. In order to use any item cost file for a repair estimate, the item cost file (file ends with .CST) must be located in the same directory as the repair cost estimator program (BRIDGE.EXE).

(6) Exit the program: This choice allows you to exit to a dos prompt.

Final notes: The repair cost estimator program will always ask if you wish to save a file before leaving the program or loading a new file. For reference, the repair cost estimator program shows the current repair cost printed on each menu and submenu while preparing a repair estimate.

B2. Features of the Item Cost File Editor

The item cost file editor (EDIT.EXE) is run by making the directory which contains the files EDIT.EXE and DEFAULT.CST the current working directory. The program is started by typing "edit" at the dos prompt and then pressing the enter key. A title screen will appear after a few seconds to indicate that the item cost editor is running. The title page will be replaced by the main menu which has the following options:

(1) Create a new item cost file: This choice will allow you to create a new item cost file to be used as a basis for calculating repair estimates. The file created will always end with the suffix .CST. The item cost file contains information about the unit measurement and unit cost associated with each item that may be used in a repair alternative. For example, one item that may be used in a repair alternative is a new plank deck. Using the item cost file editor, you could assign a new unit cost or unit measurement for the new plank deck option.

(2) Edit an item cost file: This choice allows you to modify any existing item cost file. The file that you wish to edit must be in the same directory as the item cost file editor (EDIT.EXE).

(3) Delete an item cost file: This choice allows you to delete any existing item cost file. The file that you wish to delete must be in the same directory as the item cost file editor (EDIT.EXE).

(4) Exit the program: This choice allows you to exit back to the dos prompt.