SCHOOL OF
CIVIL ENGINEERING

INDIANA

DEPARTMENT OF TRANSPORTATION

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-89/12

Executive Summary, Vol. 5

THE DEVELOPMENT OF OPTIMAL
STRATEGIES FOR MAINTENANCE,
REHABILITATION AND REPLACEMENT
OF HIGHWAY BRIDGES, FINAL
REPORT VOL. 5: PRIORITY
RANKING METHOD

Mitsuru Saito
Kumares C. Sinha

PURDUE UNIVERSITY

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-89/12

Executive Summary, Vol. 5

**THE DEVELOPMENT OF OPTIMAL
STRATEGIES FOR MAINTENANCE,
REHABILITATION AND REPLACEMENT
OF HIGHWAY BRIDGES, FINAL
REPORT VOL. 5: PRIORITY
RANKING METHOD**

**Mitsuru Saito
Kumares C. Sinha**

FINAL REPORT

The Development of Optimal Strategies for Maintenance Rehabilitation
and Replacement of Highway Bridges,
Final Report Vol. 5: Priority Ranking Method

Executive Summary

TO: Harold L. Michael, Director
Joint Highway Research Project

August 15, 1989
Revised October 5, 1990
Project: C-36-731

FROM: Kumares C. Sinha, Research Engineer
Joint Highway Research Project

File: 3-4-10

Attached is the Vol. 5 of the Final Report on the HPR Part II Study entitled, "The Development of Optimal Strategies for Maintenance Rehabilitation and Replacement of Highway Bridges." This volume presents a priority ranking method developed for the Indiana Bridge Management System. It also presents the results of a survey to determine the effectiveness of bridge rehabilitation and replacement activities with respect to bridge structural condition ratings and remaining service lives. The research for this volume was conducted by Mitsuru Saito under my direction.

This report is forwarded for review, comment and acceptance by the INDOT and FHWA as partial fulfillment of the objectives of the research.

Respectfully submitted,

K. C. Sinha
Research Engineer

KCS/rrp

cc: A.G. Altschaeffl
J.L. Chameau
W.F. Chen
W.L. Dolch
A.A. Fendrick
J.D. Fricker
D.W. Halpin
G.L. Henneke

K.R. Hoover
C.W. Letts
C.W. Lovell
D.W. Lucas
J.F. McLaughlin
R.D. Miles
D.C. Nelson
P.L. Owens

B.K. Partridge
C.F. Scholer
G.B. Shoener
K.C. Sinha
C.A. Venable
T.D. White
L.E. Wood

FINAL REPORT

The Development of Optimal Strategies for Maintenance, Rehabilitation
and Replacement of Highway Bridges,
Final Report Vol 5: Priority Ranking Method

Executive Summary

Mitsuru Saito
Graduate Research Assistant

Kumares C. Sinha
Professor of Civil Engineering

Joint Highway Research Project

Project No.: C-36-73I

File No.: 3-4-10

Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana Department of Transportation

and the

U.S. Department of Transportation
Federal Highway Administration

Purdue University
West Lafayette, IN 47907
August 15, 1989
Revised October 5, 1990

Digitized by the Internet Archive
in 2011 with funding from
LYRASIS members and Sloan Foundation; Indiana Department of Transportation

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 5: Priority Ranking Method		5. Report Date August 15, 1989 <u>Revised October 5, 1990</u>	
		6. Performing Organization Code	
7. Author(s) Mitsuru Saito and Kumares C. Sinha		8. Performing Organization Report No.	
9. Performing Organization Name and Address Joint Highway Research Project Civil Engineering Building Purdue University West Lafayette, IN 47907		10. Work Unit No.	
		11. Contract or Grant No. HPR-1(24) Part II	
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		13. Type of Report and Period Covered Executive Summary Final Report Volume 5 of 6	
		14. Sponsoring Agency Code	
15. Supplementary Notes Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration			
16. Abstract This report is the fifth of a six-volume final report and it presents the findings of the part of the research work dealing with the development of a priority ranking method for bridge project selection. The volume also includes an analysis to determine the effectiveness of bridge replacement and rehabilitation projects with respect to bridge structural condition ratings and remaining service lives. The titles of all six volumes are listed below: Vol. 1. Elements of Indiana Bridge Management System Vol. 2. A System for Bridge Structural Condition Assessment Vol. 3. Bridge Traffic Safety Evaluation Vol. 4. Cost Analysis Vol. 5. Priority Ranking Method Vol. 6. Bridge Performance and Optimization			
17. Key Words Bridge Management; Priority Ranking; Effectiveness; Condition Rating		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

The Development of Optimal Strategies for Maintenance, Rehabilitation
and Replacement of Highway Bridges,
Final Report Vol. 5: Priority Ranking Method

EXECUTIVE SUMMARY

As part of a study to develop a comprehensive bridge management system for the Indiana Department of Transportation (INDOT), an analysis was conducted of the effectiveness of bridge projects, and a ranking model was developed for bridge project selection. This report describes the methodologies applied in these analyses and presents the results of the effectiveness analysis and the bridge ranking model, as summarized below.

Effectiveness of Bridge Improvement Alternatives

The effectiveness of a bridge project can be measured in terms of various factors including improvement of structural condition, increased level of service, improved traffic safety, and so on. In order to determine the possible effects of various bridge activities on improving bridge condition rating and on extending bridge service life, a Delphi study was undertaken with bridge inspectors in Indiana Department of Transportation. Delphi technique [Linston and Turoff 1975] has been found to be an effective approach for expert opinion survey. The reason for undertaking an expert opinion survey was that the existing bridge records were not sufficient to assess the effectiveness of bridge improvement works. Therefore, the Delphi study was used to have the district and central office bridge inspectors participate in the process of reaching a consensus on the effectiveness of bridge improvement alternatives. In Table 1 is presented an example of the results arrived in the study. The table shows the expected effects of deck rehabilitation on bridge

Table 1. Effectiveness of Deck Rehabilitation Alternatives on Condition Rating and Remaining Service Life (Mean Values)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation (%)
		Before	After	Change	Minimum	Average	Maximum	
Deck Replacement	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair		N.A.			N.A.		0
	Poor	4	8	4	16	21	27	100
	V. Poor	3	8	5	16	21	27	100
Deck Reconstruction	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	7	3	7	12	17	60
	Poor	4	7	3	7	11	16	100
	V. Poor	3	7	4	7	10	15	90
Deck Patching	V. Good		N.A.			N.A.		0
	Good	6	7	1	5	7	8	60
	Fair	5	6	1	4	5	7	90
	Poor	4	6	2	3	5	7	100
	V. Poor	4	6	3	3	4	6	90

Notes: * N.A. - Not applicable, meaning that inspector would rarely recommend this activity when condition rating is in the given level.

* Percentage of the chance of recommendation was rounded to the nearest 10s.

condition ratings and remaining service lives.

Development of a Network Level Bridge Ranking Method

Ranking procedures have been widely used to evaluate and select highway projects. Bridge managers and programmers must often relay on a set of subjective judgments, such as bridge structure condition rating, benefit to the motorist, and impact on the surrounding community, to determine the comparative effectiveness of alternative bridge projects. Setting priorities on bridge related projects can be a typical multi-attribute decision-making problem, requiring decision-makers to evaluate simultaneously several related factors. Therefore, a systematic evaluation procedure is needed, which can not only help decision-makers to set the relative order of importance of different projects, but also provide an indication of how much importance one project may have over the others.

One of many existing ranking procedures and multi-attribute decision-making techniques, the analytic hierarchy process (AHP) [Saaty 1980], was selected for application in the Indiana Bridge Management System. A ranking method using the AHP was developed and evaluated for its practicality in ranking bridge projects. For dealing with a large number of bridge projects, the method was modified by incorporating a concept of utility functions.

Four objectives were considered in developing the ranking method, as listed below:

1. Maximization of bridge condition preservation,

Figure 1. Recommended Four-Strata Default Hierarchy for IBMS

2. Maximization of effectiveness of investment,
3. Maximization of bridge traffic safety,
4. Minimization of negative community impact.

Figure 1 illustrates the structure of the ranking hierarchy, its objectives and corresponding criteria. A computer program was coded for the ranking model and it can be used efficiently to rank hundreds of bridges on a micro-computer.

The use of the Delphi technique is described through examples in this report. The applicability of the AHP method is also demonstrated. The steps to be taken for implementing the ranking method is discussed in detail.

References

Linston, H.A. and M. Turroff [1975], eds., The Delphi Method: Techniques and Applications, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts.

Saaty, Thomas [1980], The Analytic Hierarchy Process: Planning, Priority Setting, and Resource Allocation, McGraw Hill, Inc., New York.

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-89/12

Final Report, Vol. 5

**THE DEVELOPMENT OF OPTIMAL
STRATEGIES FOR MAINTENANCE,
REHABILITATION AND REPLACEMENT
OF HIGHWAY BRIDGES, FINAL
REPORT VOL. 5: PRIORITY
RANKING METHOD**

**Mitsuru Saito
Kumares C. Sinha**

FINAL REPORT

The Development of Optimal Strategies for Maintenance Rehabilitation
and Replacement of Highway Bridges,
Final Report Vol. 5: Priority Ranking Method

TO: Harold L. Michael, Director
Joint Highway Research Project

August 15, 1989
Revised October 5, 1990
Project: C-36-73I

FROM: Kumares C. Sinha, Research Engineer
Joint Highway Research Project

File: 3-4-10

Attached is the Vol. 5 of the Final Report on the HPR Part II Study entitled, "The Development of Optimal Strategies for Maintenance Rehabilitation and Replacement of Highway Bridges." This volume presents a priority ranking method developed for the Indiana Bridge Management System. It also presents the results of a survey to determine the effectiveness of bridge rehabilitation and replacement activities with respect to bridge structural condition ratings and remaining service lives. The research for this volume was conducted by Mitsuru Saito under my direction.

This report is forwarded for review, comment and acceptance by the InDOT and FHWA as partial fulfillment of the objectives of the research.

Respectfully submitted,

K. C. Sinha
Research Engineer

KCS/rrp

cc: A.G. Altschaeffl
J.L. Chameau
W.F. Chen
W.L. Dolch
A.A. Fendrick
J.D. Fricker
D.W. Halpin
G.L. Henneke

K.R. Hoover
C.W. Letts
C.W. Lovell
D.W. Lucas
J.F. McLaughlin
R.D. Miles
D.C. Nelson
P.L. Owens

B.K. Partridge
C.F. Scholer
G.B. Shoener
K.C. Sinha
C.A. Venable
T.D. White
L.E. Wood

FINAL REPORT

The Development of Optimal Strategies for Maintenance, Rehabilitation
and Replacement of Highway Bridges,
Final Report Vol 5: Priority Ranking Method

by

Mitsuru Saito
Graduate Research Assistant

Kumares C. Sinha
Professor of Civil Engineering

Joint Highway Research Project

Project No.: C-36-73I

File No.: 3-4-10

Prepared as Part of an Investigation

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

in cooperation with the

Indiana Department of Transportation

and the

U.S. Department of Transportation
Federal Highway Administration

Purdue University
West Lafayette, IN 47907
August 15, 1989
Revised October 5, 1990

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle The Development of Optimal Strategies for Maintenance, Rehabilitation and Replacement of Highway Bridges, Final Report Vol. 5: Priority Ranking Method		5. Report Date August 15, 1989 Revised October 5, 1990	
		6. Performing Organization Code	
7. Author(s) Mitsuru Saito and Kumares C. Sinha		8. Performing Organization Report No.	
9. Performing Organization Name and Address Joint Highway Research Project Civil Engineering Building Purdue University West Lafayette, IN 47907		10. Work Unit No.	
		11. Contract or Grant No. HPR-1(24) Part II	
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204		13. Type of Report and Period Covered Final Report Volume 5 of 6	
		14. Sponsoring Agency Code	
15. Supplementary Notes Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration			
16. Abstract This report is the fifth of a six-volume final report and it presents the findings of the part of the research work dealing with the development of a priority ranking method for bridge project selection. The volume also includes an analysis to determine the effectiveness of bridge replacement and rehabilitation projects with respect to bridge structural condition ratings and remaining service lives. The titles of all six volumes are listed below: Vol. 1. Elements of Indiana Bridge Management System Vol. 2. A System for Bridge Structural Condition Assessment Vol. 3. Bridge Traffic Safety Evaluation Vol. 4. Cost Analysis Vol. 5. Priority Ranking Method Vol. 6. Bridge Performance and Optimization			
17. Key Words Bridge Management; Priority Ranking; Effectiveness; Condition Rating		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price

TABLE OF CONTENTS

LIST OF TABLES	Page vi
LIST OF FIGURES	vii
CHAPTER 1 - INTRODUCTION	1
1.1 Purpose and Scope of Research	1
1.2 Report Organization	2
CHAPTER 2 - EFFECTIVENESS OF BRIDGE IMPROVEMENT ALTERNATIVES ...	4
2.1 Background	4
2.2 Purpose of the Opinion Survey	5
2.3 Use of the Delphi Study	7
2.4 Implementation of a Delphi Procedure	9
2.4.1 The Panel	9
2.4.2 The Questionnaire	11
2.4.3 The Rounds	13
2.5 Results of the Delphi Study	14
2.5.1 Linguistic Rating vs. Numeric Rating	14
2.5.2 Rating vs. Severity and Extent of Distresses	16
2.5.3 Expected Remaining Service Life	17
2.5.4 Effectiveness of Improvement Activities	22
2.6 Effects of Delphi Rounds on Panelists	22
2.7 Chapter Summary	28
CHAPTER 3 - DEVELOPMENT OF A NETWORK LEVEL BRIDGE RANKING METHOD	29
3.1 Background	29
3.2 Review of the Available Ranking Methods	30
3.3 Essence of the Analytic Hierarchy Process	33
3.3.1 Hierarchies and Pairwise Comparisons	34
3.3.2 Scale Used for Pairwise Comparison	35
3.3.3 Procedure to Determine Project Weights	37
3.3.4 Consistency Check of Pairwise Comparisons	42
3.3.5 Sample Application of AHP	43
3.4 Conceptualization of the IBMS Ranking Method	47
3.4.1 Inclusion of Utility Functions to the AHP	47
3.4.2 Procedure to Develop Utility Functions	50
3.5 Sample Application of the IBMS Ranking Concept	51

3.5.1 Descriptions of Sample Bridge Replacement Projects and the Hierarchy Used	51
3.5.2 Determination of Criteria Weights	55
3.5.3 Development of Utility Curves	60
3.5.4 Ranking Results	63
3.5.5 Comparison with Other Methods	66
3.6 Steps for Implementing the IBMS Ranking Method	69
3.6.1 Selection of Ranking Factors	69
3.6.2 Structure of the Hierarchy	72
3.6.3 Determination of Weights for Objectives and Criteria .	73
3.6.4 Development of Utility Curves for Evaluation Criteria	73
3.6.5 Implementation Procedure	77
3.7 Chapter Summary	80
CHAPTER 4 - SUMMARY AND CONCLUSIONS	82
4.1 Summary of Findings	82
4.1.1 Effectiveness of Improvement Alternatives	82
4.1.2 Ranking Method	83
4.2 Limitations of the Application	83
REFERENCES	85
APPENDIX - RESULTS OF DELPHI STUDY ON EFFECTIVENESS OF IMPROVEMENT ACTIVITIES ON BRIDGE PERFORMANCE	88

LIST OF TABLES

Table		Page
2.1	Relation Between the Linguistic Condition Rating and the Severity and Extent of Distresses for Bridge Decks	18
2.2	Effectiveness of Deck Rehabilitation Alternatives on Condition Rating and Remaining Service Life (Mean Values)	23
2.3	Reduction in Standard Deviation of Estimated Remaining Service Life of Bridge Deck	25
3.1	Importance of Alternatives Scale	38
3.2	Values of the Average Random Index (R.I.) for Matrices of Order One Through Fifteen	44
3.3	Simple Example to Rank Three Bridge Improvement Projects	45
3.4	Priority Evaluation Measures by Project Number for Sample Bridge Replacement Problem	53
3.5	Priority Evaluation Criteria for the Selection of Bridge Replacement Projects	56
3.6	Reciprocal Matrix, Eigenvalue, and Eigenvector for Six Attributes	58
3.7	Final Ranking and Project Choices for Implementation by the AHP Method for the Sample Bridge Replacement Problem	65
3.8	Comparison of Ranking by the Analytic Hierarchy Process (AHP) Method and the Successive Subsetting (SS) Method ..	68
3.9	Recommended Evaluation Criteria and Possible Substitutes	70

Appendix

Table

Page

A.1	Percentage of Responses to the Relationship between the Condition Rating and Combination of Levels of Distresses of the Bridge Deck	93
A.2	Percentage of Responses to the Relationship between the Condition Rating and Combination of Levels of Distresses of the Concrete Superstructure	94
A.3	Percentage of Responses to the Relationship between the Condition Rating and Combination of Levels of Distresses of the Steel Superstructure	95
A.4	Percentage of Responses to the Relationship between the Condition Rating and Combination of Levels of Distresses of the Substructure	96
A.5	Effectiveness of Rehabilitation Alternatives on Condition Rating and Remaining Service Life of the Bridge Deck (Mean Values)	97
A.6	Effectiveness of Rehabilitation Alternatives on Condition Rating and Remaining Service Life of the Concrete Superstructure (Mean Values)	100
A.7	Effectiveness of Rehabilitation Alternatives on Condition Rating and Remaining Service Life of the Steel Superstructure (Mean Values)	101
A.8	Effectiveness of Rehabilitation Alternatives on Condition Rating and Remaining Service Life of the Substructure (Mean Values)	104

LIST OF FIGURES

Figure		Page
2.1	Schematic Representation of the Process for Determining Condition Ratings	6
2.2	Flow of Information and Tasks of Panelists and Analyst	10
2.3	Sample Survey Form for the Second Round of the Delphi Study	12
2.4	Relationship Between the Linguistic Rating and the FHWA Numeric Condition Rating	15
2.5	Panelist Estimates of Remaining Deck Service Life in Years When Do-Nothing Option is Selected at Each Condition Rating Level	20
2.6	Comparison of Deterioration Curves Developed by Delphi Study and Regression Analysis of Recorded Condition Rating Data	21
2.7	Changes in Estimates of Remaining Service Life of New Decks Over the Two Rounds	26
2.8	Changes in Estimates of Projected Additional Service Life of Decks Over the Two Rounds	27
3.1	Sample Hierarchy System for Ranking Three Bridge Improvement Projects	36
3.2	Incorporation of Utility Curves in the AHP Method	49
3.3	Transformation of Eigenvector Values to Utility Points	52
3.4	Sample Hierarchy System for Ranking a Group of Bridge Improvement Projects	57
3.5	Pairwise Comparison Matrix and Utility Curve for Condition Rating	62
3.6	Pairwise Comparison Matrix and Utility Curve for Service/Cost Ratio	64
3.7	Recommended Four-Strata Default Hierarchy for IBMS	74
3.8	A General Shape of Utility Curves for the Evaluation Criteria with Upper and Lower Bounds	76
3.9	A General Shape of Utility Curves for the Evaluation	

	Criteria with No Upper and Lower Bounds	78
3.10	Flow Chart for Implementing the Suggested Ranking Procedure	79
Appendix		
Figure		
A.1	Membership Value for the Levels of Condition Rating in Percentage (%)	88
A.2	Deck Condition Rating vs. Expected Remaining Service Life When Do-Nothing Option is Chosen	89
A.3	Concrete Superstructure Condition Rating vs. Expected Remaining Service Life When Do-Nothing Option is Chosen	90
A.4	Steel Superstructure Condition Rating vs. Expected Remaining Service Life When Do-Nothing Option is Chosen	91
A.5	Substructure Condition Rating vs. Expected Remaining Service Life When Do-Nothing Option is Chosen	92

ACKNOWLEDGMENTS

The guidance and assistance of William T. Dittrich and Joseph S. Torkos of the Indiana Department of Transportation (INDOT) and Paul A. Hoffman of the Federal Highway Administration (FHWA) Divisional Office in conducting the study is gratefully acknowledged. The help of Steven Hull of INDOT in the early phase of the study is also acknowledged. The authors are thankful for the extensive review made by Robert E. Woods of the draft reports. Thanks are extended to James Hare of the FHWA Regional Office who served as the Field Project Advisor and John O'Fallon of the FHWA Structures Division who served as the Headquarters Technical Contact. The successful completion of the project owed greatly to the generous support of the district bridge inspectors of the INDOT. Acknowledgment is also extended to Mrs. Rita Pritchett and Mrs. Cheryl Kerker who typed the report.

CHAPTER 1

INTRODUCTION

1.1 Purpose and Scope of Research

The goal of the present study was to develop improved methods for determining optimal strategies for the maintenance and preservation of the state highway bridge system in Indiana. The overall research had the following major objectives:

1. Development of a method to better use the existing bridge inspection data in selecting bridges for maintenance, rehabilitation, and replacement;
2. Development of a method to provide consistent and statewide uniform measurements for rating bridges;
3. Analysis of bridge maintenance, rehabilitation, and replacement costs, and analysis of relationships between bridge attributes and costs;
4. Development of a method to estimate remaining service life of bridges and effects of bridge activities on condition rating and

service life;

5. Development of a bridge traffic safety evaluation scheme that relates physical characteristics of bridge structure to accident potential;
6. Development of a project selection procedure using life cycle cost analysis, ranking, and optimization methods; and
7. Development of a set of guidelines that can be used by the Indiana Department of Transportation in implementing a bridge management system including data bases and organizational requirements.

The items listed above are discussed separately in various reports; the present report includes the following items:

1. Assessment of the effect of bridge activities on bridge condition rating and remaining service life; and
2. Development of a bridge project ranking procedure.

1.2 Report Organization

This report consists of four chapters and one appendix. Chapter 2 reports the results of a Delphi study conducted to assess inspectors' opinions about the effectiveness of bridge activities on bridge performance. The Delphi approach [Linston and Turoff 1975] was used to arrive at a consensus opinion of bridge inspectors. Chapter 3 discusses the development of a bridge project ranking scheme based on the Analytic Hierarchy Process proposed by

Saaty [1980]. Application of utility curves, or weighing curves, to the ranking process is explained with an example. Chapter 4 gives the summary and conclusions of the research findings. The appendix presents a complete summary of the Delphi study about the interpretation of bridge condition rating scheme and the impact of bridge related activities on bridge condition rating and remaining service life.

CHAPTER 2

EFFECTIVENESS OF BRIDGE IMPROVEMENT ALTERNATIVES

2.1 Background

The effectiveness of a bridge project can be measured in terms of various factors including improvement of the bridge structural condition, increased level of service, improved traffic safety, and so on. A major effectiveness factor considered in this study was improvement in condition rating due to a bridge activity and increase in service life. This information is difficult to arrive at on the basis of field data because of the limited amount of available condition rating data. The existing bridge records, which have been collected by InDOT since the beginning of the federal bridge inventory program in 1978, do not include variables that would help the bridge manager to assess the effectiveness of bridge improvement works. Consequently, it was decided to undertake an expert opinion survey of bridge inspectors in Indiana to generate the needed information.

Group dynamics techniques have been frequently used for forecasting trends in the future when historical data are not available for rigorous statistical analyses. One such technique was used in Pennsylvania to make esti-

mates of bridge maintenance and rehabilitation costs [Weyers et al. 1987]. In the present study, Delphi technique was selected to survey bridge inspectors because of its distinct advantages over traditional panel meetings. This technique was originally developed at the Rand Corporation and used in many kinds of decision-making situations [Linston and Turoff 1975] where participants have to make estimates on items which are not very clear to them.

2.2 Purpose of the Opinion Survey

The purpose of the opinion survey was to have the district and central office bridge inspectors participate in the process of reaching a consensus on the effectiveness of bridge improvement alternatives. There were four major objectives in conducting the survey.

1. Find relationships between the inspectors' subjective linguistic ratings and the FHWA numeric condition ratings;
2. Assess the influence of severity and the extent of distresses upon the inspectors' judgment regarding the condition rating;
3. Find relationships between the FHWA numeric condition rating and the remaining service life when no action is taken;
4. Estimate the increase in the condition rating and the remaining service life when certain improvement activities are applied.

Many factors affect the bridge inspector's judgment when he inspects a bridge. It is difficult, if not impossible, to consider all possible factors that may be encountered during the on-site inspection. Figure 2.1 shows a

Figure 2.1 Schematic Representation of the Process for Determining Condition Ratings

simplified decision-making process that may be followed by the bridge inspector to determine a numeric condition rating. The bridge inspector first observes types of distresses prevalent on various components of the bridge structure. Depending on the severity and extent of the distresses, he gives a general intuitive linguistic condition rating, such as good, fair, and poor. After that, he may either assign a numeric condition rating and make an appraisal to recommend a proper improvement alternative or select initially an improvement alternative and then assign a numeric rating hoping for its implementation. In selecting alternatives, the effectiveness of the alternatives is an important factor although it cannot be clearly quantified at the moment. The above four objectives were set in an attempt to find connections among the elements of condition rating and the appraisal process.

2.3 Use of the Delphi Study

When historical information is not available, techniques which draw help from intuitions of decision makers are often used. In analyzing certain problems, an expert or a group of experts can be used as consultants. There are many ways of extracting the knowledge and intuition of experts [Dickey and Watts 1978]. These techniques have both advantages and disadvantages. For instance, committee work is a common technique used to set directions on what will be done in the future. It does help to extract a wide range of information, but the committee decision may be easily affected by either some dominantly vocal committee members or by a tendency to conform to the majority opinion.

Delphi has three distinct features which distinguish it from the usual

methods of committee interaction. These features include: (1) anonymity, (2) iteration with controlled feed back, and (3) statistical response [Linston and Turoff 1975]. Anonymity of the procedure ensures that the group members are not made known to each other during the Delphi sequence. The interaction among the group members is handled in a completely anonymous way through the use of questionnaires. The anonymity of the entire process keeps group members from identifying a specific opinion with a particular member. The group members are therefore free to reconsider their previous opinions without publicly admitting a previous wrong assumption. The anonymity of the process also ensures that "an idea can be considered on its merits, regardless of whether the originator is held in high or low esteem by the other members of the group" [Dickey and Watts 1978].

During the Delphi sequence, controlled feedback follows the completion of the questionnaire and this controlled feedback is the only way for a member to interact with other committee members in the Delphi sequence. The analyst in charge of the Delphi sequence extracts from the questionnaires only those pieces of information relevant to the issue and presents them to the committee members through a subsequent questionnaire. The individual participant therefore is informed only of the current status of the collective opinion of the group. Both the majority and minority opinions can be preserved for the next sequence. The main purpose of this controlled feedback is to "prevent the group from making goals and objectives on its own" [Dickey and Watts 1978].

Statistical response is the third characteristic unique to the Delphi method. Typically, a committee would produce a decision containing only a majority viewpoint. However, in reality, there are occasions where minority

views prove to be as important as a majority opinion. Traditional committee techniques are not equipped with a mechanism for showing the variation of opinions quantitatively. The Delphi procedure presents, however, a statistical response which includes everyone's opinions. On a single question, for instance, the response may be presented in terms either of a median and two quartiles or a mean and a standard deviation. Consensus on the question is expressed by either the median or mean and the spread of opinion is shown by the size of the interquartile range or standard deviations [Dickey and Watts 1978].

Figure 2.2 illustrates a two-round Delphi sequence. In a Delphi sequence each successive submission of a questionnaire is referred to as a "round." The term "questionnaire" is somewhat misleading since it not only has questions but also provides feedback to the committee members about the degree of consensus and the arguments presented by the members. A committee of experts used for Delphi sequences is frequently referred to as a "panel" and the committee members as "panelists." The person or group collecting the panel responses and preparing the questionnaires is often called the "analyst" or "director".

2.4 Implementation of a Delphi Procedure

2.4.1 The Panel

The panel consisted of fourteen InDOT employees in charge of bridge inspection and bridge design. There were six bridge inspectors and one assistant inspector from the six district offices, five from the bridge inspection group of the central office and two bridge design engineers from the central

Figure 2.2 Flow of Information and Tasks of Panelists and Analyst

office. The panel consisted of inspectors who had different periods of experience in bridge inspection. The longest length of experience was sixteen years and the shortest was four months. The main reason for including only bridge inspectors and bridge designers in the panel was that some questions required on-site knowledge about bridges and it was felt that these questions could only be answered appropriately by those who actually deal with bridges either in their design or inspection. Strictly speaking, the survey did not meet the condition of anonymity because the members knew who were in the committee. However, the anonymity of responses was strictly followed.

2.4.2 The Questionnaire

The questionnaire was comprised of four parts. The first two parts attempted to establish relationships between the subjective linguistic condition rating, the FHWA's numeric condition rating, and the severity and extent of bridge distresses. The third part tried to establish the remaining service life of bridge components when no improvement activities are applied. The fourth part was included to assess the inspector's subjective assessment of the effectiveness of improvement alternatives upon bridge performance in terms of his estimate of increased condition rating and of increase in remaining service life. Figure 2.3 illustrates a sample questionnaire, used in the second round, to evaluate the inspector's opinions on the expected remaining service life of a bridge deck. Summary statistics from the first round were given as a feedback to provide the inspectors an opportunity for reconsidering their first responses. As shown in the figure, means and standard deviations were used to show the variation among their responses. Explanations in the questionnaire were limited to only essential matters to avoid distractions.

[A.] Summary of the First Round

The following table summarizes inspectors' opinions given in the first survey concerning the relationship between the condition rating and remaining service life if no repair is made at a certain condition rating. In the table, the mean indicates the average value of remaining service life in years. Whereas, the SD is the standard deviation, indicating the spread of the opinions around the mean value: the larger the standard deviation, the wider the spread in the opinions.

Remaining Service Life in Years

Condition Rating	Minimum		Average		Maximum	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
9	20.8	7.9	29.3	8.6	39.2	11.6
8	18.8	7.7	26.3	5.8	34.6	8.9
7	16.3	7.7	21.6	7.2	26.5	8.1
6	12.8	5.1	16.6	5.7	20.9	7.8
5	8.5	4.9	11.2	5.8	14.9	6.8
4	5.1	3.0	7.4	3.5	11.0	4.9
3	2.9	2.4	4.0	2.3	6.0	3.6
2	1.2	1.3	2.2	1.9	3.5	3.2
1	0.3	0.7	1.1	0.9	1.8	1.7
0	0.1	0.3	0.4	0.7	0.9	1.7

REMAINING SERVICE LIFE OF THE BRIDGE DECK

IF NO REPAIR IS MADE

[B.] Second Round

The objective of the second survey is to reach a consensus. Using the given table and graph from the first survey as a guide and your first survey response, give your second response. Fill in the form below by writing down estimates of remaining service life in years at given condition rating when no repair is made.

Condition Rating	Remaining Service Life in Years		
	Minimum	Average	Maximum
9			
8			
7			
6			
5			
4			
3			
2			
1			
0

Figure 2.3 Sample Survey Form for the Second Round of the Delphi Study

Results of the four parts of the questionnaire are discussed later in this chapter using the results of the survey for the bridge deck.

2.4.3 The Rounds

It was at first planned to run three rounds for this Delphi study; however, only two rounds were undertaken in order to minimize the time spent by the inspectors in participating in the study and, most importantly, the variation of responses was found to have reduced in almost all categories of questions after the second round. Although a three-round sequence seems to be most popular and recommended, there are cases when only two rounds were found to be satisfactory [Olsen 1982].

All fourteen of the panelists were visited by the analyst in person to explain the procedure for filling out the first round questionnaire. The four parts were carefully explained to the panelists because of the possible confusion which could arise in responding to some of the questions. The first visits to the panelists were made from the end of September, 1987, into the third week of October, 1987. The first three parts were collected on the same day of the visits. Panelists were given time for the fourth part of the questionnaire because it required careful examination of the effectiveness of improvement alternatives upon the overall performance of the bridge. It took about three weeks to get all the first survey forms back. The second round of questionnaires was sent by mail from the end of December, 1987 and into the first week of January, 1988, followed by phone calls to clear up any possible questions. It took about four weeks to receive ten completed forms. The remaining four questionnaire forms were not returned.

2.5 Results of the Delphi Study

The two-round survey provided a large amount of information. A complete description of the results is given in Appendix A. Here, only the results concerning the bridge deck are presented.

2.5.1 Linguistic Rating vs. Numeric Rating

In the field, most of the bridge inspectors rate the condition of bridge components first by a subjective linguistic rating using intuition and then assign a numeric condition rating. In order to get consistent input data into a bridge management system, it is necessary to reach a consensus upon how the bridge inspectors interpret the FHWA's numeric rating defined in the bridge recording and coding guide [FHWA 1979, 1988] so that the discrepancy among district and central office inspectors on the interpretation of the condition rating scale can be minimized. In this survey, five levels of linguistic condition ratings were used. The basic three ratings were good, fair, and poor, and two ratings, very good and very poor, were added to cover extreme cases.

Figure 2.4-(a) shows the membership functions of the five linguistic ratings relative to the numeric condition ratings. These membership functions show into what numeric condition ratings the inspectors would transform their linguistic ratings. Figure 2.4-(b) shows a different view of the membership functions given in Figure 2.4-(a). This figure gives the probabilities of a bridge being given a certain numeric condition rating when a word rating is converted. The survey results imply that bridges which receive condition ratings of 0, 1, and 2 are in very poor condition, while bridges with a condition rating of 9 are considered to be very good. These two groups are, however,

(a) The membership functions of the condition ratings as perceived by bridge inspectors

(b) Correlation between the numerical condition rating and the linguistic rating (expressed in percentage)

Figure 2.4 Relationship Between the Linguistic Rating and the FHWA Numeric Condition Rating

rarely used in the actual condition rating; bridges quickly deteriorate from a condition rating of 9, and bridges which would receive ratings of 0, 1, and 2 would rarely exist due to replacement programs. Therefore, numeric ratings of 3, 4, 5, 6, 7, and 8 are used to categorize almost all the bridges in Indiana. Roughly speaking, bridges with ratings of 3 and 4 would be considered to be in poor condition, those with ratings of 5 and 6 in fair condition, and those with ratings of 7 and 8 in good condition.

From discussions with the inspectors, it was found that the perception about how to interpret the condition rating scale was different among them. Results of this survey can be helpful to reduce discrepancies in appraisal caused by different interpretations of the condition rating scale.

2.5.2 Rating vs. Severity and Extent of Distresses

Transforming the observation of the severity and extent of distresses of bridge parts into a numeric condition rating is the first step of the condition rating process. At present, a reference guide which explicitly describes the relationship between the deterioration levels of bridge components and the numeric condition ratings is not available within the IDOH. Some states have such reference guides already available to the inspectors. For instance, a bridge inspection procedure manual prepared by the North Dakota State Highway Department [NDSHD 1985-86] provides a well-compiled inspection manual which explains in what type of deterioration levels certain numeric condition ratings should be given.

The second part of the survey was aimed at establishing a general relationship between the levels of severity and extent of bridge distresses and

the five linguistic ratings. Since there were no physical inspections of the same bridges by all of the participating inspectors, the results obtained from this part of the survey should be used with caution. However, the results do reflect a general trend of group opinion of how inspectors interpret the bridge condition. Table 2.1 shows the results from the second round. Inspectors were asked to consider the distress types listed in the figure to respond to the survey.

Results shown in Table 2.1 can be interpreted in the following manner. For example, when the severity level of a prevailing distress is medium and its extent is also at the medium level, 75 out of 100 cases can be rated to be in fair condition, and 25 out of 100 cases could be rated to be in poor condition. Hence, roughly speaking, using the result of the first part of the survey, 75 out of 100 cases will most probably get a numeric rating of either 5 or 6 with some exceptions for this severity and extent category. On the other hand, 25 out of 100 bridges will most probably receive numeric ratings of 3 or 4 in the same category. The results of this part of the study can be used in revising the current recording guide used by the inspectors to include more explicit explanations about the relationship between the levels of distresses and numeric condition ratings.

2.5.3 Expected Remaining Service Life

The remaining service life is one of the items that the FHWA recording and coding guide [FHWA 1979] requires the state to report. The remaining service life is, however, difficult to assess because it is dependent on future repair works as well as other factors such as weather and traffic. In this

Table 2.1 Relation Between the Linguistic Condition Rating and the Severity and Extent of Distresses for Bridge Decks

Item Rating															
Very Good				Good			Fair			Poor			Very Poor		
Extent	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
	44	11		78	67	56		44	33			44			
				11			89	100	33			33			
Severity	M														11
	H						33				78	67		67	100

Note: 1. Numbers in the cells show the percentage of responses.

2. If no distress is found, condition rating would be "very good."

3. Levels of severity and extent are: L for light, M for medium, and H for heavy.

List of Primary Deck Distress Types Considered for Evaluation

- * Spalling and cracking underside of deck
- * Wearing of pavement surface including spalling and cracking top of deck
- * Inoperable or leaking joints
- * Deteriorated or damaged railing
- * Deteriorated or damaged deck drains and pipes
- * Deteriorated or damaged curb, median, sidewalk, parapet, or coping
- * Inadequate deck drainage
- * Corrosion of reinforcing steel

survey it was decided to consider the estimated remaining service life at a certain condition rating, assuming that no repair was to be applied in the future. Therefore, the resultant estimate of the remaining service life would be on the conservative side. Figure 2.5 illustrates the summary of opinions of the inspectors from the second round of the survey about the expected remaining service life (expressed in years) of bridge deck. On the average, a new deck was estimated to last about 28 years if no improvements were made on it. The mean estimate of minimum life spans was about 23 years, and the mean estimate of maximum life spans was about 37 years. Results from this part of the survey can be used as a guideline to decide when to request either rehabilitation or replacement of decks.

The remaining service life information can be transformed into an approximate deck deterioration curve by computing the number of years for a deck to move from one condition rating to the next lower condition rating. Figure 2.6 shows the resulting deck deterioration curves on the basis of average and maximum estimates of remaining service life. They are shown along with the deck deterioration curves obtained by regression analyses of actual condition rating records of the state-owned bridges. In developing the regression curves, effects of major deck rehabilitation works were discounted; however, the effects of minor repair and routine maintenance could not be excluded. In the questionnaire, no distinction was made between bridges on interstates and other state highways. The difference between the deterioration curves resulting from the Delphi study and the deterioration curves by regression analyses can be primarily attributed to the fact that the Delphi study assumed no maintenance and repair. The general trend of the two sets of deterioration

Figure 2.5 Panelist Estimates of Remaining Deck Service Life in Years When Do-Nothing Option is Selected at Each Condition Rating Level

Figure 2.6 Comparison of Deterioration Curves Developed by Delphi Study and Regression Analysis of Recorded Condition Rating Data

curves implies that the Delphi procedure can provide fairly reliable information in making estimates of condition rating changes in the future. The results also indicate that the inspectors are mostly consistent in their rating approach.

2.5.4 Effectiveness of Improvement Activities

The fourth part of the opinion survey was used to reach a consensus on the effectiveness of various improvement activities for the components of a bridge. Effects were measured by two different criteria: the change in numeric condition rating and the increase in remaining service life. Some alternatives may not cause any perceptible increase in condition ratings at all; in such cases, the estimated increase in the remaining service life can be used as an alternate measurement.

Table 2.2 presents the panelists' judgments regarding the effectiveness of three major deck rehabilitation alternatives: deck replacement, deck reconstruction and deck patching. The survey results showed significant differences in projected bridge service lives. These differences may reflect variables, such as the difference in the amount of truck traffic and weather conditions, that were not explicitly used in the survey. This table also shows the expected changes in condition ratings after a repair work is undertaken. Results of this part of the questionnaire are only rough estimates by nature. However, when the data base accumulates sufficient information on bridge improvement history, the effectiveness of improvement alternatives can be better estimated.

2.6 Effects of Delphi Rounds on Panelists

In order to assess the effects of Delphi rounds on the panelists in

Table 2.2 Effectiveness of Deck Rehabilitation Alternatives on Condition Rating and Remaining Service Life (Mean Values)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation (%)
		Before	After	Change	Minimum	Average	Maximum	
Deck Replacement	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair		N.A.			N.A.		0
	Poor	4	8	4	16	21	27	100
	V. Poor	3	8	5	16	21	27	100
Deck Reconstruction	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	7	3	7	12	17	60
	Poor	4	7	3	7	11	16	100
	V. Poor	3	7	4	7	10	15	90
Deck Patching	V. Good		N.A.			N.A.		0
	Good	6	7	1	5	7	8	60
	Fair	5	6	1	4	5	7	90
	Poor	4	6	2	3	5	7	100
	V. Poor	4	6	3	3	4	6	90

Notes: * N.A. - Not applicable, meaning that inspector would rarely recommend this activity when condition rating is in the given level.

* Percentage of the chance of recommendation was rounded to the nearest 10s.

reaching a consensus, some results from the first and second rounds were compared. It seems that the Delphi rounds helped the inspectors to make some adjustments and provoked thoughts when the inspectors' first responses differed from the values accepted by other fellow inspectors.

Table 2.3 shows the reductions in standard deviations among estimates of the remaining service life of a deck when a do-nothing approach was considered taken for the entire life of a bridge deck. As shown in the table, the variation in the opinion regarding condition rating was remarkably reduced. In the range of 8 through 4, the standard deviation was reduced about 50%.

Figure 2.7 shows the change in responses among the panelists. This figure included only responses from the panelists who returned both the first and second questionnaires. It shows a slight conversion of opinions toward the average value, that is, a consensus. One panelist, who has been a bridge inspector for a relatively long time, made a significant change in the second round; this change may have resulted from an effort to correct his misinterpretation of a particular question in the first round. The second round provided him an opportunity to revise his first opinion. Figure 2.8 shows the change in opinions regarding a deck's service life due to deck patching when the condition rating is fair. In this question, one panelist, who was new to bridge inspection, gave a response which was quite removed from the consensus with other inspectors. However, in the second round, he reconsidered his first response and gave an estimate which was very close to the estimates made by others.

Table 2.3 Reduction in Standard Deviation of Estimated
Remaining Service Life of Bridge Deck

Condition Rating	First Round		Second Round		Difference in Standard Deviation
	Mean	S.D.	Mean	S.D.	
9	29.3	8.6	28.4	4.4	-4.2
8	26.3	5.8	26.0	3.9	-1.9
7	21.6	7.2	20.8	3.3	-3.9
6	16.6	5.7	16.5	3.7	-2.0
5	11.2	5.8	10.5	3.3	-2.5
4	7.4	3.5	7.5	4.0	+0.5
3	4.0	2.3	3.1	1.5	-0.8
2	2.2	1.9	2.1	1.7	-0.2
1	1.1	0.9	1.1	1.0	+0.1
0	0.4	0.7	0.7	0.8	+0.1

Figure 2.7 Changes in Estimates of Remaining Service Life of New Decks Over the Two Rounds

Figure 2.8 Changes in Estimates of Projected Additional Service Life of Decks Over the Two Rounds

These sample results show that the Delphi rounds did help panelists to approach consensus. In the survey, those who have a lot of experience in bridge inspection did not make significant modifications in their responses between the first and second rounds. This result indicates that some inspectors may not be affected much by feedback on certain questions.

2.7 Chapter Summary

The effectiveness of bridge improvement alternatives has not been well defined, although it is an essential element of a bridge management system. It is difficult to establish what actually constitutes effectiveness. In order to extract the knowledge of bridge inspectors in measuring the effectiveness of repair works, an opinion survey, based on Delphi technique, was conducted.

Although the number of rounds of the survey was limited to only two, it was possible to direct the bridge inspectors to come close to a consensus on the items presented in the questionnaire. Since a bridge management system heavily depends on the data base, it is essential that inputs to the data base be collected based on a consistent interpretation of the rating standards in order to reduce any bias.

In this chapter, results of the survey related to the bridge deck were used as examples to discuss main elements of this survey. Survey results for the remaining parts of a bridge structure (superstructure and substructure) can be found in Appendix A along with a complete set of results for the bridge deck component.

CHAPTER 3

DEVELOPMENT OF A NETWORK LEVEL BRIDGE RANKING METHOD

3.1 Background

Ranking procedures have been widely used to evaluate and select highway projects. These procedures do not necessarily give an optimal solution. Nevertheless, a ranking approach is simple to use and can provide an initial listing of bridge projects placed in order of importance. Such a list is what is needed to initiate discussions among the decision-makers for making final selections.

Bridge managers and programmers must often rely on a set of subjective judgments, such as bridge structure condition rating, benefit to the motorist, and impact on the surrounding community, to determine the comparative effectiveness of alternate bridge projects. Setting priorities on bridge related projects can be a typical multi-attribute decision-making problem requiring decision-makers to evaluate simultaneously several related factors. Therefore, a systematic evaluation procedure is needed, which not only can help decision-makers to set the relative order of importance of different projects, but also can provide an indication of how much importance one project may have

over the others. A ranking procedure which can be incorporated into the Indiana bridge management system (IBMS), therefore, needs to be one that is capable of reflecting judgments of bridge managers, programmers and other decision-makers about the evaluation criteria considered and also flexible enough for future improvements and modifications.

After a careful evaluation of advantages and disadvantages of currently available bridge project ranking procedures and multi-attribute project selection techniques, the concept of the analytic hierarchy process (AHP), developed by Saaty [1980], was selected to be included into the IBMS. The present method extends and improves a procedure developed by Harness and Sinha [1983]. A ranking method using the AHP was developed and evaluated for its practicality in ranking bridge projects. For dealing with a large number of bridge projects, the method was modified by incorporating a concept of utility functions. The objectives of this chapter are: (1) to demonstrate the usefulness of the proposed method by comparing the results from this method with the results from the successive subsetting method developed in an earlier project [Harness and Sinha 1983], and (2) to discuss in detail the steps to be taken for implementing this ranking method within the IBMS.

3.2 Review of the Available Ranking Methods

FHWA provides the states flexibility in project selection process. Some states have already developed bridge management systems which reflect their particular needs. The bridge rehabilitation and replacement project ranking procedures currently available can be grouped into three types: sufficiency rating, level-of-service deficiency rating, and cost-effectiveness rating.

The sufficiency rating approach [FHWA 1979] is often used as a reference for bridge management at the state level.

As a bridge ranking index, FHWA developed the sufficiency rating, which ranges from 0 to 100 points. This index is computed using structural condition ratings of bridge components and other information such as serviceability and essentiality of bridges [FHWA 1979]. A bridge is considered structurally deficient (SD) if its deck, superstructure, or substructure has weakened or deteriorated to the point that the bridge is inadequate to support all types of traffic [FHWA 1984]. A bridge is considered functionally obsolete (FO), if deck geometry, load carrying capacity, clearance, or approach roadway alignment no longer meets the usual criteria for the system of which it is a part [FHWA 1984]. An SD or FO bridge with a sufficiency rating of less than 50 is eligible for federal bridge funds for replacement. An SD or FO bridge with a sufficiency rating between 50 and less than 80 is eligible for federal bridge funds for rehabilitation. According to a survey of state highway agencies conducted in the present study, the Sufficiency Rating is used more often as an index to determine cut-off points for requesting federal bridge funds than as a ranking index.

The level-of-service approach was developed first in North Carolina [Johnston and Zia 1985], based on an idea that priorities must be determined by the degree to which a bridge is deficient in meeting public needs. Major indices used by this method included single-vehicle load capacity, clear bridge deck width, vertical clearance, and remaining service life. In Pennsylvania, this level-of-service technique was modified so that structural condition elements were incorporated in the ranking process [McClure and

Koretzky 1985]. A type of bridge project ranking procedure based on life-cycle cost analysis was developed in Wisconsin and used in an actual highway programming process [Hyman and Hughes 1983]. This procedure is based primarily on the cost-effectiveness approach, which was also used as a part of the bridge management system in Pennsylvania [Weyers et al. 1983].

Another area examined for developing the IBMS was the field of decision science. Decision science offers variety of techniques which can be used to deal with multi-attribute decision problems. The utility theory of Keeney and Raiffa [1977] has been used in transportation related problems [Keeney and Raiffa 1977; Mohan and Bushnak 1985]. Until recently, this technique was theoretically proven, but it was considered to be the most complex procedure among the multi-attribute decision-making techniques available [Schoemaker 1982].

Concordance analysis [Nijkamp and Delft 1977] is another technique that has been used to solve transportation problems. Janarthanan and Schneider [1986] used it for selecting the best transit improvement alternative and Shiraishi et al. [1984] used it in a bridge evaluation problem. This technique is based on a series of pairwise comparisons across a set of criteria. Concordance analysis seems to work better for a small set of project alternatives. It may be, however, inefficient for ranking a large number of bridge projects, which is often the case for a state-wide bridge project evaluation process, because matrices of pairwise comparisons become extremely large and pairwise comparisons become time-consuming.

Srinivasan and Shocker [1973] developed a multi-attribute problem-solving

process using linear programming techniques. This method is also based on pairwise comparisons, and like concordance analysis, the number of pairwise judgments increases quickly when the number of alternatives increases. It will be $n(n-1)/2$, where n is the number of alternatives. Moreover, the decision-maker must consider all included criteria simultaneously when making pairwise judgments. The outcome of this method is a set of weights for the alternatives.

In ranking projects, objectives and criteria are often placed in hierarchical order by decision-makers to sort out interacting elements. Attributes of projects are then evaluated under each criterion and the attribute values are aggregated for making final decisions. The Analytic Hierarchy Process, developed by Saaty [1980] in the early seventies, attempts to simulate this process. This approach was first used for solving problems for the Department of Defense, and it was subsequently used for a wide variety of allocation and strategic planning problems for corporate and international organizations. The application of the hierarchy theory can allow decision-makers to stratify ranking objectives and criteria into several clusters and study intricate systems to a sequence of pairwise comparisons of properly identified components. This process has been used in many areas where subjective judgments can be the only way to scale the importance of criteria and alternatives involved.

3.3 Essence of the Analytic Hierarchy Process

After considering the flexibility in reflecting the decision-maker's judgments at any level of the hierarchy of desired criteria and the potential

applicability to a large-scale problem after some modifications, the analytic hierarchy process (AHP) [Saaty 1980] was chosen for developing a ranking procedure of the IBMS. The essence of the AHP will be first discussed in the following sections with an emphasis on the procedure to determine weights of the factors at each level of the hierarchy.

3.3.1 Hierarchies and Pairwise Comparisons

Hierarchies are basic to the human way of breaking a problem into clusters and sub-clusters so that the interaction of the components in the clusters and sub-clusters, as well as their impacts on the final decision, can be studied. In a hierarchical approach, the criteria and judgments are established often by an open group process; therefore, dynamic discussion is used for structuring the hierarchy by mutual agreement and revision of views among group members. It would be a group decision to determine the variables to be considered. Initially, all possible variables are accepted, and eventually, those variables which may have low priority in decision making are discarded. In the AHP, judgments are translated into absolute numbers by using a scale value which would reflect group members' qualitative judgment on pairwise comparisons of the variables considered.

There are two major activities involved in the process: hierarchical structuring of the functions of a system and measuring of the relative impacts of any element in the hierarchy [Saaty 1980]. For the first activity, a careful abstraction of a hierarchical structure needs to be made so that the strata in the hierarchy can be as independent as possible, and that pairwise comparisons can be made among the factors in the same hierarchical level. By

decomposing a system, the function of each sub-cluster would be isolated. The isolated functions would provide clarity in making judgments. Breaking a complex system into a set of pairwise comparisons is a major feature of the AHP. As for the second activity, Saaty used mathematical matrix theory to evaluate the impact of a level to the adjacent upper hierarchical level by a synthesis of the relative contributions of the elements in that level toward the element of the adjacent upper level [Saaty 1980].

A simple three-strata hierarchy, shown in Figure 3.1, can be used to explain the second point. In the second stratum of hierarchy, three evaluation criteria are considered. Relative importance of these criteria must be determined first with respect to the adjacent upper level of hierarchy. In Figure 3.1, the first stratum refers to the goal of ranking three bridges. In the next step, three bridges are evaluated each with respect to a criterion in the adjacent upper level. In the example, this level includes the evaluation criteria of structural condition, remaining service life, and average daily traffic. For instance, considering the evaluation of Bridge A and Bridge B with respect to the structural condition criterion, the first question to be asked is which one of Bridges A and B would have the worst condition. And, the second question would be how much importance one would place to one bridge over the other. Three bridges will receive some sort of scaling values to explain the strength of preference of one bridge over the other. A series of these pairwise comparisons need to be made for all possible combinations of Bridges A, B, and C. In the following section, the scaling system recommended by Saaty [1980] is discussed.

3.3.2 Scale Used for Pairwise Comparison

Once the hierarchy is set and elements of each stratum are identified,

Figure 3.1 Sample Hierarchy System for Ranking Three Bridge Improvement Projects

pairwise comparisons of the elements of hierarchies are made with respect to an element of the adjacent upper level to obtain weights for the elements. Saaty proposed the use of a one-to-nine scale to express the decision-maker's preference and intensity of preference of one element over the other. Table 3.1 gives the definitions and explanations of the level of this scaling system. The intensity level of one (1) means the equal importance and the intensity level of nine (9) means the absolute importance of one element over the other in a pair. Saaty [1980] listed several reasons why the upper limit nine would be preferable for making comparisons. One reason stated was that the ability of the human mind to discriminate one from the other is quite limited in range and there should be considerable difference between the objects compared to make definite judgments. Another reason was that the ability to make qualitative distinctions could be represented by five attributes: equal, weak, strong, very strong, and absolute. Compromises between the adjacent attributes can be made when greater precision in separating two projects is needed. The scaling system based on this reasoning requires nine values in total.

3.3.3 Procedure to Determine Project Weights

When n projects are being considered for ranking by a group, the group's goals would be: (1) to provide judgment on the relative importance of n projects; and (2) to insure that the judgments are quantified to the extent that would permit a quantitative interpretation of the group's judgment among all projects. The second goal is especially relevant in bridge management because the number of bridges involved in a ranking process would be very large. The first goal can be satisfied by performing pairwise comparisons and by assuming

Table 3.1 Importance of Alternatives Scale

Intensity of Importance	Definition	Explanation
1	Equal Importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favour one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Very strong or demonstrated importance	An activity is favoured very strongly over another; its dominance demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between adjacent scale values	When compromise is needed
Reciprocals of above nonzero	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption

the transitivity of comparison results. The transitivity assumption states that if project A is preferred to project B, and at the same time, project B is preferred to project C, then project A must be preferred to project C. However, these pairwise comparisons do not indicate the degree of preference. Therefore, the satisfaction of the second goal is done by estimating a set of weights to be associated with individual projects from the group's quantified judgments using the one-to-nine scale.

In order to achieve the second goal, Saaty [1980] proposed a procedure that is based on matrix theory. The procedure is called an eigenvector approach, which takes advantages of characteristics of a special type of matrix called a reciprocal matrix. The reciprocal matrix consists of resulting values of pairwise comparisons by using the one-to-nine scale. Two rules are set to construct a reciprocal matrix. Using the notations used by Saaty [1980], these two rules are stated below.

Let $C_1, C_2, \dots, C_n$ be a set of activities. The quantified judgments on pairs of activities C_i, C_j are represented by an n -by- n matrix

$$\bar{A} = (a_{ij}), \quad (i, j = 1, 2, \dots, n)$$

The entries a_{ij} are defined by the following entry rules.

Rule 1. If $a_{ij} = \alpha$, then $a_{ji} = 1/\alpha$, $\alpha \neq 0$.

Rule 2. If C_i is judged to be of equal relative importance as C_j , then $a_{ij} = 1$, $a_{ji} = 1$; in particular, $a_{ii} = 1$ for all i .

Thus, the matrix $\bar{A}$ has the form

$$\bar{A} = \begin{bmatrix} 1 & a_{12} & \dots & a_{1n} \\ 1/a_{12} & 1 & \dots & a_{2n} \\ \vdots & \vdots & \dots & \vdots \\ \vdots & \vdots & \dots & \vdots \\ 1/a_{1n} & 1/a_{2n} & \dots & 1 \end{bmatrix}$$

Having recorded the quantified judgments on pairs (C_i, C_j) as numerical entries a_{ij} in the matrix $\bar{A}$, the problem now is to assign to the n activities $C_1, C_2, \dots, C_n$ a set of numerical weights $w_1, w_2, \dots, w_n$ that would "reflect the recorded judgments."

In a hierarchical structure, the term activity may indicate an objective, evaluation criterion, project, or any other element in an individual stratum of the hierarchy. Several elements of matrix theory are used to obtain a set of weights for activities. Let $\bar{w}$, a column matrix, be the set of weights for the activities, and by using other definitions already defined, let us consider the following matrix relationship.

$$\bar{A} \bar{w} = n \bar{w} \quad (3.1)$$

In matrix theory, this formula expresses the fact that $\bar{w}$ is an eigenvector of matrix $\bar{A}$ with eigenvalue n . When a reciprocal matrix is perfectly consistent, that is, all relative weights can be exactly measured, the eigenvalue becomes n for a reciprocal matrix. When the entries a_{ij} are not based on exact measurements, but on subjective judgments, which is the case for actual ranking exercises, Equation (3.1) will no longer hold.

However, two elements of matrix theory alleviate this situation and make the eigenvector approach work for general cases. The first one is related to the eigenvalue (λ). If $\lambda_1, \dots, \lambda_n$ are the numbers satisfying the equation

$$\bar{A} \bar{x} = \bar{\lambda} \bar{x}, \quad (3.2)$$

i.e., $\bar{\lambda}$ is a set of eigenvalues of $\bar{A}$, and if $a_{ii} = 1$ for all i , then

$$\sum_{i=1}^n \lambda_i = n \quad (3.3)$$

Therefore, if Equation (3.1) is satisfied and the matrix is perfectly consistent, all eigenvalues are zero, except one, which is n . Obviously, in a perfectly consistent case, n is the largest eigenvalue of matrix $\bar{A}$. The second useful element is that if one changes the entries a_{ij} of a reciprocal matrix $\bar{A}$ by small amounts, the eigenvalues also change only by small amounts.

Combining these results, we find that if the diagonal cells of a matrix $\bar{A}$ consist of ones ($a_{ii} = 1$), and if matrix $\bar{A}$ is consistent, then small variations of the a_{ij} keep the largest eigenvalue, $\lambda_{\max}$, close to n , and the remaining eigenvalues close to zero. Now, if matrix $\bar{A}$ is a reciprocal matrix consisting of pairwise comparison scale values, in order to find the activity weights, one must find the vector $\bar{w}$ which satisfies

$$\bar{A} \bar{w} = \lambda_{\max} \bar{w} \quad (3.4)$$

The vector $\bar{w}$ is the eigenvector that corresponds to the maximum eigenvalue ($\lambda_{\max}$). And, the values of this column vector $\bar{w}$ are considered to be good representatives of weights of the activities compared. Since it is desirable

to have a normalized solution, we alter $\bar{w}$ by setting $\alpha = \sum_{i=1}^n \bar{w}_i$ and replacing $\bar{w}$

by $(1/\alpha)\bar{w}$. This ensures uniqueness, and also that $\sum_{i=1}^n w_i = 1$. Hence, the

deviation of $\lambda_{\max}$ from n is taken as a measure of consistency. This subject

is discussed further in the following sub-section.

In summary, there are two main steps to determine activity weights.

1. Construct a reciprocal matrix by the results of pairwise comparisons of the activities included using the one-to-nine scale;
2. Obtain the eigenvalue and eigenvector of the reciprocal matrix.

To obtain the eigenvalue and eigenvector of a reciprocal matrix, a commercially available computer package can be used. In the present study, the EVCRG routine available from the IMSL mathematics library [IMSL 1982] was used.

3.3.4 Consistency Check of Pairwise Comparisons

It is necessary to check the consistency of pairwise comparisons before accepting the eigenvector corresponding to $\lambda_{\max}$. Deviation from consistency was defined as $(\lambda_{\max} - n)/(n-1)$, which is called the consistency index (C.I.). This is an index to assess how much the consistency of pairwise comparisons is away from the perfect consistency. The numerator signifies the deviation of the maximum eigenvalue ($\lambda_{\max}$) from the perfect consistency, which is n if the order of a reciprocal matrix is n , i.e., an $n \times n$ matrix. The denominator is needed to compute an average deviation of each pairwise comparison from the perfectly consistent judgment. A value of one was subtracted from the order of matrix n because one of the pairwise comparisons is a self-comparison, and there should be no inconsistency involved in self-comparison.

The consistency check of pairwise comparisons is made by comparing the

computed consistency index with the average consistency index of randomly generated reciprocal matrices using the one-to-nine scale. The consistency index computed this way is called the random index (R.I.), and it would signify the consistency index of a totally inconsistent matrix. Table 3.2 shows the random indices for matrices of order 1 through 15. The order of a reciprocal matrix indicates the number of activities compared at one time. The term activity may indicate any items to be compared, such as objectives, evaluation criteria, and projects. For the modified AHP method, which was developed for the IBMS, the order of 15 is large enough, as explained later in the chapter.

The consistency check is made by comparing a computed consistency index with the random index, and measured by the consistency ratio (C.R.). The consistency ratio is obtained by dividing the computed consistency index by the random index (C.I./R.I.). The consistency check is actually a check of the degree of inconsistency against the total inconsistency which results from a random assignment of pairwise comparison scale values. Saaty stated that a consistency ratio of 0.10 or less can be considered acceptable [Saaty 1980]. Therefore, the closer the maximum eigenvalue ($\lambda_{\max}$) is to n , which is the order of a reciprocal matrix, the more consistent is the result of pairwise comparisons.

3.3.5 Sample Application of AHP

By using a simple three-strata problem shown in Figure 3.1, the steps of determining priorities among the three bridges using the essence of the AHP are described in this section. Table 3.3 contains the data for this problem. Table 3.3-(a) provides data related to the three evaluation criteria. Bridge

Table 3.2 Values of the Average Random Index (R.I.) for
Matrices of Order One through Fifteen

Order of Matrix	Average Random Index (R.I.)
1	0.00
2	0.00
3	0.58
4	0.90
5	1.12
6	1.24
7	1.32
8	1.41
9	1.45
10	1.49
11	1.51
12	1.48
13	1.56
14	1.57
15	1.59

Source: Saaty [1980]

Table 3.3 Simple Example to Rank Three Bridge Improvement Projects

(a) Data for the three bridges

	Bridges		
	A	B	C
Structure Rating	3	4	5
Remaining Service Life	15	15	20
ADT	2,000	3,000	10,000

(b) Pairwise comparisons of the three evaluation criteria with respect to the ranking of bridges

	Structure Rating	Rem. Service Life	ADT
Structure Rating	1	5	7
Rem. Service Life	1/5	1	3
ADT	1/7	1/3	1

$\lambda_{\max} = 3.065$ C.I. = 0.033 C.R. = 0.06
 Eigenvector = (1.00, 0.26, 0.11) Weight = (0.73, 0.19, 0.08)

(c) Pairwise comparisons of bridge projects with respect to the three evaluation criteria

	Structure Rating (S)				Rem. Service Life (R)				ADT (T)		
	A	B	C		A	B	C		A	B	C
A	1	5	8	A	1	1	4	A	1	1/3	1/7
B	1/5	1	4	B	1	1	4	B	3	1	1/5
C	1/8	1/4	1	C	1/4	1/4	1	C	7	5	1

$\lambda_{\max} = 3.094$ C.I. = 0.047
 C.R. = 0.08
 Eigenvector = (1.00, 0.27, 0.09)

$\lambda_{\max} = 3.000$ C.I. = 0.00
 C.R. = 0.00
 Eigenvector = (1.00, 1.00, 0.25)

$\lambda_{\max} = 3.065$ C.I. = 0.03
 C.R. = 0.06
 Eigenvector = (1.00, 2.33, 9.02)

Weight = (0.73, 0.20, 0.07)

Weight = (0.44, 0.44, 0.11)

Weight = (0.08, 0.19, 0.73)

(d) Computation of normalized weights of the three bridge projects

$$\begin{array}{c}
 \begin{array}{ccc}
 & S & R & T \\
 \begin{array}{c} A \\ B \\ C \end{array} & \left(\begin{array}{ccc} 0.73 & 0.44 & 0.08 \\ 0.20 & 0.44 & 0.19 \\ 0.07 & 0.11 & 0.73 \end{array} \right) & \begin{array}{c} \left(\begin{array}{c} 0.73 (S) \\ 0.19 (R) \\ 0.08 (T) \end{array} \right) \\ \\ \end{array} & = & \begin{array}{c} \left(\begin{array}{c} 0.62 (A) \\ 0.25 (B) \\ 0.13 (C) \end{array} \right)
 \end{array}
 \end{array}$$

A has a low structure rating, fairly long remaining service life and average daily traffic (ADT) of 2,000, and so forth. First, it is necessary to determine expected weights of the three evaluation criteria.

Table 3.3-(b) shows a reciprocal matrix containing the results of pairwise comparisons of the three criteria. For instance, the structure rating was strongly important than the remaining service life, therefore a scaling value of 5 is entered in the appropriate box. It should be noted that the base for comparison is always the one on the row of matrix, that is, the structure rating in this case. Making similar pairwise comparisons, the upper-triangular matrix is filled. The diagonals always have ones. The values in the lower-triangular matrix are the reciprocals of those in the upper-triangular matrix. Once structure rating was compared with remaining service life, there will be no need to compare remaining service life with structure rating, because the relationship of the two items has already been known. The reciprocal matrix thus obtained was then solved by the EIGRF routine of the IMSL library [IMSL 1982] for the eigenvalue and eigenvector. The consistency index (C.I.) was found to be 0.033, and the random index (R.I.) for a matrix of order of 3 was 0.58 according to Table 3.2. Therefore, the consistency rating became 0.06 ($0.033/0.58$), which was less than 0.1. Therefore, the consistency of judgments was accepted. The eigenvector values were 1.00, 0.26, and 0.11 for the structure rating, remaining service life, and ADT, respectively. By normalizing these values, the expected weights of these three criteria became 0.73, 0.19, and 0.08, respectively.

After determining the criterion weights, the three projects were then compared pairwise with respect to each evaluation criterion. Resulting

parameter values, eigenvectors, and weights within each criterion are shown in Table 3.3-(c). When using the scale shown in Table 3.1, care should be taken about the sequence of comparisons. For instance, when one compares the levels of ADT, the ADT of 2,000 would be less important than the ADT of 3,000. The scale in Table 3.1 is given only for a "more important case." Therefore, when one element is inferior to the base item of comparison, a reciprocal value should be used, as $1/3$ shown in Table 3.3-(c).

Once a set of weights of the criteria and sets of weights of the bridges with respect to each criterion were obtained, the final weights of the three projects were computed. Project weights with respect to each criterion were multiplied with the weights of the individual criteria with respect to the goal of ranking. Table 3.3-(d) shows this computation step in a matrix multiplication form. The final weights of the three bridges, A, B and C, turned out to be 0.62, 0.25, and 0.13, respectively. It should be noted that the example was not based on any real world data and it is presented only as an illustration of the procedural steps.

3.4 Conceptualization of the IBMS Ranking Method

3.4.1 Inclusion of Utility Functions to the AHP

The analytic hierarchy method (AHP) is a useful tool to rank projects when subjective judgments are involved. However, a direct application of the method may not be practical when the number of projects is large. For example, even when there are only twenty-two bridge projects to compare, one has to make 231 pairwise comparisons for each evaluation criterion $(22(22 - 1)/2)$ to fill in the cells of the upper-triangular matrix of a reciprocal matrix.

With six criteria under consideration, the number of pairwise comparisons goes up to 1,386. Performing so many pairwise comparisons is not only time consuming but also may foster carelessness among the decision-makers who are asked to perform the comparisons. Furthermore, a large matrix makes it difficult to review when the consistency check was not satisfied. Since eigenvalues exist to any n -rowed square matrix, regardless of whether or not the matrix is singular or non-singular [Kreyszig 1979], it would be necessary that a reciprocal matrix be checked carefully before the maximum eigenvalue and the corresponding eigenvector are obtained. Because, in reality, the number of projects may range between 500 and 1000, the direct use of AHP is thus impractical.

The above problem, however, can be solved by the inclusion of the concept of utility. The formal definition of utility can be found elsewhere [Keeney and Raiffa 1977]. In the concept of bridge management, utility is the level of overall effectiveness that can be achieved by undertaking a project. If an appropriate utility is assigned to projects with respect to certain evaluation criteria, the expected utility of each alternative project can be calculated. Then, the best project is the alternative with the highest expected utility.

Figure 3.2 shows how the concept of utility is included in the AHP. In order to apply the concept, it is necessary to find factors which are common to all bridges. Best candidates are physical attributes of the bridges because all bridges can be described by such attributes as structural condition and bridge deck width. When a bridge is replaced or rehabilitated, bridge managers expect to bring the bridge condition to a certain desired structural adequacy level and/or level-of-service level. Utility is often

(a) Traditional AHP

(b) Modified AHP with Utility Curves

Figure 3..2 Incorporation of Utility Curves in the AHP Method

expressed by decimals from zero through one, one being the highest expected utility or the highest satisfaction. For instance, if a bridge is in a very poor condition, the decision-maker would place a high expected utility because the urgency for improvement is high and resulting benefits to the highway user and/or the surrounding community are expected to be high. However, if a bridge is still in fair condition, the improvement work may not be an urgent matter. For the levels of each selected attribute, the decision-maker would place certain utility. He would use this utility scale when comparing multiple bridges to select ones to be implemented within the constraints of available resources, available funds being the most relevant.

3.4.2 Procedure to Develop Utility Functions

There are several procedures to develop utility functions. The method recommended by Keeney and Raiffa [1977] may be the most elaborate one. However, it would be perfectly permissible to use the eigenvector approach discussed earlier in this chapter. One can consider the levels of each evaluation criterion as the elements of pairwise comparisons. In other words, one would place different expected utilities to the levels of each criterion. For instance, a bridge with condition rating 3 is far more eligible for replacement than a bridge with condition rating 5. Also, the difference between the condition ratings of 2 and 3 is far more significant to the decision-maker than the difference between the condition ratings of 5 and 6. These differences are exactly the topic of pairwise comparisons. The inclusion of the utility concept reduces the number of pairwise comparisons, while still maintaining the advantage of such comparisons.

A utility function can be developed by first defining the boundaries of interest within each criterion, and then dividing the region between the boundaries into appropriate intervals, upon consensus of the participating decision-makers. Then, reciprocal matrices of pairwise comparisons would be constructed for these intervals. Using an available software for eigenvalues and eigenvector of square matrices, the maximum eigenvalue and the corresponding eigenvector can be obtained. After consistency checks are made and requirements are satisfied, the values in the eigenvector are translated into utility points. For convenience, the maximum utility point is taken as 100 and the minimum as zero, as shown in Figure 3.3. The sample application discussed in the following section will illustrate the steps involved in the development of utility curves.

3.5 Sample Application of the IBMS Ranking Concept

3.5.1 Descriptions of Sample Bridge Replacement Projects and the Hierarchy Used

The IBMS ranking concept was used to set priorities on a set of twenty-two proposed bridge replacement projects used in a previous study [Harness and Sinha 1983]. Attributes of these bridges are found in Table 3.4. The same sample set was used to compare the results of the proposed method with the results of the successive subsetting (SS) method [Harness and Sinha 1983]. The SS method is a subjective partitioning of candidate bridges into clusters according to a given set of criteria. No scaling is involved in the method. No numerical values are assigned to the alternatives.

Figure 3.3 Transformation of Eigenvector Values to Utility Points

Table 3.4 Priority Evaluation Measures by Project Number for Sample Bridge Improvement Problem

Project No.	844	852	5	1	878	2859	2860	2861	2862	15	143
Construction Cost, State Share (\$1000)	57	95	131	30	122	67	67	67	110	136	253
Narrowing (ft), (Deck Width-Road Width)	4	8	10	5	16	12	12	11	0	0	4
Deck Width (ft)	25	28	46	30	34	34	32	33	24	22	22
Deck Pavement Condition	7	8	7	7	6	8	8	8	5	5	4
Remaining Service Life (year)	5	10	10	10	5	15	10	15	15	5	15
Substructure Condition	4	7	5	4	4	7	5	8	4	3	6
Superstructure Condition	4	6	4	8	4	7	5	7	5	3	5
ADT	1200	1900	1100	1100	1200	3000	3500	6600	1700	6300	13300
Approach Alignment Condition	8	8	7	7	8	7	7	6	3	2	5
ADT/State Share of Construction Cost	21	20	8	37	10	45	52	99	15	44	53

Source: Harness and Sinha [1983]

Table 3.4 (continued)

Project No.	167	91	1549	59	56	166	2867	888	8	889	147
Conatruction Cost, State Share (\$1000)	221	101	19	302	237	166	39	73	45	122	57
Narrowing (ft), Deck Width-Road Width	5	6	6	0	10	0	8	18	-3	12	6
Deck Width (ft)	28	34	28	30	32	24	32	40	29	32	28
Deck Pavement Width	5	5	5	7	6	8	6	4	6	7	4
Remaining Service (year)	15	10	5	10	5	5	15	5	5	20	10
Substructure Condition	7	7	3	3	4	3	4	4	3	7	4
Superstructure Condition	6	4	3	3	5	4	4	4	3	8	8
ADT	1700	7500	3100	6300	9400	3200	6300	4300	1000	900	4600
Approach Align- ment Condition	6	7	7	4	7	5	2	8	7	7	3
ADT/State Share of Conatruction Cost	8	69	163	21	40	18	162	59	22	7	81

Source: Harness and Sinha [1983]

Exactly the same criteria were used to make comparison in the same environment. These criteria are listed in Table 3.5 and include physical condition of the bridge structure, remaining service life, curb-to-curb deck width, road narrowing, approach alignment, and the ratio between ADT (average daily traffic) and the state share of construction cost. The ranking shown in Table 3.5 does not necessarily mean strong preference of one criterion over another. A weak preference, which was explained in Table 3.1, may exist between the adjacent two criteria.

The hierarchy used for this example is illustrated in Figure 3.4. It consists of three strata: objective, criteria, and projects. Under each criterion, a utility curve is attached. As discussed earlier, the levels of each criterion can be considered as a set of sub-criteria that can be evaluated with respect to that criterion. By interpreting the relationship between the levels of a criterion and the overall criterion in this manner, the concept of the analytic hierarchy process can still be valid. For convenience, the range of utility was set from 0 through 100 instead of a conventional range of 0 through 1. In this sample application, the researcher acted as the sole member of the decision-making group.

3.5.2 Determination of Criteria Weights

The six criteria were first compared pairwise according to their relative importance in contributing to the overall priority of individual bridges. Table 3.6 shows the reciprocal matrix obtained by comparing pairwise the six criteria. The upper-triangular matrix was filled using the one-to-nine scale mentioned earlier, and the cells are circled in Table 3.6. Reciprocal values

Table 3.5 Priority Evaluation Criteria for the Selection of Bridge Replacement Projects

Impact Category	Rank	Evaluation Criteria
Structural Condition	1	Minimum of Superstructure Condition and Substructure Condition
	2	Estimated Remaining Service Life in Years
Traffic Safety	3	Curb-to-Curb Deck Width
	4	Road Narrowing on Bridge
	6	Approach Alignment
Service and Highway Department Cost	5	ADT (Average Daily Traffic)/ State Share of Construction Cost

Note: The rank shown above does not necessarily mean a dominant preference of one over another. A weak preference may exist between the adjacent two criteria.

Source: Harness and Sinha [1983]

Figure 3.4 Sample Hierarchy System for Ranking a Group of Bridge Improvement Projects

of the cells in the upper-triangular matrix were assigned to the corresponding cells in the lower-triangular matrix. The numbers in the upper-triangular matrix indicate the intensity of relative importance of one criterion over the other in pairwise comparison. When one criterion is compared to itself, the relative importance is unity; hence, the value of one is assigned along the diagonal of the matrix.

The procedure of a pairwise comparison can be explained by using examples. By convention, the comparison of strength is always of an activity appearing in the column on the left against an activity appearing in the row on top. For example, let us compare the structural condition criterion with the deck width criterion. As shown in Table 3.6, structural condition was considered "weakly important" than deck width; therefore, the intensity scale value of 3 was assigned and the value was placed in the third cell of the row assigned to the structural condition criterion. In another case, road narrowing, when compared with deck width, received an intensity scale of 2. This meant that deck width was judged to be only slightly more important than road narrowing. In the same manner, all pairwise comparisons were made, and the reciprocal matrix was completed.

The resultant reciprocal matrix was fed into the EVCRG routine available from the IMSL library [IMSL 1982] to obtain the maximum eigenvalue ($\lambda_{\max}$) and the corresponding eigenvector. The eigenvector values are found in the right most column of the matrix shown in Table 3.6. For this particular reciprocal matrix, the maximum eigenvalue ($\lambda_{\max}$) was 6.12. Weights of the six criteria were estimated by normalizing the values in the eigenvector. They can be found at the bottom of Table 3.6. According to the judgment used in this

example, structural condition was placed as most important, followed by remaining service life. Deck width and road narrowing factors received relatively high weights. However, service/cost criterion and approach condition had relatively low weights.

The consistency index (C.I.) became 0.024, which is small compared to the random index (R.I.) of 1.24 for a matrix of order 6. Average random indices can be found in Table 3.2. The consistency ratio (C.R.) was obtained by dividing the consistency index by the random index and its value was 0.02, which was far less than the critical value of 0.10, indicating that the pair-wise judgment applied in this example was consistent.

3.5.3 Development of Utility Curves

Utility curves were developed for the six criteria assuming the levels of each criterion as the attributes in the next lower level of the hierarchy. The lower and upper bounds of each criterion were first set for those which can have the set boundaries of interest. These criteria included all but the service/cost criterion. After the boundaries were set, the range between these two extreme points was divided into proper segments indicating the levels within a criterion. Here, the utility curves for the structure condition rating criterion and the service/cost criterion are used as examples.

For structural condition rating, the upper and lower bounds were set as 7 and 3, respectively, because these two rating levels are the boundaries for rehabilitation or replacement project. The range was divided by ratings in between the two values, i.e., 4, 5, and 6, according to the condition rating scale used to rate bridge conditions.

In order to develop the utility curve for structural condition, condition rating levels were compared pairwise and a reciprocal matrix was obtained. However, the reciprocal matrix was found to be inconsistent, and a trial-and-error method was used to adjust the values of entries of the matrix until the consistency ratio of the matrix became less than 0.10.

Figure 3.5-(a) shows a reciprocal matrix which contains the result of pairwise comparisons of structural condition rating levels. This reciprocal matrix was fed into the EVCRG routine of the IMSL library [IMSL 1982] to obtain the eigenvector and other parameters. The maximum eigenvalue ($\lambda_{\max}$) was 5.35, and the consistency index (C.I.) was 0.09. The random index (R.I.) for a matrix of order 5 was 1.12 according to Table 3.2. Therefore, the consistency rating became 0.08, which was less than 0.10, indicating a close consistency check.

Using the values of the eigenvector, utility points were computed, and they were plotted in a utility curve, as shown in Figure 3.5-(b). In this particular case, the condition rating of 3 was given the highest utility and it was three times higher than the condition rating of 4. In the condition rating scale, a bridge with a rating of 3 is considered to be in poor condition and would require immediate repair or rehabilitation [FHWA 1979]. However, at 4, this bridge is still at a marginal condition. The potential exists for major repair or rehabilitation, but it is not as serious as the bridge with a rating of 3. The ratings of 3 and 4 are actually a key decision-making point for selecting bridges for rehabilitation based on condition rating. Therefore, it seems this utility curve can translate closely the decision-maker's judgment about the impact of structural condition on priority setting.

Condition Rating = Min (Superstructure, Substructure)

	Condition Rating					Eigenvector	Utility Point
	3	4	5	6	7		
3	1	5	7	8	9	1.0000	100.00
4	1/5	1	3	4	5	0.3375	33.75
5	1/7	1/3	1	3	4	0.1850	18.50
6	1/8	1/4	1/3	1	3	0.1035	10.35
7	1/9	1/5	1/4	1/3	1	0.0597	5.97

$\lambda_{\max} = 5.35$ C.I. = 0.09 R.I. = 1.12 C.R. = 0.08 < 0.10

(a) Pairwise Comparison Matrix, Eigenvector, and Utility Points

(b) Utility Curve for Condition Rating

Figure 3.5 Pairwise Comparison Matrix and Utility Curve for Condition Rating

Another example of the utility curve is given in Figure 3.6 using service/cost criterion. Figure 3.6-(a) presents the reciprocal matrix and the resultant parameters and the eigenvector. In this particular case, the expected bounds of interest were not clear. Therefore, the maximum value of the eigenvector was used as a temporary maximum point, receiving 100 points of utility. Figure 3.6-(b) shows the utility curve constructed from the resultant eigenvector. This curve became S-shaped like the logistic curve or the choice probability curve, which is frequently used for modeling the consumer's choice behavior [Manheim 1979]. A utility curve of this shape implies that the decision-maker is fairly indifferent to a change in the level of cost-related evaluation measure near the upper and lower limits; however, in between the limits, the decision-maker becomes very sensitive.

3.5.4 Ranking Results

For each project utility points were first computed under the existing characteristics associated with each evaluation criterion. Next, the utility points to be gained due to expected changes in bridge characteristics were computed. These values were then multiplied by the weight of individual criteria. The weighted utility values were added to get the total utility score for a given improvement alternative on a bridge. The twenty-two bridges were then sorted in descending order of total utility scores. The resultant ranking of these bridges are shown in Table 3.7, along with their utility scores. Project costs and the available budget shown in the table are exactly the same as used in the sample problem found in Reference [Harness and Sinha 1983]. According to this ranking, bridge projects can be implemented up to the eighth rank. When utility scores of some bridges are close to each other and

	Service/Cost											Eigenvector	Utility Point
	10	20	30	40	50	60	70	80	100	150			
10	1	1/3	1/3	1/4	1/5	1/5	1/6	1/7	1/8	1/9	1.0000	4.38	
20	3	1	1/3	1/4	1/4	1/5	1/5	1/6	1/7	1/9	1.3354	5.85	
30	3	3	1	1/3	1/4	1/4	1/5	1/5	1/6	1/8	1.8057	7.91	
40	4	4	3	1	1/3	1/3	1/5	1/5	1/6	1/7	2.5804	11.31	
50	5	4	4	3	1	1/3	1/3	1/5	1/5	1/7	3.6216	15.87	
60	5	5	4	3	3	1	1/3	1/3	1/5	1/6	4.8238	21.14	
70	6	5	5	5	3	3	1	1/3	1/5	1/5	6.8481	30.01	
80	7	6	5	5	5	3	3	1	1/3	1/5	9.6479	42.28	
100	8	7	6	6	5	5	5	3	1	1/3	15.1642	66.45	
150	9	9	8	7	7	6	5	5	3	1	22.8210	100.00	

$\lambda_{\max} = 11.33$ C.I. = 0.15 R.I. = 1.49 C.R. = 0.10 < 0.10

(a) Pairwise Comparison Matrix, Eigenvector, and Utility Points

(b) Utility Curve for Service/Cost Ratio

Figure 3.6 Pairwise Comparison Matrix and Utility Curve for Service/Cost Ratio

Table 3.7 Final Ranking and Project Choices for Implementation by the AHP Method for the Sample Bridge Replacement Problem

Rank	Project No.	Utility Point	Project Cost (1,000 dollars)	Available Budget (1,000 dollars)
1	15	92.49	136	1,025
2	166	79.71	166	889
3	8	77.09	45	723
4	1549	73.49	19	678
5	59	58.19	302	659
6	844	48.44	57	357
7	56	41.52	237	120
8	888	40.51	73	47
9	878	40.39	122	
10	2862	34.56	110	
11	147	32.93	57	
12	143	31.23	253	
13	2867	29.88	39	
14	1	27.02		
15	91	26.85		
16	5	23.91		
17	2860	19.70		
18	852	18.81		
19	167	12.97		
20	2861	10.94		
21	2859	8.29		
22	889	7.27		

they are at the borderline of funding cut-off points, further on-site investigation can be made for the selection of appropriate projects.

3.5.5 Comparison with Other Methods

The results of ranking bridge projects by the modified analytic hierarchy process (AHP) were compared with the results of the successive subsetting (SS) method developed earlier. The SS method was developed based on an assumption that impacts of highway improvements cannot be measured precisely, and if they could be, their limits of accuracy would be quite large [Harness and Sinha 1983]. The advantage of this method is that there is no numerical weighing factor involved in the ranking process. According to the SS method, projects are first grouped into a desired number of small groups, or subsets, by an evaluation criterion, or more than one evaluation criteria, in the highest hierarchy. This process is repeated until each subset has only one project in it; that is, the projects have been ranked. The SS method employs a graphical approach to priority setting and no numerical values are generated for comparison. An advantage of this method is that it is practical and easy to use. Also, as subjective judgments are visually translated into grouping tasks without any numerical manipulations, it is easy to understand what is happening throughout the ranking process. For this method, decision-makers' preferences are therefore implicitly accounted for during the subsetting process. A possible disadvantage of this method is that although it gives a relative order of importance of projects considered, it does not give the intensity of decision-makers' preference for a project over the others, that is, how strong the preference of one project over the others would be. Another practical problem is that it may be difficult to keep track of projects which are placed

into sub-groups when the number of projects is relatively large.

For a comparison purpose, the SS method was slightly modified in the present study by introducing MacQueen's K-Means clustering method [Dixon and Brown 1979] so that a large number of projects can be handled by the SS method. In this modified SS method, the subsetting process was done mathematically by minimizing the Euclidean distance, as expressed by the values of the selected criteria, between individual projects and the mean values of the clusters instead of subjective graphical groupings of projects. This clustering technique was applied by Garber and Bayat-Mokhtari for grouping highway links for traffic counting purpose [Garber and Bayat-Mokhtari 1986]. The K-Mean clustering routine available through the BMDP statistical analysis package [Dixon and Brown 1979] was used. The user, however, still has to specify the attributes and the desired number of groups by which a set of projects is ranked to run this package. This step agrees with the philosophy of the original SS method. The hierarchy and the number of subsets used in this exercise were exactly same as the ones used in the sample computation using the original SS method presented by Harness and Sinha [1983].

The purpose of this comparison was to show that the modified AHP method would provide similar results as the SS method, and that the former is a viable alternative to the latter. The ranking method with the modified AHP is particularly suitable for computer application. Table 3.8 gives the final ranking of the projects used in the previous example by the AHP method and the results of the rankings by the original and modified SS method. As shown in the table, the AHP method gave the ranking similar to the SS method and can be considered as a useful alternative to the SS method. There are two advantages

Table 3.8 Comparison of Ranking by The Analytic Hierachy Process (AHP) Method and the Successive Subsetting (SS) Method

Rank	Project Number		
	AHP Method	SS by Manual Technique	SS by K-Means Clustering
1	15 *	15 *	166 * .
2	166	166	8
3	8	1549	15
4	1549	8	1549
5	59	59	56
6	844	844	844
7	56	56	878
8	888	878	888
9	878	888	59
10	2862	147	147
11	147	1	91
12	143	91	1
13	2867	5	5
14	1	2862	852
15	91	2867	2860
16	5	2860	2867
17	2860	143	143
18	852	852	2862
19	167	167	2861
20	2861	2861	2859
21	2859	2859	167
22	889	889	889

* Numbers indicate bridge identification codes.

of using the modified AHP over the SS method. First, the AHP method, with the use of utility curves, is easy to adapt to computer application. Second, it can streamline the ranking process without any intermediate interruptions of the subjective project groupings. Once the hierarchy is set, there is no need for intermediate interruptions. Furthermore, the modified AHP gives utility scores which can be used to identify how close some projects are ranked together; thus, providing decision-makers the information on the extent in the difference in effectiveness between bridge projects considered.

3.6 Steps for Implementing the IBMS Ranking Method

The steps for developing and implementing a ranking method within the environment of the IBMS are discussed in this section. The IBMS ranking method would contain a modified analytic hierarchy process. There are four major steps which need to be followed in developing the IBMS ranking method. Structuring hierarchies requires participation of the decision-makers. In this section, a suggested hierarchy is given which can be used as the basis for further considerations.

3.6.1 Selection of Ranking Factors

The term "ranking factor," as used in the following discussion, refers to any element included in the hierarchy requiring the assignment of weights. In the present study, four objectives emerged as primary in bridge improvement project selection: maximization of effectiveness of investment, maximization of bridge condition preservation, maximization of bridge traffic safety, and minimization of negative community impacts. Table 3.9 shows these objectives and the criteria that can be used under each objective. Among the criteria,

Table 3.9 Recommended Evaluation Criteria and Possible Substitutes

Objectives	Recommended Criteria	Possible Substitutes Using Data Available from the SIA Bridge Records
Maximize effectiveness of investment	* $\frac{365(\text{ADT})}{\text{EUAC}_{\text{all}}}$	* (substitutions not necessary)
Maximize bridge condition preservation	* Estimated remaining service life in years * Structural condition rating	(Substitutions not necessary)
Maximize bridge traffic safety	* Bridge traffic safety index	* Difference of clear deck width from the desired width * Vertical clearance (over or under) * Lateral clearance for underbridges * Operating rating
Minimize negative community impacts	* Community impact index	* Detour length

only the structure condition rating and remaining service life can be directly used from the existing bridge data file maintained by IDOH.

The inclusion of the expected remaining service life criterion is recommended to complement the structural condition. It should be noted that both these factors should relate to these components of a bridge that would be affected by an improvement activity. For instance, if an improvement activity involves deck rehabilitation or deck replacement, the estimated remaining service life and condition rating of the deck should be used. Since a least cost improvement option has been selected for each bridge by the time of ranking, the affected bridge component, such as deck, superstructure or substructure, or the entire bridge, would be known.

The present study recommended three new evaluation criteria: the effectiveness measurement factor (EMF), bridge traffic safety index, and community impact index. Since these three criteria may not be available at the beginning of the implementation of IBMS, possible substitutions can be made using the criteria available from the the current SIA bridge records until the three new criteria would be ready for regular use. The possible substitutions are shown in Table 3.9.

Among these, the effectiveness measurement factor can be available as long as the life cycle cost sub-module is implemented. The cost can be either equivalent uniform annual cost or the first capital investment cost. For initial use, the first capital investment cost can be used.

It would take some time for the inclusion of traffic safety index for all bridges in the system in the IBMS data base. However, many bridge

attributes which are used as part of the level-of-service measurement factors are included in the traffic safety index. Therefore, if the bridge traffic safety index is used, there would be no need to take into account separately attributes such as bridge deck width, shoulder width, vertical clearance, and approach road condition, into the ranking procedure. Until the bridge traffic safety index values are included in the inspection reports, it may be desirable to use attributes which represent traffic safety on or near the bridge and which are now in the SIA bridge records. A combination of clear deck width and vertical clearance factors can be considered for this purpose. In addition, operating rating and lateral clearance for under bridges can be included, if desired.

The community impact index is yet a subjective value for possible impacts caused by bridge improvement projects. Deficient and/or obsolete bridges would cause negative impacts, but their improvement would mean positive impacts. In addition, a bridge project may cause temporary inconvenience of detouring. Consequently, the net effect of a bridge project would be highly site specific. At present, this factor has not been explicitly defined, and it is represented by expected detour length value until a composite index can be developed.

3.6.2 Structure of the Hierarchy

During the study, it was found that a four-strata hierarchy would be sufficient at present to start the program. This hierarchy would consist of an overall goal of the ranking exercise, objectives that bridge managers would like to achieve, evaluation criteria with utility curves, and individual

bridges. Figure 3.7 shows a suggested default hierarchy for the development of a ranking routine based on the result of this study. However, the program should be capable to accept other hierarchies that may be suggested by bridge managers.

3.6.3 Determination of Weights for Objectives and Criteria

After the hierarchy has been set with the selected objectives and evaluation criteria, the bridge managers first need to reach a consensus on the weights of the objectives with respect to the ranking goal; they are W_e , W_p , W_s , and W_c found in Figure 3.7. One method for determining these weights is the eigenvector approach explained earlier in this chapter. The major advantage of this method is that it offers a procedure for checking the consistency of pairwise comparisons. An alternative method would be to poll opinions of the decision-makers. These weights can be modified later if ranked bridges would not reflect the expectation of the decision-makers involved.

After determining the weights of ranking objectives, the weights of the evaluation criteria under individual objectives need to be obtained. Again, the eigenvector approach can be used. If only one criterion exists under an objective, it would receive one-hundred percent of weight with respect to the objective. When there are more than one criterion, their individual weights should be determined with respect to that objective.

3.6.4 Development of Utility Curves for Evaluation Criteria

As discussed earlier, in order to deal with a large number of bridge projects, it is necessary to provide evaluation curves that can be used to meas-

Figure 3.7 Recommended Four-Strata Default Hierarchy for IBMS

ure the degree of accomplishment of an evaluation criterion due to a proposed activity on a bridge. Such evaluation curves are called utility curves in the present study. The use of utility curves resembles the philosophy of the successive subsetting method [Harness and Sinha 1983], by which bridge projects were ranked based solely on the importance of bridge projects as perceived by decision-makers.

The eigenvector approach was suggested because pairwise comparisons are intuitive and easy to follow. Pairwise comparisons of the levels of attributes are to be made by bridge managers involved in bridge project programming. Resultant reciprocal matrices may be different among the managers and it may be necessary to get an aggregated utility curve for a criterion.

Two general types of utility curves can be considered. One type is a risk aversion function which is often used in this type of value judgments. Figure 3.8 shows this general curve. This curve can be used only when the lower and upper bounds of the range of interest are found. The bridge managers would be indifferent to the expected utility outside this range. For instance, when the condition rating is used, most bridge managers would most likely be indifferent to the rating values below 3 because a bridge with such a low rating would be placed in the replacement category regardless of the actual rating value. Hence, the utility of performing an improvement work would be 1.0 or 100 utility points. On the other hand, many bridge inspectors would be indifferent to condition ratings greater than 7 when it comes to improvement works. A bridge with such a high rating would most probably require only minor maintenance or routine maintenance. So, it would be outside the range of interest and would receive zero utility points for doing

Figure 3.8 A General Shape of Utility Curves for the Evaluation Criteria with Upper and Lower Bounds

improvement works.

Another type of general utility function can be the type of choice probability curve, as shown in Figure 3.9. This curve is recommended for evaluation criteria which do not have set lower or upper bounds. For instance, the criterion to compare the effectiveness of investment is dependent upon the equivalent uniform annual cost computed by life-cycle cost analysis or the first capital investment cost. The bridge manager would not know the boundaries until the equivalent uniform annual costs were computed for all bridges in the system. Nor would he know the size of the interest range. In such a case, it would be better to use the expected amount of deviation from the mean value as a testing scale. For instance, if the criterion value for a particular bridge is greater than the mean criterion value by three standard deviations, the bridge manager may consider the expected utility to be 1.0 or 100 points.

In developing utility curves, it would be appropriate to start by assuming them as linear. Utility curves can then be revised until the members of the management team agree upon them.

3.6.5 Implementation Procedure

Figure 3.10 gives a flow chart for implementing the suggested ranking procedure incorporating the analytic hierarchy process. A temporary ranking data base should be created from the IBMS data base. A default hierarchy was incorporated in the priority ranking package. However, these values can be changed. New hierarchies would be subject to the availability of appropriate utility functions.

Notation: σ = Standard Deviation

Figure 3.9 A General Shape of Utility Curves for the Evaluation Criteria with No Upper and Lower Bounds

Figure 3.10 Flow Chart for Implementing the Suggested Ranking Procedure

Once the hierarchy and utility functions are established, relevant attribute values for individual bridges would be read from the ranking data base for computing utility points. Utility points would be set between zero and one hundred for each given evaluation criterion. Utility values of each criterion would be used to rank bridges with respect to that criterion only. Then, combined or total ranking scores in terms of total utility points would be computed using the preset weights of the included objectives. Computed utility scores are stored in proper data fields of the ranking data base for sorting the bridges in descending order of utility points. The higher the utility point, the more attractive the bridge project would be for being selected for implementation. The sorting of bridges can be done either by the combined score or by individual objective scores. The decision-makers should be given an opportunity to examine the ranks of bridges within a given ranking objective.

3.7 Chapter Summary

Setting priorities on bridge rehabilitation and replacement projects is a typical multi-attribute decision-making problem. This chapter discussed an application of the analytic hierarchy process to setting priorities.

A ranking method using the analytic hierarchy process can incorporate various groups of decision-makers related to bridge improvement programming and can synthesize their judgments and preferences. It also allows quantitative ranking of alternatives. Once weights are generated for the elements of each hierarchical stratum, the project ranking process can be computerized for a large scale problem. The eigenvector approach allows the comparison of dif-

ferent criteria measured in different units with different importance to decision-makers. The example given in this chapter showed that the hierarchy method can be effectively applied to the selection of bridge rehabilitation and replacement projects.

The procedure for incorporating the AHP into the Indiana bridge management system was also discussed in this chapter. Hierarchies should be reassessed as the bridge management system matures. The hierarchy given in this chapter can be used as a default hierarchy at the initial stage because it reflects the results of literature survey, opinion survey, and discussions with bridge inspectors and other bridge managers in Indiana. The recommended hierarchy uses three new evaluation factors that are not directly available in the existing SIA bridge records. However, they can be reasonably substituted with the currently available factors.

CHAPTER 4

SUMMARY AND CONCLUSIONS

The main objective of this report was to discuss a ranking procedure for a bridge management system for the Indiana Department of Transportation that could be used to facilitate decisions regarding bridge maintenance, rehabilitation, and replacement. A ranking scheme was prepared for the evaluation of alternative projects. A computer program was coded in FORTRAN 77, which incorporated utility curves into AHP procedure. Using the program, bridge managers can obtain an output of ranked bridges sorted by activities and by districts.

4.1 Summary of Findings

All the analyses presented in this report were performed with data collected from bridge records and opinion surveys of bridge inspectors at the Indiana Department of Transportation. The major findings of these analyses are summarized below.

4.1.1 Effectiveness of Improvement Alternatives

An opinion survey using a Delphi study was conducted to assess the bridge inspectors' interpretation of the currently used condition rating scale [FHWA

1979] with respect to the extent and severity of distresses and to the level of effectiveness of bridge improvement activities. Delphi was selected instead of committee meetings because it was suspected that a consensus on this subject might not be achieved by traditional committee structures. The survey was started with fourteen participants and the number of participants declined to ten. Although it was difficult to maintain the enthusiasm of the participants as the Delphi rounds progressed, results of the study showed a tendency of converging opinions. A comparison of the results of the first and second rounds showed that the variation among the opinions became smaller in the second round than in the first round.

4.1.2 Ranking Method

The Analytic Hierarchy Process developed by Saaty [1980] was recommended for use as a ranking process for the IBMS with certain modifications. This method would be especially advantageous where subjective judgments can be the only way to solve problems and the evaluation process needs to be based on fuzzy and unstructured criteria measures. This is exactly the case of bridge project ranking. For determining weights of decision criteria included in the method, an eigenvector approach was recommended. This approach would allow the comparison of different criteria measured in different units with different importance to decision-makers.

4.2 Limitations of the Application

The methodologies discussed in this report were aimed for use at the Indiana Department of Transportation and therefore it would reflect the needs of this agency. The main goal of the study was to develop a project selection

procedure which would improve and streamline the current practice. This study considered only state-owned bridges. The concepts used in this study, however, could be used for managing bridges in local roads and city streets after proper modifications.

REFERENCES

Dickey, J.W. and T.M. Watts [1978], Analytic Techniques in Urban and Regional Planning. McGraw-Hill Book Company, New York, Chapter 13.

Dixon, W.J. and M.B. Brown (Eds.) [1979], BMDP-79: Biomedical Computer Programs P-Series, University of California Press, Berkeley, California, pp. 648.1-649.

Federal Highway Administration (FHWA) [1979], "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges," Washington, D.C.

Federal Highway Administration (FHWA) [1979], "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges," Washington, D.C.

Federal Highway Administration (FHWA) [1984], "Fifth Annual Report to Congress: Highway Bridge Replacement and Rehabilitation Program," U. S. Department of Transportation.

Federal Highway Administration (FHWA) [1988], "Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges," Washington, D.C.

Garber, N.J. and F. Bayat-Mokhtari [1986], "A Computerized Highway Link Classification System for Traffic Volume Counts," A paper presented at the 65th Annual Meeting of Transportation Research Board, Washington, D. C.

Harness, M.D. and Sinha, K.C. [1983], "Priority Setting of Highway Improvement Projects," Joint Highway Research Project, Purdue University, West Lafayette, IN, JHRP-83-9.

Hyman, W. A. and D. J. Hughes [1983], "Computer Model for Life-Cycle Cost Analysis of Statewide Bridge Repair and Replacement Needs," Transportation Research Record No. 899, pp. 52-61.

IMSL [1982], The IMSL Library Reference Manual, Vol. 2, International Mathematical & Statistical Libraries, Inc., (9th Edition).

Janarthanan, N. and J. Schneider [1986], "Multicriteria Evaluation of Alternative Transit System Design", A paper presented at the 65th Annual Meeting of Transportation Research Board, Washington, D. C.

Johnston, D.W. and Zia, P. [1985], "Level-of-Service System for Bridge Evaluation," Transportation Research Record 962, TRB, Washington, D.C., pp. 1-8.

Keeney, R. L. and H. Raiffa [1977], Decisions with Multiple Objectives, Wiley, New York.

Kreyszig, Erwin [1979], Advanced Engineering Mathematics, John Wiley & Sons, New York, (2nd Edition).

Linston, H.A., M. Turoff [1975], eds., The Delphi Method: Techniques and Applications, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts.

Manheim, Marvin L. [1979], Fundamentals of Transportation Systems Analysis Volume 1: Basic Concepts, The MIT Press, Cambridge, Massachusetts.

McClure, R.M. and H.P. Koretzky [1985], "The Pennsylvania Bridge Management System," A paper presented at the ASCE Structure Congress '85, Chicago, Illinois.

Mohan, S. and A. Bushnak [1985], "Multi-Attribute Utility in Pavement Rehabilitation Decisions," Journal of Transportation Engineering, ASCE, Vol. 111, No. 4, pp. 426-440.

Nijkamp, P. and A. Van Delft [1977], Multi-Criteria Analysis and Regional Decision-Making, Martinus Nijhoff Social Sciences Division, Leiden.

North Dakota State Highway Department (NDSHD) [1985-86], "North Dakota Bridge Inspection Procedures," Bismark, North Dakota.

Olsen, S.A. [1982], Group Planning and Problem Solving Methods in Engineering Management. John Wiley & Sons, New York, Chapter 4.

Saaty, Thomas [1980], The Analytic Hierarchy Process: Planning, Priority Setting, and Resource Allocation, McGraw-Hill, Inc., New York.

Schoemaker, J. H. [1982], "An Experimental Comparison of Different Approaches to Determining Weights in Additive Utility Models," Management Science, Vol. 28, No. 2, pp. 183-196.

Shiraishi, N., H. Furuta, and M. Hashimoto [1984], "Integrity Assessment of Bridges Based on the Concordance Analysis," Proceedings of Symposium on Non-Destructive Testing Methods, Tokyo, Japan, pp. 93-105, (in Japanese).

Srinivasan, V. and A.D. Shocker [1973], "Estimating the Weights for Multiple Attributes in a Composite Criterion Using Pairwise Judgements," Psychometrika, Vol. 38, No. 4, pp. 473-493.

Weyers, R.E., P.D. Cady, and J. Canelos [1987], "Costs and Lives of Bridge Maintenance and Rehabilitation Procedures by Expert Opinion." A paper presented at the 4th Annual International Bridge Conference, Pittsburgh, Pennsylvania.

Weyers, R.E., P.D. Cady, and R.M. McClure [1983], "Cost-Effective Methodology for the Rehabilitation and Replacement of Bridges," Pennsylvania Transportation Institute, Pennsylvania State University, University Park, PA, Final Report, Report No. PTI-8324.

APPENDIX

Results of Delphi Study on Effectiveness
of Improvement Activities on Bridge Performance

Figure A.1 Membership Value for the Levels of Condition Rating in Percentage (%)

Figure A.2 Deck Condition Rating vs. Expected Remaining Service Life When Do-Nothing Option is Chosen

Figure A.3 Concrete Superstructure Condition Rating vs. Expected Remaining Service Life When Do-Nothing Option is Chosen

Figure A.4 Steel Superstructure Condition Rating vs. Expected Remaining Service Life When Do-Nothing Option is Chosen

Figure A.5 Substructure Condition Rating vs. Expected Remaining Service Life When Do-Nothing Option is Chosen

Table A.1 Percentage of Responses to the Relationship between the Condition Rating and Combinations of Levels of Distresses of the Bridge Deck

		Item Rating											
		Very Good			Good			Fair			Poor		
		L	M	H	L	M	H	L	M	H	L	M	H
Extent													
	L	44	11		78	67	56		44	33			
Severity	M				11			89	100	33			11
	H							33			78	67	100

Note: 1. Numbers in the cells show the percentage of responses.
 2. If no distress is found, condition rating would be "very good."
 3. Levels of severity and extent are: L for light, M for medium, and H for heavy.

List of Primary Deck Distress Types Considered for Evaluation

- * Spalling and cracking underside of deck
- * Wearing of pavement surface including spalling and cracking top of deck
- * Inoperable or leaking joints
- * Deteriorated or damaged railing
- * Deteriorated or damaged deck drains and pipes
- * Deteriorated or damaged curb, median, sidewalk, parapet, or coping
- * Inadequate deck drainage
- * Corrosion of reinforcing steel

Table A.2 Percentage of Responses to the Relationship between the Condition Rating and Combinations of Levels of Distresses of the Concrete Superstructure

Item Rating																
		Very Good			Good			Fair			Poor			Very Poor		
		L	M	H	L	M	H	L	M	H	L	M	H	L	M	H
Extent	L	33	11		89	56	33		56	33		44				
	M				22			78	89	33		44	78			22
	H							33			78	78			44	100

Note: 1. Numbers in the cells show the percentage of responses.
 2. If no distress is found, condition rating would be "very good."
 3. Levels of severity and extent are: L for light, M for medium, and H for heavy.

List of Primary Concrete Superstructure Distress Types Considered for Evaluation

- * Beam or girder cracking including steel bar exposure
- * Deteriorated or damaged bearings
- * Deteriorated spandrell wall or pilaster (apply only for reinforced concrete arch)
- * Corrosion of reinforcing steel bars
- * Collision damages

Table A.3 Percentage of Responses to the Relationship between the Condition Rating and Combinations of Levels of Distresses of the Steel Superstructure

		Item Rating											
		Very Good			Good			Fair			Poor		
		L	M	H	L	M	H	L	M	H	L	M	H
Extent	L	33			89	33	33		67	44			
	M				11			89	67	11	67	89	11
	H							22			89	78	100

Note: 1. Numbers in the cells show the percentage of responses.

2. If no distress is found, condition rating would be "very good."

3. Levels of severity and extent are: L for light, M for medium, and H for heavy.

List of Primary Steel Superstructure Distress Types Considered for Evaluation

- * Paint deterioration
- * Crack and/or corrosion of flange, web, stiffener, or connection
- * Deteriorated or damaged bearings
- * Deteriorated or damaged connection devices of any link (bolts, welds, pins, or rivets)
- * Settlement and/or deformation of metal pipe arch underfills
- * Collision damages
- * Fatigue damages

Table A.4 Percentage of Responses to the Relationship between the Condition Rating and Combinations of Levels of Distresses of the Substructure

Item Rating																	
			Very Good			Good			Fair			Poor			Very Poor		
Extent	L	M	H	L	M	H	L	M	H	L	M	H	L	M	H		
	L	33		89	44	33		78	56			44					
Severity	M						89	67	33		56	67			33		
	H						22			89	78		56	100			

Note: 1. Numbers in the cells show the percentage of responses.

2. If no distress is found, condition rating would be "very good."

3. Levels of severity and extent are: L for light, M for medium, and H for heavy.

List of Primary Substructure Distress Types Considered for Evaluation

- * Abutment concrete deterioration - cracking, surface spalling, deterioration, or corrosion of reinforcing steel
- * Pier concrete deterioration - including concrete piles
- * Deterioration of steel piles
- * Bridge seat deterioration
- * Settlement or rotation
- * Concrete back wall failure
- * Scouring around substructure - erosion damage
- * Timber decay
- * Mortar deterioration (of masonry structure)

Table A.5 Effectiveness of Rehabilitation Alternatives on Condition Rating and Remaining Service Life of the Bridge Deck (Mean Values)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation(%)
		Before	After	Change	Minimum	Average	Maximum	
Deck Replacement	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair		N.A.			N.A.		0
	Poor	4	8	4	16	21	27	100
	V. Poor	3	8	5	16	21	27	100
Deck Reconstruction	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	7	3	7	12	17	60
	Poor	4	7	3	7	11	16	100
	V. Poor	3	7	4	7	10	15	90
Resurfacing Deck by Asphalt Overlay	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	7	2	6	9	12	70
	Poor	4	7	3	4	8	12	100
	V. Poor	3	6	3	4	7	11	80
Resurfacing Deck by Concrete Overlay	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	8	3	8	12	16	70
	Poor	4	7	3	8	12	17	100
	V. Poor	3	7	4	8	13	17	80

Notes: N.A. - Not applicable, meaning that inspectors would rarely recommend this activity when condition rating is in the given level.

Table A.5 (continued)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation (%)
		Before	After	Change	Minimum	Average	Maximum	
Deck Patching	V. Good		N.A.			N.A.		0
	Good	6	7	1	5	7	8	60
	Fair	5	6	1	4	5	7	90
	Poor	4	6	2	3	5	7	100
	V. Poor	4	6	3	3	4	6	90
Repair Curbs, Median, Sidewalk, Parapet, and Coping	V. Good		N.A.			N.A.		0
	Good	6	7	0	1	2	3	60
	Fair	5	6	1	1	2	3	100
	Poor	4	6	2	1	2	4	90
	V. Poor	3	5	2	1	2	3	90
Repair or Replace Expansion Joints	V. Good		N.A.			N.A.		0
	Good	6	8	1	5	7	9	70
	Fair	5	7	2	4	6	8	100
	Poor	4	6	2	3	6	8	90
	V. Poor	3	5	3	3	5	7	90
Repair or Replace Railings	V. Good		N.A.			N.A.		0
	Good	6	7	1	0	1	2	75
	Fair	5	6	1	1	2	3	90
	Poor	4	5	1	1	2	3	90
	V. Poor	3	5	2	1	2	3	90

Notes: N.A. - Not applicable, meaning that inspectors would rarely recommend this activity when condition rating is in the given level.

Table A.5 (continued)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation(%)
		Before	After	Change	Minimum	Average	Maximum	
Repair or Replace Drainage	V. Good	6	N.A.	1	0	N.A.	2	0
	Good		7			1		70
	Fair	5	6	1	1	2	4	100
	Poor	4	6	2	1	2	4	90
	V. Poor	3	5	3	1	2	3	90
Deck Cleaning	V. Good	7	8	0	0	1	2	80
	Good	7	7	1	1	2	3	100
	Fair	5	6	1	0	1	2	90
	Poor	4	5	1	0	1	2	90
	V. Poor	3	4	2	0	1	2	90
Major Widening in Addition to Replacement of the Entire Deck	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	8	3	11	16	20	70
	Poor	4	8	4	12	17	22	100
	V. Poor	3	8	5	12	17	21	90
Minor Widening in Conjunction with Deck Overlay	V. Good		N.A.			N.A.		0
	Good	6	8	2	6	11	14	70
	Fair	5	8	2	9	14	18	90
	Poor	4	7	3	8	11	16	100
	V. Poor	3	7	5	8	11	15	90

Notes: N.A. - Not applicable, meaning that inspectors would rarely recommend this activity when condition rating is in the given level.

Table A.6 Effectiveness of Rehabilitation Alternatives on Condition Rating and Remaining Service Life of the Concrete Superstructure (Mean Values)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation(%)
		Before	After	Change	Minimum	Average	Maximum	
Replacement of Part of Concrete Beams and Anchors	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	8	2	9	14	19	70
	Poor	4	8	4	10	17	23	100
	V. Poor	3	7	5	10	17	24	90
Repair or Patch Concrete Beams, Anchorings, and Diaphragms	V. Good		N.A.			N.A.		0
	Good	6	7	1	6	11	16	50
	Fair	5	7	2	6	10	14	100
	Poor	4	6	2	5	8	11	100
	V. Poor	3	6	3	5	8	12	90
Repair or Replace Bearing Devices	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	7	2	8	15	20	60
	Poor	4	7	3	5	10	15	100
	V. Poor	3	6	3	5	9	15	90
Resurfacing Deck by Concrete Overlay	V. Good		N.A.			N.A.		0
	Good	7	7	1	3	8	12	80
	Fair	6	7	1	4	9	12	90
	Poor	4	6	2	4	8	11	90
	V. Poor	3	5	3	3	6	9	90

Notes: N.A. - Not applicable, meaning that inspectors would rarely recommend this activity when condition rating is in the given level.

Table A.7 Effectiveness of Rehabilitation Alternatives on Condition Rating and Remaining Service Life of the Steel Superstructure (Mean Values)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation(%)
		Before	After	Change	Minimum	Average	Maximum	
Replace the Entire Superstructure	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	8	3	16	22	28	60
	Poor	4	8	4	19	25	32	100
	V. Poor	3	7	5	19	27	34	90
Repair or Replace Main Structural Members	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	7	2	9	15	20	50
	Poor	4	7	3	9	14	19	100
	V. Poor	3	7	4	9	14	19	90
Repair or Replace Secondary Structural Members	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	6	1	8	12	16	50
	Poor	4	6	2	5	9	13	100
	V. Poor	3	6	3	5	8	11	90
Tighten or Replace Bolts	V. Good		N.A.			N.A.		0
	Good	6	7	1	1	2	3	60
	Fair	5	6	1	3	6	8	80
	Poor	4	6	2	3	5	7	90
	V. Poor	3	5	3	3	4	6	90

Notes: N.A. - Not applicable, meaning that inspectors would rarely recommend this activity when condition rating is in the given level.

Table A.7 (continued)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation(%)
		Before	After	Change	Minimum	Average	Maximum	
Repair or Replace Defective Welds or Rivets	V. Good		N.A.			N.A.		0
	Good	6	7	1	1	4	5	60
	Fair	5	6	1	3	7	9	80
	Poor	4	6	2	3	6	8	90
	V. Poor	3	6	3	3	5	8	90
Strengthen Truss Members	V. Good		N.A.			N.A.		0
	Good	6	7	1	4	6	9	60
	Fair	5	6	1	5	7	11	80
	Poor	4	6	2	4	6	8	100
	V. Poor	3	6	3	4	6	8	90
Strengthen Truss Floor Beams or Stringers	V. Good		N.A.			N.A.		0
	Good	6	7	1	6	8	11	70
	Fair	5	7	1	7	10	15	90
	Poor	4	6	2	5	8	12	90
	V. Poor	3	6	3	4	7	10	90
Point Structural Members	V. Good		N.A.			N.A.		0
	Good	7	7	1	4	6	9	90
	Fair	5	7	1	5	7	10	100
	Poor	4	6	2	5	7	9	100
	V. Poor	3	6	3	4	6	7	100

Notes: N.A. - Not applicable, meaning that inspectors would rarely recommend this activity when condition rating is in the given level.

Table A.7 (continued)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation(%)
		Before	After	Change	Minimum	Average	Maximum	
Repair, Reset, or Replace Bearings and Bearing Seats	V. Good	6	N.A.	0	1	N.A.	6	0
	Good	5	7	1	4	4	10	50
	Fair	4	6	2	4	7	8	80
	Poor	3	5	3	3	6	7	100
Clean Lower Chords, Truss, or Bearing Areas	V. Poor					5		90
	V. Good	7	N.A.	1	2	N.A.	7	0
	Good	6	7	1	2	4	5	90
	Fair	4	6	1	3	4	5	90
Widen Superstructure by Adding Extra Members	Poor	3	5	2	3	4	5	90
	V. Poor							
	V. Good	7	N.A.	1	2	N.A.	8	0
	Good	6	7	1	4	5	9	90
Miscellaneous Repairs	Fair	4	6	1	3	6	6	90
	Poor	3	4	2	2	3	5	90
	V. Poor							
	V. Good	6	N.A.	1	3	N.A.	10	0
	Good	5	7	1	2	6	7	80
	Fair	4	6	2	2	4	7	90
	Poor	3	5	2	1	5	7	90
	V. Poor					3	7	90

Notes: N.A. - Not applicable, meaning that inspectors would rarely recommend this activity when condition rating is in the given level.

Table A.8 Effectiveness of Rehabilitation Alternatives on Condition Rating and Remaining Service Life of the Substructure (Mean Values)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation(%)
		Before	After	Change	Minimum	Average	Maximum	
Patch Deteriorated Concrete Bridge Seats, Piers, Abutments, and Wing Walls	V. Good	6	N.A.			N.A.		0
	Good		7	1	5	8	12	50
	Fair	5	6	1	6	9	13	90
	Poor	4	6	2	5	6	10	90
	V. Poor	3	6	3	4	6	9	90
Repair or Replace Concrete or Timber Wing Walls	V. Good	6	N.A.			N.A.		0
	Good		7	1	5	9	14	50
	Fair	5	6	1	3	7	9	80
	Poor	4	6	2	2	5	8	90
	V. Poor	2	6	3	2	4	7	90
Add or Replace Erosion Control Fixtures	V. Good	6	N.A.			N.A.		0
	Good		7	1	3	6	9	60
	Fair	5	6	1	2	4	6	90
	Poor	4	5	1	2	3	4	90
	V. Poor	3	5	2	1	3	4	90
Repoint or Dripack Masonry	V. Good	6	N.A.			N.A.		0
	Good		6	0	2	4	6	50
	Fair	5	6	1	3	5	7	70
	Poor	4	5	1	2	3	4	90
	V. Poor	3	4	2	1	2	4	100

Notes: N.A. - Not applicable, meaning that inspectors would rarely recommend this activity when condition rating is in the given level.

Table A.8 (continued)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation(%)
		Before	After	Change	Minimum	Average	Maximum	
Add Supportive Abutments and Wing Walls to the Existing Ones	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	6	1	4	7	9	70
	Poor	4	6	2	5	8	11	100
	V. Poor	3	5	3	5	7	11	90
Repair or Replace Timber Pile Caps	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	6	1	5	7	11	70
	Poor	4	6	2	5	8	11	100
	V. Poor	3	5	3	5	8	11	100
Repair or Replace Timber Piles	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	7	1	6	8	12	60
	Poor	4	6	2	6	9	12	100
	V. Poor	3	6	3	6	9	13	100
Repair or Replace Steel Substructure	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	7	2	8	12	16	70
	Poor	4	6	2	6	12	16	100
	V. Poor	3	6	4	7	11	16	90

Notes: N.A. - Not applicable, meaning that inspectors would rarely recommend this activity when condition rating is in the given level.

Table A.8 (continued)

Activity Type	Word Rating	Numeric Condition Rating			Increase in Service Life in Years			Chance of Recommendation(%)
		Before	After	Change	Minimum	Average	Maximum	
Add Temporary Support to Abutments or Piers	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	6	1	4	7	9	60
	Poor	4	5	1	4	6	9	90
	V. Poor	3	5	3	4	6	9	100
Encase Footings or Piles	V. Good		N.A.			N.A.		0
	Good		N.A.			N.A.		0
	Fair	5	6	1	4	6	10	60
	Poor	4	6	2	4	7	10	100
	V. Poor	2	5	3	4	6	10	90
Correct Stream Scour Problems	V. Good		N.A.			N.A.		0
	Good	6	7	1	1	3	5	60
	Fair	5	6	1	4	7	9	80
	Poor	4	6	2	3	5	8	90
	V. Poor	2	5	3	3	5	8	90
Clean out the Channel	V. Good		N.A.			N.A.		0
	Good	6	7	0	0	3	5	70
	Fair	5	6	1	3	5	8	70
	Poor	4	5	2	1	3	5	90
	V. Poor	2	5	3	1	2	4	90

Notes: N.A. - Not applicable, meaning that inspectors would rarely recommend this activity when condition rating is in the given level.

COVER DESIGN BY ALDO GIORGINI