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FHWA/IN/JHRP-89/10

Final Report, Vol. 3

THE DEVELOPMENT OF OPTIMAL
STRATEGIES FOR MAINTENANCE,
REHABILITATION AND REPLACEMENT
OF HIGHWAY BRIDGES, FINAL
REPORT VOL. 3: BRIDGE TRAFFIC
SAFETY EVALUATION

Sudhir Murthy
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PURDUE UNIVERSITY

JOINT HIGHWAY RESEARCH PROJECT

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Kumares C. Sinha**

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FINAL REPORT

The Development of Optimal Strategies for Maintenance, Rehabilitation
and Replacement of Highway Bridges
Final Report, Vol. 3: Bridge Traffic Safety Evaluation

TO: Harold L. Michael, Director August 15, 1989
Joint Highway Research Project Revised October 5, 1990

FROM: Kumares C. Sinha, Research Engineer Project: C-36-73I
Joint Highway Research Project File: 3-4-10

Attached is the Vol. 3 of the Final Report on the HPR Part II Study entitled, "The Development of Optimal Strategies for Maintenance Rehabilitation and Replacement of Highway Bridges, Final Report, Vol. 3: Bridge Traffic Safety Evaluation". This volume presents the findings of the part of the study dealing with bridge traffic safety evaluation. A procedure was developed to determine the bridge traffic safety index on the basis of factors related to bridge, approach roadway and environmental conditions. This research was conducted by Sudhir Murthy 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/cah

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FINAL REPORT

The Development of Optimal Strategies for Maintenance, Rehabilitation
and Replacement of Highway Bridges
Final Report, Vol. 3: Bridge Traffic Safety Evaluation

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16. Abstract This report is the third of a six-volume final report presenting the findings of the part of the research work dealing with bridge traffic safety evaluation. A procedure was developed that can be used to determine the traffic safety index of a bridge on the basis of a set of contributing factors related to bridge, approach roadway and environmental conditions. 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			
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CHAPTER 1 - INTRODUCTION

The basic input to any Bridge Management System is bridge inspection records. The main reason for conducting bridge inspection is to determine its structural condition and functional adequacy. Traffic safety is an important element of functional adequacy and this thesis is concerned with this element. Typically, traffic safety of a bridge is determined by evaluating its geometry and approach roadway alignment. Presently, few states have placed any importance on the traffic safety evaluation part of the BMS. If it is done at all, then it is in a very cursory manner. The main objective of this research work was to provide a systematic and reliable method to evaluate geometrical characteristics of a bridge and its approach roadway and determine the extent of traffic safety associated with them.

1.1 Research Objectives

1. To identify and study the factors that affect traffic safety on bridges.
2. To validate the selected contributing factors by conducting accident analyses for a selected number of bridges in Indiana.
3. To develop a model for the evaluation of traffic safety on bridges.

1.2 Research Approach

The research was conducted in three stages. These three stages corresponded to the three objectives on this study. The initial stage involved an extensive literature review. Based on this review, a list of

fourteen factors was selected. These factors were considered sufficiently comprehensive to adequately quantify the traffic safety on bridges. The review included studies conducted on bridge accidents, evaluation of safety at narrow bridge sites, safety aspects of various road components and the effect of their geometrical characteristics on traffic accidents.

The second stage of the study was an intensive accident analysis on selected number of bridges in Indiana. The basic intent of this stage was to obtain a general idea of the nature of traffic accidents on bridges and to try to verify if the selected list of factors was adequate in effectively quantifying the traffic safety aspect of a bridge. In other words, it was sought to see whether the selected factors could be identified as possible causes of the traffic accidents on bridges. The analysis did result in the verification of the selected factors as responsible in contributing to some of the traffic accidents. The rest of the accidents were caused wholly or partly either by driver error or under severe weather conditions.

The accident records were obtained from the Indiana State Police in the form of computerized accident record tapes for the period 1982 to 1984. For the study, 72 bridge sites were selected by the bridge engineers at the Indiana Department of Transportation (INDOT). In their opinion, these bridges were considered to have traffic safety problems. Due to insufficient accident data and difficulties in procuring information on the approach roadway geometrics at the selected bridge sites, no meaningful statistical analysis could be done. Instead, each accident was reconstructed based on the information available from the accident records. In most cases, upon reconstruction, the possible causes for the accident could be identified. Some cases did not lend

themselves to causal identification, either due to inadequate accident information or totally inexplicable circumstances surrounding the accident.

The third stage involved the development of a safety evaluation model for bridges and underpasses. Initially, the weights for each of the factors were determined. These weights were primarily used to represent the degree of importance of each factor in the safety evaluation model. This was done by conducting an opinion survey, through questionnaires, among the bridge engineers and inspectors in the state. The next step in this stage was to devise a rating scale, which could be used by bridge engineers during field inspection, to quantify subjectively the safety characteristics of each factor. The final step involved the development of the model which logically combined the weights and the corresponding ratings for all the factors to yield a number representing the degree of hazardousness on the bridge. This number is referred to as the Bridge Safety Index.

The most important aspect of the proposed model is highlighted by the following points.

1. The rating scale is such that it allows the bridge engineers and inspectors to characterize approximately the safety aspect of each contributing factor, without forcing them to provide precise numerical estimates of their subjective evaluation.
2. The estimates of the safety rating are taken as input to the model in the same way the bridge engineer or inspector "means" it to be.
3. The model recognizes the interaction between the contributing factors

and the cumulative effect of the factors on traffic safety.

1.3 Report Organization

The report has seven chapters. Chapter 2 deals with the identification of contributing factors. Accident analyses and results are provided in Chapter 3. In Chapter 4 is presented a brief overview of the theory of fuzzy sets, including the terms, definitions and fuzzy set operations used in the safety evaluation model. Chapter 5 deals with the development of the model, and Chapter 6 provides a set of examples. The last chapter gives the summary and conclusion of the research findings.

CHAPTER 2 - FACTORS AFFECTING BRIDGE SAFETY

Before going into the selection of the contributing factors, it is worth mentioning a few important points reported in Agent and Deen [1980]. These points reflect the nature of traffic accidents on bridges and also indicate the general direction in which the search for the contributing factors could be made.

1. The severity of bridge related accidents is generally higher than the severity of all other accidents.
2. Lack of adequate sight distance results in a large number of accidents.
3. High percentage of night time accidents suggests a problem with visual perception of the structure ahead and the need for better delineation.
4. An exceptionally high percentage of accidents is caused by snowy and icy conditions.
5. Approach roadway conditions are very important in determining the safety of primary and secondary bridges.

In order to identify and select the factors which affect traffic safety on bridges, a literature survey was conducted. The survey resulted in the identification of several factors which could be classified into the following three main groups:

1. Bridge related factors.

2. Approach roadway related factors.

3. Environmental factors.

Bridge related factors could be further grouped into two sub-groups:

1. Bridge geometric factors.

2. Structural factors.

2.1 Bridge Geometric Factors

Based on the review, four geometrical factors related to the bridge were identified. They were:

1. Roadway width.

2. Relative roadway width.

3. Shoulder width.

4. Shoulder width reduction.

A brief description of each of the above factors and their effect on traffic accidents as reported in the literature is summarized below.

2.1.1 Roadway Width

This is the curb-to-curb deck width. In other words, it is the total width of the traveled way plus the width of the shoulder on the bridge. This is one of the most important factors affecting traffic safety on bridges. In

the past, the effect of this factor has been studied by two methods.

- By estimating the regression function between the bridge width and the rate of accidents. This involves collecting accident data for a considerable number of bridges and obtaining the regression function with accident rate as the dependent variable and the bridge width as the independent variable. This method was used in the 1973 Colorado study [Colorado Division of Highways 1973]. The result of this study indicated that accidents per million vehicles decreased as the structure width increased. Similar studies in bridge traffic safety can be found in the literature [Gunnerson 1961 and Roy Jorgensen Assoc. 1978] and all of them showed comparable results.
- The second method assumes that lateral displacement is a good indicator of traffic safety. The lateral movement of the vehicle, as it approaches the bridge, while it is on the bridge and while exiting the bridge, is measured. This may be measured under simulated conditions or in the field itself. The field measurement is conducted either using test vehicles [Shelby and Tutt 1958] or by means of aerial video cameras. The final result of such a study is a regression function between lateral displacement and bridge width - which indicates a trend of decreasing lateral movement with increasing bridge width on narrow bridges [Ivey et al. 1979].

Whatever be the methodology, conclusions are the same. Bridge width definitely affects traffic safety. As the width decreases, the bridge tends to pose increased hazard to the drivers. On freeways, any lateral displacement

caused by bridge width may result in side swipe accidents with adjacent vehicles. While on other roads, lateral displacement can be more serious. As many of these bridges have two-way traffic, the chance of occurrence of head-on collisions, in addition to side swipe accidents, is much more.

2.1.2 Relative Bridge Width

This is the difference between the approach roadway width and the roadway width on the bridge. It is a measure of the extent of narrowing or funneling the roadway undergoes on the bridge. This may also be measured as a ratio between the bridge width and the approach roadway width.

Almost all the studies found in the literature considered this factor as the most important aspect in traffic safety on bridges. The effect of this factor can also be studied using either of the two methods indicated above. Studies developed regression functions either between accident rate and relative bridge width [Colorado Division of Highways 1973; Gunnerson 1961; Roy Jorgensen Assoc. 1978; Williams and Fritts 1955; Behnam and Laguros 1973; Hollingworth 1983 and Turner 1984] or lateral displacement and relative bridge width [Ivey et al. 1979]. In a recent study, Turner [1984] was able to predict accident rate quite accurately by developing a regression equation with relative bridge width as the only independent variable. Relative bridge width in this case referred to the difference between the bridge width and the approach roadway width. The number of accidents at each bridge site was given a weight or importance equal to the number of vehicular passages during the study period. Two regression functions were developed between the weighted accident rates and relative bridge width. The first equation included all the

bridges and the second excluded those with extremely narrow widths. Both equations indicated that an increase in relative bridge width resulted in a decrease in accident rate.

All the above studies indicated that more the narrowing of the roadway on the bridge, more the number of accidents. Equivalently, more the narrowing of the roadway, greater the lateral displacement, which in turn means greater the hazard on the bridge. In case of freeways, almost no narrowing occurs. But on other routes, this is a very important aspect, as in many cases vehicles face opposing traffic.

2.1.3 Shoulder Width

A plethora of material can be found on effects of shoulder on accident rates. In a study by Turner et al. [1981], it was found that two-lane roads with shoulder were better than two-lane roads without shoulder or even four-lane roads without shoulder as far as traffic accidents are concerned. Rural two-lane roads with shoulder were found to have less severe accidents, least run-off and least hit-other-car or any other fixed object type of accidents. This is because the shoulders provide a free recovery zone for vehicles that accidentally exit the traveled way. Type of shoulder was also found to affect accident rates. Cirillo et al. [1968] reported paved right shoulder to be safer than unpaved right shoulder at underpasses and adjacent to overpasses on freeways.

2.1.4 Shoulder Width Reduction

The literature generally points to the fact that a shoulder width of 4 to

6 ft. is adequate as far as traffic safety is concerned [King and Plummer 1973 and Roberts 1980]. But it is just not enough to provide wide shoulders. The shoulder width provided on the approach roadway should be carried along over the bridge without any reduction. This gives the driver the same "sense of openness" which would be experienced on the adjoining roadway. Thus the safety of the shoulder is not only dependent on its width but also on the amount of shoulder width reduction on the bridge. In conclusion, lesser the width of the shoulder and more the reduction in width, higher the contribution of the shoulder to the hazard on the bridge.

2.2 Structural Factors

In this category, only one factor was considered to affect traffic safety, the presence of approach guardrails and bridge rails. They are steel, aluminum, or concrete structural railings provided at the approach and on the bridge. Guardrails may also be found at underpasses where they are used as protectors to the bridge piers.

2.2.1 Approach Guardrails and Bridge Railings

Byrne and Kabariti [1980] reported that guardrails affect speed and lateral displacement of vehicles. Vehicles tend to reduce speed as they approach the bridge, and move slightly towards the center of the road, away from the guardrail. But the main contribution of guardrails is in the reduction of the severity of accidents. They help in redirecting vehicles when they collide with them and prevent any major injury to vehicle occupants.

Olson et al. proposed certain tentative service requirements for bridge

rail systems [Olson et al. 1970]. Some of these requirements may be used as guidelines while evaluating the safety of guardrails. The requirements relevant to bridge safety are cited below.

1. A bridge rail system must laterally restrain most of the vehicles that collide with it.
2. A bridge rail system must remain intact following a collision.
3. A bridge rail must smoothly redirect a colliding vehicle. Vehicle progression must be smooth following impact; it must not snag or pocket on bridge rail components.
4. A bridge rail system must have a compatible approach rail or other device to prevent collisions with the end of the bridge rail system.
5. A bridge rail system must define yet permit adequate visibility. The bridge rail must allow good visibility with above and below the horizontal line of sight of vehicle occupants. The driver's sight distance should not be obstructed by bridge rails.

2.3 Approach Roadway Related Factors

Accidents may be caused on the bridge due to severe approach roadway conditions. In evaluating the roadway geometry for safety, it should be checked whether the existing roadway geometry would cause any accident on the bridge or close to the bridge. The effect of the approach roadway on bridge safety should be the main thrust during safety evaluation. In other words, in order to identify contributing factors in the approach roadway, only those which

cause accidents on the bridge should be considered. A clear distinction should be made between factors of the approach roadway which affect the bridge and those which do not.

Turner and Rowan [1982] found that there was a definite increase in the number of accidents on the roadway as one approached the bridge and a decrease as one moved away from the bridge. The rate of accidents was maximum at the bridge abutment and it was twice the rate of the adjacent roadway. But they could not describe this variation of accidents near a bridge by any statistical distribution. Benham and Laguros [1973], in their statistical analysis of accidents and roadway geometrics on bridge approaches, found roadway geometry to be significant during nights and also under wet surface conditions.

After going through the relevant material in the literature, three geometrical factors pertaining to the approach roadway were identified. They were:

1. Approach sight distance.
2. Approach curvature.
3. Approach gradient.

Approach sight distance restrictions are caused mainly by roadway curves and gradients. Yet it was felt necessary to include it as a separate factor, so as to isolate the primary effect of curves and gradients on bridge safety. This would allow the identification of other effects of curves and gradients during the process of evaluating their safety characteristics. Effects like lateral displacement caused by curves or skidding due to poor surface drainage at curves and steep grades.

2.3.1 Approach Sight Distance

This is the maximum distance from where the driver approaching a bridge can clearly see the entrance to the bridge. This distance reflects upon the time available at the bridge site for the driver to prepare for crossing the bridge. Studies have shown that a safe approach sight distance is necessary for bridges, so that drivers have enough time to decide on the placement of their vehicle on the roadway, at a comfortable lateral distance from the approach guardrails.

Neuman et al. [1983] made a detailed functional analysis on sight distance requirements. The two main elements of sight distances are highway elements and environmental conditions. The highway elements are vertical grade and horizontal curvature. Other geometrical features affecting sight distances are intersections, bifurcations, hidden curves, narrow structures and railroad crossings. Environmental conditions affecting sight distances are those which affect driver behavior and vehicle maneuverability. For example, wet pavements provide lower friction, and fog, snow and rain limit visibility and create sight distance restrictions. If the elements are present in severe combinations, sight distance restrictions increase. Finally, sight distance operational requirements are also influenced by perception-reaction time of driver, the eye height of the driver and the braking distance which in turn is a function of the type of vehicle.

2.3.2 Approach Curvature and Gradient

Most of the studies in literature [Neuman et al. 1983 and Dunlap et al. 1983] on highway accidents at curves and grades generally agreed that steeper the grade or sharper the curve, more the number of accidents. Neuman et al. [1983] considered the main contributor to accidents on highway curves to be hazardous roadside design. Dunlap et al. [1983] concluded that the primary factor to be considered in accidents on curves and grades is surface drainage. During wet weather conditions, if the curved section has poor surface drainage and if the vehicle has poor tires, hydroplanes form between the pavement and tires, resulting in the vehicle skidding or going out of control.

It should be noted that most of the studies found in literature were concerned with the curvature and gradient effects irrespective of their location on the roadway. No material was found which dealt specifically with the effect of curvature and gradient when they are located adjacent to bridges. Another study which has some application to the bridge safety evaluation was reported by Glennon and Weaver [1971]. They found that vehicles exiting from a curve showed large lateral displacement. Sharper the curve, more is the displacement. Thus if the curve is located very close to the bridge, then the driver will have little time to recover from the lateral displacement before entering the bridge and this may prove to be hazardous.

If one of the approaches to the bridge has a negative gradient, it may tend to pose increased hazard during wet weather and icy conditions. On the other hand, approaches having positive gradients reduce approach sight distance and create additional perspective problems to the approaching driver.

In summary, factors contributing to increased hazard on a bridge are:

1. Sharp curvature of the approach roadway.
2. Curves close to the bridge.
3. Poor surface drainage.
4. Steep gradients.

2.4 Environmental Factors

These include all other factors which are non-geometrical in nature but which affect traffic safety on bridges. The factors identified from the review are as follows.

1. Volume/capacity ratio.
2. Lighting conditions.
3. Presences of nearby ramps, merges or intersections.
4. Presence of nearby lane drops or pavement transitions.

2.4.1 Volume/Capacity Ratio

This indicates how crowded the bridge is. With increasing traffic, the possibility of an accident occurring increases. In addition, if the capacity is restricted, then traffic conflicts may increase, especially on roads without medians where vehicles face opposing traffic. This situation increases the hazard on the bridge. In general, it was felt that high V/C ratios would cause increased rear-end collisions, as headways between vehicles decrease with increase in amount of traffic.

2.4.2 Lighting Conditions

Herd et al. [1980] conducted extensive accident analyses in the state of Kentucky on rural two-lane roads, expressways and urban roads. They found that rural roads had a higher accident rate during nights and the ratio between the night and day accident rates was greatest for rural expressways (about 1.98) and least for four-lane roads (about 1.47). On Louisville urban roads, there was no significant difference between day and night time accident rates. The results are reasonable as urban roads usually have good illumination. When the volume of traffic is high, then illumination does not matter very much as the light from the headlights of the vehicles is quite sufficient [NCHRP 1968]. Under low illumination conditions, the driver tends to navigate using the edge marking. In conclusion, better illumination at bridge sites may have a positive effect on bridge safety. Under low illumination and volume conditions, care should be taken to see if edge markings are clearly visible. Absence of clear edge markings pose hazards under low illumination conditions.

2.4.3 Presence of Nearby Ramps, Merges or Intersections

Hilton [1973] proposed that bridges located adjacent to high accident potential points, such as intersections, have higher potential for accidents. This type of situation may exist for bridges on non-freeway roads. Bridges on freeways which are located close to ramps may also have a higher accident potential.

2.4.4 Presence of Nearby Lane Drops or Pavement Transitions

Transitions tend to have an effect similar to that of widening of roadway but not the bridge. For example, if a four-lane road is transitioned into a two-lane road on the bridge, then this poses a great danger to vehicles in the process of passing other vehicles just before entering the bridge. When transitions are necessary, they should be completed well in advance of the structure to allow drivers maximum opportunity to adjust to the change prior to entering the bridge [Hilton 1973].

2.5 Contributing Factors at Underpasses

Little information was available as far as accidents at underpasses are concerned. Hence, to identify contributing factors at underpasses, discussions were held with the bridge engineers at INDOT. They felt that the factors identified for bridges could very well be applied to underpasses. Obviously, they would refer to geometrical and environmental conditions of the roadway under the bridge. In addition, they felt vertical clearance to be a very important factor at underpasses.

2.5.1 Vertical Clearance

This is the clearance between the surface of the roadway and the underside of the bridge. Most of the accidents related to this factor are associated with trucks. On freeways, this is not a major problem. Although there are some bridges with less than 16'-3" clearance, almost all interstate bridges have adequate vertical clearance. Yet they may be hazardous if the road surface is bumpy, in which case, the trucks may jump up and hit the underside of the bridge. On other roads this factor can pose a major problem as many of the bridges on these non-freeway roads may not have signs indicating their vertical clearance.

Discussions with bridge engineers at the InDOT yielded a few more additions to the already identified list of factors. It was suggested that the presence of appropriate signs, markings and delineators should also be included. When viewed from the perspective of a bridge management system, the absence of markings and signs do not affect the major decisions being made on bridge repairs or replacement. Hence, it was felt adequate to include the above factors with the lighting condition factor and consider them as one composite factor. The second addition suggested was the percentage of trucks in the traffic as one of the environmental factors. The contention was that trucks pose increased hazards, especially on narrow bridges, because of their width. They also increase the possibility of an accident at underpasses having inadequate vertical clearance.

2.6 Chapter Conclusion

As a result of the literature review and discussions with the bridge engineers, a list of fourteen factors was selected for the safety evaluation model. These factors were felt to be sufficiently comprehensive and adequate to represent the traffic safety characteristics of a bridge or an underpass. The factors selected are listed below.

A. Bridge Related Factors:

a. Bridge Geometric Factors:

1. Roadway width on the bridge.
2. Relative roadway width.

3. Shoulder width.

4. Shoulder width reduction.

b. Structural Factors:

1. Approach guardrails and bridge rails.

2. Vertical clearance (only for underpasses)

B. Approach Roadway Related Factors:

1. Approach sight distance.

2. Approach roadway curvature.

3. Approach roadway gradient.

C. Environmental Factors:

1. Volume/Capacity ratio.

2. Percentage of trucks.

3. Lighting, signing, and delineation.

4. Presence of nearby ramps, merges or intersections.

5. Presence of nearby lane drops or pavement transitions.

CHAPTER 3 - ANALYSES OF BRIDGE ACCIDENTS

3.1 Introduction

After the selection of contributing factors, an analysis of traffic accidents on bridges was conducted. The main objectives of this analysis were:

1. To get a general idea of the nature of traffic accidents on bridges.
2. To verify to what extent the selected factors were responsible in contributing to bridge safety. In other words, the selected factors would be verified, if they were identified as possible accident causes for most of the traffic accidents occurring on bridges.

3.2 Collection of Bridge Accident Data

To conduct any accident analysis, accident data is required. Generally, accident data for a period of three years is sufficient to identify any safety problems of any highway facility [FHWA 1981]. Records of accident data stored on computer tapes were obtained from the State Police for a period of three years (1982-84). These computer tapes contained accident information of all accidents that had occurred in the state of Indiana during the three year period. From this huge database, those accidents which took place on bridges had to be extracted to conduct the analysis. Before attempting to identify bridge accidents from other accidents, a complete knowledge of the kind of information stored about each accident was obtained. A brief description of the accident database is provided below.

All necessary information about each accident is recorded in the accident database in seven different categories, referred to as records. They are:

1. Environmental Record
2. Vehicle Record
3. Driver Record
4. Pedestrian Record
5. Injured Record
6. Trailer Record
7. Arrest Record

Out of these seven records, only the first three were relevant to this study. Environmental Record describes circumstances, location and surrounding conditions of the accident. Vehicle Record indicates vehicle characteristics and circumstances of the accident unique to each vehicle. Driver Record describes the driver with name, license, injury and alcohol/drug test information for each driver.

Each record type has several elements. For example, the environmental record includes elements such as date, county, day of week, time of accident, and so on. Each element is stored in a unique position within the record. Each record may be visualized as an array of numbers, and each element is stored in a unique position within the array. Those elements which take numerical values, such as time of accident and date of accident, have their

values stored as such. Some of the elements, such as, day of week, take qualitative values. In these cases, a code number is assigned to each value the element may take. The information stored is then the code number and not the qualitative value. For example, the qualitative values associated with the element, day of week, and the corresponding code numbers are given below:

Day of Week	Code Number
Sunday	1
Monday	2
Tuesday	3
Wednesday	4
Thursday	5
Friday	6
Saturday	7

After examining all the information stored in the accident database, it was found that the accident records did not contain any information indicating whether the accident occurred on a bridge or not. However, information about the exact location of each accident was available in the environmental record. If the location of a bridge could be exactly determined from the bridge inventory database, then all accidents that occurred on that bridge could be obtained. This process would require simultaneous manipulation of the accident database and the bridge inventory database.

A direct manipulation of the two computer databases could not be adopted for the following two reasons. Firstly, the two databases were extremely large and secondly, the manner in which the location of bridges was stored in the bridge inventory database was totally different from the way the location of accidents was stored in the accident database. The location of each accident was recorded as distance in feet from the nearest mile post or ramp if the accident occurred on an interstate, or the nearest intersecting road if it occurred on other roads. These roads (including mile posts) are referred to as reference roads. But the bridge location was specified as distance in miles from the nearest intersecting interstate, US or State road. To collect all the bridge related accidents in the state for the three year period would mean finding the nearest mile post, ramp or intersecting road for every bridge in the state, which is by no means an easy task.

Due to these problems, it was decided that instead of locating all the bridge accidents, it would suffice for this study, to locate all accidents on a selected number of bridges. The bridge engineers at InDOT were requested to provide a list of bridges which, in their opinion, had traffic safety problems. A total of 72 bridges was obtained. It should be noted here that the selection of these bridges was done based on the experience and judgment of bridge engineers and not by referring to any accident database. Table 3.1 shows the list of these bridges.

The location of each of these bridges as distances from the nearest mile post or ramp for interstate bridges, and the nearest intersecting road for bridges on other roads were obtained from the road inventory database.

Table 3.1 Bridges Selected for Accident Analysis.

Crawfordsville	Seymour
40-32-2046A	31-03-3362B
75-32-5160B	46-03-3301B
165-167-5550A (NBL)	50-15-2021
165-167-5550A (SBL)	50-15-3159B
165-178-5509A (NBL)	56-72-4234
165-178-5509B (SBL)	165-14-4218
170-5-4613A (EBL)	165-48-3891
170-5-4613A (WBL)	165-46-4250
174-6-4617C (EBL)	50-36-1262C
174-6-4617B (WBL)	
Greenfield	Vincennes
(170)209-30-5132A	50-14-687F
169-32-4741A	50-42-686E
170-74-5232A	50-42-4627
170-77-5716	(231)54-28-1794C
170-86-6462	58-42-3244D
170-124-5169	61-42-591G
170-141-4972B	61-63-591F
1465-127-5255A	67-28-939B
1465-127-5275A	164-25-5219A (EBL)
1465-159-4456C	164-25-5219B (WBL)
Fort Wayne	LaPorte
15-85-1743	2-71-2020
15-85-2482	24-09-2183
15-85-2482J	24-09-2382
26-27-1441	33-71-2493
30-02-2190A	33-71-2534
169-56-4760B	41-45-2177A (NBL)
169-119-4507C	41-45-2177A (SBL)
169-128-2271A	41-56-1489A (NBL)
169-128-4606A	53-45-2510
169-145-4725A	(329)29-09-2019
169-153-5038B	(421)39-08-1604A
169-153-5038JB	(421)43-66-3407
169-155-4818A	(421)43-75-1252B
169-155-4818JA	912-45-5084A
	165-255-2320A (NBL)
	180-45-2187A (EBL)
	180-45-2187A (WBL)
	194-64-2188A (EBL)
	194-64-2188A (WBL)

Although the locations of bridges could thus be identified consistent with the accident database, there still remained one more step in the process of identification of bridge accidents. The information of the reference road for a particular accident in the accident database is stored in the form of a six-digit number code called the pseudo number. Every mile post, ramp and road in the state, is assigned a unique pseudo number. The corresponding pseudo numbers for the reference roads for each of the 72 bridges were found from the Pseudo Number database. This file was obtained from the Traffic Safety Division of InDOT on a computer tape.

The steps that were followed in bridge accident data collection were:

1. Nearest mile post or ramp for interstate bridges, or the nearest intersecting road for bridges on other roads, and their distance from the center of the bridge was obtained from the road inventory database. While doing so, some of the roads were found to have been referred by road inventory numbers. In such cases, the actual names of the roads were found from the relevant county road map. This was necessary as the pseudo number could be found from the pseudo number database only if the name of the road was known.
2. The corresponding pseudo numbers for the reference roads identified in the previous step were obtained from the pseudo number database.
3. All accidents in the accident database which were keyed to a reference road by the same pseudo number obtained in the previous step were identified.

4. From the accident information collected in the previous step, all those accidents which did not occur within the length of the bridge or 100 feet on either side of the ends of the bridge were eliminated. A distance of 100 feet was considered to take care of data errors and/or measurement errors by the recording policeman as well as to study the effect of the approach roadway on bridge accidents.

3.3 Analyses of Accidents

After the information on all accidents which had occurred on the selected bridges during the given time period were obtained, it was found that the number of accidents was inadequate to conduct any significant statistical analyses. Consequently, the available data were used to identify only the general trends of bridge related accidents. However, as the number of accidents were not very high, each accident was individually analyzed in detail in two steps. The first step involved reconstructing every accident with the help of the information available in accident records and determining the circumstances surrounding each accident and the exact manner in which the collision took place. Information obtained from accident records for reconstructing the accidents are shown in Table 3.2

Upon reconstructing the accidents, the next step involved identifying if any of the selected factors were the possible accident causes. For this, specific information was required about each of the selected factors at each bridge site selected for the analysis. Most of the data concerning bridge geometry were obtained from bridge inspection field reports. But the inspection sheets lacked data about approach roadway curvature, approach gradient,

Table 3.2 Information Used in Accident Reconstruction.

Date	Time
Number of accidents	Severity
Traffic flow direction	Primary contributing circumstances
Collision diagram	Type of accident
Location of first damage or injury	Lighting condition
Weather	Road surface condition
Road surface type	Road character
Vehicle type	Speed limit
Direction of travel	Pre-accident vehicle action
Initial impact	Vehicle contributing circumstances
Collision involved	
Physical status of driver	
Traffic control	

traffic volume, traffic mix and lighting conditions. During inspection, bridge engineers may include descriptions of the above mentioned factors only in qualitative terms, if they were considered to be significant in the bridge evaluation process.

To obtain specific information on approach roadway curvature and gradient, the original roadway profile drawing sheets had to be referred. Some of the bridges had their own roadway profile drawing sheets. These were the bridges constructed solely as a bridge project. Those bridges which were constructed as part of a road project, did not have their roadway profile drawing sheets along with the other structural drawing sheets. For these bridges, the section of the road within which the bridge lies was found. The project number under which that particular roadway section was constructed was then identified. Once the project number was known, the approach roadway data could be found from the roadway profile drawing sheets of this project.

Volume of traffic on the section of the road close to bridge was obtained from the road inventory database. Currently, detailed data on percentages of trucks are not available. However, data on truck percentages on selected routes in selected counties were obtained from the Traffic Engineering Division of the Indiana Department of Transportation.

It should be noted here that to conduct detailed analysis in the two steps mentioned before, there are no well defined rules. It mostly depends on the ability of the analyst to reconstruct the accident and deduce possible accident causes from the information available. Nevertheless, the general procedure adopted was as follows. The location of each accident with respect

to the bridge was initially obtained. This information indicated if the accident occurred while the vehicle was entering or exiting the bridge or while traveling on the bridge. The exact way in which the collision occurred was deduced by examining the initial impact of the vehicles and the collision diagrams. The circumstances leading to the accident were obtained from the primary contributing circumstance, vehicle contributing circumstances and pre-accident vehicle action. In some cases, possible causes could be identified by examining information on weather, road surface condition or lighting condition. In other cases, examining the nature of collision of the vehicle, while keeping the data on the geometry of the bridge and approach roadway in perspective, led to the deduction of possible causes.

In order to form homogeneous categories of bridges with similar characteristics, the following four groups were considered:

1. Interstate Bridges.
2. Bridges on US and State roads.
3. Interstate Underpasses.
4. Underpasses on US and State roads.

The results of the analysis conducted for structures in each of the above categories are described below.

3.3.1 Interstate Bridges

The bridge inventory database specifies each interstate bridge at a par-

ticular location as two separate structures, one on each lane. But they were considered as just one bridge in this study, as the bridge geometrics and approach roadway conditions of the two adjacent structures were usually very similar. A total of 20 interstate bridges was in the sample (Table 3.1). Only those bridges which had at least one accident during the three year period are shown in Table 3.3. Initially an overall analysis was conducted. Then four bridges with the highest number of accidents were selected, and detailed analysis was conducted on each accident that occurred on these bridges.

3.3.1.1 Overall Analysis

3.3.1.1.1 Type of Accidents In the three year period considered, no fatal accident was recorded. Most of the accidents involved property damage type. There were only a few accidents with personal injury. Table 3.4 gives the number of each type of accident.

3.3.1.1.2 Road Surface Condition A frequent cause of accidents on interstate bridges was the presence of snow/ice on the bridge deck. The number of accidents associated with various road surface conditions is given in Table 3.5.

The amount of time in a year during which a bridge deck is dry is much more than when it is either icy or wet. But Table 3.5 indicates that the number of accidents during dry conditions and that during wet/icy conditions over the three year period are close. This information may be used to conclude that wet and icy bridge decks pose a serious safety hazard. During

Table 3.3 Selected Interstate Bridges with At Least One Accident.

Interstate Bridges				
No.	Structure Number	1982	1983	1984
1	I65-167-5550A		1	8
2	I65-178-5509A	6	6	6
3	I70-5-4613A	2	4	2
4	I74-6-4617C	1		
5	I69-32-4741A	1	1	3
6	I465-127-5255A	3	3	1
7	I465-159-4456C	3	3	6
8	I64-25-5219A		1	
9	I69-56-4760B	1		
10	I69-128-2271A	1	3	1
11	I69-145-4725A	2		1
12	I69-153-5038B	5		
13	I69-155-4818A			1
14	I65-255-2320A	2		
15	I80-45-2187A	2	1	5
16	I94-64-2188A	10	7	1
	TOTAL	39	30	35

Table 3.4 Number of Accidents for Each Type of Accident
on Interstate Bridges.

Type of Accidents	Number of Accidents		
	82	83	84
Fatal			
Personal Injury	8	9	17
Property Damage	31	21	18
TOTAL	39	30	35

Table 3.5 Effect of Road Surface Condition on Accidents
on Interstate Bridges.

Road Surface Condition	Number of Accidents		
	82	83	84
Dry	19	17	22
Snow/Ice	14	9	8
Wet	5	4	5

bridge inspection, the surface drainage on the bridge should be carefully examined. Precaution must be taken to remove snow from the bridge deck as soon as possible and warning must be given to drivers of possible ice on the bridge deck.

3.3.1.1.3 Lighting Conditions Another interesting information obtained was the number of accidents under daylight and darkness. This is presented in Table 3.6. The amount of traffic can be expected to be less during the night than during the daytime. But the percentage of accidents in Table 3.6 do not show significant difference. Thus it can be expected that lighting condition at the bridge may contribute to the safety of the bridge. All accidents which had occurred during the night were further analyzed and the following observation could be made.

1. Lighting conditions played a critical role during abnormal weather conditions like rain or snow. Most of the night time accidents occurred either under icy or wet bridge deck conditions.
2. The second major cause for night time accidents was driver inattention. Some of the accidents were caused by the driver falling asleep while driving.

3.3.1.1.4 Primary Contributing Circumstances This is the factor which was determined by the investigating officer to be the major cause of an accident recorded in the database. Three significant circumstances were detected, as shown in Table 3.7.

Table 3.6 Effect of Lighting Conditions on Accidents
on Interstate Bridges.

Lighting condition	Percentage of Accidents		
	82	83	84
Daylight	51	53	51
Dark	47	40	46

Table 3.7 Significant Primary Causes For Accidents
on Interstate Bridges.

Primary Contributing Circumstances	Number of Accidents		
	82	83	84
Driver Inattention	6	6	7
Unsafe Speed	4	6	9
Material on Surface	10	2	1

Driver inattention was cited as the cause of accidents that occurred during the course of vehicles changing lanes, or straying away from their lanes and while passing. Unsafe speed and material on surface contributed to more than 50 percent of the accidents. Almost all accidents under these two circumstances had occurred under icy or wet bridge deck conditions.

3.3.1.1.5 Collision Diagram This is the pictorial diagram or verbal representation indicating the directional analysis and angle of impact of the first event between vehicles or vehicle and object involved in the accident. The significant information from collision diagrams are shown in Table 3.8.

Rear end collisions occurred mostly on wet and icy roads. They also were found in accidents caused by the driver in the rear following the vehicle in front too closely. This was seen on bridges located on urban interstates with possibly high volume-to-capacity ratios. Head-on collisions involved single vehicle accidents. The collisions in these cases were usually either with the bridge guardrail or with animals present on the road. Same direction accidents were found in cases involving improper lane usage by the driver resulting in collision with another vehicle in the adjacent lane. These accidents may have been caused by the lateral displacement of vehicles on entering the bridge due to the effect of reductions in roadway or shoulder width. Off road collisions generally involved collisions with the bridge guardrail and this almost always occurred under icy deck conditions. Some of the accidents were due to drivers falling asleep and straying outside the traveled way and colliding with the guardrail. Right angle accidents involved collisions either with animals on the bridge or with the guardrail under

Table 3.8 Types of Accidents on Interstate Bridges.

Type of Accident	Number of Accidents		
	82	83	84
Rear End, Neither Turning	8	4	10
Head On, Neither Turning	5	3	6
Same Direction	6	3	6
Off Road Collision	8	7	6
Right Angle	8	7	2

ice/wet deck conditions. In the latter case, the vehicles had skidded on the surface and collided at right angle to the guardrails.

After having known that icy and wet pavements were the main causes for accidents on interstate bridges, all the accidents that had occurred on dry pavements were extracted. Those accidents which occurred on dry pavements and dark lighting conditions usually were due to animals being present on the roadway. During the day, the accidents on dry pavements were primarily due to driver inattention. These accidents occurred either during passing, lane changing, following the vehicle in front too closely or plainly due to the driver falling asleep while driving.

3.3.1.2 Detailed Analyses The bridges with high accident occurrences in the sample were:

1. I65-178-5509
2. I70-5-4613
3. I465-159-4456
4. I94-64-2188

A brief description of the accidents on each of the above bridges and their possible causes are given below.

3.3.1.2.1 Structure No. I65-178-5509 Though this bridge experienced many accidents, none of them was caused by the bridge itself. Most of the accidents had occurred at night, due to the presence of animals on the road-

way. Two other accidents took place under icy deck conditions. But in both cases the investigating officer cited that the vehicles were moving at unsafe speeds. Even the bridge inspection field reports do not indicate any cause for hazard on the bridge.

3.3.1.2.2 Structure No. 170-5-4613 This bridge was involved in three very similar accidents. All three accidents occurred under icy deck conditions. The bridge has significant amount of roadway width reduction (8 feet) and inadequate shoulder, as indicated by the bridge inventory database. These reductions may have caused the drivers to apply brakes, in order to reduce their speeds, either while approaching the bridge or while traveling on the bridge. With ice on the bridge deck, nothing can be more hazardous than applying brakes. This may cause the vehicle to skid. In fact, the accident information of the three accidents did indicate that the pre-accident vehicle action was skidding before finally colliding with the guardrails. Thus, this incident validates the fact that factors such as reduction in roadway width and shoulder width do affect safety on bridges, more so under icy deck conditions.

3.3.1.2.3 Structure No. 1465-159-4456 Accidents similar to the ones above involving collision of vehicles with the guardrails under icy deck conditions, were also recorded on this bridge. The reasons could be attributed to roadway width reduction of 9 feet and poor shoulders on the bridge, as indicated in the bridge inventory database.

3.3.1.2.4 Structure No. 194-64-2188 The bridge had accidents which occurred mostly under icy deck conditions. In addition to this, three other factors were considered to have been responsible for causing accidents on this bridge.

The factors identified for this bridge are as follows. The first one was high volume of traffic (ADT = 53,700). High volume bridges, in the overall analysis presented in the previous section, indicated higher number of rear-end and side-on collisions, the latter being caused during lane changing. The second factor identified was the presence of a nearby ramp. The bridge had experienced an accident under snowy conditions, in which a vehicle entering the freeway from the on-ramp, had collided with the bridge guardrails. Due to the proximity of the on-ramp to the bridge, the vehicle was still in the process of accelerating and merging while traveling on the bridge. Due to the presence of ice on the deck, it had skidded out of control. The final factor identified was the approach roadway gradient. Two accidents involved vehicles which had skidded on the roadway under wet and icy road conditions, while exiting from the bridge. The bridge geometrical data collected from the roadway profile drawing sheets, indicate the exit of the bridge has a slight downward gradient. This may have contributed to the possible cause for the two accidents.

3.3.2 Interstate Underpasses

The number of underpasses considered in the sample was very small. Moreover, each had insignificant number of accidents in the three year period. Hence, it was not possible to conduct any kind of accident analysis. All the information about accidents at underpasses had to be obtained through discussions with the bridge engineers at INDOT. Presented in Table 3.9 is the number of accidents on those underpasses with at least one accident.

Table 3.9 Selected Interstate Underpasses
with At Least One Accident.

Interstate Underpasses				
No.	Structure Number	1982	1983	1984
1	I65-14-4218A	1		
2	I65-46-4250B	1		
3	I70-74-5232A	1		
4	I70-124-5169	1	1	
	TOTAL	4	1	

3.3.3 Bridges on US and State Roads

Out of the 72 bridges in the original list, 28 of them were bridges belonging to this category. All those bridges which had more than one accident in the three year period are given in Table 3.10. Unlike the overall analyses of accidents on interstate bridges, in this case no meaningful information could be developed by lighting condition, collision diagram, primary contributing circumstances, and so on.

3.3.3.1 Detailed Analysis Bridges with the highest number of accidents were selected and a detailed analysis of every accident on those bridges was made. The selected bridges were:

1. 31-03-3362
2. 50-15-3159B
3. 56-72-4234
4. 50-14-687F
5. 30-20-2190
6. 912-45-5084

A summary of the analysis follows.

3.3.3.1.1 Structure No. 31-03-3362 This bridge had experienced accidents in which only vehicles moving south were involved. All the accidents were in one way or the other due to the traffic lights located to the south of the bridge. Some of the accidents were caused by ice on the deck. These may have been

Table 3.10 Selected Bridges on US and State Roads
with At Least One Accident.

Bridges on US and State Roads				
No.	Structure Number	1982	1983	1984
1	31-03-3362B	3	2	1
2	46-03-3301B		1	2
3	50-15-3159B	4	1	5
4	56-72-4234	2	3	2
5	50-14-687F	1	1	4
6	50-42-686E	1	2	
7	58-42-3244D		5	
8	61-42-591G	1	1	1
9	67-28-939B		1	
10	26-27-1441			1
11	30-02-2190A	4		4
12	24-09-2382	1		
13	(421)43-66-3407		1	1
14	(421)43-75-1252B		1	
15	912-45-5084A	2	6	1
	TOTAL	19	25	22

caused when vehicles tried to brake as they approached the traffic signals and skidded on the icy surface. A few of the accidents were rear end collisions wherein the primary cause of the accidents was cited as being due to driver inattention. On checking the bridge geometry, it was found that the bridge had a slight gradient which restricted the sight distance and the oncoming vehicles could not see the queue in front of the traffic lights until they were half way across the bridge, thus giving them very little time to come to a halt.

3.3.3.1.2 Structure No. 50-15-3159B This bridge has traffic signals located to the west of it and all accidents on the west bound lane of this bridge were similar to those on the previous structure. This verifies the fact that bridges located close to intersections are potentially hazardous. The east bound lane had four similar accidents where vehicles on the right lane moved toward their left and collided with the vehicle on the adjacent lane. The lateral displacement may have been caused by the effect of reduction in roadway or shoulder width. The other accidents that occurred on this bridge involved vehicles in the left lane colliding with vehicles on the right lane. This kind of accidents is, in most cases, due to the lateral displacement of the vehicles on the left lane caused by the effect of the oncoming traffic from the opposite direction.

3.3.3.1.3 Structure No. 56-72-4234 This bridge is located very close to the I65 diamond interchange. Left turning vehicles taking the exit to I65 have to stop on the road before crossing the opposite lane and entering the exit ramp. The bridge causes sight distance restrictions due to a slight gradient of the approach roadway. Hence, vehicles approaching the bridge cannot see those

vehicles that have stopped to take the exit. This was considered to be a possible cause for the rear end collisions that had occurred on the bridge.

3.3.3.1.4 Structure No. 50-14-687F This bridge presents a classic case of traffic accidents on narrow bridges. The curb-to-curb deck width is 20 ft. All the accidents had occurred with vehicles being left of the center line and most of them involved trucks. Now the bridge has been designated as a one lane bridge.

3.3.3.1.5 Structure No. 30-20-2190 This bridge has an approach roadway width of 68 ft and the roadway width on the bridge is 61 ft. The bridge has curved approaches on both sides located close to it. It has been observed that vehicles moving on curves tend to move towards the center line. To overcome this effect, drivers tend to drive as close to the right edge marking as possible. At the time vehicles exit the curve, they are close to the right edge and on approaching the bridge have to move towards their left, if there is any reduction in the roadway or shoulder width. If this reduction is more, the lateral displacement is also more, resulting in the vehicle encroaching the adjacent left lane. This situation was considered to have resulted in many side-on collisions on this bridge, with vehicles on the right lane colliding with vehicles on the adjacent left lane.

3.3.3.2 Structure No. 912-45-5084 Even though this bridge did experience many accidents, it was difficult to identify the possible causes due to the presence of extraneous factors such as nearby exit ramps and signalized inter-sections. However it did highlight the fact that if a bridge is located near a potentially hazardous area, the probability of having an accident on the bridge increases.

3.3.4 Underpasses on US and State roads

Out of the 16 underpasses in the original list, only six of them had at least one accident in the three year period. The number of accidents was considered inadequate to determine the possible causes of the accidents. However, two underpasses showed a high number of accidents. But both of them were located at an intersection and almost all the accidents could be attributed as being caused by the intersection rather than by the underpasses. Only one other underpass (53-45-2510) had an accident involving a truck and the underside of the bridge due to inadequate vertical clearance. Information on factors affecting traffic safety at underpasses on US and State roads was obtained from discussions with the district and state bridge engineers. A list of underpasses having at least one accident is given in Table 3.11.

3.4 Chapter Conclusions

1. Most of the contributing factors selected in the previous chapter were found to be associated with bridge traffic safety. It should be noted that the validation of the selected factors was done by reasoning and deduction of possible causes of each accident. A more concrete and unambiguous validation would require a more comprehensive data set than what was available.
2. No statistical analyses and analytical methods of verification of the selected factors could be done due to the small sample sizes of accident records.

Table 3.11 Selected Underpasses on US and State Roads
with At Least One Accident.

Underpasses on US and State Roads				
No.	Structure Number	1982	1983	1984
1	50-15-2021			1
2	164-25-5219B (WBL)	1		
3	2-71-2020	2	8	7
4	33-71-2493	1	4	1
5	33-71-2534			2
6	53-45-2510		1	
	TOTAL	5	13	11

3. Future accident recording should indicate the accident location by facility so that bridge traffic safety can be monitored more effectively.
4. The present accident information records are inadequate in identifying accident causes. Circumstances surrounding any accident and its possible causes cannot be easily deduced with the currently stored information in the accident database.
5. Some of the bridges selected by the INDOT bridge engineers did not have any accident at all in the three year period. This was because, while selecting bridges, the bridge engineers picked those which had experienced accidents in the recent past. Probably these bridges may have had an increase in the number of accidents after the year 1984. This increase could be attributed either to development of nearby areas or to significant changes in traffic volume and speed characteristics. This presumption, however, could not be verified due to unavailability of more recent accident data.

CHAPTER 4 - APPLICATION OF FUZZY SETS IN BRIDGE SAFETY EVALUATION

4.1 Introduction

To obtain a subjective evaluation of a complex phenomenon or any system characteristic being studied, it is convenient to divide the system into component parts and then conduct an evaluation on each of its components. This principle of "Divide and Conquer" was used in the proposed model to evaluate traffic safety on bridges. The safety characteristic of a bridge is then the combined effect of the safety characteristic of each of its contributing factors. In the proposed model, the extent to which each of the selected contributing factors affects traffic safety on a bridge is subjectively evaluated and assigned a safety rating. Safety ratings of all factors are then combined to yield a measure of traffic safety on the bridge. This measure is called the Bridge Safety Index (BSI).

To develop such a model, we should be able to appropriately represent subjective evaluations. Representing the safety characteristic of each factor by a single numerical value is highly inappropriate, as numbers are too precise to be used in the complex process of subjective evaluation. Currently, numerical values are used to specify condition ratings during bridge inspection. But in reality, when a bridge inspector specifies a condition rating, say 7, he would have actually meant it to be approximately 7, implying a range of numbers around 7, with 7 being the most representative value of the implied range. But representing the subjective evaluation simply as a range will have the following defect. A range of numbers implies that all the numbers within

the range have equal possibilities of being considered the representative value of the subjective evaluation. But this is not the case. The representation should be such that the numbers at the ends of the range have a lesser degree of possibility of being considered as the representative value, and more for numbers closer to the center of the range. Thus, the most appropriate method of representing any subjective evaluation would be not only to specify a range of numbers but also to associate each number within the range with another number, say between 0 and 1, which would indicate the degree of possibility of that number being the representative value of the evaluation. A degree of possibility, 0, would indicate the least representative number and a degree of possibility, 1, the best representative number of the evaluation. This type of representation can be best achieved by what is known as Fuzzy Sets.

4.2 Fuzzy Sets

A fuzzy set, in its general sense, refers to a set of objects within the totality of all objects. This totality of objects is called the universe of discourse. Each object in the set is associated with a number between 0 and 1 to indicate the extent to which it belongs to that set. For example, consider a set of tall men. The universe of discourse, in this case, will be all living men on earth. The set of tall men refers to a group of men who have relatively greater heights than normal men. But such a set does not have a definite boundary. There are a group of people who only belong to this set to a certain degree. Such a set or group of objects, with objects having varying degrees of belongingness or membership to the set, is called a fuzzy set. To specify the degree of membership of an object to a fuzzy set, each object in

the universe of objects being considered, is associated with a number between 0 and 1. The number, 0, would indicate that the object does not belong to the fuzzy set at all, while the number, 1, would specify complete membership of the object to the fuzzy set. This association is brought about by what is called the membership function, also referred to as the characteristic function. Thus the characteristic function defines a fuzzy set in the universe of discourse. A more formal definition is given below.

4.2.1 Definition of a Fuzzy Set

A fuzzy subset A of a universe of discourse U, is characterized by a membership function $\mu_A: \mu \rightarrow [0,1]$, which associates with each object y in U a number $\mu_A(y)$ in the interval [0,1] which represents the grade of membership of y in A.

Following are definitions of some terms which will be referred to later. The support of A is a set of those objects in U, whose degree of membership in the fuzzy set A is greater than zero. The crossover point of the fuzzy set A is an object in U whose grade of membership in A is 0.5.

If the objects of discourse do not form an ordered sequence, then the membership value (say μ_1), of a fuzzy set (say A), is specified for each object (say x_1), separately. Then A, in terms of fuzzy set notation, would be represented as:

$$A = \mu_1/x_1 + \mu_2/x_2 + \dots + \mu_n/x_n \quad 4.1$$

But if the objects form an ordered sequence, like in case of real numbers on the number line, increasing uniformly from zero to infinity, the

characteristic function may be specified as an algebraic function. In that case, the fuzzy set representation would be:

$$A = \int \mu(x)/x \quad 4.2$$

In Equations 4.1 and 4.2, the + and the $\int$ signs should not be interpreted to mean summation. They represent a union of all objects that belong to the fuzzy set. Figure 4.1 shows a definition of a fuzzy set approximately 5, with its support and crossover points. Here the characteristic function is an assumed algebraic function only for the sake of illustration. Figure 4.1 Pictorial Representation of a Fuzzy Set approximately 5.

4.3 Fuzzy Numbers

Let us reconsider the above example of the fuzzy set approximately 5. The assumed membership function for the fuzzy set takes a value of zero for all numbers between 0 and 3, uniformly increases to 1 between 3 and 5, then uniformly decreases to zero between 5 and 7. Such a fuzzy set is also referred to as a Fuzzy Number [Dubois and Prade 1978]. In general, a fuzzy set is a fuzzy number if its characteristic function is defined on the real number line and has the following properties:

- i. zero on $(-\infty, c]$,
- ii. strictly increasing on $[c, a]$,
- iii. constantly equal to 1 on $[a, b]$,
- iv. strictly decreasing on $[b, d]$,

Figure 4.1 Pictorial Representation of a Fuzzy Set
approximately 5.

v. zero on $[d, +\infty)$

where, $c < a < b < d$ are any four real numbers. If $a = b$, then the fuzzy number is said to have a value equal to approximately a . Fuzzy numbers do not have standardized membership functions. Any convenient membership function satisfying the above properties may be used. It is frequently convenient to employ standardized functions with adjustable parameters such as the standard Π function. This Π function is a combination of two S functions. The definition of both the S and Π functions are given below [Zadeh 1976] and their plots are presented in Figures 4.2 and 4.3.

$$\begin{aligned}
 S(v; \alpha, \beta, \gamma) &= 0 \quad \text{for } v < \alpha \\
 &= 2 \left| \frac{v - \alpha}{\gamma - \alpha} \right| \\
 &= 1 - 2 \left| \frac{v - \gamma}{\gamma - \alpha} \right| \\
 &= 1 \quad \text{for } v > \gamma \\
 \Pi(v; \beta, \gamma) &= S(v; \gamma - \beta, \gamma - \frac{\beta}{2}, \gamma + \beta) \quad \text{for } v < \gamma \\
 &= 1 - S(v; \gamma, \gamma + \frac{\beta}{2}, \gamma + \beta)
 \end{aligned}$$

where, v is any object in the universe of discourse and α , β and γ are the adjustable parameters. In $S(v; \alpha, \beta, \gamma)$, the parameter β is the crossover point and α and γ are the least and the greatest values of v , respectively. In $\Pi(v; \beta, \gamma)$, β is the bandwidth, that is, the distance between the crossover points of Π , while γ is the point at which Π is unity. In some cases, instead of specifying an algebraic function for the membership of a fuzzy number, it may be convenient to specify the membership function at discrete points in the support of the fuzzy number. For example, consider the fuzzy number approxi-

Figure 4.2 Plot of S Function.

Figure 4.3 Plot of Π Function.

mately 5. Let us assume its support is the range of numbers between (3,7). Then, its membership function may be specified either in the form of an algebraic function (say, a Π function) as

$$\Pi(v;3,5,7)$$

or at discrete points in its support as:

$$0.0/3 + 0.5/4 + 1.0/5 + 0.5/6 + 0.0/7$$

4.4 Linguistic Rating Scale

In the preceding sections of this chapter it was shown that an appropriate method of representing subjective evaluation is by using fuzzy sets. Then it was indicated that fuzzy sets, when applied to the universe of discourse of real numbers, are referred to as fuzzy numbers. Hence it would seem that the the most appropriate method of representing the safety rating of each factor, subjectively assigned by the bridge inspector, would be through fuzzy numbers. But this poses a certain problem. If fuzzy numbers are used directly for safety evaluation, the bridge inspector should provide the most representative numerical value of the safety rating so that the appropriate fuzzy number may be defined. However, this would take us back to where we started in our effort to prevent bridge inspectors from being forced to provide a single numerical value. In a study conducted by Kochen and Badre [1974], they found through experimentation that when subjects were asked for subjective evaluations, they responded more consistently when they were allowed to give a verbal imprecise response than when they were forced to give a precise answer. Hence, instead

of using fuzzy numbers directly, words may be used. These words should be such that they should refer to the same fuzzy number that would have been obtained if fuzzy numbers were directly used. This would require the definition of a set of words which refers to fuzzy numbers at various levels of the rating scale. In other words, we need to construct a so called linguistic scale, wherein the graduations of the scale are words, instead of numbers.

In the construction of the linguistic scale, to begin with, a numerical base scale between 0 and 10 was selected. On this numerical scale, five words were defined so that they referred to fuzzy numbers at five different levels. The words selected for the linguistic rating scale were such that they pointed to five distinct levels of safety without any ambiguity in meaning. The words used in the rating scale, the fuzzy numbers to which they referred to and the functional form of their membership functions in terms of their parameters are given in Table 4.1. A pictorial representation of the rating scale is provided in Figure 4.4

Once the linguistic scale is defined, the safety characteristics of any factor can be approximately evaluated and appropriately represented as it was "meant" by the bridge inspector. Thus safety of each factor takes on words as its value rather than numbers. Such variables are called linguistic variables. A complete discussion on linguistic variables is presented by Zadeh [1975].

4.5 Operation on Fuzzy Numbers

Once we obtain the safety ratings of the selected contributing factors, in order to calculate the bridge safety index, we need to combine these indi-

Table 4.1 Words Used in the Linguistic Rating Scale.

Rating	Corresponding Fuzzy Number	Functional Form of the Membership Function
very critical	approximately 0	$1-S(0,1,2)$
critical	approximately 2	$\Pi(2,2)$
moderately critical	approximately 5	$\Pi(2,5)$
not critical	approximately 8	$\Pi(2,8)$
highly not critical	approximately 10	$S(8,9,10)$

Figure 4.4 The Linguistic Rating Scale.

vidual ratings, either by addition or multiplication or by taking a weighted average of the safety ratings of all the contributing factors. If the safety ratings were to be ordinary numbers, this would be a trivial exercise. But in this case, the safety ratings are words, each of which refer to a fuzzy number. Consequently, we need to be able to add, multiply or take weighted averages of fuzzy numbers. All the operations which can be done on ordinary numbers can also be done on fuzzy numbers by using the extension principle [Dubois and Prade 1978].

4.5.1 Extension Principle

Consider any two fuzzy numbers M and N with membership functions $f(x)$ and $g(y)$, respectively. Let A be any fuzzy number which is a function of the fuzzy numbers M and N, i.e., $A = F(M, N)$. Let its membership function be denoted by $h(z)$. Here, x , y and z are all real numbers in the support of M, N and A, respectively. As the fuzzy number A is a function of M and N, therefore z will be a function of x and y , i.e., $z = F(x, y)$. Then the membership function of A is defined by the extension principle as follows:

$$\max [\min (f(x) , g(y))] \quad 4.3$$

where, the minimization is done between the membership values of all combinations of x and y which yield the same value of z , and the maximum of all minima gives the membership value of z in the fuzzy number A. This is repeated for all possible combinations of x and y . The procedure of minimization and maximization involved in the extension principle is explained by a numerical example as indicated below.

Let the membership functions of M and N be defined at discrete points in their supports as follows:

$$f(x) = 0.3/7 + 0.5/8 + 0.8/9 + 1.0/10$$

$$g(y) = 1.0/1 + 0.7/2 + 0.4/3 + 0.1/4$$

and let the fuzzy number A be the sum of M and N.

$$A = M + N$$

The stepwise procedure of implementing the extension principle is as follows.

1. Find all combinations of x and y.

That is,

$$\begin{aligned} & (7,1), (7,2), (7,3), (7,4) \\ & (8,1), (8,2), (8,3), (8,4) \\ & (9,1), (9,2), (9,3), (9,4) \\ & (10,1), (10,2), (10,3), (10,4) \end{aligned}$$

2. For each combination in the previous step, find the value of $z = F(x,y)$ and the minimum between $f(x)$ and $g(y)$.

$$A = M + N \Rightarrow z = x + y$$

Therefore, for the combination (7,1):

$$z = 7 + 1 = 8$$

$$\min(f(x=7), g(y=1)) = \min (0.3, 0.1) = 0.1$$

Similarly, (minimum/z)

0.1/8	0.3/9	0.3/10	0.1/11
0.5/9	0.5/10	0.4/11	0.1/12
0.8/10	0.7/11	0.4/12	0.1/13
1.0/11	0.7/12	0.4/13	0.1/14

3. Take the maximum value of all the minima found in Step 3 for those combinations of (x,y) which yield the same value of z. This is the membership value for the value of z. If any z has a unique (x,y) combination, then the membership function is equal to the minimum found in the previous step.

For example,

$$h(z=11) = \max (0.1, 0.4, 0.7, 1.0) = 1.0$$

Similarly, the membership function of the fuzzy number A is:

$$h(z) = 0.3/8 + 0.5/9 + 0.8/10 + 1.0/11 \\ + 0.7/12 + 0.4/13 + 0.1/14$$

4.6 Implementation of the Extension Principle

In the previous section, the extension principle was implemented for the simple operation of adding two fuzzy numbers with their membership functions

specified at discrete points in their supports. Though this procedure is simple, it is a highly approximate procedure for implementing the extension principle, as the continuous support of the fuzzy numbers is discretized into finite number of points [Dong and Wong 1987]. Due to this, the resulting membership function is obtained only at discrete points. Given the discontinuous nature of the max-min operations, in certain cases, the membership function obtained may be highly irregular, having more than one local minimum and/or maximum.

In order to overcome this defect, Bass and Kwarkernaak [1982] proposed an exact method for solving for the membership function of the resulting fuzzy set by formulating the extension principle as a non-linear programming problem. In this method, the membership function of the fuzzy numbers are considered in their algebraic form and the membership function of the resulting fuzzy number will also be in its exact algebraic form. But the disadvantages of this method are that it requires very restrictive conditioning and its implementation is cumbersome except for the simplest operations between fuzzy numbers.

Recently, Dong and Wong [1987] proposed an algorithm for the implementation of the extension principle. The method is based conceptually on the ideas of discretization and non-linear programming. Unlike previous approximate methods which involved discrete points in the support, this method makes use of discrete membership values. Before presenting the algorithm, a brief discussion on interval analysis and α -cuts representation of fuzzy numbers is provided. This is necessary to fully understand the algorithm.

4.6.1 Interval Analysis

Interval analysis is used to extend operations, like addition, subtraction and so on, from between single numbers to ranges of numbers. For example, if (a,b) and (c,d) are any two ranges of positive real numbers, with $a < b$ and $c < d$, then some of the operations between these two ranges are as follows:

$$(a,b) + (c,d) = (a+c, b+d)$$

$$(a,b) \times (c,d) = (a \times c, b \times d)$$

$$\frac{(a,b)}{(c,d)} = (a/d, b/c)$$

4.6.2 Representation of Fuzzy Numbers using α -cuts

We know that the membership values of a fuzzy number vary between $(0,1)$. Consider any number between 0 and 1, say α . The α -cuts of a fuzzy number is that range of numbers where every number within that range has a degree of membership greater than or equal to α . For example, consider the fuzzy number approximately 5. The α -cuts for that fuzzy number, when α is equal to 0.5, is the range of numbers between $(4,6)$. Figure 4.5 provides the pictorial representation of the above example. In certain cases, it may be more convenient to represent the membership function using α -cuts instead of an algebraic function. This is done by specifying ranges of numbers at discrete levels of α . More the levels of α , more precisely the membership function may be specified. The fuzzy number approximately 5, whose membership function in algebraic form is $\Pi(2,5)$, may also be specified using α -cuts representation as shown in Table 4.2.

Figure 4.5 Pictorial Representation of α -cuts of *approximately 5* at $\alpha = 0.5$.

Table 4.2 α -cuts Representation of *approximately 5*.

α	Range
0.0	[3.00,7.00]
0.1	[3.45,6.55]
0.2	[3.63,6.37]
0.3	[3.77,6.23]
0.4	[3.89,6.11]
0.5	[4.00,6.00]
0.6	[4.11,5.89]
0.7	[4.23,5.77]
0.8	[4.37,5.63]
0.9	[4.55,5.45]
1.0	[5.00,5.00]

4.6.3 Addition of Fuzzy Numbers

In this section, an alternate method for adding two fuzzy numbers will be shown by means of a numerical example. This method involves α -cuts and interval analysis and it is much simpler than the one previously illustrated. Let us consider two fuzzy numbers approximately 2 and approximately 5 with the following membership functions.

$$\text{approximately 2} = \Pi(4, 2)$$

$$\text{approximately 5} = \Pi(4, 5)$$

where, the first parameter of the Π function refers to the bandwidth and the second to the point where the membership function has a value of unity. The α -cuts representation of the two fuzzy numbers is provided in Table 4.3. The sum of the two fuzzy numbers is obtained by adding the range of numbers at each level of α . This results in a series of range of numbers at discrete levels of membership values, which in other words, is the α -cuts representation of the sum. The result is provided in Table 4.4.

Table 4.4 indicates that the membership function of the sum of the two fuzzy numbers reaches a value of unity at 7.00. Hence, the sum of approximately 2 and approximately 5 is equal to approximately 7. It should be noted here that the above method is applicable in addition of fuzzy numbers and to only certain algebraic operations between fuzzy numbers. For example, the above method will fail if the algebraic expression has multiple occurrences of variables. The concept of multiple occurrences of variables and the reason for failure of the above method is explained below.

Table 4.3 α -cuts Representation of Fuzzy Numbers.

<i>approximately 2</i>		<i>approximately 5</i>	
α	Range	α	Range
0.0	[0.00,4.00]	0.0	[3.00,7.00]
0.1	[0.45,3.55]	0.1	[3.45,6.55]
0.2	[0.63,3.37]	0.2	[3.63,6.37]
0.3	[0.77,3.23]	0.3	[3.77,6.23]
0.4	[0.89,3.11]	0.4	[3.89,6.11]
0.5	[1.00,3.00]	0.5	[4.00,6.00]
0.6	[1.11,2.89]	0.6	[4.11,5.89]
0.7	[1.23,2.77]	0.7	[4.23,5.77]
0.8	[1.37,2.63]	0.8	[4.37,5.63]
0.9	[1.55,2.45]	0.9	[4.55,5.45]
1.0	[2.00,2.00]	1.0	[5.00,5.00]

Table 4.4 α -cuts Representation of the Sum of
approximately 2 and *approximately 5*.

α	range
0.0	[3.00,11.00]
0.1	[3.90,10.10]
0.2	[4.26,9.74]
0.3	[4.54,9.46]
0.4	[4.78,9.22]
0.5	[5.00,9.00]
0.6	[5.22,8.78]
0.7	[5.46,8.54]
0.8	[5.74,8.26]
0.9	[6.10,7.90]
1.0	[7.00,7.00]

4.6.4 Multiple Occurrence of Variables

In interval analysis, if any variable occurs more than once in the algebraic expression, then that variable should be simultaneously considered. For example, consider the expression

$$y = \frac{wx}{w}$$

where x and w are the range of numbers (2,4) and (0.4,1), respectively. If interval analysis is used to find the range of y, the stepwise solution is as follows:

$$\frac{(0.4,1) \times (2,4)}{(0.4,1)} = \frac{(0.8,4)}{(0.4,1)} = (0.8,10)$$

The above range is wider than the actual range which is (2,4). The reason for this is that the variable w occurs twice in the above expression (once in the numerator and once in the denominator) and these two occurrences are treated independently. To take care of multiple occurrences of variables in algebraic expressions, Dong and Wong [1987] proposed a combinatorial interval analysis. This concept was incorporated in their Fuzzy Weighted Averages (FWA) algorithm. A detailed explanation of the algorithm and its application in the proposed model follows.

4.7 FWA Algorithm

In the development of the model to estimate bridge safety index, the concept of weighted averages was used. The bridge safety index, BSI, was

construed as a function of the weighted average of safety ratings of all factors. The weighted average ($\bar{r}$) may be obtained using the following equation:

$$\bar{r} = \frac{\sum_{i=1}^N w_i r_i}{\sum_{i=1}^N w_i} \quad 4.4$$

where N is the number of factors, w_i is the weighting coefficient and r_i is the rating of the i^{th} factor. But, in the proposed model, both the weighting coefficient, called the degree of importance and the safety rating of each factor, are fuzzy numbers. A weighted average can still be evaluated using Equation 4.4 and the extension principle. The resulting average which is also a fuzzy number, is referred to as the fuzzy weighted average. In this section, the procedure to implement the extension principle to calculate the fuzzy weighted average using the FWA algorithm will be explained. The explanation is provided with a numerical example to fully clarify the methodology. For the sake of simplicity, in the numerical example, we will consider only two factors. But the algorithm may be extended for any number of factors.

Let us consider a hypothetical model to evaluate the traffic safety on bridges. Let us assume that the model has only two contributing factors, such as, roadway width on the bridge and shoulder width on the bridge. Further, let us assume that the degree of importance of each of these factors are fuzzy numbers, approximately 8 and approximately 6, with their safety ratings being critical and definitely not critical, respectively. From Table 4.1, critical refers to the fuzzy number approximately 2 and highly not critical corresponds to approximately 10. The steps involved in the FWA algorithm in order to

calculate the fuzzy weighted average for the two factors are as follows:

1. Discretize the range of membership values $[0,1]$ into finite number of α levels.

Let us consider eleven levels of α , beginning from 0.0 to 1.0, with increments of 0.1.

0.0, 0.1, 0.2, 0.3, ..., 0.9, 1.0

2. Obtain the α -cuts representation of every fuzzy number.

In all we have four fuzzy numbers. Assuming that their membership functions are as follows,

degree of importance:

$$\begin{aligned} &H(2,8) \\ &H(2,6) \end{aligned}$$

safety rating:

$$\begin{aligned} &H(2,2) \\ &S(8,9,10) \end{aligned}$$

the α -cuts representation of each of the above fuzzy numbers is provided in Tables 4.5 and 4.6.

3. Consider a particular level of α . Each α level will have $2N$ ranges of

Table 4.5 α -cuts Representation for Fuzzy Numbers
Indicating Degree of Importance.

Degree of Importance			
<i>approximately 8</i>		<i>approximately 6</i>	
0.0	(6.00,10.00)	0.0	(4.00,8.00)
0.1	(6.45,9.55)	0.1	(4.45,7.55)
0.2	(6.63,9.37)	0.2	(4.63,7.37)
0.3	(6.77,9.23)	0.3	(4.77,7.23)
0.4	(6.89,9.11)	0.4	(4.89,7.11)
0.5	(7.00,9.00)	0.5	(5.00,7.00)
0.6	(7.11,8.89)	0.6	(5.11,6.89)
0.7	(7.23,8.77)	0.7	(5.23,6.77)
0.8	(7.37,8.63)	0.8	(5.37,6.63)
0.9	(7.55,8.45)	0.9	(5.55,6.45)
1.0	(8.00,8.00)	1.0	(6.00,6.00)

Table 4.6 α -cuts Representation for Fuzzy Numbers
Indicating Safety Rating.

Safety Rating			
<i>approximately 2</i>		<i>approximately 10</i>	
0.0	(0.00,4.00)	0.0	(8.00,10.00)
0.1	(0.45,3.55)	0.1	(8.45,10.00)
0.2	(0.63,3.37)	0.2	(8.63,10.00)
0.3	(0.77,3.23)	0.3	(8.77,10.00)
0.4	(0.89,3.11)	0.4	(8.89,10.00)
0.5	(1.00,3.00)	0.5	(9.00,10.00)
0.6	(1.11,2.89)	0.6	(9.11,10.00)
0.7	(1.23,2.77)	0.7	(9.23,10.00)
0.8	(1.37,2.63)	0.8	(9.37,10.00)
0.9	(1.55,2.45)	0.9	(9.55,10.00)
1.0	(2.00,2.00)	1.0	(10.00,10.00)

numbers, where N is the number of factors. Consider only the end points of each range. Taking one end point at a time from each range, obtain all possible combinations. The total number of combinations are 2^N . For each such combination, obtain the value of $\bar{r}$ from Equation 4.4.

For example, let us choose the α level to be 0.4. >From Tables 4.5 and 4.6, the four ranges of numbers corresponding to $\alpha=0.4$ are:

(6.89,9.11), (4.89,7.11), (0.89,3.11), (8.89,10.00)

where, the first two ranges are the α -cuts of the two degrees of importance at $\alpha=0.4$ and the last two are for the safety ratings. Let us refer to the first two ranges as w_1 and w_2 and the last two as r_1 and r_2 , respectively. Taking one end point from each range at a time, the 2^N combinations are:

w_1	w_2	r_1	r_2	w_1	w_2	r_1	r_2
(6.89, 4.89, 0.89, 8.89)	(6.89, 4.89, 0.89, 10.00)						
(9.11, 4.89, 0.89, 8.89)	(9.11, 4.89, 0.89, 10.00)						
(6.89, 7.11, 0.89, 8.89)	(6.89, 7.11, 0.89, 10.00)						
(9.11, 7.11, 0.89, 8.89)	(9.11, 7.11, 0.89, 10.00)						
(6.89, 4.89, 3.11, 8.89)	(6.89, 4.89, 3.11, 10.00)						
(9.11, 4.89, 3.11, 8.89)	(9.11, 4.89, 3.11, 10.00)						
(6.89, 7.11, 3.11, 8.89)	(6.89, 7.11, 3.11, 10.00)						
(9.11, 7.11, 3.11, 8.89)	(9.11, 7.11, 3.11, 10.00)						

Consider the first combination.

$$\begin{aligned}w_1 &= 6.89, w_2 = 4.89 \\r_1 &= 0.89, r_2 = 8.89 \\ \bar{r} &= \frac{6.89 \times 0.89 + 4.89 \times 8.89}{6.89 + 4.89}\end{aligned}$$

Similarly, the corresponding values of $\bar{r}$ for each combination are:

4.21, 3.68, 4.95, 4.40, 5.51, 5.13, 6.05, 5.64,
4.67, 4.07, 5.52, 4.88, 5.97, 5.52, 6.61, 6.13.

4. From the values of $\bar{r}$ calculated in the previous step, find the least and the greatest values. These form the end points of the range of numbers for $\bar{r}$ at that particular level of α . In other words, this range would be the α -cuts of the fuzzy weighted average.

Hence, the α -cuts for the example at $\alpha=0.4$ is

(3.68, 6.61)

5. Repeat Steps 3 and 4 for all levels of α . This results in the α -cuts representation of the fuzzy weighted average.

The α -cuts representation of the fuzzy weighted average of safety ratings of the two factors is shown in Table 4.7.

From Table 4.7, we can see that the fuzzy weighted average of safety ratings of the two factors is approximately 5.43. In the proposed model, to be explained in the next chapter, a similar method as presented above, is followed to calculate the fuzzy weighted average of the safety ratings. This fuzzy number is then reduced into an ordinary number to obtain the bridge safety index (BSI). This reduction is carried out by taking a weighted average of the mid point of each range of numbers. This is explained below by means of a numerical example.

Table 4.7 α -cuts Representation of the Fuzzy
Weighted Average.

α	Range
0.0	(2.86, 7.43)
0.1	(2.99, 7.03)
0.2	(3.28, 6.86)
0.3	(3.50, 6.72)
0.4	(3.68, 6.61)
0.5	(3.86, 6.50)
0.6	(4.02, 6.39)
0.7	(4.21, 6.27)
0.8	(4.43, 6.21)
0.9	(4.73, 5.93)
1.0	(5.43, 5.43)

Let us consider the fuzzy weighted average that was obtained previously. This fuzzy number is reduced into an ordinary number by using the following equation:

$$r = \frac{\sum_{\alpha=0.0}^{1.0} \alpha \left(\frac{X_{\min}^{\alpha} + X_{\max}^{\alpha}}{2} \right)}{\sum_{\alpha=0.0}^{1.0} \alpha} \quad 4.5$$

where, $X_{\min}^{\alpha}$ and $X_{\max}^{\alpha}$ are the end points of the range at that level of α . The calculations for the results shown in Table 4.7 is presented in Table 4.8. On reducing the fuzzy weighted average, the ordinary number obtained is

$$\frac{28.97}{5.5} = 5.27$$

Table 4.8 Reduction of a Fuzzy Number to an Ordinary Number.

(1) Range	(2) Mid Point	(3) α	(4) $(2) \times (3)$
(2.86, 7.43)	5.14	0.0	0.00
(2.99, 7.03)	5.01	0.1	0.50
(3.28, 6.86)	5.07	0.2	1.01
(3.50, 6.72)	5.11	0.3	1.53
(3.68, 6.61)	5.14	0.4	2.06
(3.86, 6.50)	5.18	0.5	2.59
(4.02, 6.39)	5.21	0.6	3.13
(4.21, 6.27)	5.24	0.7	3.67
(4.43, 6.21)	5.32	0.8	4.26
(4.73, 5.93)	5.33	0.9	4.79
(5.43, 5.43)	5.43	1.0	5.43
	TOTAL	5.5	28.97

CHAPTER 5 - BRIDGE SAFETY EVALUATION MODEL

5.1 Introduction

Many of the existing bridges need to be up-graded, both structurally as well as functionally. To keep bridges functionally adequate, periodic bridge inspection should be conducted to determine its traffic safety. This information should form one of the input data for a Bridge Management System. This chapter deals with the development of a model to estimate the level of traffic safety associated with a bridge.

The main objective of a Bridge Safety Evaluation Model is to quantify the extent of hazardousness existing on the bridge. Two techniques have been used in the past for this purpose. These techniques are discussed below before the proposed model is presented.

5.2 Review of Existing Models

Accident rate is a good indicator of the degree of hazardousness. One approach is to predict accident rate on a bridge given its geometric data and traffic conditions. This involves the development of regression functions through statistical methods [Behnam and Laguros 1973; Hollingworth 1983; Turner 1984]. One of the disadvantages of this method is that a lot of historical bridge accident data is needed to develop significant results. The number of accidents on a bridge per year may vary between 0 to 5. This means that in order to get a good sample, the number of bridges to be included in the analysis can be very large. Another problem with this method is that causal reasons of the accidents on a bridge are not examined. Consequently, a

bridge may have a high accident rate even under adequate geometrical characteristics. This situation may arise when these are accidents caused either by animals being present on the roadway or due to drunken driving by the driver.

The second approach is particularly suitable when the available bridge accident data are not sufficient. This approach involves rating each of the contributing factors considered to affect traffic safety by an on-site bridge inspection. These safety ratings are then combined to get the Bridge Safety Index (BSI) [Ivey et al. 1979; Radhakumari et al. 1984]. This approach has the advantage of being very simple, and does not require an exhaustive database of bridge accidents. The safety rating of any factor is based on the subjective evaluation of the inspecting bridge engineer and his knowledge of the accident history of the bridge.

An example of the second approach is NCHRP model [Ivey et al. 1979]. The proposed model is also based on NCHRP model but there are significant differences, as mentioned below.

1. The NCHRP model requires the knowledge of the geometrical measurement of each factor to determine its rating. The proposed model allows the bridge engineer to provide directly the safety rating. The effect of any factor on the safety of a bridge is highly site-specific. A factor with the same geometry at two different locations may affect safety in different ways. It was considered impossible and inappropriate to quantify the safety rating of a factor with respect to its geometrical measurement.

2. The NCHRP model weighs many of the factors equally. The proposed model uses fuzzy sets approach to determine the relative importance of each of the contributing factors.
3. Rating given to any factor in the NCHRP model are all precise numbers. The proposed model makes use of words instead of numbers, to represent faithfully the fuzziness involved in any subjective evaluation.

The proposed model uses the ranking and rating procedure based on fuzzy sets as developed by Bass and Kwakernaak [1982]. The main idea is that, a weighted average is estimated of safety ratings of various factors and then an overall bridge safety index (BSI) is obtained. The development and procedures of the model are presented below.

5.3 Proposed Model

The development of the proposed model took place in three steps. The first step involved the determination of the weight or the degree of importance for each of the contributing factors. These weights were obtained by means of a questionnaire survey among the bridge engineers and inspectors at INDOT. The next step was the construction of the rating scale for evaluating the safety rating of each factor. Safety rating is the subjective evaluation by the bridge inspector of the effect a particular factor has on traffic safety of a bridge. The final step was the development of a methodology to combine "logically" the weights and safety ratings of all factors to obtain the bridge safety index. A complete discussion of each step is provided below.

5.3.1 Degrees of Importance

Among the contributing factors listed in Chapter 2, there are some which affect traffic accidents on bridges in varying degrees of severity. Factors like ramps, lane drops and other environmental factors do not have as much of an effect on bridge safety as do the approach roadway related factor, which in turn do not affect as much as the bridge related factors. To take these points into consideration, each factor had to be assigned a weight indicating its degree of importance in the determination of traffic safety on bridges.

As mentioned earlier, these weights were obtained through a questionnaire survey of bridge engineers in the State of Indiana. Each bridge engineer was asked to indicate the degree of importance of each of the factors. It could be any of the words indicated below. Like the words used in the rating scale, these words too were defined to refer to a particular fuzzy number. The value of the fuzzy number which each word represented is provided in parenthesis.

1. very high (approximately 10)
2. high (approximately 8)
3. medium (approximately 5)
4. low (approximately 2)
5. very low (approximately 0)

It was felt that the degree of importance of any factor also depended on the type of highway as well as the type of bridge. Therefore, bridge

engineers were asked to give the degree of importance for each of the factors under the following four categories.

1. Interstate bridges
2. Bridges on US and State roads
3. Interstate underpasses
4. Underpasses on US and State roads

A copy of the questionnaire used is presented in Appendix A. Obviously, different bridge engineers indicated different degrees of importance for various factors according to their judgement. The results of the survey are included in Appendix B. For example, under interstate bridges, for the factor of roadway width, the percentage of bridge engineers who felt a particular degree of importance was appropriate is given in Table 5.1.

Due to this variation in opinion, it was necessary to calculate the average. As the degrees of importance are words referring to various fuzzy numbers, the average degree of importance will also be a fuzzy number. An appropriate procedure to calculate this fuzzy average is by using the FWA algorithm presented in Chapter 4. But the resulting fuzzy average will not have its membership function in the same functional form as the original fuzzy numbers. Therefore, in order to maintain the same functional form, a weighted average of only the most representative value of each fuzzy number was calculated. This average is the most representative value of the average degree of importance. Once the most representative value was known, the membership function of the average

Table 5.1 Percentages of Various Degree of Importance
for Roadway Width On Interstate Bridges

Degree of Importance	Percentage
<i>very high</i>	21.43
<i>high</i>	64.28
<i>medium</i>	7.14
<i>low</i>	7.14
<i>very low</i>	0.00

degree of importance was specified by the standard II function.

For example, the average degree of importance for roadway width on interstate bridges was obtained as follows. The most representative value of the fuzzy numbers that are referred to by the various degrees of importance are given below.

Degree of Importance	Most Representative Value of the Corresponding Fuzzy Number
very high	10
high	8
medium	5
low	2
very low	0

With percentages as the weighting coefficients, a weighted average of the most representative values were calculated using Equation 4.4.

$$\frac{21.43 \times 10 + 64.28 \times 8 + 7.14 \times 5 + 7.14 \times 2}{100.0} = 7.77$$

The number, 7.77, is the most representative value of the average degree of importance. The membership function of the average degree of importance was specified as

11(2,7.77)

The average degree of importance was calculated for all factors in each category. The results are shown in Table 5.2 and Table 5.3.

Until now, the term average degree of importance was used to indicate that the importance of each factor was obtained as an average of the opinion of all bridge engineers. The importance of each factor, from now on, will be referred to as just degree of importance.

5.3.2 Safety Rating

The concept of safety rating was discussed in Chapter 4. Safety rating is a subjective evaluation of the safety characteristics of a given factor with respect to traffic safety on bridges. The rating could be any of the following terms.

1. very critical
2. critical
3. moderately critical
4. not critical
5. highly not critical

The pictorial representation of the above terms was given in Figure 4.4.

Table 5.2 Degree of Importance of Each Factor for Bridges.

Contributing factors	Degree of importance	
	Interstate	US & State
BRIDGE RELATED		
Roadway width	7.77	8.14
Relative roadway width	7.57	7.36
Shoulder width	6.86	7.14
Shoulder width reduction	6.50	7.00
Approach guardrail	6.56	6.10
APPROACH ROADWAY RELATED		
Approach sight distance	6.71	7.71
Approach roadway curvature	7.57	7.57
Approach gradient	5.21	4.93
ENVIRONMENTAL RELATED		
Volume/capacity ratio	7.50	8.00
Percentage of trucks	6.00	6.54
Lighting, signing and delineation	4.69	4.17
Presence of nearby ramps, merges or intersections	5.50	6.00
Presence of nearby lane drops or pavement transitions	5.92	5.90

Table 5.3 Degree of Importance of Each Factor
for Underpasses.

Contributing factors	Degree of importance	
	Interstate	US & State
BRIDGE RELATED		
Roadway width	7.31	7.64
Relative roadway width	6.33	7.36
Shoulder width	6.00	6.00
Shoulder width reduction	5.50	5.50
Approach guardrail	5.00	5.00
Vertical clearance	7.57	7.69
APPROACH ROADWAY RELATED		
Approach sight distance	6.43	6.86
Approach roadway curvature	6.36	7.00
Approach gradient	4.50	5.77
ENVIRONMENTAL RELATED		
Volume/capacity ratio	6.86	7.07
Percentage of trucks	6.77	6.85
Lighting, signing and delineation	5.09	4.82
Presence of nearby ramps, merges or intersections	5.29	6.00
Presence of nearby lane drops or pavement transitions	6.00	6.00

5.3.3 Bridge Safety Index

To obtain the bridge safety index, the weight and the safety rating of each contributing factor were combined in such a manner so as to take the interaction between the factors into account. Some of the contributing factors within each group, as listed in Chapter 2, interact with one another. That is, the effect of one factor is influenced by the effect of another factor. They do not act independently but affect traffic safety in a combined manner. For example, if the bridge had a narrow roadway, but no reduction of roadway width on the bridge and the shoulders were wide, then the effect of the narrow roadway on traffic safety would be greatly offset due to the positive effect of other two factors. Consequently, the combined effect of the three factors would not be as severe as the effect of the narrow roadway. To represent this combined effect, a weighted average of the safety rating of the factors in each group was calculated using the FWA algorithm of Chapter 4. The fuzzy weighted average of the safety rating of all bridge geometric factors was termed as the Bridge Safety Index with respect to bridge geometric factors (BSI_b). Bridge geometric factors is one of the sub-groups of the group, bridge related factors. The effect of the other sub-group, structural factors, will be considered later. Similarly, the bridge safety indices with respect to the approach roadway related factors (BSI_r) and the environmental factors (BSI_e) were also calculated. The basic calculations in the proposed model are as follows. The above three BSI values are combined to obtain BSI' . It represents traffic safety on a bridge considering the effect of the sub-group, bridge geometric factors and the two groups, approach roadway related factors and environmental factors. BSI' is then adjusted to reflect the

severity of accidents occurring of the bridge. This adjusted value is denoted by $\overline{BSI}$. Finally, $\overline{BSI}$, which is a fuzzy number, is reduced to an ordinary number. This number is the bridge safety index, BSI.

From Tables 5.2 and 5.3, it is clearly evident that the bridge related factors are most important in contributing to traffic safety on bridges. Next in importance are the approach roadway factors and finally the environmental factors. Hence, BSI_b is the most important determinant of traffic safety and the effect of roadway and environmental factors is only to further decrease the BSI_b value. The three groups of factors are not interactive. Therefore, even in case of the approach roadway and environmental conditions being good, they cannot be assumed to reduce the value of BSI_b . But on the other hand, if these two conditions were hazardous, then it can be assumed, without the loss of generality, that they increase the hazardous effect of bridge geometric factors, thus resulting in a decrease in the BSI_b value.

Initially, BSI' was set to BSI_b . From this, the effect of approach roadway (BSI_r) and the effect of environmental factors (BSI_e) were subtracted. It is very difficult to determine the effect of approach roadway and environmental factors on bridge traffic safety. In other words, it is impossible to know the extent of decrement in traffic safety for given values of BSI_r and BSI_e . In the proposed model, the effect of the approach roadway was assumed to be such that, if the approach roadway were to have a BSI_r equal to approximately 0 or very critical, indicating very severe conditions, the BSI_b would be reduced by approximately 1. That is, the fuzzy number BSI_b is shifted on the abscissa of the linguistic scale towards zero by one unit. As the degree of importance of the approach roadway factors was higher than the environmental factors, the

effect of the environment was assumed to shift the BSI_b by only half a unit, under severe conditions of the environment. This means that if BSI_e is equal to approximately 0 or very unsafe, BSI_b will be reduced by approximately 0.05. But on the other hand, if both BSI_r and BSI_e are equal to approximately 10, indicating perfect environmental conditions and very safe approach roadway, no decrement is given to BSI_b . These assumptions are reflected in the equation given below.

$$BSI' = BSI_b - (10 - BSI_r) \times 0.1$$

The above equation may be evaluated using interval analysis. Finally, the bridge safety index should also reflect the severity of accidents occurring on the bridge. In any accident that occurs on a bridge, the vehicle either collides with another vehicle or with the approach guardrails or bridge rails. Hence, the factor that affects severity of accidents is the approach guardrails and bridge rails. Therefore, BSI' has to be further adjusted depending on the safety rating of this factor. If the rating of the approach guardrails is safe or above, then BSI' should be increased to reflect the fact that even though accidents may occur, they would not be very severe. A rating lower than safe would indicate an increased severity of accidents, and hence BSI' should be reduced. A factor of 0.08 was assumed in the following equation, which was the proportion of the degree of importance of the approach guardrails to the total degree of importance of all the other factors.

$$BSI = BSI' + (\text{guardrail rating} - \text{safe}) \times 0.08$$

The resulting BSI is a fuzzy number. Its membership function will be in the form of α -cuts representation. This fuzzy number was then reduced to a single number as shown in Chapter 4. This number is referred to as the Bridge Safety Index BSI. While interpreting the BSI, a value of 0.00 would indicate the bridge to be very critical requiring immediate attention towards safety improvement and a value of 10.00 would indicate adequate conditions for safe movement of traffic on the bridge. A computer program was written to calculate the bridge safety index. The program was coded in the C programming language. Some important highlights of the program are in the usage of linked lists, dynamic memory allocation and recursion. The source listing of the program is provided in Appendix C.

CHAPTER 6 - APPLICATION OF THE PROPOSED MODEL

To illustrate the proposed model, five bridges were selected by a state bridge inspector at InDOT. The bridges were selected based on their past accident experience and to get at least one bridge on each type of highway facility.

6.1 Safety Rating

The information needed for rating the bridge related factors, such as the factors associated with bridge geometrics and structural factors, was obtained from bridge inspection field reports and photographs of the structure taken during previous bridge inspections. Safety ratings of the approach roadway and environmental factors were based on the bridge inspector's knowledge and recollection of the existing conditions on the bridge, from his previous inspections of the selected bridges. It should be noted that although an on-site inspection was not conducted in this example application of the model, the implementation of the proposed procedure should include a thorough on-site bridge inspection.

The calculation of the BSI was done by means of the computer program. The program requires an input file called "input". It should have 15 lines of input. The first line is a code number for the type of highway facility and structure. The different types of highway facilities and structures with their corresponding code numbers are given in Table 6.1.

Table 6.1 Code Numbers for Highway Facility and
Type of Structure.

Code No.	Type
1	Interstate Bridge
2	Bridge on US or State Road.
3	Interstate Underpass
4	Underpass on US and State Road.

The next 14 lines of input contain code numbers of the safety rating of the fourteen contributing factors. The code numbers for the safety ratings are given in Table 6.2.

Tables 6.3 through 6.7 provide the safety ratings of the selected bridge sites.

6.2 Discussion of Results

The safety indices of the bridges considered were compared with the number of accidents they experienced in the three year period of 1981-84. The BSI values of the bridges, 50-36-1262D, 40-32-2046A and 15-85-1743A, were low indicating safety hazard for traffic movement. However, the accident database developed in the study could not locate any accident on these bridges in the three year period. Probable reasons for this disparity could be the following.

1. Selection of the 72 bridges for the analysis was done purely based on the opinion and past experience of the bridge engineers and not by going through any bridge accident database. This is because, at present, no bridge accident database is maintained and made available to the bridge engineers.
2. The bridge engineers may have selected only those bridges which have had accidents in the recent past. Though geometrical factors at bridge sites do not change with time, yet possible changes in traffic speed and volume characteristics, due to development of nearby areas, may have resulted in an increase in the number of accidents after the year 1984.

Table 6.2 Code Numbers for Safety Ratings.

Code No.	Type
1	highly critical
2	critical
3	moderately critical
4	not critical
5	highly not critical

Table 6.3 Safety Rating of Bridge I65-178-5509B (NBL)

STRUCTURE NO: I65-178-5509B (NBL)	
CONTRIBUTING FACTORS	SAFETY RATING
BRIDGE RELATED FACTORS	
Roadway width	not critical
Relative roadway width	not critical
Shoulder width	not critical
Shoulder width reduction	not critical
Vertical clearance	not applicable
Approach guardrails and bridge rails	moderately critical
APPROACH ROADWAY FACTORS	
Approach sight distance	highly not critical
Approach roadway curvature	highly not critical
Approach gradient	not critical
ENVIRONMENTAL FACTORS	
Volume/capacity ratio	not critical
Percentage of trucks	not critical
Lighting, signing and delineation	not critical
Presence of nearby ramps, merges or intersections	not present
Presence of nearby lane drops or pavement transitions	not present

Bridge Safety Index estimated by the model = 7.64

Table 6.4 Safety Rating of Bridge I74-6-4417D (WBL)

STRUCTURE NO: I74-6-4417D (WBL)	
CONTRIBUTING FACTORS	SAFETY RATING
BRIDGE RELATED FACTORS	
Roadway width	moderately critical
Relative roadway width	moderately critical
Shoulder width	critical
Shoulder width reduction	critical
Vertical clearance	not applicable
Approach guardrails and bridge rails	not critical
APPROACH ROADWAY FACTORS	
Approach sight distance	not critical
Approach roadway curvature	not critical
Approach gradient	not critical
ENVIRONMENTAL FACTORS	
Volume/capacity ratio	moderately critical
Percentage of trucks	moderately critical
Lighting, signing and delineation	not critical
Presence of nearby ramps, merges or intersections	not present
Presence of nearby lane drops or pavement transitions	not present

Bridge Safety Index estimated by the model = 3.27

Table 6.5 Safety Rating of Bridge 50-36-1262D

STRUCTURE NO: 50-36-1262D	
CONTRIBUTING FACTORS	SAFETY RATING
BRIDGE RELATED FACTORS	
Roadway width	moderately critical
Relative roadway width	not critical
Shoulder width	moderately critical
Shoulder width reduction	moderately critical
Vertical clearance	moderately critical
Approach guardrails and bridge rails	moderately critical
APPROACH ROADWAY FACTORS	
Approach sight distance	moderately critical
Approach roadway curvature	moderately critical
Approach gradient	not present
ENVIRONMENTAL FACTORS	
Volume/capacity ratio	not critical
Percentage of trucks	not critical
Lighting, signing and delineation	not critical
Presence of nearby ramps, merges or intersections	not present
Presence of nearby lane drops or pavement transitions	not present

Bridge Safety Index estimated by the model = 3.41

Table 6.6 Safety Rating of Bridge 40-32-2046A

STRUCTURE NO: 40-32-2046A	
CONTRIBUTING FACTORS	SAFETY RATING
BRIDGE RELATED FACTORS	
Roadway width	critical
Relative roadway width	moderately critical
Shoulder width	critical
Shoulder width reduction	moderately critical
Vertical clearance	not applicable
Approach guardrails and bridge rails	not critical
APPROACH ROADWAY FACTORS	
Approach sight distance	critical
Approach roadway curvature	critical
Approach gradient	moderately critical
ENVIRONMENTAL FACTORS	
Volume/capacity ratio	moderately critical
Percentage of trucks	not critical
Lighting, signing and delineation	moderately critical
Presence of nearby ramps, merges or intersections	moderately critical
Presence of nearby lane drops or pavement transitions	not present

Bridge Safety Index estimated by the model = 2.61

Table 6.7 Safety Rating of Bridge 15-85-1743A

STRUCTURE NO: 15-85-1743A	
CONTRIBUTING FACTORS	SAFETY RATING
BRIDGE RELATED FACTORS	
Roadway width	critical
Relative roadway width	critical
Shoulder width	critical
Shoulder width reduction	moderately critical
Vertical clearance	moderately critical
Approach guardrails and bridge rails	moderately critical
APPROACH ROADWAY FACTORS	
Approach sight distance	not critical
Approach roadway curvature	not present
Approach gradient	not critical
ENVIRONMENTAL FACTORS	
Volume/capacity ratio	not critical
Percentage of trucks	not critical
Lighting, signing and delineators	not critical
Presence of nearby ramps, merges or intersections	highly not critical
Presence of nearby lane drops or pavement transitions	not present

Bridge Safety Index estimated by the model = 1.20

However, this presumption could not be confirmed due to unavailability of recent accident records.

3. Errors while recording accident locations by the investigating police officer or during data entry are possible. Due to this, all accidents which had occurred on a bridge may have not been collected.
4. The bridge engineer who was used to test the model was different from the individuals who suggested the initial set of bridges. Consequently, it may be possible that the bridge engineer was not very familiar with some of the parameters associated with the individual bridges or he may not have clearly understood the task of rating various items.
5. No on-site inspection was conducted by the bridge engineer.

6.3 Chapter Conclusion

In this chapter the proposed model was applied to five sample bridges. The model can be easily implemented provided the bridge inspectors are appropriately trained in rating various items involved in safety index. The application indicated the feasibility of considering the procedure in evaluating bridge deficiencies. Further validation would, however, be useful in confirming the applicability of the model.

CHAPTER 7 - SUMMARY AND CONCLUSION

7.1 Summary

An extensive literature review was conducted which resulted in the selection of fourteen factors that contribute to bridge traffic safety. An attempt was made to verify these factors by conducting accident analyses on selected number of bridges in the State of Indiana. The accident file kept by the State Police does not record the type of facility on which an accident occurs making it difficult to reconstruct an accident, particularly on a bridge.

A model to evaluate traffic safety on bridges was developed. The model made use of three groups of factors: bridge related, approach roadway related and factors related to the environment. These factors were given fuzzy weights to indicate their degree of importance. These weights were developed on the basis of a survey among the bridge engineers and inspectors in Indiana. The weights and safety ratings were combined in a logical manner, taking into consideration the interaction between factors in the same group and the hierarchy of importance between groups. The output of the model is a number called the bridge safety index. The BSI represents the degree of hazardousness of the bridge. It may take values between 0 and 10, where 0 indicates presence of very unsafe conditions for traffic safety and 10 represents conditions having no effect on the traffic. The model was applied to data from five sample bridges. A computer program was written that can be used to compute the bridge safety index on the basis of given input data.

7.2 Conclusion

1. The study identified a set of factors that affects the safety of traffic on bridges and at underpasses. This set of factors is sufficiently comprehensive and adequate to quantify effectively bridge safety. The factors can be grouped into three groups, with factors within each group being interactive.
2. Accident analysis is the most effective way of studying the safety aspects of any facility. However, in case of bridges, the number of accidents occurring on a bridge or the sample size, is insufficient to conduct any significant statistical analysis. Study of vehicle lateral displacement may be used instead of accident analysis. The present study used an accident reconstruction approach to examine bridge safety aspects.
3. The current method of recording accident information about each accident should be improved. The accident data should enable safety researchers to deduce unambiguously the circumstances under which each accident took place.
4. Recording the location of accidents by facility would enable efficient management and monitoring of traffic safety on bridges.
5. Fuzzy sets mathematics provide an appropriate way to represent subjective evaluations of bridge safety characteristics by bridge inspectors. Though the amount of computations to be done for any fuzzy set operation is large, the use of a computer program would make the task a simple one.

6. The proposed model combines safety ratings of various factors and their corresponding weights in a manner so as to reflect the inherent characteristics of the factors, such as factor interaction and hierarchy of importance between the groups of factors.
7. The bridge safety index calculated by the proposed model quantifies the traffic safety aspect of a bridge or an underpass. It also highlights any severe conditions of the contributing factors existing on a bridge or an underpass.

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APPENDICES

A. BRIDGE GEOMETRICS:

Very high

High

Medium

Low

Very low

Irrelevant

1. Roadway width on the Bridge.
2. Relative roadway width.
3. Shoulder width.
4. Shoulder width reduction.
5. Vertical Clearance.

B. APPROACH ROADWAY GEOMETRICS:

1. Approach sight distance.
2. Approach roadway curvature.
3. Approach gradient

C. ENVIRONMENTAL CONDITIONS:

1. Volume / capacity ratio.
2. Percentage of trucks .
3. Lighting conditions .
4. Presence of nearby ramps.
5. Presence of nearby pavement transitions .

A 5x6 grid of squares, totaling 30 squares.

UNDERPASS ON US
AND STATE ROADS.

Very high

High

Medium

Low

Very low

Irrelevant

A. BRIDGE GEOMETRICS:

1. Roadway width on the Bridge.
2. Relative roadway width.
3. Shoulder width.
4. Shoulder width reduction.
5. Vertical clearance.

B. APPROACH ROADWAY GEOMETRICS:

1. Approach sight distance.
2. Approach roadway curvature.
3. Approach gradient

C. ENVIRONMENTAL CONDITIONS:

1. Volume / capacity ratio.
2. Percentage of trucks .
3. Lighting conditions .
4. Presence of nearby intersection.
5. Presence of nearby pavement transitions .

A 6x6 grid of squares, totaling 36 squares.

Appendix B

Tables Presenting the Results of the Questionnaire Survey

Table B.1 Percentages of Degree of Importance for Interstate Bridges.

Contributing factors	V. High	High	Medium	Low	V. Low	Irrelevant
Bridge Geometrics:						
Roadway width on bridge	21.43	64.28	7.14	7.14		
Relative roadway width	21.43	57.14	14.28	7.14		
Shoulder width	28.57	28.57	28.57	14.28		
Shoulder width reduction	7.14	21.43	28.57	35.71	7.14	7.14
Approach guardrail	10.00	30.00	50.00		10.00	
Approach Roadway Geometrics:						
Approach sight distance	21.43	28.57	42.86	7.14		
Approach roadway curvature	21.43	50.00	28.57			
Approach gradient		21.43	64.28	14.28		
Environmental Conditions:						
Volume/capacity ratio	7.14	71.43	21.43			
Percentage trucks	7.14	50.00	14.28	28.57		
Lighting conditions	7.14	7.14	50.00	28.57		7.14
Presence of nearby ramps	14.28	14.28	50.00	21.43		
Presence of nearby pavement transitions	21.43	7.14	50.00	14.28	7.14	

Table B.2 Percentages of Degree of Importance for
Bridges on US and State Roads.

Contributing factors	V. High	High	Medium	Low	V. Low	Irrelevant
Bridge Geometrics:						
Roadway width on bridge	28.57	64.28		7.14		
Relative roadway width	21.43	42.86	35.71			
Shoulder width	21.43	42.86	28.57	7.14		
Shoulder width reduction	14.28	14.28	28.57	35.71		7.14
Approach guardrail	10.00	40.00	30.00	20.00		
Approach Roadway Geometrics:						
Approach sight distance	28.57	42.86	28.57			
Approach roadway curvature	21.43	50.00	28.57			
Approach gradient	7.14	7.14	64.28	21.43		
Environmental Conditions:						
Volume/capacity ratio	21.43	64.28	14.28			
Percentage trucks	7.14	57.14	7.14	21.43	7.14	
Lighting conditions	7.14	14.28	14.28	50.00	7.14	7.14
Presence of nearby ramps	7.14	28.57	57.14	7.14		
Presence of nearby pavement transitions	21.43	14.28	35.71	21.43	7.14	

Table B.3 Percentages of Degree of Importance for Interstate Underpasses.

Contributing factors	V. High	High	Medium	Low	V. Low	Irrelevant
Bridge Geometrics:						
Roadway width on bridge	21.43	42.86	21.43	7.14		7.14
Relative roadway width	14.28	28.57	28.57	14.28	14.28	
Shoulder width	14.28	28.57	28.57	21.43	7.14	
Shoulder width reduction		21.43	28.57	21.43	14.28	14.28
Vertical clearance	42.86	28.57	14.28	14.28		
Approach Roadway Geometrics:						
Approach sight distance	7.14	50.00	28.57	14.28		
Approach roadway curvature	14.28	28.57	50.00	7.14		
Approach gradient	7.14	7.14	50.00	35.71		
Environmental Conditions:						
Volume/capacity ratio	7.14	50.00	42.86			
Percentage trucks	7.14	57.14	14.28	14.28	7.14	
Lighting conditions	14.28	7.14	28.57	28.57	14.28	7.14
Presence of nearby ramps	14.28	21.43	28.57	35.71		
Presence of nearby pavement transitions	21.43	14.28	28.57	21.43	14.28	

Table B.4 Percentages of Degree of Importance for Underpasses on US and State Roads.

Contributing factors	V. High	High	Medium	Low	V. Low	Irrelevant
Bridge Geometrics:						
Roadway width on bridge	14.28	71.43	7.14	7.14		
Relative roadway width	21.43	42.86	35.71			
Shoulder width	7.14	42.86	28.57	21.43		
Shoulder width reduction		28.57	28.57	28.57	7.14	7.14
Vertical clearance	28.57	42.86	14.28	7.14	7.14	
Approach Roadway Geometrics:						
Approach sight distance	7.14	57.14	28.57	7.14		
Approach roadway curvature	14.28	42.86	42.86			
Approach gradient	14.28	14.28	50.00	14.28		7.14
Environmental Conditions:						
Volume/capacity ratio	7.14	57.14	35.71			
Percentage trucks	21.43	35.71	21.43	14.28		7.14
Lighting conditions	14.28	7.14	21.43	35.71	7.14	14.28
Presence of nearby ramps	7.14	28.57	57.14	7.14		
Presence of nearby pavement transitions	14.28	21.43	42.86	14.28	7.14	

Appendix C

Computer Program to Calculate the Bridge Safety Index and Sample Input File

```
#include <stdio.h>
#include <math.h>
main ()
{
    int i, r, type;
    int NotPresent[14];
    float rating[14];
    FILE *fopen(), *in;

    if ((in = fopen ( "input", "r" )) == NULL )
        printf ( "Input file not found0 );
    fscanf ( in, "%d", &type );
    i = 0;
    while ( fscanf ( in, "%d", &r ) != EOF )
    {
        switch (r)
        {
            case 1:
                rating[i] = 0.0;
                NotPresent[i] = 1;
                break;
            case 2:
                rating[i] = 2.0;
                NotPresent[i] = 1;
                break;
            case 3:
                rating[i] = 5.0;
                NotPresent[i] = 1;
                break;
            case 4:
                rating[i] = 8.0;
                NotPresent[i] = 1;
                break;
            case 5:
```

```
        rating[i] = 10.0;
        NotPresent[i] = 1;
        break;
    case 6:
        rating[i] = 11.0;
        NotPresent[i] = 0;
        break;
    }
    ++i;
}
if ( i != 14 )
{
    printf ( "Incorrect number of input data0 );
    exit(0);
}
switch ( type )
{
    case 1:
        ISBridges ( rating, NotPresent );
        break;
    case 2:
        USBridges ( rating, NotPresent );
        break;
    case 3:
        ISUnderpass ( rating, NotPresent );
        break;
    case 4:
        USUnderpass ( rating, NotPresent );
        break;
}
}

struct FuzzySet {
    float point1;
    float point2;
    struct FuzzySet *predloc;
};
float ymin, ymax;
FILE *out;

ISBridges ( pr, pnp )
float pr[];
int pnp[];
{
    int i;
```

```
float BSI (), bsi;
static float weight [14] = {7.77, 7.57, 6.86, 6.50, 6.50, 6.56,
                           6.71, 7.57, 5.21,
                           7.50, 6.00, 4.69, 5.50, 5.92 };
struct FuzzySet *Bridge (), *Roadway (), *Enviro ();
struct FuzzySet *bsib, *bsir, *bsie;

for ( i = 0; i < 14; ++i )
    weight[i] *= pnp[i];
pr[4] *= pnp[4];
bsib = Bridge ( pr, weight );
bsir = Roadway ( pr, weight );
bsie = Enviro ( pr, weight );
bsi = BSI ( bsib, bsir, bsie, pr[4], pr[5] );
printf ( "%.2f0, bsi );
}
USBridges ( pr, pnp )
float pr[];
int pnp[];
{
    int i;
    float BSI (), bsi;
    static float weight [14] = {8.14, 7.36, 7.14, 7.00, 7.00, 6.10,
                               7.71, 7.57, 4.93,
                               8.00, 6.54, 4.17, 6.00, 5.92 };
    struct FuzzySet *Bridge (), *Roadway (), *Enviro ();
    struct FuzzySet *bsib, *bsir, *bsie;

    for ( i = 0; i < 14; ++i )
        weight[i] *= pnp[i];
    pr[4] *= pnp[4];
    bsib = Bridge ( pr, weight );
    bsir = Roadway ( pr, weight );
    bsie = Enviro ( pr, weight );
    bsi = BSI ( bsib, bsir, bsie, pr[4], pr[5] );
    printf ( "%.2f0, bsi );
}

ISUnderpass ( pr, pnp )
float pr[];
int pnp[];
{
    int i;
    float BSI (), bsi;
    static float weight [14] = {7.31, 6.33, 6.00, 5.50, 7.00, 5.00,
```

```

                                6.43, 6.36, 4.50,
                                6.86, 6.77, 5.09, 5.29, 6.00);
struct FuzzySet *Bridge (), *Roadway (), *Enviro ();
struct FuzzySet *bsib, *bsir, *bsie;

for ( i = 0; i < 14; ++i )
    weight[i] *= pnp[i];
pr[4] *= pnp[4];
bsib = Bridge ( pr, weight );
bsir = Roadway ( pr, weight );
bsie = Enviro ( pr, weight );
bsi = BSI ( bsib, bsir, bsie, pr[4], pr[5] );
printf ( "%.2f0, bsi );
}

USUnderpass ( pr, pnp )
float pr[];
int pnp[];
{
    int i;
    float BSI (), bsi;
    static float weight [14] = {7.64, 7.36, 6.00, 5.50, 7.69, 7.69,
                                6.86, 7.00, 5.77,
                                7.07, 6.85, 4.82, 6.00, 6.00};
    struct FuzzySet *Bridge (), *Roadway (), *Enviro ();
    struct FuzzySet *bsib, *bsir, *bsie;

    for ( i = 0; i < 14; ++i )
        weight[i] *= pnp[i];
    pr[4] *= pnp[4];
    bsib = Bridge ( pr, weight );
    bsir = Roadway ( pr, weight );
    bsie = Enviro ( pr, weight );
    bsi = BSI ( bsib, bsir, bsie, pr[4], pr[5] );
    printf ( "%.2f0, bsi );
}

float Point1 ( m, alpha )
float m, alpha;
{
    float temp;
    static float b = 2.0;

    if ( alpha < 0.5 )
```



```
        temp = m - b + b * sqrt ( alpha/2 );
    else
        temp = m - b * sqrt (( 1 - alpha )/2 );
    return (temp);
}
float Point2 ( m, alpha )
float m, alpha;
{
    float temp;
    static float b = 2.0;

    if ( alpha < 0.5 )
        temp = m + b - b * sqrt ( alpha/2 );
    else
        temp = m + b * sqrt (( 1 - alpha )/2 );
    return (temp);
}
float BigArray [11][2];
int index[6];
Process ( no, level, maxlevel )
int no, level, maxlevel;
{
    int i;
    float top, bottom, y;

    index[level] = no;
    if ( level == maxlevel )
    {
        top = bottom = 0.0;
        for ( i = 1; i < maxlevel/2 + 1; ++i )
        {
            top += BigArray [i][index[i]]
                * BigArray [i+maxlevel/2 ][index[i+maxlevel/2]];
            bottom += BigArray [i+maxlevel/2 ][index[i+maxlevel/2 ]];
        }
        y = top/bottom;
        if ( y < ymin ) ymin = y;
        if ( y > ymax ) ymax = y;
    }
    else
    {
        Process ( 0, ++level, maxlevel );
        Process ( 1, level, maxlevel );
    }
}
```

```
}

struct FuzzySet *
Bridge ( pr, pw )
float pr[], pw[];
{
    float i;
    int j, m;
    struct FuzzySet *p, *pv;
    float Point1(), Point2();

    pv = NULL;
    for ( i = 1.0, m = 0; m < 10; i -= 0.1, ++m )
    {
        for ( j = 1; j < 5; ++j )
        {
            BigArray [j][0] = Point1 ( pr[j - 1], i );
            BigArray [j][1] = Point2 ( pr[j - 1], i );
        }
        for ( ; j < 9; ++j )
        {
            BigArray [j][0] = Point1 ( pw [j - 5], i );
            BigArray [j][1] = Point2 ( pw [j - 5], i );
        }
        ymax = 0.0;
        ymin = 10000.0;
        Process ( 0, 0, 8 );
        p = ( struct FuzzySet * ) malloc ( sizeof ( struct FuzzySet ));
        p->point1 = ymin;
        p->point2 = ymax;
        p->predloc = pv;
        pv = p;
    }
    return (p);
}

struct FuzzySet *
Roadway ( pr, pw )
float pr[], pw[];
{
    float i;
    int j, m;
    struct FuzzySet *p, *pv;
    float Point1(), Point2();

    pv = NULL;
```

```
for ( i = 1.0, m = 0; m < 10; i -= 0.1, ++m )
{
    for ( j = 1; j < 4; ++j )
    {
        BigArray [j][0] = Point1 ( pr[j + 5], i );
        BigArray [j][1] = Point2 ( pr[j + 5], i );
    }
    for ( ; j < 7; ++j )
    {
        BigArray [j][0] = Point1 ( pw [j+2], i );
        BigArray [j][1] = Point2 ( pw [j+2], i );
    }
    ymax = 0.0;
    ymin = 10000.0;
    Process ( 0, 0, 6);
    p = ( struct FuzzySet * ) malloc ( sizeof ( struct FuzzySet ));
    p->point1 = ymin;
    p->point2 = ymax;
    p->predloc = pv;
    pv = p;
}
return (p);
}
struct FuzzySet *
Enviro ( pr, pw )
float pr[], pw[];
{
    float i;
    int j, m;
    struct FuzzySet *p, *pv;
    float Point1(), Point2();

    pv = NULL;
    for ( i = 1.0, m = 0; m < 10; i -= 0.1, ++m )
    {
        for ( j = 1; j < 7; ++j )
        {
            BigArray [j][0] = Point1 ( pr[j+8], i );
            BigArray [j][1] = Point2 ( pr[j+8], i );
        }
        for ( ; j < 12; ++j )
        {
            BigArray [j][0] = Point1 ( pw [j+2], i );
            BigArray [j][1] = Point2 ( pw [j+2], i );
        }
    }
}
```

```
        ymax = 0.0;
        ymin = 10000.0;
        Process ( 0, 0, 10);
        p = ( struct FuzzySet * ) malloc ( sizeof ( struct FuzzySet ));
        p->point1 = ymin;
        p->point2 = ymax;
        p->predloc = pv;
        pv = p;
    }
    return (p);
}

float BSI ( pb, pr, pe, r4, r5 )
struct FuzzySet *pb, *pr, *pe;
float r4, r5;
{
    float i;
    int m;
    float sum;
    float x1, x2, x11, x22;
    float Point1(), Point2();

    sum = 0.0;
    for ( i = 0.1, m = 0; m < 10; i += 0.1, ++m )
    {
        x1 = pb->point1 - (10.0 - pr->point1) * 0.1
            - (10.0 - pe->point1) * 0.05;
        x2 = pb->point2 - (10.0 - pr->point2) * 0.1
            - (10.0 - pe->point2) * 0.05;
        if ( r4 != 0.0 )
        {
            x1 -= ( 10 - Point1 ( r4, i )) * 0.15;
            x2 -= ( 10 - Point2 ( r4, i )) * 0.15;
        }
        x11 = x1 + ( Point1 ( r5, i ) - Point1 ( 8.0, i )) * 0.08;
        x22 = x2 + ( Point2 ( r5, i ) - Point2 ( 8.0, i )) * 0.08;
        sum += ( x11 + x22 )/2 * i;
    }
    sum /= 5.5;
    if ( sum < 0.0 ) sum = 0.0;
    if ( sum > 10.0 ) sum = 10.0;
    return ( sum );
}
```

Sample Input File for Table 6.3

1
4
4
4
4
4
6
3
5
5
4
4
4
4
6
6

Note: In addition to code numbers given in Table 6.2, code number 6 is to be used to represent the rating *not present*.

COVER DESIGN BY ALDO GIORGINI