NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 203

SAFETY AT NARROW BRIDGE SITES

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL

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AREAS OF INTEREST:
- STRUCTURES DESIGN AND PERFORMANCE
- MAINTENANCE
- TRANSPORTATION SAFETY
- (HIGHWAY TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. JUNE 1979

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity; it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

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FOREWORD

By Staff
Transportation Research Board

This report will be of interest to persons responsible for selection, design, and construction of safety improvements at bridge sites. It describes a bridge safety index (BSI) for assessing the hazards associated with bridges having restricted widths and methods for reducing such hazards. The BSI concept has the advantage of being simple and uses readily available information. It should be used on a trial basis by individual agencies to develop local verification and modifications.

This research was undertaken following testimony concerning highway safety and, more specifically, narrow bridge problems, at hearings of the Subcommittee on Investigation and Review, Committee on Public Works, U.S. House of Representatives. The objectives of the study were to define the narrow bridge problem, appraise the effectiveness of corrective measures, and develop guidelines for corrective treatment at various bridge sites.

A nationwide narrow bridge survey conducted as part of the project indicated that there may be as many as 60,000 highway bridges in the United States that are deficient in width. Field studies were conducted at 25 selected bridge sites in 7 states. Driver performance in terms of speed and lateral position was determined for each site. Modifications of signing and delineation were made at several sites. Before-and-after accident experience was available for one section of road where corrective treatments had been applied to several narrow bridges.

On the basis of the data collection and analysis, and the experience of the researchers, the BSI was developed as the combination of 10 individual bridge site rating factors. Its development is considered the most significant accomplishment of the research effort. For most bridges, it can be used to determine a reasonable estimate of the relative degree of hazard of the site in comparison with other sites.

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The research reported herein was performed under NCHRP Project 20-7, Task 7, by the Texas Transportation Institute, Texas A & M University. The Texas A & M Research Foundation was the contractor for the study.

Charles J. Keese, Director, Texas Transportation Institute, was the principal investigator. The authors of the report are Don L. Ivey, Research Engineer, together with Robert M. Olson, Research Engineer; N. E. Walton, Research Engineer; and Graham D. Weaver, Associate Research Engineer, all of the Texas Transportation Institute. In addition, assistance received from other personnel at the Texas Transportation Institute include: Donald C. Woods, Research Engineer; Robert L. Liverman, Research Associate; and Wilbur M. Moore, Research Engineer; also Lynn Whitehurst Furr, Consulting Editor.

Special thanks are extended to Benjamine W. Bohuslav, Senior Traffic Engineer, Texas State Department of Highways and Public Transportation, for the innovative implementation and evaluation project described in this report. Personnel at the Federal Highway Administration Maine Facility acquired data on traffic movements. Their valuable contribution is gratefully acknowledged.

SUMMARY

Many roads in the United States were built before the adoption of modern design standards. In consequent attempts to improve the capacity and safety of these roads, pavement widening often has been used, although in many cases funds have not been available to widen the bridges. These "narrow" bridges stand as potential hazards to users. This report describes methods (other than widening of a bridge) for reducing hazards associated with a narrow bridge. A major feature is the development of a bridge safety index (BSI) for determining priorities for improvement of bridges having restricted width.

It is difficult to quantitatively define a "narrow" bridge in terms of actual bridge width because this implies that width is the only factor in the narrow bridge problem. Such factors as bridge width in relation to approach pavement width, sight distance, traffic volume, traffic speed, and distractions all influence safety at a selected bridge site. In an attempt to define the narrow bridge problem, data on speed and lateral position of vehicles at 25 bridge sites of various geometric characteristics were collected and analyzed by the Texas Transportation Institute. From these data it was determined that there was little lateral movement of vehicles when approaching bridges more than 24 ft in width (the clear width of pavement measured at right angles to the center of the roadway). There was a movement of more than 2 ft toward the center of the roadway in bridges 15 ft or less in width. On bridges 17 to 18 ft wide, most drivers place the left edge of their vehicle on the centerline when unopposed by traffic. Some observations drawn from the data are as follows:

1. Any bridge less than 24 ft wide should be considered a restricted-width bridge, but not necessarily a hazardous bridge site.
2. Any bridge less than 18 ft in width should be considered a one-lane bridge.
3. Any bridge with a width of 15 ft or less should be considered a hazardous site.

On the basis of the data collected and the experience of the researchers, the BSI was developed as the sum of ten individual bridge site rating factors. The BSI approach is presented in the form of tables and figures readily usable by practicing engineers. It is considered suitable for trial implementation as a technique for making a reasonable estimate of the relative degree of hazard at various restricted-width bridge sites. By use of an example problem, the BSI is explicitly defined to permit its direct application in practice. As a result, corrective action can be taken at the more hazardous sites even if extensive accident records are not available.

The report identifies a number of corrective measures that can be applied to hazardous bridge sites when widening is not economically feasible. The recommended corrective measures are approaches that can be considered, along with engineering judgment, to reduce the possibility and severity of accidents at potentially hazardous sites.

"Before" and "after" evaluations of corrective measures at restricted-width bridge sites were obtained from a Texas improvement project. Accident data over a two-year period indicated that the fatal accident rate of a section of U.S. 90 near Gonzales, Texas was 56 percent higher than the statewide average. Many of the reported accidents were located in the vicinity of bridges. A comprehensive safety program was conducted, including extensive corrective measures of the bridge rails. The bridges were predominantly 24 and 26 ft wide. There were two types of railing. One railing was constructed of concrete posts with concrete beams; the other type was concrete posts with steel beams. The roadway had a 24-ft paved surface width with 8-ft paved shoulders and thus was substantially wider than the bridges. The corrective measures appear to have been effective in reducing the number of reported accidents. In the 22 months prior to application of corrective measures, 20 accidents involving the bridges were reported. During the 17 months following the applications, only 4 reportable accidents occurred. This verification, though limited, provides sufficient evidence to indicate good probability of success when the recommended corrective measures are implemented.

The BSI concept is a technique that has the advantage of being simple and that uses readily available information. It should be used on a trial basis to develop information for verification and modification of the technique. When employed by highway agencies, the collection and analysis of additional information should result in a revised concept of greater precision and effectiveness.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

THE PROBLEM

The Subcommittee on Investigations and Review of the Committee on Public Works of the U.S. House of Representatives met in Washington, D.C., June 12-14, 1973. The subcommittee hearings have been published and include the results of an investigation by its staff (*1*) The staff report contains the following statement:

> Highways have two necessary components, viz: roadways and bridges. Clearly, there can be no functional value in one without the other. Highway bridges have always been the subject of specialized engineering effort and for a variety of reasons. They cost more than the roadways connecting them, and more sophisticated engineering analyses are required for their design. Traditionally, the purpose of the extra effort has been to insure that the bridge structure will support a certain design load without failure. Until recently, the width of the bridge roadway has rarely been a paramount concern, and often the width has been compromised for economic reasons. The legacy of this practice are [sic] the narrow bridges that today stand as potential hazards to all who use them. The life span anticipated in bridge design is typically longer than that for roadway design. All these and other factors have combined to create a hazardous differential between the traffic adequacy of many of today's bridges and roadways.

The Texas Transportation Institute, under the National Cooperative Highway Research Program Project 20-7, "Research for AASHTO Standing Committee on Highways," undertook a study of narrow bridges. It should be emphasized that the study has been a first step and has been limited to bridges that are structurally sound although deficient in width. Structural adequacy has not been an item of study. Replacement or widening of all bridges that are narrower than the approach pavement and shoulders would provide drivers with more room to maneuver and avoid collisions with structural components or with other vehicles. However, because the cost of widening or rebuilding bridges is prohibitive, this research has been concerned with methods of reducing the hazards associated with narrow bridges exclusive of widening.

OBJECTIVES

Three objectives have been pursued:

1. Define the narrow bridge problem.
2. Appraise the effectiveness of current corrective measures.
3. Develop guidelines for treatment at narrow bridge sites.

The three objectives have been approached by tasks as follows:

Task A -- *Compare current driver behavior with earlier studies on speed and placement.* In 1941, Walker (2) developed an expression for computing bridge width as a function of lateral placement. The adequacy of this expression was tested at three sites in Texas and at the Maine Facility (an instrumented, computer-monitored, two-lane roadway in Maine). In addition, 20 other sites throughout the U.S. were observed to determine driver behavior at or near bridges.

Task B -- *Examine the efficacy of current remedial treatments at bridge sites.* A case study was made of narrow bridge sites in Texas. Statistics on accidents "before" remedial treatments and "after" remedial treatments were examined.

Task C -- *Propose corrective measures at selected sites and, in cooperation with highway engineers, install these features.* Observations were made of driver behavior before and after corrective treatments to determine if speed and placement turbulence and uncertainties had been eliminated. Intensive data gathering and analyses were also conducted at the Maine Facility before and after corrective treatments.

Task D -- *Synopsis of reports and recommendations of study groups on recent fatal accidents on or near narrow bridges.* The Wright subcommittee report (*1*) and the New Mexico accident report (*3*) were studied and **appraised for use in** development of guidelines for improvement.

Task E -- *Study available standards, recommendations, and suggestions concerning safer conditions at or near bridges.* The *Manual on Uniform Traffic Control Devices for Streets and Highways (4)*, the new handbook of *Highway Design and Operational Practices Related to Highway Safety (5)*, and other published and unpublished reports were carefully studied.

Task F -- Prepare suggested guidelines. Results and findings from Tasks A through E were used to develop guidelines for treatment at narrow bridge locations.

RESEARCH APPROACH

Speed and lateral placement of vehicles were studied by using motion picture photography and visual observations in conjunction with radar. Motion picture photography in a car-following process recorded speed and placement as vehicles approached a bridge, crossed a bridge, and departed from a bridge. This method proved effective but was confined to a limited number of sites since collection and analysis of data was slow and expensive.

Data collection by visual observations and radar extended the coverage. In this method, stripes were placed on the pavement parallel to the roadway at one-foot intervals from the centerline of the roadway/bridge approach to the shoulder. These marks permitted estimation of vehicle placement to the nearest 1/4 foot. These estimations were made by an observer using binoculars. Three measuring points were set up on each bridge approach. Radar was used to measure speeds at the observation points.

The data collection provided for determination of mean, variance, and standard deviation of placement and speeds at the measuring points, plus a comparison between the points. These comparisons, and comparisons between "before" and "after" conditions, indicated the effectiveness of the various experimental corrective treatments.

Twenty-five bridge sites (located in Arizona, Maine, Minnesota, Missouri, New Mexico, Texas, and Virginia) were selected for the driver behavior studies. Descriptive characteristics and photographs at each site are presented in Appendix A. Average daily traffic, posted speed, and average speed at each site are listed in the table of characteristics.

Passive remedial treatments were recommended and installed at the Maine Facility and at three sites in Texas. Data acquired in Maine and Texas after remedial treatments were made are discussed in Appendix A.

In addition, a separate case study was also made of "before" and "after" treatments on U.S. 90 in Texas. This study was based on information collected by the Texas Highway Department for the period of 1969 to 1972 and supplied accident information that was not available at other sites. Statistical treatment was made of the data to determine significant relationships.

A survey was made of state highway departments concerning their definitions and treatments of narrow bridges. This survey was utilized in developing information for recommended treatment guidelines.

DEFINITIONS

The following terms from *AASHO Highway Definitions* (6), adopted in June 1968, were applied by the researchers:

BRIDGE

Bridge-A structure including supports erected over a depression or an obstruction, as water, highway or railway, and having a track or passageway for carrying traffic or other moving loads and having an opening measured along the center of the roadway of more than twenty feet between undercopings of abutments or spring lines of arches or extreme ends of openings for multiple boxes; may include multiple pipes where the clear distance between openings is less than half of the smaller contiguous opening.

- Bridge length-The greater dimension of a structure measured along the center of the roadway between backs of abutment backwalls or between ends of bridge floor.
- Bridge roadway width-The clear width of structure measured at right angles to the center of the roadway between the bottom of curbs or, if curbs are not used, between the inner faces of parapet or railing.

CROSS SECTION

Curb loading zone-Roadway space adjacent to a curb and reserved for exclusive use of vehicles during loading or unloading of passengers or property.

Lane

- Auxiliary lane-The portion of the roadway adjoining the traveled way for parking, speed change, turning, storage for turning, weaving, truck climbing or for other purposes supplementary to through traffic movement.
- Median lane-A speed-change lane within the median to accommodate left-turning vehicles.
- Parking lane-An auxiliary lane primarily for the parking of vehicles.
- Speed-change lane-An auxiliary lane, including tapered areas, primarily for the acceleration or deceleration of vehicles entering or leaving the through traffic lanes.
- Traffic lane-The portion of the traveled way for the movement of a single line of vehicles.

Median-The portion of a divided highway separating the traveled ways for traffic in opposite directions.

Outer separation-The portion of an arterial highway between the traveled ways of a roadway for through traffic and a frontage street or road.

Roadside-A general term denoting the area adjoining the outer edge of the roadway. Extensive areas between the roadways of a divided highway may also be considered roadside.

Roadway-(General) The portion of a highway, including shoulders, for vehicular use. A divided highway has two or more roadways. *(In construction specifications)* The portion of a highway within limits of construction.

Shoulder-The portion of the roadway contiguous with the traveled way for accommodation of stopped vehicles for emergency use, and for lateral support of base and surface courses.

Traveled way-The portion of the roadway for the movement of vehicles, exclusive of shoulders and auxiliary lanes.

Observation of practice in the field however, led to development of the following definition:

Roadway width - The clear width of pavement measured at right angles to the center of the roadway. This width is either
(a) the traveled way as defined by AASHTO, or
(b) the traveled way and paved shoulders, where paved shoulders are constructed contiguous to the traveled way.

The need for this definition became apparent during the course of this study when it was observed that drivers may not distinguish between traveled way and paved shoulders. Skid marks on portions of paved shoulders at some locations support this observation. Also, at some sites, although edge lines were painted to delineate traveled way, skid marks on the paved shoulders near the end of a bridge indicated that some drivers were operating their vehicles on the shoulders.

CHAPTER TWO

FINDINGS

The research into the narrow bridge problem resulted in three principal findings. A major development was the bridge safety index (BSI). On the basis of data collected at 25 bridge sites throughout the U.S., and the experience of the researchers, a bridge safety index (BSI) was developed to meet the following criteria:

1. General enough to account for the most important factors relating to almost all bridges.
2. Simple enough to allow for the evaluation of a bridge in a short time with relatively little field study.
3. Specific enough to imply the appropriate remedial treatment while determining the factors influencing the index value.

Another result of the study was the identification of a number of corrective measures that could be applied to hazardous bridge sites when widening was not considered economically feasible.

These corrective measures are approaches that can be considered, along with engineering judgment, to reduce the probability and severity of accidents at potentially hazardous sites. It should be recognized that such factors as traffic volume and the proportion of commercial vehicles will influence the selection of the appropriate corrective measure.

The third finding was the recognition of driver behavior as an indicator of potential bridge hazards. Field observations showed that drivers slowed down only slightly when approaching a bridge. However, they gradually moved their vehicles toward the centerline. The researchers contend that this lateral movement of the vehicles was evidence that a hazard existed whether or not it was recognized as such by the driver. Not all of the lateral movement was necessary to clear the bridge rail; a large part of it signified movement in response to recognition of a hazard, or a desire to allow more space for easy clearance.

DEVELOPMENT OF A BRIDGE SAFETY INDEX (BSI)

Defining a "narrow bridge" is difficult because the term itself implies that narrowness is the total problem. It may be more appropriate to ask the question: "What is a hazardous bridge?" Much more is involved in answering this question than merely determining the bridge width.

The highway bridge environment is subject to such wide variation that efforts to include all factors in a bridge safety index (BSI) result in undue complexity, whereas relying on engineering judgment allows the procedure outlined to be limited only by the imagination and subsequent refinement of the user. Some of the factors included in the BSI were developed solely on the basis of the experience and judgment of the researchers, and are not the result of studies performed on this project.

Table 1 illustrates the factors selected to determine the bridge safety index (BSI). Ten factors are specified: F_1, F_2, and F_3 -- Bridge Geometric Factors and a Roadside and Bridge Rail Structural Factor; F_5, F_6, and F_7 -- Highway Geometric Factors; F_8, and F_9 -- Traffic Factors; and F_{10} -- Distraction and Roadside Activities Factor. F_4 is a combined road geometric/traffic factor. With the exception of F_1, F_2, and F_3, which are rated from 0 to 20, ratings from 1 to 5 are given for each of these factors. A rating of 1 represents a critical situation, and a rating of 5 represents favorable bridge conditions. The BSI is the sum of the ten individual rating factors:

$$BSI = F_1 + F_2 + \cdot \cdot \cdot + F_{10} \quad (1)$$

The most ideal bridge site conditions would produce a BSI of 95, and critically hazardous sites would have values less than 20.

TABLE 1

FACTORS USED TO DETERMINE SIMPLIFIED BRIDGE SAFETY INDEX

	BRIDGE EVALUATION FACTOR	FACTOR RATING FOR F_1, F_2, and F_3				
		0	5	10	15	20
F_1	Clear Bridge width (ft)	(See Figure 1)				
F_2	Bridge lane width (ft) / Approach lane width (ft)	≤0.8	0.9	1.0	1.1	≥1.2
F_3	Guardrail and Bridge rail structure	Critical	Poor	Average	Fair	Excellent
		FACTOR RATING FOR F_4 - F_{10}				
		1	2	3	4	5
F_4	Approach sight distance (ft) / 85% approach speed (mph)	≤5	7	9	11	≥14
F_5	100 + Tangent distance to curve (ft) / Curvature (degree)	≤10	60	100	200	≤300
F_6	Grade continuity (%)*	10	8	6	4	≤2
F_7	Shoulder reduction (%)	100	75	50	25	None
F_8	Volume/Capacity	0.50	0.40	0.30	0.10	0.05
F_9	Traffic Mix	Wide discontinuities	Non-uniform	Normal	Fairly uniform	Uniform
F_{10}	Distractions and roadside activities	Continuous	Heavy	Moderate	Few	None

* Average grade + (Approach grade - exit grade).

It is apparent that all factors should not have the same significance in determining the BSI, but the current state of knowledge does not permit this refinement. The observations reported here tend to make two factors of primary importance. These are F_1 and F_2, the absolute and relative bridge width. The bridge rail factor, F_3, is also of critical importance due to the severity of guardrail collisions which occur. Therefore, the authors have chosen to rank these three factors above the other seven, giving them weightings of up to 20 of the possible 95. As highway agencies begin to use the BSI, they should give consideration to the development of weighting factors that reflect local conditions. In the interim, the proposed weightings should provide reasonably comparative evaluations of various bridges. The bridge width factor, F_1, is defined by Figure 1. Because drivers regard bridges 24 ft wide as reasonably safe, the factor F_1 for this width is high. As the width decreases to about 18 ft, the factor F_1 is assumed to decrease rapidly as shown in Figure 1. A 14-ft wide bridge (7-ft lane width) would barely permit two opposing passenger vehicles (P) to meet on the bridge, and even this would necessitate crawl speed operation. Therefore a low rating of 0 is given this condition.

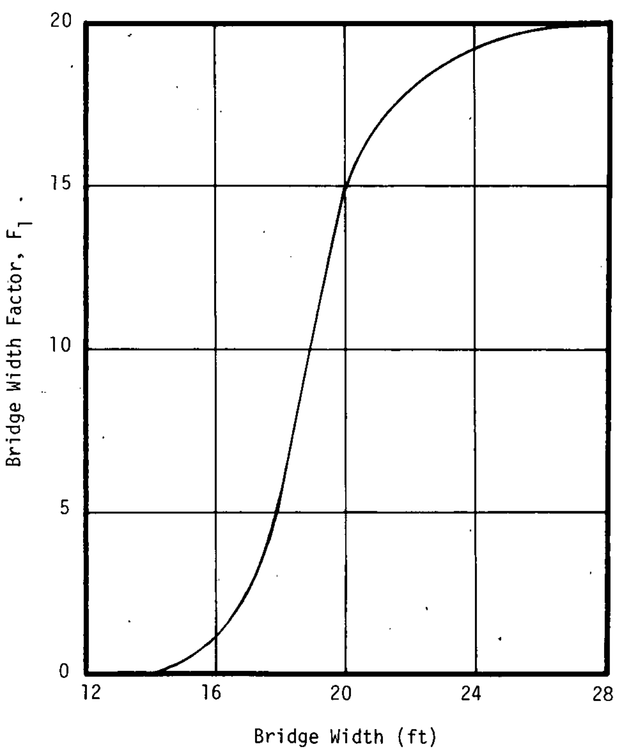

Figure 1. Weighting of bridge width factor.

Many of the factors given in Table 1 are self-explantory; however, clarification of others is necessary for reasonably consistent applications.

F_1 -- Implicit in this work is the premise that the major problems are associated with two-lane, two-way bridges. F_1 is determined by entering Figure 1 with the clear bridge width. The clear bridge width includes shoulders if they are carried across the structure. In the case of a two-lane bridge without shoulders, the factor F_1 is obtained using twice the lane width from Figure 1.

F_2 -- The ratio of bridge width to approach roadway width is a measure of the relative constriction of lateral movement as a vehicle travels from the approach lane onto the bridge. The upper value of 0.8 is derived from a reduction of a 12-ft wide approach lane to a 10-ft wide bridge lane (24-ft approach roadway to a 20-ft wide bridge). This represents a 16 percent width reduction. The 1.2 value is produced by a 20 percent <u>increase</u> in bridge lane width, representing a 10-ft approach lane to a 12-ft bridge lane (20-ft wide approach roadway to a 24-ft wide bridge).

F_3 -- The approach guardrail and bridge rail structural factor attempts to define the safety aspects of the rail and the contribution to bridge perspective that the approach rail offers to an oncoming driver. Desirable guardrail or bridge rail features are well documented in *NCHRP Report No. 86* (7). Accepted safety treatments to approach guardrails (such as turned down, flared, or otherwise anchored end terminals; adequate structural anchorage at the bridge maintaining beam strength across the connection; continuation of approach rail onto or across the bridge, etc.) contribute to selection of a high value of F_3. Bridge rails exhibiting high probabilities of snagging, poor redirection characteristics, or vaulting (such as can be expected with use of step curbs in front of the rail) are considered to be unsafe and consequently the F_3 values are given a low rating.

F_4 -- The ratio of approach sight distance to approach speed indicates the time in which a driver may prepare for the bridge crossing.

Using an assumed 10-second preparation time, the values of F_4 are computed for 60 mph and 30 mph as boundary conditions and are arbitrarily apportioned for intermediate values.

F_5 -- A driver exiting from a horizontal curve in advance of a bridge needs recovery time to position his vehicle for the bridge crossing. The need for recovery distance is apparent from research indicating large lateral movements at the ends of horizontal curves *(8)*. The factor shown in the numerator (a constant plus the tangent distance from the bridge to the curve) to the curvature is proposed to be indicative of the hazard. In using a denominator of degree of curvature, it is recognized that the problem becomes more critical as the degree of curvature increases (other factors such as speed remaining constant).

F_6 -- Vertical alignment is treated independently in factor F_6. Vertical curvature in advance of the bridge creates additional perspective problems to an approaching driver. The grade continuity factor, F_6, denotes average grade throughout the bridge zone, (G_A), and the algebraic difference in approach and departing grades. Figure 2 illustrates, through several examples, the computation of F_6.

F_7 -- This factor is defined as the percentage that the shoulder width on the approach roadway is reduced as it is carried across the bridge. For example; if the full shoulder width is continued across the bridge, the reduction is zero; if an approach shoulder of 6 ft is decreased to 3 ft across the bridge, the factor is a 50 percent reduction. On an approach roadway with unpaved shoulders, the reduction would be zero.

F_8 -- The ratio of volume to capacity is an indirect way of accounting for the number of conflicts on the bridge. The most critical case is taken to be 0.5, since higher traffic volumes should result in progressively slower speeds. Thus, dense traffic should reduce the severity of collisions.

F_9 -- A bridge that is barely wide enough to permit opposing passenger cars to meet may be too narrow to permit two trucks to meet as they cross the structure simultaneously. If the traffic composition includes relatively high percentages of large truck traffic (> 10%), narrow bridges can become <u>critically</u> narrow. Similarly, slow-moving large vehicles such as farm machinery, logging trucks, or other atypical vehicles produce adverse effects on the traffic flow, particularly where pavement constrictions occur. Contributions of traffic composition to the bridge crossing problem are represented by F_9, a scalar quantification. The value of 5 would represent a low percentage of commercial vehicles (1 to 3 percent), whereas greater than 10 percent would yield a rating of 1. If a rating of 3 were selected after determining that there were 6 percent commercial vehicles, the rating might be decreased to 2 based on the knowledge that mobile farm machinery was common on the road.

F_{10} -- The distractions and roadside activities factor is the least objective of all factors proposed. Such things as distracting lights, advertisements, the presence of bars, or excessive roadside parking could result in ratings as low as 1. An occasional vehicle along the road or access from a farm road could be given a rating of 4. The goal should be consistency in the evaluation of a number of bridges within a geographical area. National consistency is not necessary.

The Overriding Effect of Traffic Speed

Because traffic speed influences the relative safety of a site, it was decided to modify the BSI by the ratio of the appropriate speed, V_a, for a given site and the 85th percentile traffic speed, V_{85}, (see Fig. 3). The 85th percentile speed was chosen because the setting of speed zones by this percentile is an established precedent. Thus, the speed-modified value is

$$BSI' = (V_a/V_{85})\ BSI \qquad (2)$$

The suggested way to make this modification is to determine the 85th percentile speed on a specific bridge; plot that speed on Figure 3 at the appropriate "<u>unmodified</u>" BSI level and determine the ratio of V_a (the appropriate vehicle speed) to V_{85} (the 85th percentile speed). The ratio of these two speeds V_a/V_{85} is the required factor necessary to determine BSI'.

The use of this factor has shown that in some cases traffic will slow down to speeds close to those indicated as reasonable by Figure 3, in a natural response to recognition of a significant roadway constriction. In most cases, however, the speed term significantly lowers the value of BSI, sometimes as much as 50%. The use of this factor is not recommended if it is greater than 1. That is, it can be used to reduce the BSI but not to increase it.

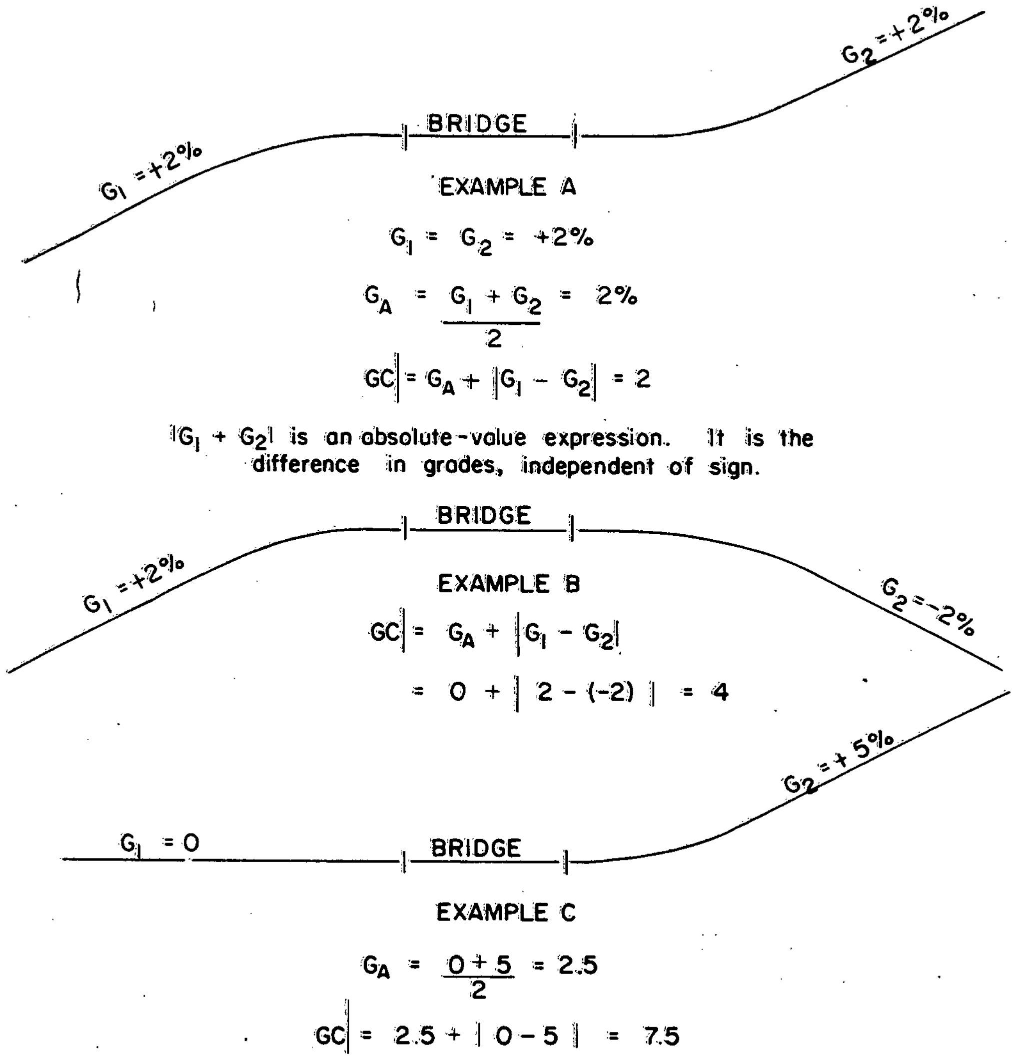

Figure 2. Examples of grade continuity factors.

BSI' As An Indicator of Need for Corrective Treatment

After ratings have been developed for a number of bridges, relative BSI values can be used to assist in the establishment of a priority ranking for treatment. Table 2 relates the BSI to suggested probable need for corrective treatment. Examples of applications of the BSI are given in Chapter Three.

Table 2 is presented as illustrative of the way policy might be set if state DOT's and highway departments choose to do so. Specific values are given for illustrative purposes only and are not to be construed as scientifically justifiable at this time.

TABLE 2

BSI' AS AN INDICATION OF THE NEED FOR CORRECTIVE TREATMENT
(for illustrative purposes only)

BSI"	NEED FOR CORRECTIVE TREATMENT
≥70	Treatment probably not required
40 - 70	Some treatment indicated
20 - 40	Treatment strongly indicated
<20	Immediate treatment indicated

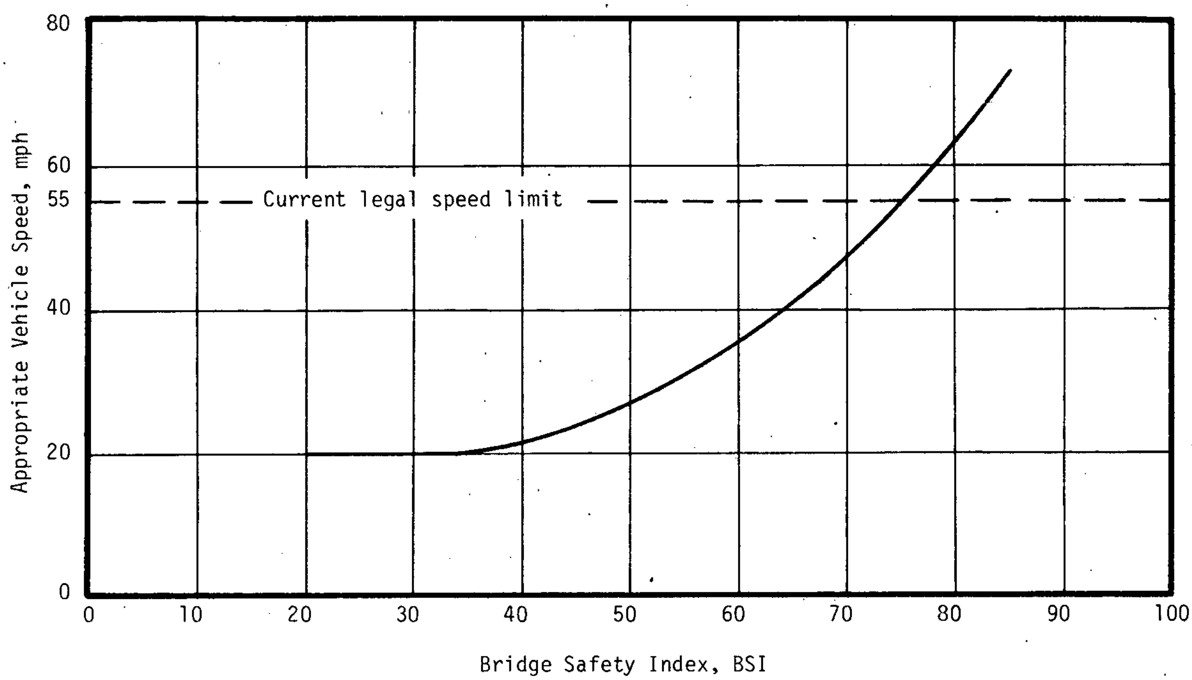

Figure 3. Appropriate vehicle speed vs BSI.

EFFECTIVENESS OF CORRECTIVE MEASURES AS INDICATED BY ACCIDENT REDUCTION

By the summer of 1970, only one relatively short section of Interstate Highway 10 between San Antonio and Houston, Texas, remained to be constructed. Interstate highway traffic at this point had to be carried on U.S. 90 in Gonzales County. This portion of the highway had a 24-ft paved surface with 8-ft paved shoulders. More than 50 bridges, 26 ft wide or less were present in this section.

A study conducted by the Texas Highway Department District Traffic Engineering Office revealed that the accident rate for this section normalized to adjust for volume differences was some 24 percent above the statewide average for two-lane rural highways. More significantly, the fatal and personal injury accidents were about 31 percent higher, and fatal accidents some 56 percent higher than the statewide average. An analysis by accident type and contributing circumstances is presented in Table 3.

A review of the data presented in Table 3 reveals an accident pattern that is indicative of the narrow bridge problem. For example, the predominant accident type is "struck a bridge or culvert"; the "ran off the road" and "head-on or sideswipe" accidents are relatively high. The accidents occurred throughout the day when predominantly dry and clear weather conditions existed. The traffic stream was composed of about 24 percent trucks or cars with trailers (actually 24.6% in 1969 and 23.4% in 1970), and these vehicles were overly involved in the accident data. All of these indicators point to narrow structures as a significant problem.

Another interesting finding of the accident study was the report from the Department of Public Safety officers that the typical bridge accident involved impacting the face of the bridge rail at some point along the bridge rather than impacting the end of the bridge rail. This led to the concept that the entire bridge and not just the rail end and its approach had to be treated.

As a result, the Texas Highway Department District 13 staff proposed a comprehensive safety program for this section of U.S. 90, one phase of which involved extensive treatment of the bridges. The findings reported in this section are primarily the results of a study of accidents "before" remedial treatment and "after" these treatments. (See also Appendix A.)

Location of the Study Site

The study site is located in northeastern Gonzales County approximately 11-1/2 miles north of the city of Gonzales, Texas. The site begins at the Gonzales-Caldwell county line just east of Luling, Texas, and continues to the Gonzales-Fayette county line west of Flatonia, Texas. The detailed location is presented on a portion of the Gonzales County map in Figure 4, and the general location is shown on the Houston-San Antonio corridor in Figure 5.

TABLE 3

ACCIDENT TYPE AND CONTRIBUTING FACTORS
U.S. 90 FLATONIA TO LULING
GONZALES COUNTY, TEXAS
DATA FOR THE PERIOD JUNE 1, 1968 TO MAY 31, 1970

TYPE	NUMBER	PERCENT
Struck bridge or culvert	40	37
Ran off the road	27	25
Head-on or sideswipe	15	14
Right angle	2	2
Rear-end	13	12
Other	11	10
TOTALS	108	100
TIME OF DAY		
Day	57	53
Night	51	47
TOTALS	108	100
WEATHER CONDITIONS		
Rain or wet pavement	21	20
Fog	10	9
Dry and Clear	77	71
TOTALS	108	100
TYPES OF VEHICLES INVOLVED		
Passenger vehicle	61	56
Trucks or cars with trailers	47	44
TOTALS	108	100

TABLE 4

APPROACH AND BRIDGE DATA

Structure No.	Mile Post	Name	Length (ft)	Width (ft) f to f	Width (ft) Approach	Width (ft) Shoulder	Rail Type
17	2.575	Mule Creek	171	24	24	8	K
18	7.670	Sandy Fork	286	24	24	8	K
19	10.529	Buck Branch	228	24	24	8	K
21	12.275	Bee Branch	171	24	24	8	K
24	15.826	Bald Ridge Creek	200	24	25	8	K
49	39.164	No Name Creek	54	34	24	8	L
50	39.683	Peach Creek	840	26	24	8	L
51	41.241	Little 5 Mile Crk	280	26	24	8	L
52	41.563	Big 5 Mile Creek	300	26	24	8	L
53	41.885	Big 5 Mile Relief	240	26	24	8	L
54	42.613	Cedar Springs Crk	80	26	24	8	L

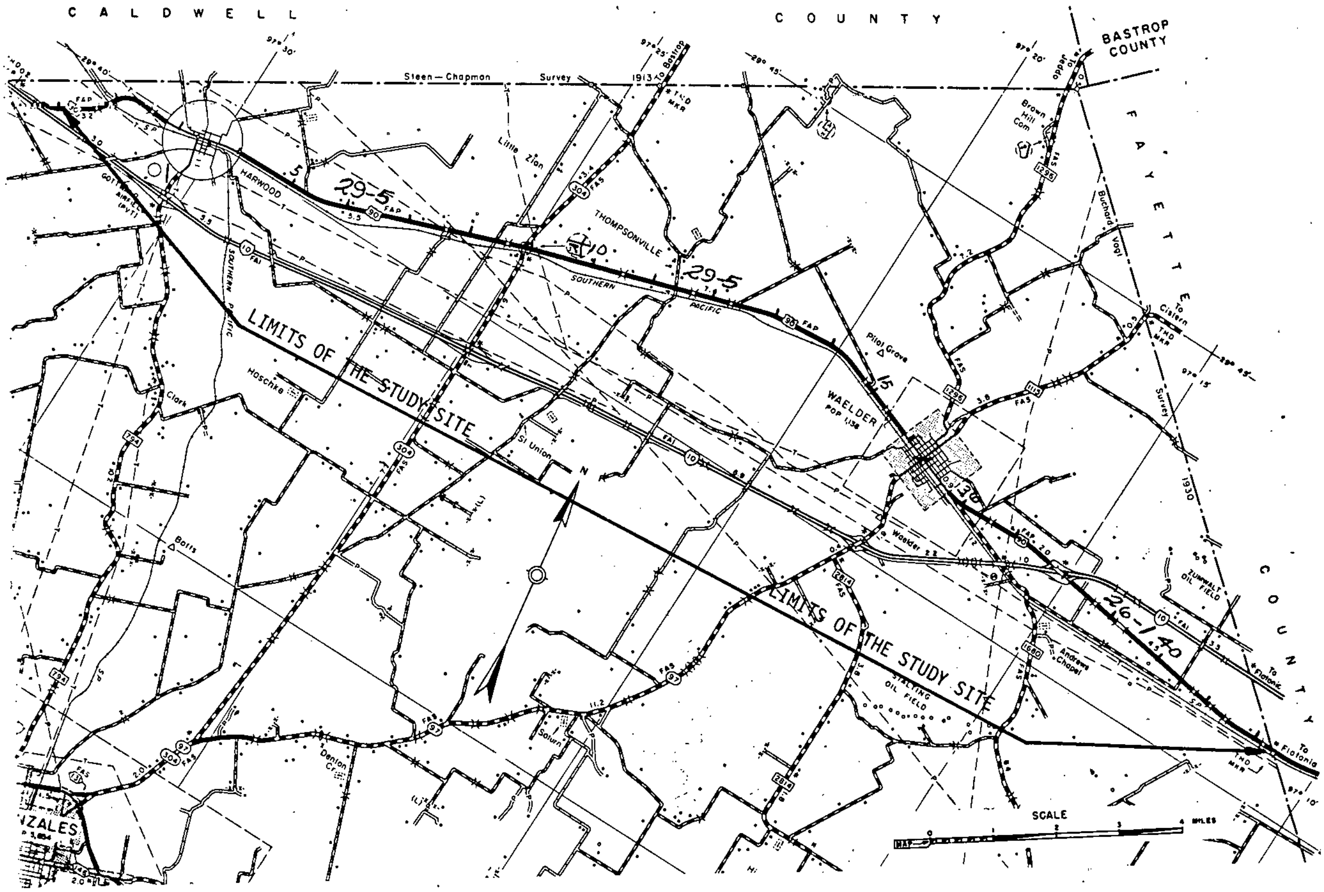

Figure 4. Specific site location map.

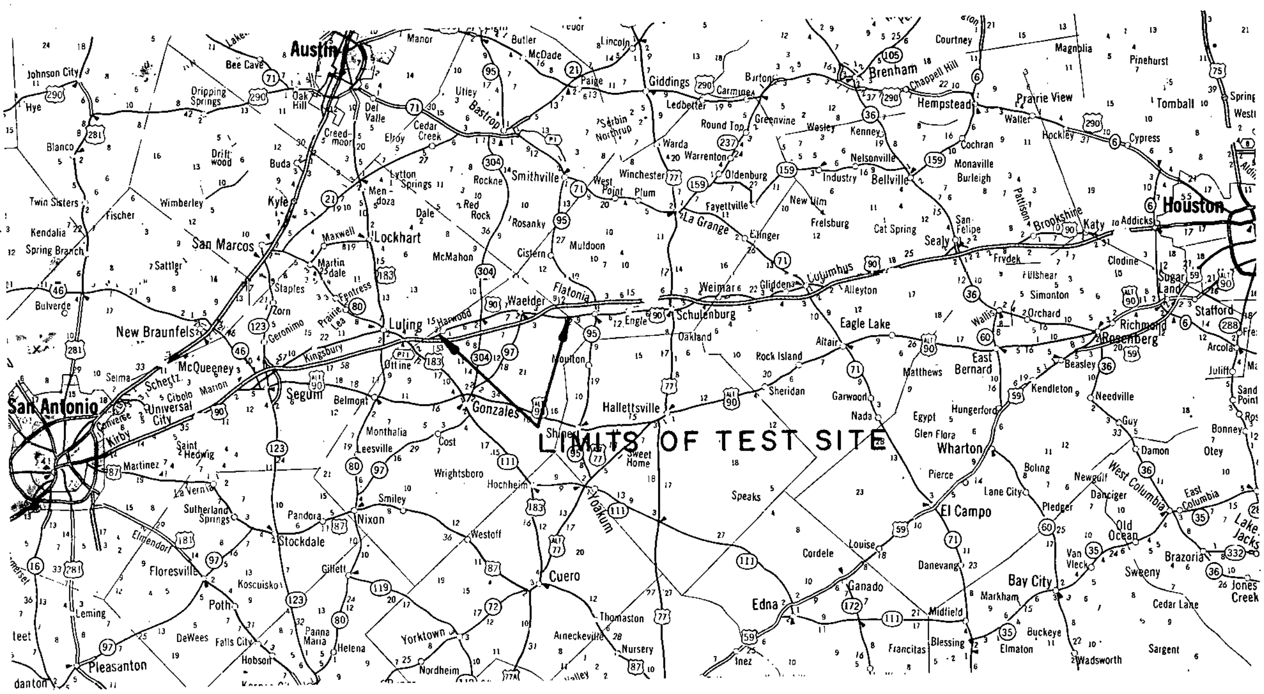

Figure 5. General site location map.

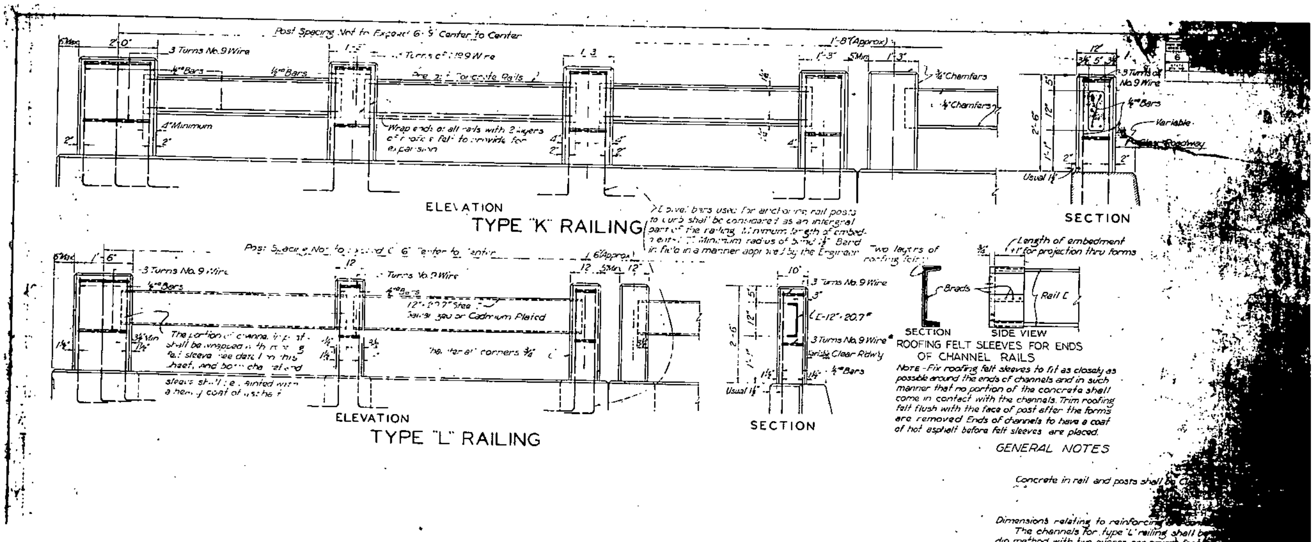

Figure 6. Original plan of type K and type L railing. (Drawing dated 1932)

Description of the Narrow Bridges

The bridges located in this section of U.S. 90 are typical of those on many miles of older two-lane highways in Texas. Two general types of bridge rails are present: (1) a concrete rail system with a curb (Type K Rail System) and (2) concrete posts with a 12-inch steel channel rail (Type L Rail System). The details of both the Type K and Type L bridge rails are presented in Figure 6. This figure was taken from the original plans, dated 1932. The two general bridge types located in the study section can be grouped according to the type of bridge rail used. Approach and bridge data are presented in Table 4.

Traffic Characteristics at the Study Site

Traffic classification data for the years 1969 and 1970 are presented in Table 5. These data are representative of the traffic pattern throughout the study section.

Speed data were not available; however, the posted speed for both the "before" and "after" periods was 70 mph. It is assumed that the speed trends on this section approximated the trends for the entire state of Texas. Thus, an average speed near 65 mph with an 85th percentile slightly over 70 mph is the assumption.

"Before" Treatment of Narrow Bridges

A recognition that the bridges in the study section represented a significant hazard resulted in some safety treatment prior to the extensive modifications undertaken in the summer of 1970. In general, similar treatments were applied to all the bridges in the area with local variations to adapt to specific site conditions. The basic treatment for each end of the structures is shown in Figure 7.

"After" Treatment of Narrow Bridges

The safety treatment recommendations for the restricted-width bridges were fundamentally the same, varying only in the treatment of the approach rail after its passage onto the bridge. Where no safety walk was provided, the approach rail was continued across the bridge and anchored directly to the concrete posts of the old bridge rail. For appearances, the top of the posts and the old concrete rail were removed and the posts were recapped. Where a safety walk was provided,

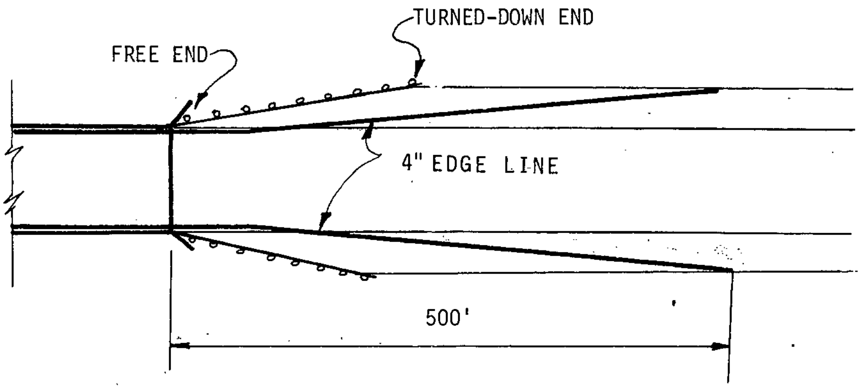

Figure 7. Typical "before" treatment.

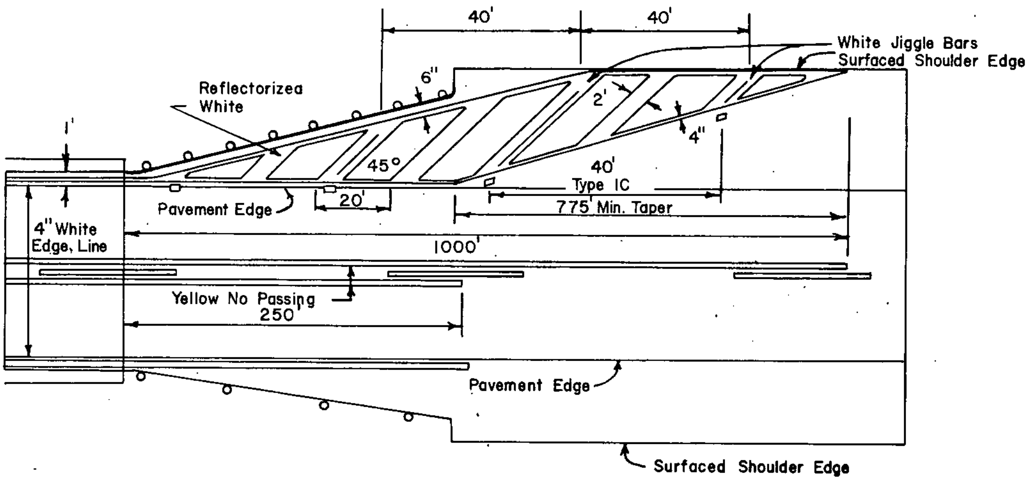

Figure 8. Typical approach treatment of restricted-width bridges.

TABLE 5

VEHICLE CLASSIFICATION DATA
1969 and 1970

		1969	1970	
ADT		4780 vpd	5690 vpd	
Cars		3635	4315	
Trucks (SU)	24.6%	511	647	23.4%
Trucks (combinations) and cars with trailers		607	683	
Buses		24	29	

the guardrail was turned down and bolted to the safety walk on the bridge. Figure 8 shows the typical approach treatment of restricted-width bridges. The corrective measures included:

1. A 4-in. edge line from a point 1,000 ft from the bridge on the outside edge of the shoulder, tapering to the roadway pavement edge approximately 225 ft from the bridge and extending across the bridge.

2. Two-foot wide diagonal shoulder markers at 45°, placed at 20-ft centers.

3. Raised jiggle bars on every fourth diagonal shoulder marker.

4. Raised pavement markers just inside the edge line on 40-ft centers.

5. Approach guardrail beginning about 225 ft in advance of the structure and at an offset of 8 ft, tapering to the bridge and continuing onto or across the bridge. The length of the approach rail varied as necessary to meet local conditions.

6. Post-mounted delineators placed behind the guardrail.

In all instances, a smooth and continuous bridge rail resulted from the treated condition.

A typical installation of the metal beam guardrail is illustrated in Figures 9 through 16. Figure 15 shows the approach treatment clearly.

Figure 9. Existing structure with approach guard fence.

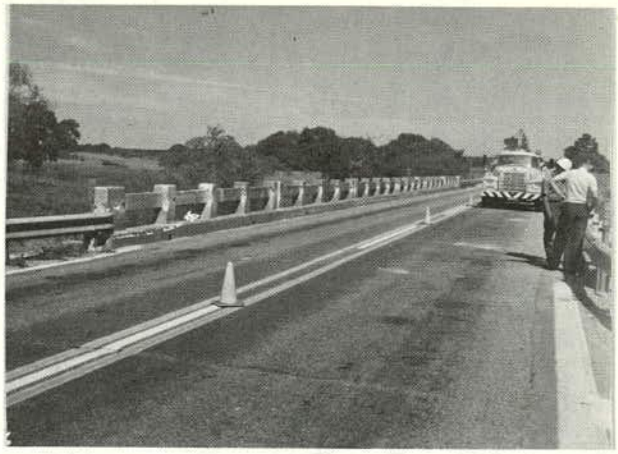

Figure 10. Chipping corners of concrete railing to expose reinforcing steel so that it could be cut.

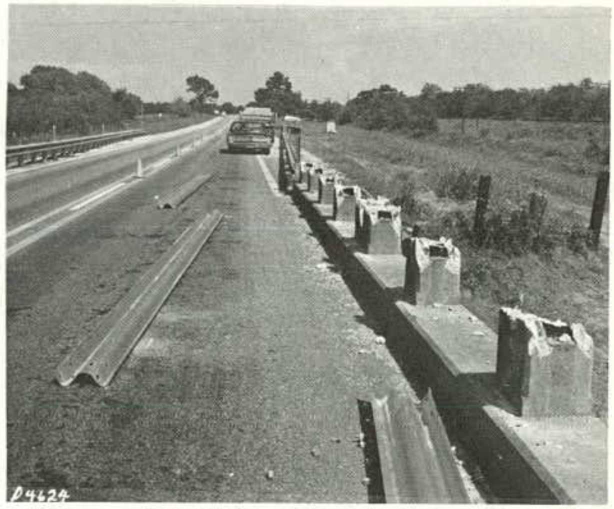

Figure 11. Concrete posts and rail broken off.

Figure 12. Picture shows how a tamp-in was placed in this existing concrete post so that the flex-beam rail could be attached.

Figure 13. Flex-beam rail attached to concrete posts.

Figure 15. Completed project picture shows flex-beam rail across bridge with approach rail attached.

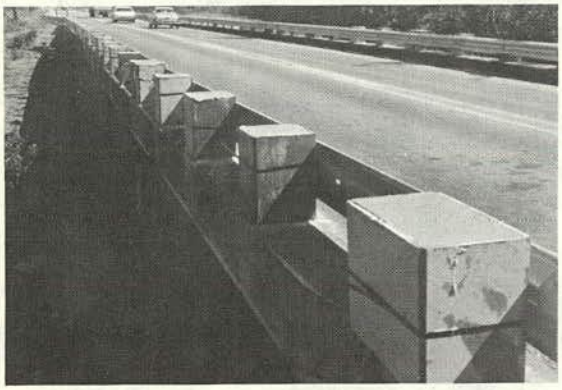

Figure 14. Tops of broken concrete posts formed and concrete poured.

Figure 16. Another picture from opposite end showing completed project.

Comparison of "Before" and "After" Accident Experience

The "before" and "after" accident experience for the study section is presented in Table 6. Table 7 contains the annual accident rate adjusted for the difference in time periods of data accumulation and traffic volume for both the "before" and "after" conditions. The "before" rate has been used to compute the expected accident experience for the "after" period. The expected accident values and the observed accident experience during the "after" period are presented in Table 8. The Poisson statistic has been used to compute the probability of the observed "after" accident experience that could occur by chance alone.

Assuming a random accident pattern with an expected rate of 9.2 accidents/17 months, the significance of the accident reduction can be determined using the Poisson statistic.

Hit Side of Bridge

$m = 9.2$

$P(x>1) = 1 - [P_{(0)} + P_{(1)}] = 1 - 0.001$

$= 0.999$

∴ The accident reduction is highly significant.

Hit Bridge End or Approach

$m = 9.2$

$P(x>3) = 1 - [P_{(0)} + P_{(1)} + P_{(2)}$

$+ P_{(3)}] = 1 - 0.018 = 0.982$

∴ The accident reduction is highly significant.

The derivation of the number 9.2 (the number of accidents expected in a 17-month "after" period) is as follows:

(1) $\frac{\text{10 accidents x 12 mo/yr}}{\text{22 "before" months}}$

= 5.45 accidents/yr.

(2) 5.45 acdt/yr ÷ 4.780 No. of thousands of ADT "before"

= 1.14 acdt/yr/1000 ADT.

(3) 1.14 x 5.69 No. of thousands of ADT "after" x $\frac{\text{17 "after" mo}}{\text{12 mo/yr}}$

= 9.2 accidents expected in 17-month "after" period.

This safety treatment achieved a highly significant reduction in reportable accidents on the restricted-width structure. The accident analysis shown may be favorably biased due to regression artifacts. Therefore, the level of effectiveness of the bridge treatments in question may be a bit optimistic.

TABLE 6

"BEFORE" AND "AFTER" ACCIDENT EXPERIENCE

			Accidents (No.), by Type			
Time Span	Time period (months)	ADT (vpd)	Hit Side of Bridge	Hit Bridge End	Hit Approach Bridge Rail	Total
(Before) Jan 69 - Oct 70	22	4780	10	7	3	20
(After) Nov 70 - Mar 72	17	5690	1	2	1	4

TABLE 7

"BEFORE" AND "AFTER" ACCIDENT RATE
(Combining Hit Bridge End and Hit Bridge Approach End)

	Rates	
	Hit Side of Bridge	Hit End of Bridge or Approach Rail
Before	1.14 acdt/yr/1000 ADT	1.14 acdt/yr/1000 ADT
After	0.12 acdt/yr/1000 ADT	0.37 acdt/yr/1000 ADT

TABLE 8

EXPECTED AND OBSERVED ACCIDENT EXPERIENCE FOR "AFTER" PERIOD

	Hit Side of Bridge	Hit End of Bridge or Approach Rail (accidents/year)
Expected (based on before rate)	9.2	9.2
Observed	1	3

Cost of Safety Improvements

The cost of safety improvements was estimated on the basis of force account work. Funds were allocated by these estimates, and the work was accomplished within the funds available. Table 9 contains the Texas Highway Department's cost estimate for the safety improvements within the study section.

TABLE 9

ESTIMATED COST OF RESTRICTED-WIDTH BRIDGE IMPROVEMENTS ON U.S. 90

Item	Cost
Guard fence	$20,500
Shoulder markings	5,200
Break-back of concrete posts	8,510
Engineering and contingency costs	3,290
TOTAL COST	$37,500

The average cost to treat bridges with a concrete rail was $3,240 per structure and with the steel channel rail $3,550 per structure.

DRIVER BEHAVIOR AS AN INDICATOR OF POTENTIAL BRIDGE HAZARD

Field observations of traffic behavior at 25 bridge sites showed that drivers slow down approximately 2 mph when approaching a bridge. If drivers recognized the bridge as a potential hazard, this recognition did not result in significant speed reductions. However, driver reaction to a hazard was indicated by the lateral movement of a vehicle approaching the bridge; that is, a gradual movement of the vehicle toward the centerline. In extreme cases a vehicle crossed the centerline. Where the bridge width is less than the roadway width, part of the lateral movement is absolutely necessary in order to avoid a collision with the bridge rail. In this case the driver may not recognize a hazard but does recognize a need to move toward the centerline. This repositioning is evidence that a hazard exists whether or not it is recognized by drivers.

The linear regression function shown in Figure 17 was determined by the method of least squares. Examination of this function shows that lateral repositioning varies from less than 1 ft on bridges more than 27 ft wide to more than 2 ft for bridges 15 ft wide.

Figure 18 illustrates the relationship between average lateral movement and the ratio of bridge width to roadway width.

When Figure 17 is compared to Figure 18, it is seen that relative bridge width is a better predictor of lateral movement (LM_{avg}) than absolute bridge width; i.e., the linear regression of LM_{avg} on *absolute* bridge width accounts for 43% of the variance in LM_{avg} while the regression of LM_{avg} on *relative* bridge width accounts for 61% of the variance. In fact, the ratio concept explains why the data from the Mammoth Bridge (on U.S. 77, Arizona) falls so far from the main data trend in Figure 17. Although the Mammoth Bridge is 24 ft wide, the approach roadway width is 40 ft. This means that drivers can position their cars well to the right of the centerline which requires a *relatively* large lateral movement when a *relatively* narrow bridge is approached. Thus, not only *absolute* narrowness needs to be considered, but also *relative* narrowness. Since end points of hazard recognition have been defined with respect to *absolute* narrowness, it is now appropriate to define end points with respect to *relative* narrowness. Figure 18 shows that little lateral adjustment takes place if the ratio of bridge width to roadway width is 1.25 or greater. As this ratio decreases to 0.5, severe lateral movement of 4 ft is indicated. This represents an extreme constriction of the available lateral space where the bridge width is half the width of the approach roadway. One might expect that there would be a relatively high degree of correlation between the *absolute* narrowness and the *relative* narrowness of the bridges studied. However, Figure 19 shows that absolute bridge width and relative bridge width are only slightly correlated (R^2 = .078). Considering the relatively small correlation between these two variables, it follows that the safety of a bridge should be defined in terms of both absolute width and relative width.

Hazard, the reciprocal of safety, should also be defined in terms of absolute bridge width and relative bridge width.

The argument that lateral movement indicates the driver's recognition of potential hazard is extended by another statistic which should relate directly to degree of hazard. This statistic is the proportion of drivers who violate the centerline while crossing a bridge. In opposed traffic, this statistic is a low number. This means that opposing traffic represents a constraint to the driver's behavior. However, in unopposed traffic, the centerline violations represent the position that the driver would prefer for his vehicle. The number of centerline violations on two-way bridges where traffic speeds are not exceptionally low appears to indicate the potential hazard of a bridge.

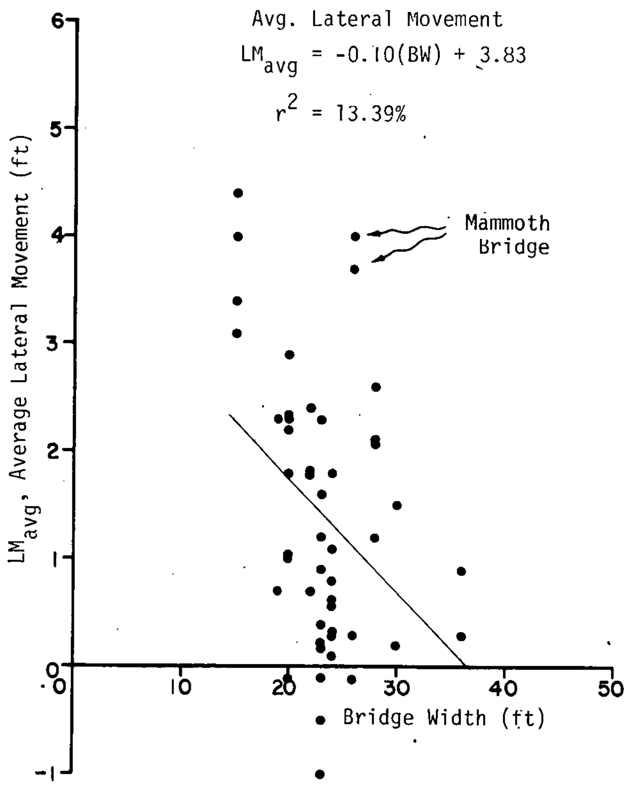

Figure 17. Average lateral movement as a function of bridge width [$LM_{avg} = D_1$ (1200 ft from bridge end) - D_1 (at bridge end)].

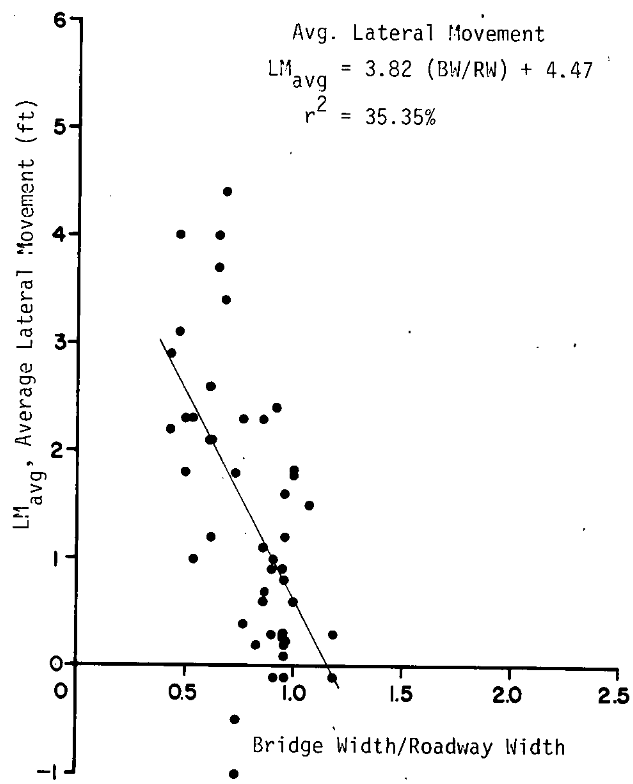

Figure 18. Average lateral movement as a function of the ratio of bridge width to roadway width.

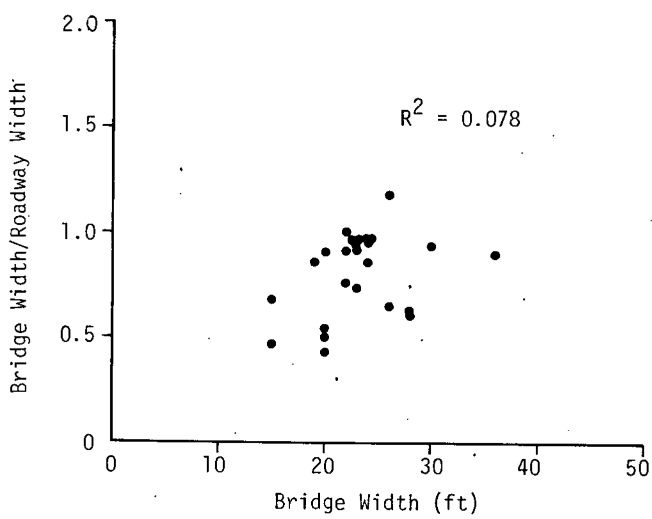

Figure 19. Relationship between relative and absolute measures of bridge width.

Interpretation of the Narrow Bridge Problem

The narrow bridge problem is but one of the situations where hazards are increased by restriction of access to the roadside or by the reduction of effective roadway width. For economic reasons, bridge railings must be placed close to the pavement edge. Thus, all bridges represent a vehicle-fixed-object collision potential. When the constriction at a bridge is perceived as a hazard, the driver may attempt to compensate by slowing down or laterally shifting position, or both. These maneuvers may conflict with other vehicle movements and result in vehicle-vehicle or vehicle-bridge collisions. The roadside constriction caused by a bridge reduces the opportunity for a driver to successfully complete an evasive maneuver, whether the need for the maneuver stems from a bridge influence or from an unrelated condition.

Drivers reduce speed and move toward or across the centerline at certain bridge sites. This observation suggests that drivers recognize the bridge and other vehicles as hazards. The regression line in Figure 17 indicates that the average lateral movement varies from 2.3 ft (at a 15-ft wide bridge) to 0 ft (at a 36-ft wide bridge). For bridge widths between 23 ft and 27 ft, the average lateral movement varies between 1.4 ft and 1.0 ft. The points indicate considerable scatter. However, the conclusion is that bridges less than 23 to 27 ft wide might be considered narrow. Undoubtedly, the relation between roadway width and bridge width has an effect, but this effect has not been demonstrated.

The drivers observed in this research also made large lateral position adjustments when approaching *relatively* narrow bridges (where the bridge roadway width was less than the approach roadway width). Thus, any bridge where the *relative width ratio is less than 1.25* should also be considered *narrow*.

The research also indicated that in an unopposed condition, most drivers will place the left edge of their vehicles on the centerline on bridges 18 ft wide and slightly less. Thus, for automobiles, a bridge roadway *narrower than 18 feet* should be considered a *one-lane bridge*. Where commercial vehicles are a significant percentage of the traffic volume, any bridge roadway *narrower than 20 feet* should be considered a *one-lane bridge*. The importance of the facility and its traffic volume will influence the determination of degree of hazard and the selection of the appropriate treatment.

CHAPTER THREE

APPRAISAL AND APPLICATION OF RESULTS

APPRAISAL

The research performed in pursuit of project objectives can be summarized under the following topics:

1. A Nationwide Narrow Bridge Survey.
2. The Field Study of 25 Selected Bridges.
3. The Analysis and Interpretation of Data from these Field Studies.
4. The Discovery of an Effective Treatment at Several Narrow Bridge Sites.
5. The Development of a Bridge Safety Index.
6. The Development of Guidelines for Treatment of Potentially Hazardous Bridges.

In developing an appraisal of the results, there is a serious inclination to emphasize the positive aspects and pass over the areas that are still relatively undefined or that present unexplained anomalies. However, this chapter will tell the reader where we stand in our search to define, understand, and correct the narrow bridge problem in the United States.

1. The Narrow Bridge Survey was a questionnaire sent to each of the 50 states and District of Columbia. The specific questions that were asked were designed to determine the extent of the individual state's experience in recognizing, defining, and correcting hazardous bridge sites. The range of responses was predictable, varying from none to comprehensive. The main findings from the survey show that there is a prevalent narrow bridge problem, and that many states are seeking appropriate ways to deal with it.

2. The Field Studies conducted at 25 selected bridge sites in the states of Arizona, Maine, Minnesota, Missouri, New Mexico, Texas, and Virginia resulted in specific data which defined vehicle speed and lateral position in terms of absolute and relative bridge width. The information is valuable if these two factors can be shown to indicate relative degrees of safety.

3. The Analysis and Interpretation of Data from the field studies took several forms, each limited because only two dependent variables were observed

(speed and lateral movement) and because of the relatively short observation times on the 25 bridges.

One analysis attempted to rank the independent variables in order of their relative influence on the dependent variables. The results were predictable, with approach speed, the most significant factor influencing change in speed; and bridge width, the primary influence on change in lateral position.

Other analyses of change in lateral position as a function of bridge *absolute* width and *relative* width (the ratio of bridge width to roadway width) provided the main relationships used to define potential hazard and to indicate the need for corrective measures.

Several "low profile" signing and delineation treatments were applied to four bridges. Analysis of traffic behavior before and after these treatments yielded generally small changes, or no change at all.

4. The Discovery of a Highly Effective Treatment of a series of bridges on U.S. 90 in Gonzales County, Texas, supplied an important case study of narrow bridge sites. By using sound engineering principles in the application of signing, delineation, channelization, and refurbishment of bridges, the accident rate was substantially reduced. This limited verification provided sufficient evaluation to indicate good probability of success when recommended corrective measures are implemented.

5. The Development of a Bridge Safety Index (BSI) is a significant accomplishment of this study. It is based on a limited amount of data plus the experience and opinions of the researchers and should be verified and/or modified by operating highway agencies. However, it has the advantage of being quite simple and uses readily available information. Because of the need for a realistic method of estimating the relative degree of hazard of various bridge sites where extensive accident records are not available, the BSI concept should be used on a trial basis to develop verification and modification information. The numerical values of the bridge evaluation factors may need to be revised with the collection and analysis of more information. However, when considering the criticality of the need for immediate corrective actions at restricted-width bridge sites to reduce accidents, it is apparent that use of any available tools with reasonable probability of success is imperative.

6. The Development of Guidelines for treatment of potentially hazardous bridges is another area where many liberties have been taken in the interest of expediency. Examples show the effectiveness of some treatments and the ineffectiveness of others. However, no treatments are recommended that have had any negative influence on safety. Corrective treatments involving speed control, channelization delineation, and refurbishment are presented. These measures will not solve all the problems, but they will alleviate some. Realizing the expedient method of selection, these corrective treatments and recommendations are not advanced as a proposed standard, but merely as treatments which could be considered for implementation for further evaluation based on an engineering analysis of a problem location.

ANALYTICAL PREDICTIVE METHODS AND ACCIDENT ANALYSES

Two methods are available to define hazardous bridges. The first is the analysis of particular bridge-roadway environments to determine the existence of a potential hazard; the second is the identification of hazardous bridges from accident records. The first method has been the primary thrust of this work, because it is based on engineering information as observed and evaluated in the field.

The second method relies on the use of statistics which provide a history of collisions with the structure, or with other vehicles, or a combination of the two. Such information can be used to substantiate the engineering analyses suggested in this report. Accident data should be monitored on a continuing basis to supplement analytical and predictive techniques. In some instances, accident statistics may be the most important indicator for action. An appraisal of conditions at selected sites should be made, however, even in the absence of accident information.

Thus, through experience and deduction we might develop comprehensive predictive tools. Continuing effort should be devoted to developing improved classification techniques. The goal of such an effort would be the reduction or elimination of accidents. Therefore, the prediction of hazardous bridges (Method 1) has some advantages over the discovery of hazardous bridges (Method 2).

APPLICATION OF BSI TO SPECIFIC BRIDGES

The BSI concept may be applied to evaluate bridge hazard if specific roadway, bridge, and traffic operational features are defined. These include:

1. Bridge roadway width.
2. Approach roadway width at a distance of approximately 1200 ft in advance of the bridge.
3. Approach lane width in advance of the bridge (1200 ft).
4. Shoulder width in advance of the bridge (1200 ft).
5. Shoulder width on the bridge.
6. Approach sight distance in advance of the bridge.
7. Traffic speed in the bridge vicinity.
8. Degree of horizontal curvature on bridge approach.

9. Tangent distance from a horizontal curve to the bridge.

10. Approach and departing roadway grade.

11. Presence of intersections, roadside commercial establishments, railway grade crossings, or other such potential conflict points within the 1200-ft approach that would adversely affect the driver's bridge crossing task.

12. Traffic volume, from which may be determined a volume/capacity ratio.

13. Traffic composition, with particular emphasis on percentage of large trucks and/or slow-moving atypical vehicles.

14. Structural evaluation of bridge rail, approach and departing guardrail, and anchorage connections both at the bridge and at the free ends of the approach or departing guardrail system from the viewpoint of impact safety.

Many of the above may be determined from photographs, inventory records, photologging records (if a state uses this technique), "as-built" plans or construction plans, and records of traffic operating characteristics. In addition, maintenance personnel who are familiar with the bridges in their area generally constitute a valuable information source regarding bridge and highway characteristics. Establishing photographic procedures to obtain much of the necessary information could be easily accomplished.

One of the 25 study bridges is evaluated in detail to illustrate the application of the BSI concept. When necessary, the reason for selection of a particular F-factor is amplified. Table 10 presents a BSI and BSI' determination for each study bridge. All ratings were developed from photographs of each bridge and from sketches and notes made by the researchers while conducting the studies.

Bridge - U.S. 89, Near Tucson, Arizona (See also Appendix A)

Figure A-1 (page 30) includes photographs of this bridge. The perspective of this bridge is one of "openness," straight alignment, and "clean" bridge rail lines; in essence, a bridge that by many of the criteria in the BSI determination should rank relatively high on the rating scale. The F-factors and reasons for their selection are presented below.

F_1 -- Bridge width = 36 ft, therefore F_1 = 20. (See Figure 1, page 6).

F_2 -- Bridge width/approach width = 36/40 = 0.9, therefore F_2 = 5.

F_3 -- Approach guardrail and energy absorbing bridge rail continuous and safety treated (flared) at the free ends. Vehicle snagging is not expected with the railing type. The guardrail factor, F_3, is therefore 20.

F_4 -- Approach sight distance is 800 to 1000 ft; approach speed is 54 mph. This ratio is at least 800/54 or approximately 15; therefore F_4 = 5.

F_5 -- Tangent distance in advance of this bridge is in excess of 1000 ft with no horizontal curvature. The ratio is >300, therefore F_5 = 5.

F_6 -- The bridge and both approach and departing roadway are on level grade, thus the grade continuity factor, F_6, is 5.

F_7 -- 8-ft approach shoulder is reduced to 6 feet on bridge; (i.e., a 25 percent reduction); therefore F_7 = 4.

F_8 -- Average daily traffic of approximately 3400 vehicles yields volume to capacity ratio of approximately 0.15; thus F_8 is assigned a value of 4.

F_9 -- Because traffic composition data are not readily available for this bridge, an F_9 value of 3 was selected. Knowledge of the traffic composition on this highway would permit refinement of the factor.

F_{10} -- Few roadside distracting features are evident from the photograph. On-site inspection or review of roadway inventory records would permit better assignment of the appropriate factor. The F_{10} value selected was 4.

The sum of the above factors produces a BSI of 75. Finally the value of the speed ratio is determined as follows: (1) The "appropriate speed" is determined from Figure 3 (page 9) for a BSI value of 75 as 55 mph. This is V_a. Then the 85th percentile speed of traffic on this bridge is determined from the on-site speed survey. This value, V_{85}, is 59 mph. The value of this speed ratio is then 55/59 or 0.93. By multiplying this ratio by BSI (0.93 x 75) the value of BSI' is determined to be 70.

The factors having values less than 4 indicate features that might be modified to improve bridge safety. However, the close correspondence of the 85th percentile speed and the "appropriate speed" indicates the bridge may be reasonably safe from an operational standpoint.

USE OF BSI TO EVALUATE PRIORITIES AND ISOLATE APPROPRIATE TREATMENTS

The ultimate use of all information developed in this research and all previous related research is the determination of cost-effective priorities and treatments. These determinations provide a tool for expending public funds so that maximum effectiveness is achieved.

TABLE 10

BSI FOR STUDY BRIDGES - BASED ON TTI STUDY

Bridge	F_1	F_2	F_3	F_4	F_5	F_6	F_7	F_8	F_9	F_{10}	BSI	BSI'
Figure A-1 U.S. 89 --Tucson	20	5	20	5	5	5	4	4	3	4	75	70
Figure A-1 S.H. 77 -- Arizona	20	1	5	4	4	4	2	4	3	5	52	26
Figure A-1 S.H. 85 (S) -- Arizona	19	5	1	3	5	5	1	5	3	5	52	24
Figure A-1 S.H. 85 (N) -- Arizona	17	5	1	3	5	4	5	5	3	5	54	27
Figure A-2 -- Sibley U.S. 2 -- Maine	20	20	1	3	5	5	5	4	3	3	69	66
Figure A-2 -- Sebasticook U.S. 2 -- Maine	18	15	1	4	5	3	5	4	3	1	59	44
Figure A-3 -- St. Croix T.H. 48 -- Minnesota	0	1	5	3	5	4	1	5	3	5	32	14
Figure A-3 -- Gray's Bay T.H. 101 Minnesota	19	1	1	3	5	4	1	3	3	5	45	35
Figure A-3 -- B.N.Tr. T.H. 10 -- Minnesota	17	1	1	3	5	4	1	1	3	5	41	16
Figure A-3 -- Rum River CSAH 7 - Minnesota	0	1	5	3	3	5	1	5	3	4	30	15
Figure A-4 -- Camdenton U.S. 54 -- Missouri	15	1	10	3	5	5	1	4	3	4	51	26
Figure A-4 -- Damsel U.S. 54 -- Missouri	15	1	1	2	4	4	1	3	3	2	36	17
Figure A-4 -- Osage U.S. 50 & 63 -- Missouri	20	1	20	5	5	5	2	3	3	5	69	56
Figure A-4 -- Schubert U.S. 50 & 63 -- Missouri	15	1	1	3	5	4	1	3	3	4	40	16
Figure A-5 -- Santa Fe (1) U.S. 285 -- New Mexico	19	10	1	5	5	5	1	5	3	5	59	33
Figure A-5 -- Santa Fe (2) U.S. 285 -- New Mexico	19	10	1	3	5	5	1	5	3	4	56	31
Figure A-5 -- Los Alamos S.H. 4 -- New Mexico	19	10	1	3	3	4	1	3	3	4	51	32
Figure A-5 -- Glorietta S.H. 50 -- New Mexico	18	5	1	3	3	4	1	5	3	3	40	18
Figure A-6 -- Caldwell S.H. 21 -- Texas	18	5	5	4	4	5	1	4	1	4	51	24
Figure A-6 -- Navasota S.H. 6 -- Texas	20	1	10	5	5	5	2	3	1	5	57	30
Figure A-6 -- La Grange U.S. 77 -- Texas	20	10	5	3	5	5	3	4	1	5	61	35
Figure A-7 -- Zion U.S. 250 -- Virginia	19	10	5	1	5	2	5	4	3	4	58	36
Figure A-7 -- Verona U.S. 11 -- Virginia	19	1	1	2	4	4	1	3	3	2	40	17
Figure A-7 -- Fork Union Rt. 6 -- Virginia	19	10	1	1	1	5	5	5	3	4	54	30
Figure A-7 -- Palmyra U.S. 15 -- Virginia	19	10	1	2	3	3	5	4	3	3	53	30

Note: Figures A-1 through A-7 are found in Appendix A.

In general, the choice of best treatments and priorities would be determined by choosing those projects that maximize the net dollar benefit from the treatments. Unfortunately, with the current state of the art, it is not possible to measure the value of the treatments in dollar terms. Therefore, in this effort it is necessary to use a priority method that simply gives a conceptual ranking criterion which may be augmented by the decision-maker's judgment.

The BSI can be used as the basic tool for evaluating alternatives and setting priorities. Conceptually, as the BSI decreases, the need for treatment increases. In addition, as the number of drivers who would benefit from the treatment increases, so would the relative priority. This conceptual relationship would continue to hold unless the cost of providing the treatments became excessive as compared to the effectiveness of the treatments. Thus, in setting priorities, it is necessary to consider the hazard associated with the bridge, the degree to which this hazard may be reduced, the number of people benefiting from reducing the hazard, and the cost associated with reducing the hazard (by treatments).

A generalized model for setting priorities may be expressed:

$$PI = \frac{(BSI_A - BSI_B) \times KADT}{C} \qquad (3)$$

where: PI = priority index
BSI_B = bridge safety index before treatment
BSI_A = bridge safety index after treatment
$KADT$ = average daily traffic, in 1000's
C = cost of the treatment or bridge hazard improvement

The immediate problem with this model is the determination of BSI_A. In other words, given a BSI_B and a specific treatment, what changes would occur in the BSI? Obviously, if a bridge were widened from less than 20 ft to something greater than 24 ft a significant change would occur (see Figure 1, page 6). Thus, the bridge safety index would change. However, if the treatment is an edge line rather than widening, does this treatment effect a change in relative bridge lane width? It probably does. The question then becomes one of estimating how much effect the treatment has on the bridge safety index. This estimate cannot be determined at present except by very subjective judgments. It is desirable, therefore, simply to reduce the priority procedure to:

$$PI = \frac{KADT}{BSI} \qquad (4)$$

With this it is only necessary to evaluate current conditions at the bridge and the average daily traffic. The quotient of these two factors will give a relatively sensitive measure. The simplified model should be sufficient to give the initial impetus to corrective treatments. The procedure should be revised as data from valid evaluations of various bridge treatments and modifications become available. Then, the specification of various levels of treatments and their effectiveness in terms of dollars and benefits may be achieved.

The overall BSI does indicate the nature of appropriate corrective treatments. If the BSI indicates narrow lane widths, then the lanes could be widened. If this is not feasible from a cost standpoint, then motorists should be advised of the narrow lane widths and control exerted if it is impossible for vehicles to meet on the bridge. The extent of the advice and control becomes much greater as the probability for conflict on the bridge increases. Thus, not only does the BSI indicate that treatment is necessary, it also, along with ADT, suggests a level of treatment and an urgency of treatment.

After a suitable period of application of the BSI by a state, it should be possible to relate BSI, levels of treatment, effectiveness of treatment, and treatment costs. This could then be used to implement the more detailed priority model that includes cost-effective treatments determination.

Predictive methods are useful in identifying hazardous locations; then however, corrective measures need to be applied. Monitoring the results of corrective measures following installation is necessary to evaluate effectiveness. Thus, each of three steps--identification, correction, and evaluation--must be taken.

Recommended Corrective Treatments

Each of the bridge evaluation factors shows a need for some corrective treatment. This treatment may be applied to reduce the probability of accidents or to reduce the severity of accidents. Table 11 lists the several corrective treatments. Table 12 gives those treatments applicable to various desired changes. The following paragraphs discuss the treatment alternatives. It should be recognized that such factors as traffic volume and the proportion of commercial vehicles will influence the selection of an appropriate measure.

Widen Bridge --. This would be the most desirable of all alternatives from the safety standpoint although not necessarily fiscally prudent. The decision to increase lane widths (widen bridge) becomes increasingly more prudent as the average daily traffic and percentage of commercial vehicle traffic increases. To allow an extremely narrow bridge to exist on a facility with

TABLE 11

TREATMENT ALTERNATIVES

Treatment No.	Treatment Description
1	Change approach grades
2	Realign roadway
3	Install smooth bridge rail
4	Install approach guardrail
5	Place edge lines
6	Remove centerline for one-way operation
7	Place pavement transition markings
8	Install narrow bridge sign
9	Install stop, yield, or signalization
10	Transition shoulders to bridges
11	Advisory speed signs
12	Re-route commercial vehicles
13	Environmental control
14	Approach bridge delineation

TABLE 12

APPROPRIATE TREATMENT ALTERNATIVES

To Reduce Probability of Accidents	To Reduce Severity of Accidents
1. Manage speed -- use treatment alternatives 8, 9, 11	1. Manage speed -- use treatment alternatives 8, 9, 11
2. Change physical conditions -- use treatment alternatives 1, 2, 9, 13	2. Change physical conditions -- use treatment alternatives 2, 3, 4, 13
3. Change visual conditions -- use treatment alternatives 2, 3, 4, 6, 7, 10, 14	
4. Manage lateral position -- use treatment alternatives 2, 3, 4, 5, 6, 7, 10	
5. Increase expectancy -- use treatment alternatives 2, 4, 8, 9, 10, 11, 14	
6. Change traffic mix -- use treatment alternative 12	

an ADT of 10,000 and 10% commercial vehicles would be hard to justify, whereas the same bridge on a facility carrying 100 local drivers may be reasonable. Thus, the widening of a bridge should be related to the importance of the traffic facility. One treatment resulting in bridge widening without actual structural change is shown in Figure 20. This treatment, however, must include an analysis of increased loading and drainage changes.

Change Approach Grades --. Where grade continuity is a problem, consideration should be given to major changes in grades of the approaching roadway.

Realign Roadway --. Where sight distance problems are apparent and traffic measures appear to fail, realignment of the bridge approach roadways may be the only acceptable alternative.

Install Smooth Bridge Rail --. A smooth bridge rail decreases the probability of snagging and increases the probability of redirection with less damage to vehicles. Also, depending on the manner of installation, the absolute width of the bridge may be increased as shown in Figure 21. Thus, this alternative may be extremely desirable, especially if frequent "on bridge" impacts with railing have been observed.

Install Approach Guardrail --. Approach guardrail should be used at all restricted-width bridge locations, following the examples and standards in *Highway Design and Operational Practice Related to Highway Safety* (5). The approach guardrail serves several functions, including redirecting errant vehicles at critical points and preventing vehicles from impacting the ends of bridges. The approach rail must be correctly tied to the bridge end and/or bridge rail system.

Place Edge Lines --. Edge lines are effective visual guides for the driver. They are useful in showing width continuity from the approach roadway to the structure. Edge lines also can be used in the transition from a wide roadway approach to a restricted-width bridge.

Remove Centerline Stripes on One-Lane Bridges --. Where one-lane operation is necessary on the bridge, any centerline stripes should be removed from the bridge and approaches. Markings should be provided for the transition from two-lane to one-lane operations.

Place Pavement Transition Markings --. Pavement transition markings are necessary where large differences exist between the approach roadway width and the bridge width. On higher-speed highways the single edge line may not be sufficient. In these areas, diagonal shoulder markers, rumble strips, and raised reflectors can be used effectively.

Install Narrow Bridge Sign --. Where a bridge is 24 ft or less in width or where the bridge width is substantially less than the approach width, the narrow bridge sign (W5-2, MUTCD) should be considered (4). Where the width is less than 20 ft, the one-lane bridge sign (W5-3, MUTCD) should be considered (4). Advance warning of the situation should be given.

Install Stop, Yield Sign or Signalization --. Where a bridge is less than 18 ft wide (20 ft where there is a high proportion of commercial vehicles), appropriate signs (such as one-lane, yield, stop, and advance warning) should be installed in accordance with MUTCD requirements (4). Where extremely high risk is involved, positive control (such as traffic-actuated signalization) should be considered.

Transition Shoulders --. When gross discontinuities occur (such as when a shoulder is dropped at the bridge) the driver should be warned. This may be done by paint markings, delineators, or pavement reflectors, which should begin approximately 1000 ft in advance of the bridge and gradually taper to the bridge. It is not suggested that the shoulder itself be tapered as the shoulder provides a necessary recovery area. Positive transition can be accomplished using the suggested measures.

Advisory Speed Signs --. Appropriate advisory speed signs may be used in conjunction with warning signs at narrow bridge locations.

Re-Route Commercial Vehicles --. This alternative in most cases probably is not viable. However, there may be situations where through commercial traffic should be re-routed around restricted or one-lane bridge sites.

Environmental Control --. Consideration should be given to the control or elimination of access, extraneous development, distracting lights, and other roadside disturbances (such as boat ramps and fishing docks) in the vicinity of restricted-width bridge sites. Excessive roadside activities are undesirable distractions to the driver.

Install Approach and Bridge Delineation --. Nighttime negotiation of narrow bridges appears to be especially hazardous. Appropriate delineation of bridge approach and the bridge railing should be provided the driver. Positive nighttime delineation of width transition is also desirable.

Possible Innovative Treatments --. The short-run goal of producing easily implemented research results precludes an extensive bridge-widening program or other such costly alternatives. However, there are possible innovative treatments that may be cost-effective methods of improving the safety of narrow bridges.

One interesting innovation has been used successfully at dangerous street locations in the city of Charlotte, North Carolina, and on nearby highways.

In June 1973, Mr. Herman J. Hoose, Director of Traffic Engineering, city of Charlotte, North Carolina, testified before the Subcommittee on Investigation and

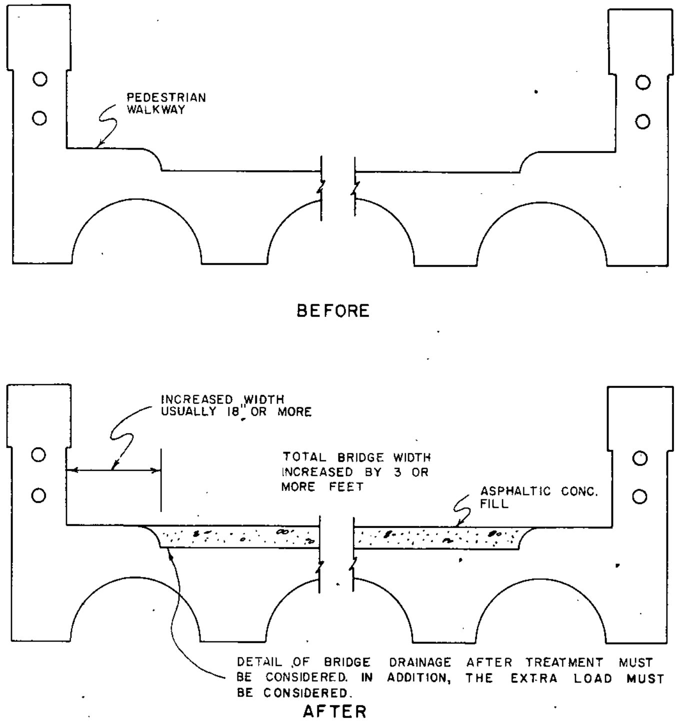

Figure 20. Increasing effective bridge width by elimination of pedestrian walks.

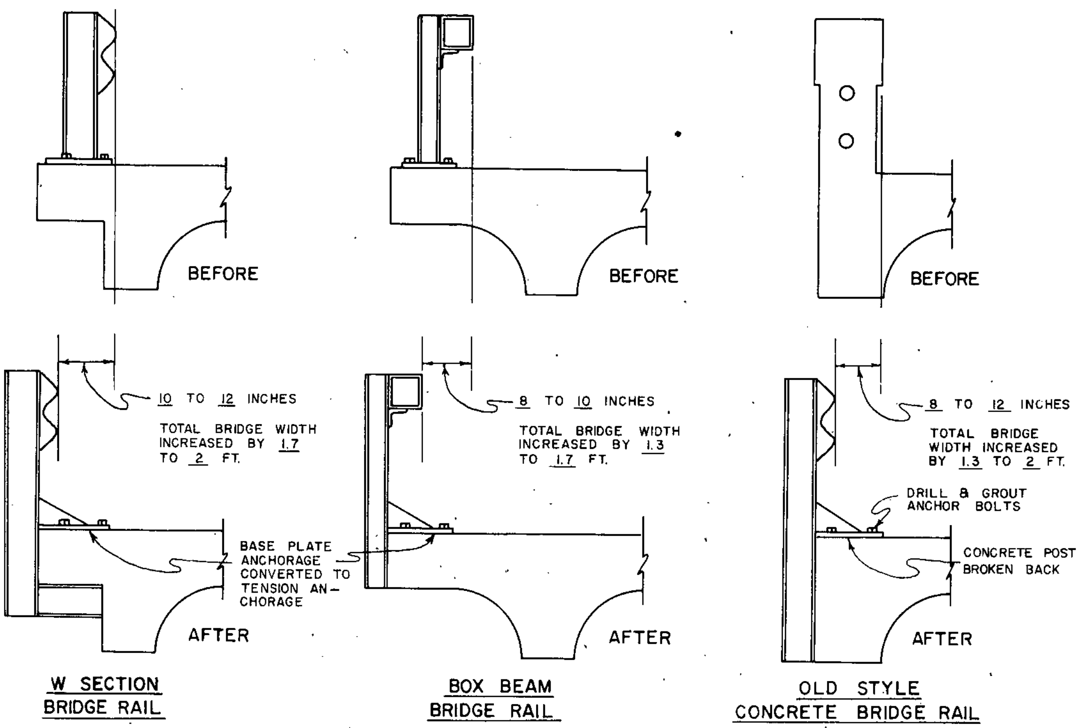

Figure 21. Examples of increasing effective bridge width without modifying basic structure by changing bridge rail structure.

Review of the House Committee on Public Works (*1*) concerning the development and installation of an electronic device employing loop detectors. The concept of this installation is to alert motorists of the major street that someone is attempting to enter or cross the intersection, and also to alert the motorist on the minor street that he is approaching a stop condition. The discussion and details of the devices employed in Charlotte indicate that similar devices can be used in some locations where painted stripes, delineation, and other passive measures need to be supplemented with active measures.

Such innovations are not "standard practice," but their use in hazardous locations is a feasible alternative which must be considered in solving the narrow bridge problem. The idea is to alert motorists that a bridge is either occupied by another vehicle or that the bridge is unoccupied. This concept might be applied where it is impossible for two vehicles to pass on the bridge or where such passing must be done at a crawl speed.

Where sight distance or other problems prevent the driver from observing the bridge at sufficient distance to determine if it will be occupied or unoccupied when he reaches it, it is necessary to advise the driver by other means. Detectors with actuated signal equipment and even variable message signs could be used for this purpose. This is not a viable solution for all narrow bridges, but on certain important facilities it may be acceptable and even cost-effective.

CHAPTER FOUR

CONCLUSIONS AND SUGGESTED RESEARCH

CONCLUSIONS

1. There is a significant national problem of hazardous highway bridges, and many states are searching for the most effective way of dealing with this problem.

2. A narrow bridge is not necessarily a hazardous bridge. Conversely, not all hazardous bridges are narrow.

3. The change in lateral position when approaching a bridge is related to the bridge *absolute* width and to the bridge *relative* width. As the bridge width decreases, the movement of vehicles toward and over the centerline increases. As the ratio of bridge width to roadway width increases, the lateral movement decreases, becoming minimal when values of BW/RW are larger than 1.

4. The change in lateral position when approaching a bridge may be taken as an indication of the driver's recognition of potential hazard. A definite hazard exists, whether recognized or not, in those cases where the bridge rail dictates lateral movement from the unconstricted normal position. (If vehicles move closer to or over the centerline they are obviously a greater potential hazard to opposing traffic.)

5. The average lateral movement of traffic becomes less significant for bridge widths between 20 ft and 30 ft. The data regression shows, in general, movements less than 1 ft laterally for bridge widths greater than 27 ft.

6. When both bridge and roadway widths are within the range of 30 to 40 ft, traffic lateral positioning on the roadway will be approximately equal to traffic lateral positioning on the bridge. This conclusion will not be valid unless bridge width is equal to or somewhat greater than roadway width.

7. There are a number of effective treatments available to increase the safety of highway bridges.

8. Specific combinations of treatments identified in this report have been shown to reduce bridge accidents significantly. Although the relative influence of individual treatments has not been shown, it may be concluded that safer bridges are produced by well-engineered combinations reflecting the objectives of (1) early warning, (2) bridge delineation, and (3) crashworthiness of rail structures.

9. The use of the Bridge Safety Index (BSI) and the associated Priority Index (PI) allows a rational determination of priorities in dealing with the hazardous bridge problem. Judgment must be exercised in using BSI and PI at bridge sites shown to be hazardous by the BSI and at the same time low in priority due to a low ADT.

RECOMMENDATIONS FOR FUTURE RESEARCH

There are two approaches to developing better definition and correction of the narrow bridge problem that are quite different in philosophy. The first may be termed the <u>direct</u> approach; the second, the method of <u>successive trial</u>.

The direct approach is taken by developing the basic data on all aspects of the narrow bridge problem and determining how each factor influences the situation. Once all factors are defined in terms of cause and effect, the situation is fully understood; and effective countermeasures are apparent.

The method of successive trial (or indirect approach) involves using whatever facts and opinions are available to arrive at interim definitions and treatments to solve a problem, to observe the degree of success of these definitions and treatments, and to make changes in them as experience allows discovery of errors and shortcomings.

Almost all problem solutions that are successful over a span of time rely on combinations of the two approaches. The current work has developed certain basic data in keeping with the direct approach and has monitored experience with certain treatments of the problem according to the indirect approach. The findings now can be applied on a trial basis, but careful records should be kept on the degree of success of the solutions recommended. It is time for a trial run.

It is recommended that each state enter into its own trial implementation period to apply and evaluate the concepts and proposed treatments that have been developed in this study. The states may first establish new weighting factors for the BSI for their use; the values provided in this report were based largely on the researchers' judgment and a limited sampling of bridges. At the most comprehensive level, state work might include the following:

1. Identification of all potentially hazardous bridges.
2. Priority ranking of bridges for treatment.
3. "Before" studies of driver behavior and accident records.
4. Determination of most effective feasible treatments.
5. Documentation of treatments used, including costs.
6. "After" studies of driver behavior and accident records.
7. Appraisal of treatment cost effectiveness.

After a period of at least two years, it may be of value to compile those data from all states and to reappraise the conclusions and recommendations made in this report.

TTI stands ready to consult with all states on the implementation of such an evaluation program.

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APPENDIX A

DRIVER BEHAVIOR STUDIES

Vehicle speeds and lateral positions on and adjacent to bridges were studied to identify parameters influencing safety at narrow bridges. The 25 study bridges were located in Arizona, Maine, Minnesota, Missouri, New Mexico, Texas, and Virginia. Data collected at these sites were compared with driver behavior reported previously by Walker (2). Only two-lane, two-way operations were considered for these comparisons.

SITE SELECTION

Highway department personnel in the respective states were given considerable latitude in selecting the potential study bridges. General guidelines included bridges meeting the following criteria:

1. Bridges were to be located on two-lane highways.

2. Bridges were to include:

(a) Those having widths less than the approach roadway (e.g., 22-ft bridge, 24-ft approach roadway).

(b) Those having widths greater than the traffic lanes, but less than the approach roadway (e.g., 28-ft bridge, 2 12-ft traffic lanes).

(c) Those having widths equal to the approach roadway.

3. Bridge length was unrestricted.

4. Average daily traffic was to be at least 100 vehicles per day.

5. Bridges were to include through and open truss, open deck type structures with or without curbs, and a variety of railing configurations.

A variety of roadway widths, bridge widths, lengths, types and geometry were selected so that different combinations of these factors could be included in this study. Roadway widths varied from 46 ft on 2 highways to 22 ft on several others. Bridge widths varied from 44 ft to 15 ft and bridge lengths from 1630 ft to 27 ft. The bridges studied were composed of pony and through trusses and concrete deck structures having post-and-beam railings.

Figures A-1 through A-7 show the bridge sites. Descriptive characteristics, average daily traffic, posted speed at each site are listed in the table of characteristics

SPEEDS AND TRANSVERSE POSITIONS OF VEHICLES ON BRIDGES.

Transverse positions and speeds of more than 2000 vehicles were obtained by both visual and filmed methods. In most cases vehicle placement and speed measurements were made at 1200 ft and 300 ft from each end of the bridge and also at each bridge end. The filmed data were reduced with a Vanguard Motion Analyzer to yield lateral placement and speed. The visual data were obtained by the use of binoculars and a radar speedgun. Reference marking patterns (see Fig. A-8) placed on the pavement using temporary marking tape were used in both techniques to obtain placement data.

Considerable similarities in the traffic movement on most bridge locations were noted:

1. The distance from the left wheels of the vehicle to the centerline of the highway, D_1, as shown in Figure A-9, was greater for vehicles facing oncoming traffic than for vehicles facing no traffic. This was observed 1200 ft from a bridge end. (Drivers tend to allow more space between their vehicles and the centerline when facing opposing traffic.)

2. The distance, D_1, was usually greater at 1200 ft from a bridge than at the bridge end. This was observed for vehicles in both meeting and non-meeting configurations. (Drivers move closer to the centerline when approaching a bridge.)

3. Vehicle speeds 1200 ft in advance of the bridge were, in general, slightly higher than speeds at the bridge. At 23 of the 25 sites, the 85th percentile speed exceeded the posted speed limit.

In order to generalize, the data were divided into two traffic situations: vehicles in the absence of oncoming traffic, and vehicles in the presence of oncoming traffic. The number of observations made with opposing traffic was fewer than observations with unopposed traffic. The data were averaged for all sites at a point 1200 ft in advance of the bridge. The overall average values were determined.

For the less critical case (no oncoming traffic), the averages were:

$$\begin{array}{rl} D_1(1200') & = 2.6 \text{ ft} \\ -D_1(\text{bridge}) & = 1.4 \text{ ft} \\ \hline \Delta D_1 & = 1.2 \text{ ft} \end{array}$$

$$\begin{array}{rl} \text{Speed}(1200') & = 49 \text{ mph} \\ -\text{Speed(bridge)} & = 47 \text{ mph} \\ \hline \Delta\text{Speed} & = 2 \text{ mph} \end{array}$$

D_3/D_1	for roadway (1200') (lane plus shoulder)	= 2.6
D_3/D_1	for travel lane (1200')	= 1.4
D_3/D_1	for bridge	= 3.5

On the average, a driver traveling toward the bridge unopposed will move toward the centerline of the bridge slightly over 1 ft and will reduce his speed slightly. At 1200 ft the driver does not appear to center his vehicle in his lane, but drives closer to the centerline. When he reaches the bridge, he maintains much more room between the right wheels of his vehicle and the bridge rail than he does between the left wheels and the centerline. It is recognized that drivers sit on the left side of most vehicles operated in the United States. Therefore, the centerline and oncoming vehicles serve as primary cues for positioning vehicles. The centering ratio may be influenced by these cues.

For the more critical cases (vehicles opposed by traffic), the averages were:

$$\begin{array}{rl} D_1(1200') & = 3.8 \text{ ft} \\ -D_1(\text{bridge}) & = 2.5 \text{ ft} \\ \hline \Delta D_1 & = 1.3 \text{ ft} \end{array}$$

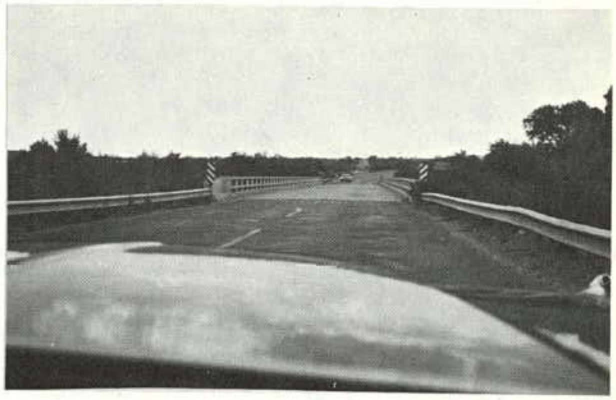
$$\begin{array}{rl} \text{Speed}(1200') & = 49 \text{ mph} \\ -\text{Speed(bridge)} & = 47 \text{ mph} \\ \hline \Delta\text{Speed} & = 2 \text{ mph} \end{array}$$

D_3/D_1	for roadway (1200') (lane plus shoulder)	= 1.9
D_3/D_1	for travel lane (1200')	= 1.0
D_3/D_1	for bridge	= 1.9

Bridge Type	Location	Length (ft)	Roadway Width (ft)	Bridge Width (ft)	ADT	Posted Speed (mph)	Average Speed (mph)	85% Speed (mph)
Open Deck	U. S. 89 South of Tucson	56	40 (1)	36	3428	55	54	59
Open Deck	S. H. 77 Near Mammoth	295	40 (1)	26	2697	55	55	59
Open Deck	S. H. 85 North of Ajo	278	28 (1)	24	1512	55	56	63
Open Deck	S. H. 85 South of Ajo	36	22 (2)	20	734	55	56	60

Notes: (1) Two 12-foot paved traffic lanes, two paved shoulders.
(2) Two 11-foot paved traffic lanes.

U.S. 89
South of Tucson



S.H. 77
Near Mammoth
Aravaipa Creek

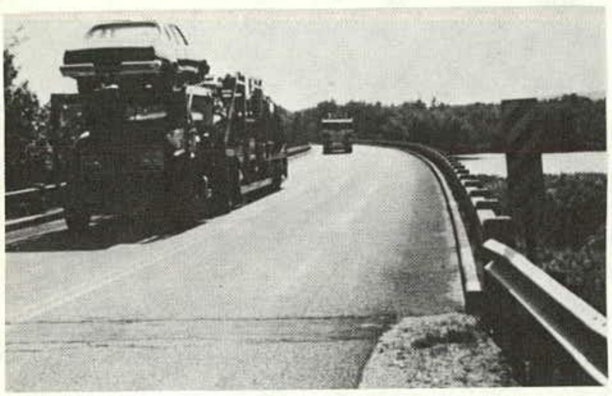
S.H. 85
5 Mi. North of Ajo

S.H. 85
South of Ajo

Figure A-1. Bridge sites in Arizona.

Bridge Type	Location	Length (ft)	Roadway Width (ft)	Bridge Width (ft)	ADT	Posted Speed (mph)	Average Speed (mph)	85% Speed (mph)
Open Deck	U. S. 2 Sibley Pond	790	22 (1)	26	2000	45	49	48
Truss	U. S. 2 Sebasticook River	205	22 (1)	22	2000	45	44	46

Note: (1) Two 11-foot traffic lanes.



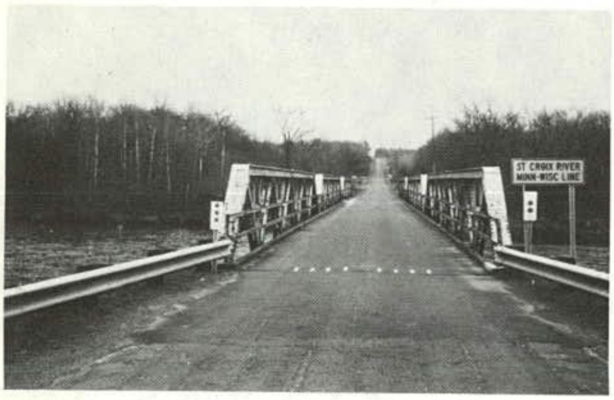
U.S. 2
Sibley Pond

U.S. 2
Sebasticook River

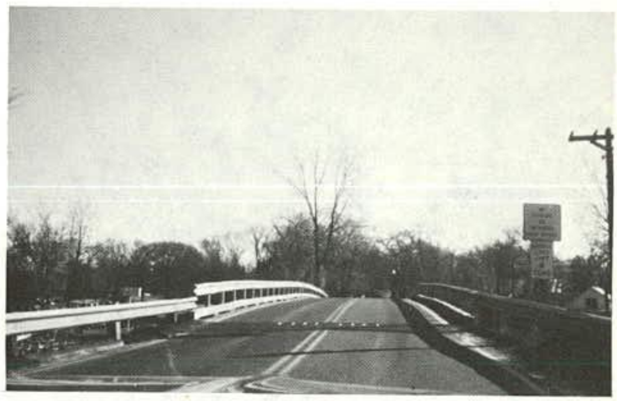
Figure A-2. Bridge sites in Maine.

Bridge Type	Location	Length (ft)	Roadway Width (ft)	Bridge Width (ft)	ADT	Posted Speed (mph)	Average Speed (mph)	85% Speed (mph)
Pony Truss	T. H. 48 St. Croix River	216	32 (1)	15	400	55	39	46
Open Deck	T. H. 101 Gray's Bay	173	30 (1)	23	6900	15 & 30	29	32
Open Deck	T. H. 10 B. N. Tracks	170	58 (2)	44 (4)	9585	55	53	57
Truss	C.S.A.H. 7 Rum River	241	22 (3)	15	492	20	29	40

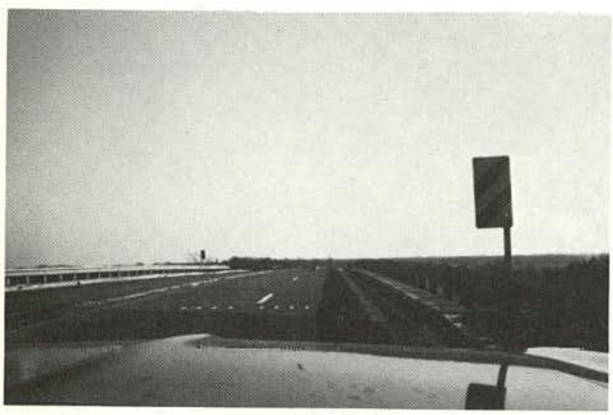
Notes: (1) Two 12-foot paved traffic lanes, two paved shoulders.
(2) Four 12-foot paved traffic lanes, two paved shoulders.
(3) Two 11-foot paved traffic lanes.
(4) Two 21-foot lanes, and 2-foot median divider.



T.H. 48
St. Croix River



T.H. 101
Gray's Bay



T.H. 10
B.N. Tracks

C.S.A.H. 7
Rum River

Figure A-3. Bridge sites in Minnesota.

Bridge Type	Location	Length (ft)	Roadway Width (ft)	Bridge Width (ft)	ADT	Posted Speed (mph)	Average Speed (mph)	85% Speed (mph)
Truss	U. S. 54	1229	46 (1)	20	3927	55	47	56
Open Deck	U. S. 54	1630	40 (1)	20	7618	35	39	44
Open Deck	U. S. 50 & 63	1178	46 (1)	28	5690	55	53	57
Open Deck	U. S. 50 & 63	53	37 (1)	20	5690	55	52	56

Note: (1) Two 12-foot paved traffic lanes, two paved shoulders.

U.S. 54
West of Camdenton

U.S. 54
Northeast of Damsel
(Lake of the Ozarks)

U.S. 50 & 63
Southeast of Schubert
(Osage River)

U.S. 50 & 63
Creek Southeast of Schubert

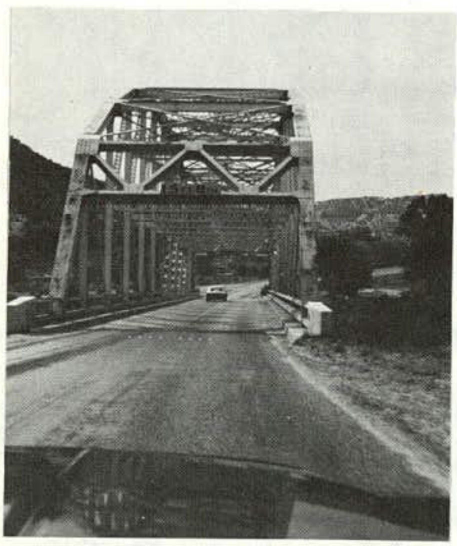
Figure A-4. Bridge sites in Missouri.

Bridge Type	Location	Length (ft)	Roadway Width (ft)	Bridge Width (ft)	ADT	Posted Speed (mph)	Average Speed (mph)	85% Speed (mph)
Open Deck	U. S. 285 Sante Fe	134	25 (1)	24	1300	55	49	60
Open Deck	U. S. 285 Sante Fe	240	25 (1)	24	905	55	53	60
Truss	S. H. 4	290	Variable (2)	24	3729	50 & 55	46	44
Open Deck	S. H. 50 Glorietta	27	22 (3)	19	1470	40	44	50

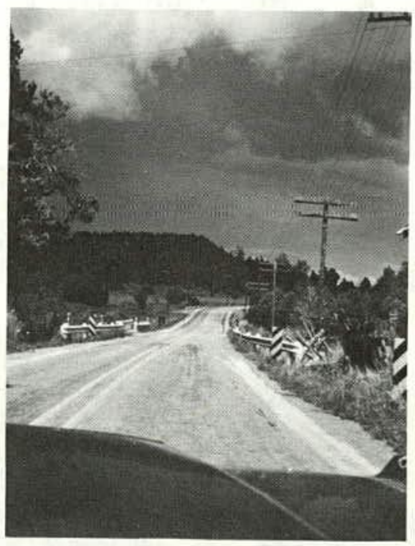
Notes: (1) Two 12-foot paved traffic lanes, two paved shoulders.
(2) Two 11-foot paved traffic lanes.

U.S. 285
South of Santa Fe

U.S. 285
South of Santa Fe



S.H. 4
Near Los Alamos



S.H. 50
Glorietta

Figure A-5. Bridge sites in New Mexico.

Bridge Type	Location	Length (ft)	Roadway Width (ft)	Bridge Width (ft)	ADT	Posted Speed (mph)	Average Speed (mph)	85% Speed (mph)
Truss	S. H. 21 Caldwell (Brazos River)	1187	24 (1)	22	3100	55	54	59
Open Deck	S. H. 6 Navasota	318	45 (2)	28	5200	55	57	63
Open Deck	U. S. 77 La Grange	548	Variable (3)	30	2700	55	56	62

Notes: (1) Two 12-foot paved traffic lanes.
(2) Two 12-foot paved traffic lanes, two paved shoulders.
(3) Two 12-foot paved traffic lanes, two paved shoulders: North of bridge - 2-foot wide; and South of bridge - 6-foot wide.

S.H. 21
Caldwell

S.H. 6
Navasota

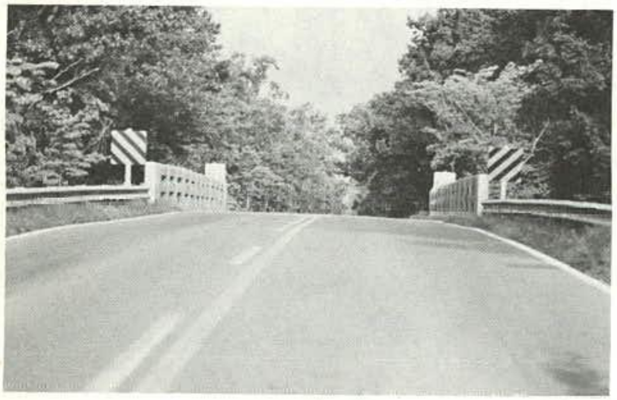
U.S. 77
(View of approach guardrail)
La Grange

U.S. 77
(View of bridge rail)
La Grange

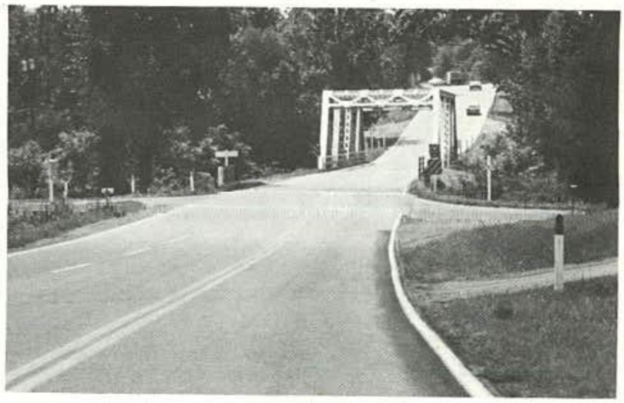
Figure A-6. Bridge sites in Texas.

Bridge Type	Location	Length (ft)	Roadway Width (ft)	Bridge Width (ft)	ADT	Posted Speed (mph)	Average Speed (mph)	85% Speed (mph)
Open Deck	U. S. 250 Zion Crossroads	114	24 (1)	23	2880	55	47	53
Truss	U. S. 11 Verona (Middle River)	144	31 (2)	23	5310	55 & 40	47	52
Pony Truss	Route 6 Fork Union (Rivanna River)	489	24 (1)	23	1270	55	48	54
Open Deck	U. S. 15 Palmyra	131	24 (1)	23	2460	35 & 55 NB SB	48	52

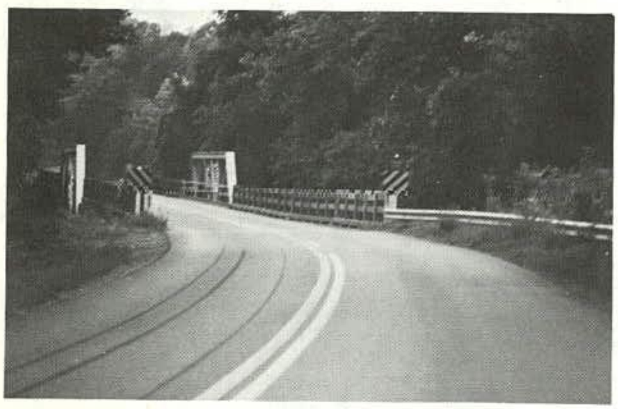
Notes: (1) Two 12-foot paved traffic lanes.
(2) Two 12-foot paved traffic lanes, two paved shoulders.



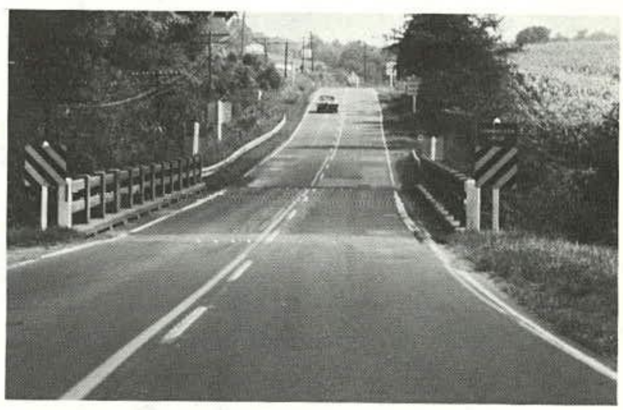
U.S. 250
Zion Crossroads



U.S. 11
Verona



Route 6
Fork Union



U.S. 15
Palmyra

Figure A-7. Bridge sites in Virginia.

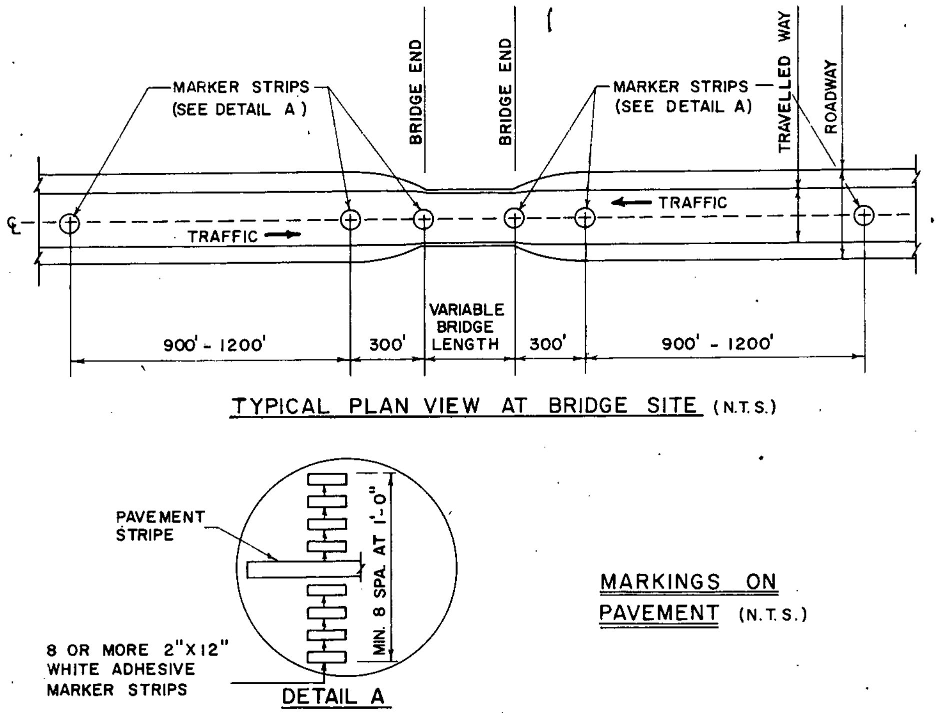
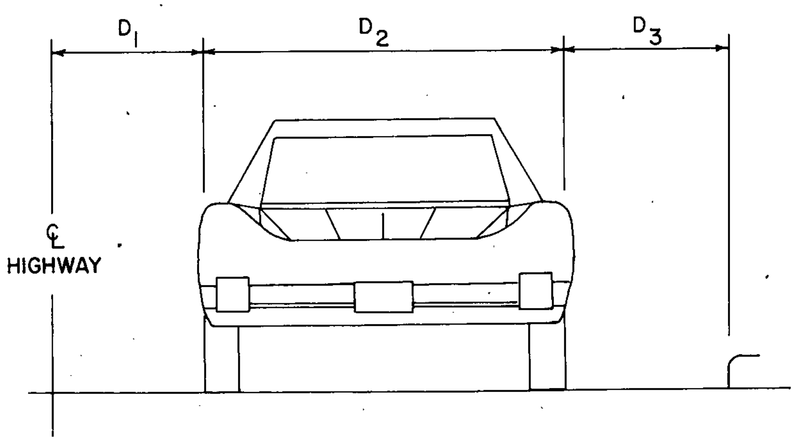


Figure A-8. Marking patterns for field studies.



D_1 = DISTANCE FROM ℄ OF HIGHWAY TO OUTSIDE OF LEFT TIRE

D_2 = DISTANCE FROM OUTSIDE OF LEFT TIRE TO OUTSIDE OF RIGHT TIRE*

D_3 = "SHY DISTANCE"; DISTANCE FROM OUTSIDE OF RIGHT TIRE TO FACE OF CURB, GUARD RAIL, PAVEMENT EDGE, ETC.

D_3/D_1 = CENTERING RATIO

Figure A-9. Definition of vehicle lateral position.

Thus, even when opposed by traffic, a typical driver will still move slightly more than 1 ft toward the centerline of a bridge and will slow only a modest amount. At 1200 ft when opposed, the driver usually centers his vehicle in the travel lane ($D_3/D_1 \approx 1$). When a driver reaches the bridge he will also maintain about as much room between his vehicle and the bridge rail as he does between his vehicle and the opposing traffic for any bridge widths ($D_3/D_1 \approx 2$).

Figure A-10 shows the relationship between the distance of the left wheel to the centerline, D_1, as a function of bridge widths for both opposed and unopposed traffic. These linear regressions compare qualitatively to the curves derived by W. P. Walker in his paper, "Influence of Bridge Widths on Transverse Positions of Vehicles" (2), in the 20- to 30-ft region. Beyond that there is considerable divergence, perhaps because of changes in roadway widths and traffic between the early 40's and the mid-70's. Both linear regressions and Walker's curves show that D_1 for unopposed traffic is less than D_1 for opposed traffic at every bridge width. As bridge width increases, D_1 increases.

By extrapolation, D_1 approaches 0 ft for unopposed traffic situations at bridge widths between 15 and 20 ft. This suggests that a driver would position his car with the left wheels on the centerline on a 17-ft bridge, and that the bridge would be too narrow for two cars to pass. Obviously, many cars have passed each other successfully on 17-ft structures by deviating from their preferred unopposed position. The requirement for this deviation may itself reflect a decrease in facility safety.

Figure A-11 shows the variation in D_1 for roadways of different widths. Similar to the curves in Figure A-10, these curves indicate that D_1 increases as roadway width increases. The vehicles facing opposing traffic have a greater D_1 than unopposed vehicles. This suggests opposing traffic is recognized as a potential hazard.

Figures A-12 and A-13 compare the bridge and roadway centering ratios for two conditions of traffic: Figure A-12, unopposed, and Figure A-13, opposed. On a bridge, this ratio (as seen graphically in Fig. A-9) is the ratio of the distance from the bridge rail to the right side of an automobile, divided by the distance from the centerline to the left side of an automobile (D_3/D_1). For the corresponding ratios on the roadway 1200 ft in advance of the bridge, D_3 is measured from the right side of the vehicle to the outer edge of the paved shoulder.

A striking similarity is shown in the regression lines between the opposed and unopposed conditions. That is, the lines cross between bridge and roadway widths of 30 to 40 ft. In both opposed and unopposed conditions the centering ratio increases with width on the road but decreases with width on the bridge. The decrease with bridge width is a reflection of bridge lateral constraint. On wider bridges, drivers position their vehicles farther from the centerline and <u>relatively</u> closer to the bridge rail. The slightly positive slope shown for roadway centering ratios would seem to be created in part by the influence of the paved shoulder on the value of D_3 for the higher values of roadway width. This shoulder is not usually recognized by drivers as a legitimate area for vehicle travel as contrasted with a wide bridge lane.

If one will accept the following hypothesis --

> relative lateral placement of vehicles on a bridge should be the same as relative lateral placement of vehicles on the adjoining roadways; i.e., the ratio D_3/D_1 should be the same on the bridge as it is on the roadway --

a conclusion may be drawn from Figures A-12 and A-13. These figures indicate that <u>both</u> adjoining roadways and bridges should be between 30 and 40 ft wide for this condition to be achieved. If this argument is accepted, it may be most critical to the traditional problem of defining narrow bridges in absolute dimensions and may further reinforce the premise that they must be defined relative to roadway width. A specific example would be two 12-ft lanes with two 6-ft paved shoulders (a 36-ft road width) corresponding to a 36-ft bridge width; i.e., two 18-ft bridge lanes. It should be noted, however, that the definition between the travel lane and the paved shoulder should be marked continuously across the bridge to reduce the tendency of some drivers to convert them into four-lane facilities.

Another observation based on Figures A-12 and A-13 is that the centering ratio is approximately twice as large for unopposed traffic as for opposed traffic, a reflection of a natural tendency on the part of drivers to allow extra distance from the bridge rail and even to infringe on the centerline or opposing lane when no oncoming traffic confronts them. Figure A-10 also substantiates this in that the values of D_1 are significantly greater for the opposed condition than for the unopposed.

The various curves shown in this section appear to have potential for defining adequate bridge widths or bridge/roadway dimensions.

CORRECTIVE MEASURES IN MAINE AND TEXAS

Recommendations on methods to improve safety conditions at four two-lane, two-way bridge sites were made and implemented so that the corrective measures could be evaluated using "before" and "after" studies. The four bridge sites selected were the Sebasticook River bridge at the

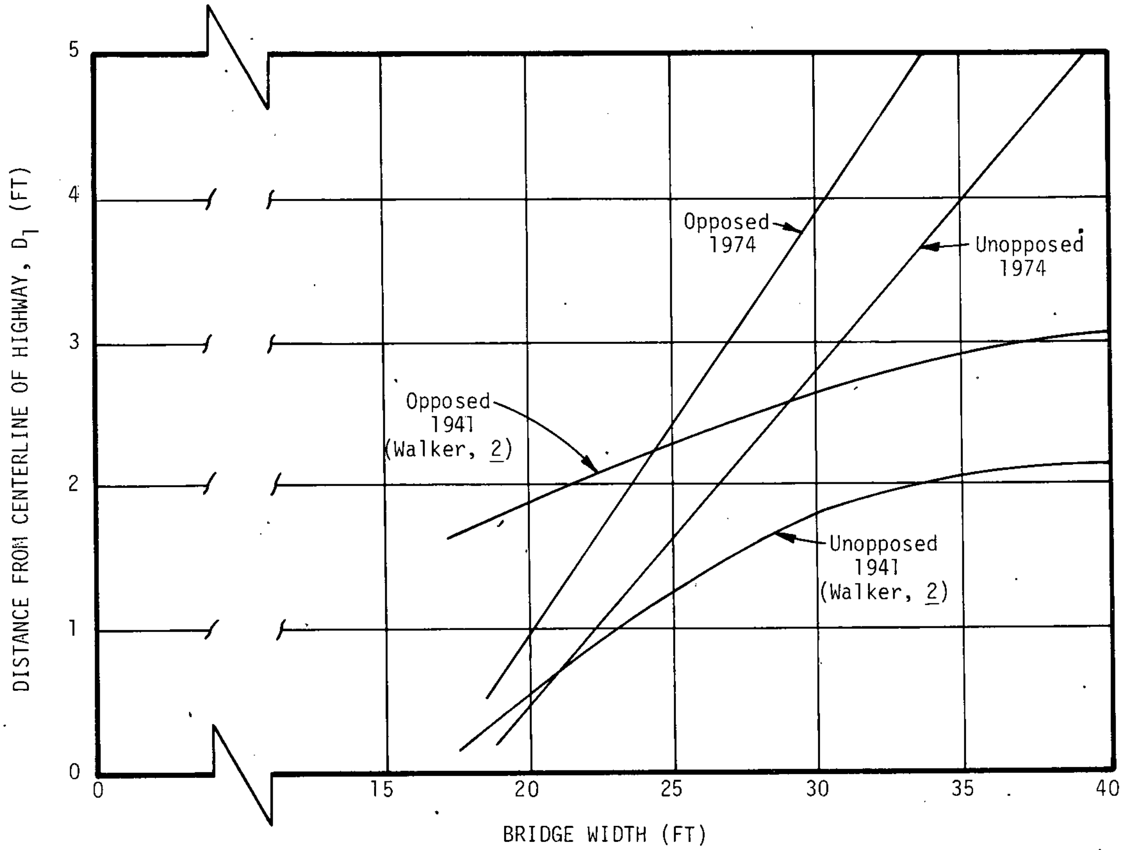


Figure A-10. Comparison of 1974 with 1941 data, distance from centerline vs bridge width.

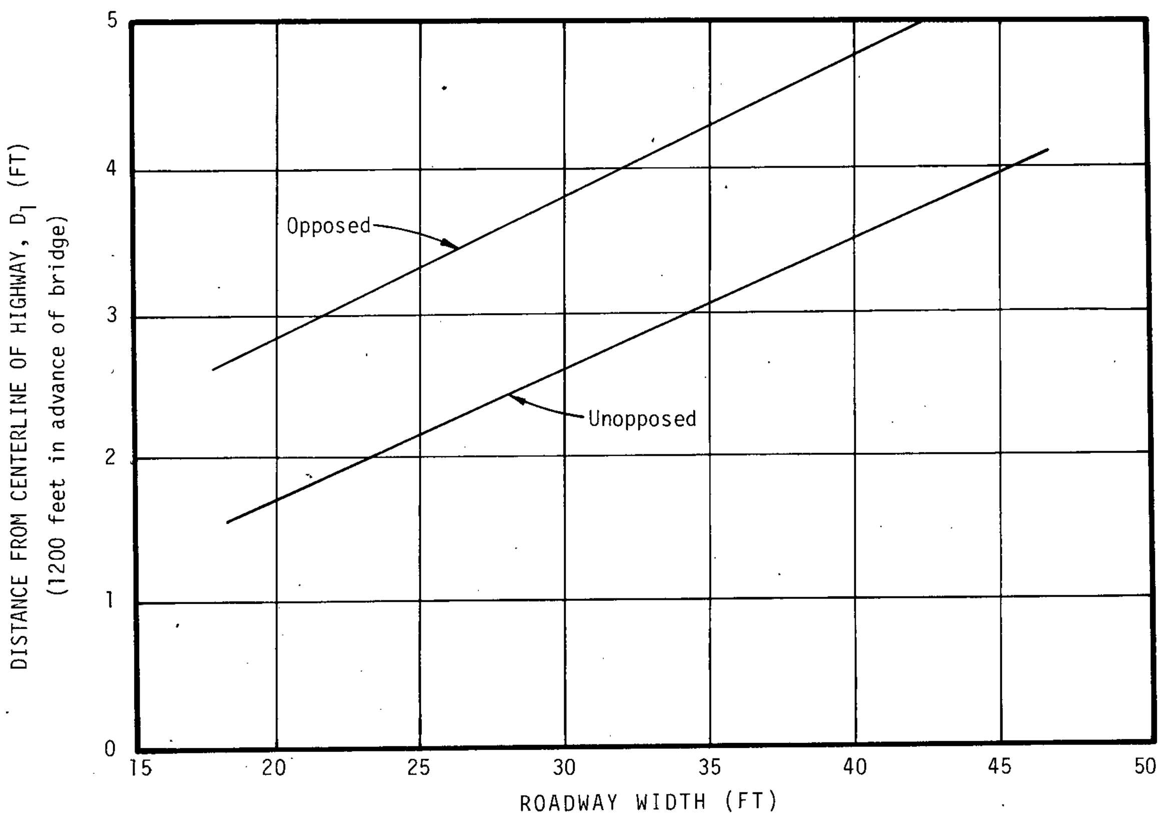


Figure A-11. Average distance from the highway centerline, unopposed compared to opposed.

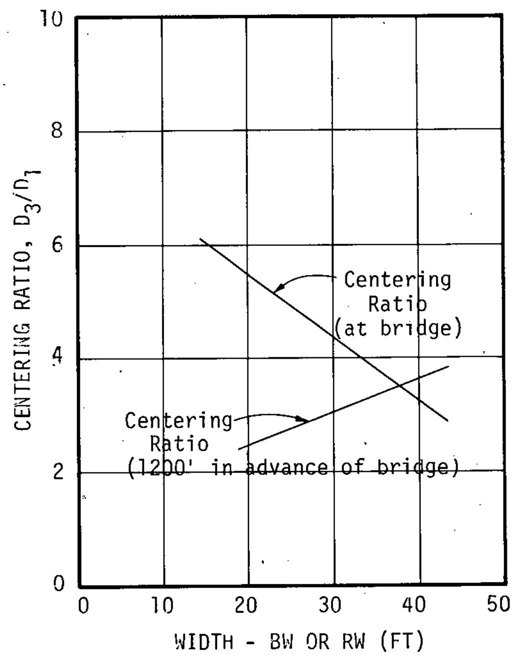


Figure A-12. Unopposed centering ratios for various bridge and roadway widths.

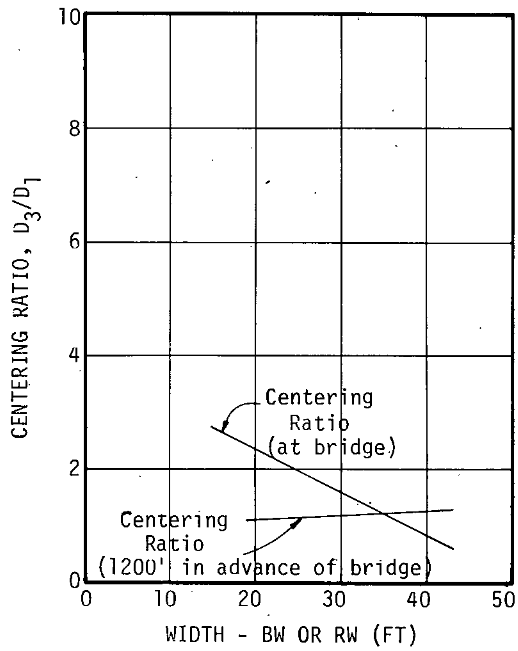


Figure A-13. Opposed centering ratios for various bridge and roadway widths.

Maine Facility, and three sites in Texas: the Navasota River bridge on S.H. 6, the Brazos River bridge near Caldwell on S.H. 21, and a bridge on U.S. 77 near LaGrange.

The objectives sought for all bridge sites were to:

1. Define the presence of the restricting structure.
2. Define its width relative to the driving surface.
3. Provide continuity in definition of the clear driving surface across the bridge.
4. Provide consistent right-hand reference for the driver.
5. Provide positive wet-weather guidance.
6. Provide a continuous right-hand barrier that would satisfactorily redirect vehicles.

To satisfy some of these objectives the following corrective treatments were studied:

1. White edge lines.
2. Use of standard or innovative narrow bridge signs.
3. Approach metal beam guard fence which is continuous across bridge.
4. Type 2 or type 3 object markers in line with closest obstruction.

Studies at the Maine Facility

The Maine Facility is a computer-controlled, instrumented, two-lane roadway extending approximately 15 miles on U.S. 2 between Canaan and Newport, Maine. The continuously instrumented road (406 loop detectors on approximately 200-ft centers) provides excellent real-time data collection capabilities for a variety of vehicle operational maneuvers.

Both bridges on the Maine Facility were selected for study of vehicle operating characteristics under a variety of conflict maneuvers.

Sebasticook River Bridge

The Sebasticook River bridge is a 205-ft steel through truss bridge that runs east and west. Curb-to-curb width is 22 ft; approach roadway width is 22 ft. Posted speed in the bridge vicinity is 45 mph. The bridge and adjacent roadway sections are shown in Figure A-14.

Sibley Pond Bridge

The Sibley Pond bridge, a 790-ft open concrete railing curved bridge, is located near the east end of the Maine Facility. The approach roadway width (no paved shoulders) is 22 ft; the bridge width is 26 ft railing-to-railing face. Figure A-15 shows the Sibley Pond bridge.

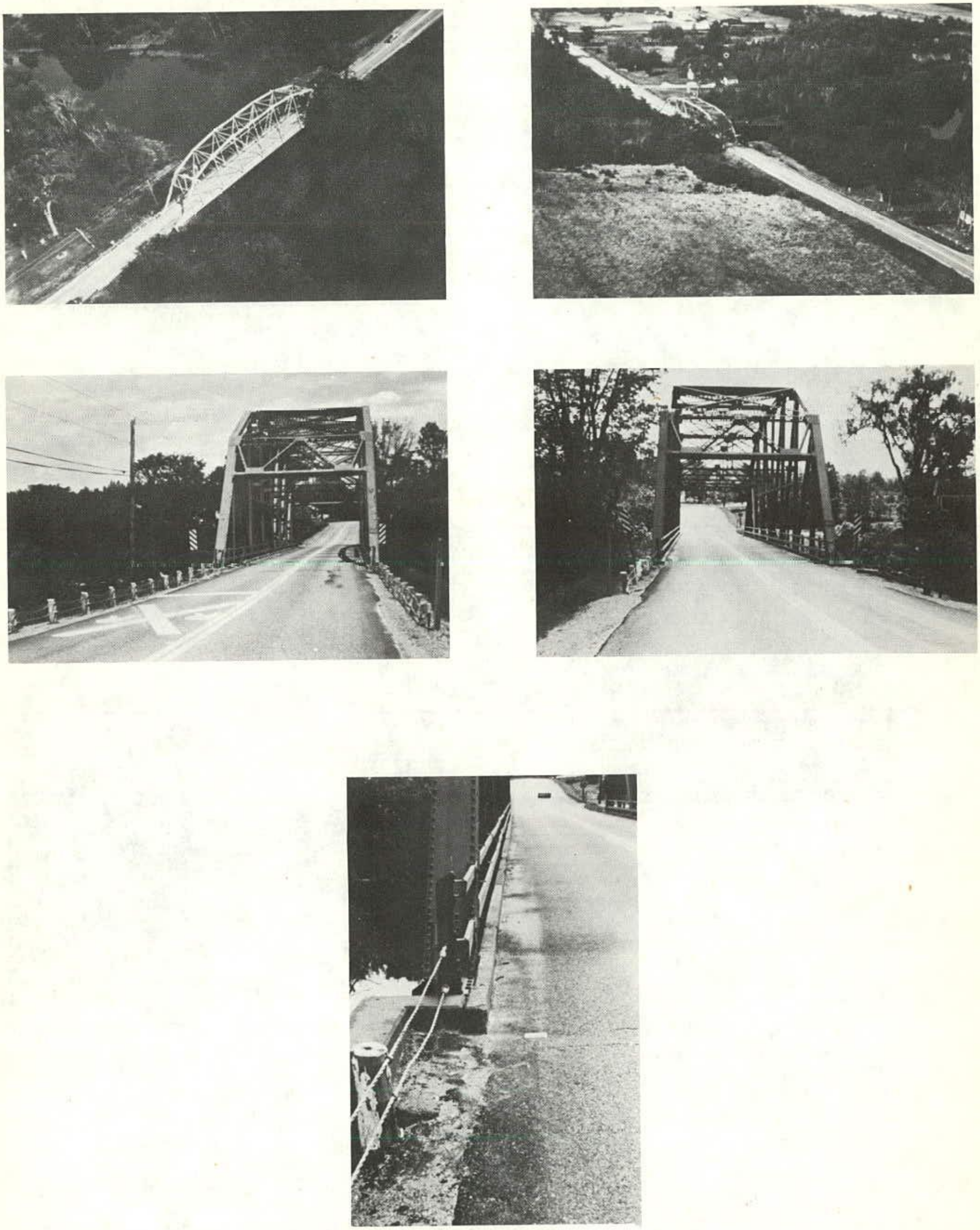
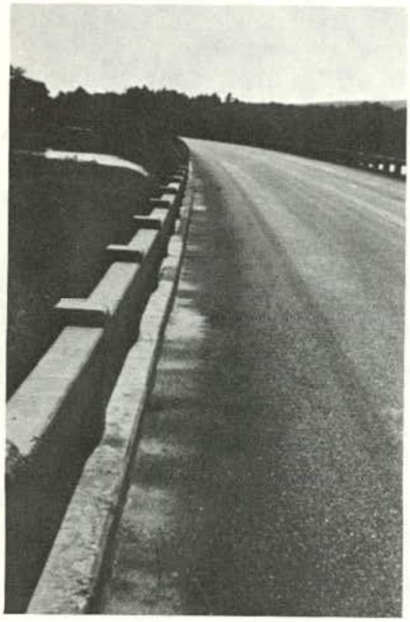
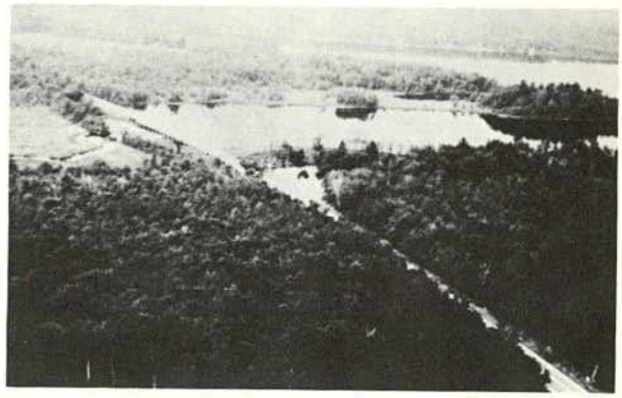


Figure A-14. Photos of Sebasticook Bridge (truss bridge).





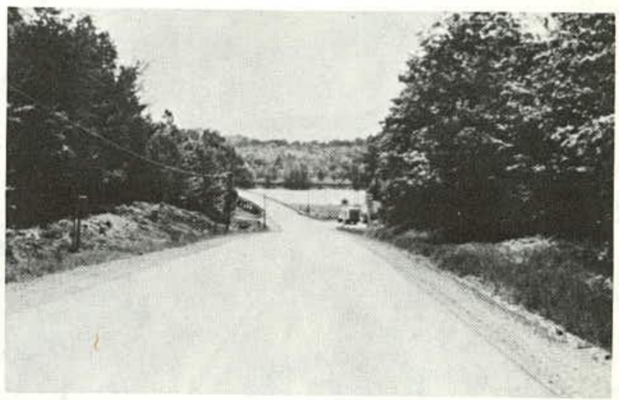


Figure A-15. Photos of Sibley Pond Bridge.

Site Characteristics

Average daily traffic on the Maine Facility roadway is estimated to range from about 1000 to 4000 vehicles per day. Daily traffic during the summer months approaches 7000 to 8000 vehicles per day. Truck traffic ranges from 8 to 12 percent. The large truck percentage is prevalent in the Sebasticook River Bridge area because a lumber and wood-milling plant is located at the west end of the bridge.

Pavement width on the Maine Facility ranges from 20 to 24 ft. Shoulder widths are from 2 to 10 ft; however, in the vicinity of both bridges, there are no paved shoulders. The road is a two-lane asphaltic concrete pavement without edge-line striping. Maximum grade is 7 percent. The maximum grade in the vicinity of the Sebasticook River Bridge is approximately 5 percent at the east end in conjunction with a horizontal curve.

The posted speed limit at the Sebasticook River Bridge is 45 mph. Maximum posted speed on the Maine Facility is 50 mph.

Traffic control devices at the truss bridge (post and cable barriers at approaches, delineators, hazard paddle markers, etc.) were repaired prior to data collection. No additional traffic control devices were added that would constitute a "corrective treatment." Only minor improvements such as the straightening of paddle boards, replacement of several reflective delineators on the posts, and installation of one or two cable guard posts at the east end were required.

Similar repairs to meet minimum state requirements were made at the Sibley Pond low-profile bridge prior to data collection.

General Study Description

The studies at the Maine Facility bridges were conducted to obtain vehicle approach speed and lateral placement data with which to evaluate the effect on driver performance of the various geometric, structural, operational, and environmental factors associated with bridge crossing. The experimental design involved "before" and "after" measurements of vehicle speed and lateral position on the bridge and at both approaches. The "before" studies were conducted to obtain a data base on which the effect of several recommended treatments could be evaluated. Three treatments were studied and are discussed later in this Appendix.

Data at the Sebasticook River Bridge were collected in two phases: (1) photographically, and (2) electronically using the loop detectors and the computer facility at the control center. Data at the Sibley Pond Bridge were collected using only photographic techniques.

Pavement Marking System -- "Before" Studies

Pavement reference markings for film analysis were placed along the centerline as shown in Figure A-16. The marking system began at each end of the bridge and extended along the centerline on 40-ft centers.

The marking pattern extended approximately 600 ft eastward from the east end of the Sebasticook Bridge (defined as the expansion joint at the east end of the truss). Similarly, the westward pattern extended from the west end of the bridge approximately 800 ft, terminating slightly west of the railroad tracks crossing the highway.

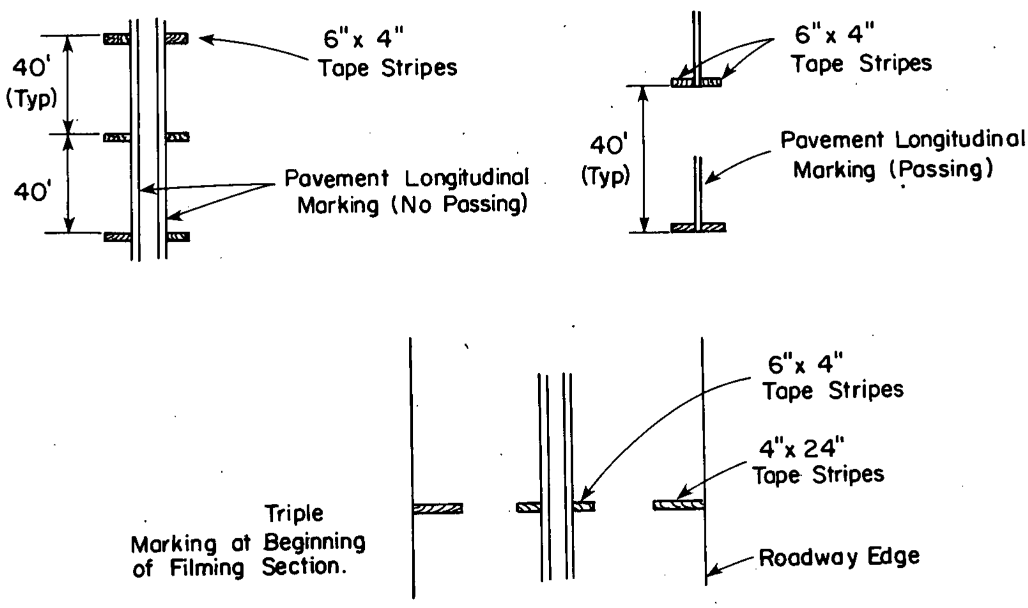


Figure A-16. Pavement marking system for "before" studies.

The marking pattern at the Sibley Pond Bridge extended 640 ft outward from both ends of the bridge.

"Before" Film Studies, Sebasticook River Bridge

Approximately 50 vehicles from each bridge approach were filmed under the following conditions:

1. Opposing vehicle (filming car meeting car).
2. Opposing vehicle (filming truck meeting truck).
3. Free-flowing car (no opposing or leading vehicles).
4. Free-flowing truck (no opposing or leading vehicles).
5. Opposing vehicle (filming car meeting truck).
6. Opposing vehicle (filming truck meeting car).

The above data blocks constitute 600 individual filming conditions (300 from each approach). Some categories (such as truck meeting truck) were difficult to complete. Certain conflicts were artificially produced using a second test vehicle to oppose the filmed vehicle where such action was necessary. Natural-occurring conflicts were filmed where possible to avoid data bias.

Conflicts between opposing vehicles were classified in two categories:

Type 1 Conflict -- occurred when two opposing vehicles were on the bridge at the same time. A Type 1 conflict also included opposing vehicles that were both within the distance between Loops No. 167 and 168 at the same time (see Fig. A-17 for location of loop detectors).

Type 2 Conflict -- occurred when one vehicle was between Loops (Box) 167 and 168 while

(a) an opposing westbound vehicle was between Loops (Box) 166 and 167, or

(b) an opposing eastbound vehicle was between Loops (Box) 168 and 169.

Either type of conflict constituted an "opposing vehicle" designation; however, the particular type of conflict was identified in each case.

"Before" Film Studies -- Sibley Pond Bridge

Approximately 50 vehicles were filmed from each approach direction without regard to type of vehicle, type of or lack of conflict, etc. Each vehicle was filmed continuously from a point 640 ft in advance of the bridge to a point 320 ft beyond the departing end of the bridge.

Photographic study operations on the Sibley Pond Bridge were considered second priority to those at the truss bridge.

"After" Studies -- Sebasticook River Bridge

"After" studies were conducted electronically and photographically (chase-vehicle technique) at the Sebasticook River Bridge only. No "after" studies were conducted at the Sibley Pond Bridge.

Pavement Marking Pattern

A pavement marking pattern different from that in the "before" studies was used. Figure A-17 shows the pattern. This marking pattern permitted direct measurement of vehicle placement during film analysis, thus replacing the time-consuming measurements (on the film image) used to analyze the "before" film data.

Film Study Procedure

Subject vehicles were filmed continuously between locations A and B (refer to Fig. A-17) for both eastbound and westbound travel directions. Filming of eastbound vehicles was started prior to the time the subject vehicle reached the railroad track. This positively identified the direction of travel for film analysis and also assured that cine speed had stabilized before the subject vehicle crossed the first set of reference markings east of the railroad tracks.

Sample Size

Approximately 100 vehicles from each bridge approach direction were filmed for each corrective treatment without regard to type of, or lack of, conflict conditions as outlined in the "before" studies. When conflicts occurred, the type was noted on the film log sheets (ex: subject vehicle, automobile; opposing vehicle, car, truck, etc.). Conflicts between opposing vehicles were classified according to the vehicle position described previously.

Corrective Treatments

Three corrective treatments were studied. The treatments were structured to allow "stage development" with film and electronic data collected at each stage. The corrective treatments installed and studied at the truss bridge were selected by Maine DOT and FHWA personnel. The treatments are discussed in the order in which they were studied. Photographs depicting the three treatments are shown in Figure A-18.

Treatment No. 1 -- Edge Lines

In addition to installation of MUTCD required or recommended signing and delineation, a 4-in. wide, white, solid pavement edge line was proposed for both outer edges of the roadway. The edge lines extended 1000 ft outward from each end of the bridge and were continuous across the bridge immediately adjacent to the face of the 6-in. curb. The edge lines were transitioned smoothly from the end of the bridge to the edge of the approach pavement where the bridge curb-to-curb width and approach pavement width are not equal.

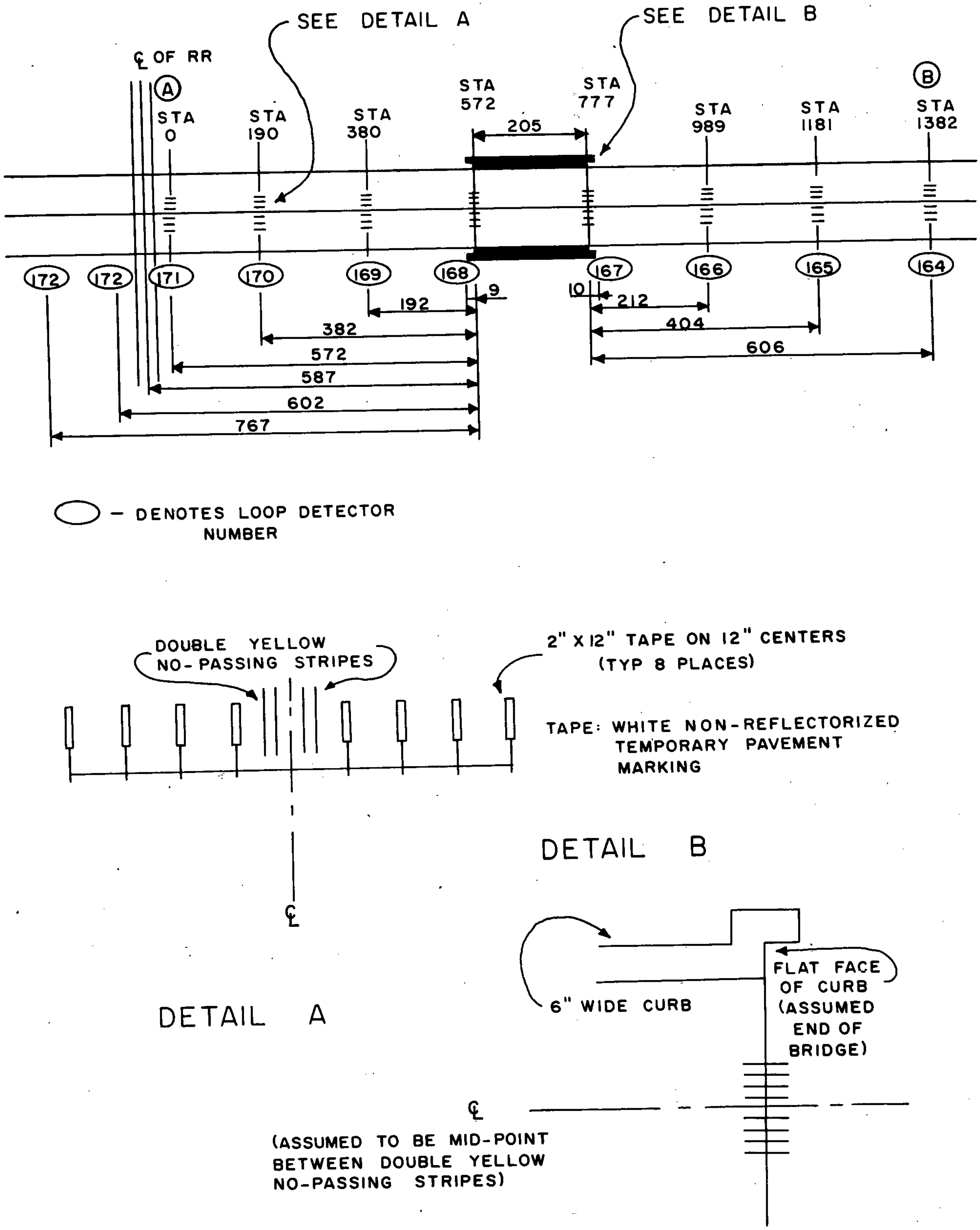
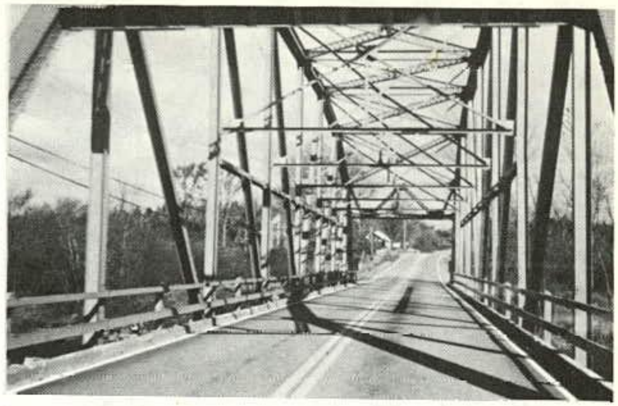


Figure A-17. Location of marking system for "after" studies, showing loop detector numbering at Sebasticook River Bridge.

(a) Treatment No. 1 (edgelines)



(b) Treatment No. 1 (edgeline on bridge)

(c) Treatment No. 2 (edgelines and sign)

(d) Treatment No. 3 (edgeline, sign, and guardrail)

(e) Guardrail end treatment

Figure A-18. Corrective treatments at Sebasticook River Bridge.

Since no paved shoulders existed alongside the approach roadway, no pavement markings other than the edge lines were used to increase the target value of the transition region onto the bridge or provide a funneling perspective (such as tapered shoulder cross hatching).

The existing NARROW BRIDGE sign was left in its current location, as was the Type 3 black and yellow hazard marker at each end of the bridge.

Treatment No. 2 -- Edge Lines and Warning Sign

Treatment No. 2 included, in addition to Treatment No. 1, the installation of two non-MUTCD hazard warning signs, shown in Figure A-19. One sign was located on the right side of both the east and west approaches 200 ft from the ends of the bridge. Each sign was located 2 ft from the approach lane outer edge at standard MUTCD height for rural road signs.

The combination of graphic and supplementary word message was similar to the LOW CLEARANCE sign (MUTCD, W12-2) in that it was intended to denote a vehicle clearance dimension less than would be generally expected. The arrows on the proposed sign pointed inward rather than outward. This was to emphasize a constriction rather than merely to present dimensional information.

The supplementary word-message panel was intended to specifically advise the motorist that the constriction was due to a bridge (no shoulder). It also advised the motorist to reduce his speed to 10 mph less than the 45-mph posted speed limit near the bridge.

Colors, borders, and shape conformed to MUTCD standards. The size of the arrows and dimension on the diamond-shaped sign were similar to the W12-2 sign message. Letter size and type on the supplementary panel were similar to the W7-2b MUTCD sign (three-line legend on rectangular sign blank).

Treatment No. 3 -- Guardrail Installation

This treatment is the most expensive of the three.

Guardrail height and safety end treatment were in accordance with current Federal specifications. The approach guardrail on the right side was proposed to

Diamond Sign:	36" x 36" Black Legend on Yellow Background (Legend Dimension Similar to MUTCD W12-2)
Rectangular Supplementary Panel:	18" x 24" Black Legend on Yellow Background (Legend Dimension Similar to MUTCD W7-2b)

Both Signs reflectorized

Mounting Height and Offset as per MUTCD

Figure A-19. Non-MUTCD warning sign.

extend 150 ft in advance of the bridge end plus the end safety treatment (approximately 25 ft). Departing guardrail was to be a minimum of 50 ft plus end safety treatment length. The W-section guardrail was continued across the bridge and was blocked out from the existing bridge rail so that the face of the W-section rail was parallel to a vertical plane at the curb face.

Results of Corrective Treatments

The results of the placement measurements made for the unopposed vehicles at the approach end of the bridge are given in Table A-1. The average value of D_1 (see Fig. A-9) for eastbound traffic was 0.76 ft; the average value of D_1 for westbound traffic was 0.29 ft. Apparently the curve on the east approach to the bridge caused westbound vehicles to be driven closer to the centerline when approaching the bridge. After Treatment No. 1 was imposed, there was little change in average lateral placement for unopposed eastbound traffic. For unopposed westbound traffic there was a significant average lateral movement away from the centerline and toward the bridge rail.

Treatments 2 and 3 had little effect on average lateral placement for unopposed eastbound traffic. For unopposed westbound traffic, Treatment No. 2 produced a significant average lateral movement away from the centerline and toward the bridge rail. Treatment No. 3 had little effect on lateral placement of unopposed westbound traffic.

Studies at Texas Bridges

Corrective treatments to Texas bridges on U.S. 90 were discussed in Chapter Two. Further details are presented in this appendix.

Brazos River Bridge --. The Brazos River bridge (Fig. A-6) is a 1187-ft through steel truss bridge that runs east-west on S.H. 21. Curb-to-curb bridge width is 22 ft and the approach roadway width is 24 ft. There is a mild horizontal curve that straightens out about 900 ft from the bridge on the east end (westbound traffic) and there are more than 1800 ft of tangent on the west end (eastbound traffic). The eastbound approach to the bridge has a T-intersection located about 1000-ft south of the bridge. Side slopes on the westbound approach are about 3:1 and on the eastbound approach they are relatively flat. Existing conditions at the site for the initial study were: (a) flared metal beam guardrails, (b) standard MUTCD W5-2 narrow bridge sign, (c) post-mounted delineators, and (d) hazard paddle markers.

Two corrective treatments were selected and installed by the Texas Highway Department. An 8-in. wide edge line was added at both sides of the pavement and extended 900 ft outward from the ends of the bridge. Also added were object markers in line with the bridge guardrail.

The results of the placement measurements for unopposed vehicles at the approach end of the bridge are given in Table A-1. Average lateral placement (D_1) for the eastbound traffic was 0.93 ft; average lateral placement (D_1) for the westbound traffic was 1.39 ft. The treatment had little effect on unopposed westbound traffic. For unopposed eastbound traffic average lateral placement (D_1) after treatment was significantly larger than before treatment; i.e., after imposition of the treatment, vehicles were driven farther away from the centerline and closer to the bridge rail.

LaGrange Bridge --. The LaGrange bridge (Fig. A-6) is a 548 ft long, open deck, concrete bridge that had discontinuous guardrails with snagging capability. It is located on U.S. 77 about 10 miles north of the city of LaGrange. The bridge is 30 ft wide; the southbound approach roadway is 28 ft wide; the northbound approach roadway is 36 ft wide. The highway is virtually straight in the test section, with relatively flat side slopes. Existing conditions at the site for the initial study were basically centerline marking and a few post delineators. There were no approach guardrails nor were there signs or hazard markers.

Two corrective treatments were selected and installed by the Texas Highway Department. A 4-in. wide edge line was added at both sides of the pavement and extended more that 1200 ft outward from each end of the bridge. Metal beam guardrails were tied to the bridge end and extended out from it about 200 ft from each corner.

The results of the placement measurements for unopposed vehicles at the approach end of the bridge are given in Table A-1. Vehicle placement in both directions was similar and was not significantly changed by the treatments.

Navasota River Bridge --. The Navasota River bridge (Fig. A-6) is a 318-ft open deck bridge with low smooth guardrails. It is located on S.H. 6 and runs in a north-south direction. Curb-to-curb bridge width is 28 ft and the approach roadway width including shoulders is 45 ft. The highway is straight in the vicinity of the bridge and the side slopes are relatively flat along the entire test section. Existing conditions at the site for the initial study included flared metal beam guardrails, standard MUTCD W5-2 narrow bridge sign, post-mounted delineators, and hazard paddle markers.

The same two corrective treatments used at the Brazos River Bridge were selected and installed by the Texas Highway Department; i.e., 8-in. wide edge lines extended 900 ft outward from the ends of the bridge and object markers in line with the bridge guardrail.

The results of the placement measurements made for unopposed vehicles at the approach end of the bridge are given in Table A-1. Vehicle placement in both directions was found to be similar before treatment and was not significantly changed by the treatments.

TABLE A-1
"BEFORE AND "AFTER" STUDIES OF UNOPPOSED VEHICLE PLACEMENT AT APPROACH END OF BRIDGES.

Traffic Direction	Time	No. Obs.	D_1 Value	D_1 Std. Dev.	Dunnett's Test of Significance (two tail tests)
	(a) SEBASTICOOK RIVER BRIDGE				
Eastbound	Before	87	0.76	1.18	
	After 1	81	0.85	1.08	$t_{(340)}$ = -.54, NS
	After 2	77	0.87	1.08	$t_{(340)}$ = -.66, NS
	After 3	99	0.58	0.96	$t_{(340)}$ = 1.14, NS
Westbound	Before	183	0.29	1.16	
	After 1	101	0.65	1.02	$t_{(424)}$ = -2.82, p<.05
	After 2	59	0.90	0.77	$t_{(424)}$ = -3.95, p<.05
	After 3	85	0.56	0.89	$t_{(424)}$ = -2.00, NS
	(b) BRAZOS RIVER BRIDGE				
Westbound	Before	33	1.39	0.52	
	After	50	1.29	0.71	$t_{(81)}$ = 0.68, NS
Eastbound	Before	32	0.93	0.71	
	After	50	1.40	0.87	$t_{(80)}$ = -2.52, p<.05
	(c) LA GRANGE BRIDGE				
Northbound	Before	48	1.99	1.10	
	After	49	2.20	0.92	$t_{(95)}$ = -1.04, NS
Southbound	Before	46	1.92	1.18	
	After	48	1.62	0.94	$t_{(92)}$ = 1.41, NS
	(d) NAVASOTA RIVER BRIDGE				
Northbound	Before	12	2.63	1.10	
	After	44	2.75	0.82	$t_{(54)}$ = -0.41, NS
Southbound	Before	22	2.60	0.96	
	After	48	2.31	1.07	$t_{(68)}$ = 1.07, NS

APPENDIX B

NARROW BRIDGE SURVEY

The following paragraphs describe the results of a survey on the number of "narrow bridges" in use on state, county, and municipal highways. A questionnaire was prepared to be sent to each state. In this effort, considerable time was devoted to attempting to define a "narrow bridge." It was expected that different states would have different definitions and, thus, the questionnaire itself might limit the collection and usefulness of data. A letter, asking **six questions,** was sent to the chief engineer of each state highway department. These questions were formed to permit ready answers and unstructured responses. In this way each state was at liberty to provide its own definition of "narrow bridge." The six questions were as follows:

1. Has your state prepared an inventory of bridges on your highway system which indicates the total number of bridges, and those considered deficient in width?
2. If so, will you furnish us with a summary?
3. Has your state prepared an inventory of bridges on county or municipal roads which indicates the total number of bridges, and those considered deficient in width?
4. If so, can you furnish us a summary?
5. Has your state undertaken any measures to improve safety conditions on narrow bridges; such as, warning signs, pavement markings, edge stripes, or other delineation?
6. If so, will you furnish us copies of reports or procedures?

DEFINITION BY THE STATES

The data from the responses were studied and summarized to list definitions of "narrow bridge" and categories of narrowness as seen by the states.

State No. 1. Narrow bridges have a maximum width of 23 ft - 11 in. For widths of 20 ft - 0 in. to 23 ft - 11 in., the bridge is simply narrow. For widths less than 20 ft - 0 in., the bridge is one lane. There are no other distinct categories.

State No. 2. A narrow bridge is one with a roadway width less than 24 ft but not less than 18 ft where the bridge is narrower than the sum of the lane widths on the approach. All narrow bridges are categorized as follows:

- two-way (< 18 ft).
- two-way (18 ft - 24 ft, width < approach width).
- two-way (≥ 24 ft, width < approach width).
- one-way (< 18 ft, width < approach width).
- one-way (18 ft - 24 ft, width < approach width).
- one-way (≥ 24 ft, width < approach width).

State No. 3. A narrow bridge includes widths less than 23 ft. There are no categories.

State No. 4. Widths less than 28 ft are of "deficient width." There are no categories.

State No. 5. A narrow bridge is one having a clear two-way roadway of 16-18 ft inclusive, or any bridge having a roadway clearance less than the approach width. There are no categories.

State No. 6. A narrow bridge is 18 ft or less. No other categories.

State No. 7. A narrow bridge is one having the bridge roadway width less than 2 ft wider than the approach lane. There are no categories.

State No. 8. A narrow bridge has a width equal to or less than the approach width. Categorized for treatment only.

State No. 9. A narrow bridge is less than 22 ft. There are no categories.

State No. 10. A narrow bridge is one having a width less than the approach width. Bridges 18 ft or less in width are one-lane bridges.

State No. 11. Narrow bridges are 22 ft or less in width. Categories are:

- Group I - ≤ 16 ft.
- Group II - 16 - 18 ft.
- Group III - 18 - 20 ft.
- Group IV - 20 - 22 ft.

State No. 12. No definitions or inventories, but narrow bridges are defined in treatment. A narrow bridge is signed as such if between 17 and 19 ft. It is signed as a one-lane bridge if less than 17 ft wide.

State No. 13. Narrow bridge is defined as one equal to or less than 24 ft wide. Categories are:

- ≤ 20 ft.
- 20 - 24 ft.

State No. 14. Narrow bridge defined as less than 20 ft wide on the county federal-aid system and less than 23 ft wide on the state system. Categories are by 1-ft increments from 15 ft or less up to 36 ft or over.

State No. 15. This state has 165, or 20 percent of its bridges, deficient in width. Deficient is not defined.

State No. 16. Bridges less than 24 ft wide are deficient. No categories.

State No. 17. A narrow bridge is less than 26 ft wide on the state system and less than 24 ft wide on the county system.

State No. 18. An arbitrary definition of narrow bridge is less than 20 ft wide on the state system and less than 18 ft wide on the county-municipal system. Categories on the state system are:

- ≤ 18 ft.
- 18 - 20 ft.

State No. 19. A narrow bridge is 24 ft wide or less for 2 lanes, or where the width is less than the approach width.

State No. 20. A narrow bridge is defined as having a width less than or equal to 18 ft. For treatment purposes, the following classifications are used:

Narrow bridge:	16 - 18 ft.
One-lane bridge:	< 16 ft.
	< 18 ft with high commercial vehicle percentage.

State No. 21. A narrow bridge is any bridge with a width less than 18 ft or having a width less than the approach width. Bridges less than 16 ft wide are one-lane bridges.

State No. 22. Narrow bridges are less than 22 ft wide or have a width less than the approach width. Categories for classification are:

- 16 ft - 17 ft.
- 18 ft - 19 ft.
- 20 ft.
- 21 ft - 22 ft.

In addition, anything less than the current standards is considered to be deficient. Current standards are:

Interstate	-- 40 ft.
Primary	-- 44 ft.
Secondary	-- 36 ft.

Also, any bridge on the primary system less than 30 feet in width is being replaced.

State No. 23. A narrow bridge is defined on the basis of road classification. These are:

Interstate -- 32 ft width or less.
US, SH, Loop, Spurs -- 26 ft width or less.
FM, Park Roads -- 20 ft width or less.

State No. 24. A narrow bridge is one less than 24 ft in width. No categories.

State No. 25. Narrow bridge is not defined. However, for treatment the state defines narrow bridge as 16 - 18 ft or any bridge with a width less than the approach width.

State No. 26. Narrow bridges are not defined. However, for treatment all bridges are "narrow" or "hazardous." Hazard markers of different types are used for the following categories:

- < 17 ft.
- 17 ft - 24 ft.
- > 24 ft.

<u>Similarities in Definitions</u>

General statements may be made regarding the similarity of "narrow bridge" definitions made by the states:

1. The lower limit for two-way operations appears to fall generally in the range of 16 to 20 ft.
2. In general, a bridge is considered to be narrow if the clear roadway width on the bridge is equal to or less than the approach roadway width. The range is from about 2 ft less than the approach width to 2 ft greater than the approach width.
3. Treatment of narrow bridges generally depends on the bridge width.

<u>Magnitude of Narrow Bridge Problem</u>

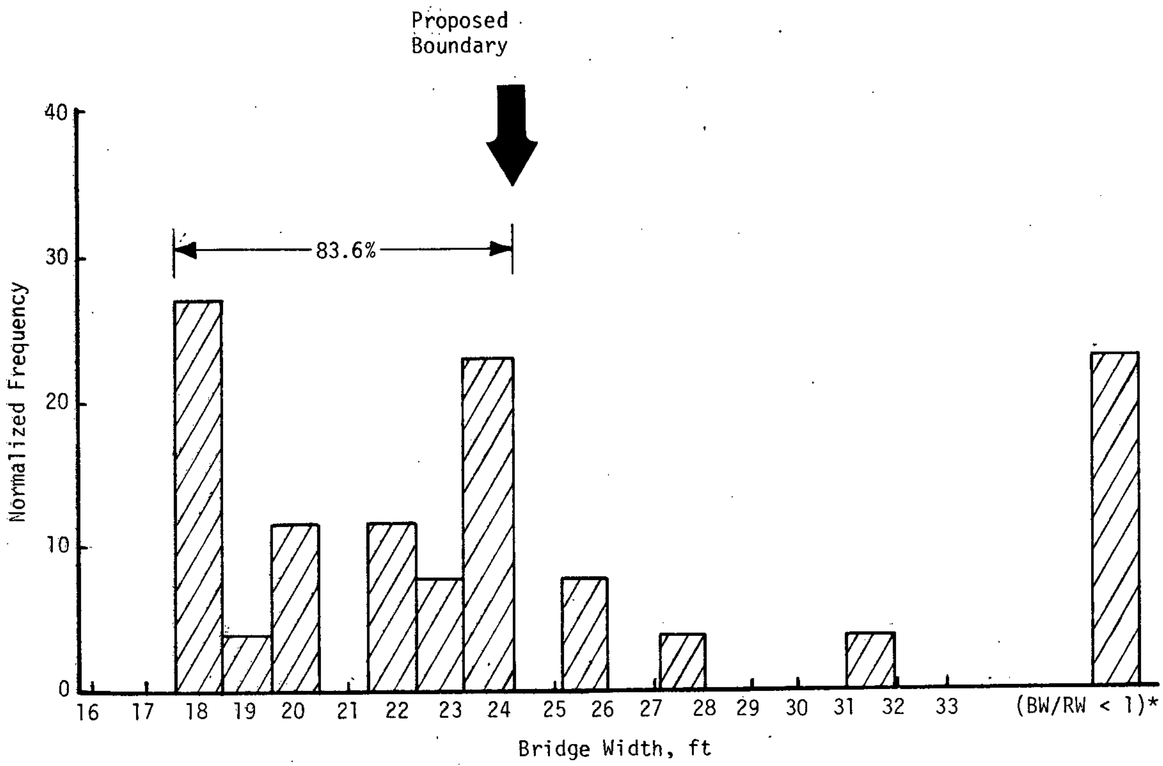
From the responses to the questionnaire, summary tabulations were made of the magnitude of the narrow bridge problem. These summary tabulations are presented in Table B-1. The table indicates both the definition of "narrow bridge" and the category breakdowns received from the states. It is noted that the tabulations are those listed by the various states under the different breakdowns, and the numbers are not cumulative. Figure B-1 also shows the definition and an upper boundary for narrowness.

TABLE B-1

NARROW BRIDGE PROBLEMS, QUESTIONNAIRE SUMMARY[a]

Questionnaires sent out	51
Replies received	43
State bridges (total)	131,049
Deficient in width (no width listed)	21,293
16' or less	2,496
18' or less	7,211
16' - 20'	684
18' - 20'	504
20' or less	5,965
21'	170
22'	453
23' or greater	4,734
24' or less	1,364
20' - 22'	85
22' or less	7
21' - 24'	1,200
26' or less	86
24' - 30'	125
30' or greater	12
County and municipal bridges (total)	118,608
Deficient in width (no width listed)	15,433
18' or less	2,326
20' or less	566
22' or less	91
16' or less	7,905
16 - 20'	2,827
21'	203
22'	243
23' or greater	900
24' or less width; 6' or greater length	4,891
24' or less	968
24' - 30'	164
30' or greater	8
More than 2 lanes less than 12'/lane	42

[a] The numbers are those listed by the various states under the different breakdowns. The numbers are not cumulative.



*BW/RW is the ratio of bridge width to roadway width.

Figure B-1. How responding states voted on the definition of narrow bridges.

RECOMMENDED TREATMENTS FOR NARROW BRIDGES

Data were also summarized from the questionnaire regarding measures to improve safety conditions on narrow bridges (such as warning signs, pavement markings). The following measures are either used or recommended by the states responding to the particular questions (5 and 6):

1. Delineators, reflective signs, raised pavement markers, edge stripes, and reflective paint on end posts.
2. Standard "narrow bridge" sign.
3. Standard "one-lane bridge" sign.
4. Eleven-inch edge line from 50 ft in advance of bridge with the inside edge of the stripe in line with the inside edge of the bridge abutment, or curb line if curbing exists. The stripe shall extend for 150 ft then taper to the edge of roadway. The length of taper, L, is equal to the speed limit, S, times the transition width, W, which is the right-angle distance from the edge of the roadway to the inside edge of the bridge abutment or curb line. The width of transition is measured 200 ft in advance of the bridge.
5. For one-lane bridges, the broken centerline will be as follows:
   a. Two-way roadway -- remove the centerline on each approach back to the beginning of the edge line stripe.
   b. One-way roadway -- remove the centerline on the approach end for a distance of 400 ft from the beginning of the edge line stripe, and on the exit end of the bridge remove the centerline beyond the bridge for a distance equal to the taper length (L) plus 200 ft. On two-way roadways where a one-lane bridge exists, a no-passing line is installed a minimum

distance of 500 feet on each approach. (See Figs. B-2 - B-7 for example illustration of items 4 and 5.)

6. Use a team approach for diagnosing problem areas and recommending treatment.

7. All signing and marking done in accordance with the *Manual on Uniform Traffic Control Devices* (4).

8. Installation of traffic lights for assignment of right-of-way.

9. Use barrier rails to divert traffic away from parapets and wingwalls.

10. The abutment would be striped with reflective white and black stripe. A button-type delineator would also be placed at this location to accent the bridge end. In advance of the abutment, several treatments have been utilized. Where there is guardrail, delineators will be placed on this guardrail. In many cases, for several hundred feet in advance of the bridge the black and white striped panels are used to lead the driver into the proper bridge lanes. Narrow bridge signs would be utilized as an additional standard. Pavement delineators may also be used on the centerline and edge line to give additional warning to the driver and guide him across the bridge.

11. Use warning signs at preceding cross roads.

12. Use rumble strips.

13. Use channelizing guardrail, reflectorized standard MUTCD signs and a triple 3-in. amber delineator at all four corners of the bridge. Also, use clearance markers at the corners.

14. Standard MUTCD treatment.

15. Standard MUTCD signs with placement corresponding to 85th percentile speed. Placement varies from 250 ft for 35 mph and below to 750 ft for 56 mph and over.

16. Use no passing zones, including use of no passing signs and pennants along with standard MUTCD signs and delineators.

17. End walls marked with black and white striped panels (reflectorized).

18. Flared W-section guardrail with MUTCD hazard markers and signs.

19. Yellow and black hazard panels at end of bridge.

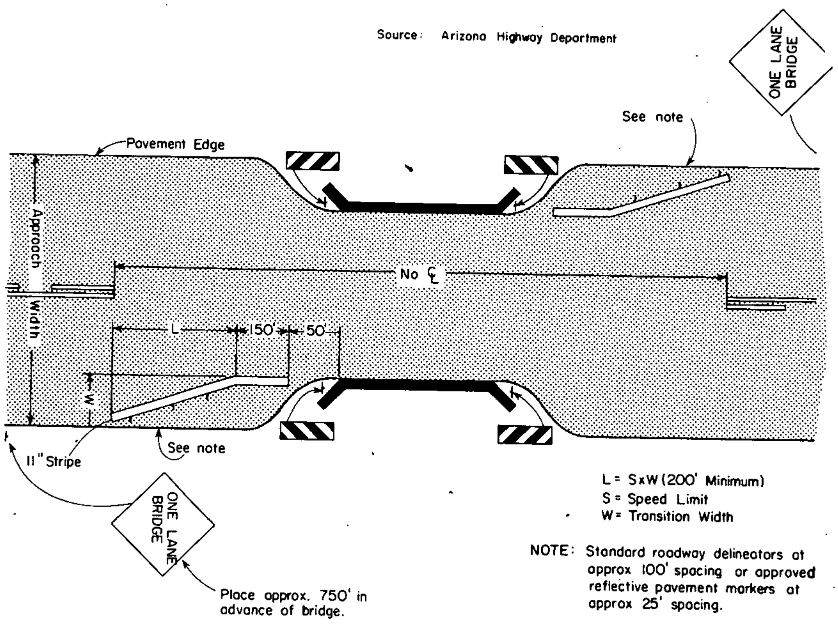


Figure B-2. Standard #1 -- two-way roadways -- bridges less than 18' wide.

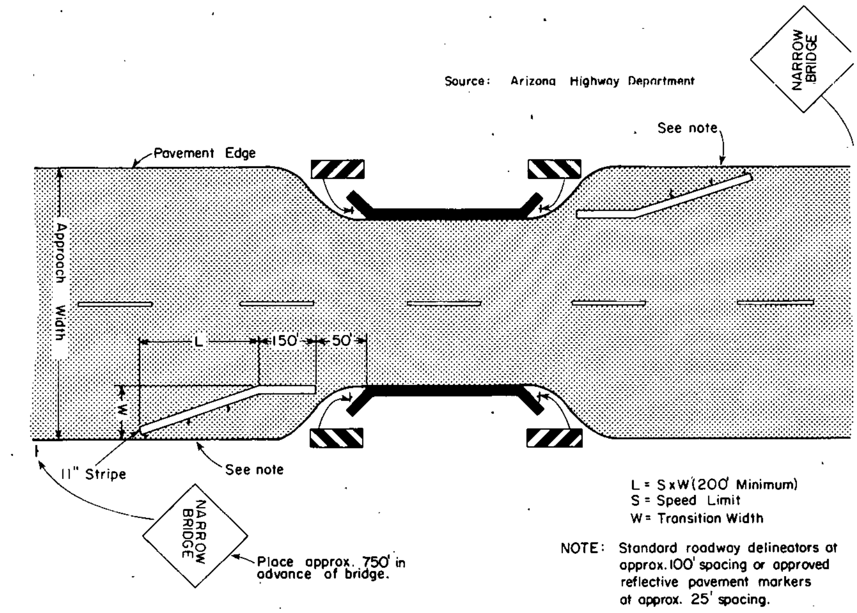


Figure B-3. Standard #2 -- two-way roadways -- bridges 18' to less than 24' W (where bridge is narrower than the sum of the lane widths on the approach).

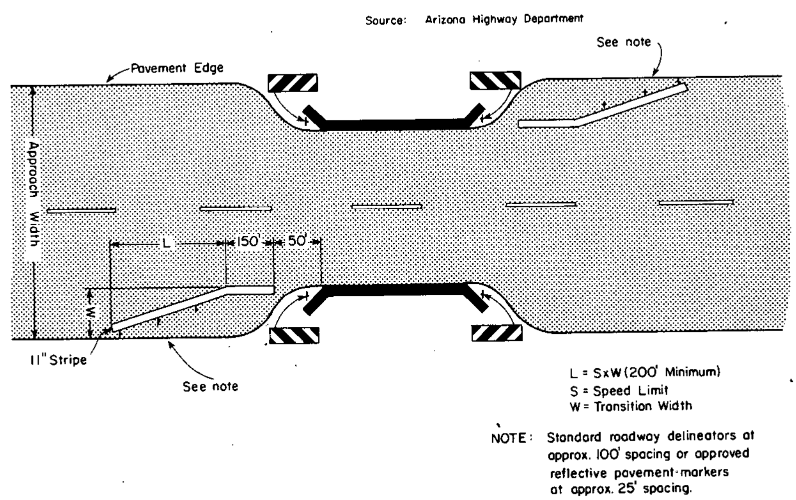


Figure B-4. Standard #3 -- two-way roadways -- bridges 24' or wider (where bridge is narrower than the approach pavement).

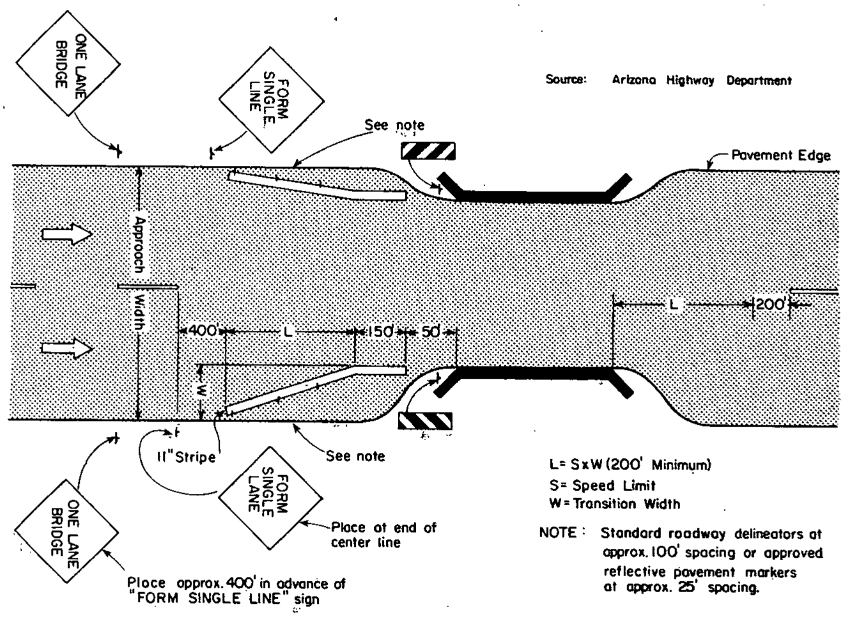


Figure B-5. Standard #4 -- one-way roadways -- bridges less than 18' wide.

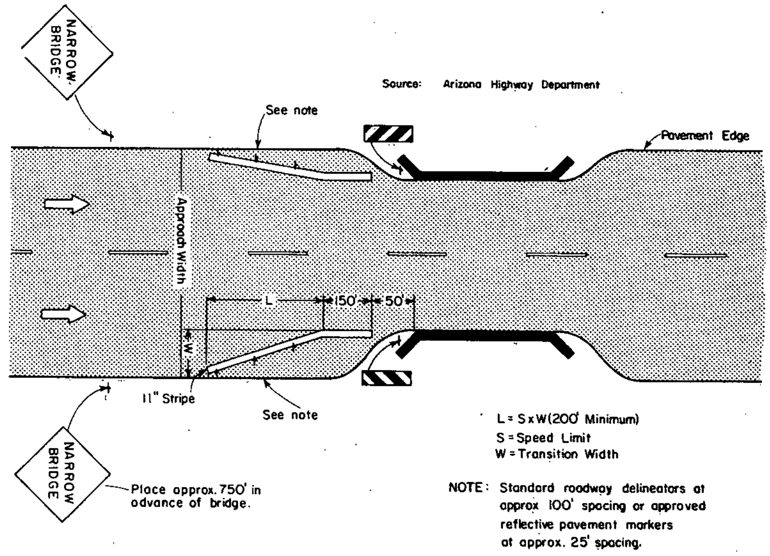


Figure B-6. Standard #5 -- one-way roadways -- bridges 18' to less than 24' wide (where bridge is narrower than the sum of the lane widths on the approach).

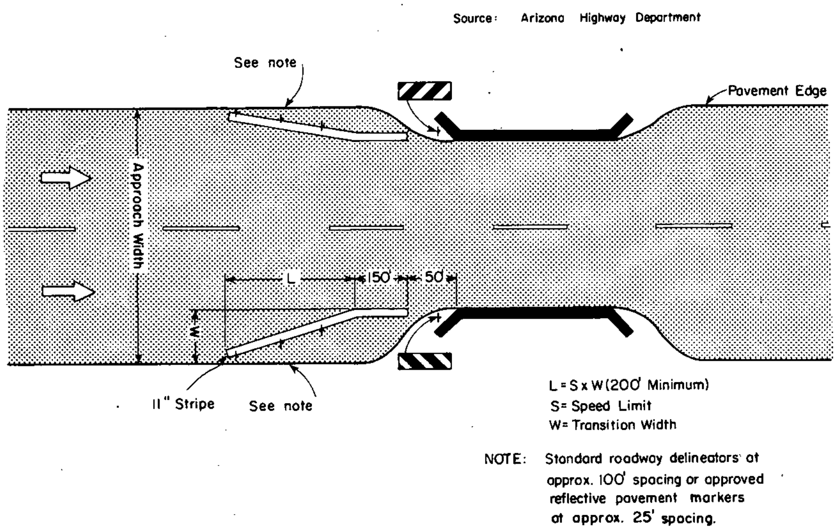


Figure B-7. Standard #6 -- one-way roadways -- bridges 24' or wider (where bridge is narrower than the approach pavement).

APPENDIX C
BIBLIOGRAPHY

NARROW BRIDGES

1. Archibald, R., "Significant Changes in Modern Bridge Design." *Roads and Streets*, Vol. 90 (2) pp. 57-59 (Feb. 1947).
   Illustrated description of hazardous highway bridges and of recently built bridges whose dimensions, pavement and type of structure are in accordance with requirements of steadily increasing traffic.
2. Beaton, J. L., and Rooney, H. A., "Raised Reflective Markers for Highway Lane Lines." *Hwy. Res. Rec. No. 105*, pp. 1-7 (1966).
   Describes wedge and button reflective white markers as used by the California Division of Highways. These markers are used to delineate the center strip and outside edges of pavements. They are particularly effective during rain, when traffic stripes tend to disappear. These particular markers can be used on either asphaltic pavement or portland cement concrete. They have been proven to be durable and are considered very serviceable in California.
3. Behnam, J., and Laguros, J. G., "Accidents and Roadway Geometrics at Bridge Approaches." *Pub. Works*, pp. 67-70 (Apr. 1973).
   Report defines the variables to be used in this study and illustrates their use as parameters. A mathematical model is described and three example problems are given.
4. Blatnik, J. A., Prisk, C. W., and D'Amico, S. J., *Roadside Hazards*. Eno Foundation for Hwy. Traffic Control, 68 pp. (1968).
   Blatnik's article outlines the highway safety problem, especially the dangers in roadside design and construction, the analysis of roadside hazards, and how they can be corrected, and the need for highway departments to design safer roads. Prisk's article discusses guardrails, signs and supports, curbs, drainage elements, bridges, bridge approaches, bridge railings, shoulders and slopes, and lighting from the hazard point of view. A section of photos of typical hazards is included. /HSL/
5. Clary, J. N., "New Highway Bridge Dimensions for Safety." *ASCE J Transportation Eng.*, Vol. 97 (TE2), Proc. Paper 8152, pp. 371-381 (May 1971).
   Currently accepted methods for providing maximum safety for motor vehicle traffic operating over or under highway bridges are presented. Abutments, piers, parapets, and railings of bridges may be safety hazards if placed too close to traveled

lanes; greater distances to such fixed objects are desirable. Details and clearances are described and shown. Continuity of bridge railing and approach guardrail with an appropriate transition is described and illustrated. Details of connections and transitions are also shown. /Author/

6. Dale, J. M., "Pavement Marking -- Danish Style." *Better Roads,* Vol. 40 (2), pp. 28-29, & 31, 3 fig, 2 ref, (Feb. 1970).

Danish practices, in terms of pavement markings, are outstanding from the standpoint of daytime delineation. All expressways and primary roads are marked with 20-in.-wide edge lines, which are highly visible because of their size and their contrast with the predominantly used asphaltic-concrete riding surfaces. Thermoplastic markings are used and maintained, even in Copenhagen. The thermoplastic material used consists of approximately 22 percent organic binder, 5 percent pigment and 73 percent fine and coarse fillers and aggregates. One of the things that distinguishes the Danish thermoplastic from its English and American counterparts is the use of synthetic aggregate called Sinopal in its manufacture. It is a very hard, white, skid-resistant synthetic aggregate that has visibility characteristics, particularly when wet, that are superior to natural aggregates. Sinopal is principally used as an admixture to the aggregate fraction of asphaltic concrete to provide skid resistance and brightness to pavement surfaces. The thermoplastic material is a solid, is melted and heated and applied by a spreader box that is drawn along the road surface. A primer is employed when applications are made over portland cement concrete. Because of the rapid solidification time of the thermoplastic, it is not necessary to use warning cones. The life of the thermoplastic markings in Copenhagen is closely related to the traffic density on new highways in Denmark, because Edge line, a grooving machine, is run along the edge to provide this line, which the thermoplastic-application machine then follows. By depressing the edge marking in this fashion, a means for water runoff is provided and depression storage and ice patches are avoided.

7. Godwin, M. H., "Small Spans Replace Old Bridges." *Better Roads,* Vol. 18 (9), pp. 25-28 (Sept. 1948).

Illustrated examples show progress made in California in replacing obsolete and unsafe bridges with culverts and similar structures, simultaneously improving alignment, gradient and sight distance.

8. Gunnerson, H. E., "Iowa Narrow Bridge Accident Study." *Hwy. Res. Abstracts* (July 1961), p. 23.

The Iowa narrow bridge study included a total of 72 bridges, including 65 bridges with less than 24-ft horizontal clearance on all roads with 24-ft surfaces, together with 7 control bridges, all with 30-ft horizontal clearance on roads with 24-ft surface.

The accident records from the files of the Traffic and Highway Planning Division were checked for a 12-yr period from Jan. 1, 1948 to Dec. 31, 1959.

These accidents were separated into two groups. The first group included accidents occurring before, and the second group happened after, the road surface was widened to 24 ft. The number of accidents, bridges hit, injuries and property damage were compiled for each bridge, together with the number of months the bridge was in either category. The 65 bridges were placed in three groups based on daily traffic. Group 1 carried 0 to 999 veh/day and included 12 bridges; Group 2 carried 1,000 to 2,999 veh/day and included 46 bridges; Group 3 carried 3,000 and more veh/day and included 7 bridges. The control bridges were grouped according to accidents before the road and bridge were widened and those after the widening. The control bridges were not separated into traffic groups. The traffic ranged from 1,580 to 3,630 veh/day on the control bridges. The accident figures were then added to give a total for each of the foregoing items.

The term "bridge-months" was arrived at by taking the number of bridges in each category times 144 (12 years x 12 months). For example, Group 1 with 12 bridges would be as follows: 12 bridges x 12 years x 12 months = 1,728 bridge-months. There were 902 bridge-months before widening and 826 after widening, or a total of 1,728.

9. Hilton, M. H., "Some Case Studies of Highway Bridges Involved in Accidents." *Hwy. Res. Rec. No. 432,* pp. 41-51 (1973).

Accident reports, field evaluations, state police and highway engineer questionnaire replies, and other data sources were used to conduct a general study of accidents involving highway bridges in Virginia. Several geometric characteristics were found to predominate at many of the arterial and primary system bridges investigated. Some of the more salient characteristics were pavement transitions on bridge approaches, approach roadway curvature to the left, narrow bridge roadway widths, intersections adjacent

to bridges, and combinations of these and other geometric factors. On Interstate highway bridges, poor surface conditions were found to prevail during a significantly high proportion of accidents. Several case studies are presented that illustrate some of the characteristics of bridge sites that have been involved in highway accidents.

10. Hilton, M. H., and Redick, J. R., "A Study of Accidents Involving Highway Bridges." Virginia Hwy. Res. Council (Mar. 1971).

Accident reports, field evaluations, state police and highway engineer questionnaire replies, and other data sources were used to conduct a general study of accidents involving highway bridges in Virginia. The bridges included in the study were divided into three groups. These were: (a) arterial and primary system bridges, (b) Interstate system bridges, and (c) draw and swing span bridges.

Several geometric-type characteristics were found to predominate at many of the arterial and primary system bridges investigated. On Interstate bridges poor surface conditions were found to prevail during a significantly high number of accidents, and rear end collisions proved to be a significant problem on several toll draw or swing span structures. A more detailed listing of these and other findings is summarized under the conclusions of the report.

The upgrading of existing bridge rail-approach guardrail systems, widening of certain narrow roadway width bridges, and certain precautionary considerations for use during planning and design are among a number of recommendations offered at the end of the report.

11. Hopkins, T. C., and Deen, R. C., "The Bump at the End of The Bridge." *Hwy. Res. Rec. No. 302*, pp. 72-75, 5 fig (1970).

The general relationship is summarized between the appearance of bridge approach settlement and various conditions at bridge sites. Data obtained from a survey of existing bridge approaches conducted in the summers of 1964 and 1968 provided general information as to the prevalence of embankment or foundation problems in Kentucky. The approaches were classified according to one of the following settlement categories: (1) Group 1 Settlement, no maintenance necessary and no approach fault noticeable, (2) Group 2 Settlement, no maintenance performed, however, an approach fault was observed, and (3) Group 3 Settlement, maintenance performed on the approach. The criterion used to distinguish between Groups 1 and 2 was whether or not a bump was evident when an automobile passed onto or off the bridge deck. Additional information was obtained by visually inspecting each approach. The ages of the approaches were noted. From these data, it is evident that present design and construction procedures are not sufficient to guarantee smooth bridge approaches. A comparison of portland cement concrete and bituminous concrete approaches shows a markedly higher percentage of bituminous concrete approaches with patching than rigid approach pavements with mud jacking in 1964. However, in 1968 the difference in percentage of mud jacked and patched approaches, as well as smooth approaches, was almost insignificant. Apparently, for a short period of time the rigidity of portland cement concrete pavement reduced the occurrence of the approach fault by bridging the presumed depressment behind the abutment. A comparison of the most commonly used type of abutments with respect to the three settlement groups revealed that the open-column (open-end) type was more commonly associated with settlement group 3 than either the pile-end-bent (open-end) type or stub (closed-end) type in 1964. However, in 1968 there was an increase in percentage of faulted approaches for all types of abutments, with the percentages for pile-end-bent increasing the most. There were small differences in percentages between the pile-end-bent and open-column abutment. The performance of bridge approaches with and without special granular backfill was compared. No advantage was shown and the influence of different geological and soil conditions was only slightly noticeable.

12. Hopkins, T. C., and Scott, G. D., "Estimated and Observed Settlements of Bridge Approaches." *Hwy. Res. Rec. No. 302*, pp 76-86, 8 fig, 7 ref (1970).

Mercury-filled settlement gages were installed on the original ground of the approach embankment foundation at four selected bridge sites, and settlement plates installed at one other bridge site, to determine if the settlement at bridge abutments is primarily a result of volume changes in the embankment and/or foundation and to compare observed and predicted foundation settlements. By continually obtaining elevations of points located on the pavement, settlement of the pavement was obtained. Embankment settlement was taken as the difference between the pavement settlement and foundations settlement. Undisturbed soil samples were collected from the foundation soils at each of the five sites, and consolidation tests were performed on these samples. These data and Terzaghi's theory of consolidation were used to calculate expected foundation settlements. The following conclusions were

substantiated by findings from field and laboratory investigations: (1) The analysis procedures used are quite adequate for predicting embankment foundation settlements, (2) Settlement of the approach foundation can contribute significantly to settlement of bridge approaches; the amount contributed is highly dependent upon the time at which approach pavement is constructed, (3) Settlement of the embankment can contribute significantly to settlement of the approach pavements, and (4) The results of settlement investigation performed at the sites of proposed bridge construction projects can provide a much needed basis for design to control or minimize the effect of approach settlement.

13. "How Indiana Rebuilds Narrow Bridges." *Wood Preserving News*, Vol. 38 pp. 5-8 (Dec. 1960).

History of the state-wide bridge-widening project in Indiana. The state had hundreds of 16- to 20- ft bridges on both primary and secondary road systems. A study indicated 16- to 20- ft bridges were serving roads 20 - 22 ft wide. The narrow bridges caused motorists to lose control of their vehicles. A description of procedures used by highway department is given. Time varies for complete widening from 2 hours to 3 or 4 days, depending on numerous conditions, length of span being most important.

14. Korfhage, G. R., "Special Rumble Seal Coat Strips for Traffic Warning." Final Report, Minnesota Dept. of Highways, *Special Study No. 279*, 23 pp. (1968).

The purpose of this study was to evaluate the aggregate types and gradations, and bituminous binders, used in the construction of special seal coats installed as traffic warning devices. The construction and performance of these rumble strips are described. Tentative recommendations are made regarding the type and quantity of aggregate and bituminous binder for maximum noise intensity and aggregate retention. The subject of rumble strip configuration (length and spacing) was not investigated.

15. "Low-Level Lighting for Bridges Is Tried Out." *Better Roads*, Vol. 29 (3) p. 50 (Mar. 1959).

Lighting on Manahawking Causeway Bridge on New Jersey Route 72 consists of 384 separate fluorescent lighting units mounted on top railing of 2400-ft long bridge balustrade; each 42-in. long unit spaced 2 ft from next and light rays are directed to bridge's four-lane concrete roadway at right angles to traffic; test procedures; results indicate uniformity of illumination, elimination of glare, and greater effectiveness in fog, rain and snow.

16. Mills, G. M., "Widening and Reconstruction of Road Bridges." *Instn Mun Engrs--J*, Vol. 88 (1) pp. 8-15 (Jan. 1961).

Assessment of existing bridges; widening of superstructure by addition of new bridge to existing structure; widening by cantilevering is possible where abutments are of adequate strength; strengthening of existing superstructures and raising of soffit; widening of abutments needs thorough investigation of foundation; strengthening of abutments by chemical consolidation, injection of cement grout, underpinning with piles, and increasing area of foundation.

17. Moncur, G., "Warning Device for Low Bridge." *Mun Engrs J*, Vol. 86 (5) pp. 157-160 (May 1959).

Photoelectric sensing device measures height of vehicle approaching low bridge at Burton upon Trent, Great Britian, and gives visual and audible signal when vehicle cannot pass; infrared ray projecting 1 1/2 in. lower than headroom above entire roadway registers objects reaching this height.

18. Mosher, W. W., *The Highway Environment and Safety*. Eno Foundation, pp. 69-90, 22 ref (1967).

Highway safety studies approach the problem by the basic components, the highway environment, the driver, and the vehicle. The general problems concerning traffic safety are reviewed. Factors such as signing messages, congestion, sight distance, speed limits, lighting, weather, road condition, intersection placement, geometric design, and law enforcement comprise highway environment. Factors of the complex interactions between the vehicle and the driver include bridge abutments, sign structures, light standards, median dividers, other automobiles, pedestrians, median and shoulder geometry, building placement, and maintenance. The post-accident factors include accident detection, availability of emergency equipment, methods of removal of injured, and ease of reaching the scene of the accident. Ramp placement in the vicinity of freeway-to-freeway interchanges is discussed as it affects accidents.

19. "New Type of Aggregate Used on Bangor Project." *Maine Highway News*, Vol. 11 (11), p. 4 (Nov. 1968).

A new type of aggregate has been used in the bituminous mix placed on a short section of a road in Bangor. The man-made aggregate is white and will result in a light-colored roadway once traffic wears away the top layer of asphalt. The material is produced by melting sand and lime and has been tested in pavement mixes in Illinois and Michigan. The mix used in Bangor was 30 percent of the

white aggregate plus standard aggregate and asphalt. Tests seem to indicate that pavement surfaces containing the new material possess anti-skid qualities and aid in visibility at night. This last quality would seem to make it useful in delineating approaching roadways at intersections, the ramps of interchanges, and pedestrian crosswalks.

20. Shelby, M. D., and Tutt, P. R., "Vehicle Speed and Placement Survey." *HRB BULL. 170*, Part 2, pp. 33-38 (1958).

The paper reports factual data obtained from three separate surveys, as follows:

1. Speed and placement by vehicle type, maneuver, and light condition on two-lane rural highways at twelve observation sites. The sites included lane widths from a minimum of 11 to a maximum of 19 ft. Shoulder conditions included asphalt-sealed, gravel, and grass. The purpose of the study was to obtain data to support a possible change in recommended lane width.

2. Relative placements by vehicle type, maneuver, and light condition on six different width roadways of rural bridges from a minumum of 24 to a maximum of 44 ft were obtained. These data, plus vehicle speeds, were obtained on the approach roadway to each of these six structures. All approach pavements were 24 ft wide with sealed shoulders with fair to good color contrast. The purpose of this study was to obtain data to support a possible change in recommended width of restricted roadway bridges.

3. Relative effect on traffic operation of a parked vehicle on a 6-ft wide shoulder on a one-way two-lane urban grade separation structure. This study was very limited in scope, but was made in an effort to gain a partial answer as to the effectiveness of this narrow shoulder. Speed and placement by vehicle type, maneuver, and light condition were obtained on each of two consecutive days. The first day was without a vehicle parked on the shoulder, the second day with a passenger vehicle parked on the shoulder. Although the presence of the parked vehicle had a marked effect on the traffic flow, the two lanes of traffic could move over the structure at reasonable speeds.

21. Steward, Carl F., *Bridge Widening Problems.*, Bridge Dept., California Div. of Highways, SSR 2-65, 10 pp. (Apr. 1965).

The Bridge Department of the California Division of Highways widened 341 bridge structures between 1950 and 1963. Maintenance history of these widenings indicates that methods used to reclaim the portion of deck surface under the original curb and to effect attachment of new to original decks have produced widely varying results. Most of the methods have been satisfactory, but some have produced unsightly decks and maintenance problems.

To determine the most effective methods of handling the various problems encountered in widening structures, a study, including a field performance survey and a search of maintenance history records, was made on a number of structures widened during this period. Conclusions indicate that, compared with conventional monolithic structures, widened structures are proportionally a greater source of bridge maintenance because of one, or a combination, of the following: (a) spalling of bituminous concrete over the longitudinal joint; (b) unusually high escarpments along the longitudinal joint; (c) spalling of the original concrete in the reclaimed deck area; and (d) spalling of patches placed over the cut-off curb dowels and the temporary railing hold-downs or in low spots of the reclaimed deck. A smoother riding surface is obtained, bridge deck maintenance is reduced, and deck appearance is improved by attaching widened decks to the original through lapped deck reinforcing steel.

22. Tamburri, T. N., Hammer, C. I., Glennon, J. C., and Lew, A., "Evaluation of Minor Improvements." *Hwy. Res. Rec. No. 257*, pp. 34-79, 10 fig, 55 tab, 15 ref (1968).

These investigations evaluated the current effectiveness of (1) center-suspended and advance warning flashing beacons in reducing accidents, (2) safety lighting installations in reducing night accidents, (3) various delineation devices, and (4) protective guardrail in reducing reported accidents. A before-and-after study method was used to evaluate 45 flashing beacons, 41 safety lighting projects, 32 delineation locations, and 14 guardrail locations. In addition, the current warrants for intersection flashing beacons and for safety lighting were compared with other possible warrants to determine if more effective criteria could be established. Two methods of predicting future accidents are also reviewed. /Author/

23. *Uniform Traffic Control Devices for Canada.* CNCL Uniform Traffic Contr Devices /Can/ Second Ed., 206 pp. 55 fig, 7 tab (May 1966).

The manual is divided into three major areas: traffic signs, traffic signals, and markings. Regulatory signs, pedestrian signs, warning signs, construction and detour signing guide, and guide signs are covered. The area traffic signals describe in detail the general aspects of traffic control signals, installation warrants for traffic control signals, operational requirements for traffic control signals, traffic control signal timing, traffic control signal head and detector locations, and miscellaneous traffic signals. Pavement and curb markings, and hazard and delineation markings are described. Definitions of all major traffic engineering terms are given. These established standards for signs, signals, and pavement markings for Canada place emphasis on the use of the recommended symbolic traffic signs. /CGRA/

24. West, A. R., "Special Gutters Drain Roadway of Bridge." *Better Roads*, Vol. 19 (5), pp. 33-34 (May 1949).

Faulty drainage from roadway of Hill-to-Hill Bridge in Bethlehem, Pa., remedied by construction of special gutters; former drainage was handled by grooving pavement to drain to gutters on each side; during winter months drains froze, resulting in breakage.

25. White, A. M., "Safety and Bridges." *Proc. Convention Committee Meeting Papers*, AASHO, pp. 264-267 (1965).

An engineer with the Mississippi State Highway Department discusses bridges and drivers. He points out that the average automobile driver assumes that all parts of a road are safe for travel in all segments and at all speeds. He feels that one of the major causes of sight restriction is the bridge rail, particularly when the bridge is located on a vertical curve. He points out that the people who build the bridges do not necessarily design them, but that closer coordination between the bridge engineer and design engineer can eliminate some of the problems. He feels that all signs should be 10 - 15 ft from the edge of the pavement. He points out that during the night hours or bad weather, bridge rails and obstructions are hardest to see. The Mississippi Highway Department uses reflectors on the bridges and paints the bridge abutments to increase their visibility. Bumps caused by the settlement of bridge end slabs are also discussed. The handling of traffic during maintenance and construction and the things to do to improve traffic movement are considered briefly.

26. Wilkes, W. J., "Bridges and Safety." *1967 Proc., Convention Committee Meeting Papers*, AASHO, pp. 200-212 (1967).

An official in the Bridge Division of the Federal Highway Administration discusses bridges and safety. With photographic illustrations and several lists of things to do, he outlines what the official Federal Highway Administration policy is on bridge safety. He does not favor the items that he calls "road clutter" and includes in that category guardrails and signs. He feels that the bridge engineers should properly design and locate these particular items.

27. Wylie, R. K., Accident Report.

This is the official report by an officer of the New Mexico State Police on an accident that occurred December 26, 1972 east of Ft. Sumner, New Mexico. The vehicles involved were a cattle truck and a bus loaded with young people enroute to a church vacation area in New Mexico. Included are diagrams and narrative from Officer Wylie and a list of the fatalities and injured. Eighteen fatalities occurred along with 15 injured. The diagrams indicate that the two-lane highway was only 21 ft wide, but the bridge on which the accident occurred narrowed to 20 ft. The bridge had a total length of 94.3 ft, and that it was 500 ft from the end of the bridge to a sign marked "Narrow Bridge".

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