NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT 239

# MULTIPLE-SERVICE-LEVEL HIGHWAY BRIDGE RAILING SELECTION PROCEDURES

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RESEARCH SPONSORED BY THE AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS IN COOPERATION WITH THE FEDERAL HIGHWAY ADMINISTRATION

AREAS OF INTEREST:
- FACILITIES DESIGN
- STRUCTURES DESIGN AND PERFORMANCE
- (HIGHWAY TRANSPORTATION)
- (PUBLIC TRANSIT)
- (RAIL TRANSPORTATION)

TRANSPORTATION RESEARCH BOARD
NATIONAL RESEARCH COUNCIL
WASHINGTON, D.C. NOVEMBER 1981

## NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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# FOREWORD

*By Staff*
*Transportation*
*Research Board*

This report contains the findings of an extensive analytical and experimental investigation intended to advance procedures for development of bridge railing systems. A lower cost bridge railing system, intended for use when warranted by particular site conditions, was developed and evaluated by full-scale crash tests. Furthermore, an approach was developed for selecting the appropriate category of railing system based on a classification of conditions at the particular bridge site. These findings are recommended for immediate application and will be of interest to bridge engineers and others concerned with design and performance of bridge railings and vehicle barrier systems in general.

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Current design specifications for bridge railing systems are predicated on a general performance requirement of ensured containment. The "average" vehicle referred to in AASHTO specifications is not defined, but is generally considered to be a full-size domestic passenger car. Impacts by 4,000- to 4,500-lb (1,820 to 2,040 kg) vehicles at speeds in the 50- to 70-mph (80.5 to 112.6 kph) range with impact angles of up to 25° have been considered to be appropriate full-scale crash test conditions. Excessive vehicle decelerations or penetration of the bridge railing under these test conditions have been considered to constitute unacceptable performance.

Bridge railing systems used on primary and Interstate highways can be categorized as "normal service level" railings and must meet the foregoing performance requirements. These are generally designed through application of static-elastic design criteria expressed in the AASHTO Standard Specifications for Highway Bridges. The resulting designs may have substantial structural integrity and a concomitant substantial cost. Routine verification of these designs through full-scale impact testing is not required by AASHTO specifications.

Many secondary or local roads are designed for and subjected to operating speeds, traffic volumes, vehicle weights, and possibly vehicle-barrier impact angles that are somewhat less than the normal service level. These roadways can be considered to serve a "lower service" need and, in the view of some, the application of normal service level bridge railing design criteria may not be cost-effective in these instances.

There are also situations where circumstances call for a higher level of performance than usual on primary or on Interstate highways. This may be due to heavy traffic volume, a preponderance of truck traffic, severe geometric conditions, or vulnerable habitation beneath the bridge. In these cases designers may consider using a high-performance railing.

Accordingly, the development of an array of service levels, performance criteria, and design criteria would prove useful to those desiring to use more appropriate and cost-effective bridge railings.

The objectives of this project were (1) to identify and document realistic performance criteria and correlated design criteria for bridge railing systems on roadways providing various levels of service; and (2) to develop a lower-cost bridge railing system, based on criteria for a lower service level, and to validate this system using analytical and full-scale testing methods.

This report contains detailed information on a newly developed, lower-cost bridge railing system. The system was evaluated by full-scale crash tests with cars and a school-type bus. In addition, recommendations are offered for modification of the current AASHTO specifications on bridge railings. The proposed modifications would require performance testing and adoption of a multiple-service-level approach. The results of this research were presented at the regional meetings of the AASHTO Subcommittee on Bridges and Structures in 1981.

# CONTENTS

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# MULTIPLE-SERVICE-LEVEL HIGHWAY BRIDGE RAILING SELECTION PROCEDURES


## SUMMARY

This report presents procedures that permit the rapid service level selection for a bridge site based on functional classification and traffic volume. The multiple-service-level approach (MSLA) of this project is formulated from consideration of frequency and severity of bridge railing collisions. By comparing the benefits of bridge railing with the cost of bridge railing, benefit and cost (B/C) ratios are determined for typical bridge sites. Determination of service level is readily achieved by using these B/C ratios as a basis.

As a result of the research conducted under Project 22-2(3), a new low-cost ($10/linear ft, installed) bridge railing was designed, developed, and evaluated by crash test. Crash test evaluations involved cars and a school bus. On the basis of the project findings, use of these new railings could be widespread on low-volume roads.

An in-depth investigation of all aspects of bridge railing technology was conducted. Findings include the recommendation for performance testing of bridge railings. Static load or force criteria for bridge railings are not recommended.

Current bridge railings are assessed for service level designation and estimated installed cost. The full range of four service levels is represented by bridge railing systems with crash test experience.

The current AASHTO bridge railing specification is discussed and recommendations made for revision and additions. These recommendations, which include performance testing, are consistent with an observed national trend toward the adoption of a limited number of carefully developed and demonstrated barrier systems.

Guidelines are presented that will aid a user agency in applying the MSLA procedures to existing construction. Use of these guidelines will enable the agency to develop a priority procedure for upgrading bridge railings with demonstrated inadequate capacity.

Traffic volume at a bridge site was identified as generally the most important variable with regard to service level designation. Thus, Chart 1 summarizes the service level designation according to traffic volume. A more in-depth service level identification is contained in the selection tables of Chapter Two and in the discussion in Appendix A.

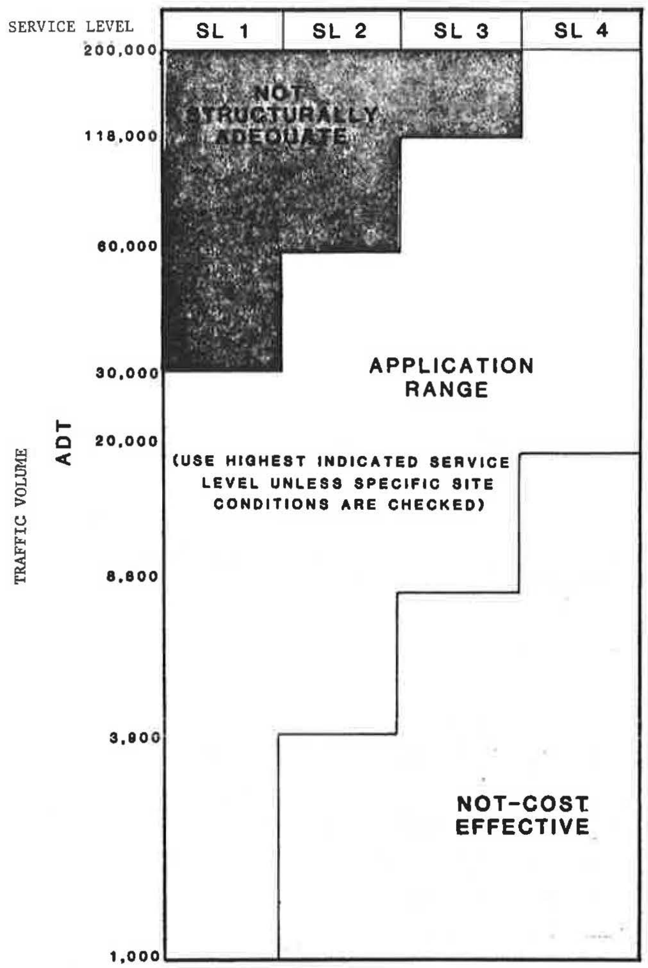



*Chart 1. Traffic volume and bridge railing service level category summary. (This chart includes both Texas and Washington data; the text explains consideration of these two sets of data.)*

CHAPTER ONE

# INTRODUCTION AND RESEARCH APPROACH

## INTRODUCTION

Only one bridge railing level of service is currently recognized by AASHTO (*1,2*). At the same time, concern has been expressed by highway engineers that this single service level may be overly expensive and not cost-effective for low-volume roads. In addition, the current railing specification may not be appropriate for highways with high traffic volume and with a high percentage of truck traffic.

The primary objective of this research was to develop a rational procedure for determining bridge railing service levels. Other objectives were to design and develop a low-cost bridge railing system; to assess current bridge railings in relation to multiple service levels, and make retrofit recommendations; and to recommend changes to the AASHTO specification regarding bridge railings.

## RESEARCH APPROACH

Tasks necessary to accomplish these objectives included a critical assessment of all factors relating to bridge railing technology. This led to several possible approaches for determining a rational procedure for bridge railing stratification by service levels. The multiple-service-level approach (MSLA) of this project is based on comparing the benefits of bridge railing with the cost of bridge railing. As accident frequency, severity, and consequences vary in the range from a single lane rural bridge to a multilane urban freeway, the benefits of bridge railing vary accordingly. A strategy recommended in this project involves the matching of bridge railing benefits with bridge railing cost.

The scope of this project included development of a multiple-service-level selection procedure based on frequency and severity of bridge railing collisions and on bridge railing costs (accident, installation).

During the development of the MSLA, a large number of parameters were examined and their relationship to the overall cost-effectiveness of bridge railing selection was ascertained. In some cases, published data, previous research, and accident statistics were used to support elements of the MSLA; in other cases, the authors relied on rational developments. Much of the technology of the MSLA involves derivation of relationships heretofore not used by the highway community. The final product is a rational selection procedure for determining different levels of service according to bridge site conditions and bridge railing(s) performance/cost.

Computer simulations, component testing, crash test evaluations for car and bus impacts, and cost analyses were used in the design and development of a low-cost bridge railing system for a level of service below the current AASHTO requirements.

Bridge railings with known crash test experience were analyzed for performance and cost, and subsequently rated for service level designation. Factors relating to bridge railing upgrading were also examined.

On the basis of the findings of the project, recommendations for changes in the AASHTO specification regarding bridge railings are made. Design drawings and specifications are included.

### ORGANIZATION OF REPORT

The MSLA procedures are presented in Chapter Two. (They are described in detail in Appendix A along with the supporting data. Although the probabilistic model that predicts occurrence and severity of vehicle impact is complex, the procedures to be used by design engineers in determining appropriate service levels are simple and require a matter of minutes.

Chapter Three contains a general discussion of bridge railing performance and design based on current technology; drawings and specifications along with a brief discussion of the development of the low-cost bridge railing are included. (Details on the design and development of the systems are contained in Appendix C.) The assessment of current railings as to service level designation and retrofit guidelines is also discussed in this chapter (design drawings are included in Appendix B).

Chapter Four contains an appraisal of the project and suggested application of the findings; also included are recommendations for revisions to the AASHTO bridge railing specification.

To expedite publication the appendixes included herein are reproduced as submitted by the research agency.

CHAPTER TWO

# DEVELOPMENT OF BRIDGE RAILING SERVICE LEVEL SELECTION CRITERIA

### INTRODUCTION

The multiple-service-level approach (MSLA) for selecting appropriate bridge rail designs for particular highway sites is presented in this chapter. The finalized procedures are the result of an in-depth investigation of bridge railing technology; these procedures are believed to represent the best approach based on available data.

Elements of the MSLA can be conveniently grouped by referring to a collision model, a barrier assessment model, and a cost model.

The collision model is structured to project bridge railing impacts and quantify the frequency and severity of the impacts. The barrier assessment model relates barrier capacity to impact severity. The cost model interprets the performance of a range of bridge rail service levels, thus permitting a comparison of bridge railing accident costs with bridge railing costs (i.e., a benefit and cost ratio can be determined).

Although the MSLA probabilistic collision model is comprehensive, it has been applied for a complete range of typical urban and rural highway conditions and results have been summarized in tabular form. With these tables, a designer knowing the bridge functional classification and traffic volume can determine the appropriate service level in a matter of minutes. For unusual bridge sites that deviate significantly from the typical, guidelines are provided at the end of this chapter and in Appendix A.

This chapter is intended to describe briefly the MSLA procedures and present the findings. Details and supporting information are contained in Appendix A.

### MSLA PROCEDURE DESCRIPTION

The MSLA developed in this project is based on cost/benefit technology as shown in Figure 1. The beginning of the formulations involves a series of complex equations relating to frequency and severity of vehicle impacts with bridge railings (collision model). Bridge railing performance is measured by the number of projected collisions (i.e., critical impacts or penetrations) that exceed the railing capacity for a specified period of time. Thus, at a given bridge site, the number of critical impacts depend on the capacity of the bridge railing. The MSLA concept involves the comparison of bridge railing requirements (distribution of impacts) with bridge railing capacity to contain a certain number of the projected impacts.

The benefits of bridge railing are expressed in terms of dollars by comparing accident costs with and without the

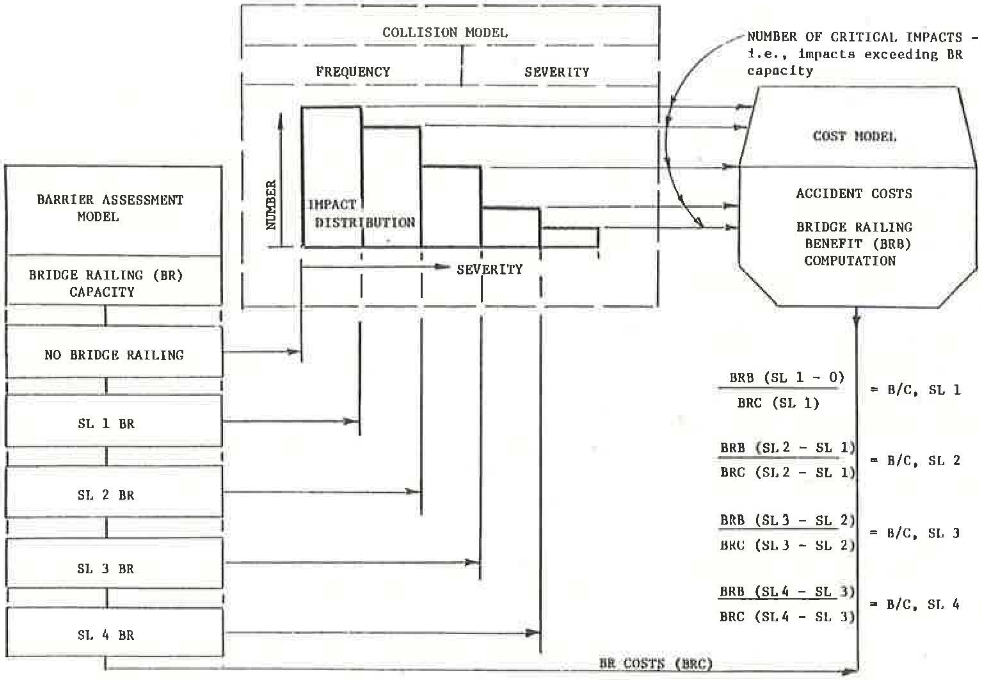



*Figure 1. MSLA formulation diagram.*

benefit of bridge railing containment of the impacting vehicle. By using this comparison with railings of different capacities, the incremental benefits are derived from the difference in accident costs. The incremental benefit and cost ratio is obtained by dividing benefit increments by bridge railing cost increments as shown in Figure 1.

## Collision Model

Bridge railings in service are subjected to a wide range of impacts represented by various vehicles (cars, buses, trucks, and the like) and impact conditions (speed, angle). A collision model was constructed for this project to predict the number and severity distribution of bridge railing accidents.

### *Frequency*

The frequency of bridge railing accidents is dependent on the rate of vehicles leaving the traveled way (encroachment rate) and the distance from the traveled way to the barrier (lateral travel distribution). These two factors (defined as follows) combined with the average daily traffic (ADT) determine the number of bridge railing collisions:

1. Enchroachment rate—vehicle departure from the traveled way; expressed in this project as encroachments per 10 miles per 10 years per ADT as determined from bridge railing accident statistics.
2. Lateral travel distribution—all encroachments do not produce bridge railing accidents if sufficient distance is available for the vehicle to recover before striking the barrier. Thus, the greater the lateral distance, the greater the chance of vehicle recovery. The lateral distance distribution was determined from state-of-the-art data. For bridge railings, this lateral distance is generally the same as the shoulder width.

### *Severity*

The term severity as used here relates to barrier loading. Because a wide range of impact possibilities exists, it was necessary to first develop an expression for determining equivalent impacts (e.g., at what speed and angle does a 40,000-lb (18,000-kg) bus impact with the same severity as a 4500-lb (2040-kg) car at 60 mph (95 km/h) and a 25-deg angle). A great deal of effort was expended in this project to develop an expression referred to as the Redirection Index (RI). The RI value for an impact is a linear momentum expression for impact severity in terms of barrier loading. With this expression, distribution of impact probabilities are quantified and directly related.

The distribution of impact severities is a measure of the probabilities dependent on the following: traffic distribution (truck percentage, etc.); and impact conditions (vehicle size, impact speed, impact angle).

The traffic distribution determined from sales and vehicle count data identified five traffic mixes composed of eight vehicle types as being typical (see Table 1). The appropriate traffic mix for a bridge is identified from the roadway functional classification. A 40,000-lb (18,000-kg) bus is used as a surrogate for all heavy vehicles as discussed in Appendix A.

Impact conditions are determined from a point mass model that has been used by many researchers to predict impact angle distribution for given speed and distance from the barrier. A distribution of vehicle impacts is computed by using this expression and the percentages of eight vehicle types for five traffic mixes. The RI expression permits the quantification of the range of impacts predicted.

## Barrier Assessment Model

This model includes the stratification of bridge railing service level by capacity and provides a basis for estimating the cost for constructing bridge railings conforming to the different levels.

*Level Capacity*

Four levels of service were identified from currently used crash test conditions and a range of RI values as given in Table 2. With this range of barrier capacities based on RI value, the number of critical impacts is determined from the impact distribution set. Service Level (SL) 2 corresponds to the current AASHTO bridge railing crash test option specification. Test experience has demonstrated that many railings designed to the AASHTO 10-kip (44.5-kN) static force are not significantly damaged when impacted with the corresponding crash test conditions; on the other hand, others designed to the 10-kip (44.5-kN) criteria have failed to perform satisfactorily in crash tests. Thus, the ultimate containment capacity of this railing design can be much greater than the level indicated by the crash test conditions.

*Bridge Railing Cost Estimates*

In order to determine the benefit and cost ratio, it is necessary to identify costs for bridge railings at the various service levels. Accordingly, an effort was undertaken to determine representative costs for bridge railing systems. This effort is described in detail in Appendix A, and much of the material in the next chapter will also treat the subject. Basically, a set of three bridge railing systems was designed for each of the four service levels, and cost estimates were made for inclusion in the MSLA procedures. The basic systems are described in the following and summarized in Table 3 along with the cost estimates. The advantages of flexible railing systems are shown in Figure 2. Flexibility can be achieved if railing splices are adequate for tensile forces.

*Flexible Beam/Post Systems.* These designs were determined by allowing a maximum dynamic deflection of up to one-half the vehicle width as simulated using BARRIER VII. On the basis of crash test investigations, it has been determined that successful redirection can be obtained at least within this limit.

*Rigid Beam/Post Systems.* These designs were determined by limiting the maximum dynamic deflection to less than 6 in. (180 mm).

*Rigid Concrete Systems.* Both beam/post systems were designed using the BARRIER VII computer program; however, the rigid concrete systems were designed based on recent work at TTI by Hirsch (*3*) and Buth (*4*).

**Cost Model**

The cost model is used to compute the benefits of bridge railing. The basis for computing bridge railing benefits (BRB) for this project is accident data from Texas and Washington and accident cost values from the National Safety Council (NSC) (*5*).

Bridge-related accidents considered relevant to this study include primarily those involving a vehicle striking a bridge rail, and secondarily those involving a vehicle striking a bridge end. Much of the current adverse accident experience of bridge ends is attributed to the poor treatment of transitioning from either no approach guardrail or a flexible

Table 1. Traffic mix description.

| Vehicle Type | Traffic Mix Number* 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Passenger Cars | | | | | |
| 2700 lb | 25.8 | 26.6 | 28.1 | 29.6 | 31.9 |
| 4000 lb | 27.2 | 28.0 | 29.6 | 31.2 | 33.6 |
| 4700 lb | 14.3 | 14.7 | 15.5 | 16.4 | 17.6 |
| 6000 lb | 0.7 | 0.7 | 0.7 | 0.8 | 0.8 |
| Subtotal (%) | 68 | 70 | 74 | 78 | 84 |
| Pickups and Panels | | | | | |
| 5000 lb | 5.3 | 7.0 | 5.7 | 4.9 | 3.7 |
| 8000 lb | 7.7 | 10 | 8.3 | 7.1 | 5.3 |
| Subtotal (%) | 13 | 17 | 14 | 12 | 9 |
| Other Trucks and Buses | | | | | |
| 20,000 lb | 8.0 | 7.0 | 10.0 | 6.0 | 6.0 |
| 40,000 lb** | 11.0 | 6.0 | 2.0 | 4.0 | 1.0 |
| Subtotal (%) | 19 | 13 | 12 | 10 | 7 |
| Total Traffic (%) | 100 | 100 | 100 | 100 | 100 |

*Based on traffic count data
**Used as a surrogate for all vehicles weighing more than 23,000 lb

Metric conversion: Multiply lb x 0.45 to obtain kg

Table 2. Bridge railing service level crash test performance conditions.

| | Service Level (SL) 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Vehicle | Car | Car | Bus | Bus |
| Vehicle Weight, lb | 4,500 | 4,500 | 20,000 | 40,000 |
| Vehicle $I_z$, in.-lb-sec$^2$ | 48,000 | 48,000 | 800,000 | 1,900,000 |
| Impact Speed, mph | 60 | 60 | 60 | 60 |
| Impact Angle, deg | 15 | 25 | 15 | 15 |
| Redirection Index (RI) Value* (nominal) | 3,000 | 6,000 | 8,500 | 13,000 |

*The redirection index described in detail in Appendix A is a measure of primary impact severity in terms of barrier loading. The RI values shown represent a linear momentum relationship with the higher values representing the higher loading.

approach guardrail to a rigid bridge rail or an abutment. Although the approach guardrail/bridge rail transition is extremely important, it is a consideration after a bridge railing level of service has been determined and does not affect the service level selection. Bridge end accidents are considered in this discussion because these accidents have been, and in some cases still are, *smeared-in* with bridge railing data presently available.

*Consequences of Bridge Accidents*

Table 4 gives data on the consequences of bridge accidents; the very descriptive Washington and Texas data provide insight into what happened as a result of these single vehicle collisions (approximately 90 percent of bridge-related accidents are single vehicle accidents) both in terms of vehi-

Table 3. Bridge railing service level cost summary*.

| SL | Railing** | Post | Post Spacing (ft-in.) | Beam Height (in.) | Estimated Cost ($/l.f.) |
|---|---|---|---|---|---|
| 1. Maximum Deflection ≤ Vehicle Half-Width | | | | | |
| 1 | Thrie | 6x6 wood | 8-4 | 32 | 8.37*** |
| 1 | Thrie | TS 3 x 6 | 8-4 | 32 | 11.73 |
| 2 | 12 T.T. | W6 x 9 | 8-4 | 32 | 26.16 |
| 3 | 12 T.T. | W6 x 15.5 | 6-3 | 34 | 31.31 |
| 4 | 12 T.T. | W6 x 15.5 | 4-2 | 38 | 35.86 |
| 2. Maximum Deflection ≤ 6 in. | | | | | |
| 1 | 12 T.T. | W6 x 9 | 8-4 | | 26.16 |
| 2 | 12 T.T. | W6 x 25 | 8-4 | | 34.77 |
| 3 | 12 T.T. | W8 x 31 | 6-3 | | 49.37 |
| 4 | 10 T.T. | W12 x 36 | 4-2 | | 79.86 |
| 3. Concrete Safety Shape Bridge Parapet | | | | | |
| 1 | Concrete s.s. 32 in. high | | | | 20.91 |
| 2 | Concrete s.s. 32 in. high | | | | 24.81 |
| 3 | Concrete s.s. 38 in. high | | | | 31.49 |
| 4 | Concrete s.s. 38 in. high | | | | 39.53 |

*See supporting cost figures, Appendix A
**Thrie - Standard Thrie beam, 12 ga
12 T.T. - 12 ga Tubular Thrie
10 T.T. - 10 ga Tubular Thrie
***Does not include cost consideration for additional deck width required for wood post as compared to steel post.

cle containment/redirection and occupant injury profile. From the Texas and Washington files, vehicle behavior can be categorized as vehicle retained on bridge, vehicle went through rail, and vehicle went over rail. It will be demonstrated from the Texas and Washington data that the presence of a bridge railing improves the safety of bridges by reducing average accident costs through vehicle containment.

### *Accident Costs*

In order to quantify bridge railing benefits, it is necessary to assign values to accident costs. For the purposes of this project, the National Safety Council (NSC) values are used. The average cost for "retained" and "through or over" (penetration) accidents is computed using the NSC injury costs combined with the injury profile of Table 4, as outlined in Table 5. Appendix A (A.1.2.3) provides discussion of accident cost considerations.

### *Benefit Computation*

By assuming that the benefit of a bridge railing can be expressed by the difference between "penetration" (through or over) and "retained" costs, a benefit value is obtained by subtracting the retained cost from the penetration cost. This approach is considered to be conservative because the "retained" cost is based on reported accidents only; the average "retained" cost would be reduced by the undetermined, but presumed low cost of driveaway (nonreported) accidents. The benefits of bridge railing are thus computed, as given in Table 5, by assuming a 20-year life for the railing. No sophisticated economic factors are included although it is recognized that various agencies could apply their own economic methodology to these costs.

### *Benefit/Cost Computation*

With the determination of bridge railing benefits and bridge railing costs, computation of the benefit and cost (B/C) ratio is readily accomplished:

1. Service Level (SL) 1 B/C—The benefits and costs of SL 1 railing systems are compared to values with no bridge railing. Thus, all predicted bridge railing impacts are considered penetrations with no bridge railing. The benefits of SL 1 railing are a measure of the number of penetrations prevented for the 20-year period. The SL 1 B/C is expressed

$$B/C\ (SL\ 1) = \frac{BRB\ (SL\ 1-0)}{BRC\ (SL\ 1)} \quad (1)$$

where:

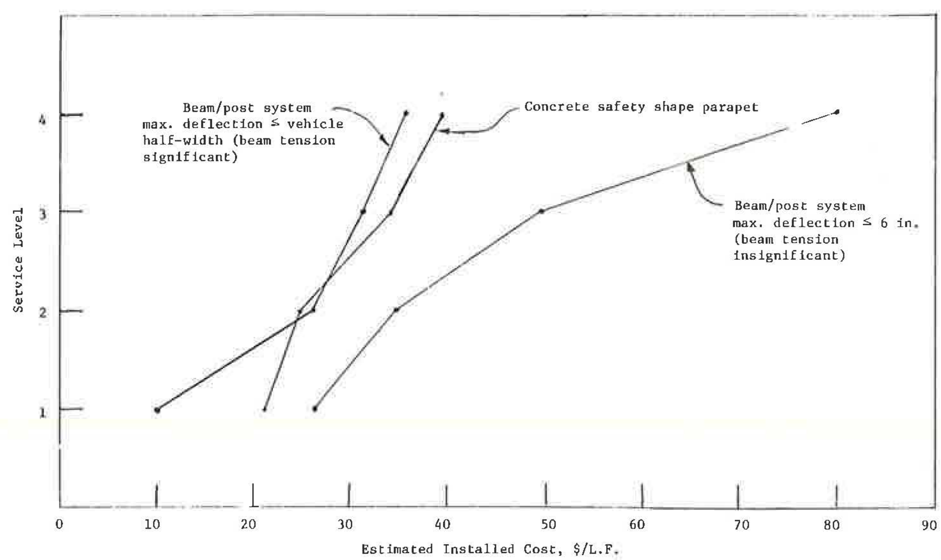



*Figure 2. Estimated bridge railing costs for four service levels.*

Table 4. Texas and Washington bridge accident data.

| | Injury Severity | | | | | |
|---|---|---|---|---|---|---|
| | Non-Injury | Possible Injury | Nonincapacitating | Incapacitating | Fatal | Total |
| 1. TEXAS (2 Years)-(1978, 1979) | | | | | | |
| Bridge End | | | | | | |
| Vehicle Retained | 711 (68)<br>(95) | 71 ( 7)<br>(83) | 133 (13)<br>(82) | 86 ( 8)<br>(74) | 38 ( 4)<br>(45) | 1039 (100)<br>(87) |
| Vehicle Went Thru | 11 (22)<br>( 1) | 8 (16)<br>( 9) | 8 (16)<br>( 5) | 11 (22)<br>( 9) | 13 (25)<br>(15) | 51 (100)<br>( 4) |
| Vehicle Went Over | 23 (22)<br>( 3) | 7 ( 7)<br>( 8) | 21 (20)<br>(13) | 20 (19)<br>(17) | 34 (32)<br>(40) | 105 (100)<br>( 9) |
| Total | 745 (62)<br>(100) | 86 ( 7)<br>(100) | 162 (14)<br>(100) | 117 (10)<br>(100) | 85 ( 7)<br>(100) | 1195 (100)<br>(100) |
| Bridge Railing | | | | | | |
| Vehicle Retained | 3607 (63)<br>(97) | 583 (10)<br>(92) | 1084 (19)<br>(91) | 387 ( 7)<br>(80) | 70 ( 1)<br>(53) | 5731 (100)<br>(93) |
| Vehicle Went Thru | 51 (39)<br>( 1) | 11 ( 8)<br>( 2) | 30 (23)<br>( 3) | 25 (19)<br>( 5) | 15 (11)<br>(11) | 132 (100)<br>( 2) |
| Vehicle Went Over | 87 (28)<br>( 2) | 35 (11)<br>( 6) | 69 (22)<br>( 6) | 71 (23)<br>(15) | 46 (15)<br>(35) | 308 (100)<br>( 5) |
| Total | 3745 (61)<br>(100) | 629 (10)<br>(100) | 1183 (19)<br>(100) | 483 ( 8)<br>(100) | 131 ( 2)<br>(100) | 6171 (100) |
| 2. WASHINGTON (5 Years)-(1974-1978) | | | | | | |
| Bridge End | 205 (41) | 40 ( 8) | 151 (30) | 81 (16) | 24 ( 5) | 501 (100) |
| Bridge Railing | | | | | | |
| Vehicle Retained | 1362 (60)<br>(97) | 258 (11)<br>(95) | 480 (21)<br>(95) | 171 ( 7)<br>(90) | 14 ( 1)<br>(67) | 2285 (100)<br>(96) |
| Thru,Under or Over | 43 (41)<br>( 3) | 14 (13)<br>( 5) | 24 (23)<br>( 5) | 18 (17)<br>(10) | 7 ( 7)<br>(33) | 106 (100)<br>( 4) |
| Total | 1405 (59)<br>(100) | 272 (11)<br>(100) | 504 (21)<br>(100) | 189 ( 8)<br>(100) | 21 ( 1)<br>(100) | 2391 (100) |

Numbers in parentheses are percentages in columns and rows as shown; i.e., total is 100 percent.

BRB = bridge railing benefit, \$/L.F.;
BRC = bridge railing cost, \$/L.F.; and
L.F. = linear foot of bridge railing.

2. Other SL B/C—The B/C ratio for other levels is incrementally determined

$$B/C\ (SL\ n) = \frac{BRB\ (SL\ n - SL\ m)}{BRC\ (SL\ n - SL\ m)} \qquad (2)$$

3. B/C Significance—Using the incremental B/C procedure previously described, the user is guided into a service level selection process. It is assumed that no user would opt for a $B/C \leq 1.0$, which means less benefits than cost.

## FINDINGS

Probably the most basic concept of "level of service" common to most in the highway community is the "functional classification system." Much of the data discussed in this chapter previously and in Appendix A is presented according to functional classification and it was used as a basis for this investigation.

The MSLA procedures previously described were formulated into a series of computer codes for solution of a wide range of highway applications. Results of these investigations are presented in this section.

1. Functional Classification Considerations—A new AASHTO document, "A Policy on Geometric Design of Highways and Streets" (*6*), now in draft form describes the functional classification of roadways. The data summarized in Table 6 are from this source with the exception of the

Table 5. Bridge railing benefit computation.

1. Accident Costs

A. Use latest National Safety Council figures:

| PDO | Possible Injury | Non-Incapacitating Injury | Incapacitating Injury | Fatal |
|---|---|---|---|---|
| \$800 | \$880 | \$3,500 | \$11,900 | \$135,000 |

B. Use Texas and Washington data for average costs of being retained by bridge railing or penetrating bridge railing

| Retained Accidents | PDO | P.I. | N.I.I. | I.I. | Fatal | Avg Cost,\$ |
|---|---|---|---|---|---|---|
| Texas (%) | 63 | 10 | 19 | 7 | 1 | 3708 |
| Wash. (%) | 60 | 11 | 21 | 7 | 1 | 3029 |
| | | | | | Use Avg | 3370 |
| **Penetration Accidents** | | | | | | |
| Texas (%) | 31 | 10 | 23 | 22 | 14 | 20,443 |
| Wash. (%) | 41 | 13 | 23 | 17 | 7 | 12,169 |

2. Benefits

A. Benefits of bridge railing are expressed as difference between average penetration and average retained cost - use 20-yr life

Texas data

$$BRB = \frac{NP_p}{10\ mi\text{-}10\ yr} \quad \frac{(20{,}443-3370)\ (20\ yr\ life)}{(5280\ ft/mi)} = \$0.65/L.F.\ NP_p$$

Washington data

$$BRB = \frac{NP_p}{10\ mi\text{-}10\ yr} \quad \frac{(12{,}169-3370)\ (20\ yr\ life)}{(5280\ ft/mi)} = \$0.33/L.F.\ NP_p$$

where :

BRB = bridge railing benefit value using NSC accident costs, \$/L.F./20-yr life;

$NP_p$ = number of penetrations prevented per 10 yr per 10 mi (Note: use of 10 mi-10 yr will be discussed later; it is merely a way of expressing penetration rate); and

L.F. = linear foot of bridge railing.

Metric conversion: multiply ft by 0.3 to obtain m
multiply mi by 1.6 to obtain km

Table 6. Functional classification—bridge summary.

| FUNCTIONAL CLASSIFICATION | ADT | DESIGN SPEED MPH | LANE WIDTH FT | NO. OF LANES* | TRAFFIC MIX** | SHOULDER WIDTH FT | BR LENGTH ENCROACHMENT RATE, NO. PER 10 MI-10 YR-ADT |
|---|---|---|---|---|---|---|---|
| 1. Rural Arterials | | | | | | | |
| Principal Arterial | | | 12 | 4D | 1 | 10-12 | 0.050 |
| Interstate } Freeways | | > 60 | 12 | 2, TB | 1 | 10-12 | 0.032 |
| Major Arterial } Freeways | | | 12 | 2, TB | 1 | 10-12 | 0.032 |
| Major Arterial | | < 60 | 11-12 | 2 | 2 | 10 | 0.072 |
| | | | 11-12 | 2 | 2 | 4 | 0.072 |
| Minor Arterial | | < 60 | 11-12 | 2 | 4 | 8 | 0.072 |
| | | | 11-12 | 2 | 4 | 4 | 0.072 |
| 2. Urban Arterials | | | | | | | |
| Principal Arterial | | | 12 | 4D | 4 | 10 | 0.050 |
| Interstate } Freeways | | > 60 | 12 | 2, TB | 4 | 10 | 0.032 |
| Major Arterial } Freeways | | | 12 | 6D | 4 | 10 | 0.011 |
| | | | 12 | 3, TB | 4 | 10 | 0.019 |
| Major Arterial | | < 60 | 12 | 2 | 4 | 10 | 0.072 |
| | | | 12 | 2 | 4 | 4 | 0.072 |
| | | | 12 | 4 | 4 | 10 | 0.051 |
| Minor Arterial | | < 60 | 12 | 2 | 4 | 8 | 0.072 |
| | | | 12 | 2 | 4 | 4 | 0.072 |
| 3. Rural Collectors & Roads | | | | | | | |
| Collector 1 | 250-400 | | 10 | 2 | 5 | 2 | 0.102 |
| 2 | 400-750 | | 10 | | | 3 | 0.072 |
| 3 | 750-2000 | 20-30 | 11 | | | 3 | 0.072 |
| 4 | 2000-4000 | | 11 | | | 4 | 0.072 |
| 5 | > 4000 | | 12 | | | 8 | 0.072 |
| 6 | 250-400 | | 10 | | | 2 | 0.102 |
| 7 | 400-750 | | 11 | | | 3 | 0.072 |
| 8 | 750-2000 | 40 | 11 | | | 3 | 0.072 |
| 9 | 2000-4000 | | 11 | | | 4 | 0.072 |
| 10 | > 4000 | | 12 | | | 8 | 0.072 |
| 11 | 250-400 | | 10 | | | 2 | 0.072 |
| 12 | 400-750 | | 11 | | | 3 | 0.072 |
| 13 | 750-2000 | | 11 | | | 3 | 0.072 |
| 14 | 2000-4000 | | 12 | | | 4 | 0.072 |
| 15 | > 4000 | | 12 | 2 | 5 | 8 | 0.072 |
| Local Roads 1 | < 50 | | 8 | 2 | 5 | 2 | 0.225 |
| 2 | 50-250 | 20-30 | 9 | | | 2 | 0.244 |
| 3 | 250-400 | | 10 | | | 2 | 0.102 |
| 4 | > 400 | | 10 | | | 4 | 0.072 |
| 5 | < 50 | | 10 | | | 2 | 0.102 |
| 6 | 50-250 | 40-50 | 10 | | | 2 | 0.102 |
| 7 | 250-400 | | 10 | | | 2 | 0.102 |
| 8 | > 400 | | 11 | 2 | 5 | 4 | 0.072 |
| 4. Urban Collectors & Streets | | | | | | | |
| Collector 1 | 250-400 | | 10 | 2 | 3 | 2 | 0.102 |
| 2 | 400-750 | | 10 | | | 3 | 0.072 |
| 3 | 750-2000 | 20-30 | 11 | | | 3 | 0.072 |
| 4 | 2000-4000 | | 11 | | | 4 | 0.072 |
| 5 | > 4000 | | 12 | | | 8 | 0.072 |
| 6 | 250-400 | | 10 | | | 2 | 0.102 |
| 7 | 400-750 | | 11 | | | 3 | 0.072 |
| 8 | 750-2000 | 40 | 11 | | | 3 | 0.072 |
| 9 | 2000-4000 | | 11 | | | 4 | 0.072 |
| 10 | > 4000 | | 12 | | | 8 | 0.072 |
| 11 | 250-400 | | 10 | | | 2 | 0.102 |
| 12 | 400-750 | | 11 | | | 3 | 0.072 |
| 13 | 750-2000 | | 11 | | | 3 | 0.072 |
| 14 | 2000-4000 | | 12 | | | 4 | 0.072 |
| 15 | > 4000 | | 12 | 2 | 3 | 8 | 0.072 |
| Local Roads 1 | < 50 | | 8 | 2 | 3 | 2 | 0.225 |
| 2 | 50-250 | 20-30 | 9 | | | 2 | 0.244 |
| 3 | 250-400 | | 10 | | | 2 | 0.102 |
| 4 | > 400 | | 10 | | | 4 | 0.072 |
| 5 | < 50 | | 10 | | | 2 | 0.102 |
| 6 | 50-250 | 40-50 | 10 | | | 2 | 0.102 |
| 7 | 250-400 | | 10 | | | 2 | 0.102 |
| 8 | > 400 | | 11 | 2 | 3 | 4 | 0.072 |

*D - divided, TB - twin bridge
**See Tables A.16 and A.17 in Appendix A

traffic mix and encroachment rate. These were determined from other sources as stated previously.

The data in this table represent the input necessary for using the MSLA, with the following exceptions: no ADT values are given for the arterials (1 and 2), and no cost values are given.

2. Service Level Determination for Typical Roadways —Traffic volume values for typical roadways were determined from 1978 Highway Statistics (7) (see Table 7). These values were used as input for the arterials described in Table 6. A range of traffic volume for each classification is provided by using the highest FHWA regional average, the national average, and the lowest FHWA regional average. Costs used included Texas and Washington accident costs and the flexible (set 1) bridge railing costs of Table 3. Data from all roadways described by functional classification in Table 6 were used to generate a series of tables as described in Table 8. This table presents benefits and incremental B/C ratios for the range of ADT values. Also, at the lower part of the table an ADT value is shown that produces a B/C = 1.0.

The data of Table 8 are summarized in Table 9 by selecting the lowest cost bridge railing that produces a B/C ratio ≥1.0. By knowing the ADT, the SL can be determined.

Another way of summarizing the SL designation is to present a summary of the ADT value at a given bridge site for B/C ratio = 1.0 as shown in Table 10. Only the Texas data are given in Table 10 because the ADT values for Washington accident costs would be almost twice the Texas value because of the linear relationship with bridge railing benefit value. Table 10 can also be used to consider B/C ratios greater than 1.0 (e.g., if a B/C ratio of 3.0 is desired, the ADT value from Table 10 would be three times that given in the table).

3. Other Site Conditions—For sites where bridge characteristics differ significantly from those described in Table 6, basic tables can be used to determine a more appropriate SL designation if desired.

a. Other Encroachment Rates—Table 11 contains the complete set of encroachment data as developed for this project. Data which were not shown in Table 6 are shown for bridges not covered by that table.

b. Critical Impact Tables—Table 12 contains an example of collision model summary for a given roadway. These basic tables have been generated for bridges with 8-, 9-, 10-, 11-, and 12-ft (2.4-, 2.7-, 3.1-, 3.4-, and 3.7-m) lanes with shoulder widths from 0–10 ft (0–3.1 m). The table lists the number of hits in the far right column. This number of hits corresponds to the number of critical impacts (penetrations) occurring with no bridge rail. The number of penetrations prevented (NPP) by each railing service level is listed for all traffic mixes and incremental shoulder widths for a bridge with two 12-ft wide lanes. Use of this table to generate data for nontypical bridges is illustrated in the Table 12 Example. For comparison, the example corresponds to a typical roadway as shown in Table 8. With the complete set of tables in Appendix A, almost all conceivable roadways could be investigated if typical values such as in Tables 8, 9, and 10 were not considered appropriate.

Table 7. National mileage and traffic figures. (Source: Ref. 7)

| | Federal-Aid Highways | | | | | | | Non-Federal-Aid Highways | | | | | | All Highway Classes | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Interstate Arterial | | Primary Arterial | | Urban System | | Secondary Collector | Arterial | | Collector | | Local | | | | |
| | Rural | Urban | Rural | Urban | Arterial | Collector | Rural | Rural | Urban | Rural | Urban | Rural | Urban | Rural | Urban | Total |
| National Total Million Vehicle-Miles of Travel | 136,535 | 157,412 | 272,920 | 175,394 | 259,589 | 63,043 | 133,971 | 5,295 | 23,118 | 46,682 | 13,694 | 94,553 | 166,009 | 689,953 | 858,260 | 1,548,213 |
| National Total Road and Street Mileage | 31,161 | 9,048 | 233,040 | 27,422 | 77,299 | 47,028 | 294,955 | 3,264 | 8,007 | 323,711 | 14,475 | 2,295,321 | 416,450 | 3,281,448 | 599,720 | 3,881,166 |
| National Average ADT | 12,000 | 48,000 | 3,200 | 17,500 | 9,200 | 3,700 | 1,244 | 4,500 | 8,000 | 400 | 2,600 | 115 | 1,050 | 580 | 3,900 | 1,100 |
| Average ADT-Region High, Region * | 16,000 (3) | 82,000 (9) | 5,000 (3) | 41,800 (9) | 11,000 (9) | 4,300 (3) | 2,000 (1) | 18,400 (1) | 20,100 (1) | 1,030 (9) | 5,070 (10) | 280 (1) | 1,400 (6) | 1,090 (1) | 8,000 (4) | 2,230 (1) |
| Low, Region * | 5,300 (8) | 30,800 (8) | 1,340 (8) | 11,600 (7) | 5,400 (10) | 2,700 (7) | 310 (8) | 1,180 (8) | 3,240 (8) | 95 (7 & 8) | 1,440 (8) | 45 (8) | 580 (9) | 215 (8) | 2,800 (8) | 330 (8) |

Typical ADT Values $\begin{cases} \text{Low} \\ \text{High} \\ \text{Avg} \end{cases}$

*Highest or lowest average; FHWA region number is in parentheses.

Table 8. Example bridge service level determination.

| | 1 | | 2 | | | | 3 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | ROAD DESCRIPTION<br>*** RURAL IH 2 TB 12FTLN *** | | (- - - - - - BENEFIT $/FT-NSC- | SERVICE LEVEL | | - - - - -)(- - - -INCREMENTAL BENEFIT/COST- - - -) | SERVICE LEVEL | | | |
| | ACCIDENT COST BASIS | ADT | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| 4 | WASHINGTON | 16000. | 57.14 | 73.46 | 76.28 | 77.45 | 5.71 | 1.01 | .55 | .26 |
| | $0.33/L.F. | 12000. | 42.85 | 55.09 | 57.21 | 58.09 | 4.29 | .76 | .41 | .19 |
| | | 5300. | 18.93 | 24.33 | 25.27 | 25.66 | 1.89 | .33 | .18 | .09 |
| | TEXAS | 16000. | 112.55 | 144.68 | 150.25 | 152.56 | 11.25 | 1.99 | 1.08 | .51 |
| | $0.65/L.F. | 12000. | 84.41 | 108.51 | 112.69 | 114.42 | 8.44 | 1.49 | .81 | .38 |
| | | 5300. | 37.28 | 47.93 | 49.77 | 50.54 | 3.73 | .66 | .36 | .17 |
| | ACCIDENT COST BASIS/ADT FOR B/C=1.0 | | | | | | | | | |
| 5 | WASHINGTON-$0.33/L.F. | | 2600. | 15847. | 29164. | 62033. | | | | |
| | TEXAS -$0.65/L.F. | | 1422. | 8045. | 14807. | 31494. | | | | |

Explanation:

1 Road Description - IH, interstate; 10-12 ft shoulder
2TB, 2-lane twin bridge
12 FT LN, 12-ft wide lanes

2 Benefit value for each level of service, $/L.F. of bridge railing

3 Incremental benefit/cost ratio for each service level

4 Texas and Washington accident costs

5 ADT for B/C = 1.0

Table 9. Bridge railing service level by functional classification for B/C ≥ 1.0.

| FUNCTIONAL CLASSIFICATION | ADT | | | DESIGN SPEED MPH | LANE WIDTH FT | NO. OF LANES* | SHOULDER WIDTH FT | SERVICE LEVEL DESIGNATION | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | TEXAS | | | WASHINGTON | | |
| | | | | | | | | ADT (TABLE 7) | | | ADT (TABLE 7) | | |
| | | | | | | | | HI AVG | AVG | LO AVG | HI AVG | AVG | LO AVG |
| 1. Rural Arterials | HI | AVG | LOW | | | | | | | | | | |
| Principal | 16,000 | 12,000 | 5,300 | > 60 | 12 | 4D | 10-12 | 3 | 3 | 2 | 2 | 2 | 1 |
| Interstate | | | | | 12 | 2TB | 10-12 | 2 | 2 | 1 | 2 | 1 | 1 |
| Major | | | | | 12 | 2TB | 10-12 | 1 | 1 | <1 | 1 | 1 | < 1 |
| Major | 5,000 | 3,200 | 1,340 | < 60 | 11-12 | 2 | 10 | 2 | 1 | 1 | 1 | 1 | 1 |
| | | | | | 11-12 | 2 | 4 | 2 | 1 | 1 | 1 | 1 | 1 |
| Minor | 18,400 | 4,500 | 1,180 | < 60 | 11-12 | 2 | 8 | 3 | 2 | 1 | 2 | 1 | 1 |
| | | | | | 11-12 | 2 | 4 | 3 | 1 | 1 | 2 | 1 | 1 |
| 2. Urban Arterials | HI | AVG | LOW | | | | | | | | | | |
| Principal | 82,000 | 48,000 | 30,800 | > 60 | 12 | 4D | 10 | 4 | 4 | 3 | 4 | 3 | 3 |
| Interstate | | | | | 12 | 2TB | 10 | 4 | 3 | 3 | 3 | 3 | 2 |
| Major | | | | | 12 | 6D | 10 | 3 | 2 | 2 | 3 | 3 | 3 |
| | | | | | 12 | 3TB | 10 | 4 | 4 | 4 | 4 | 3 | 2 |
| Major | 41,800 | 17,500 | 11,600 | < 60 | 12 | 2 | 10 | 4 | 3 | 3 | 3 | 2 | 2 |
| | | | | | 12 | 2 | 4 | 3 | 2 | 2 | 3 | 2 | 2 |
| | | | | | 12 | 4 | 10 | 4 | 3 | 2 | 3 | 2 | 1 |
| Minor | 20,100 | 8,000 | 3,240 | < 60 | 12 | 2 | 8 | 2 | 2 | 2 | 2 | 2 | 1 |
| | | | | | 12 | 2 | 4 | 2 | 2 | 2 | 2 | 1 | 1 |
| 3. Collectors, Roads & Streets | | | | | | | | Hi | | | Hi | | |
| Collector 1 | 250-400 | | | 20-30 | 10 | 2 | 2 | | | | | | |
| 2 | 400-750 | | | | 10 | | 3 | | | | | | |
| 3 | 750-2000 | | | | 11 | | 3 | | | | | | |
| 4 | 2000-4000 | | | | 11 | | 4 | | | | | | |
| 5 | > 4000 | | | | 12 | | 8 | 2 | | | | | |
| 6 | 250-400 | | | 40 | 10 | | 2 | | | | | | |
| 7 | 400-750 | | | | 11 | | 3 | | | | | | |
| 8 | 750-2000 | | | | 11 | | 3 | | | | | | |
| 9 | 2000-4000 | | | | 11 | | 4 | | | | | | |
| 10 | > 4000 | | | | 12 | | 8 | 2 | | | | | |
| 11 | 250-400 | | | 50 | 10 | | 2 | | | | | | |
| 12 | 400-750 | | | | 11 | | 3 | | | | | | |
| 13 | 750-2000 | | | | 11 | | 3 | | | | | | |
| 14 | 2000-4000 | | | | 12 | | 4 | | | | | | |
| 15 | > 4000 | | | | 12 | 2 | 8 | 2 | | | | | |
| Local Roads & Streets 1 | < 50 | | | 20-30 | 8 | 2 | 2 | < 1 | | | <1 | | |
| 2 | 50-250 | | | | 9 | | 2 | | | | | | |
| 3 | 250-400 | | | | 10 | | 2 | | | | | | |
| 4 | > 400 | | | | 10 | | 4 | | | | | | |
| 5 | < 50 | | | 40-50 | 10 | | 2 | < 1 | | | < 1 | | |
| 6 | 50-250 | | | | 10 | | 2 | | | | < 1 | | |
| 7 | 250-400 | | | | 10 | | 2 | | | | | | |
| 8 | > 400 | | | | 11 | 2 | 4 | | | | | | |

NOTE: All collectors and roads are Service Level 1 except as noted.

*D - Divided
TB - Twin Bridge

**Using ADT values for functional classification benefit/cost ratio = 1, accident costs, TX or WA avg

Table 10. ADT values for B/C = 1.0.

| FUNCTIONAL CLASSIFICATION | ADT | DESIGN SPEED MPH | LANE WIDTH FT | NO. OF LANES | SHOULDER WIDTH FT | ADT for B/C = 1.0 SL Texas Data* 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| 1. Rural Arterials | | | | | | | | | |
| Principal Arterial | | | 12 | 4D | 10-12 | 910 | 5,149 | 9,476 | 20,156 |
| Interstate } Freeways | | > 60 | 12 | TB | 10-12 | 1,422 | 8,045 | 14,807 | 31,494 |
| Major Arterial } | | | 12 | TB | 10-12 | 1,380 | 8,775 | 19,780 | 45,671 |
| Major Arterial | | < 60 | 11-12 | 2 | 10 | 613 | 3,900 | 8,791 | 20,298 |
| | | | 11-12 | 2 | 4 | 343 | 4,719 | 14,215 | 36,587 |
| Minor Arterial | | < 60 | 11-12 | 2 | 8 | 490 | 4,356 | 12,113 | 31,621 |
| | | | 11-12 | 2 | 4 | 337 | 5,285 | 17,695 | 49,779 |
| 2. Urban Arterials | | | | | | | | | |
| Principal Arterial | | | 12 | 4D | 10 | 859 | 6,035 | 15,352 | 37,319 |
| Interstate } Freeways | | > 60 | 12 | TB | 10 | 1,343 | 9,430 | 23,988 | 58,311 |
| Major Arterial } | | | 12 | 6D | 10 | 2,777 | 15,058 | 30,212 | 59,559 |
| | | | 12 | TB | 10 | 2,467 | 13,376 | 26,837 | 52,906 |
| Major Arterial | | < 60 | 12 | 2 | 10 | 597 | 4,191 | 10,661 | 25,916 |
| | | | 12 | 2 | 4 | 337 | 5,285 | 17,695 | 49,779 |
| | | | 12 | 4 | 10 | 859 | 6,035 | 15,352 | 37,319 |
| Minor Arterial | | < 60 | 12 | 2 | 8 | 490 | 4,356 | 12,113 | 31,621 |
| | | | 12 | 2 | 4 | 337 | 5,285 | 17,695 | 49,779 |
| 3. Collectors, Roads & Streets | | | | | | RURAL 1 | RURAL 2 | URBAN 1 | URBAN 2 |
| Collector 1 | 250-400 | | 10 | 2 | 2 | 201 | 5,148 | 204 | 4,818 |
| 2 | 400-750 | | 10 | | 3 | 310 | 7,027 | 314 | 6,584 |
| 3 | 750-2000 | 20-30 | 11 | | 3 | 315 | 6,237 | 321 | 5,865 |
| 4 | 2000-4000 | | 11 | | 4 | 345 | 5,860 | 350 | 5,468 |
| 5 | > 4000 | | 12 | | 8 | 535 | 3,946 | 550 | 3,701 |
| 6 | 250-400 | | 10 | | 2 | 198 | 6,107 | 201 | 5,481 |
| 7 | 400-750 | | 11 | | 3 | | | | |
| 8 | 750-2000 | 40 | 11 | | 3 | {308 | 6,838 | 314 | 6,187} |
| 9 | 2000-4000 | | 11 | | 4 | 336 | 6,354 | 343 | 5,692 |
| 10 | > 4000 | | 12 | | 8 | 504 | 4,342 | 520 | 3,956 |
| 11 | 250-400 | | 10 | | 2 | 196 | 6,987 | 282 | 8,539 |
| 12 | 400-750 | | 11 | | 3 | | | | |
| 13 | 750-2000 | 50 | 11 | | 3 | {305 | 7,474 | 311 | 6,519} |
| 14 | 2000-4000 | | 12 | | 4 | 337 | 5,989 | 345 | 5,228 |
| 15 | > 4000 | | 12 | 2 | 8 | 489 | 4,702 | 507 | 4,185 |
| Local Roads 1 | < 50 | | 8 | 2 | 2 | 88 | 3,667 | 89 | 3,324 |
| & Streets 2 | 50-250 | 20-30 | 9 | | 2 | 83 | 2,585 | 84 | 2,387 |
| 3 | 250-400 | | 10 | | 2 | 201 | 5,148 | 204 | 4,818 |
| 4 | > 400 | | 10 | | 4 | 338 | 6,603 | 343 | 6,149 |
| 5 | < 50 | | 10 | | 2 | | | | |
| 6 | 50-250 | 40-50 | 10 | | 2 | {196 | 6,987 | 199 | 6,028} |
| 7 | 250-400 | | 10 | | 2 | | | | |
| 8 | > 400 | | 11 | 2 | 4 | 332 | 6,863 | 340 | 5,936 |

* ADT for Washington data ≈ 2 times value shown.

Table 11. Bridge rail length encroachment rates.

| | | Bridge Narrowness Strata | | | Bridge Rail Length Encroachment Rate |
|---|---|---|---|---|---|
| | | No. Lanes | Bridge Width | Shoulder Reduction | ENCR/10 Mi-10 Yr-ADT* |
| Single Structures | Undivided | 1 | ≤18' | - | .233 |
| | | | >18' | - | - |
| | | 2 | ≤18', <Approach | - | .308 |
| | | | ≤18', ≥Approach | - | - |
| | | | 18'-20', <Approach | - | .234 |
| | | | 18'-20', ≥Approach | - | .225 |
| | | | 20'-22', <Approach | - | .168 |
| | | | 20'-22', ≥Approach | - | .244 |
| | | | 22'-24', <Approach | - | .109 |
| | | | 22'-24', ≥Approach | - | .102 |
| | | | >24' | >50% | .081 |
| | | | >24' | 1-50% | .062 |
| | | | >24' | none | .072 |
| | | 4 | n/a | >50% | - |
| | | | | 1-50% | - |
| | | | | none | .051 |
| | Divided | 4 | n/a | >50% | .028 |
| | | | | 1-50% | .050 |
| | | | | none | .050 |
| | | other | n/a | >50% | .016 |
| | | | | 1-50% | - |
| | | | | none | .017 |
| Twin Structures | Divided | 2 | ≤24' | - | .029 |
| | | | >24' | >50% | .025 |
| | | | >24' | 1-50% | .026 |
| | | | >24' | none | .032 |
| | | other | n/a | >50% | .026 |
| | | | | 1-50% | .033 |
| | | | | none | .019 |

*Corrected for difference in bridge length and bridge rail length; median barrier on bridge is not considered bridge rail.

CHAPTER THREE

# CURRENT BRIDGE RAILING TECHNOLOGY

## INTRODUCTION

During the course of this project, an in-depth investigation of all aspects of bridge railing technology was conducted. On the basis of preliminary findings, a new low-cost bridge railing conforming to SL 1 requirements was designed and developed. A critical assessment of the existing AASHTO Bridge Specification was made and deficiencies were noted. Current bridge railings with known performance evaluations were examined for SL designation according to comparable crash test conditions. Guidelines for implementing upgrading programs using the MSLA for identifying priorities were also investigated.

## SERVICE LEVEL 1 BRIDGE RAILING DESIGN AND DEVELOPMENT

### Background

For the purposes of this project, it was determined that low-cost bridge-railing systems to be considered would be constructed of metal beams mounted on equally spaced posts. Performance of the concrete safety shape bridge parapet is well documented and no further work was considered desirable for this system; however, the concrete safety shape should be considered as a possible alternative to the other systems developed in this effort. Preliminary design efforts were conducted using computer simulations to determine design requirements. Experimental work was accomplished to provide performance data on the component posts, and finally crash test evaluation of the systems was accomplished. Revisions made to the systems based on the findings of the initial crash test experiments were accomplished prior to crash test evaluation of the recommended designs.

Results of the final crash tests were compared to the simulations used in the design effort. Certain modifications were made to the input based on observations of the test results.

### Criteria

Basically, the SL 1 criteria require the containment of a 4500-lb (2040-kg) vehicle impacting at 60 mph (95 km/h) and a 15-deg angle. Service Level 2 requirements correspond to the current AASHTO (*1,2*) specification crash test option;

Table 12. Example critical impact table.

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
BRIDGE WITH 50/50 TRAFFIC SPLIT 12'LN CON

DESIGNATED SPEED (MPH) = 55.0
NUMBER OF PENETRATIONS PREVENTED*

| SHOULDER WIDTH (FT) | VEHICLE MIX | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT |
|---|---|---|---|---|---|---|
| 0. | | | | | | |
| | 1 | .8902 | .9486 | .9572 | .9597 | .95979E+00 |
| | 2 | .8906 | .9432 | .9488 | .9502 | .95030E+00 |
| | 3 | .8944 | .9449 | .9487 | .9493 | .94935E+00 |
| | 4 | .8970 | .9450 | .9443 | .9503 | .95031E+00 |
| | 5 | .9026 | .9465 | .9490 | .9494 | .94937E+00 |
| 2. | | | | | | |
| | 1 | .7408 | .8126 | .8220 | .8254 | .82561E+00 |
| | 2 | .7469 | .8087 | .8152 | .8173 | .81744E+00 |
| | 3 | .7540 | .8106 | .8155 | .8166 | .81667E+00 |
| | 4 | .7550 | .8107 | .8159 | .8174 | .81744E+00 |
| | 5 | .7633 | .8125 | .8160 | .8166 | .81663E+00 |
| 4. | | | | | | |
| | 1 | .6131 | .6994 | .7100 | .7142 | .71467E+00 |
| | 2 | .6238 | .6969 | .7047 | .7073 | .70759E+00 |
| | 3 | .6325 | .6991 | .7052 | .7068 | .70689E+00 |
| | 4 | .6339 | .6993 | .7055 | .7074 | .70760E+00 |
| | 5 | .6444 | .7014 | .7058 | .7068 | .70689E+00 |
| 6. | | | | | | |
| | 1 | .5049 | .5992 | .6120 | .6170 | .61762E+00 |
| | 2 | .5169 | .5984 | .6078 | .6111 | .61150E+00 |
| | 3 | .5253 | .6012 | .6086 | .6107 | .61089E+00 |
| | 4 | .5277 | .6011 | .6087 | .6112 | .61151E+00 |
| | 5 | .5386 | .6038 | .6093 | .6108 | .61090E+00 |
| 8. | | | | | | |
| | 1 | .4139 | .5111 | .5262 | .5321 | .53305E+00 |
| | 2 | .4254 | .5171 | .5232 | .5272 | .52778E+00 |
| | 3 | .4329 | .5155 | .5243 | .5269 | .52725E+00 |
| | 4 | .4359 | .5152 | .5243 | .5273 | .52778E+00 |
| | 5 | .4462 | .5185 | .5251 | .5270 | .52725E+00 |
| 10. | | | | | | |
| EX. | 1 | .3382 | .4348 | .4515 | .4584 | .45966E+00 |
| | 2 | .3485 | .4370 | .4495 | .4543 | .45511E+00 |
| | 3 | .3549 | .4408 | .4509 | .4542 | .45465E+00 |
| | 4 | .3580 | .4404 | .4508 | .4545 | .45511E+00 |
| | 5 | .3673 | .4442 | .4519 | .4543 | .45469E+00 |

*Based on 1.0 ENCR/10 Mi-10 Yr-ADT.

Table 12 Example

Given: Bridge description 2 lane rural interstate highway, twin bridge
12 ft lanes, 10 ft shoulder, traffic volume = 16,000 ADT
no shoulder reduction

- From Table 6, traffic mix = 1 .
- From Table 11, encr. rate = .032 ENCR/10 Mi-10 Yr-ADT
- From Table 5, BRB (TX) = \$0.65/L.F. $NP_p$, BRB (WA) = \$0.33/L.F. $NP_p$ — Bridge railing benefits
- From Table 12,

| | SL 1 | SL 2 | SL 3 | SL 4 |
|---|---|---|---|---|
| $NP_p$ = | .3382 | .4348 | .4515 | .4584 |

Based on 1 ENCR/10 Mi-10 Yr-ADT

- From Table 3, BRC

| SL 1 | SL 2 | SL 3 | SL 4 |
|---|---|---|---|
| 10.00 | 26.16 | 31.31 | 35.86 |

- Compute Bridge Railing Benefits and Incremental Benefit/Cost-Ratio

| TX | 0.65 x ADT x ENCR x BRB = BRB | ΔBRB | BRC | ΔBRC | $\frac{\Delta BRB}{\Delta BRC}$ = B/C |
|---|---|---|---|---|---|
| SL 1 | 0.65 x 16,000 x .032 x .3382 = 112.55 | 112.55 | 10.00 | 10.00 | 11.26 |
| SL 2 | 0.65 x 16,000 x .032 x .4348 = 144.92 | 32.00 | 26.16 | 16.16 | 1.98 |
| SL 3 | 0.65 x 16,000 x .032 x .4515 = 150.26 | 5.34 | 31.31 | 5.15 | 1.04 |
| SL 4 | 0.65 x 16,000 x .032 x .4584 = 152.56 | 2.30 | 35.86 | 4.55 | 0.51 |

barriers designed to the AASHTO barrier criteria are known to be essentially unyielding barriers for these test conditions. Thus, SL 1 system performance requirements are considerably less demanding than the current crash test specification option of AASHTO and even less demanding than the design load criteria. The crash test option of AASHTO also requires conformance with the small car impact severity test of *TRB Circular 191 (8)*. No known bridge railing system has been shown to meet this part of the criteria, although this was a design goal of the SL 1 system of this project.

#### Current Systems

A limited investigation of current systems that might be candidates for SL 1 application was conducted. This investigation did not result in candidate selection for further investigation.

#### Design Considerations

For this design effort, beam on post concepts were considered exclusively. Appendix C describes in detail the systematic design, development, and evaluation of the two SL 1 bridge railing systems. The systems are constructed of thrie beams mounted on posts spaced at 8′4″ (25 cm) centers. The post and attaching hardware represent the significant difference in the two systems; one used steel posts and the other wood. These new railing designs essentially meet the acceptance criteria of *TRB Circular 191(8)* with the exception of the new structural adequacy test requirements.

The concrete safety shape has recently become a widely used bridge barrier system. Performance of this barrier is documented in numerous reports. Installation costs have varied widely, but it seems reasonable that any new barrier system, including the SL 1 systems described in the following, should be compared on a local level with the safety shape for both performance and economics.

#### Evaluation Findings

Crash tests conducted during the development and final evaluation are summarized in Table 13. Included in the table is Test NCHRP-1 which utilized a school bus.

##### *Bridge Railings—General*

The bridge railing designs developed in this project exhibited behavior that is dramatically different from previous bridge railing investigations. However, the large deflections and subsequent vehicle movement below the bridge deck, which occurred in the experiments of this program, did not result in failure of the system to contain and redirect the vehicle. It should be emphasized that any impact is a rare occurrence on SL 1 bridges. The structural adequacy test conditions represent a most infrequent impact at locations where SL 1 use is warranted.

The significance of rail tension and post behavior was also demonstrated in this test series. Without tension capacity (e.g., splice adequacy) these railings would not have contained the vehicles. Post separation from the deck support and beam before large deflections occurred assured that wheel snagging did not occur.

##### *SL 1 Bridge Railing—Wood Post*

Of particular significance in the wood post tests was the criticality of material properties. In the past it has not been a requirement that timber barrier posts be grade stamped. One crash test (W-4) resulted in extremely poor barrier performance; the failure of the barrier to perform as designed was attributed to wood that was inferior to the grade/stress level specified.

Another finding pertinent to wood posts was the snagging of vehicle wheels on side-mounted post brackets. This contributed to wheel snagging and compromised barrier performance.

##### *SL 1 Bridge Railing—Steel Post*

This system proved to be very predictable, and no major modifications were made to the initial design. Similar to the wood post results, the maximum deflections of the simulations were lower than experimental values; otherwise, the results of both simulation and experiment were quite close, with exception of small-car longitudinal accelerations. This has occurred in other projects at SwRI using BARRIER VII. Because the lateral acceleration is always the controlling value for compliance with *TRB Circular 191* criteria, this discrepancy is not considered significant.

#### Appraisal

SL 1 bridge railing systems were evaluated for performance and cost.

##### *Performance*

As shown in Table 13, the structural adequacy test requirements for SL 1 were met in Tests W-3 and S-3. The impact severity requirements of *TRB Circular 191* were met in Tests W-5 and S-4. Although the lateral acceleration value of 5.2 g's for Test S-6 slightly exceeded the acceptable level of 5 g's, this value is considered marginally acceptable.

##### *Cost*

Two costs are generally considered for barriers; that is, initial cost and maintenance (including restoration following impact) cost. Only the former is considered applicable to the SL 1 designs. Because the SL 1 devices will be used only in locations where impact probabilities are practically nil, the damage repair of these systems will not be significant.

The estimated installed costs of the wood and steel post systems are $8.37/L.F. and $11.73/L.F., respectively, as described in Appendix A. These costs are based on the recommended drawings shown in Figures 3 and 4.

The wood post system has an apparent economic advantage over the steel post system. However, it should be emphasized that for the same distance between railings (width of bridge), the steel post system would require a deck with a width 1 ft (0.3 m) less than that for wood. This is due to the necessity of recessing the wood post in the deck. The additional cost of the 1-ft (0.3-m) strip of deck is not easily obtained, but should be considered when comparing the two systems.

Table 13. Summary of crash test results.

| Test No. | Test Purpose [1] | Barrier [2] | Vehicle Weight (lbs) | Impact Speed (mph) | Impact Angle (deg) | Max. Vehicle Accelerations, g's (50 msec avg) | | Maximum Dynamic Defl. (ft) | Number of Posts Failed [3] | Number of Rail Sections Damaged | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Long. | Lat. | | | | |
| W-1 | S.T. | A | 4500 | 44.0 | 20.0 | -2.3 | -4.0 | 3.5 | 4C | 2 | Anchor bolt damage severe due to vehicle wheel contact, vehicle redirected |
| W-2 | S.T. | B | 4500 | 58.9 | 16.3 | -1.7 | -2.4 | 4.2 | 8C | 3 | Vehicle wheel snagged on post projections causing increased vehicle involvement and bolt damage |
| W-3 | S.T. | C | 4500 | 61.9 | 14.5 | -4.1 | -3.3 | 2.6 | 6C, 1P | 2 | Vehicle smoothly redirected |
| W-4 | I.S. | C | 2250 | 63.0 | 18.7 | -2.7 | -5.6 | 3.8 | 9C, 1P | 2 | Vehicle smoothly redirected; wheels rode against outside of bridge deck for significant time |
| W-5 | I.S. | C | 2250 | 60.1 | 15.9 | -2.3 | -4.2 | 1.6 | 2C, 1P | 1 | Vehicle smoothly redirected |
| S-3 | S.T. | D | 4500 | 61.7 | 16.6 | -3.1 | -3.2 | 2.5 | 3C | 2 | Vehicle smoothly redirected |
| S-4 | I.S. | E | 2250 | 58.6 | 16.0 | -1.8 | -4.6 | 0.8 | 1P | 1 | Vehicle smoothly redirected, concrete deck damage at Post 4 influenced post behavior |
| S-6 | I.S. | E | 2250 | 60.0 | 16.0 | -2.9 | -5.2 | 1.2 | 1C, 1P | 1 | Vehicle smoothly redirected, anchor bolt failure not considered pertinent |
| NCHRP-1 | S.T. | E | 20,000 | 44.7 | 7.7 | -0.5 | 1.4 | 1.7 | 3C | 4 | Vehicle smoothly redirected with max. roll angle of 15 deg |

(1) S.T. - Structural Adequacy Test
I.S. - Impact Severity Test

(3) C - complete failure
P - partial failure

(2) A - 12-ga Thrie beam mounted on 6x6 wood post @ 8'-4" centers, post bracket protruding from bridge deck
B - 12-ga Thrie beam mounted on 6x6 wood post @ 8'-4" centers, post bracket protruding from bridge deck
C - 12-ga Thrie beam mounted on 6x6 wood post @ 8'-4" centers, recessed post mounting
D - 12-ga Thrie beam mounted on TS3x6 steel box beam posts @ 8'-4" centers, strap beam mounting
E - 12-ga Thrie beam mounted on TS3x6 steel box beam posts @ 8'-4" centers, bolted beam mounting

Metric conversion:
Multiply lb by 0.45 to obtain kg
Multiply mph by 1.6 to obtain km/hr
Multiply ft by 0.3 to obtain m

### Application

The SL 1 bridge railing systems are recommended for installation where warranted according to the criteria of Chapter Two. The recommended design drawings are shown in Figures 3 and 4. Limited information regarding bridge deck design is shown on the drawings. Because bridge deck designs will vary considerably, a working stress design force of 10 kips (45 kN) applied at 22 in.(550 mm) above the deck is recommended in the drawing notes. Use of this design force and working stresses should assure the designer that no significant bridge deck damage occurs during an impact (i.e., the failure load of the post will control).

## BRIDGE RAILING PERFORMANCE AND DESIGN CONSIDERATIONS

### Background

During the course of this project, a comprehensive bridge rail investigation was being conducted at the Texas Transportation Institute (TTI) for the FHWA (*4*). This project could, and probably will, advance the state of the art significantly regarding bridge railing behavior and dynamic force interactions. Because of the large amount of data gathered and the timing with respect to this project, much of the insight to be gained from this effort is yet to be realized. Nevertheless, the reader is encouraged to follow the progress of this contract and some of the findings are cited in this report. Some of the statements made in this chapter may be dated in light of this recent work; however, based on the author's knowledge at this time, the following is offered.

Currently, bridge railing systems are designed to the AASHTO specification (*1,2*). This specification uses a basic 10-kip (44.5-kN) force which is applied to the beam and posts according to relationships described in the specification. An alternate way of qualifying bridge railing designs is by crash test. The crash test criteria as specified in *TRB Circular 191* have been revised in *NCHRP Report 230 (9)*.

There is apparently no relationship between AASHTO load criteria and the crash test requirement. Although not stated as a design objective, the static force criterion is generally believed to guarantee little or no damage to the railing system during the severe strength crash test (4500-lb (2040-kg) car, 60 mph (95 km/h), 25 deg)(*10*). The ultimate containment capacity of these railing systems is not known. Furthermore, the margin of safety to which the system has been designed to this static criterion will influence its ultimate capacity. In other words, the AASHTO static force is a lower limit and overdesigned bridge railings are not prohibited. The current AASHTO specification does not specify behavior of the barrier past the elastic range. The failure of a post, for example, could occur either above the deck or within the deck itself. Designs with forces limited by deck failure are considered to be unsatisfactory for a number of reasons:

1. The failure mechanism in the concrete deck is complex and therefore cannot be reasonably predicted.
2. Bridge deck repair is a costly item compared to simple replacement of posts and beam.
3. Deck damage may go unnoticed until a more severe impact causes noticeable failure. The weakened structure will not perform as designed.

Other railing components such as beams and hardware should also be considered for ultimate performance. A bridge railing system that performs well in the elastic/small deflection range, but breaks down far below its ultimate capacity because of some undesirable failure mechanism (e.g., lowered system height allowing vaulting, beam splice failure due to fastener inadequacy, etc.) represents inefficient use of materials.

Careful study of the relative merits of the AASHTO "prescriptive" design method and the performance standards approach has led to a number of observations and conclusions. After 12 years of intensive barrier development and testing using all available tools, design methods, computer simulations, laboratory experiments and full-scale vehicle crash tests, the authors are convinced that the prescriptive design approach is inadequate to effect barriers with predictable containment and safety performance. On the other hand, with performance standard approach, a trend is foreseen toward a limited number of carefully developed standard barrier designs; this trend will be accompanied with a decrease in design time spent by every agency in devising its own unique systems, a reduction in material costs because of standardization and smaller number of inventory items, and an improvement in safety performance because of the more comprehensively developed barrier designs.

A pertinent example of use of computer simulation and/or crash test methods is the concrete safety shape. On the basis of design load criteria, there could be no selection of the standard New Jersey profile over the General Motors profile (both can be constructed to the same structural requirements). Crash tests and computer simulations (HVOSM) demonstrated that vehicle rollover occurred with a subcompact vehicle impacting the GM barrier at 57 mph (91 km/h) and 16-deg angle) . A similar test with the New Jersey barrier (59 mph (94 km/h) and 16-deg angle) resulted in smooth redirection of the vehicle with a roll angle of 20 deg.

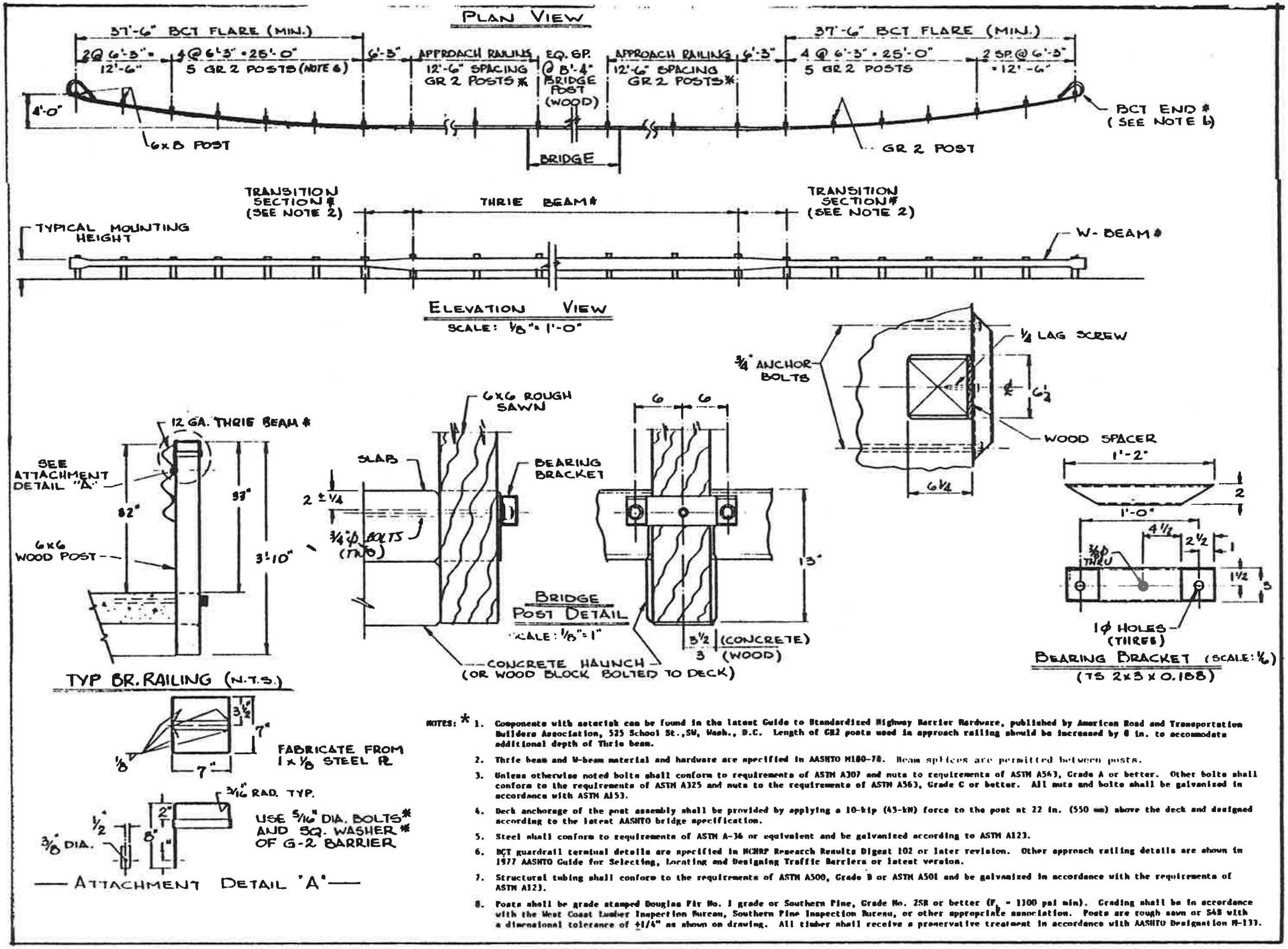
### Bridge Railing Performance

Bridge railing systems function satisfactorily by containing and redirecting impacting vehicles. The performance of a system may be measured by the threshold impact conditions where the system could be expected to fail. The development of a redirection index described in detail in Appendix A facilitates the calculation of equivalent impacts. Thus, critical impacts are determined that describe the performance limit of a particular design based on a defined impact.

#### *Performance Goals*

Bridge railing performance must be quantified to provide a basis for evaluation; i.e., does this barrier system perform satisfactorily at the desired service level? Two criteria are primarily used to evaluate longitudinal barrier systems (*8,9*):

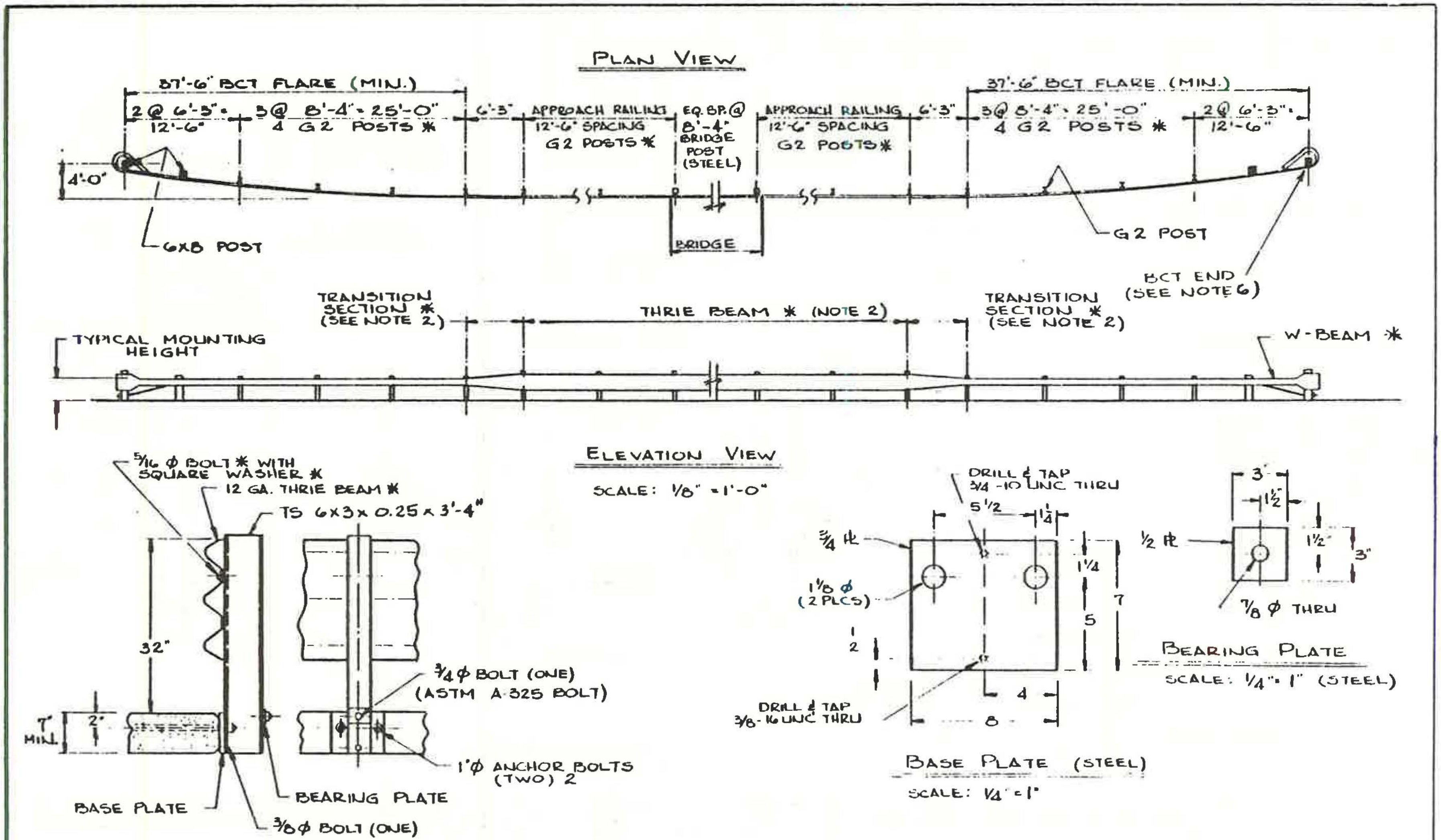
1. Occupant risk—Ideally, the bridge railing will redirect (without rollover) small passenger cars with minimal occupant injury potential. This criterion as recently changed *(9)* generally represents less demanding performance of bridge railings than the previous criterion*(8)*. The occupant injury criterion is based on impacts occurring at 60 mph (95 km/h) and a 15-deg angle in recognition that impacts of higher angle are infrequent at this speed.
2. Structural adequacy—Unlike occupant risk, barrier




NOTES: *

1. Components with asterisk can be found in the latest Guide to Standardized Highway Barrier Hardware, published by American Road and Transportation Builders Association, 525 School St.,SW, Wash., D.C. Length of GR2 posts used in approach railing should be increased by 8 in. to accommodate additional depth of Thrie beam.
2. Thrie beam and W-beam material and hardware are specified in AASHTO M180-78. Beam splices are permitted between posts.
3. Unless otherwise noted bolts shall conform to requirements of ASTM A307 and nuts to requirements of ASTM A563, Grade A or better. Other bolts shall conform to the requirements of ASTM A325 and nuts to the requirements of ASTM A563, Grade C or better. All nuts and bolts shall be galvanized in accordance with ASTM A153.
4. Deck anchorage of the post assembly shall be provided by applying a 10-kip (45-kN) force to the post at 22 in. (550 mm) above the deck and designed according to the latest AASHTO bridge specification.
5. Steel shall conform to requirements of ASTM A-36 or equivalent and be galvanized according to ASTM A123.
6. BCT guardrail terminal details are specified in NCHRP Research Results Digest 102 or later revision. Other approach railing details are shown in 1977 AASHTO Guide for Selecting, Locating and Designing Traffic Barriers or latest version.
7. Structural tubing shall conform to the requirements of ASTM A500, Grade B or ASTM A501 and be galvanized in accordance with the requirements of ASTM A123.
8. Posts shall be grade stamped Douglas Fir No. 1 grade or Southern Pine, Grade No. 2SR or better ($F_b$ = 1100 psi min). Grading shall be in accordance with the West Coast Lumber Inspection Bureau, Southern Pine Inspection Bureau, or other appropriate association. Posts are rough sawn or S4S with a dimensional tolerance of ±1/4" as shown on drawing. All timber shall receive a preservative treatment in accordance with AASHTO Designation M-133.

*Figure 3. Service level 1 bridge railing drawing—wood post.*



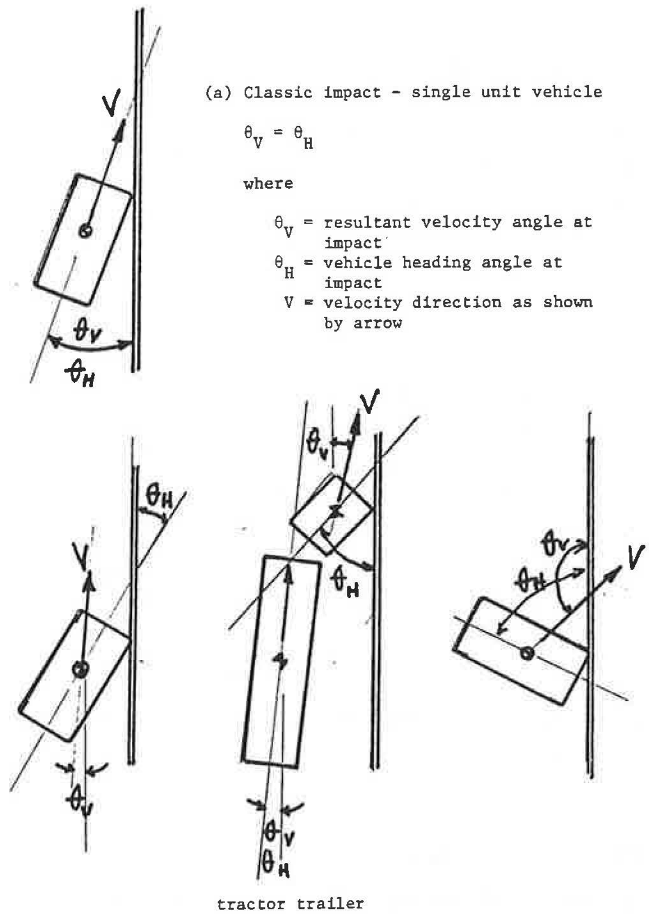

NOTES:

1. Components with asterisk can be found in the latest Guide to Standardized Highway Barrier Hardware, published by American Road and Transportation Builders Association, 525 School St.,SW, Wash., D.C. Length of G2 posts used in approach railing should be increased by 8 in. to accommodate additional depth of Thrie beam.
2. Thrie beam and W-beam material and hardware are specified in AASHTO M-180-78.
3. Unless otherwise noted bolts shall conform to requirements of ASTM A307 and nuts to requirements of ASTM A563, Grade A or better. Other bolts shall conform to the requirements of ASTM A325 and nuts to the requirements of ASTM A563, Grade C or better. All nuts and bolts shall be galvanized in accordance with ASTM A153.
4. Deck anchorage of the post assembly shall be provided by applying a 10-kip (45-kN) force to the post at 22 in. (550 mm) above the deck and designed according to the latest AASHTO bridge specification.
5. Steel shall conform to requirements of ASTM A-36 or equivalent and be galvanized according to ASTM A123.
6. BCT guardrail terminal details are specified in NCHRP Research Results Digest 102 or later revision.
7. Post elements shall conform to the requirements of ASTM A500 Grade B or ASTM A501 and be galvanized in accordance with the requirements of ASTM A123.

*Figure 4. Service level 1 bridge railing drawing—steel post.*

structural adequacy performance demands increase as the vehicle size increases for a given speed. The 25-deg angle used in the 4500-lb (2040-kg) vehicle structural adequacy tests used for a number of years is generally agreed to be a surrogate for a more shallow angle impact with a heavier vehicle. The use of a 25-deg angle represents a much more severe impact than the 15-deg angle for a given speed as demonstrated in the RI expression. Thus, the 15-deg angle test of SL 1 is more representative of expected passenger car impacts than the surrogate 25-deg test of SL 2.

Containment and redirection can readily be accomplished with passenger cars with barriers no higher than 27 in. (0.7 m) because of the low (19–25-in. (0.5–0.6-m)) vertical c.g. range. However, when considering the heavier vehicles, factors such as vertical c.g., cargo shift, and so on, definitely warrant consideration in terms of performance expectations. The function of the barrier can then be expressed in two different terms: (a) the design impact results in the vehicle being contained, redirected, and remaining upright; and (b) the design impact results in the vehicle being contained, redirected, but rollover has occurred. Thus, the specifier must decide if satisfactory performance is based on (a) or (b). Strength sufficient for containment is not necessarily accompanied by redirection without rollover.




(b) Examples of real world accidents not occurring in classical experimental manner

*Figure 5. Conditions of impact.*

### *Impact Conditions*

Experimental conditions of impact currently used and as proposed in the MSLA of Chapter Two represent a simplification of "real world" impacts that occur as described in Figure 5. In Figure 5(a), the impact conditions are represented by specified single unit vehicles impacting at specified angles and speeds. Accidents occurring in the field consist of a myriad of different conditions of impact as illustrated in Figure 5(b). In order to provide an orderly basis for testing and design purposes, the conditions of impact are simplified and standardized. Impact conditions include definition of design vehicle, impact speed, and impact angle. Variations in any of these factors can greatly change the performance requirements. With the inclusion of heavy vehicles, the selection of the vehicle and method of ballasting the vehicle to the design weight are especially critical.

As shown in the development of vehicle mixes used in Chapter Two, the predominant vehicle on U.S. highways is the passenger car of which there is a certain range of weight (1500–6000 lb (700–2700 kg)) and other dimensional variations. The balance of the vehicle fleet consists of pickups, vans, and panel trucks in the 3000–10,000-lb (1400–4500-kg) range and other large single unit buses and single unit and articulated trucks weighing up to over 70,000 lb (32,000 kg). Buses represent an ideal vehicle to characterize because the payload for a design gross weight configuration is readily specified by passengers in seats and cargo for balance of gross weight. Trucks, on the other hand, represent an infinite variety of configurations (both empty and burdened). Articulated tractor-trailers are considered the most complex of all to characterize.

The effects of vehicle variations are not as yet fully understood; however, the technology of containing and redirecting heavy vehicles has advanced significantly during recent years. It is accurate to state that the larger, heavier vehicles impose two distinct loadings of the barrier as the rear end slap in many cases is the most severe. For passenger cars, this is not the case.

### *Barrier Construction*

Performance of a barrier will vary according to construction. There are basically two types of bridge railings with certain variations; metal beam/post systems and concrete systems (shaped, beam/post type, vertical parapet, vertical parapet with metal rail on top). The systems can be designed to function as essentially rigid barriers or to deform under conditions leading up to the critical impact. Figure 6 shows that barrier "loading" is a function of the behavior of the barrier during a given impact. This figure describes barrier loading from simulated impacts on three barrier systems of different strength. The rigid system experienced high forces over a short time duration, whereas the most flexible system experienced low force levels over a much longer time period. The total impulse during the primary impact was essentially the same, consistent with the RI derivation. For a given impact condition, the more flexible metal beam/post systems are more economical to construct because of the lower force levels imposed. For concrete systems, there is also economic advantage in permitting ultimate strength to be approached at the critical impact level.

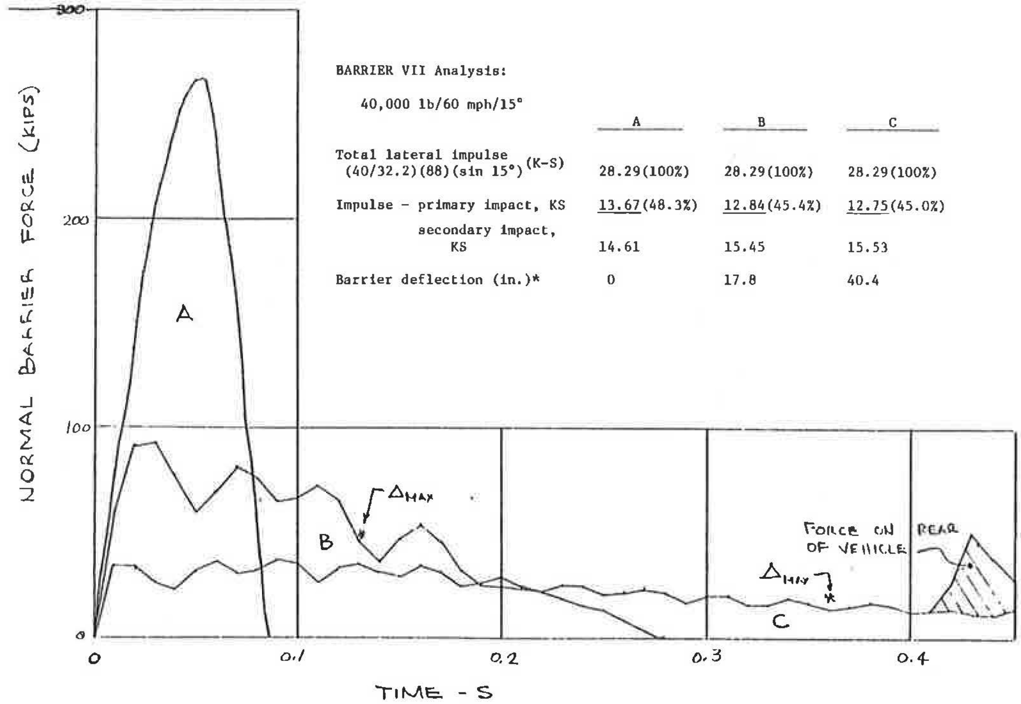



*Figure 6. Primary force–time curves for three railing systems (same impact conditions as in Fig. 5).*

## *Barrier Impact Dynamics*

A number of sequential events occur during a vehicle impact with the barrier, as shown on Figure 7. For passenger cars, the significant forces on the barrier generally occur when the front quadrant is in barrier contact. For the longer, heavier vehicle, two distinct impacts occur as a result of front panel and rear panel impacts. The large percentage of payload in the heavy vehicle also introduces load shift complexities. Barrier and vehicle interactions are interdependent and cannot be separated.

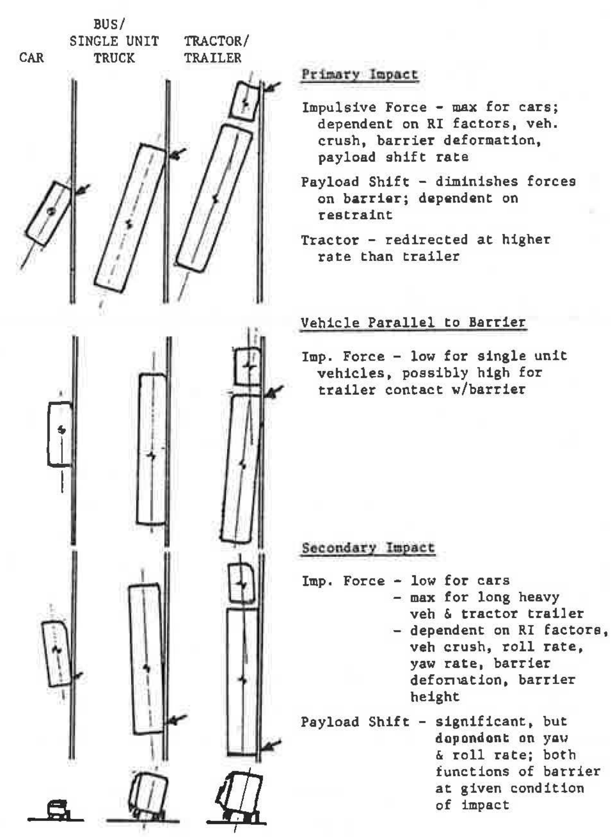



*Figure 7. Simplified description of complex vehicle/ barrier interaction.*

## Performance Predictions

Use of a single force to design a service level traffic barrier is not recommended in this report. Bridge railing performance beyond the elastic range requires analysis methods that go far beyond the current static method. Such sophisticated methods of analysis are considered unnecessary when available computer simulations can be employed that actually relate to a vehicle impact and are no more complicated to use than a dynamic structural analysis program. Computer simulation programs currently available*(11,12,13)* are considered superior to such an approach and provide reasonable assurance that the simulated impact forces are being applied to the barrier during the redirection process. In addition, use of a rollover vaulting algorithm (RVA)*(14)*, coupled with 2-dimensional barrier models, can predict rollover or vaulting due to insufficient rail height. Wedging under a beam and so-called pocketing are difficult phenomena to ascertain from the current programs.

The currently available barrier simulation models are briefly described:

1. BARRIER VII *(11)*—A large displacement, inelastic, dynamic structural analysis problem is solved. The barrier is idealized as a plane framework made up of inelastic one-dimensional elements of a variety of types. The vehicle is idealized as a plane rigid body surrounded by discrete inelastic springs. The BARRIER VII program has been extensively validated for passenger vehicle impacts in the FHWA program on cost-effectiveness of guardrail systems *(15)*. To a lesser extent, it was also used to design the collapsing ring bridge railing systems for heavy vehicle impacts*(16)*.

2. HVOSM*(12)*—an 11 degree-of-freedom vehicle is combined with terrain and barrier considerations. The deformable barrier is represented by a polynomial expression for load-deflection. The HVOSM program was used extensively in the pooled funds concrete median barrier research program conducted at SwRI*(17)*.

3. GUARD*(13)*—This three-dimensional barrier program is a product of an FHWA study. Use of this program is limited, but potentially could provide design insight into barrier concepts requiring three-dimensional analysis. This program was used to evaluate effects of FMVSS 215 (required on all post-1973 cars) bumpers on guardrail collisions. Although not validated by crash test, results indicate that under certain conditions of impact, results are significantly different.

4. Rollover Vaulting Algorithm (RVA)*(14)*—This algorithm predicts rollover vaulting using a 6 degree-of-freedom rigid vehicle.

5. RVA-2*(19)*—This algorithm is RVA modified to evaluate effects of load shift in vehicles during barrier collisions.

All of these programs were developed for FHWA and are available.

Another FHWA program examined containment of heavy vehicles*(18)*. In this report an attempt was made using BARRIER VII to relate vehicle impact conditions to maximum dynamic forces, as shown in Table 14 and Figure 8. Given the forces shown in Table 14, it is not readily apparent as to how a bridge railing designer would use these forces to design a bridge railing system. If elastic design procedures are used, it is presumed that the structure would be essentially unyielding for the applied forces. If plastic deformations were permitted, the method of analysis would be quite complex, and would require design procedures not presently employed by most bridge railing designers. There is a feeling among the highway community that given a design deflection, a bridge railing can be designed using a single force to assure containment of selected vehicle impact conditions. Use of such single force could permit bridge railings to be designed in a manner similar to the current AASHTO specification if elastic design procedures were used. If plastic deformations are considered desirable, a much more sophisticated analysis would be necessary. The futility of such an approach is evident from results given in Table 15 from Ref. *18*. The 65,000-lb (30,000-kg) concrete truck impacting at 60 mph (95 km/h) and 15 deg was examined for seven different railing systems. As shown in Figure 9, the maximum force could not be related to maximum deflection (e.g., a designer selecting a 48-in. (1220-mm) design deflection would have a choice of 370 kip (1650 kN) or 150 kip (670 kN); an approximate load of 225 kip (1000 kN) yields deflections of 31 in. (800 mm) or 51 in. (1300 mm). Thus, the concept of using a singular force to approximate a barrier impact condition cannot be supported. Reference *18* represented the state of the art regarding prediction of heavy vehicle containment and is recommended for further information on this subject along with the previously cited work at TTI*(4)*.

Table 14. Minimum lateral impact force by vehicle weight (60 mph/15°) impacts. (Ref. *18*)

| Vehicle | Maximum Lateral Impact Force (lbs) |
|---|---|
| Passenger Vehicle | 30,000 |
| School Bus 20,000 lb | 70,000 |
| Commercial Bus 40,000 lb | 150,000 |
| Concrete Mixer Truck 70,000 lb | 250,000 |

Metric conversion: Multiply lbs x 0.45 to obtain kg
Multiply mph x 1.61 to obtain km/h
Multiply lbs x 4.4 to obtain N

## Performance and Design Criteria

### *Vehicle Containment*

The proposed bridge railing service levels are related to vehicle impact conditions given in Table 2, and containment of the impacting vehicle for these respective impacts is recommended as the structural adequacy test for each railing category. Balanced designs in which the ultimate strength of the material is approached for structural adequacy impact conditions are considered to be the most efficient use of bridge railing structure. (This approach deviates from the current AASHTO static design crtieria for bridge railing design.) This ultimate containment approach requires an understanding of the failure mechanisms of the structural systems as the ultimate loading thereshold is reached. From the knowledge of the ultimate containment capacity, the full

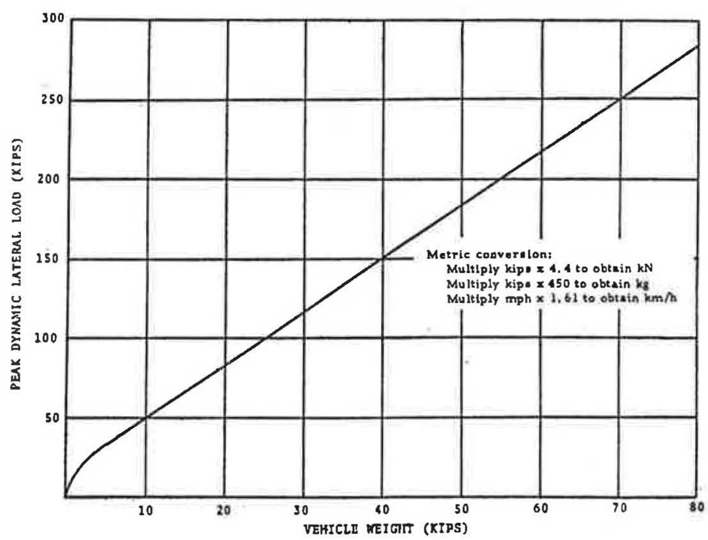



*Figure 8. Trend of peak dynamic lateral force vs. vehicle weight (60 mph/15°) impacts). (Ref.* 18)

Table 15. Maximum lateral force and deflection values for various simulated vehicle/barrier impacts. (Ref. *18*)

| BARRIER | VEHICLE | IMPACT CONDITIONS VEL. (MPH) | IMPACT CONDITIONS ANGLE (DEG.) | MAXIMUM FORCE (POUNDS) | MAXIMUM DEFLEC. (INCHES) |
|---|---|---|---|---|---|
| New York Box | 4540 lb. car | 64.0 | 25 | 34,290 | 47.86 |
| | 4540 lb. car | 49.0 | 10 | 14,040 | 4.71 |
| Alum. Balanced | 4017 lb. car | 68.1 | 25 | 51,960 | 23.75 |
| | 3965 lb. car | 58.0 | 23 | 51,990 | 11.84 |
| Texas T-1 | 3620 lb. car | 61.4 | 25 | 69,690 | 9.10 |
| Comb. NY/T-1 | 4000 lb. car | 60.0 | 25 | 48,880 | 18.32 |
| Mod. Alum. (3 rail 2" cable) | 4000 lb. car | 60.0 | 25 | 60,960 | 14.73 |
| Texas T-1 | 65,000 lb. concrete truck | 40.0 | 20 | 255,790 | 27.60 |
| | | 40.0 | 15 | 337,290 | 12.05 |
| | | 60.0 | 15 | 372,840 | 46.80 |
| | | 60.0 | 7 | 313,880 | 9.70 |
| Aluminum Balanced | 65,000 lb. concrete truck | 40.0 | 20 | 54,200 | 67.50 |
| | | 40.0 | 15 | 52,160 | 39.00 |
| | | 60.0 | 15 | 58,860 | 65.00 |
| | | 60.0 | 7 | 81,880 | 29.40 |
| Yielding Ring | 40000 lb. bus | 55.0 | 15 | 118,780 | 21.05 |
| | 40000 lb. trac/trlr | 55.0 | 15 | 155,610 | 22.75 |
| | 65000 lb. conc.tr. | 60.0 | 15 | 147,560 | 42.76 |
| | 19000 lb. sch. bus | 59.0 | 15 | 76,340 | 18.19 |
| Mod. Alum. Barriers | | | | | |
| 2 rail 1.5" cable | 65,000 lb. concrete truck | 40.0 | 25 | 110,450 | 44.60 |
| 2 rail 2.0" cable | | 60.0 | 15 | 240,290 | 50.83 |
| 3 rail 1.5" cable | | 60.0 | 15 | 201,540 | 37.87 |
| 3 rail 2.0" cable | | 60.0 | 15 | 253,670 | 38.61 |
| 2 rail 1.5" cable 4' spacing | | 60.0 | 15 | 173,290 | 45.53 |
| 3 rail 1.5" cable 4' spacing | | 60.0 | 15 | 217,710 | 30.67 |

Metric conversion:
Multiply lbs x 4.4 to obtain N
Multiply lbs x 0.45 to obtain kg
Multiply mph x 1.61 to obtain km/h
Multiply in. x 25 to obtain mm

range of barrier performance is understood. Although full-scale crash tests at each performance level are considered necessary, preliminary designs can be formulated using computer simulation models.

*Barrier Height Determination*

Based on current experience, it is recommended that SL 1 and 2 barriers be a minimum of 27 in. (0.7 m) high. Service level 3 and 4 barriers should be 34–38 in. (0.0–1.0 m) high to keep the design vehicles upright during redirection.

*Good Design Practice*

Recent crash test experiments with both heavy vehicles and automobiles have revealed certain deficiencies in barrier behavior which can be averted by good design practice. These include the following:

1. Undesirable lowering of barrier height because of ductile post behavior reduces effectiveness of barrier in preventing vaulting and rollover.
2. Beams considered as flexural members fail in tension during large inelastic deflections because of inadequate splice or tensile anchorage.
3. Unpredictable failure mechanisms of post and parapets make ultimate loads indeterminate and unpredictable.
4. Barrier height is too low for heavy vehicle impacts.
5. Beam and vehicle interface is inadequate for full range of automobiles.
6. Beam and post geometry permits wheel snagging at even moderate impact angles.

Bridge railing performance criteria for each service level are given in Chapter Four. The performance test criteria of *NCHRP Report 230* recognize the need for giving redirection to the small passenger cars. This class of vehicle currently constitutes approximately 25 percent of total traffic.

## CURRENT BRIDGE RAILING ASSESSMENT

### Background

Current bridge railings with known performance evaluations were assessed regarding SL designation. Because the data for the latest occupant risk considerations were not in the form that permitted ready evaluation, the impact severity criteria of *TRB Circular 191 (8)* were used for this evaluation.

Inasmuch as the concrete safety shape bridge parapet is the most commonly specified bridge railing today, an evaluation of 17 state standards was made for cost and strength comparisons.

*Current Railing Assessment*

All known railings with crash test evaluation experience are categorized according to SL crash test conditions of this project in Table 16. Design drawings are included in Appendix B.

*Concrete Safety Shape Bridge Parapet*

An analysis of 17 different state standards was made as described in detail in Appendix B. Costs of these parapets ranged from 32.90 to 92.85 $/L.F., including some systems with metal railings on top. The highest basic concrete parapet cost was $46.60/L.F. Estimated strength of the weakest basic barrier was 36 percent of the highest strength. There was no consistent correlation between cost and strength. Recommendation for optimum reinforcement placement of concrete parapets is also included in Appendix B.

**UPGRADING GUIDELINES**

Because many of the existing bridge railings might be considered inadequate for the bridge site service level conditions, it would be desirable to develop some strategy for setting upgrading priorities based on the MSLA. The MSLA procedures of Chapter Two are appropriate for this task; however, some guidance regarding the categorizing of existing railings is desirable in order to determine if bridge rail requirements (site SL) are being met by the existing railing (railing capacity).

Two bridge railing characterisitcs should be examined in this regard:

1. Structural adequacy—probably the best strength guidelines for determining this factor would be found in work by Hirsch*(3)* and Buth*(4)*; additionally, the work by Buth provides some basis for barrier height requirements. Suggested barrier heights of 27 in. (0.7 m) for SL 1 and 2 and 34–38 in. (0.9–1.0 m) for SL 3 and 4 have been made; however, for barriers mounted on curbs or sidewalks a series of simulations were performed using the HVOSM computer model. Four commonly used test vehicles were used to assess the effect of safety walks and curbs. As shown in Figures 10 through 13, the climb of the bumper height is an indicator of vaulting problems. The designer should consider the effects of vaulting in determining adequacy of the existing railing.
2. Occupant risk (impact severity)—little guidance can be given in this regard other than comparing the existing system with crash-tested systems for some commonality.

Reference is also made to the criteria for *bridges to remain in place* found in Ref. *6*, and summarized in text tables of Section A.1.1 of Appendix A. Upgrading of bridge railing may not be desirable if these criteria are to be met.

A special set of upgrading references (including crash test results, analytical investigations, and actual upgrading reports) is included in a bibliography following the list of cited references at the end of this report.

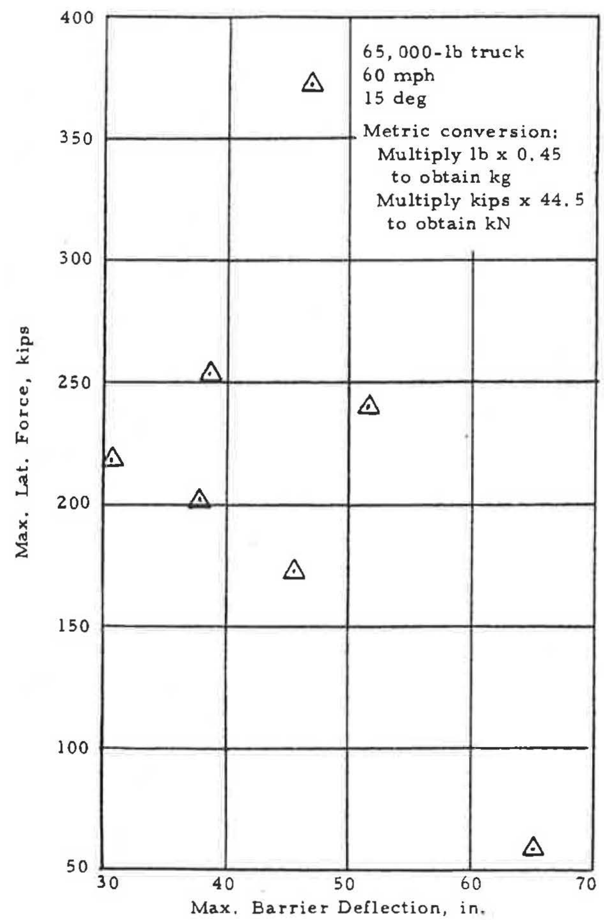



*Figure 9. Maximum load vs. maximum deflection, heavy vehicle impact. (Ref.* 18)

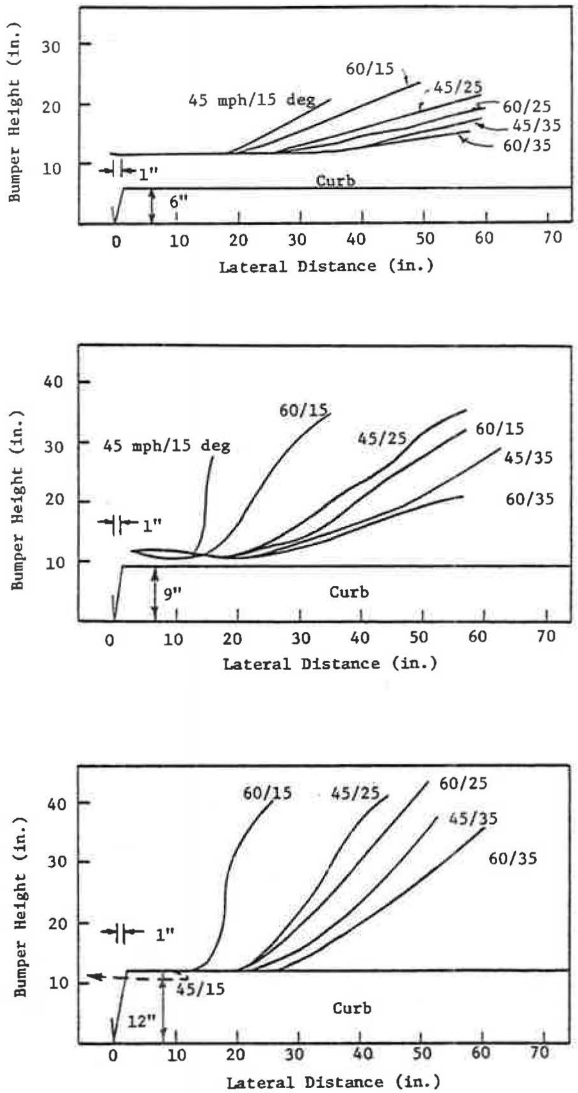



*Figure 10. Subcompact simulations (2,250 lb).*

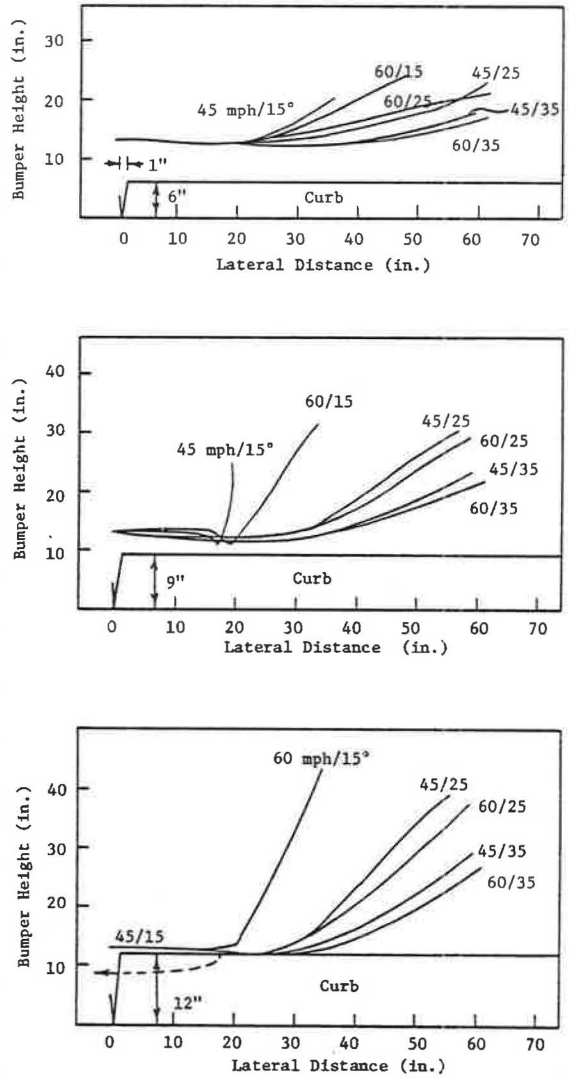



*Figure 11. Sedan simulations (4,370 lb).*

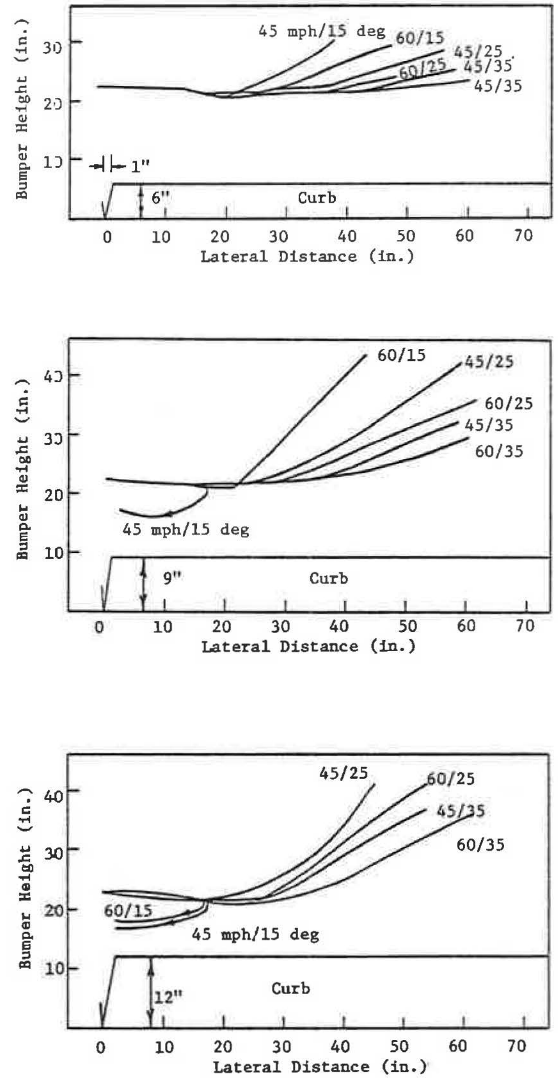
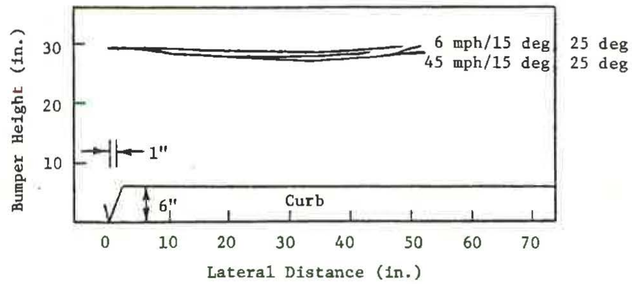



*Figure 12. School bus simulations (20,000 lb).*

Table 16. Summary of current evaluated bridge railing.

| Systems | Description | Evaluation History: Strength | Evaluation History: Impact Severity | Reference | Estimated Cost $/lin. ft |
|---|---|---|---|---|---|
| 1. Service Level One | | | | | |
| SL1 (S) | 12 ga Thrie beam - steel posts @ 8' 4" | passed | marginal pass | Chapter 3 | 11.73 |
| SL1 (W) | 12 ga Thrie beam - wood posts @ 8' 4" | passed | marginal pass | Chapter 3 | 8.37 |
| BR4 | two steel box beams on steel posts @ 6' 3" | passed | none | AASHTO Barrier Guide(20) | 35.00 |
| 2. Service Level Two | | | | | |
| Texas T6 | tubular W-beam on steel posts @ 6' 3" | passed | failed (6.9g's lat) | Ref. 21 | 23.53 |
| BR1 | New Jersey shape concrete parapet | passed | marginal pass | AASHTO Barrier Guide(20) | 32-38 |
| BR2 | concrete parapet - metal rail | passed | none | AASHTO Barrier Guide(20) | 50-100 |
| BR3 | steel box beams on fabricated post @ 8' 9" | passed (3500-lb vehicle, 55 mph, 25 deg) | none | AASHTO Barrier Guide(20) | 35.00 |
| 3. Service Level Three | | | | | |
| Texas 101 | two steel box beams on steel posts @ 8' 4" | passed (front axle displaced from bus) | failed (7.3g's lat) | Ref. 4 | 38.80 |
| 4. Service Level Four | | | | | |
| C.R.B.R.S. | four-rail system w/collapsing ring first stage | passed | none | Ref. 16 | 80.00 |
| Texas T202 modified | | passed | unavailable | Appendix B | 43.00 |



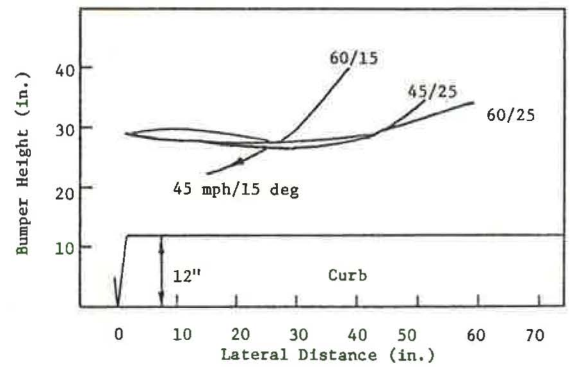




*Figure 13. Intercity bus simulations (40,000 lb).*

CHAPTER FOUR

# DISCUSSION AND APPLICATION OF FINDINGS

## DISCUSSION

### Bridge Railing Service Levels

The multiple-service-level bridge railing approach (MSLA) is a major change from current practice, both from a technical and administrative view. Rather than the conventional design of a bridge railing system, it requires selection from a group of systems crash tested to specific impact conditions.

The creation of unique bridge railing designs from prescriptive specifications using static loading and elastic design results in a proliferation of barrier systems that are not fully evaluated in terms of vehicle containment capacity. In recent years, it has become evident that the simple static/elastic design method is inadequate for the task of producing predictable vehicle redirection characteristics and cost-effective systems. Because of the complexity of the barrier/vehicle redirection mechanisms, the authors are convinced that each operational barrier system should be evaluated by a series of crash tests. Computer simulation models can be most helpful and cost-effective in early stages of a barrier development, as described in the development of the SL 1 system; even these tools, which possess capability greatly in excess of the simple static/elastic approach, may only reduce but not replace the need for vehicle crash tests.

The national trend is toward the adoption of a limited number of carefully developed and demonstrated traffic barrier systems. The movement is prompted by requirement for increased safety performance of the barriers and the realization of cost savings in design, fabrication and maintenance of widely accepted standard systems. These limited number of bridge railing designs can be developed on cooperative programs (such as NCHRP) in which the development costs are shared.

Thus, the multiple-service-level bridge rail approach takes into account the trend toward standardization of bridge rail systems and presents a technique for selecting the most appropriate system for particular site conditions based on benefit and cost technology.

### Service Level Selection Parameters

The service level parameters were selected based on what was considered the state of the art in 1980. Certain parameters in the MSLA are linear in the final product and thus may be varied by simple multiplication. These linear factors include: ADT, enchroachment rate, adverse conditions as related to encroachment rate, costs (accident and bridge railing), and B/C ratios.

Other factors as they influence the final results are more complex, and reformulation of probability equations is required if these values are changed. These nonlinear factors include: shoulder width as it relates to encroachment distribution, encroachment distribution (lateral distance transversed), vehicle mix characteristics (mass, geometry, etc.), speed (or speed distribution if available), impact angle distribution, and traffic distribution (e.g., lane distribution variances, more than three lanes, etc.)

It is recognized that parameter values such as encroachment frequencies, vehicle mix characteristics, impact speed, and angle distributions are based on tenuous and sometimes scant research data. Possibly, refined values for these parameters may be forthcoming from future research effort. Nevertheless, the authors of this report strongly believe that the lack of precision in the values will not change the systematic method of selection nor should it be a reason to deter or delay the implementation of the MSLA.

### MSLA Results

Bridges on roadways with high ADT, multilanes, wide shoulders, and large truck percentages will require bridge railing structures with greater containment capacity than that specified by the current AASHTO Specification. Conversely, bridges on roadways with low ADT and mostly automobile and pickup traffic will require a bridge railing less demanding than the current AASHTO Specification. The collector, road, and street functional classification bridges, as presently defined, require primarily only SL 1 systems, whereas arterial bridges require a wide range including SL 1 through SL 4.

The MSLA procedures as described in Chapter Two and Appendix A relied on two sets of costs: (1) accident costs based on Texas and Washington accident data and National Safety Council latest accident cost values; and (2) bridge railing costs based on designs of Table 3. The researchers were unable to develop a rationale for combining the Texas and Washington costs into one set of values. Although the bridge railing "retained" accident costs of both were quite close, the Texas "penetration" costs were considerably higher than the Washington costs. No data were available to discern this difference; therefore, the two sets were kept separated. The flexible bridge railing costs are considered to be realistic, achievable values although no damage repair factors have been included. A user agency may determine that other costs for either railing and/or accidents may be appropriate for their needs. The fundamental logic of the MSLA is recommended and the costs cited earlier are recommended in lieu of other available data.

For bridge sites where the consequences of railing penetration are judged to be significantly different (either higher or lower than those indicated by the two-state data), it will be necessary to estimate penetration accident costs if the typical selection tables are not used.

For unusual sites where bridge railing penetration would have extraordinary consequences, it may be desirable to "target" a design impact (vehicle, speed, angle) and design, develop and evaluate a railing system for this purpose. The MSLA procedures presented are general and cannot provide the appropriate answer for every bridge site.

#### Service Level 1 Bridge Railings

Two Service Level 1 bridge railing systems were systematically designed and developed using computer simulations, component testing, and crash testing. The performance criteria of SL 1 were met by these designs as evaluated in tests of the finalized designs of Figures 3 and 4.

The designs developed in this project will eliminate the most serious shortcoming of many existing bridge railing installations (i.e., the transition from a flexible or semirigid approach railing to a rigid bridge railing). By using inexpensive weak post guardrail approach systems, compatible integration with the SL 1 bridge railing is readily accomplished.

In addition, the use of a relatively low strength post permits the use of the SL 1 system on bridge decks with minimal strength properties. The current AASHTO *(1,2)* post design criteria require much stronger post connection details, and significant deck failure has resulted with many of the current systems.

The systems tested in this project demonstrated that vehicles can be redirected with over 2 ft (0.6 m) of deflection with wheels dropping below the bridge deck.

*Wood Post SL 1 Systems*

Properly graded posts are essential for the performance of this system; a grade stamp on all posts is required. Although the cost of this design is apparently lower than the steel post system, it requires a 1-ft (0.3-m) wider bridge deck for the same clearance between rails as the steel post system. The wood posts provide a desirable breakaway performance when fracture occurs, thus minimizing wheel and post involvement.

*Steel Post SL 1 system*

This system is a predictable structure that performs very much as initially designed. The unique breakaway feature of the post attachment to the base plate assures minimal vehicle and post involvement and also provides predictable control over the post failure mechanism. The steel post system with side-mounted posts maximizes clearance between railings for a given bridge deck width.

*School Bus Considerations*

The SL 1 systems are capable of containing and redirecting 20,000-lb (9070-kg) school buses impacting at 7 deg with a speed in excess of 45 mph (70 km/h).

### APPLICATION OF FINDINGS

#### Service Level Selection

A rational basis has been derived which provides maximum protection where impacts are likely to occur and further accounts for degrees of collision severity based on a number of factors. The use of the MSLA on a regional or national basis requires a knowledge of barrier containment capacities both existing and proposed, and costs for accidents and bridge railing. All parameters used can be readily varied as policy or additional findings permit.

#### AASHTO Bridge Railing Specification Changes

The shortcomings of simplified barrier design were discussed with supporting data cited. Currently available barrier simulation computer programs provide insight for installed systems as well as new designs. It is considered desirable to evaluate new and upgraded designs by crash test to prove the containment capacity. A recommended change to the AASHTO Bridge Railing Specification is offered in Exhibit 1.

#### SL 1 Bridge Railing

A low-cost bridge railing has been developed to SL 1 requirements. Use of this system could be widespread in the collector, road, and street category. Other advantages of the low-cost system include less demanding approach guardrail transition requirements which further enhance vehicle safety. Recommended design drawings and specifications are shown in Figures 3 and 4.

#### Upgrade/Replace Existing Bridge Rails

The multiple-service-level bridge rail procedures pre-

*Exhibit 1. Recommended revision and addition to bridge railing specification*

**1.1.8—RAILINGS**

Railing shall be provided at the edge of structures for the protection of traffic and for the protection of pedestrians if pedestrian walkways are provided.

Where pedestrian walkways are provided adjacent to roadways on other than urban expressways, a traffic railing or barrier may be provided between the two with a pedestrian railing outside. (See Article 1.1.7—CURBS AND SIDEWALKS)

**(A) Traffic Railing**

(1) General

~~While the primary purpose of traffic railing is to contain the average vehicle using the structure, consideration should also be given to protection of the occupants of a vehicle in collision with the railing, to protection of other vehicles near the collision, to vehicles or pedestrians on roadways being overcrossed, and to appearance and freedom of view from passing vehicles.~~

Materials for traffic railing shall be concrete, metal, timber, or a combi-

(A) Traffic Railing

(1) General

Traffic railings are placed on bridge structures to contain and redirect vehicles in order to protect and minimize harm to:

a. occupants of vehicles in collision with bridge railing,
b. occupants of vehicles in proximity to the collision; i.e., either on, near, or under the bridge,
c. innocent pedestrians and property near or under the bridge.

Materials for traffic railing shall be concrete, metal, timber, or a combi ...

(2) Level of Service

Four levels of service are recommended according to site conditions. The roadway functional classification, bridge geometrics and traffic characteristics determine the bridge rail level of service as shown in Table 9 of Ref*. If the candidate bridge is not considered typical, the designer may use more representative data to determine the service level. In special cases where containment of a specific vehicle is considered crucial, the performance criteria should reflect this circumstance (see next section).

(3) Performance Criteria

(a) Vehicle Containment. The bridge railing service levels are related to vehicle impact conditions presented in Table 1, and containment of the impacting vehicle for these respective impacts is recommended as the structural adequacy test for each railing SL.

(b) Occupant Risk. The majority of bridge railing impacts occur at shallow angles with passenger cars. Accordingly, assessment of occupant injury due to bridge railing collision is determined by the occupant risk test of Table 1.

(c) Full-scale Crash Tests. Bridge railings are evaluated for performance by crash testing to the required service level structural adequacy test of Table 1. In addition, occupant risk for all railing levels is evaluated by the same passenger car test as shown in Table 1. The crash test procedures and test vehicles described in NCHRP Report 230** should be used for these evaluations.

*This NCHRP Report. **Or superseding document

*Exhibit 1. Continued*

(d) Approach Railing Transition. When approach railings are used at a bridge, a crash test evaluated transition is required if structural/geometrical characteristics for bridge and approach railing are different. The barrier installation should be terminated where it is no longer considered needed.

(e) Additional Test Conditions. For those circumstances where containment of a vehicle or condition not specified in Table 1 is considered crucial, this vehicle or condition should be used in crash test evaluations to determine if the proposed railing is adequate for desired structural adequacy test performance. Consideration for passenger car impacts (occupant risk) is still required.

(4) Bridge Railing Description

Bridge railings for each level of service are implemented after crash test evaluation. The implementation of each system requires complete drawings and specifications that reflect all significant values from the barrier system subjected to crash test. Critical tolerances should be specified; bridge "deck" requirements at barrier/deck juncture are part of specification and should be adequately described to permit use of a railing system on a variety of bridge deck configurations.

TABLE 1

BRIDGE RAILING PERFORMANCE CRITERIA

| Service Level: | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| 1. Crash Test Requirements* | | | | |
| Impact Conditions | | | | |
| A. Strength test<br>Vehicle Weight (lbs) | 4500 | 4500 | 20,000 | 40,000 |
| Impact Speed (mph) | 60 | 60 | 60 | 60 |
| Impact Angle (deg) | 15 | 25 | 15 | 15 |
| B. Occupant risk | -----2250-lb auto, 60 mph, 15 deg-----<br>or 1800-lb auto | | | |
| 2. Dynamic Performance | ------------------ALL------------------ | | | |
| A. Posts/parapets | Controlled, repeatable failure mechanisms outside bridge deck are required. Ductile failures of posts are discouraged unless separation of beam from post prior to rail lowering is controlled and repeatable. The post anchorage is designed to ultimate stresses using ultimate post failure load. | | | |
| B. Beam | Full tension of net section should be developed by attachments at splice. The AASHTO Standard Specifications for Highway Bridges,(1) Article 1.7.19, provide a good splice specification. Beam should be anchored (expansion joints require special treatment). | | | |
| C. Vehicle performance | The preferred vehicle acceleration criteria are found in recommendations of NCHRP Report 230 (9). Values shown in this document are subject to change as technology becomes available. Other requirements specified for automobiles in Report 230 are considered applicable also. | | | |
| 3. Guidelines | | | | |
| A. Geometry | | | | |
| *1. Barrier height (in. (min.) | 27 | 27 | 34-38 | 34-38 |
| 2. Beam spacing (Ref. 4) | | | | |

*Barrier height is a minimum; this height must be increased if beam/post interaction allows beam to drop below this height.

| | |
|---|---|
| B. Maximum dynamic deflection | As a guide for design, the maximum dynamic deflection during the structural adequacy test should not exceed the vehicle half-width. This value may be exceeded during crash test if redirection/containment is achieved. |

Metric conversions: Multiply in. x 25.4 to obtain mm
Multiply mph x 1.6 to obtain km/h
Multiply lbs. x .45 to obtain kg

*Crash test procedures and test vehicles are described in NCHRP Report 230.

sented in this report are applicable to existing bridges as well as new construction. Although beyond the scope of this program, the following general steps are envisioned for a state agency to systematically upgrade bridge rails on a specific highway system or general area:

1. Classify existing bridge railing designs by appropriate NCHRP SL. This may or may not be a straightforward task. In order of preference, the following is suggested for evaluating bridge railing capacity:
   a. Crash test
   b. Computer simulation
   c. Comparison with other evaluated systems for similitude
   d. Estimate
2. Using the assigned SL, determine the number of critical impacts for the bridge type considered and inventory all candidate bridges accordingly. The results could be displayed for analysis as shown:

| Bridges | | Predicted Number of |
|---|---|---|
| Number | Total Length (ft) | Critical Impacts (Range) |
| 75 | 15,000 | 50 and up |
| 45 | 10,000 | 39-49 |
| 60 | 12,000 | 10-29 |
| 150 | 24,000 | 5-9 |
| 1000 | 200,000 | 1-4 |

3. The agency could then commence upgrading the existing structures beginning with those with the highest number of critical impacts and progressing to the next levels until all funds were allocated.

A number of references for analyzing bridge railing designs and upgrading technology are included in the bibliography following the list of references.

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# APPENDIX A

## SUPPORTING INFORMATION FOR MULTIPLE SERVICE LEVEL APPROACH FOR BRIDGE RAILINGS

This appendix contains information, findings, and results that support or describe assumptions and procedures used in the multiple service level approach (MSLA).

### A.1 Multiple Service Level Parameters

MSLA is a comprehensive systems approach used in selecting the most cost-effective bridge railing designs for specific highway sites. During development of MSLA, a number of parameters were examined and their relationship to the overall cost-effectiveness of barrier selection ascertained. In some cases, published facts, previous research, and/or accident statistics were used to support elements of the MSLA. In other cases, the authors relied on rational developments to support assumptions. Parameters that were considered include the following:

- Functional Classification
  - rural or urban
  - arterial
  - minor arterial
  - collectors
  - roads and streets
- Bridge Rail Accidents
  - consequences
  - frequency
  - costs
  - benefits of bridge railing
- Impact Probability
  - encroachment frequency (rural/urban location, number of lanes, direction of traffic and bridge width)
  - lateral distance traveled



- Collision Conditions
  - vehicle size distribution
  - impact speed
  - impact angle
- Barrier Behavior
  - vehicle containment
  - redirection severity
  - post-impact trajectory
- Barrier Design Alternatives
  - rigid metal or concrete
  - flexible metal
  - costs
- Service Level Selection Criteria
  - cost effectiveness
  - cost/benefit ratio (B/C)

#### A.1.1 Functional Classification

The functional classification of the roadway bridge identifies critical aspects relating to the MSLA; specifically

- vehicle mix
- geometrics
- range of traffic volume (ADT)
- design speed
- accident rate

A fabic functional classification as described in Reference 6 is given in Table A.1. Characteristics of bridges for roadways by functional classification are developed in following sections.

A.1.1.1 Local Roads and Streets. Local roads and streets constitute a high proportion of the roadway mileage in the United States.

a. Local rural roads. Two travel lanes usually can accommodate traffic volumes on these roads. Bridge width and shoulder requirements are given in Table A.2. Table A.3 provides minimum requirements for bridges to remain in place. The values in Table A.3 do not apply to

TABLE A.1

FUNCTIONAL CLASSIFICATION SUMMARY TABLE

**Typical Distribution of Rural Functional Systems**

| Systems | Percentage of Total Rural Miles |
|---|---|
| Principal arterial system | 2-4 |
| Principal arterial plus minor arterial system | 6-12, with most states falling in 7-10 percent range |
| Collector (major plus minor) system | 20-25 |
| Local road system | 65-75 |

**Typical Distribution of Urban Functional Systems**

| Systems | Range (percent) Travel Volume | Miles |
|---|---|---|
| Principal arterial system | 40-65 | 5-10 |
| Principal arterial plus minor arterial street systems | 65-80 | 15-25 |
| Collector street system | 5-10 | 5-10 |
| Local street system | 10-30 | 65-80 |

Note: The metric conversion unit is 1 mi = 1.6 km



TABLE A.2

CLEAR ROADWAY BRIDGE WIDTHS AND DESIGN LOADINGS FOR NEW AND RECONSTRUCTED BRIDGES, LOCAL ROADS

| Current ADT | Min. Clear Roadway Width of Bridge | Design Loading Structural Capacity |
|---|---|---|
| 400 and under | Surface + 4 ft | HS 20 |
| over 400 | Surface + 6 ft | HS 20 |

**Minimum Width of Surfacing and Graded Shoulder**

**Width (ft) for Design Volume**

| Design Speed (mph) | Current ADT Less Than 50 | Current ADT 50-250 | Current ADT 250-400 | Current ADT Over 400 |
|---|---|---|---|---|
| | Width of Surfacing | | | |
| 20 | 16 | 18 | 20 | 20 |
| 30 | 16 | 18 | 20 | 20 |
| 40 | 20 | 20 | 20 | 22 |
| 50 | 20 | 20 | 20 | 22 |
| | Width of Graded Shoulder Each Side | | | |
| All | 2 | 2 | 2 | 4 |

Note: The metric conversion units are 1 ft = 0.3 m, 1 mi = 1.6 km



TABLE A.3

SUGGESTED MINIMUM STRUCTURAL CAPACITIES AND MINIMUM ROADWAY WIDTHS FOR BRIDGES TO REMAIN IN PLACE, LOCAL ROADS

| Traffic Current ADT | Design Loading Structural Capacity Minimum | Roadway Clear Width (ft)[(a)] Minimum[(b)] |
|---|---|---|
| 0-50 | H-10 | 20[(c)] |
| 250 | H-15 | 20 |
| 250+ | H-15 | 22 |

[(a)] Clear width between curbs or rails, whichever is the lesser.

[(b)] Minimum clear widths that are 2 ft narrower may be used on roads with few trucks. In no case shall the minimum clear width be less than the approach surfacing width.

[(c)] For one lane bridges use 18 ft.

Note: The metric conversion unit is 1 ft = 0.3 m.



structures with total length greater than 100 ft (30.5 m). These structures should be analyzed individually.

b. Local urban streets. Design speed for local streets is generally 20 to 30 mph (32 to 48 km/h). The minimum clear width for all new bridges or streets with curbed approaches should be the same as the curb-to-curb width of the approaches. For streets with shoulders and no curbs, the clear roadway width preferably should be the same as the approach roadway width but in no case less than the width given in Table A.2.

A.1.1.2 Collector Roads and Streets. A definition of the collector can be developed by referring to its upper and lower limits - the arterial and local road or street.

a. Rural collectors. A major part of the rural highway system consists of two-lane collector highways. Rural collectors are generally designed for speeds of about 50 mph (80 km/h). The minimum clear roadway width for this classification is given in Table A.4.

b. Urban collectors. Two moving traffic lanes plus additional width for shoulders and parking are sufficient for most collector streets. The minimum clear width for all new bridges on collector streets with curbed approaches should be the same as the curb-to-curb width of the approaches. The bridge rail should be placed immediately beyond the curb if no sidewalk is present to avoid vaulting of vehicles. For collector streets with shoulders and no curbs, the full width of approach roadways preferably should be extended across bridges. Sidewalks on the approaches should be extended across all new structures. Desirably there should be at least one sidewalk on all street bridges.



TABLE A.4

MINIMUM CLEAR ROADWAY WIDTHS FOR NEW AND RECONSTRUCTED BRIDGES - RURAL COLLECTORS

| Current ADT Volume | Minimum Clear Roadway Width of Bridge |
|---|---|
| Under 400 | Surface width plus 4 ft |
| 400 - 2,000 | Surface width plus 6 ft |
| 2,000 - 4,000 | Surface width plus 8 ft |
| Over 4,000 | Approach roadway width |

Notes: Where the approach roadway, including shoulders, is surfaced for the full crown width that surfaced width should be carried across all structures.

For bridges in excess of 100 ft in length with traffic volumes greater than 2000 ADT, the minimum surface width plus 6 ft will be acceptable.

The metric conversion unit is 1 ft = 0.3 m.

**Surface Width in Feet for Design Volume of:**

| Design Speed (mph) | Current ADT Under 400 | ADT 400-750 | ADT 750-2,000 | ADT 2,000-4,000 | ADT Over 4,000 |
|---|---|---|---|---|---|
| 20 | 20 + 4 | - | - | - | - |
| 30 | 20 + 4 | 20 + 6 | 22 + 6 | 22 + 8 | 24 + 16 |
| 40 | 20 + 4 | 22 + 6 | 22 + 6 | 22 + 8 | 24 + 16 |
| 50 | 20 + 4 | 22 + 6 | 22 + 6 | 24 + 8 | 24 + 16 |
| 60 | 20 + 4 | 22 + 6 | 22 + 6 | 24 + 8 | 24 + 16 |
| | **Width of Graded Shoulder - Each Side of Pavement** | | | | |
| All | 2 | 4 | 6 | 8 | 8 |

Note: The metric conversion units are 1 mph = 1.6 km/h, 1 ft = 0.3 m

A.1.1.3 Arterial Roads and Streets. Arterials functionally provide the high-speed high-volume network for long distance travel between major points. They vary from two-lane roadways with some limited-access consideration to the multilane freeway with fully controlled access.

a. Rural arterials. Principal rural arterials include the Interstate System and most rural freeways. Minor rural arterials link the urban centers to larger towns.

The full width for the approach roadways should normally be provided across all new bridges. Exceptions may be made when (1) the bridge is considered a major structure on which the design dimensions should be subject to individual economic studies because of the high unit cost, and (2) isolated two-lane bridges are to be replaced, with only incidental approach roadway work to be performed concurrently. In the latter case the minimum horizontal clearance from traffic lanes to the face of the bridge parapets should not be less than 4 ft (1.22 m). When project planning indicates a need for adjusted roadway widths in the foreseeable future, current bridge construction should be consistent with such widths.

Bridges to remain in place should have adequate strength and at least the width of the full traffic lanes plus 2-ft (0.61-m) clearances, but should be considered for ultimate widening or replacement if they do not provide at least 3-ft (0.92-m) clearances. All bridges that are less than full width should be considered for special narrow bridge treatments such as signing and pavement marking.

An ideal two-lane rural arterial would consist of two 12 ft (3.66 m) traffic lanes and have usable shoulders 10 ft (3.05 m) wide. Under restrictive or special conditions, 11-ft (3.66-m) lanes may be acceptable, and it is not always economically feasible or justifiable to



provide shoulders 10 ft (3.05 m) wide. The logical approach on shoulder widths is to provide a width related to the traffic demands.

Table A.5 provides the widths of shoulder that should normally be considered for the volumes indicated. These widths are summarized broadly in terms of ranges for four volume classifications.

b. Urban arterials. Lane widths of 12 ft (3.66 m) are desirable on urban arterials having high-speed free-flow conditions. Under interrupted-flow operating conditions at speeds up to 40 mph (64 km/h), narrower lane widths are normally adequate and have some advantages.

The minimum clear width for all new bridges on arterial streets should be the same as the curb-to-curb width of the street. If design speeds in excess of 50 mph (80 km/h) are used, a minimum 4-ft (1.22-m) clearance should be provided from the edge of the driving lane to the face of the curb. Urban arterials having rural-type shoulders should have the full shoulder widths provided across structures. When a sidewalk is provided adjacent to the roadway, the normal curb-to-curb width can be provided for speeds of 50 mph (80 km/h) or less. Long structures or high speeds should have sidewalks separated from traffic lanes with bridge-type rails.

A.1.1.4 Freeways. The highest type of arterial highway is the freeway, which is defined as an expressway with fully controlled access.

Freeways should have a minimum of four lanes. Through-traffic lanes should be 12 ft (3.66 m) wide. There should be continuous paved shoulders on both the right and left sides of all freeway facilities. The width of the right shoulder should be at least 10 ft (3.05 m), and where the truck traffic exceeds 250 DHV, it should preferably be 12 ft (3.66 m) wide. The full width of the right shoulder should be



TABLE A.5

WIDTHS OF SHOULDERS FOR TWO-LANE RURAL ARTERIALS

| Design Volume | | Usable Shoulder Width (ft)* | |
|---|---|---|---|
| Current ADT | DHV | Recommended Range | |
| 250-400 | - | 4 | 8 |
| 400-750 | 100-200 | 6 | 10 |
| - | 200-400 | 8 | 10 |
| - | Over 400 | 8 | 12 |

*Usable shoulder width indicated is normally the surfaced width or, where stabilized shoulders are provided, the width that has adequate strength to support the majority of the vehicles may use them for emergency parking.

Note: The metric conversion unit is 1 ft = 0.3 m.



paved. On four-lane freeways the median shoulder or left shoulder is normally 4 to 8 ft (1.22 to 2.44 m) wide. At least 4 ft (1.22 m) should be paved, and the remainder should be surfaced to some extent. On freeways of six or more lanes, the median shoulder should also be 10 ft (3.05 m), and preferably 12 ft (3.66 m) wide, where the truck traffic exceeds 250 DHV. The full width should be paved.

On the basis of the information provided in Reference 6 and previously discussed, a summary (Table A.6) was prepared that defines recommended design features for new construction based on functional classification and ADT (in some cases). Also shown in this table is the vehicle traffic mix which will be discussed later.

A.1.2 Bridge Rail Accidents

Since a bridge is a unique feature of the highway which generally is regarded as an "automatic" warrant for bridge rail placement, an examination of current bridge accident experience is in order.

Accordingly, a number of sources of accident data were interrogated to provide insight into the nature and frequency of bridge-related accidents in general and bridge railing accidents in particular. The best available data were determined to be that which could be obtained from the sources listed in Table A.7. In order to make nationwide projections from certain more limited data, bridge mileage values were obtained from the FHWA Office of Engineering as shown in Table A.8. From these data, the frequency and consequences of striking a bridge railing based on current accident statistics can be perceived.

A.1.2.1 Bridge Accidents. Bridge-related accidents considered appropriate to this study include primarily those involving a vehicle striking a bridge rail and secondarily those involving a vehicle

# TABLE A.6

## FUNCTIONAL CLASSIFICATION - BRIDGE SUMMARY

| FUNCTIONAL CLASSIFICATION | ADT | DESIGN SPEED MPH | LANE WIDTH FT | NO. OF LANES* | TRAFFIC MIX** | SHOULDER WIDTH FT |
|---|---|---|---|---|---|---|
| 1. Rural Arterials | | | | | | |
| Principal Arterial | | | 12 | 4D | 1 | 10-12 |
| Interstate } Freeways | | > 60 | 12 | 2, TB | 1 | 10-12 |
| Major Arterial } Freeways | | | 12 | 2, TB | 1 | 10-12 |
| Major Arterial | | < 60 | 11-12 | 2 | 2 | 10 |
| | | | 11-12 | 2 | 2 | 4 |
| Minor Arterial | | < 60 | 11-12 | 2 | 4 | 8 |
| | | | 11-12 | 2 | 4 | 4 |
| 2. Urban Arterials | | | | | | |
| Principal Arterial | | | 12 | 4D | 4 | 10 |
| Interstate } Freeways | | > 60 | 12 | 2, TB | 4 | 10 |
| Major Arterial } Freeways | | | 12 | 6D | 4 | 10 |
| | | | 12 | 3, TB | 4 | 10 |
| Major Arterial | | < 60 | 12 | 2 | 4 | 10 |
| | | | 12 | 2 | 4 | 4 |
| | | | 12 | 4 | 4 | 10 |
| Minor Arterial | | < 60 | 12 | 2 | 4 | 8 |
| | | | 12 | 2 | 4 | 4 |
| 3. Rural Collectors & Roads | | | | | | |
| Collector 1 | 250-400 | | 10 | 2 | 5 | 2 |
| 2 | 400-750 | | 10 | | | 3 |
| 3 | 750-2000 | 20-30 | 11 | | | 3 |
| 4 | 2000-4000 | | 11 | | | 4 |
| 5 | > 4000 | | 12 | | | 8 |
| 6 | 250-400 | | 10 | | | 2 |
| 7 | 400-750 | | 11 | | | 3 |
| 8 | 750-2000 | 40 | 11 | | | 3 |
| 9 | 2000-4000 | | 11 | | | 4 |
| 10 | > 4000 | | 12 | | | 8 |
| 11 | 250-400 | | 10 | | | 2 |
| 12 | 400-750 | | 11 | | | 3 |
| 13 | 750-2000 | | 11 | | | 3 |
| 14 | 2000-4000 | | 12 | | | 4 |
| 15 | > 4000 | | 12 | 2 | 5 | 8 |
| Local Roads 1 | < 50 | | 8 | 2 | 5 | 2 |
| 2 | 50-250 | 20-30 | 9 | | | 2 |
| 3 | 250-400 | | 10 | | | 2 |
| 4 | > 400 | | 10 | | | 4 |
| 5 | < 50 | | 10 | | | 2 |
| 6 | 50-250 | 40-50 | 10 | | | 2 |
| 7 | 250-400 | | 10 | | | 2 |
| 8 | > 400 | | 11 | 2 | 5 | 4 |
| 4. Urban Collectors & Streets | | | | | | |
| Collector 1 | 250-400 | | 10 | 2 | 3 | 2 |
| 2 | 400-750 | | 10 | | | 3 |
| 3 | 750-2000 | 20-30 | 11 | | | 3 |
| 4 | 2000-4000 | | 11 | | | 4 |
| 5 | > 4000 | | 12 | | | 8 |
| 6 | 250-400 | | 10 | | | 2 |
| 7 | 400-750 | | 11 | | | 3 |
| 8 | 750-2000 | 40 | 11 | | | 3 |
| 9 | 2000-4000 | | 11 | | | 4 |
| 10 | > 4000 | | 12 | | | 8 |
| 11 | 250-400 | | 10 | | | 2 |
| 12 | 400-750 | | 11 | | | 3 |
| 13 | 750-2000 | | 11 | | | 3 |
| 14 | 2000-4000 | | 12 | | | 4 |
| 15 | > 4000 | | 12 | 2 | 3 | 8 |
| Local Roads 1 | < 50 | | 8 | 2 | 3 | 2 |
| 2 | 50-250 | 20-30 | 9 | | | 2 |
| 3 | 250-400 | | 10 | | | 2 |
| 4 | > 400 | | 10 | | | 4 |
| 5 | < 50 | | 10 | | | 2 |
| 6 | 50-250 | 40-50 | 10 | | | 2 |
| 7 | 250-400 | | 10 | | | 2 |
| 8 | > 400 | | 11 | 2 | 3 | 4 |

*D - divided, TB - twin bridge

**See Tables A.16 and A.17 in Appendix A

TABLE A.7

SOURCES OF BRIDGE RAIL ACCIDENT DATA

| Source | Description |
|---|---|
| 1. Five State File (Ref. 22) | This data base includes reported accidents on 11,880 bridges (including 500 ft from each end of bridge). The data are from years 1975-1977 on selected bridges in Arizona, Michigan, Montana, Texas, and Washington |
| 2. Texas Accident File (Ref. 23) | For this study, the Texas file for two years (1978 and 1979) was interrogated for vehicle behavior and occupant injury for impacts on bridge rails and ends. |
| 3. Washington File (Ref. 24) | For this study, the Washington file was interrogated for bridge rail and end accidents for five years (1974-1978). |
| 4. 1979 FARS File (Ref. 25) | This fatal accident reporting system lists bridges (vehicle passing over) as first harmful event and most harmful event in 95% of all accidents in the country with fatalities reported. |

A.13

TABLE A.8

SUMMARY OF ESTIMATED BRIDGE MILEAGE IN U.S.*

| Category | No. of Bridges | Length, Miles |
|---|---|---|
| Fed. Aid System | 261,479 | 9,015 |
| Off-System | 315,789 | 4,356 |
| TOTAL, U.S. | 577,268 | 13,371 |
| Selected States | | |
| Texas | | |
| Fed. Aid | 23,764 | 803 |
| Off-System | 9,441 | 130 |
| Total, Texas | 33,205 | 933 |
| Washington | | |
| Fed. Aid | 4,013 | 203 |
| Off-System | 3,032 | 46 |
| Total, Washington | 7,045 | 249 |

*Bridge Inventory File, FHWA Washington, D.C., Office of Engineering
All bridges ≥ 20 ft length

A.14

striking a bridge end. Much of the current adverse accident experience of bridge ends is attributed to the poor treatment of transitioning from either a no approach guardrail or a flexible approach guardrail to a rigid bridge rail or an abutment. While the approach guardrail/bridge rail transition is considered extermely important, it is a consideration after a bridge railing level of service has been determined and does not affect the service level selection. Bridge and accident data are presented in this discussion because these accidents have been, and in most cases still are, smeared-in with bridge railing data presently available.

A.1.2.2 Consquences of Bridge Accidents. Tables 4, A.9 and A.10 give data on the consequences of bridge accidents. The very descriptive Washington and Texas data (Table 4) provide insight into what happened as a result of these single vehicle collisions (approximately 90% of bridge-related accidents are single vehicle accidents) both in terms of vehicle containment/redirection and occupant injury profile. The five-state file and FARS file are less specific in this regard. From the Texas and Washington files, vehicle behavior can be categorized as vehicle retained on bridge, vehicle went through rail, and vehicle went over rail. It can be generally inferred from the Texas and Washington data that the presence of bridge railing improves the safety of bridges.

From the Texas file (Table 4), there were a total of 5731 bridge railing accidents where the vehicle was contained/redirected. Of this total only 70 (1%) fatal and 387 (7%) incapacitating injury accidents were recorded. During the same time period, 440 vehicles went through or over bridge railings resulting in 61 fatal (14%) and 96 (22%) incapacitating injury accidents. Thus the fatal accident rate for vehicles going over

A.15

TABLE A.9

BRIDGE RAIL ACCIDENTS*ONLY, FIVE STATE FILE

| Functional Classification | Number of Bridges | Number of Accidents per Year** | Number of Accidents per Million Vehicles** | Number of Accidents per Year per Mile** | Accidents 10 mi-10 yr/ADT** |
|---|---|---|---|---|---|
| Urban Interstate | 323 | 0.288 | 0.026 | 6.238 | 0.021 |
| Major Arterial | 622 | 0.151 | 0.030 | 3.353 | 0.024 |
| Minor Arterial | 206 | 0.092 | 0.047 | 2.651 | 0.049 |
| Collector | 26 | 0.063 | 0.057 | -- | 0.090 |
| Rural Interstate | 839 | 0.135 | 0.045 | 3.267 | 0.040 |
| Major Arterial | 2,109 | 0.086 | 0.061 | 2.271 | 0.059 |
| Minor Arterial | 2,246 | 0.047 | 0.065 | 1.429 | 0.072 |
| Collector | 5,509 | 0.028 | 0.093 | 0.998 | 0.121 |
| Total | 11,880 | 0.064 | 0.048 | 1.931 | 0.053 |

*Reported accidents; unreported collisions may range from 2 to 8 times the reported accidents.
** Per bridge.

A.16

TABLE A.10

1979 FARS DATA, PARTIAL LISTING OF FATAL ACCIDENTS

First Harmful Event

| Most Harmful Event | (CO-L/FIX OBJ) CURB OR WALL | (CO-L/FIX OBJ) DIVIDER | (CO-L/FIX OBJ) EMBANKMENT | (CO-L/FIX OBJ) FENCE | (CO-L/FIX OBJ) GUARDRAIL | (CO-L/FIX OBJ) LIGHT SUPPORT | (CO-L/FIX OBJ) SIGN POST | (CO-L/FIX OBJ) TREE/SHRUBBERY | (CO-L/FIX OBJ) UTILITY POLE | (CO-L/FIX OBJ) OTHER POLES/SUPPORT | (CO-L/FIX OBJ) IMPACT ATTENUATOR | (CO-L/FIX OBJ) OTHER | (CO-L/FIX OBJ) BRIDGE OR OVERPASS (PASSING UNDER) | (CO-L/FIX OBJ) BRIDGE OR OVERPASS (PASSING OVER) | UNKNOWN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ACCIDENT TOTAL............. | 1,002 | 163 | 1,343 | 445 | 1,464 | 152 | 385 | 2,940 | 1,645 | 317 | 19 | 719 | 237 | $\boxed{616}$ | 71 |
| MOST HARMFUL EVENT | | | | | | | | | | | | | | | |
| DID NOT EXIST..... | 14 | 1 | 1 | 5 | 6 | 2 | 3 | 9 | 6 | 8 | - | 16 | 1 | 4 | 32 |
| (NON-COL) OVERTURN | 244 | 40 | 583 | 158 | 464 | 13 | 134 | 259 | 173 | 85 | 4 | 207 | 18 | 126 | 2 |
| (NON-COL) FIRE/EXPLOSION. | 16 | - | 20 | 3 | 39 | 1 | 2 | 64 | 31 | 6 | 1 | 10 | 3 | 21 | - |
| (NON-COL) IMMERSION....... | 16 | 1 | 38 | 10 | 57 | - | 6 | 16 | 7 | 2 | - | 15 | 7 | 33 | 1 |
| (NON-COL) GAS INHALATION..... | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| (NON-COL) FELL FROM VEH........ | 13 | 2 | 13 | 3 | 14 | - | 3 | 6 | 4 | 2 | - | 4 | 1 | 1 | 1 |
| (NON-COL) INJURED IN VEH.......... | - | - | - | 1 | 1 | - | - | 1 | 1 | - | - | 2 | - | - | - |
| (NON-COL) OTHER... | - | - | 1 | 1 | 2 | - | - | - | 1 | 1 | - | 1 | - | 2 | - |
| (COL/WITH) PEDESTRIAN..... | 7 | 1 | 1 | 5 | 5 | 2 | 3 | 6 | 4 | 6 | - | 13 | - | 3 | - |
| (COL/WITH) PEDALCYCLE..... | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| (COL/WITH) RAILWAY TRAIN.......... | 1 | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| (COL/WITH) ANIMAL. | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| (COL/WITH) MOTOR VEH TRANSPORT.. | 64 | 30 | 13 | 3 | 65 | - | 6 | 13 | 10 | 9 | 2 | 21 | 4 | 25 | - |
| (COL/WITH) MOTOR VEH IN OTHER ROADWAY........ | 13 | 15 | 3 | 1 | 14 | - | 2 | - | - | - | - | 1 | - | 2 | - |

TABLE A.10 (Cont'd)

| Most Harmful Event | First Harmful Event: (COL/FIX OBJ) CURB OR WALL | (COL/FIX OBJ) DIVIDER | (COL/FIX OBJ) EMBANKMENT | (COL/FIX OBJ) FENCE | (COL/FIX OBJ) GUARDRAIL | (COL/FIX OBJ) LIGHT SUPPORT | (COL/FIX OBJ) SIGN POST | (COL/FIX OBJ) TREE/SHRUBBERY | (COL/FIX OBJ) UTILITY POLE | (COL/FIX OBJ) OTHER POLES/SUPPORT | (COL/FIX OBJ) IMPACT ATTENUATOR | (COL/FIX OBJ) OTHER | (COL/FIX OBJ) BRIDGE OR OVERPASS (PASSING UNDER) | (COL/FIX OBJ) BRIDGE OR OVERPASS (PASSING OVER) | UNKNOWN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ACCIDENT MOST HARMFUL EVENT | | | | | | | | | | | | | | | |
| (COL/FIX OBJ) TREE/SHRUBBERY | 83 | 10 | 63 | 87 | 41 | 6 | 57 | 2,514 | 72 | 21 | - | 50 | 2 | 7 | 1 |
| (COL/FIX OBJ) UTILITY POLE | 113 | 4 | 19 | 26 | 23 | 1 | 20 | 22 | 1,310 | 10 | - | 25 | - | 2 | - |
| (COL/FIX OBJ) OTHER POLES/SUPPORT | 17 | - | 2 | 1 | 6 | - | 1 | 2 | 3 | 150 | - | 1 | - | - | 1 |
| (COL/FIX OBJ) IMPACT ATTENUATOR | - | - | - | - | 2 | - | - | - | - | - | 9 | - | 2 | - | - |
| (COL/FIX OBJ) OTHER | 23 | 3 | 8 | 6 | 8 | - | 3 | 2 | 4 | 7 | - | 316 | 1 | 1 | 1 |
| (COL/FIX OBJ) BRIDGE OR OVERPASS (PASSING UNDER) | 7 | 2 | - | 3 | 21 | 3 | 8 | - | - | 1 | 1 | 1 | 198 | - | - |
| (COL/FIX OBJ) BRIDGE OR OVERPASS (PASSING OVER) | 4 | - | 1 | 1 | 38 | - | 10 | 1 | - | 1 | - | 3 | 1 | $\boxed{401}$ | 1 |
| UNKNOWN | 4 | - | 8 | 2 | 2 | - | - | 2 | 3 | 4 | - | 18 | - | - | 59 |

or through a bridge railing was 14 times that for retained vehicles. Similarly, the disabling injury rate was also substantially lower for retained accidents.

From the Washington data, the fatal accident rate for vehicles going through or over the railing was seven times that for the retained vehicles. Similarly, incapacitating injury rates were lower for the retained vehicle.

A.1.2.3 Benefits of Bridge Railing. The placement of bridge railing is justified by a marked improvement in the safety of the bridge site. As a measure of this improvement, the reduction in accident costs is calculated as the benefit.

a. Accident costs. In order to quantify bridge railing benefits, it is necessary to assign values to accident costs. There is currently a large number of different accident cost values used by various highway agencies (see Table A.11) with no clear consensus. For the purposes of this project, the National Safety Council (NSC) values are used. One of the advantages of using the NSC values is the injury definition which corresponds to the bridge rail accident profiles of Table 4. The average cost for "retained" and "through or over" accidents can be computed using the NSC injury costs combined with the injury profile of Table 4, as outlined in Table 5.

b. Benefit computation. By assuming that the benefit of a bridge railing can be expressed by the difference between "penetration" (through or over) and "retained" costs, a benefit value can be obtained by subtracting the retained cost from the penetration cost. This approach is considered to be conservative since the "retained" cost is based on reported accidents only; the average "retained" cost would be



TABLE A.11

REPRESENTATIVE ACCIDENT COSTS PER REPORTED ACCIDENT

| Source | Fatal Accidents (dollars) | Injury Accidents (dollars) | Property Damage Only (dollars) | Dollar Value, Year |
|---|---|---|---|---|
| 1. National Safety Council (Ref. 5) | 135,000 | 11,900*<br>3,500<br>880 | 800 | 1977 |
| 2. CALTRANS - rural<br>(Ref. 26) - urban | 160,000<br>130,000 | 5,300<br>4,100 | 1,600<br>1,200 | 1978 |
| 3. AASHTO Barrier Guide (Ref. 20) | 200,000 | 10,000 | 700 | 1976 |
| 4. NHTSA (Ref. 27) | 287,175 | 3,185 | 520 | 1975 |

*$11,900 incapacitating; $3,500 nonincapacitating; $880 possible injury

Note: Each source has its own dollar value; i.e., the costs are represented by the dollar value at time report was compiled.



reduced by the undetermined, but presumed low cost of driveaway (nonreported) accidents. The benefits of bridge railing are thus computed as shown in Table A.11 by assuming a 20-year life for the railing. No sophisticated economic factors are included, although it is recognized that various agencies could apply their own economic methodology to these costs.

A.1.s Impact Probability

Before a bridge railing impact occurs, two sequential events occur: (1) an errant vehicle leaves the pavement (i.e., encroachment) and (2) the vehicle traverses the lateral distance from the pavement edge to the barrier. Impact probability can be calculated from encroachment rates and the barrier offset distance.

A.1.3.1 Encroachment Rate. Encroachment rate data used in previous investigations were considered initially for this project; however, accident rates and statistics for bridges and typical roadways vary significantly. Therefore it was decided to use bridge rail accident statistics to predict bridge railing encroachment values.

Accident rates for bridges from a 5-state study are given in Table A.12. These rates by themselves are insufficient for benefit to cost analysis because the total number of collisions is needed, including both reported and nonreported accidents. The ratio of nonreported to total collisions will vary with the dynamic performance capability of the existing bridge rail and with site conditions that affect the impact severity (i.e., bridge width, operating speed, shoulder width, etc.).

As an upper bounds for the ratio K of total collisions to reported accidents, a Pennsylvania study (28) on a flexible median barrier revealed a K value of 8; as a lower bounds, there has to be at least



one collision for each reported accident, or K of 1. The better performing bridge rails on the Interstate System in urban areas should have a K of about 8 and as the functional classification changes from Interstate, to major arterial, to minor arterial, and finally to collector, intuitively one would reason that the age of the bridge and systems is greater and the technology more obsolete. Accordingly, by assuming K for the Interstate System is 8 and calculating a ratio of accident rates in each column of Table A.12, one can determine a K for each of the functional highway classifications; these are:

| Highway Classification | K |
|---|---|
| Urban | |
| Interstate | 8.0 |
| Major arterial | 7.0 |
| Minor arterial | 3.5 |
| Collector | 1.4 |
| Rural | |
| Interstate | 4.1 |
| Major arterial | 2.8 |
| Minor arterial | 2.3 |
| Collector | 1.4 |

Then using the equation

$$E_R \left( \frac{l_i}{K} \right) = \text{Accident Rate} \qquad \text{(A.1)}$$

Where $E_R$ is encroachment rate in numbers of encroachment per mile per ADT, $l_i$ is reduction factor due to shoulder width and K is the ratio of total collisions to reported accidents, the effective encroachment rate $E_R$ can be determined for each bridge narrowness stratum. The following observations are made:

- Encroachment rates decrease as the bridge width increases, with increase in number of lanes and with increase in lane width
- A higher percentage of rural accidents is reported; thus the rural accident may be a more severe collision or it may be that the less frequent rural accidents are more often reported than in the congested urban areas.

# TABLE A.12

## ACCIDENT RATE* SUMMARY - FIVE STATE FILE

| Bridge Narrowness Strata | | | | | Functional Classification | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Urban | | | | Rural | | | |
| | | No. Lanes | Bridge Width | Shoulder Reduction | Inter-State | Major Arterial | Minor Arterial | Collector | Inter-State | Major Arterial | Minor Arterial | Collector |
| Single Structures | Undivided | 1 | <18' | - | - | - | - | - | - | - | - | 0.333 |
| | | | >18' | - | - | - | - | - | - | - | - | - |
| | | 2 | <18', <Approach | - | - | - | - | - | - | | 0.268 | 0.549 |
| | | | <18', >Approach | - | - | - | - | - | - | - | - | - |
| | | | 18'-20', <Approach | - | - | | | | - | 0.167 | 0.204 | 0.343 |
| | | | 18'-20', >Approach | - | - | - | - | - | - | | - | 0.322 |
| | | | 20'-22', <Approach | - | - | - | - | - | - | 0.120 | 0.146 | 0.245 |
| | | | 20'-22', >Approach | - | - | - | - | - | - | - | - | 0.349 |
| | | | 22'-24', <Approach | - | - | 0.031 | .063 | 0.155 | - | 0.076 | 0.092 | 0.155 |
| | | | 22'-24', >Approach | - | - | 0.029 | .060 | 0.147 | - | 0.072 | 0.088 | 0.147 |
| | | | >24' | >50% | - | 0.020 | .040 | 0.100 | - | 0.049 | 0.059 | 0.100 |
| | | | >24' | 1-50% | - | 0.013 | .028 | 0.068 | - | 0.033 | 0.040 | 0.068 |
| | | | >24' | None | - | 0.014 | .028 | 0.070 | - | 0.034 | 0.042 | 0.070 |
| | | 4 | N/A | >50% | - | - | - | - | - | - | - | - |
| | | | | 1-50% | - | - | - | - | - | - | - | - |
| | | | | None | - | 0.007 | 0.014 | 0.034 | - | 0.016 | 0.020 | 0.034 |
| | Divided | 4 | N/A | >50% | 0.012 | 0.014 | - | - | 0.023 | 0.034 | 0.042 | - |
| | | | | 1-50% | 0.016 | 0.019 | - | - | 0.031 | 0.046 | 0.056 | - |
| | | | | None | 0.012 | 0.013 | - | - | 0.022 | 0.033 | 0 | - |
| | | Other | N/A | >50% | 0.007 | 0.008 | - | - | - | - | | - |
| | | | | 1-50% | - | - | - | - | - | - | - | - |
| | | | | None | 0.004 | 0.004 | - | - | - | - | - | - |
| Twin Structures | Divided | 2 | <24' | - | - | 0.033 | - | - | - | 0.080 | 0.098 | - |
| | | | >24' | >50% | 0.022 | 0.025 | - | - | 0.041 | 0.061 | 0.074 | - |
| | | | >24' | 1-50% | 0.017 | 0.019 | - | - | 0.032 | 0.048 | 0.058 | - |
| | | | >24' | None | 0.017 | 0.020 | - | - | 0.033 | 0.048 | 0.059 | - |
| | | Other | N/A | >50% | 0.022 | - | - | - | - | - | - | - |
| | | | | 1-50% | 0.021 | - | - | - | - | - | - | - |
| | | | | None | 0.009 | 0.010 | - | - | 0.017 | | - | - |
| | | | TOTAL | | | | | | | | | |

*Bridge rail accidents/10 mi/10 yr - ADT

The encroachment rate values thus determined are given in Table A.13. Also shown in Table A.13 are the impacts predicted by the collision model (see next section) for this encroachment rate.

a. Number of lanes. The number of lanes and the distribution of traffic among lanes affect encroachment frequency. Motorists encroaching from an inside lane have greater lateral distance to recover, but also have a potential for striking the barrier at a greater angle. The MSLA accommodates multilane highways with any specified split of traffic in each lane. A description of this effort is presented in Section A.1.4.3.

b. Direction of traffic. From a recent study by Lampela(29), it was shown that of all fatal accidents on one side of the highway, 0.4 of the vehicles came from the opposing lane and 0.6 of the vehicles came from the adjacent lane of the two-lane bidirectional highway. For a four-lane divided highway, the origin of lane for encroaching vehicle is unknown; however, using the rational technique presented in Section A.1.4.3, 0.3 of encroachments to the right are vehicles originating from the inside lane and 0.7 come from the adjacent lane. Apparently the frequency of encroachments to the right or left side of the pavement is about the same regardless of whether the highway is two-lane bidirectional or four-lane divided.

A.1.3.2 Lateral Distance Traveled. The probability of an encroachment becoming an impact is affected by the distance from the pavement edge to the barrier. In general, the greater the offset distance, the greater the opportunity for the errant motorist to regain control of the vehicle and avoid barrier collision. (Although the number of impacts decreases with increasing offset distance, the maximum possible severity of an impact in-



creases because the impact angle can be larger; this will be discussed in a later section.)

The percentage of encroachments that result in barrier impacts is determined from the relationship(15) shown in Figure A.1, which is developed from Figure A.2. Entering the figure with offset distance, the percentage (P) of vehicles that recover without striking the barrier is read, and the percentage striking the barrier is (100-P).

A refinement used in the MSLA is the estimate of traffic lane origin for encroachments and barrier impacts. For this approach, offset distance is measured from the lane divider or pavement edge, whichever the vehicle crosses first, to the barrier. Hence, vehicles encroaching from an inside lane or from opposing lanes will have a greater lateral distance in which to recover; therefore fewer of these vehicles will impact the barrier. This refinement affects primarily the distribution of probable impact angles.

Validation of this refinement is presented in Section A.1.4.3.

A.1.4 Collision Conditions

Collision conditions are the vehicle size, impact speed, and impact angle. Given the traffic characteristics and highway geometrics, the MSLA determines the probability of collision conditions for all predicted impacts. Development of data for the part of the MSLA is presented in this section.

A.1.4.1 Vehicle Size Distribution. The Federal Highway Administration Office of Highway Planning compiles vehicle classification count data submitted by the states by the roadway system described in Table A.14. Vehicle distribution for the various highway systems is



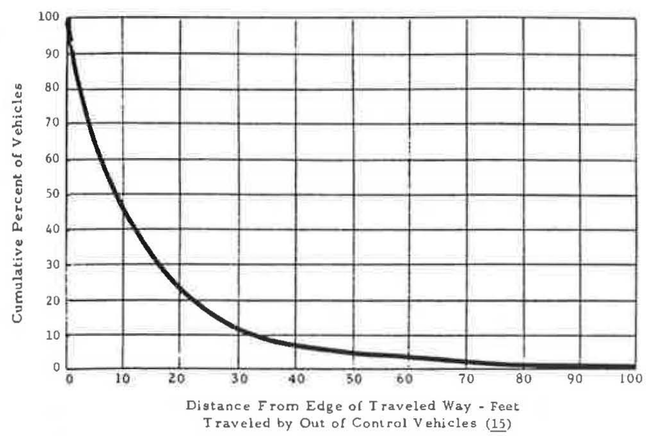



FIGURE A.1 DISTRIBUTION OF LATERAL DISPLACEMENTS



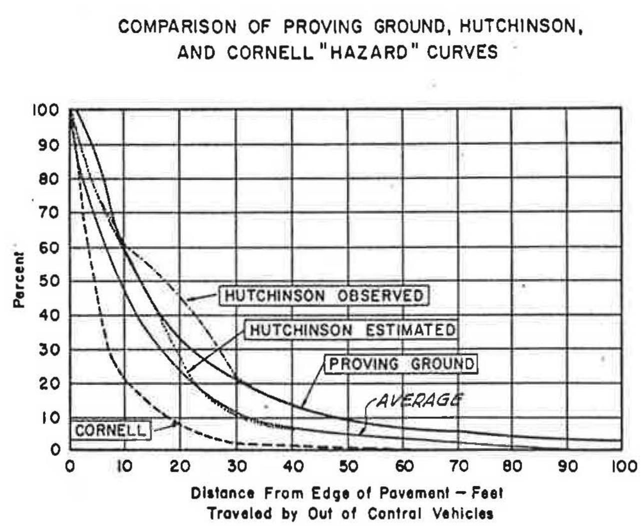



FIGURE A.2 DISTRIBUTION OF LATERAL DISPLACEMENTS (15)

# TABLE A.13

## FUNCTIONAL CLASSIFICATION ENCROACHMENT AND IMPACT RATES

| FUNCTIONAL CLASSIFICATION | ADT | DESIGN SPEED MPH | LANE WIDTH FT | NO. OF LANES* | TRAFFIC MIX | SHOULDER WIDTH FT | ENCROACHMENT RATE, NO. PER 10 MI-10 YR-ADT | IMPACT RATE, NO. PER 10 MI-10 YR-ADT |
|---|---|---|---|---|---|---|---|---|
| 1. Rural Arterials | | | | | | | | |
| Principal Arterial | | | 12 | 4D | 1 | 10-12 | 0.050 | 0.023 |
| Interstate } Freeways | | > 60 | 12 | 2D, TB | 1 | 10-12 | 0.032 | 0.014 |
| Major Arterial } Freeways | | | 12 | 2D, TB | 1 | 10-12 | 0.032 | 0.028 |
| Major Arterial | | < 60 | 11-12 | 2 | 2 | 10 | 0.072 | 0.033 |
| | | | 11-12 | 2 | 2 | 4 | 0.072 | 0.050 |
| Minor Arterial | | < 60 | 11-12 | 2 | 4 | 8 | 0.072 | 0.037 |
| | | | 11-12 | 2 | 4 | 4 | 0.072 | 0.050 |
| 2. Urban Arterials | | | | | | | | |
| Principal Arterial | | | 12 | 4D | 4 | 10 | 0.050 | 0.023 |
| Interstate } Freeways | | > 60 | 12 | 2D, TB | 4 | 10 | 0.032 | 0.014 |
| Major Arterial } Freeways | | | 12 | 6D | 4 | 10 | 0.011 | 0.005 |
| | | | 12 | 3D, TB | 4 | 10 | 0.019 | 0.008 |
| Major Arterial | | < 60 | 12 | 2 | 4 | 10 | 0.072 | 0.033 |
| | | | 12 | 2 | 4 | 4 | 0.072 | 0.050 |
| | | | 12 | 4 | 4 | 10 | 0.051 | 0.023 |
| Minor Arterial | | < 60 | 12 | 2 | 4 | 8 | 0.072 | 0.037 |
| | | | 12 | 2 | 4 | 4 | 0.072 | 0.050 |
| 3. Rural Collectors & Roads | | | | | | | | |
| Collector 1 | 250-400 | 20-30 | 10 | 2 | 5 | 2 | 0.102 | 0.083 |
| 2 | 400-750 | | 10 | | | 3 | 0.072 | 0.054 |
| 3 | 750-2000 | | 11 | | | 3 | 0.072 | 0.054 |
| 4 | 2000-4000 | | 11 | | | 4 | 0.072 | 0.050 |
| 5 | > 4000 | | 12 | | | 8 | 0.072 | 0.037 |
| 6 | 250-400 | 40 | 10 | | | 2 | 0.102 | 0.083 |
| 7 | 400-750 | | 11 | | | 3 | 0.072 | 0.054 |
| 8 | 750-2000 | | 11 | | | 3 | 0.072 | 0.054 |
| 9 | 2000-4000 | | 11 | | | 4 | 0.072 | 0.050 |
| 10 | > 4000 | | 12 | | | 8 | 0.072 | 0.037 |
| 11 | 250-400 | | 10 | | | 2 | 0.072 | 0.059 |
| 12 | 400-750 | | 11 | | | 3 | 0.072 | 0.054 |
| 13 | 750-2000 | | 11 | | | 3 | 0.072 | 0.050 |
| 14 | 2000-4000 | | 12 | | | 4 | 0.072 | 0.032 |
| 15 | > 4000 | | 12 | 2 | 5 | 8 | 0.072 | 0.050 |
| Local Roads 1 | < 50 | 20-30 | 8 | 2 | 5 | 2 | 0.225 | 0.199 |
| 2 | 50-250 | | 9 | | | 2 | 0.244 | 0.195 |
| 3 | 250-400 | | 10 | | | 2 | 0.102 | 0.082 |
| 4 | > 400 | | 10 | | | 4 | 0.072 | 0.050 |
| 5 | < 50 | 40-50 | 10 | | | 2 | 0.102 | 0.082 |
| 6 | 50-250 | | 10 | | | 2 | 0.102 | 0.082 |
| 7 | 250-400 | | 10 | | | 2 | 0.102 | 0.082 |
| 8 | > 400 | | 11 | 2 | 5 | 4 | 0.072 | 0.082 |
| 4. Urban Collectors & Streets | | | | | | | | |
| Collector 1 | 250-400 | 20-30 | 10 | 2 | 3 | 2 | 0.102 | 0.083 |
| 2 | 400-750 | | 10 | | | 3 | 0.072 | 0.054 |
| 3 | 750-2000 | | 11 | | | 3 | 0.072 | 0.054 |
| 4 | 2000-4000 | | 11 | | | 4 | 0.072 | 0.050 |
| 5 | > 4000 | | 12 | | | 8 | 0.072 | 0.037 |
| 6 | 250-400 | 40 | 10 | | | 2 | 0.102 | 0.083 |
| 7 | 400-750 | | 11 | | | 3 | 0.072 | 0.054 |
| 8 | 750-2000 | | 11 | | | 3 | 0.072 | 0.054 |
| 9 | 2000-4000 | | 11 | | | 4 | 0.072 | 0.050 |
| 10 | > 4000 | | 12 | | | 8 | 0.072 | 0.037 |
| 11 | 250-400 | | 10 | | | 2 | 0.072 | 0.059 |
| 12 | 400-750 | | 11 | | | 3 | 0.072 | 0.054 |
| 13 | 750-2000 | | 11 | | | 3 | 0.072 | 0.050 |
| 14 | 2000-4000 | | 12 | | | 4 | 0.072 | 0.032 |
| 15 | > 4000 | | 12 | 2 | 3 | 8 | 0.072 | 0.050 |
| Local Roads 1 | < 50 | 20-30 | 8 | 2 | 3 | 2 | 0.225 | 0.199 |
| 2 | 50-250 | | 9 | | | 2 | 0.244 | 0.195 |
| 3 | 250-400 | | 10 | | | 2 | 0.102 | 0.082 |
| 4 | > 400 | | 10 | | | 4 | 0.072 | 0.050 |
| 5 | < 50 | 40-50 | 10 | | | 2 | 0.102 | 0.082 |
| 6 | 50-250 | | 10 | | | 2 | 0.102 | 0.082 |
| 7 | 250-400 | | 10 | | | 2 | 0.102 | 0.082 |
| 8 | > 400 | | 11 | 2 | 3 | 4 | 0.072 | 0.082 |

TABLE A.14

HIGHWAY SYSTEM DEFINITIONS

| | | |
|---|---|---|
| Group A: | FA-I/R | - Federal-Aid Interstate Rural, including the Interstate traveled-way |
| | FA-I/U | - Federal-Aid Interstate Urban, including the Interstate traveled-way |
| | FA-U | - Federal-Aid Urban |
| | P/R | - Federal-Aid Primary Rural |
| | P/U | - Federal-Aid Primary Urban |
| | S/R | - Secondary Rural roads, including Federal-Aid state and local jurisdiction and other state and local roads |
| | S/U | - Secondary Urban roads, including Federal-Aid state and local jurisdiction and other state and local roads |
| Group B: | M/R | - Main Rural roads, including Federal-Aid Interstate rural, Federal-Aid primary rural, Federal-Aid secondary rural under state jurisdiction, and non-Federal-Aid rural state highways |
| | L/R | - Local Rural roads, including Federal-Aid secondary rural under local jurisdiction, and local rural streets |
| | U | - All Federal-Aid and non-Federal-Aid Urban roads |

Note: Group A and Group B each contain the same information, but distributed into different categories.



categorized by considering vehicles as given in Table A.15. A nationwide summary of the classification count data compiled for 1978 was obtained from the FHWA for use in this project. A summary of these data is given in Table A.16. These data were analyzed and reduced to form five different traffic mixes as given in Table A.17.

Sales and registration data found in the literature were used to determine weight distribution for the vehicles identified by the classification count. As shown in Table A.18, U.S. sales and registration data compare quite closely based on last 8-year and last 3-year figures. Accordingly, sales and registration data were used to determine vehicle distributions. Retail car, bus, and truck sales data are given in Table A.19. The truck and bus data indicate a shift from light to heavier trucks in the less than 10,000-lb (4500-kg) range. The 1979 passenger car data indicate a trend that sees a shift from regular to subcompact vehicles. Table A.19 gives adequate data for truck and bus weight distribution; the distribution of passenger cars is given only by class. Passenger car registration data obtained from Texas, as given in Table A.20, provide insight into this distribution. The numbers grouped by the brackets compare closely to the grouping given in Table A.19. On the basis of these data, the car class percentages shown for 1979 in Table A.19 are applied to weight distribution shown at the bottom of Table A.20 to provide passenger car weight distribution. The smaller percentages of trucks and buses are combined, as shown by brackets, to provide these bus and truck weight distribution values of 5,000, 8,000, 23,000 and 40,000 lb (2,300, 3,600, 10,400 and 18,100 kg).

On the basis of the traffic mix data of Table A.17 and the weight distribution data of Tables A.19 and A.20, vehicle weight distribution data are determined as given in Table A.21.



TABLE A.15

GUIDE TO CLASSIFICATION SUMMARY TABLE

| | Column Heading | Definition |
|---|---|---|
| Group I | 071000 | Standard and Compact Automobiles, In-State |
| | 061000 | Small Automobiles, In-State |
| | 072000 | Standard and Compact Automobiles, Out-of-State |
| | 062000 | Small Automobiles, Out-of-State |
| | SB-TOT | Subtotal of All Passenger Cars |
| | 030000 | Motorcycles and Motorscooters |
| | 150000 | Commercial Buses |
| | 180000 | Non-revenue Buses |
| | SB-TOT | Subtotal of Other Passenger Vehicles |
| | SB-TOT | Subtotal of All Passenger Vehicles |
| Group II | 200000 | Panel and Pickup Trucks |
| | 210000 | Other Two-axle, Four-tire Trucks |
| | 220000 | Two-axle, Six-tire Trucks |
| | 230000 | Three-axle Trucks |
| | 240000+ | Four or More Axle Trucks |
| | SB-TOT | Subtotal of All Single-unit Trucks |
| | 321000 | Two-axle Tractor, One-axle Trailer |
| | 322000 | Two-axle Tractor, Two-axle Trailer |
| | 323000 | Two-axle Tractor, Three-axle Trailer |
| | 331000 | Three-axle Tractor, One-axle Trailer |



TABLE A.15 (Cont'd)

| | | |
|---|---|---|
| Group III | 332000 | Three-axle Tractor, Two-axle Trailer |
| | 333000 | Three-axle Tractor, Three-axle Trailer |
| | 521100 | Two-axle Tractor, One-axle Trailer, One-axle Trailer |
| | 521200 | Two-axle Tractor, One-axle Trailer, Two-axle Trailer |
| | 522200 | Two-axle Tractor, Two-axle Trailer, Two-axle Trailer |
| | 531200 | Three-axle Tractor, One-axle Trailer, Two-axle Trailer |
| | 532200 | Three-axle Tractor, Two-axle Trailer, Two-axle Trailer |
| | OTHERS | Other Tractor/Trailer Combinations |
| | SB-TOT | Subtotal of All Tractor/Trailer Combinations |
| | 421000 | Two-axle Truck, One-axle Trailer |
| Group IV | 422000 | Two-axle Truck, Two-axle Trailer |
| | 423000 | Two-axle Truck, Three-axle Trailer |
| | 431000 | Three-axle Truck, One-axle Trailer |
| | 432000 | Three-axle Truck, Two-axle Trailer |
| | 433000 | Three-axle Truck, Three-axle Trailer |
| | OTHERS | Other Truck/Trailer Combinations |
| | SB-TOT | Subtotal of All Truck/Trailer Combinations |
| | SB-TOT | Subtotal of All Combinations |
| | SB-TOT | Subtotal of All Trucks |
| | GR-TOT | Grand Total of All Vehicles |

Note: Average counts are rounded down to the nearest whole number.

TABLE A.16

CLASSIFICATION SUMMARY TABLE

| | | | 1978 | | | | |
|---|---|---|---|---|---|---|---|
| Highway System Definitions | | % Passenger Cars | % Buses | % Panel & Pickups | % 3 Axle Tractor 2 Axle Trailer | % Sub Total All Trucks | * |
| Group A | FA-I/R - Federal-Aid Interstate Rural, including the Interstate traveled-way. | 67 | < .5 | 12 | 12 | 32 | 1 |
| | FA-I/U - Federal-Aid Interstate Urban, including the Interstate traveled-way. | 77 | < .5 | 8 | 7 | 23 | 4 |
| | P/R - Federal-Aid primary rural. | 70 | < .5 | 17 | 6 | 29 | 2 |
| | P/U - Federal-Aid primary urban. | 78 | < .5 | 13 | 2 | 21 | 4 |
| | S/R - Secondary rural roads, including Federal-Aid State and local jurisdiction and other State and local roads. | 79 | < .5 | 12 | 3 | 20 | 5 |
| | S/U - Secondary urban roads, including Federal-Aid State and local jurisdiction and other State and local roads. | 74 | < .5 | 14 | 2 | 25 | 3 |
| Group B | M/R - Main Rural Roads, including Federal-Aid Interstate Rural, Federal-Aid primary rural, Federal-Aid secondary rural under State jurisdiction, and non-Federal-Aid rural State highways. | 69 | < .5 | 14 | 10 | 31 | 2 |
| | L/R - Local Rural Roads, including Federal-Aid secondary rural under local jurisdiction, and local rural streets. | 84 | < .5 | 9 | 1 | 15 | 5 |
| | U - All Federal-Aid and non-Federal-Aid urban roads. | 77 | < .5 | 12 | 3 | 22 | 4 |

Note: Group A and Group B each contain the same information, but distributed into different categories.

*Traffic mix number, see Table A.17.

TABLE A.17

TRAFFIC MIX BASED ON CLASSIFICATION

| Mix No. | |
|---|---|
| 1 | • 68% passenger cars, 13% pickups & panels, 19% other trucks |
| 2 | • 70% passenger cars, 17% pickups & panels, 13% other trucks |
| 3 | • 74% passenger cars, 14% pickups & panels, 12% other trucks |
| 4 | • 78% passenger cars, 12% pickups & panels, 10% other trucks |
| 5 | • 84% passenger cars, 9% pickups & panels, 7% other trucks |

TABLE A.18

COMPARISON OF SALES AND REGISTRATIONS (Ref.21)

| Sales | Last 8 Years (thousands) | % Last 8 Years | Last 3 Years (thousands) | % Last 3 Years |
|---|---|---|---|---|
| Passenger cars | 83,174 | 77 | 33,168 | 75 |
| Trucks & buses | 24,369 | 23 | 11,265 | 25 |
| Total | 107,543 | 100 | 44,433 | 100 |
| **Registrations** | | | | |
| Passenger cars | 769,449 | 79 | 307,538 | 77 |
| Trucks & buses | 207,240 | 21 | 91,370 | 23 |
| Total | 976,689 | 100 | 398,908 | 100 |



TABLE A.19

VEHICLE SALES FIGURES (Ref. 30)

| Year: | 1972 | 1973 | 1974 | 1975 | 1976 | 1977 | 1978 | 1979 | 8 Year Total | % Last 8 Years | % Last 3 Years | % 1979 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Vehicle Class** | U.S. New Car Retail Sales by Class (thousands) | | | | | | | | | | | |
| 1. Subcompact Total Import | 2516 | 2836 | 2211 | 2290 | 2497 | 3028 | 2991 | 4097 | 22,466 | 28 | 31 | 38 |
| 2. Sports Car Compact Intermediate | 3971 | 4510 | 4154 | 4187 | 5649 | 5365 | 5590 | 4279 | 33,734 | 42 | 46 | 40 |
| 3. Standard | 3486 | 3360 | 1947 | 1552 | 1899 | 2277 | 2083 | 2194 | 18,798 | 24 | 20 | 21 |
| 4. Luxury | 977 | 733 | 561 | 614 | 385 | 459 | 635 | 100 | 4,464 | 6 | 4 | 1 |
| **GVW (lb)** | U.S. Truck and Bus Sales (thousands) | | | | | | | | | | | |
| 6000 and less | 1498 | 1754 | 1467 | 1101 | 1318 | 1306 | 1334 | 1271 | 11,049 | 45 | 36 | |
| 6000 - 10,000 | 599 | 758 | 696 | 952 | 1401 | 1803 | 2139 | 1574 | 9,922 | 41 | 51 | |
| 10,000 - 16,000 | 65 | 53 | 24 | 24 | 43 | 40 | 82 | 21 | 349 | 1 | 1 | |
| 16,000 - 19,500 | 29 | 16 | 14 | 9 | 9 | 5 | 5 | 3 | 90 | 0 | 0 | 7 |
| 19,500 - 26,000 | 182 | 236 | 207 | 159 | 181 | 192 | 179 | 173 | 1,509 | 6 | 5 | |
| 26,000 - 33,000 | 35 | 37 | 31 | 23 | 24 | 29 | 41 | 52 | 272 | 1 | 1 | 6 |
| Over 33,000 | 126 | 155 | 145 | 83 | 101 | 142 | 178 | 176 | 1,106 | 5 | 5 | |

Weight distribution based on last 3 years:

| | | | |
|---|---|---|---|
| 36% | 5,000 lb | 7% | 23,000 lb |
| 51% | 8,000 lb | 6% | 40,000 lb |

Metric conversion: Multiply lb x 0.45 to obtain kg



TABLE A.20

PASSENGER CAR DATA - REDUCED WEIGHT GROUPS
(1979 Registration Year)

| Weighted Average* | Weight (lb) | No. of Vehicles | % | |
|---|---|---|---|---|
| | 0 - 1,000 | 430 | 0.006 | |
| | 1,001 - 1,500 | 5,089 | 0.071 | |
| 1. 2,400 | 1,501 - 2,000 | 241,554 | 3.370 | 23.4 |
| | 2,001 - 2,500 | 599,298 | 8.361 | |
| | 2,501 - 3,000 | 830,101 | 11.581 | |
| 2. 3,565 | 3,001 - 3,500 | 1,187,128 | 16.562 | 40.9 |
| | 3,501 - 4,000 | 1,741,125 | 24.291 | |
| 3. 4,374 | 4,001 - 4,500 | 1,762,414 | 24.588 | 32.7 |
| | 4,501 - 5,000 | 582,597 | 8.128 | |
| | 5,001 - 5,500 | 169,876 | 2.370 | |
| | 5,501 - 6,000 | 5,519 | 0.077 | |
| | 6,001 - 6,500 | 3,226 | 0.045 | |
| | 6,501 - 7,000 | 3,297 | 0.046 | |
| | 7,000 - 7,500 | 4,301 | 0.060 | |
| 4. 5,732 | 7,501 - 8,000 | 4,946 | 0.069 | 3.0 |
| | 8,001 - 8,500 | 4,659 | 0.065 | |
| | 8,501 - 9,000 | 4,151 | 0.058 | |
| | 9,001 - 9,500 | 4,014 | 0.056 | |
| | 9,501 - 10,000 | 3,512 | 0.049 | |
| | 10,000 & over | 10,537 | 0.147 | |
| | TOTAL | 7,167,780 | 100.000 | |

Add 300 lb (150-lb driver + 150-lb passenger) to curb weight.

1. 2,400 + 300 = 2,700 → 2,700
2. 3,565 + 300 = 3,865 → 4,000
3. 4,374 + 300 = 4,674 → 4,700
4. 5,732 + 300 = 6,032 → 6,000

Metric conversion: Multiple lb x 0.45 to obtain kg

TABLE A.21

SUMMARY OF TRAFFIC WEIGHT DISTRIBUTION CALCULATIONS

| Traffic Mix No. | ① Passenger Cars % | ② Pickups % | ③ 3-Axle Tractor 2-Axle Trailer % | ④ Other Trucks Buses % | Weight Distribution: Passenger Car % 2700 lb ① x 0.38 | % 4000 lb ① x 0.40 | % 4700 lb ① x 0.21 | % 6000 lb ① x 0.01 | Trucks and Buses % 5000 lb ② x 0.41 | % 8000 lb ② x 0.59 | % 23,000 lb ④ | % 40,000 lb ③ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 68 | 13 | 11 | 8 | 25.8 | 27.2 | 14.3 | 0.7 | 5.3 | 7.7 | 8.0 | 11.0 |
| 2 | 70 | 17 | 6 | 7 | 26.6 | 28.0 | 14.7 | 0.7 | 7.0 | 10.0 | 7.0 | 6.0 |
| 3 | 74 | 14 | 2 | 10 | 28.1 | 29.6 | 15.5 | 0.7 | 5.7 | 8.3 | 10.0 | 2.0 |
| 4 | 78 | 12 | 4 | 6 | 29.6 | 31.2 | 16.4 | 0.8 | 4.9 | 7.1 | 6.0 | 4.0 |
| 5 | 84 | 9 | 1 | 6 | 31.9 | 33.6 | 17.6 | 0.8 | 3.7 | 5.3 | 6.0 | 1.0 |

Metric conversion: Multiply lb by 0.45 to obtain kg

Typical passenger vehicle properties from Reference 32 are given in Table A.22. Yaw mass moment of inertia for the passenger vehicles in this program will be estimated using the 2/3 power law given by the empirical expression

$$I_{yaw} = \frac{0.103\ W_T\ 1.67}{g} \qquad (A.2)$$

where:

$I_{yaw}$ = vehicle mass moment of inertia about the vertical axis;
$W_T$ = vehicle weight, total; and
$g$ = gravitational constant.

An FHWA project in progress at SwRI (31) includes measurement of selected vehicle mass properties. These measured properties are summarized in Table A.23 and Figure A.3. Bus and truck properties are available on a limited basis. Other vehicle information was obtained from manufacturers catalogs as shown in Figures A.4 through A.6. A summary of the pertinent vehicle data is given in Table A.24.

As can be seen from Table A.24, vehicles weighing more than 40,000 lb (18,000 kg) were not considered in this study. These heavier vehicles, which are generally articulated tractor-trailer rigs, have performance limits that result in larger minimum radii of curvature and hence represent a less formidable impact possibility for a given weight, speed, and offset distance. The mechanics of articulated vehicle impacts are very complex and cannot be included in this study because of lack of current information. The inclusion of vehicles weighing up to 40,000 lb (18,000 kg) provides a wide range of impacting vehicle possibilities. Fortunately, data are available as discussed on single unit 40,000-lb vehicles. In addition, recent crash tests(16) conducted with this vehicle class have demonstrated that the 40,000-lb (18,000-kg)



TABLE A.22

TYPICAL VALUES FOR THE PASSENGER CLASS OF VEHICLES(32)

| Parameter (Symbol) (Units) | Vehicle Category: Subcompact | Compact | Intermediate | Standard: Weight Category No. 1 | Weight Category No. 2 | Weight Category No. 3 |
|---|---|---|---|---|---|---|
| Wheelbase length ($\ell_w$) (in) | 95.0 | 106.8 | 115.7 | 120.9 | 124.4 | 127.5 |
| Overall length ($L_o$) (in) | 162.9 | 190.1 | 203.6 | 213.8 | 220.7 | 220.8 |
| Overall width ($W_o$) (in) | 62.1 | 71.2 | 75.7 | 79.1 | 80.0 | 80.0 |
| Overall height ($H_o$) (in) | 54.0 | 54.7 | 54.8 | 54.9 | 54.9 | 55.0 |
| Front wheel track ($T_F$) (in) | 50.8 | 56.7 | 59.6 | 61.9 | 63.0 | 63.0 |
| Rear wheel track ($T_R$) (in) | 50.4 | 56.3 | 59.3 | 61.6 | 62.0 | 62.0 |
| Front overhang ($\ell_F$) (in) | 23.6 | 28.7 | 31.4 | 33.5 | 34.9 | 35.2 |
| Rear overhang ($\ell_R$) (in) | 32.7 | 42.6 | 48.1 | 52.4 | 55.4 | 58.1 |
| Tire size (radius) ($R_w$) (in) | 13 | 14 | 14 | 15 | 15 | 15 |
| Unladen or curb weight ($W_T$) (lb) | 1932 | 2003 | 3491 | 3983 | 4339 | 4672 |
| Front/rear distribution (%) | 55.4/44.6 | 54.8/45.2 | 54.4/45.6 | 54.2/45.8 | 54/46 | 53.8/46.2 |
| Total unsprung weight ($W_{1,T}$) (lb) | 341 | 449 | 514 | 569 | 608 | 645 |
| Front unsprung weight ($W_{1,F}$) (lb) | 131 | 173 | 198 | 219 | 234 | 248 |
| Total vehicle vertical C.G. above ground ($Z_{CG}$) (in) | 21.77 | 22.01 | 22.15 | 22.27 | 22.33 | 22.42 |
| Front wheel centre height above ground ($z_F$) (in) | 12.46 | 13.20 | 13.05 | 13.92 | 13.83 | 13.74 |
| Rear wheel centre height above ground ($z_R$) (in) | 12.57 | 13.34 | 13.20 | 14.09 | 14.00 | 13.92 |
| Total vehicle moment of inertia (slug-ft²) Yaw ($I_z$) | 958 | 1690 | 2570 | 3201 | 3692 | 4176 |
| Total vehicle moment of inertia (slug-ft²) Pitch ($I_y$) | 733 | 1446 | 1906 | 2448 | 2825 | 3195 |
| Sprung mass moment of inertia (slug-ft²) Yaw ($I_z$) | 809 | 1594 | 2168 | 2701 | 3116 | 3524 |
| Sprung mass moment of inertia (slug-ft²) Roll ($I_x$) | 112 | 222 | 302 | 376 | 434 | 490 |
| Sprung mass roll-yaw product of inertia − ($I_{xz}$) (slug-ft²) (λ = 3°) | 36 | 72 | 88 | 122 | 141 | 159 |
| Rear unsprung mass moment of inertia in roll ($I_R$) (lb-sec²-in) | 172 | 282 | 358 | 428 | 464 | 493 |
| Wheel rate (lb/in) Front ($K_F$) | 73 | 94 | 102 | 105 | 106 | 106 |
| Wheel rate (lb/in) Rear ($K_R$) | 91 | 112 | 117 | 118 | 117 | 114 |
| Rear spring spacing at the axle ($T_s$) (in) coil spring | 32.25 | 30.03 | 37.95 | 39.42 | 39.68 | 39.68 |
| Rear spring spacing at the axle ($T_s$) (in) leaf spring | 38.50 | 43.01 | 45.30 | 47.00 | 47.37 | 47.37 |
| Total front roll stiffness ($R_T$)$_F$ (lb-ft/deg) no roll bar | 157 | 240 | 283 | 312 | 328 | 326 |
| Total front roll stiffness ($R_T$)$_F$ (lb-ft/deg) with roll bar | 294 | 460 | 546 | 604 | 632 | 632 |
| Total rear roll stiffness ($R_T$)$_R$ (lb-ft/deg) coil spring | 127 | 164 | 180 | 191 | 192 | 186 |
| Total rear roll stiffness ($R_T$)$_R$ (lb-ft/deg) leaf spring | 185 | 238 | 262 | 277 | 278 | 273 |
| Suspension stop spring rate (lb/in) Front | 1200 | 865 | 500 | 600 | 500 | 500 |
| Suspension stop spring rate (lb/in) Rear | 210 | 265 | 625 | 375 | 375 | 375 |
| Suspension Coulomb damping (lb) Front ($C'_F$) | 58 | 58 | 58 | 58 | 58 | 58 |
| Suspension Coulomb damping (lb) Rear ($C'_R$) | 97 | 97 | 97 | 97 | 97 | 97 |
| Suspension viscous damping (lb-sec/in) Front ($C_F$) | 3.32 | 3.23 | 3.69 | 4.00 | 4.19 | 4.34 |
| Suspension viscous damping (lb-sec/in) Rear ($C_R$) | 3.65 | 5.10 | 5.79 | 6.25 | 6.53 | 6.72 |
| Rear roll centre height above ground (in) | − | − | − | − | − | − |
| Rear roll steer ($K_{RS}$) (°/°) | − | − | − | − | − | − |
| Wheel travel in jounce and rebound (in) | − | − | − | − | − | − |
| Camber angle (φ,) (deg) as a function of front wheel vertical travel (δ) (in) | − | − | − | − | − | − |

Class 1

Class 2

Class 3

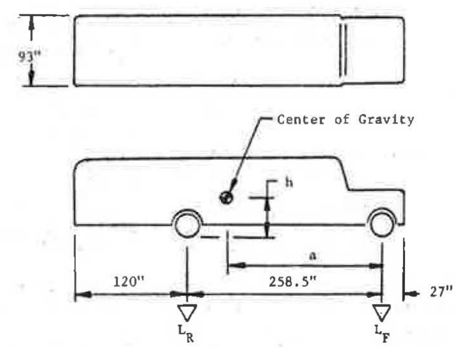
Class 4

TABLE A.23

VEHICLE PROPERTY SUMMARY

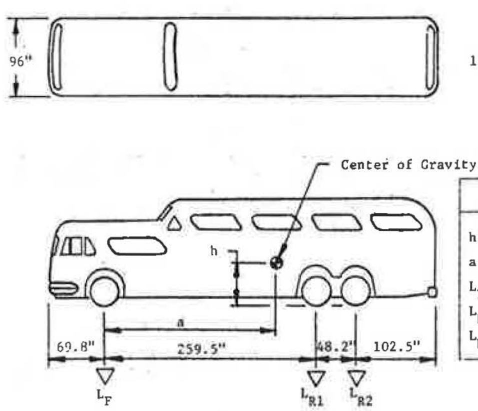
| | Vehicle | | | |
|---|---|---|---|---|
| | 1974 Vega | 1970 Ford/ Wayne School Bus | 1969 Chevrolet/ Blue Bird School Bus | 1955 GMC Scenicruiser Bus |
| 1. Wheel Base, in. | 97 | 258 | 254 | 283.6 |
| 2. Empty Properties | | | | |
| Weight, lb | 2,281 | 12,840 | 13,780 | 28,200 |
| C.G. - a, in. | 40.5 | 156.0 | 157.6 | 216.1 |
| b, in. | 56.5 | 102.0 | 96.4 | 67.5 |
| h, in. | 21.8 | 39.2 | 40.8 | 55.8 |
| $I_x$, in.-lb-sec$^2$ | 7,300 | 60,000 | 68,000 | 275,000 |
| $I_y$, in.-lb-sec$^2$ | 19,900 | 592,000 | 619,000 | 1,900,000 |
| $I_z$, in.-lb-sec$^2$ | 16,000 | 591,000 | 582,000 | 1,500,000 |
| 3. Design Weight Properties | | | | |
| Weight, lb | 2,611 | 20,000 | 20,000 | 40,000 |
| C.G. - a, in. | 42.1 | 178.3 | 172.3 | 206.7 |
| b, in. | 54.9 | 79.7 | 81.7 | 76.9 |
| H, in. | 23.0 | 45.6 | 45.3 | 54.3 |
| $I_x$, in.-lb-sec$^2$ | 7,500 | 74,000 | 81,000 | 330,000 |
| $I_y$, in.-lb-sec$^2$ | 20,100 | 776,000 | 751,000 | 2,200,000 |
| $I_z$, in.-lb-sec$^2$ | 16,400 | 783,000 | 722,000 | 1,800,000 |






1970 Ford, Wayne Body

| Qty | Bus Empty | Bus Ballasted |
|---|---|---|
| h, in. | 39.2 | 45.6 |
| a, in. | 156.0 | 178.3 |
| $L_F$, lb | 5090 | 6202 |
| $L_R$, lb | 7750 | 13,795 |



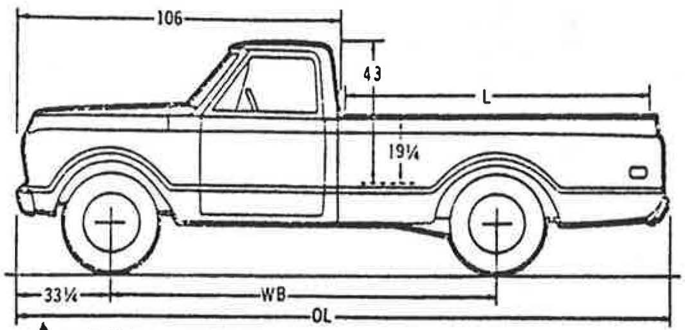

1956 GMC PD-4502

| Qty | Bus Empty | Bus Ballasted |
|---|---|---|
| h, in. | 55.8 | 54.3 |
| a, in. | 216.1 | 206.7 |
| $L_F$, lb | 6,720 | 11,477 |
| $L_{R1}$, lb | 10,961 | 14,547 |
| $L_{R2}$, lb | 10,532 | 13,976 |

FIGURE A.3 REFERENCE 35 TEST VEHICLES

## GMC C-1500 PICKUP

### CHASSIS DIMENSIONS




| MODEL NO. | C-1570 | C-1590 |
|---|---|---|
| WB Wheelbase | 115 | 127 |
| OL Bumper to end of body | 188½ | 207¼ |

Turning Diameter. See Steering Section.

USE 190

USE 120

**C-15934 PICKUP**

78½ Width Over Front Bumper 42¼ Rear Spring Centers

## GMC C-1500 PICKUP

**LOAD CAPACITY CHART** Maximum load at ground must not exceed capacity of minimum components (axles, springs, tires).

| GVW◆ | GCW | Tires Front | Tires Rear | Axle & Springs Front | Maximum Loading Front◆ | Axle & Springs Rear | Maximum Loading Rear | Other Equipment Required |
|---|---|---|---|---|---|---|---|---|
| | | MINIMUM REQUIRED EQUIPMENT FOR GVW RATING | | | | | | |
| 4700 | — | G78-15B | G78-15B | B.E. | 2925 | B.E. | 2800 | Not available w/SM465 |
| 5025 | | G78-15B | G78-15B | B.E. | 2925 | B.E. | 2800 | Power Brakes RPO J70 |
| 5400 | | H78-15B(c) | H78-15B(c) | RPO F60 | 3100 | RPO G50 | 3220 | Power Brakes RPO J70 |

B.E.—Base Equipment. All capacities listed are in pounds and are maximum load at the ground. (c) Or 6.50/16, C(6).

**STANDARD CHASSIS WEIGHTS** Weights of base models with standard specifications and 10-gal. fuel.

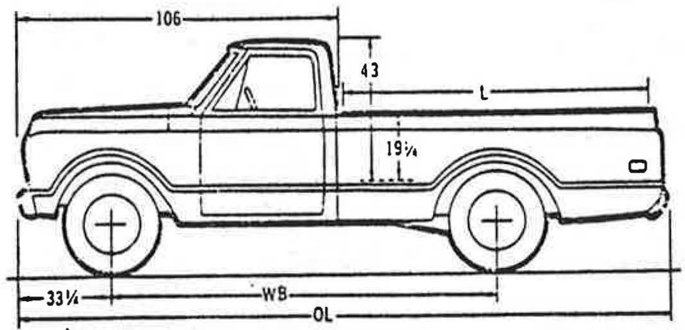
| Model No. V-8 | CE-15734 | CE-15934 | CE-15704 | CE-15904 |
|---|---|---|---|---|
| Front | 2160 | 2255 | 2155 | 2245 |
| Rear | 1530 | 1520 | 1465 | 1450 |
| Total | 3690 | 3775 | 3620 | 3695 |
| **Model No. 6** | **CS-15734** | **CS-15934** | **CS-15704** | **CS-15904** |
| Front | 2050 | 2145 | 2040 | 2130 |
| Rear | 1510 | 1505 | 1445 | 1440 |
| Total | 3560 | 3650 | 3485 | 3570 |

**WEIGHT DISTRIBUTION.** See section Truck Selection for body and payload distribution.

FIGURE A.4 CLASS 1 PICKUP DATA, 5000 LB

## GMC C-3500 PICKUP

### CHASSIS DIMENSIONS




| MODEL NO. | C-3600 |
|---|---|
| WB Wheelbase | 133 |
| OL Bumper to end of body. Fender-Side | 217¼ |
| Wide-Side | 213¾ |
| Turning Diameter. See Steering section. | |

USE 220

USE 80

**C-36034 PICKUP**

78½ Width Over Front Bumper

32 Front Spring Centers

40 Rear Spring Centers

## GMC C-3500 PICKUP

**LOAD CAPACITY CHART** Maximum load at ground must not exceed capacity of minimum components (axles, springs, tires).

| | | | MINIMUM REQUIRED EQUIPMENT FOR GVW RATING | | | | | |
|---|---|---|---|---|---|---|---|---|
| GVW | GCW | Tires Front | Tires Rear | Axle & Springs Front | Maximum Loading Front | Axle & Springs Rear | Maximum Loading Rear | Other Equipment Required |
| 6,600 | — | 8.75-16.5C (6) | 8.75-16.5C (6) | B.E. | 3,500 | B.E. | 3,980 | |
| 8,000 | | 9.50-16.5D (8) | 9.50-16.5D (8) | RPO F60 | 3,800 | RPO G50 | 5,560 | |
| 9,000 | | | 9.50-16.5E (10) | | 3,800 | RPO G60 | 6,340 | |

B.E.—Base Equipment All capacities listed are in pounds and are maximum load at the ground.

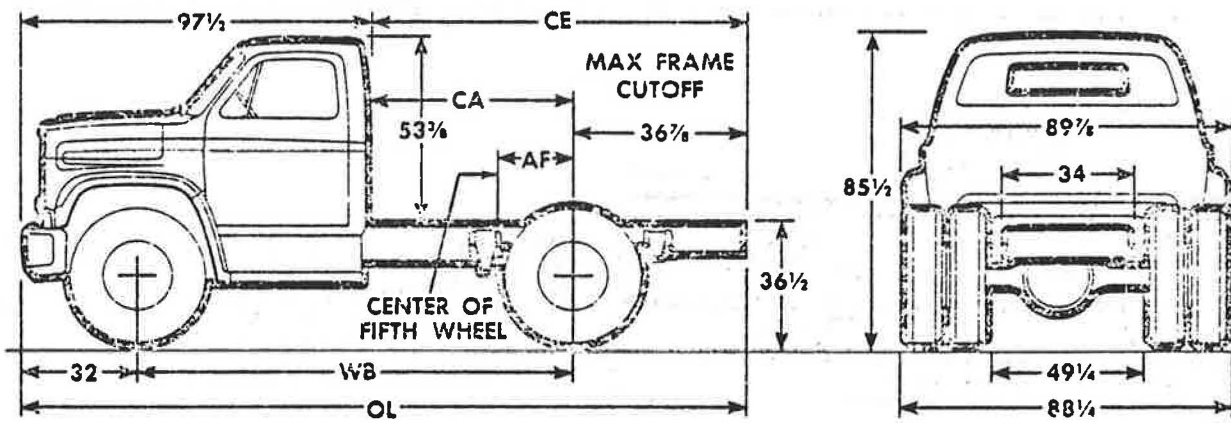
**STANDARD CHASSIS WEIGHTS** Weights of base models with standard specifications and 10-gal. fuel.

| C-3500 MODELS | Fender-Side Pickup | Wide-Side Pickup |
|---|---|---|
| Model No. V-8 | CE-36004 | CE-36034 |
| Front | 2385 | 2390 |
| Rear | 1750 | 1825 |
| Total | 4135 | 4215 |
| Model No. 6 | CS-36004 | CS-36034 |
| Front | 2275 | 2285 |
| Rear | 1730 | 1805 |
| Total | 4005 | 4090 |

**WEIGHT DISTRIBUTION.** See section Truck Selection for body and payload distribution.

FIGURE A.5 CLASS 2 PICKUP DATA, 8000 LB

## CM-6500




NOTE: Frame and Cab height dimensions are shown with std. tires.

### BODY-PAYLOAD WEIGHT DISTRIBUTION*(% FRONT/% REAR)

| Cab Models | Dimensions (In.) | | | | | Body Lengths (Ft.) | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | WB | CA | CE | OL | AF | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 |
| CM6600 | 125 | 60 | 100 | 197 | | 8/92 | *3/97* | | | | | | | | | | | |
| CM6620 | 137 | 72 | 120 | 217 | | | 11/89 | 7/93 | *3/97* | | | | | | | | | |
| CM6640 | 149 | 84 | 132 | 229 | | | | 14/36 | 11/89 | *6/94* | *3/97* | | | | | | | |
| CM6670 | 167 | 102 | 162 | 259 | | | | | | 16/84 | 13/87 | 8/92 | *2/98* | | | | | |
| CM6700 | 189 | 124 | 226¼ | 323 | | | | | | | | 20/80 | 14/86 | 7/93 | *1/99* | | | |
| CM6730 | 203 | 138 | 231 | 328 | | | | | | | | | | 20/80 | 14/86 | 8/92 | *1/99* | |
| CM6750 | 218 | 152 | 252¾ | 350 | | | | | | | | | | 24/76 | 19/81 | 14/86 | 8/92 | *2/9* |
| | | | | | | | | | | | | | | | | | | |

*Estimate based on water-level loading.

*Italicized Numbers indicate possible poor axle loadi*

### MAXIMUM LOAD AT GROUND MUST NOT EXCEED CAPACITY OF MINIMUM COMPONENTS (AXLES, SPRINGS, TIRES).

| GVW | GCW | Note: These are minimum components for this model. | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | Maximum Loading Front | Maximum Loading Rear | Minimum Tires Front | Minimum Tires Rear | Axle & Springs Front | Axle & Springs Rear | Other Minimum Equipment |
| VACUUM MODELS | | | | | | | | |
| 21,000 | | 7,000 | 14,200 | 8.25 - 20E | 8.25 - 20E | Std. | Std. | |
| 23,000 | | 7,000 | 16,160 | 8.25 - 20E | 9.00 - 20E | Std. | Std. | |
| 25,000 | | 9,000 | 16,160 | 8.25 - 20F | 9.00 - 20E | F43 + F94/F96 | Std. | Requires RPO "L" |
| 25,500 | | 7,000 | 18,500 | 8.25 - 20E | 10.00 - 20F | Std. | H63/H72 | |
| 27,500 | | 9,000 | 18,500 | 8.25 - 20F | 10.00 - 20F | F43 + F94/F96 | H63/H72 | Requires RPO "L" |
| AIR MODELS | | | | | | | | |
| 21,000 | | 7,000 | 14,200 | 8.25 - 20E | 8.25 - 20E | Std. | Std. | |
| 23,000 | | 7,000 | 16,160 | 8.25 - 20E | 9.00 - 20E | Std. | Std. | |
| 25,000 | | 9,000 | 16,160 | 8.25 - 20F | 9.00 - 20E | F43 + F94/F96 | Std. | Requires RPO "L" |
| 25,500 | 45,000 | 7,000 | 18,500 | 8.25 - 20E | 10.00 - 20F | Std. | H63/H72 | 32,000 GCW w/SM465 |
| 27,500 | | 9,000 | 18,500 | 8.25 - 20F | 10.00 - 10F | F43 + F94/F96 | H63/H72 | Requires RPO "L" |
| 29,500 | | 9,000 | 20,760 | 8.25 - 20F | 11.00 - 20F | F43 + F94/F96 | H75 | Requires RPO "L" |
| | | | | | | | | |

B.E.—Base Equipment

All capacities listed are in pounds and are maximum Load at the ground.

FIGURE A.6 CLASS 3 TRUCK DATA, 23,000 LB

TABLE A.24
SUMMARY OF VEHICLE DATA

| Class | Weight (lb) | Wheelbase (in.) | Overall Length (in.) | Overall Width (in.) | Front Overhang (in.) | Weight Distribution (Front/Rear) | Dist. Front Wheel to C.G. (in.) | a (in.) | Performance Limit | $I_{yaw}$ (slug ft$^2$) |
|---|---|---|---|---|---|---|---|---|---|---|
| Passenger Vehicle Properties: | | | | | | | | | | |
| 1 | 2,700 | 95 | 163 | 62 | 24 | 55/45 | 43 | 67 | 1.00 | 1,675 |
| 2 | 4,000 | 116 | 204 | 76 | 31 | 54/46 | 53 | 84 | 1.00 | 3,224 |
| 3 | 4,700 | 121 | 214 | 79 | 34 | 54/46 | 56 | 90 | 1.00 | 4,218 |
| 4 | 6,000 | 128 | 227 | 80 | 36 | 54/46 | 59 | 95 | 1.00 | 6,337 |
| Truck/Bus Properties: | | | | | | | | | | |
| 1 | 5,000 (pickup, van) | 120 | 190 | 80 | 34 | 43/57 | 68 | 102 | 1.00 | 4,170 |
| 2 | 8,000 (pickup, van) | 133 | 220 | 80 | 34 | 40/60 | 80 | 114 | 1.00 | 8,400 |
| 3A | 20,000 (66-passenger school bus) | 254 | 400 | 96 | 27 | 31/69 | 172.3 | 212 | 0.47 | 65,300 |
| 3B | 23,000 (single unit truck) | 167 | 260 | 88 | 32 | 30/70 | 117 | 149 | 0.47 | 29,000 |
| 4 | 40,000 (intercity bus) | 283 | 480 | 96 | 70 | 29/71 | 202 | 272 | 0.47 | 154,166 |

single unit vehicles do provide a more severe structural test than does the same weight articulated vehicle. Based on crash test results with the collapsing ring bridge rail system, the following comparisons can be made:

| Vehicle | Vehicle Weight (lb) | Impact Speed (mph) | Impact Angle (deg) | Max. Deflection (in.) |
|---|---|---|---|---|
| Intercity Bus | 40,000 | 53.9 | 15 | 48 |
| Tractor/Trailer | 70,000 | 44.4 | 10 | 12 |

Thus, the inclusion of a 40,000-lb (18,000-kg) single unit vehicle (as well as the 20,000-lb (10,000-kg) vehicle) gives assurance that single unit vehicles in this weight range are adequately considered and it can be inferred, as demonstrated above, that articulated vehicles weighing in excess of 40,000 lb (18,000 kg) are also included due to performance limits previously discussed. Another beneficial aspect of using the intercity bus is the predictable weight distribution for the fully loaded bus. Assuming a full load of 150-lb (68-kg) passengers, the balance of the payload can be placed in the baggage compartment. For trucks, the number of c.g./load combinations is unlimited.

A.1.4.2 Impact Speed. Speed of impact is probably the least accurate item from accident investigations. Although impact speed estimation and distribution have been reported(29), the data are combined for all highway types and speed zones. It is generally known that all traffic does not move at the posted or design speed of the highway. A portion of traffic exceeds the posted limit and a part moves at less than that value. The distribution of speed of traffic for a specific highway probably varies with time of day and day of week. Accordingly, the vehicle encroachment speed and impact speed probably vary in a similar manner.



As will be shown later, impact speed distribution is not a highly sensitive parameter. As vehicle speed increases, the maximum possible approach angle decreases, and this results in a fairly constant maximum vehicle impact severity.

For the MSLA, four designated speeds of 30, 40, 50, and 55 mph (50, 65, 80, and 90 km/h) were used in the model, and it was assumed that all traffic moved, encroached, and impacted the barrier at one of these speeds.

A.1.4.3 Impact Angle. Distribution of automobile impact angles used in the MSLA is based on the point mass model that has been used for a number of years to predict maximum impact angles for given speeds and offset distances(33,34). Ross(33) collected impact angle data and showed that the angle distribution was normal using the following assumptions:

- 100 percent of traffic was in Lane 1 (see Figure A.7).
- Traffic speed at 60 mph (95 km/h).
- Maximum angle obtained from point mass model was the 95th-percentile and the zero-degree angle was the 5-percentile angle.

Comparison of the theoretical distribution and field data is shown in Figure A.8.

It was of interest to check the field data with other models that would include distribution of traffic in both lanes of Figure A.7. Consequently, a series of small computer runs was conducted that included various combinations of traffic distribution and pavement coefficient of friction. Also included were the offset probabilities for each lane (i.e., less chance for vehicle in Lane 2 to impact the barrier). Vehicle speed was maintained at 60 mph (95 km/h). A typical output sheet is shown in Figure A.9.



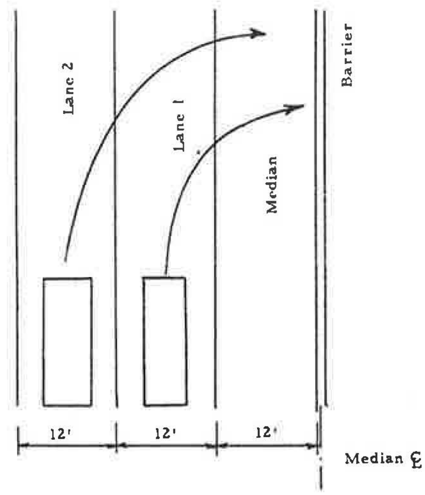



FIGURE A.7 TRAFFIC DISTRIBUTION



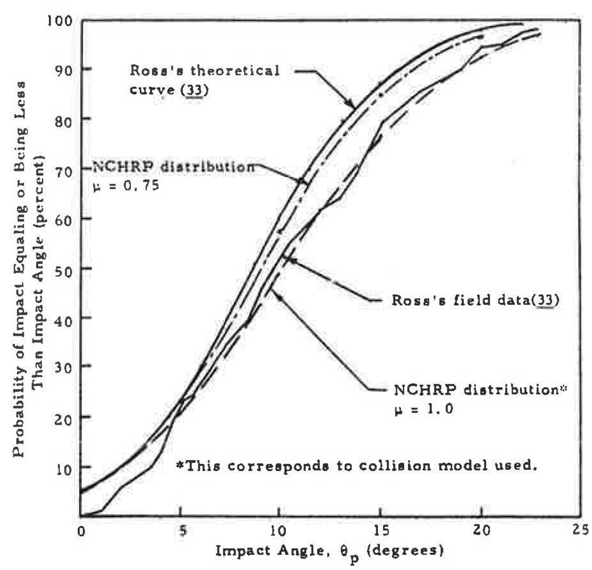



FIGURE A.8 IMPACT ANGLE VERSUS PROBABILITY OF IMPACT, MEDIAN DISTANCE = 12 FEET

DISTRIBUTION OF IMPACT ANGLES

LANE DISTRIBUTION FRACTIONS
LEFT LANE = .50
RIGHT LANE = .50

COEFFICIENT OF FRICTION = 1.00

95-PERCENTILE ANGLES
LEFT SIDE = 25.47 DEGREES
RIGHT SIDE = 18.74 DEGREES

STANDARD DEVIATION AND MEAN
LEFT SIDE = 4.58 AND 18.31
RIGHT SIDE = 3.32 AND 13.27

IMPACT FRACTIONS BY LANE
LEFT LANE = .30
RIGHT LANE = .70

ZERO DEGREES = 0-PERCENTILE ANGLE

| ANGLE | CUMULATIVE PROBABILITY |
|---|---|
| 5. | .50 |
| 10. | 12.40 |
| 15. | 55.98 |
| 20. | 87.83 |
| 25. | 97.82 |
| 30. | 99.84 |
| 35. | 100.00 |
| 40. | 100.00 |
| 45. | 100.00 |
| 50. | 100.00 |
| 55. | 100.00 |
| 60. | 100.00 |

FIGURE A.9 TYPICAL OUTPUT FOR IMPACT ANGLE DISTRIBUTION



Results from two of the computer outputs are superimposed on Figure A.8. Note that the data with $\mu = 0.75$ gives results that are closer to the theoretical distribution by Ross. The traffic split of 50 percent in Lane 1 and 50 percent in Lane 2 gives results that are quite close to the field data. Thus, it was assumed that a more realistic split of traffic, particularly for two-lane, two-way bridges, could be used in subsequent analyses. To be noted is that although the model was verified for the 60 mph (95 km/h) data, it was assumed adequate for the entire speed range of 0 to 65 mph (105 km/h).

The point mass model is sufficient to describe automobile behavior, but must be modified with regard to heavy vehicles with higher center of gravity. Relationships were developed in an FHWA program for these heavy vehicles(35). These relationships were based on performance limits reported by Weir(36) on a 36,000-lb (16,000-kg) intercity bus and a 41,000-lb (19,000-kg) tank truck. Angles of impact as a function of lateral offset distance are plotted in Figure A.10 for the truck and bus along with automobile mass data from work by Ross(33). Essentially, the coefficient of friction was reduced for these large vehicles to account for overturning tendency.

The minimum turning radius is described for vehicles in general

$$r_{min} = \frac{v^2}{g\mu} \qquad (A.3)$$

where $r_{min}$ is minimum turning radius in feet, g is acceleration due to gravity in fps$^2$, and $\mu$ is pavement coefficient of friction. The coefficient of friction is 1.0 for passenger cars and small trucks and 0.47 for large trucks and buses (the 0.47 value is from Ref. 36).



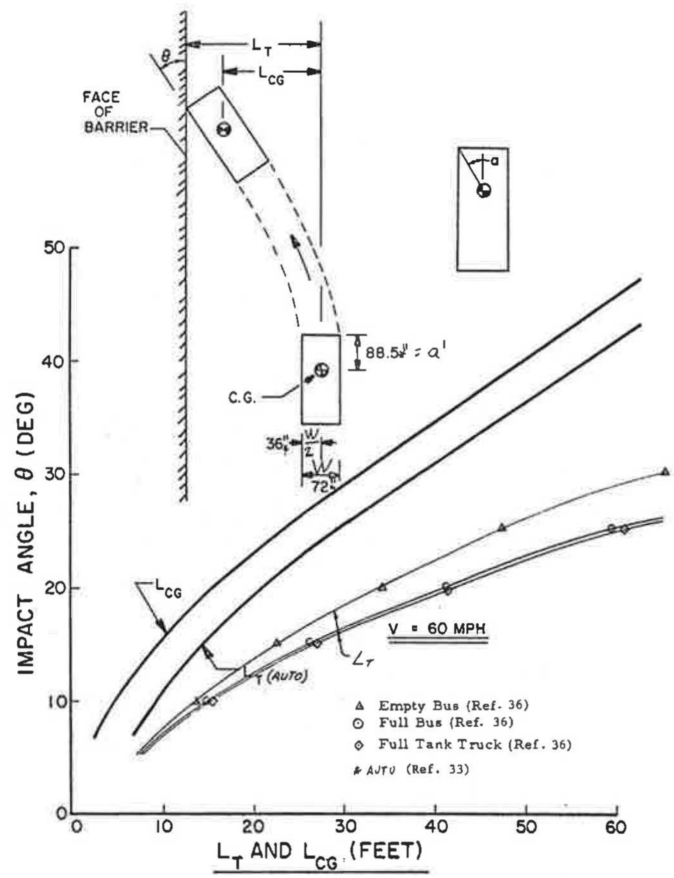



FIGURE A.10 60 MPH IMPACT ANGLE DATA



A.1.4.4 Vehicle Encroachment Trajectories. A summary of the previously discussed collision consideration is presented in Figure A.11.

A.1.5 Barrier Behavior

The safety performance of a longitudinal barrier such as a bridge railing is evaluated on three basic factors(8):

- Structural adequacy in containing and redirecting the impacting vehicle.
- Redirection severity imposed on vehicle occupants.
- Postimpact trajectory of the redirected vehicle.

These three behavior characteristics are examined for basis of establishing an objective multiple service level performance criterion.

A.1.5.1 Structural Adequacy. From TRB Circular 191(8) one level of service was recognized by AASHTO. Structural adequacy of a bridge railing design, evaluated by crash testing, was subjected to a 4500-lb (2040-kg) passenger car impacting the barrier at 60 mph (95 km/h) and 25 deg. Requirements were that the vehicle must not penetrate, pocket, or wedge under the system for these impact conditions. Of the three evaluation factors (i.e., structural adequacy, redirection severity, post impact trajectory), only structural adequacy can be clearly determined by a yes/no standard. In general, the vehicle was either contained on the bridge or it penetrated the railing.

A dimension of structural adequacy not addressed specifically in NCHRP Report 230 is maximum allowable lateral deflections of the barrier. Historically, bridge railing designs have been relatively stiff structures (when proportioned to AASHTO static specifications) and have exhibited at most only 3 in. or 4 in. of deflection when impacted by the NCHRP Report 230 heavy car. Bridge railing designers have expressed a

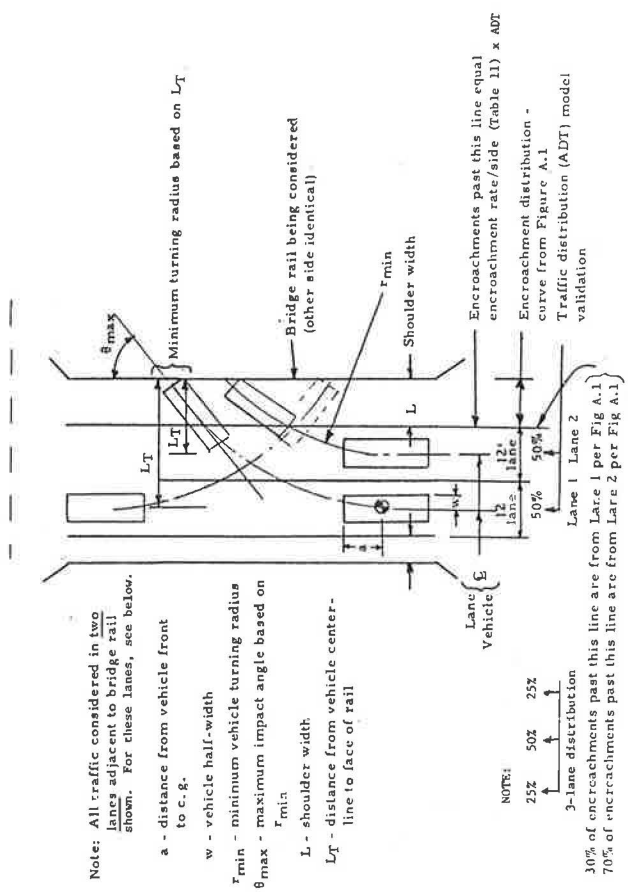



FIGURE A.11 VEHICLE ENCROACHMENT TRAJECTORIES



concern that the vehicle may drop from the structure if the dynamic barrier deflections are too large. The authors know of no instances, either in experiments or accident cases, where this has occurred. Vehicles that have gone off bridge structures on known occurrences have done so for a number of reasons:

- Barrier failure - i.e., the barrier element strength was not sufficient to contain the vehicle.
- Vehicle was launched over the system.
- Vehicle rolled over the system.

It is known from crash test experience that dynamic deflections of at least the vehicle half-width have been measured in successful redirection(16). On the basis of these observations, it is suggested that allowable barrier deflections be related to vehicle widths during design efforts.

In the MSLA, the concept of degree of impact severity is introduced. That is, levels of impact severity are identified by vehicle size, impact angle, and impact speed. A redirection index RI is presented later that establishes the relative ranking or severity among an unlimited number of impact conditions. The RI ranges in linear values in direct proportion to the impact severity. An important assumption in the MSLA is that a barrier that has demonstrated structural adequacy at a specific RI (i.e., say 5000) will contain all impacts with an RI of 5000 or less.

A.1.5.2 Redirection Severity. Redirection severity has been evaluated in terms of vehicle accelerations specified in TRB Circular 191. NCHRP Report 230(9), which supersedes TRB Circular 191, includes different criteria for assessing occupant injury during collisions. These new criteria will greatly change the evaluation procedures as related to occupant injury. Based on limited analysis of crash test data, it would



appear that rigid bridge railings that do not snag the vehicle will come much closer to meeting the new acceptance criteria. Although the redirection severity criteria are important in evaluating barriers, they cannot be incorporated into the MSLA formulations.

A.1.5.3 Postimpact Trajectory. Postimpact trajectory of a redirected vehicle is important because it can cause interference with other traffic and subsequent multivehicle collisions. Ideally, the redirected vehicle will remain close to the bridge railing and will not be abruptly thrust back into the traffic lanes. The hazard of a vehicle being redirected back into the traffic is unknown; accident statistics are unavailable to indicate the number of such yearly occurrences.

The postimpact trajectory is rarely a predictable or repeatable result. Consequently, this factor is not used in the MSLA procedure.

A.1.6 Barrier Design Alternatives

Traditionally, bridge railings designed according to the applicable AASHTO specification have resulted in barrier's designs conforming to working stress theory. In reality, these barriers may, and have been, stressed far beyond the elastic limit; and lack of ultimate strength design has prevented some barriers from functioning satisfactorily up to the ultimate level. For the purposes of establishing reasonable bridge railing costs for the multiple service level cost benefit analysis, three different barrier types were designed for each of the service levels. The three types as described in Chapter Two are:

1. Flexible beam/post systems - barrier deflection permitted up to vehicle half-width.
2. Rigid beam/post systems - barrier deflection limited to less than 6 in. (40 mm).



3. Concrete safety shape parapets - a shaped barrier is considered necessary to meet small car occupant risk test requirements.

The beam/post systems were designed using the BARRIER VII computer(11) program and the vehicle properties of Table A.24. The concrete systems were designed using yield line theory as discussed by Hirsch(3) with loads based on work by Buth(4).

A.1.6.1 Beam/Post Systems. The basic beams used in the design effort were thrie and tubular thrie beams. Properties of these beams are summarized in Table A.25. Posts were standard wideflange sections with exception of the wood and box beam steel posts developed in SL 1 investigations (see Chapter 3 and Appendix C).

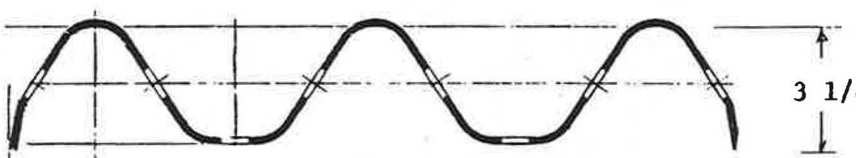
Basic beam/post design effort is summarized in Figure A.12. Ultimate strength procedures and material properties were used to develop the designs, and costs were developed from unit costs of Table A.26. Costs of the beam/post systems are given in Table A.27.

A.1.6.2 Concrete Safety Shape Parapets. Continuous concrete parapets can be efficient bridge railings because of the continuous interface with the bridge deck slab; intermittent posts tend to concentrate the slab loading. The concrete barriers used in this project for cost estimates were all constructed using the safety shape profile; this is considered necessary to meet the occupant risk criteria of NCHRP Report 230(9). Barrier heights of 32 in. (0.8 m) were considered adequate for SL 1 and 2 whereas 38 in. (1.0 m) was considered appropriate for SL 3 and 4 because of heavy vehicle stability consideration.

a. Barrier loading. Barrier force criteria as determined from Buth(4) are summarized in Table A.28. Some adjustments to the data reported by Buth were considered necessary as described in this table.

TABLE A.25 (a) THRIE AND (b) TUBULAR THRIE BEAM SYSTEM PROPERTIES

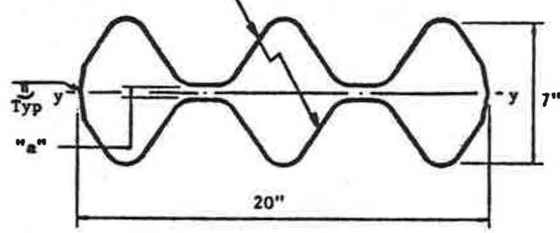
(a)




APPROXIMATE SECTION PROPERTIES

| | 12 ga. | 10 ga. |
|---|---|---|
| Nom. Thickness | 0.1046 | 0.1340 |
| Area, in.$^2$ | 3.2 | 4.0 |
| Iyy, in.$^4$ | 3.74 | 4.81 |
| Syy, in.$^3$ | 2.23 | 2.86 |

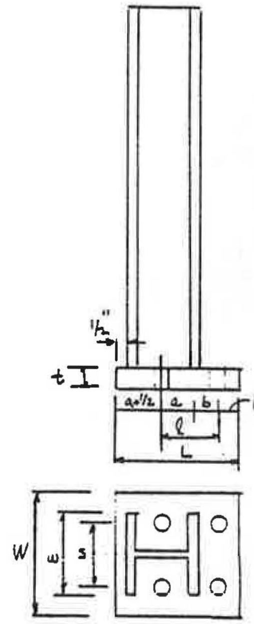
(b)




APPROXIMATE SECTION PROPERTIES

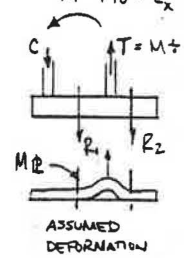
| | a = 1/2" | | a = 0 | |
|---|---|---|---|---|
| | 12 ga. | 10 ga. | 12 ga. | 10 ga. |
| Nom. Thickness, in. | 0.1046 | 0.134 | 0.1046 | 0.134 |
| Area, in.$^2$ | 6.3 | 8.0 | 6.3 | 8.0 |
| $I_{yy}$, in.$^4$ | 27 | 35 | 21 | 28 |
| $S_{yy}$, in.$^3$ | 7.8 | 9.9 | 7.1 | 9.2 |

Metric conversion:
to convert in. to mm multiply by 25.4



For Steel, Use $F_{TU} = 60$ KSI

$M = F_{TU} \times Z_x = 60\,Z_x$




$R_2 = \frac{a^2(a+3b)}{l^3}\,T$

$M_{PL} = \frac{a^2 b}{l^2}$

PLATE BENDING

$F_{bu} = \frac{4M}{wt^2}$

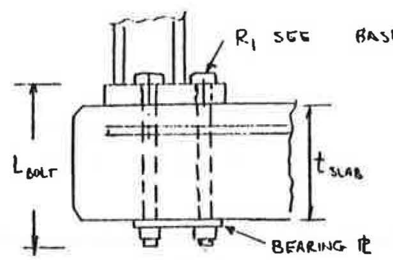
(a) BASE PL DESIGN

| POST | M, IN KIP | T, KIP | a, in | b, in | $l$, in | $R_1$ KIP | $M_{PL}$ IN KIP | w, in | $t = \sqrt{\frac{4M_{PL}}{60w}}$ | L, in | Vol. PL in³ | Wt PL LBS | POST WT, LBS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| W6x9 | 372 | 62 | 3 | 1 3/4 | 4 3/4 | 43 | 43 | 6 | 0.69 ≈ 3/4" | 10 | 37.5 | 10.6 | 24.8 |
| W6x16 | 702 | 117 | 3 | | | 81 | 82 | 9 | 0.78 ≈ 7/8" | 10 | 78.8 | 22.3 | 44.0 |
| W6x25 | 1134 | 189 | 3 | | 4 3/4 | 130 | 132 | 9 | 0.98 ≈ 1" | 10 | 90.0 | 25.5 | 68.8 |
| W8x31 | 1824 | 228 | 4 | | 5 3/4 | 178 | 193 | 11 | 1.17 ≈ 1 1/8" | 12 | 148.5 | 42.0 | 85.3 |
| W12x36 | 3072 | 256 | 6 | 1 3/4 | 7 3/4 | 222 | 268 | 10 | 1.34 ≈ 1 3/8" | 16 | 220.0 | 62.3 | 96.3 |

| | POST + BASE PL WT, LBS | COST, \$ (\$0.54/LB) | COST \$ (\$0.55/LB) |
|---|---|---|---|
| W6x9 | 35.4 | 19.12 | |
| W6x16 | 66.3 | 35.80 | |
| W6x25 | 94.3 | 50.92 | |
| W8x31 | 127.3 | | 75.11 |
| W12x36 | 158.6 | | 97.60 |

FIGURE A.12 BEAM/POST DESIGNS

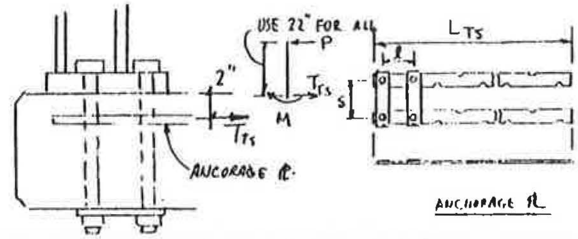





| POST | $R_1$ KIP | BOLT DIA, IN | BOLT LENGTH, IN | BRG. PL | BRG PL WT, LB |
|---|---|---|---|---|---|
| W6x9 | 43 | 5/8 | 10 | 6x8x1/4 | 3.4 |
| W6x16 | 81 | 3/4 | 10 1/2 | 8x9x1/4 | 5.1 |
| W6x25 | 130 | 1 | 14 | 8x9x1/4 | 5.1 |
| W8x31 | 178 | 1 1/4 | 16 | 9x10x1/4 | 6.4 |
| W12x35 | 222 | 1 1/2 | 18 | 9x11x1/4 | 7.0 |

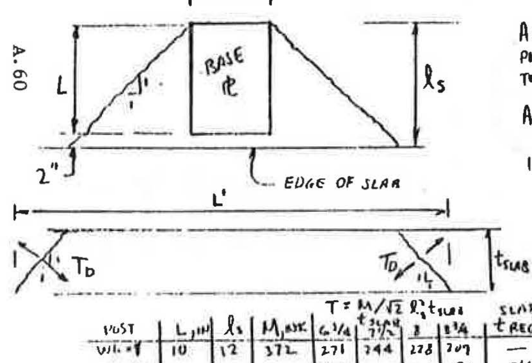
| POST | BRG PL \$0.54/LB | BOLT \$/4 |
|---|---|---|
| W6x9 | 1.83 | 11.71 |
| W6x16 | 2.75 | 14.83 |
| W6x25 | 2.75 | 23.18 |
| W8x31 | 3.40 | 35.10 |
| W12x35 | 3.70 | 53.42 |

(a) ANCHOR BOLT




| POST | M, IN-K | P = $T_{TS}$ KIP | $A = \frac{T_{TS}}{60}$ IN² | $L_{TS}$, IN | VOL, IN³ | $W_T$ | COST \$0.75/LB |
|---|---|---|---|---|---|---|---|
| W6x9 | 372 | 17 | 0.28 | 24 | 6.7 | 1.9 | 1.40 |
| W6x16 | 702 | 32 | 0.53 | 30 | 15.9 | 4.5 | 3.40 |
| W6x25 | 1134 | 52 | 0.87 | 36 | 31.3 | 8.9 | 6.70 |
| W8x31 | 1824 | 83 | 1.38 | 42 | 58.0 | 16.4 | 12.30 |
| W12x36 | 3072 | 140 | 2.33 | 48 | 111.8 | 31.7 | 23.80 |

(d) ANCHORAGE PL REQUIREMENTS




ASSUME LOCAL BENDING OF POST IS REACTED BY DIAGONAL TENSION OF CONCRETE SLAB

$\text{AREA} = 2\left(\frac{l_s}{\cos 45°}\right)\left(\frac{t_{SLAB}}{\cos 45°}\right) = 4\,l_s t_{SLAB}$

IF $T_D$ IS UNIFORM

$T_D = \frac{M}{\sqrt{2}\,l_s^2 t}$

for $f'_c = 4000$,

$T_{ALL} = 7.5\sqrt{f'_c} = 474$ psi

$T = M/\sqrt{2}\,l_s^2 t_{SLAB}$

| POST | L, IN | $l_s$ | M, IN-K | $t_{SLAB}$ = 6 3/4 | 7 1/2 | 8 | 8 3/4 | SLAB t REQD | L', IN | ADD'L VOL, C.Y. | COST \$200/C.Y. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| W6x9 | 10 | 12 | 372 | 271 | 244 | 228 | 209 | — | 41.5 | — | |
| W6x16 | 10 | 12 | 702 | 511 | 46.0 | 431 | 394 | 7 1/2 | 48.0 | — | |
| W6x25 | 10 | 12 | 1134 | | 742 | 696 | 1.36 | 11.1 | 55.2 | 0.09 | 18.52 |
| W8x31 | 12 | 14 | 1824 | | | | | 13.1 | 65.2 | 0.18 | 36.00 |
| W12x36 | 16 | 18 | 3072 | | | | | 13.4 | 18.8 | 0.21 | 42.00 |

(c) SLAB THICKNESS REQUIREMENTS

FIGURE A.12 (Cont'd.)

TABLE A.26

SUMMARY OF BRIDGE RAILING ESTIMATED INSTALLED COSTS

| Item | Unit | Unit Cost ($-1980) |
|---|---|---|
| 1. Beams | $/lin.ft | |
| A. Thrie (AASHTO M180) 12 ga | | 5.75 |
| B. Tubular thrie 12 ga | | 21.85 |
| C. Tubular thrie 10 ga | | 25.30 |
| 2. Posts | | |
| A. TS3x6x0.25 | $/lb | 0.60 |
| B. W6x9 | ↑ | 0.54 |
| C. W6x16 | | 0.54 |
| D. W6x25 | | 0.54 |
| E. W8x31 | | 0.59 |
| F. W12x36 | ↓ | 0.59 |
| G. 6x6 wood x 3'-10" | $0.60/bd ft | |
| 3. Anchor Bolts | | |
| A. 5/8" dia x 10" | $/ea | 3.29 |
| B. 3/4" dia x 10-1/2" | $/ea | 4.16 |
| C. 1" dia x 14" | $/ea | 6.37 |
| D. 1-1/4" dia x 16" | $/ea | 10.54 |
| E. 1-1/2" dia x 18" | $/ea | 16.25 |
| 4. Slab Reinforcement | | |
| A. Rebar | $/lb | 0.50 |
| B. Concrete | $/c.y. | 200.00 |
| C. Form huanch | $/s.f. | 3.00 |
| D. Bolt anchorage ₧s | $/lb | 0.75 |

A.61

TABLE A.27
SUMMARY OF COSTS FOR BEAM/POST BRIDGE RAIL DESIGNS

| | Steel Posts | | | | | | Wood Post |
|---|---|---|---|---|---|---|---|
| | TS 3x 6x0.25 | W6x9 | W6x16 | W6x25 | W8x31 | W12x35 | 6x6 x3'-10" |
| Post | | | | | | | 7.20 |
| Post/Base | 31.88 | 19.12 | 35.80 | 50.92 | 75.10 | 93.60 | |
| Anchor Bolts | 15.30 | 11.71 | 14.83 | 23.18 | 38.80 | 59.62 | 6.20 |
| Bearing Plates | - | 1.83 | 2.75 | 2.75 | 3.40 | 3.70 | 1.35 |
| Haunch (If Req'd.) | - | - | - | 18.52 | 36.00 | 42.00 | 2.00 |
| Bolt Anchorage ₧ S | - | 1.40 | 3.40 | 6.70 | 12.30 | 23.80 | |
| Bearing Bracket | | | | | | | 3.91 |
| | 47.18 | 34.06 | 56.78 | 102.07 | 165.60 | 222.72 | 20.66 |

Use 150 ft length to calculate cost in $/L.F.

SL1 = 150(5.75) + 47.18(19) = 11.73
150(5.75) + 20.66(19) 8.37

20.10 Avg = $10.00/L.F.

SL2 150(21.85) + 19(34.06) + 19(34.06) = $26.16/L.F.
SL3 150(21.85) + 56.78(25) = $31.31/L.F.
SL4 150(21.85) + 56.78(37) = $35.86/L.F.

SL1 150(21.85) + 19(34.06) = $26.16/L.F.
SL2 150(21.85 + 19(102.07) = $34.77/L.F.
SL3 150(21.85) + 25(165.60) = $49.37/L.F.
SL4 150(25.30) + 37(222.72) = $80.24/L.F.

A.62

TABLE A.28
ASSUMED DESIGN FORCES FOR CONCRETE PARAPET DESIGN

| SL | RI | $\overline{F}_i$,kip | $\overline{F}_{im}$,kip | $\overline{Y}_i$,in | $d_i$,ft | $W_i$,in | $\overline{F}_f$,mp | $\overline{Y}_f$,in | $d_f$,in |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2934 | 52.5 | 32.0 | 21.4 | 7.3 | 4.9 | - | - | - |
| 2 | 5505 | 59.9 | 60.0 | 21.8 | 6.5 | 4.4 | - | - | - |
| 3 | 8247 | 63.7 | 95.0 | 29.0 | 12.3 | 4.2 | 73.8 | 32.7 | 25.5 |
| * | 13316 | 85.0 | 169.0 | 26.3 | 6.3 | 4.2 | 212.9 | 28.4 | 15.0 |
| 4 | 13787 | | 170.0 | 26.3 | 6.3 | 4.2 | | | |

*32000-lb bus, 60 mph, 15 deg (nom)

Note:

RI = redirection index value for fully loaded vehicle assuming all payload effective;

$F_i$ = measured average barrier force (50 msec) during initial impact, Ref 4;

$F_{im}$ = modified $F_i$ based on RI of SL2 corresponding to 60 kip;

$\overline{Y}_i$ = vertical distance from bridge deck to resultant force $\overline{F}_i$;

$d_i$ = apparent horizontal distance over vehicle $\overline{F}_i$ is distributed based on overhead camera coverage;

$W_i$ = horizontal force distribution length used for design;

$\overline{F}_f$ = measured average barrier force (50 msec) during final impact;

$\overline{Y}_f$ = vertical distance from bridge deck to resultant force $\overline{F}_f$; and

$d_f$ = apparent horizontal distance over vehicle $\overline{F}_f$ is distributed.

A.63

b. Barrier design. Yield line theory developed for bridge parapets by Hirsch(3) and shown in Figure A.13 were used to design the parapets. Basic slab designs of Texas Dept. of Highways and Public Transportation, as described in Table A.29, were used in the analysis.

The basis for the parapet design includes the following assumptions:

1. If no failure of the parapet occurs during the initial impact, the vehicle will be redirected although actual forces on the barrier will be greater during the secondary impact for SL 3 and 4.

2. All forces ($W\ell$) are applied at the top of the barrier (conservative).

3. The ultimate moment capacity $M_c$ (see Figure A.13) is controlled by the slab moment; i.e., $M_c \simeq$ slab moment capacity. Typical slab designs and moment capacities are summarized in Table A.29.

Design of the barriers, as described in Figure A.14, was accomplished with parametric solution of equations from Figure A.13 for optimum design. Table A.30 provides a summary of estimated costs for the designs described.

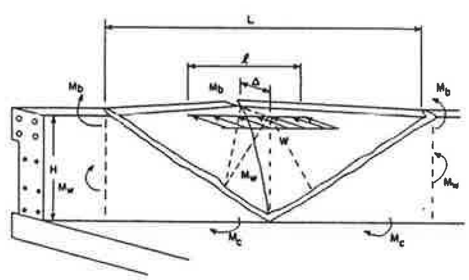
A.2 Performance Criteria

Parameters presented and discussed in Section A.1 are combined in an overall MSLA mathematical model.

A.2.1 Redirection Index

Severity of a vehicle collision with a bridge railing may be assessed by at least three resulting consequences: (a) number of injuries and fatalities of vehicle occupants, (b) amount of damage sustained by the vehicle and/or bridge railing, and (c) the intensity of vehicle/barrier interactive forces developed during the impact. Although there appears to be a






Total Load = $W\ell$

External Work = Internal Energy Absorbed

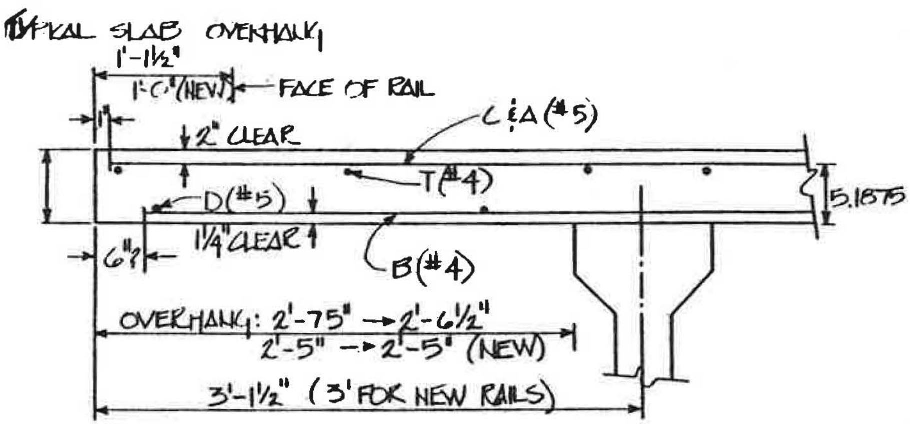
$$W\ell\, \Delta \left(\frac{L - \ell/2}{L}\right) = M_b \times 4 \times \frac{\Delta}{L/2} + M_w H \times 4 \times \frac{\Delta}{L/2} + M_c L \frac{\Delta}{H}$$

$$W\ell \left(\frac{L - \ell/2}{L}\right) = \frac{8M_b}{L} + \frac{8M_w H}{L} + \frac{M_c L}{H}$$

$$L = \frac{\ell}{2} + \sqrt{\left(\frac{\ell}{2}\right)^2 + 8H\left(\frac{M_b + M_w H}{M_c}\right)}$$

FIGURE A.13 YIELD LINE THEORY AS APPLIED TO CONCRETE BRIDGE PARAPETS

# TABLE A.29
## TYPICAL BRIDGE SLAB DESIGNS




| Standard Roadways | t | B, C and A Bars Max Bar Spacing | Overhang |
|---|---|---|---|
| 26 h | 8 3/4" | 12" | 2' - 7 1/2" |
| 34 HS 40HS | 7 1/2" | 10 1/2" | |
| 44 HS | 7 1/4" | 11" | |
| 48 HS | 7 1/2" | 10 1/2" | |
| Others | | | Max Overhang |
| | 6 3/4" | 12" | 2' - 11" |
| | 7" | 11 1/2" | 3' - 0 1/2" |
| | 7 1/4" | 11" | 3' - 2 1/2" |
| | 7 1/2" | 10 1/2" | 3' - 4 1/2" |
| | 7 3/4" | 10" | 3' - 7" |
| | 8" | 9 1/2" | 3' - 10" |

| Slab | B,C, and A Bars Max Bar Spa, in. | d in. | $A_S$ in.$^2$/ft | $\rho$ | $A_S$* Allow | M, in. kip/ft Basic | M, in. kip*/ft Allow |
|---|---|---|---|---|---|---|---|
| 8-3/4 | 12 | 6.44 | 0.62 | 0.0080 | 1.66 | 201 | 485 |
| 7-1/2 | 10-1/2 | 5.19 | 0.70 | 0.0112 | 1.34 | 177 | 315 |
| 7-1/4 | 11 | 4.94 | 0.68 | 0.0115 | 1.26 | 163 | 282 |
| | | | | | | | |
| 6-3/4 | 12 | 4.44 | 0.62 | 0.0116 | 1.14 | 133 | 230 |
| 7 | 11-1/2 | 4.69 | 0.64 | 0.0114 | 1.20 | 146 | 255 |
| 7-1/4 | 11 | 4.94 | 0.68 | 0.0115 | 1.26 | 163 | 282 |
| 7-1/8 | 10-1/2 | 4.82 | 0.70 | 0.0121 | 1.24 | 163 | 271 |
| 7-3/4 | 10 | 8.44 | 0.74 | 0.0113 | 1.40 | 196 | 345 |
| 8 | 9-1/2 | 5.69 | 0.78 | 0.0114 | 1.46 | 216 | 377 |

*Based on $\rho_{all} = 0.75\ \rho_b$, Ref 1

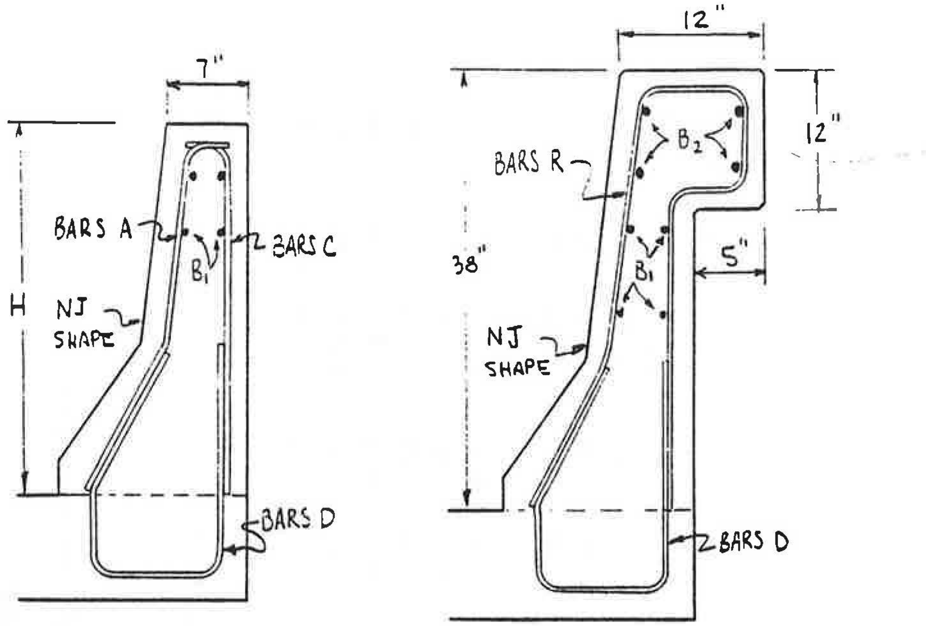
Use $f_y = 60$ ksi

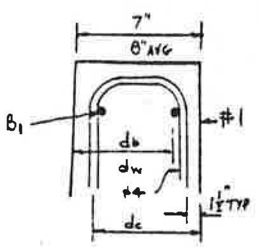
$f'_c = 4$ ksi

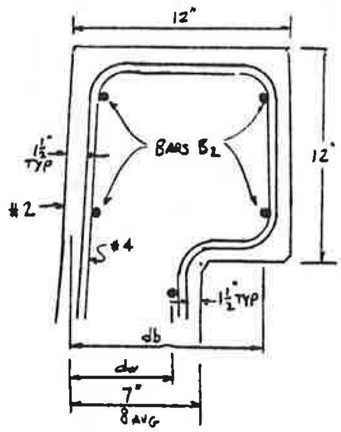
$\phi M_n = \phi\left[Asfyd\left(1-0.6\rho\ \frac{fy}{f'c}\right)\right]$ Ref 1, Eq. (6-1)

$\rho_b = \frac{.85\beta_1 f'c}{fy}\ \frac{87,000}{87,000 + fy} = 0.0285$

$\rho_{all} = 0.75\ \rho_b = 0.0214$




| BARS | LENGTH | SIZE | WEIGHT/FT, LBS; SPA. 6" | 12" | 18" |
|---|---|---|---|---|---|
| $A_{32}$ | 3'-0" | #4 | 4.0 | 2.0 | 1.3 |
| $A_{38}$ | 3'-6" | | 4.7 | 2.3 | 1.6 |
| D | 4'-0" | | 5.3 | 2.7 | 1.8 |
| R | 7'-3" | | 9.8 | | |
| $C_{32}$ | 2'-10" | | 3.8 | 1.9 | 1.3 |
| $C_{38}$ | 3'-4" | #4 | 4.5 | | |

STEEL SUMMARY

| SL | BARS A LB/FT | D LB/FT | C,R LB/FT | B NO. | B SIZE | B WT, LB/FT | TOTAL LB/FT | COST $/L.F. |
|---|---|---|---|---|---|---|---|---|
| 1 | 1.3 | 1.9 | 1.3 | 6 | #4 | 4.0 | 8.4 | 4.20 |
| 2 | 2.0 | 2.3 | 1.9 | 12 | #4 | 8.0 | 14.2 | 7.10 |
| 3 | 4.7 | 5.3 | 4.5 | 12<br>2 | #4<br>#5 | 8.0<br>2.1 | 24.6 | 12.30 |
| 4 | — | 5.3 | 9.8 | 8<br>2<br>1 | #4<br>#5<br>#6 | 5.3<br>2.1<br>12.0 | 34.5 | 17.25 |

USE $f_y = 60$ ksi
$f'_c = 4$ ksi

$M_B + M_W$ #1

| BARS $B_1$ | $A_s$ in.² | AVG d in. | $\rho$ | $A_s f_y d$ | $M$ in,kip | $M$ ft,kip |
|---|---|---|---|---|---|---|
| #4 @ 6" | 0.40 | $6\frac{3}{4}$ | 0.0049 | 162 | 139 | 11.6 |
| #4 @ 8" | 0.30 | | 0.0037 | 122 | 106 | 8.8 |
| #4 @ 10" | 0.24 | | 0.0030 | 97 | 85 | 7.1 |
| #4 @ 12" | 0.20 | | 0.0025 | 81 | 71 | 5.9 |
| #4 @ 18" | 0.13 | | 0.0016 | 53 | 47 | 3.9 |
| #5 @ 6" | 0.62 | $6\frac{3}{4}$ | 0.0060 | | 210 | 17.5 |

$M_B$ #2

| BARS $B_2$ | $d_b$ in. | $A_s$ in.² | $\rho$ | $A_s f_y d$ | $M$ in,kip | $M$ ft,kip |
|---|---|---|---|---|---|---|
| 8 #6 | $8\frac{1}{2}$ | 1.76 | 0.017 | 898 | 654 | 57 |
| 4 #6 | $8\frac{1}{2}$ | 0.88 | 0.008 | 449 | 364 | 30 |

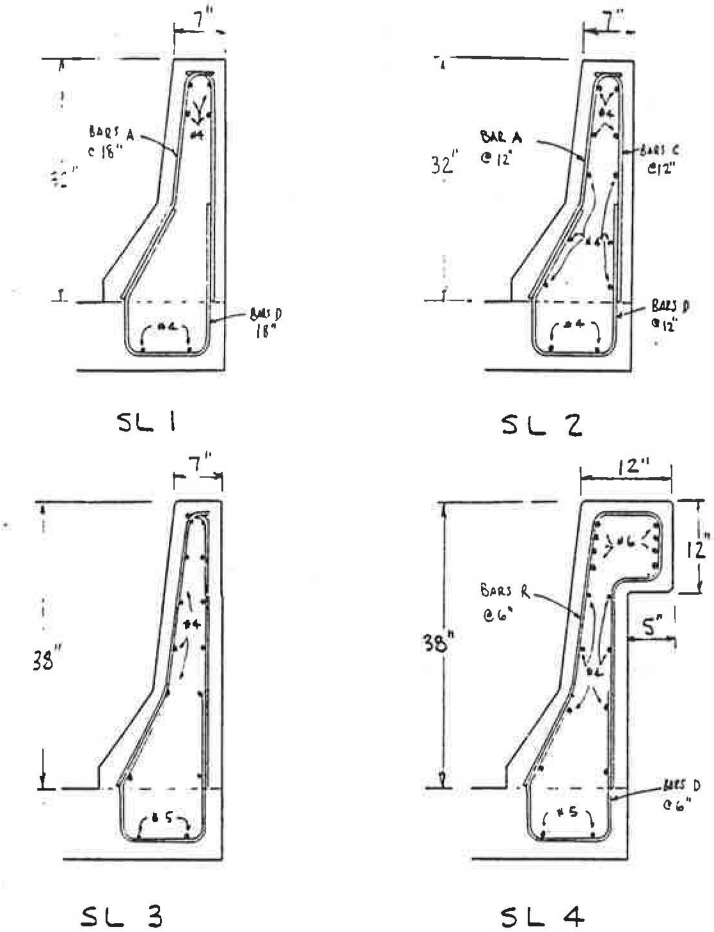
CONCRETE SUMMARY

| SL | VOL C.Y./FT | COST (USING $200/C.Y.) $/L.F. |
|---|---|---|
| 1 | 0.084 | 16.71 |
| 2 | 0.084 | 16.71 |
| 3 | 0.096 | 19.19 |
| 4 | 0.111 | 22.28 |

FIGURE A.14 SUMMARY OF CONCRETE PARAPET DESIGN

TABLE A.30

SUMMARY OF CONCRETE PARAPET DESIGNS




| SL | $M_b$ FT-KIP/FT | $M_w$ FT-KIP/FT | $M_c$ FT-KIP/FT | $W\ell$ KIP | L FT | ESTIMATED COST $/L.F. |
|---|---|---|---|---|---|---|
| 1 | 11.6 | 0.0 | 3.9 | 31.5 | 10.8 | 20.91 |
| 2 | 11.6 | 8.8 | 5.9 | 60.4 | 13.7 | 24.81 |
| 3 | 11.6 | 11.6 | 11.6 | 94.1 | 12.4 | 31.49 |
| 4 | 57.0 | 7.1 | 23.5 | 172.0 | 11.6 | 39.53 |



direct relationship between collision severity and occupant injuries and fatalities and vehicle/barrier damage, this relationship is inadequately defined at this time to be of practical use in the program. Intensity of vehicle/barrier interactive forces appears to be a suitable severity assessment criterion for developing bridge railings to specific containment capabilities.

Considering physical properties of the vehicle, approach angle, vehicle speed as well as geometry and stiffness of the barrier, there is an unlimited number of unique vehicle/barrier impact conditions. To simplify the analysis of this matrix and to develop predictive equations whereby the interactive forces are determined from impact conditions, attempts have been made by the authors (NCHRP Report 115) and by others (NCHRP Report 86) to analyze the impacts by classical mechanics (i.e., vehicle momentum, vehicle kinetic energy). These attempts using passenger vehicles only have produced equations that correlate at best with results from a limited few crash tests and are, therefore, not generally reliable. The vehicle/barrier collision involves a complex sequence of dynamic events and cannot be adequately modeled by a theoretically derived closed form expression.

The redirection index (RI) expression estimates the lateral impulse on a longitudinal barrier during vehicle collision from the instant of impact until the vehicle becomes parallel or loses contact with the barrier, whichever occurs first; see Figure A.15. The general expression, cast as a function of total lateral momentum, is as follows:

$$RI = kAB\ (mv \sin \theta) = K\ (mv \sin \theta) \tag{A.4}$$

where

k = nondimensional constant; 0.891 for rigid barriers and 0.955 for flexible barriers



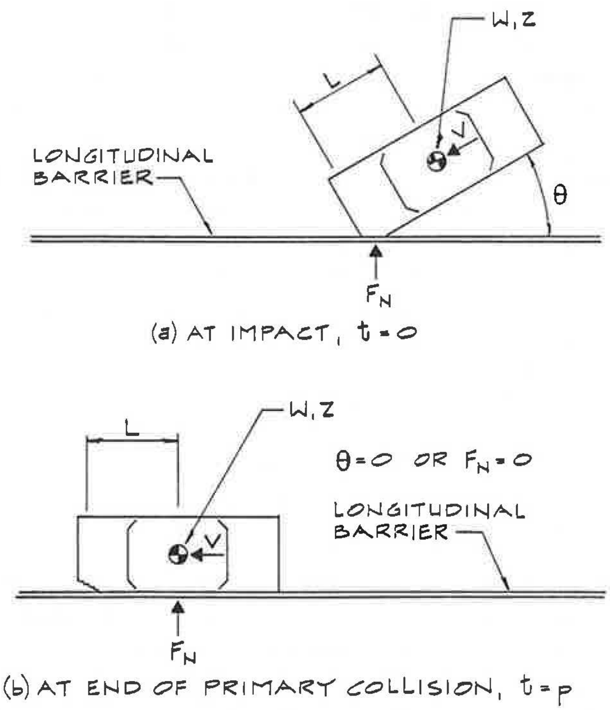



FIGURE A.15 VEHICLE REDIRECTION THRU PRIMARY COLLISION PHASE

A = nondimensional vehicle property term $\left[\frac{Z/12}{W/32.2\ L^2}\right]^{0.6424}$ $\left[\frac{100{,}000}{W}\right]^{0.090}$ where Z is yaw moment of inertia, in-lb-$s^2$, W is vehicle weight, lb, and L is longitudinal distance from vehicle center of mass to front corner strong point

B = nondimensional vehicle impact condition $\left[\frac{1}{\cos\theta}\right]^{3.897}$ where $\theta$ is the approach angle, deg

$mv \sin\theta$ = vehicle momentum normal to the barrier at instant of impact, lb-s; m is vehicle mass in slugs, v is impact speed, fps, and $\theta$ is approach angle, deg

The primary purpose of the expression is to provide a method to rank order the innumerous combinations of vehicle types, sizes and impact conditions with respect to dynamic structural loading on a barrier.

With exception of a 7 percent change in the k constant between a rigid (i.e., 0.891) to a flexible barrier (i.e., 0.955), the RI is independent of barrier design and flexibility. On the other hand, for the same RI conditions (or vehicle momentum change during primary collision), the vehicle-barrier normal force level will be much higher for a rigid system, where the vehicle is quickly redirected, than for a flexible barrier where the vehicle is redirected less abruptly. Thus while RI is independent of barrier flexibility, the normal force developed between the vehicle and barrier is dependent on both RI and the barrier design.

RI is a measure of only the primary collision; this phase of the event is defined as occurring from instant of impact until either the vehicle is redirected parallel or it loses contact with the barrier, whichever occurs first. The primary impulse may be composed of more than one force



peak depending on vehicle geometry, crush properties, and hard point locations. There may or may not be a secondary collision; secondary collision is characterized by the vehicle continuing to yaw after the primary collision with the rear of the vehicle striking the barrier. The impulse loading on the barrier during the secondary collision may exceed that of the first collision and may result in additional deformation and damage to the barrier. From a vehicle containment view, it is believed that the barrier design function is achieved if the vehicle is redirected during primary collision irrespective of subsequent barrier deformation and damage.

RI Development. From Newton's second law of motion, a vehicle-longitudinal barrier collision can be described by

$$\int_0^t F_y\, dt = m v_{y_0} - m v_{y_P} \qquad \text{(A.5)}$$

where

$F_y$ = dynamic force, lb, normal to the barrier,

m = vehicle inertial mass, slugs,

$v_{y_0}$, $v_{y_P}$ = vehicle cg velocity, fps, normal to the barrier at times o and t, respectively.

This equation ignores angular momentum that may be imparted to the vehicle during the redirection. Moreover, $v_{y_P}$ at the conclusion of the primary collision is generally not 0 with the vehicle center of mass either moving toward or away from the barrier. For this reason, the linear impulse on the barrier cannot be determined by equation (A.5) and must be estimated by an empirical expression such as equation (A.4).

The RI was developed by multiple regression procedures of a matrix of vehicle-barrier impact conditions as the independent variables and the vehicle lateral momentum change during primary collision as the dependent



variable. For each set of vehicle impact conditions, the vehicle lateral momentum change was calculated by BARRIER VII computer simulations. BARRIER VII uses a two-dimensional analog of the vehicle simulating motions in the plane of the road; roll, pitch and vertical motions are not simulated.

The barrier used in the RI development simulations was a rigid vertical wall. The barrier does not deflect during the collision; thus the RI expression is a function of the impact conditions and is essentially independent of the barrier design.

Twenty-three cases were included in the BARRIER VII computer simulation matrix. Included were vehicles ranging from 2250 to 40,000 lb (1020 to 18,100 kg), impact angles from 5 to 25 deg, and impact speeds from 30 to 60 mph (50 to 95 km/h). Vehicle size and yaw moments of inertia were also subtle variations. These cases are presented in Table A.31 along with the output from the computer simulations.

Vehicle lateral momentum change was determined from the BARRIER VII cases in the following manner. At instant of impact, the vehicle velocity normal to the barrier was read; a second vehicle velocity normal to the barrier was read from the computer output at the time that the vehicle heading angle was 0 (parallel to the barrier) or when barrier contact was lost, whichever occurred first. The change in this normal velocity multiplied by the vehicle inertial mass is the change in lateral momentum. It is noted that due to possible yawing motion of the vehicle, the lateral velocity of the center of mass of the vehicle is not necessarily zero when the heading angle is zero or loss of contact occurs.

Using the 23 cases and the variables of Z, W, L, v, and $\theta$, the RI expression has an index of determination in the log regime of 0.991.

## TABLE A.31

## RIGID BARRIER SIMULATION CASES AND RI FORMULATION

| Case No. | Vehicle Properties[(a)] Mass (lb) | Vehicle Properties[(a)] Yaw Moment of Inertia ($lb\text{-}in.\text{-}s^2$) | Vehicle Properties[(a)] Yaw Length[(b)] (ft) | Impact Speed (mph) | Impact Angle (deg) | Curve Fit Assessment RI[(c)] (lb-s) | Curve Fit Assessment $\overline{M}$[(d)] (lb-s) | Curve Fit Assessment $RI/\overline{M}$ |
|---|---|---|---|---|---|---|---|---|
| 1 | 2,250 | 15,600 | 6.50 | 60 | 25 | 2,822 | 2,750 | 1.0262 |
| 2 | 2,250 | 15,600 | 6.50 | 60 | 15 | 1,349 | 1,315 | 1.0259 |
| 3 | 2,250 | 15,600 | 6.50 | 40 | 25 | 1,882 | 1,866 | 1.0086 |
| 4 | 2,250 | 15,600 | 6.50 | 40 | 15 | 899 | 865 | 1.0393 |
| 5 | 4,500 | 47,000 | 7.75 | 60 | 25 | 5,505 | 5,477 | 1.0051 |
| 6 | 4,500 | 47,000 | 7.75 | 60 | 15 | 2,630 | 2,656 | 0.9902 |
| 7 | 4,500 | 47,000 | 7.75 | 40 | 25 | 3,670 | 3,743 | 0.9805 |
| 8 | 4,500 | 47,000 | 7.75 | 40 | 15 | 1,753 | 1,783 | 0.9932 |
| 9 | 8,000 | 100,000 | 9.50 | 60 | 25 | 8,029 | 8,097 | 0.9916 |
| 10 | 8,000 | 100,000 | 9.50 | 60 | 15 | 3,836 | 3,913 | 0.9803 |
| 11 | 8,000 | 100,000 | 9.50 | 40 | 25 | 5,353 | 5,520 | 0.9697 |
| 12 | 8,000 | 100,000 | 9.50 | 40 | 15 | 2,557 | 2,631 | 0.9719 |
| 13 | 8,000 | 100,000 | 9.50 | 30 | 25 | 4,015 | 4,161 | 0.9649 |
| 14 | 8,000 | 100,000 | 9.50 | 30 | 15 | 1,918 | 1,979 | 0.9692 |
| 15 | 23,000 | 1,000,000 | 17.91 | 60 | 15 | 9,891 | 10,026 | 0.9865 |
| 16 | 23,000 | 1,000,000 | 17.91 | 60 | 5 | 2,953 | 2,829 | 1.0438 |
| 17 | 23,000 | 1,000,000 | 17.91 | 40 | 25 | 13,801 | 13,451 | 1.0260 |
| 18 | 23,000 | 1,000,000 | 17.91 | 40 | 15 | 6,594 | 6,569 | 1.0038 |
| 19 | 23,000 | 1,000,000 | 17.91 | 30 | 25 | 10,351 | 10,036 | 1.0314 |
| 20 | 40,000 | 2,100,000 | 22.49 | 60 | 15 | 13,787 | 14,047 | 0.9815 |
| 21 | 40,000 | 2,100,000 | 22.49 | 40 | 25 | 19,238 | 19,768 | 0.9732 |
| 22 | 40,000 | 4,200,000 | 22.49 | 40 | 25 | 30,029 | 29,661 | 1.0124 |
| 23 | 40,000 | 1,050,000 | 22.49 | 40 | 25 | 12,325 | 12,098 | 1.0188 |
| | | | | | | | | $\bar{x} = 0.9997$ |
| | | | | | | | | $\sigma = 0.0245$ |

(a) Inertial properties of vehicle; all mass rigidly secured to vehicle structure.

(b) Longitudinal dimension from vehicle center of mass to forward contact point.

(c) Calculated from expression:

$$RI = 0.8911\left[\frac{Z/12}{W/32.2\ L^2}\right]^{0.6424}\left[\frac{100,000}{W}\right]^{0.09}\left[\frac{1}{\cos\theta}\right]^{3.897}\left[\left(\frac{W}{32.2}\right)\left(\frac{88V}{60}\right)\sin\theta\right]^{1.0}$$

(d) Determined from computer simulations; change in vehicle lateral momentum during primary collision.

The RI values were calculated for each case to compare with the lateral impulse input; a ratio was determined to show percentage difference and standard deviation. As shown, the standard deviation is 2.5%, and the RI expression is equally valid over the full range of cases.

Limitations. Due to procedures and techniques used in developing the RI, there are several important limitations of the RI that potential users should be aware of:

- Impacting vehicle is assumed to remain planar during redirection and thus does not exhibit significant rolling, pitching or vertical displacements. This constraint is due to the BARRIER VII computer program 2D analogue. It is noted that preferred vehicle behavior during interactions with well-behaved barrier systems is generally planar without rolling and pitching.
- The height of vehicle-barrier contact is not specified in the RI expression. In general, the loading height will be greater for the larger vehicles when the barrier has a rigid, wide vertical contact surface. The loading height variation becomes less definitive as the principal barrier rail element becomes narrow and flexible.
- The RI is based on the normal impulse delivered to the barrier during only the primary collision phase and does not reflect the total magnitude of the collision. The impulse delivered to the barrier during the secondary collision may be less than, equal to, or more than the primary impulse collision.
- The RI is applicable to nonarticulated vehicles such as passenger sedans, pickups, buses, and van type trucks. Articulated vehicles such as tractor-trailers are not addressed by the expression.
- The range of RI should be confined to impact conditions within the scope of cases shown in Table A.14. That is, vehicle mass should not exceed 40,000 lb (18,100 kg) and impact speed should not exceed 60 mph (95 km/h).

Validation. The RI expression was evaluated for two stages of validation: (1) comparison of RI values with those from BARRIER VII computer cases of a typical flexible bridge rail and (2) comparison of RI values or coefficients with appropriate values from vehicle crash tests.

Flexible Barrier Computer Cases. Eleven BARRIER VII computer simulation cases were performed on a proposed bridge rail consisting of a



12-ga tubular thrie beam mounted on W6x15.5 posts at 6.25-ft (1.9-m) centers. These cases are given in Table A.32. To be noted is that the RI is varied from 2241 (Case C10) to 23,171 (Case C32) lb-s, impact speed from 23 to 60 mph (37 to 95 km/h), vehicle mass from 2250 to 40,000 lb (1020 to 18,100 kg), and impact angle either 15 or 25 deg. Also, it is noted that barrier deflection ranges from 2.04 in. (50 mm) to over 30 in. (0.8 m) and installation estimated damage from 0 to 5 posts knocked down.

The RI was calculated from the vehicle properties and impact conditions given in Table A.33. $\overline{M}$ (vehicle lateral momentum change) was determined from the results of BARRIER VII computer simulation runs in a manner similar to that used in Table A.31:

$$\overline{M} = m\,(v_{y_o} - v_{y_p}) \tag{A.6}$$

The ratio of RI and $\overline{M}$ indicate the relative degree of prediction at each case. Overall, the standard deviation is determined to be 0.053 or 5.3 percent and is considered to be most adequate for this type of work.

Crash Test Results. In Table A.33 vehicle crash test results are compared to RI prediction values. Crash tests were selected from experimental programs previously conducted at SwRI and TTI for FHWA. Dynamic deflection of the barrier installation was essentially nil in all cases shown in Table A.33, and the RI constant k of 0.955 was used. For the experimental cases, the effective yaw length of the vehicle was defined as the longitudinal distance from the vehicle center of mass to the midpoint between the front axle and the bumper. It should be noted that Z, W, L, V, and θ are all critical input parameters. In most cases, all of the parameters were not measured, and therefore it was necessary to estimate their values. It should be recognized that the RI is sensitive to the parameters and considerable error can be introduced by poor estimates.



TABLE A.32

COMPARISON OF RI WITH FLEXIBLE BARRIER SIMULATION CASES

| | Vehicle Properties | | | Impact | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Case No. | Mass (lb) | Yaw Moment of Inertia (lb-in.-s²) | Yaw Length (ft) | Speed (mph) | Angle (deg) | Posts Out (No.) | Deflection (in.) | $\overline{M}$ (lb-s) | RI (lb-s) | RI/$\overline{M}$ |
| C10 | 2,250 | 14,400 | 6.50 | 46.8 | 25.0 | 0 | 2.04 | 2,190 | 2,241 | 1.0232 |
| C11 | 4,500 | 50,000 | 7.75 | 60.0 | 15.0 | 0 | 2.12 | 3,177 | 2,934 | 0.9235 |
| C12 | 4,500 | 50,000 | 7.75 | 34.0 | 25.0 | 0 | 2.03 | 3,306 | 3,479 | 1.0523 |
| C13 | 20,000 | 795,600 | 17.70 | 29.8 | 15.0 | 0 | 2.92 | 4,481 | 4,446 | 0.9922 |
| C14 | 40,000 | 2,100,000 | 22.41 | 23.0 | 15.0 | 0 | 3.59 | 5,867 | 5,690 | 0.9698 |
| C20 | 4,500 | 50,000 | 7.75 | 60.0 | 25.0 | 1 | 8.92 | 5,593 | 6,140 | 1.0978 |
| C21 | 20,000 | 795,600 | 17.70 | 52.6 | 15.0 | 1 | 8.56 | 7,803 | 7,848 | 1.0058 |
| C22 | 40,000 | 2,100,000 | 22.41 | 40.6 | 15.0 | 1 | 10.42 | 10,367 | 10,045 | 0.9689 |
| C31 | 40,000 | 2,100,000 | 22.41 | 60.0 | 15.0 | 3 | 20.76 | 15,460 | 14,845 | 0.9602 |
| C32 | 40,000 | 4,200,000 | 22.41 | 60.0 | 15.0 | 5 | 30.84 | 22,665 | 23,171 | 1.0223 |
| C33 | 40,000 | 1,050,000 | 22.41 | 60.0 | 15.0 | 1 | 13.30 | 8,810 | 9,510 | 1.0795 |

$\bar{x} = 1.0087$

$\sigma = 0.0531$

## TABLE A.33

## COMPARISON OF RI WITH EXPERIMENTAL DATA

| Test No. | Vehicle | Mass (lb) | Yaw Moment of Inertia(a) (in.-lb-s$^2$) | Yaw Length(b) (ft) | Impact Speed (mph) | Impact Angle (deg) | Impact Impulse(c) (lb-s) | $\Delta V_N / V_N$ (d) | $\bar{H}$(e) (lb-s) | RI(f) (lb-s) | H/RI |
|---|---|---|---|---|---|---|---|---|---|---|---|
| RF-1 | '71 Pinto | 2,140 | 12,000 | 4.56 | 63.6 | 16.8 | 1,792 | 31.47/23.84 | 2,666 | 2,172 | 1.2274 |
| RF-2 | '74 Ambassador | 4,300 | 45,000 | 6.28 | 66.6 | 23.9 | 5,285 | 47.70/38.84 | 6,490 | 7,127 | 0.9107 |
| RF-4 | '69 Toyota | 2,130 | 12,000 | 4.23 | 57.0 | 15.5 | 1,478 | 28.66/24.30 | 1,743 | 1,930 | 0.9032 |
| RF-5 | '71 Pinto | 2,140 | 12,000 | 4.56 | 56.7 | 17.1 | 1,625 | 26.45/27.07 | 1,587 | 1,983 | 0.8006 |
| RF-6 | '73 Mercury | 4,370 | 47,000 | 6.33 | 60.0 | 25.0 | 5,047 | 41.89/37.19 | 5,684 | 7,084 | 0.8025 |
| RF-10 | '69 Chrysler | 4,350 | 47,700 | 5.86 | 60.0 | 21.7 | 4,396 | 37.93/34.78 | 4,794 | 6,263 | 0.7655 |
| RF-11 | '70 Opel | 2,050 | 11,000 | 4.54 | 64.5 | 15.1 | 1,569 | 25.45/23.62 | 1,690 | 1,806 | 0.9361 |
| RF-21 | '71 Pinto | 2,140 | 12,000 | 4.56 | 44.1 | 16.2 | 1,200 | 17.84/18.39 | 1,164 | 1,436 | 0.8101 |
| RF-28 | Int. Bus | 40,000 | 1,800,000 | 20.05 | 56.3 | 14.5 | 25,682 | 10.25/16.94 | (15,539) | (13,020) | (g) |
| | | 28,200 | 1,500,000 | 20.84 | 56.3 | 14.5 | 18,106 | 10.25/16.94 | 10,956 | 10,036 | 1.0922 |
| TTR-2 | School Bus | 20,000 | 722,000 | 16.50 | 56.1 | 17.8 | 15,622 | 21.65/27.60 | (12,254) | (10,030) | (g) |
| | | 13,800 | 582,000 | 14.30 | 56.1 | 17.8 | 10,780 | 21.65/27.60 | 8,456 | 9,503 | 0.8898 |
| 3451-29 | '74 Honda | 2,050 | 9,200 | 4.27 | 59.0 | 15.5 | 1,472 | - | 1,600 | 1,647 | 0.9715 |
| 3451-30 | '74 Vega | 2,800 | 18,800 | 5.19 | 58.3 | 14.8 | 1,893 | - | 1,900 | 2,048 | 0.9277 |
| 3451-31 | '74 Vega | 2,830 | 18,800 | 5.19 | 55.9 | 18.5 | 2,288 | - | 3,100* | 2,651 | * |
| 3451-32 | '74 Fury | 4,680 | 48,600 | 6.04 | 59.7 | 16.5 | 3,613 | - | 6,300* | 4,202 | * |
| 3451-34 | '70 Ford School Bus | 20,030 | 722,000 | 16.50 | 57.6 | 15.0 | 13,601 | - | (8,800) | (8,247) | (g) |
| | | 12,800 | 582,000 | 14.30 | 57.6 | 15.0 | 8,691 | - | 8,800 | 7,655 | 1.1496 |
| 3451-35 | '62 Int. C. Bus | 32,020 | 1,250,000 | 17.08 | 56.9 | 15.7 | 22,456 | - | (8,800) | (13,316) | (g) |
| | | 20,310 | 768,000 | 17.50 | 56.9 | 15.7 | 14,244 | - | 8,800 | 8,356 | 1.0531 |
| 3451-36 | '75 Plymouth | 4,740 | 48,600 | 6.04 | 59.9 | 24.0 | 5,260 | - | 6,600 | 7,318 | 0.9019 |
| | | | | | | | | | | $\bar{x}$ = | 0.9336 |
| | | | | | | | | | | $\sigma$ = | 0.1179 |
| | | | | | | | | | | $\sigma/\bar{x}$ | 0.126 or 12.5% |

(a) Estimated

(b) Long. distance from center-of-mass to midpoint between front wheel axle and front bumper

(c) mv sin θ for impact conditions, where v is impact velocity

(d) Ratio of velocity change (mph) to impact velocity, normal to barrier; values taken from test cine data

(e) Primary collision impulse measured from instrumented wall data or change in vehicle momentum

(f) Redirection index or prediction of vehicle momentum change during primary collision; rigid

(g) Loose ballast not effective in primary collision; only vehicle test inertial mass values are shown and used

* Test results appear high; value not used

A comparison of $\overline{M}$ and RI is shown in Table A.33. The standard deviation for these 15 cases is about 12 percent and is considered good. To be noted is that significant experimental error may exist in some of these tests and that the crash test results should not necessarily be accepted as the true value. Moreover, vehicle properties of yaw moments of inertia and yaw length were not measured for the crash tests and had to be estimated. Finally, the effect of shifting ballast during primary collision of the heavy vehicles can have important effects on the impulse; it is surmised that the ballast, although partially restrained, has some influence on the primary collision, but this fact cannot be evaluated for these tests.

Discussion and Appraisal - Primary Collision Only. In view of the facts that maximum barrier deflection, maximum vehicle accelerations, and considerable barrier damage may occur during a rear end slap when the rear of the vehicle swings around and strikes the installation, one may question the reasoning in using only the primary collision for basis of the RI.

From a barrier strength, vehicle containment goal, the primary collision is believed to be the most important factor. That is, if the vehicle can be redirected to a 0 heading angle, the vehicle will be contained on the traffic side of the barrier in most if not all cases. Accident data are not available to show that vehicles retained during primary collision and subsequently penetrating an installation during secondary collision is a problem.

As shown in Tables A.31, A.32, and A.33, the dynamics of the primary collision are predictable within 12 percent standard deviation over a wide range of conditions. However, subsequent vehicle dynamics and kinematics are a function of (a) the primary collision, (b) the barrier



flexibility, and (c) the installation damage, and thus become more indeterminate. It is believed that extending the range of the RI to include possible secondary vehicle collision would degrade its usefulness in evaluating the primary collision.

In the past, passenger sedan vehicles have been the principal design vehicle for structural adequacy testing of longitudinal barriers; load or ballast shift during barrier collision has not been an important factor. However, with the downsized car, the unsecured occupant mass represents an important portion of the minicompact vehicle mass. Also, with consideration of buses and trucks, the passenger and cargo load can exceed 40 to 50 percent of the vehicle inertial mass. Whereas the primary collision is affected by this shiftable mass, the secondary collision is more importantly influenced and becomes less determinate for both barrier loading and vehicle stability.

Impulse as Severity Indicator. The RI expression is formulated as barrier loading impulse or the equivalent change in vehicle momentum normal to the barrier during primary collision. For the extreme case, barrier loading severity can be quantified objectively by whether or not the vehicle penetrated the installation. For less extreme cases, loading severity may be inferred by the number of posts that are knocked down. Another measure is the maximum dynamic deflection that occurs during the primary collision. The RI does not predict any of these directly but the impulse measure may serve as a surrogate indicator.

A comparison of barrier deflection with RI for cases given in Table A.32 is shown in Figure A.16. It is noted that the relationship between RI and barrier deflection is linear. This same relationship holds for posts that are knocked down.



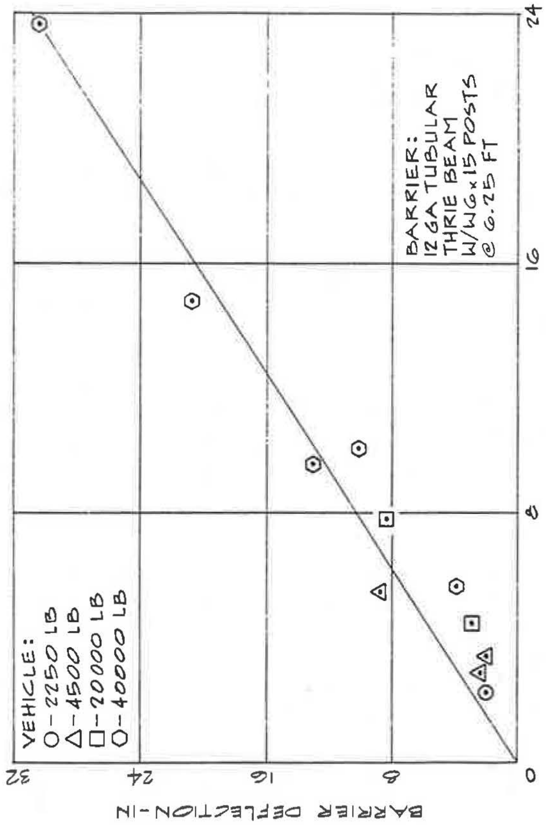



FIGURE A.16 COMPARISON OF FLEXIBLE BARRIER DEFLECTION WITH RI



For this study, it appears that RI is nearly independent of barrier flexibility, varying about 7 percent between a rigid concrete wall and a system that deflects up to 30 inches. Thus the RI is nearly independent of barrier design and flexibility. For a given barrier design, the RI-deflection relationship can be established (see Figure A.16) with two or three crash test conditions; other impact conditions can then be evaluated for barrier deflection.

Other Indicators. In addition to impulse, other barrier loading indicators were examined but were deemed less desirable for one or more reasons.

Force. Contact force between the vehicle and the barrier is certainly an indicator of the collision severity. However, the force is highly dependent on vehicle crush properties and barrier flexibility. By using a rigid barrier in the basic RI formulation, the barrier effect is essentially removed; however, vehicle crush characteristics remain. Another factor is the minimum time duration of importance; should the force be instantaneous values or averaged over finite time intervals such as 50 or 100 ms? Using the RI expression based on rigid wall peak force for nonrigid barriers, the force prediction becomes less meaningful. Hence, this approach was not pursued.

Total Impulse. As shown in Figure A.17, primary collision barrier deflections are presented as a function of total vehicle momentum normal to the barrier at the instant of impact for the 11 cases presented in Table A.32. Although there is a general trend in the points, several fall away from the curve.

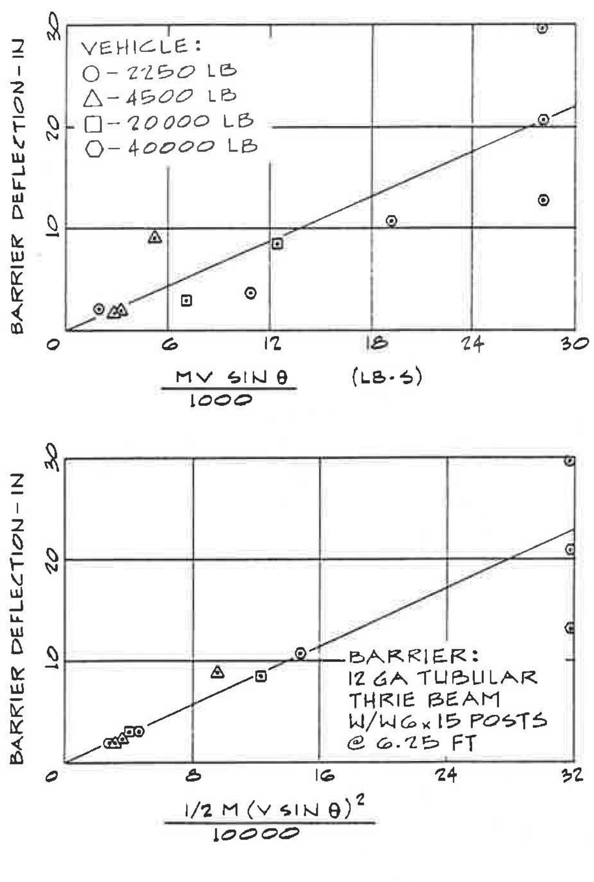



FIGURE A.17 BARRIER DEFLECTION AS FUNCTION OF IMPACT MOMENTUM AND KINETIC ENERGY



Energy. Impact loading severity can be inferred by a quasi-kinetic energy equation:

$$LE = 1/2\ m v^2\ (\sin\theta)^2 \qquad (A.7)$$

where LE is lateral kinetic energy of the vehicle at impact, ft-lb. Assigning a vector sense to a scaler quantity, such as energy, is of course technically meaningless. However, there appears to be a direct relationship between this parameter and maximum barrier deflection during primary collision, at least for the uniformly loaded vehicles. As shown in Figure A.17, the two points which represent nonuniform distribution of vehicle mass fall away from the curve and thus are not predicted by the linear relationship. In considering a vehicle population that includes trucks with unusual cargo mass distribution, the LE method is deemed insufficient for predicting critical barrier loading.

RI Observations. The nondimensional A term of equation (A.4) is a vehicle property that is a function of Z, W, and L. For non-cargo carrying vehicles, the A term is practially constant for a specific model of vehicle. On the other hand, A may vary greatly due to the location of cargo and its effect on Z and L.

To have a minimum RI value for a specific mass vehicle and impact conditions, the cargo mass should be located near the vehicle center of mass to minimize the yaw moment of inertia Z, and/or the cargo should be located at extreme end of the vehicle to maximize the yaw length L.

In the computer simulation cases used to formulate and verify the RI expression, the yaw length L was measured longitudinally from the vehicle center of mass to the impact corner of the vehicle because of convenience and the degree of definition of the analog vehicle. Sub-



sequently, in calculating RI for crash tests, L was measured longitudinally from the vehicle center of mass to the midpoint of the vehicle front and front wheel axle. Actually, L varies during a crash test from the former definition to the latter. Using the midpoint approach, the RI values appear to be conservative or on the high side of crash test results.

Summary. A redirection index (RI) has been developed to compare the relative barrier loading intensity of various vehicles and impact conditions. The expression was developed from a multiple regression analysis of results from 23 computer simulations of vehicle-rigid barrier interactions. The expression is also applicable to flexible longitudinal barriers. When compared to full-scale vehicle crash test results, the RI predictions are within an 11-percent standard deviation.

Although subsequent vehicle dynamics can produce barrier damage and larger barrier deflections, the RI expression is based on the primary collision and uses impulse as the indicator of loading intensity.

Principal uses of the RI are to rank order the innumerous combinations of vehicle impact conditions:

- **A finite number of carefully selected vehicle crash tests can be rationally formulated that will represent a large percentage of highway accidents.**
- **Serve as a basis of cost-effectiveness evaluation of barrier systems and design approaches such as the multiple service level approach for bridge rail selection.**
- **Provide basic insight into the vehicle/barrier interaction.**

### A.2.2 Bridge Railing Service Levels

Four bridge railing service levels are shown in Table 2 with the corresponding RI; these levels were chosen to provide a range of



RI values and correspond to conditions of impact that are currently used in experimental crash test programs.

Service Level (S.L. ) 2 corresponds to the TRB Circular 191 structural adequacy requirement. S.L. 1 was set by specifying a 4500-lb (2040-kg) vehicle impacting at 60 mph (26.8 m/s) and 15 deg. S.L. 3 is an intermediate impact of a 20,000-lb (18,100-kg) bus and S.L. 4 is a severe impact with a 40,000-lb (18,100-kg) intercity bus.

### A.2.3 MSLA Computer Program (MSLA-2)

A logic flow diagram of the MSLA computer program (MSLA-2) is shown in Figure A. 18.

Two sets of tables are included that are output from the computer program. The first set (Table A.34), as illustrated by Table 12 in Chapter Two, permits the examination of a large array of bridge site possibilities. These critical impact tables contain data for two-lane bridges of 8, 9, 10, 11, and 12 ft (2.4, 2.7, 3.0, 3.4, and 3.7 m) lane widths with shoulder increments from 0-10 ft (0-3.0 m).

Although speed is not a critical factor in the MSLA formulations, speeds of 30, 40, 50, and 55 mph are also included. The data in these tables include the number of bridge railing impacts predicted and the number of penetrations prevented by each service level railing. These values can be used to calculate B/C ratios as described in example of Table 12.

The second set of tables (Table A.35) comprises the complete set of typical roadway tests as described in Table 8 of Chapter Two. Using these tables, a designer can readily select service levels based on B/C rather than 1.0 by using the ADT for B/C = 1.0 and ratioing accordingly.

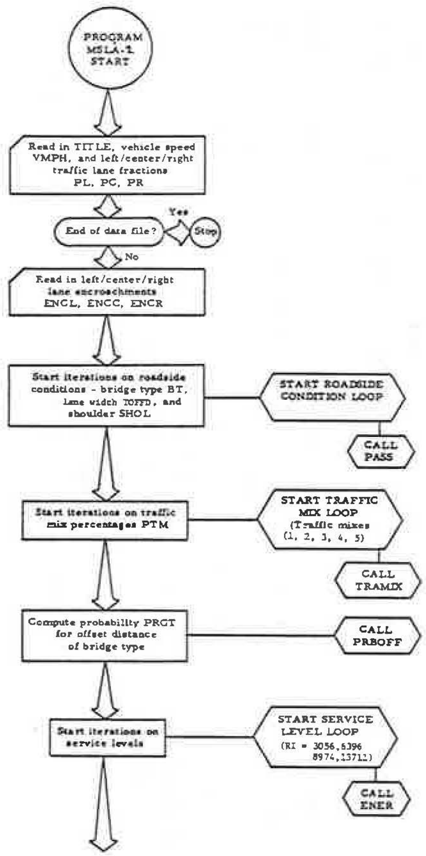



FIGURE A.18 MSLA COMPUTER PROGRAM FLOW DIAGRAM

A.87

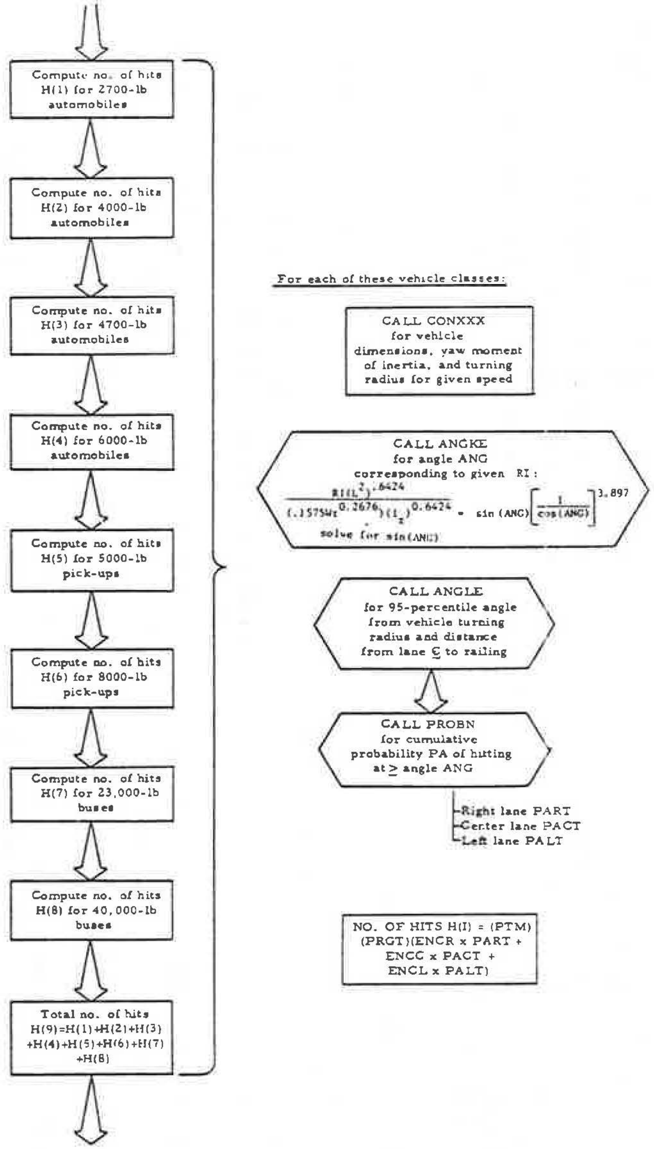



FIGURE A.18 (Cont'd)

A.88

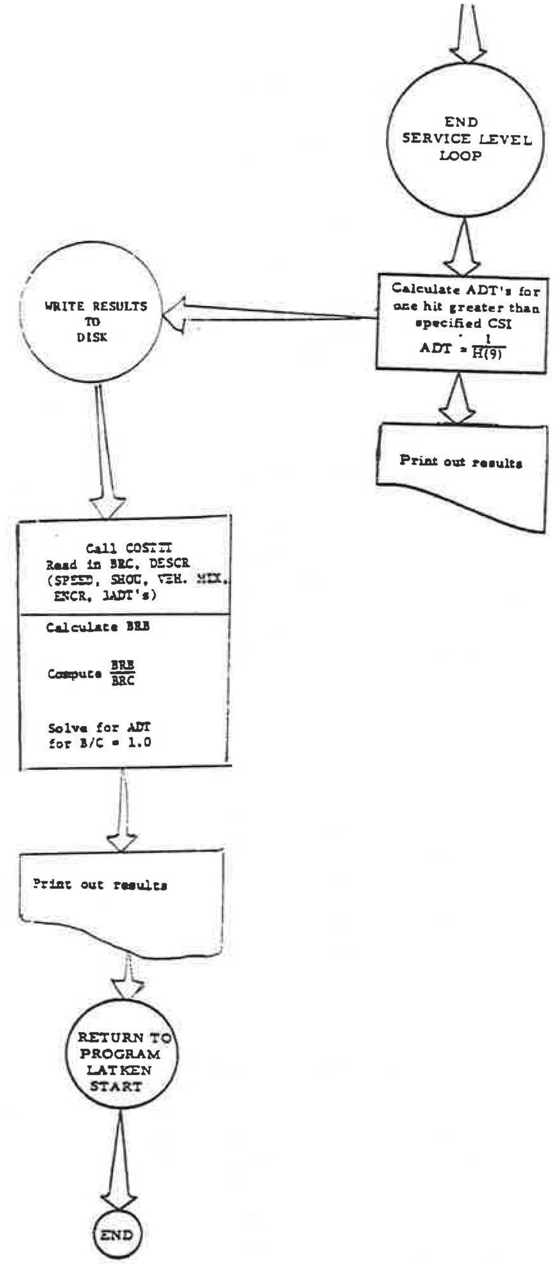



FIGURE A.18 (Cont'd)

A.89

TABLE A.34

CRITICAL IMPACT TABLES

2LANE

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
BRIDGE WITH 50/50 TRAFFIC SPLIT 12'LN CO=1

DESIGNATED SPEED (MPH) = 55.0
NUMBER OF PENETRATIONS PREVENTED

3 LANE

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
BRIDGE WITH 25/50/25 TRAFFIC SPLIT CO=1

DESIGNATED SPEED (MPH) = 55.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | 2 LANE: NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT | 3 LANE: NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0. | | | | | | | | | | | |
| | 1 | .8902 | .9486 | .9572 | .9597 | .95979E+00 | .7357 | .9082 | .9413 | .9567 | .95988E+00 |
| | 2 | .8906 | .9432 | .9488 | .9502 | .95030E+00 | .7495 | .9117 | .9374 | .9483 | .95039E+00 |
| | 3 | .8944 | .9449 | .9487 | .9493 | .94935E+00 | .7591 | .9187 | .9403 | .9481 | .94944E+00 |
| | 4 | .8970 | .9450 | .9493 | .9503 | .95031E+00 | .7648 | .9184 | .9401 | .9488 | .95039E+00 |
| | 5 | .9026 | .9465 | .9490 | .9494 | .94937E+00 | .7792 | .9256 | .9426 | .9485 | .94945E+00 |
| 2. | | | | | | | | | | | |
| | 1 | .7408 | .8126 | .8220 | .8254 | .82561E+00 | .6047 | .7715 | .8049 | .8218 | .82566E+00 |
| | 2 | .7469 | .8087 | .8152 | .8173 | .81744E+00 | .6183 | .7760 | .8027 | .8148 | .81748E+00 |
| | 3 | .7540 | .8106 | .8155 | .8166 | .81662E+00 | .6278 | .7828 | .8060 | .8149 | .81667E+00 |
| | 4 | .7550 | .8107 | .8159 | .8174 | .81744E+00 | .6324 | .7828 | .8056 | .8154 | .81749E+00 |
| | 5 | .7633 | .8125 | .8160 | .8166 | .81663E+00 | .6459 | .7899 | .8085 | .8153 | .81667E+00 |
| 4. | | | | | | | | | | | |
| | 1 | .6131 | .6994 | .7100 | .7142 | .71467E+00 | .4978 | .6588 | .6920 | .7101 | .71470E+00 |
| | 2 | .6238 | .6969 | .7047 | .7073 | .70759E+00 | .5112 | .6638 | .6911 | .7044 | .70762E+00 |
| | 3 | .6325 | .6991 | .7052 | .7068 | .70689E+00 | .5202 | .6702 | .6946 | .7047 | .70692E+00 |
| | 4 | .6339 | .6993 | .7055 | .7074 | .70760E+00 | .5244 | .6705 | .6942 | .7050 | .70762E+00 |
| | 5 | .6444 | .7014 | .7058 | .7068 | .70689E+00 | .5371 | .6774 | .6974 | .7052 | .70692E+00 |
| 6. | | | | | | | | | | | |
| | 1 | .5049 | .5992 | .6120 | .6170 | .61762E+00 | .4089 | .5605 | .5935 | .6122 | .61764E+00 |
| | 2 | .5169 | .5984 | .6078 | .6111 | .61150E+00 | .4212 | .5660 | .5936 | .6076 | .61152E+00 |
| | 3 | .5253 | .6012 | .6086 | .6107 | .61089E+00 | .4290 | .5721 | .5971 | .6082 | .61091E+00 |
| | 4 | .5277 | .6011 | .6087 | .6112 | .61151E+00 | .4331 | .5724 | .5967 | .6084 | .61152E+00 |
| | 5 | .5386 | .6038 | .6093 | .6108 | .61090E+00 | .4445 | .5791 | .6000 | .6088 | .61091E+00 |
| 8. | | | | | | | | | | | |
| | 1 | .4139 | .5111 | .5262 | .5321 | .53305E+00 | .3352 | .4754 | .5078 | .5269 | .53306E+00 |
| | 2 | .4254 | .5171 | .5232 | .5272 | .52778E+00 | .3459 | .4811 | .5086 | .5233 | .52779E+00 |
| | 3 | .4329 | .5155 | .5243 | .5269 | .52725E+00 | .3526 | .4869 | .5121 | .5240 | .52726E+00 |
| | 4 | .4359 | .5152 | .5243 | .5273 | .52778E+00 | .3565 | .4873 | .5118 | .5241 | .52779E+00 |
| | 5 | .4462 | .5185 | .5251 | .5270 | .52725E+00 | .3664 | .4937 | .5151 | .5246 | .52726E+00 |
| 10. | | | | | | | | | | | |
| | 1 | .3382 | .4348 | .4515 | .4584 | .45966E+00 | .2745 | .4024 | .4337 | .4529 | .45967E+00 |
| | 2 | .3485 | .4370 | .4495 | .4543 | .45511E+00 | .2836 | .4081 | .4350 | .4500 | .45512E+00 |
| | 3 | .3549 | .4408 | .4509 | .4542 | .45465E+00 | .2853 | .4134 | .4384 | .4509 | .45466E+00 |
| | 4 | .3580 | .4404 | .4508 | .4545 | .45511E+00 | .2928 | .4139 | .4381 | .4509 | .45512E+00 |
| | 5 | .3673 | .4442 | .4519 | .4543 | .45465E+00 | .3013 | .4200 | .4414 | .4516 | .45466E+00 |

JOB FINISHED
19.20.25.UCLP. 08L03MT . 1.40KLNS.

TABLE A.34 (Cont'd)

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 8-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 30.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT |
|---|---|---|---|---|---|---|
| 0.0 | | | | | | |
| | 1 | .7852 | .8160 | .8171 | .8172 | .81722E+00 |
| | 2 | .8166 | .8419 | .8428 | .8429 | .84287E+00 |
| | 3 | .8283 | .8507 | .8513 | .8514 | .85143E+00 |
| | 4 | .8450 | .8677 | .8684 | .8685 | .86853E+00 |
| | 5 | .8712 | .8907 | .8913 | .8913 | .89134E+00 |
| 2.0 | | | | | | |
| | 1 | .7668 | .8076 | .8110 | .8116 | .81172E+00 |
| | 2 | .7605 | .7961 | .7989 | .7994 | .79947E+00 |
| | 3 | .7652 | .7984 | .8006 | .8010 | .80111E+00 |
| | 4 | .7684 | .8014 | .8038 | .8043 | .80438E+00 |
| | 5 | .7742 | .8043 | .8063 | .8068 | .80684E+00 |
| 3.0 | | | | | | |
| | 1 | .7051 | .7492 | .7541 | .7552 | .75540E+00 |
| | 2 | .6997 | .7389 | .7428 | .7438 | .74399E+00 |
| | 3 | .7042 | .7413 | .7445 | .7454 | .74552E+00 |
| | 4 | .7072 | .7440 | .7475 | .7484 | .74856E+00 |
| | 5 | .7129 | .7469 | .7498 | .7507 | .75085E+00 |
| 4.0 | | | | | | |
| | 1 | .6450 | .6943 | .7005 | .7023 | .70266E+00 |
| | 2 | .6415 | .6850 | .6901 | .6917 | .69205E+00 |
| | 3 | .6466 | .6874 | .6917 | .6931 | .69347E+00 |
| | 4 | .6491 | .6898 | .6945 | .6960 | .69630E+00 |
| | 5 | .6551 | .6927 | .6967 | .6981 | .69843E+00 |
| 6.0 | | | | | | |
| | 1 | .5283 | .5942 | .6028 | .6063 | .60724E+00 |
| | 2 | .5294 | .5868 | .5941 | .5971 | .59807E+00 |
| | 3 | .5362 | .5892 | .5957 | .5984 | .59930E+00 |
| | 4 | .5379 | .5912 | .5979 | .6008 | .60174E+00 |
| | 5 | .5455 | .5940 | .6000 | .6026 | .60358E+00 |
| 8.0 | | | | | | |
| | 1 | .4236 | .5057 | .5170 | .5221 | .52410E+00 |
| | 2 | .4273 | .5000 | .5097 | .5142 | .51618E+00 |
| | 3 | .4343 | .5026 | .5112 | .5154 | .51724E+00 |
| | 4 | .4361 | .5041 | .5131 | .5174 | .51935E+00 |
| | 5 | .4442 | .5070 | .5150 | .5190 | .52094E+00 |

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 8-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 40.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT |
|---|---|---|---|---|---|---|
| 0.0 | | | | | | |
| | 1 | .7870 | .8159 | .8171 | .8172 | .81718E+00 |
| | 2 | .8198 | .8421 | .8428 | .8428 | .84283E+00 |
| | 3 | .8321 | .8510 | .8514 | .8514 | .85138E+00 |
| | 4 | .8492 | .8680 | .8685 | .8685 | .86849E+00 |
| | 5 | .8762 | .8911 | .8913 | .8913 | .89130E+00 |
| 2.0 | | | | | | |
| | 1 | .7723 | .8084 | .8113 | .8117 | .81169E+00 |
| | 2 | .7671 | .7973 | .7992 | .7994 | .79944E+00 |
| | 3 | .7723 | .7999 | .8010 | .8011 | .80108E+00 |
| | 4 | .7759 | .8028 | .8042 | .8043 | .80435E+00 |
| | 5 | .7827 | .8060 | .8067 | .8068 | .80681E+00 |
| 3.0 | | | | | | |
| | 1 | .7104 | .7509 | .7547 | .7554 | .75537E+00 |
| | 2 | .7067 | .7410 | .7436 | .7440 | .74397E+00 |
| | 3 | .7122 | .7436 | .7453 | .7455 | .74549E+00 |
| | 4 | .7154 | .7463 | .7482 | .7485 | .74854E+00 |
| | 5 | .7223 | .7495 | .7507 | .7508 | .75083E+00 |
| 4.0 | | | | | | |
| | 1 | .6490 | .6969 | .7016 | .7026 | .70264E+00 |
| | 2 | .6481 | .6881 | .6914 | .6920 | .69203E+00 |
| | 3 | .6548 | .6908 | .6931 | .6934 | .69345E+00 |
| | 4 | .6573 | .6932 | .6958 | .6963 | .69628E+00 |
| | 5 | .6652 | .6964 | .6981 | .6984 | .69841E+00 |
| 6.0 | | | | | | |
| | 1 | .5341 | .5987 | .6052 | .6071 | .60723E+00 |
| | 2 | .5381 | .5918 | .5967 | .5980 | .59806E+00 |
| | 3 | .5464 | .5947 | .5984 | .5992 | .59928E+00 |
| | 4 | .5486 | .5966 | .6006 | .6016 | .60173E+00 |
| | 5 | .5583 | .5999 | .6028 | .6035 | .60357E+00 |
| 8.0 | | | | | | |
| | 1 | .4346 | .5118 | .5208 | .5237 | .52409E+00 |
| | 2 | .4409 | .5070 | .5138 | .5159 | .51617E+00 |
| | 3 | .4490 | .5102 | .5155 | .5170 | .51723E+00 |
| | 4 | .4516 | .5116 | .5174 | .5191 | .51934E+00 |
| | 5 | .4615 | .5151 | .5195 | .5207 | .52093E+00 |

TABLE A.34 (Cont'd)

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 8-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 50.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT |
|---|---|---|---|---|---|---|
| 0.0 | | | | | | |
| | 1 | .7870 | .8154 | .8171 | .8171 | .81714E+00 |
| | 2 | .8205 | .8418 | .8427 | .8428 | .84279E+00 |
| | 3 | .8332 | .8510 | .8513 | .8513 | .85134E+00 |
| | 4 | .8504 | .8678 | .8684 | .8684 | .86845E+00 |
| | 5 | .8780 | .8910 | .8912 | .8913 | .89125E+00 |
| 2.0 | | | | | | |
| | 1 | .7741 | .8081 | .8113 | .8117 | .81166E+00 |
| | 2 | .7697 | .7973 | .7992 | .7994 | .79941E+00 |
| | 3 | .7752 | .8000 | .8010 | .8011 | .80105E+00 |
| | 4 | .7791 | .8028 | .8042 | .8043 | .80432E+00 |
| | 5 | .7863 | .8062 | .8067 | .8068 | .80678E+00 |
| 3.0 | | | | | | |
| | 1 | .7112 | .7508 | .7547 | .7553 | .75535E+00 |
| | 2 | .7091 | .7412 | .7436 | .7439 | .74395E+00 |
| | 3 | .7154 | .7440 | .7453 | .7455 | .74547E+00 |
| | 4 | .7186 | .7465 | .7483 | .7485 | .74852E+00 |
| | 5 | .7265 | .7499 | .7507 | .7508 | .75080E+00 |
| 4.0 | | | | | | |
| | 1 | .6490 | .6971 | .7017 | .7026 | .70262E+00 |
| | 2 | .6501 | .6886 | .6915 | .6920 | .69201E+00 |
| | 3 | .6580 | .6915 | .6932 | .6934 | .69343E+00 |
| | 4 | .6604 | .6938 | .6959 | .6963 | .69626E+00 |
| | 5 | .6696 | .6972 | .6983 | .6984 | .69839E+00 |
| 6.0 | | | | | | |
| | 1 | .5356 | .5995 | .6055 | .6071 | .60721E+00 |
| | 2 | .5415 | .5930 | .5970 | .5980 | .59804E+00 |
| | 3 | .5506 | .5961 | .5988 | .5993 | .59927E+00 |
| | 4 | .5531 | .5979 | .6010 | .6017 | .60172E+00 |
| | 5 | .5640 | .6014 | .6033 | .6035 | .60355E+00 |
| 8.0 | | | | | | |
| | 1 | .4392 | .5131 | .5215 | .5239 | .52408E+00 |
| | 2 | .4469 | .5089 | .5146 | .5161 | .51616E+00 |
| | 3 | .4556 | .5124 | .5164 | .5172 | .51722E+00 |
| | 4 | .4587 | .5137 | .5182 | .5193 | .51933E+00 |
| | 5 | .4697 | .5175 | .5203 | .5209 | .52091E+00 |

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 9-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 30.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT |
|---|---|---|---|---|---|---|
| 0.0 | | | | | | |
| | 1 | .8964 | .9399 | .9430 | .9435 | .94351E+00 |
| | 2 | .8889 | .9264 | .9288 | .9293 | .92931E+00 |
| | 3 | .8943 | .9289 | .9308 | .9312 | .93123E+00 |
| | 4 | .8979 | .9325 | .9346 | .9350 | .93504E+00 |
| | 5 | .9046 | .9358 | .9375 | .9379 | .93792E+00 |
| 2.0 | | | | | | |
| | 1 | .7539 | .8036 | .8098 | .8115 | .81174E+00 |
| | 2 | .7480 | .7927 | .7978 | .7992 | .79948E+00 |
| | 3 | .7527 | .7954 | .7996 | .8009 | .80112E+00 |
| | 4 | .7561 | .7982 | .8028 | .8041 | .80439E+00 |
| | 5 | .7621 | .8015 | .8054 | .8066 | .80685E+00 |
| 3.0 | | | | | | |
| | 1 | .6922 | .7448 | .7524 | .7549 | .75541E+00 |
| | 2 | .6876 | .7350 | .7413 | .7435 | .74400E+00 |
| | 3 | .6924 | .7377 | .7431 | .7450 | .74552E+00 |
| | 4 | .6954 | .7402 | .7460 | .7481 | .74857E+00 |
| | 5 | .7014 | .7435 | .7485 | .7503 | .75085E+00 |
| 4.0 | | | | | | |
| | 1 | .6312 | .6895 | .6984 | .7018 | .70267E+00 |
| | 2 | .6289 | .6807 | .6882 | .6912 | .69206E+00 |
| | 3 | .6346 | .6834 | .6900 | .6926 | .69347E+00 |
| | 4 | .6370 | .6857 | .6927 | .6954 | .69630E+00 |
| | 5 | .6437 | .6889 | .6950 | .6976 | .69843E+00 |
| 6.0 | | | | | | |
| | 1 | .5142 | .5891 | .6001 | .6054 | .60725E+00 |
| | 2 | .5163 | .5821 | .5916 | .5962 | .59808E+00 |
| | 3 | .5234 | .5847 | .5934 | .5975 | .59930E+00 |
| | 4 | .5252 | .5867 | .5955 | .5999 | .60175E+00 |
| | 5 | .5333 | .5897 | .5977 | .6017 | .60358E+00 |
| 8.0 | | | | | | |
| | 1 | .4111 | .5002 | .5139 | .5208 | .52410E+00 |
| | 2 | .4153 | .4950 | .5068 | .5130 | .51619E+00 |
| | 3 | .4223 | .4978 | .5085 | .5141 | .51724E+00 |
| | 4 | .4242 | .4993 | .5103 | .5161 | .51935E+00 |
| | 5 | .4325 | .5024 | .5123 | .5177 | .52094E+00 |

# TABLE A.34 (Cont'd)

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 9-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 40.0
NUMBER OF PENETRATIONS PREVENTED

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 9-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 50.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | 40.0 MPH: NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT | 50.0 MPH: NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | | | | | | | | | | | |
| | 1 | .9017 | .9404 | .9432 | .9435 | .94346E+00 | .9035 | .9399 | .9431 | .9434 | .94342E+00 |
| | 2 | .8955 | .9274 | .9291 | .9293 | .92927E+00 | .8980 | .9272 | .9290 | .9292 | .92922E+00 |
| | 3 | .9014 | .9302 | .9311 | .9312 | .93118E+00 | .9043 | .9302 | .9311 | .9311 | .93114E+00 |
| | 4 | .9056 | .9336 | .9349 | .9350 | .93500E+00 | .9087 | .9336 | .9348 | .9350 | .93496E+00 |
| | 5 | .9133 | .9372 | .9378 | .9379 | .93788E+00 | .9169 | .9373 | .9378 | .9378 | .93784E+00 |
| 2.0 | | | | | | | | | | | |
| | 1 | .7616 | .8060 | .8108 | .8117 | .81171E+00 | .7642 | .8060 | .8108 | .8117 | .81168E+00 |
| | 2 | .7571 | .7956 | .7989 | .7994 | .79946E+00 | .7607 | .7960 | .7989 | .7994 | .79943E+00 |
| | 3 | .7624 | .7986 | .8008 | .8011 | .80110E+00 | .7667 | .7992 | .8009 | .8011 | .80107E+00 |
| | 4 | .7662 | .8014 | .8039 | .8044 | .80437E+00 | .7706 | .8019 | .8040 | .8043 | .80434E+00 |
| | 5 | .7733 | .8050 | .8066 | .8068 | .80683E+00 | .7784 | .8056 | .8067 | .8068 | .80680E+00 |
| 3.0 | | | | | | | | | | | |
| | 1 | .6983 | .7482 | .7540 | .7553 | .75538E+00 | .6995 | .7487 | .7541 | .7553 | .75536E+00 |
| | 2 | .6960 | .7390 | .7431 | .7439 | .74398E+00 | .6990 | .7398 | .7432 | .7439 | .74396E+00 |
| | 3 | .7022 | .7420 | .7450 | .7455 | .74550E+00 | .7064 | .7430 | .7452 | .7455 | .74548E+00 |
| | 4 | .7053 | .7446 | .7478 | .7485 | .74855E+00 | .7095 | .7454 | .7480 | .7485 | .74853E+00 |
| | 5 | .7130 | .7482 | .7504 | .7508 | .75083E+00 | .7184 | .7492 | .7506 | .7508 | .75081E+00 |
| 4.0 | | | | | | | | | | | |
| | 1 | .6363 | .6941 | .7007 | .7025 | .70265E+00 | .6370 | .6949 | .7010 | .7026 | .70263E+00 |
| | 2 | .6369 | .6859 | .6907 | .6920 | .69204E+00 | .6398 | .6871 | .6910 | .6920 | .69202E+00 |
| | 3 | .6444 | .6889 | .6926 | .6934 | .69345E+00 | .6485 | .6903 | .6930 | .6934 | .69344E+00 |
| | 4 | .6469 | .6912 | .6952 | .6962 | .69629E+00 | .6510 | .6926 | .6956 | .6962 | .69627E+00 |
| | 5 | .6557 | .6948 | .6977 | .6984 | .69841E+00 | .6612 | .6963 | .6981 | .6984 | .69839E+00 |
| 6.0 | | | | | | | | | | | |
| | 1 | .5221 | .5955 | .6040 | .6069 | .60723E+00 | .5249 | .5970 | .6047 | .6071 | .60722E+00 |
| | 2 | .5272 | .5892 | .5957 | .5978 | .59806E+00 | .5318 | .5912 | .5965 | .5980 | .59805E+00 |
| | 3 | .5358 | .5923 | .5976 | .5991 | .59929E+00 | .5412 | .5946 | .5984 | .5992 | .59927E+00 |
| | 4 | .5382 | .5943 | .5998 | .6015 | .60173E+00 | .5440 | .5964 | .6006 | .6017 | .60172E+00 |
| | 5 | .5484 | .5978 | .6022 | .6034 | .60357E+00 | .5554 | .6003 | .6030 | .6035 | .60356E+00 |
| 8.0 | | | | | | | | | | | |
| | 1 | .4242 | .5083 | .5194 | .5234 | .52409E+00 | .4301 | .5105 | .5206 | .5238 | .52408E+00 |
| | 2 | .4309 | .5041 | .5126 | .5156 | .51617E+00 | .4382 | .5068 | .5139 | .5160 | .51616E+00 |
| | 3 | .4341 | .5075 | .5145 | .5168 | .51723E+00 | .4469 | .5107 | .5159 | .5171 | .51722E+00 |
| | 4 | .4419 | .5090 | .5163 | .5189 | .51934E+00 | .4503 | .5120 | .5176 | .5192 | .51933E+00 |
| | 5 | .4521 | .5128 | .5186 | .5205 | .52093E+00 | .4615 | .5161 | .5200 | .5209 | .52092E+00 |

# TABLE A.34 (Cont'd)

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 10-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 30.0
NUMBER OF PENETRATIONS PREVENTED

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 10-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 40.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL (30.0 MPH) 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT (30.0 MPH) | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL (40.0 MPH) 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT (40.0 MPH) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | | | | | | | | | | | |
| | 1 | .8814 | .9359 | .9420 | .9434 | .94363E+00 | .8899 | .9380 | .9428 | .9436 | .94359E+00 |
| | 2 | .8744 | .9231 | .9279 | .9292 | .92940E+00 | .8842 | .9257 | .9289 | .9294 | .92937E+00 |
| | 3 | .8798 | .9260 | .9300 | .9311 | .93131E+00 | .8902 | .9290 | .9310 | .9313 | .93128E+00 |
| | 4 | .8837 | .9294 | .9337 | .9349 | .93512E+00 | .8947 | .9322 | .9347 | .9351 | .93508E+00 |
| | 5 | .8907 | .9330 | .9367 | .9378 | .93799E+00 | .9027 | .9363 | .9378 | .9379 | .93795E+00 |
| 2.0 | | | | | | | | | | | |
| | 1 | .7413 | .7985 | .8077 | .8110 | .81175E+00 | .7500 | .8030 | .8099 | .8116 | .81172E+00 |
| | 2 | .7358 | .7881 | .7959 | .7988 | .79949E+00 | .7464 | .7933 | .7982 | .7994 | .79947E+00 |
| | 3 | .7406 | .7911 | .7979 | .8004 | .80113E+00 | .7522 | .7967 | .8003 | .8011 | .80111E+00 |
| | 4 | .7440 | .7939 | .8010 | .8036 | .80440E+00 | .7559 | .7994 | .8034 | .8043 | .80438E+00 |
| | 5 | .7501 | .7975 | .8037 | .8061 | .80686E+00 | .7635 | .8034 | .8062 | .8068 | .80684E+00 |
| 3.0 | | | | | | | | | | | |
| | 1 | .6789 | .7394 | .7499 | .7542 | .75541E+00 | .6856 | .7451 | .7529 | .7552 | .75539E+00 |
| | 2 | .6753 | .7301 | .7391 | .7428 | .74401E+00 | .6848 | .7364 | .7423 | .7439 | .74399E+00 |
| | 3 | .6806 | .7330 | .7410 | .7444 | .74553E+00 | .6919 | .7398 | .7444 | .7454 | .74551E+00 |
| | 4 | .6834 | .7355 | .7438 | .7474 | .74857E+00 | .6948 | .7423 | .7472 | .7484 | .74855E+00 |
| | 5 | .6899 | .7390 | .7464 | .7497 | .75086E+00 | .7033 | .7463 | .7499 | .7508 | .75084E+00 |
| 4.0 | | | | | | | | | | | |
| | 1 | .6172 | .6840 | .6956 | .7009 | .70267E+00 | .6234 | .6908 | .6995 | .7024 | .70265E+00 |
| | 2 | .6160 | .6756 | .6856 | .6903 | .69206E+00 | .6255 | .6831 | .6898 | .6918 | .69204E+00 |
| | 3 | .6224 | .6786 | .6876 | .6918 | .69348E+00 | .6337 | .6865 | .6919 | .6933 | .69346E+00 |
| | 4 | .6246 | .6809 | .6901 | .6945 | .69631E+00 | .6362 | .6888 | .6944 | .6961 | .69629E+00 |
| | 5 | .6320 | .6843 | .6926 | .6967 | .69843E+00 | .6458 | .6927 | .6971 | .6983 | .69842E+00 |
| 6.0 | | | | | | | | | | | |
| | 1 | .5003 | .5836 | .5969 | .6040 | .60725E+00 | .5104 | .5920 | .6025 | .6066 | .60724E+00 |
| | 2 | .5033 | .5769 | .5886 | .5949 | .59808E+00 | .5163 | .5862 | .5945 | .5976 | .59807E+00 |
| | 3 | .5107 | .5798 | .5905 | .5962 | .59930E+00 | .5251 | .5896 | .5966 | .5989 | .59929E+00 |
| | 4 | .5126 | .5817 | .5926 | .5986 | .60175E+00 | .5278 | .5915 | .5987 | .6013 | .60174E+00 |
| | 5 | .5211 | .5849 | .5949 | .6004 | .60359E+00 | .5384 | .5954 | .6013 | .6032 | .60357E+00 |
| 8.0 | | | | | | | | | | | |
| | 1 | .3990 | .4945 | .5104 | .5192 | .52410E+00 | .4142 | .5045 | .5176 | .5230 | .52409E+00 |
| | 2 | .4037 | .4897 | .5035 | .5114 | .51619E+00 | .4212 | .5008 | .5111 | .5153 | .51618E+00 |
| | 3 | .4107 | .4927 | .5054 | .5126 | .51724E+00 | .4243 | .5046 | .5132 | .5165 | .51723E+00 |
| | 4 | .4127 | .4941 | .5071 | .5145 | .51935E+00 | .4324 | .5060 | .5150 | .5185 | .51934E+00 |
| | 5 | .4211 | .4974 | .5092 | .5161 | .52094E+00 | .4427 | .5101 | .5174 | .5202 | .52093E+00 |

# TABLE A.34 (Cont'd)

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 10-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 50.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT |
|---|---|---|---|---|---|---|
| 0.0 | 1 | .8935 | .9378 | .9427 | .9435 | .94356E+00 |
| | 2 | .8886 | .9259 | .9289 | .9293 | .92933E+00 |
| | 3 | .8949 | .9294 | .9311 | .9312 | .93124E+00 |
| | 4 | .8997 | .9326 | .9347 | .9350 | .93505E+00 |
| | 5 | .9082 | .9368 | .9378 | .9379 | .93791E+00 |
| 2.0 | 1 | .7528 | .8037 | .8101 | .8117 | .81170E+00 |
| | 2 | .7507 | .7944 | .7985 | .7994 | .79945E+00 |
| | 3 | .7575 | .7980 | .8007 | .8011 | .80108E+00 |
| | 4 | .7613 | .8006 | .8037 | .8043 | .80436E+00 |
| | 5 | .7699 | .8048 | .8066 | .8068 | .80681E+00 |
| 3.0 | 1 | .6872 | .7463 | .7533 | .7553 | .75537E+00 |
| | 2 | .6885 | .7380 | .7427 | .7439 | .74397E+00 |
| | 3 | .6969 | .7416 | .7449 | .7455 | .74549E+00 |
| | 4 | .6998 | .7441 | .7477 | .7485 | .74853E+00 |
| | 5 | .7097 | .7482 | .7505 | .7508 | .75082E+00 |
| 4.0 | 1 | .6251 | .6925 | .7001 | .7025 | .70263E+00 |
| | 2 | .6293 | .6852 | .6905 | .6919 | .69203E+00 |
| | 3 | .6387 | .6888 | .6926 | .6934 | .69344E+00 |
| | 4 | .6414 | .6910 | .6952 | .6962 | .69627E+00 |
| | 5 | .6524 | .6951 | .6979 | .6984 | .69840E+00 |
| 6.0 | 1 | .5145 | .5943 | .6037 | .6069 | .60722E+00 |
| | 2 | .5221 | .5891 | .5958 | .5979 | .59805E+00 |
| | 3 | .5317 | .5928 | .5980 | .5992 | .59928E+00 |
| | 4 | .5348 | .5946 | .6000 | .6016 | .60172E+00 |
| | 5 | .5467 | .5989 | .6026 | .6035 | .60356E+00 |
| 8.0 | 1 | .4212 | .5076 | .5194 | .5236 | .52408E+00 |
| | 2 | .4296 | .5045 | .5131 | .5158 | .51617E+00 |
| | 3 | .4383 | .5087 | .5153 | .5170 | .51722E+00 |
| | 4 | .4419 | .5100 | .5170 | .5191 | .51933E+00 |
| | 5 | .4533 | .5145 | .5195 | .5208 | .52092E+00 |

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 11-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 30.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT |
|---|---|---|---|---|---|---|
| 0.0 | 1 | .8670 | .9304 | .9400 | .9430 | .94368E+00 |
| | 2 | .8603 | .9182 | .9261 | .9288 | .92944E+00 |
| | 3 | .8657 | .9215 | .9284 | .9307 | .93135E+00 |
| | 4 | .8697 | .9248 | .9320 | .9345 | .93516E+00 |
| | 5 | .8767 | .9288 | .9351 | .9374 | .93802E+00 |
| 2.0 | 1 | .7286 | .7924 | .8047 | .8101 | .81176E+00 |
| | 2 | .7238 | .7826 | .7932 | .7979 | .79950E+00 |
| | 3 | .7288 | .7859 | .7954 | .7996 | .80114E+00 |
| | 4 | .7321 | .7885 | .7983 | .8028 | .80441E+00 |
| | 5 | .7385 | .7924 | .8012 | .8052 | .80687E+00 |
| 3.0 | 1 | .6653 | .7333 | .7466 | .7531 | .75542E+00 |
| | 2 | .6628 | .7244 | .7360 | .7417 | .74401E+00 |
| | 3 | .6668 | .7276 | .7382 | .7433 | .74554E+00 |
| | 4 | .6714 | .7301 | .7408 | .7463 | .74858E+00 |
| | 5 | .6784 | .7338 | .7436 | .7485 | .75087E+00 |
| 4.0 | 1 | .6029 | .6780 | .6920 | .6995 | .70267E+00 |
| | 2 | .6030 | .6700 | .6823 | .6890 | .69206E+00 |
| | 3 | .6100 | .6731 | .6845 | .6905 | .69348E+00 |
| | 4 | .6121 | .6754 | .6869 | .6932 | .69631E+00 |
| | 5 | .6201 | .6790 | .6895 | .6953 | .69844E+00 |
| 6.0 | 1 | .4867 | .5776 | .5931 | .6023 | .60725E+00 |
| | 2 | .4904 | .5714 | .5850 | .5932 | .59808E+00 |
| | 3 | .4980 | .5744 | .5871 | .5946 | .59930E+00 |
| | 4 | .5000 | .5763 | .5891 | .5969 | .60175E+00 |
| | 5 | .5088 | .5797 | .5915 | .5987 | .60359E+00 |
| 8.0 | 1 | .3875 | .4885 | .5066 | .5172 | .52410E+00 |
| | 2 | .3924 | .4841 | .4999 | .5094 | .51619E+00 |
| | 3 | .3994 | .4874 | .5019 | .5107 | .51724E+00 |
| | 4 | .4015 | .4887 | .5035 | .5126 | .51936E+00 |
| | 5 | .4100 | .4922 | .5058 | .5142 | .52094E+00 |

TABLE A.34 (Cont'd)

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 11-FOOT LANES  BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH)  = 40.0
NUMBER OF PENETRATIONS PREVENTED

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 11-FOOT LANES  BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH)  = 50.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL (40.0 MPH) | | | | NO. OF HITS (40.0 MPH) | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL (50.0 MPH) | | | | NO. OF HITS (50.0 MPH) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 10YR-10MI-ADT | 1 | 2 | 3 | 4 | 10YR-10MI-ADT |
| 0.0 | | | | | | | | | | | |
| | 1 | .8782 | .9347 | .9419 | .9436 | .94365E+00 | .8835 | .9353 | .9420 | .9436 | .94361E+00 |
| | 2 | .8729 | .9232 | .9283 | .9294 | .92941E+00 | .8789 | .9241 | .9285 | .9294 | .92938E+00 |
| | 3 | .8788 | .9270 | .9306 | .9313 | .93132E+00 | .8851 | .9282 | .9309 | .9313 | .93128E+00 |
| | 4 | .8835 | .9302 | .9342 | .9351 | .93512E+00 | .8902 | .9312 | .9345 | .9351 | .93509E+00 |
| | 5 | .8916 | .9347 | .9375 | .9380 | .93799E+00 | .8988 | .9360 | .9377 | .9379 | .93794E+00 |
| 2.0 | | | | | | | | | | | |
| | 1 | .7376 | .7994 | .8086 | .8115 | .81173E+00 | .7405 | .8011 | .8091 | .8116 | .81171E+00 |
| | 2 | .7352 | .7903 | .7973 | .7993 | .79948E+00 | .7401 | .7924 | .7979 | .7994 | .79946E+00 |
| | 3 | .7418 | .7941 | .7996 | .8010 | .80112E+00 | .7479 | .7964 | .8003 | .8011 | .80109E+00 |
| | 4 | .7453 | .7967 | .8026 | .8042 | .80439E+00 | .7514 | .7990 | .8033 | .8043 | .80437E+00 |
| | 5 | .7535 | .8011 | .8056 | .8067 | .80685E+00 | .7610 | .8036 | .8063 | .8068 | .80682E+00 |
| 3.0 | | | | | | | | | | | |
| | 1 | .6725 | .7415 | .7514 | .7550 | .75540E+00 | .6747 | .7437 | .7523 | .7552 | .75538E+00 |
| | 2 | .6732 | .7333 | .7411 | .7437 | .74399E+00 | .6777 | .7360 | .7421 | .7439 | .74397E+00 |
| | 3 | .6812 | .7370 | .7434 | .7453 | .74552E+00 | .6869 | .7399 | .7445 | .7454 | .74550E+00 |
| | 4 | .6840 | .7395 | .7462 | .7483 | .74856E+00 | .6898 | .7423 | .7471 | .7485 | .74854E+00 |
| | 5 | .6933 | .7438 | .7491 | .7506 | .75085E+00 | .7006 | .7468 | .7502 | .7508 | .75083E+00 |
| 4.0 | | | | | | | | | | | |
| | 1 | .6106 | .6871 | .6978 | .7021 | .70266E+00 | .6132 | .6898 | .6990 | .7024 | .70264E+00 |
| | 2 | .6140 | .6799 | .6884 | .6916 | .69205E+00 | .6188 | .6831 | .6897 | .6919 | .69203E+00 |
| | 3 | .6229 | .6835 | .6908 | .6931 | .69346E+00 | .6288 | .6869 | .6921 | .6934 | .69345E+00 |
| | 4 | .6254 | .6858 | .6933 | .6959 | .69630E+00 | .6316 | .6892 | .6946 | .6962 | .69628E+00 |
| | 5 | .6357 | .6900 | .6961 | .6981 | .69842E+00 | .6433 | .6937 | .6975 | .6984 | .69840E+00 |
| 6.0 | | | | | | | | | | | |
| | 1 | .4990 | .5880 | .6007 | .6061 | .60724E+00 | .5043 | .5913 | .6025 | .6067 | .60722E+00 |
| | 2 | .5055 | .5828 | .5929 | .5972 | .59807E+00 | .5126 | .5867 | .5949 | .5977 | .59805E+00 |
| | 3 | .5145 | .5865 | .5952 | .5986 | .59929E+00 | .5223 | .5908 | .5973 | .5991 | .59928E+00 |
| | 4 | .5174 | .5883 | .5973 | .6009 | .60174E+00 | .5257 | .5926 | .5993 | .6015 | .60173E+00 |
| | 5 | .5264 | .5925 | .6000 | .6029 | .60357E+00 | .5379 | .5971 | .6021 | .6034 | .60356E+00 |
| 8.0 | | | | | | | | | | | |
| | 1 | .4044 | .5005 | .5156 | .5224 | .52409E+00 | .4126 | .5045 | .5181 | .5233 | .52408E+00 |
| | 2 | .4117 | .4973 | .5094 | .5147 | .51618E+00 | .4212 | .5020 | .5121 | .5157 | .51617E+00 |
| | 3 | .4198 | .5013 | .5117 | .5160 | .51723E+00 | .4299 | .5065 | .5145 | .5169 | .51722E+00 |
| | 4 | .4230 | .5027 | .5134 | .5180 | .51935E+00 | .4337 | .5078 | .5161 | .5189 | .51934E+00 |
| | 5 | .4334 | .5071 | .5160 | .5198 | .52043E+00 | .4452 | .5127 | .5189 | .5207 | .52092E+00 |

# TABLE A.34 (Cont'd)

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 12-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 30.0
NUMBER OF PENETRATIONS PREVENTED

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 12-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 40.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL (30.0 MPH) 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL (40.0 MPH) 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.0 | | | | | | | | | | | |
| | 1 | .8536 | .9237 | .9368 | .9422 | .94371E+00 | .8669 | .9308 | .9406 | .9435 | .94368E+00 |
| | 2 | .8470 | .9120 | .9233 | .9280 | .92947E+00 | .8617 | .9200 | .9273 | .9293 | .92944E+00 |
| | 3 | .8523 | .9158 | .9258 | .9299 | .93138E+00 | .8676 | .9242 | .9299 | .9312 | .93134E+00 |
| | 4 | .8564 | .9189 | .9292 | .9337 | .93518E+00 | .8724 | .9274 | .9334 | .9350 | .93515E+00 |
| | 5 | .8633 | .9233 | .9325 | .9365 | .93804E+00 | .8805 | .9323 | .9369 | .9379 | .93801E+00 |
| 2.0 | | | | | | | | | | | |
| | 1 | .7156 | .7857 | .8009 | .8087 | .81177E+00 | .7246 | .7954 | .8068 | .8112 | .81174E+00 |
| | 2 | .7117 | .7763 | .7896 | .7965 | .79951E+00 | .7237 | .7868 | .7959 | .7991 | .79949E+00 |
| | 3 | .7173 | .7798 | .7920 | .7982 | .80115E+00 | .7312 | .7909 | .7985 | .8008 | .80112E+00 |
| | 4 | .7204 | .7824 | .7949 | .8014 | .80442E+00 | .7344 | .7936 | .8014 | .8040 | .80440E+00 |
| | 5 | .7272 | .7865 | .7979 | .8039 | .80687E+00 | .7435 | .7983 | .8046 | .8066 | .80685E+00 |
| 3.0 | | | | | | | | | | | |
| | 1 | .6513 | .7267 | .7426 | .7514 | .75542E+00 | .6594 | .7374 | .7495 | .7546 | .75541E+00 |
| | 2 | .6500 | .7182 | .7322 | .7401 | .74402E+00 | .6616 | .7298 | .7396 | .7434 | .74400E+00 |
| | 3 | .6567 | .7217 | .7346 | .7417 | .74554E+00 | .6703 | .7337 | .7422 | .7450 | .74552E+00 |
| | 4 | .6592 | .7241 | .7372 | .7446 | .74858E+00 | .6730 | .7362 | .7448 | .7480 | .74857E+00 |
| | 5 | .6669 | .7280 | .7401 | .7469 | .75087E+00 | .6832 | .7408 | .7480 | .7504 | .75085E+00 |
| 4.0 | | | | | | | | | | | |
| | 1 | .5886 | .6717 | .6879 | .6977 | .70268E+00 | .5979 | .6830 | .6958 | .7016 | .70266E+00 |
| | 2 | .5899 | .6640 | .6784 | .6871 | .69207E+00 | .6026 | .6763 | .6868 | .6912 | .69205E+00 |
| | 3 | .5974 | .6673 | .6808 | .6887 | .69348E+00 | .6119 | .6801 | .6893 | .6928 | .69347E+00 |
| | 4 | .5995 | .6695 | .6831 | .6914 | .69632E+00 | .6145 | .6825 | .6918 | .6955 | .69630E+00 |
| | 5 | .6080 | .6733 | .6859 | .6935 | .69844E+00 | .6255 | .6869 | .6948 | .6978 | .69842E+00 |
| 6.0 | | | | | | | | | | | |
| | 1 | .4735 | .5715 | .5890 | .6001 | .60725E+00 | .4878 | .5838 | .5985 | .6055 | .60724E+00 |
| | 2 | .4778 | .5656 | .5811 | .5911 | .59808E+00 | .4949 | .5790 | .5911 | .5966 | .59807E+00 |
| | 3 | .4855 | .5688 | .5834 | .5925 | .59931E+00 | .5040 | .5830 | .5936 | .5981 | .59929E+00 |
| | 4 | .4876 | .5706 | .5853 | .5947 | .60175E+00 | .5071 | .5849 | .5956 | .6004 | .60174E+00 |
| | 5 | .4967 | .5742 | .5878 | .5966 | .60359E+00 | .5183 | .5893 | .5985 | .6024 | .60358E+00 |
| 8.0 | | | | | | | | | | | |
| | 1 | .3764 | .4824 | .5025 | .5149 | .52410E+00 | .3950 | .4962 | .5134 | .5216 | .52409E+00 |
| | 2 | .3815 | .4783 | .4960 | .5072 | .51619E+00 | .4025 | .4935 | .5075 | .5140 | .51618E+00 |
| | 3 | .3885 | .4818 | .4982 | .5085 | .51725E+00 | .4106 | .4979 | .5099 | .5154 | .51724E+00 |
| | 4 | .3907 | .4830 | .4997 | .5103 | .51936E+00 | .4134 | .4992 | .5116 | .5174 | .51935E+00 |
| | 5 | .3992 | .4867 | .5021 | .5120 | .52094E+00 | .4243 | .5039 | .5143 | .5192 | .52093E+00 |

# TABLE A.34 (Cont'd)

BRIDGE RAIL SERVICE LEVEL SELECTION CRITERIA
TWO 12-FOOT LANES BRIDGE WITH 50/50 TRAFFIC SPLIT

DESIGNATED SPEED (MPH) = 50.0
NUMBER OF PENETRATIONS PREVENTED

| SHOULDER WIDTH (FT) | VEHICLE MIX | NPP/10 MI-10 YR-ADT BARRIER SERVICE LEVEL 1 | 2 | 3 | 4 | NO. OF HITS 10YR-10MI-ADT |
|---|---|---|---|---|---|---|
| 0.0 | | | | | | |
| | 1 | .8734 | .9324 | .9411 | .9435 | .94365E+00 |
| | 2 | .8690 | .9220 | .9279 | .9293 | .92941E+00 |
| | 3 | .8753 | .9265 | .9306 | .9313 | .93131E+00 |
| | 4 | .8805 | .9295 | .9340 | .9351 | .93512E+00 |
| | 5 | .8893 | .9347 | .9375 | .9380 | .93798E+00 |
| 2.0 | | | | | | |
| | 1 | .7276 | .7983 | .8080 | .8115 | .81172E+00 |
| | 2 | .7290 | .7901 | .7971 | .7993 | .79947E+00 |
| | 3 | .7379 | .7944 | .7998 | .8010 | .80110E+00 |
| | 4 | .7412 | .7970 | .8027 | .8043 | .80438E+00 |
| | 5 | .7517 | .8020 | .8060 | .8068 | .80683E+00 |
| 3.0 | | | | | | |
| | 1 | .6623 | .7408 | .7510 | .7550 | .75539E+00 |
| | 2 | .6666 | .7336 | .7412 | .7438 | .74398E+00 |
| | 3 | .6768 | .7378 | .7439 | .7454 | .74550E+00 |
| | 4 | .6797 | .7403 | .7465 | .7484 | .74855E+00 |
| | 5 | .6914 | .7451 | .7497 | .7508 | .75083E+00 |
| 4.0 | | | | | | |
| | 1 | .6016 | .6868 | .6977 | .7022 | .70264E+00 |
| | 2 | .6084 | .6806 | .6888 | .6917 | .69204E+00 |
| | 3 | .6187 | .6848 | .6914 | .6933 | .69345E+00 |
| | 4 | .6218 | .6870 | .6938 | .6961 | .69628E+00 |
| | 5 | .6342 | .6918 | .6970 | .6983 | .69841E+00 |
| 6.0 | | | | | | |
| | 1 | .4944 | .5881 | .6012 | .6064 | .60723E+00 |
| | 2 | .5031 | .5840 | .5939 | .5975 | .59806E+00 |
| | 3 | .5129 | .5885 | .5965 | .5990 | .59928E+00 |
| | 4 | .5166 | .5902 | .5985 | .6013 | .60173E+00 |
| | 5 | .5291 | .5952 | .6015 | .6033 | .60356E+00 |
| 8.0 | | | | | | |
| | 1 | .4041 | .5012 | .5167 | .5229 | .52408E+00 |
| | 2 | .4130 | .4993 | .5110 | .5154 | .51617E+00 |
| | 3 | .4216 | .5041 | .5135 | .5167 | .51723E+00 |
| | 4 | .4256 | .5054 | .5152 | .5187 | .51934E+00 |
| | 5 | .4371 | .5106 | .5181 | .5205 | .52092E+00 |

# TABLE A.35

## TYPICAL BRIDGE SERVICE LEVEL SELECTION TABLES

ROAD DESCRIPTION
* URBAN IN 4D 12FT LN ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 82000. | 484.44 | 595.91 | 609.88 | 614.95 | 48.44 | 6.90 | 2.71 | 1.12 |
| $0.33/L.F. | 48000. | 283.57 | 346.83 | 357.00 | 359.97 | 28.36 | 4.04 | 1.59 | .65 |
| | 30800. | 181.96 | 223.83 | 229.08 | 230.98 | 18.20 | 2.59 | 1.02 | .42 |
| TEXAS | 82000. | 954.20 | 1173.76 | 1201.27 | 1211.27 | 95.42 | 13.59 | 5.34 | 2.20 |
| $0.65/L.F. | 48000. | 558.56 | 687.06 | 703.16 | 709.03 | 55.86 | 7.95 | 3.13 | 1.29 |
| | 30800. | 350.41 | 440.86 | 451.21 | 454.96 | 35.84 | 5.10 | 2.01 | .83 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON=$0.33/L.F. | 1693. | 11888. | 30239. | 73508. |
| TEXAS =$0.65/L.F. | 859. | 6035. | 15352. | 37319. |

ROAD DESCRIPTION
* URBAN IN 2DTB 12FT L ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 82000. | 310.04 | 381.38 | 390.32 | 393.57 | 31.00 | 4.41 | 1.74 | .71 |
| $0.33/L.F. | 48000. | 181.49 | 223.25 | 228.46 | 230.38 | 18.15 | 2.56 | 1.02 | .42 |
| | 30800. | 116.45 | 143.25 | 146.61 | 147.83 | 11.65 | 1.66 | .65 | .27 |
| TEXAS | 82000. | 610.69 | 751.21 | 768.81 | 775.21 | 61.07 | 8.70 | 3.42 | 1.41 |
| $0.65/L.F. | 48000. | 357.42 | 439.73 | 450.04 | 453.78 | 35.75 | 5.09 | 2.00 | .82 |
| | 30800. | 229.36 | 282.16 | 288.77 | 291.16 | 22.94 | 3.27 | 1.26 | .53 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON=$0.33/L.F. | 2645. | 18574. | 47248. | 114856. |
| TEXAS =$0.65/L.F. | 1343. | 9430. | 23988. | 58311. |

ROAD DESCRIPTION
* U ART 2L 10FT SH ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 41800. | 355.60 | 437.43 | 447.68 | 451.40 | 35.56 | 5.06 | 1.99 | .82 |
| $0.33/L.F. | 17500. | 148.66 | 183.13 | 187.43 | 188.99 | 14.89 | 2.12 | .83 | .34 |
| | 11600. | 98.66 | 121.39 | 124.24 | 125.27 | 9.87 | 1.41 | .55 | .23 |
| TEXAS | 41800. | 700.43 | 861.60 | 881.79 | 889.13 | 70.04 | 9.97 | 3.92 | 1.61 |
| $0.65/L.F. | 17500. | 293.24 | 360.72 | 369.17 | 372.24 | 29.32 | 4.18 | 1.64 | .68 |
| | 11600. | 194.36 | 239.10 | 244.71 | 246.74 | 19.44 | 2.77 | 1.09 | .45 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON=$0.33/L.F. | 1175. | 8255. | 20999. | 51047. |
| TEXAS =$0.65/L.F. | 597. | 4191. | 10661. | 25916. |

ROAD DESCRIPTION
* U ART 2L 4FT SH ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 41800. | 629.59 | 694.48 | 700.65 | 702.59 | 62.96 | 4.02 | 1.20 | .43 |
| $0.33/L.F. | 17500. | 263.56 | 290.75 | 293.34 | 294.15 | 26.36 | 1.68 | .50 | .18 |
| | 11600. | 174.72 | 192.73 | 194.44 | 194.98 | 17.47 | 1.11 | .33 | .12 |
| TEXAS | 41800. | 1240.10 | 1367.91 | 1380.08 | 1383.90 | 124.01 | 7.91 | 2.36 | .84 |
| $0.65/L.F. | 17500. | 519.18 | 572.69 | 577.78 | 579.38 | 51.92 | 3.31 | .99 | .35 |
| | 11600. | 344.14 | 379.61 | 382.99 | 384.05 | 34.41 | 2.19 | .66 | .23 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON=$0.33/L.F. | 664. | 10410. | 34854. | 98050. |
| TEXAS =$0.65/L.F. | 337. | 5285. | 17695. | 49779. |

TABLE A.35 (Cont'd)

ROAD DESCRIPTION
RURAL IH 4D 12FT LN ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 18000. | 89.28 | 114.77 | 119.19 | 121.02 | 8.93 | 1.56 | .86 | .40 |
| $0.33/L.F. | 12000. | 66.96 | 86.08 | 89.39 | 90.77 | 6.70 | 1.18 | .64 | .30 |
| | 5300. | 29.57 | 38.02 | 39.48 | 40.09 | 2.96 | .52 | .28 | .13 |
| TEXAS | 18000. | 175.85 | 226.07 | 234.76 | 238.38 | 17.59 | 3.11 | 1.69 | .79 |
| $0.65/L.F. | 12000. | 131.89 | 169.55 | 176.07 | 178.78 | 13.19 | 2.33 | 1.27 | .60 |
| | 5300. | 58.25 | 74.89 | 77.77 | 78.96 | 5.83 | 1.03 | .56 | .26 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON=$0.33/L.F. | 1792. | 10142. | 16665. | 39701. |
| TEXAS =$0.65/L.F. | 910. | 5149. | 9476. | 20156. |

ROAD DESCRIPTION
RURAL IH 2UTH 12FTLN ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 16000. | 57.14 | 73.46 | 76.28 | 77.45 | 5.71 | 1.01 | .55 | .26 |
| $0.33/L.F. | 12000. | 42.85 | 55.09 | 57.21 | 58.09 | 4.29 | .76 | .41 | .19 |
| | 5300. | 18.93 | 24.33 | 25.27 | 25.66 | 1.89 | .33 | .18 | .09 |
| TEXAS | 16000. | 112.55 | 144.68 | 150.25 | 152.56 | 11.25 | 1.99 | 1.08 | .51 |
| $0.65/L.F. | 12000. | 84.41 | 108.51 | 112.69 | 114.42 | 8.44 | 1.49 | .81 | .38 |
| | 5300. | 37.28 | 47.93 | 49.77 | 50.54 | 3.73 | .66 | .36 | .17 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON=$0.33/L.F. | 2600. | 15847. | 29164. | 62033. |
| TEXAS =$0.65/L.F. | 1422. | 8045. | 14807. | 31494. |

ROAD DESCRIPTION
RURAL ART2UTH 12FTLN ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 5000. | 18.40 | 23.07 | 23.73 | 23.99 | 1.84 | .29 | .13 | .06 |
| $0.33/L.F. | 3200. | 11.77 | 14.77 | 15.19 | 15.35 | 1.18 | .19 | .08 | .04 |
| | 1340. | 4.93 | 6.18 | 6.36 | 6.43 | .49 | .08 | .03 | .01 |
| TEXAS | 5000. | 36.24 | 45.45 | 46.75 | 47.25 | 3.62 | .57 | .25 | .11 |
| $0.65/L.F. | 3200. | 23.19 | 29.09 | 29.92 | 30.24 | 2.32 | .36 | .16 | .07 |
| | 1340. | 9.71 | 12.18 | 12.53 | 12.66 | .97 | .15 | .07 | .03 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON=$0.33/L.F. | 2710. | 17284. | 34860. | 69458. |
| TEXAS =$0.65/L.F. | 1380. | 8775. | 19780. | 45671. |

ROAD DESCRIPTION
RURAL ART 2L 10FT SH ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 5000. | 41.40 | 51.41 | 53.40 | 53.97 | 4.14 | .65 | .29 | .13 |
| $0.33/L.F. | 3200. | 26.49 | 33.23 | 34.18 | 34.54 | 2.65 | .42 | .18 | .08 |
| | 1340. | 11.09 | 13.91 | 14.31 | 14.46 | 1.11 | .17 | .08 | .03 |
| TEXAS | 5000. | 81.54 | 102.26 | 105.18 | 106.31 | 8.15 | 1.26 | .57 | .25 |
| $0.65/L.F. | 3200. | 52.18 | 65.44 | 67.32 | 68.04 | 5.22 | .82 | .36 | .16 |
| | 1340. | 21.85 | 27.40 | 28.19 | 28.49 | 2.19 | .34 | .15 | .07 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON=$0.33/L.F. | 1205. | 7682. | 17316. | 39961. |
| TEXAS =$0.65/L.F. | 613. | 3900. | 8791. | 20298. |

TABLE A.35 (Cont'd)

ROAD DESCRIPTION
RURAL ART 2L 4FT SH ***

| ACCIDENT COST BASIS | ADT | (- - - - - - BENEFIT $/FT-NSC- - - - - -) SERVICE LEVEL 1 | 2 | 3 | 4 | (- - - -INCREMENTAL BENEFIT/COST- - - -) SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 5000. | 74.11 | 82.80 | 83.72 | 84.03 | 7.41 | .54 | .16 | .07 |
| $0.33/L.F. | 3200. | 47.43 | 52.99 | 53.58 | 53.78 | 4.74 | .34 | .11 | .04 |
| | 1340. | 19.88 | 22.19 | 22.44 | 22.52 | 1.99 | .14 | .05 | .02 |
| TEXAS | 5000. | 145.97 | 163.09 | 164.90 | 165.52 | 14.60 | 1.06 | .35 | .14 |
| $0.65/L.F. | 3200. | 93.42 | 104.38 | 105.54 | 105.93 | 9.34 | .68 | .23 | .09 |
| | 1340. | 39.12 | 43.71 | 44.19 | 44.36 | 3.91 | .28 | .09 | .04 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 675. | 9296. | 27999. | 72065. |
| TEXAS -$0.65/L.F. | 343. | 4719. | 14215. | 36587. |

ROAD DESCRIPTION
RURAL M A 2L 6FT SH ***

| ACCIDENT COST BASIS | ADT | (- - - - - - BENEFIT $/FT-NSC- - - - - -) SERVICE LEVEL 1 | 2 | 3 | 4 | (- - - -INCREMENTAL BENEFIT/COST- - - -) SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 18400. | 190.58 | 225.23 | 229.20 | 230.55 | 19.06 | 2.14 | .77 | .30 |
| $0.33/L.F. | 4500. | 46.61 | 55.08 | 56.06 | 56.38 | 4.66 | .52 | .19 | .07 |
| | 1180. | 12.22 | 14.44 | 14.70 | 14.79 | 1.22 | .14 | .05 | .02 |
| TEXAS | 18400. | 375.38 | 443.64 | 451.46 | 454.11 | 37.54 | 4.22 | 1.52 | .58 |
| $0.65/L.F. | 4500. | 91.81 | 108.50 | 110.41 | 111.06 | 9.18 | 1.03 | .37 | .14 |
| | 1180. | 24.07 | 28.45 | 28.95 | 29.12 | 2.41 | .27 | .10 | .04 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 965. | 8581. | 23659. | 62285. |
| TEXAS -$0.65/L.F. | 490. | 4356. | 12113. | 31621. |

ROAD DESCRIPTION
RURAL M A 2L 4FT SH ***

| ACCIDENT COST BASIS | ADT | (- - - - - - BENEFIT $/FT-NSC- - - - - -) SERVICE LEVEL 1 | 2 | 3 | 4 | (- - - -INCREMENTAL BENEFIT/COST- - - -) SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 18400. | 277.14 | 305.70 | 308.42 | 309.26 | 27.71 | 1.77 | .53 | .19 |
| $0.33/L.F. | 4500. | 67.78 | 74.76 | 75.43 | 75.64 | 6.78 | .43 | .13 | .05 |
| | 1180. | 17.77 | 19.60 | 19.78 | 19.83 | 1.78 | .11 | .03 | .01 |
| TEXAS | 18400. | 545.88 | 602.14 | 607.50 | 609.18 | 54.59 | 3.48 | 1.04 | .37 |
| $0.65/L.F. | 4500. | 133.50 | 147.26 | 148.57 | 148.98 | 13.35 | .85 | .25 | .09 |
| | 1180. | 35.01 | 38.62 | 38.96 | 39.07 | 3.50 | .22 | .07 | .02 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 664. | 10410. | 34854. | 98050. |
| TEXAS -$0.65/L.F. | 337. | 5285. | 17645. | 49779. |

TABLE A.35 (Cont'd)

ROAD DESCRIPTION
*** U ART 2L 10FT SH ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON $0.33/L.F. | 20100. | 171.00 | 210.34 | 215.27 | 217.06 | 17.10 | 2.43 | .96 | .39 |
| | 8000. | 68.06 | 83.72 | 85.68 | 86.39 | 6.81 | .97 | .38 | .16 |
| | 3240. | 27.56 | 33.91 | 34.70 | 34.99 | 2.76 | .39 | .15 | .06 |
| TEXAS $0.65/L.F. | 20100. | 336.61 | 414.31 | 424.02 | 427.55 | 33.66 | 4.80 | 1.89 | .78 |
| | 8000. | 134.65 | 164.90 | 168.76 | 170.17 | 13.41 | 1.91 | .75 | .31 |
| | 3240. | 54.29 | 66.78 | 68.35 | 68.92 | 5.43 | .77 | .30 | .13 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 1175. | 8255. | 20999. | 51047. |
| TEXAS -$0.65/L.F. | 597. | 4191. | 10661. | 25916. |

ROAD DESCRIPTION
*** U ART 2L 4FT SH ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON $0.33/L.F. | 20100. | 302.75 | 333.95 | 336.92 | 337.85 | 30.27 | 1.93 | .58 | .20 |
| | 8000. | 120.50 | 132.91 | 134.10 | 134.47 | 12.05 | .77 | .23 | .08 |
| | 3240. | 48.80 | 53.83 | 54.31 | 54.46 | 4.88 | .31 | .09 | .03 |
| TEXAS $0.65/L.F. | 20100. | 596.32 | 657.78 | 663.63 | 665.46 | 59.63 | 3.80 | 1.14 | .40 |
| | 8000. | 237.34 | 261.80 | 264.13 | 264.86 | 23.73 | 1.51 | .45 | .16 |
| | 3240. | 96.12 | 106.03 | 106.97 | 107.27 | 9.61 | .61 | .18 | .07 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 604. | 10410. | 34854. | 98050. |
| TEXAS -$0.65/L.F. | 337. | 5285. | 17695. | 49779. |

ROAD DESCRIPTION
*** U M ART 2L 8FT SH ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON $0.33/L.F. | 11000. | 113.93 | 134.65 | 137.02 | 137.83 | 11.39 | 1.20 | .46 | .18 |
| | 9200. | 95.29 | 112.62 | 114.60 | 115.27 | 9.53 | 1.07 | .39 | .15 |
| | 5400. | 55.93 | 66.10 | 67.27 | 67.66 | 5.59 | .63 | .23 | .09 |
| TEXAS $0.65/L.F. | 11000. | 224.41 | 265.22 | 269.90 | 271.48 | 22.44 | 2.53 | .91 | .35 |
| | 9200. | 187.69 | 221.82 | 225.73 | 227.06 | 18.77 | 2.11 | .76 | .29 |
| | 5400. | 110.17 | 130.20 | 132.49 | 133.27 | 11.02 | 1.24 | .45 | .17 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 965. | 8581. | 23859. | 62285. |
| TEXAS -$0.65/L.F. | 490. | 4356. | 12113. | 31621. |

ROAD DESCRIPTION
*** U M ART 2L 4FT SH ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON $0.33/L.F. | 11000. | 165.68 | 182.76 | 184.38 | 184.89 | 16.57 | 1.66 | .32 | .11 |
| | 9200. | 138.57 | 152.85 | 154.21 | 154.64 | 13.86 | .86 | .26 | .09 |
| | 5400. | 81.33 | 89.72 | 90.52 | 90.77 | 8.13 | .52 | .15 | .06 |
| TEXAS $0.65/L.F. | 11000. | 326.34 | 359.98 | 363.18 | 364.18 | 32.63 | 2.06 | .62 | .22 |
| | 9200. | 272.94 | 301.07 | 303.75 | 304.59 | 27.29 | 1.74 | .52 | .18 |
| | 5400. | 160.20 | 176.72 | 178.29 | 178.78 | 16.02 | 1.02 | .31 | .11 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 664. | 10410. | 34854. | 98050. |
| TEXAS -$0.65/L.F. | 337. | 5285. | 17695. | 49779. |

TABLE A.35 (Cont'd)

ROAD DESCRIPTION
*** URBAN IH 6D 12 FT L ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 82000. | 149.91 | 194.59 | 201.66 | 204.86 | 14.99 | 2.76 | 1.38 | .70 |
| $0.33/L.F. | 48000. | 87.75 | 113.90 | 118.06 | 119.92 | 8.78 | 1.62 | .81 | .41 |
| | 30900. | 56.31 | 73.09 | 75.75 | 76.95 | 5.63 | 1.04 | .52 | .26 |
| TEXAS | 82000. | 295.26 | 383.28 | 397.26 | 403.52 | 29.53 | 5.45 | 2.71 | 1.38 |
| $0.65/L.F. | 48000. | 172.85 | 224.36 | 232.54 | 236.21 | 17.28 | 3.19 | 1.59 | .81 |
| | 30900. | 110.91 | 143.96 | 149.21 | 151.57 | 11.09 | 2.05 | 1.02 | .52 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 5470. | 29660. | 59508. | 117314. |
| TEXAS -$0.65/L.F. | 2777. | 15058. | 30212. | 59559. |

ROAD DESCRIPTION
*** U ART 3LANES TH 10SH ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 41800. | 86.03 | 111.67 | 115.74 | 117.56 | 8.60 | 1.59 | .79 | .40 |
| $0.33/L.F. | 17500. | 36.02 | 46.75 | 48.45 | 49.22 | 3.60 | .66 | .33 | .17 |
| | 11600. | 23.87 | 30.99 | 32.12 | 32.63 | 2.39 | .44 | .22 | .11 |
| TEXAS | 41800. | 169.45 | 219.95 | 227.97 | 231.56 | 16.94 | 3.12 | 1.56 | .79 |
| $0.65/L.F. | 17500. | 70.94 | 92.08 | 95.44 | 96.95 | 7.09 | 1.31 | .65 | .33 |
| | 11600. | 47.02 | 61.04 | 63.26 | 64.26 | 4.70 | .87 | .43 | .22 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 4859. | 26347. | 52860. | 104209. |
| TEXAS -$0.65/L.F. | 2467. | 13376. | 26837. | 52906. |

ROAD DESCRIPTION
*** U ART 3LANES TB 10SH ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 20100. | 41.37 | 53.70 | 55.65 | 56.53 | 4.14 | .76 | .38 | .19 |
| $0.33/L.F. | 8000. | 16.46 | 21.37 | 22.15 | 22.50 | 1.65 | .30 | .15 | .08 |
| | 3240. | 6.67 | 8.66 | 8.97 | 9.11 | .67 | .12 | .06 | .03 |
| TEXAS | 20100. | 81.48 | 105.76 | 109.62 | 111.35 | 8.15 | 1.50 | .75 | .38 |
| $0.65/L.F. | 8000. | 32.43 | 42.10 | 43.63 | 44.32 | 3.24 | .60 | .30 | .15 |
| | 3240. | 13.13 | 17.05 | 17.67 | 17.95 | 1.31 | .24 | .12 | .06 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 4859. | 26347. | 52860. | 104209. |
| TEXAS -$0.65/L.F. | 2467. | 13376. | 26837. | 52906. |

ROAD DESCRIPTION
*** U ART 4L 10FT SH ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 41800. | 246.95 | 303.77 | 310.89 | 313.48 | 24.69 | 3.52 | 1.38 | .57 |
| $0.33/L.F. | 17500. | 103.39 | 127.18 | 130.16 | 131.24 | 10.34 | 1.47 | .58 | .24 |
| | 11600. | 68.53 | 84.30 | 86.28 | 86.99 | 6.85 | .98 | .38 | .16 |
| TEXAS | 41800. | 486.41 | 598.33 | 612.35 | 617.45 | 48.64 | 6.93 | 2.72 | 1.12 |
| $0.65/L.F. | 17500. | 203.64 | 250.50 | 256.37 | 258.50 | 20.36 | 2.90 | 1.14 | .47 |
| | 11600. | 134.96 | 166.04 | 169.94 | 171.35 | 13.50 | 1.92 | .76 | .31 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 1693. | 11888. | 30239. | 73508. |
| TEXAS -$0.65/L.F. | 859. | 6035. | 15352. | 37319. |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 1 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 400. | 10.10 | 10.74 | 10.82 | 10.85 | 1.01 | .04 | .02 | .01 |
| $0.33/L.F. | 325. | 8.21 | 8.72 | 8.79 | 8.82 | .82 | .03 | .01 | .01 |
| | 250. | 6.31 | 6.71 | 6.76 | 6.78 | .63 | .02 | .01 | .00 |
| TEXAS | 400. | 19.89 | 21.15 | 21.31 | 21.36 | 1.99 | .06 | .03 | .01 |
| $0.65/L.F. | 325. | 16.16 | 17.18 | 17.32 | 17.37 | 1.62 | .06 | .03 | .01 |
| | 250. | 12.43 | 13.22 | 13.32 | 13.36 | 1.24 | .05 | .02 | .01 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 396. | 10141. | 24602. | 55732. |
| TEXAS -$0.65/L.F. | 201. | 5148. | 12490. | 28295. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 2 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 750. | 12.29 | 13.17 | 13.30 | 13.36 | 1.23 | .05 | .03 | .01 |
| $0.33/L.F. | 575. | 9.43 | 10.10 | 10.20 | 10.24 | .94 | .04 | .02 | .01 |
| | 400. | 6.56 | 7.02 | 7.09 | 7.12 | .66 | .03 | .01 | .01 |
| TEXAS | 750. | 24.22 | 25.94 | 26.20 | 26.31 | 2.42 | .11 | .05 | .02 |
| $0.65/L.F. | 575. | 18.57 | 19.89 | 20.09 | 20.17 | 1.86 | .08 | .04 | .02 |
| | 400. | 12.92 | 13.84 | 13.97 | 14.03 | 1.29 | .06 | .03 | .01 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 610. | 13842. | 29391. | 59242. |
| TEXAS -$0.65/L.F. | 310. | 7027. | 14922. | 30077. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 3 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 2000. | 32.24 | 34.87 | 35.34 | 35.57 | 3.22 | .16 | .09 | .05 |
| $0.33/L.F. | 1375. | 22.16 | 23.97 | 24.29 | 24.45 | 2.22 | .11 | .06 | .04 |
| | 750. | 12.09 | 13.08 | 13.25 | 13.34 | 1.21 | .06 | .03 | .02 |
| TEXAS | 2000. | 63.50 | 68.68 | 69.60 | 70.06 | 6.35 | .32 | .18 | .10 |
| $0.65/L.F. | 1375. | 43.66 | 47.22 | 47.85 | 48.17 | 4.37 | .22 | .12 | .07 |
| | 750. | 23.81 | 25.76 | 26.10 | 26.27 | 2.38 | .12 | .07 | .04 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 620. | 12285. | 22171. | 38647. |
| TEXAS -$0.65/L.F. | 315. | 6237. | 11256. | 19621. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 4 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 4000. | 58.93 | 64.53 | 65.53 | 66.08 | 5.89 | .35 | .19 | .12 |
| $0.33/L.F. | 3000. | 44.20 | 48.40 | 49.15 | 49.56 | 4.42 | .26 | .15 | .09 |
| | 2000. | 29.47 | 32.27 | 32.77 | 33.04 | 2.95 | .17 | .10 | .06 |
| TEXAS | 4000. | 116.08 | 127.11 | 129.08 | 130.17 | 11.61 | .68 | .38 | .24 |
| $0.65/L.F. | 3000. | 87.06 | 95.33 | 96.81 | 97.62 | 8.71 | .51 | .29 | .18 |
| | 2000. | 58.04 | 63.55 | 64.54 | 65.08 | 5.80 | .34 | .19 | .12 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 679. | 11543. | 20544. | 33083. |
| TEXAS -$0.65/L.F. | 345. | 5860. | 10430. | 16796. |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 5 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 5070. | 48.09 | 58.63 | 60.48 | 61.67 | 4.81 | .65 | .36 | .26 |
| $0.33/L.F. | 2600. | 24.66 | 30.07 | 31.01 | 31.63 | 2.47 | .33 | .18 | .13 |
| | 1440. | 13.66 | 16.65 | 17.18 | 17.52 | 1.37 | .19 | .10 | .07 |
| TEXAS | 5070. | 94.72 | 115.49 | 119.13 | 121.48 | 9.47 | 1.28 | .71 | .52 |
| $0.65/L.F. | 2600. | 48.58 | 59.22 | 61.09 | 62.30 | 4.86 | .66 | .36 | .27 |
| | 1440. | 26.90 | 32.80 | 33.83 | 34.50 | 2.69 | .36 | .20 | .15 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 1054. | 7772. | 14132. | 19293. |
| TEXAS -$0.65/L.F. | 535. | 3946. | 7175. | 9795. |

DESIGNATED SPEED (MPH) = 40.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 6 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 400. | 10.28 | 10.82 | 10.86 | 10.86 | 1.03 | .03 | .01 | .00 |
| $0.33/L.F. | 325. | 8.35 | 8.79 | 8.82 | 8.83 | .84 | .03 | .01 | .00 |
| | 250. | 6.42 | 6.76 | 6.78 | 6.79 | .64 | .02 | .00 | .00 |
| TEXAS | 400. | 20.25 | 21.31 | 21.38 | 21.40 | 2.02 | .07 | .01 | .00 |
| $0.65/L.F. | 325. | 16.45 | 17.31 | 17.37 | 17.38 | 1.65 | .05 | .01 | .00 |
| | 250. | 12.65 | 13.32 | 13.36 | 13.37 | 1.27 | .04 | .01 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 389. | 12030. | 53206. | 244415. |
| TEXAS -$0.65/L.F. | 198. | 6107. | 27012. | 124088. |

DESIGNATED SPEED (MPH) = 40.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 7 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 750. | 12.35 | 13.25 | 13.35 | 13.38 | 1.24 | .06 | .02 | .01 |
| $0.33/L.F. | 575. | 9.47 | 10.16 | 10.23 | 10.26 | .95 | .04 | .01 | .00 |
| | 400. | 6.59 | 7.07 | 7.12 | 7.13 | .66 | .03 | .01 | .00 |
| TEXAS | 750. | 24.34 | 26.11 | 26.29 | 26.35 | 2.43 | .11 | .04 | .01 |
| $0.65/L.F. | 575. | 18.66 | 20.02 | 20.16 | 20.20 | 1.87 | .08 | .03 | .01 |
| | 400. | 12.98 | 13.92 | 14.02 | 14.05 | 1.30 | .06 | .02 | .01 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 607. | 13469. | 40720. | 126758. |
| TEXAS -$0.65/L.F. | 308. | 6838. | 20673. | 64354. |

DESIGNATED SPEED (MPH) = 40.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 8 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 2000. | 32.95 | 35.35 | 35.60 | 35.67 | 3.29 | .15 | .05 | .02 |
| $0.33/L.F. | 1375. | 22.65 | 24.30 | 24.47 | 24.52 | 2.27 | .10 | .03 | .01 |
| | 750. | 12.35 | 13.25 | 13.35 | 13.38 | 1.24 | .06 | .02 | .01 |
| TEXAS | 2000. | 64.89 | 69.62 | 70.12 | 70.26 | 6.49 | .29 | .10 | .03 |
| $0.65/L.F. | 1375. | 44.61 | 47.86 | 48.21 | 48.30 | 4.46 | .20 | .07 | .02 |
| | 750. | 24.34 | 26.11 | 26.29 | 26.35 | 2.43 | .11 | .04 | .01 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 607. | 13469. | 40720. | 126758. |
| TEXAS -$0.65/L.F. | 308. | 6838. | 20673. | 64354. |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 40.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 9 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 4000. | 60.42 | 65.58 | 66.16 | 66.35 | 6.04 | .32 | .11 | .04 |
| $0.33/L.F. | 3000. | 45.31 | 49.19 | 49.62 | 49.76 | 4.53 | .24 | .08 | .03 |
| | 2000. | 30.21 | 32.79 | 33.08 | 33.17 | 3.02 | .16 | .06 | .02 |
| TEXAS | 4000. | 119.00 | 129.18 | 130.32 | 130.68 | 11.90 | .63 | .22 | .08 |
| $0.65/L.F. | 3000. | 89.25 | 96.88 | 97.74 | 98.01 | 8.93 | .47 | .17 | .06 |
| | 2000. | 59.50 | 64.59 | 65.16 | 65.34 | 5.95 | .31 | .11 | .04 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 662. | 12515. | 35543. | 98172. |
| TEXAS -$0.65/L.F. | 336. | 6354. | 18045. | 49841. |

DESIGNATED SPEED (MPH) = 40.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 10 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 5070. | 51.12 | 60.70 | 61.96 | 62.54 | 5.11 | .59 | .24 | .13 |
| $0.33/L.F. | 2600. | 26.21 | 31.13 | 31.77 | 32.07 | 2.62 | .30 | .13 | .07 |
| | 1440. | 14.52 | 17.24 | 17.60 | 17.76 | 1.45 | .17 | .07 | .04 |
| TEXAS | 5070. | 100.69 | 119.56 | 122.04 | 123.19 | 10.07 | 1.17 | .48 | .25 |
| $0.65/L.F. | 2600. | 51.63 | 61.31 | 62.59 | 63.18 | 5.16 | .60 | .25 | .13 |
| | 1440. | 28.60 | 33.96 | 34.66 | 34.99 | 2.86 | .33 | .14 | .07 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 992. | 8552. | 20694. | 39454. |
| TEXAS -$0.65/L.F. | 504. | 4342. | 10506. | 20031. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 11 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 400. | 10.37 | 10.84 | 10.86 | 10.86 | 1.04 | .03 | .00 | .00 |
| $0.33/L.F. | 325. | 8.42 | 8.80 | 8.82 | 8.83 | .84 | .02 | .00 | .00 |
| | 250. | 6.48 | 6.77 | 6.79 | 6.79 | .65 | .02 | .00 | .00 |
| TEXAS | 400. | 20.42 | 21.34 | 21.39 | 21.40 | 2.04 | .06 | .01 | .00 |
| $0.65/L.F. | 325. | 16.59 | 17.34 | 17.38 | 17.38 | 1.66 | .05 | .01 | .00 |
| | 250. | 12.76 | 13.34 | 13.37 | 13.37 | 1.28 | .04 | .01 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 386. | 13763. | 85815. | 548597. |
| TEXAS -$0.65/L.F. | 196. | 6987. | 43567. | 278519. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 12 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 750. | 12.49 | 13.31 | 13.37 | 13.38 | 1.25 | .05 | .01 | .00 |
| $0.33/L.F. | 575. | 9.57 | 10.20 | 10.25 | 10.26 | .96 | .04 | .01 | .00 |
| | 400. | 6.66 | 7.10 | 7.13 | 7.14 | .67 | .03 | .01 | .00 |
| TEXAS | 750. | 24.59 | 26.21 | 26.33 | 26.35 | 2.46 | .10 | .02 | .00 |
| $0.65/L.F. | 575. | 18.85 | 20.10 | 20.19 | 20.20 | 1.89 | .08 | .02 | .00 |
| | 400. | 13.12 | 13.98 | 14.04 | 14.05 | 1.31 | .05 | .01 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 601. | 14722. | 65581. | 298335. |
| TEXAS -$0.65/L.F. | 305. | 7474. | 33295. | 151463. |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 13 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON $0.33/L.F. | 2000. | 33.30 | 35.49 | 35.65 | 35.68 | 3.33 | .14 | .03 | .01 |
| | 1375. | 22.89 | 24.40 | 24.51 | 24.53 | 2.29 | .09 | .02 | .00 |
| | 750. | 12.49 | 13.31 | 13.37 | 13.38 | 1.25 | .05 | .01 | .00 |
| TEXAS $0.65/L.F. | 2000. | 65.56 | 69.91 | 70.21 | 70.27 | 6.56 | .27 | .06 | .01 |
| | 1375. | 45.09 | 48.06 | 48.27 | 48.31 | 4.51 | .18 | .04 | .01 |
| | 750. | 24.59 | 26.21 | 26.33 | 26.35 | 2.46 | .10 | .02 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 601. | 14722. | 65581. | 298335. |
| TEXAS -$0.65/L.F. | 305. | 7474. | 33295. | 151463. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 14 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON $0.33/L.F. | 4000. | 60.27 | 65.75 | 66.24 | 66.37 | 6.03 | .34 | .10 | .03 |
| | 3000. | 45.20 | 49.31 | 49.68 | 49.78 | 4.52 | .25 | .07 | .02 |
| | 2000. | 30.14 | 32.88 | 33.12 | 33.18 | 3.01 | .17 | .05 | .01 |
| TEXAS $0.65/L.F. | 4000. | 118.72 | 129.51 | 130.48 | 130.72 | 11.87 | .67 | .19 | .05 |
| | 3000. | 89.04 | 97.13 | 97.86 | 98.04 | 8.90 | .50 | .14 | .04 |
| | 2000. | 59.36 | 64.76 | 65.24 | 65.36 | 5.94 | .33 | .09 | .03 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 664. | 11797. | 42053. | 146361. |
| TEXAS -$0.65/L.F. | 337. | 5989. | 21350. | 74306. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** RCR--COLLECTOR 15 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON $0.33/L.F. | 5070. | 52.66 | 61.51 | 62.41 | 62.71 | 5.27 | .55 | .18 | .07 |
| | 2600. | 27.00 | 31.54 | 32.00 | 32.16 | 2.70 | .28 | .09 | .03 |
| | 1440. | 14.96 | 17.47 | 17.73 | 17.81 | 1.50 | .16 | .05 | .02 |
| TEXAS $0.65/L.F. | 5070. | 103.72 | 121.15 | 122.93 | 123.51 | 10.37 | 1.08 | .35 | .13 |
| | 2600. | 53.19 | 62.13 | 63.04 | 63.34 | 5.32 | .55 | .18 | .07 |
| | 1440. | 29.46 | 34.41 | 34.91 | 35.08 | 2.95 | .31 | .10 | .04 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 963. | 9261. | 28939. | 77709. |
| TEXAS -$0.65/L.F. | 489. | 4702. | 14692. | 39452. |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** RCR--LOCAL ROADS 2 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 250. | 15.34 | 16.13 | 16.21 | 16.24 | 1.53 | .05 | .02 | .01 |
| $0.33/L.F. | 150. | 9.20 | 9.68 | 9.73 | 9.74 | .92 | .03 | .01 | .00 |
| | 50. | 3.07 | 3.23 | 3.24 | 3.25 | .31 | .01 | .00 | .00 |
| TEXAS | 250. | 30.22 | 31.78 | 31.93 | 31.98 | 3.02 | .10 | .03 | .01 |
| $0.65/L.F. | 150. | 18.13 | 19.07 | 19.16 | 19.19 | 1.81 | .06 | .02 | .01 |
| | 50. | 6.04 | 6.36 | 6.39 | 6.40 | .60 | .02 | .01 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 163. | 5092. | 16587. | 46610. |
| TEXAS -$0.65/L.F. | 83. | 2585. | 8421. | 23663. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** RCR--LOCAL ROADS 2 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 250. | 15.34 | 16.13 | 16.21 | 16.24 | 1.53 | .05 | .02 | .01 |
| $0.33/L.F. | 150. | 9.20 | 9.68 | 9.73 | 9.74 | .92 | .03 | .01 | .00 |
| | 50. | 3.07 | 3.23 | 3.24 | 3.25 | .31 | .01 | .00 | .00 |
| TEXAS | 250. | 30.22 | 31.78 | 31.93 | 31.98 | 3.02 | .10 | .03 | .01 |
| $0.65/L.F. | 150. | 18.13 | 19.07 | 19.16 | 19.19 | 1.81 | .06 | .02 | .01 |
| | 50. | 6.04 | 6.36 | 6.39 | 6.40 | .60 | .02 | .01 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 163. | 5092. | 16587. | 46610. |
| TEXAS -$0.65/L.F. | 83. | 2585. | 8421. | 23663. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** RCR--LOCAL ROADS 3 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 400. | 10.10 | 10.74 | 10.82 | 10.85 | 1.01 | .04 | .02 | .01 |
| $0.33/L.F. | 325. | 8.21 | 8.72 | 8.79 | 8.82 | .82 | .03 | .01 | .01 |
| | 250. | 6.31 | 6.71 | 6.76 | 6.78 | .63 | .02 | .01 | .00 |
| TEXAS | 400. | 19.89 | 21.15 | 21.31 | 21.38 | 1.99 | .08 | .03 | .01 |
| $0.65/L.F. | 325. | 16.16 | 17.18 | 17.32 | 17.37 | 1.62 | .06 | .03 | .01 |
| | 250. | 12.43 | 13.22 | 13.32 | 13.36 | 1.24 | .05 | .02 | .01 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 396. | 10141. | 24602. | 55732. |
| TEXAS -$0.65/L.F. | 201. | 5148. | 12490. | 28295. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** RCR--LOCAL ROADS 4 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 1400. | 21.02 | 22.76 | 23.04 | 23.17 | 2.10 | .11 | .05 | .03 |
| $0.33/L.F. | 1050. | 15.77 | 17.07 | 17.28 | 17.38 | 1.58 | .08 | .04 | .02 |
| | 400. | 6.01 | 6.50 | 6.58 | 6.62 | .60 | .03 | .02 | .01 |
| TEXAS | 1400. | 41.41 | 44.83 | 45.38 | 45.65 | 4.14 | .21 | .11 | .06 |
| $0.65/L.F. | 1050. | 31.05 | 33.62 | 34.04 | 34.23 | 3.11 | .16 | .08 | .04 |
| | 400. | 11.83 | 12.81 | 12.97 | 13.04 | 1.18 | .06 | .03 | .02 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 666. | 13005. | 25926. | 47299. |
| TEXAS -$0.65/L.F. | 338. | 6603. | 13162. | 24013. |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** RCR--LOCAL ROADS 5 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 50. | 1.30 | 1.35 | 1.36 | 1.36 | .13 | .00 | .00 | .00 |
| $0.33/L.F. | 40. | 1.04 | 1.08 | 1.09 | 1.09 | .10 | .00 | .00 | .00 |
| | 30. | .78 | .81 | .81 | .81 | .08 | .00 | .00 | .00 |
| TEXAS | 50. | 2.55 | 2.67 | 2.67 | 2.67 | .26 | .01 | .00 | .00 |
| $0.65/L.F. | 40. | 2.04 | 2.13 | 2.14 | 2.14 | .20 | .01 | .00 | .00 |
| | 30. | 1.53 | 1.60 | 1.60 | 1.60 | .15 | .00 | .00 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 386. | 13763. | 85815. | 548597. |
| TEXAS -$0.65/L.F. | 196. | 6987. | 43567. | 278519. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** RCR--LOCAL ROADS 6 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 250. | 6.48 | 6.77 | 6.79 | 6.79 | .65 | .02 | .00 | .00 |
| $0.33/L.F. | 150. | 3.89 | 4.06 | 4.07 | 4.07 | .39 | .01 | .00 | .00 |
| | 50. | 1.30 | 1.35 | 1.36 | 1.36 | .13 | .00 | .00 | .00 |
| TEXAS | 250. | 12.76 | 13.34 | 13.37 | 13.37 | 1.28 | .04 | .01 | .00 |
| $0.65/L.F. | 150. | 7.66 | 8.00 | 8.02 | 8.02 | .77 | .02 | .00 | .00 |
| | 50. | 2.55 | 2.67 | 2.67 | 2.67 | .26 | .01 | .00 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 386. | 13763. | 85815. | 548597. |
| TEXAS -$0.65/L.F. | 196. | 6987. | 43567. | 278519. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** RCR--LOCAL ROADS 7 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 400. | 10.37 | 10.84 | 10.86 | 10.86 | 1.04 | .03 | .00 | .00 |
| $0.33/L.F. | 325. | 8.42 | 8.80 | 8.82 | 8.83 | .84 | .02 | .00 | .00 |
| | 250. | 6.48 | 6.77 | 6.79 | 6.79 | .65 | .02 | .00 | .00 |
| TEXAS | 400. | 20.42 | 21.34 | 21.39 | 21.40 | 2.04 | .06 | .01 | .00 |
| $0.65/L.F. | 325. | 16.59 | 17.34 | 17.38 | 17.38 | 1.66 | .05 | .01 | .00 |
| | 250. | 12.76 | 13.34 | 13.37 | 13.37 | 1.28 | .04 | .01 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 386. | 13763. | 85815. | 548597. |
| TEXAS -$0.65/L.F. | 196. | 6987. | 43567. | 278519. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** RCR--LOCAL ROADS 8 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 1400. | 21.40 | 23.07 | 23.20 | 23.23 | 2.14 | .10 | .02 | .01 |
| $0.33/L.F. | 1050. | 16.05 | 17.31 | 17.40 | 17.42 | 1.61 | .08 | .02 | .00 |
| | 400. | 6.11 | 6.59 | 6.63 | 6.64 | .61 | .03 | .01 | .00 |
| TEXAS | 1400. | 42.15 | 45.45 | 45.70 | 45.76 | 4.22 | .20 | .05 | .01 |
| $0.65/L.F. | 1050. | 31.61 | 34.09 | 34.28 | 34.32 | 3.16 | .15 | .04 | .01 |
| | 400. | 12.04 | 12.99 | 13.06 | 13.07 | 1.20 | .06 | .01 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 654. | 13519. | 56183. | 228519. |
| TEXAS -$0.65/L.F. | 332. | 6863. | 28524. | 116018. |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** UCR--COLLECTOR 1 ***

| ACCIDENT COST BASIS | ADT | (- - BENEFIT $/FT-NSC - -) SERVICE LEVEL 1 | 2 | 3 | 4 | (- - INCREMENTAL BENEFIT/COST - -) SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 400. | 9.97 | 10.65 | 10.74 | 10.78 | 1.00 | .04 | .02 | .01 |
| $0.33/L.F. | 325. | 8.10 | 8.65 | 8.73 | 8.76 | .81 | .03 | .01 | .01 |
| | 250. | 6.23 | 6.66 | 6.71 | 6.74 | .62 | .03 | .01 | .00 |
| TEXAS | 400. | 19.64 | 20.96 | 21.16 | 21.23 | 1.96 | .08 | .03 | .01 |
| $0.65/L.F. | 325. | 15.96 | 17.05 | 17.19 | 17.25 | 1.60 | .07 | .03 | .01 |
| | 250. | 12.27 | 13.11 | 13.23 | 13.27 | 1.23 | .05 | .02 | .01 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 401. | 9491. | 22607. | 54183. |
| TEXAS -$0.65/L.F. | 204. | 4818. | 11477. | 27508. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** UCR--COLLECTOR 2 ***

| ACCIDENT COST BASIS | ADT | (- - BENEFIT $/FT-NSC - -) SERVICE LEVEL 1 | 2 | 3 | 4 | (- - INCREMENTAL BENEFIT/COST - -) SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 750. | 12.13 | 13.06 | 13.21 | 13.26 | 1.21 | .06 | .03 | .01 |
| $0.33/L.F. | 575. | 9.30 | 10.01 | 10.12 | 10.17 | .93 | .04 | .02 | .01 |
| | 400. | 6.47 | 6.97 | 7.04 | 7.07 | .65 | .03 | .01 | .01 |
| TEXAS | 750. | 23.89 | 25.73 | 26.01 | 26.13 | 2.39 | .11 | .05 | .03 |
| $0.65/L.F. | 575. | 18.32 | 19.73 | 19.94 | 20.03 | 1.83 | .09 | .04 | .02 |
| | 400. | 12.74 | 13.72 | 13.87 | 13.93 | 1.27 | .06 | .03 | .01 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 618. | 12969. | 27122. | 57420. |
| TEXAS -$0.65/L.F. | 314. | 6584. | 13770. | 29152. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** UCR--COLLECTOR 3 ***

| ACCIDENT COST BASIS | ADT | (- - BENEFIT $/FT-NSC - -) SERVICE LEVEL 1 | 2 | 3 | 4 | (- - INCREMENTAL BENEFIT/COST - -) SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 2000. | 31.76 | 34.58 | 35.08 | 35.32 | 3.18 | .17 | .10 | .05 |
| $0.33/L.F. | 1375. | 21.85 | 23.77 | 24.12 | 24.28 | 2.18 | .12 | .07 | .04 |
| | 750. | 11.92 | 12.97 | 13.15 | 13.25 | 1.19 | .06 | .04 | .02 |
| TEXAS | 2000. | 62.60 | 68.11 | 69.09 | 69.57 | 6.26 | .34 | .19 | .11 |
| $0.65/L.F. | 1375. | 43.03 | 46.82 | 47.50 | 47.83 | 4.30 | .23 | .13 | .07 |
| | 750. | 23.47 | 25.54 | 25.91 | 26.09 | 2.35 | .13 | .07 | .04 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 629. | 11553. | 20576. | 37324. |
| TEXAS -$0.65/L.F. | 320. | 5865. | 10447. | 18949. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** UCR--COLLECTOR 4 ***

| ACCIDENT COST BASIS | ADT | (- - BENEFIT $/FT-NSC - -) SERVICE LEVEL 1 | 2 | 3 | 4 | (- - INCREMENTAL BENEFIT/COST - -) SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 4000. | 57.97 | 63.98 | 65.05 | 65.62 | 5.80 | .37 | .21 | .13 |
| $0.33/L.F. | 3000. | 43.48 | 47.98 | 48.79 | 49.22 | 4.35 | .28 | .16 | .09 |
| | 2000. | 28.99 | 31.99 | 32.53 | 32.81 | 2.90 | .19 | .10 | .06 |
| TEXAS | 4000. | 114.19 | 126.01 | 128.13 | 129.26 | 11.42 | .73 | .41 | .25 |
| $0.65/L.F. | 3000. | 85.64 | 94.51 | 96.10 | 96.94 | 8.56 | .55 | .31 | .19 |
| | 2000. | 57.10 | 63.01 | 64.07 | 64.63 | 5.71 | .37 | .21 | .12 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | | | | |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 690. | 10771. | 19128. | 31896. |
| TEXAS -$0.65/L.F. | 350. | 5468. | 9711. | 16193. |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** UCR--COLLECTOR 5 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 5070. | 46.80 | 58.04 | 60.01 | 61.26 | 4.68 | .70 | .38 | .27 |
| $0.33/L.F. | 2600. | 24.00 | 29.76 | 30.78 | 31.41 | 2.40 | .36 | .20 | .14 |
| | 1440. | 13.29 | 16.48 | 17.04 | 17.40 | 1.33 | .20 | .11 | .08 |
| TEXAS | 5070. | 92.18 | 114.32 | 118.21 | 120.66 | 9.22 | 1.37 | .75 | .54 |
| $0.65/L.F. | 2600. | 47.27 | 58.63 | 60.62 | 61.88 | 4.73 | .70 | .39 | .28 |
| | 1440. | 26.18 | 32.47 | 33.57 | 34.27 | 2.62 | .39 | .21 | .15 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 1083. | 7291. | 13234. | 18538. |
| TEXAS -$0.65/L.F. | 550. | 3701. | 6719. | 9411. |

DESIGNATED SPEED (MPH) = 40.0
ROAD DESCRIPTION
*** UCR--COLLECTOR 6 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 400. | 10.13 | 10.73 | 10.78 | 10.79 | 1.01 | .04 | .01 | .00 |
| $0.33/L.F. | 325. | 8.23 | 8.71 | 8.76 | 8.76 | .82 | .03 | .01 | .00 |
| | 250. | 6.33 | 6.70 | 6.73 | 6.74 | .63 | .02 | .01 | .00 |
| TEXAS | 400. | 19.95 | 21.13 | 21.22 | 21.24 | 1.99 | .07 | .02 | .00 |
| $0.65/L.F. | 325. | 16.21 | 17.17 | 17.25 | 17.26 | 1.62 | .06 | .02 | .00 |
| | 250. | 12.47 | 13.20 | 13.27 | 13.28 | 1.25 | .05 | .01 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 395. | 10796. | 41452. | 168909. |
| TEXAS -$0.65/L.F. | 201. | 5461. | 21045. | 95908. |

DESIGNATED SPEED (MPH) = 40.0
ROAD DESCRIPTION
*** UCR--COLLECTOR 7 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 750. | 12.14 | 13.13 | 13.25 | 13.28 | 1.21 | .06 | .02 | .01 |
| $0.33/L.F. | 575. | 9.31 | 10.07 | 10.16 | 10.18 | .93 | .05 | .02 | .01 |
| | 400. | 6.47 | 7.00 | 7.07 | 7.08 | .65 | .03 | .01 | .00 |
| TEXAS | 750. | 23.91 | 25.87 | 26.09 | 26.16 | 2.39 | .12 | .04 | .01 |
| $0.65/L.F. | 575. | 18.33 | 19.83 | 20.01 | 20.06 | 1.83 | .09 | .03 | .01 |
| | 400. | 12.75 | 13.80 | 13.92 | 13.95 | 1.28 | .06 | .02 | .01 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 618. | 12186. | 33703. | 104104. |
| TEXAS -$0.65/L.F. | 314. | 6187. | 17111. | 52853. |

DESIGNATED SPEED (MPH) = 40.0
ROAD DESCRIPTION
*** UCR--COLLECTOR 8 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 2000. | 32.37 | 35.02 | 35.33 | 35.42 | 3.24 | .16 | .06 | .02 |
| $0.33/L.F. | 1375. | 22.25 | 24.08 | 24.29 | 24.35 | 2.23 | .11 | .04 | .01 |
| | 750. | 12.14 | 13.13 | 13.25 | 13.28 | 1.21 | .06 | .02 | .01 |
| TEXAS | 2000. | 63.76 | 68.98 | 69.59 | 69.76 | 6.38 | .32 | .12 | .04 |
| $0.65/L.F. | 1375. | 43.84 | 47.43 | 47.84 | 47.96 | 4.38 | .22 | .08 | .03 |
| | 750. | 23.91 | 25.87 | 26.09 | 26.16 | 2.39 | .12 | .04 | .01 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 618. | 12186. | 33703. | 104104. |
| TEXAS -$0.65/L.F. | 314. | 6187. | 17111. | 52853. |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 40.0
ROAD DESCRIPTION
*** UCH--COLLECTOR 9 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON $0.33/L.F. | 4000. | 59.20 | 64.96 | 65.65 | 65.87 | 5.92 | .36 | .13 | .05 |
| | 3000. | 44.40 | 48.72 | 49.24 | 49.40 | 4.44 | .27 | .10 | .04 |
| | 2000. | 29.60 | 32.46 | 32.83 | 32.94 | 2.96 | .18 | .07 | .02 |
| TEXAS $0.65/L.F. | 4000. | 116.60 | 127.96 | 129.31 | 129.75 | 11.66 | .70 | .26 | .10 |
| | 3000. | 87.45 | 95.97 | 96.98 | 97.31 | 8.75 | .53 | .20 | .07 |
| | 2000. | 58.30 | 63.98 | 64.66 | 64.87 | 5.83 | .35 | .13 | .05 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 676. | 11212. | 29914. | 82042. |
| TEXAS -$0.65/L.F. | 343. | 5692. | 15187. | 41652. |

DESIGNATED SPEED (MPH) = 40.0
ROAD DESCRIPTION
*** UCH--COLLECTOR 10 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON $0.33/L.F. | 5070. | 49.46 | 59.97 | 61.42 | 62.09 | 4.95 | .65 | .28 | .15 |
| | 2600. | 25.36 | 30.76 | 31.50 | 31.84 | 2.54 | .33 | .14 | .07 |
| | 1440. | 14.05 | 17.03 | 17.45 | 17.63 | 1.40 | .18 | .08 | .04 |
| TEXAS $0.65/L.F. | 5070. | 97.42 | 118.13 | 120.99 | 122.29 | 9.74 | 1.28 | .55 | .29 |
| | 2600. | 49.96 | 60.58 | 62.04 | 62.71 | 5.00 | .66 | .28 | .15 |
| | 1440. | 27.67 | 33.55 | 34.36 | 34.73 | 2.77 | .36 | .16 | .08 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 1025. | 7791. | 17998. | 34752. |
| TEXAS -$0.65/L.F. | 520. | 3956. | 9137. | 17643. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** UCH--COLLECTOR 11 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON $0.33/L.F. | 400. | 7.20 | 7.58 | 7.61 | 7.61 | .72 | .02 | .00 | .00 |
| | 325. | 5.85 | 6.16 | 6.18 | 6.19 | .58 | .02 | .00 | .00 |
| | 250. | 4.50 | 4.74 | 4.76 | 4.76 | .45 | .01 | .00 | .00 |
| TEXAS $0.65/L.F. | 400. | 14.18 | 14.94 | 14.99 | 15.00 | 1.42 | .05 | .01 | .00 |
| | 325. | 11.52 | 12.14 | 12.18 | 12.18 | 1.15 | .04 | .01 | .00 |
| | 250. | 8.86 | 9.34 | 9.37 | 9.37 | .89 | .03 | .01 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 556. | 16820. | 80488. | 460254. |
| TEXAS -$0.65/L.F. | 282. | 8539. | 40863. | 233667. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** UCH--COLLECTOR 12 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON $0.33/L.F. | 750. | 12.24 | 13.19 | 13.27 | 13.28 | 1.22 | .06 | .02 | .00 |
| | 575. | 9.38 | 10.11 | 10.17 | 10.18 | .94 | .04 | .01 | .00 |
| | 400. | 6.53 | 7.03 | 7.08 | 7.08 | .65 | .03 | .01 | .00 |
| TEXAS $0.65/L.F. | 750. | 24.11 | 25.97 | 26.13 | 26.17 | 2.41 | .12 | .03 | .01 |
| | 575. | 18.49 | 19.91 | 20.03 | 20.06 | 1.85 | .09 | .02 | .01 |
| | 400. | 12.88 | 13.85 | 13.94 | 13.95 | 1.29 | .06 | .02 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 613. | 12841. | 47443. | 195103. |
| TEXAS -$0.65/L.F. | 311. | 6519. | 24086. | 99052. |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** UCR--COLLECTOR 13 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 2000. | 32.64 | 35.16 | 35.38 | 35.42 | 3.26 | .16 | .04 | .01 |
| $0.33/L.F. | 1375. | 22.44 | 24.17 | 24.32 | 24.35 | 2.24 | .11 | .03 | .01 |
| | 750. | 12.24 | 13.19 | 13.27 | 13.28 | 1.22 | .06 | .02 | .00 |
| TEXAS | 2000. | 64.30 | 69.25 | 69.68 | 69.77 | 6.43 | .31 | .08 | .02 |
| $0.65/L.F. | 1375. | 44.20 | 47.61 | 47.91 | 47.97 | 4.42 | .21 | .06 | .01 |
| | 750. | 24.11 | 25.97 | 26.13 | 26.17 | 2.41 | .12 | .03 | .01 |
| ACCIDENT COST BASIS/ADT FOR B/C=1.0 | | | | | | | | | |
| WASHINGTON-$0.33/L.F. | | 613. | 12841. | 47443. | 195103. | | | | |
| TEXAS -$0.65/L.F. | | 311. | 6519. | 24086. | 99052. | | | | |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** UCR--COLLECTOR 14 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 4000. | 58.80 | 65.08 | 65.72 | 65.89 | 5.88 | .39 | .12 | .04 |
| $0.33/L.F. | 3000. | 44.10 | 48.81 | 49.29 | 49.42 | 4.41 | .29 | .09 | .03 |
| | 2000. | 29.40 | 32.54 | 32.86 | 32.95 | 2.94 | .19 | .06 | .02 |
| TEXAS | 4000. | 115.82 | 128.19 | 129.44 | 129.78 | 11.58 | .77 | .24 | .08 |
| $0.65/L.F. | 3000. | 86.87 | 96.14 | 97.08 | 97.34 | 8.69 | .57 | .18 | .06 |
| | 2000. | 57.91 | 64.09 | 64.72 | 64.89 | 5.79 | .38 | .12 | .04 |
| ACCIDENT COST BASIS/ADT FOR B/C=1.0 | | | | | | | | | |
| WASHINGTON-$0.33/L.F. | | 680. | 10298. | 32404. | 103882. | | | | |
| TEXAS -$0.65/L.F. | | 345. | 5228. | 16451. | 52740. | | | | |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** UCR--COLLECTOR 15 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 5070. | 50.79 | 60.73 | 61.86 | 62.25 | 5.08 | .62 | .22 | .08 |
| $0.33/L.F. | 2600. | 26.05 | 31.14 | 31.72 | 31.92 | 2.60 | .32 | .11 | .04 |
| | 1440. | 14.43 | 17.25 | 17.57 | 17.68 | 1.44 | .17 | .06 | .02 |
| TEXAS | 5070. | 100.05 | 119.62 | 121.85 | 122.61 | 10.00 | 1.21 | .43 | .17 |
| $0.65/L.F. | 2600. | 51.31 | 61.34 | 62.49 | 62.88 | 5.13 | .62 | .22 | .09 |
| | 1440. | 28.42 | 33.98 | 34.61 | 34.82 | 2.84 | .34 | .12 | .05 |
| ACCIDENT COST BASIS/ADT FOR B/C=1.0 | | | | | | | | | |
| WASHINGTON-$0.33/L.F. | | 998. | 8243. | 23075. | 59770. | | | | |
| TEXAS -$0.65/L.F. | | 507. | 4185. | 11715. | 30345. | | | | |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** UCR--LOCAL ROADS 1 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 50. | 2.84 | 2.96 | 2.97 | 2.97 | .28 | .01 | .00 | .00 |
| $0.33/L.F. | 45. | 2.27 | 2.37 | 2.38 | 2.38 | .23 | .01 | .00 | .00 |
| | 40. | 1.70 | 1.76 | 1.78 | 1.76 | .17 | .00 | .00 | .00 |
| TEXAS | 50. | 5.60 | 5.84 | 5.85 | 5.86 | .56 | .02 | .00 | .00 |
| $0.65/L.F. | 40. | 4.46 | 4.67 | 4.68 | 4.69 | .45 | .01 | .00 | .00 |
| | 30. | 3.36 | 3.50 | 3.51 | 3.51 | .34 | .01 | .00 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 176. | 6547. | 32048. | 130338. |
| TEXAS -$0.65/L.F. | 89. | 3324. | 16271. | 66172. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** UCR--LOCAL ROADS 2 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 250. | 15.15 | 16.01 | 16.10 | 16.12 | 1.52 | .05 | .02 | .01 |
| $0.33/L.F. | 150. | 9.09 | 9.61 | 9.66 | 9.67 | .91 | .03 | .01 | .00 |
| | 50. | 3.03 | 3.20 | 3.22 | 3.22 | .30 | .01 | .00 | .00 |
| TEXAS | 250. | 29.84 | 31.54 | 31.70 | 31.75 | 2.98 | .10 | .03 | .01 |
| $0.65/L.F. | 150. | 17.91 | 18.92 | 19.02 | 19.05 | 1.79 | .06 | .02 | .01 |
| | 50. | 5.97 | 6.31 | 6.34 | 6.35 | .60 | .02 | .01 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 165. | 4702. | 15131. | 45591. |
| TEXAS -$0.65/L.F. | 84. | 2387. | 7682. | 23146. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** UCR--LOCAL ROADS 3 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 400. | 9.97 | 10.65 | 10.74 | 10.78 | 1.00 | .04 | .02 | .01 |
| $0.33/L.F. | 325. | 8.10 | 8.65 | 8.73 | 8.76 | .81 | .03 | .01 | .01 |
| | 250. | 6.23 | 6.66 | 6.71 | 6.74 | .62 | .03 | .01 | .00 |
| TEXAS | 400. | 19.64 | 20.96 | 21.16 | 21.23 | 1.96 | .08 | .03 | .01 |
| $0.65/L.F. | 325. | 15.96 | 17.05 | 17.19 | 17.25 | 1.60 | .07 | .03 | .01 |
| | 250. | 12.27 | 13.11 | 13.23 | 13.27 | 1.23 | .05 | .02 | .01 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 401. | 9491. | 22607. | 54183. |
| TEXAS -$0.65/L.F. | 204. | 4818. | 11477. | 27508. |

DESIGNATED SPEED (MPH) = 30.0
ROAD DESCRIPTION
*** UCR--LOCAL ROADS 4 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 1400. | 20.70 | 22.57 | 22.87 | 23.01 | 2.07 | .12 | .06 | .03 |
| $0.33/L.F. | 1050. | 15.53 | 16.93 | 17.15 | 17.26 | 1.55 | .09 | .04 | .02 |
| | 400. | 5.92 | 6.45 | 6.53 | 6.57 | .59 | .03 | .02 | .01 |
| TEXAS | 1400. | 40.76 | 44.46 | 45.05 | 45.33 | 4.08 | .23 | .11 | .06 |
| $0.65/L.F. | 1050. | 30.59 | 33.35 | 33.79 | 33.99 | 3.06 | .17 | .09 | .05 |
| | 400. | 11.65 | 12.70 | 12.87 | 12.95 | 1.17 | .07 | .03 | .02 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 676. | 12113. | 24016. | 45730. |
| TEXAS -$0.65/L.F. | 343. | 6149. | 12194. | 23217. |

TABLE A.35 (Cont'd)

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** UCR--LOCAL ROADS 5 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 50. | 1.27 | 1.34 | 1.35 | 1.35 | .13 | .00 | .00 | .00 |
| $0.33/L.F. | 40. | 1.02 | 1.07 | 1.08 | 1.08 | .10 | .00 | .00 | .00 |
| | 30. | .76 | .81 | .81 | .81 | .08 | .00 | .00 | .00 |
| TEXAS | 50. | 2.51 | 2.65 | 2.65 | 2.66 | .25 | .01 | .00 | .00 |
| $0.65/L.F. | 40. | 2.01 | 2.12 | 2.12 | 2.12 | .20 | .01 | .00 | .00 |
| | 30. | 1.51 | 1.59 | 1.59 | 1.59 | .15 | .00 | .00 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 392. | 11873. | 56815. | 324885. |
| TEXAS -$0.65/L.F. | 199. | 6028. | 28845. | 164942. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** UCR--LOCAL ROADS 6 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 250. | 6.37 | 6.71 | 6.74 | 6.74 | .64 | .02 | .00 | .00 |
| $0.33/L.F. | 150. | 3.82 | 4.03 | 4.04 | 4.04 | .38 | .01 | .00 | .00 |
| | 50. | 1.27 | 1.34 | 1.35 | 1.35 | .13 | .00 | .00 | .00 |
| TEXAS | 250. | 12.56 | 13.23 | 13.27 | 13.28 | 1.26 | .04 | .01 | .00 |
| $0.65/L.F. | 150. | 7.53 | 7.94 | 7.96 | 7.97 | .75 | .02 | .01 | .00 |
| | 50. | 2.51 | 2.65 | 2.65 | 2.66 | .25 | .01 | .00 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 392. | 11873. | 56815. | 324885. |
| TEXAS -$0.65/L.F. | 199. | 6028. | 28845. | 164942. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** UCR--LOCAL ROADS 7 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 400. | 10.20 | 10.74 | 10.78 | 10.79 | 1.02 | .03 | .01 | .00 |
| $0.33/L.F. | 325. | 8.29 | 8.73 | 8.76 | 8.76 | .83 | .03 | .01 | .00 |
| | 250. | 6.37 | 6.71 | 6.74 | 6.74 | .64 | .02 | .00 | .00 |
| TEXAS | 400. | 20.09 | 21.16 | 21.23 | 21.24 | 2.01 | .07 | .01 | .00 |
| $0.65/L.F. | 325. | 16.32 | 17.19 | 17.25 | 17.26 | 1.63 | .05 | .01 | .00 |
| | 250. | 12.56 | 13.23 | 13.27 | 13.28 | 1.26 | .04 | .01 | .00 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 392. | 11873. | 56815. | 324885. |
| TEXAS -$0.65/L.F. | 199. | 6028. | 28845. | 164942. |

DESIGNATED SPEED (MPH) = 50.0
ROAD DESCRIPTION
*** UCR--LOCAL ROADS 8 ***

| ACCIDENT COST BASIS | ADT | BENEFIT $/FT-NSC SERVICE LEVEL 1 | 2 | 3 | 4 | INCREMENTAL BENEFIT/COST SERVICE LEVEL 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|---|---|---|---|
| WASHINGTON | 1400. | 20.92 | 22.85 | 23.02 | 23.06 | 2.09 | .12 | .03 | .01 |
| $0.33/L.F. | 1050. | 15.69 | 17.14 | 17.27 | 17.30 | 1.57 | .09 | .03 | .01 |
| | 400. | 5.98 | 6.53 | 6.58 | 6.59 | .60 | .03 | .01 | .00 |
| TEXAS | 1400. | 41.20 | 45.01 | 45.35 | 45.43 | 4.12 | .24 | .07 | .02 |
| $0.65/L.F. | 1050. | 30.90 | 33.76 | 34.01 | 34.07 | 3.09 | .18 | .05 | .01 |
| | 400. | 11.77 | 12.86 | 12.96 | 12.98 | 1.18 | .07 | .02 | .01 |

ACCIDENT COST BASIS/ADT FOR B/C=1.0

| | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| WASHINGTON-$0.33/L.F. | 669. | 11692. | 41746. | 154802. |
| TEXAS -$0.65/L.F. | 340. | 5936. | 21194. | 78592. |

APPENDIX B

ASSESSMENT OF CURRENT BRIDGE RAILINGS

B.1 Service Levels

The Figures B.1 through B.7 are design drawings of bridge railing systems that have passed at least the structural adequacy test conforming to one of the four service levels as summarized in Table 16. The NCHRP SL systems are shown in Figures 3 and 4 of Chapter Three.

B.2 Concrete Safety Shape Parapets

Seventeen state standards were examined for cost and strengths.

B.2.1 Concrete Safety Shape Parapet Costs. During this project, 17 concrete safety shape designs were submitted to the Portland Cement Association (PCA) for cost analysis. These designs are included in Figure B.8. PCA referred the information to the Concrete Reinforcing Steel Institute (CRSI). No cost estimate data were obtained; a suggestion was made to obtain estimates from local sources. The CRSI submittal did include some suggestions for improved rebar geometry as shown in Figure B.9.

The designs were submitted to a local contractor for cost analysis (see Table B.1). In order to test the data, estimated cost for one design (No. 5) was compared to recent bid prices. The latest bid prices for this concrete parapet were $32.37 per lineal ft based on 12 jobs and 44,000 lineal ft. The estimate submitted by the contractor was $41.30. An adjustment in the form unit prices was made after a discussion with the contractor. This adjustment lowered the estimated cost for Design 5 to $34.21/lineal ft. Data given in Table B.1 reflect the adjustment in form unit price for all designs.



Table B.1 data indicate little differences in cost of most designs. Of the basic designs (no rail or granite), 13 of 14 designs were in the range of $32-$40/lineal ft.

B.2.2 Concrete Safety Shape Parapet (CSSP) Strength. Analysis of the strength of concrete parapets was accomplished as summarized in Table B.2. Although costs of the systems were similar, the estimated strength of the various designs varied considerably. A recent analysis of the Texas concrete safety shape design by Hirsch(3) predicted an ultimate load capacity of 60 kips. In this analysis, 2/3 of the load capacity was due to the vertical steel. Accordingly, in order to simplify analysis of the various designs of Table B.2 the ultimate moment capacity of the design was determined for vertical steel only. It should be noted that longitudinal steel is important in distributing load to vertical steel.

All 32-in. (0.8-m) high concrete safety shaped parapets are classified as SL 2.

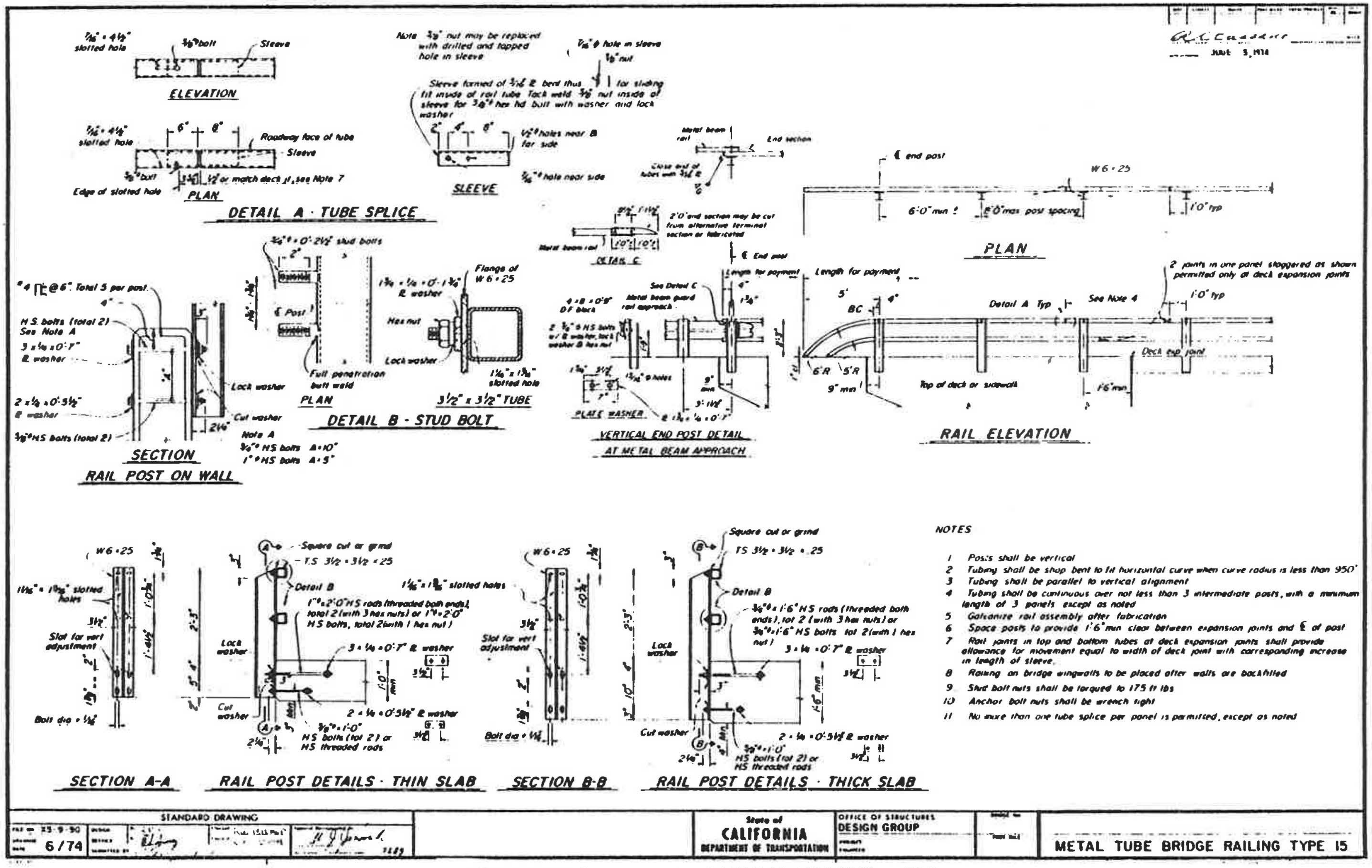



FIGURE B.1 BRIDGE RAILING BR4(20), SL1

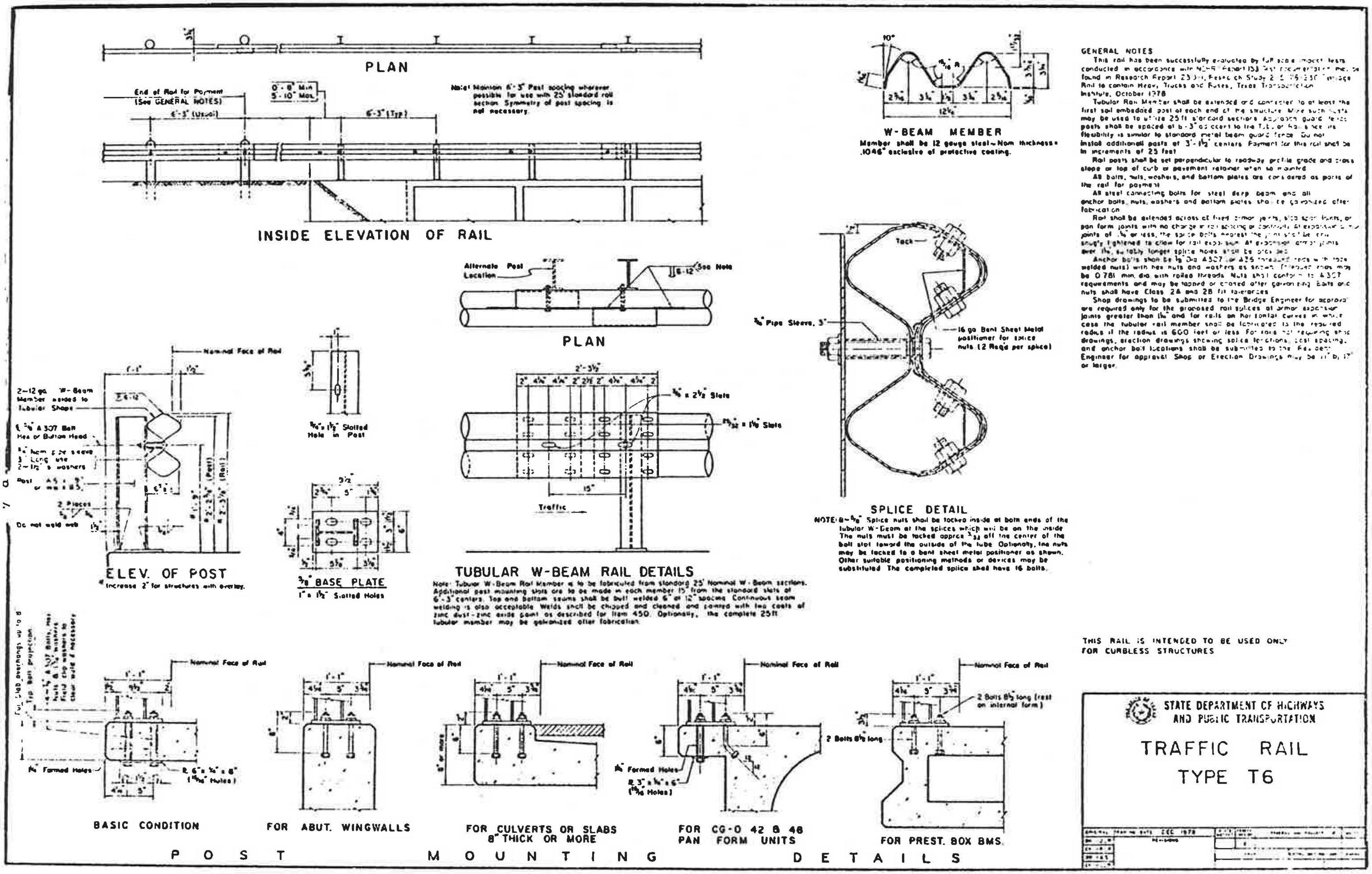



FIGURE B.2 TEXAS TYPE T6 RAILING, SL2

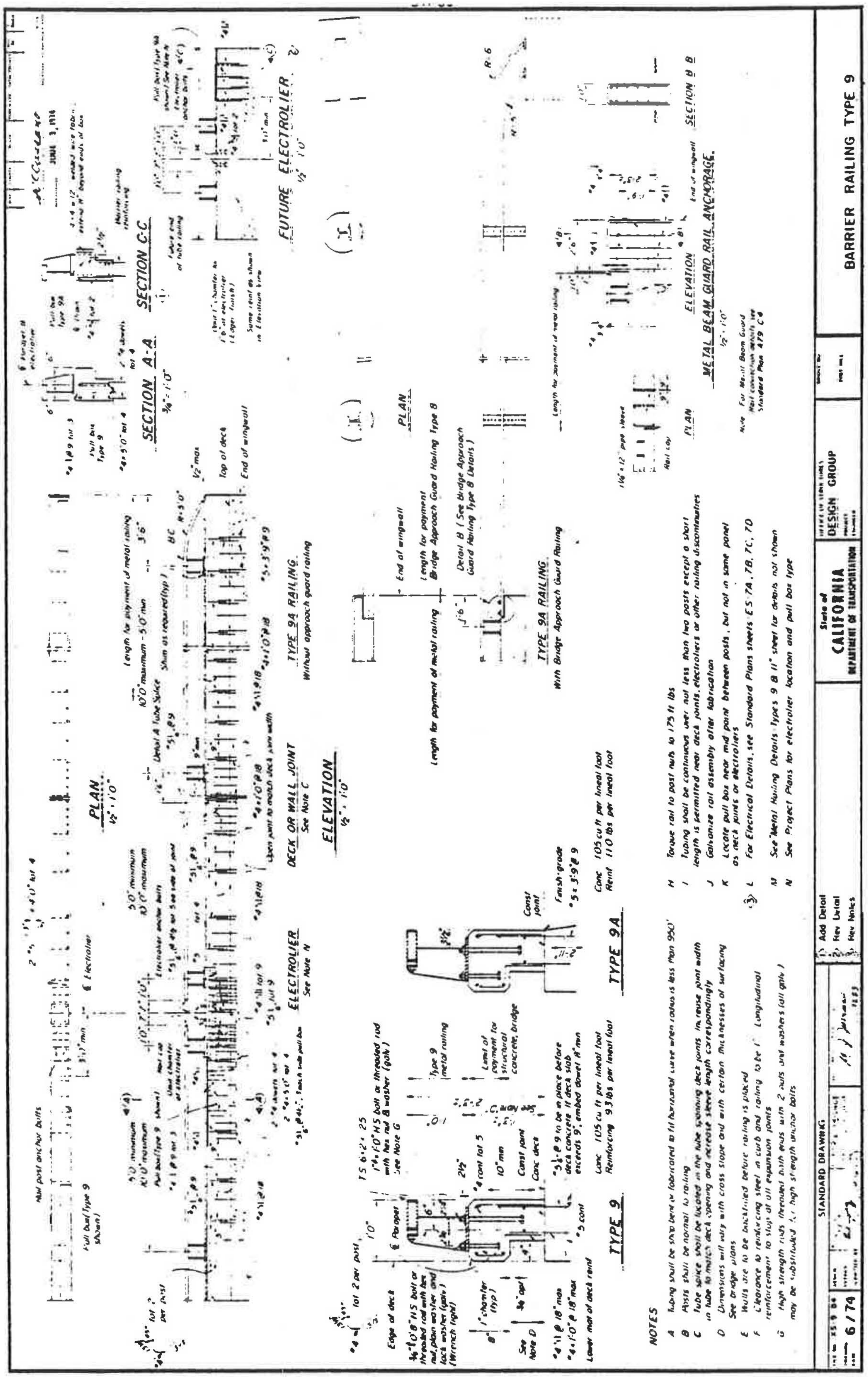



FIGURE B.3 BRIDGE RAILING BR2 (20), SL2

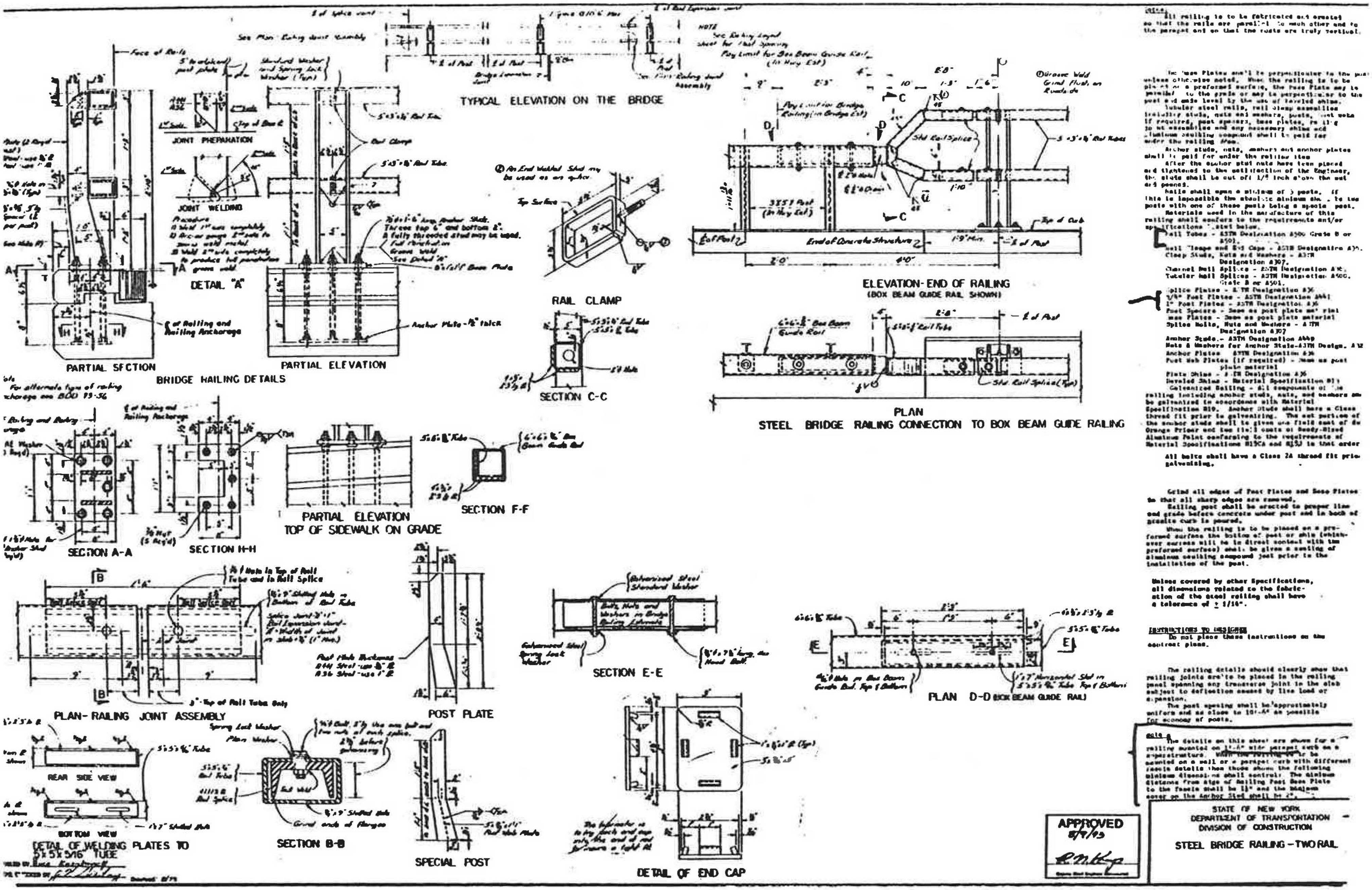



FIGURE B.4 BRIDGE RAILING BR3 (20), SL2

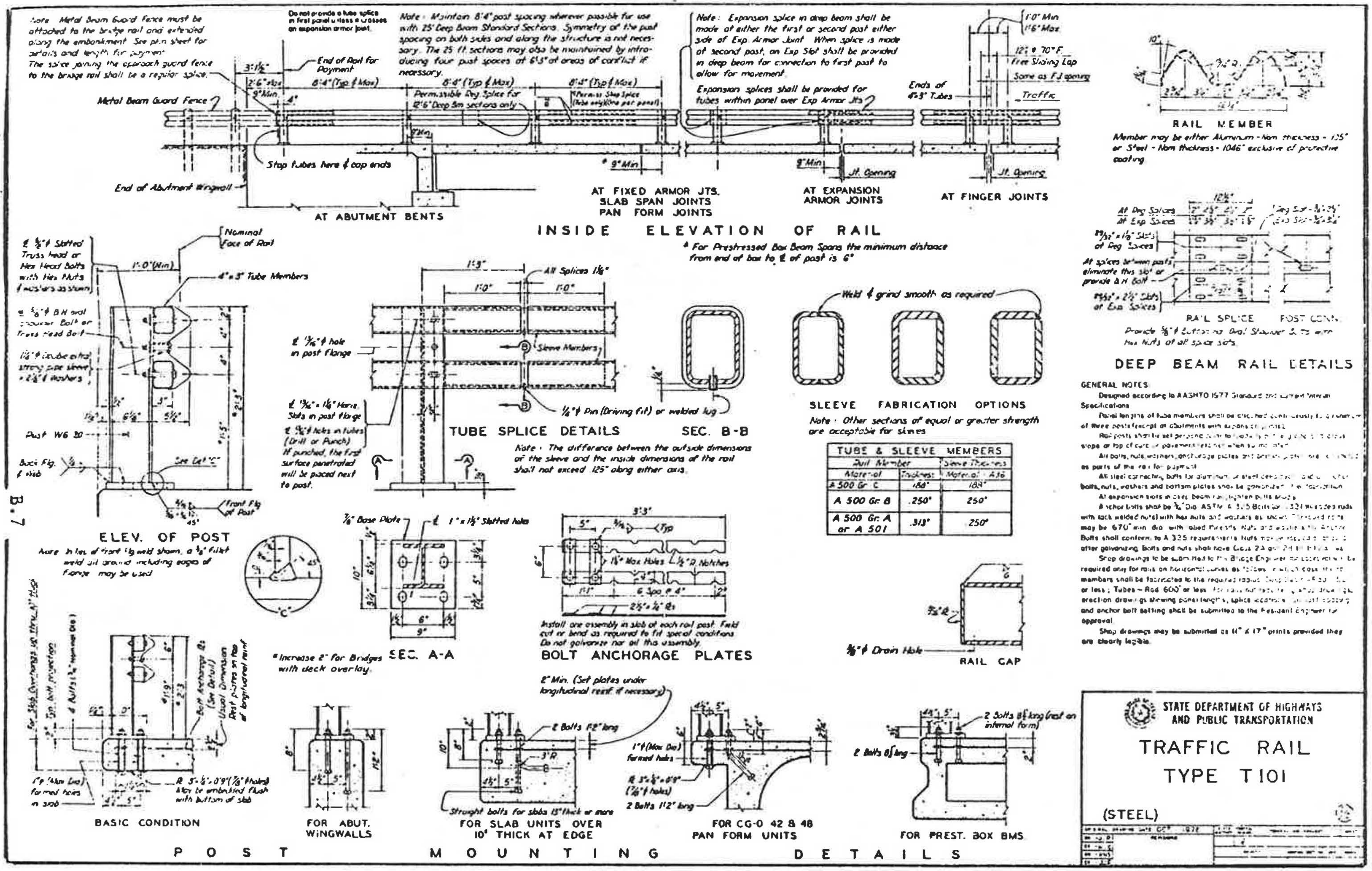



FIGURE B.5 TEXAS TYPE T101 RAILING, SL3

B.8

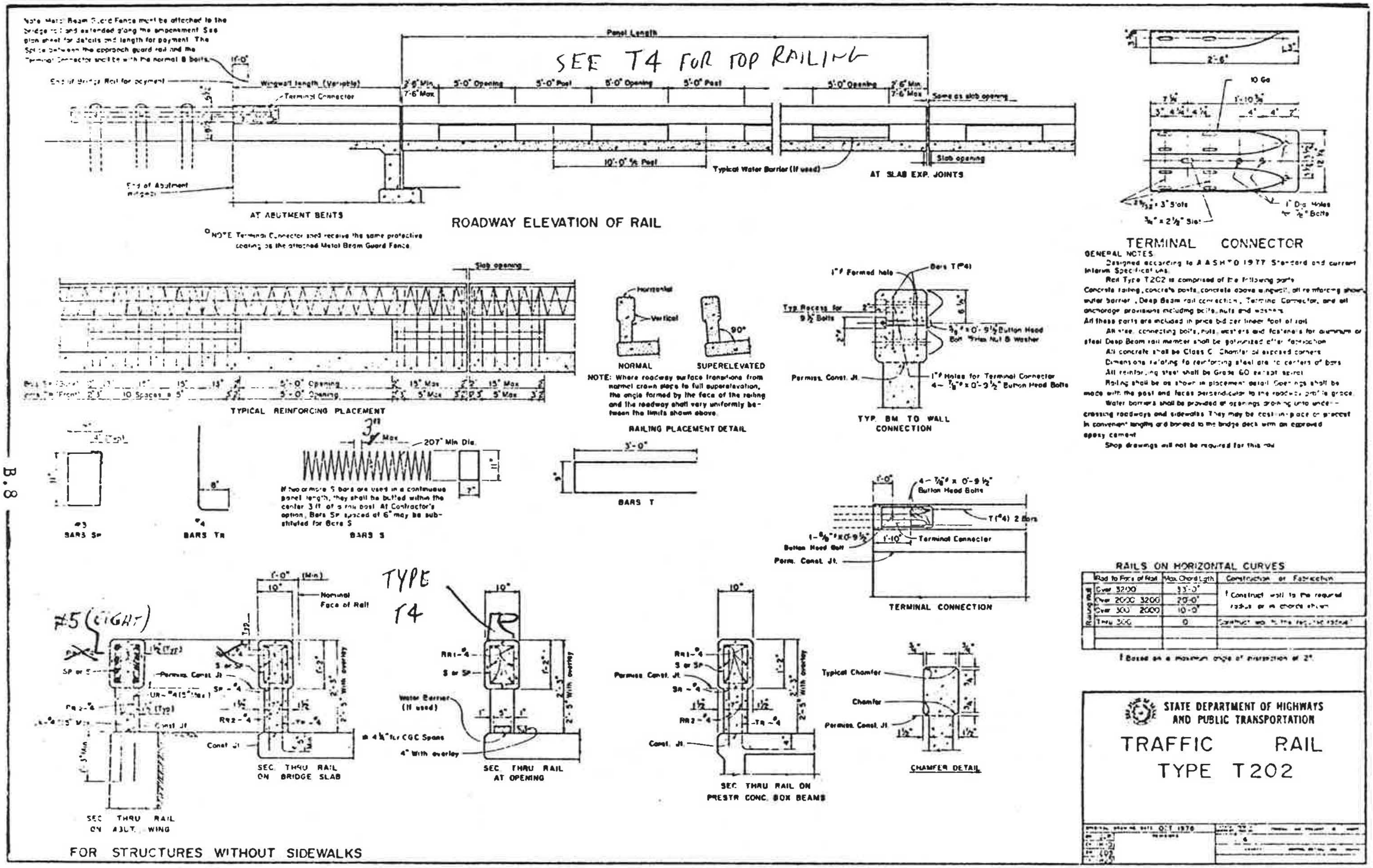



FIGURE B.6 TEXAS TYPE T202 RAILING (MODIFIED) - TEXAS TYPE T4 IS MOUNTED ON TOP, SI4

B.9

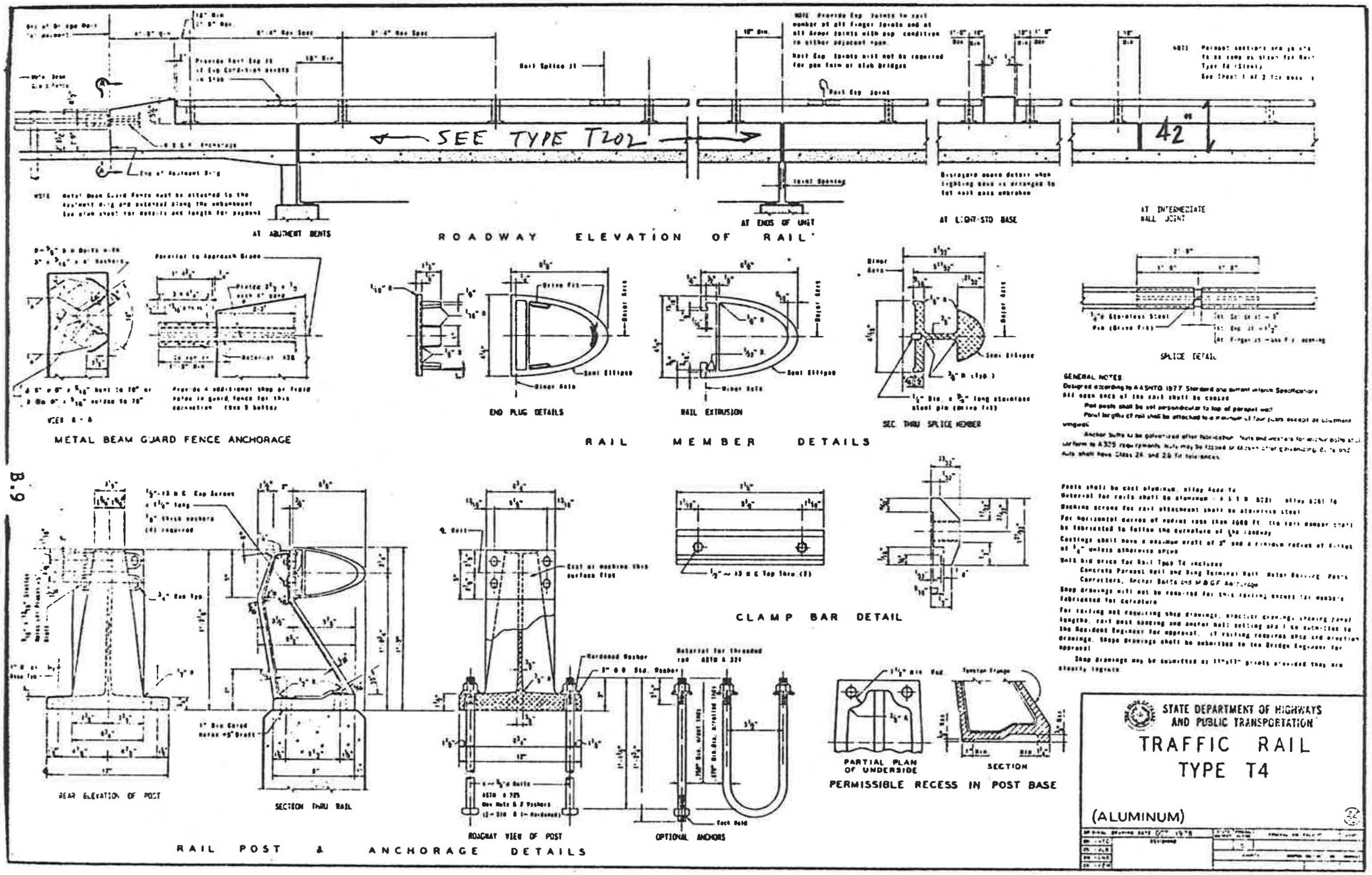



FIGURE B.6 (Cont'd)

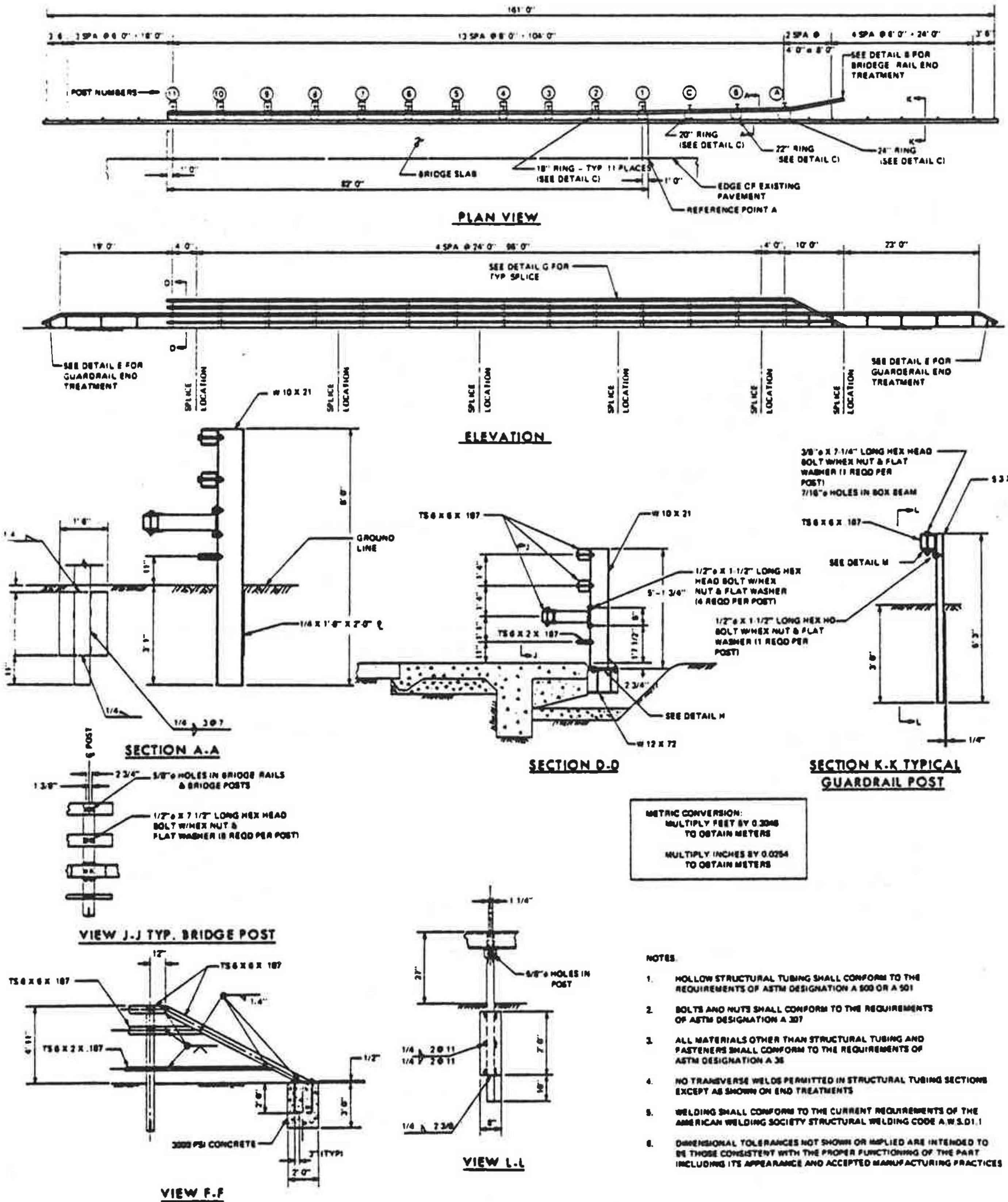



FIGURE B.7 COLLAPSING RING BRIDGE RAILING, SL4

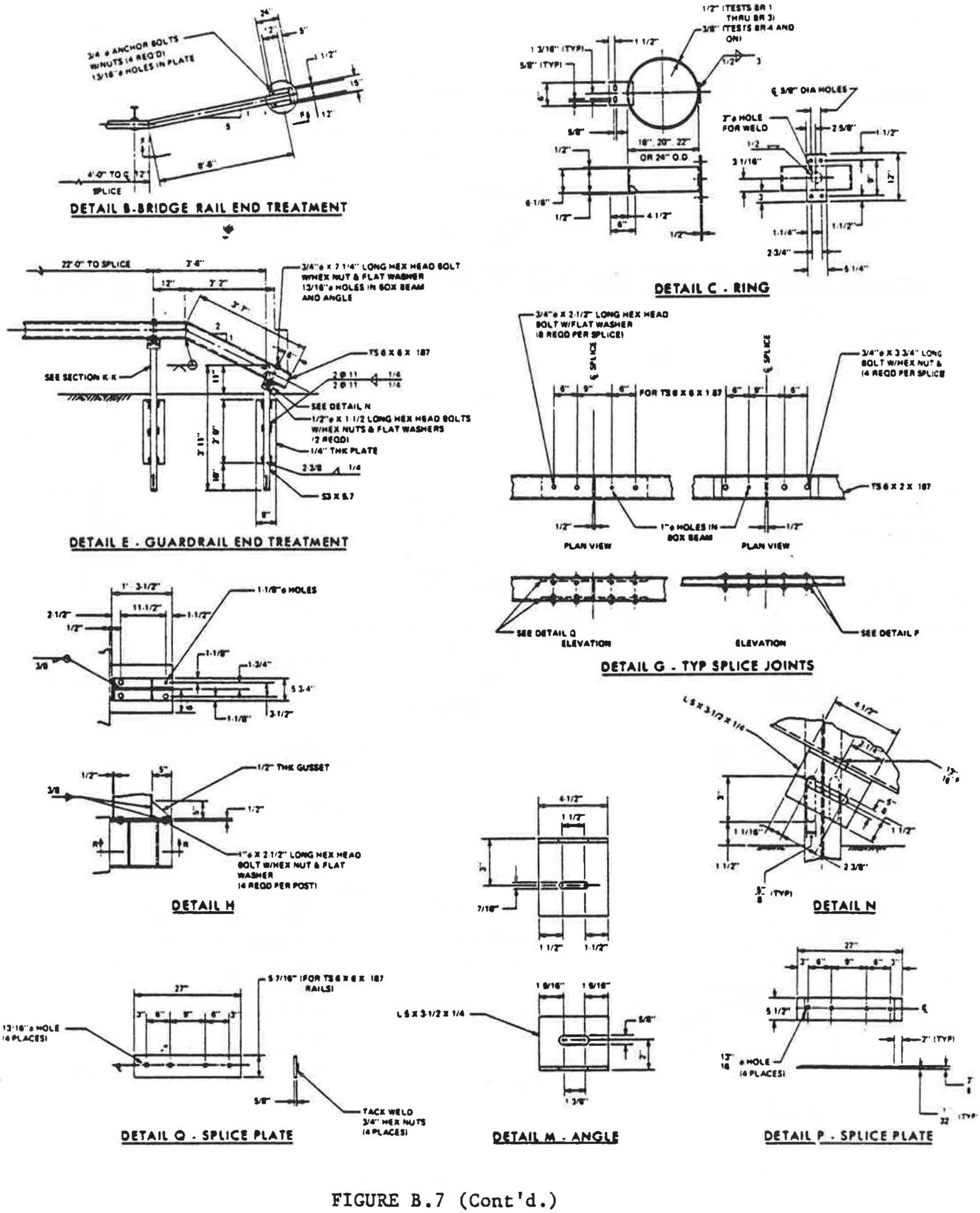
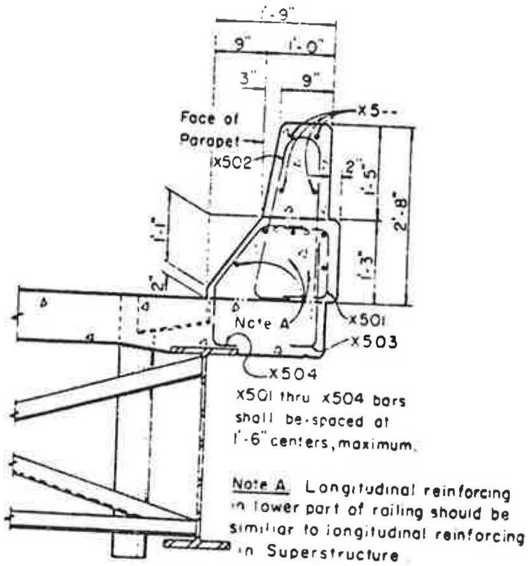



FIGURE B.7 (Cont'd.)

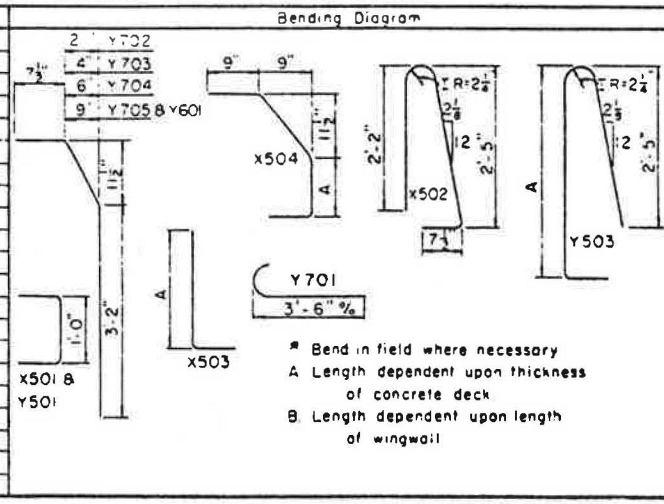



SECTION A-A

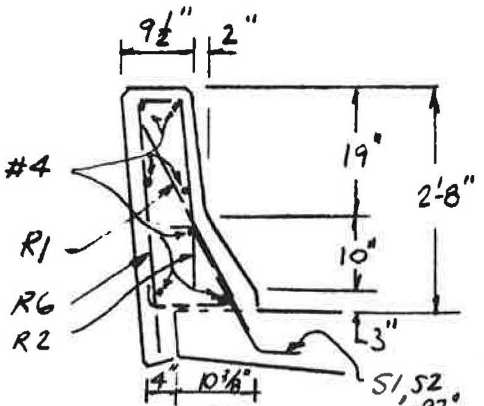
**RAILING REINFORCING STEEL**

| Mark | Length | Shape |
|---|---|---|
| X501 | 2'-0" | Bt |
| X502 | 5'-4" | Bt |
| X503 | A | Bt |
| X504 | A | Bt |
| X5-- | | St |
| | | |
| Y501 | 2'-0" | Bt |
| Y502 | A | St |
| Y503 | A | Bt |
| Y504 | B | St * |
| Y505 | 7'-3" | St |
| Y506 | B | St |
| Y507 | 2'-10" | St |
| | | |
| Y601 | 4'-11" | Bt * |
| | | |
| Y701 | 4'-4" | Bt |
| Y702 | 4'-8" | Bt |
| Y703 | 4'-9" | Bt |
| Y704 | 4'-0" | Bt |
| Y705 | 4'-11" | Bt |

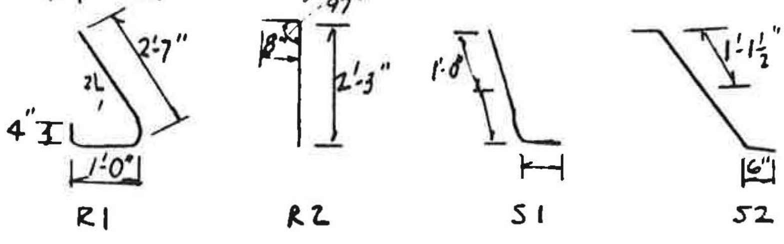
Bending Diagram




Design #1

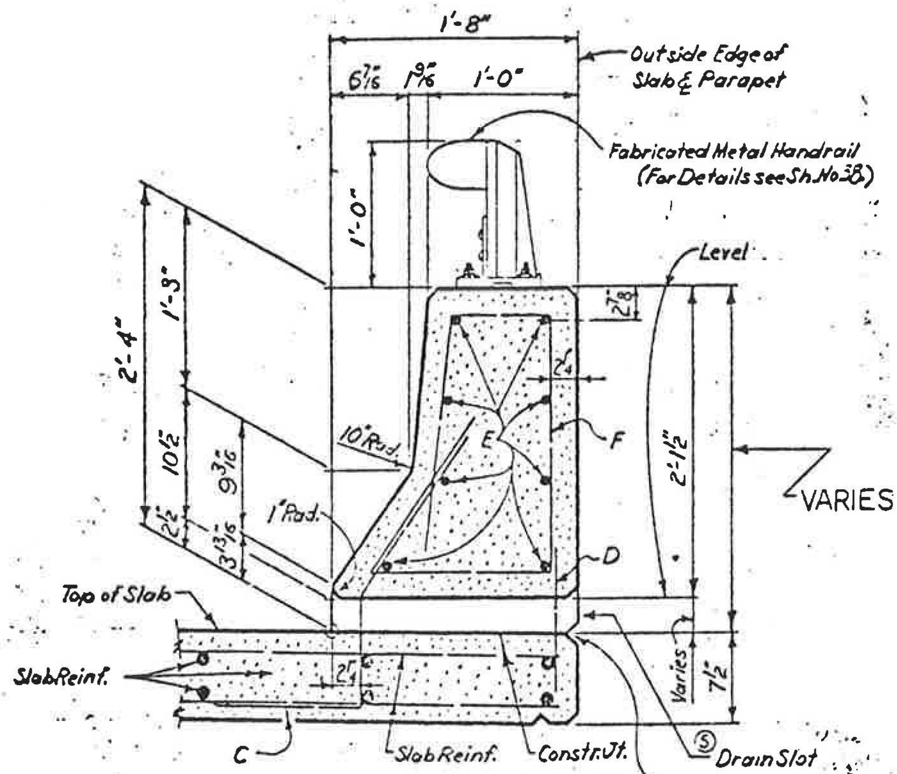



| BAR | SIZE | LENGTH | SPA |
|---|---|---|---|
| R1 | #5 | 3'-8" | 8" |
| R2 | #4 | 2'-9" | 1'-4" |
| R6 | #4 | 3'-1" | 1'-4" |
| S1 | #5 | | 8" |
| S2 | #4 | | 1'-4" |



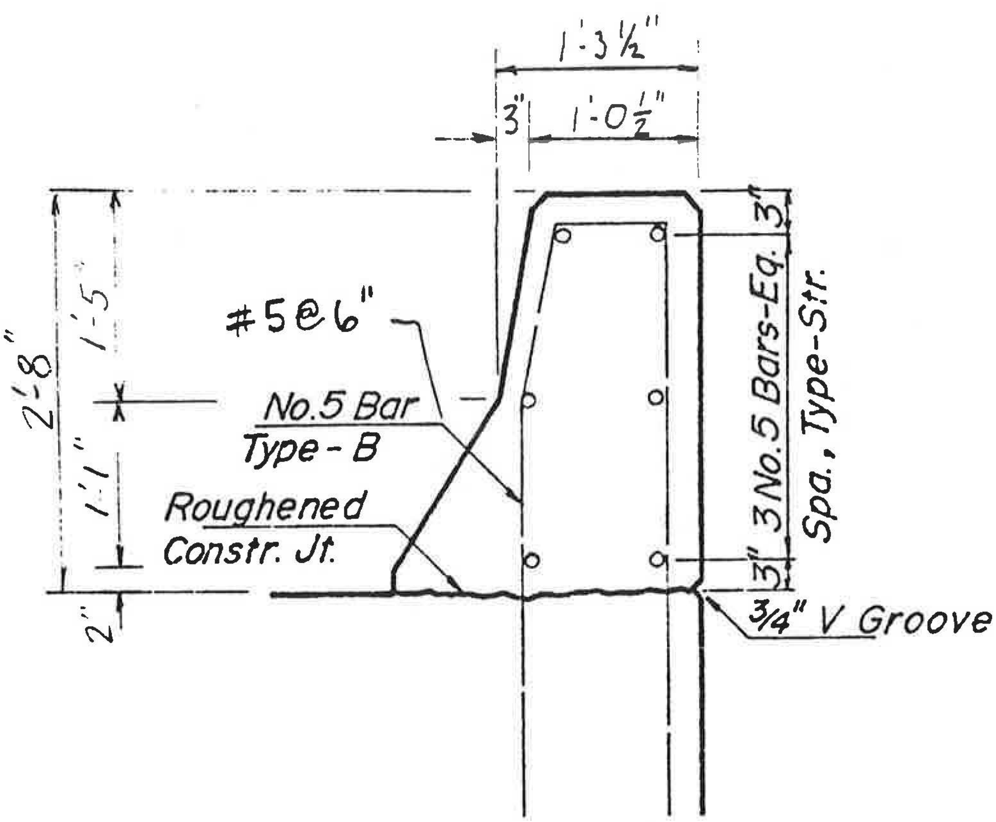

Design #2

FIGURE B.8 CONCRETE BRIDGE RAILING DESIGNS




SECTION THRU PARAPET
(SECTION PERPENDICULAR OR RADIAL TO OUTSIDE OF SLAB)

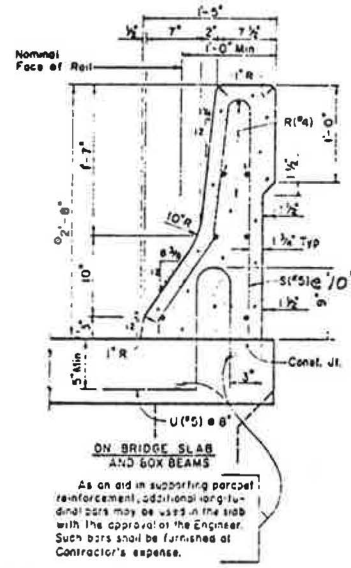
Design #3

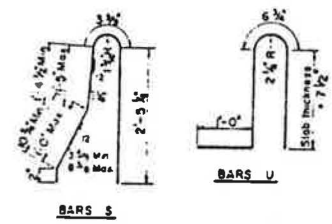



Design #4

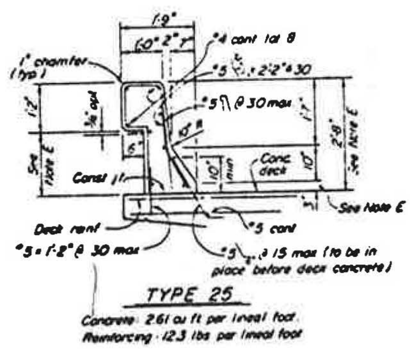
FIGURE B.8 (Cont'd)

B.13





Design #5

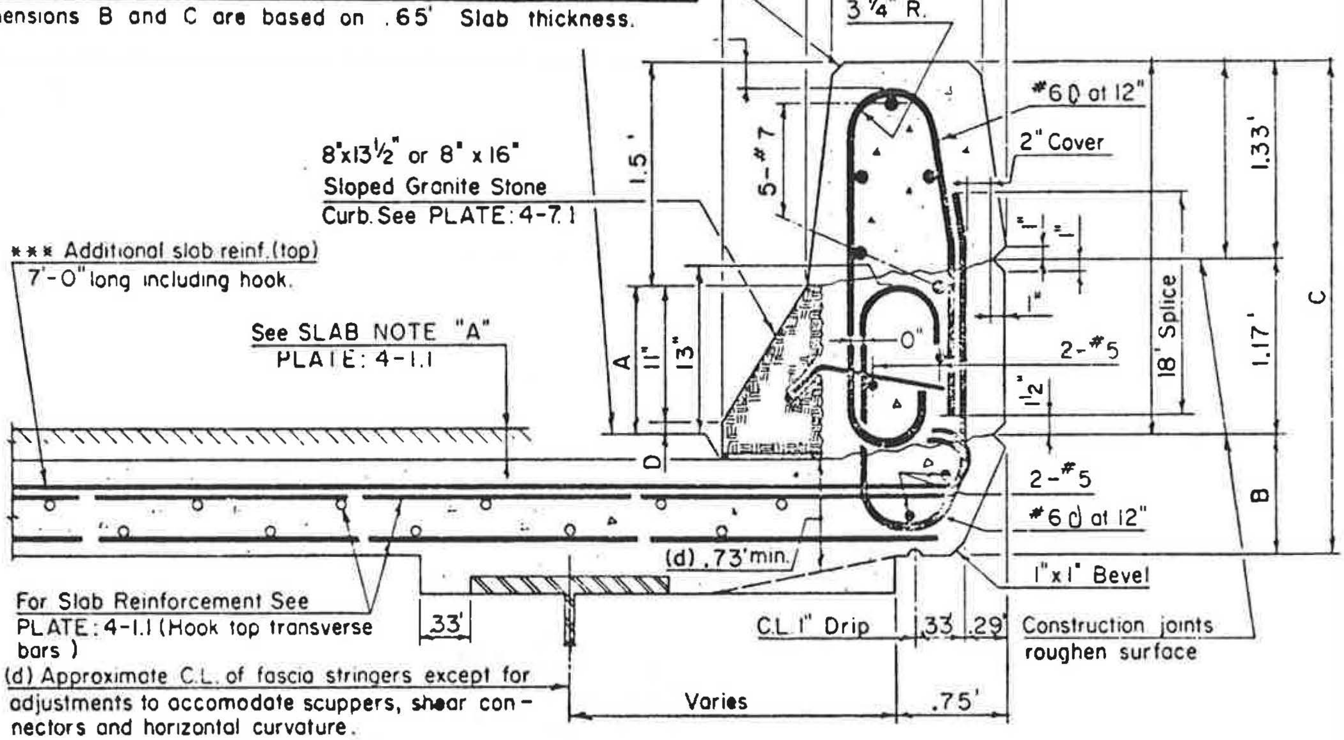


Design #6

FIGURE B.8 (Cont'd)

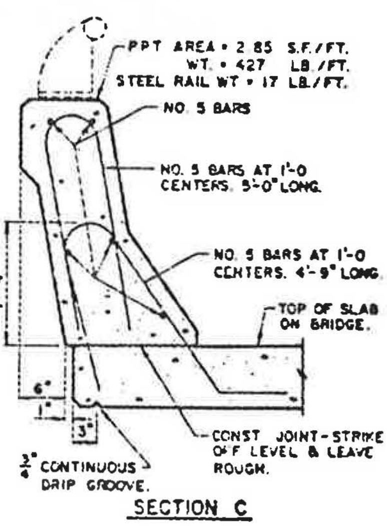
| DIMENSION | A | B | C | D |
|---|---|---|---|---|
| Without Wearing Surface | 1.17' | .81' | 3.31' | .25' |
| With Wearing Surface | 1.38' | 1.02' | 3.52' | .46' |

NOTE. Dimensions B and C are based on .65' Slab thickness.



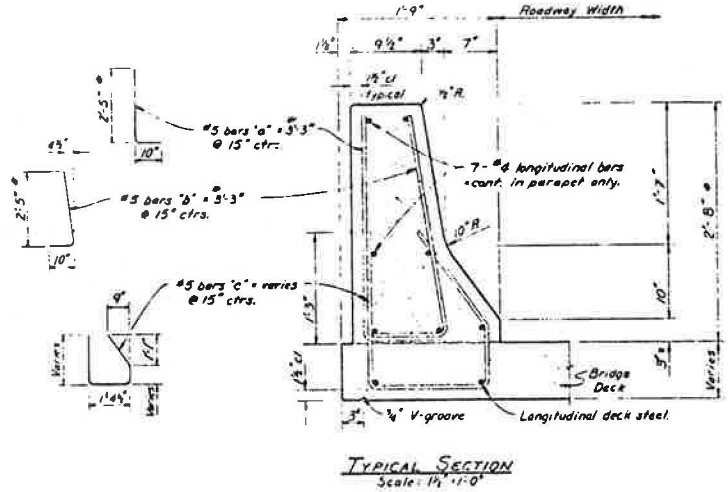

NOTES: All bars in parapet shall have 2" cover, except as noted.

Design #7

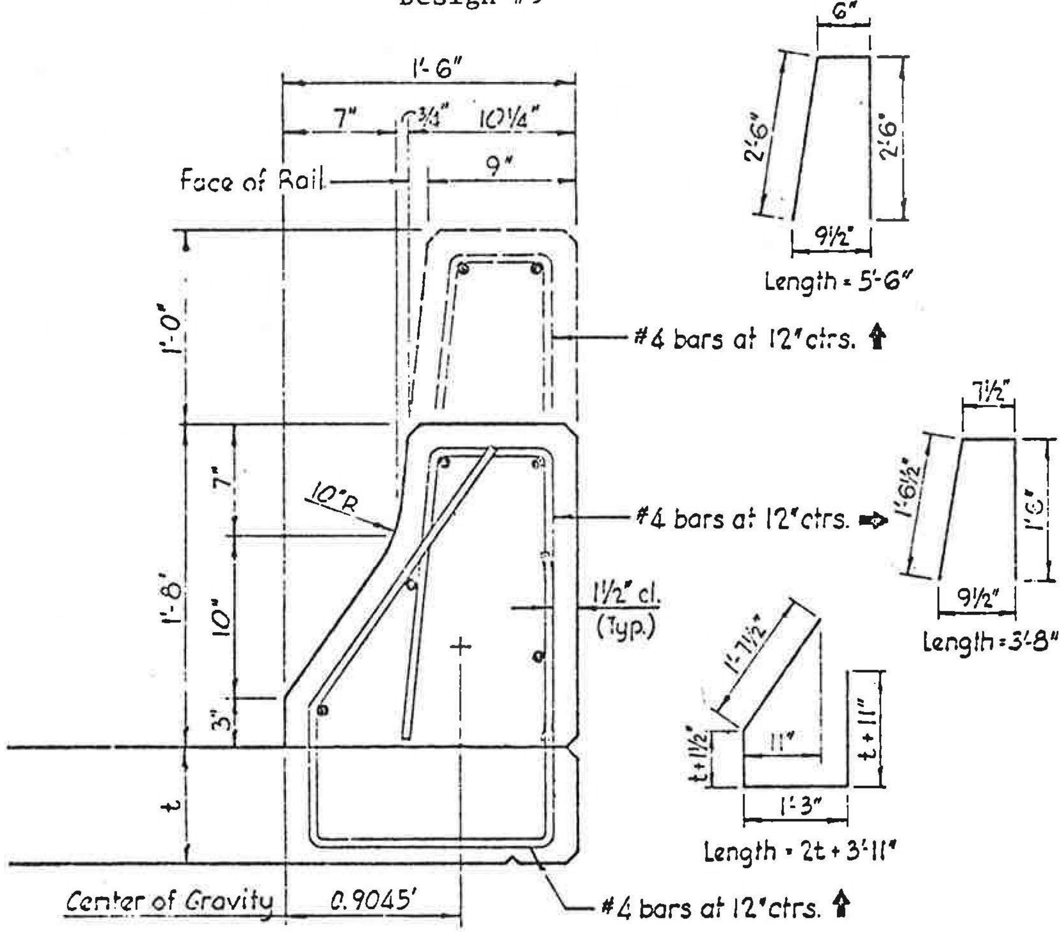



Design #8

FIGURE B.8 (Cont'd)



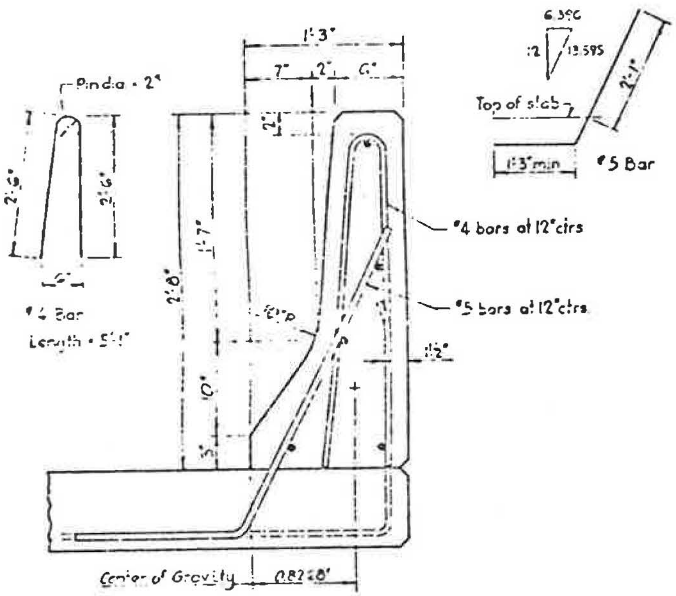

Design #9




Cross-sectional area = 1.8985 sq. ft.
Weight per linear foot = 284.77 lbs.
Note: All longitudinal bars #4's placed as shown.
½" Pref. Exp. Jts. at 15'-0" max. and at Piers.

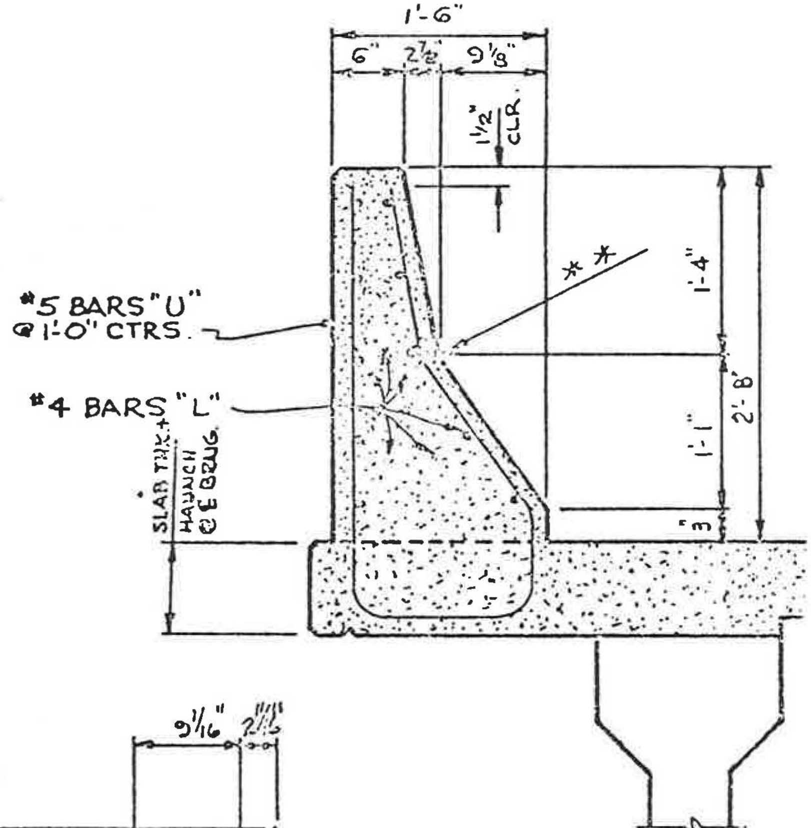
Design #10

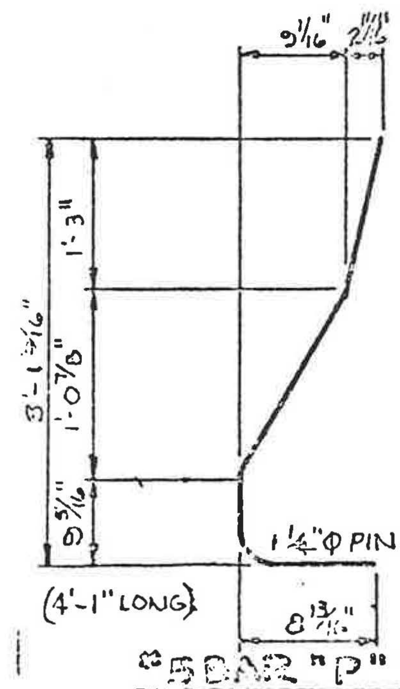
FIGURE B.8 (Cont'd)




Cross-sectional area = 2.0547 ft²
Weight per linear foot = 305.205 lbs.
Note: All longitudinal bars #4's placed as shown.
½" Pref. Exp. Jts. at 15'-0" max. and at Piers.

Design #11



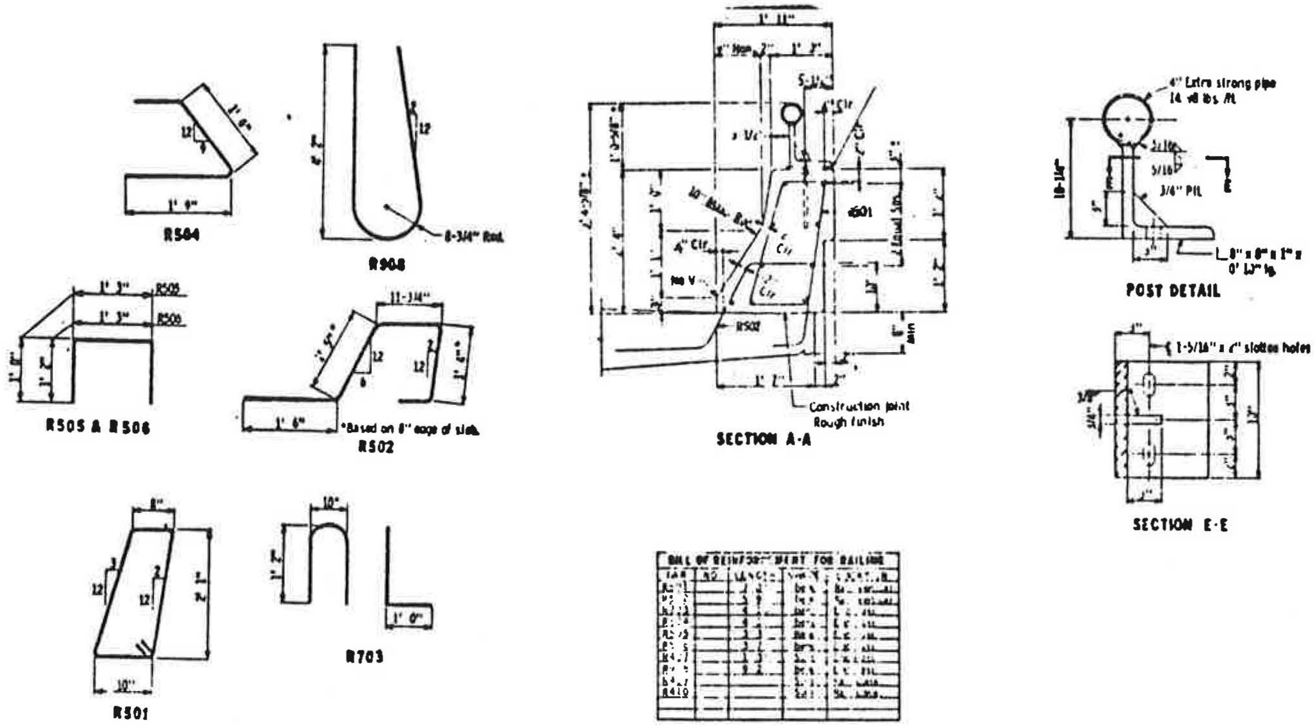

CONTINUOUS
BARRIER RAILING

AREA - 2.41 SQ. FT.
WEIGHT - 362 LBS./LIN. FT.

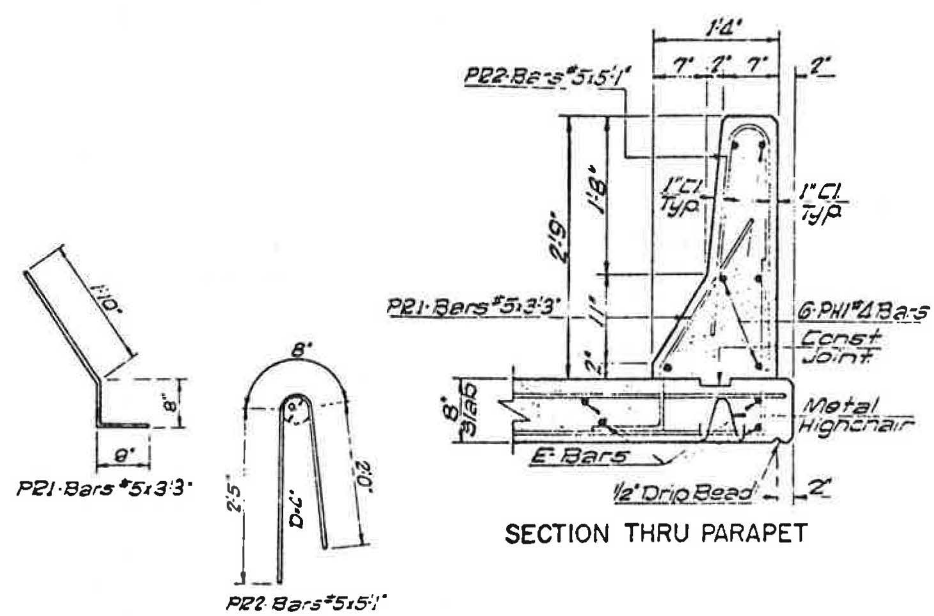
NOTE:
No. 4 BARS "L" AND No. 5 BARS "P" & "U" ARE TO BE PAID FOR WITH THE BARRIER RAILING PER LINEAR FOOT OF RAILING

Design #12

FIGURE B.8 (Cont'd)

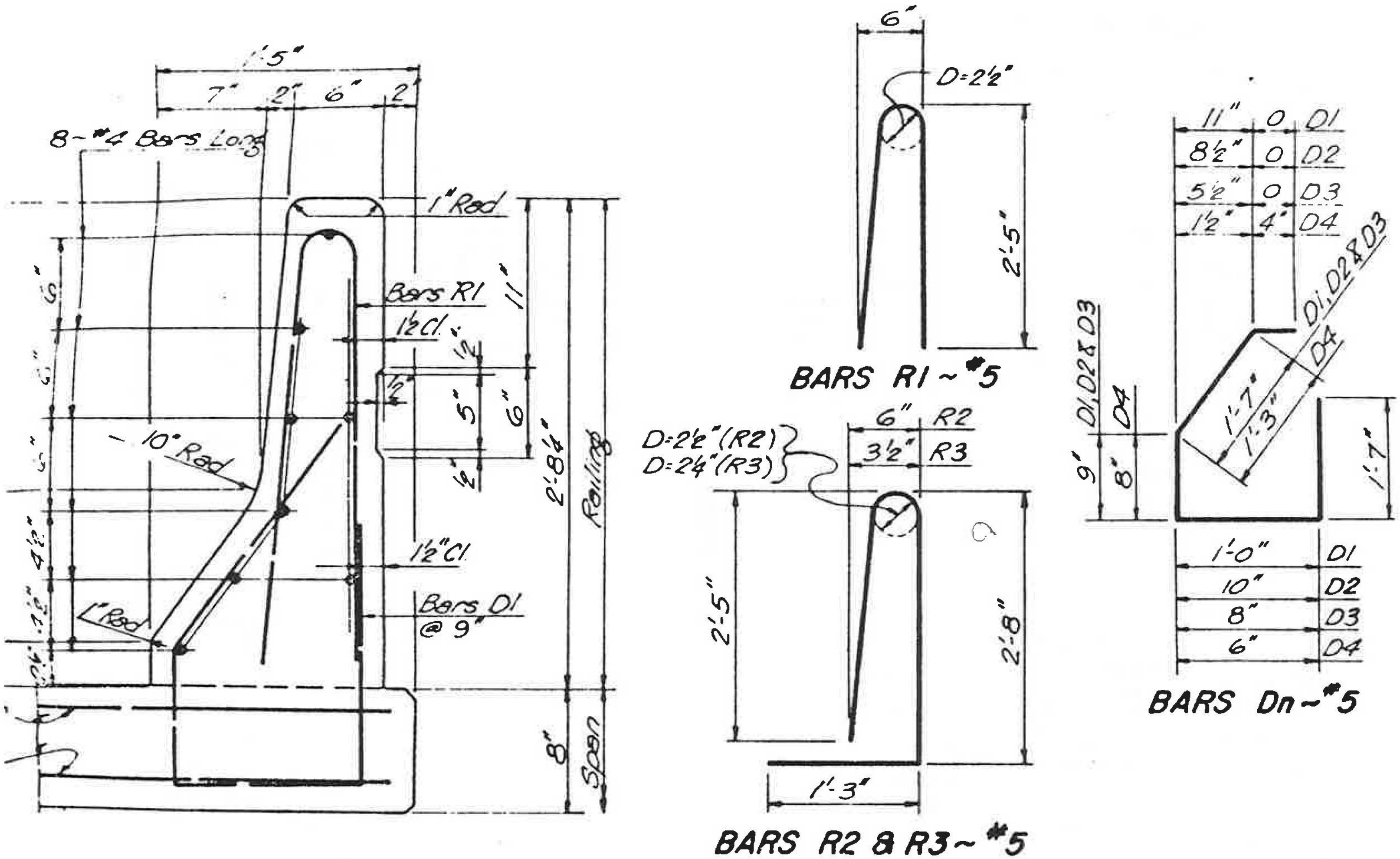



Design #13



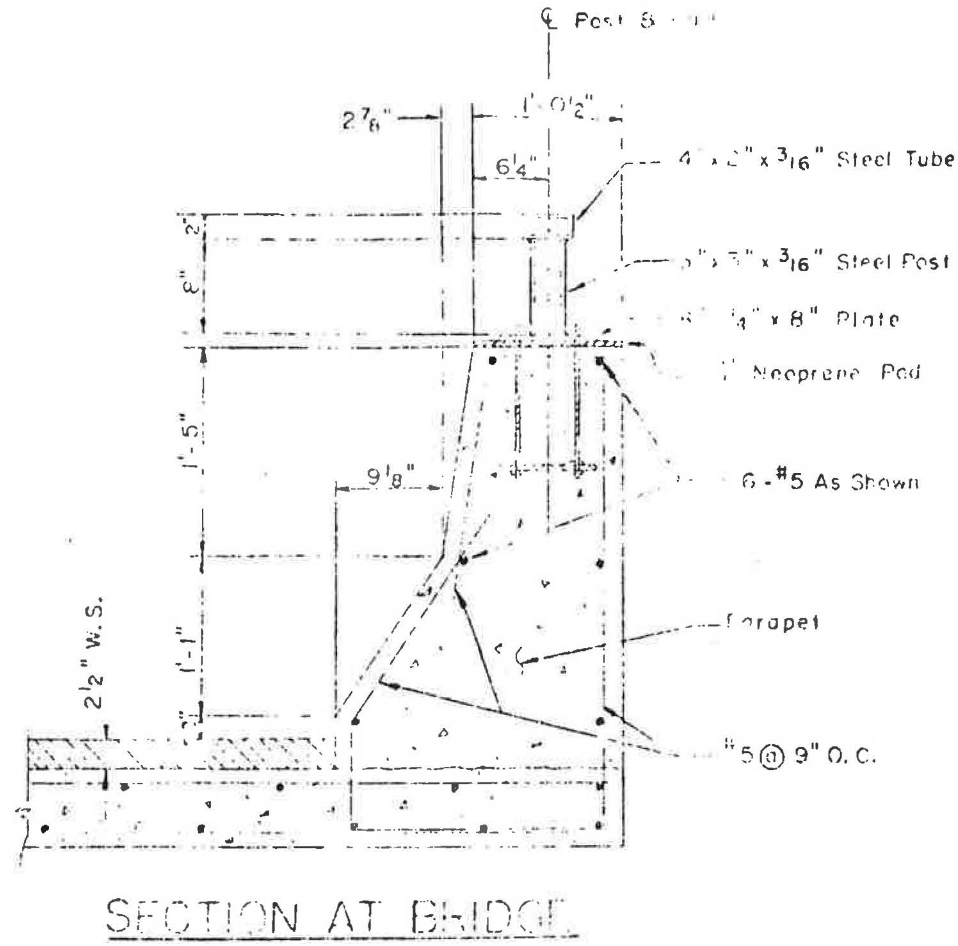

Design #14

FIGURE B.8 (Cont'd)
B.18

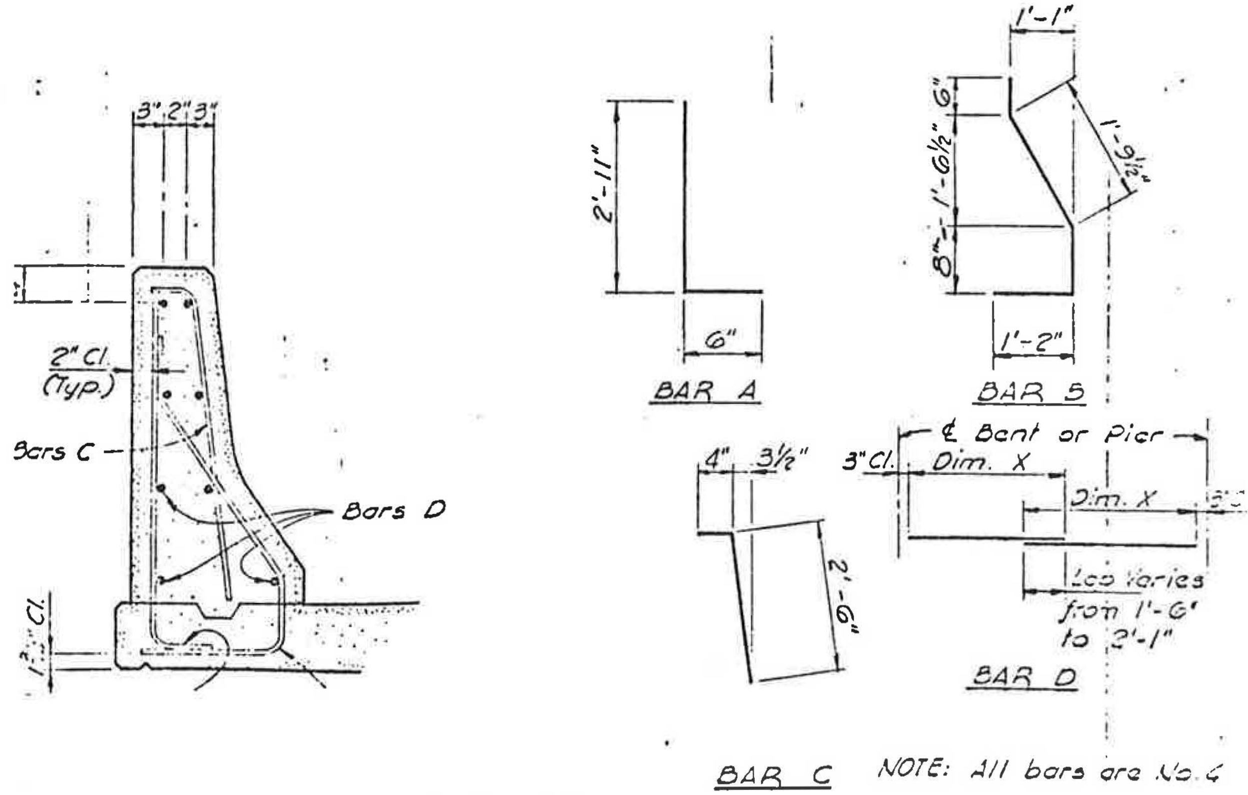



Design #15

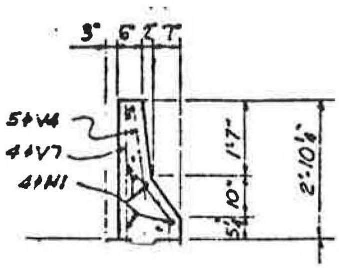
FIGURE B.8 (Cont'd)




Design #16




Design #17




| BAR | LENGTH |
|---|---|
| 5# V 4 | 2'-0 |
| 4# V 5 | 4'-4" |
| 4# V 6 | 5'-6" |
| 4# V 7 | 3'-9 |

Design #18

FIGURE B.8 (Cont'd)



TABLE B.1

SUMMARY OF ESTIMATED COSTS

CONCRETE BRIDGE PARAPET DESIGN

| Design No. | Concrete ($ft^3/ft$) | Steel (lbs/ft) | Estimated Cost ($/ft) |
|---|---|---|---|
| 1 | 3.24 | 13.80 | 34.15 |
| 2 | 2.43 | 16.51 | 37.14 |
| 3 | 2.97 | 17.85 | 38.25 |
| 4 | 3.78 | 21.25 | 39.63 |
| 5 | 2.43 | 17.02 | 34.21 |
| 6 | 2.70 | 12.06 | 34.18 |
| 7 w/granite (w/o granite) | 3.24 | 26.68 | 92.85 (41.10) |
| 8 | 3.51 | 15.76 | 36.49 |
| 9 | 3.24 | 14.58 | 34.73 |
| 10 | - | - | - |
| 11 | 2.16 | 14.06 | 34.38 |
| 12 | 2.43 | 10.88 | 32.89 |
| 13 | - | - | - |
| 14 | 2.16 | 15.81 | 34.02 |
| 15 | 2.70 | 49.51 | 46.60 |
| 16 w/metal rail (w/o metal rail) | 4.32 | 20.90 | 52.40 (38.22) |
| 17 | 2.43 | 28.29 | 39.37 |
| 18 | 2.43 | 8.98 | 33.70 |

## TABLE B.2

### CSSP STRENGTH SUMMARY

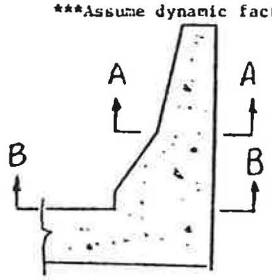
| Design | Section A-A $A_S$, in.$^2$ | Section A-A d, in. | Section B-B $A_S$, in.$^2$ | Section B-B d, in. | Section B-B % Reduction* | $\phi$ M, kip-in./ft A-A | $\phi$ M, kip-in./ft B-B | B-B red. | Predicted Ultimate Load, kips | Predicted Dynamic Ult. Load, kips*** |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 0.21 | 10.0 | 0.21 | 19.0 | 80 | 124 | 237 | 190 | 76 | 152 |
| 2 | 0.47 | 9.5 | 0.47 | 12.38 | 50 | 258 | 339 | 170 | 68 | 136 |
| 3 | | | | | | | | | | |
| 4 | 0.62 | 13.5 | 0.62 | 13.5 | 50 | 485 | 485 | 243 | 97 | 194 |
| 5 | 0.37 | 4.25 | 0.93 | 7.5/2.5 | 80 | 88 | 234 | 187 | 75** | 150 |
| 6 | 0.10 | 6.0 | 0.25 | 13.0 | 50 | 36 | 192 | 96 | 39 | 78 |
| 7 | 0.44 | 12.0 | 0.44 | 12.0 | 80 | 308 | 308 | 246 | 99 | 198 |
| 8 | 0.31 | 11.0 | 0.31 | 13.0 | 50 | 200 | 238 | 119 | 48 | 96 |
| 9 | 0.25 | 10.5 | 0.25 | 19.0 | 80 | 155 | 282 | 226 | 91 | 182 |
| 10 | 0.20 | 9.5 | 0.20 | 16.5 | 80 | 112 | 196 | 157 | 63 | 126 |
| 11 | 0.20 | 6.5 | 0.31 | 13.0 | 50 | 76 | 238 | 119 | 48 | 96 |
| 12 | 0.31 | 6.0 | 0.31 | 16.5 | 80 | 107 | 303 | 242 | 97 | 194 |
| 13 | | 13.0 | | 17.0 | 50 | | | | | |
| 14 | 0.41 | 8.0 | 0.41 | 15.0 | 50 | 189 | 362 | 181 | 73 | 146 |
| 15 | 0.41 | 6.5 | 0.41 | 13.5 | 80 | 152 | 325 | 260 | 104 | 208 |
| 16 | 0.41 | 13.38 | 0.41 | 22.5 | 80 | 322 | 546 | 437 | 175 | 350 |
| 17 | 0.13 | 8.0 | 0.13 | 15.0 | 80 | 62 | 116 | 93 | 37 | 74 |

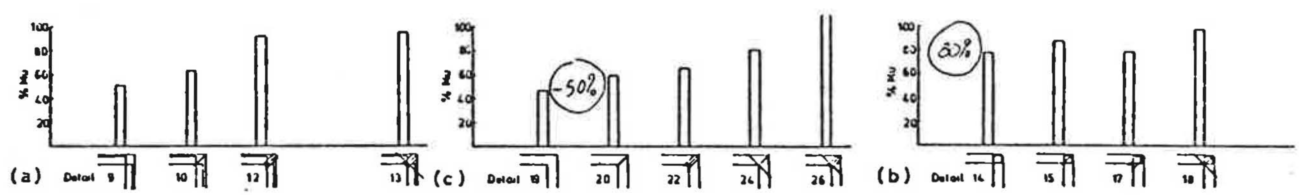
*See sketch

**Ref 1. $P_{ULT}$ = 75 kip ($f_y$ = 60 ksi, $f'_c$ = 4.0 ksi)
60 kip ($f_y$ = 40 ksi, $f'_c$ = 3.6 ksi)

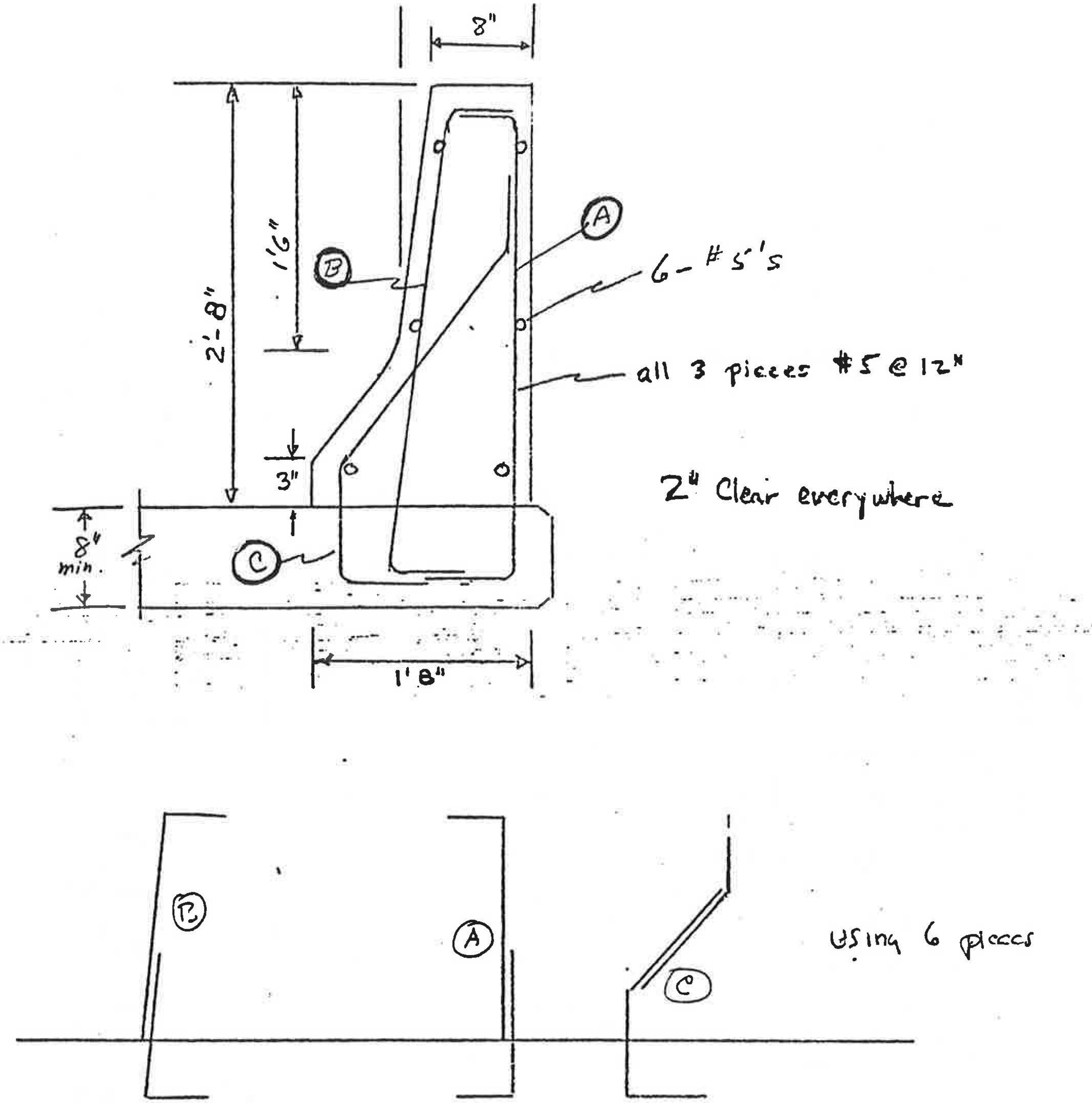
***Assume dynamic factor of 2.0

Example: Design 1 strength = $\frac{190}{187}$ (75) = 76 kip




* Influence of diagonal reinforcement on ultimate strength (load opening corner)




Alternate Steel Fabrication – Lower poured with deck
Upper steel tied to lower steel and formed and poured

FIGURE B.9 RECOMMENDED DESIGN - CRSI

APPENDIX C

DETAILS OF SERVICE LEVEL ONE
BRIDGE RAILING DESIGN AND DEVELOPMENT

A. **Design Consideration**

1. **Design procedures.** Preliminary designs were evaluated using the BARRIER VII computer program(11). This program is particularly suitable for beam/post systems. The posts, post spacing, and beams are selected to satisfy the structural adequacy test requirements.

2. **Beam.** The steel W-beam guardrail element is the most widely used traffic barrier element in existence. Not only has it become the standard guardrail element for this country, but it also has widespread use in Europe, South America, and Africa. Although other beam elements have been frequently proposed, it remains the most widely specified traffic barrier beam. Accordingly, it was considered as a primary candidate for use in this program because of its economy and proven performance as a traffic barrier beam.

Although the performance of the W-beam in the field has been surmised to be good, some problems have occurred with its use. A New York study(37) revealed that standard passenger cars were going over the G2 (W-beam on weak post) systems which had a 30-in. (760-mm) mounting height. This increase in mounting height placed the bottom of the beam at 21 in. (530 mm) above grade. This lower bound is considered by many to be too high for the smaller cars. Many states have adopted the MB4W median barrier system first developed by California. This system uses a 30-in. (760-mm) W-beam mounting height with a channel rub rail to minimize wheel snagging on the strong posts during large deflections. Accordingly, a new beam element evolved that makes the mounting height of the beam less critical



for the range of vehicles on the road. This new element known as the Thrie beam is simply a W-beam made deeper by an additional rib as shown in Figure C.1. As shown in Figure C.1, the normal mounting heights for the W-beam and Thrie beam place the center of each beam at an optimum location with respect to automobile center of gravity (c.g.) range. However, as illustrated in Figure C.1, the Thrie beam provides additional protection against wheels getting under the beam and additional height for higher c.g. vehicles.

Tests conducted by SwRI on this configuration revealed that this new beam when mounted at 32 in. (800 mm) above grade does not require a rub rail for strong posts(37). Furthermore, improved vehicle redirection is evident as shown in comparison of three tests in Figure C.2. The tests of Figure C.2 were essentially identical; i.e., same vehicle model and impact conditions (4,300-lb (1950-kg) vehicle, 60 mph (95 km/h) and 25 deg). The wider Thrie beam imparted substantially less rolling and pitching motion to the vehicle.

Current 1980 material prices for the Thrie beam and W-beam are $5.00 and $3.75 per lineal ft, respectively. Installation costs will be slightly higher for the Thrie beam due to additional splice bolts and heavier weight; however, the additional cost is considered more than justified due to increased performance expected for the full range of vehicles.

3. Posts. The posts considered for this project were designed such that they behave as a breakaway device. The advantages of this type of post behavior are:

(1) The failure load will be repeatable

(2) No lowering of the system will occur due to ductile post behavior



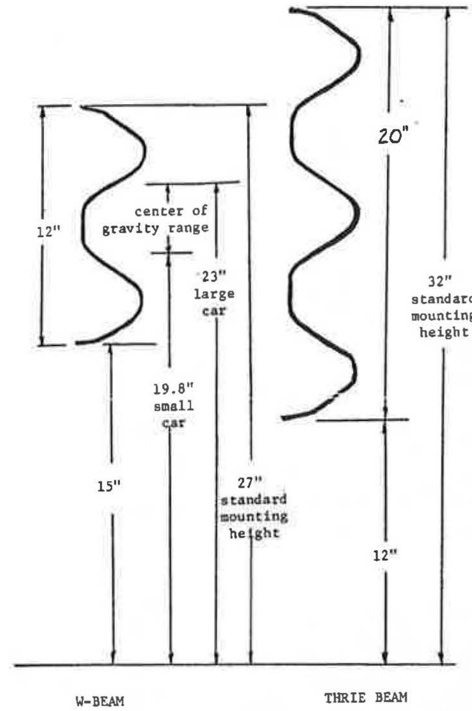
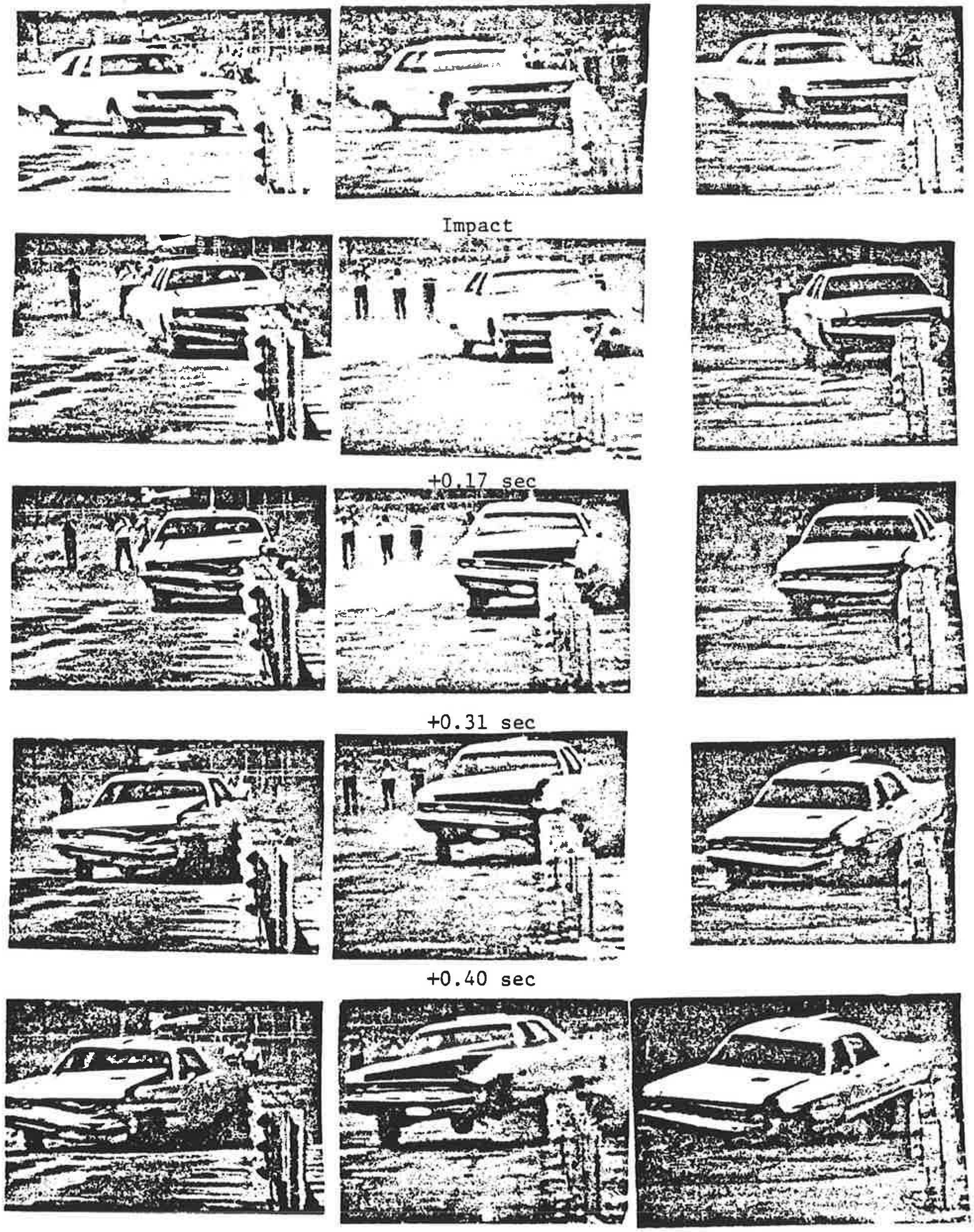



FIGURE C.1 W-BEAM AND THRIE BEAM GEOMETRY




Thrie Beam W-Beam W-Beam

FIGURE C.2 CHARLEY POST CRASH TEST SERIES (ALL IMPACT CONDITIONS THE SAME)

(3) Bridge deck damage will be eliminated by setting the deck connection strength well above the failure load of the post

(4) Snagging of the vehicle wheels on posts is minimized with posts that separate during large deflections.

Both wood and metal posts were considered appropriate for consideration. Priority was given to placing posts outside bridge deck to provide maximum clearance.

B. Barrier Design Methodology

1. Program. Although other options were available, the BARRIER VII computer program was considered the best available program for the SL1 investigations. The program utilizes a finite element barrier model and is excellent for modeling of complex flexible barriers. Specifically, the elements can be posts, beams, cables, springs, friction dampers, viscous dampers, simple hinges, pinned links, and yielding hinges. Additional components can be formed from parallel or series combinations of elements. With the addition of pre-stress input, any force-deflection response shape can be formed. The barrier model is capable of simulating large plastic deformations right up to failure of the various elements. The vehicle is modeled as a lumped mass surrounded by a sheet metal periphery modeled as a layer of two-stage springs. The BARRIER VII program has been shown to give excellent correlation with full-scale tests.

2. Preliminary Investigations. It was considered appropriate to investigate performance of a bridge railing system which was designed to the 10-kip (45-kN) force of AASHTO (1). Accordingly, BARRIER VII was used to evaluate an existing bridge rail design and also other designs



which might be used for lower containment requirements to provide designers with a comparison of both design technique and projected performance.

a. Texas T-1-1/2 Bridge Rail. In NCHRP Report 118, a bridge railing is shown that met the 1973 AASHTO bridge specification; due to geometrical deviations, it does not meet the current AASHTO criteria (2). This barrier was selected as an example because it was designed using the 10-kip (45-kN) force and it has been crash tested. The crash tests were performed using subcompact and standard sedans. Initially the bridge rail was tested in the configuration described in Section A-A, Figure C.3. During the 25-deg angle test with a standard sedan, local tearing of the W-beam face element occurred and the impacting front wheel snagged on a post. Vehicle accelerations were high and destruction of the vehicle was total; redirection of the vehicle occurred without the vehicle ever becoming parallel to the barrier. Maximum deflection of the basic barrier system was nil; i.e., structural channel and W6x25 post were not damaged.

A convenient design change was incorporated as shown in Figure C.3 and tested using a 3620-lb (1640-kg) vehicle impacting at 61.4 mph (99 km/h) and a 25-deg angle (Test 505T 1-D). Smooth redirection resulted with the modified system as the beam tearing and snagging were prevented. Maximum barrier deflection was recorded at 2 in. (50 mm); considerable damage occurred within the bridge deck. No major damage was sustained by the other barrier elements.

b. BARRIER VII Simulations. Test 505T 1-D simulation results are shown in Figure C.4. Accelerometer data from the test are

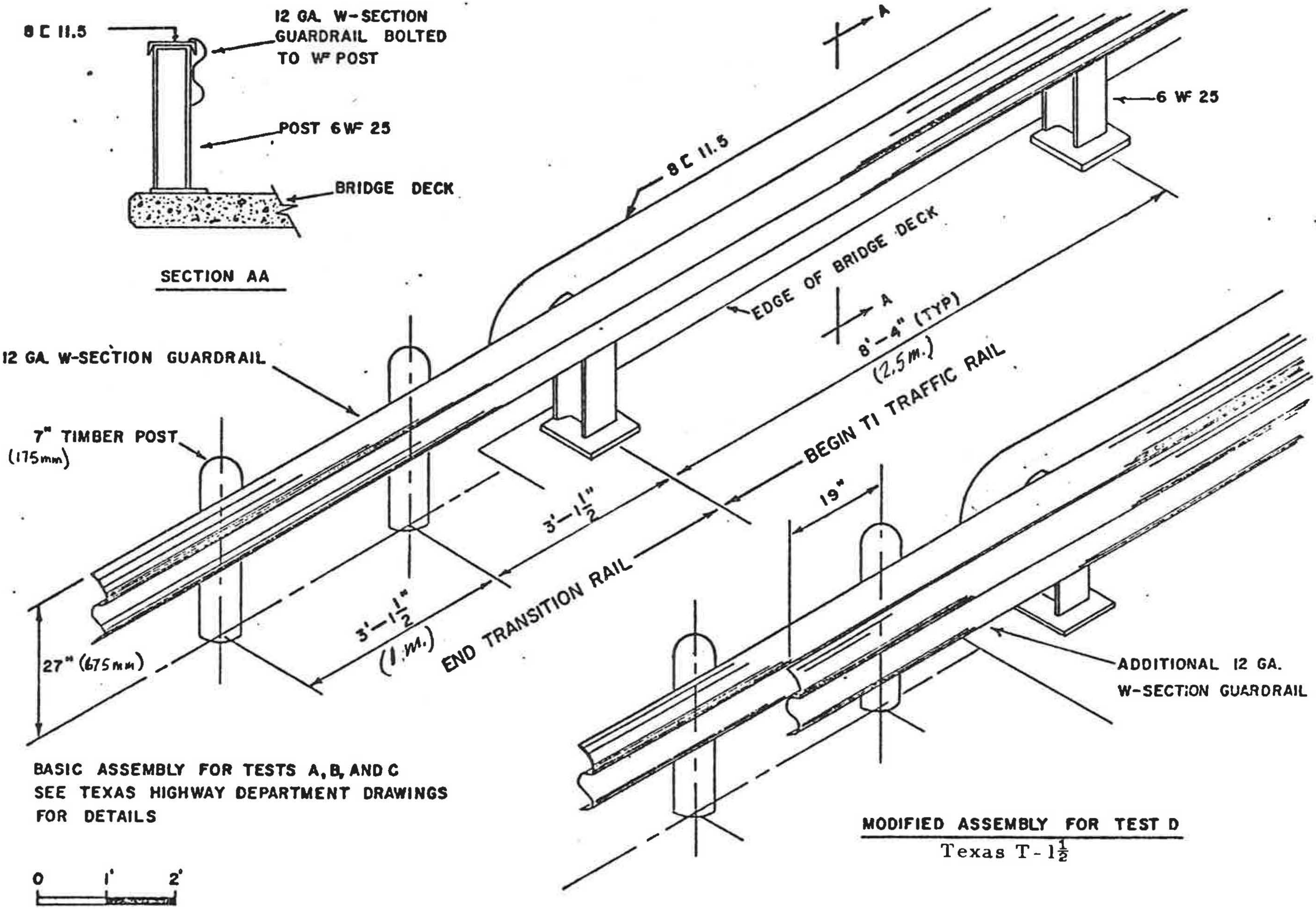



FIGURE C.3 TEXAS T-1-1/2 BRIDGE RAILINGS

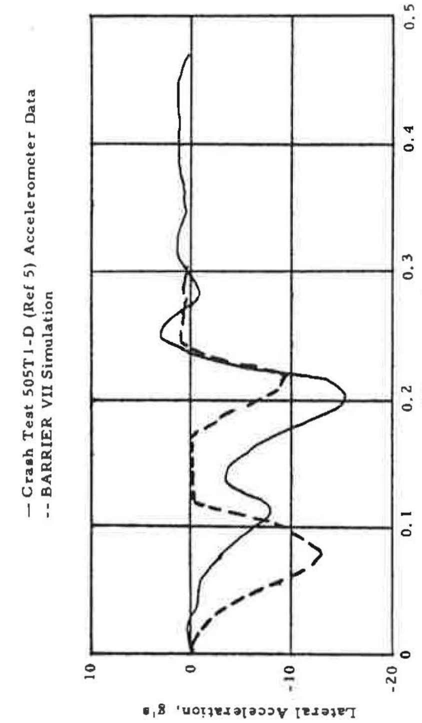



FIGURE C.4 TEST AND SIMULATION DATA



shown along with the simulation results. Although correlation was not precise, it was considered satisfactory. Maximum dynamic deflections for both test and simulation were 2 in. (50 mm).

As a comparison, a prototype bridge rail system was designed for comparison to the rigid T-1-1/2 system. The barrier utilizing a Thrie beam mounted on 10-kip (45-kN) (breakaway) posts spaced at 8' 4" (2.5 m) was subjected to identical impact conditions as the test case. As shown in the data summary of Table C.1 (Case B), the prototype barrier deflected almost 35 in. (0.9 m); vehicle accelerations were substantially reduced. Another case was conducted using the same test conditions and the same basic prototype barrier with the post breakaway strength increased to 20 kips (90 kN). Results of this case are summarized in Table C.1.

In order to examine the performance of the bridge rail systems for less severe impacts, other cases were also investigated:

- 2250-lb (1020-kg) vehicle, 60 mph (95 km/h), 15 deg
  - Texas T-1-1/2
  - Prototype barrier, 10-kip (45-kN) post
  - Prototype barrier, 20-kip (90-kN) post
- 4500-lb (2040-kg) vehicle, 60 mph (95 km/h), 15 deg
  - Texas T-1-1/2
  - Prototype barrier, 10-kip (45 kN) post
  - Prototype barrier, 20-kip (90 kN) post

A summary of the crash test data and the simulation data is presented in Table C.1.

c. Discussion. The simulated results shown for the Texas T-1-1/2 system are considered to be accurate for most bridge rail designs which use the 10-kip (45-kN) force as a criterion. The snagging which occurred in the test of the basic T-1 system cannot be predicted by the computer simulation. On the other hand, it would be difficult for a



TABLE C.1

SUMMARY OF BARRIER DATA

| Test/Case | Barrier* | Vehicle Weight (lbs) | Vehicle Speed (mph) | Impact Angle (deg) | Vehicle Accelerations, 50 ms average, g's long. | lat. | Maximum Barrier Deflection (in.) |
|---|---|---|---|---|---|---|---|
| Test 505-B | T-1 | 3900 | 58.0 | 25 | -8.0 | -6.0 | 0 |
| Test 505-D | T-1½ | 3620 | 61.4 | 25 | -3.0 | -13.0 | 2.0 |
| Case A | T-1½ | 3620 | 61.4 | 25 | -13.1 | -11.4 | 2.0 |
| Case B | P-10k | 3620 | 61.4 | 25 | -5.3 | -5.7 | 34.7 |
| Case C | P-20k | 3620 | 61.4 | 25 | -7.3 | -5.6 | 15.6 |
| Case D | T-1½ | 2250 | 60.0 | 15 | -7.7 | -9.1 | 0 |
| Case E | P-10k | 2250 | 60.0 | 15 | -4.8 | -4.9 | 9.1 |
| Case F | P-20k | 2250 | 60.0 | 15 | -6.3 | -7.3 | 2.1 |
| Case G | T-1½ | 4500 | 60.0 | 15 | -6.7 | -7.9 | 0.3 |
| Case H | P-10k | 4500 | 60.0 | 15 | -2.7 | -3.7 | 16.6 |
| Case I | P-20k | 4500 | 60.0 | 15 | -4.6 | -5.1 | 6.4 |

*Barrier code:
T-1, Texas T-1 Bridge Rail
T-1-1/2, see Figure 3
P-10k, Prototype bridge rail w/10-kip post @ 8'-4"
P-20k, Prototype bridge rail w/20-kip post @ 8'-4"

Metric conversion:
Multiply in. x 25.4 to obtain mm
Multiply mph x 1.6 to obtain km/h
Multiply lbs x 0.45 to obtain kg



designer to have forecast the wheel snagging based on current design criteria.

The significance of barrier deflection is evident from the generally reduced accelerations achieved with the more flexible systems. The rather controversial nature of the present vehicle acceleration criteria as they relate to occupant injury is evident from observing the Case B and Case C results. Using TRB Circular 191(8) criteria, the two cases would compare closely based on vehicle acceleration, although the deflection of Case B is over twice that of Case C. It was determined during this project that severity indices based on the relationship

$$S.I. = \sqrt{\frac{G^2\ long.}{G^2_{XL}} + \frac{G^2\ lat.}{G^2_{YL}}}$$

where $G_{XL}$ and $G_{YL}$ are the maximum tolerable accelerations in the longitudinal and lateral directions, respectively

are not necessarily reduced with increased barrier deflection. The redirection process, which includes both primary and secondary impacts is one explanation. Another is the structural changes occurring due to post failures, beam plastic hinges, etc. Vehicle acceleration considerations become more complicated when recognizing the possible shortcomings of tuning a system to one or two impact conditions and possibly penalizing other impact conditions not investigated.

The preceding discussion is not intended to picture the barrier design process as a hopeless task which cannot be reasonably accomplished. Rather, it is intended to demonstrate that the process is not a straightforward structural problem which civil engineers are accustomed to solving.

Comparisons can be made to the concrete safety shape based on experimental data (safety shape performance cannot be modeled in BARRIER VII). Table C.2 provides this comparison. As shown, the prototype system was comparable to the CMB regarding vehicle accelerations. The T-1-1/2 railing produced significantly high decelerations.

3. Parametric Investigations. Computer simulations were conducted using the BARRIER VII simulation program. Preliminary findings included the fact that of the three impact conditions given in Table 1 of Ref. 38 for Service Level 1, the 25-deg angle impact with the 2250-lb (1020-kg) vehicle produced the greatest maximum deflections. For this reason the 17 cases summarized in Table C.3 were conducted with this vehicle at 25 deg. Both W-beam and Thrie beam were investigated; results of the 2D simulations indicated little difference in performance for the two beams including dynamic deflection. One apparent difference was the amount of beam damage; the Thrie beam generally sustained much less permanent beam damage. Systems using the 5-kip (22-kN) breakaway post were penetrated for all but the 3' 1-1/2" (1 m) post spacing. A plot of dynamic deflection versus post strength is shown in Figure C.5. From this figure, it appears that the 10-kip (45-kN) post spaced at 12' 6" (3.8 m) centers is on a steep portion of the curve indicative of rapidly increasing deflection.

As a check the other two impact conditions for SL 1 were investigated for 12' 6" (3.8 m) spacing with 10-kip (45-kN) posts. Table C.4 summarizes the results of these investigations (Cases 18 and 19). It is noteworthy that the equivalent impacts for SL 1, as shown in Table 1, were determined by the collision severity indicator (CSI) described in the Phase I report(38). The CSI has since been replaced by a new expression, the redirection index (RI). The deflections for the three impacts



TABLE C.2

VEHICLE ACCELERATION DATA

| Barrier | T-1½ | Thrie Beam 10 kip post 8' 4" span | New Jersey Shape CMB* | Configuration F Shape CMB* |
|---|---|---|---|---|
| Vehicle Weight, lb | 2250 | 2250 | 2250 | 2250 |
| Impact Speed, mph | 60 | 60 | 58.9 | 56.4 |
| Impact Angle, deg | 15 | 15 | 15.5 | 14.3 |
| Maximum Accelerations, 50 msec average | | | | |
| Film Longitudinal, g's | | | -3.6 | -3.8 |
| Lateral, g's | | | -5.1 | -4.6 |
| Accelerometer Longitudinal, g's | | | -0.9 | n/a |
| Lateral, g's | | | -6.0 | -7.3 |
| BARRIER VII Longitudinal, g's | -7.7 | -4.8 | | |
| Lateral, g's | -9.1 | -4.9 | | |

*Reference 12



TABLE C.3

SUMMARY OF SL 1 IMPACT SIMULATIONS

| Case | Beam | Post* | Post Spacing (ft-in.) | Maximum Deflection (in.) | Max. 50 msec Avg. Accelerations Long. (g's) | Lat. (g's) | Posts Damaged |
|---|---|---|---|---|---|---|---|
| 1 | W-beam | 10K | 6-3 | 17.1 | 8.6 | 6.5 | 6 |
| 2 | W-beam | 10K | 8-4 | 20.4 | 7.6 | 6.3 | 4 |
| 3 | W-beam | 10K | 12-6 | 24.0 | 6.0 | 4.6 | 3 |
| 4 | Thrie | 10K | 6-3 | 15.0 | 8.7 | 6.7 | 6 |
| 5 | Thrie | 10K | 8-4 | 18.7 | 7.7 | 6.3 | 4 |
| 6 | Thrie | 10K | 12-6 | 24.9 | 6.3 | 6.4 | 4 |
| 7 | W-beam | 20K | 6-3 | 12.4 | 12.4 | 9.7 | 2 |
| 8 | W-beam | 20K | 8-4 | 11.1 | 11.1 | 8.3 | 2 |
| 9 | W-beam | 20K | 12-6 | 8.3 | 8.3 | 6.6 | 2 |
| 10 | Thrie | 20K | 6-3 | 12.0 | 12.0 | 9.4 | 2 |
| 11 | Thrie | 20K | 8-4 | 10.3 | 10.3 | 7.8 | 2 |
| 12 | Thrie | 20K | 12-6 | 8.5 | 8.5 | 6.4 | 2 |
| 13 | Thrie | 5K | 3-1-1/2 | 20.7 | 10.0 | 7.8 | 27 |
| 14 | Thrie | 5K | 6-3 | penetration† | - | - | - |
| 15 | Thrie | 5K | 8-4 | penetration† | - | - | - |
| 16 | Thrie | 5K | 12-6 | penetration† | - | - | - |
| 17 | Thrie | 15K | 12-6 | 15.5 | | | 2 |

*Post code: 10K - 10 kip breaking load
15K - 15 kip breaking load, etc.

†Penetration indicates barrier has deflection more than vehicle half-width. This does not necessarily mean that penetration would have occurred.



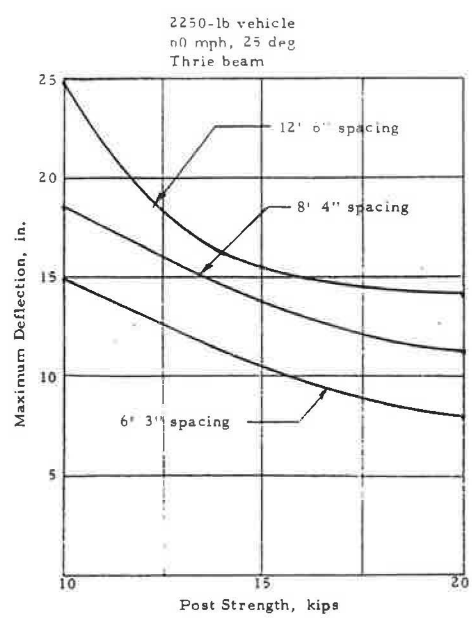



FIGURE C.5 BARRIER DYNAMIC DEFLECTION AS A FUNCTION OF POST STRENGTH AND SPACING

TABLE C.4

SUMMARY OF MISCELLANEOUS BARRIER VII SIMULATIONS

| Case | 18 | 19 | 20 | 21 | 22 | 23 |
|---|---|---|---|---|---|---|
| Vehicle Weight (lb) | 4500 | 23,000 | 4500 | 4500 | 4500 | 2250 |
| Impact Speed (mph) | 60 | 40 | 60 | 60 | 60 | 60 |
| Impact Angle (deg) | 15 | 7 | 25 | 25 | 15 | 15 |
| Beam | Thrie | Thrie | Thrie | Thrie | Thrie | Thrie |
| Post | 10K | 10K | 10K | 20K | 20K | 10K |
| Post Spacing (ft-in.) | 12-6 | 12-6 | 8-4 | 12-6 | 12-6 | 12-6 |
| Max. Deflection (in.) | 22.6 | 15.8 | penetration† | 29.5 | 11.1 | 14.2 |
| Max. 50-msec Avg. Acceleration | | | | | | |
| Long. (g's) | 2.2 | 0.3 | - | 5.8 | 4.9 | 3.5 |
| Lat. (g's) | 3.3 | 0.6 | - | 4.7 | 4.8 | 4.0 |
| Posts Damaged | 4 | 4 | - | 4 | 2 | 2 |
| Beam Length Damaged (ft) | 37 | 27 | - | 36 | 8 | 23 |

†Penetration indicates barrier has deflection more than vehicle half-width. This does not necessarily mean that penetration would have occurred.



(6, 18, 19) were comparable. These deflections illustrate that the CSI was reasonably accurate in predicting equivalent impacts using maximum deflection as the indicator of severity of the impact for both flexible and rigid systems.

Table C.4 also shows data from other simulations. Since the concept of these barriers is new, some of these data are presented for information only. For example, the current AASHTO criteria as found in TRB Circular 191(3) gives a 4500 lb (2040 kg), 60 mph (95 km/h), 25-deg angle impact for strength test criteria. As shown in Case 20, a Thrie beam barrier with 10-kip (45-kN) posts spaced at 8' 4" (2.5 m) is not adequate to contain this impact based on an allowable deflection of 3 ft (0.9 m). A Thrie beam barrier with 20-kip (90-kN) posts spaced at 12' 6" (3.8 m) provides adequate containment as shown for Case 21. Case 22 provides large car data for 60 mph, 15-deg angle impact conditions. Case 23 provides data for comparison to the TRB Circular 191 criteria summarized in Table C.5. As shown in Tables C.1 (Case E) and C.4 (Case 23), both the 12' 6" (3.8 m) and 8' 4" (2.5 m) spacing barriers satisfied the acceptable criteria for impact severity, and the 12' 6" (3.8 m) spacing results (lateral acceleration) were very near the preferred value.

4. Initial Designs. From the parametric investigations, several design options were available. Basically, the process involved selection of a post and post spacing that satisfied the goals. The 5-kip (22-kN) post was not considered further because of the close post spacing required to satisfy containment goals of Service Level (SL) 1. The costs associated with posts would appear to favor maximum spacing. The system which appeared to best satisfy the criteria of SL 1 was the Thrie beam system with 10-kip (45-kN) posts spaced at 12' 6" (3.8 m) centers; however the

TABLE C.5

TRB CIRCULAR 191 CRITERIA

CRASH TEST CONDITIONS FOR MINIMUM MATRIX

| Appurtenance | Test Vehicle Mass,[d] lb (kg) | Speed mph (m/s) | Angle (deg)[e] | Target Vehicle Kinetic Energy[h] 1000 ft-lb (kJ) | Impact Point[k] |
|---|---|---|---|---|---|
| I. Longitudinal Barrier[a] | | | | | |
| A. Length-of-need | | | | | |
| Test 1 | 4500 (2040) | 60 (26.8) | 25[f] | 540 ± 40 (733) | For post and beam system, midway between posts. |
| Test 2 | 2250 (1020) | 60 (26.8) | 15[f] | 270 ± 20 (366) | Same as Test 1 |
| B. Transition | | | | | |
| Test 1 | 4500 (2040) | 60 (26.8) | 25[f] | 540 ± 40 (733) | 15 ft (4.5 m) upstream of second system. |
| C. Terminal | | | | | |
| Test 1 | 4500 (2040) | 60 (26.8) | 0[f] | 540 ± 40 (733) | Center of nose device. |
| Test 2 | 4500 (2040) | 60 (26.8) | 25[f] | 540 ± 40 (733) | At beginning of length-of-need section. |
| Test 3 | 2250 (1020) | 30 (13.4) | 0[f] | 68 ± 9 (92) | Center nose of device. |
| Test 4 | 2250 (1020) | 60 (26.8) | 15[f] | 270 ± 20 (366) | Midway between nose and beginning of length-of-need. |
| II. Crash Cushions[b] | | | | | |
| Test 1 | 4500 (2040) | 60 (26.8) | 0[g] | 540 ± 40 (733) | Center nose of device. |
| Test 2 | 2250 (1020) | 60 (26.8)[i] | 0[g] | 270 ± 20 (366) | Center nose of device. |
| Test 3 | 4500 (2040) | 60 (26.8) | 20[g] | 540 ± 40 (733) | Alongside, midlength. |
| Test 4 | 4500 (2040) | 60 (26.8) | 10-15[g] | 540 ± 40 (733) | 0-3 ft (0-1 m) offset from center of nose of the device. |

SAFETY EVALUATION GUIDELINES

**II. Impact Severity** (See Section VII of Commentary for discussion and limitation of guideline values)

A. Where test article functions by *redirecting* vehicle, maximum vehicle acceleration (50 msec avg) measured near the center of mass should be less than the following values:

| Maximum Vehicle Accelerations (g's) | | | |
|---|---|---|---|
| Lateral | Longitudinal | Total | Remarks |
| 3 | 5 | 6 | Preferred |
| 5 | 10 | 12 | Acceptable |

These rigid body accelerations apply to impact tests at 15 deg or less.

steepness of the deflection curve (Figure C.5) indicated that normal variance in post breakaway strength could result in excessive deflection.

Since idealized post properties were used in the parametric studies, any post with strength characteristics that provide small deflections prior to "breakaway" at the design load could be used. Two post types were considered for design; a metal post system and a wood post system.

The design philosophy of the posts was:

a. metal post stress is below elastic stability value at failure load and wood post fractures at failure load;

b. damage is not sustained by bridge deck;

c. separation of beam from post is achieved by use of consistent mechanism;

d. consequences of post element dropping from structure are not considered significant (except over freeways);

e. in order to maximize clearance, posts were mounted external to bridge deck.

By designing a post failure mechanism that occurred at small deflections, the barrier system would behave as a weak post system; this eliminates need for a block-out or spacer to eliminate wheel snagging. Designs for wood and steel post systems are described on the following pages.

a. Initial Metal Post Design. Since metal posts exhibit a ductile failure during large deflections which can result in wheel snagging, it was necessary to design failure mechanisms that activate below the elastic stability load of the post. Accordingly, several concepts were investigated for achieving this type of performance. The use of welded base plates was dismissed as being too costly and weld failure strength would be difficult to control; a scheme which utilized bolt tension as



failure mechanism was selected as a method which would function without welded parts. Because of elastic stability considerations, a tubular post was selected to ensure post stability prior to breakaway.

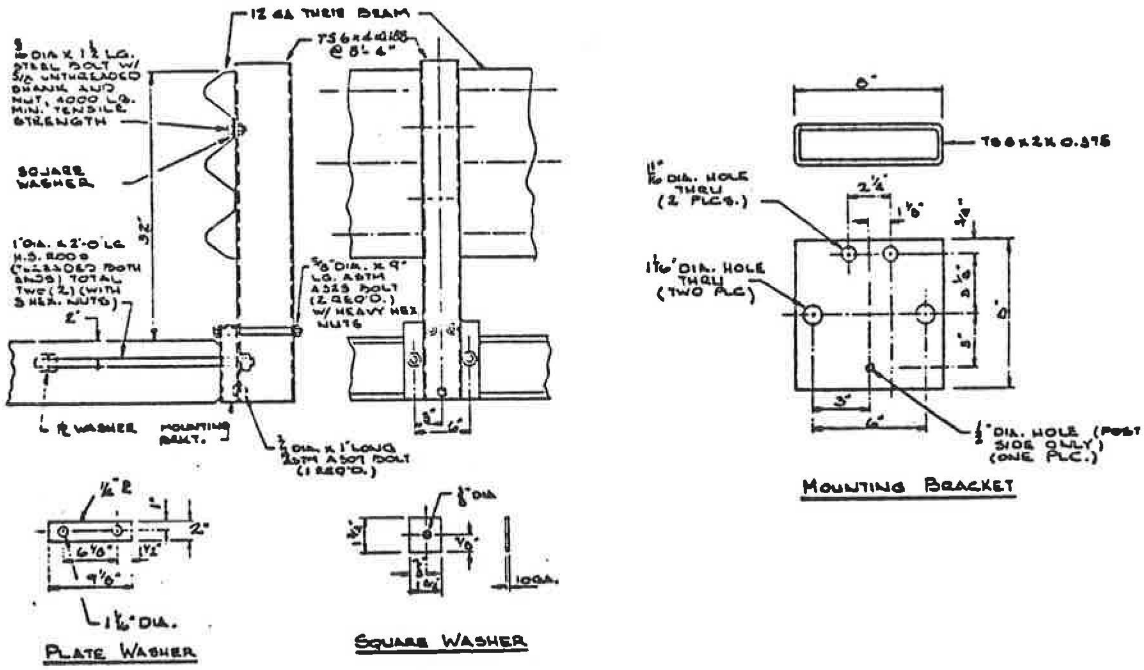
As shown in Figure C.6a, a steel post was selected, although an aluminum alternate could have been specified. Steel, as opposed to aluminum, was selected on the basis of widespread current use.

b. Initial Wood Post Design. The wood post system of Figure C.6b was designed to develop ultimate strength of a 6x6 wood post; anchor bolts and hardware attachments were designed for this purpose.

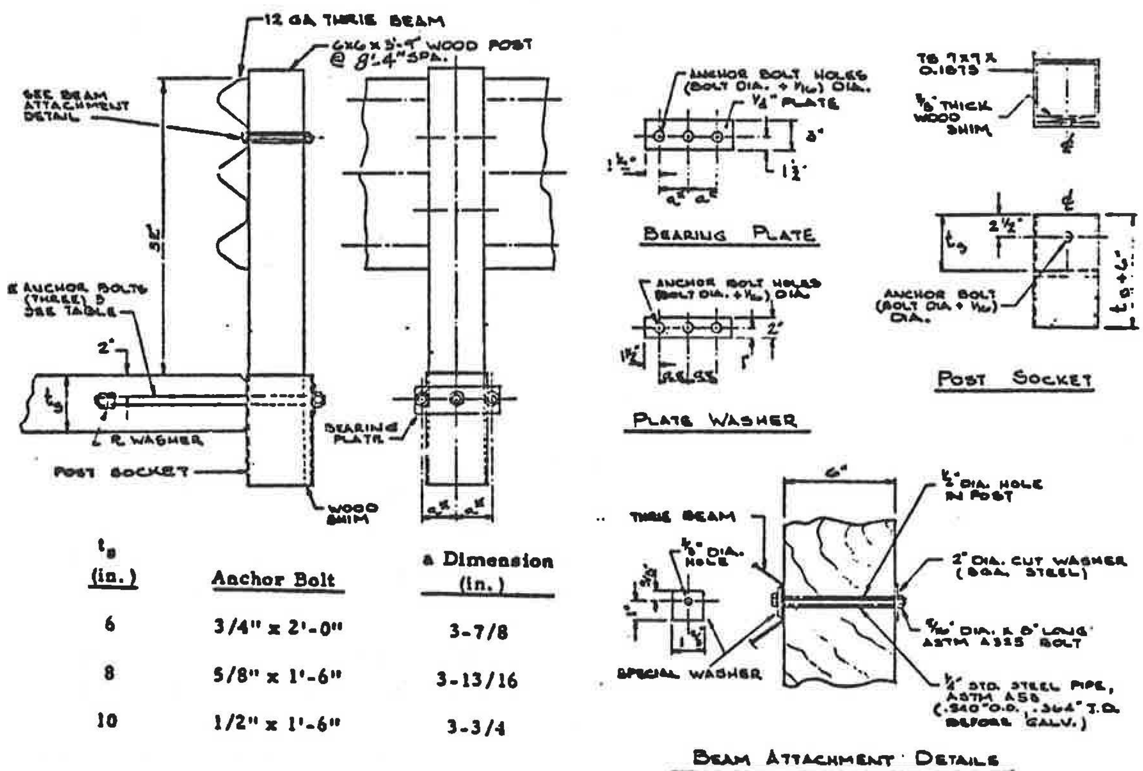
5. Pendulum Tests. In order to evaluate the performance of the basic post and attaching hardware, component tests were conducted in the SwRI pendulum facility using simulated bridge decks, as shown in Figures C.7 and C.9.

a. Test Procedures. The posts were tested in the SwRI pendulum impact facility using a 2250-lb (1020-kg) pendulum mass impacting at either 15 or 30 fps. A rigid pendulum nose [8 in. (200 mm) dia.] faced with a 1-in. (25-mm) thick neoprene pad was used; a styrofoam pad attached to the post provided a cushion to minimize transducer spike. Electronic accelerometers mounted on the mass provided a record of force versus time for the events. Documentation was also provided by a high speed camera operating at 500 frames/sec.

b. Steel Post Tests. The first steel post test (SP-1) was conducted on the configuration described in Figure C.6a. Considerable deformation of the box beam post and mounting bracket occurred; the bolts did fail in tension as designed. During rebound, the pendulum mass destroyed the concrete slab; a steel fixture was substituted in succeeding tests.



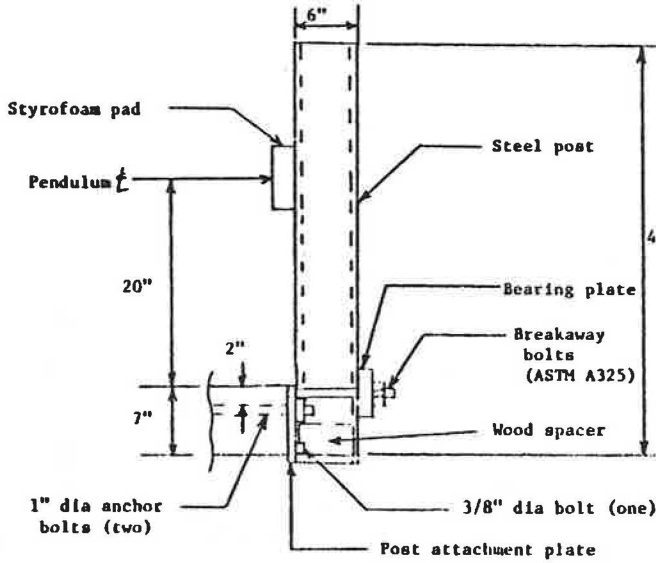

(a) Steel Post

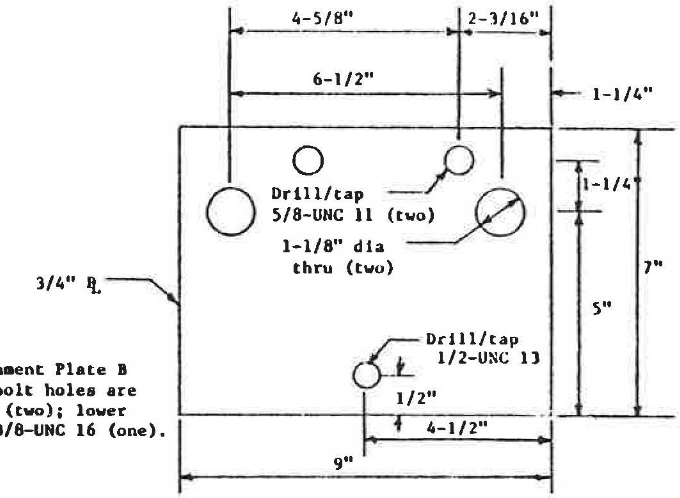



| $t_s$ (in.) | Anchor Bolt | a Dimension (in.) |
|---|---|---|
| 6 | 3/4" x 2'-0" | 3-7/8 |
| 8 | 5/8" x 1'-6" | 3-13/16 |
| 10 | 1/2" x 1'-6" | 3-3/4 |

(b) Wood Post

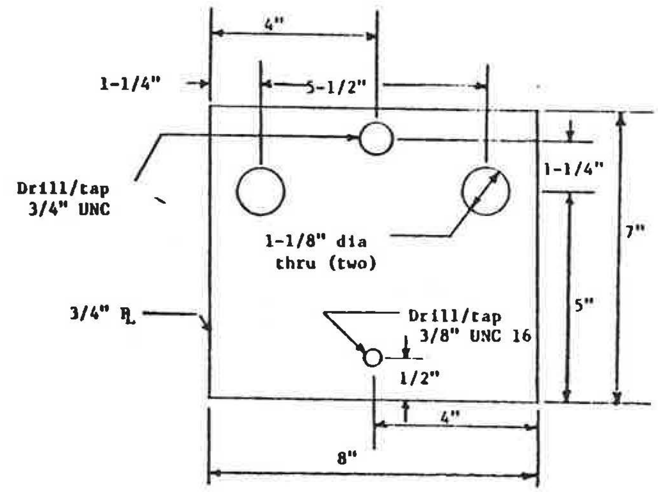
FIGURE C.6 INITIAL SL 1 BRIDGE RAILING DESIGNS




NOTE: Attachment Plate B breakaway bolt holes are 1/2-UNC 14 (two); lower bolt hole 3/8-UNC 16 (one).

POST ATTACHMENT PLATE A




POST ATTACHMENT PLATE C



| Configuration | Breakaway Bolts Test | Bolt Dia. | No. | Bearing Plate | Steel Post | Wood Spacer | Attachment Plate |
|---|---|---|---|---|---|---|---|
| B | -2 | 5/8 | 2 | 3" x 1" x 6" | TS 6 x 4 x 0.1875 | No | A |
| C | -3 | 5/8 | 2 | 3" x 1" x 6" | TS 6 x 4 x 0.1875 | Yes | A |
| C | -4 | 1/2 | 2 | 3" x 1" x 6" | TS 6 x 4 x 0.1875 | Yes | B |
| D | -5 | 1/2 | 2 | 3" x 1" x 6" | TS 6 x 4 x 0.1875 | Yes | B |
| D | -6 | 1/2 | 2 | 3" x 1" x 6" | TS 6 x 4 x 0.1875 | Yes | B |
| D | -7 | 1/2 | 2 | 3" x 1" x 6" | TS 6 x 4 x 0.1875 | Yes | B |
| D | -8 | 1/2 | 2 | 3" x 1" x 6" | TS 6 x 4 x 0.1875 | Yes | B |
| E | -9 | 3/4 | 1 | 3" x 1" x 4" | TS 6 x 4 x 0.1875 | Yes | B |
| E | -10 | 3/4 | 1 | 3" x 1/2" x 3" | TS 6 x 3 x 0.25 | No | C |

FIGURE C.7 STEEL POST PENDULUM TEST DESCRIPTION

The steel post design was modified as shown in Figure C.7. A plate was attached to the bridge deck edge. The attachment plate was drilled/tapped to receive both breakaway bolt(s) and counterflexure bolt. The first test (SP-2) with this new design resulted in local crushing of the post at the lower end.

A wood spacer was incorporated into the next test specimen at the bottom of the post to minimize crushing. Use of wood spacer was selected for economy and to eliminate welding. In Test SP-4 breakaway performance was achieved; however, significant crushing of the post occurred despite the use of wood block. As shown in Table C.6 and Figure C.8, the breakaway load was higher than the design goal of 10 kips (45 kN). Accordingly, the breakaway bolts were reduced to 1/2 in. (13 mm) dia. for Test SP-5. Results of Test SP-5 were encouraging although "lower" post deformation occurred. Test SP-6 was conducted to demonstrate repeatable performance when compared to SP-5. A large initial peak load was recorded in this test; this was attributed to inertia and a decision was made to reduce the impact velocity. The effects of inertia are not considered pertinent to barrier performance although they may be significant in pendulum impact studies. The impact velocity was lowered to 15 fps (4.6 m/s) to minimize inertia effects when measuring dynamic performance of the post assembly.

Tests SP-7 and SP-8 resulted in desirable performance at the force level desired; however, the high speed films of Test SP-8 revealed a failure of one bolt before the other that had not been noticeable in any of the previous tests. A decision was made to try a one-bolt breakaway design to eliminate the preceding occurrence. In addition, the post element was changed to TS6x3x0.25 to eliminate need for wood spacer. This



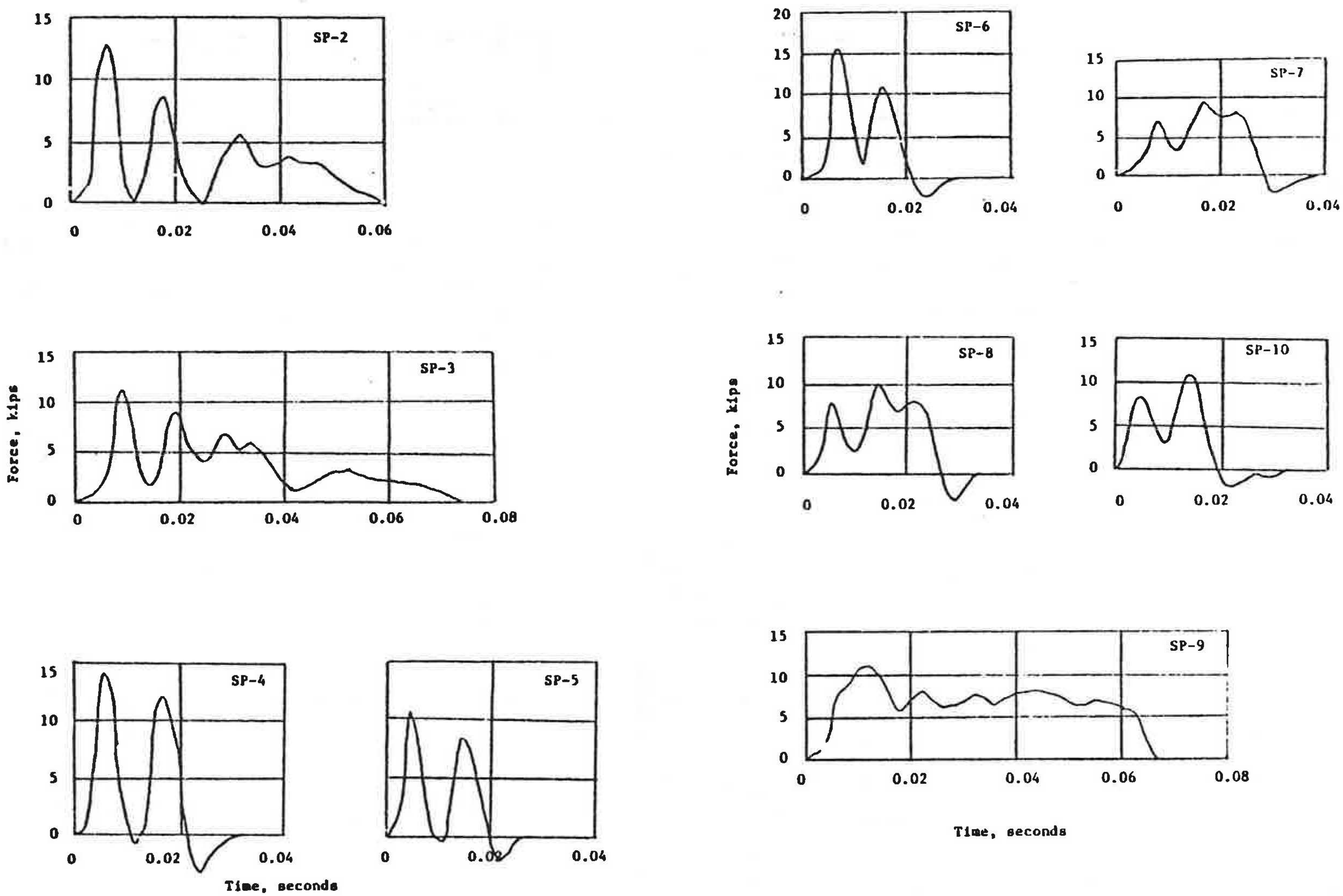
TABLE C.6

SUMMARY OF STEEL POST TESTS

| Test | Specimen Description* | Impact Velocity, fps | Initial Peak Force, kips | Second Peak Force, kips | Remarks |
|---|---|---|---|---|---|
| SP-1 | A | 30 | - no data - | | Failure of design elements |
| SP-2 | B | 30 | 12.7 | 8.9 | Local crushing of post at bridge deck bottom |
| SP-3 | C | 30 | 11.5 | 9.3 | Fixture failure prevented valid test |
| SP-4 | C | 30 | 14.3 | 12.5 | Crushing of lower post area not completely prevented by wood block; breakaway achieved |
| SP-5 | D | 30 | 10.6 | 8.6 | Breakaway achieved |
| SP-6 | D | 30 | 17.3 | 11.5 | Breakaway achieved; high initial force |
| SP-7 | D | 15 | 6.7 | 10.2 | Desirable performance |
| SP-8 | D | 15 | 7.7 | 9.5 | Desirable performance, but one bolt failed prior to other |
| SP-9 | E | 15 | 7.2 | 10.2 | Desirable performance, but deformation of lower post significant |
| SP-10 | E | 15 | 8.7 | 10.9 | Desirable performance; little post deformation |

Specimen description: see Figure C.7

Metric conversion: Multiply fps x 0.3 to obtain m/s
Multiply kips x 4.5 to obtain kN




Metric conversion: Multiply kips x 4.5 to obtain kN

FIGURE C.8 STEEL POST DATA

change results in a slightly heavier post, but will not add significant cost because of elimination of the spacer. Test SP-10 resulted in desired performance, as shown in Table C.6 and Figure C.8.

c. **Wood Post Tests**. The post described in Figure C.6b was installed on a small slab section, as shown in Figure C.9. The slab was 7 in. (175 mm) thick and had three 3/4-in. (19-mm) dia. anchor bolts projecting from the outer edge. Results of the tests are summarized in Table C.7 and Figure C.10. The breakaway load measured in the first two tests (WP-1 and WP-2) was 10.0 (45 kN) and 12.3 kips (55 kN), respectively. These values are considered within an acceptable range of the nominal 10-kip (45-kN) force desired for the initial low-cost design.

In the third test (WP-3), the box beam section was eliminated and two anchor bolts were used instead of three. This was an attempt to effect some economy into the design. The result was considerable deformation of the anchor bolts and bearing plate before post failure. This was considered undesirable due to damage sustained by the anchor bolts. In the fourth test (WP-4), all three anchor bolts were used again without the box beam bracket; failure (flexural) of the anchor bolts occurred before the post fractured.

Sequential photographs of Tests WP-1 and WP-2 are shown in Figure C.11. Since results of WP-1 and WP-2 were satisfactory, design details from these tests were selected for prototype crash test evaluation.

6. **Prototype Designs**. The details of pendulum tests WP-1 (wood post) and SP-10 (steel post) were incorporated into design drawings as shown in Figures C.12 and C.13. Both systems were essentially identical with exception of the post material and associated hardware. A W-beam approach

C.26

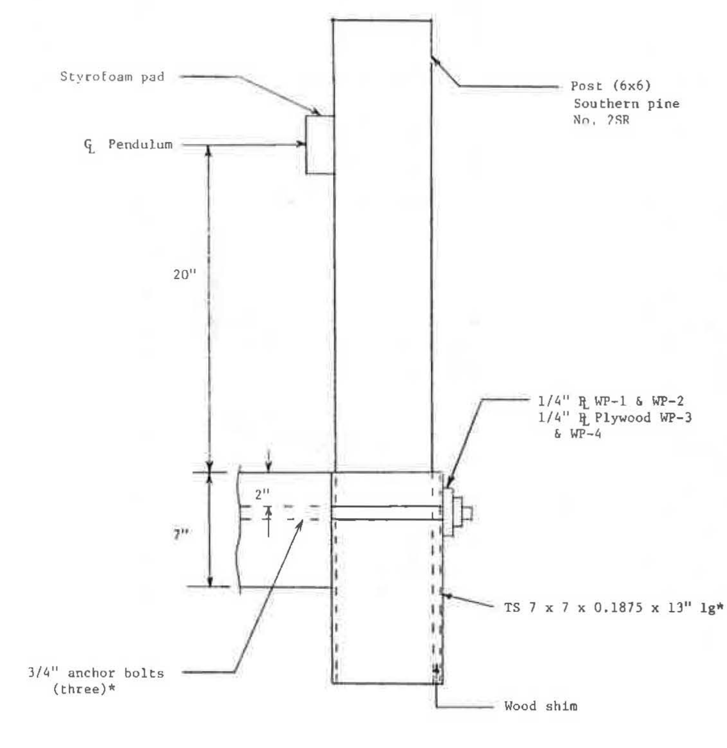
TABLE C.7

SUMMARY OF WOOD POST TESTS

| Test | Specimen Size | Impact Velocity (fps) | Initial Peak Force (kips) | Second Peak Force (kips) | Remarks |
|---|---|---|---|---|---|
| WP-1 | 5-3/4 x 5-3/4 | 30 | 8.4 | 10.0 | Flexural post failure |
| WP-2 | 5-3/4 x 5-3/4 | 30 | 8.4 | 12.3 | Flexural post failure |
| WP-3 | 5-1/2 x 5-3/4 | 30 | 11.4 | 9.8 | Yielding of support before post failure |
| WP-4 | 5-1/2 x 5-3/4 | 30 | 11.5 | 2.0 | Support failure |

Metric conversion: Multiply fps x 0.3 to obtain m/s
Multiply kips x 4.5 to obtain kN

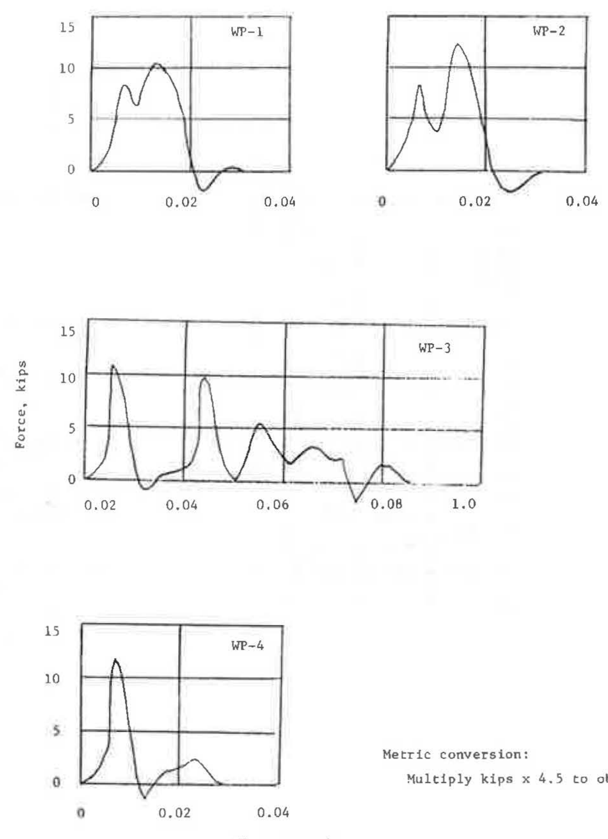
C.28




*Test WP-3 only two anchor bolts used w/out box beam
*Test WP-4 three anchor bolts used w/out box beam

FIGURE C.9 WOOD POST PENDULUM TEST CONFIGURATION

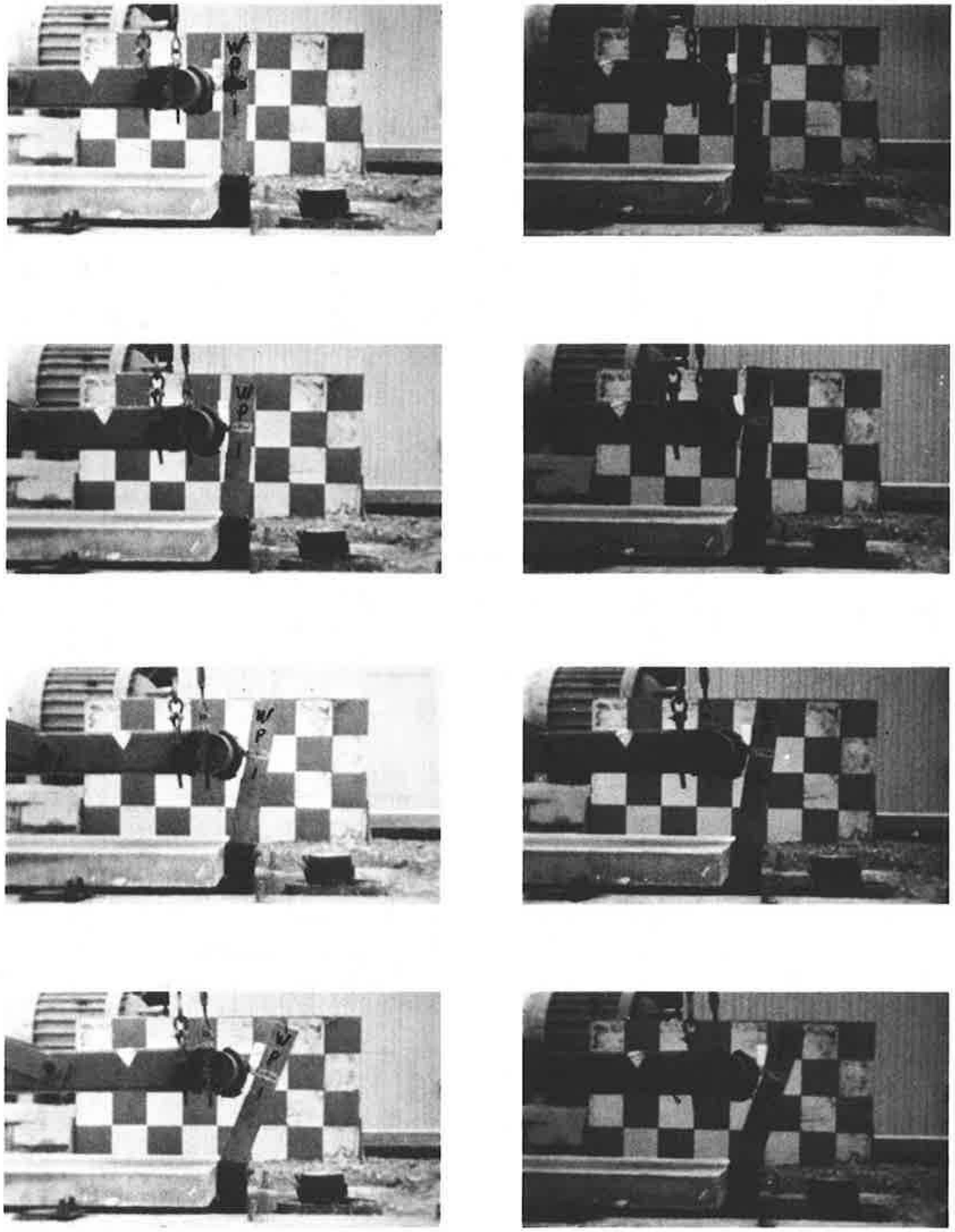
C.27




Metric conversion:
Multiply kips x 4.5 to obtain kN

FIGURE C.10 WOOD POST DATA

C.29



WP-1

WP-2

FIGURE C.11. WOOD POST SEQUENTIAL PHOTOGRAPHS

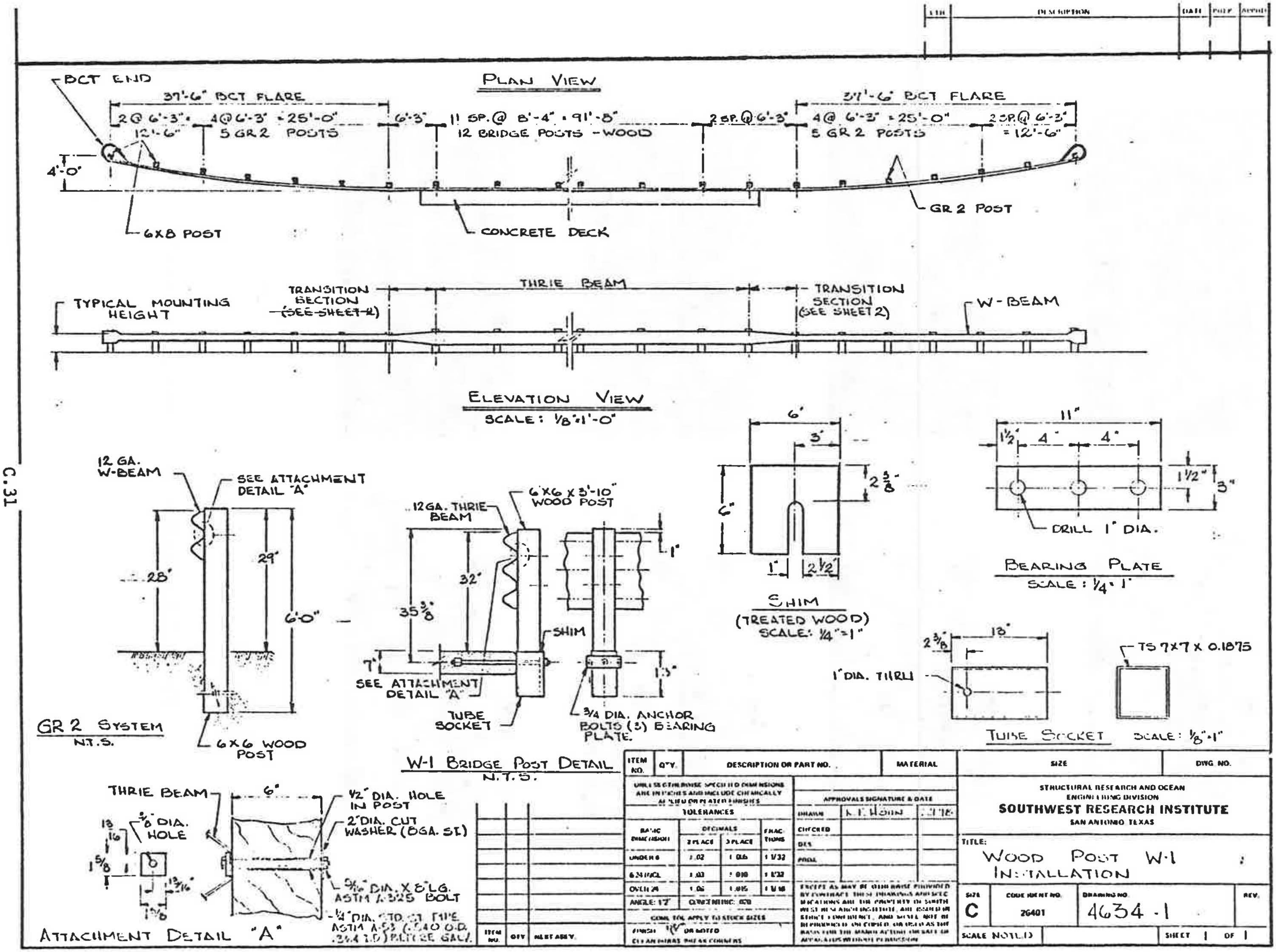



FIGURE C.12 WOOD POST PROTOTYPE DRAWING FOR SL 1 BRIDGE RAILING

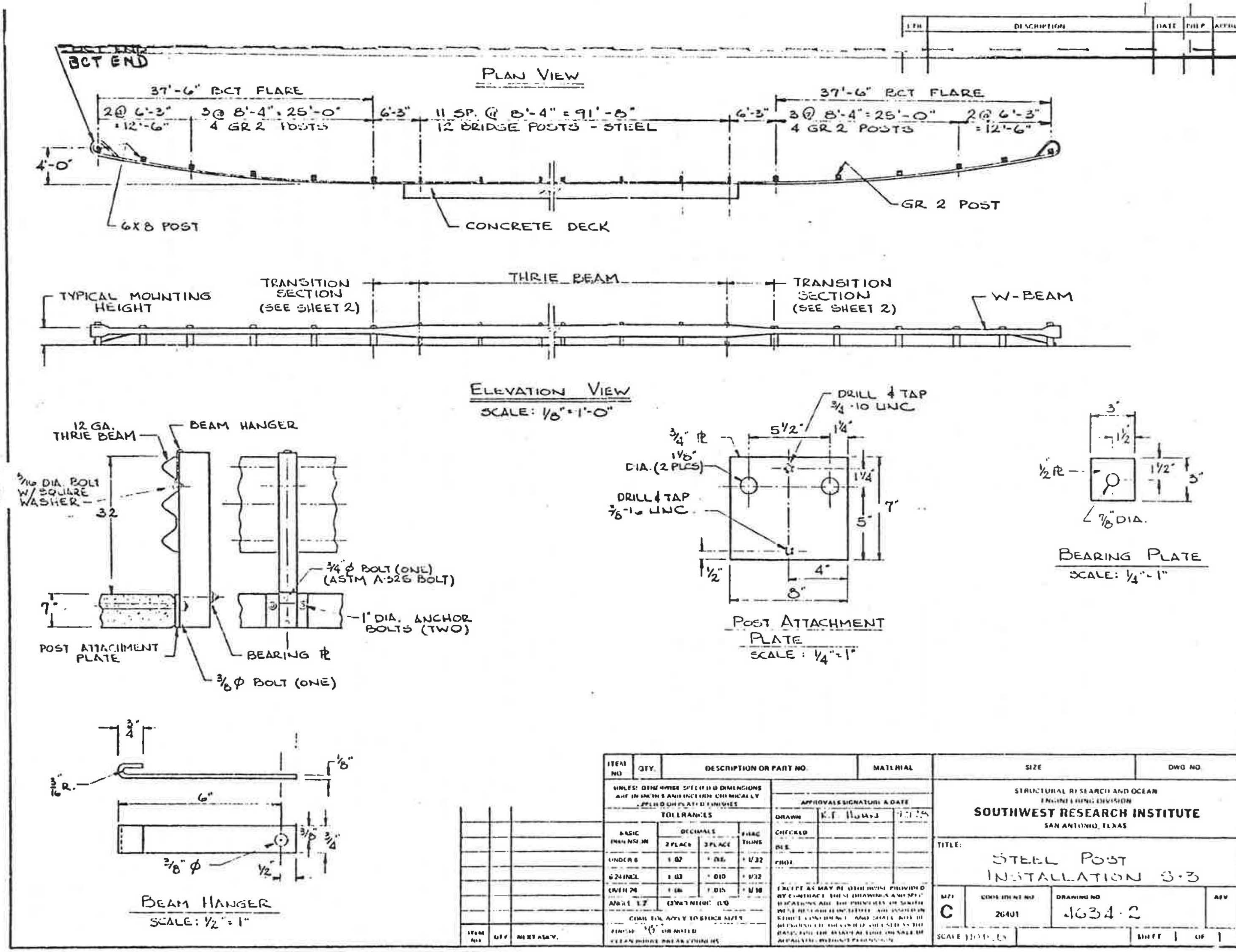



FIGURE C.13 STEEL POST PROTOTYPE DRAWINGS FOR SL 1 BRIDGE RAILING

railing was used with a transition to the Thrie beam bridge railing. This detail will permit use of the BCT or other approved terminal; no approved terminal has been developed for the Thrie beam. Prototype barriers were constructed for crash test evaluation according to these drawings.

C. Crash Test Program

A simulated bridge deck was constructed at the SwRI test site for the purpose of further developing the SL 1 bridge railing systems by crash test evaluation. These crash tests were conducted according to the procedures of TRB Circular 191(8) with one exception:

- The structural adequacy test for SL 1 systems is specified by 4500-lb (2040-kg) vehicle, 60-mph (95-km/h) speed, and 15-deg impact angle. The change from 25 to 15 deg represents the difference between SL 1 and current AASHTO(1) crash test option criteria.

The structural adequacy test was conducted first; modifications and subsequent crash tests were accomplished until satisfactory results were obtained. The impact severity test followed the successful adequacy test.

1. Wood Post System Tests. Five tests were conducted on wood post systems as summarized in Table 13. A minor and a major modification to the prototype design were necessary to accomplish the test objectives. The tests and results are described in this section; more detailed information is contained in Appendix E.

a. Test W-1. This structural adequacy test was conducted on the system described in Figures C.12 and C.14. Although the vehicle was redirected as shown in Figure C.15, considerable damage to the anchor bolts occurred due to wheel involvement.

C.33

b. Test W-2. Since bridge deck damage (e.g., anchor bolts) was considered undesirable, a modification to the anchor bolts/post bracket was accomplished as shown in Figure C.14(c). The vehicle was smoothly redirected until a dramatic change in front wheel angle occurred at 0.41 sec after impact as shown in Figure C.16. This change in steer angle resulted in redirecting the vehicle into the barrier resulting in increased barrier damage and deflection. The change in steer angle was attributed to wheel snagging on the projection of the post bracket.

c. Test W-3. The behavior of the vehicle in the previous test was considered undesirable; a decision was made to recess the wood post in the bridge deck as shown in Figures C.14(d) and 3. A 6-in. (150-mm) strip of concrete was added to the bridge deck and the anchor bolts extended to facilitate this change.

The vehicle was smoothly redirected in this structural adequacy test, as shown in Figure C.17, with a maximum deflection of 2.6 ft (0.8 m). The wheels on the impact side dropped considerably below the deck; when this occurred, the wheels were momentarily trapped against the deck edge before these wheels climbed up the deck. Six posts were fractured completely and one post was cracked as shown in Figure C.18.

d. Test W-4. This impact severity test was conducted on the same design as Test W-3. As shown in Figure C.19, failure of the posts in the impact area contributed to significant vehicle penetration into the system; both vehicle wheels on the impact side dropped below the deck and the vehicle was essentially trapped in this position for an extended time period before the wheels returned to the deck top. Both the dynamic deflection and installation damage greatly exceeded that of the previous test. Since this test was less severe in terms of impact conditions, the results were surprising.

C.36

Behavior of the posts was considered the most likely factor for the results of this test; therefore, post segments from the impact area were evaluated for flexural strength. From the results of these tests and visual observations it was apparent that some of the posts did not conform to the stress grade specified (as much as 50% below strength). The post supplier visited SwRI and confirmed that the posts in question were not of the proper grade.

e. Test W-5. Southern pine posts, Grade No. 2SR [$F_b$ = 1100 psi (7600 kPa)] were installed for Test W-5. In addition a new mounting bracket was designed and installed (Attachment Detail A, Figure 3) to assure beam separation from the post. The beam attachment detail used as described in Figure C.12 had not been performing for all posts in previous tests. Separation of the beam from the post is considered essential to prevent undesirable lowering of the beam as the post rotates about the base prior to complete separation.

The subcompact vehicle impacted the railing (Figure 3 drawing) as shown in Figure C.20 and was smoothly redirected as the system performed as designed. The maximum dynamic deflection was 1.6 ft (0.5 m) and two posts were completely fractured as shown in Figure C.21. The tire rolled off the rim during braking after leaving the barrier.

2. Steel Post System Tests. The steel post system was installed as described in Figure C.13 and shown in Figure C.22. Three tests were conducted as summarized in Table 13. The first test (S-3) was conducted using a beam "hanger" detail as shown in Figure C.22. The purpose of this hanger was to facilitate separation of the beam from the posts during impact with a flexible connection that would not cause separation during brush impacts such as experienced by New York with snow plow operations.

C.41

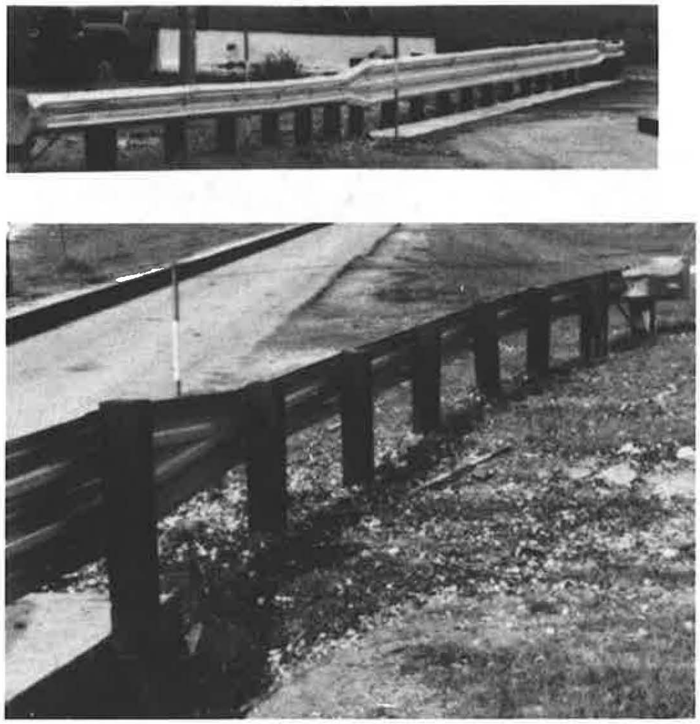
The steel post system performed much as originally designed with the beam mounting detail representing the only modification. The test results are described briefly in this section; detailed information is contained in Appendix C.

a. Test S-3. As shown in Figure C.23, the vehicle was smoothly redirected with a maximum dynamic deflection of 2.5 ft (0.8 m). Although the wheels on the impact side dropped below the top of the deck, the wheels readily climbed up as the vehicle was redirected. The beam hangers failed to resist the counterflexure forces causing separation of the beam from all the bridge posts. None of the approach railing attachments failed [5/16" (8 mm) dia. bolts].

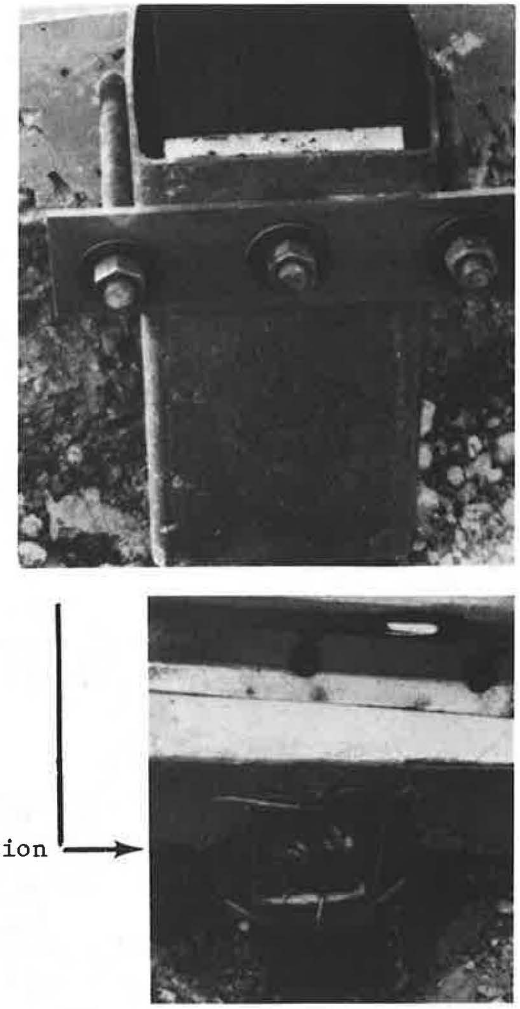
b. Test S-4. The beam hangers were replaced by standard 5/16" (8 mm) dia. bolts for this test; otherwise all details were the same as for Test S-3. The subcompact vehicle was smoothly redirected during this impact severity test; however, at one post location crushing of the deck permitted the post to rotate about the anchor bolts without post separation occurring. This allowed a vehicle wheel to contact the post although no snagging occurred. Examination of the deck revealed that the concrete was honeycombed and possibly some undetected damage had occurred during the previous test. Sequential photographs are given in Figure C.24.

c. Test S-6. The bridge deck damage of the preceding test was repaired and the impact severity test was repeated. As shown in Figure C.25, the vehicle was smoothly redirected with a maximum deflection of 1.2 ft (0.4 m). Discussion of an anchor bolt failure, which did not influence the test results, is in Appendix E. Figure C.26 shows photographs after Tests S-3 and S-6 were conducted.

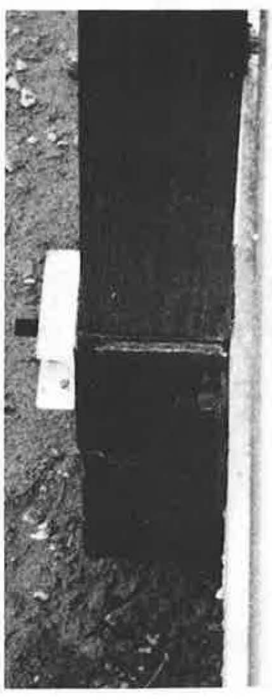
C.45



(a) Wood post installation



(b) W-1 post installation

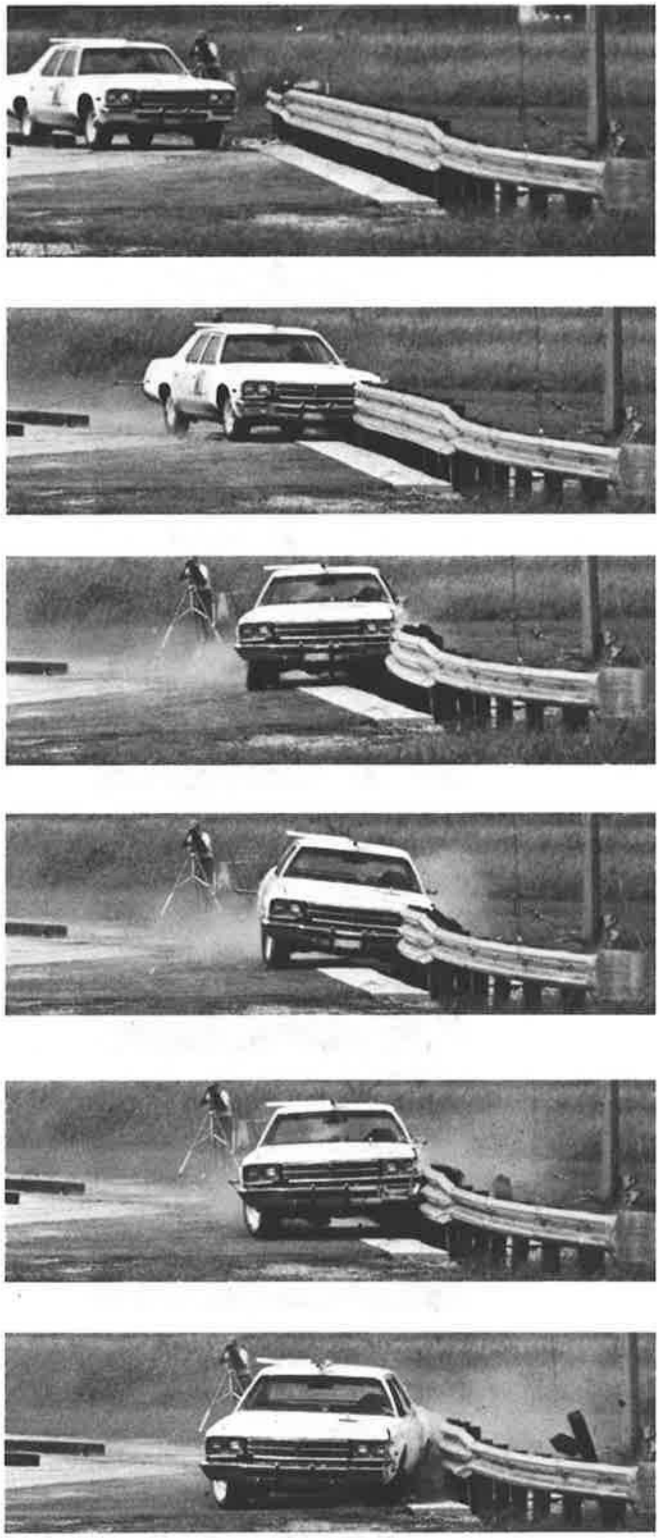


(c) W-2 post bracket

(d) W-3 thru W-5 post installation

FIGURE C.14. WOOD POST SYSTEM PHOTOGRAPHS

FIGURE C.15. TEST W-1 SEQUENTIAL PHOTOGRAPHS



NOTE: Change of vehicle direction from previous photo.

FIGURE C.16. TEST W-2 SEQUENTIAL PHOTOGRAPHS

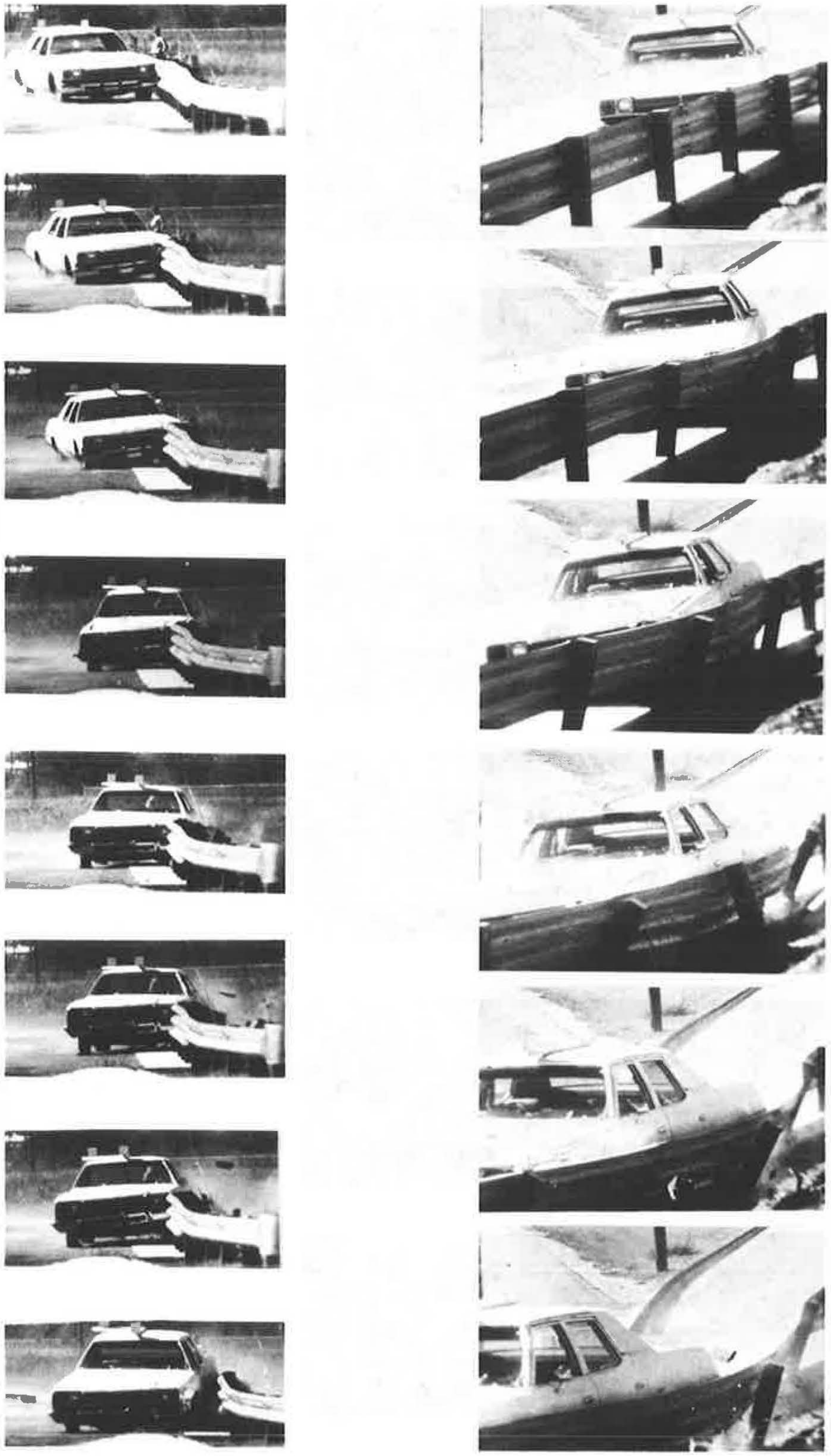


FIGURE C.17. TEST W-3 SEQUENTIAL PHOTOGRAPHS

FIGURE C.18. PHOTOGRAPHS AFTER TEST W-3

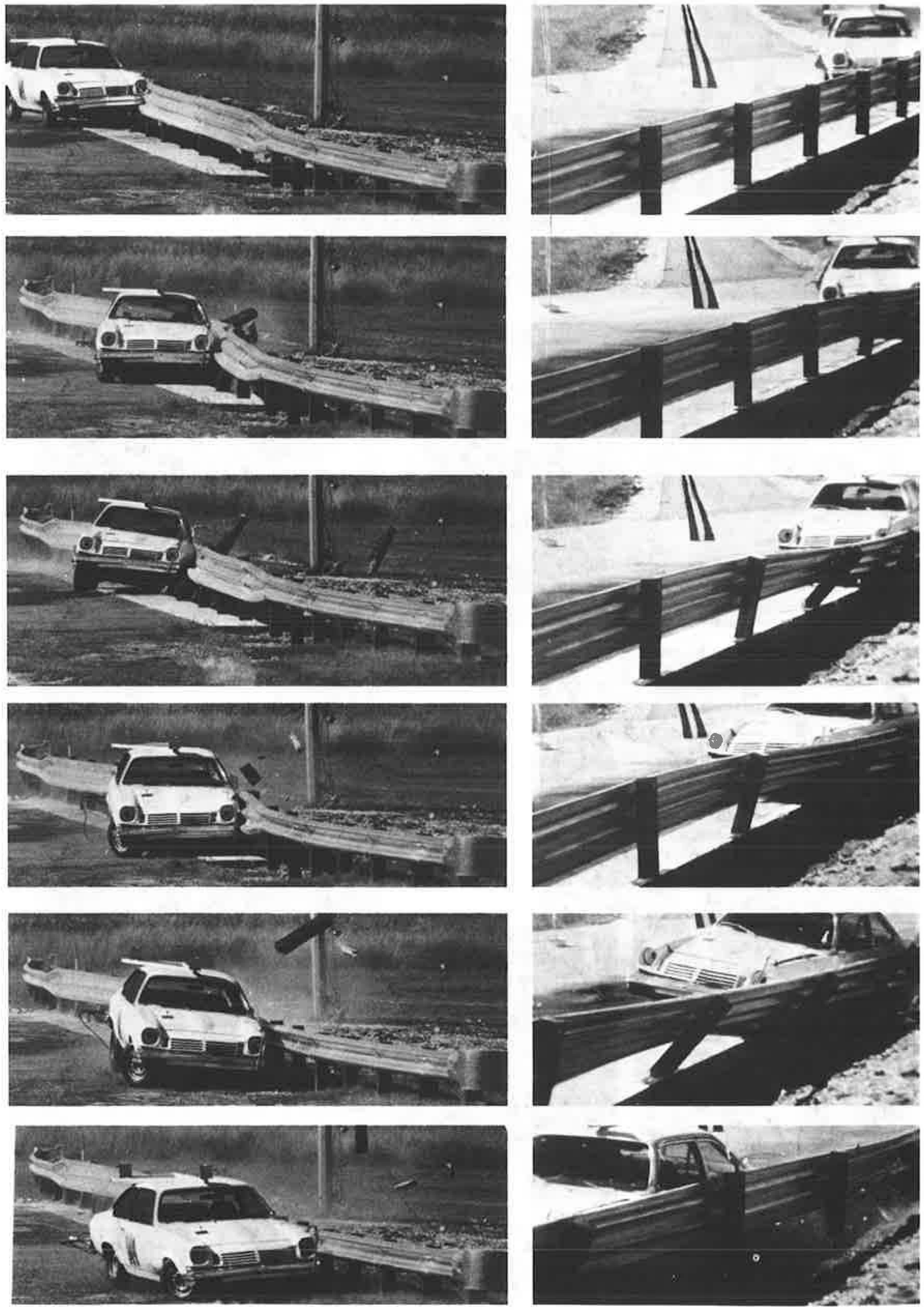


FIGURE C.19. TEST W-4 SEQUENTIAL PHOTOGRAPHS

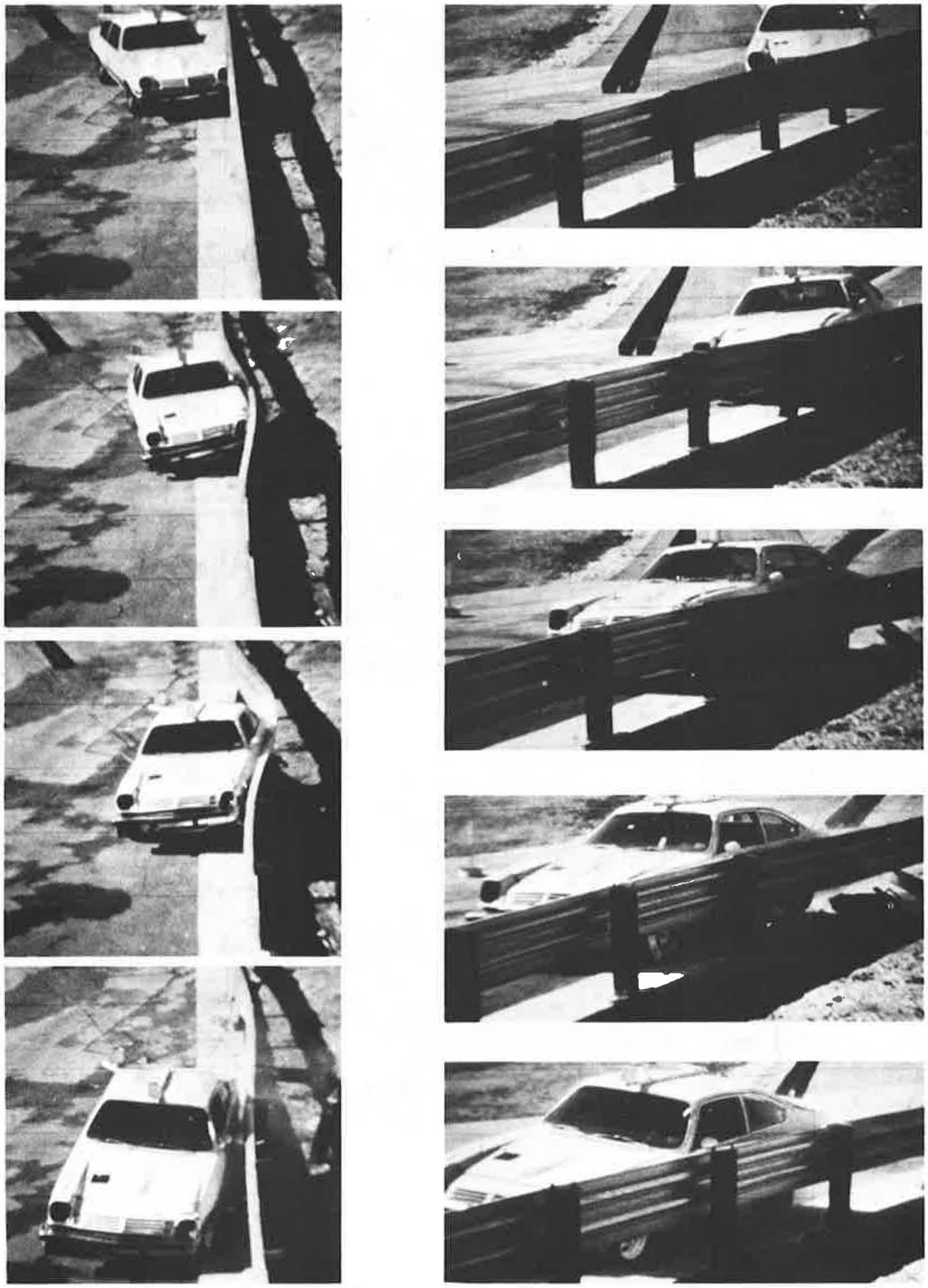


FIGURE C.20 TEST W-5 SEQUENTIAL PHOTOGRAPHS

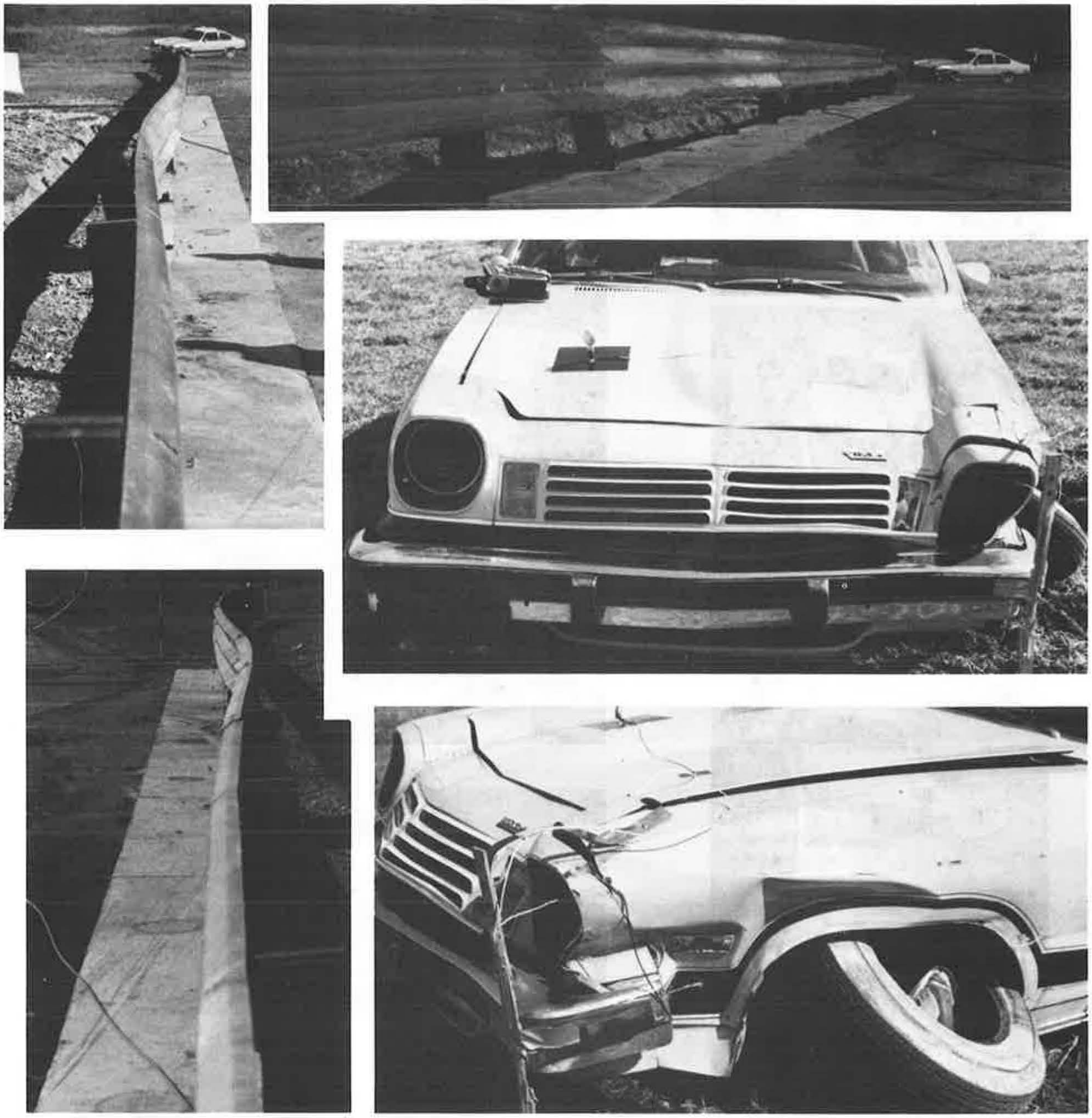
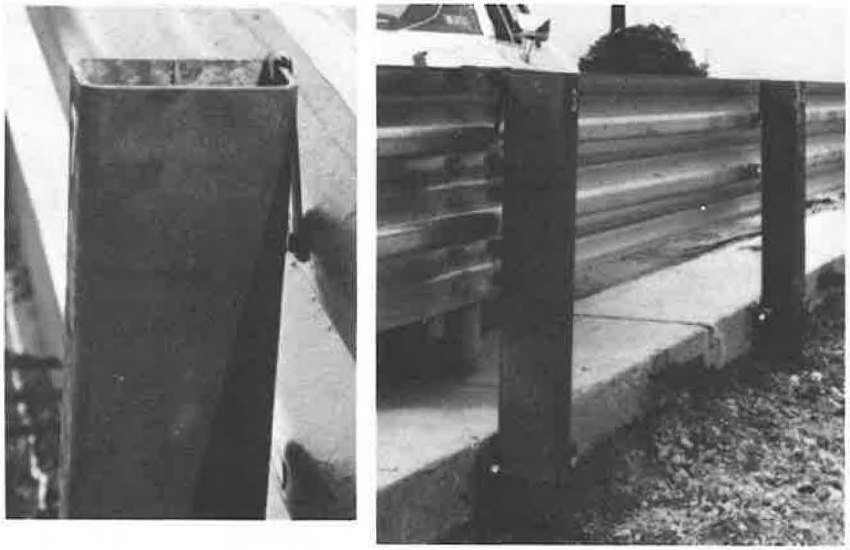
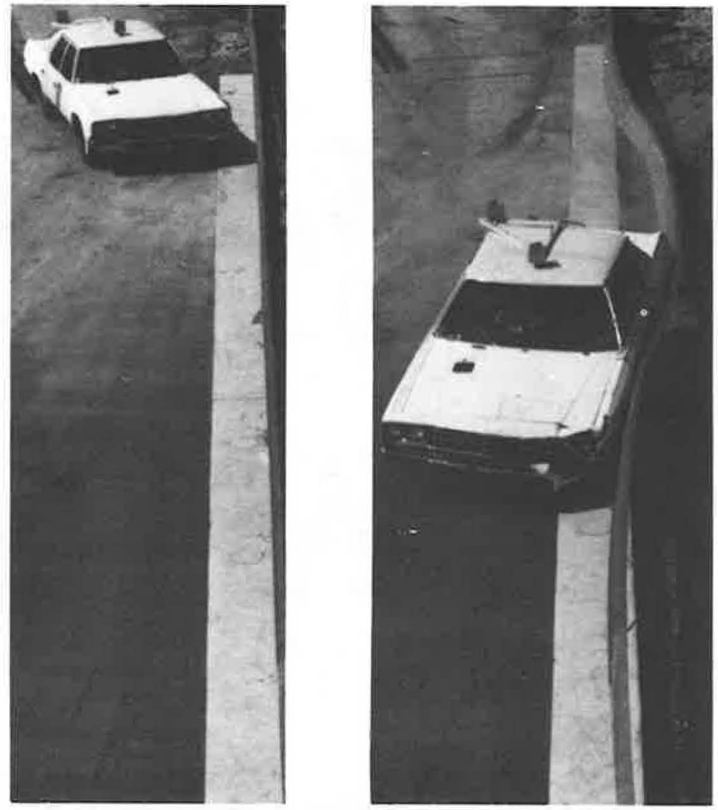


FIGURE C.21. PHOTOGRAPHS AFTER TEST W-5

(a) S-3 installation



(b) View from behind railing



(c) Overhead sequence

FIGURE C.22. S-3 TEST PHOTOGRAPHS

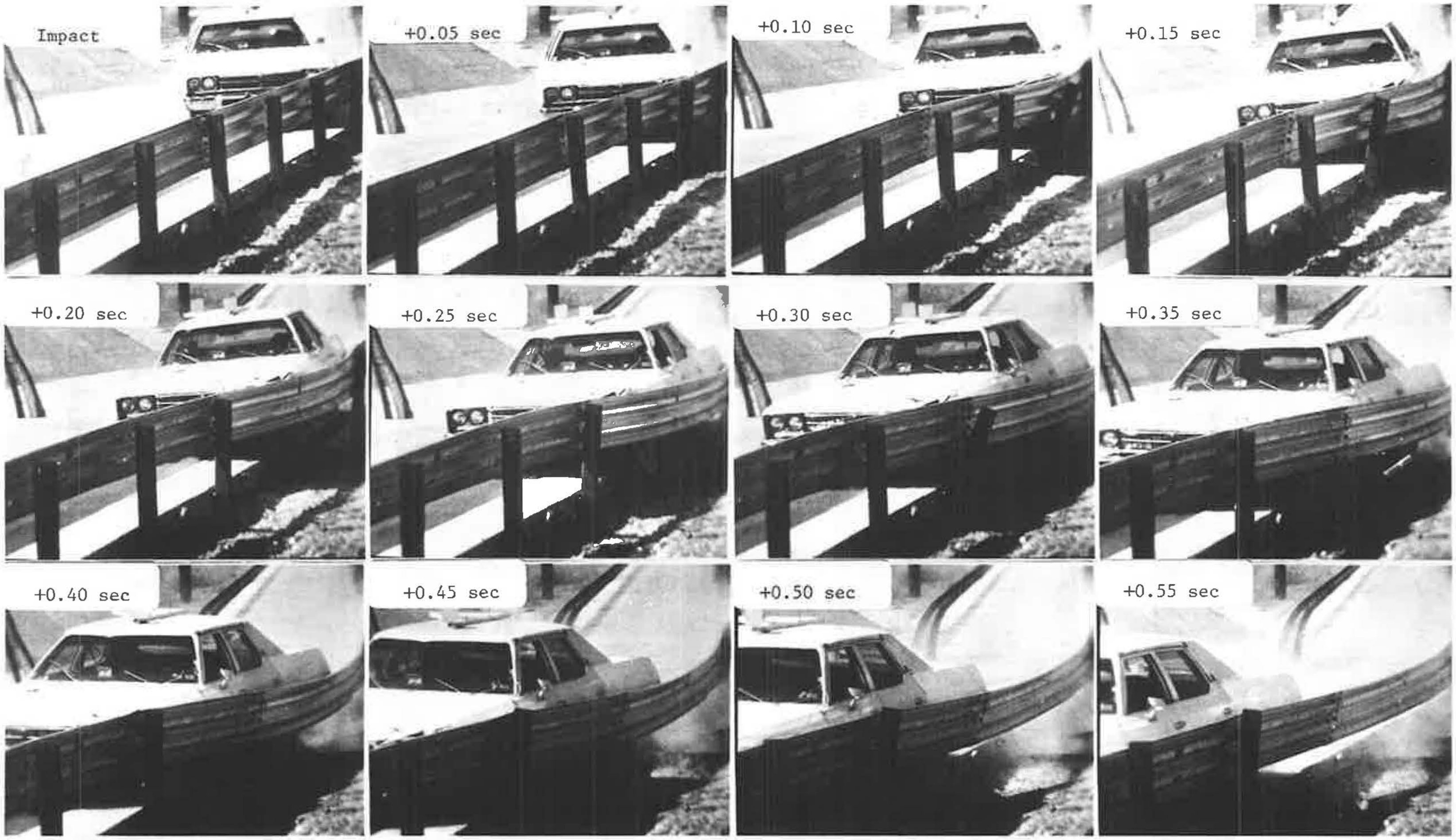



FIGURE C.23. TEST S-3 IMPACT SEQUENCE

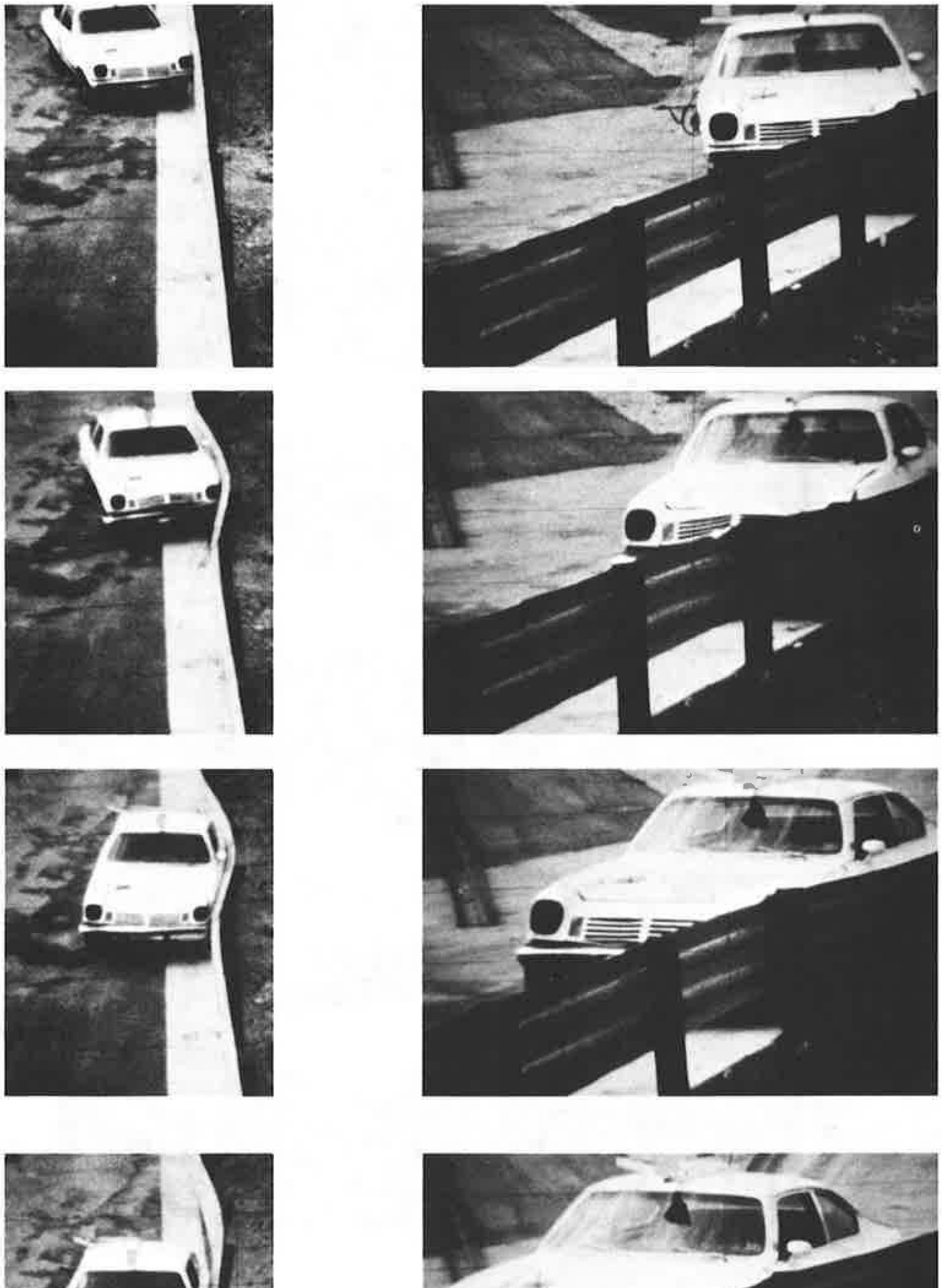


FIGURE C.24. TEST S-4 SEQUENTIAL PHOTOGRAPHS

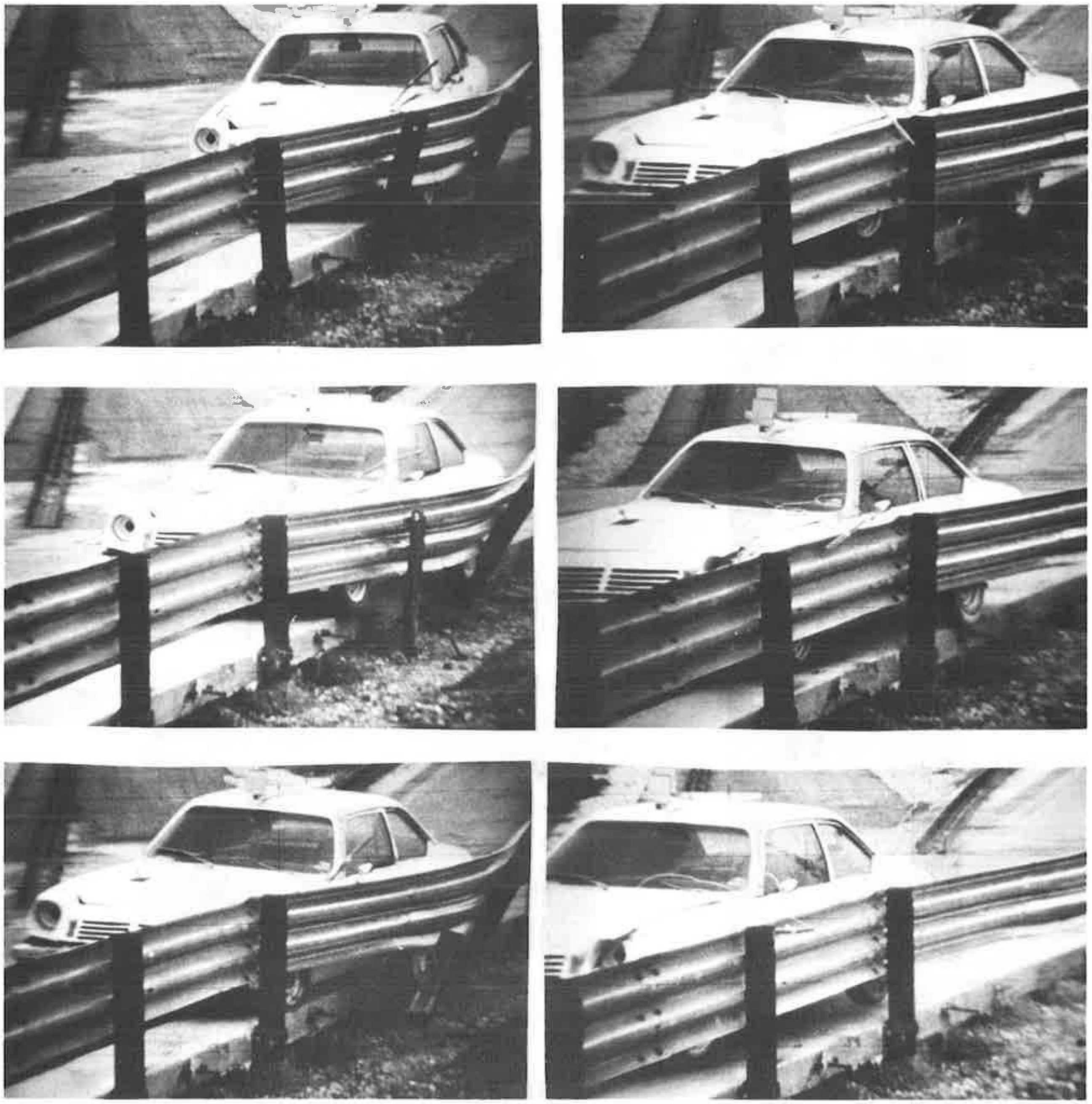
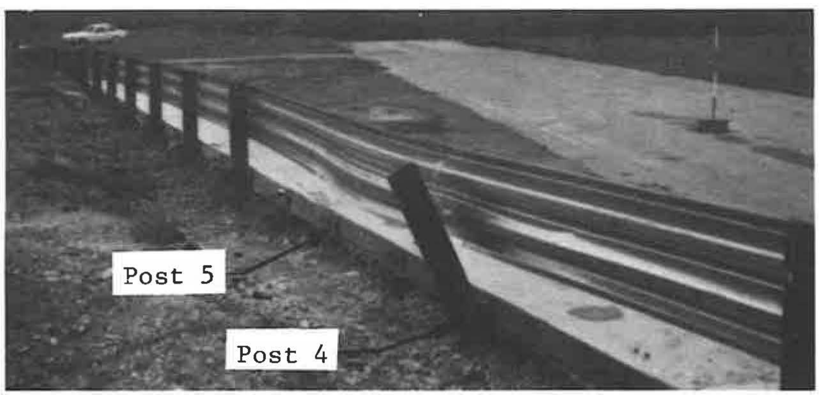


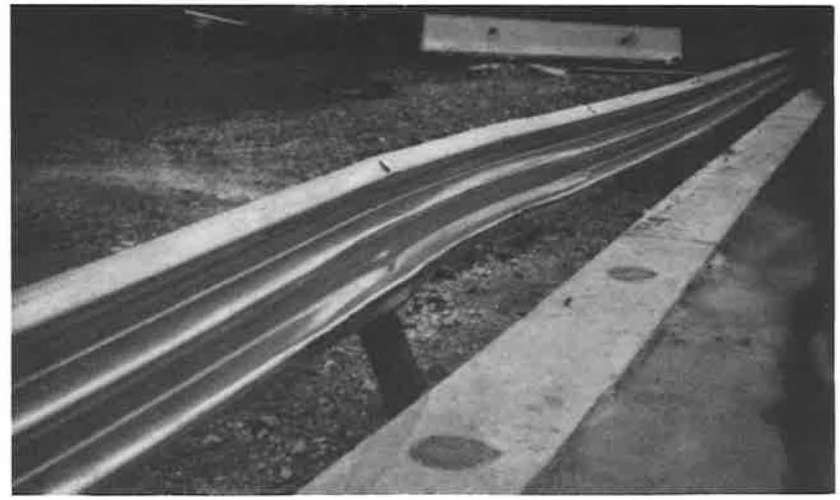
FIGURE C.25. S-6 SEQUENTIAL PHOTOGRAPHS

(a) After Test S-3

(b) S-3 Vehicle




(c) After Test S-6



(d) Test S-6

(e) S-6 Vehicle

(f) Post 5

failed anchor bolt

(g) Post 4

FIGURE C.26. PHOTOGRAPHS AFTER TESTS S-3 AND S-6

d. Test NCHRP-1. Objective of this test was to evaluate the structural adequacy of the SL 1 steel post (Figure 4) barrier syste when impacted by a 20,000-lb (9,072-kg) school bus at 45 mph (72.4 kmph and a 7-deg angle. A 1966 International chassis with a 72-passenger superior school bus body was the test vehicle. To achieve the desired 20,000-lb (9072-kg) weight, 6,600 lb (2994 kg) of ballast (sandbags) we added. Sandbags were placed in each seat to achieve a 100 lb (45 kg) per seating position average; bags were not secured.

Impact conditions were 44.7 mph (71.9 kmph) and a 7.7-deg angle. As seen in the impact sequence of Figure C.27, the barrier easily redirected the bus as it was deflected rearward a maximum of 20 in.(508 mm) contact with the bus rear end. Maximum roll angle attained by the bus was 15 deg. After losing contact with the test installation the bus initiated a sharp turn to the left and subsequent body roll to the right. This was probably due to the ballast shifting to the right, particularly in the rear section of the bus. Maximum (50 msec avg) vehicle accelerations were - 0.5 g's in the longitudinal direction and 1.4 g's in the lateral direction.

As shown in Figure C.28 damage to the test installatio consisted of four moderately deformed rail sections and the threads in the attachment plates at posts 9, 10, and 11 stripped. Posts 9 through 12 had slight deformation at lower end but are considered reusable. A concrete failure was experienced at post 8, but deformation of the attachment plate similar to posts 9, 10, and 11 indicated that the attachment bolt load was essentially developed at this post. It is significant to note that the anchor bolts for the installation were plac in the unreinforced concrete runway using high-strength epoxy grout.



Posts 9, 10, and 11 remained intact with the attachment plates as the lower 3/8 in.dia counterflexure bolts remained in place.

Damage to the school bus was minor. The fender sheet metal and front bumper at the right front corner were pushed back into the tire causing some thread damage. The only other damage was scraping at the right rear corner of the bus. Vehicle damage photographs are shown in Figure C.29.

D. Comparison of Simulations and Experimental Results

The use of computer simulations to design the SL 1 barrier was discussed in Section B of this appendix. Generally, the deflections and barrier damage in the experiments exceeded the simulation values. After the pendulum and crash tests had been completed, the simulation input was revised based on experimental values.

1. Experimental Observations. Results from both pendulum and crash tests provide measured input rather than estimated values used in the preliminary design effort.

a. Pendulum Results. The pendulum tests demonstrated desired breakaway force was being achieved. Actual post load/deformation values obtained after the tests, as shown in Appendix D, were used in the final simulation cases.

b. Crash Test Results. The larger barrier deflections of the experimental program were partially accounted for by adjusting the Thrie beam modulus of elasticity to account for the slotted splice connections. This adjustment is described in Appendix D. The crash test series was conducted using the same beam and approach railing; thus only elements damaged in preceding tests were subsequently replaced. It is possible that



much of the longitudinal "play" in the beam slots was stretched out during the tests and that latter tests would have more "play" in the impact area elements as illustrated in Figure C.30.

Another source of discrepancy in determining the post behavior was the point of force application. In the original simulations the force transmitted from the beam to the post was assumed to be acting at the centerline of the beam. It is possible that this assumption was not valid in all cases; therefore other lines of force were investigated.

The actual strength of each post has some variance and this would also affect the behavior of the systems; other post strengths were also used in simulations.

In many of the crash tests the vehicle deflected beyond the bridge deck and wheels actually dropped below the deck level. This phenomenon undoubtedly causes increased loading of the barrier which cannot be accounted for in the simulations. Thus, this is one factor which cannot be adjusted to improve simulations.

2. Final Simulation Results. As summarized in Table C.8, simulation cases were conducted for the purpose of comparing crash test results. The improvements of post and beam properties discussed in Appendix D were used for the cases shown. As also shown, it was necessary to reduce the post strength for the wood post in order to achieve reasonable simulation results.

The simulations for the steel post provided good comparison; simulated deflection values were still low, but there are factors which cannot be accounted for as previously discussed.

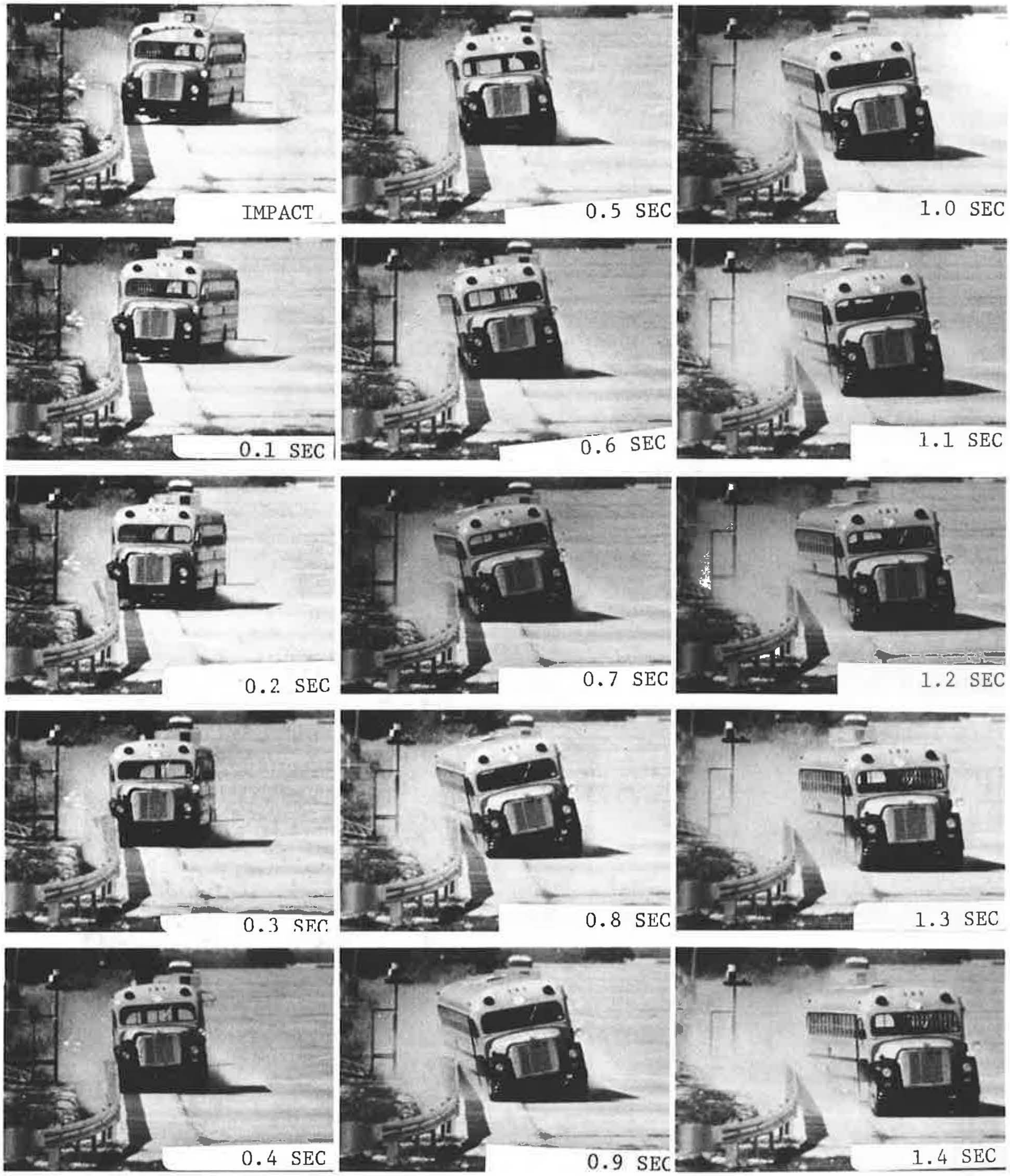



FIGURE C.27. TEST NCHRP-1 IMPACT SEQUENCE

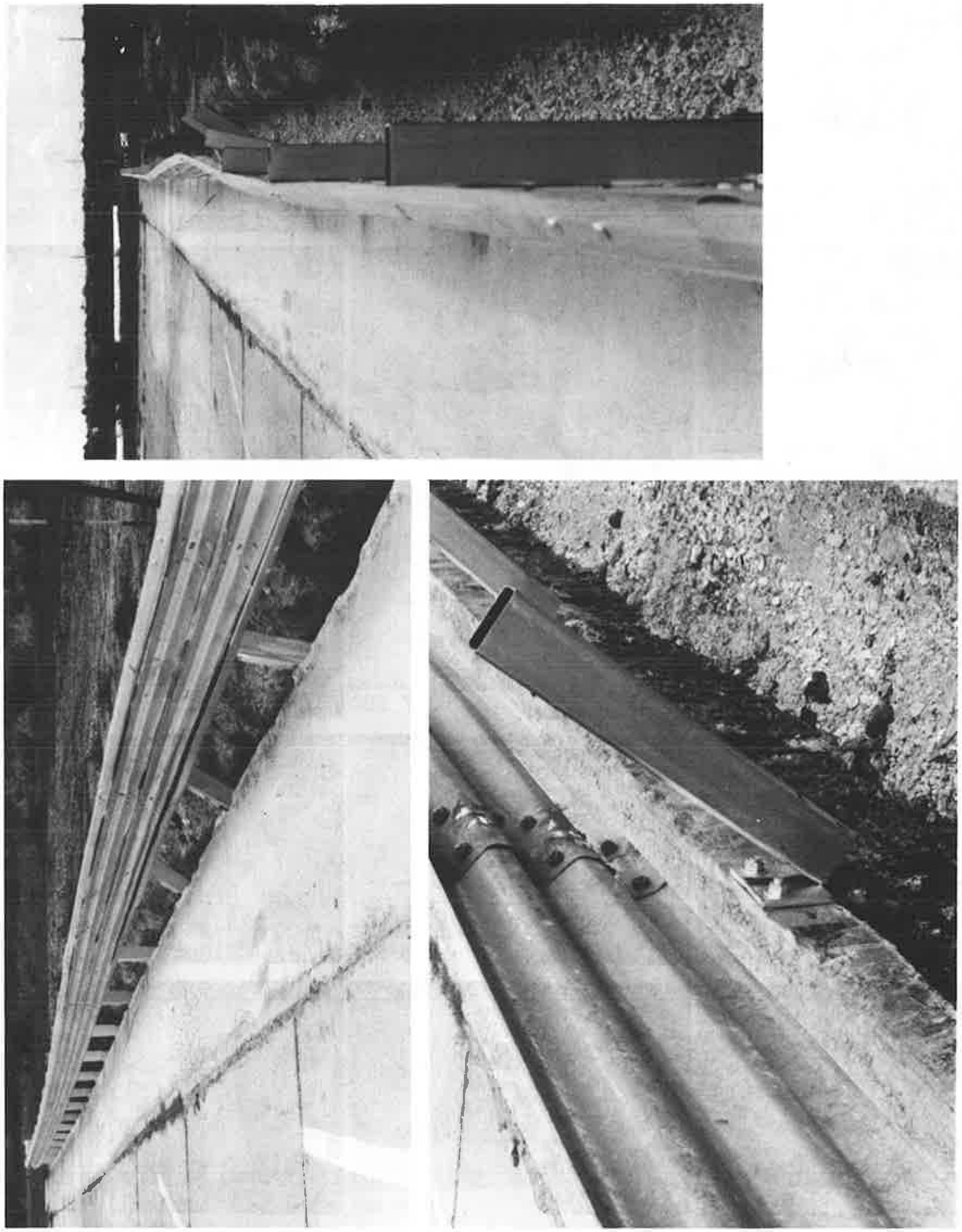


FIGURE C.28. BARRIER DAMAGE, TEST NCHRP-1

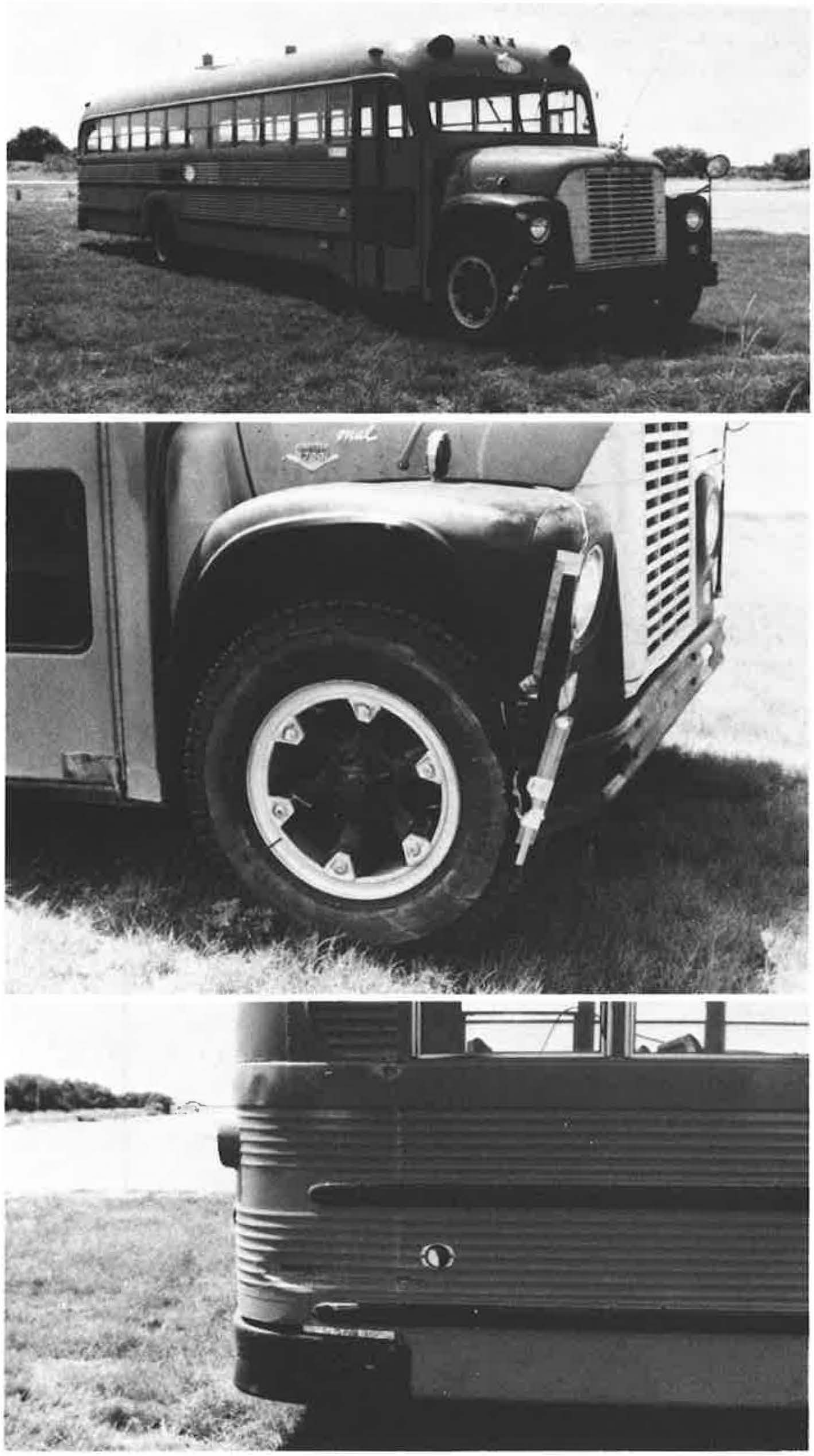
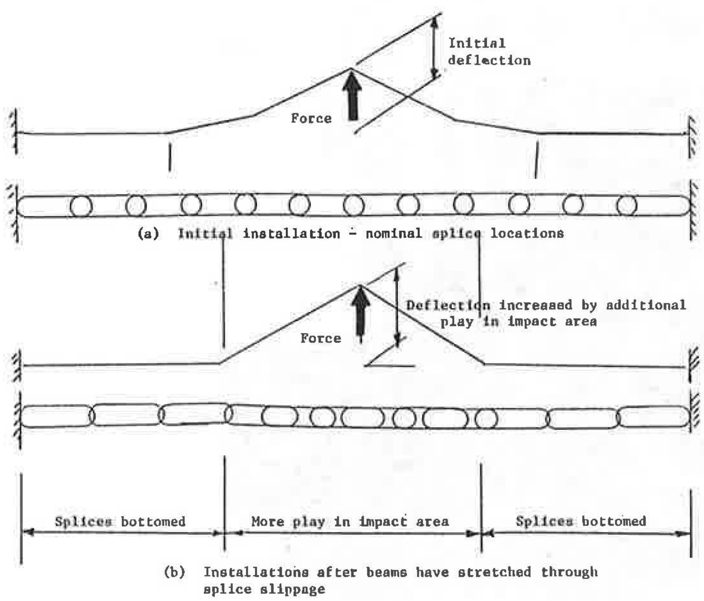


FIGURE C.29. VEHICLE DAMAGE, TEST NCHRP-1

To be noted are the lack of beam damage and the relatively high longitudinal subcompact vehicle accelerations predicted by the simulations. No apparent explanation is offered for these two discrepancies.






NOTE: A chain is used for illustration.

FIGURE C.30 BARRIER DEFLECTION CONSIDERATIONS

TABLE C.8

COMPARISON SUMMARY OF SIMULATIONS AND CRASH TESTS

| Case/Test† No. | Vehicle Weight (lbs) | Impact Speed (mph) | Impact Angle (deg) | Max. Vehicle Accelerations, g's (50 msec avg) | | Maximum Dynamic Defl. (ft) | Number of Posts Failed * | Number of Rail Sections Damaged |
|---|---|---|---|---|---|---|---|---|
| | | | | Long. | Lat. | | | |
| Test W-3 | 4500 | 61.9 | 14.5 | -4.1 | -3.3 | 2.6 | 6C, 1P | 2 |
| Case W-3** | 4500 | 60.0 | 15.0 | -2.8 | -3.5 | 1.8 | 4C, 1P | 0 |
| Test S-3 | 4500 | 61.7 | 16.6 | -3.1 | -3.2 | 2.5 | 3C | 2 |
| Case S-3 | 4500 | 60.0 | 15.0 | -3.1 | -3.4 | 1.8 | 3C | 0 |
| Test W-5 | 2250 | 60.1 | 15.9 | -2.3 | -4.2 | 1.6 | 2C, 1P | 1 |
| Case W-5 | 2250 | 60.1 | 15.9 | -5.3 | -5.9 | 0.6 | 1C | 0 |
| Case W-5** | 2250 | 60.1 | 15.9 | -4.3 | -4.8 | 0.8 | 2C, 1P | 0 |
| Test S-4 | 2250 | 58.6 | 16.0 | -1.8 | -4.6 | 0.8 | 1P | 1 |
| Case S-4 | 2250 | 58.6 | 16.0 | -5.2 | -5.8 | 0.6 | 1C | 0 |
| Test S-6 | 2250 | 60.0 | 16.0 | -2.9 | -5.2 | 1.2 | 1C, 1P | 1 |
| Case S-6 | 2250 | 60.0 | 16.0 | -5.0 | -5.5 | 0.7 | 1C | 0 |

† Test - crash test results, Case - computer simulation
* C - complete separation of post; P - permanent post displacement, but post intact
**7-kip (30-kN) breakaway post, 22-in. (0.55-m) node height

Metric conversion:
Multiply lb by 0.45 to obtain kg
Multiply mph by 1.6 to obtain km/hr
Multiply ft by 0.3 to obtain m