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16. Abstract

This project evaluated bridge railings. State bridge rail designs submitted to the Federal Highway Administration (FHWA) were rated and the best of each type were selected for crash test evaluation. When necessary, the designs were improved and retested. Most of the crash tests were conducted with 4500-lb (2025-kg) cars at 60 mph (95 km/h) and a 25-degree angle and 1800-lb (800-kg) cars at 60 mph (95 km/h) and a 20-degree angle.

Performance standards proposed in 1986 are presented, along with bridge railing geometric design considerations to minimize vehicle snagging. Design drawings of the successfully tested bridge rails are included.

This volume is the first of three volumes as listed:

Vol. No.	FHWA No.	Short Title
I	RD-87/049	Research Report
II	RD-87/050	Appendix B
III	RD-87/051	Appendixes C through E

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METRIC (SI*) CONVERSION FACTORS

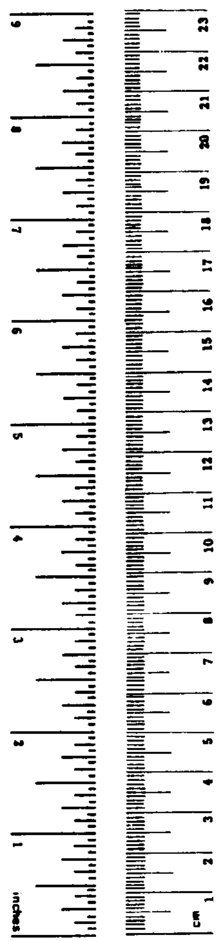
APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

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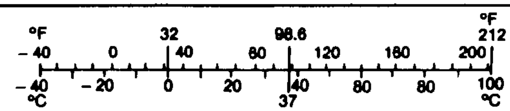

These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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1. Introduction and Research Approach

a. Statement of the Problem

The performance standards approach calls for full-scale crash tests or validated equivalent laboratory tests to be used as the basis for determination of traffic barrier system acceptability. In practice, this performance standards approach has been endorsed by the FHWA as the recommended or mandated approach for all roadside safety devices except for bridge rails. Section 6-2-1-1 of the Federal Highway Program Manual and Part 625 of the Federal Regulation (CFR-23) contain the FHWA's position for the design and selection of traffic barriers. These documents cite:

- The AASHTO Bridge Design Specifications[(1)] as the basis for the design and selection of bridge rails.

- The AASHTO Barrier Guide,[(2)] which is based on performance criteria, for other traffic barriers.

The first recommended standard crash test and evaluation procedures for all roadside safety structures were published in 1974 in NCHRP Report No. 153.[(3)] The 1977 AASHTO Barrier Guide endorsed these test and evaluation procedures, and only barrier systems judged to essentially meet the NCHRP Report 153 criteria (including bridge railings) are shown as "operational" in this guide.

Bridge railings may be designed in accordance with the AASHTO Bridge Design Specifications, which call for railings to meet specific geometric criteria and to resist specified static loads without exceeding the allowable stresses in their elements. Railings that meet these criteria and loading conditions are deemed acceptable. Full-scale crash testing is not required. On the other hand, railings that have been successfully crash tested are considered acceptable even though they may not meet the static loading analysis and geometric requirements. The 1980 AASHTO interim

Bridge Design Specifications do not specify what constitutes a successful crash test; i.e., no reference is given for making the judgment.

AASHTO adopted a major change in the design criteria for bridge railings in 1964 and refined these criteria in 1973. In the 10 years after the last major change in the AASHTO Bridge Design Specifications, there was a significant amount of research on bridge railings. Many of the programs included the use of heavy vehicles and the 1800-lb (810-kg) minicompact vehicle. For example:

- Five retrofit railings were crash tested and developed under Contract DOT-FH-8100, "Upgrading Safety Performance in Retrofitting Traffic Railing Systems."(4)

- One of the barrier systems developed in the above project was evaluated for school bus and intercity bus impacts and was found to be deficient; both buses rolled over during 60-mph (96-km/h), 15-degree angle impact. A modified retrofit design proved to be satisfactory for both bus impacts and for a 60-mph (96-km/h), 15-degree angle impact with an 1800-lb (810-kg) minicompact car.(5)

- A new concept for selecting bridge railings, the Multiple Service Level Approach (MSLA) and two "low service level" bridge railings were developed under NCHRP Project 22-2(3).(6)

- NCHRP Report No. 230, "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances,"(7) was developed to supercede NCHRP Report No. 153.

- Five existing bridge railings were crash tested with light and heavy vehicles and performance standards were developed under Contract DOT-FH-11-9181, "Development of Safer Bridge Railings."(8)

- The Indiana 5A railing that was tested in the above contract was redesigned to increase its strength and to improve its performance for minicompact cars.[9]

- A high-performance, self-restoring retrofit railing was developed under Contract DTFH61-81-C-00103, "Self-Restoring Median Barriers and Bridge Railings."[10] Five existing bridge railings were also tested under NCHRP Project 22-4, "Performance of Longitudinal Traffic Barriers."[11]

It was expected at the start of this study that these recent developments and current activities would lead to changes in the bridge railing acceptance criteria. FHWA supported the performance standards approach as being in the public interest and intended to work with the States to develop an array of standard barrier systems to cover the service levels and local requirements of the States. This study was undertaken to develop these bridge rail designs and performance standards.

b. Objectives and Scope

As indicated in the statement of work, the objectives of this study were the following:

- To test and evaluate existing and improved bridge railing designs to meet currently available bridge railing performance standards.

- To develop a bridge railing geometrics relationship between the frontal areas of the railings, the vertical openings and the post setback that will eliminate bumper and wheel snagging problems.

The stated scope of work was as follows:

This requirement shall consist of reviewing recent research and development work related to bridge railings, selection of performance standards, computer simulation, analysis and design of bridge railings, static and pendulum tests of barrier components, full-scale tests of bridge railings with light and heavy vehicles, and preparation of standard design drawings and specifications.

c. Research Approach and Report Organization

This project was composed of five major research tasks. These tasks, along with their corresponding specifications taken from the statement of work, are shown in table 1.

The review of previous performance standards and development of proposed new standards (task A) is discussed in chapter 2. Details of the rating and selection process of existing bridge rail designs (task B) are discussed in chapter 3. Ratings of the various State designs are included in appendix D. The final bridge rail configurations are shown in appendix A.

Summaries of the 24 full-scale crash tests conducted (task C) are given in chapter 4. Complete test reports are included in appendix B. Details of the upgrading of bridge railing designs (task D) and bridge railing geometrics (task E) are discussed in chapters 5 and 6, respectively. Analytical procedures and development details of a small interactive computer program BRIDGE to check the bridge railings against AASHTO specifications are presented in appendix C.

Findings of the study are detailed in chapter 7. Finally, conclusions and recommendations resulting from the study are presented in chapter 8.

Table 1. Research tasks and specifications.

Task A. Review of Performance Standards

Review the results of previous research and development work on bridge railings, performance standards, testing procedures, barrier warrants and the Multiple Service Level Approach (MSLA) for selecting bridge railings and then select performance standards for evaluating the bridge railings that will be tested in task C.

Task B. Selection of Bridge Railing Designs

- Review the existing bridge railing designs shown in the 1977 AASHTO Barrier Guide and in the State Standard Plans that will be loaned to the contractor by FHWA in order to identify those railings that either meet, or are judged likely to meet, the task A performance standards and select a minimum of 10 candidate bridge railing designs to be tested and evaluated in task C.

  NOTE: The goal is to identify and/or develop a family of bridge railings that meet the whole gamut of national needs. Therefore, in selecting railings, due consideration shall be given to their operational and maintenance requirements and environmental factors, as well as their potential to meet current performance standards and Multiple Service Level considerations.

- Review the candidate bridge railing designs to see if they meet the provisions of the AASHTO Bridge Specifications.

- Develop and submit for approval a tentative test matrix for full-scale testing a minimum of 6 bridge railings in task C.

  NOTE: The recommended bridge railings can include railings which have previously been tested.

- Prepare any additional drawings of the bridge railings that are necessary to construct them at the contractor's test site.

Task C. Full-Scale Tests

Conduct up to 20 full-scale tests of bridge railings with automobiles and buses in accordance with the approved tentative test matrix which was prepared in task B-3. Furnish and install all of the necessary appurtenances to construct complete test layouts for testing at the contractor's test site and furnish and prepare all test vehicles, vehicle guidance systems, propulsion systems, instrumentation, personnel, film, and photographic equipment.

TECHNICAL REQUIREMENTS

- Test procedures, test instrumentation, evaluation of the full-scale test results and the report contents shall be in accordance with the guidelines in National Cooperative Highway Research Program (NCHRP) Report No. 230. (7) These procedures may be modified by the contractor when test conditions dictate, provided the deviations are approved by the COTR. The vehicle maximum 50 msec accelerations, and the changes in vehicle velocity and momentum shall also be reported. Data shall be recorded in analog form on oscillographic records and magnetic tape. Two fully-instrumented 50th percentile male anthropometric dummies shall be placed in the front

Table 1. Research tasks and specifications (continued).

seat of each car in order to assess the probability of occupant injury. One dummy shall be unrestrained. The other dummy shall be restrained with the shoulder and lap belts that come with the vehicle. A fully-instrumented 50th percentile male anthropometric dummy driver, restrained with a lap belt, shall be placed in each bus. An unrestrained, fully-instrumented 50th percentile male anthropometric dummy shall be placed in the second seat (outside position) from the front on the impact side of the bus. In order to achieve the 40,000 lb test weight of the intercity bus, 6,000 lbs of unrestrained 100 lb sandbags shall be placed in the passenger seats and the remaining weight of sandbags shall be divided equally between the two lower cargo compartments. A composite film shall be spliced together from work prints in order to facilitate review of the full-scale bridge railing tests. High-speed and real-time films, slides, and still photographs shall be made of each test.

- The full-scale test data shall be digitized in accordance with the SAE-J211, Class 100 specification and a magnetic data tape shall be prepared as specified in NHTSA's "Dynamic Crash Test Information Reference Guide" (14).

- In order to measure the vehicle crush depth, a minimum of six measurements shall be made before and after each full-scale test. The depth measurement points shall be equally spaced along the length of the damaged area in order to generally describe the damage penetration profile. The maximum static crush distance (damage penetration) shall also be measured and reported, regardless of its location. End, top and lateral view photographs shall be taken of the full length of each damaged vehicle. The vehicle trajectory after impact shall also be measured and reported.

- The bridge railings shall be instrumented in order to measure the loads in the rail elements.

NOTES TO OFFEROR:

- For budget estimating purposes, assume that eight 1980 or later model Honda Civic sedans will be needed for the tests with 1,800 lb vehicles. Assume that two 40,000 lb intercity buses, two 1980 or later model 20,000 lb school buses, and eight 1978 or later model 4,500 lb sedans also will have to be purchased under the contract.

- The test facilities must be flexible enough to accommodate 60 mph impacts with 4,500 lb vehicles at 15 or 25 degrees, and to accommodate 60 mph impacts with 1,800 lb vehicles at 15 or 20 degrees at selected points along the test barrier.

- It will be advantageous to leave all of the test barriers in place until the end of the contract so additional tests can be conducted with cars and buses to better define their service levels and performance limits.

Table 1. **Research tasks and specifications (continued).**

Task D. Upgrading of Bridge Railing Designs

- After consultation with the Contracting Officer's Technical Representative (COTR), redesign bridge railings which have already been tested in order to either improve their performance or raise their service level.

- Use computer simulation or other analytical tools in order to gain insight into bridge railing strength and behavior, and to provide an analytical basis for redesigning bridge railings.

- Make static tests and pendulum tests of barrier components in order to provide data needed for redesigning bridge railings. (As a minimum, 30 static tests and 5 pendulum tests shall be conducted.)

  NOTE: It is intended that some of the full-scale tests in task C will be used to evaluate the bridge railings that are redesigned in task D.

- Prepare detailed standard drawings, sketches and specifications for the final tested bridge railing designs.

  NOTES:

  - The contractor shall carefully document the material properties of the bridge deck and the bridge railing components.

  - The drawings, sketches, and specifications shall be prepared in such a form that Texas Transportation Institute can readily incorporate the material into the "Road-Side Safety Technology Text and Guide" publications which will be prepared under Contract DTFH61-82-C-00088.

Task E. Bridge Railing Geometrics

Develop a bridge railing geometrics relationship between the frontal areas of the railing, the vertical openings and the post setback which will eliminate bumper and wheel snagging problems.

NOTE: The bridge railing geometrics relationship should not only eliminate snagging problems for 1,800 lb front-wheel-drive minicompact cars, but also provide safe railing geometries for larger vehicles.

2. Performance Standards for Bridge Rails

a. Introduction

1. Objective

The objective of task A of this study was to review the previous methods used in developing and evaluating bridge rails and to propose performance standards that will meet the changing needs of the highway system. A critical review of performance standards is contained in appendix E, consisting of (a) history of barrier performance standards, (b) current vehicle crash testing and evaluation methods, and (c) a synopsis of pertinent research.

This chapter describes the development of the performance standards proposed in 1986. The standards evolved from recommendations presented in NCHRP Report 230[7] and reflected findings from recent research and the specific requirements and functions of the bridge rail.

2. Background

a. Prescriptive Design Versus Performance Testing

Since the 1940's, bridge rails have been designed according to prescriptive procedures contained in various editions of the AASHTO Bridge Design Specifications. Bridge rails have been required to meet specific geometric criteria and to resist specified static loads without exceeding allowable material stresses in the elements. (The 1977 edition of the Specifications have included a performance test option, but this has been used infrequently[1].) The simplicity of the prescriptive approach has encouraged the proliferation of unique systems. In the past 20 years, the specifications have been continually revised and upgraded to address deficiencies as they became known.

In contrast, performance standard approach procedures as recommended in NCHRP Report 230[7] call for candidate railing systems to be assessed for a matrix of full-scale vehicle crash tests that approximate a range of highway collision conditions, and the test findings are evaluated according to specified assessment criteria. This empirical approach is relatively expensive (compared to the prescriptive design method), and thus tends to limit the number of bridge rail systems that a user agency would develop.

In practice, the performance standard approach has been endorsed by highway agencies as the recommended or mandated approach for all roadside safety devices except for bridge rails. There is a growing case for extending mandatory performance standards to bridge rails:

- Gross accident statistics indicate that 367 vehicle fatal accidents occur annually as a result of an initial collision with bridge rail (265) and bridge parapet ends (102).[12] Based on length alone, bridges are about six times more hazardous than the average highway section (i.e., 367 fatal accidents on 15,000 miles of bridges in contrast to 14,396 single vehicle fatal accidents on 3.8 million miles of highways). From these data, one could conclude that bridge rails--which have been mostly developed according to prescriptive design procedures--may lack sufficient safety performance capabilities.

- While prescriptive design procedures may be adequate to effect barriers that successfully sustain collision loadings, an experimental approach is deemed necessary to examine the complex dynamic vehicle/barrier interaction, to measure dynamic forces in the barrier and their load distribution to the bridge structure, to reveal vehicle snagging and stability problems, and to document the vehicle trajectory during and after collision. These added capabilities, inherent in the performance standard approach, are necessary to refine safety performance of bridge rails beyond the prescriptive static design procedures.

There are benefits in moving to fewer, more extensively developed bridge rail systems encouraged by performance standards:

- Maintenance of barriers and inventory stocking of replacement parts are simplified.
- Highway agencies will have a stronger position in accident tort liability cases.

For these reasons, it may be timely for FHWA and AASHTO to endorse performance standards as the preferred method for developing new bridge rail systems.

b. Linkage

Ultimately, the safety performance of a bridge rail design is judged by its in-service collision experience and is measured in terms of injury and fatal accidents. Ideally, a candidate barrier system is subjected to a matrix of crash test conditions and the test engineer projects the in-service performance of the barrier system from a limited amount of test results. In some cases, a pass-fail (safe-unsafe) criterion has evolved for certain classes of roadside hardware such as breakaway supports. In reality, there is an element of risk associated with even the best roadside hardware, and the safe-unsafe assessment criterion is a gross simplification and can be misleading. Moreover, there is a tacit assumption that there are known relationships (a) between the vehicle test matrix and the actual collisions that occur in-service and (b) between crash test results and occupant injury levels. With regard to the former, the range of actual collisions varies with site and traffic conditions. As to the latter, only recently have we begun to address the relationship (or linkage) between test results and in-service injury levels through the use of special accident data collection programs.[13] Nevertheless, there is evidence that barrier systems are performing reasonably well overall, as about 80-90 percent of barrier collisions result in drive-aways and go unreported.[14,15] Yet, there is a need to continually refine the performance standards to reflect the changing vehicle designs and our increasing knowledge of the linkage between test results and occupant injuries. This chapter will suggest improved bridge rail performance standards based on recent research.

b. Recent Research Developments

Within the past 20 years, the area of highway safety research has been extremely active. In-depth accident investigations and data analyses have identified highway features that are involved in a large number of injury-producing accidents. Engineering studies of collision dynamics and human tolerance to impact forces have identified limits of vehicle-appurtenance interactions. Improved appurtenance hardware has been developed to perform with an expanded array of vehicle sizes. All of these items have affected performance standards and have prompted upgrading and modification of the standards. Since publication of NCHRP Report 230 in 1981, a number of important research findings have become available, and these findings, discussed in this section, have been incorporated in the proposed bridge rail performance standards.

1. Test Vehicles

Since the mid-1960's, the principal vehicle for the single service level strength test has been a large passenger sedan with curb weight of 4500-lb (2025-kg). Test conditions of 60 mph (96 km/h) and 25-degree approach angle are considered severe in comparison to nearly all passenger car accidents. On the other hand, these severe test conditions are believed by many to be a surrogate collision for larger vehicle accidents. In moving to the multiple service level approach, there was a consensus in the NCHRP Reports 230 and 239 advisory panels to retain the 4500-lb

(2025-kg) vehicle and the impact test conditions as a direct tie between future hardware performance and previous testing programs conducted on many currently operational bridge rails and other appurtenances. Even with the change from a 60 mph (96 km/h) to 55 mph (88 km/h) national speed limit for highways in the mid-1970's, the NCHRP Report 230 advisory panel opted to retain the 60-mph (96-km/h) impact test speed.

With the downsizing of the passenger car fleet brought on by the need for more fuel-efficient cars, the number of passenger cars in the 4500-lb (2025-kg) range has diminished, and this car size will be a rarity in a few years. Hence, the test will be unrepresentative of any highway accident; more importantly, the demise of the 4500-lb (2025-kg) car is becoming a practical issue as candidate test vehicles with model age of six years or less are becoming difficult to procure.

A number of alternative vehicles or replacements for the 4500-lb sedan/60 mph/25-degree angle (2025-kg/96 km/h/25-degree angle) test have been considered[13], among which are the following:

- Ballast a 3200-lb (1440-kg) sedan to 4000 lb (1800 kg) and set impact conditions at 65 mph (104 km/h) and 25 degrees to maintain Service Level 2 (SL2) impact severity. A crash test revealed that the smaller vehicle lacked sufficient structural strength to sustain the change of energy as exhibited by the collapse of the frontal area, which in turn caused the vehicle to snag on an operational barrier system.

- Use a small van and ballast to at least 4500-lb (2025-kg) for the 60-mph (96-km/h) test. Concern for rollover potential for this high center-of-gravity vehicle as well as exposure of the front wheel to submarining under beam and post type barriers ruled out this choice.

- Use a 3/4-ton pickup ballasted to 5400 lb (2430 kg). In recognition of the sensitivity of the 25-degree impact for producing vaulting or submarining of the beam and post barrier systems and the severe amount of damage caused to the vehicle suspension and wheel system, an impact angle of 20-degrees is now considered more appropriate than the 25-degree angle. For a 5400-lb (2430-kg) pickup mass and 20-degree angle, an impact speed of 65 mph (104 km/h) is required to produce the equivalent impact condition. (The importance of impact angle is discussed further in a following section.)

Even though the 5400-lb (2430-kg) pickup is now considered the most promising replacement vehicle, the 4500-lb (2025-kg) sedan was used in this program as the SL2 test vehicle. Rationale for this decision was that sufficient test experience to adequately appraise the alternatives was lacking at the start of the crash test phase and that the future replacement test will probably not deviate significantly from the current SL2 conditions.

During development of NCHRP Report 230, the 1800-lb (810-kg) car was just beginning to appear in significant numbers in the traffic stream. Minimum accident data were available, and, essentially, there was no research or testing experience with this car. There was concern that much of the current operational appurtenance hardware would not function properly with the 1800-lb (810-kg) car. For these reasons, Report 230 recommended the continued use of the 2250-lb (1012-kg) sedan while research experience was being acquired with the 1800-lb (810-kg) car. Since 1981, several research agencies have acquired successful experience with the 1800-lb (810-kg) car on a variety of appurtenance hardware. It is now deemed appropriate to reinforce the requirement for the smaller 1800-lb (810-kg) car, particularly for longitudinal barriers such as bridge rails; at the same time, the need for the "intermediate" 2250-lb (1012-kg) car has diminished. Additionally, there was concern in 1981 that a 15-degree angle was the maximum practical impact condition from the viewpoint of vehicle snagging and excessive occupant risk. However, recent crash test findings[16] indicate that representative barrier systems readily redirect the 1800-lb (810-kg) sedan impacting at 20-degrees and 60 mph (96 km/h) and that severe occupant injury will not generally occur for these conditions.[13] Thus, the 1800-lb (810-kg) sedan impacting at 60 mph (96 km/h) and a 20-degree angle is deemed to be a more discerning evaluation for bridge rail systems. This test was used in the project.

2. Multiple-Service Level Approach (MSLA)[6]

Prior to 1970, typical highway traffic stream was composed predominantly of passenger sedans in a narrow 2500-4500-lb (1125-2025-kg) mass range. And while there were highway segments that carried high traffic volumes and those that carried only a few hundred vehicles per day, the high volume segments were relatively few in number. Only one bridge rail "level of service" was deemed necessary and appropriate for this narrow range of conditions.

Today, the traffic stream is composed of a significant number of cars weighing less than 2500 lb (1125 kg) and vehicles weighing greater than 5000 lb (2250 kg) [including 80,000-lb (36,000-kg) tractor-trailers]. Moreover, the number and mileage of highway segments that carry high-volume traffic (i.e., greater than 50,000 ADT) have increased. The single service level bridge rail may be overly expensive and not cost-effective for the numerous low-volume roads and may not be appropriate for highways with high traffic volume and a high percentage of truck traffic.

The Multiple Service Level Approach to selecting bridge rails (MSLA) is based on the premise that higher service level barriers are more expensive to construct than lower service level systems and that the cost differential is significant. Whereas the MSL model is comprehensive and considers most major factors that affect barrier performance and societal costs and benefits, local site conditions and traffic patterns may differ markedly from the model input data. Users of MSLA are encouraged to examine the model assumptions and exercise engineering judgment when site conditions deviate from the more general cases.

Because of the complexity of the vehicle-barrier redirection and the large number of ill-defined factors that can affect safety performance, it has been necessary to simplify barrier performance requirements to basically vehicle containment (or barrier strength) in the formulation of MSLA. That is, service levels represent a gradation of barrier strengths, each capable of containing a range of vehicle impacts. Other factors such as redirection severity, vehicle stability, or after-impact trajectory are not directly addressed by MSLA but are considered in the test performance evaluation criteria.

Considering only vehicle containment, it is necessary to estimate barrier dynamic loading during a wide range of impact conditions with variable speed, impact angle, vehicle type and size, crush properties, cargo mass and distribution, etc. Several collision models have been examined for utility in estimating barrier dynamic loading and to rank-order the spectrum of impacts for cost-benefit studies; these include:

- Lateral Momentum

  $$I = mv\sin\theta \qquad (1)$$

  where m is vehicle mass and v and θ are impact speed and approach angle, respectively.

- Severity Index[7]

  $$SI = \frac{1}{2}\, m\, (v\sin\theta)^2 \qquad (2)$$

- Average Redirection Force, $\bar{F}$ [17]

  $$\bar{F} = \frac{m\,(v\sin\theta)^2}{2\,[L\sin\theta - B\,(1 - \cos\theta) + D]} \qquad (3)$$

  where L and B are vehicle dimensions and D is barrier deflection.

- Redirection Index[6]

  $$RI = kAB\ (mv\sin\theta) \qquad (4)$$

  where k is a barrier constant, A is a vehicle geometric and mass property constant, and B is an approach angle constant. This was used in the NCHRP Report 239 MSLA.

It is noted that equations 1 and 2 represent point mass models and do not reflect effects of vehicle geometry. Equation 3 is a refinement of equation 2 with vehicle geometry properties L and B included. These three expressions assume that all the vehicle lateral momentum is dissipated in vehicle and barrier crush prior to the vehicle becoming parallel to the barrier. This is appropriate for relatively short vehicles such as passenger sedans impacting flexible barriers; however, for longer vehicles such as buses and trucks, an important part of the lateral momentum is converted to rotational momentum. Equation 4 considers the impulse delivered to the barrier as determined by BARRIER VII simulations and thus accounts for the rotational momentum. None of the expressions are applicable to barrier loading due to articulated vehicles such as tractor-trailer rigs. However, the 40,000-lb (18,000-kg) intercity bus was determined to subject a barrier to a more critical loading than a heavily loaded tractor-trailer.[6] Experimental data of tractor-trailers impacting bridge rails (Hirsch[16]) indicate that the redirection force can be approximated by multiplying the center axle load by a 6-g factor.

Comparisons of vehicle impact conditions and collision indexes are presented in table 2. Also indicated are those test conditions identified with service or performance levels as described in NCHRP Report 230 and Report 239. Also presented are recommended test conditions for a revised matrix of performance levels with vehicles that are more representative of current and projected highway traffic. Specific changes include:

- A new low performance level, designated Performance Level I or PLI, which specifies the 1800-lb (810-kg) sedan impacting at 60 mph (96 km/h) and 20 degrees.

- A modified Service Level 1 uses the 3400-lb (1530-kg) passenger sedan impacting the longitudinal barrier at 60 mph (96 km/h) and 20 degrees with a new identification of PLII; the severity of PLII impact condition slightly exceeds that of SL1.

- Performance Level III is roughly equivalent to the Reports 230 and 239 SL2; however, a 5400-lb (2430-kg) pickup replaces the 4500-lb (2025-kg) sedan and the impact angle is 20 degrees instead of 25 degrees. PLIII is conducted at 65 mph (104 km/h).

- Performance Level IV utilized a 15,000-lb (7,000-kg) 2 1/2-ton truck impacting the barrier at 60 mph (96 km/h) and 15 degrees. Although this test is akin to the school bus experiment, vehicle geometry and load distribution produce different barrier loadings.

- Performance Level V using the 40,000-lb (18,000-kg) intercity bus at 60 mph (96 km/h) and 15 degrees is unchanged from SL4 or SL3 as presented in Report 239 and Report 230, respectively.

Consideration was given to include one or more articulated tractor-trailers in the recommended test matrix; however this option was eliminated due to the following factors:

- Tractor-trailers are difficult to handle during testing due to their propensity to jackknife.

- Vehicle/barrier loading is more complex than for a non-articulated vehicle resulting in uncertainty with regard to severity of test.

- Vehicle stability after an impact is always questionable.

For these reasons, non-articulated vehicles are considered more reliable with respect to introducing a specific impact loading to the barrier and remaining stable during a redirection trajectory.

Apart from MSLA, there are unique bridge sites that warrant special bridge rail systems that can readily contain articulated vehicles and their cargo, and, hence, appropriate tests are needed for these systems. Accordingly, several tractor-trailer tests are shown in table 2.

3. Redirection Severity

Since the 1960's, the development of longitudinal barriers such as guardrails and bridge rails has been greatly influenced by two basic assumptions about the causes of occupant injuries when such devices are impacted. First, it has been assumed that occupants are subjected to the highest risk during the vehicle's initial collision with a barrier; a possible subsequent collision with other roadside features was presumed to be less hazardous because of lower vehicle speeds. Hence, subsequent impacts were generally ignored. Secondly, the probability of severe occupant injuries were presumed to be directly related to the intensity of vehicle collision accelerations; thus it was thought that by lessening the intensity of these accelerations through design of the roadside hardware, the frequency and severity of occupant injuries would be diminished.

In an effort by Michie[13] to establish a relationship between redirection severity as defined by vehicle accelerations, occupant risk values, etc., with occupant injuries, a number of redirectional accidents involving longitudinal barriers were reconstructed to define impact conditions. Only cases in which injuries could be definitely assigned to the redirection event were selected; cases with penetrations, rollovers, and most secondary impacts were eliminated.

The unexpected finding was that when the vehicle was smoothly redirected, remained upright and did not subsequently impact another feature, occupants suffered only minor injuries if at all. This finding was further supported by results of laboratory sled tests in which a 50th percentile male side impact anthropometric dummy (SID) positioned in a Honda Civic passenger compartment was subjected to sled lateral accelera-

Table 2. Comparison of impact conditions for multiple service level approach.

	Vehicle Mass (lb)				Collision Indices				Performance/Service Level		
Vehicle Type	Gross	Inertial	Speed (mph)	Angle (deg)	I[a]	SI[b]	$\overline{F}$[c]	RI[d]	Report 239	Report 230	Recommended
Sedan	1800	1800	45	20	1.26	14.2	8.96	1.71			
			55	20	1.54	21.3	13.4	2.09			
			60	15	1.27	14.5	11.8	1.55			
			60	20	1.68	25.3	15.9	2.28			I
Sedan	2250	2250	60	15	1.59	18.1	11.8	1.77			
Sedan	3400	3400	45	20	2.38	26.9	12.2	2.67			
			55	20	2.91	40.2	18.3	3.26			
			60	20	3.18	47.8	21.8	3.56			II
Sedan	4500	4500	60	15	3.18	36.2	19.9	3.08	1	1	
			60	25	5.20	96.6	33.8	6.44	2	2	
Pickup	5400	5400	40	20	3.36	33.8	13.1	3.20			
			55	20	4.63	63.8	24.8	4.40			
			60	20	5.05	76.0	29.5	4.80			
			65	20	5.47	89.1	34.6	5.20			III
Truck (Single Unit)	15,000	15,000	50	15	8.8	83.9	27.6	5.00			
			50	20	11.7	146.5	37.0	7.37			
			60	15	10.6	120.8	39.8	6.01			IV
			60	20	14.0	211.0	53.3	8.84			
Bus (School)	20,000	13,800	45	7	3.45	13.9	7.6	2.63			
			50	15	8.13	77.2	20.2	6.89			
			60	15	9.76	111.2	29.0	8.27	3		
			60	20	14.0	211.0	53.2				
Bus (Intra City)	32,000	20,000	60	15	14.15	161.1	32.1	6.55			
Bus (Inter City)	40,000	28,200	60	15	19.95	227.1	37.7	11.18	4	3	V
Tractor-T (Van)	50,000		49	20							
	72,000		48	20							
			56	20							
Tractor (Tanker)	80,000		50	15							
			60	20							

(a) $I = mv\sin\theta/(1000)$

(b) $SI = \frac{1}{2} m (v\sin\theta)^2/(1000)$

(c) $\overline{F} = \frac{1}{2} m (v\sin\theta)^2/[1000(L\sin\theta - B(1 - \cos\theta) + D]$

(d) $SI = kAB(mv\sin\theta)/(1000)$; $k = 0.891$ for rigid barriers,

$A = [(I_{ZZ}/12)/(ML^2)]^{0.6424} [100{,}000/W]^{0.090}$

$B = [1/\cos\theta]^{3.897}$

tions of over 18 g's, well in excess of values generally recorded during vehicle crash tests. Dummy responses were subcritical by NHTSA recommended criteria. Accordingly, the NCHRP Report 230 occupant lateral risk design value of 20 fps (6.1 m/s) is deemed unnecessarily conservative and should be increased to 25 fps (7.6 m/s). Moreover, the maximum lateral 50 ms average vehicle acceleration may be increased from the TRC 191 recommended value of 5 g's to 15 g's without adversely affecting redirectional accident injury patterns. It has been observed that in crash tests in which the vehicle is smoothly redirected, the occupant risk values as well as vehicle accelerations will generally not be discerning factors.

4. Smooth Redirection

The importance of smoothness of redirection was recognized in NCHRP Report 230 (p. 13, Evaluation Criterion A), but no objective methods were presented to define smooth. Buth(8) recommended the use of limits on vehicle longitudinal accelerations as a means of separating impacts into smooth-not smooth impacts with values of 5, 8, and 11 g's for 15, 20, and 25-degree impacts, respectively, all at 60 mph (96 km/h). These values were established as 125 percent of those measured during vehicle impacts with an instrumented vertical face rigid wall.

In examining the data base of reconstructed longitudinal barrier collisions, Michie(13) defined non-smooth when (1) the vehicle was abruptly stopped and/or (2) the rear of the vehicle rotated away from the barrier with these events occurring during the initial phase of the collision. Thus, smooth redirection was determined when the vehicle departed the barrier with some longitudinal speed and the rear of the vehicle did not rotate away from the barrier during the redirection; for practical limits, up to an arbitrary 5-degree yaw was deemed acceptable in these reconstructed accidents. As previously discussed, when these conditions were met, the vehicle remained upright and did not experience a subsequent impact, then occupants were not seriously injured regardless of the impact conditions.

It is recommended that the term <u>smooth</u> be defined in terms of the aft end of the vehicle not rotating more than 5 degrees away from the barrier during the initial collision. With regard to limits on vehicle speed change, the occupant longitudinal risk factor sets an appropriate limit of 30 fps (9.1 m/s).

As a further evaluation of smooth redirection, an effective coefficient of friction μ as calculated by Olson formula[17] is recommended:

$$\mu = \left[\frac{\cos\theta - V_P/V_I}{\sin\theta} \right] \quad (5)$$

where θ is the approach angle, V_I is impact speed and V_P is vehicle speed when the vehicle first becomes parallel to the barrier. A recommended assessment range is as follows:

μ	Assessment
0-0.25	Good
0.26-0.35	Fair
> 0.35	Marginal

5. After Impact Trajectory

As shown in table 3, less than 30 percent of bridge site accidents involve no secondary event after a redirection impact as compared to about 74 percent for guardrails and median barrier accidents. Possible explanations for this difference include:

- Bridge rails are generally more rigid than barriers in general, absorbing less of the vehicle kinetic energy.

- Bridge rails are located near the traveled way; any rebound will propel the vehicle across the road and into another bridge rail or fixed object.

Table 3. Comparison of bridge site and guiderail/median barrier secondary events.

Secondary Event	SwRI Bridge Site Accident Study (12)		New York Guiderail/ Median Barrier Study (15)	
	No	Percent	No	Percent
None	35	28.2	2431	73.6
Another Vehicle	5	4.0	6	0.2
Another Roadside Object	41	33.1	461	14.0
Same or Another Barrier	34	27.4	122	3.7
Rollover	6	4.8	258	7.8
Other	3	2.4	24	0.7
TOTAL	124	100.0	3302	100.0

- Many approach guardrails at bridge sites are flared; impacting vehicles are essentially directed across the traveled way and into the off-side bridge rail.

An interesting finding from these studies is that another vehicle is seldom involved, with the percentage ranging from 0.2 to 4.0.

When a secondary event occurs after a longitudinal barrier impact, the severe injury frequency increases markedly. As shown in table 4, severity of secondary events is indicated by percentage that result in a A + K injury.[15] Overturns and fixed-object impacts are particularly hazardous, ranging from 3 to 4 times more likely to produce severe injury than when the vehicle experiences no secondary event. To be noted is that the injury scale includes results of secondary impacts after both redirected and nonredirected vehicles.

From these findings, it is apparent that the occupants are at less risk when the redirected vehicle remains upright and does not collide with a fixed object. Ideally, the vehicle should exit the bridge rail at a small angle and proceed parallel to the barrier until the driver can regain control of the vehicle. In contrast, vehicles that exit at a large angle are more likely to traverse the traveled way and strike the off-side barrier before the driver can regain control.

Vehicle damage, including tire blow-outs, may determine the vehicle trajectory and stability. Hence, there is a need to effect barriers that redirect vehicles without major damage to the vehicle suspension system. Testing at larger angles (e.g., 25 degrees) into rigid barriers generally produces major damage to the vehicle suspension system. The damage-controlled trajectory is not indicative of trajectories that occur after less severe and more typical accident impact conditions. Accordingly, approach angles for crash tests should be less than 25 degrees if post-impact trajectory performance of the barrier is to be evaluated.

Table 4. Second event after redirection (15).

Second Event	Number	(%)	Fatal Plus A Injury Frequency (%)*
Overturn	125	5.6	27.1
Fixed Object	328	14.6	21.8
Other	15	0.7	--
None	1775	79.1	6.8
TOTAL	2243	100.0	

* Severity of second event for redirected and non-directed impacts.

(As previously noted, crash testing in this program utilized the historical 4500-lb (2025-kg) car and 25-degree impact angle.

To date, little effort has been directed to the evaluation of the after-collision trajectory of the vehicle in barrier crash tests. This lack of emphasis on the post-impact trajectory can be attributed to both the unrecognized importance of this phase of the test by the technical community and to the unpredictability and frequently erratic behavior of the vehicle caused by wheel and frame damage and imprecise braking controls. Even with improved braking controls, the authors are not confident that the after-collision vehicle trajectory will be a reliable crash test assessment criterion. On the other hand, by changing the emphasis of barrier design from reducing vehicle accelerations during a collision to effecting more predictable vehicle trajectories, longitudinal barrier developers may be able to improve the vehicle's post-impact trajectory.

6. Summary of Changes

A number of changes and development of new findings have occurred in roadside safety technology since NCHRP Report 230 was published in 1981. Those items that affect bridge rail performance have been presented in this chapter and are briefly summarized as follows:

- Test vehicles. The 1800-lb (810-kg) sedan has replaced the 2250-lb (1012-kg) car for evaluating the low end of the collision spectrum. Moreover, a 20-degree rather than a 15-degree impact angle for the 60-mph (96-km/h) redirectional occupant severity test is deemed more appropriate for evaluating both barrier snagging potential and occupant risk.

  A 3400-lb (1530-kg) passenger sedan, representative of the downsized 4500-lb (2025-kg) large sedan, is added to the test matrix. Together with the 1800-lb (810-kg) sedan, barrier performance for a major part of passenger sedan fleet is evaluated.

A 3/4-ton pickup rigidly ballasted to 5400 lb (2430 kg) has replaced the historical 4500-lb (2025-kg) passenger sedan. To maintain equivalency in the impact conditions and to reflect the need to examine post-impact trajectory, the impact conditions are established at 20 degrees and 65 mph (104 km/h).

A 2 1/2-ton truck rigidly ballasted to 15,000 lb (7,000 kg) replaces the previously specified 72-passenger school bus for the NCHRP Report 239 SL3 test.

- Multiple Service Level. A new low service level has been added to the Report 239 test matrix:

NCHRP Report 239		Recommended	
(NONE)		PLI	1800-lb sedan/ 60 mph/20 deg
SL1	4500-lb sedan/ 60 mph/15 deg	PLII	3400-lb sedan/ 60 mph/20 deg
SL2	4500-lb sedan/ 60 mph/25 deg	PLIII	5400-lb pickup/ 65 mph/20 deg
SL3	20,000-lb bus/ 60 mph/15 deg	PLIV	15,000-lb truck/ 60 mph/15 deg
SL4	40,000-lb bus/ 60 mph/15 deg	PLV	40,000-lb bus/ 60 mph/15 deg

- Redirection severity. Whereas occupant risk measurements are maintained, new emphasis is placed on the definition and assessment of smoothness of redirection. A redirection is deemed smooth if the rear of the vehicle does not rotate or yaw away from the barrier while the vehicle is in contact with the barrier. A smooth redirection is further assessed according to the effective friction developed between vehicle and barrier during the initial stage of the redirection sequence.

- After-impact trajectory. The importance of vehicle behavior after it departs from the bridge rail is recognized and an intuitive assessment criterion for evaluating a performance test is recommended.

These changes have been incorporated in the proposed bridge rail performance standards presented in the following section. The changes are driven primarily by a rapid evolution in the traffic composition and by detailed findings for accident studies and laboratory tests.

c. Proposed Performance Standards

1. Scope

The proposed performance standards presented in this section evaluate the potential safety performance of bridge rails using full-scale tests with controlled vehicles. Safety performance of candidate bridge rails is evaluated primarily according to measures of degree of risk to which occupants of impacting vehicles would be subjected.

Other service requirements of bridge rails, such as environmental and operational requirements and aesthetics are not addressed by these standards, but certainly must be considered when system designs are assessed.

2. Test Matrix

The bridge rail test matrix is shown in table 5 for the five performance levels. Impact conditions for the seven unique tests are described in table 6 along with evaluation criteria to be used in assessing

Table 5. Test matrix for bridge rail performance levels.

Performance Level No.	Containment		Redirection Severity	
	Required	Supplementary	Required	Supplementary
0	None	None	None	None
I	Test 101 (1800/60/20)	--	Test 101 (1800/60/20)	--
II	Test 201 (3400/60/20)	--	Test 101 (1800/60/20)	--
III	Test 301 (5400/65/20)	--	Test 101 (1800/60/20)	Test 201 (3400/60/20)
IV	Test 401 (15,000/60/15)	Test 301 (5400/65/20)	Test 101 (1800/60/20)	Test 201 (3400/60/20)
V	Test 501 (40,000/60/15)	Test 301 (5400/65/20)	Test 101 (180/60/20)	Test 201 (3400/60/20)
V-B	Test 601 (72,000/50/15)	Test 301 (5400/65/20)	Test 101 (1800/60/20)	Test 201 (3400/60/20)
V-C	Test 602 (72,000/50/15)	Test 301 (5400/65/20)	Test 101 (1800/60/20)	Test 201 (3400/60/20)

Table 6. Bridge rail test conditions and applicable evaluation criteria.

Test No.	Vehicle		Impact Conditions		Applicable Evaluation Criteria*					
	Type	Mass (lb)	Speed (mph)	Angle (deg)	A	B	C	D	E	F
101	Sedan	1800	60	20	■	■	■	■	■	■
201	Sedan	3400	60	20	■	■	■	■	■	■
301	Pickup	5400	65	20	■	■	■	■	■	■
401	Truck	15,000	60	15	■	■	■			
501	Bus	40,000	60	15	■	■	■			
601	Tractor-trailer	72,000	50	15	■	■	□			
602	Tractor-tanker	72,000	50	15	■	■	□			

_ - Required

_ - Preferred

* See table 7 for evaluation criteria description.

test results. For a particular performance level, a series of two to four tests is proposed:

- Containment - This is principally a strength test to ensure that the barrier structure is sufficient to contain the vehicle and its cargo on the traffic side of the bridge rail.

- Redirection Severity - This test examines the degree of occupant risk during the barrier collision and subsequent vehicle trajectory.

These are considered the minimum matrices for the five service levels. The user agency is encouraged to look at additional impact conditions and vehicle types that may be pertinent to special applications or sites.

3. Assessment Criteria

Assessment criteria for judging results from vehicle crash tests are listed in table 7. These criteria are formulated specifically for bridge rails, which are typically more rigid and located closer to the traveled way than longitudinal barriers in general, and therefore may not necessarily be applicable to all longitudinal barriers. It is noted that the six evaluation factors are each applicable to one or more crash tests. Further, all evaluation factors specified for a given test must be met before the test results are deemed successful. Purposes of the six evaluation factors are as follows:

Factor A - This is principally a dynamic strength test and is judged on vehicle containment. A barrier designated for a specific performance level shall contain the appropriate test vehicle and its cargo on the traffic side of the barrier (i.e., no penetration, vaulting or submarining under the barrier). Controlled lateral deflection of a bridge rail is acceptable but should be limited to less than 1/2 the vehicle's width.

Table 7. Safety evaluation guidelines for bridge rails.

Evaluation Criteria	Applicable to Bridge Rail Test Number (see Table 2)
A. Test article shall contain vehicle; neither the vehicle nor its cargo shall penetrate or go over. the installation. Controlled lateral deflection of the test article is acceptable.	ALL
B. Detached elements, fragments, or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	ALL
C. The vehicle shall remain upright during and after collision. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.	Tests 101, 201, 301, 401, and 501
D. Test article shall smoothly redirect the vehicle. A redirection is deemed smooth if the rear of the vehicle does not yaw more than 5 deg away from the barrier from time of impact until the vehicle separates from the barrier. The smoothness of the vehicle-barrier interaction is further assessed by the effective coefficient of friction μ: μ — Assessment 0 - 0.25 — Good 0.26 - 0.35 — Fair > 0.35 — Marginal where $\mu = (\cos\theta - V_P/V_I)(1/\sin\theta)$, θ is the impact angle, V_I is impact speed, and V_P is speed when vehicle is parallel to barrier.	Tests 101, 201, and 301
E. Impact velocity of hypothetical front seat passenger against vehicle interior, calculated from vehicle accelerations and 2.0 ft (0.61 m) forward and 1.0 ft (0.30 m) lateral displacements, shall be less than: Occupant Impact Velocity - fps Longitudinal: 30 — Lateral: 25 and vehicle highest 10 ms average accelerations subsequent to instant of hypothetical passenger impacts should be less than: Occupant Ridedown Accelerations - g's Longitudinal: 15 — Lateral: 15	Tests 101, 201 and 301
F. Vehicle exit angle from the barrier shall not be more than 10 deg; and within 100 ft after losing contact with the barrier, the vehicle shall move no more than 20 ft from the barrier line on the traffic side. A subsequent impact of the test barrier by the vehicle is deemed acceptable if all six evaluation factors are met; lateral flail distance for subsequent impacts is increased from 1.0 to 2.0 ft for item E.	Tests 101, 201, and 301

Factor B prohibits barrier systems that break up during a collision into fragments or elements that could penetrate the passenger compartment or present undue hazard to other traffic.

Factor C - This pertains to occupant risk which is assessed according to the vehicle remaining upright and the passenger compartment remaining intact. Although some rollovers may be survivable, current interpretation of accident statistics indicates that the probability of occurrence and the severity of occupant injury are great for the rollover event mode. And if the passenger compartment is crushed or is penetrated by a barrier element, occupant risk is greatly increased.

Factor D - For tests with passenger sedans and pickups, the vehicle should be smoothly redirected without exhibiting any sign of vehicle snagging. A definition of "smooth" is that the vehicle redirection is completed without the rear of the vehicle yawing momentarily away from the barrier more than 5 degrees. Such a yawing motion would in most cases be caused by a large and abrupt vehicle longitudinal force introduced by the barrier. Findings from reconstructed bridge rail accidents suggest that when this yawing test of "smooth redirection" is met, occupant injuries are minimal as a result of the collision event.

A further evaluation of smoothness of redirection is based on the effective coefficient of friction between the vehicle and barrier averaged from impact until the vehicle is parallel to the barrier. Preferably, the friction factor should be less than 0.25. For values exceeding 0.25, the vehicle will generally interact with the posts.

Factor E - The impact velocity of a hypothetical unrestrained front seat passenger against the vehicle interior is another control on impact severity. This velocity or velocities are calculated using the vehicle collision accelerations and the assumption that the occupant continues to travel at the pre-barrier impact speed until it displaces across the compartment and strikes the dash or side window. It is noted that such factors as the occupant seating position with respect to the vehicle center of gravity, yaw motion of the vehicle, and lateral and longitudinal accelerations are needed in the impact velocity determination. For crash tests involving left side vehicle impacts, the driver becomes the hypothetical occupant and the steering wheel is assumed removed when calculating impact velocity. (The steering wheel would reduce the flail space distance and make the determination less critical.) Recent findings indicate that the occupant risk factors are seldom exceeded as long as the vehicle is smoothly redirected (i.e., see Factor D).

Factor F - This assessment standard is specifically designed for bridge rails or for longitudinal barriers that may be located within 10 feet (3.0 m) of the traveled way. Its purpose is to screen out those barrier systems that propel or damage the car to the extent that it is redirected back into and across the traveled way. This requirement is based on accident data (see section b above) that show (1) a large proportion of bridge rail redirected vehicles are involved in one or more subsequent impacts with other roadside features and (2) the probability of occupant injury increases with the number of impacts. It is recognized that Factor F may be the controlling evaluation criterion and may dictate the barrier design performance mechanism. Because vehicle braking in a test can influence the vehicle trajectory, it is necessary to permit the vehicle to travel at least 100 feet (30.5 m) after losing contact with the barrier before vehicle brakes are applied (usually remotely by test engineer).

4. Other Requirements

Crash test procedures described in NCHRP Report 230 except as modified herein are applicable to the proposed bridge rail performance standards. In particular, installation details, data acquisition systems, and report format are not affected and should continue to be used.

d. Evaluation of Bridge Rail Performance Tests

1. Modified Evaluation Criteria

Eighteen vehicle crash tests were conducted to evaluate dynamic performance of nine bridge rail systems. As a second program effort, crash test performance and assessment procedures for bridge rails were critically examined in reference to recent research findings and a proposed modified performance standard was developed; this performance standard was presented in section c. For contract scheduling, it was necessary to initiate vehicle crash testing before the performance standard review was completed and the modified performance standard was developed. Test conditions as presented in NCHRP Report 230 were used in the 18 crash tests and these differ in some respects from the proposed test conditions. Since the proposed assessment criteria (table 7) is directly tied to the test conditions, a valid appraisal of the assessment criteria by the 18-test program could not be accomplished. However, considerable technical insight into the feasibility of the proposed standards was gained in the application of the assessment criteria to the 18 tests.

Each barrier system was subjected to the structural adequacy experiment, Test 10 [4500-lb (2025-kg) sedan, 60 mph (96 km/h), 25 degrees)] and to an occupant severity experiment, Test S13 [1800-lb (810-kg) sedan, 60 mph (96 km/h), 20 degrees]. It is noted that Test S13 is more severe than Test 11 due to a 20 rather than a 15-degree impact angle. Successful performance of a bridge rail for both tests is a requirement for a Service Level 2 system.

The most significant change for Service Level 2 matrix (which is the newly proposed Performance Level III) is the replacement of the 4500-lb (2025-kg) sedan with a 5400-lb (2430-kg) pickup and impact conditions of 65 mph (104 km/h) and 20 degrees in contrast to 60 mph (96 km/h) and 25 degrees for the old Test 10 conditions. With regard to impact severity as determined by the collision indexes (see table 2), both tests are approximately the same. However, it is believed that the 20-degree impact angle will result in less damage to the vehicle chassis and front structure and provide an after-impact trajectory that is more dependent on barrier behavior.

A second change in test performance is the control of vehicle braking after the vehicle departs the bridge rail. In Report 230, it was recommended that brake application should be delayed as long as safely feasible to establish the unbraked runout trajectory; as a minimum, brakes should not be applied until the vehicle has moved at least two vehicle lengths from the point of last contact with the barrier. In view of the increasing awareness of the number of injury-producing events that occur during the after-impact trajectory, both test controls and assessment have been modified to reflect this new awareness. As previously discussed, impact angles in excess of 20 degrees generally produce significant vehicle damage that can affect the after-impact trajectory and this damage tends to obscure performance capability of the longitudinal barrier. Since after-impact trajectory assessment criteria presented in table 7 is based on a 20-degree vehicle impact, appraisal of the 25-degree impact tests of bridge rail systems conducted in the program may not be an appropriate evaluation. Moreover, in the proposed assessment criteria, the vehicle trajectory is evaluated for a distance of 100 ft (30.5 m) after loss of contact and before brakes are applied. In several of the 18 tests, brakes were applied according to Report 230 and before the 100-ft (30.5-m) runout; and in several cases, the full trajectory was not documented. Nevertheless, it is deemed instructive to evaluate the after-impact trajectory of the 25-degree tests recognizing that the evaluation may be overly severe.

A third change in the performance criteria is the objective assessment of smoothness of a redirection. As described in item D of table 7, a redirection is deemed smooth if the rear of the vehicle does not yaw significantly away from the barrier during the initial contact phase. Further, an effective friction coefficient μ between vehicle and barrier is assessed according to recommended guideline values.

A final change in the relaxation of the lateral occupant risk value from 20 (6.1 m/s) to 25 fps (7.6 m/s) as shown in item E of table 7, reflects findings from laboratory sled tests with anthropometric dummies and analyses of longitudinal barrier accidents.

2. Test Appraisal

A summary of test results from eighteen tests and evaluations are contained in table 8. A nineteenth test involving a 40,000-lb (18,000-kg) intercity bus impact of the NBR system was conducted, but is not included in this evaluation.

All barriers except for the KBR system successfully passed the containment, structural integrity, and vehicle stability provisions of the evaluation guidelines: items A, B, and C, respectively.

With respect to item D, smooth redirection, all vehicles except KBR-2 were redirected without exhibiting the reverse yaw characteristic of snagging or pocketing. This determination was made reviewing overhead cine and from heading angle data contained in the test reports. As a further evaluation of smoothness, the vehicle/barrier friction for the 16 tests, KBR-2 not included, are contained in table 9 and the values are plotted as a function of impact angle in figure 1. Three barrier systems are judged to be marginal as shown by Tests KBR-1, NBBR-2, MKS-1, and MKS-2. Two tests, NBBR-1 and OBR-2, are deemed to exhibit a fair coefficient of friction and the remainder fall in the range designated as good. Lack of data prevented evaluation of NCBR-2.

Table 8. Assessment.

SwRI Test No.	Bridge Rail System	Impact Conditions: Vehicle Mass (lb)	Speed (mph)	Angle (deg)	Occupant Risk (fps): Long.	Lat.	Veh. 50 ms Accel.: Long.	Lat.	Evaluation Guideline A: Vehicle Containment	B: Structural Integrity	C: Vehicle Stability	D: Redirection Smoothness	E: Occupant Risk	F: After Impact Trajectory
NBR-1	NV Safety Shape	1746	60.7	19.3	7.2	21.8	5.8	12.6	Pass	Pass	Pass	Pass/Good	Pass	Pass
NBR-2	NV Safety Shape	4320	61.4	24.9	3.0	21.6	6.3	8.4	Pass	Pass	Pass	Pass/Good	Pass	Pass
NBBR-1	NE Tubular Thrie	1805	61.4	20.0	1.3	11.4	4.9	13.5	Pass	Pass	Pass	Pass/Fair	Pass	Pass
NBBR-2	NE Tubular Thrie	4370	58.4	24.3	3.8	20.0	5.9	8.2	Pass	Pass	Pass	Pass/Marginal	Pass	Pass
OHBR-1	OH Reinforced W	1815	60.6	19.6	7.3	20.6	5.6	11.4	Pass	Pass	Pass	Pass/Good	Pass	Pass?
OHBR-2	OH Reinforced W	4460	60.0	25.0	7.0	25.1	6.1	12.1	Pass	Pass	Pass	Pass/Good	Pass*	Pass
NCBR-1	NC Beam/Par.	1825	59.7	18.8	4.8	22.7	8.1	12.9	Pass	Pass	Pass	Pass/Good	Pass	
NCBR-2	NC Beam/Par.	4330	60.0	25.0	NO DATA									
OBR-1	OR Three Beam	1829	58.6	18.8	0.8	19.9	3.3	10.2	Pass	Pass	Pass	Pass/Good	Pass	Pass?
OBR-2	OR Three Beam	4430	60.8	24.3	1.3	21.2	5.1	7.9	Pass	Fail	Fail	Pass/Fair	Pass	Pass
OBR-3	OR Two Beam	4640	60.0	25.0	0.9	28.2	5.2	15.9	Pass	Pass	Pass	Pass	Fail	Pass
KBR-1	KS Conc. Beam	1806	61.9	20.3	11.5	20.4	7.5	11.2	Pass	Pass	Pass	Pass/Marginal	Pass	Pass
KBR-2	KS Conc. Beam	4330	60.5	24.0	30.0	23.3	8.3	13.4	Pass	Fail	Fail	Fail	Fail	Fail
MKS-1	Mod. KS	1685	59.0	18.9	14.0	18.2	9.5	10.6	Pass	Pass	Pass	Pass/Marginal	Pass	Pass
MKS-2	Mod. KS	4360	59.2	24.9	13.9	24.9	9.4	12.6	Pass	Pass	Pass	Pass/Marginal	Pass	Pass
OKBR-1	OK Conc. Beam	1815	58.7	18.9	24.6	19.9	8.7	11.5	Pass	Pass	Pass	Pass/Good	Pass	Pass
OKBR-2	OK Conc. Beam	4330	59.1	25.4	26.4				Pass	Pass	Pass	Pass/Good	Pass	Pass
LABR-1	LA Tube Thrie	1735	60.4	18.8	0.9	23.6	4.4	12.8	Pass	Pass	Pass	Pass/Good	Pass	Pass
LABR-2	LA Tube Thrie	4305	59.7	19.1	6.6	20.2	5.3	10.8	Pass	Pass	Pass	Pass/Good	Pass	Pass

Table 9. Vehicle/barrier coefficient of friction.

Test No.	Ref	Impact Angle (deg)	Vehicle Speed (fps) Impact	Vehicle Speed (fps) Parallel	μ(1)	Rating(2)
LABR-1	1	18.8	88.6	77.0	0.24	G
LABR-2	1	19.1	87.6	77.7	0.18	G
NBBR-1	1	20.0	90.1	76.1	0.28	F
NBBR-2	1	24.2	85.7	65.4	0.36	M
NCBR-1	1	18.0	87.6	78.2	0.19	G
KBR-1	1	20.3	90.9	70.5	0.47	M
NBR-1	1	19.3	89.0	77.0	0.24	G
NBR-2	1	24.9	90.0	74.0	0.20	G
OHBR-1	1	19.6	88.9	79.0	0.16	G
OHBR-2	1	25.0	88.0	73.2	0.18	G
OBR-1	1	18.8	86.0	79.9	0.05	G
OBR-2	1	24.3	89.2	68.8	0.34	F
OKBR-1	1	18.9	85.7	75.2	0.21	G
OKBR-2	1	25.4	85.7	71.0	0.17	G
MKS-1	1	18.9	86.5	65.3	0.59	M
MKS-2	1	24.9	86.9	64.1	0.40	M

(1) $\mu = \left[\frac{(\cos\theta - V_P/V_I)}{\sin\theta} \right]$

(2) G - good, F - fair, M - marginal

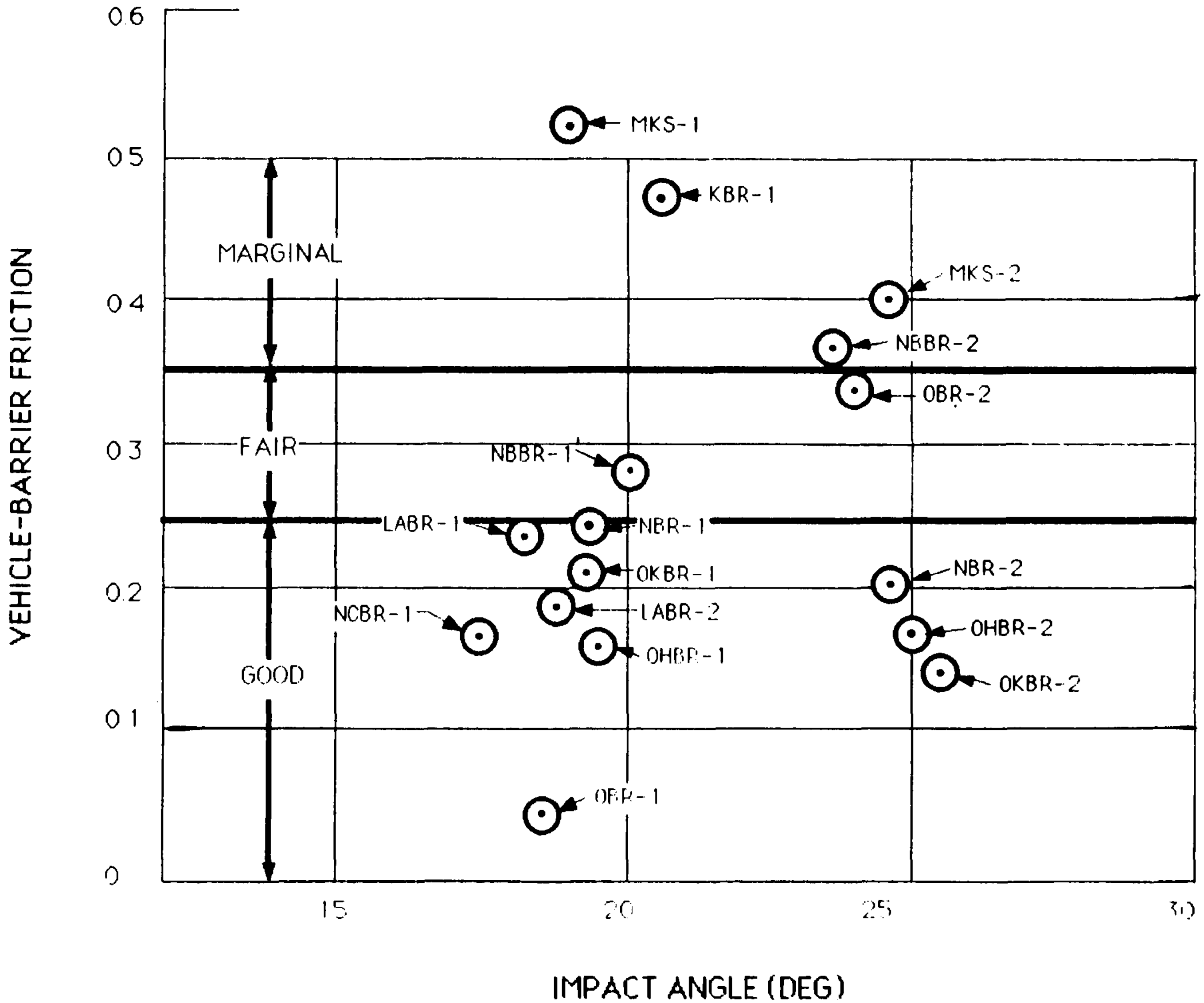


Figure 1. Vehicle-barrier friction.

In the occupant risk evaluation, some tests exhibited questionable findings. In Test KBR-2, the longitudinal value is 30 fps (9.1 m/s) (see table 8) and reflects the fair value of coefficient of friction; severe snagging of the vehicle occurred. In Test OHBR-2, the lateral risk value is 25.1 fps (7.7 m/s) which exceeds the recommended value of 25 fps (7.6 m/s); the authors opine that in view of data acquisition and processing techniques, the findings should be considered acceptable. In Test OBR-2, hood snagging caused passenger compartment intrusion. The use of the ΔV analysis for 25-degree angle impacts is new and the 20-degree test now recommended for Service Level III should result in lower values.

For after-impact trajectory, all tests were evaluated with the new criteria (item F) as data permitted. In several cases, the trajectory out to 100 ft (30.5 m) from the last barrier contact was not documented and the authors had to make a projection.

3. Discussion

As previously noted, the appraisal of the proposed bridge rail performance standards is not valid. However, the nine bridge rail systems in general exhibited good dynamic and safety-related performance.

The major deficiency observed in several of the bridge rail systems would be the snagging tendency as evidenced by vehicle damage and relatively high vehicle/barrier friction. This deficiency is not unexpected as most of the barrier design effort has been directed to vehicle containment and less has been applied to the interface.

As the importance of the redirection smoothness is recognized by bridge rail designers, it is projected that most designs will exhibit a friction factor of 0.25 or less.

e. Summary

Proposed performance standards for bridge rail systems are presented to evaluate the dynamic and safety-related behavior of candidate barrier designs during a matrix of full-scale crash tests. The performance standard method of developing new or modifying existing bridge rails is considered preferable to prescriptive/static design procedures. The performance standards are essentially based on NCHRP Report 230 with the following modifications to reflect recent research:

- The use of the multiple service level approach (MSLA) in selecting bridge rails to match specific site conditions is encouraged.

- The 2250-lb (1012-kg) car test has been eliminated and the 1800-lb (810-kg) car test at 60 mph (96 km/h) and 20-degree angle has been delineated as the redirection test.

- A new 3400-lb car/60 mph/20-degree angle (1530-kg/96 km/h/ 20-degree angle) test has been added to replace the old SL1 test [i.e., 4500-lb sedan/60 mph/15 degrees (2025-kg/ 96 km/h/15 degrees)]

- The term "smooth" when used in the redirection assessment criterion has been objectively defined in terms of vehicle yawing and effective coefficient of friction.

- Acceptable vehicle redirection trajectory has been redefined in terms of exit angle and rebound distance during the initial 100 feet (30.5 m) of vehicle travel after leaving the barrier.

3. Selection of Bridge Rail Designs

a. Introduction

At the start of this study, FHWA provided State Standard Plans for the various bridge railing designs in current use. The objective of task B was to review these plans, rate the bridge rail designs, and select a minimum of ten candidate systems to be tested and evaluated by full-scale tests in task C.

This chapter discusses the rating process that was developed and the final configurations selected for further evaluation. The procedure used to check the final systems for conformance with AASHTO specifications is presented in appendix C. Finally, results of the screening for the 161 included bridge rail types is included in appendix D.

b. Bridge Rail Rating Criteria

AASHTO bridge specifications state that structural continuity in the rail members, including anchorage of ends, is essential. Thus, continuity was the first criterion, and systems were rated as pass or fail, as shown in table 10.

The geometry of the railing systems were compared with the AASHTO limits shown in figure 2 to establish geometric acceptability. Also, the potentials of the railing systems for higher service levels were tentatively established by comparing the heights with the limits shown in table 11.

To judge the potentials of the railing systems for wheel snagging in table 10, the relationship shown in figure 3 was used. Effective railing heights to prevent vehicle rollover are shown in table 12. This effective height is not the geometric height but is the lower distance from the pavement surface to the centroid of the resisting force provided by the

Table 10. Screening criteria summary.

1. Structural Continuity - Check railing for continuity, including end anchorage:

   continuous = P
   discontinuous = F

2. Curbs:

   behind rail = P
   flush with rail = M
   in front of rail = F

3. Potential Service Level - Use railing height to select service level:

   $<$ 27 in = 1
   27-34 in = 2
   $>$ 34 in = 3 or 4

4. Geometric Acceptability - Compare railing with AASHTO minimums of figure 2.

5. Wheel Snagging - Compare railing with figure 3:

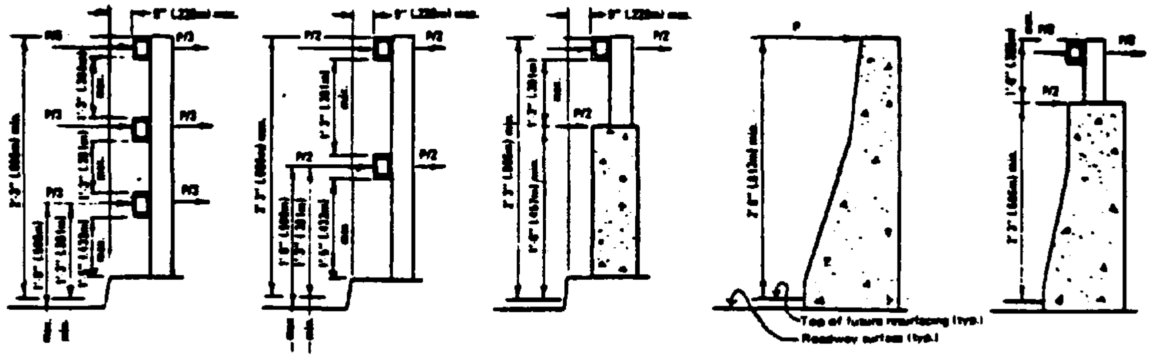
   below line = P
   on line = M
   above line = F

6. Vehicle Rollover - Use distance from pavement to centroid of top rail (beam and post systems) or 3 inches below top (concrete parapet or wall systems):

   $>$ 30 in = P
   24-30 in = M
   $<$ 24 in = F

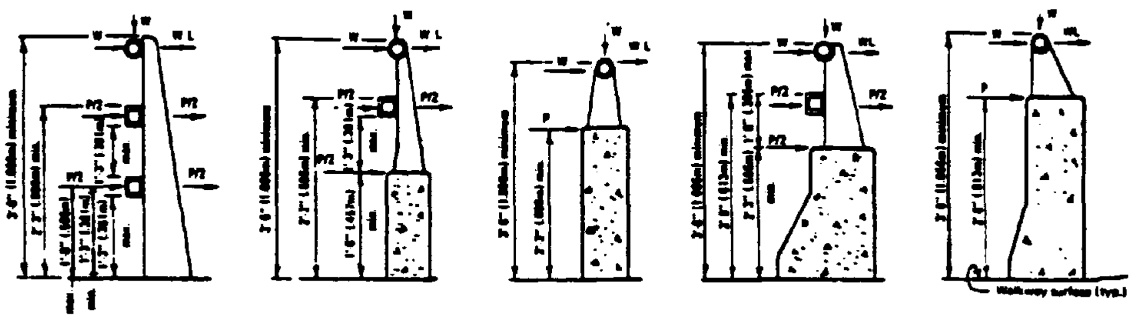
   Use center of top corrugations for W and Thrie beams.

7. Performance Acceptability - Make subjective judgment concerning acceptability from items 1 through 6 and any available test results on the system or similar systems.



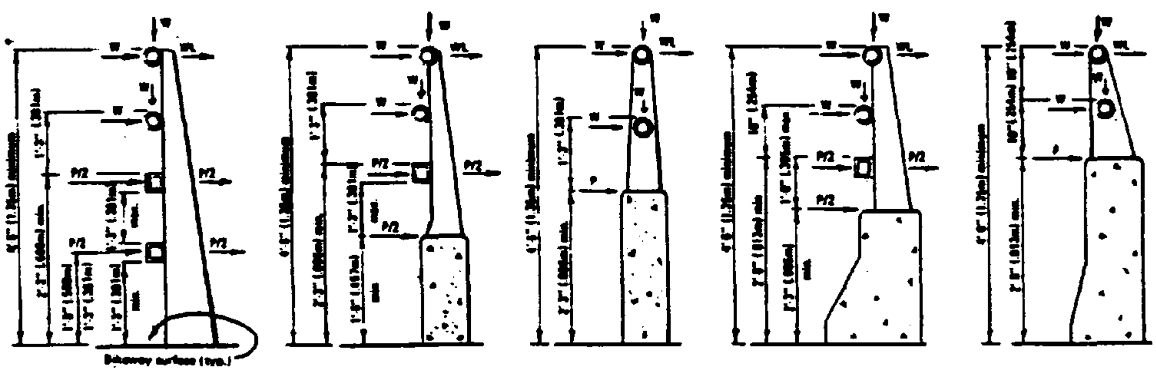
(To be used where there is no curb or curb projects 9" (.229m) or less from traffic face of railing.)

TRAFFIC RAILING



(To be used when curb projects more than 9" (.229m) from the traffic face of railing).

COMBINATION TRAFFIC AND PEDESTRIAN RAILING



COMBINATION TRAFFIC AND BICYCLE RAILING

NOTES:

1. Loadings on left are applied to rails.
2. Loadings on right are applied to posts.
3. The shapes of rail members are illustrative only. Any material or combination of materials listed in Article 1.1.8 may be used in any configuration.

NOMENCLATURE:

- P = Highway design loading = 10 kips (44.48 kN)
- h = Height of top of top rail above reference surface (in.) (metre)
- L = Post spacing (ft.) (metre)
- W = Pedestrian loading = 50 pounds per linear foot (74.45 kg/m)

$$C = 1 + \frac{h-33}{18} > 1 \qquad \left[1 + \frac{h}{.457} - \frac{33}{18}\right] \text{ in S.I. Units}$$

Figure 2. AASHTO geometries and load application points (reference 1).

Table 11. Bridge rail performance criteria (reference 6).

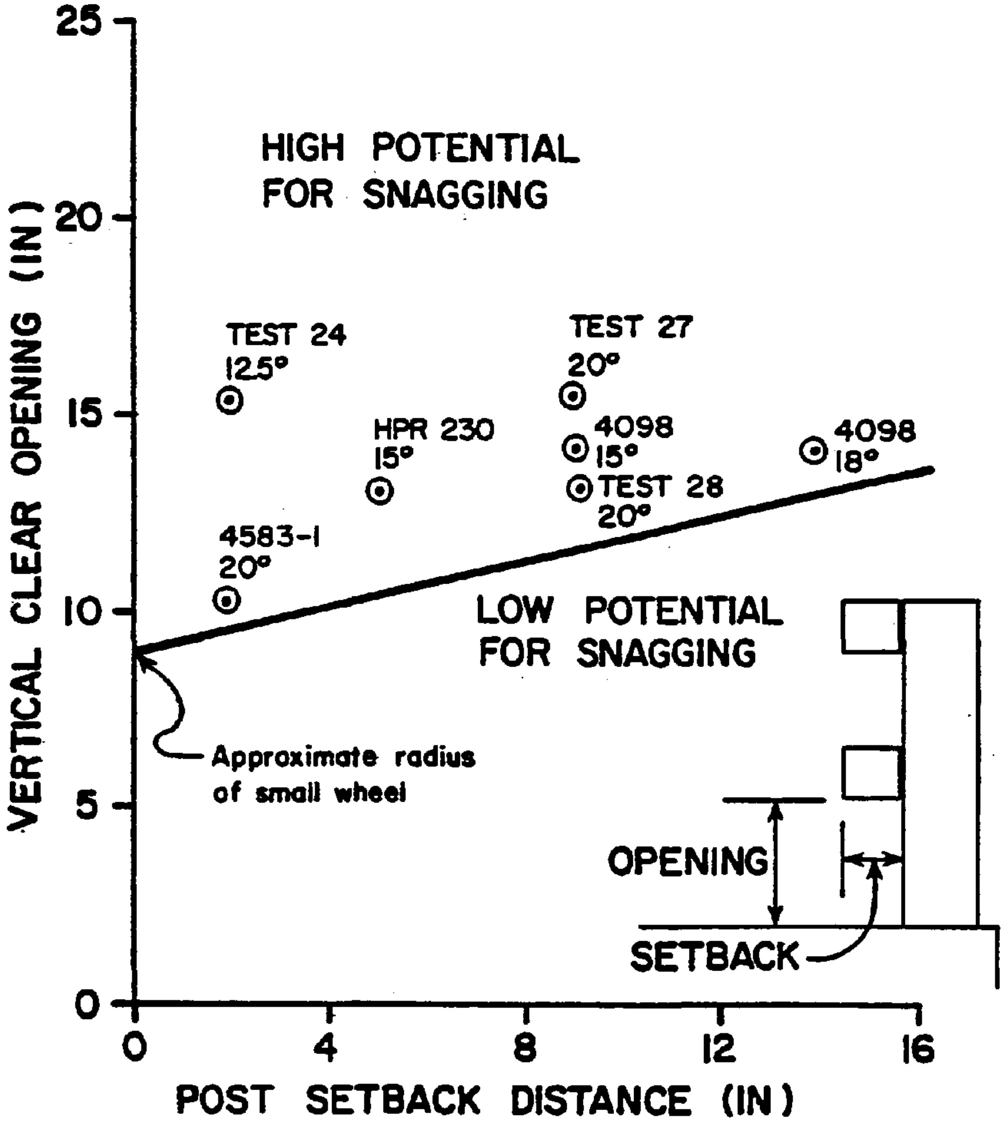
Service Level:	1	2	3	4
1. Crash Test Requirements*				
Impact Conditions				
A. Strength test				
Vehicle Weight (lbs)	4500	4500	20,000	40,000
Impact Speed (mph)	60	60	60	60
Impact Angle (deg)	15	25	15	15
B. Occupant risk	-----2250-lb auto, 60 mph, 15 deg------ or 1800-lb auto			
2. Dynamic Performance	-----------------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.



1 in = 0.0254 m
1 mph = 1.609 kph

Figure 3. Influence of vertical clear opening and post setback on potential for snagging of Honda Civic front wheel for test conditions up to 60 mph (96 km/h) and 20 degrees (reference 8).

Table 12. Required effective height of railing to prevent rollover of vehicle (reference 8).

VEHICLE	TEST CONDITIONS	REQUIRED MINIMUM EFFECTIVE RAILING HEIGHT (in)
Automobiles 1,800 to 4,500 lb	60 mph and up to 25 deg	24
School Bus 20,000 lb	60 mph/15 deg	34
Intercity Bus 32,000 lb	60 mph/15 deg	30

1 lb = 0.454 kg
1 mph = 1.609 kph
1 in = 0.025 m

railing system. Reference 8 suggestions of the centroid of the top rail element in beam and post systems and 2 to 3 inches below the top extremity of concrete parapets or walls was used as the screening criterion. Finally, curbs, either flush or protruding, should not be used as part of a bridge railing system[8] and were rated as shown in table 10.

The criteria discussed above were straightforward and simple to apply. Though more difficult to apply, the loadings and points of application shown in figure 2 could have been used in detailed elastic analyses to check conformance with the AASHTO specifications. Table 12 shows results of such analyses for the five railing systems tested in the study of reference 8. To perform these analyses on each of the furnished bridge railing systems would have been a monumental task and was not done. Further, from the standpoint of performance standards, compliance with the AASHTO specifications does not result in a necessarily successful system, nor does noncompliance result in a necessarily unsuccessful system. For example, note that none of the systems in table 13 met AASHTO strength requirements.

The same problem existed in screening the bridge railing systems for compliance with performance standards. For those systems with no test results, no information was available for judgment. BARRIER VII simulation runs could have been made on each of the systems for guidance, but, again, this would have been a prohibitive effort for the large number of systems.

Thus, the screening criteria used consisted primarily of the objective elements discussed above (geometry, post setback, etc.), along with some subjective judgments concerning strengths and performance standards, as summarized in table 10. Ratings for the 161 included bridge rail designs are included in appendix D.

Relative ratings of the bridge rail designs in appendix D could not be readily ascertained with the multiplicity of rating criteria. Thus, it was decided to establish as single rating index by assigning numerical

Table 13. Computed allowable loads for railings (kips) (reference 8).

Failure Mode \ Railing Design	Colorado Type 5	Texas T101	New Hampshire	North Carolina	Indiana 5A
Bending of top rail element	20.4	10.5	8.2	5.2	4.2
Bending of second rail element	----	----	8.2	----	4.2
Concrete parapet	----	----	---	22.2	---
Sum of all rail elements	20.4	10.5	16.4	27.4	8.4
Bending of post	11.3	10.2	9.5	5.9	9.0
Post-to-baseplate connection	13.6	10.2	7.9	4.6	7.3
Baseplate Thickness	3.5	8.2	---	---	---
Baseplate Bearing	8.4	4.6	6.9	4.1	6.4
Baseplate/Sail	---	---	1.4	4.8	1.3
Anchor bolts	8.9	8.7	6.9	4.2	6.5
Meets AASHTO strengths rqmts	No	No	No	No	No
Meets AASHTO geometric rqmts	No	Yes	No	Yes	Yes

1 kip = 4.448 kN

scores to the various criteria and summing these scores. The following numbers were used:

P = Pass = 2
M = Marginal = 1
F = Fail = 0
> SL2 - add 1
Total Possible Points = 1

In applying these numbers, an F in either flexure or tension was made F in structural continuity. Joints were assumed allowable and rated P in concrete bridge rails, such as safety shapes. For the more recent single rail systems, shown in appendix D as having no example for AASHTO geometric acceptability, a rating of P was assigned. Numbers shown on the right margins in appendix D are the final scores.

c. Selection of Candidate Bridge Rail Designs

The plan for selection of the final candidate bridge rail designs was to perform the screening process discussed and, from this process, select the ten best systems for evaluation in greater detail. Detailed elastic analyses would then be performed to check compliance with AASHTO specifications, and up to two BARRIER VII simulation runs would be conducted as a basis for judging performance standard acceptability. From the results of this detailed evaluation of the ten candidate designs, the six with the greatest potential for meeting the performance standards would be selected for subsequent full-scale crash tests.

A preliminary screening of 161 bridge rail designs in appendix D was first performed. The results are summarized in table 14, where the number of candidates has been reduced to 51. Reasons for drops from the maximum of 11 are indicated. Of the ten candidate systems to be selected, it was expected that about eight would be Service Level 2 and two of higher service level. Because of the prevalent use of safety shapes, the list was expected to include one high wall (e.g., the Michigan Safety Shape), one

Table 14. Summary of bridge rails.

Rating of 10

	State	Type	Reason for Drop
1.	KY	Conc	SL2
2.	MD	1 - Rail	Flush curb
3.	MI	SS	Rollover
4.	NC	SS	SL2
5.	PR	SS	Rollover

Rating of 9

	State	Type	Reasons for Drop
1.	AL	SS	SL2 - Rollover
2.	AR	SS	SL2 - Rollover
3.	AZ	SS	SL2 - Rollover
4.	CA (25)	SS	SL2 - Rollover
5.	CA (26)	Conc/Curb	Curb
6.	CA (18)	2 - Rail	Tension Continuity
7.	CO	SS	SL2 - Rollover
8.	DC	SS	SL2 - Rollover
9.	FL	SS	SL2 - Rollover
10.	GA	SS	SL2 - Rollover
11.	ID (IV)	SS	SL2 - Rollover
12.	IN	SS	SL2 - Rollover
13.	IA	SS	SL2 - Rollover
14.	KS	SS	SL2 - Rollover
15.	KY	SS	SL2 - Rollover
16.	LA	4 - Rail	Curb
17.	MD	SS	SL2 - Rollover
18.	MI	1 - Rail	Tension Continuity
19.	MA (ST-1)	1 - Rail	Tension Continuity
20.	MN	1 - Rail	Tension Continuity
21.	MN	SS	SL2 - Rollover
22.	MS	SS	SL2 - Rollover

Table 14. Summary of bridge rails (continued).

Rating of 9 (Cont'd)

	State	Type	Reasons for Drop
23.	MO	SS	SL2 - Rollover
24.	MO	1 - Rail	SL2 - Rollover
25.	NE	SS	SL2 - Rollover
26.	NC	SS	SL2 - Rollover
27.	NC	1 - Rail	Curb
28.	OH	SS	SL2 - Rollover
29.	OR	2 - Rail	Wheel Snagging
30.	PA	SS	SL2 - Rollover
31.	PA	2 - Rail	Geometry
32.	PR	1 - Rail	Curb
33.	PR	Conc/W-Beam	SL2 - Rollover
34.	SC	SS	SL2 - Rollover
35.	SC	1 - Rail	Tension Continuity
36.	SD	SS	SL2 - Rollover
37.	SD	2 - Rail	SL2 - Rollover
38.	TN	SS	SL2 - Rollover
39.	TX	SS	SL2 - Rollover
40.	VA (KP)	SS	SL2 - Rollover
41.	VA (PB-A)	Conc	Curb
42.	UT	SS	SL2 - Rollover
43.	UT	SS mod.	SL2 - Rollover
44.	WI	1 - Rail	SL2 - Rollover
45.	WI (B)	SS	SL2 - Rollover
46.	WV	SS	SL2 - Rollover

standard safety shape with upper metal rail, and one standard safety shape without upper rail.

Work was then concentrated on selecting the ten bridge rail designs for further analysis. Several iterations were made through the State Standards with an objective of grouping the designs by type (i.e, open concrete, tubular W-beam, etc.). Judgment was then exercised on each of the resulting ten groupings to recommend one design from each group for further analysis. Selection criteria included the numerical rating that had been given and judgment about the design strength and the likelihood of passing the performance standards. The groups, along with the recommended designs, were then submitted to FHWA for review and evaluation. In the interim, a small interactive computer program BRIDGE was prepared for use in conducting elastic analyses of bridge rails. Formulation details, program listing, and sample inputs and output results are included in appendix C.

As a result of the FHWA review and evaluation, the following six systems were initially selected for further evaluation:

- New York 4-rail.
- Nevada safety shape w/upper steel rail.
- Kansas corral without curb.
- Ohio flush-mounted W-beam w/box beam back-up.
- Nebraska flush-mounted tubular thrie beam.
- Colorado straight parapet w/upper rail.

Instructions were given to evaluate these systems as follow:

- Check systems for conformance to AASHTO specifications.
- Set up tentative test matrix.
- Prepare construction drawings.
  Look for best system using curb.

Typical of State Standards, the bridge rail standards on hand did not include details of the bridge deck. Such details were needed. For example, safety shapes have undergone extensive testing, but as median barriers and not as bridge rails. To get missing bridge deck details, particularly those concerned with geometry and reinforcement, contacts were made with bridge divisions of the appropriate State agencies. Responses were promptly received.

As the detailed evaluation proceeded, construction difficulties were foreseen with the Nevada and Colorado selections, primarily because of the extreme tolerances necessary. On consultation with the COTR, the Colorado system was eliminated and the steel rail of the Nevada system was replaced with the aluminum rail. The North Carolina aluminum rail on concrete parapet was substituted for the eliminated Colorado system. Also, because of the very high material cost quotes received for the New York four-rail system, it was eliminated in favor of the Oregon three-rail system.

The small BRIDGE program of appendix C was exercised to check some of the selected bridge rail systems and other candidates for possible replacement of eliminated systems. Preliminary results are summarized in table 15. Similar to results of the reference 8 rails in table 13, none of the systems appeared to satisfy all of the AASHTO strength requirements.

This iteration process of evaluating the candidate bridge rail designs and consulting with the COTR resulted in the selection of the final systems for full-scale crash testing. The final selections, along with others that were subsequently added by contract modification, were as follow:

- Nevada system with concrete safety shape with upper aluminum railing.
- Kansas Corral system with concrete railing and posts.

Table 15. Summary of preliminary elastic analyses.

	New York 4-Rail*	New York as 3-Rail System	Oklahoma Straight Parapet w/Upper Rail	Oregon Flush Curb - Mounted	Colorado Type 8	Nevada S.S. w/Upper Steel Rail
Bending of top rail element	5.8	5.8	4.4 < 5.0 X	3.6 < 5.1 X	14.0	8.1
Bending of middle rail element	2 @ 6.1	6.1	--	5.3	--	--
Bending of bottom rail element*	2.4 < 3.8 X	6.1	--	5.3	--	--
Sum of all rail elements	20.4	18.0	--	14.2 < 15.3 X	--	--
Concrete parapet	N/A	N/A	6.7 < 10.0 X	N/A	7.3 < 10.0 X	12.2 < 14.4 X
Bending of post	25.1 (n=4)	19.1 (n=4)	15.8 (n=4)	15.0 (n=4)	21.4 (n=4)	15.8
Post-to-base plate connection	25.1	19.1	13.1 (n=4)	12.4 (n=4)	11.4 (n=4)	11.4
Base plate thickness	12.3 X	10.1	10.2 (n=4)	15.0 (n=4)	--	6.7 (n=4) < 7.2 X
Base plate bearing	8.1 < 10 X	6.6 < 10 X	7.6 (n=4)	8.7 < 10.0 (n=4) X	9.6 < 10.0 X	8.8
Anchor bolts	18.7	15.6	13.5 (n=4)	9.1 < 10.0 (n=4) X	20.9	9.7
Meets AASHTO strength requirements	No	No	No	No	No	No
Meets AASHTO geometric requirements	Yes	Yes	Yes	Yes	Yes	Yes

* Per State contact, this rail is not considered a traffic rail. Rerun using top three rails only. See New York as 3-Rail System.

X = Does not satisfy strength requirements.

- North Carolina system with concrete parapet and upper aluminum railing.

- Ohio system with W-beam/box beam railing and steel posts attached to side of bridge deck.

- Oregon system with three box beam railings and steel posts. This system was subsequently modified to eliminate the small top railing.

- Nebraska system with tubular thrie beam railing and steel posts attached to a prestressed concrete bridge deck.

- The 1985 version of the Kansas Corral system, modified for larger concrete railing and posts.

- Oklahoma modified TR-1 system with concrete railing and posts (added by contract modification).

- Louisiana system with tubular thrie beam railing and steel posts attached to steel floor beams with concrete deck and curb (added by contract modification).

Drawings for these bridge rail systems are shown in appendix A. Full-scale crash tests are summarized in chapter 4, and complete test reports are presented in appendix B.

d. Analysis of Bridge Rail Systems

Each of the final bridge rail systems was evaluated for conformance with AASHTO geometric and strength requirements. Elastic analyses were conducted by the BRIDGE program discussed in appendix C. Results are shown in table 16. It is of interest to note that of the final six selected systems, only the Ohio system completely satisfied the AASHTO strength requirements. A re-analysis was made of the Oregon three-rail system by treating the top rail as a pedestrian rail, and the system was satisfactory. However, AASHTO shows the combination traffic and pedestrian railing to be used when the curb projects more than nine inches (22.5 cm) from the traffic face of railing. This was not the case with the flush-mounted Oregon railing. However, the system was modified to eliminate the upper rail and subsequently tested (see chapter 4).

Table 16. Computed allowable loads for railing (kips).

Failure Mode	RAILING SYSTEMS: North Carolina	Req'd. AASHTO Load	Nebraska	Req'd. AASHTO Load	Ohio	Req'd. AASHTO Load	Kansas	Req'd. AASHTO Load	Oregon	Req'd. AASHTO Load	Nevada	Req'd. AASHTO Load	Revised Kansas System	Req'd. AASHTO Load	Revised Oklahoma System	Req'd. AASHTO System
Bending of top rail element	4.1*	5.0	22.0	10.0	22.4	10.0	16.5	10.0	3.6*	5.1	4.9*	6.6	13.4	10.0	29.6	10.0
Bending of middle rail element	--	--	--	--	--	--	--	--	5.3	5.1	--	--	--	--	--	--
Bending of bottom rail element	--	--	--	--	--	--	--	--	5.3	5.1	--	--	--	--	--	--
Sum of all rail elements	4.1*	5.0	22.0	10.0	22.4	10.0	16.5	10.0	14.2*	15.3	4.9*	6.6	13.4	10.0	29.6	10.0
Concrete parapet	14.9	10.0	--	--	--	--	--	--	7.8*	10.0	13.6	10.0	--	--	--	--
Bending of post	5.9	5.0	11.0	10.0	10.5	10.0	7.8*	10.0	15.0	10.0	10.8	6.6	15.6	10.0	19.5	10.0
Post-to-base plate connection	4.6*	5.0	6.3*	10.0	--	--	--	--	12.4	10.0	--	--	--	--	--	--
Base plate thickness	--	--	12.6	10.0	--	--	--	--	15.1	10.0	7.5	6.6	--	--	--	--
Base plate bearing	3.9*	5.0	14.1	10.0	--	--	--	--	10.4	10.0	5.9*	6.6	--	--	--	--
Base plate/sail	4.8*	5.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Anchor bolts	4.4*	5.0	25.9	10.0	14.3	10.0	--	--	9.2*	10.0	10.0	6.6	--	--	--	--
Bridge deck	12.2	10.0	32.9	10.0	32.6	10.0	7.3*	10.0	10.7	10.0	12.9	10.0	14.6	10.0	11.5	10.0
Meets AASHTO strength requirements	No		No		Yes		No		No		No		Yes (1)	--	Yes	--
Meets AASHTO geometric requirements	Yes		Yes		Yes		Yes		Yes		Yes		Yes (2)	--	Yes (2)	--

* Allowable elastic load does not meet AASHTO specification.

(1) Original system did not meet strength requirements. Stirrups were required and added in both railing and posts.

(2) Original system had only one inch of concrete cover. Geometry was changed for 1 1/2-inch minimum cover.

The 1985 version of the Kansas corral and Oklahoma modified TR-1 systems both met the simple AASHTO strength requirements. However, as shown in table 16, neither of the systems met the 1983 AASHTO specifications with their one-inch (2.5 cm) of concrete cover on the posts. Also, a more detailed analysis was desired to check for web reinforcement, particularly with the optional open joint in posts of the Kansas system. The analysis revealed that stirrups were needed with the Kansas system both in the posts and railing. Additional railing or post web reinforcement were not required with the Oklahoma system. Both systems were modified before test to obtain the 1 1/2-inch (3.8 cm) minimum concrete cover.

The Louisiana tubular thrie beam system was not analyzed for conformance with AASHTO specifications but was checked for performance standards with the BARRIER VII computer simulation program. Results shown in appendix C, indicated the probability of satisfactory response. Also included in appendix C are analyses of (1) a Mississippi extruded aluminum bridge railing conducted with the ADINA finite element program and (2) a bridge rail and median barrier system proposed for the Cochrane Bridge in Mobile, Alabama.

e. Summary

This chapter has detailed the process used in evaluating the existing bridge rail designs and selecting the nine systems for further analysis and full-scale crash tests. To meet the goal of the study, the selected systems were diverse in geometric and material configurations so that a family of bridge railings would be developed that meets the whole gamut of national needs.

The most significant finding from this chapter is that the majority of existing designs apparently do not fully conform to the AASHTO geometric and strength requirements. However, these requirements need not be satisfied if the system successfully passes the full-scale crash tests. Summaries of the tests conducted on the various systems are discussed in the following section.

4. Summary of Full-Scale Crash Tests

Crash tests conducted in this project included systems discussed in section 3. In addition, other identified designs were tested during the project. The bridge rail designs tested included:

System		Description
NBR	-	Concrete safety shape parapet w/aluminum rail on top
NBBR	-	Tubular thrie beam/post system on precast panels
OHBR	-	Steel box beam/post system mounted on deck edge
NCBR	-	Flat concrete parapet w/aluminum rail on top
OBR	-	Multiple steel box beam/post system on mountable curb
KBR	-	Concrete open parapet
MKS	-	Modified concrete open parapet
OKBR	-	Concrete open parapet
LABR	-	Steel ballaster rail w/tubular thrie beam retrofit (versions 1, 2, & 3)
BL	-	3400-lb vehicle baseline tests

The geometries of these systems are described in figure 4.

Test procedures and results are briefly described in this section. Detailed information on the test installations and results is contained in appendix B; a summary of the test results is contained in table 17.

a. Test Procedures

All bridge rail systems with few exceptions were tested at 60 mph (95 km/h) with the 1800-lb (800-kg) minicar impacting at 20 degrees and the 4500-lb (2025-kg) sedan impacting at 25 degrees. One system (NBR) was evaluated using a 40,000-lb (18,000-kg) intercity bus impacting at 60 mph

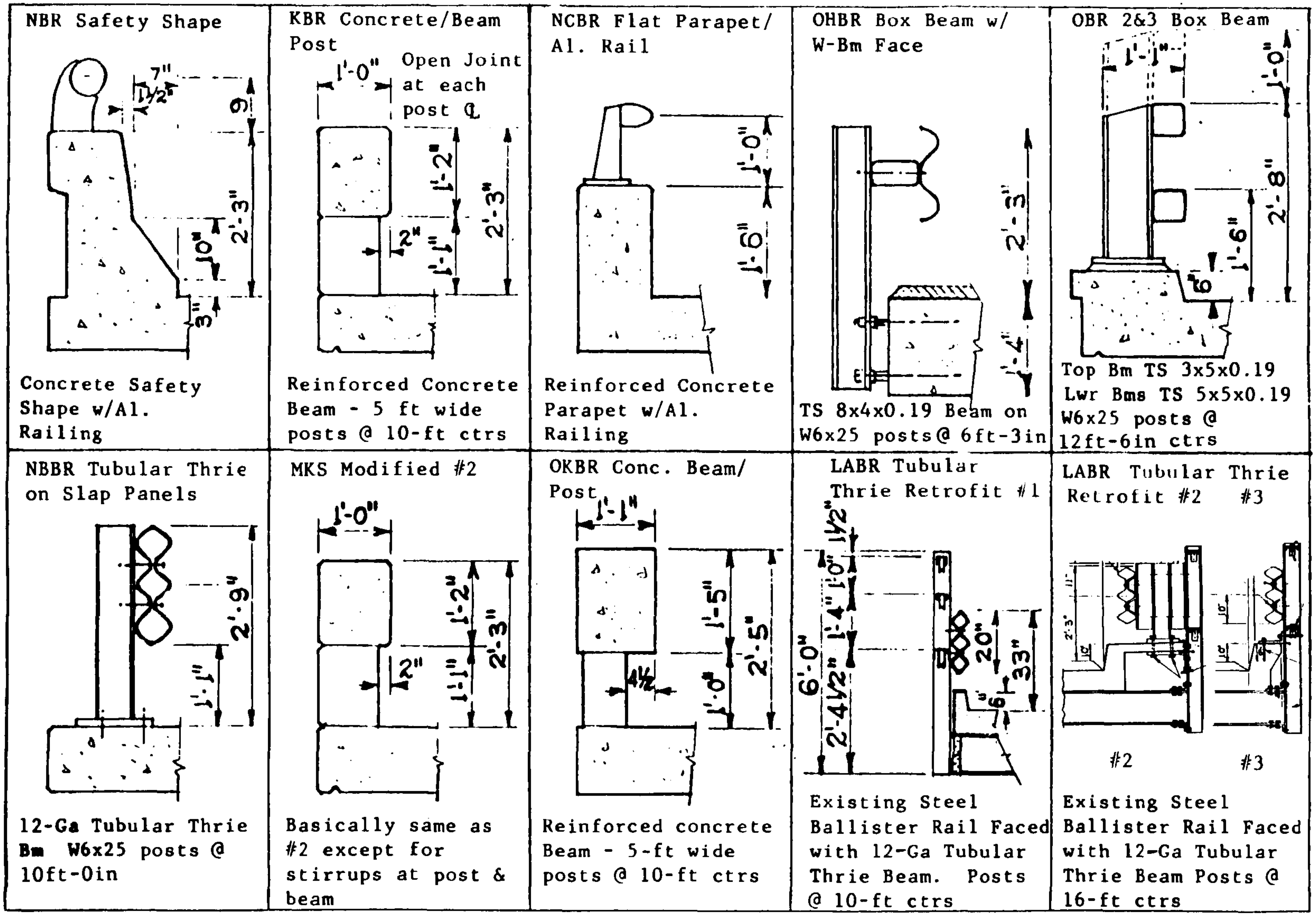


Figure 4. Selected bridge railing geometry/characteristics.

Table 17. Summary of full-scale tests.

Test No.	NBR-1	NBR-2	NBR-3	NBBR-1	NBBR-2	OHBR-1	OHBR-2
Report 230 Test No.	S13	10	S15	S13	10	S13	10
Test Vehicle	1978 Honda	1978 Dodge	1955 Intercity Bus	1979 Honda	1978 Plymouth	1979 Honda	1977 Plymouth
Gross Vehicle Weight, lb	1911	4650	40,000	1970	4700	1980	4790
Impact Speed (film) , mph	60.7	61.4	58.9	61.4	58.4	60.6	60
Impact Angle, deg	19.3	24.9	16.4	20.0	24.3	19.6	25
Exit Angle (film), deg	-8.5	-3.9	parallel	-1.3	-7.0	-5.9	N/A
Maximum 50 msec Avg Accel (film/accelerometer)							
Longitudinal	-4.5/-5.8	-6.3(film)	1.5/-1.7	-2.9/-4.9	-4.4/-5.9	-2.9/-5.6	-6.1(accel)
Lateral	8.4/12.6	8.4 (film)	2.8/7.3	8.3/13.5	7.0/8.2	8.5/11.4	12.1 (accel)
Occupant Risk, NCHRP Report 230 (film/accelerometer)							
ΔV long., fps (30) *	-1.4/-7.2	3.0 (film)	-4.0/0.6	10.1/5.3	4.7/3.8	7.7/7.3	-7.0 (accel)
ΔV lat., fps (20)	-22.6/21.8	-21.6 (film)	-5.9/-13.9	-22.5/-20.7	-19.4/-20.0	-23.3/-20.6	-25.1 (accel)
Ridedown Accelerations, g's (accel)							
Longitudinal (15)	**	**	**	**	**	**	**
Lateral (15)	8.3	6.8	11.9	11.4	9.9	11.9	16.5
NCHRP Report 230 Evaluation							
Structural Adequacy (A,D)	Passed	Passed	Passed	Passed	Passed	Passed	Passed
Occupant Risk (E, F, G)	lat ΔV>20	Passed	Passed	lat ΔV>20	Passed	lat ΔV>20	Passed
Vehicle Trajectory (H,I)	Passed	Passed	Passed	Passed	Passed	Passed	Passed

* Numbers in parentheses are recommended in NCHRP Report 230
** Occupant did not travel flail distance

Table 17. Summary of full-scale tests (continued).

Test No.	NCBR-1	NCBR-2	OBR-1	OBR-2	OBR-3	KBR-1	KBR-2
Report 230 Test No.	S13	10	S13	10	10	S13	10
Test Vehicle	1979 Honda	1978 Plymouth	1978 Honda	1977 Plymouth	1978 Plymouth	1978 Honda	1978 Dodge
Gross Vehicle Weight, lb	1990	4660	1994	4760	4640	1971	4660
Impact Speed (film), mph	59.7	60	58.6	60.8	60	61.9	60.5
Impact Angle, deg	18.8	25	18.8	24.3	25	20.3	24.0
Exit Angle (film), deg	-6.7	N/A	-3.2	-13.0	-0.2	-1.7	N/A
Maximum 50 msec Avg Accel (film/accelerometer)							
Longitudinal	-3.2/-8.1	-6.9(accel)	-2.6/-3.3	-5.1/-5.2	-5.2(accel)	-5.7/-7.5	-5.8/-8.3
Lateral	7.1/12.9	17.9 (accel)	8.4/10.2	7.9/13.7	15.9 (accel)	9.0/11.2	5.9/13.4
Occupant Risk, NCHRP Report 230 (film/accelerometer)							
ΔV long., fps (30) *	4.8/14.0	16.6 (accel)	-4.4/0.8	1.3/-20.9	-0.9/-28.8	12.4/11.5	28.5/30.0
ΔV lat., fps (20)	-20.7/-22.7	-31.2 (accel)	-22.7/-19.9	-21.2/-26.0		23.3/20.4	-18.6/-23.3
Ridedown Accelerations, g's (accel)							
Longitudinal (15)	N/A	-1.8	**	N/A	**	-0.6	N/A
Lateral (15)	N/A	10.4	24.4	N/A	19.8	8.1	N/A
NCHRP Report 230 Evaluation							
Structural Adequacy (A,D)	Passed	Passed	Passed	Passed	Passed	Passed	Failed
Occupant Risk (E, F, G)	lat ΔV>20	Passed	Passed	Failed	Passed	lat ΔV>20	Failed
Vehicle Trajectory (H,I)	Passed	Passed	Passed	Passed	Passed	Passed	Failed

* Numbers in parentheses are recommended in NCHRP Report 230
** Occupant did not travel flail distance

Table 17. Summary of full-scale tests (continued).

Test No.	MKS-1	MKS-2	OKBR-1	OKBR-2
Report 230 Test No.	S13	10	S13	10
Test Vehicle	1979 Honda	1978 Dodge	1979 Honda	1978 Plymouth
Gross Vehicle Weight, lb	1850	4690	1980	4660
Impact Speed (film), mph	59.0	59.2	58.7	59.1
Impact Angle, deg	18.9	24.9	18.9	25.4
Exit Angle (film), deg	-4.7	-6.1	-6.0	-5.5
Maximum 50 msec Avg Accel (film/accelerometer)				
Longitudinal	-3.3/-9.5	-3.7/-9.4	-2.4/-8.7	-3.7/-11.8
Lateral	-6.2/-10.6	-6.3/-12.6	6.4/11.5	7.1/17.6
Occupant Risk, NCHRP Report 230 (film/accelerometer)				
ΔV long., fps (30) *	9.2/14.0	6.7/13.9	7.0/24.6	6.2/26.4
ΔV lat., fps (20)	19.5/18.2	19.3/24.9	-19.8/-19.9	-20.1/-26.9
Ridedown Accelerations, g's (accel)				
Longitudinal (15)	1.4	-1.7	-1.4	-5.3
Lateral (15)	-14.8	-13.9	12.1	8.9
NCHRP Report 230 Evaluation				
Structural Adequacy (A,D)	Passed	Passed	Passed	Passed
Occupant Risk (E, F, G)	Passed	Passed	Passed	Passed
Vehicle Trajectory (H,I)	Passed	Passed	Passed	Passed

* Numbers in parentheses are recommended in NCHRP Report 230

** Occupant did not travel flail distance

Table 17. Summary of full-scale tests (continued).

Test No.	LABR-1	LABR-2	LABR-3	LABR-4
Report 230 Test No.	S13	10	S13	S13
Test Vehicle	1979 Honda	1978 Dodge	1980 Honda	1980 Honda
Gross Vehicle Weight, lb	1900	4635	1990	1965
Impact Speed (film) , mph	60.4	59.7	59.7	59.9
Impact Angle, deg	18.8	19.1	18.7	20.3
Exit Angle (film), deg	-9.7	-4.9	-6.7	-4.6
Maximum 50 msec Avg Accel (film/accelerometer)				
Longitudinal	-3.4/-4.4	-2.6/-5.3	-3.4/-6.4	-3.8/-5.8
Lateral	6.9/12.8	7.0/10.8	7.8/11.1	7.8/10.6
Occupant Risk, NCHRP Report 230 (film/accelerometer)				
ΔV long., fps (30) *	4.5/0.9	6.6/14.0	-3.5/-0.6	6.4/2.0
ΔV lat., fps (20)	-21.0/-23.6	-20.2/-22.8	-20.8/-18.1	-21.4/-20.8
Ridedown Accelerations, g's (accel)				
Longitudinal (15)	**	-1.7	**	**
Lateral (15)	13.6	7.5	8.7	10.4
NCHRP Report 230 Evaluation				
Structural Adequacy (A,D)	Passed	Passed	Passed	Passed
Occupant Risk (E, F, G)	lat ΔV>20	Passed	latΔV>20	latΔV>20
Vehicle Trajectory (H,I)	Passed	Passed	Passed	Passed

* Numbers in parentheses are recommended in NCHRP Report 230

** Occupant did not travel flail distance

Table 17. Summary of full-scale tests (continued).

Test No.	BLNV-1	BLO-1
Report 230 Test No	N/A(see note)	N/A(see note)
Test Vehicle	1982 Malibu	1981 Malibu
Gross Vehicle Weight, lb	3380	3430
Impact Speed (film) , mph	62.3	62.5
Impact Angle, deg	19.6	20.7
Exit Angle (film), deg	-1.8	-9.8
Maximum 50 msec Avg Accel (film/accelerometer)		
Longitudinal	-4.6/-5.4	-2.5(film)
Lateral	7.3/10.7	7.6(film)
Occupant Risk, NCHRP Report 230 (film/accelerometer)		
ΔV long., fps (30) *	8.6/10.7	2.5(film)
ΔV lat., fps (20)	-23.2/-29.9	-22(film)
Ridedown Accelerations, g's (accel)		
Longitudinal (15)	-1.3	**(film)
Lateral (15)	11.6	7.7(film)
NCHRP Report 230 Evaluation		
Structural Adequacy (A,D)	Passed	Passed
Occupant Risk (E, F, G)	lat ΔV>20	lat ΔV>20
Vehicle Trajectory (H,I)	Passed	Passed

* Numbers in parentheses are recommended in NCHRP Report 230
** Occupant did not travel flail distance
Note: FHWA Specified Test --3400s/60 mph/20 deg

(95 km/h) and 15-degree angle. Two tests were conducted with a downsized sedan type that has replaced the 4500-lb (2025-kg) sedan as the representative sedan of the current vehicle fleet. Barriers evaluated using this 3400-lb (1530-lb) car were the OBR two-rail system and a 32-in (80-cm) high concrete safety shape. A restrained 50th percentile male, Part 572 dummy was placed in the driver's seat of all vehicles; a like unrestrained dummy was placed in the right front-passenger seat of the full-size sedan and in the far right, row 2 seat of the bus. Impact events were recorded from transducers mounted in the dummies and on the vehicle. Extensive film coverage also documented the barrier, vehicle, and dummy behavior.

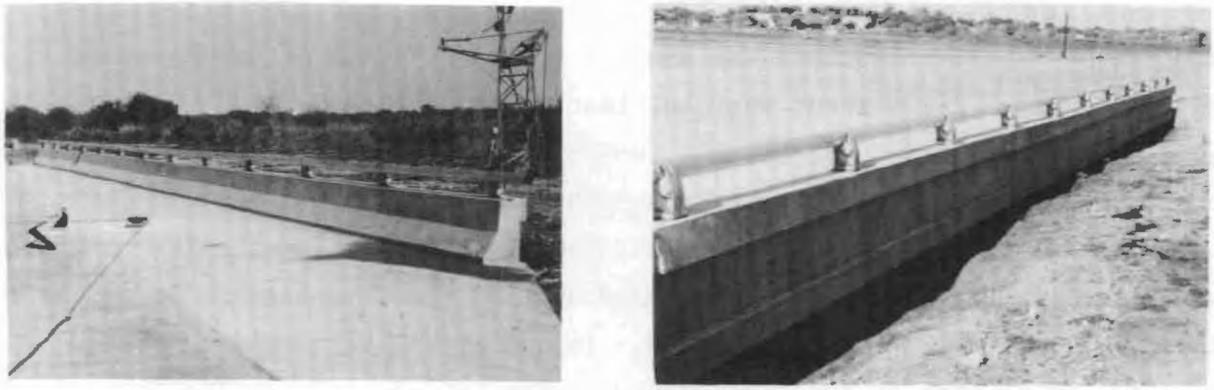
b. NBR Tests

The barrier evaluated in this series was a 27-in (68.5-cm) high concrete safety shape parapet with an aluminum railing on top as shown in figure 5.

NBR-1. The 1911-lb (867-kg) vehicle struck the barrier at 60.7 mph (97.7 km/h) and a 19.3-degree angle, and was redirected as shown in figure 6 after 9.8 ft (3.0 m) of barrier contact. The maximum vehicle roll angle was 11.5 degrees. Damage to the vehicle and barrier is shown in figure 5. There was no evidence of vehicle contact with the aluminum top railing.

NBR-2. The 4650-lb (2109-kg) car struck the barrier at 61.4 mph (98.7 km/h) and a 24.9-degree impact angle as shown in figure 7. The vehicle remained in contact with the barrier for 11.6 ft (3.5 m) and the maximum roll angle was 9.5 degrees. As shown in figure 5, there was some vehicle contact with the upper railing although there was no railing damage.

NBR-3. The 40,000-lb (18,000-kg) intercity bus struck the barrier at 58.9 mph (94.8 km/h) and a 16.4-degree angle. As shown in figure 8, the vehicle rolled toward the barrier with a maximum angle of 55 degrees during the redirection. Although the bus lost contact with the concrete portion



NBR Test Installation

After Test NBR-1

After Test NBR-2

Figure 5. NBR series photographs.

After Test NBR-3.

Figure 5. NBR series photographs (continued).

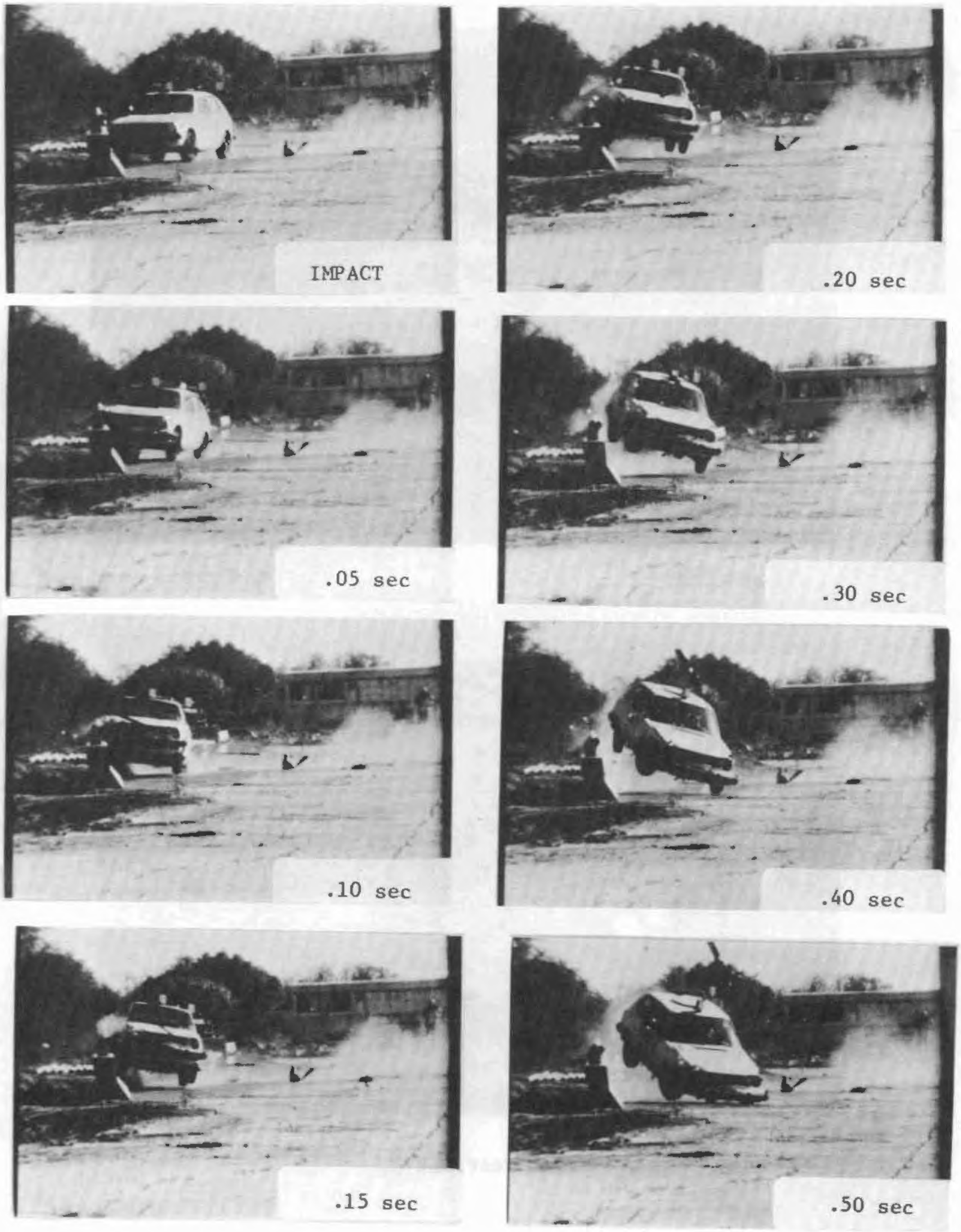


Figure 6. Sequential photographs, Test NBR-1.

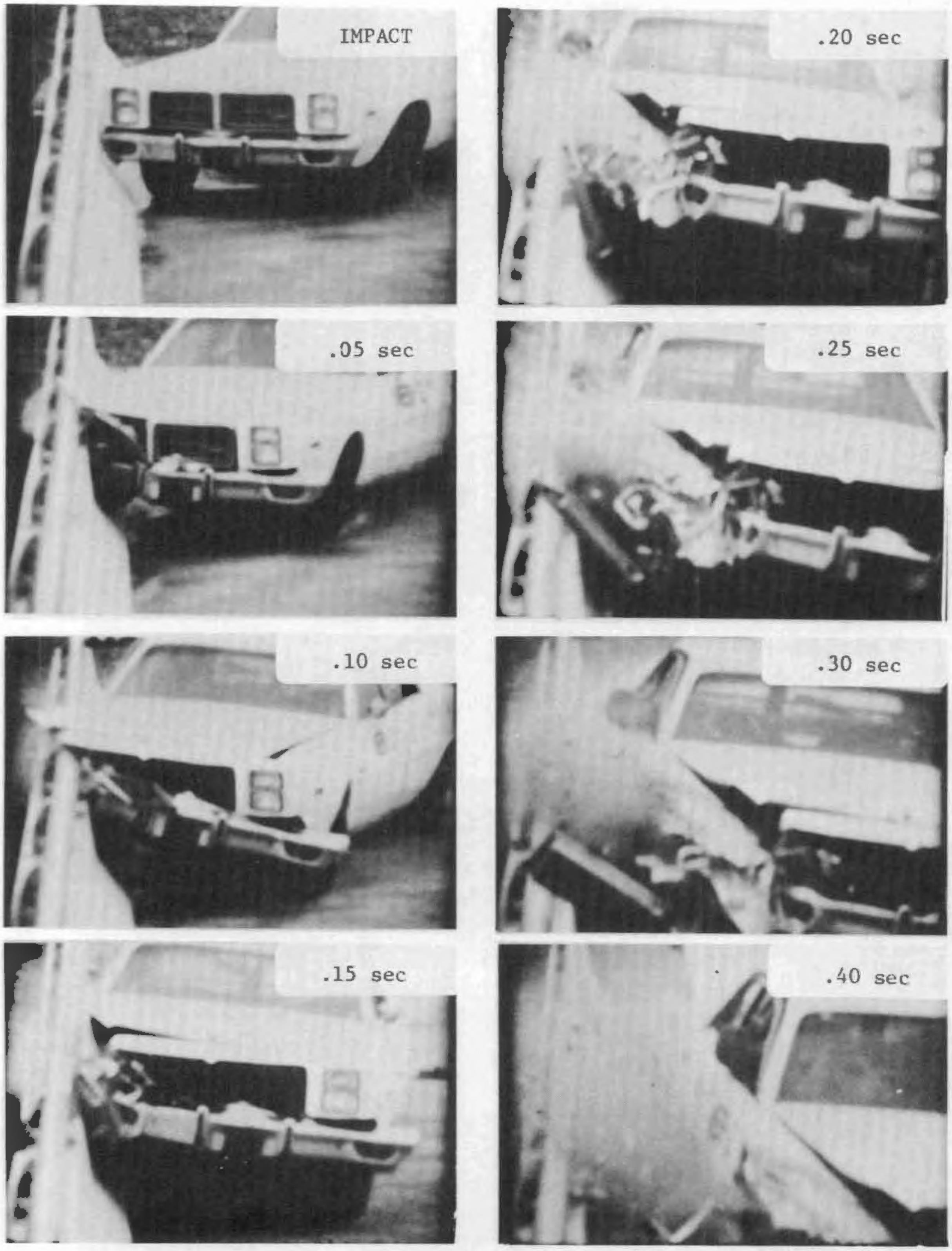


Figure 7. Sequential photographs, Test NBR-2.

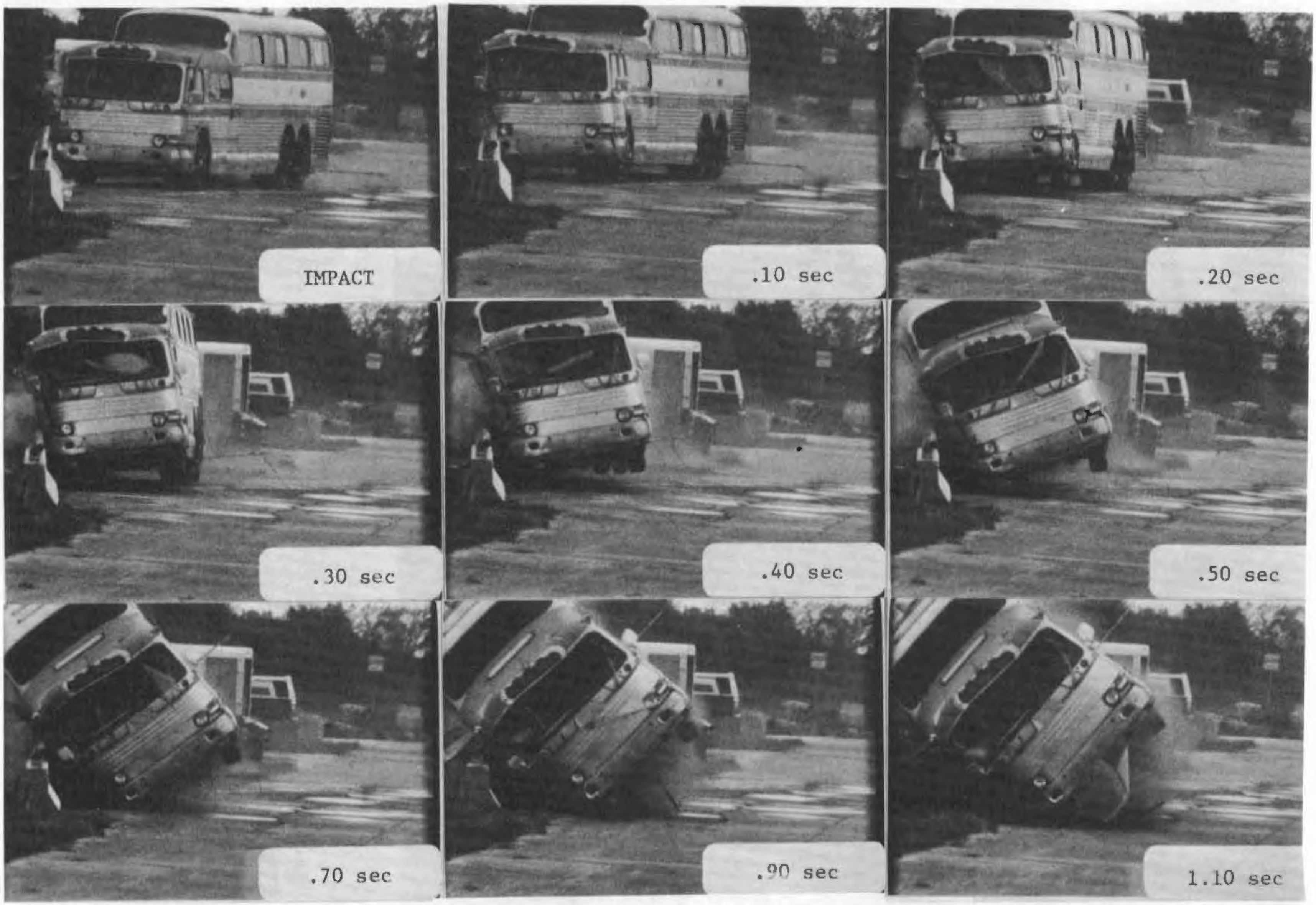


Figure 8. Sequential photographs, Test NBR-3.

of the barrier after 30 ft (9.1 m), the side of the bus remained in contact with the aluminum railing from initial impact to the end of the system. Damage to the vehicle and barrier as shown in figure 5 included severe deformation of several posts with some permanent "set" in the railing.

c. NBBR Tests

This system as shown in figure 9 included a tubular thrie beam mounted on steel posts spaced at 10-ft (3.0-m) centers. The posts were attached to precast slab panels.

NBBR-1. The 1970-lb (893-kg) vehicle struck the barrier at 61.4 mph (98.8 km/h) and a 20-degree impact angle. As shown in figure 10, the vehicle was smoothly redirected after 9.8 ft (3.0 m) of barrier contact. Minimal deformation occurred in the beam as shown in figure 9; there was considerable vehicle damage, some of which was caused by a secondary impact with another barrier.

NBBR-2. The 4700-lb (2132-kg) vehicle struck the barrier at 58.4 mph (94.0 km/h) and a 24.3-degree angle. The maximum dynamic deflection was 13 in (33 cm). The vehicle remained in contact with the barrier for 14.0 ft (4.3 m) before redirection as shown in figure 11. The vehicle maintained a smooth trajectory until a steep angle contact with another barrier system occurred. Damage to the barrier consisted of flattening and deformation of 2 sections of tubular thrie beam. The bridge deck anchorage was severely damaged as shown in figure 9.

d. OHBR Series

Two tests were conducted on the box beam/steel post system shown in figure 12. The 4x6 box beam is mounted on W6x25 posts spaced at 6-ft 3-in (1.9-m) centers, mounted on the deck edge. A standard W-beam is placed on the traffic side of the box beam.

After Test NBBR-1

After Test NBBR-2

Figure 9. NBBR series photographs.

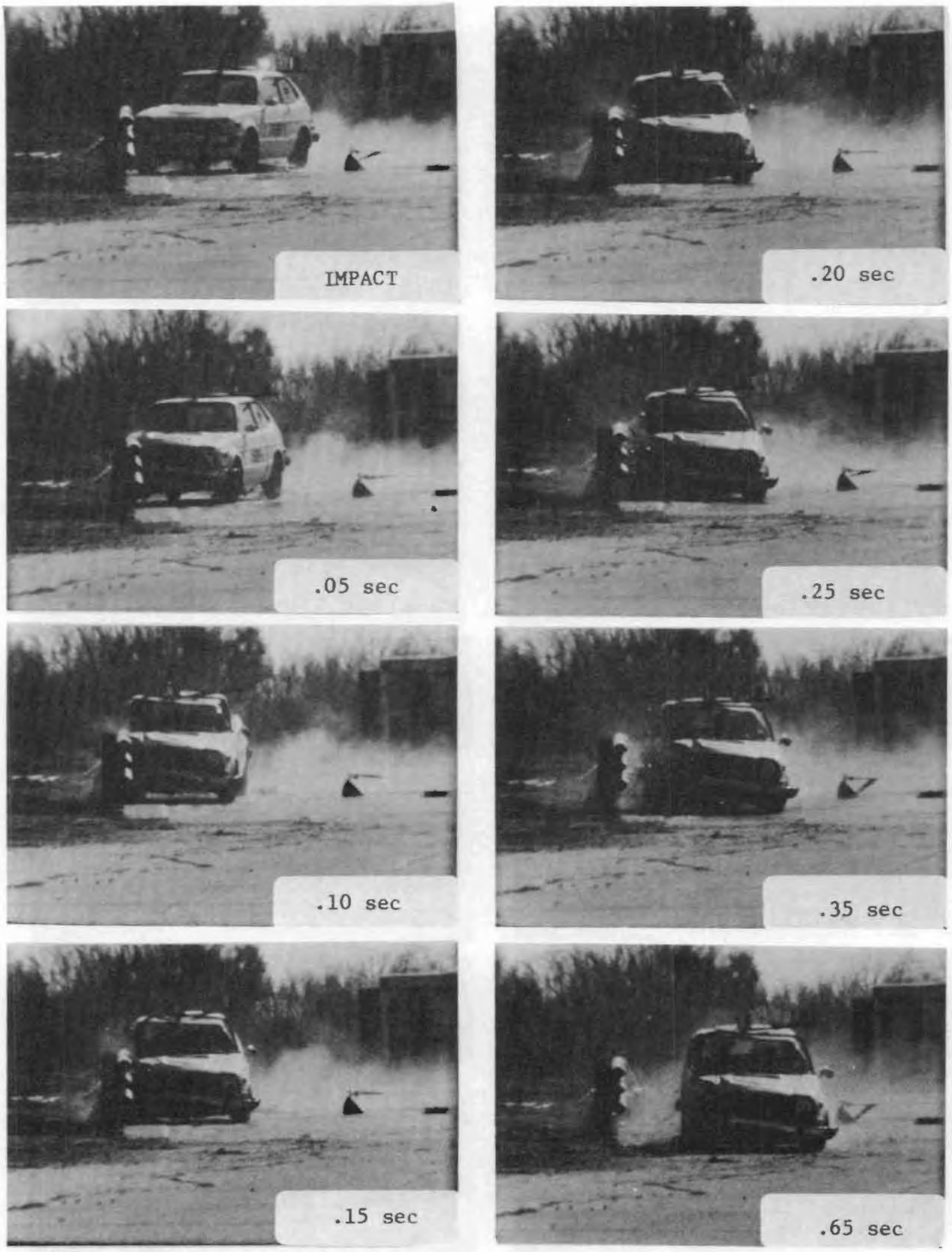


Figure 10. Sequential photographs, Test NBBR-1.

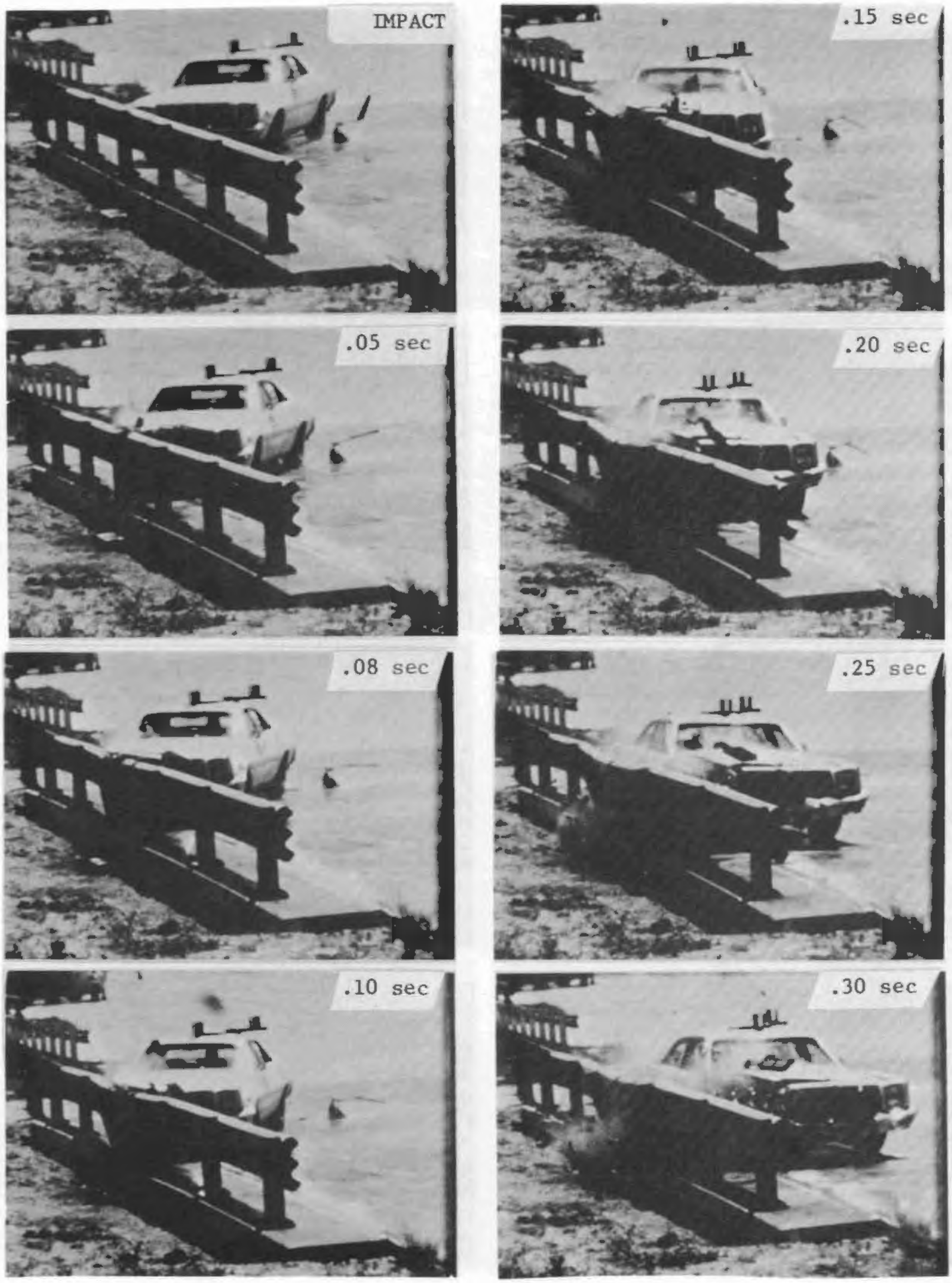
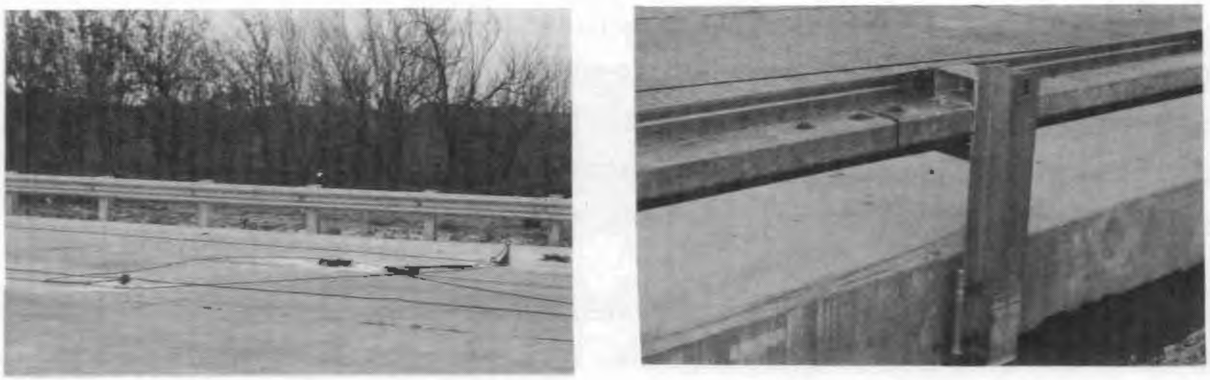


Figure 11. Sequential photographs, Test NBBR-2.



OHBR Test Installation

After Test OHBR-1

After Test OHBR-2

Figure 12. OHBR series photographs.

OHBR-1. The 1980-lb (898-kg) vehicle struck the barrier at 60.6 mph (97.5 km/h) with a 19.6-degree angle as shown in figure 13. The vehicle remained in contact with the barrier for 7.8 ft (2.4 m) during redirection. One section of W-beam sustained minor deformation as shown in figure 12. Vehicle damage is also shown in figure 12.

OHBR-2. The 4790-lb (2172-kg) vehicle struck the barrier at 60 mph (97 km/h) and a 25-degree angle as shown in figure 14. The vehicle was in contact with the barrier for 12 ft (3.7 m) during redirection. One section of W-beam sustained deformation and the lower corrugation was torn as shown in figure 12. Some bridge deck damage occurred at post 4. Damage to the vehicle and barrier is shown in figure 12.

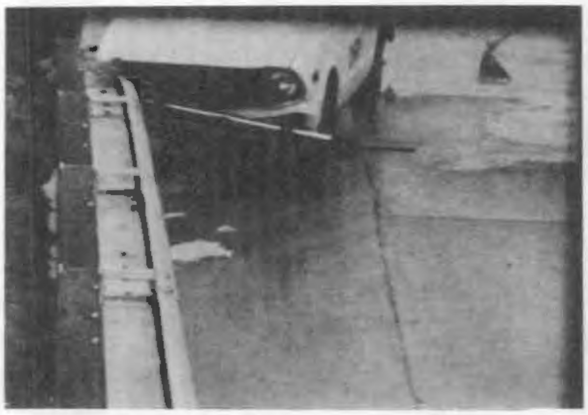
e. NCBR Series

Two tests were conducted on the flat parapet with aluminum railing as shown in figure 15. The system heights include 1 ft-6 in (0.5 m) for the parapet and 2 ft-6 in (0.8 m) for the railing centerline.

NCBR-1. The 1990-lb (903-kg) vehicle struck the barrier at 59.7 mph (96.0 km/h) and an angle of 18 degrees as shown in figure 16. The vehicle remained in contact with the barrier for 7.5 ft (2.3. m) during redirection. There was no barrier deflection or damage as shown in figure 15. Vehicle damage is also shown in figure 15.

NCBR-2. The 4660-lb (2113-kg) vehicle struck the barrier at 60 mph (97 km/h) and a 25-degree angle as shown in figure 17. The vehicle remained in contact with the barrier for 12.6 ft (3.8 m) during redirection. There was no barrier deformation or damage as shown in figure 15. Vehicle damage is also shown in this figure.

IMPACT



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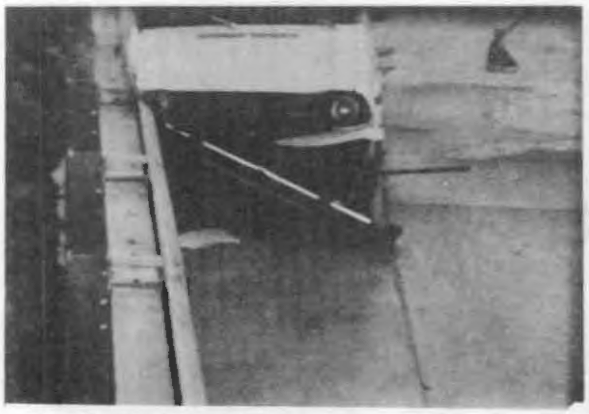

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Figure 13. Sequential photographs, Test OHBR-1.

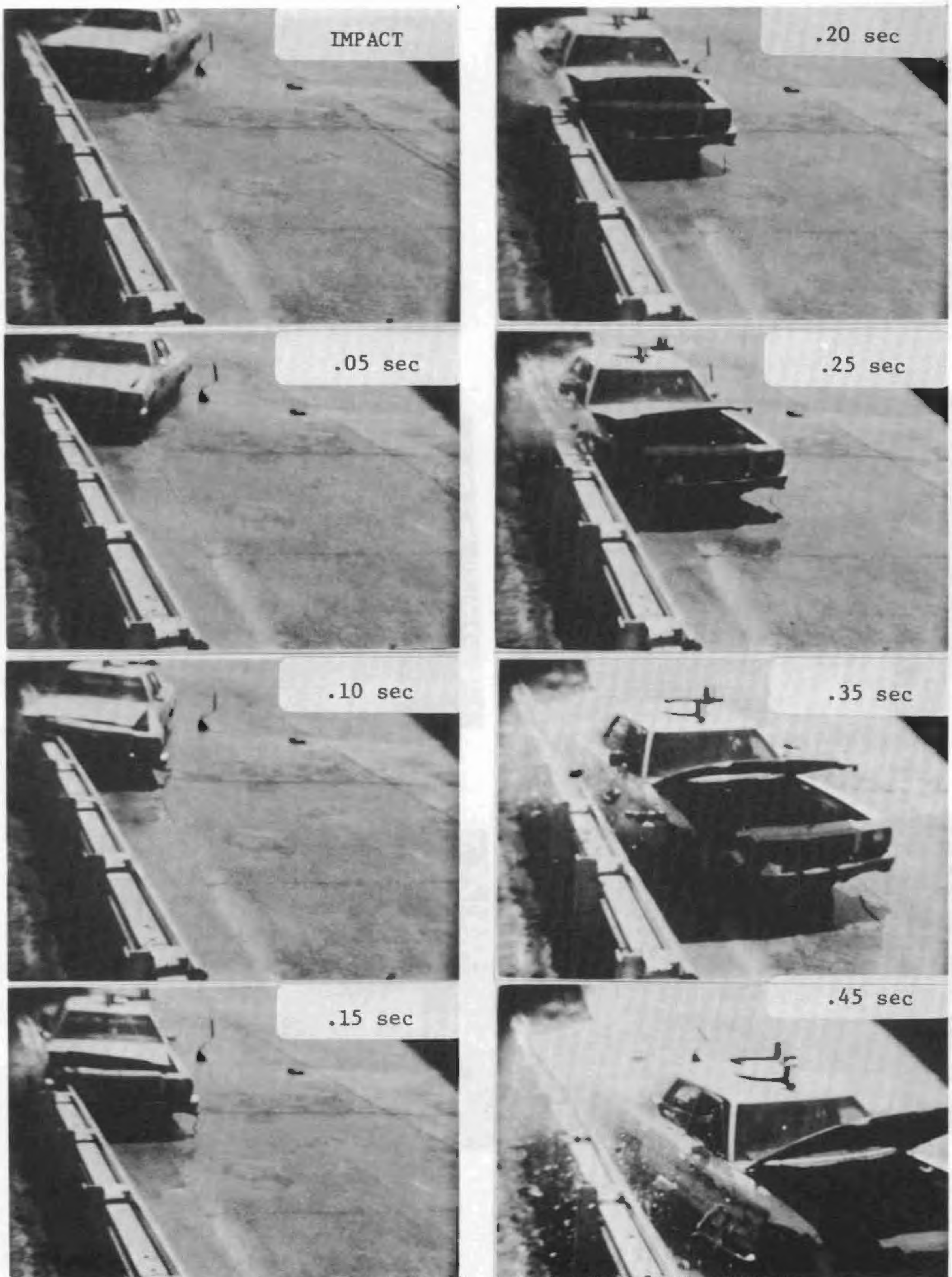
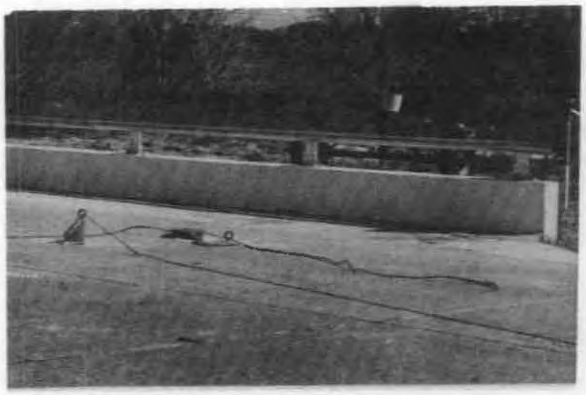
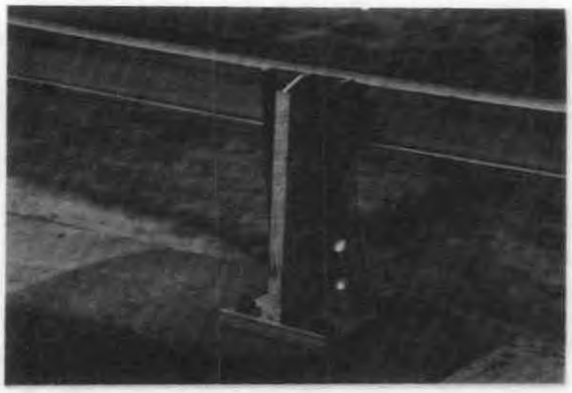


Figure 14. Sequential photographs, Test OHBR-2.





NCBR Test Installation

After Test NCBR-1

After Test NCBR-2.

Figure 15. NCBR series photographs.

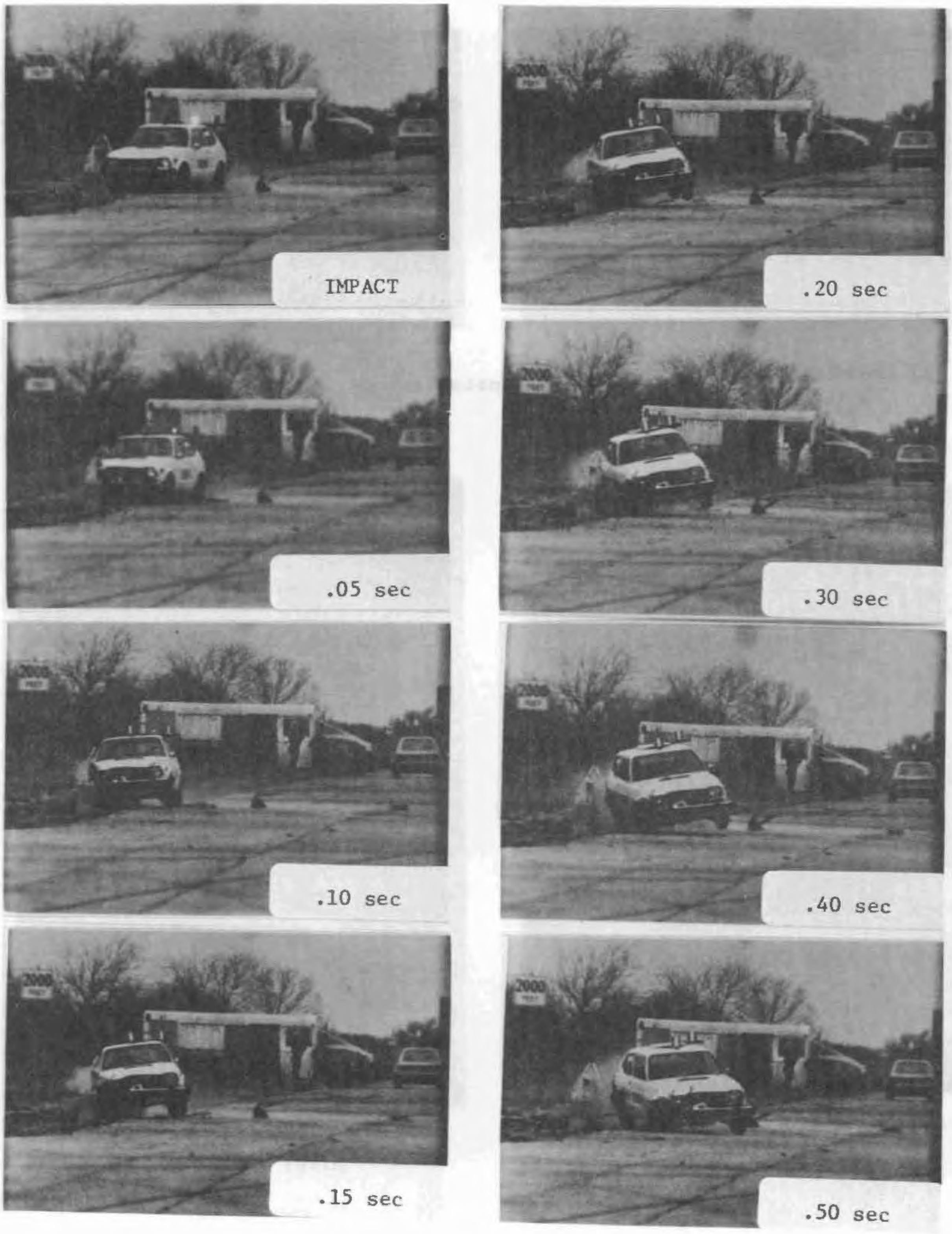


Figure 16. Sequential photographs, Test NCBR-1.

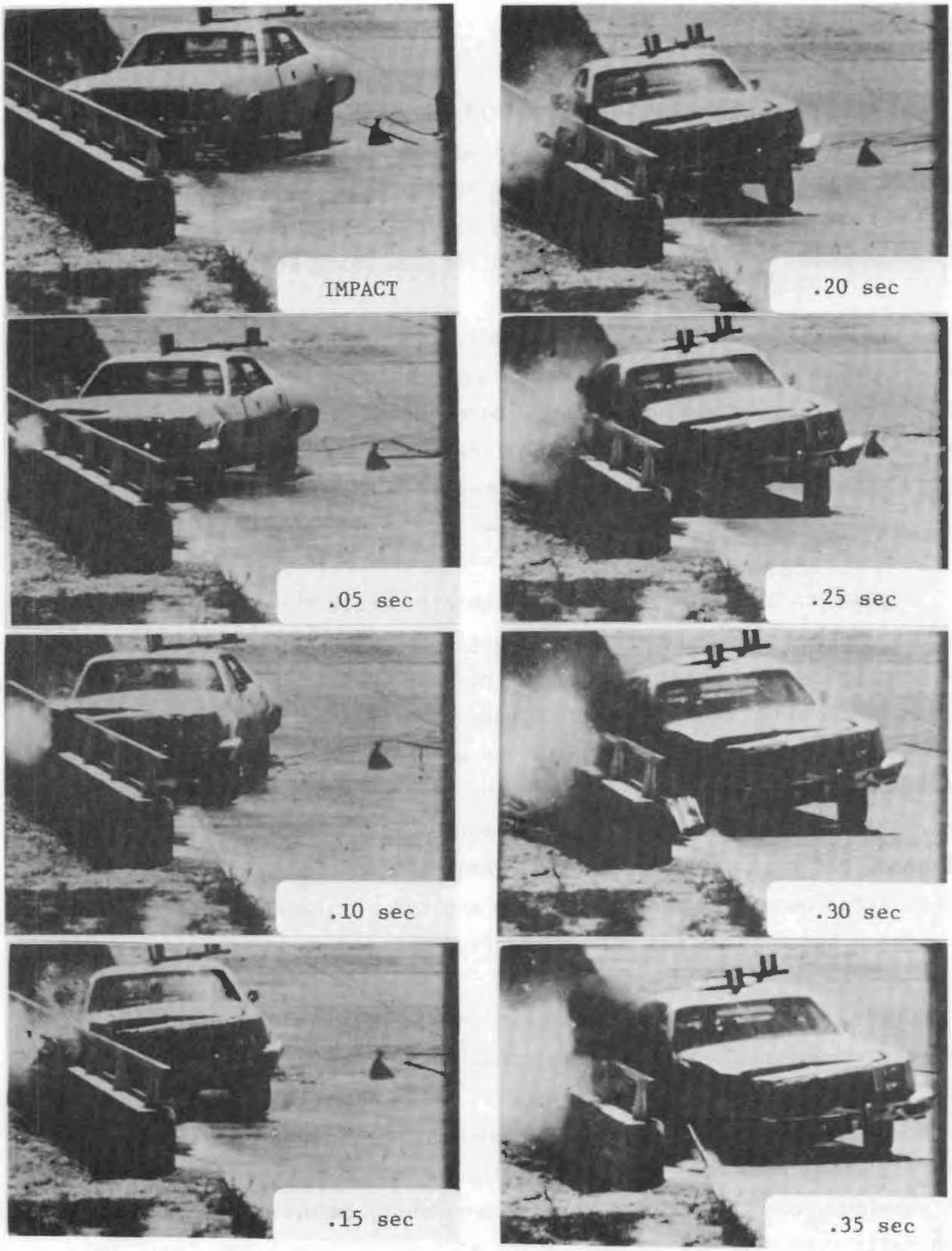


Figure 17. Sequential photographs, Test NCBR-2.

f. OBR Series

Three tests were conducted on this system as shown in figure 18. The first two tests evaluated a three rail system using two 5x5 box beams and an upper 3x5 box beam mounted on posts spaced at 12-ft 6-in (3.8-m) centers. As a result of hood snagging with full-size sedan, the upper rail was eliminated, and the post shortened for the third test.

OBR-1. The 1994-lb (904-kg) vehicle struck the barrier at 58.6 mph (94.4 km/h) and an 18.8-degree impact angle as shown in figure 19. The vehicle remained in contact with the barrier for 8.8 ft (2.7 m) during redirection. There was no barrier deflection or damage as shown in figure 18. There was no evidence of vehicle contact with the upper railing. Vehicle damage is shown in figure 18.

OBR-2. The 4760-lb (2159-kg) vehicle struck the barrier at 60.8 mph (98.0 km/h) and a 24.3-degree impact angle as shown in figure 20. During the impact the hood snagged on post 3 between the upper and middle rails, causing detachment from the right hinge. The detachment allowed the hood to translate rearward and penetrate the windshield on the passenger side. The vehicle remained in contact with the barrier for 9.5 ft (2.9 m) during redirection. The maximum dynamic deflection was not obtained; the maximum permanent deflection was 5.5 in (14.0 cm) at the middle railing. The lower two railings were permanently deformed and the slab was extensively damaged at posts 2 and 3. The vehicle and barrier damage are shown in figure 18.

OBR-3. Based on the previous hood snagging results the top railing was removed and posts shortened for this test. The 4640-lb (2104-kg) vehicle struck the barrier at 60 mph (97 km/h) and a 25-degree impact angle as shown in figure 21. The vehicle remained in contact with the barrier for 11.3 ft (3.4 m) during redirection. The maximum dynamic deflection was not obtained, but the upper rail was permanently deformed 2.0 in (5.1 cm). Both rails were deformed in the impact area and the deck was fractured behind post 4 as shown in figure 18. Vehicle damage is shown in figure 18.

OBR Test Installation

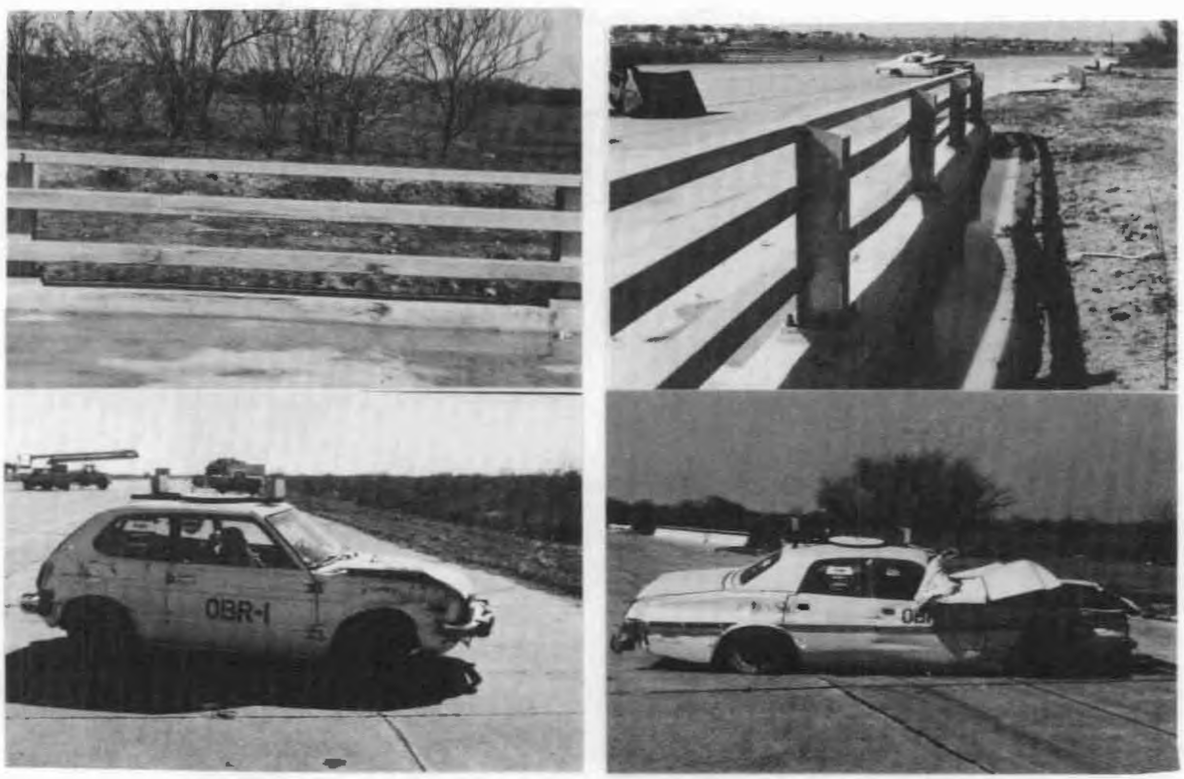
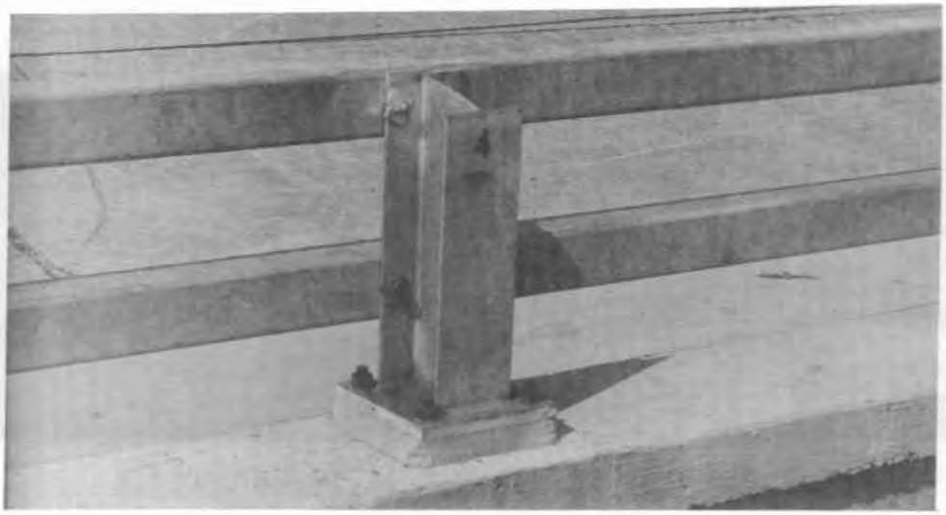


Figure 18. OBR series photographs.



OBR-3 Test Installation

After Test OBR-3

Figure 18. OBR series photographs (continued).

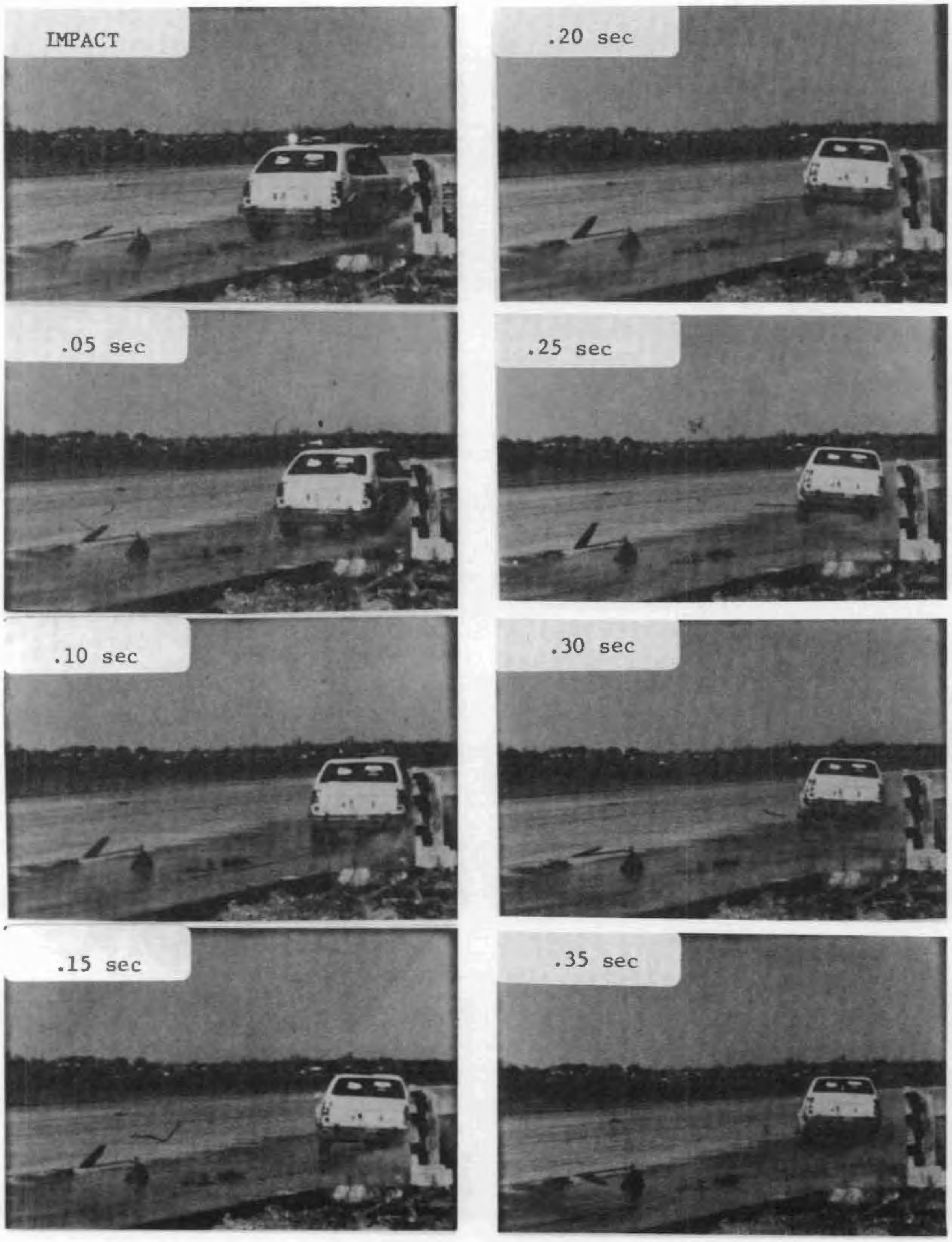


Figure 19. Sequential photographs, Test OBR-1.

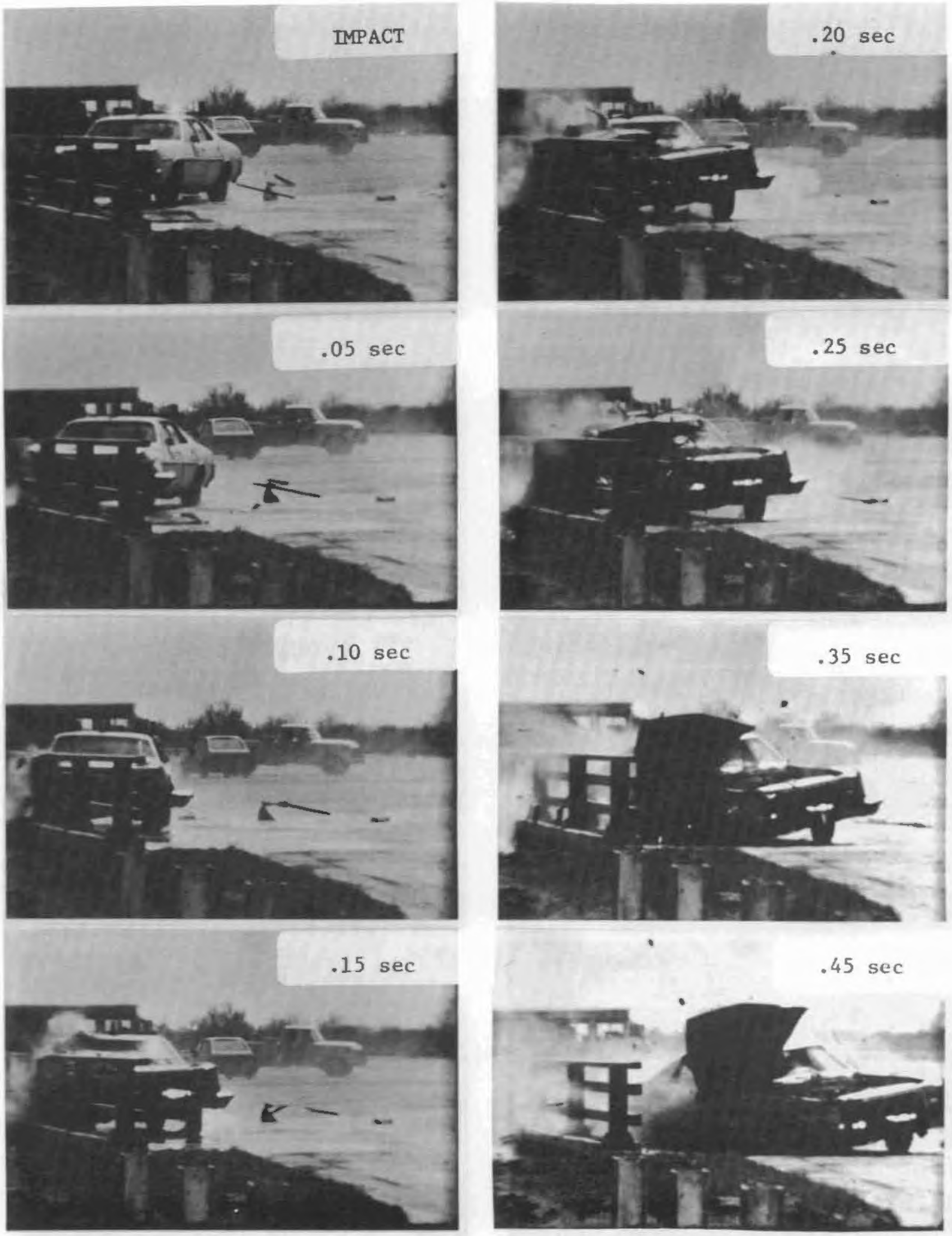


Figure 20. Sequential photographs, Test OBR-2.

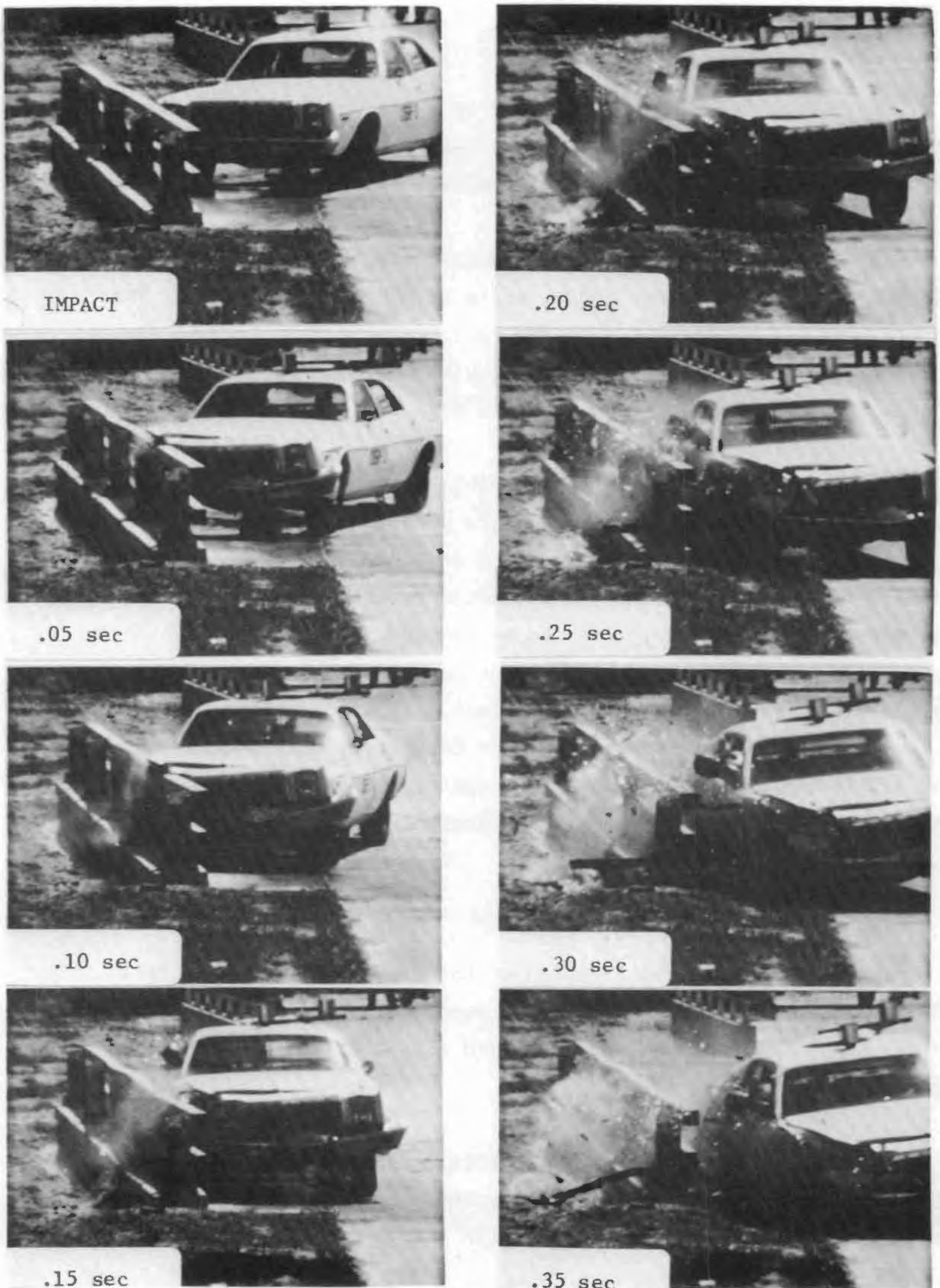


Figure 21. Sequential photographs, Test OBR-3.

g. KBR Series

The system as shown in figure 22 is a concrete beam/post design. A unique feature of this design is the 0.5-in (1.3-cm) gap between post segments as shown. Two tests were conducted on this system.

KBR-1. The 1971-lb (894-kg) vehicle struck the barrier at 61.9 mph (99.5 km/h) and 20.3-degree impact angle as shown in figure 23. The vehicle remained in contact with the railing for 7.5 ft (2.3 m) during redirection. Front tire/wheel contact with the edge of post 5 was noted. Vehicle and barrier damage are shown in figure 22.

KBR-2. The 4660-lb (2113-kg) vehicle struck the barrier at 60.5 mph (97.3 km/h) and 24.0-degree impact angle as shown in figure 24. The concrete beam and posts 3A and 3B began to fracture at 0.07 seconds after impact. After these failures, the vehicle snagged on post 4B, causing the entire right side of the vehicle to be removed. This caused passenger compartment intrusion by the beam. The passenger dummy was ejected from the vehicle and decapitated. The vehicle initial contact was for 15.4 ft (4.7 m) and the vehicle recontacted the barrier at post 6 before coming to rest 9.5 ft (29 m) from the point of impact. As shown in figure 22, both vehicle and barrier were extensively damaged.

h. MKS Series

This design is a modification of the KS design which basically consisted of adding longitudinal beam steel and stirrups in both beam and posts. The 0.5 in (1.3 cm) gap remained a part of the design as shown in figure 25.

MKS-1. The 1971-lb (839-kg) vehicle struck the barrier at 59.0 mph (95.0 km/h) and a 18.9-degree angle as shown in figure 26. The vehicle remained in contact with the barrier for 7.8 ft (2.4 in) during

KBR Test Installation

After Test KBR-1

After Test KBR-2

Figure 22. KBR series photographs.

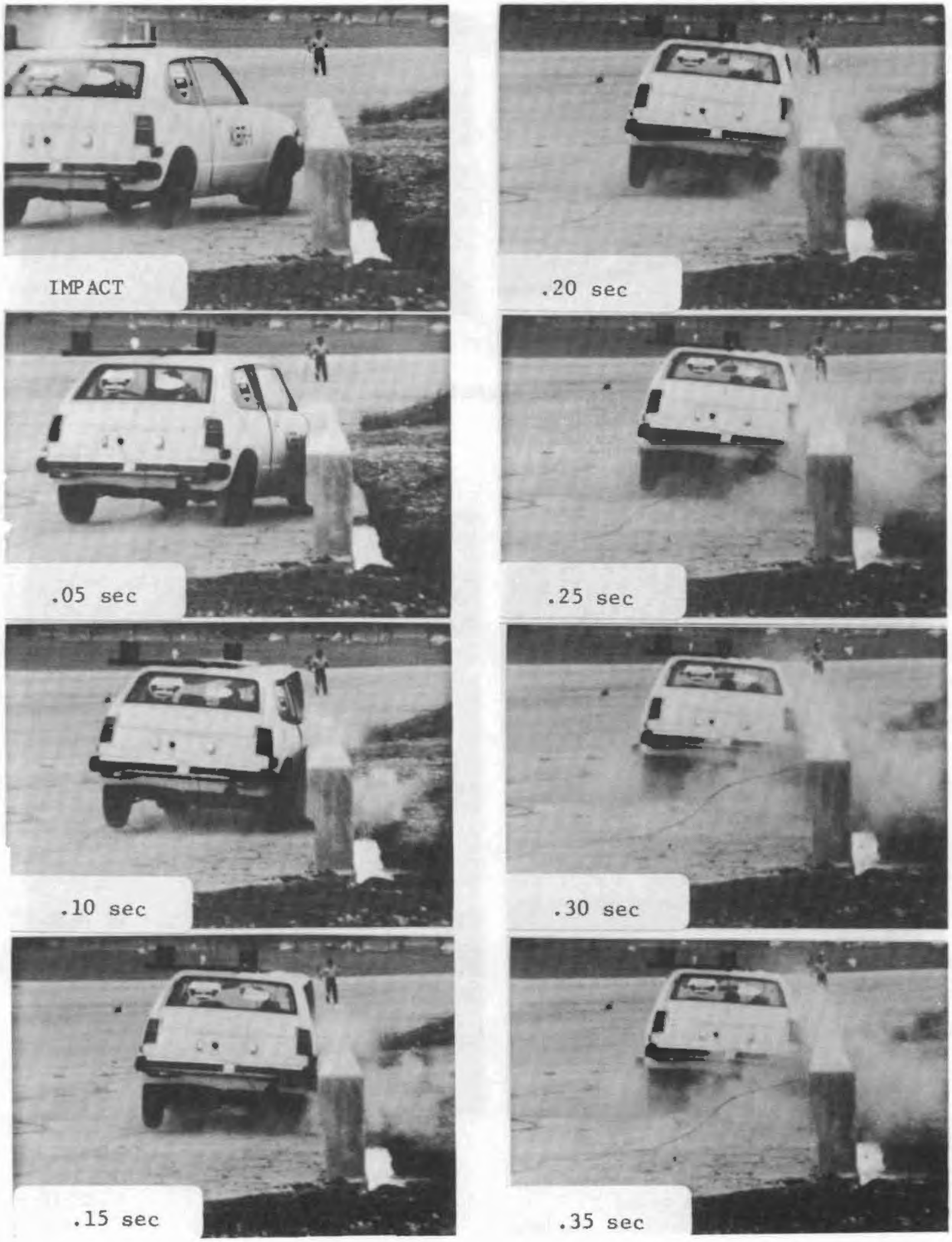


Figure 23. Sequential photographs, Test KBR-1.

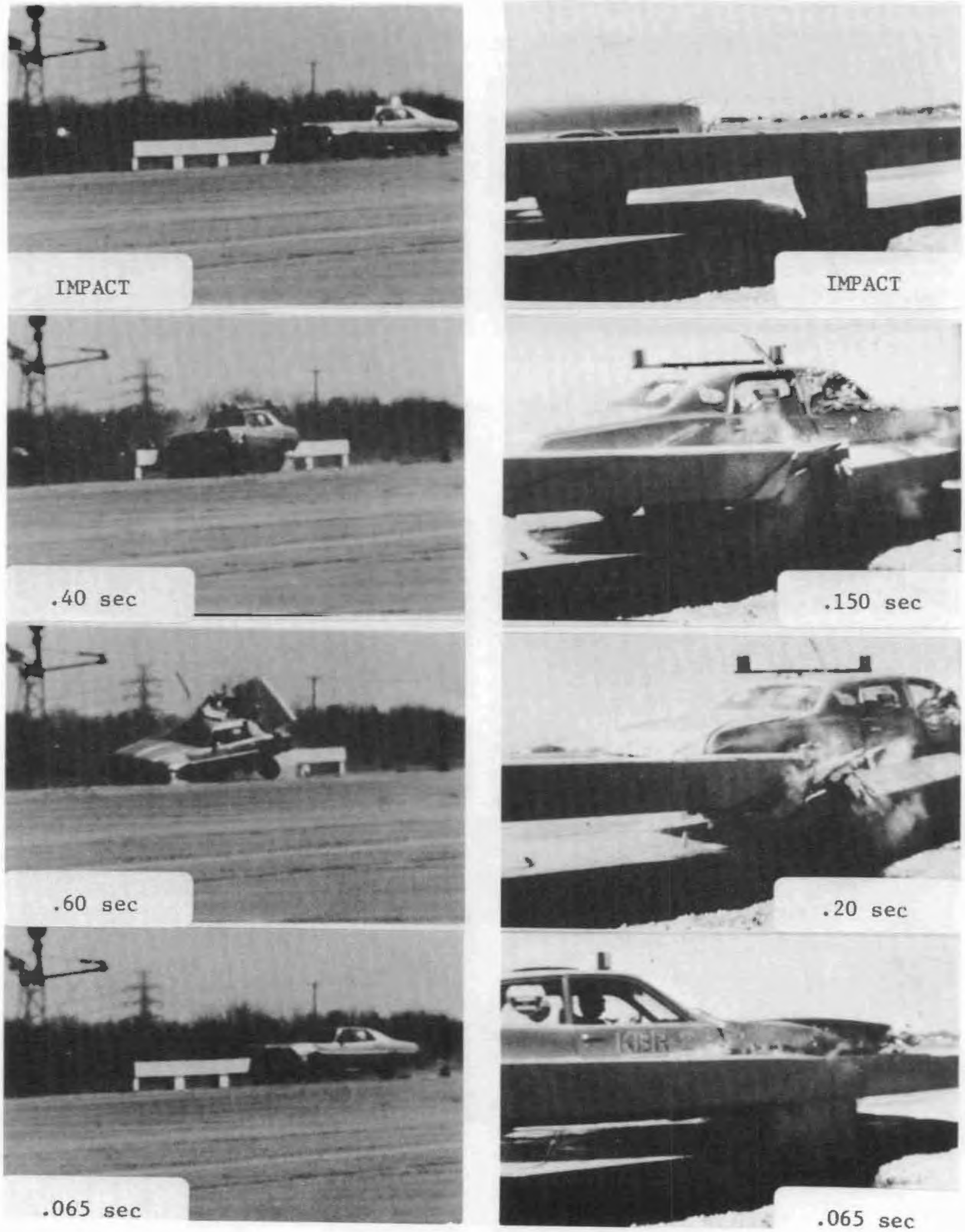


Figure 24. Sequential photographs, Test KBR-2.

MKS Test Installation

After Test MKS-1

After Test MKS-2

Figure 25. MKS series photographs.

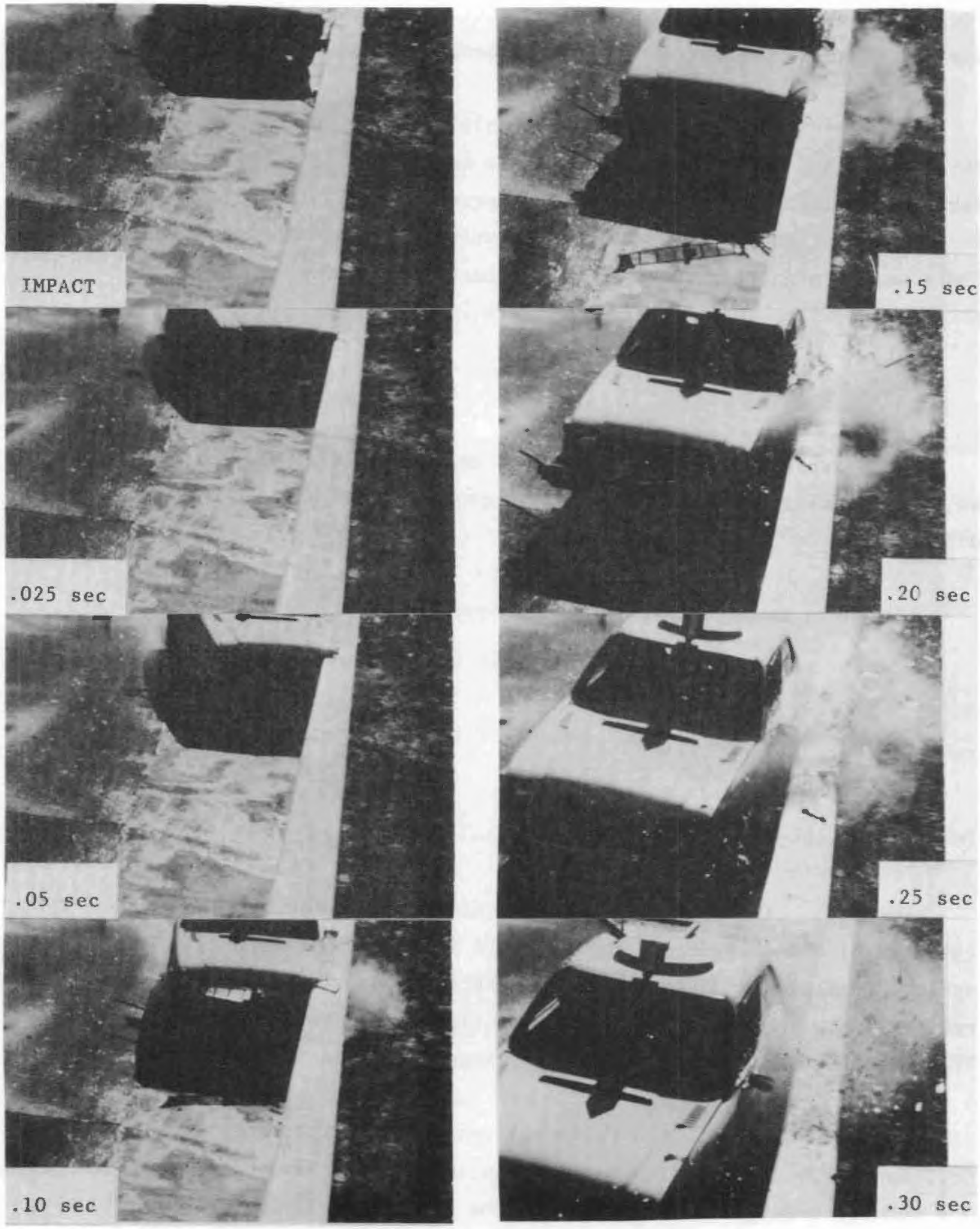


Figure 26. Sequential photographs, Test MKS-1.

redirection. There was tire/wheel contact on the edge of post 4. There was no damage to the barrier. Vehicle damage is shown in figure 25.

MKS-2. The 4690-lb (2127-kg) vehicle struck the barrier at 59.2 mph (95.3 km/h) and 24.9-degree impact angle as shown in figure 27. The vehicle remained in contact with the barrier for 12.2 ft (3.7 m) during redirection. There was no evidence of wheel contact with a post edge. There was no significant damage to the barrier. Vehicle and barrier photographs after the test are in figure 25.

i. OKBR Series

This series evaluated a concrete beam/post system shown in figure 28 which was similar to the KS and MKS in geometry, but with some significant differences:

1. There was no gap in the beam/post.
2. The overhang of beam was 4.5 in (11.4 cm) as compared to 2 in (5 cm) for the KS and MKS.
3. The width and overall height of the beam was greater than the KS and MKS designs.

The system was evaluated in two tests.

OKBR-1. The 1980-lb (898-kg) vehicle struck the barrier at 58.7 mph (94.5 km/h) and 18.9-degree impact angle as shown in figure 29. The vehicle remained in contact with the barrier for 9.1 ft (2.8 m) during redirection. There was no evidence of tire/wheel contact with a post edge. There was no barrier damage; vehicle damage is shown in figure 28.

OKBR-2. The 4660-lb (2113-kg) vehicle struck the barrier at 58.7 mph (94.5 km/h) and an 18.9-degree impact angle as shown in figure 30. The vehicle remained in contact with the barrier for 13.8 ft (4.2 m) during redirection. There was no evidence of tire/wheel contact with a post edge.

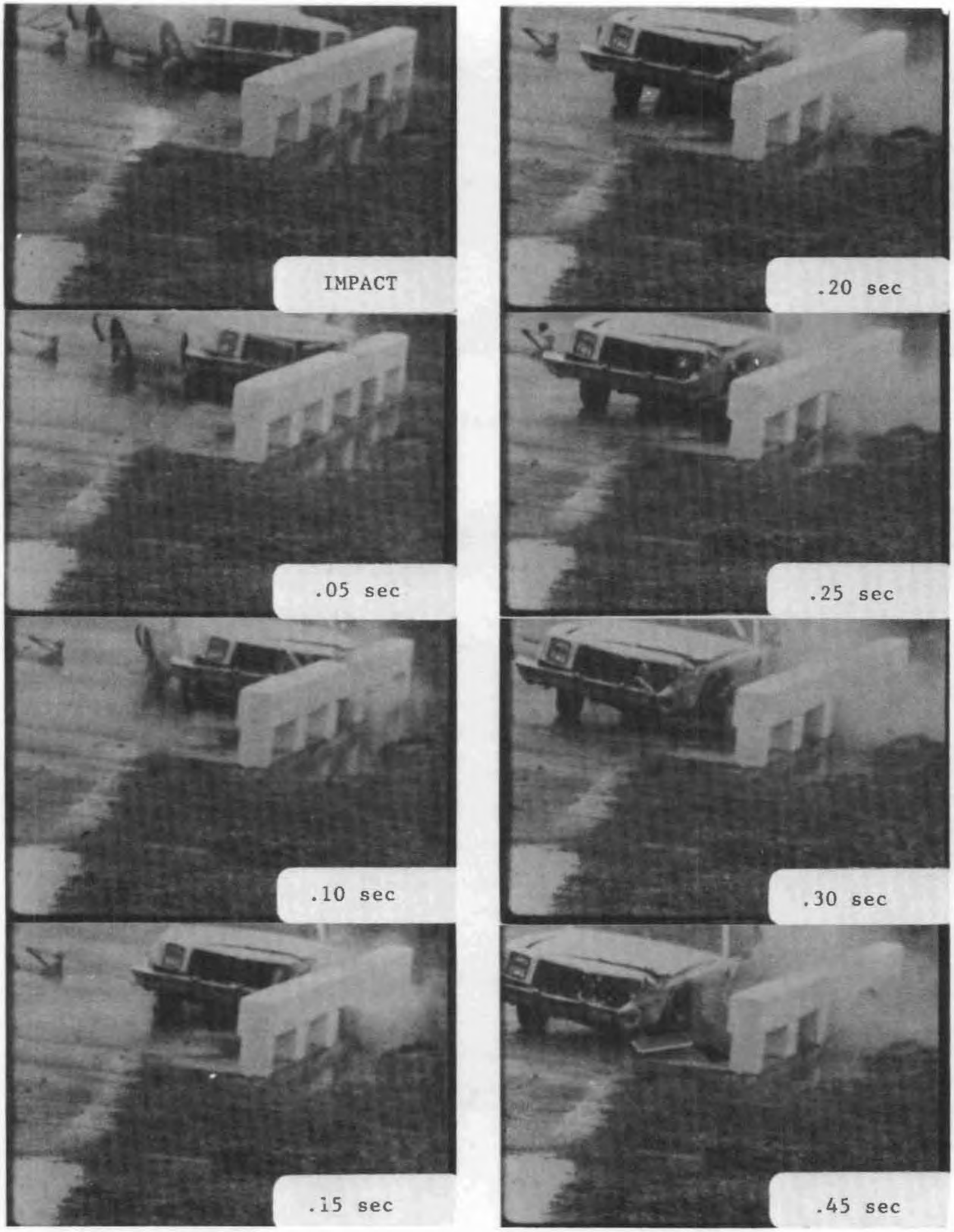
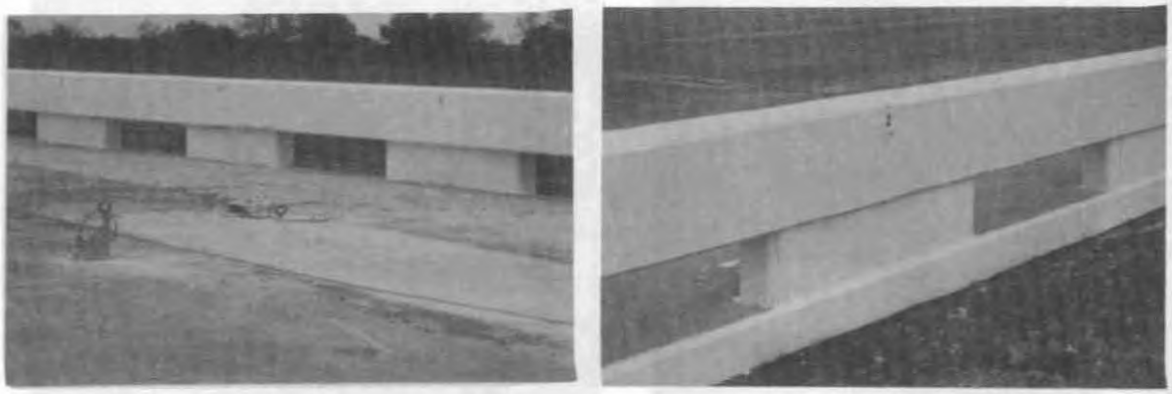


Figure 27. Sequential photographs, Test MKS-2.



OKBR Test Installation

After Test OKBR-1

After Test OKBR-2

Figure 28. OKBR series photographs.

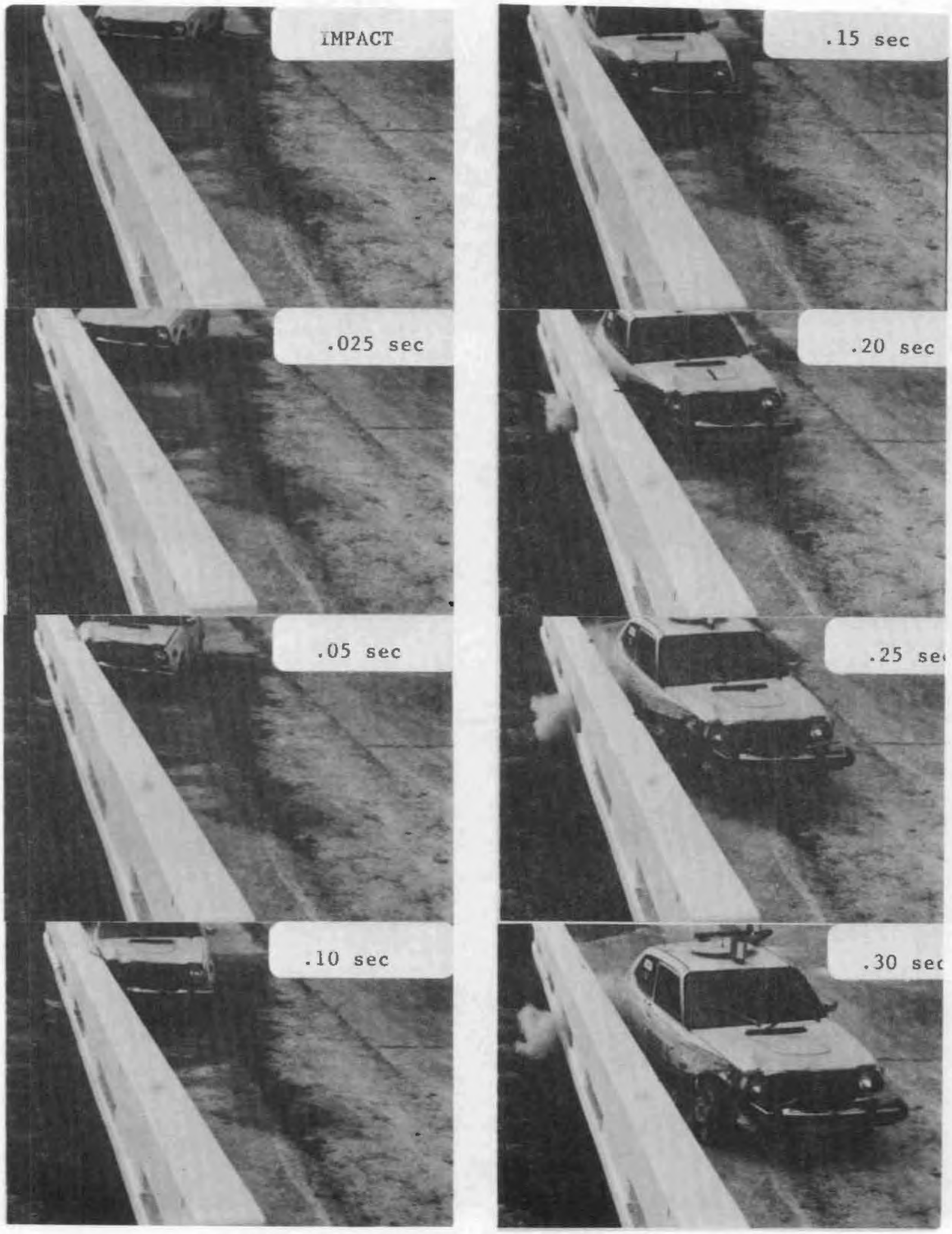


Figure 29. Sequential photographs, Test OKBR-1.

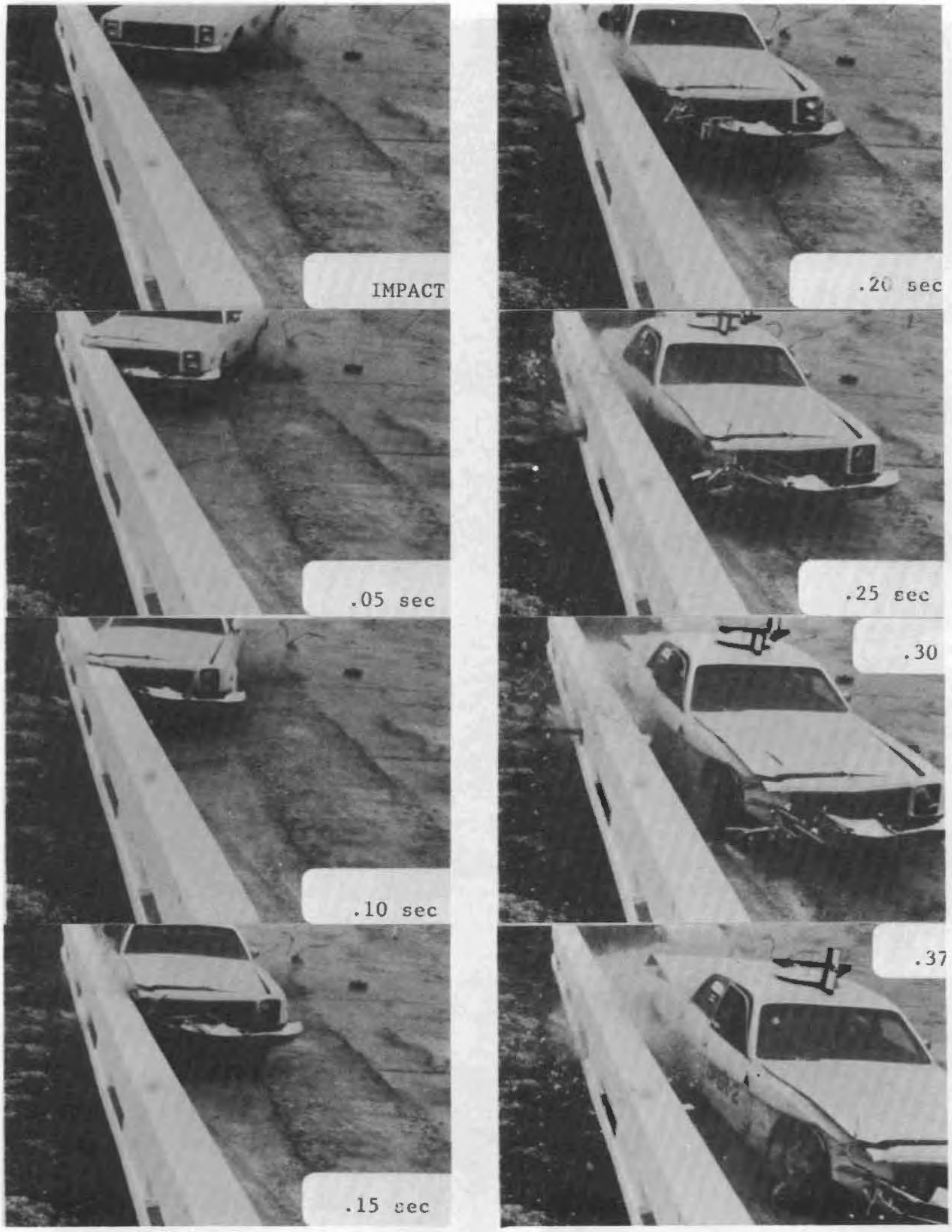


Figure 30. Sequential photographs, Test OKBR-2.

There were some hairline cracks on the backside of the beam and diagonal shear cracks were also noted in the deck from the front face of post 3 to the rear of the deck. Vehicle and barrier photographs after the test are in figure 28.

j. LABR Series

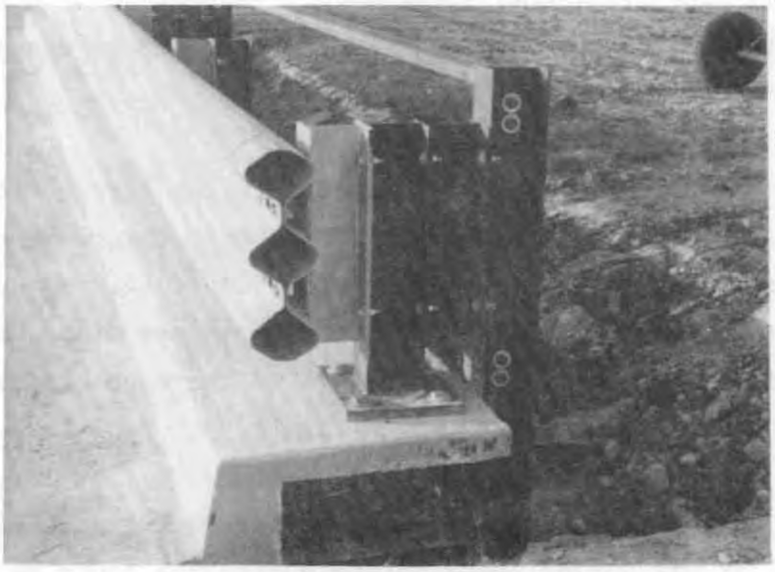
This series of tests evaluated three different barrier configurations involving a tubular thrie beam retrofit of an existing ballaster rail as shown in figure 31. The first configuration was evaluated for both minicar and full-size sedan impacts. The last two configurations were evaluated for minicar performance only.

LABR-1. The 1900-lb (862-kg) vehicle struck the barrier at 60.4 mph (97.2 km/h) at an 18.8-degree impact angle as shown in figure 32. The vehicle remained in contact with the barrier for 7.1 ft (2.2 m) during redirection. One section of tubular thrie beam sustained minor deformation in the impact area. Minor cracks were observed in the curb at posts 3 and 4. Vehicle and barrier damage are shown in figure 33.

LABR-2. Due to the cracking of the curb around the anchor bolts in the previous test, it was conjectured that this cracking could be a potential maintenance problem. Accordingly, the anchor bolts were removed before the next test along with the attaching clip angle.

The 4635-lb (2104-kg) car struck the barrier at 59.7 mph (96.0 km/h) and a 19.1-degree impact angle as shown in figure 34. The vehicle remained in contact with the barrier for 13.0 ft (4.0 m) during redirection. No significant vehicle snagging occurred and maximum dynamic deflection was 3.0 in (7.6 cm). Posts 3 and 4 were permanently displaced, but to a minimal extent. One section of tubular thrie beam sustained minor deflection. Vehicle and barrier damage are shown in the photographs of figure 33.

LABR-1 & 2 Test Installation



LABR-3 Test Installation

LABR-4 Test Installation

Figure 31. LABR series test installations.

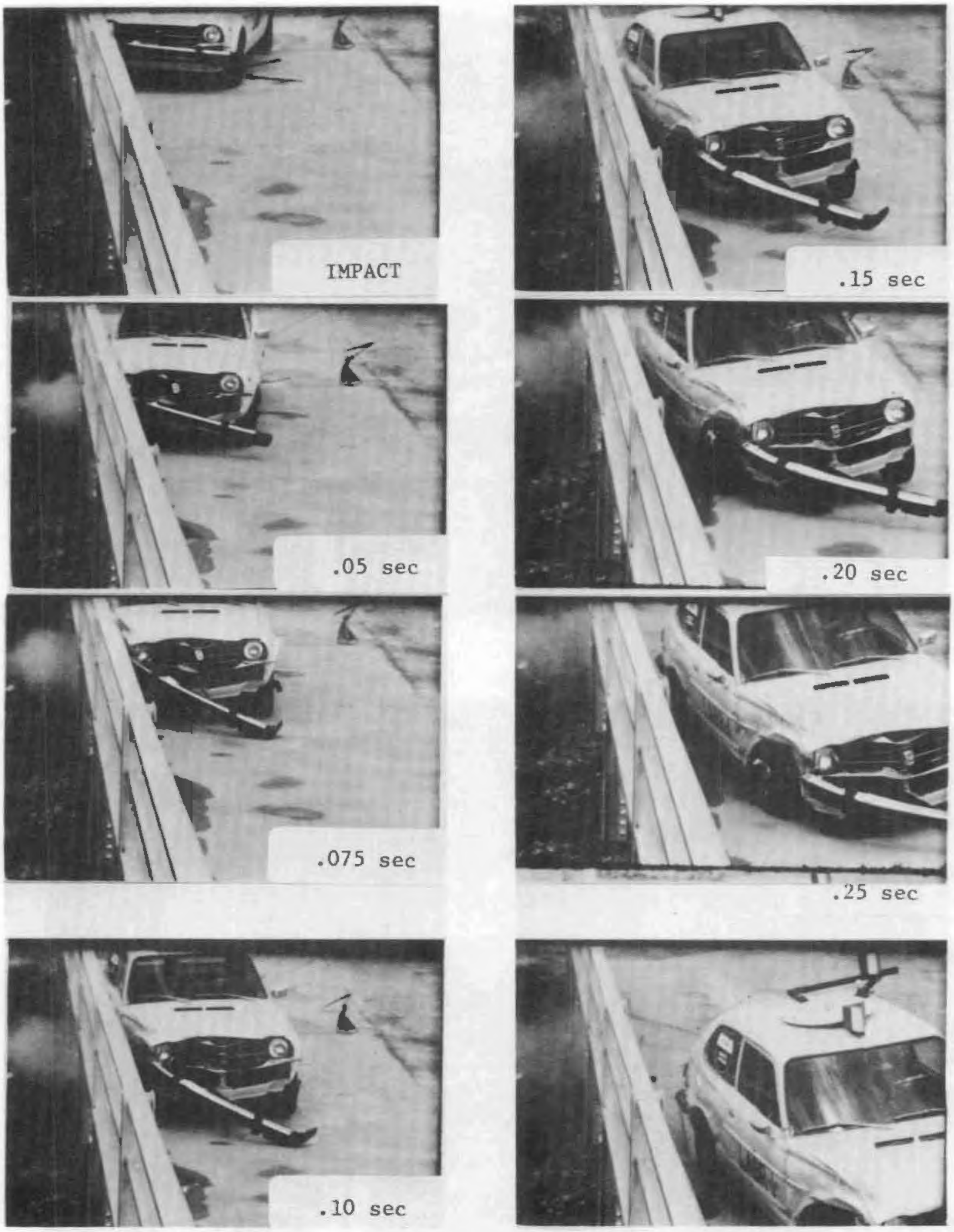


Figure 32. Sequential photographs, Test LABR-1.

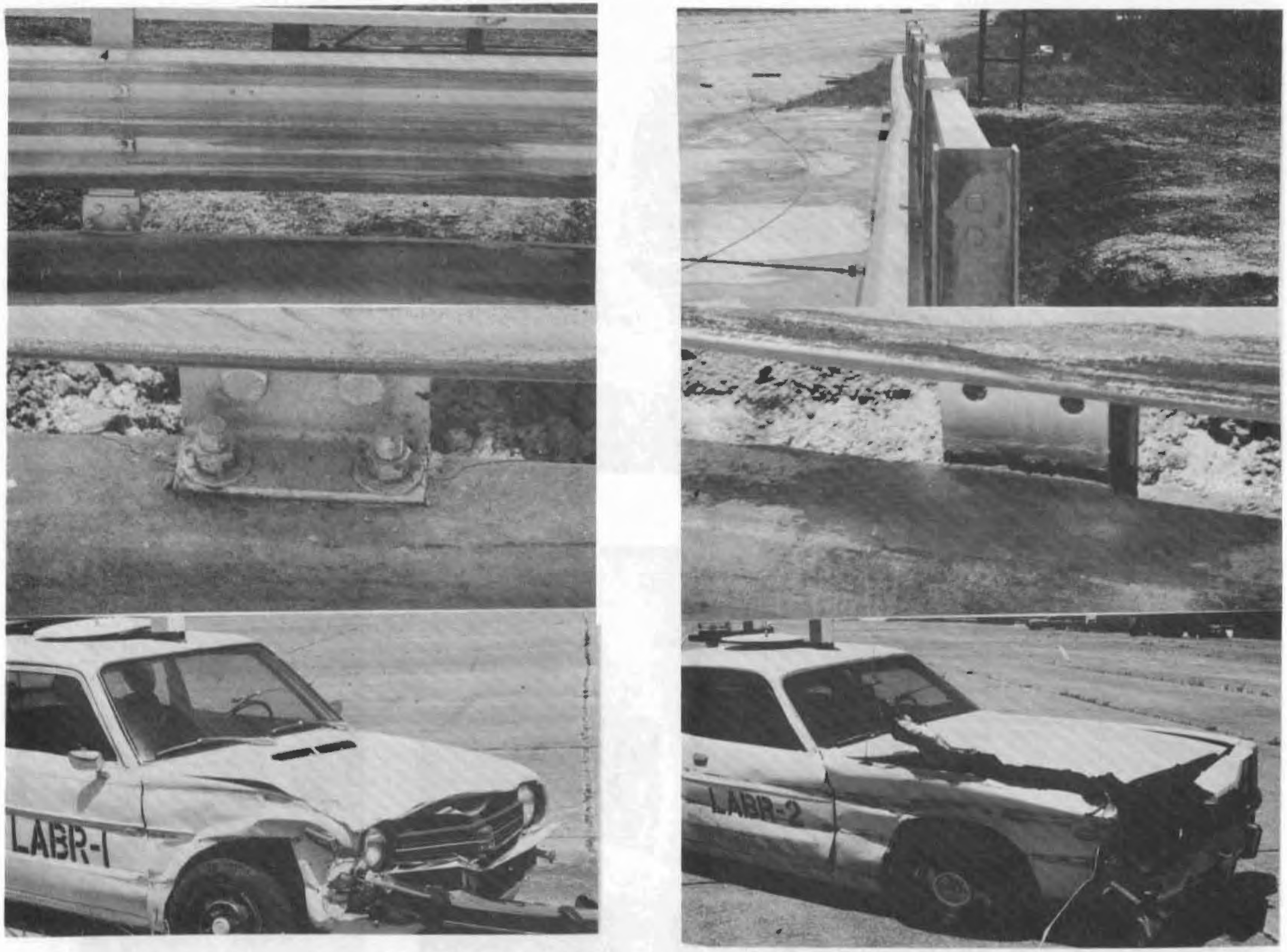


Figure 33. LABR-1 and LABR-2 after-test photographs.

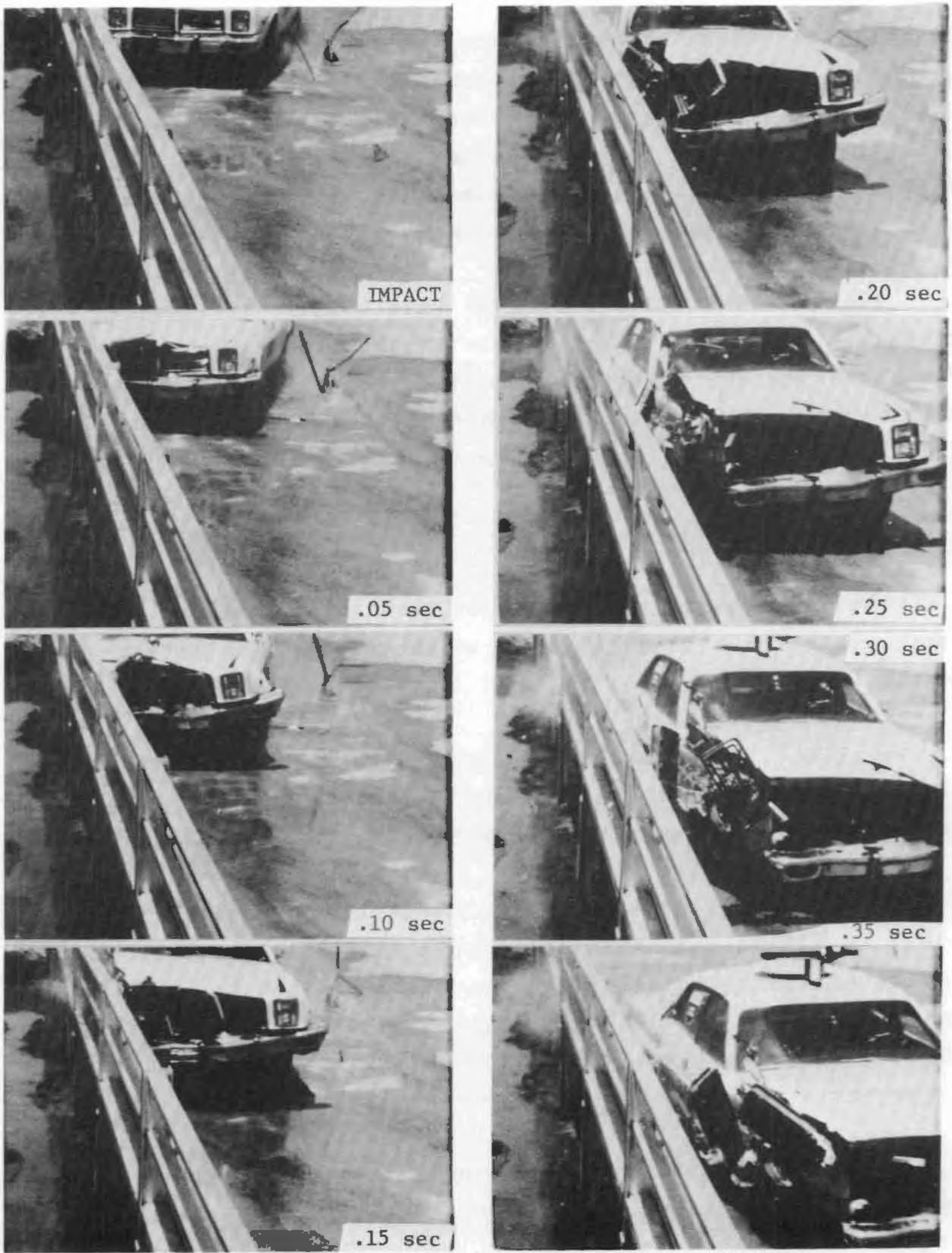


Figure 34. Sequential photographs, Test LABR-2.

LABR-3. This test evaluated the retrofit #2 installed with a safety walk. The 1990-lb (903-kg) vehicle struck the barrier at 59.7 mph (96.0 km/h) and an angle of 18.7 degrees. The vehicle was redirected as shown in figure 35 with a maximum barrier deflection of 3.0 in (7.6 cm). Damage to the retrofit system was minimal with the exception of significant cracking of the sidewalk as shown in figure 36.

LABR-4. This test evaluated the retrofit #3 design installed with the curb. The 1965-lb (890-kg) vehicle struck the barrier at 59.9 mph (96.4 km/h) and 20.3 degrees as shown in figure 37. The vehicle was smoothly redirected after a maximum dynamic deflection of 4.2 in (10.7 cm). Vehicle and barrier damage are shown in figure 36.

k. 3400-lb (1530-kg) Vehicle Tests

Two tests were conducted using the downsized sedan with minimal impact conditions of 60 mph (95 km/h) and 20 degrees. The tests are briefly described:

• BLNV-1. The aluminum railing from the NBR series was removed and the height of the concrete safety shape (New Jersey) increased to 32 in (80 cm) for the tests as shown in figure 38.

• The 3380-lb (1534-kg) vehicle struck the barrier at 62.3 mph (100.2 km/h) and a 19.6-degree impact angle as shown in figure 39. The vehicle remained in contact with the barrier for 10.5 ft (3.2 m) before smooth redirection at a 1.8-degree angle. The maximum vehicle roll angle was 12 degrees (away from the barrier). No damage occurred to the barrier; damage to the vehicle is shown in figure 38.

• BLO-1. This test evaluated the OBR two-rail system for a 60 mph (95 km/h), 20-degree angle impact with a 3400-lb (1530-kg) car.

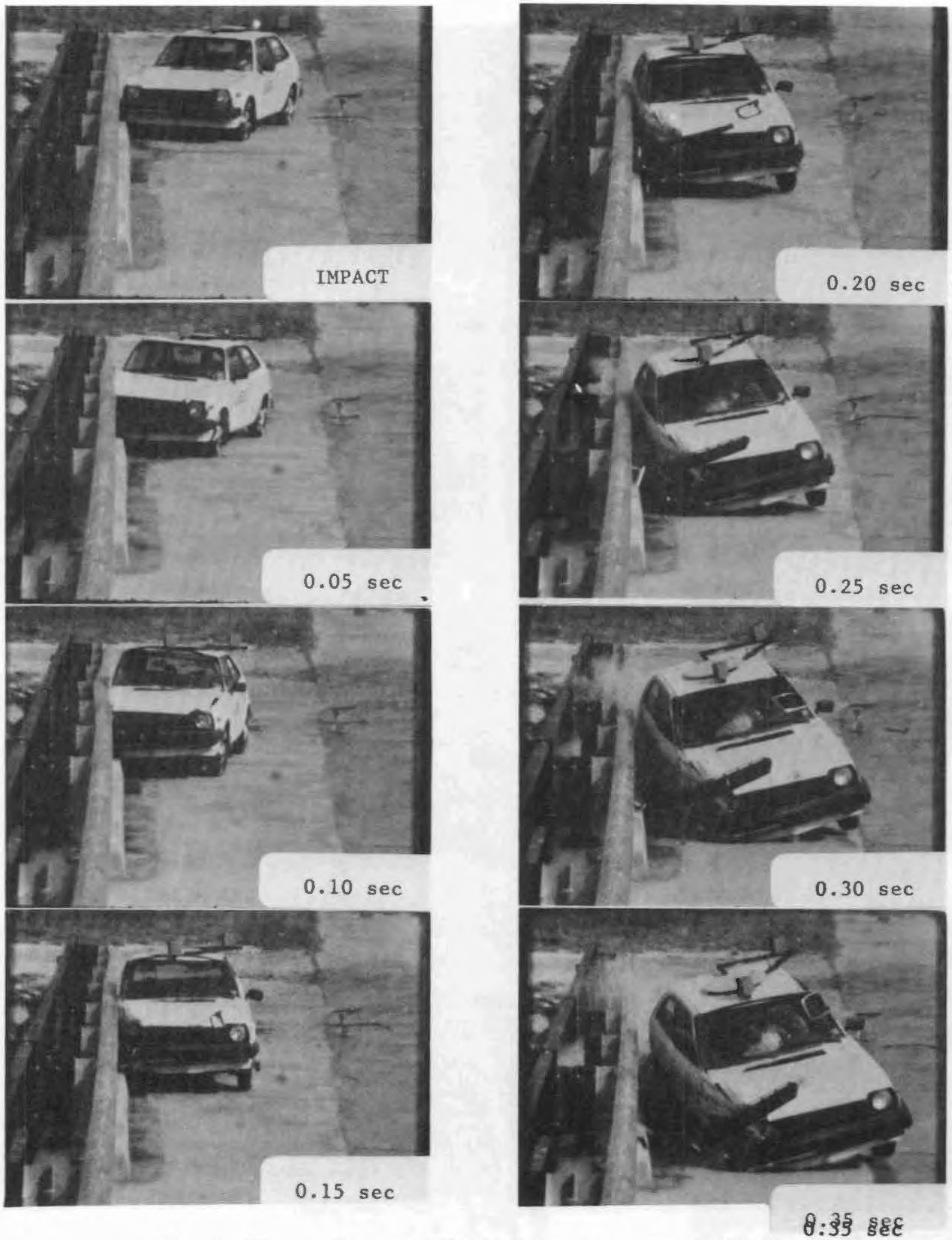


Figure 35. Sequential photographs, Test LABR-3.

LABR-3 After Test

LABR-4 After Test

Figure 36. LABR-3 and LABR-4 series photographs.

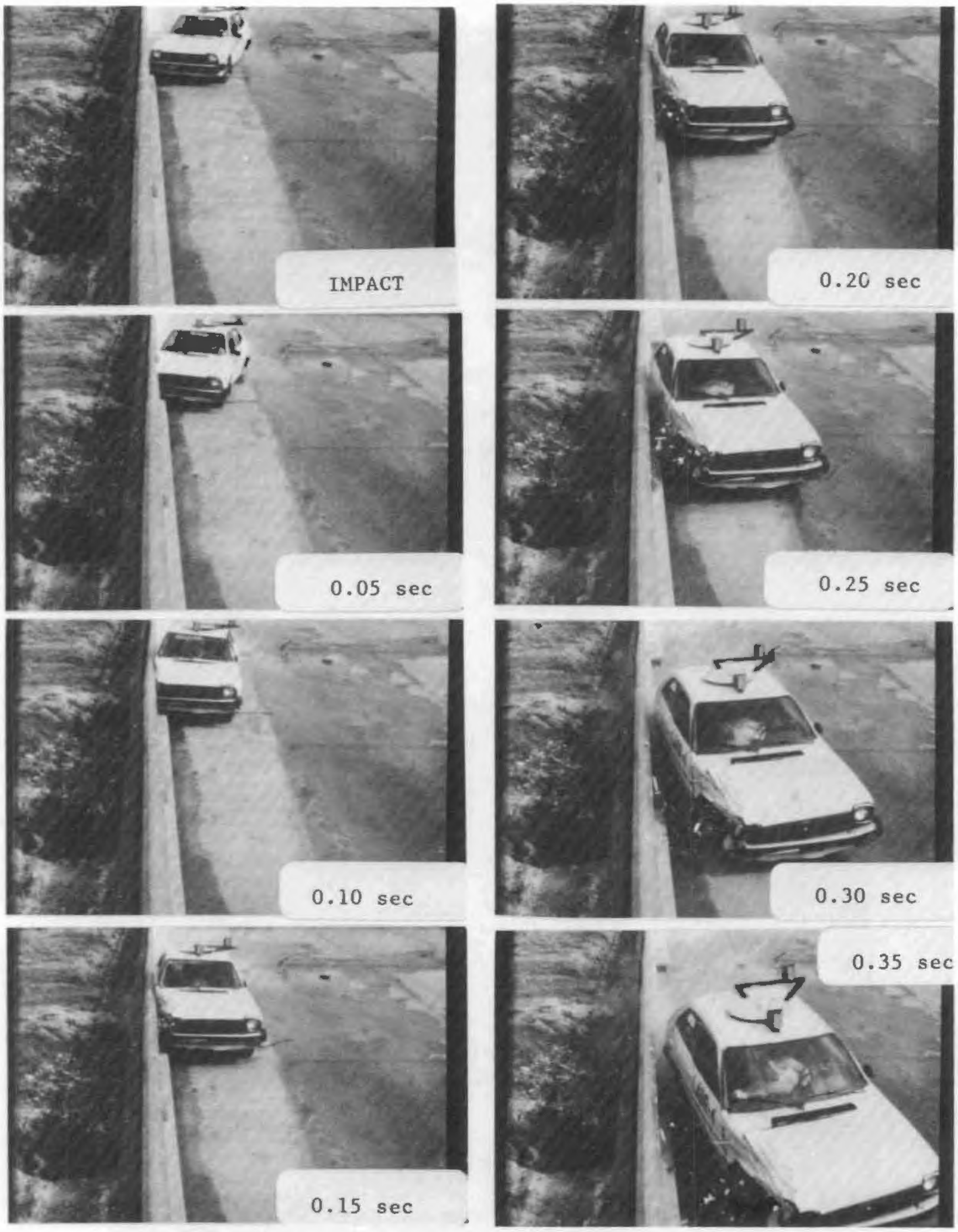
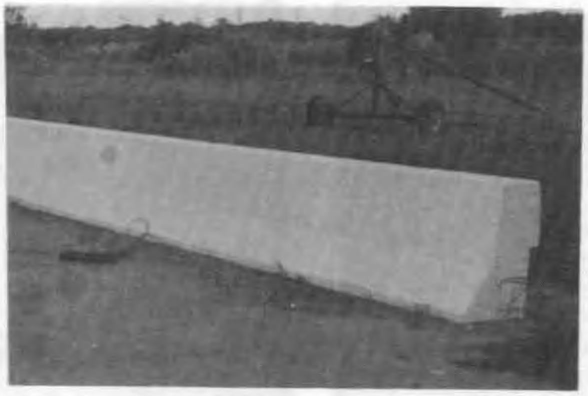


Figure 37. Sequential photographs, Test LABR-4.



BLNV Test Installation

BLNV-1 After Test

Figure 38. 3400-lb vehicle baseline series photographs.

BLO After Test

Figure 38. 3400-lb vehicle baseline series photographs (continued).

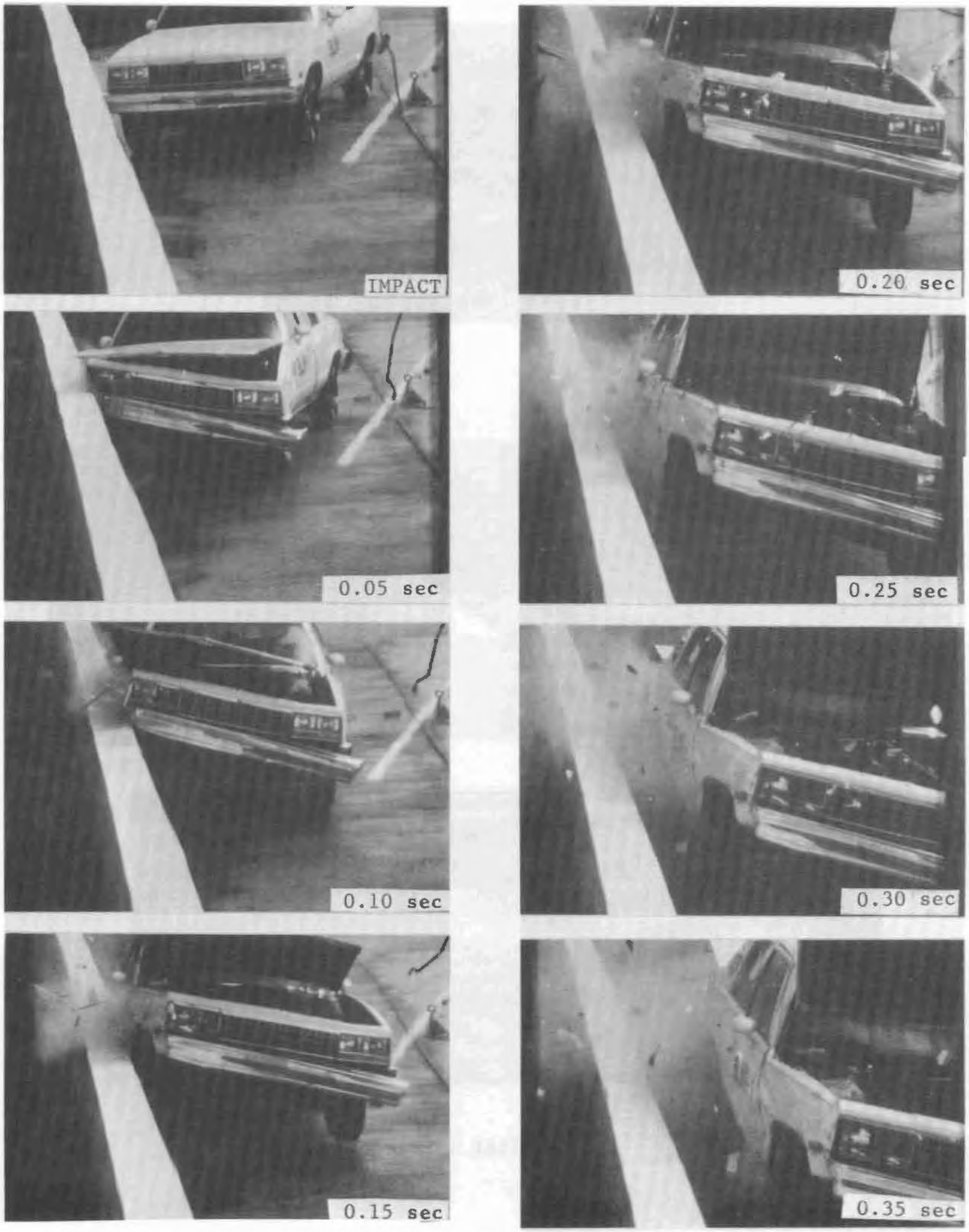


Figure 39. Sequential photographs, Test BLNV-1.

• The 3450-lb (1566-kg) vehicle struck the barrier at 62.5 mph (100.6 km/h) and an angle of 20.7 degrees. As shown in figure 40, the vehicle was smoothly redirected after a maximum dynamic deflection of 3.9 in (10.0 cm). Damage to the vehicle and barrier are shown in figure 38.

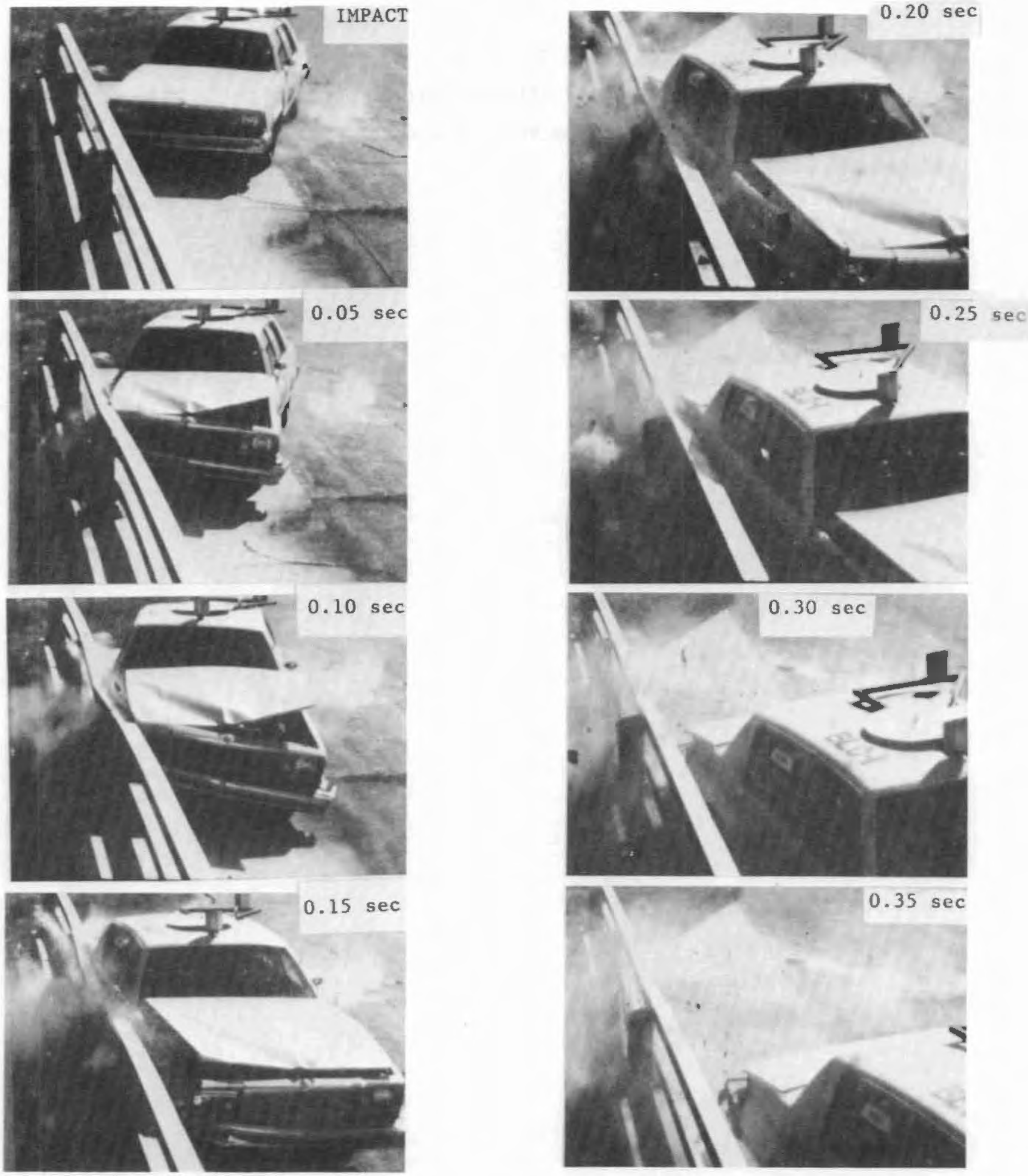


Figure 40. Sequential photographs, Test BLO-1.

5. Upgrading of Bridge Rail Designs

For the most part, the barriers evaluated in this project performed in an acceptable manner, and there was little need for redesign. The notable exception to this was the KBR bridge rail system which sustained a failure in the full-size sedan test. Another system failure was due to the vehicle hood snagging on a post segment between rail elements. Other deficiencies noted in the test series were associated with bridge deck anchorage damage. Although the deck failures did not result in system failure, extensive repairs would be necessary in the field for the damaged decks for impacts represented by the full-size car test.

a. KBR Design

Based on the results of the crash test KBR-2, a redesign was required to resist the 4500-lb (2025-kg) car, 60 mph (95 km/h), 25-degree angle impact. Based on analyses, it was determined that stirrups were required in both the beam and the posts in order to meet the ASSHTO 10 kips (450 kg) force requirement. In addition, the longitudinal steel was increased as shown in the analyses of appendix C. The modified design performed satisfactorily as described in crash tests MKS-1 and MKS-2.

b. OBR Design

The configuration evaluated in Tests OBR-1 and OBR-2 used 3 box beams mounted on posts. Passenger compartment intrusion occurred when the 4500-lb (2025-kg) vehicle hood snagged on the post segment between the upper two rails. A retest with the upper rail and post segment removed resulted in satisfactory performance although some cracking of the deck occurred at the anchorage.

c. Deck/Anchorage Damage

Several of the designs tested resulted in moderate to severe deck damage. Although system failure did not result from any of these occurrences, it may be desirable to reevaluate the anchorage design to prevent costly repairs. The systems with visible anchorage damage are briefly discussed.

- NBBR. The system drawing specifies maximum pullout load values for 3/4 in (1.9 cm) inserts and 1 in (2.5 cm) inserts of 3000 and 4000 lb (1360 and 1810 kg), respectively. In order to minimize the deck damage, the anchorage requirements could be increased to develop the ultimate strength of the post which would require about 20 kips (9000 kg) capacity based on the same anchorage geometry.

- OBR. Considerable cracking of the slab occurred in the full-size car tests of this system. The anchorage design would have to be considerably strengthened to avoid damage for severe impacts characterized by the full-size car test.

6. Bridge Railing Geometrics

Geometrical consideration of bridge railings include:

a. Effective height of railing.
b. Vertical openings between rail and deck on multiple railings.
c. Vertical opening design guidelines.
d. Use of curbs with railings.

a. Effective Height of Railing

The height requirements of a bridge railing are directly related to the design impact conditions for the barrier. Barriers as low as 22 in (56 cm) have successfully contained full-size cars impacting at 60 mph (95 km/h) and 25 degrees(18); higher barriers requirements for vehicles with higher c.g. are demonstrated in many crash test programs. The behavior of the barrier system itself affects the effective height of the barrier. Sloped barriers such as the concrete safety shape result in different performance when compared to flat walls. Yielding barriers can contribute to vehicle override if the effective barrier height is reduced during redirection; however, yielding barriers also result in lower forces imparted to the vehicle and this can have a stabilizing effect on the vehicle. Due to the complexity of the vehicle/barrier interaction during impact events, performance testing is perhaps the only reliable way of determining the effective barrier height.

Thus, it is recommended that the effective height of a barrier be determined by crash test using the upper limit design (i.e., service level) impact to determine height effectiveness. If barriers are known to be unyielding for certain impacts, then comparisons with other tested systems may be valid; otherwise for systems evaluated for impacts resulting in large deformations, it may be necessary to perform a crash test for each system at the desired service level.

Guidelines from reference 8 provide more guidance for barrier height requirements to prevent vehicle rollover. However, these findings are based primarily on crash test results with specific barriers (see table 12, section 3).

b. Vertical Openings Between Rail and Deck on Multiple Railings

Vertical openings in railing systems have led to vehicle snagging problems with many designs. The effects of vertical openings are dependent on several factors based on observation of crash tests in this project and others. They are:

- The location and size of the opening.

- The offset (setback) distance of the rail from the vertical member (e.g., post).

- The flexibility of the railing system.

- The shape of the railing member.

These factors are discussed in the following sections.

- Location/Size

The location and size of the opening determine what portions of the vehicle structure are likely to penetrate through the opening and snag on the post edge. For passenger cars, critical elements that have caused undesirable snagging include the wheel, bumper, and hood. Fortunately, the location and size of these elements is relatively uniform for passenger cars in this country. The smaller 12-in (30-cm) wheels of some minicars represent a lower bound for this element. The bumper location is in the 18-in (45-cm) high range with various width and geometries present. The hood height and geometry is probably the biggest variable, with some aerodynamically styled cars having hoods that slope to the bumper height.

Research by SwRI and NY DOT has addressed the concern about vehicle underride and override[18,19] properties. These data are summarized in figure 41.

- Setback Distance

The distance between the front face of the beam and the front face of the post is a factor in minimizing snagging. Obviously, if the distance is great enough, no interaction or snagging will occur.

- Barrier Flexibility

The structural characteristics of the barrier influence vehicle snagging. If posts are designed to perform in a breakaway manner, snagging potential may be minimal. On the other hand, if the post is ductile and the barrier flexible, the lower portion of the post becomes more of a snagging problem as illustrated in figure 42. For rigid systems, the snagging potential is easier to quantify.

- Railing Shape

As illustrated in figure 43, the shape of the railing determines the effective size and location of the vertical opening. Round or elliptical railing faces are not as effective as flat railing surfaces in terms of barrier openings.

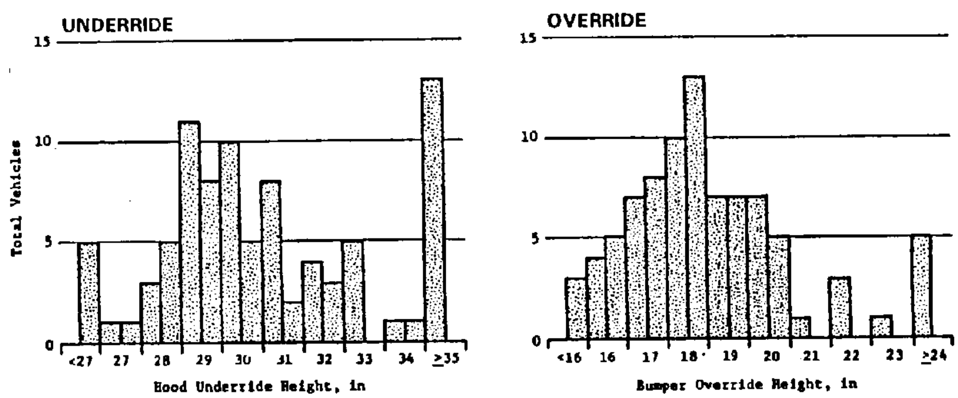
c. Vertical Opening Design Guidelines

Based on crash test data, vertical opening design guidelines are presented in figure 44. These guidelines are based on rigid barrier systems for passenger car impacts. For impacts resulting in beam deflec-

Geometric properties of 1983 vehicles.

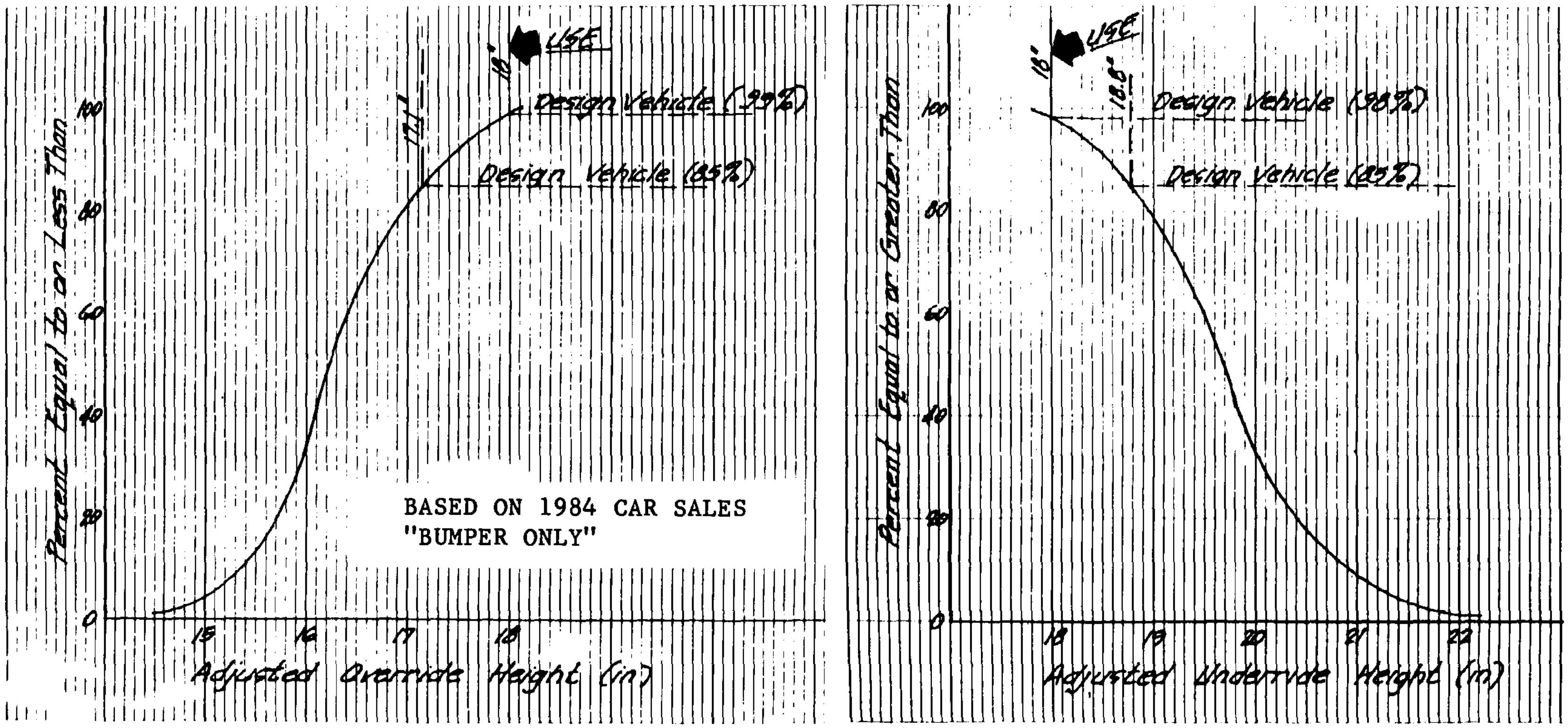
Vehicle Type	Override Height, in		Underride Height, in	
	Lowest	Highest	Lowest	Highest
Subcompact, domestic	16	20	27-1/2	30-1/2
Subcompact, foreign	15-1/2	20-1/2	27	30
Compact, domestic	17	21	28	31
Compact, foreign	16	22	29	31-1/2
Intermediate, domestic	17-1/2	19	28-1/2	33
Intermediate, foreign	17	18 1/2	29	32
Full size, domestic	17	19	30	34
Sports, specialty	13-1/2	20-1/2	13-1/2	31
Utility 4x4, full size	24	24	44	44
Utility 4x4, compact	19	24	29-1/2	39-1/2
Pickup, full size	16-1/2	24-1/2	40	44
Pickup, 4x4	24	24	45	45
Pickup, compact	16-1/2	22	33	34-1/2
Van	18	18	44	44

Distribution of barrier underride and override heights for 1983 model passenger vehicles, utility vehicles, and light trucks.



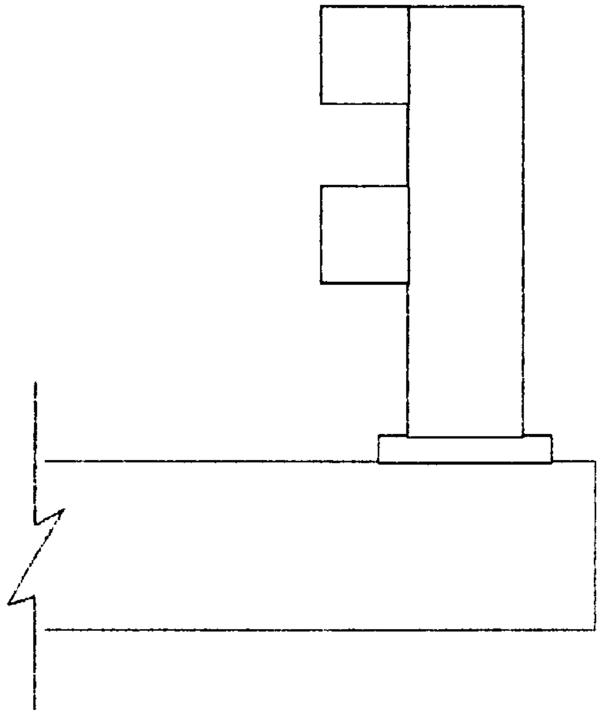
(a) Reference 19 data

Figure 41. Barrier underride/override considerations.

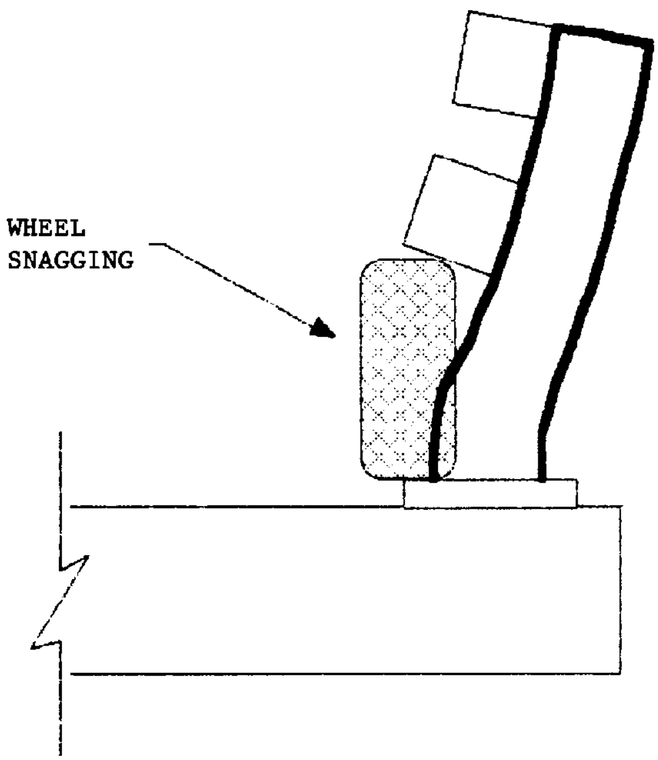


(b) Reference 18 data, 18 in selected as design height

Figure 41. Barrier underride/override considerations (continued).



(a) Bridge rail system



(b) Ductile post resulting in reduction in setback distance

Figure 42. Flexible barrier considerations.

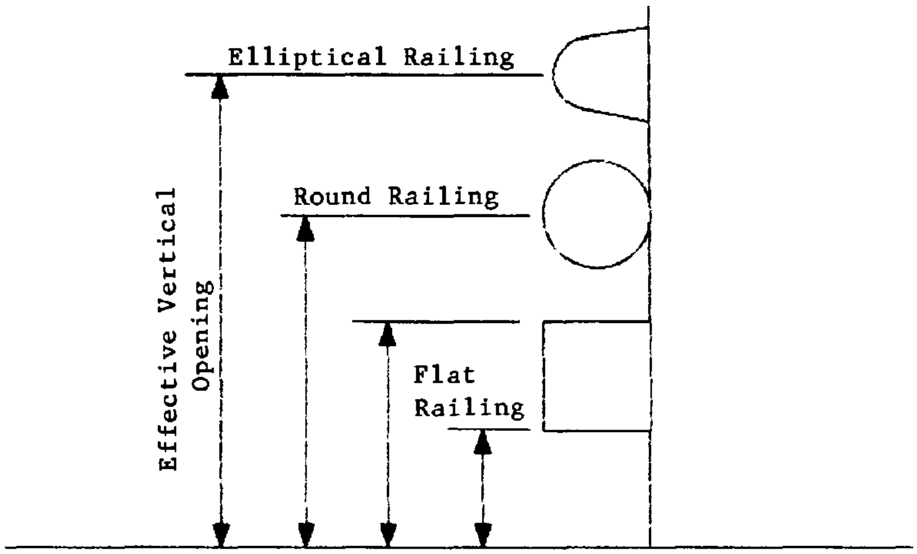
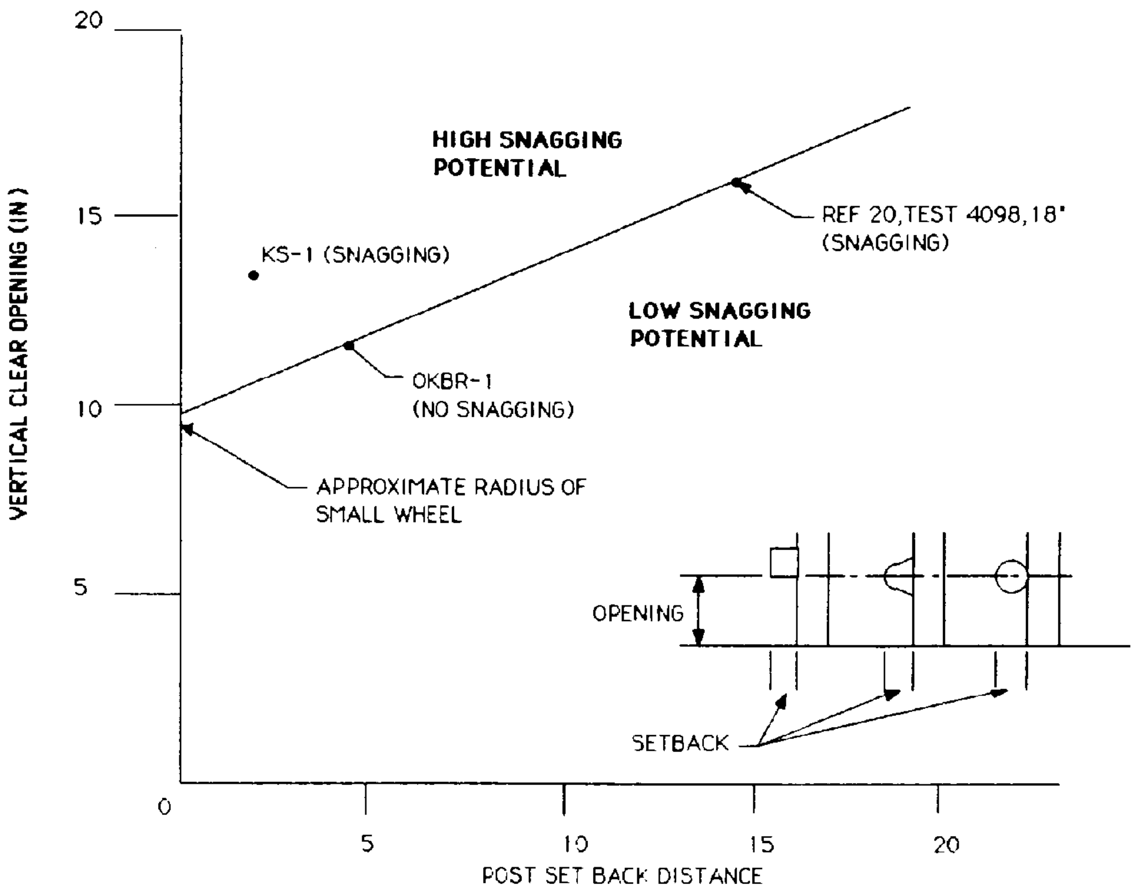
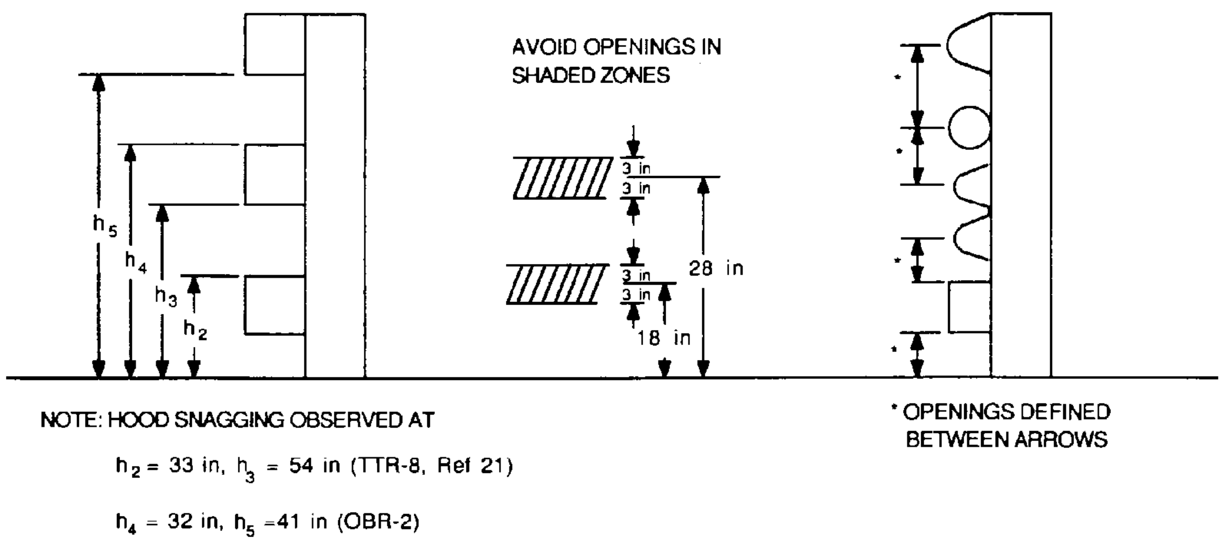


Figure 43. Effective railing considerations.



(a) Lower Opening Considerations (Based on Honda Civic Front Wheel for Test Conditions up to 60 mph [95 km/h] and 20 degrees)



(b) Upper Openings Considerations (Based on 4500-lb [2025-kg] Car, 60 mph [95 km/h] impact at 25 degrees, rigid barriers)

Figure 44. Vertical opening design guidelines.

tion of 6 in (15 cm) or more and larger vehicle impact considerations, these guidelines are not appropriate. Crash tests used for developing these guidelines are indicated.

d. Use of Curbs with Railings

Use of curbs with traffic barrier systems is normally discouraged. If curbs must be used, they should be as low as possible and the face of the railing or parapet should be in line with the face of the curb to minimize vaulting or tripping of impacting vehicles. Where safety walks are required for pedestrian/bicycle traffic, it is recommended that the traffic railing be placed between the vehicular and pedestrian/bicycle traffic.

7. Discussion of Findings

The findings from the project are briefly discussed.

a. State of the Art (1984)

A large number of operational bridge railing systems were specified by the State transportation agencies. Many of these systems, while designed to current AASHTO[1] specifications, did not fully conform to the criteria. Few of the 160 designs reviewed in this project had been subjected to any crash test evaluations. The selected systems performed well in most of the crash tests, but some failures were observed.

The concrete safety shape (New Jersey) parapet is widely used although the barrier and deck reinforcement schemes varied considerably.

b. Barrier Types

Bridge rail system can be grouped into categories as shown:

- Continuous parapets
  - concrete and metal safety shapes
  - vertical walls
- Concrete parapet with metal rails on top
  - safety shape
  - vertical wall
- Open concrete parapets
  - concrete beam/post systems
- Metal beam/post systems, geometry
  - single beam
  - double beam
  - 3 or more beams
- Metal beam/post systems, mounting
  - curb mounted
  - edge mounted
  - flush mounted
- Retrofit railings

All of these railing types were evaluated in this project.

c. Performance Testing

The need for performance testing was clearly demonstrated in this project. Design details which proved to be deficient were clearly identified and remedied in some cases. The use of actual bridge slab conditions illustrated the need for improved design for anchorage or post behavior. In one instance, a two-rail system provided improved performance over a three-rail system of the same design. From the performance testing results, the service level of the system is clearly identified.

The matrix for barrier performance testing is currently an active topic. The FHWA effort of updating the 1977 AASHTO Barrier Guide is currently underway. Table 5 of section 2 contains a recommendation from the SwRI project staff on this subject; however, it is expected that the revised AASHTO Barrier Guide will be the design and evaluation criteria for the various levels of service and test conditions required. The inclusion of these new criteria for bridge railings may also be forthcoming.

The evaluation criteria developed in section 2 represents the Institute's latest approach to this difficult subject. The application of the occupant risk values to the 25-degree angle tests may be too conservative in light of the recommended 20-degree angle tests for passenger cars and light trucks. Only further testing experience can answer this question.

d. Geometric Guidelines

Guidelines for geometrics are given, but performance testing is expected to verify these recommendations. The complexities of barrier structural behavior were discussed as they relate to barrier geometry.

e. LABR Retrofit Series

The test conditions used in Test LABR-2 were based on the narrow bridge to be retrofitted. It was determined that a 25-degree angle at 60 mph (95 km/h) was impossible, and the angle was reduced to 20 degrees for the full-size car evaluation.

f. Baseline Tests of the 3400-lb (1530-kg) Sedan

The downsized sedan behaved similarly to the 4500-lb (2025-kg) vehicle in both crash tests. The results of the tests indicated no unique features attributable to the smaller vehicle with the exception of high lateral velocities incurred during redirection.

8. Conclusions and Recommendations

a. Conclusions

Based on the findings of this project, the following conclusions are made.

- Bridge railings designed to the current AASHTO Bridge Specifications can be expected to perform reasonably well for the range of impacts of passenger cars used currently. Certain design deficiencies of the specification may best be discovered by crash test evaluations. Other design deficiencies may occur due to the incomplete analysis of the barrier system or a misinterpretation of design procedures.

- The number of different bridge rail designs currently specified by the States is probably excessive. The implementation of standardized barrier systems that have been fully developed and evaluated by crash tests would seem to be in the best interest of the user agencies. Many of the specific needs addressed by certain design details are shared by many agencies and standardization would benefit everyone.

- Performance evaluation by crash testing with representative vehicles is considered the only reliable proof test of a barrier design.

- The use of multiple service (performance) level technology will allow user agencies to address critical problem areas and possibly reduce requirements on bridges with low accident frequency and/or severities. A test matrix for multiple service level evaluations was recommended that was in 1986 is shown in chapter 2.

- Many aspects of the new test evaluation procedures are new and together with some new recommended test conditions (e.g., 5400-lb pickup, 65 mph, 20 degrees) make for some uncertainty regarding the appropriateness of the recommended values. As further test experience is gained, this new insight could lead to further refinements.

b. Recommendations

Based on the project findings, the following recommendations are offered:

- Performance testing of bridge railing systems is recommended. A test matrix using multiple service levels is recommended in table 5 of section 2. Also recommended in section 2 is an applicable evaluation criteria (table 6).

- Bridge rail system development based on a small number of national standards is recommended. Performance testing of these systems would be required.

- Controlled failure mechanisms that prevent extensive deck damage for severe impacts are recommended for beam/post systems. This will enhance barrier performance in terms of repeatability and prevent expensive bridge deck repair.

- The demise of the 4500-lb (2025-kg) car has led the researchers of this project and others in a search for a replacement vehicle/test condition. It is recommended that this issue be resolved as soon as possible to reduce the need for further testing. The current 5400-lb (2430-kg) pickup/65 mph (104 km/h)/20-degree angle test is recommended by the authors as a replacement test condition for the long-time conditions of 4500-lb (2025-kg) car, 60 mph (95 km/h) and 25 degrees.

- Further research into the evaluation of traffic barriers is definitely warranted, and experience with new test conditions should be applied to resolving this difficult issue.

• Drawings for the barriers evaluated in this project are in appendix A. The recommended systems, appropriate service level, and comments follow. It should be noted that the 4500-lb (2025-kg) car/60 mph (95 km/h)/25-degree angle impact is considered to be equivalent to the new 5400-lb (2430-kg) pickup, 65 mph (104 km/h), 20-degree angle impact now shown for Service Level III.

Performance Level*	Barrier System	Comments
V	NBR	--
III	OHBR, NCBR, MKS, OKBR	Virtually no barrier or deck damage in crash tests
III	NBBR, OHBR	Barrier and deck damage in tests
II	LABR	Retrofit designs evaluated for narrow roadway impact conditions
	KBR	Unsatisfactory design, not recommended

Larger drawings of the recommended barrier systems shown in Appendix A, i.e., NBR, OHBR, NCBR, MKS, OKBR, NBBR, and OHBR can be obtained from FHWA's Office of Engineering (HNG-14).

* See section 2, table 5.

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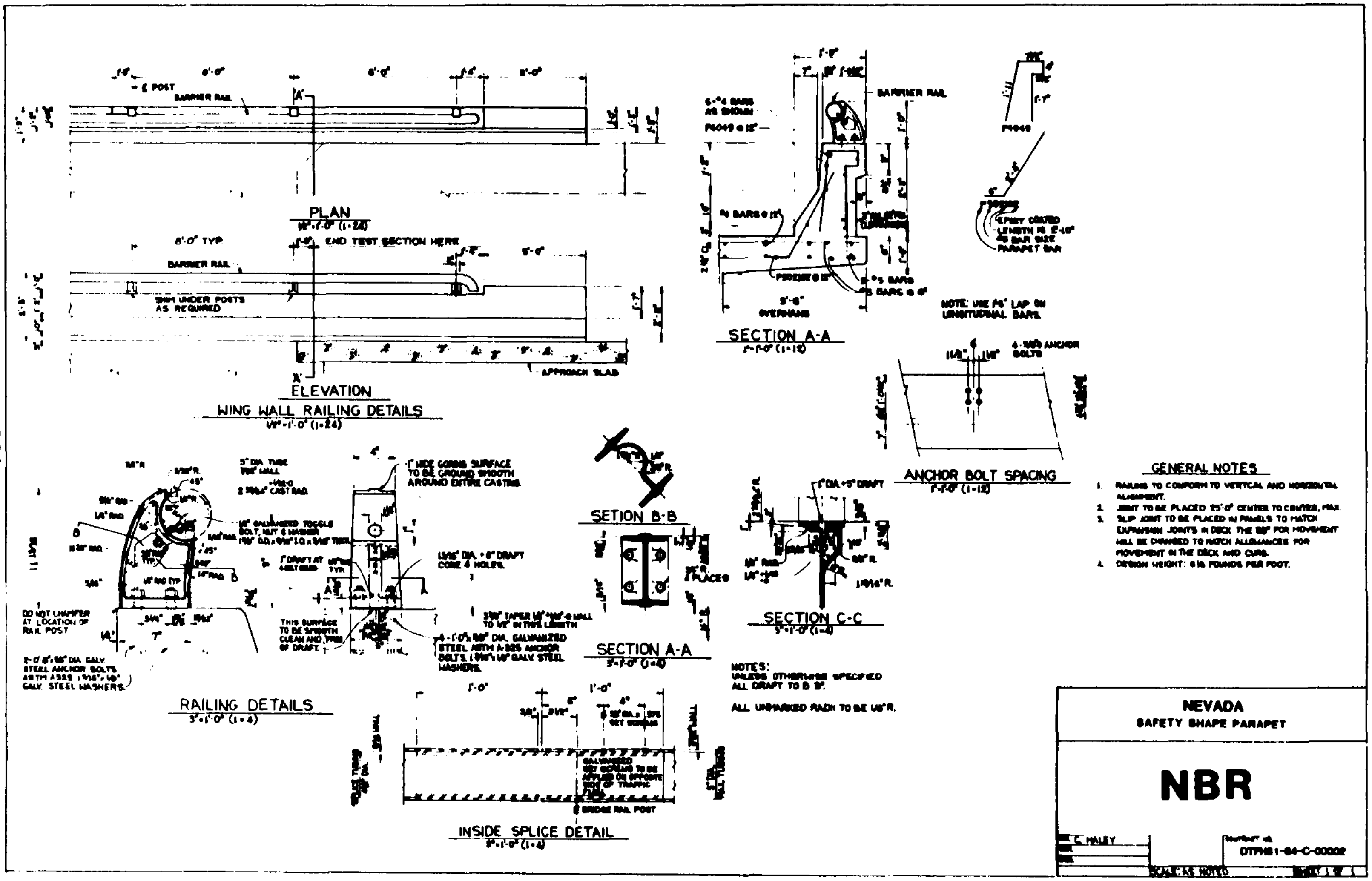


Figure 45. NBR design drawings.

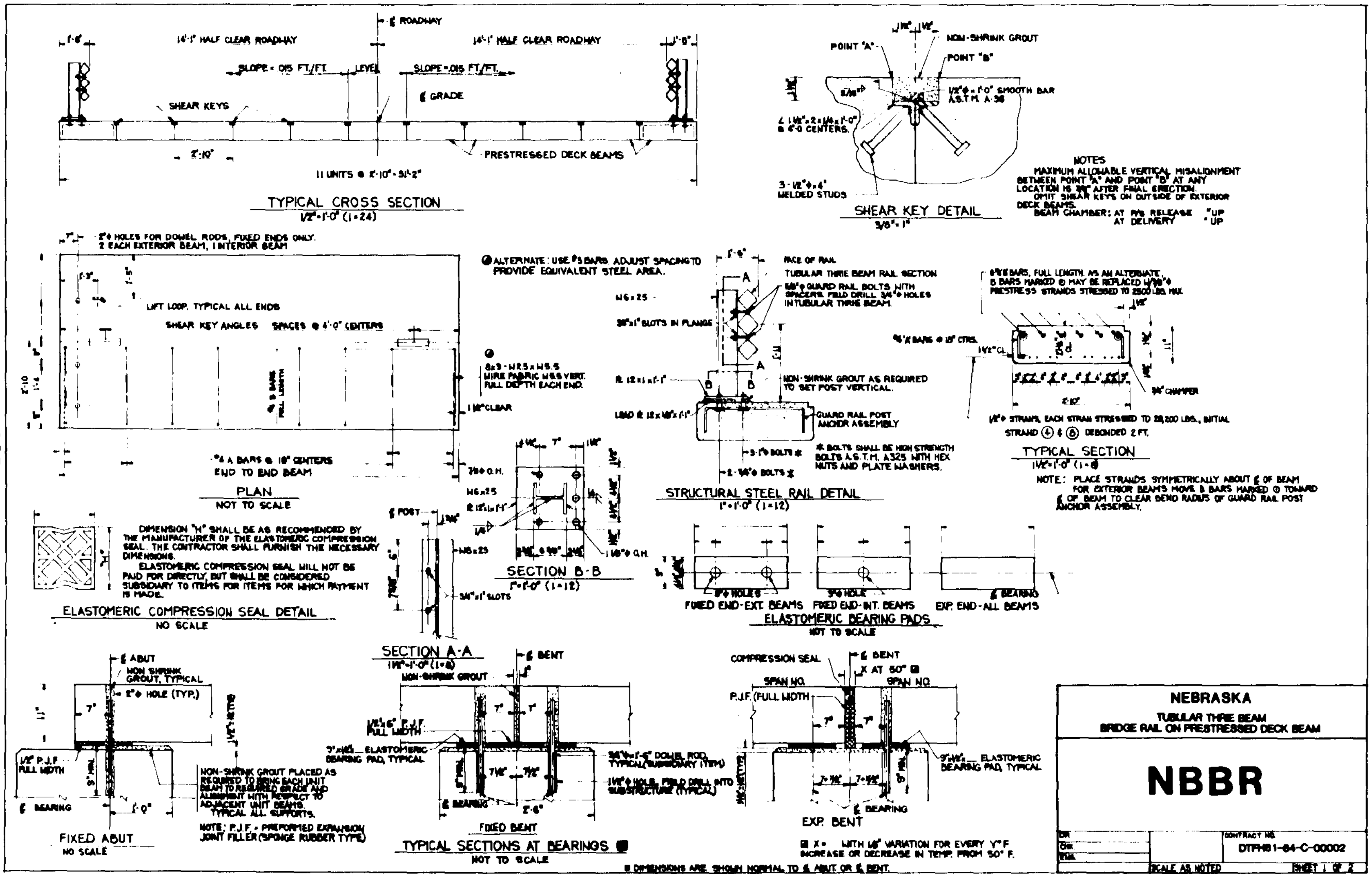


Figure 46. NBBR design drawings.

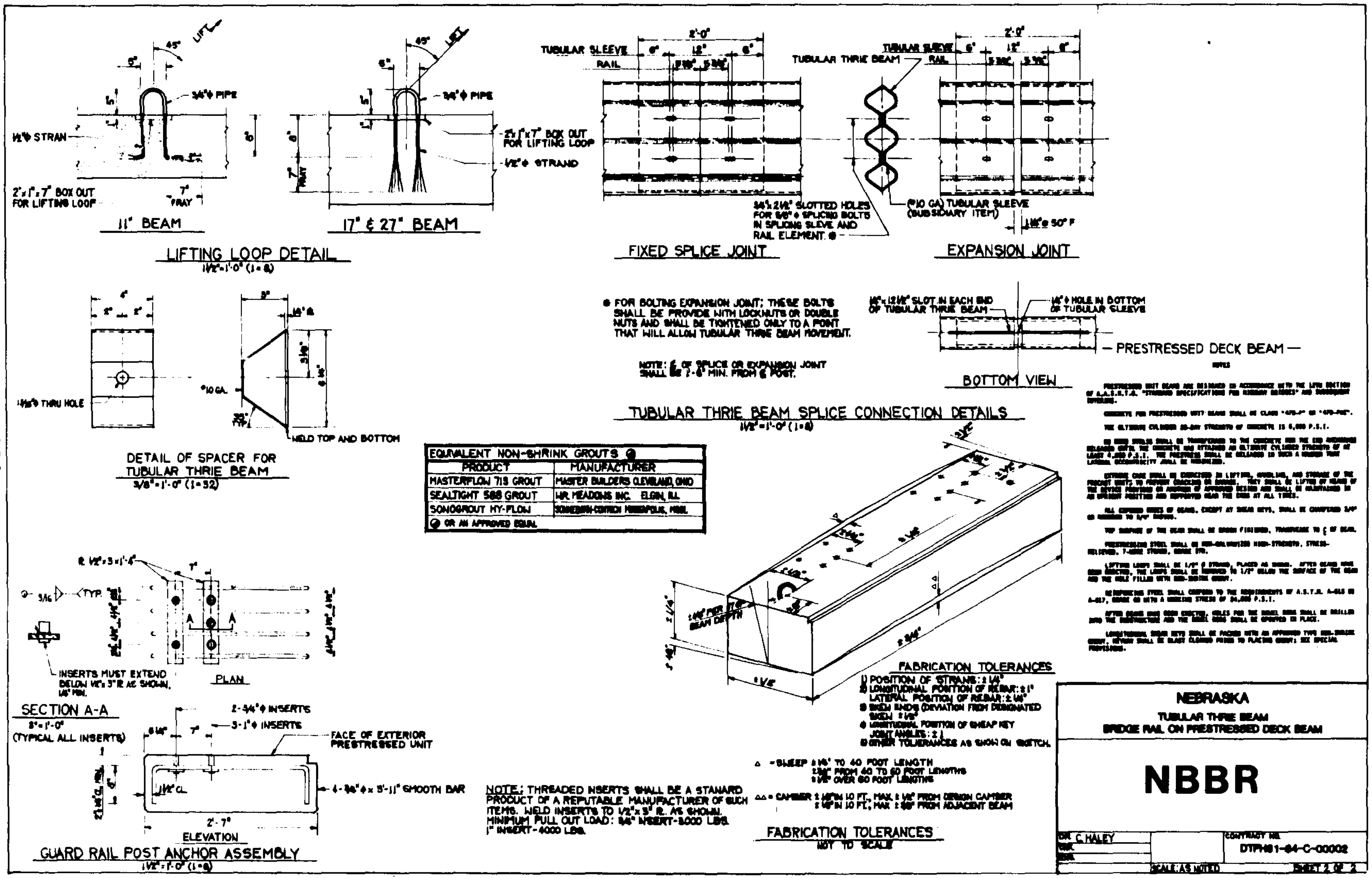


Figure 46. NBBR design drawings (continued).

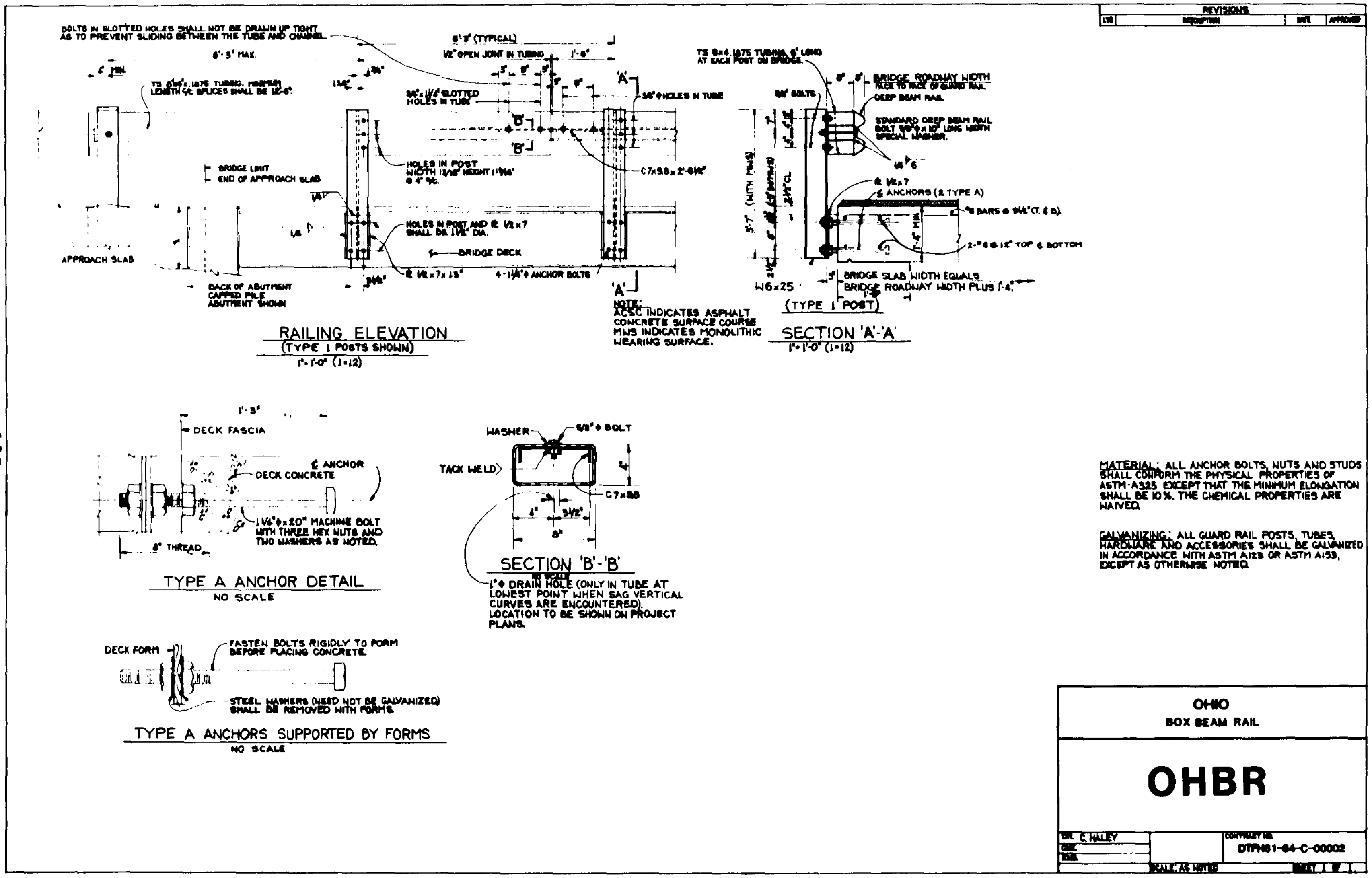


Figure 47. OHBR design drawings.

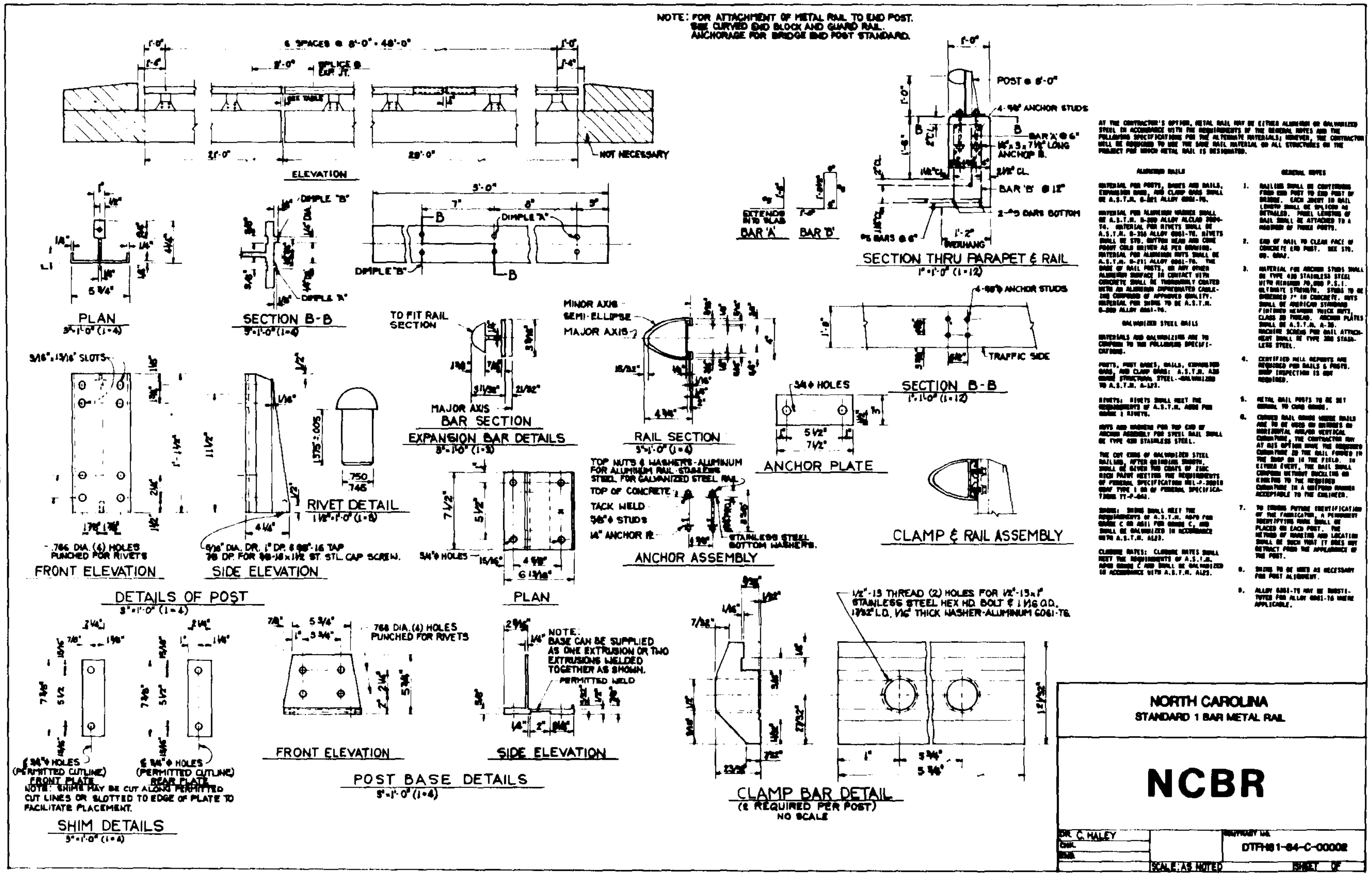


Figure 48. NCBR design drawings.

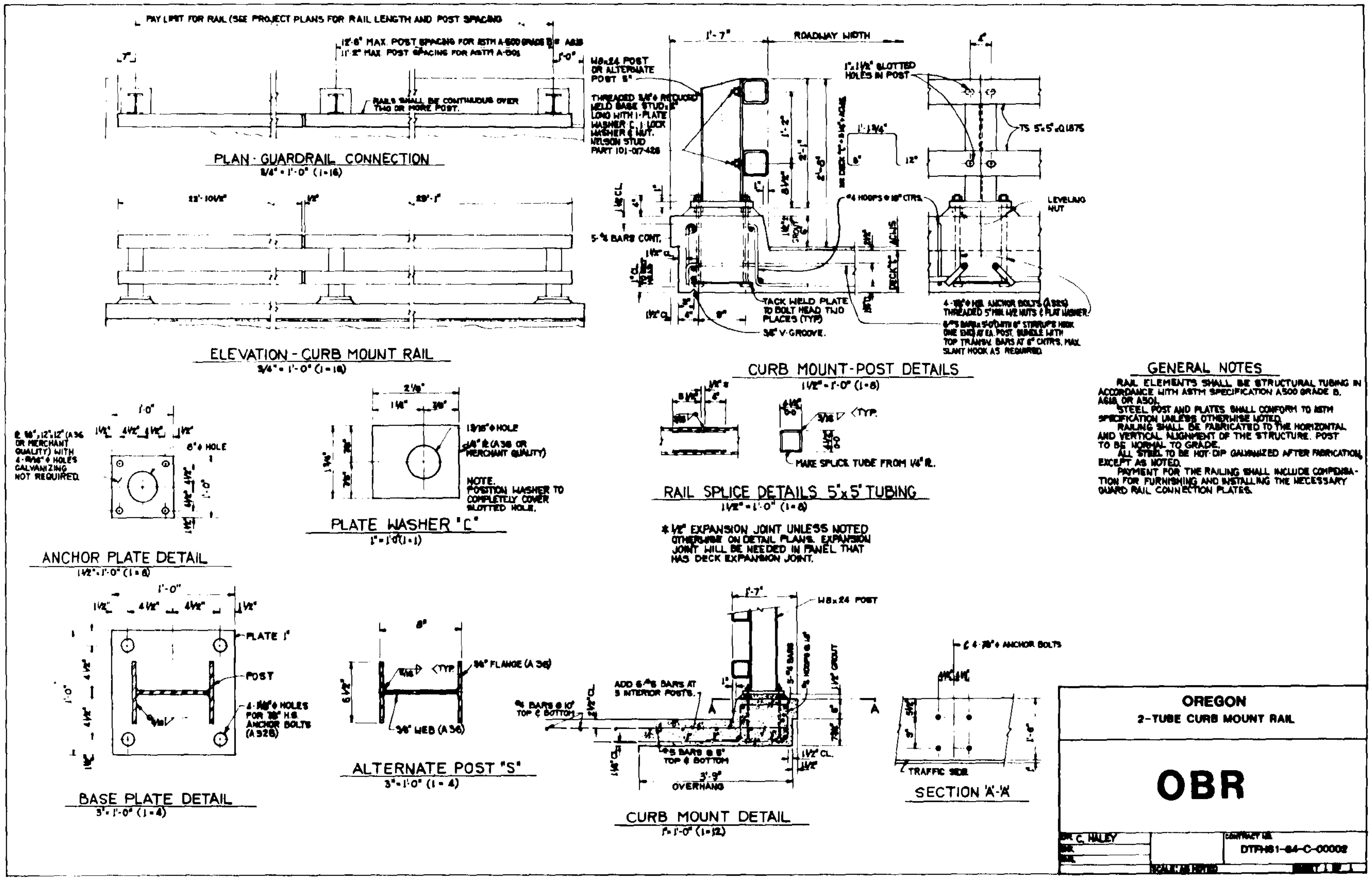
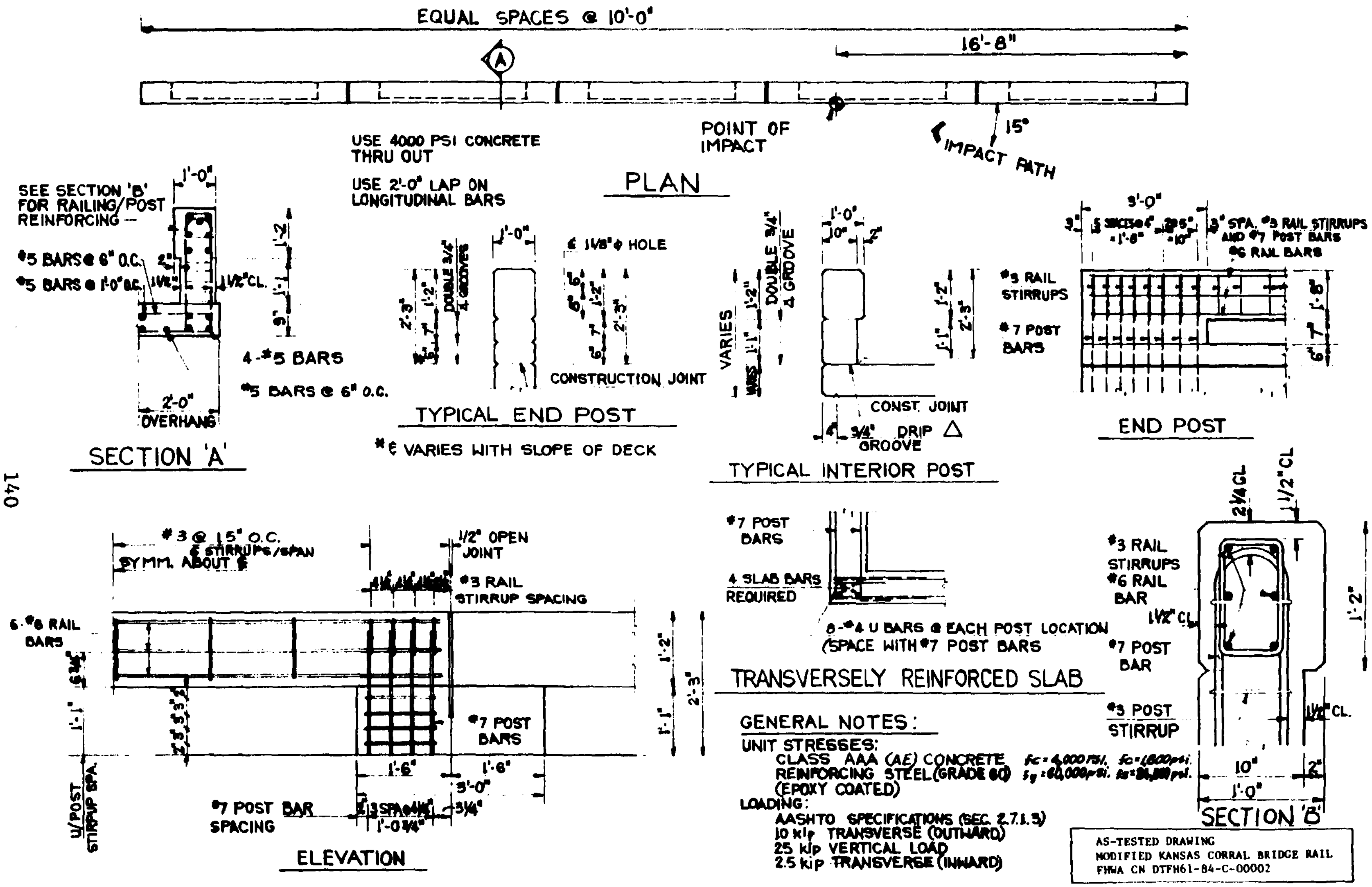


Figure 49. OBR design drawings.



MKS

Figure 50. MKS design drawings.

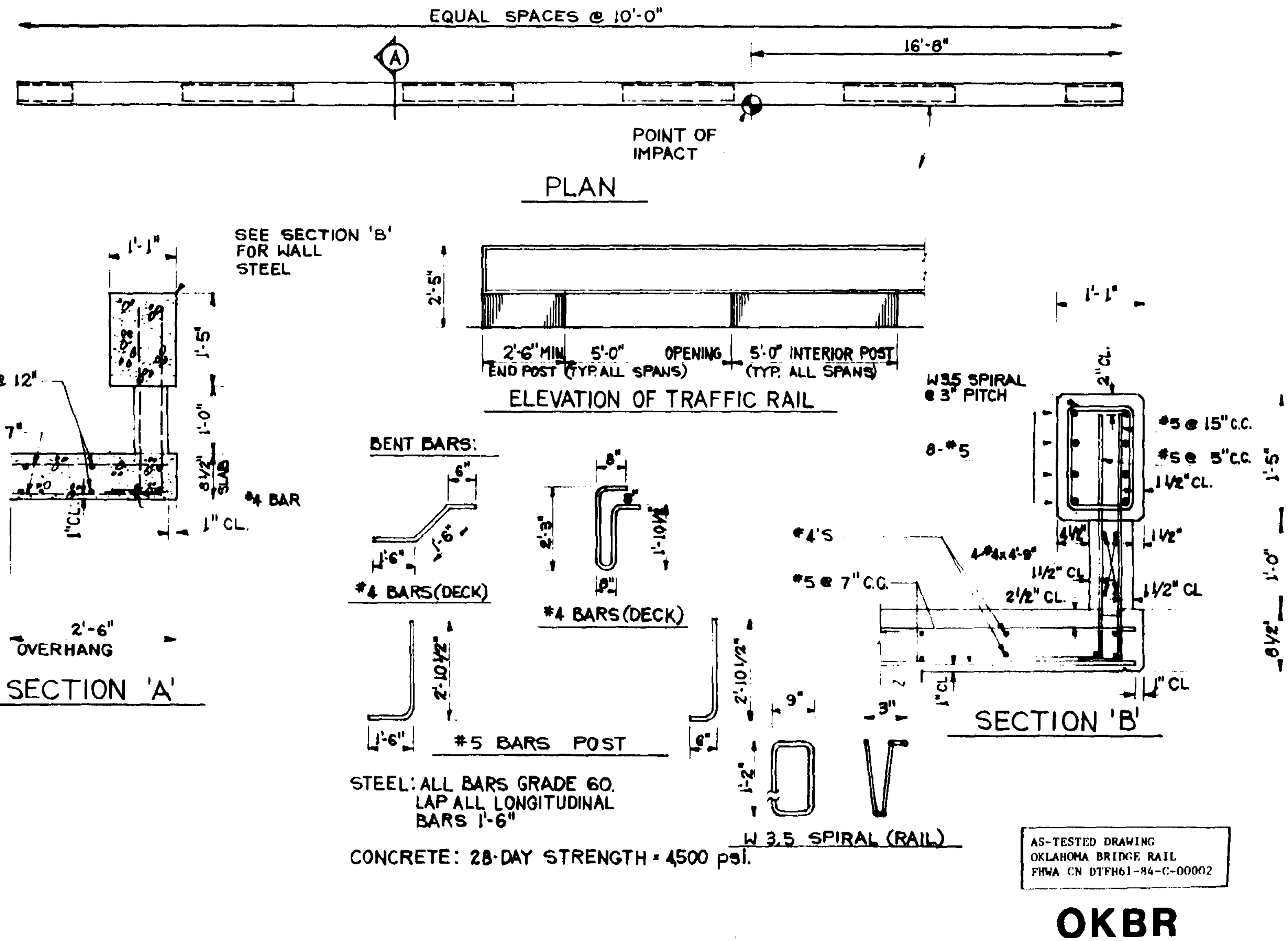


Figure 51. OKBR design drawings.

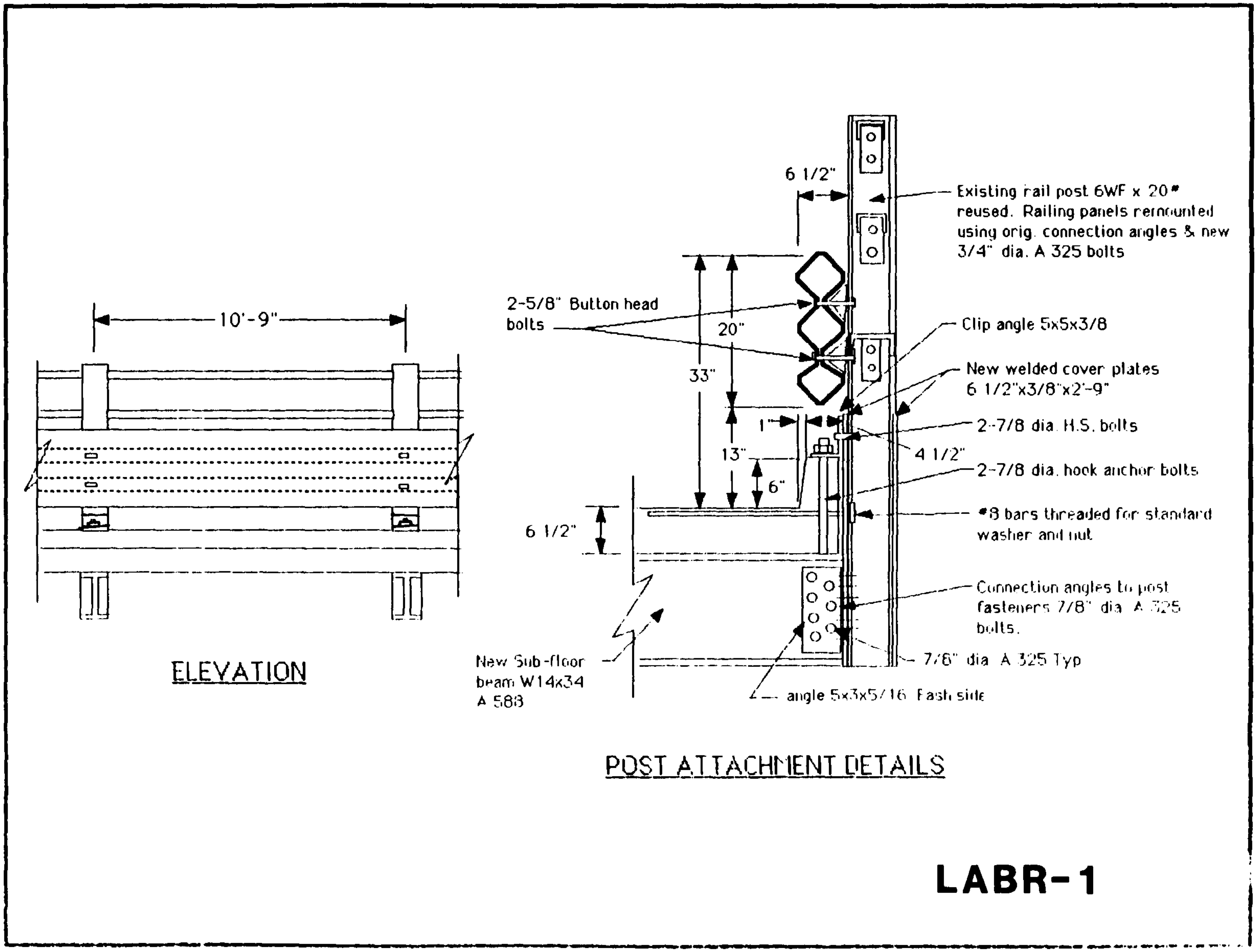


Figure 52. LABR-1 design drawings.

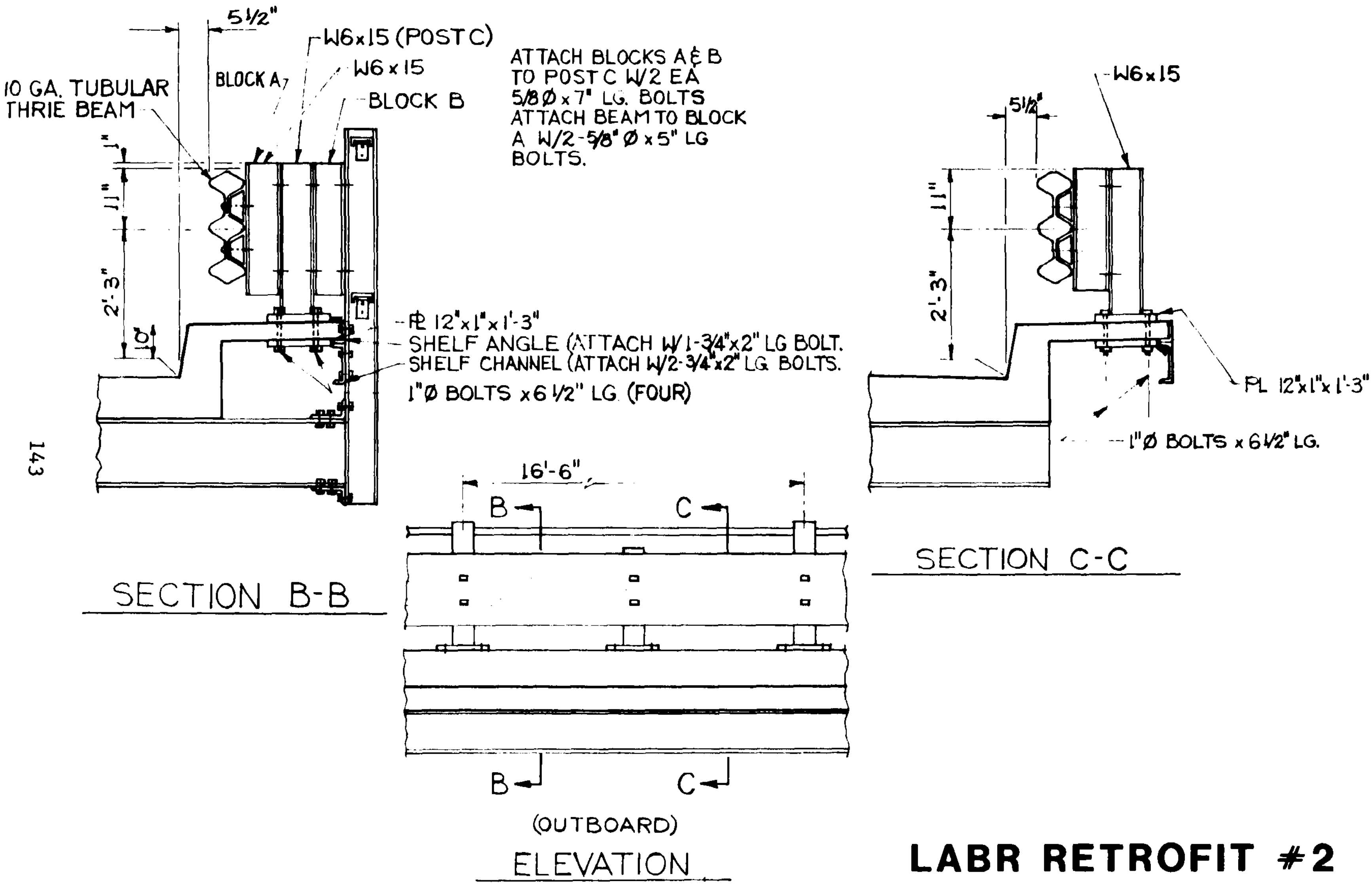


Figure 53. LABR retrofit #2 design drawings.

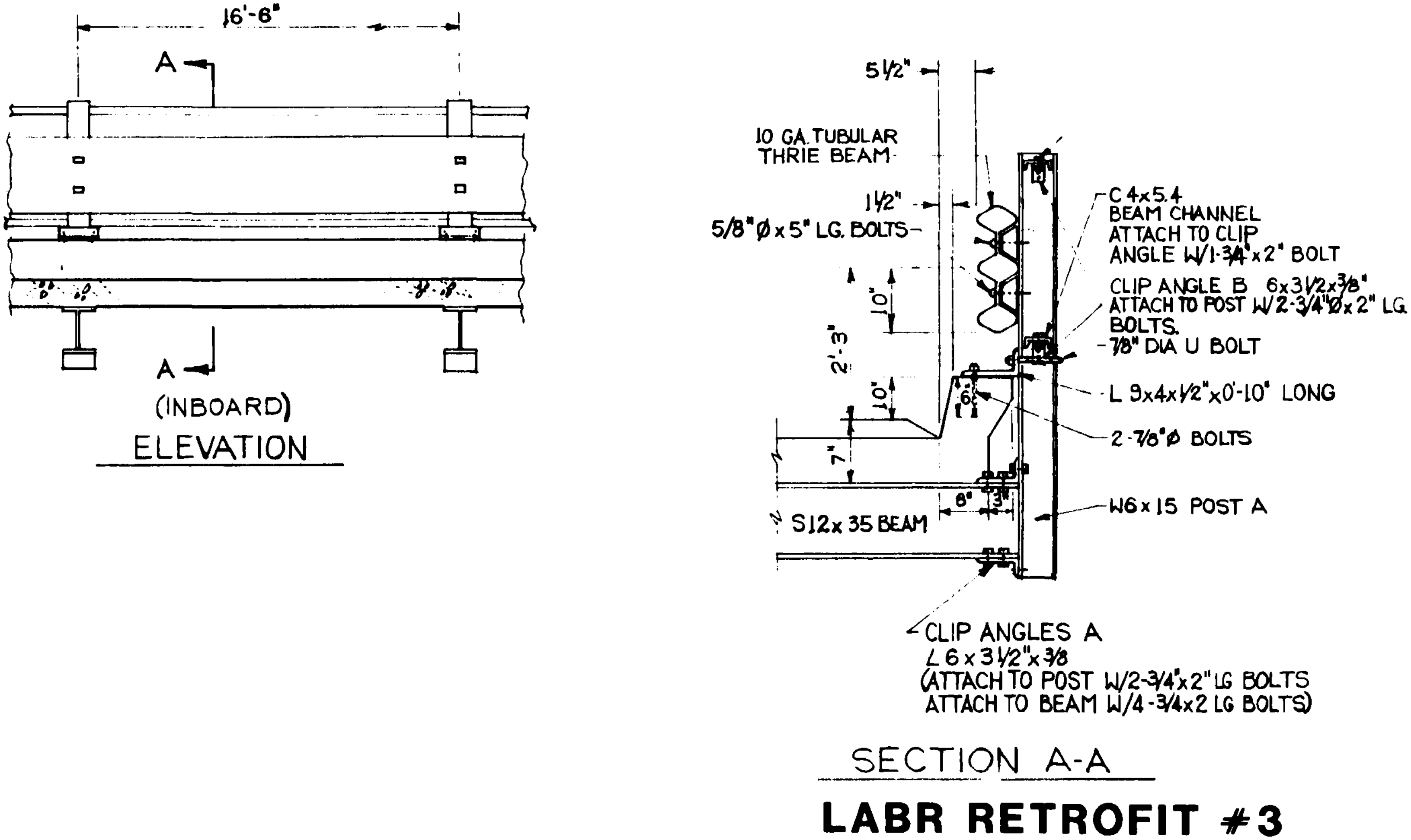


Figure 54. LABR retrofit #3 design drawings.

FEDERALLY COORDINATED PROGRAM (FCP) OF HIGHWAY RESEARCH, DEVELOPMENT, AND TECHNOLOGY

The Offices of Research, Development, and Technology (RD&T) of the Federal Highway Administration (FHWA) are responsible for a broad research, development, and technology transfer program. This program is accomplished using numerous methods of funding and management. The efforts include work done in-house by RD&T staff, contracts using administrative funds, and a Federal-aid program conducted by or through State highway or transportation agencies, which include the Highway Planning and Research (HP&R) program, the National Cooperative Highway Research Program (NCHRP) managed by the Transportation Research Board, and the one-half of one percent training program conducted by the National Highway Institute.

The FCP is a carefully selected group of projects, separated into broad categories, formulated to use research, development, and technology transfer resources to obtain solutions to urgent national highway problems.

The diagonal double stripe on the cover of this report represents a highway. It is color-coded to identify the FCP category to which the report's subject pertains. A red stripe indicates category 1, dark blue for category 2, light blue for category 3, brown for category 4, gray for category 5, and green for category 9.

FCP Category Descriptions

1. **Highway Design and Operation for Safety**
   Safety RD&T addresses problems associated with the responsibilities of the FHWA under the Highway Safety Act. It includes investigation of appropriate design standards, roadside hardware, traffic control devices, and collection or analysis of physical and scientific data for the formulation of improved safety regulations to better protect all motorists, bicycles, and pedestrians.

2. **Traffic Control and Management**
   Traffic RD&T is concerned with increasing the operational efficiency of existing highways by advancing technology and balancing the demand-capacity relationship through traffic management techniques such as bus and carpool preferential treatment, coordinated signal timing, motorist information, and rerouting of traffic.

3. **Highway Operations**
   This category addresses preserving the Nation's highways, natural resources, and community attributes. It includes activities in physical maintenance, traffic services for maintenance zoning, management of human resources and equipment, and identification of highway elements that affect the quality of the human environment. The goals of projects within this category are to maximize operational efficiency and safety to the traveling public while conserving resources and reducing adverse highway and traffic impacts through protections and enhancement of environmental features.

4. **Pavement Design, Construction, and Management**
   Pavement RD&T is concerned with pavement design and rehabilititation methods and procedures, construction technology, recycled highway materials, improved pavement binders, and improved pavement management. The goals will emphasize improvements to highway performance over the network's life cycle, thus extending maintenance-free operation and maximizing benefits. Specific areas of effort will include material characterizations, pavement damage predictions, methods to minimize local pavement defects, quality control specifications, long-term pavement monitoring, and life cycle cost analyses.

5. **Structural Design and Hydraulics**
   Structural RD&T is concerned with furthering the latest technological advances in structural and hydraulic designs, fabrication processes, and construction techniques to provide safe, efficient highway structures at reasonable costs. This category deals with bridge superstructures, earth structures, foundations, culverts, river mechanics, and hydraulics. In addition, it includes material aspects of structures (metal and concrete) along with their protection from corrosive or degrading environments.

9. **RD&T Management and Coordination**
   Activities in this category include fundamental work for new concepts and system characterization before the investigation reaches a point where it is incorporated within other categories of the FCP. Concepts on the feasibility of new technology for highway safety are included in this category. RD&T reports not within other FCP projects will be published as Category 9 projects.

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