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Concept Development of a Short-Radius Guardrail System for Intersecting Roadways

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16. Abstract (Limit: 200 words)

This research study consisted of the concept development of a short-radius guardrail system for protection near intersecting roadways. The objective of the research study was to perform the preliminary analysis and design of a new short-radius guardrail system capable of meeting the Test Level 3 (TL-3) impact conditions of NCHRP Report No. 350 criteria. However, the research was only to include the development of a design concept and not the fabrication and subsequent testing. The research into the development of a new short-radius design, described herein, consisted of six parts: (1) a literature search; (2) a design space analysis; (3) construction of an appropriate NCHRP Report No. 350 test matrix in order to validate the design; (4) development and selection of a potential short-radius design; (5) computer simulation using LS-DYNA of the most promising design concept; and (6) selection of a final design along with recommendations and suggestions for future work.

After considerable background research and investigations of various design considerations, a final design concept was developed that consisted of a thrie beam guardrail short-radius system with a 2,426-mm radius. The nose section has a pair of steel cables placed behind it to ensure capture of impacting vehicles in the event of rail rupture. The nose section and the first section of guardrail on each side of it are cut with horizontal slots in the valleys to aid in the capture of impacting vehicles as well as reduce the formation of large kinks as the guardrail deforms. The primary roadway side of the system terminates into an approach guardrail transition to a bridge rail, while the secondary roadway side of the system terminates into a FLEAT end terminal. Simulation of the design concept under NCHRP Report No. 350 test 3-33 impact conditions, a 100 km/h impact of a 2,000-kg pickup truck on the center of the nose at an angle of 15 degrees from the roadway, demonstrated that the design concept had significant potential for safely capturing and containing an impacting pickup truck. It was suggested that further development of the short-radius design concept be done including full-scale compliance testing.

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The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the state highway departments participating in the Midwest State's Regional Pooled Fund Program or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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1 INTRODUCTION

There are many situations where driveways or secondary roadways intersect a high speed roadway near a bridge. In this situation, an approach guardrail is required to protect motorists from the hazards associated with the end of the bridge rail and the area under the bridge. Unfortunately, the intersecting street or highway is often too close to the bridge to provide adequate approach guardrail runout.

A common safety treatment for this type of situation, called a short-radius guardrail, involves a curved section of guardrail placed around the corner of the intersecting roadway with tangent sections on each end that parallel the respective roadways. The tangent sections of guardrail along the primary roadway are generally attached to an approach guardrail transition attached to a bridge rail, while the sections along the secondary roadway are generally attached to a guardrail end terminal. A short-radius guardrail system is intended to perform in a similar manner to a bullnose median barrier or crash cushion. For example, when a high angle impact occurs in the curved portion of the system, the vehicle is to be captured and brought to a controlled stop. In addition, the system must still be capable of redirecting impacting vehicles along the tangent sections of the guardrail installation.

Currently, several states have short-radius guardrail designs in their standard plans that may be capable of meeting the NCHRP Report No. 230 (1) safety requirements that were set forth in 1981. However, it is not believed that these designs will prove capable of meeting the current NCHRP Report No.350 (2) criteria. Recently, the Midwest States Regional Pooled Fund States have contracted with the Midwest Roadside Safety Facility (MwRSF) to investigate the feasibility and concept development of a new short-radius guardrail design. This report describes the initial effort to develop this new short-radius guardrail design.

1.1 Objective and Project Plan

The objective of this research study was to perform the preliminary analysis and design of a new short-radius guardrail system capable of meeting the Test Level 3 (TL-3) impact conditions of NCHRP Report No. 350 criteria. However, the research was only to include the development of a design concept and not the fabrication and subsequent testing.

The research into the development of a new short-radius design, described herein, consisted of six parts: (1) a literature search; (2) a design space analysis; (3) construction of an appropriate NCHRP Report No. 350 test matrix in order to validate the design; (4) development and selection of a potential short-radius design; (5) computer simulation using LS-DYNA of the most promising design concept; and (6) selection of a final design along with recommendations and suggestions for future work.

The first portion of the work consisted of a comprehensive literature search on all available research and testing of short-radius designs, as well as collecting the existing short-radius standards for each of the pooled fund states. The second phase was an analysis of the short-radius design space limits and other design considerations based on the data gained from the literature search as well as existing texts on roadway design and geometries. This task would include determination of the limits, extent, and possibilities of the allowable design space. Additional design factors that were relevant to possible short radius designs were also included. Third, NCHRP Report No. 350 testing guidelines would be applied to determine the proper test matrix for acceptance of any new short-radius system. Development of the short-radius design concept followed, and a potential design for the new short-radius system was chosen. Subsequently, computer simulation of the design concept using LS-DYNA was used to investigate the feasibility of the new design. The simulation was analyzed to determine possible problems and suggest possible improvements to the design. A final design concept was then chosen based on all of the information collected in the previous phases of the project.

2 BACKGROUND AND PREVIOUS RESEARCH

The first phase of the research consisted of an extensive literature search into existing information and testing of short-radius guardrail systems. This included collecting all available test data for short-radius designs, as well as compiling a list of state standards for short-radius designs from the Midwest pooled fund states.

2.1 Previous Short-Radius Guardrail Testing

Ideally, in a head-on impact with a short-radius guardrail, the front bumper of the vehicle is captured by the rail, minimizing the chance for the vehicle to travel over or under the system. After impact, the rail should wrap around the front of the vehicle, forming a "cradle" to hold the vehicle as it travels into the system. The force produced by the deformation of the rail and breaking of the posts decelerates the vehicle to a controlled stop. For an oblique impact along the side of the system, the barrier should redirect the vehicle similarly to that of a normal guardrail system.

Several studies have been conducted on short-radius guardrail systems in the past. Details of these studies and designs are located in Appendix A. The Southwest Research Institute (SwRI) has conducted two studies in an effort to evaluate the performance of W-beam short-radius guardrail systems. The first study consisted of six NCHRP Report No. 230 crash tests conducted on a 2,590-mm radius design used by the State of Washington (3,4). Several modifications were made on the system throughout the testing program. As a result, a system was developed to contain both a 2,000-kg sedan and an 820-kg small car, although the performance was marginal. It should be noted that during the course of the testing, SwRI found that a tangent guardrail length of 7,620 mm or more was necessary to develop sufficient tensile capacity in the rail when impacted in the radius region.

A second study, performed for Yuma County, Arizona, resulted in the development of a short-radius guardrail system with an 8-ft radius and designed for low volume roads (5). This system was tested according to the test matrix for Performance Level 1 (PL-1) of the 1989 AASHTO Bridge Specifications (6). These criteria specify a 72.5-km/h impact with a 2,450-kg ballasted pickup and an 80.5-km/h impact with an 820-kg small car. The system was successfully tested at this lower service level.

A 1992 study was conducted by the Texas Transportation Institute (TTI) to design a W-beam short-radius guardrail treatment to meet NCHRP Report No. 230 criteria (7). The newly developed system used a 4,875-mm radius of nested-W-beam which was supported by five 1,980-mm long CRT posts. A series of six tests was performed with modifications being made throughout the testing to improve its safety performance. The design proved capable of passing the small car criteria but did not meet the 2,000-kg. sedan criteria set forth under NCHRP Report No. 230. After the sixth test, TTI concluded that the system was a possible interim solution for use as an NCHRP 230 accepted short-radius guardrail system.

In 1994, TTI attempted to improve upon the previous design by developing a short-radius thrie beam guardrail system which would satisfy the criteria found in NCHRP Report No. 350 (8). Initial testing of the system showed that it was not capable of containing a 2,000-kg pickup truck when subjected to an oblique impact into the curved portion of the rail. After considering the effort and resources required to redesign the system to accommodate a pickup impact, the scope of the project was redefined to develop the thrie-beam system according to NCHRP Report No. 230 criteria. The study consisted of five full-scale crash tests, with one system modification consisting of the removal of several post bolts in the curved section. In the small car test, the rail failed to capture the front bumper, allowing the vehicle to underride the system. The vehicle was brought to a stop when the rail snagged on the front A-pillars of the small car. During the 2,000-kg car impact into the curved section, the vehicle was nearly stopped when the end anchorage system failed. It was determined that the failure was a result of using bolts which were smaller than the specified size. The investigators concluded that the failure would not have occurred if the specified bolts had been used. Though these test results were not ideal, the system was judged to meet NCHRP Report No. 230 criteria.

Tables summarizing the full-scale vehicle crash tests, test summary pages of short-radius systems, and system drawings are presented in Appendix A.

Additionally, the Federal Highway Administration (FHWA) published a technical advisory with regards to curved W-beam guardrail installations at intersecting roadways (9). This document discussed the need for short-radius guardrail systems and reviewed the short-radius testing that had been done to date. It went on to suggest recommendations for the installation of short-radius guardrail systems including design drawings, capture area criteria based on radius size, slopes, and other important installation guidelines. The design drawings recommended by the FHWA in the advisory are located in Appendix B of this report.

The short-radius guardrail testing performed to date shows that there are two main problems with the current designs. The first of these is the inability to absorb the energy of a vehicle impacting on the curved portion of the rail. With the very limited amount of space which is available in this type of system, it is very difficult to design a system which will be 'soft' enough to stop a small vehicle with acceptable deceleration levels, but stiff enough to stop a large vehicle in the available distance. The second problem is, that in order to contain vehicles which impact along the curved portion of the system, the rail must be capable of capturing a wide variety of frontal geometries in various impact scenarios. Once the vehicle is captured, the posts in the system must break free without excessive rotation so that ramping of the test vehicle is not initiated. It should be noted that it is equally important that the short-radius system be designed to prevent underride of the guardrail by the impacting vehicle as well.

2.2 Current State Standards

In addition to the crash test data collected, the roadside hardware standards containing details for short-radius guardrail systems from all of the pooled fund states were collected. The purpose of collecting these standards was to gain an understanding of what types of designs the state departments of transportation are currently using in intersecting roadway situations. It also served as an aid in determining proper design space limitations further into the project. The state standards for short-radius systems for the Midwest State's Regional Pooled Fund states are provided in Appendix C.

3 DESIGN SPACE ANALYSIS

After the literature search and collection of the state standards was complete, a design space analysis was performed to determine the geometric limits for the short-radius design. This analysis included examination of the following: (1) possible nose section radii; (2) tangential side lengths; (3) the capture area; (4) intersecting road angles; and (5) end connections. Some additional design criteria relevant to short-radius guardrail design were also considered. These areas of analysis will be discussed in the following sections.

3.1 Possible Radius Sizes

The first component considered in the design space analysis was the size of the radius used in the short-radius guardrail. With regards to the performance of the design, a smaller radius size will result in a stiffer curved section, while larger radii will tend to decrease the stiffness of the curved section. The size of the radius will also be partially dependent on the geometry of the intersecting roads and the available space for the short radius guardrail system.

As discussed in Section 2.1, the smallest radius tested in the past was 2440 mm, which corresponded to the Yuma County study conducted by SwRI (5). For this project, the design was only tested under the PL-1 safety performance criteria. The smallest radius tested according to the NCHRP 230 criteria was 2,590 mm, which corresponded to the Washington State short-radius design that was also tested by SwRI (3,4). It is noted that this radius size performed acceptably under the given test conditions. The largest radius tested was 10,670 mm, which corresponded to a Washington State design that was tested by SwRI (3,4) However, this guardrail test was conducted at reduced speed and angle and does not give a good indication of the performance of large radii under more severe impacts. Subsequently, TTI tested 4,875-mm short radius systems using both W-beam and thrie beam configurations under NCHRP Report No. 230 test conditions (7,8). TTI found that the 4,875-mm radius was a viable option for both beam types. Although it was not a short-radius system, a bullnose guardrail system with a curved nose section was successfully tested according to NCHRP Report No. 350 safety criteria (10-12). This system used a 3,810-mm long nose section curved to form a 1,580-mm radius.

Based on the previous research, the use of smaller radii seems to demonstrate more promise for short radius designs. No one has successfully tested any short-radius system radii larger than 4,875-mm to either the NCHRP 230 or 350 criteria. The use of smaller radii also creates a stiffer curved section and allows for easier adaptation of a short-radius design to a variety of intersecting road geometries.

3.2 Tangential Side Lengths

Another important consideration in the design space analysis of a new short-radius guardrail design was the lengths of the tangent guardrail sections adjacent to the curved portion of the guardrail. In investigating the side lengths, it was important to consider the various end connections used in the field (i.e., end terminals), the need for approach guardrail transition sections, and development of sufficient anchorage for the curved portion of the guardrail during impact.

SwRI concluded during their testing of the Washington State short-radius design (3,4) that at least 7,620 mm of tangential guardrail was needed to develop an effective stroke for the curved section during impact. Originally, the short-radius tested in that study had only 3,810 mm of guardrail installed tangent, including the transition to the bridge rail, but this configuration did not provide sufficient anchorage. The final design tested by SwRI used 7,620 mm of tangent guardrail in conjunction with an additional cable anchorage system.

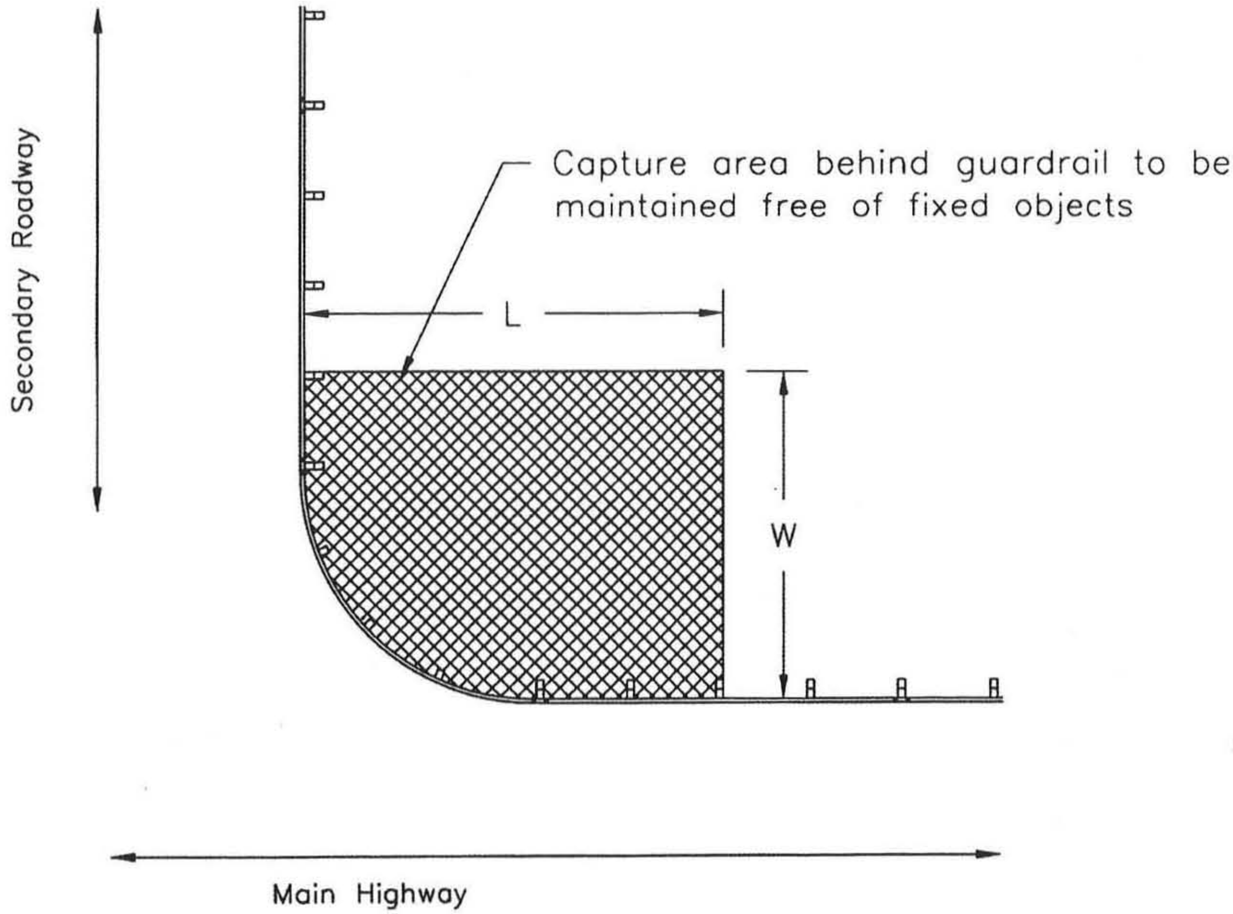
FHWA's technical advisory on short-radius guardrails (9) also recommends a minimum of 7,620-mm of guardrail installed tangent between the curved section and the end of the approach guardrail transition or guardrail end terminal for all short-radius systems. It should be noted that this length should be considered an absolute minimum and will likely be greater due to other design considerations. For example, consider a side that terminates with an approach guardrail transition attached to a bridge rail. The degree of stiffness of NCHRP 350 accepted transition designs is much greater than the stiffness of the adjacent curved section. Therefore, a much more gradual change in stiffness may be required to transition between these two regions, potentially resulting in additional intermediate sections of guardrail.

A similar increase in the 7,620-mm minimum tangent length is possible when the system terminates using a guardrail end terminal. High-speed, NCHRP 350 accepted guardrail end terminals, such as the BEST or SKT designs, require more than 7,620 mm of guardrail for proper installation. Additionally, the possible use of thrie beam guardrail in the curved section will create a need for an added transition section to W-beam before the end terminal can be applied. These factors will increase the tangent guardrail length adjacent to the radius well beyond the 7,620-mm minimum specified by the FHWA.

Based on these observations, the researchers believe that any NCHRP 350 short-radius design will have a minimum tangential guardrail length well over 7,620 mm. Although it may be possible that the 7,620 mm minimum may be achieved in some cases with proper anchorage, it is likely that tangential lengths may be closer to 11,430-mm.

3.3 Capture Area

The capture area required for the safe containment of an impacting vehicle in a short-radius



Area Behind Guardrail to be Maintained Free of Fixed Objects

Radius	No. of CRT Posts	Required Area Free of Fixed Objects L W
8'-6"	5	25' x 15'
17'-0"	6	30' x 15'
25'-6"	8	40' x 20'
35'-0"	11	50' x 20'

Figure 1. FHWA Recommended Capture Area Based on Radius

guardrail design consists of an area clear of obstacles and obstructions directly behind the curved section of the design. Examination of this design space included the consideration for the size of the area and the surrounding ground slopes.

The FHWA technical advisory (9) recommended capture area sizes based on the radius of the curved section. Figure 1 shows the recommended capture areas specified by the FHWA. These areas were determined by the FHWA through analysis of previous testing and research. The capture areas should be kept free of any obstacles or obstructions that may pose a hazard to impacting vehicles. It should be noted that the areas given consider only containment of the impacting vehicle. In addition, they do not account for flying debris from the guardrail system upon impact with the vehicle. Several of the past tests of short-radius guardrails demonstrated that debris from the impact may pose a hazard far outside these recommended capture areas, and this potential safety hazard should be considered in design.

The FHWA advisory also provides slope guidelines for the area surrounding the guardrail installation. A slope of no greater than 15:1 is specified in front of the curved section of the guardrail in order to prevent override or underride of the guardrail beam. Embankment slopes of 2:1 or flatter are specified for the capture area behind the guardrail. The 2:1 slope represents the steepest slope tested according to NCHRP 230 in conjunction with a short-radius design (3,4). However, it should be noted that little testing has been performed on guardrail systems adjacent to slopes in accordance with the NCHRP Report No. 350 criteria. Due to this lack of testing experience, it is believed that the use of flatter slopes in the short-radius design would improve the capture and controlled deceleration of the impacting vehicle. The use of steep slopes behind a short-radius guardrail system may adversely affect the performance of the system by increasing the potential for override of the guardrail.

The FHWA also specifies a minimum of 610 mm of nearly horizontal fill behind the guardrail posts in the system before a much steeper embankment slope may begin. The amount of soil left behind the posts will in a large part determine how the posts react during impact as well as the magnitude of the post-soil forces generated. The 610-mm guideline recommended by the FHWA potentially may not be sufficient to produce the desired post behavior in the case of a short-radius design, which is also dependent on the post type and the embedment depth. Therefore, an increase in the horizontal fill behind the posts may be necessary.

3.4 Intersecting Roadway Angles

Consideration of roadway geometry and the angle between the intersecting roads also was warranted in the conceptual design of the new short-radius system as it relates to the design space analysis. The upper and lower limits of the intersecting road angles provide limitations to the size and radius of the curved section of guardrail and determines the geometry of the tangent lengths adjacent to the radius.

Currently, no testing has been conducted on short-radius designs with intersecting roadway angles other than 90 degrees. Guidelines and handbooks for roadway design show that intersecting road angles vary from 180 degrees (a "U" turn) to as low as a 30 degree turn angle (13). These angles are defined as the turning angles of the vehicle and not an actual angle of the intersecting roadways. The extremes of these limits may not be applicable for short-radius guardrail systems and instead may be better served by other designs. For example, a very sharp turning intersection will likely be better protected by a bullnose-type guardrail system, while a shallow angle intersection may only require a curved section of standard guardrail.

Investigation of the state standards found that only one state had a short radius guardrail installation on an intersecting roadway with an angle other than 90 degrees. Iowa Department of Transportation has a standard for a short-radius guardrail where the angle between the intersecting roadways is 60 degrees.

Based on the collected data, it is difficult to determine exact limits for roadway angles for a short-radius design. Test data and current state standards yield intersecting roadway angles in the range of 60 degrees to 90 degrees. It is noted that roadway design does allow for angles outside of this range. However, any application of short-radius designs with intersecting angles much greater than 90 degrees or much below 60 degrees will require engineering judgement to determine if the intersection may be better served by another type of protection. In any case, NCHRP 350 crash testing of such a design will likely be performed on a system with a 90-degree intersection angle as it seems to be the most prevalent.

3.5 End Connections

The end connections used on a new short-radius design will be critical in order to achieve an acceptable safety performance of the system. These end connections will likely consist of either guardrail end terminals, approach guardrail transitions, or a continuation of W-beam or thrie beam guardrail along the intersecting roadway.

All of the current testing of short-radius guardrails has been conducted with either turned-down end terminals or some form of the Breakaway Cable Terminal (BCT) end terminal. None of the previously tested short-radius guardrail systems have been tested with NCHRP 350 approved end terminals although it is not believed that the tensile capacity in the anchor systems will be a problem. The list of approved NCHRP 350 guardrail end terminals that could be used in conjunction with the new short-radius guardrail design is quite large. Consequently, the choice of end terminal may affect the tangent length due to the various design lengths of the newer end terminals. In any event, the selection of the end terminal should be based on what is best suited to the individual installation. It should be noted, however, that the end terminal chosen will need some form of a cable anchor in order to develop rail tension when impacted on the curved portion of the guardrail.

For situations where the short-radius tangent section terminates into a bridge rail, connection situation, an approved NCHRP 350 approach guardrail transition should be placed between the short-radius guardrail and the bridge rail. Again, this will likely affect the tangent length of the design depending on the length of guardrail needed to provide a gradual change in stiffness as well as provide a transition between the various guardrail shapes.

Finally, there exists the possibility that the short-radius guardrail will simply continue with conventional guardrail sections installed tangent to the roadway.

3.6 Miscellaneous Design Considerations

For the design space analysis, several other design considerations were deemed relevant to the development of a new short-radius guardrail. Some of these considerations have an effect on the design space and have been touched on previously, while others are simply pertinent information to be used in the design.

One of the most important considerations was the choice of guardrail beam type to be used in the new design. Both thrie beam and W-beam short-radius designs have been tested previously, but neither type of rail has been used with complete success. W-beam guardrail is very common and would be easy to implement; however, it did not demonstrate sufficient strength or capture properties in previous testing. The 312-mm depth of section in W-beam guardrail provides less section for capture of the vehicle and less material for strength. Nesting of the W-beam could be used to increase its strength, but its vehicle capture ability would not be improved. Thrie beam provides both increased vehicle capture capabilities and strength, but past testing also showed the potential for vehicle override and underride. Recent testing according to NCHRP 350 criteria by the MwRSF of a bullnose median barrier design (10-12) showed that the potential exists for a curved section of thrie beam guardrail to be used in short-radius guardrail applications. Although curved thrie beam may prove to be overly stiff, horizontal rail slots could be cut into the guardrail valleys. This technique was used previously in the bullnose system. These rail slots weaken the rail as well as aid in the capture of impacting vehicles. Based on the above discussion, thrie beam guardrail seems the most advantageous rail type for use in the design of a new short-radius system.

Another important consideration in the design of a short-radius guardrail is the post selection and layout. All of the previously tested short-radius designs used breakaway CRT posts without blockouts and spaced 1,905-mm on centers throughout the curved section of the guardrail. CRT posts were used since they typically break upon impact, thus reducing the potential for vehicle vaulting. TTI researchers determined that it was necessary to use 1,980-mm long CRT posts with 1,118-mm embedment to achieve the proper soil-post behavior (7). It is also important to note that the post to guardrail connection in all of the final designs consisted of a single bolt with no plate washer. Eliminating the washer allows the post to separate from the guardrail during impact instead of pulling it downward after the posts fracture. For the short-radius design, some of the posts adjacent to the curved section may need to be weakened as well. Weakening additional posts should provide for a softer system, allow more deformation of the guardrail, reduce the loading of the guardrail, and reduce the potential for rail rupture. Finally, the remaining posts in the system will depend on the system requirements for the end terminals and transitions used.

A final consideration in the development of a new short-radius guardrail system was the use of steel cables to reinforce the nose section of the design. Previous experience with the bullnose system showed that a slotted thrie beam guardrail may rupture in the event of an impact and allow vehicles to penetrate through the system (10-12). It was found that the use of a pair of steel cables set in the valleys of the nose section of guardrail could prevent this behavior. Based on this previous experience, the researchers believed that a similar set of reinforcing cables should be applied to the short radius design. These cables would serve to capture the impacting vehicles in the event of guardrail tearing and failure.

4 NCHRP 350 TESTING AND EVALUATION CRITERIA

4.1 Test Requirements

Due to the nature of potential impacts into the curved section of a short-radius guardrail system, it was believed necessary to classify it as either a terminal or crash cushion for the purpose of determining the appropriate NCHRP Report No. 350 crash tests and evaluation criteria. A short-radius guardrail should be defined as a non-gating device and must fulfill the requirements for non-gating terminals. A non-gating device is one designed to contain and redirect a vehicle when impacted downstream from the end of the device. According to NCHRP Report No. 350, non-gating end terminals and crash cushions must be subjected to eight full-scale vehicle crash tests, five using a 2000-kg pickup truck and three using an 820-kg small car. The required 2000-kg pickup truck crash tests for a Test Level 3 (TL-3) device are:

(1) Test 3-31, a 100 km/h impact at a nominal angle of 0 degrees on the tip of the barrier nose,
(2) Test 3-33, a 100 km/h impact at a nominal angle of 15 degrees on the tip of the barrier nose,
(3) Test 3-37, a 100 km/h impact at a nominal angle of 20 degrees on the beginning of the LON (Length-of-Need),
(4) Test 3-38, a 100 km/h impact at a nominal angle of 20 degrees on the Critical Impact Point (CIP), and
(5) Test 3-39, a 100km/h reverse direction impact at an angle of 20 degrees one half of the LON from the end of the terminal.

The required 820-kg small car crash tests for a TL-3 device are:

(1) Test 3-30, a 100 km/h impact at a nominal angle of 0 degrees on the tip of the barrier nose with a ¼-point offset,
(2) Test 3-32, a 100 km/h impact at a nominal angle of 15 degrees on the tip of the barrier nose, and
(3) Test 3-36, a 100 km/h impact at a nominal impact angle of 15 degrees on the beginning of the LON.

A diagram showing the impact location for the eight crash tests is shown in Figure 2.

The critical impact point mentioned above is defined for non-gating terminals as the point along the installation where it is unknown whether the guardrail will capture the impacting vehicle or redirect it.

4.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the terminal to contain, redirect, or allow controlled vehicle penetration in a predictable manner. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Vehicle trajectory after collision is a measure of the potential for the post-impact trajectory of the vehicle to cause subsequent multi-vehicle accidents, thereby subjecting occupants of other vehicles to undue hazard or to subject the occupants of the impacting vehicle to secondary collisions with other fixed objects. These three evaluation criteria are defined in Table 1.

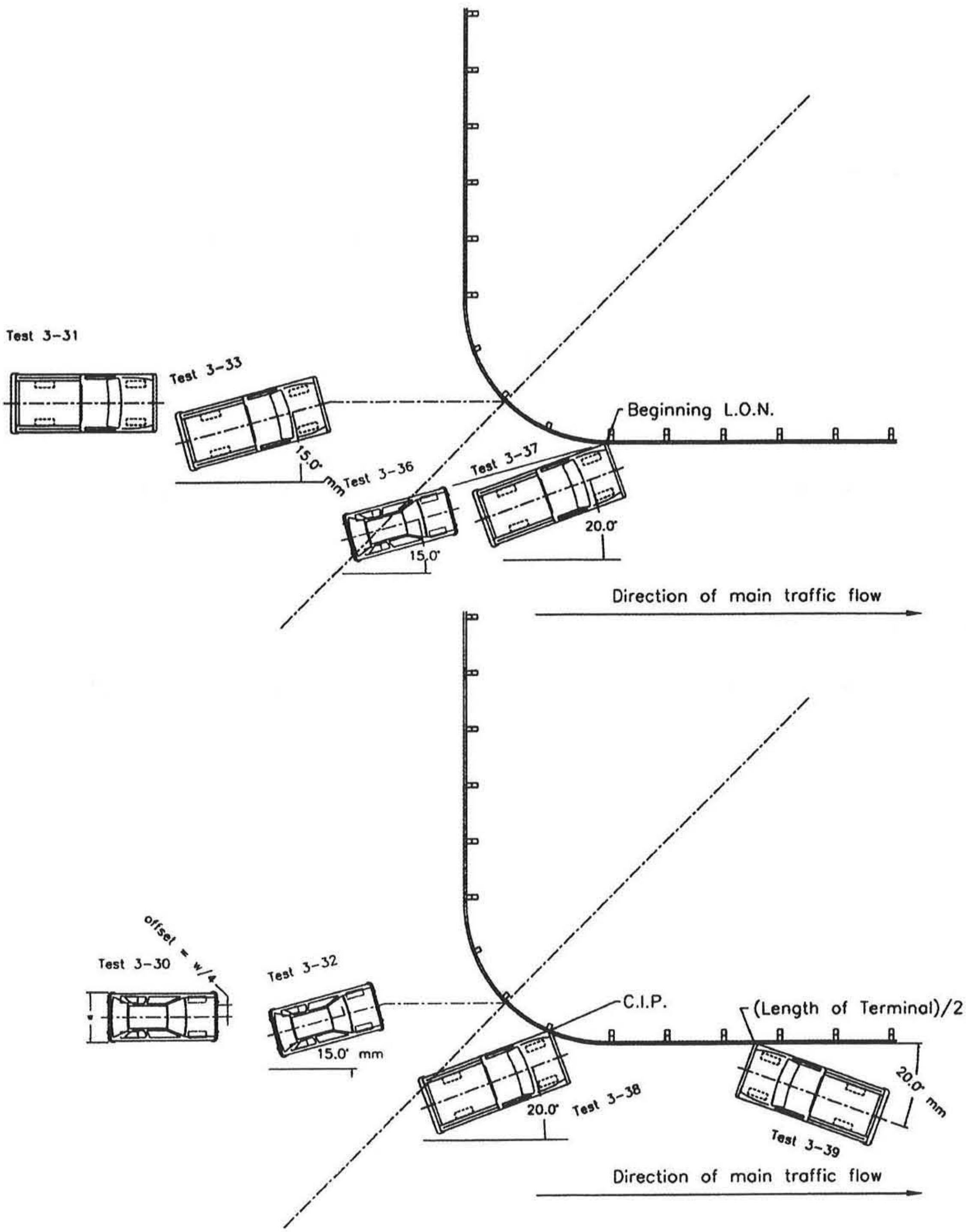


Figure 2. Proposed Full-Scale Crash Tests For Short-Radius Guardrail Evaluation

Table 1. NCHRP Report 350 Evaluation Criteria for 2000P Pickup Truck and 820C Small Car Tests

Evaluation Factors	Evaluation Criteria	Applicable Tests
Structural Adequacy	D. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	3-37 3-38
	C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.	3-30 3-31 3-32 3-33 3-39
Occupant Risk	D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.	ALL
	F. The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.	ALL
	H. Occupant impact velocities should satisfy the following: **Occupant Impact Velocity Limits (m/s)** Component — Preferred — Maximum Longitudinal and Lateral — 9 — 12	3-30 3-31 3-32 3-33 3-36
	I. Occupant ridedown accelerations should satisfy the following: **Occupant Ridedown Acceleration Limits (G's)** Component — Preferred — Maximum Longitudinal and Lateral — 15 — 20	3-30 3-31 3-32 3-33 3-36
Vehicle Trajectory	K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	ALL
	L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 G's.	3-37 3-38 3-39
	M. The exit angle from the test article preferably should be less than 60 percent of the test impact angle, measured at the time the vehicle lost contact with the device.	3-36 3-37 3-38 3-39
	N. Vehicle trajectory behind the test article is acceptable.	3-30 3-31 3-32 3-33 3-39

5 DEVELOPMENT OF INITIAL DESIGN CONCEPT

5.1 Design Parameters

The initial design of the short-radius system began with discussion of the design parameters that would govern the design of the new system. This discussion focused on the information gained in the literature search and design space analysis conducted previously. Experience gained by the researchers during the development of the bullnose median barrier system at the MwRSF (10-12) was also applied.

The basic geometric details of the new design were the first parameters discussed in the development of the design concept. The layout of the system was chosen to accommodate a 90-degree angle between intersecting roadways. This system would terminate into a bridge rail along the primary road, while the section of the system along the secondary road would terminate into a TL-2 guardrail end terminal. This basic layout was chosen because it provided the most common intersection geometry. An approach guardrail transition and bridge rail were positioned along the primary road because it was believed to provide the worst case scenario (i.e., greatest potential for pocketing and/ or snagging).

Next, it was desired that the length of the tangent sections adjacent to the radius of the guardrail be kept to a minimum for several reasons. First, if the system was successfully tested with the minimum length of the tangent section, then it is reasonable to assume that longer lengths would also be acceptable and not require additional crash testing. Second, a system with shorter sides is much simpler to adapt to field situations with lower material and installation labor costs. Therefore, the short-radius guardrail was designed to minimize the length along both roadways.

Finally, several features were also chosen for implementation into the new short-radius guardrail system based on their successful use in the bullnose median barrier mentioned previously. Due to some of the inherent similarities between these two designs, it seemed prudent to consider those features for use in the development of the bullnose for this effort. Thrie beam guardrail was chosen for the design of the new system based on its increased strength and improved capture abilities. The incorporation of slots in the valleys of several sections of thrie beam guardrail was made to improve the ability of the guardrail to capture incoming vehicles and to allow the guardrail to deform without creating large kinks. The nose cables used on the bullnose system were also included in the short-radius design to contain the impacting vehicle in the event of guardrail rupture, as was observed in the testing of the bullnose median barrier. Finally, the use of double, chamfered blockouts was desired on several posts in the system. Testing of the bullnose barrier had shown that the double, chamfered blockouts reduced wheel snag on the posts and improved the capture of the vehicle's front end by the guardrail.

5.2 Nose Section Design

After reviewing the Midwest Regional Pooled Fund member states' standards and the previously tested short-radius systems, a 2,426-mm radius design was selected for use in the current study. The small radius reduced the overall size of the system and allowed for easier application of the design into a variety of intersections. The nose section was formed using one 3810-mm long, curved section of thrie beam guardrail. The curve radius was sized based on the constraint that the nose bend would form a 90 degree angle between the leg ends.

The front-end section of the short-radius system was designed without a post at the centerline of the nose, since the end post typically rotates backwards after impact, often creating a potential for the vehicle to vault over the rail. It was determined that a nose section without the centerline post would have sufficient structural strength to maintain the shape of the rail without rail sagging while also reducing the vaulting hazard.

5.3 Barrier Design Details

The layout of the initial design concept for the short-radius guardrail system is shown in Figures 3 through 5. For the short-radius system, the nose section consists of a 2,426-mm radius nose section bent to form a 90-degree arc with two tangential sides. The primary roadway side is 11,430-mm long, while the side along the secondary roadway is 13,335-mm long. After post no. 9P on the primary roadway side of the system, a 3,810-mm long approach guardrail transition system is used to adapt the short-radius system to a safety-shape concrete bridge rail. Details on the approach guardrail transition can be found in previous publications by MwRSF (14,15). Actual installations of the short-radius guardrail system could use any NCHRP Report No. 350 approved approach transition. On the secondary roadway, a 7,620-mm long Test Level 2 (TL-2) FLEAT end terminal was attached at post no. 4S in order to terminate that side of the system. Details on the FLEAT can be found in the Transportation Research Record No. 1690 (16). A TL-2 end terminal was chosen for the design based on expectations of lower speeds along the secondary roadway and the desire to keep the length of the side of the system to a minimum. In the following sections, barrier details are given for the remaining the short-radius system, excluding these end connections.

The system was configured with twenty-four wood posts with fifteen posts positioned along the primary roadway and nine posts along the secondary roadway. Starting from the radius, the first post on each side of the system was a 140-mm wide by 190.5-mm deep by 1830-mm long Breakaway Cable Terminal (BCT) post set in 2440-mm long foundation tubes. Post no. 1 on each side of the barrier used a single 150-mm wide by 200-mm deep by 360-mm long thrie blockout that

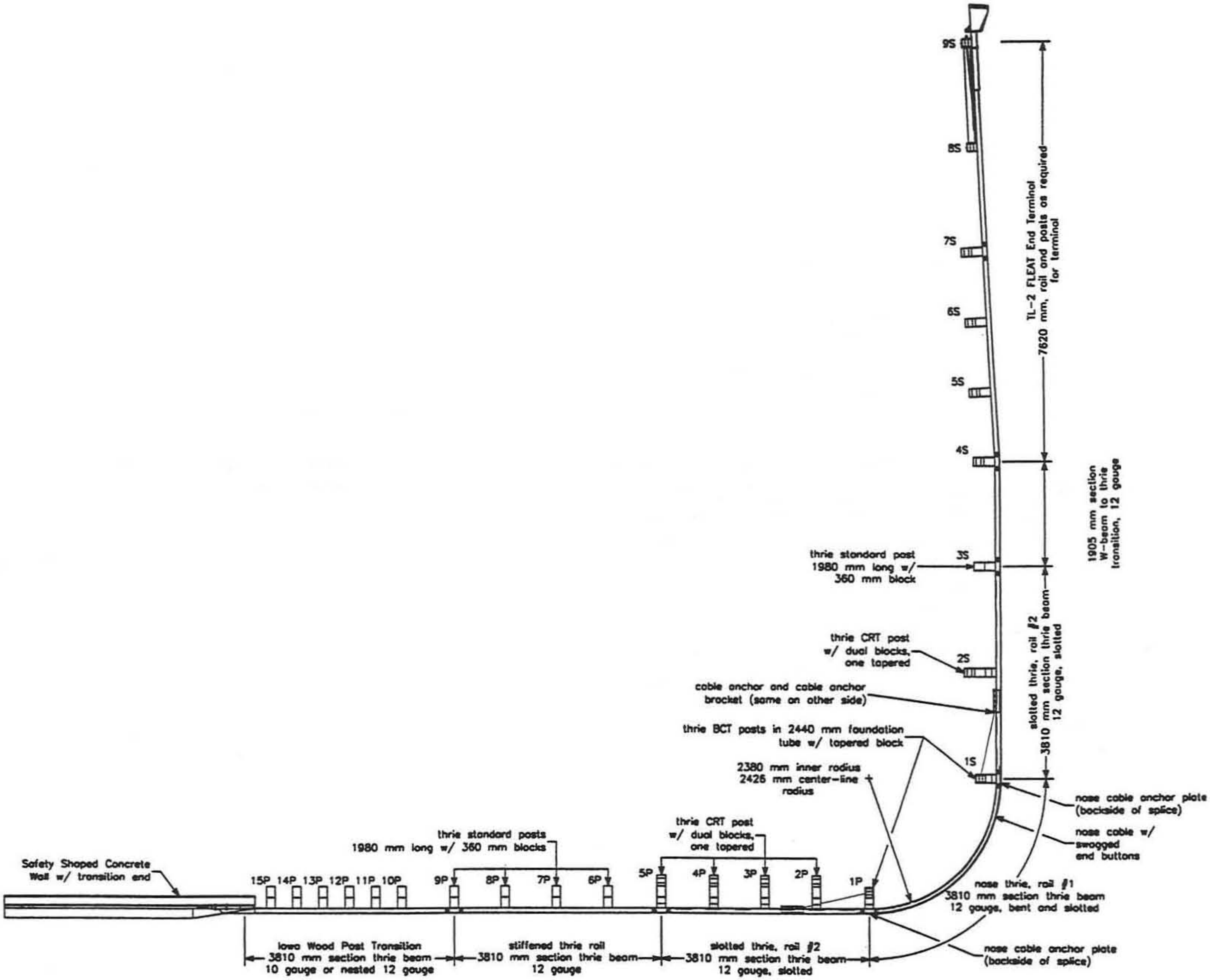


Figure 3. Short-Radius Design Concept

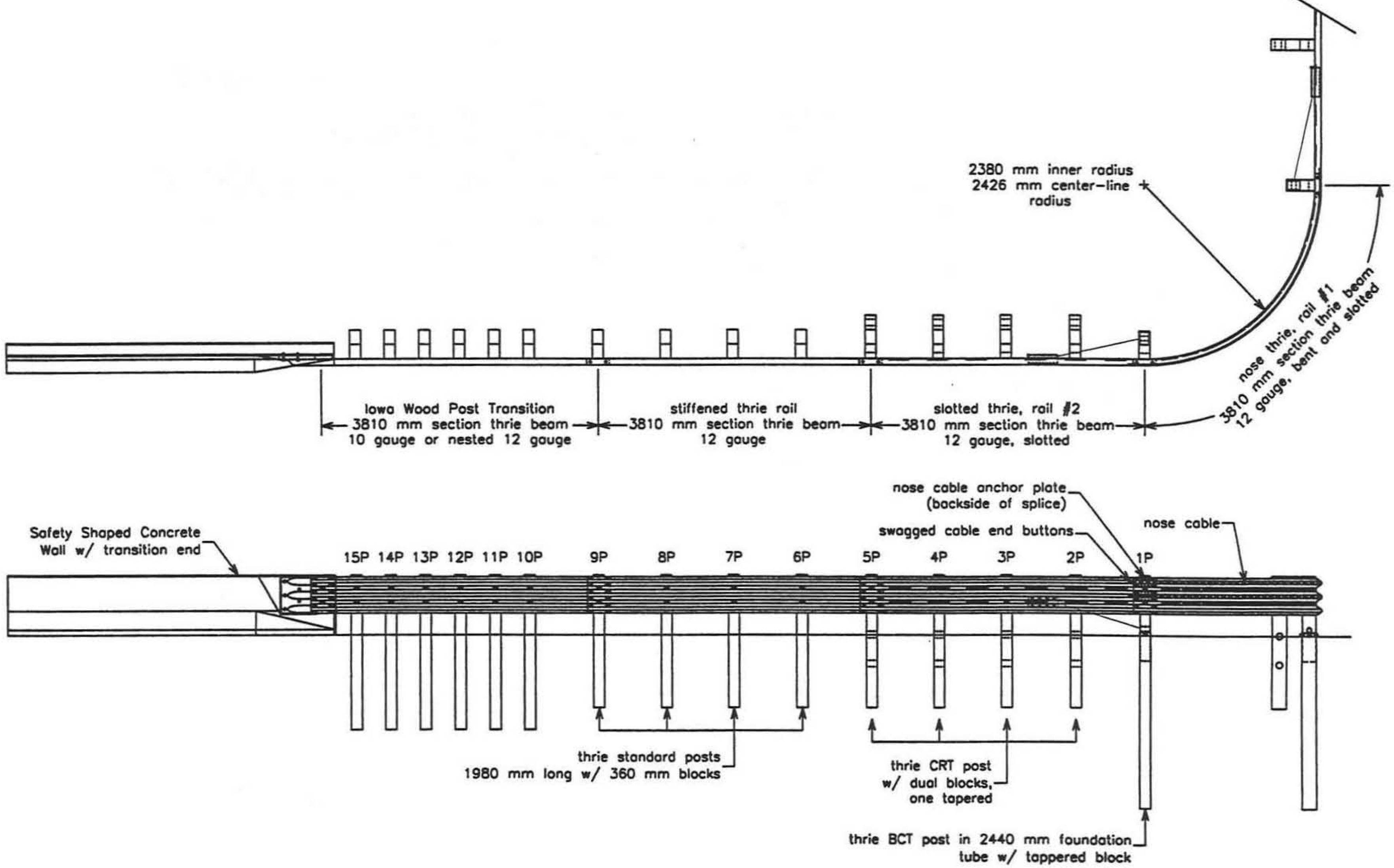


Figure 4. Short-Radius Design Concept, Bridge Transition Side View

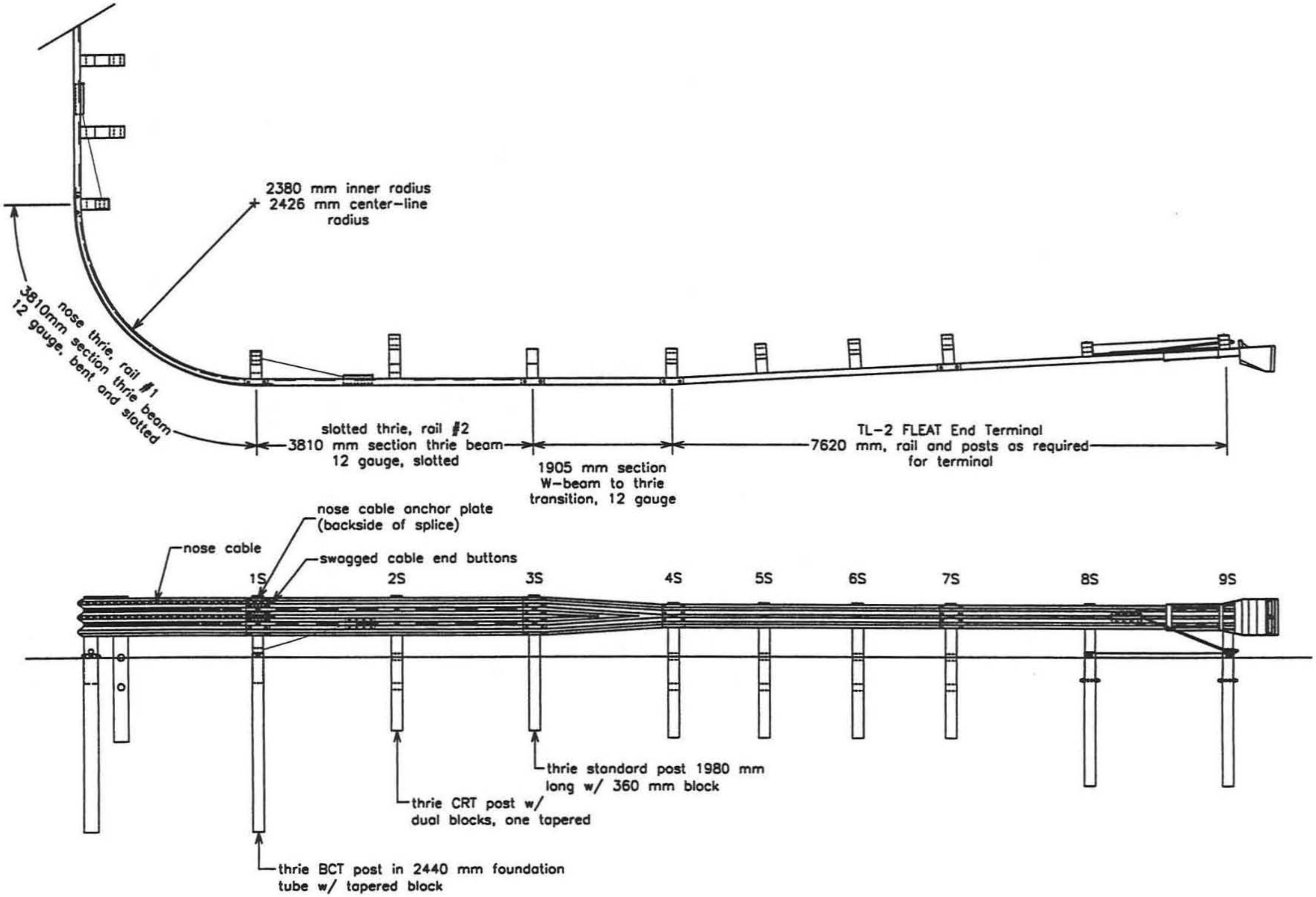


Figure 5. Short-Radius Design Concept, FLEAT Terminal Side View

was chamfered at a 25-degree angle from the middle of the front face of the blockout to the bottom. Post nos. 2P through 5P along the primary roadway and post no. 2S along the secondary roadway were 1980-mm long CRT posts. Each of these posts included double 150-mm wide by 200-mm deep by 360-mm long thrie blockouts to space the rail away from the post. The front blockouts on the double blockout posts were chamfered in a similar manner to that used with post no. 1. Post nos. 6P through 9P along the primary roadway and post no. 3S along the secondary roadway were standard 150-mm wide by 200-mm deep by 1,980-mm long wood posts. Each of these posts included a 150-mm wide by 200-mm deep by 360-mm long thrie blockout to space the rail away from the post. Post spacing for all of the posts up to post no. 9P along the primary roadway is 952.5 mm. Post spacing for all post up to post no. 4S along the secondary roadway was 1,905 mm. The top mounting height of the rail was 804 mm, as measured from the ground surface. Post nos. 2P through 9P along the primary roadway and post nos. 2S through 4S along the secondary roadway had a soil embedment depth of 1,153 mm. Details of these posts are shown in Figure 6a through Figure 6b.

A cable anchor system was attached between the thrie beam and post no. 1 on each side of the system in order to develop the tensile strength of the thrie beam guardrail downstream from the nose section. With the intermediate posts used in this design, it was necessary to mount the cable anchor bracket to the backside of the bottom valley of the thrie beam in order to eliminate cable clearance issues with the blockout located at post no. 2P. Details of the anchor system are shown in Figure 7.

Four guardrail sections used in the short-radius system consisted of 12-gauge steel thrie beam. The 3,810-mm long sections were spliced together using a standard, bolted lap splice on each interior end. The first three rail sections were cut with slots in the valleys. The nose section of the

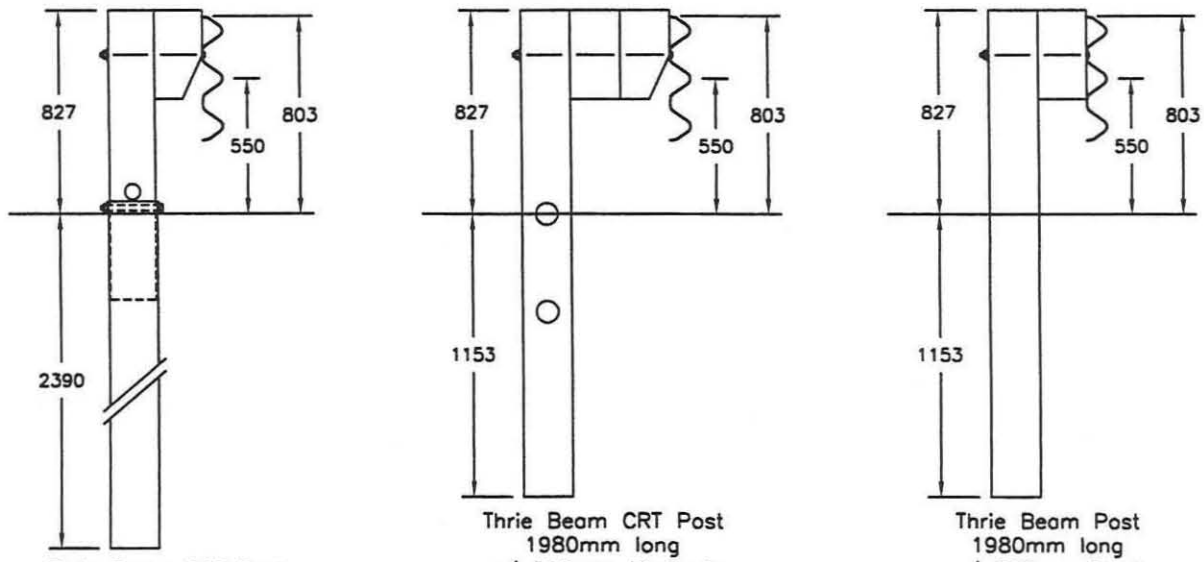


Figure 6a. Short-Radius Post Details

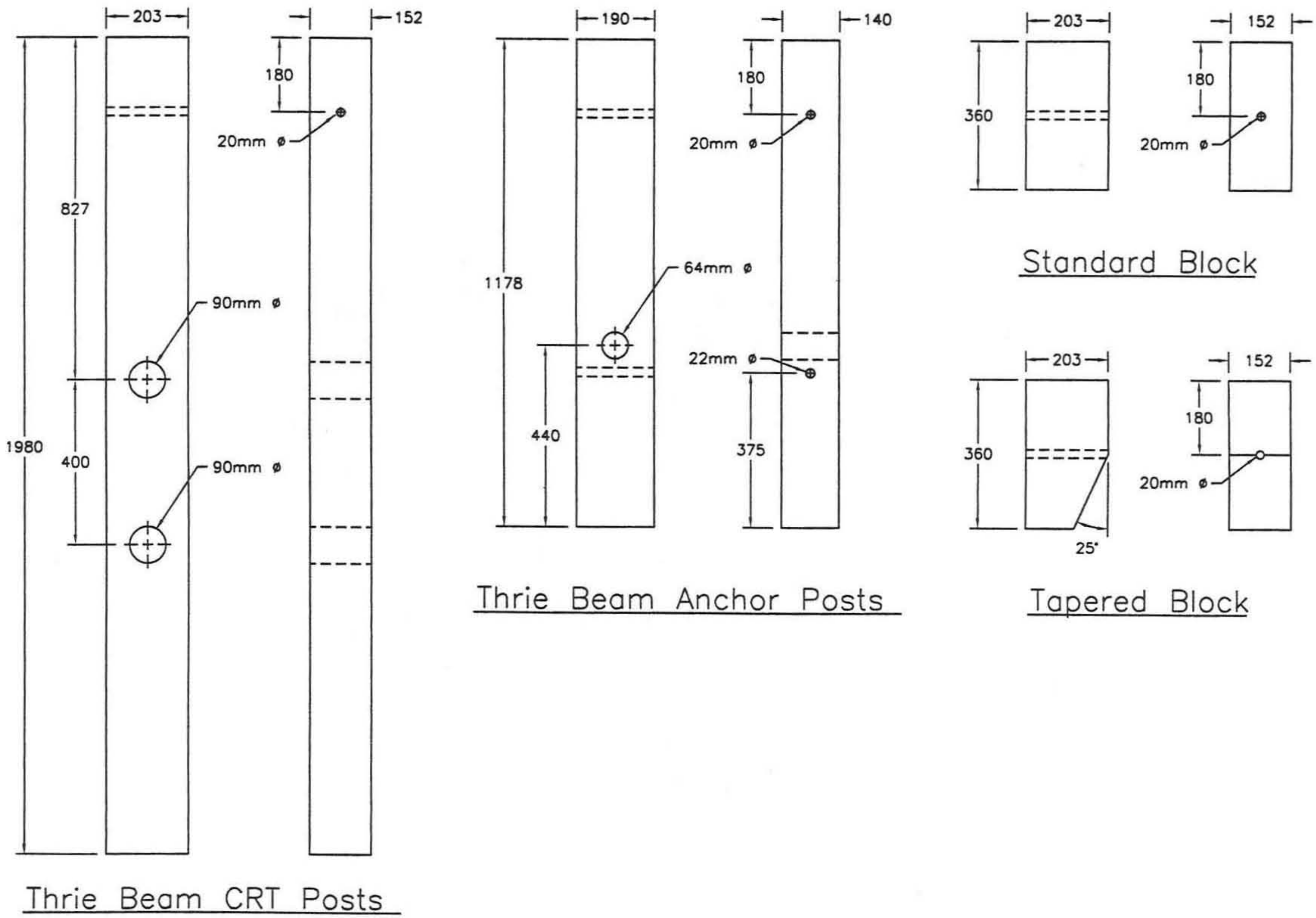


Figure 6b. Short-Radius Post Details

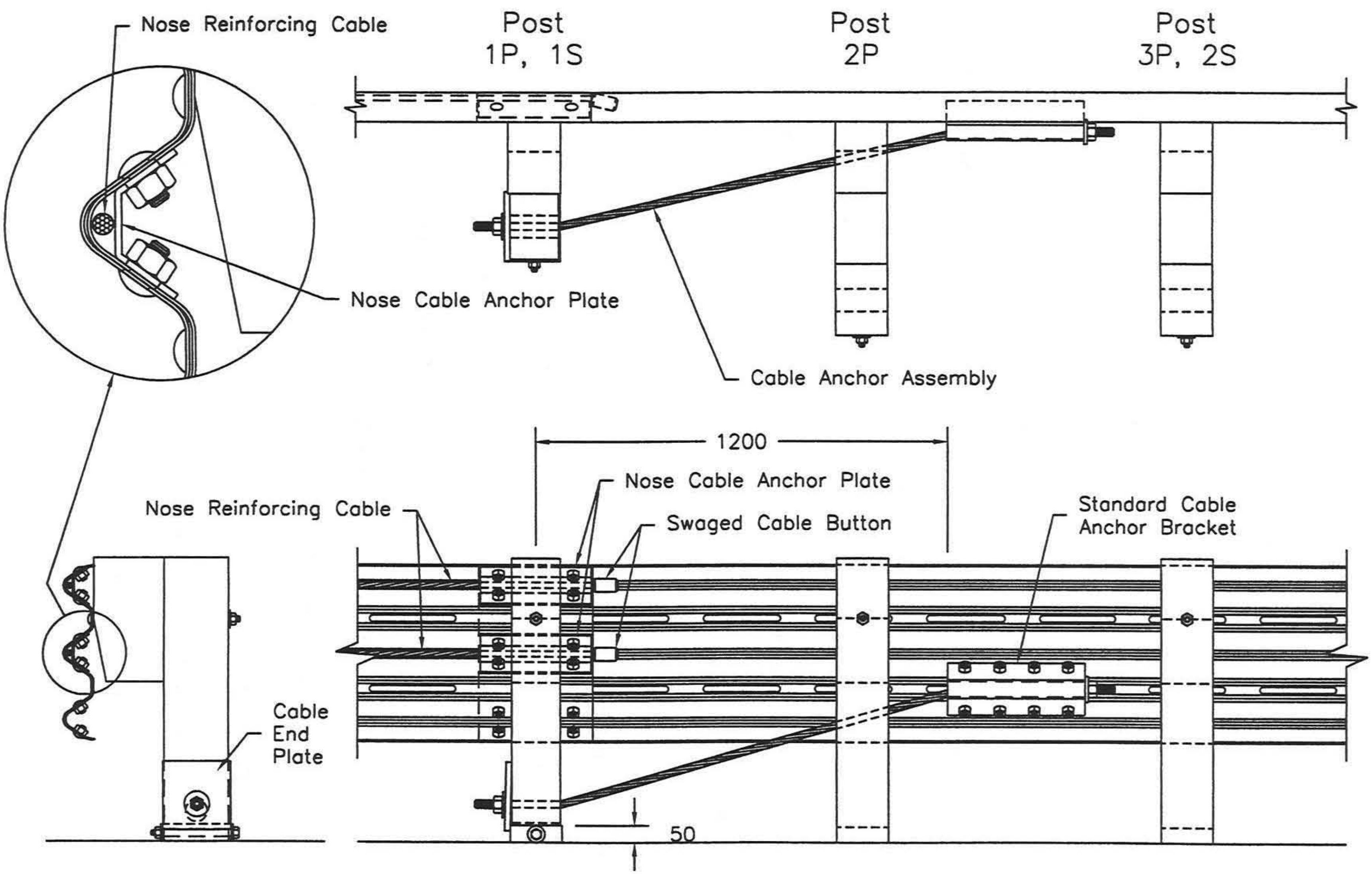
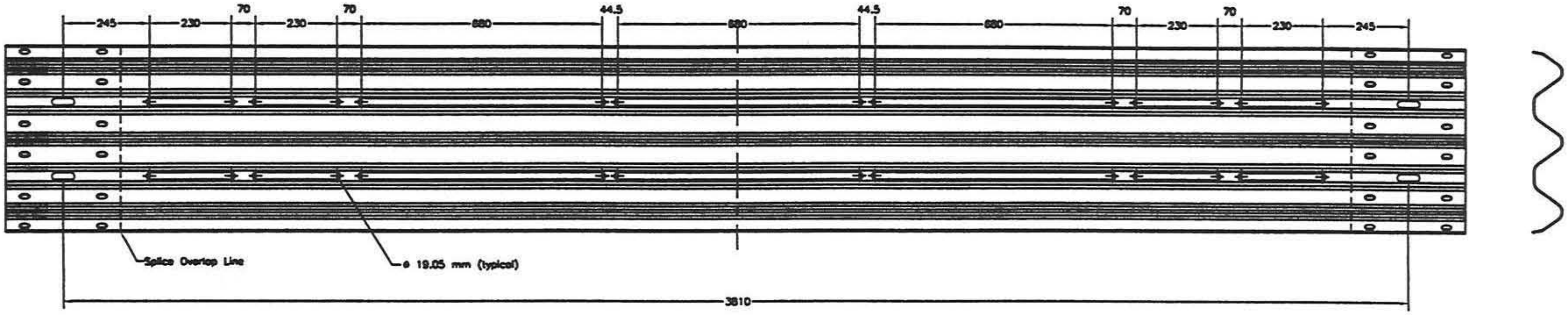


Figure 7. Short-Radius Cable Assembly

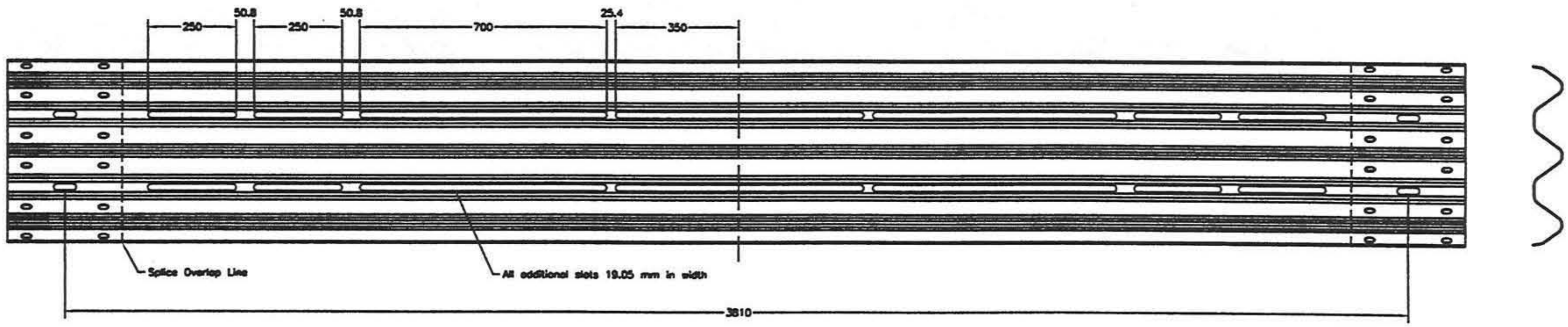
rail (rail section no. 1) consisted of a 3,810-mm long beam bent into a 2,426-mm radius. The nose section was cut with slots in the valleys to aid in vehicle capture, as shown in Figure 8. There were six primary 700-mm long slots centered about the midspan of the rail, three in each valley. The primary slots were divided from one another by 25-mm wide slot tabs. Eight additional smaller 230-mm long slots, four on each end of the rail section, were also cut with a 50-mm wide slot tab between them. All slots were 25-mm wide. The second rail section on each side was straight section of thrie beam guardrail. These sections were cut with a different pattern of slots, as shown in Figure 9. The slot pattern for this section used on each side consisted of two sets of six 300-mm long slots centered between post slots. The slots were separated by 250-mm wide slot tabs, which provided three slots per valley between posts. The remaining section of thrie beam guardrail along the primary roadway was not slotted.

A 12-gauge thrie beam to W-beam transition section was placed between post nos. 3S and 4S along the secondary roadway. The transition section was necessary in order to end the guardrail with an approved W-beam guardrail end terminal, such as the FLEAT.

A set of steel retention cables were attached to the back of the nose section to contain impacting vehicles in the event of rail rupture. A 4.38-m long by 15.9-mm diameter cable was added behind the top and middle humps of the nose section of thrie beam rail. A 7 x 19 cable was chosen such that one of the two cables was capable of containing the impacting vehicle. It is noted that the steel cables were only placed behind rail section no. 1. Since it was believed that the rail sections beyond the nose section would remain active and intact throughout the impact event, the use of longer cable lengths was not deemed necessary. The cables were attached to the guardrail using three 6.35-mm diameter U-bolts per cable to fix the cables behind the top and middle humps of the thrie



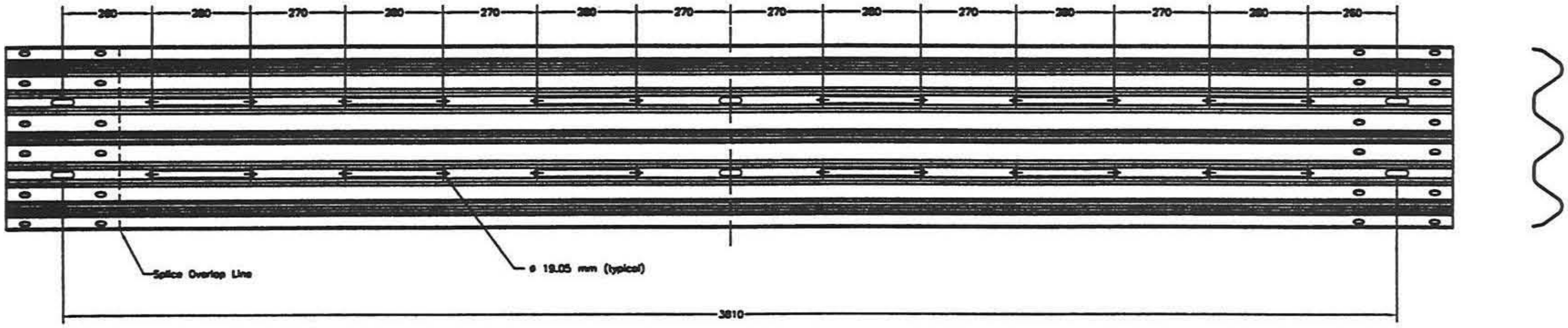
Rail Section 1 ("Nose" Section)



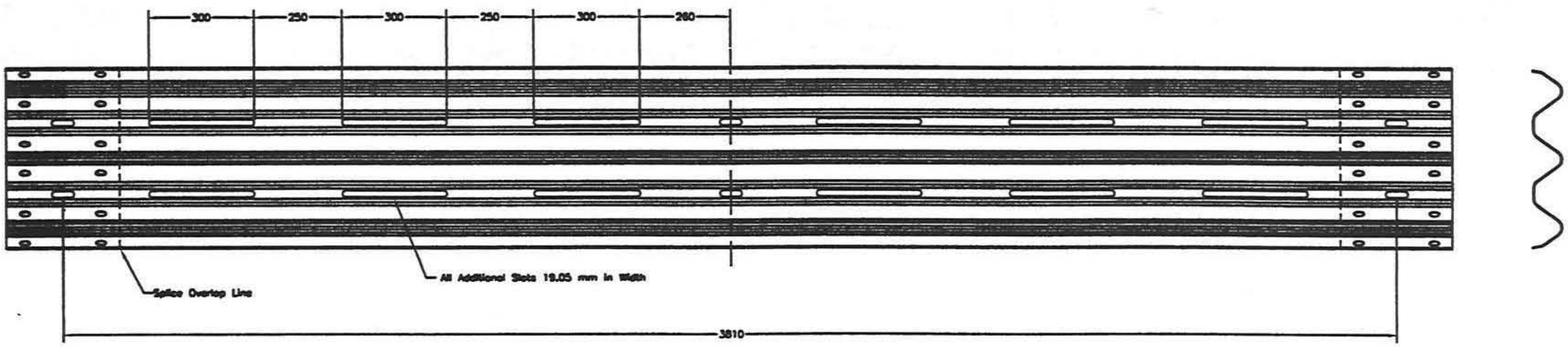
Rail Section 1 ("Nose" Section)

Note: All units are in mm unless specifed otherwise

Figure 8. Short-Radius Rail Section No. 1



Rail Section 2



Rail Section 2

Note: All units are in mm unless specified otherwise

Figure 9. Short-Radius Rail Section No. 2

beam. The ends of each cable were fitted with "Cold Tuff" buttons and clamped between formed steel plates located at the guardrail splice at post no. 1 on each side. The "Cold Tuff" buttons are swaged-grip button ferrules. As such, any similarly sized swaged-grip button ferrule could be substituted into the design. The cable plate and the cable detail are shown in Figure 10, while the assembly details are shown in Figure 7.

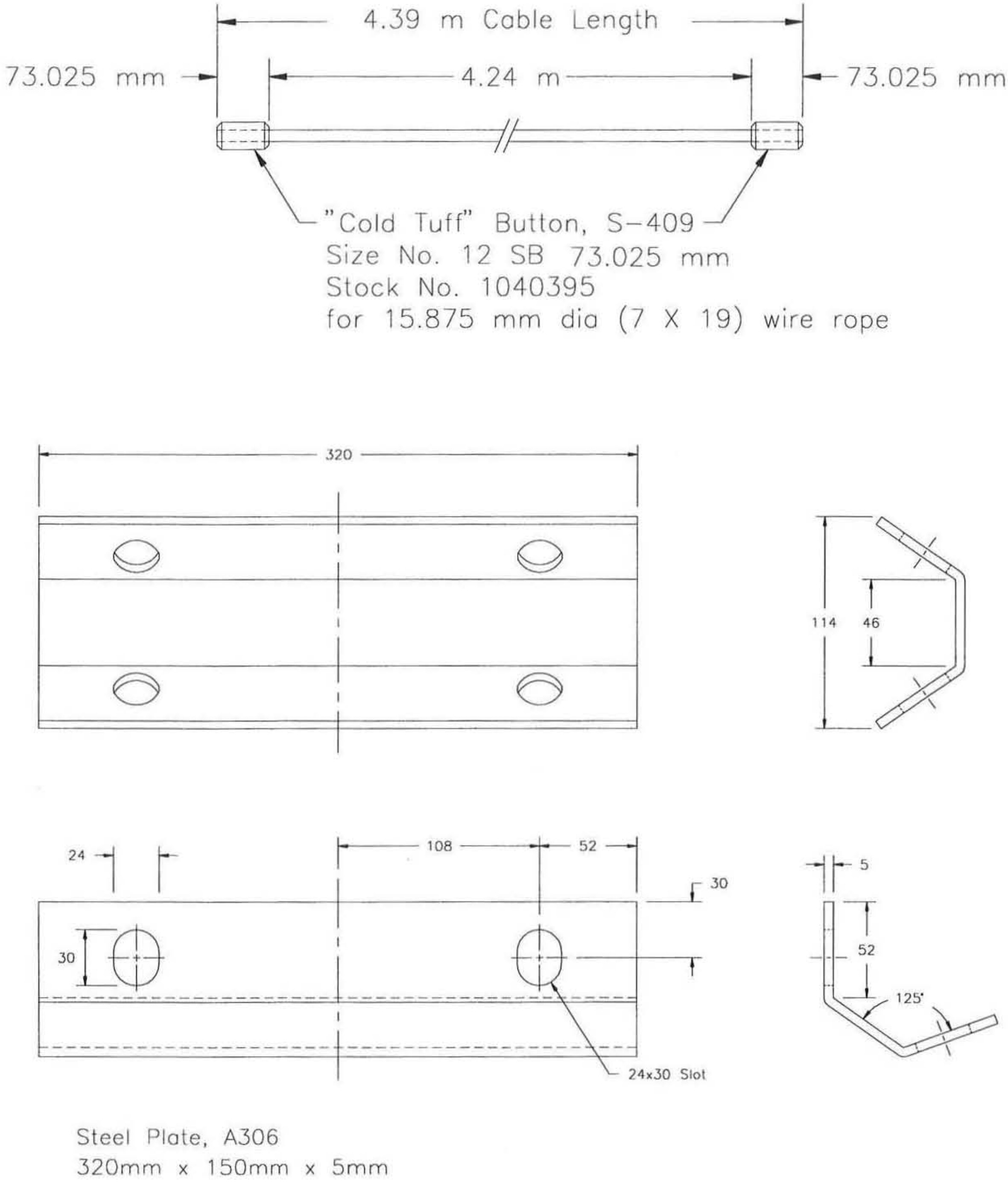


Figure 10. Cable Detail and Cable Plate

6 COMPUTER SIMULATION

6.1 Simulation Objective

Following the development of the initial design concept, the next phase consisted of a nonlinear finite element simulation of the design using LS-DYNA (17). The objective of the simulation effort was to evaluate the feasibility of the new design prior to any full-scale testing. It was believed that simulation of the short-radius design would aid in the identification of flaws in the design.

The initial simulation of the new short-radius design was set up to according to the NCHRP Report No. 350 test 3-33 specifications. Test 3-33 consists of a 2,000-kg pickup truck impact on the nose of the system at a speed of 100 km/h and at an angle of 15 degrees from the primary roadway. The decision to simulate test 3-33 was based on the researcher's previous experience with the simulation of the bullnose barrier design (10-12). The test 3-33 impact condition was highly similar to the impacts simulated in the development of the bullnose barrier. Therefore, it was believed that the experience gained from the previous research study would significantly reduce the time commitment necessary for creating a reliable short-radius system model.

Due to the complex nature of the simulation of the short-radius design, a series of models with increasing sophistication were developed. The use of these incremental models allowed simulation errors to be identified and corrected in a sequential manner rather than having to sort many problems out of a large, full-system model. A total of three models were developed in the process of simulating the short-radius design concept under the test 3-33 impact requirements: (1) a model of the first three guardrail sections and the nose cable; (2) a model of the first three guardrail sections with the posts and cable anchors; and (3) a final model with six fully modeled guardrail sections. Each of these models is discussed in greater detail in the following sections.

All of the simulation models were impacted with the UNL C2500 truck model.

6.2 Model with Three Guardrail Sections

The initial model developed for the simulation of the short-radius design concept was a model of three guardrail sections, as shown in Figure 11. This model included the nose section of guardrail and the first tangent section on each side of the nose. The splices between the sections were modeled by simply doubling the thickness in the splice area. No posts were included in the model at this time.

Slots were added to the valleys of the thrie beam guardrail by simply deleting elements in the appropriate locations. Tearing of the slot tabs was a critical behavior deemed necessary to incorporate into the simulation of the short-radius system as it provides the mechanism for the humps of the thrie beam to separate and more effectively capture the front of the impacting vehicle. Thus, the slot tabs in the nose section of guardrail in the model were defined as a separate material in order to facilitate tearing of the tabs. Material properties for the tabs were developed previously through component testing during Phase II of the bullnose project (12).

In addition to the guardrail, the nose cables located behind the top two humps of rail section no. 1 were included in the model. The nose cable model was comprised of many discrete beam cable elements. For simulation purposes, the U-bolt cable attachments were modeled as spotwelds that tied the cable to the guardrail at several locations, and the cables were modeled with an elastic material model.

Simulation of the three guardrail section model yielded good results with only one major simulation problem. The deformation of the thrie beam guardrail was reasonable and no contact

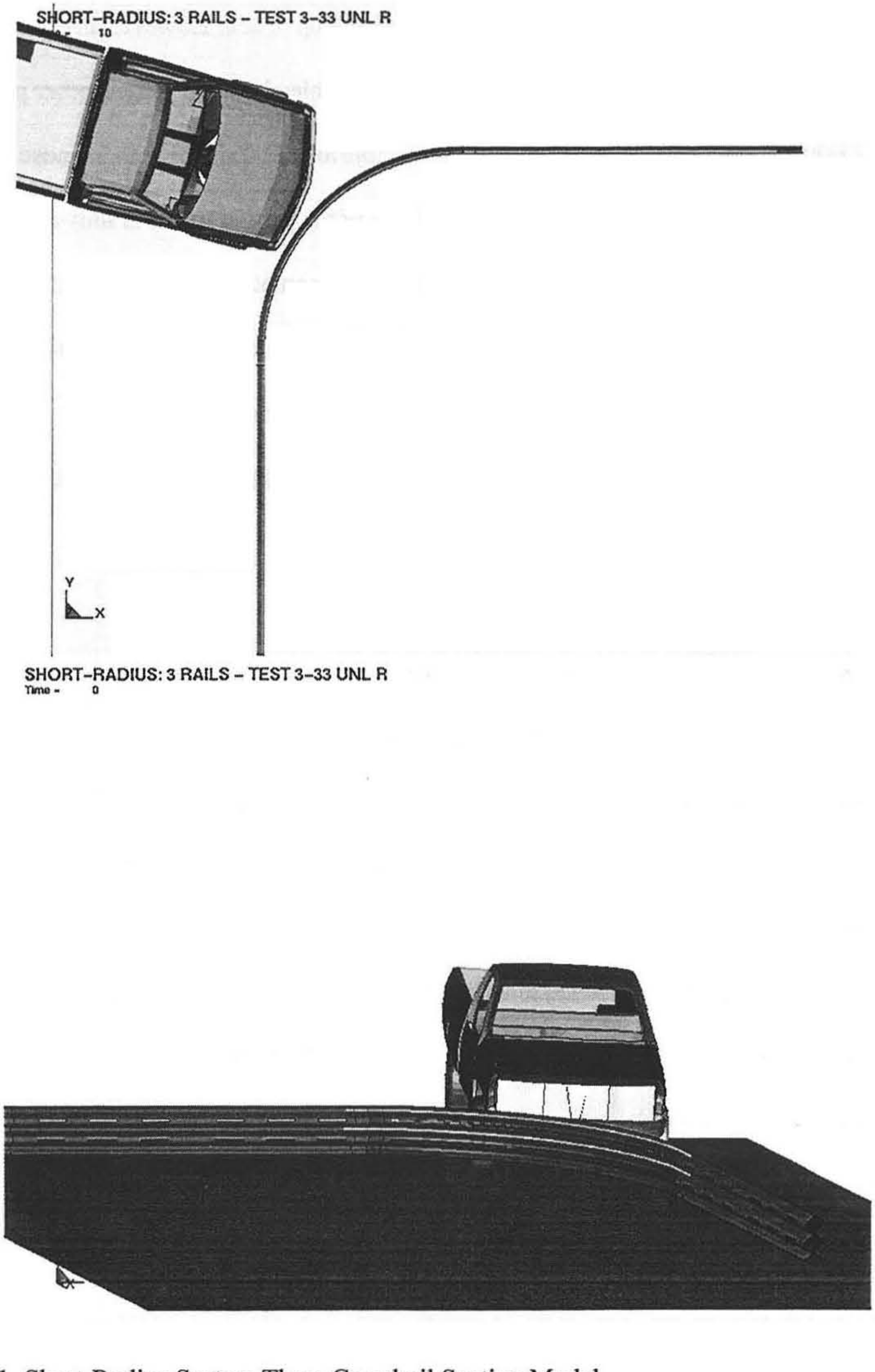


Figure 11. Short-Radius System Three Guardrail Section Model

problems were observed between the guardrail and the pickup truck. However, the problem with the simulation was found in the contact between the nose cable elements and the other parts in the model. The cable contact was flawed as the cable was able to pass through both the nose section of the guardrail as well as the bumper and radiator sections of the pickup truck, as shown in Figure12. Originally, surface to surface contact was used to define the contact for the cable. However, it was later determined that this contact type was not sufficient to handle the interaction between the discrete cable beam elements and the shell elements. The problem was corrected by switching the contact definition between the components to an automatic single surface contact. This modification vastly improved the contact, as shown in Figure 13.

6.3 Model with Three Guardrail Sections and Posts

After the successful simulation of the first three guardrail sections, a more complex simulation effort of the short-radius design concept was attempted. The new simulation model added all of the posts and the cable anchor assemblies to the first three guardrail sections, as shown in Figure 14. The guardrail and nose cable components used in the model were identical to those used in the previous model.

Three types of posts were added to the model: (1) Breakaway Cable Terminal (BCT) posts; (2) CRT posts; and (3) standard timber thrie beam posts. All of the posts were modeled using a plastic, kinematic material model with appropriate wood properties. The hole section of the BCT and CRT posts used a separate material which incorporated a set failure pressure to erode the elements and allow the posts to break away. A tube of completely constrained, rigid shell elements was used to model the soil foundation tubes used in conjunction with the BCT posts. Simulation of the interaction between the remaining posts and the soil was accomplished using pairs of nonlinear

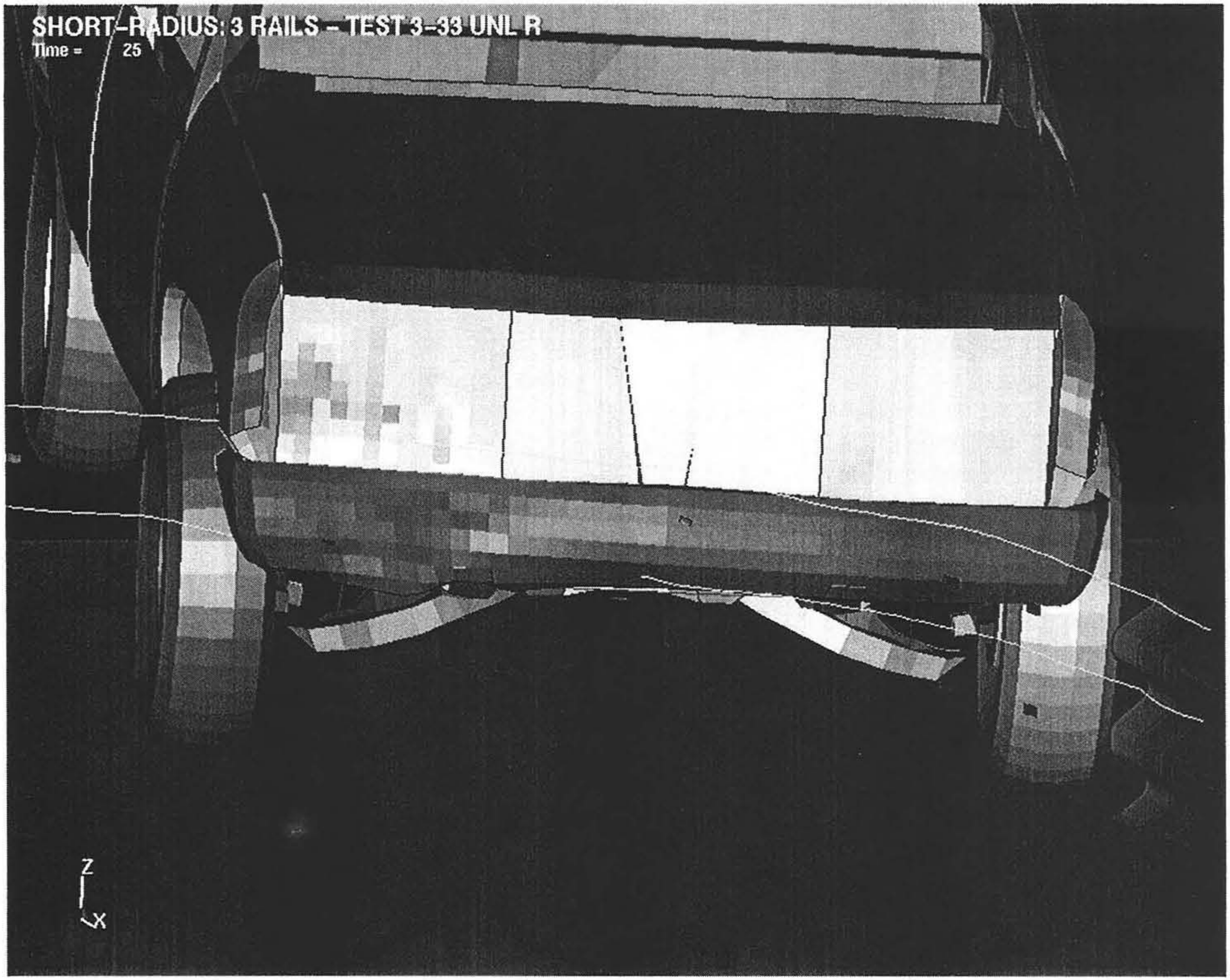


Figure 12. Failed Cable Contact

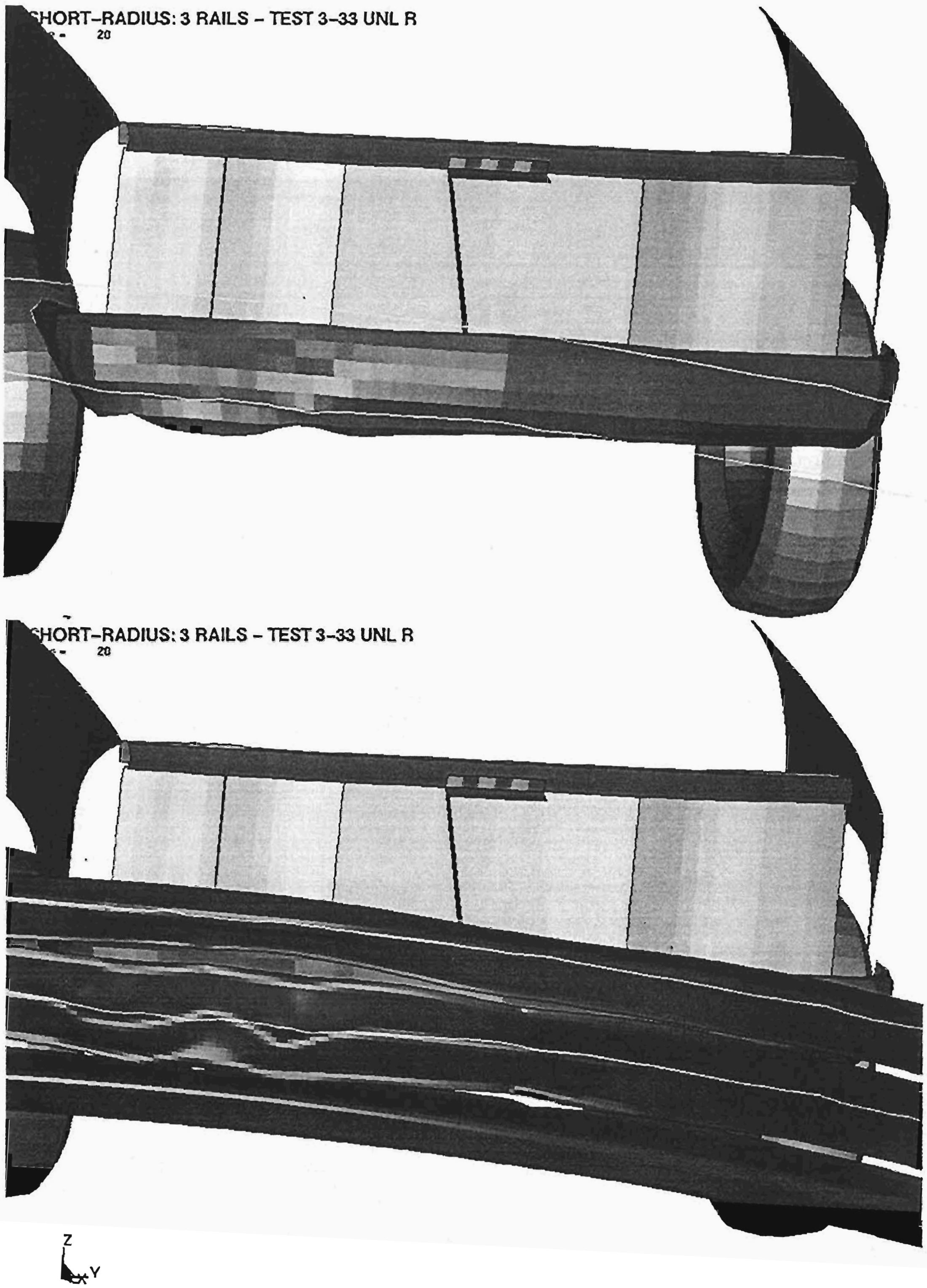


Figure 13. Improved Cable Contact

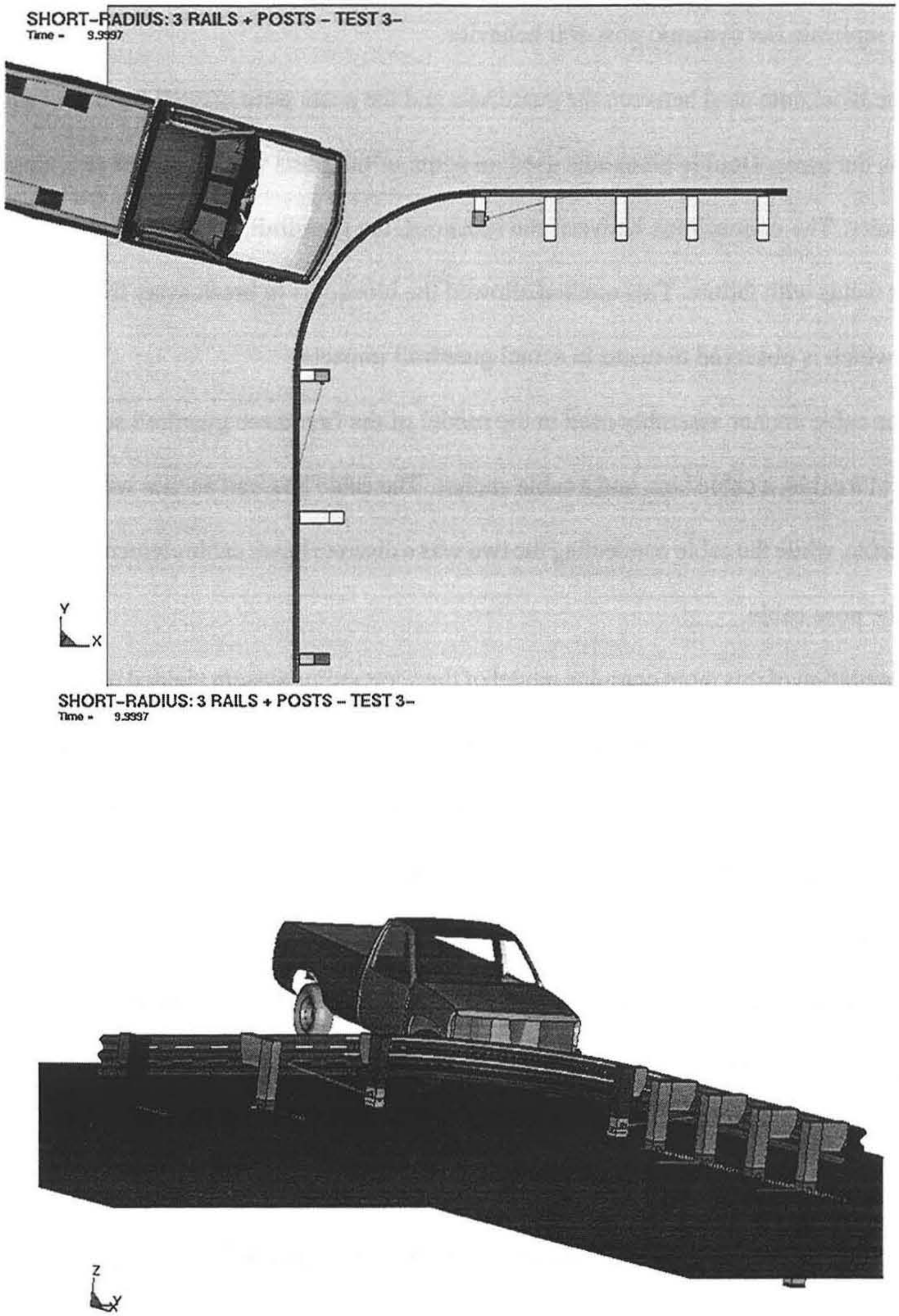


Figure 14. Short-Radius System Three Guardrail Sections with Posts Model

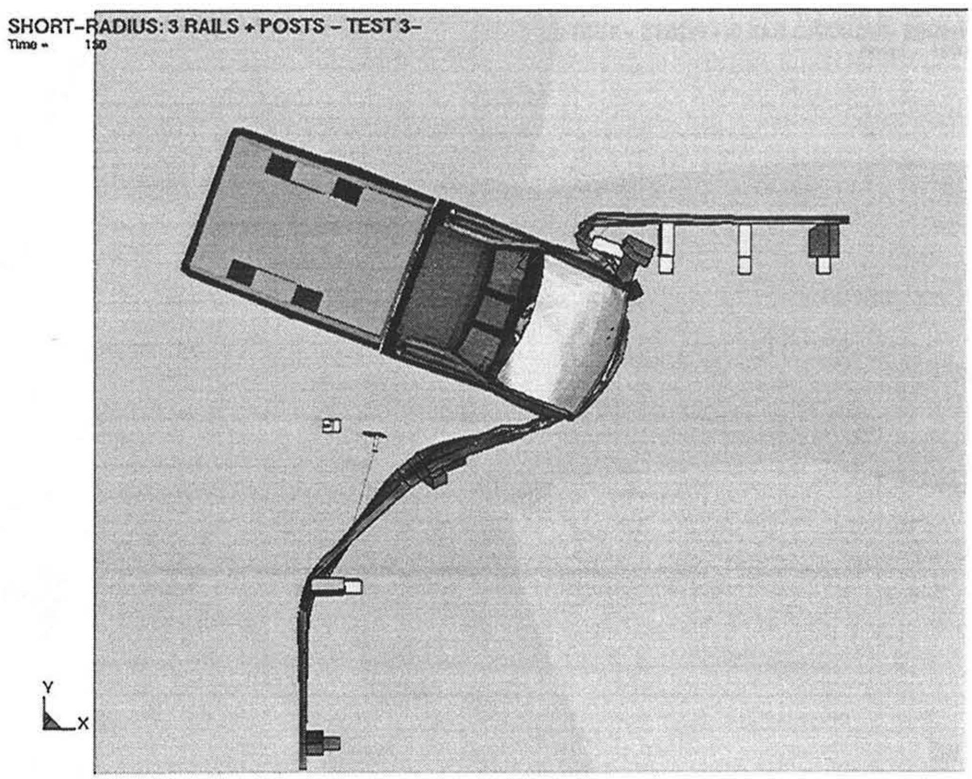
springs to replicate the dynamic post-soil behavior.

The blockouts used between the guardrails and the posts were created from the same wood material as the posts. Double blockouts used on some of the posts were modeled as a single piece for simplicity. The connections between the blockout, the guardrail, and the posts were modeled using spot welds with failure. This method allowed the blockouts to break away from the posts and guardrail which is observed to occur in actual guardrail impacts.

The cable anchor assembly used in the model of the first three guardrail sections and posts consisted of a cable, a cable box, and a cable anchor. The cable box and anchor were modeled with rigid elements, while the cable connecting the two was a discrete beam cable element similar to those used for the nose cable.

Simulation of this more complex model of the short radius system yielded promising results, as shown in Figure 15. Rail capture of the impacting pickup truck looked very good as the top two corrugations of the thrie beam wrapped snugly around the vehicle's front bumper and grill. Aside from the guardrail, the other newly added components used in the model such as the posts, cable, and cable anchors functioned properly as well. Fracture of the breakaway posts was observed as expected, and the cable anchor and blockouts performed without error. No contact failures or other modeling issues were observed with the added components.

While the model of three guardrail sections with posts performed well, some potential simulation problems were identified. A first problem consisted of a contact issue between the radiator of the pickup truck and the thrie beam guardrail, as shown in Figure 16. As the guardrail deformed, the edge of the one of the corrugations of guardrail passed through the edge of the radiator mesh and snagged in it. As the simulation continued, the snagged guardrail mesh pulled the radiator



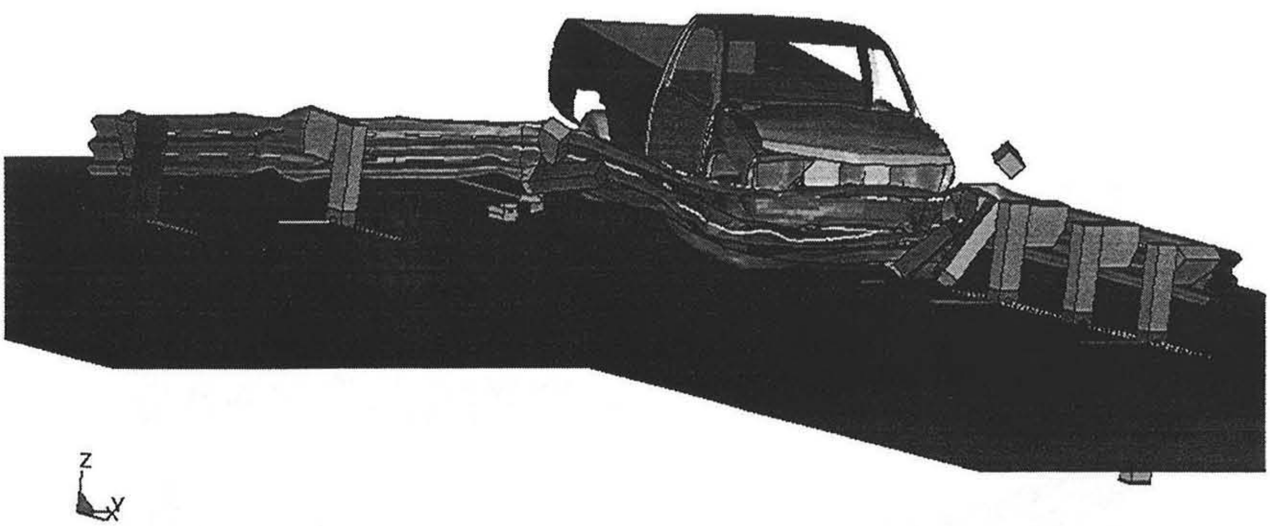


Figure 15. Simulation Results for Three Guardrail Sections with Posts Model

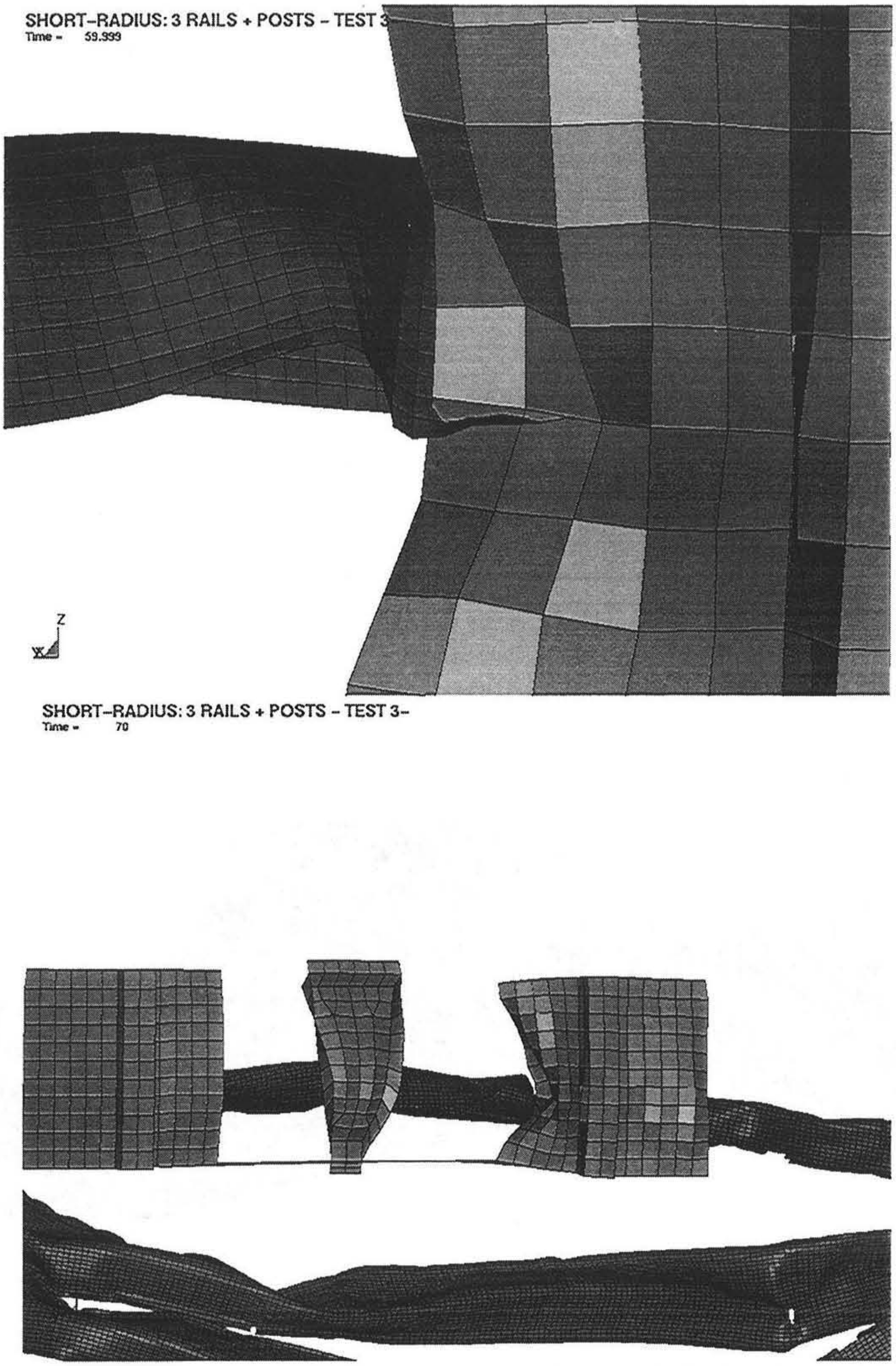


Figure 16. Thrie Beam and Radiator Contact Issue

with it, causing unrealistic interaction and deformation of the system components. However, the problem was attributed to the artificially high stiffness of the partial model. This model rigidly constrained the guardrail on both ends of the short-radius system. This may have stiffened the system's response and pushed the guardrail into the radiator more severely than a simulation with less stiff end conditions. Therefore, it was not deemed necessary to fix the problem unless it showed up again in the simulation of the next generation of the model.

During the review of the simulation results of this model of the short-radius system, a major difference in the behavior of the guardrail was identified between the current model and the simulation and testing results from the bullnose median barrier (10-12). It was noticed that in previous full-scale testing of the bullnose barrier, the front tires of the pickup truck always rolled over the lowest corrugation of the nose section of thrie beam shortly after impact. Due to the similarity in the design of the nose section of the short-radius design, it seemed reasonable that a similar behavior would be observed in the short-radius simulation. However, simulation of the current model did not result in rollover of the lower thrie corrugation by the front tires, as shown in Figure 17.

A couple of potential causes for the lack of rail rollover by the front tires were considered. First, it may seem plausible that the rollover of the bottom corrugation of guardrail by the front tires may not occur due to the differences the geometry of the short-radius and bullnose designs. Second, the vehicle impact orientation with the short-radius nose section is much different than that used during the testing of the bullnose system. A third possible reason for the lack of rollover was that the contact definitions used in the short-radius guardrail model may not be sophisticated enough at this stage of the study. Finally, it was possible that the guardrail and truck contacts used in the model

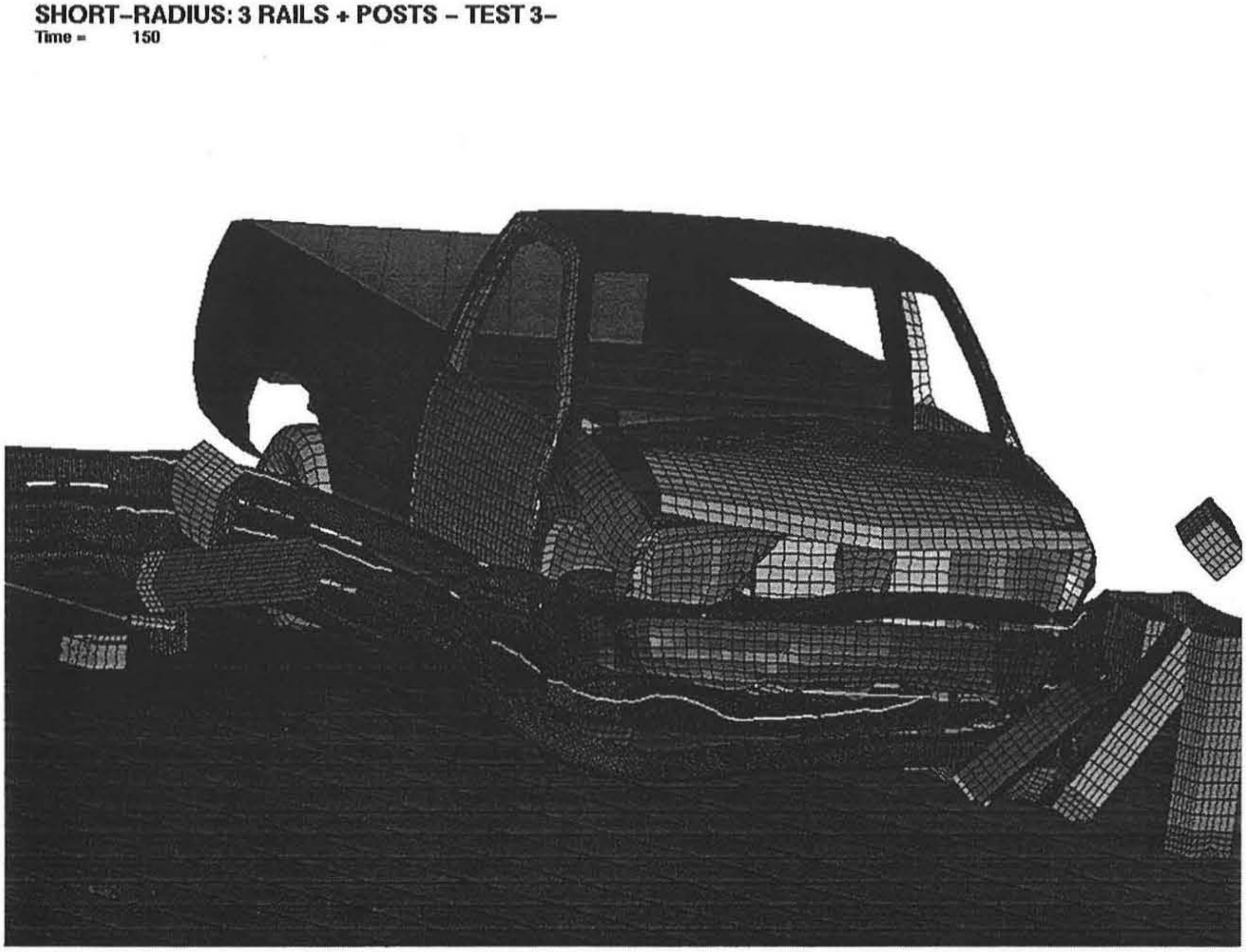


Figure 17. Questionable Guardrail and Tire Interaction

were not applied correctly, and that the behavior might improve if the contacts between them were redefined. Based on the difficulty with the cable contact that was mentioned previously and the lack of any observable contact errors, it seemed unnecessary to change the contacts at this time.

Without full-scale testing of the short-radius system, it is not possible to ascertain with confidence whether or not the front tires will roll over the lower corrugation of the thrie beam guardrail, or determine if it is a valid and necessary behavior to predict. Therefore, it was decided to refrain from further investigation of the discrepancy until such time that the true behavior is revealed through full-scale crash testing.

6.4 Short-Radius Model with Six Guardrail Sections

The final computer simulation model of the short-radius design concept contained six sections of guardrail, as shown in Figure 18. The added sections of guardrail resulted in a system length of 7620 mm being modeled on each side of the nose section. A total of thirteen posts were included in the model. The cable anchor assembly and the nose cable were carried over from the previous models. Two new features were also added to the model for this simulation. First, a W-beam to thrie beam transition section was added between post nos. 3S and 4S along the secondary roadway. After this transition section, the remaining guardrail consisted of standard W-beam. Second, nonlinear springs were attached to each end of the guardrail in order to terminate it and provide tensile capacity, thus approximating the response of the additional guardrail from longer installations. It is noted that the ends of the guardrail were also constrained from moving perpendicular to their respective roadways.

The six guardrail section model of the short-radius system achieved the full complexity desired for the simulation of NCHRP Report No. 350 test 3-33 impact condition. The researchers

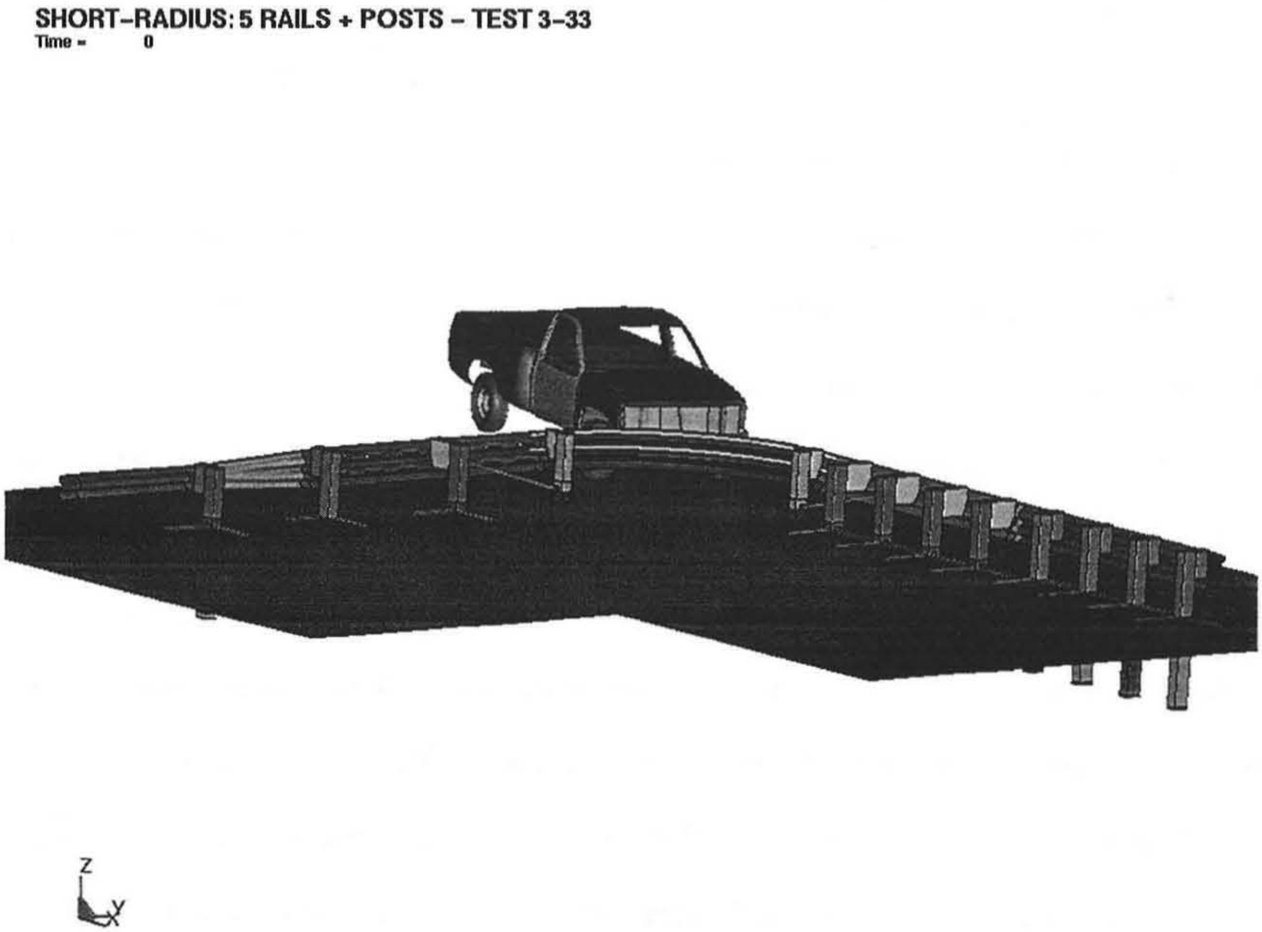


Figure 18. Short-Radius System Six Guardrail Section Model

believe that the extent the system was modeled provided a reasonably acceptable indication of the short-radius concept's safety performance, both with respect to vehicle capture and occupant risk potential.

Simulation of the six guardrail section model was very successful. The correction of modeling flaws in the previous models resulted in no major modeling errors in this model. This final model was used to simulate NCHRP Report No. 350 test 3-33 for analysis purposes.

6.5 NCHRP 350 Test 3-33 Simulation Results

Simulation of NCHRP Report No. 350 test 3-33 was performed using the UNL C2500 truck model to impact the center of the nose of the six guardrail section model of the short-radius system at a speed of 100 km/h and at an angle of 15 degrees from the primary roadway. The model was run for 340 msec on a SGI O2000 workstation using two CPU's. The total CPU time needed to run the simulation was approximately 165 hours.

Plots of the simulation results of test 3-33 are shown in an overhead view and a view behind the system in Figures 19 and 20 respectively. The results looked very promising. The simulation began with the C2500 truck impacting the nose of the system. After impact, the slot tabs in the nose section tore and the guardrail flattened out and captured the front of the truck. The top and middle corrugations of thrie beam captured the grill and the bumper, respectively, as shown in Figure 21. Cable contact remained stable and there were no signs of override or vaulting of the guardrail. As the truck continued into the barrier, the bumper of the truck impacted and broke post no. 1P along the primary roadway at approximately 70 msec into the simulation. Post no. 1S along the secondary roadway was broken almost simultaneously when the guardrail wrapped around it. The guardrail along the primary side buckled and kinked as the truck proceeded farther into the system. However,

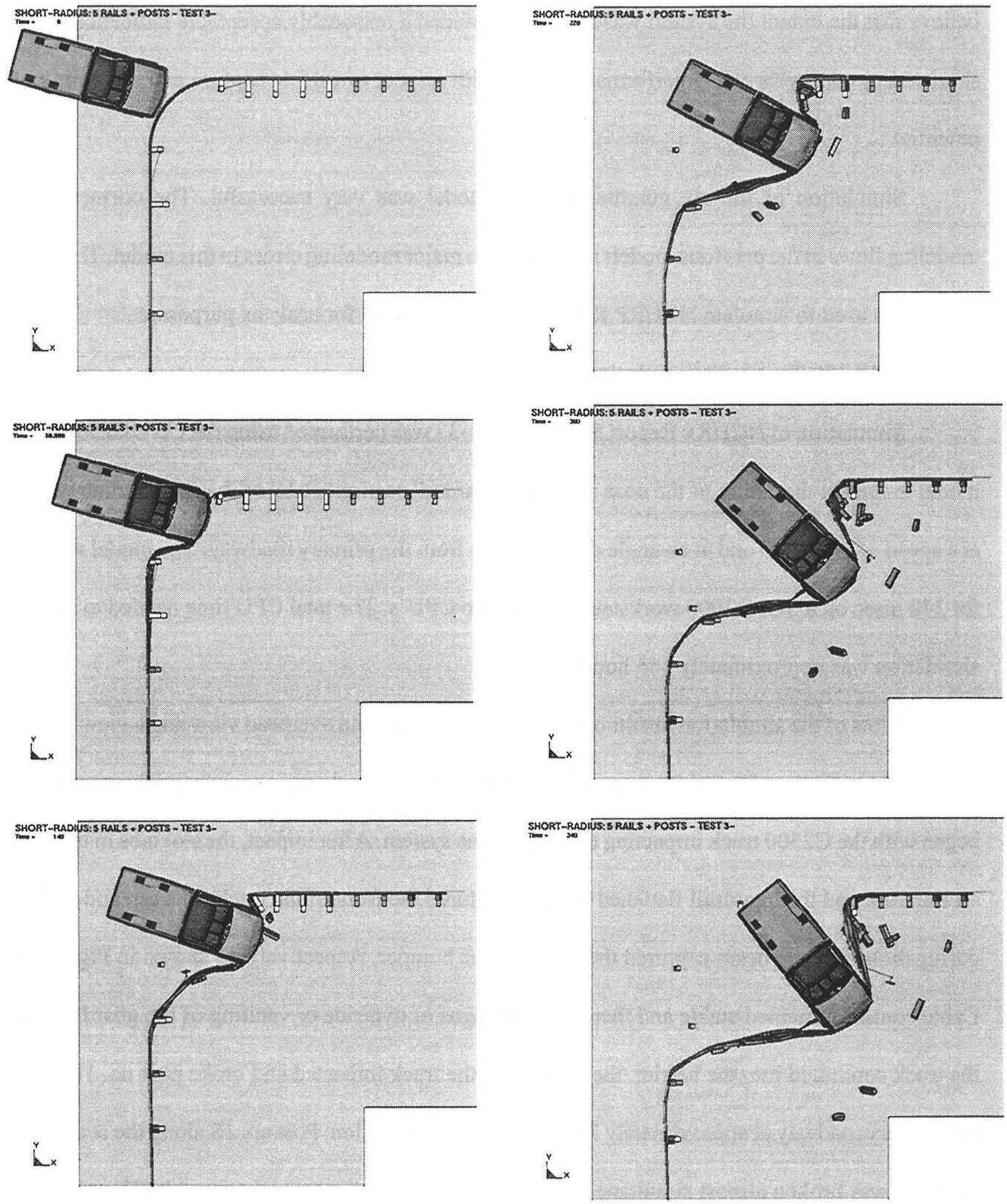


Figure 19. Results of Test 3-33 Short-Radius Simulation, Overhead View

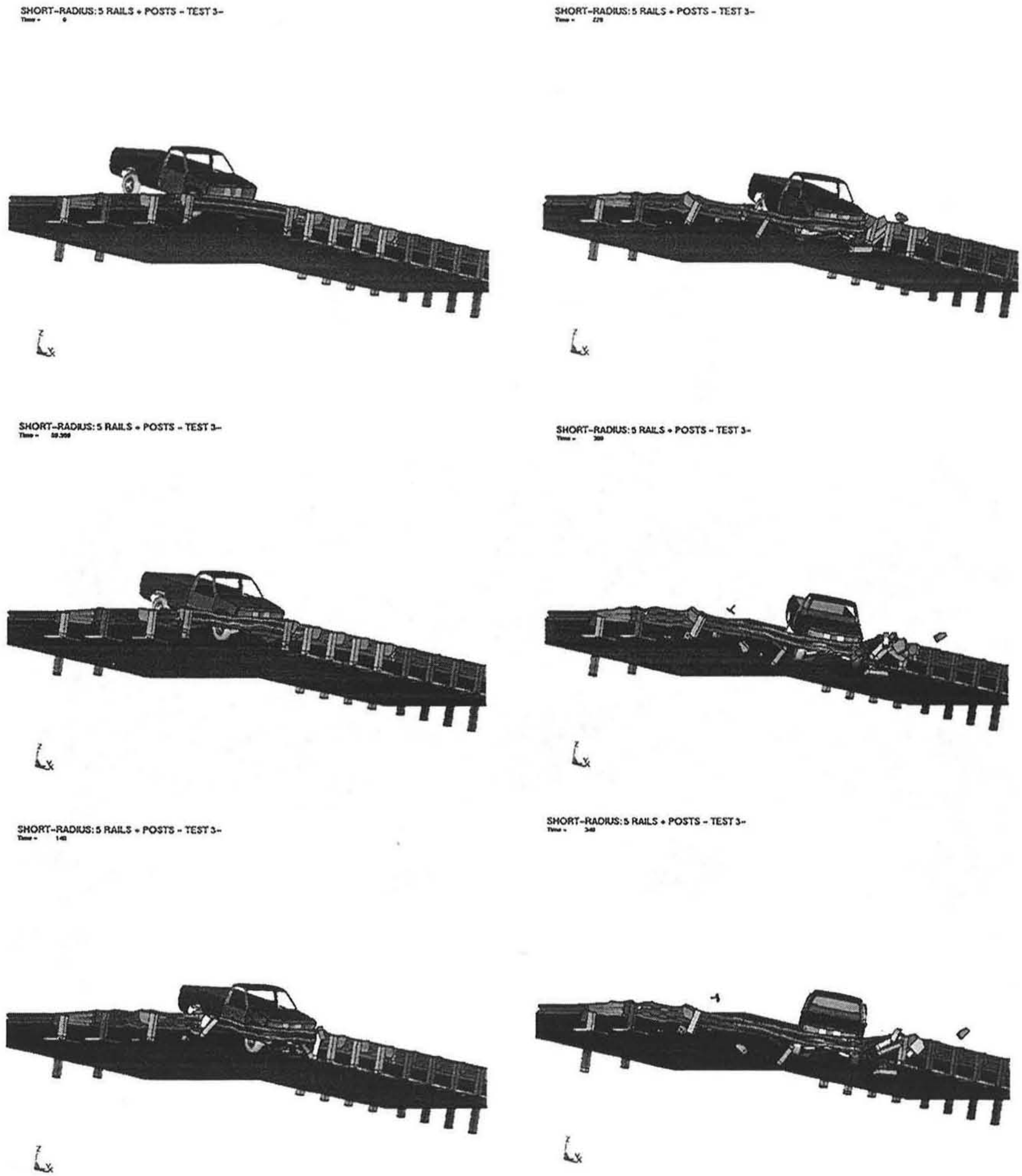


Figure 20. Results of Test 3-33 Short-Radius Simulation, Behind System View

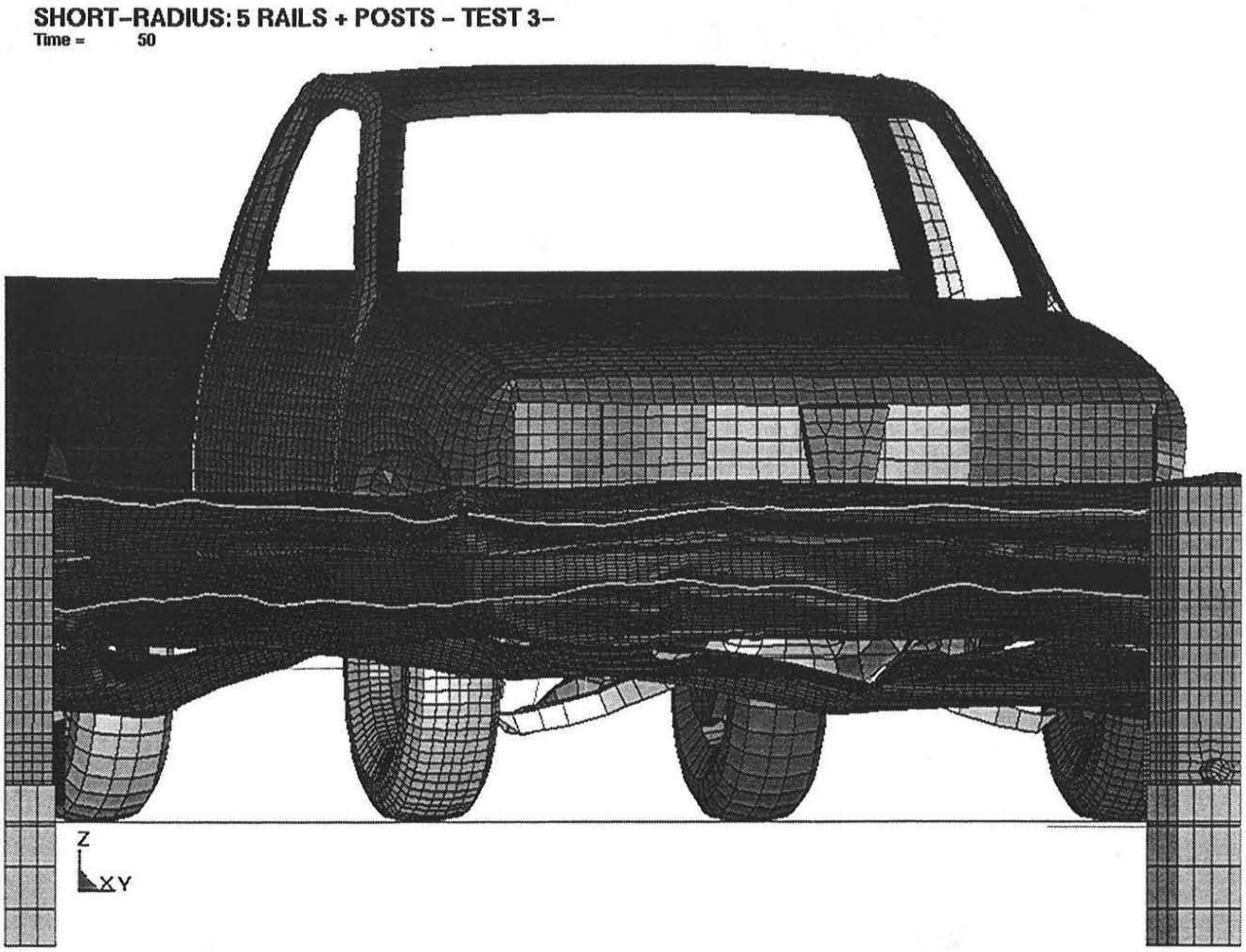


Figure 21. Capture of Front of Pickup Truck

no large kinks were formed due to the weakening of the guardrail by the slots.

At approximately 130 msec, the front bumper of the pickup truck impacted post no. 2P along the primary roadway, causing it to break. By the time the pickup had reached post no. 2P, the guardrail had wrapped firmly around the entire front of the pickup truck. Significant tearing of the guardrail was observed; however, it did not tear completely through or become slack as the impact continued. The unimpaired portions of the guardrail retained enough tension to remain upright, which aided in the continued capture of the vehicle.

After the pickup truck had fractured post no. 2P, the pickup truck began to yaw clockwise. The yawing of the truck was caused by both vehicle interaction with the short-radius system and the impact conditions. As the pickup truck moved past post no. 2P along the primary roadway, the guardrail upstream of post no. 2P wrapped around the left-front corner of the pickup. The wrapping of the guardrail formed a kink at post no. 2P that impacted the truck near the left-front tire. The deformed guardrail and kink along the primary roadway were pushed into the side of the vehicle at approximately 175 msec, as shown in Figure 22. The combination of the kink and the wrapping of the rail around the left-front corner of the vehicle caused the pickup truck to pivot clockwise around that left-front corner due to the unbalanced force applied to that region. The yawing of the pickup truck subsequently caused the body of the truck to roll to the left as it proceeded farther into the system. Both of the wheels on the right side of the vehicle lifted off of the ground slightly due to the roll motion. However, neither the roll nor the yaw of the truck were particularly violent, and the capture and the stability of the pickup truck never seemed to be compromised.

By the end of the simulation or at 340 msec, the front of the pickup truck was even with post no. 4P along the primary roadway. The procession of the truck into the system had fractured post

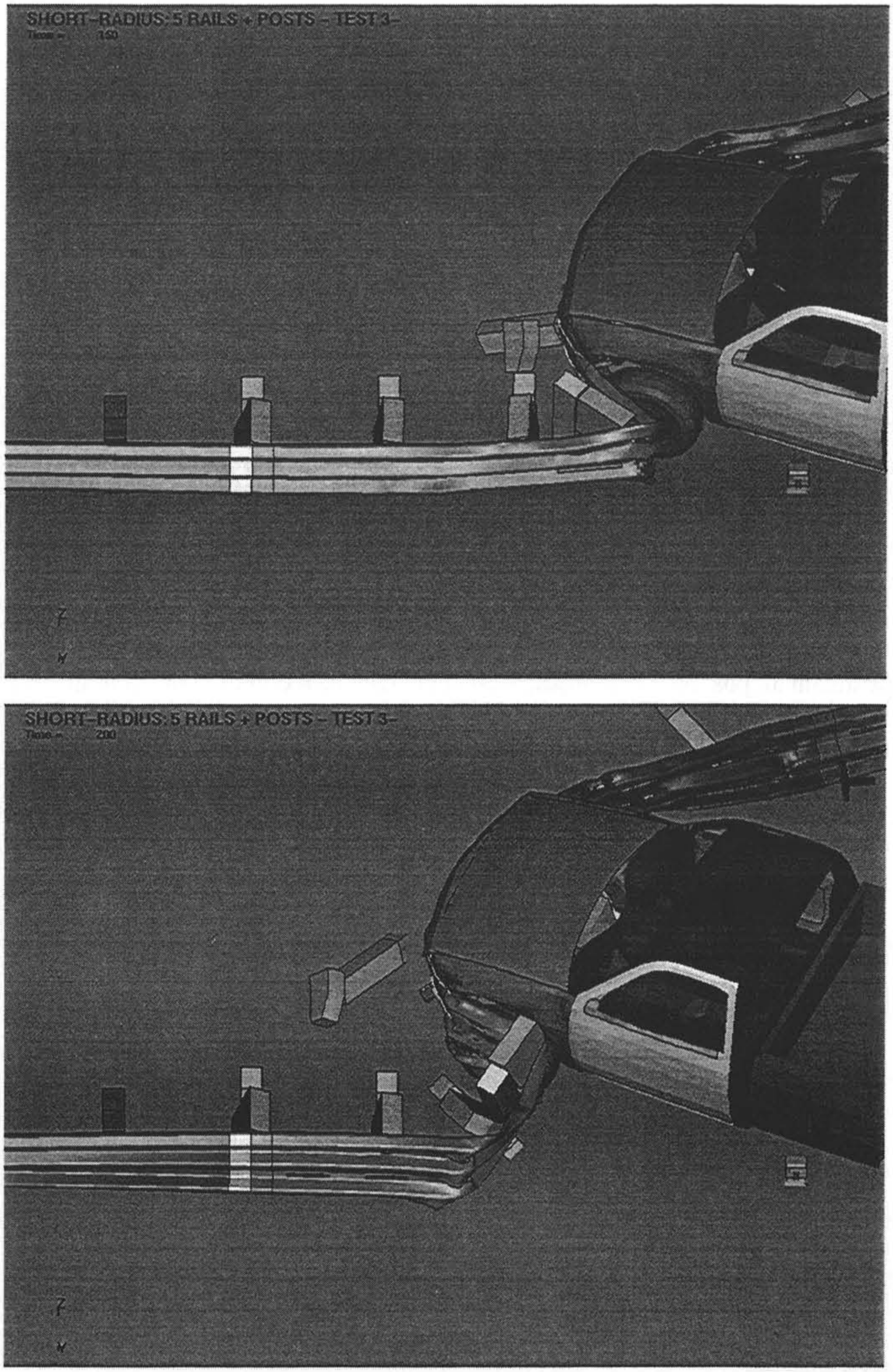


Figure 22. Guardrail Kink Begins Vehicle Yaw

nos. 1P through 3P along the primary roadway and post nos. 1S and 2S along the secondary roadway. The yawing of the truck continued, and the truck was positioned at a 50 to 55-degree angle with respect to the roadway at the end of the simulation. Capture of the pickup truck remained adequate, and no major instability was observed in the trajectory of the pickup truck. The damage observed on the truck was minor and occurred mainly to the front fenders, the bumper, and the grill. The velocity of the pickup truck at the end of the simulation run was approximately 15.3 m/s (55.1 km/h), as shown in Figure 23.

Simulation of NCHRP Report No. 350 test 3-33 was stopped after 340 msec with no contact errors or other major modeling problems. The simulation was stopped because it was believed that reasonable results had been obtained for the modeling of the test 3-33 impact condition. Continuing the simulation for extended times beyond 340 msec would have been time consuming and unnecessary with regards to achieving the goals of this project.

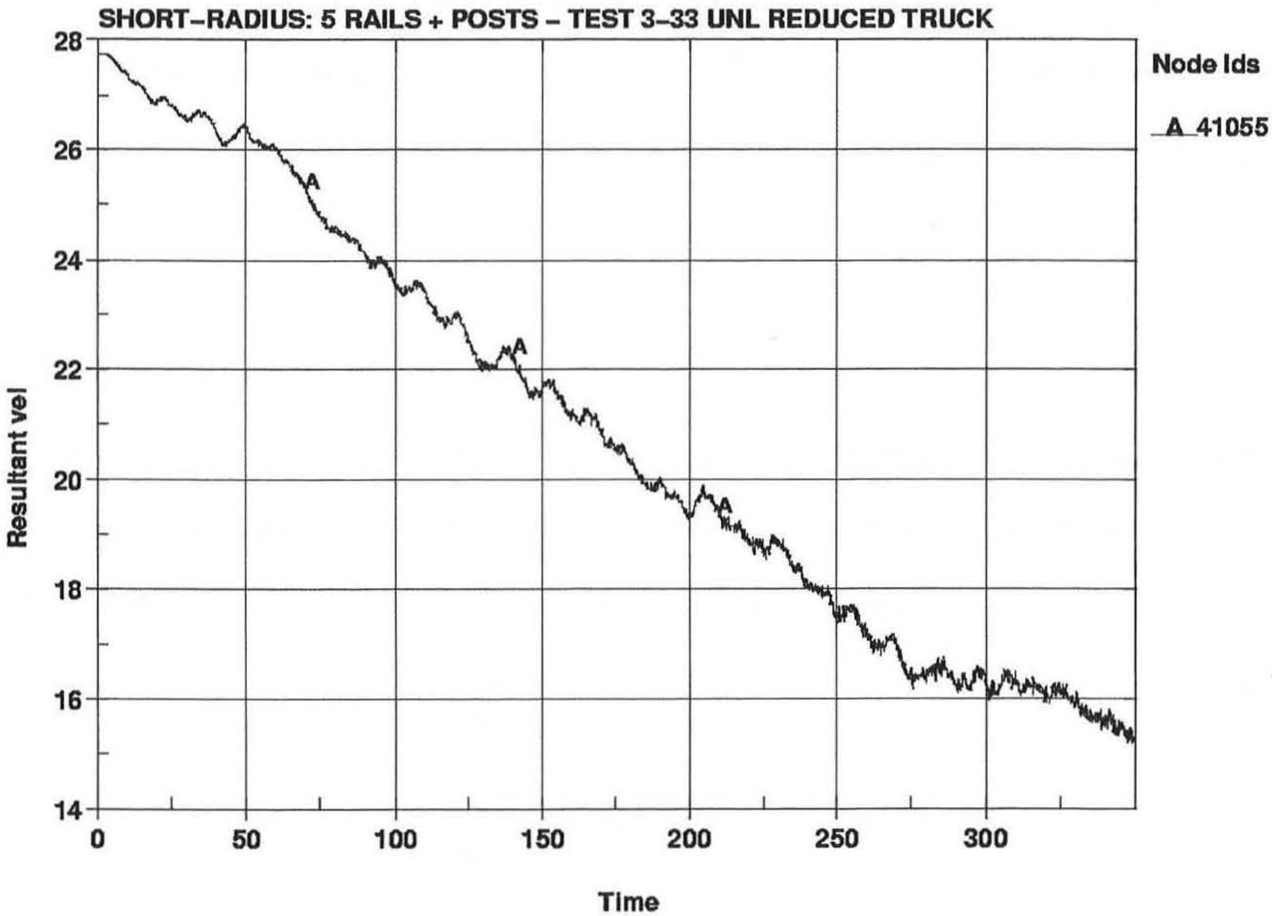


Figure 23. Pickup Truck Velocity, Simulation of Test 3-33

7 ANALYSIS OF SIMULATION RESULTS

Following the successful completion of the simulation of the short-radius design concept, the researchers believed that it was necessary to disseminate the preliminary results regarding its potential safety performance. It should be noted that a majority of the simulation and analysis focused on the modeling of the test 3-33 impact condition, since it was believed to be one of the critical tests. However, there remains uncertainty with the simulation results as they could not be verified or compared with any existing test data. As a result, the analysis was concluded based on the simulation performance alone.

Based on the results of the simulation of the short-radius design under the NCHRP Report No. 350 test 3-33 impact conditions, the initial performance of the new concept looked very promising. Vehicle capture provided by the system was very good initially and continued to be consistent throughout the impact. Upon impact, the top two corrugations of the thrie beam guardrail in the nose section were flattened, and wrapped around the grill and front bumper throughout the simulation. The guardrail did not rupture completely across the section as was observed in three of the tests of the bullnose median barrier (10-12). There were also no indications for the potential for the vehicle to override or underride the system.

The deformation of the guardrail as the pickup truck impacted the system performed as desired. The slots in the first three sections of guardrail weakened the rail and prevented the formation of any large kinks or buckles in the guardrail. No sections of guardrail were observed to buckle and impact the occupant compartment in any way.

The short-radius system displayed the ability to contain and safely decelerate the impacting vehicle in a controlled manner. Containment of the pickup truck was consistent for the duration of the simulation, and no significant instabilities in the vehicle's trajectory were observed. Although moderate yaw and roll motions of the truck were seen during the simulation, the yaw and roll motions were not believed excessive and did not pose a serious threat to the stability of the pickup truck. The deceleration of the pickup truck also appeared to be smooth and controlled.

Damage to the impacting pickup truck and the risk posed to the vehicle occupant were not severe. Pickup truck damage was constrained to the front of the vehicle and was relatively minor. It should be noted that damage estimation using the deformed truck model should be considered a rough estimate at best due to modeling concessions made in the truck model to make it run more efficiently. Therefore, analysis of the vehicle damage was restricted to identification of damaged areas with no evaluation of the extent or severity of the damage. Crushing of the bumper and the grill and local buckling of the front fenders were the regions of maximum observed damage.

One area of possible concern in the simulation of the test 3-33 impact condition was the interaction between the wheel of the pickup truck and the soil tube, as shown in Figure 24. The left-front tire of the pickup truck rolled over the soil foundation tube as well as the debris of fractured post no. 1P along the primary roadway at approximately 100 msec into the simulation. Past experience has revealed that the interaction between the tire and the foundation tubes has the potential to push the wheel upward and cause it to climb the guardrail. This could lead to vaulting or override of the guardrail by the pickup truck, although it was not observed in the simulation. Since vehicle capture has occurred by the time the wheel rolled over the tube and post debris, it is unlikely that the wheel will be pushed up the guardrail.

Based on the analysis of the results of the simulation of the short-radius system, it is believed that the short-radius design is capable of meeting the NCHRP Report No. 350 safety requirements

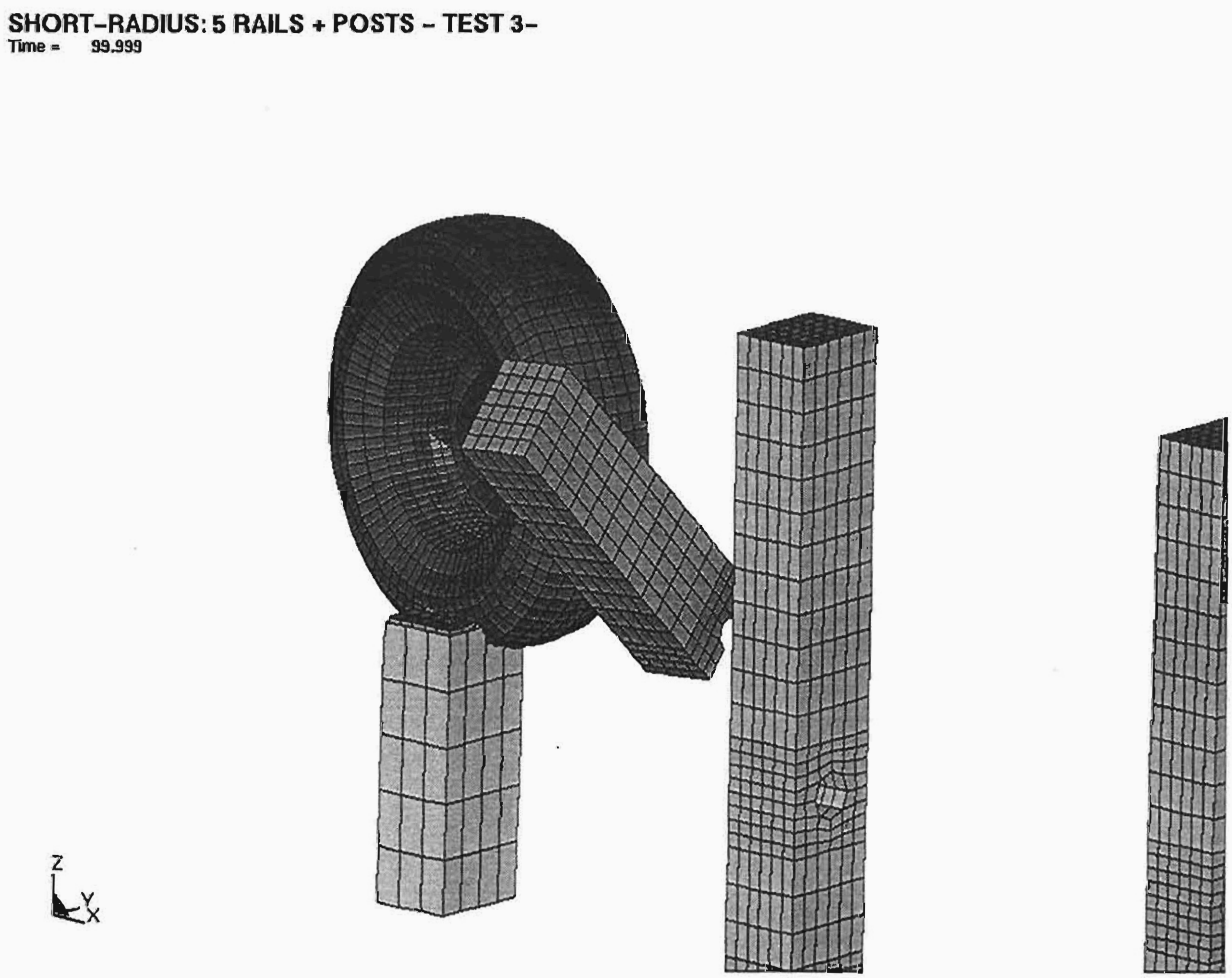


Figure 24. Tire Interaction with Remnants Post No. 1

for the test 3-33 impact condition. These results indicate that the short-radius system has the ability to safely capture and contain the impacting vehicle. It also suggests that the design has the potential to meet other impact conditions from the required NCHRP Report No. 350 compliance test matrix.

8 SUMMARY AND CONCLUSIONS

A new short-radius guardrail system for use in the protection of intersecting roadways was developed to meet current federal impact safety standards. The creation of the new short-radius system included only the development of the design concept, but no fabrication or testing of the design. The new design concept was developed through a thorough research effort. The first part of the design concept consisted of the research into short-radius design and the many factors that would need to be addressed for in the design of a new system. Initially, an extensive literature search was done to collect all of the existing test data on short-radius systems as well as the current state standards. A total of four sets of test data, seven state standards, and an FHWA technical advisory were collected. Then a design space analysis was completed which used the collected data to gain insight into the necessary design criteria and constraints. This analysis included examination of radius size, tangential side lengths, capture area, intersecting roadway angles, end connections, and other relevant design considerations. Thirdly, a NCHRP Report No. 350 test matrix for short-radius systems was created to map out the necessary compliance tests for validation of a new system. The test matrix included five 2,000-kg pickup truck tests and three 820-kg small car tests.

As these phases of the project where completed, a comprehensive picture of the design parameters for the new short-radius design were mapped out and a design concept was developed. The short-radius design concept was developed around a slotted thrie beam nose section with a 2,426-mm radius. The new design consisted of a tangent section that terminated into a bridge transition along the primary roadway and into a TL-2 FLEAT end terminal along the secondary roadway. Breakaway posts as well as the post spacing used in the design were chosen to provide the system with the ability to capture vehicle impacts on or near the nose of the system while redirecting vehicle impacts along the tangential sides.

Computer simulation of the design concept was conducted using LS-DYNA to help determine the feasibility of the new design and to suggest areas for improvement in the design. A model of the first six guardrail sections of the short-radius design was constructed beginning with a simple model of the guardrail alone and progressing with increasing complexity until the final model was achieved. The use of incremental models to develop the full system model allowed for the correction of modeling flaws as complexity was added and increased the confidence in the final model.

The refined model of the short-radius system was used to simulate full-scale crash tests of NCHRP Report No. 350 test 3-33. Simulation of test 3-33 yielded a great deal of information about the short-radius design. The system proved capable of capturing and containing the impacting pickup truck in a controlled manner. The results of the simulation suggested that the short-radius design concept was capable of passing NCHRP Report No. 350 test 3-33.

Based on the analysis of the simulation results and the other collected research, it is believed that the newly developed short-radius design concept shows a great deal of potential for meeting NCHRP Report No. 350 safety requirements. The results of simulation of the new design suggest that the design is capable of meeting one or more of the federal compliance tests. Further development of this design through full-scale testing and simulation seems warranted.

9 RECOMMENDATIONS

A new design concept for a short-radius guardrail system for the protection of intersecting roadways was developed through a thorough process of background research, design concept development, and computer simulation modeling. The results of this research suggest that there is significant potential for the further development of the short-radius guardrail design. Simulation of test 3-33 suggests that the design may be capable of passing at least one of the compliance tests without modification. Thus, it is suggested that the research collected herein be further developed through a combination of full-scale compliance testing and computer simulation with the goal being to develop of a NCHRP Report No. 350 short-radius system to meet TL-3.

During the concept development phase of the short-radius guardrail system, an effort was made to simplify the overall design. The design presented previously in this report required the use of several different post and blockout combinations along with some additional hardware specific to the short-radius system. While most of the complexity was necessary due to the unique requirements of a short-radius guardrail, it was believed that some changes could be made to simplify the design. These design modifications consist of the following: (1) replacing post nos. 6P through 9P as well as post no. 3S with thrie beam CRT posts; (2) using a solid blockout at post nos. 2P through 9P and 2S through 3S instead of two separate, unique pieces; and (3) removing the single, chamfered blockouts at post nos. 1P and 1S. As a result of these changes, all of the posts in the system would consist of CRT posts except post nos. 1P and 1S. It would also make for fewer post blockouts required in the system, as well as making them be of one size and type. Drawings detailing the simplified short-radius design are provided in Appendix D.

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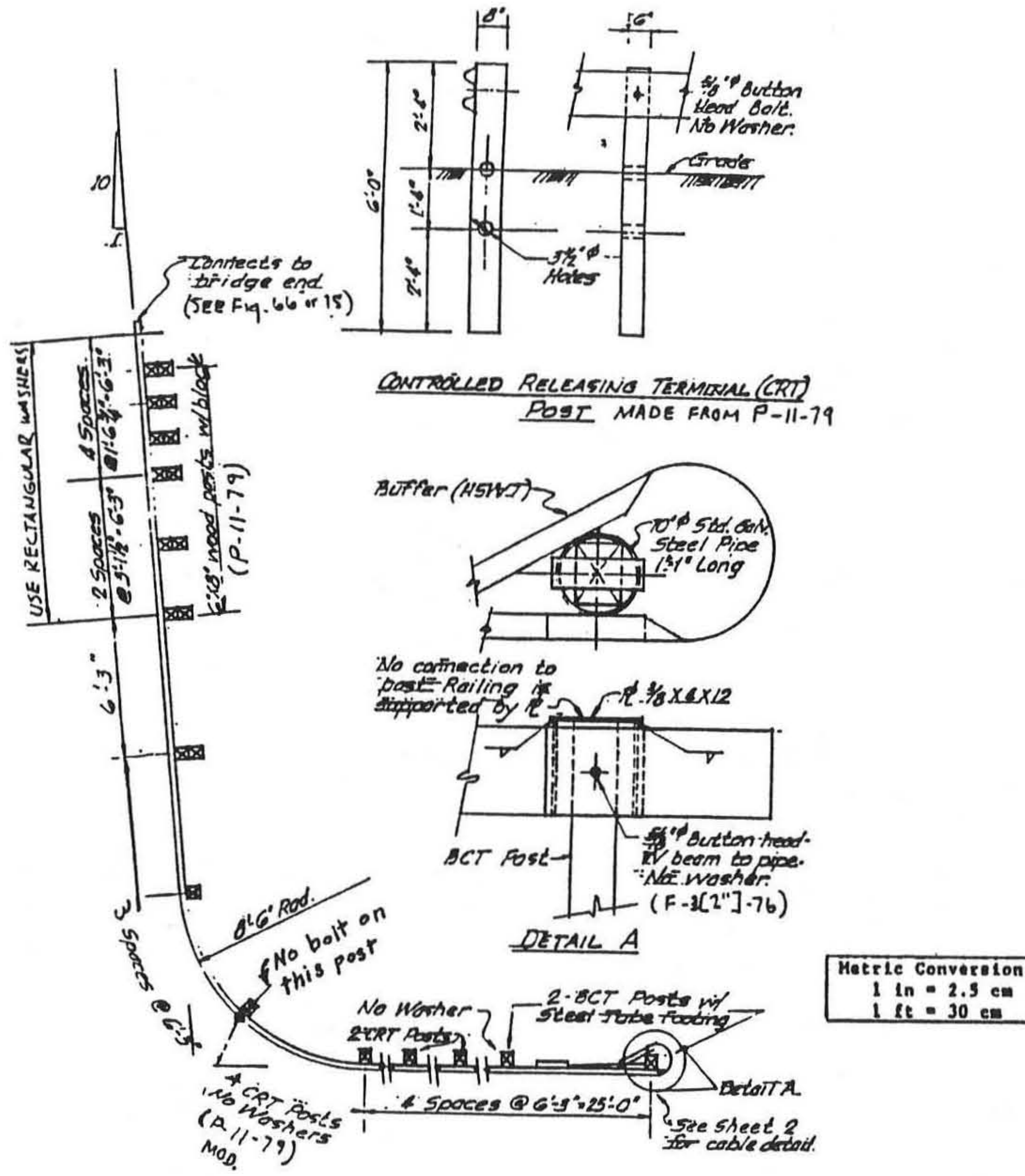
11 APPENDIX

APPENDIX A - DETAILS OF SHORT-RADIUS SYSTEM TESTING

Table A-1. SwRI 1988 Short-Radius Study (3,4).

Test No.	Test Vehicle	Impact Specification	System Configuration	Test Results
WA-1	4500 lb car	60 mph @ shallow angle with centerline of vehicle approximately aligned with center of bridge rail.	-8.5 ft radius curved section of w-beam guardrail	-leaning of posts caused the launching and rollover of the test vehicle **-test failed**
WA-1M	1800 lb. car	60 mph @ 25 degree angle into curved section of guardrail.	-same configuration as WA-1 with changes to posts and beam anchorage -breakaway posts in the curved section	-longitudinal change in velocity surpassed the design values outlined in NCHRP Report No. 230 **- test marginally passed**
WA-2M	4500 lb. car	60 mph @ 15 degree angle into curved section of guardrail.	-additional 12.5 ft of rail was added to the secondary road end of the system	-all posts on the secondary road end of the system fractured, allowing vehicle to completely penetrate. **-test failed**
WA-3M	4500 lb. car	60 mph @ 15 degree angle into curved section of guardrail	-additional end anchorage incorporated at secondary roadway end of the system	-beam failed upon impact due to snagging of a bolt head. **-test failed**
WA-4M	4500 lb. car	60 mph @ 15 degree angle into curved section of guardrail	-bolt where rail tear occurred in the previous test was omitted	-considerable vehicle yaw, but system remained stable. **-test passed**
WA-5M	4500 lb. car	60 mph @ shallow angle with centerline of vehicle approximately aligned with center of bridge rail.	same configuration as WA-4M	-smooth redirection, system performance was successful **-test passed**

Barrier components with F, P, and RE prefixes are found in latest edition of "A Guide to Standardized Highway Barrier Rail Hardware," a report prepared approved by the AASHTO-AGC-ARTBA Joint Cooperative Committee.

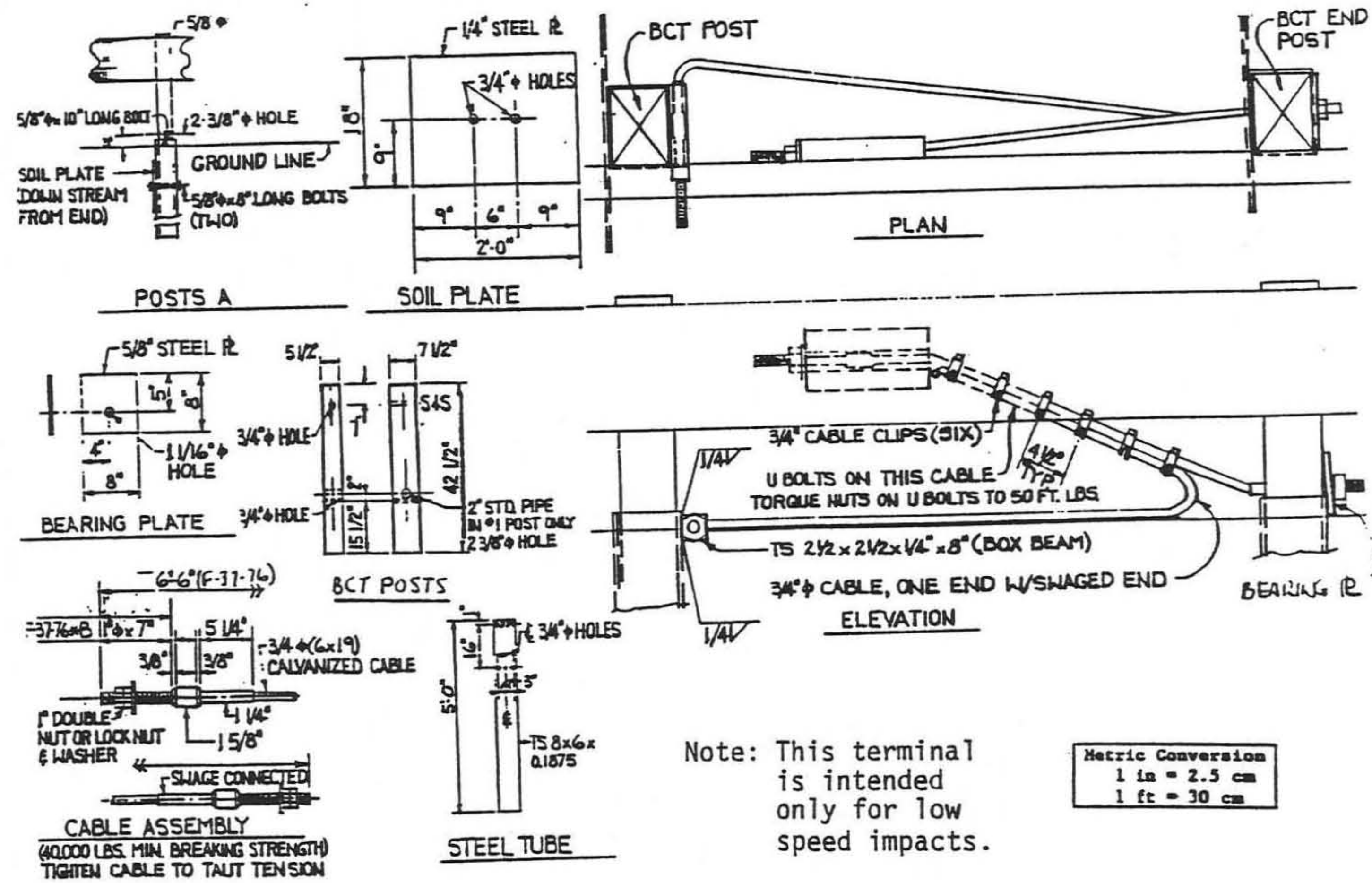


Metric Conversion
1 in = 2.5 cm
1 ft = 30 cm

Figure 82. Intersecting roadway transition design. (sheet 1 of 2)

Figure A-1a. SwRI 1988 Short-Radius Study (3,4)

Barrier components with F, P, and RE prefixes are found in latest edition of "A Guide to Standardized Highway Barrier Rail Hardware," a report prepared and approved by the AASHTO-AGC-ARTBA Joint Cooperative Committee.



Note: This terminal is intended only for low speed impacts.

Metric Conversion
1 in = 2.5 cm
1 ft = 30 cm

Figure A-1b. SwRI 1988 Short-Radius Study (3,4)

Test No.	WA-1	WA-1M	WA-2M	WA-3M	WA-4M	WA-5M
Barrier	State Design	---------------------- Modified Design		----------------------	--------- See Figure 1	---------
Test Vehicle	1978 Plymouth	1978 Honda	1977 Dodge	1978 Dodge	1978 Plymouth	1978 Plymouth
Gross Vehicle Weight, lb	4520	1903	4789	4640	4650	4640
Impact Speed (film), mph	60.0	60.8	60.6	58.9	58.8	59.0
Impact Angle, deg	0	23.7	13.4	16.6	14.6	-1.1
Impact Duration, sec	.47	Not Avail.	Not Avail.	Not Avail.	Not Avail.	.57
Maximum Deflection, in						
Dynamic	Not Avail.	Not Avail.	Not Avail.	Rail fractured	Barrier on ground	3.5
Permanent	Barrier on ground	153	Barrier on ground	Rail fractured	Barrier on ground	3.0
Exit Angle, deg						
Film	Did not exit	Did not exit	Did not exit	Did not exit	Did not exit	-19.6
Yaw Rate Transducer	Did not exit	Did not exit	Did not exit	Did not exit	Did not exit	-9.6
Exit Speed, mph						
Film	Did not exit	Did not exit	Did not exit	Did not exit	Did not exit	41.6
Accelerometer	Did not exit	Did not exit	Did not exit	Did not exit	Did not exit	40.0
Maximum 50 ms Avg Accel (film/accelerometer)						
Longitudinal	Not Avail.	-11.0/-12.2	-4.3/-6.7	-4.3/Not Avail.	-5.3/-8.3	-2.3/-5.5
Lateral	Not Avail.	5.4/7.4	-1.7/-1.7	-1.7/Not Avail.	-1.3/-5.4	2.7/4.1
Occupant Risk, NCHRP <u>Report 230</u> (film/accelerometer)						
ΔV long., fps (30)	Not Avail.	37.9/Not Avail.	19.9/18.9	13.9/Not Avail.	16.7/18.1	16.2/18.0
ΔV lat, fps (20)	Not Avail.	-16.6/Not Avail.	7.5/5.6	7.9/Not Avail.	6.3/6.5	-7.7/-10.5
Ridedown Acceleration, g's (accelerometer)						
Longitudinal (15)	Not Avail.	Not Avail.	-8.8	Not Avail.	-10.5	-7.6
Lateral (15)	Not Avail.	Not Avail.	-4.6	Not Avail.	-7.1	8.0
NCHRP <u>Report 230</u> Evaluation						
Structural Adequacy (A,D)	Failed	Passed	Failed	Failed	Passed	Passed
Occupant Risk (E,F,G)	Failed (E)	40 < ΔV > 30	Passed	Passed	Passed	Passed
Vehicle Trajectory (H,I)	Failed	Passed	Failed	Failed	Passed	Passed

Figure A-2 Summary of Testing for W-beam Approach at Intersecting Roadways (<u>3,4</u>)

Table A-2. Summary of Yuma County Short-Radius Guardrail Testing (5).

Test No.	Test Vehicle	Impact Specifications	System Configuration	Test Results
YC-1	5400 lb. pickup	45.0 mph @ 1.4 degrees to the roadway -centerline of test vehicle aligned with bridge rail	-12 gauge w-beam -8 ft radius curved section with an -18 ft straight section along primary roadway -12.5 ft straight section along secondary roadway -2 independent posts behind the curved section	vehicle redirected with no signs of instability, accelerometer data was within NCHRP 230 limits **-test passed**
YC-2	1800 lb. car	50.3 mph @ -0.7 degrees to the roadway -centerline of test vehicle aligned with the bridge rail	same configuration as above	-redirection was smooth vehicle sustained only minor damage **-test passed**
YC-3	5400 lb. pickup	44.8 mph into the curved section @ 19.7 degrees to the roadway	same configuration as YC-1 and YC-2	-the anchoring system failed, allowing the system to release **-test failed**
YC-4	5400 lb. pickup	44.9 mph into the curved section @ 20.1 degrees to the roadway	same configuration as previous with an additional 12.5 ft of guardrail length along the secondary roadway	**-test passed**
YC-5	1800 lb. car	44.2 mph into the curved section @ 20.0 degrees to the roadway	same configuration as YC-4	-vehicle was contained with acceptable values for occupant risk **-test passed**
YC-6	1800 lb. car	51.1 mph into transition section @ 19.4 degrees to the roadway	same configuration as YC-4	-lateral change in velocity exceeded the range specified in NCHRP 230 **-test marginally passed**
YC-7	5400 lb. pickup	45.2 mph into transition section @ 20.7 degrees to the roadway	same configuration as YC-4	-no observed wheel snag or pocketing -accelerometer data fell within limits outlined in NCHRP 230 **-test passed**

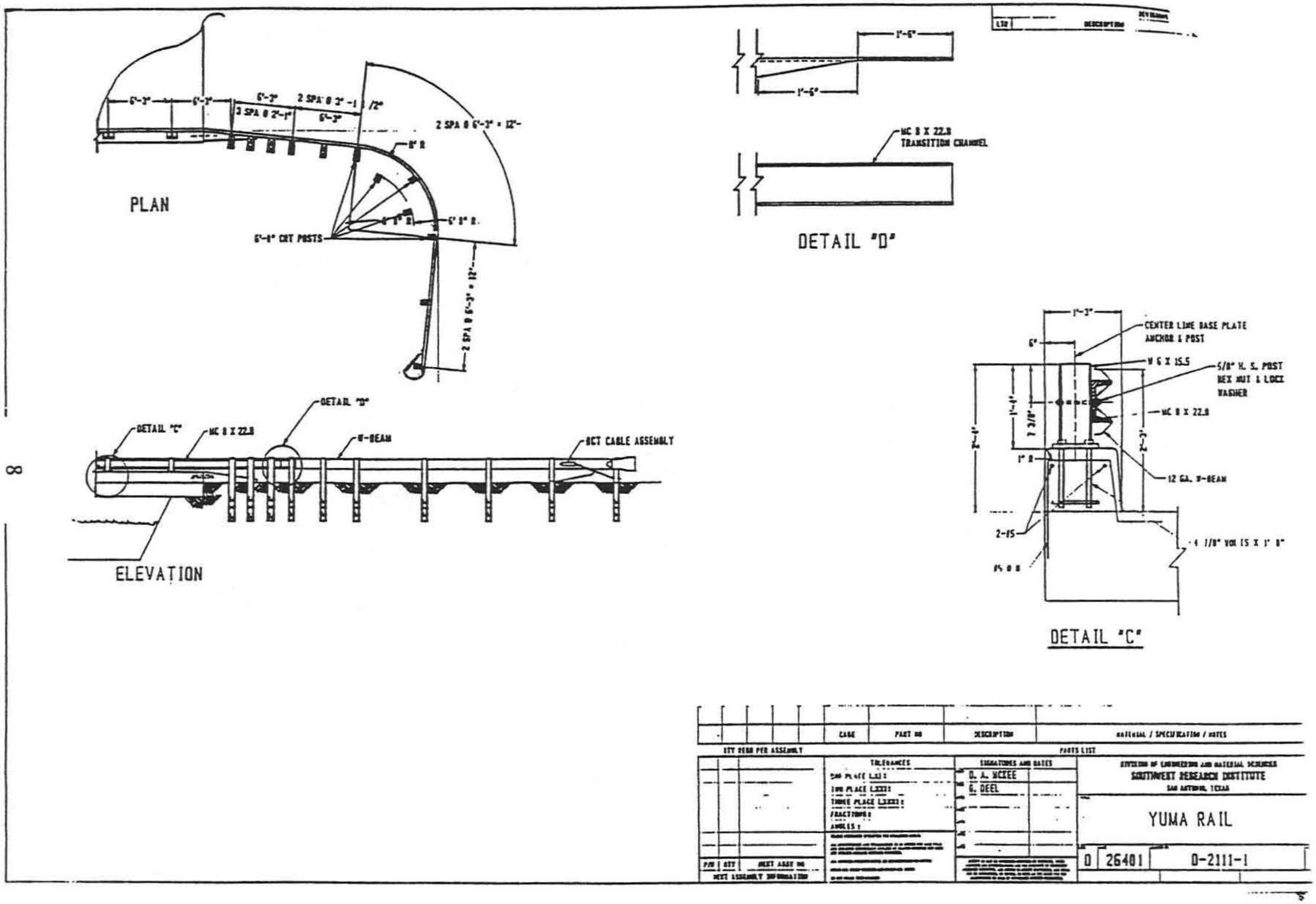


Figure A-3a. Yuma County Short-Radius Guardrail Design (5)

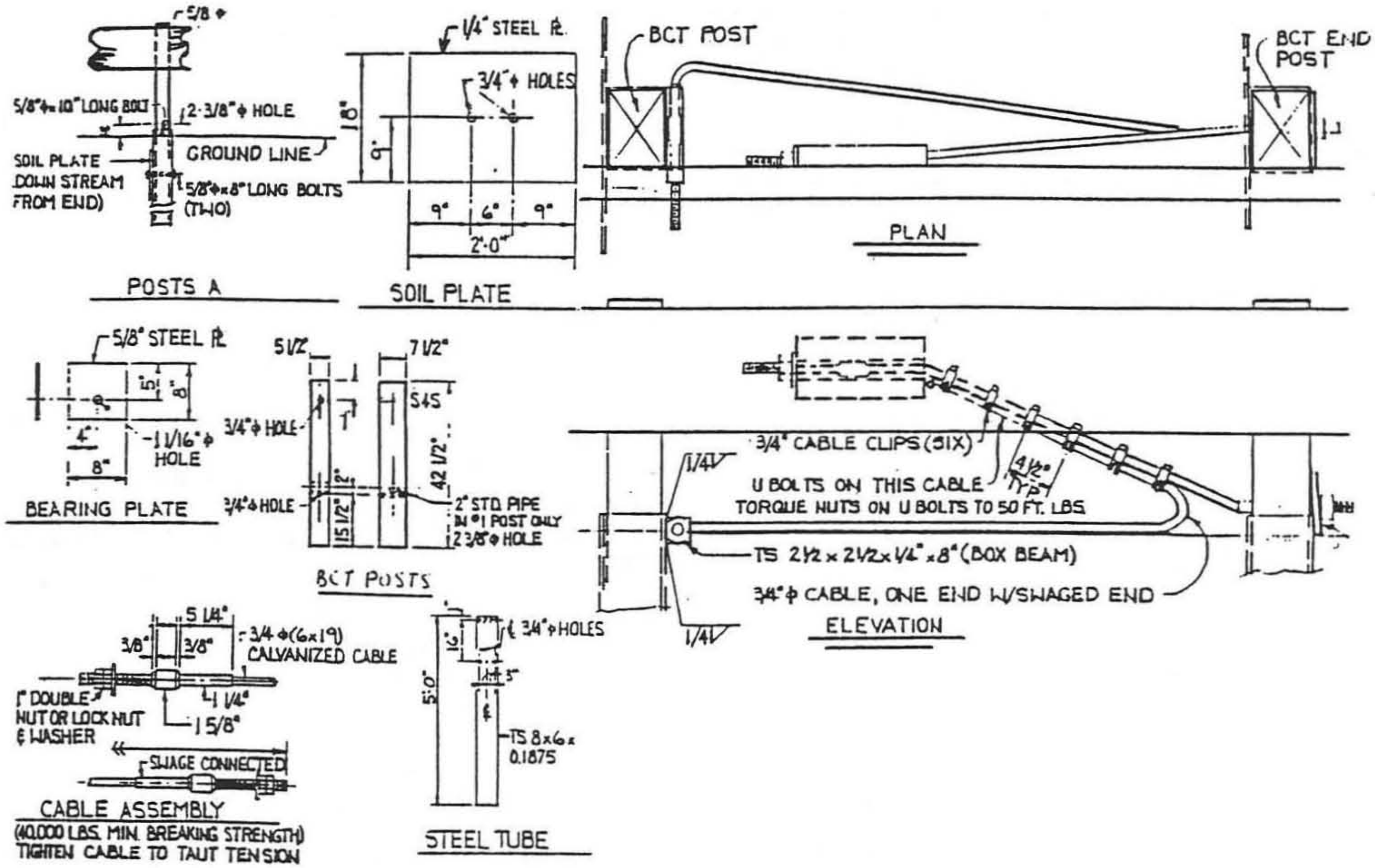


Figure A-3b. Yuma County Short-Radius Guardrail Design (5)

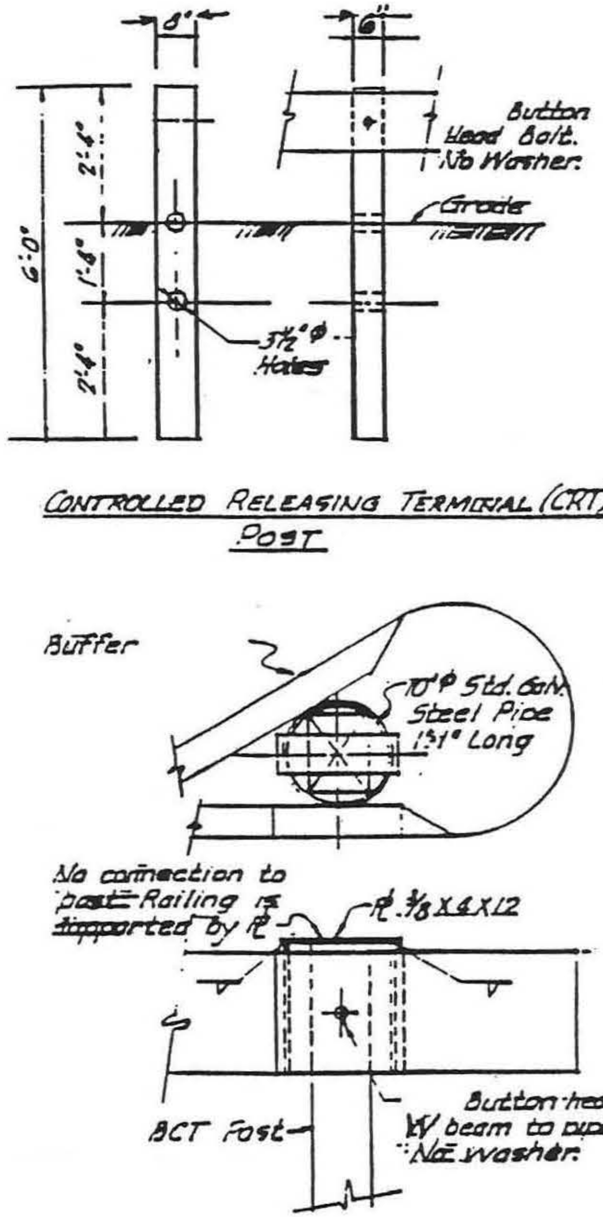


Figure A-3c. Yuma County Short-Radius Guardrail Design (5)

SUMMARY OF RESULTS

Test No	YC-1	YC-2	YC-3	YC-4	YC-5	YC-6	YC-7
Test Parameters for PL1 Service	5400lb/0 deg/45mph	1800lb/0 deg/50mph	5400lb/20deg/45mph	5400lb/20deg/45mph	1800lb/20deg/50mph	1800lb/20deg/50mph	5400lb/20deg/45mph
Test Vehicle	1982 Chevrolet P/U	1982 V. W. Rabbit	1984 Ford P/U	1984 Ford P/U	1982 V. W. Rabbit	1982 V. W. Rabbit	1984 Ford P/U
Gross Vehicle Weight - [lb]	5376	1978	5380	5381	1980	1980	5424
Impact Speed (film) - [mph]	45	50.3	44.8	44.9	44.2	51.1	45.2
Impact Angle - [degrees]	1.4	0.7	19.7	20.1	20.0	19.4	20.7
Exit Angle (film) - [degrees]	18.8	-12.4	Did Not Exit	Did Not Exit	Did Not Exit	-7.6	-15.4
Exit Speed (film) - [mph]	32.8	44.4	Did Not Exit	Did Not Exit	Did Not Exit	34.2	32.5
Maximum 50 msec Avg Accel (film/accelerometer)							
Longitudinal - [g's]	-2.2/-3.3	-1.8/-3.3	-6.3/-4.2	-4.0/-4.4	-4.6/-7.9	-5.8/-7.6	-4.2/-3.9
Lateral - [g's]	-2.1/-3.6	-6.1/-6.4	-4.4/2.87	3.3/4.1	1.8/2.6	-7.4/-12.3	-5.0/-5.8
Occupant Risk, NCHRP Report 230 (film/accelerometer)							
Δ V long. - [fps] (30)	12.0/14.4	5.9/9.4	19.1/14.5	20.7/20.1	24.9/27.8	19.1/6.8	6.5/2.2
Δ V lat. - [fps] (20)	11.8/7.8	14.6/16.0	-9.5/-8.3	-14.6/-11.0	-8.2/-7.3	20.5/22.7	18.9/18.7
Ridedown Accelerations, [g's] (accel)							
Longitudinal (15)	-2.7	-0.7	-6.5	-5.6	-10.5	-0.1	-2.8
Lateral (15)	-7.1	-4.7	4	-2.9	3.3	-6.8	-8.9
NCHRP Report Evaluation							
Structural Adequacy (A, D)	Passed	Passed	Failed	Passed	Passed	Passed	Passed
Occupant Risk (E)	Passed	Passed	Passed	Passed	Passed	Marginal, lat vel. >20fps	Passed
Vehicle Trajectory (H, I)	Passed	Passed	Passed	Passed	Passed	Passed	Passed

* Numbers in parentheses are recommended in NCHRP Report 230.

Figure A-4. Summary of Yuma County Short-Radius Guardrail Testing (5)

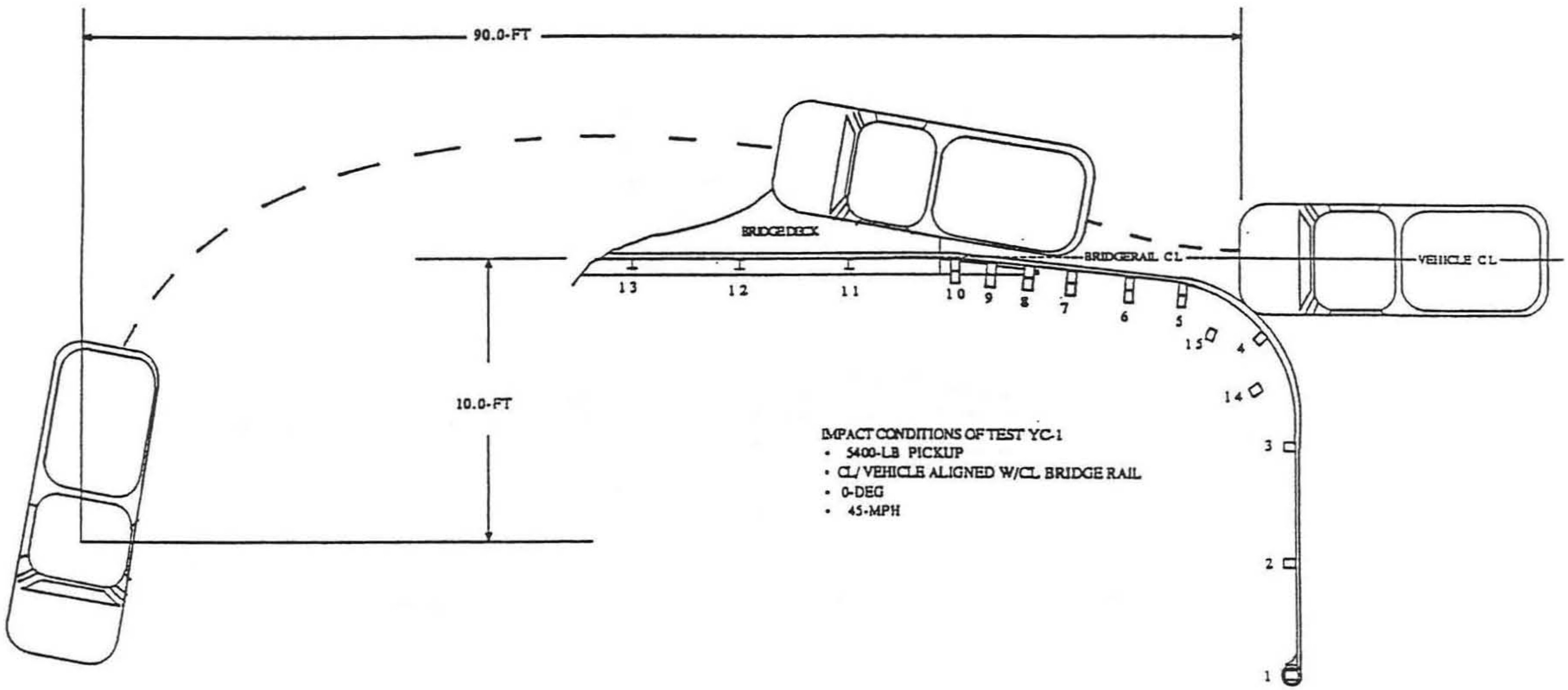


Figure A-5. Summary of Yuma County Short-Radius Guardrail Test YC-1 (5)

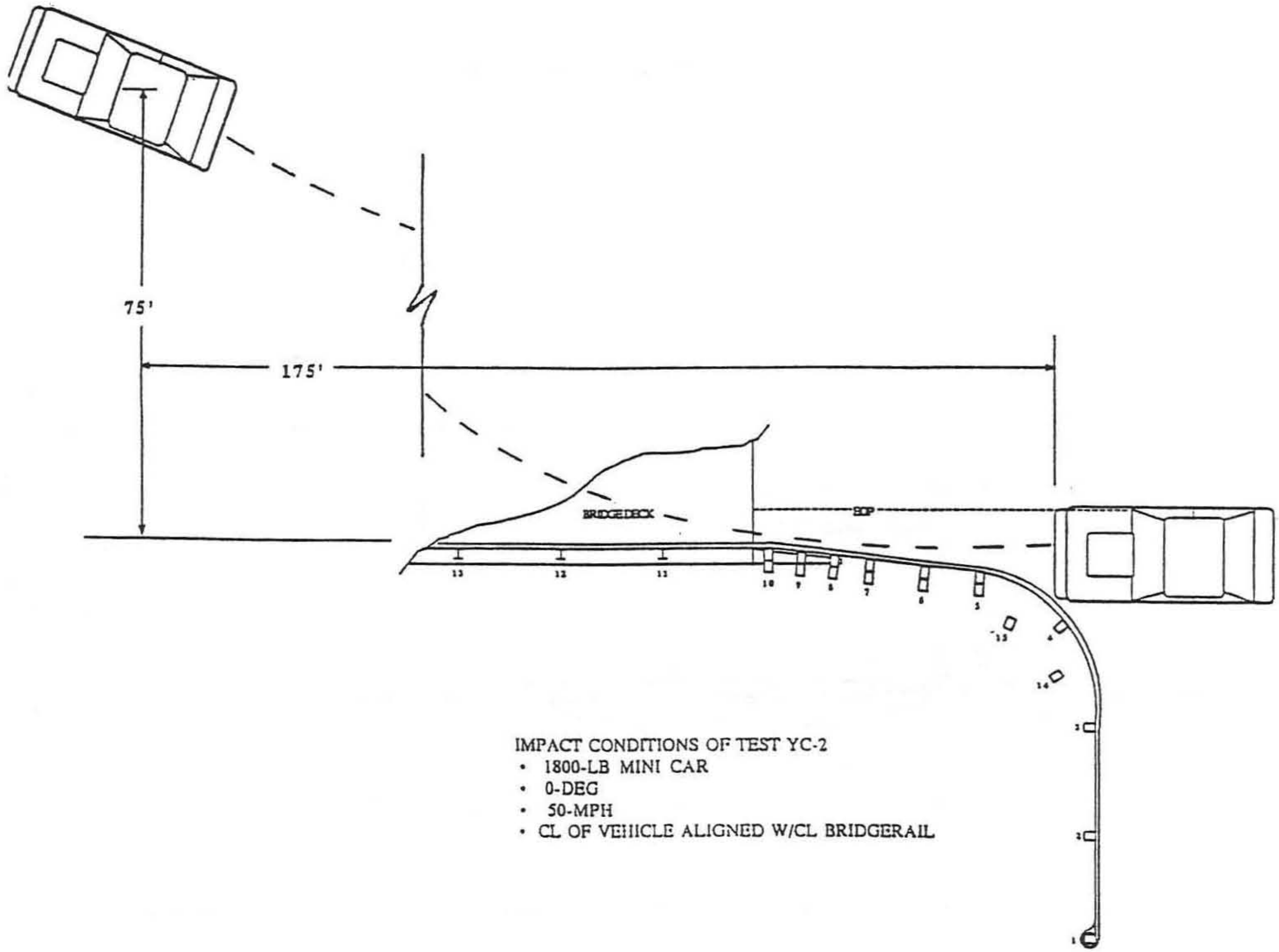


Figure A-6. Summary of Yuma County Short-Radius Guardrail Test YC-2 (5)

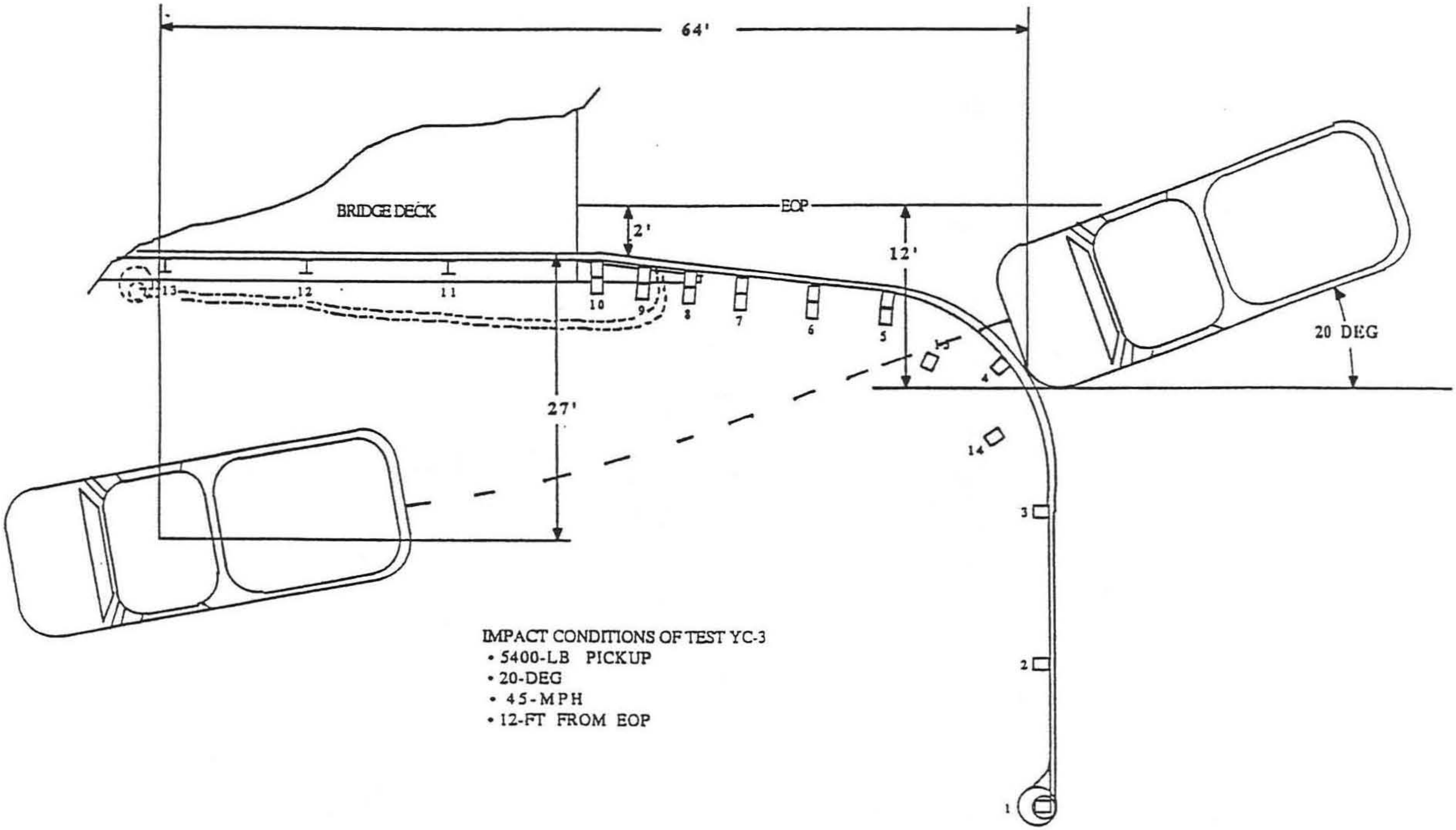


Figure A-7. Summary of Yuma County Short-Radius Guardrail Test YC-3 (5)

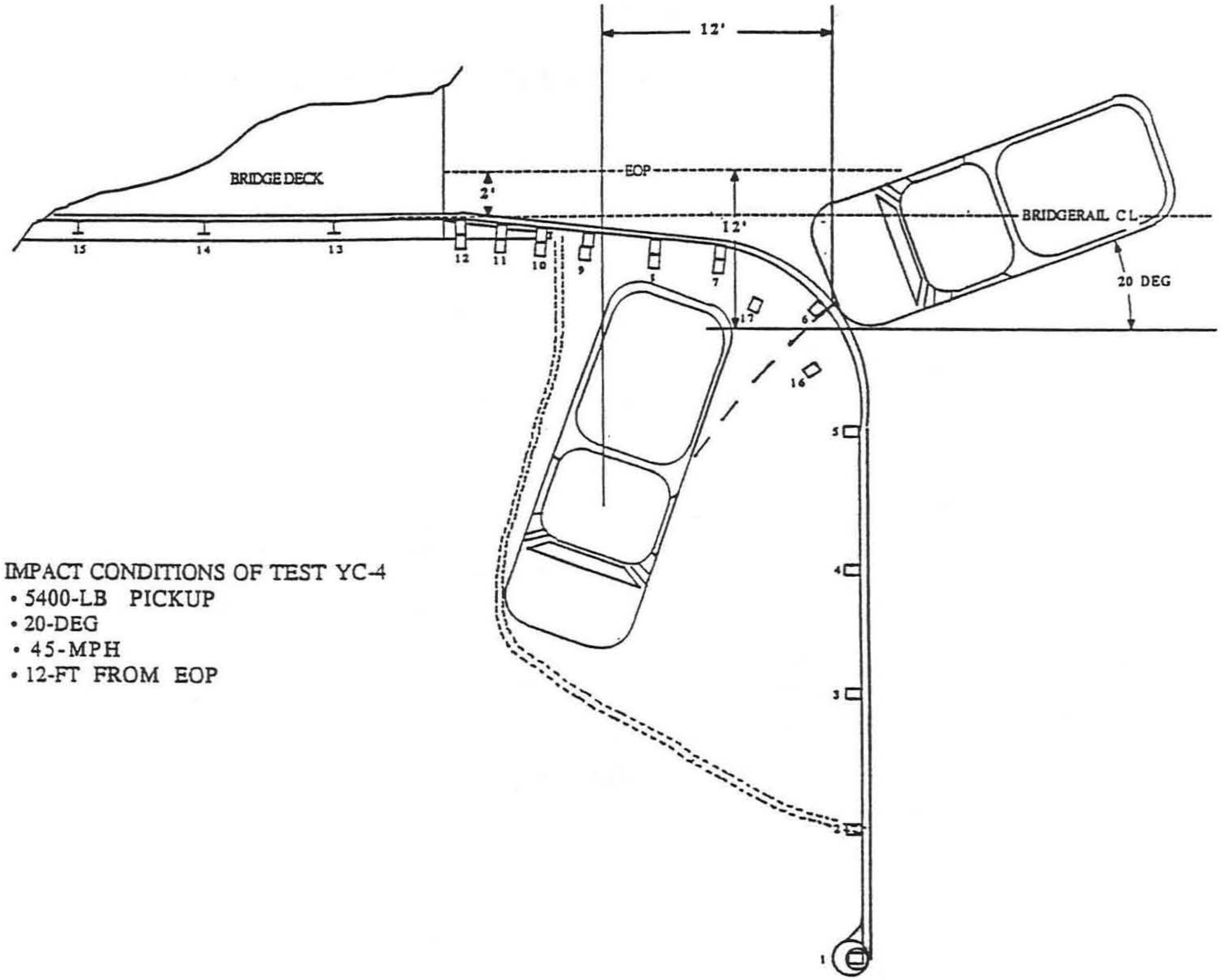


Figure A-8. Summary of Yuma County Short-Radius Guardrail Test YC-4 (5)

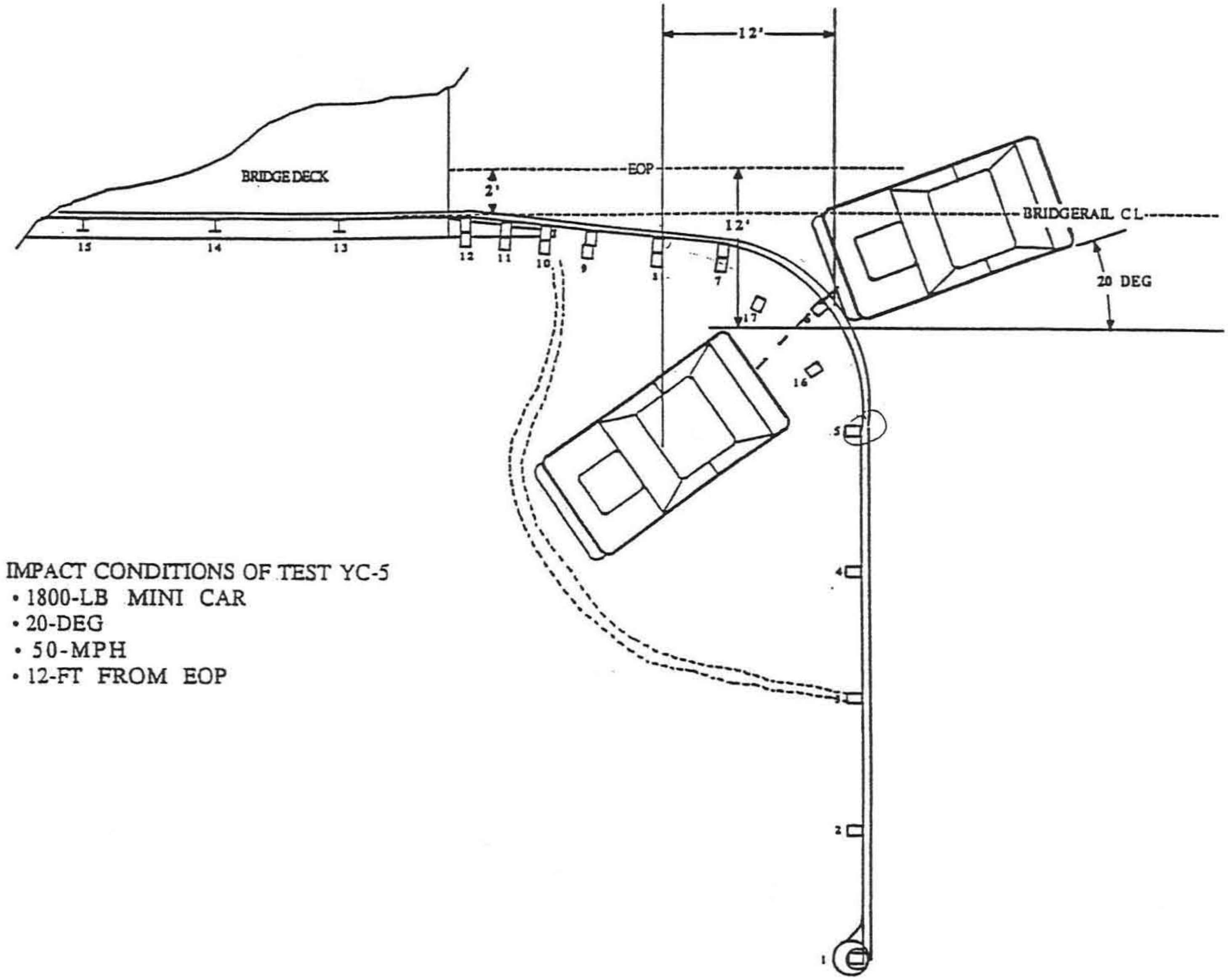


Figure A-9. Summary of Yuma County Short-Radius Guardrail Test YC-5 (5)

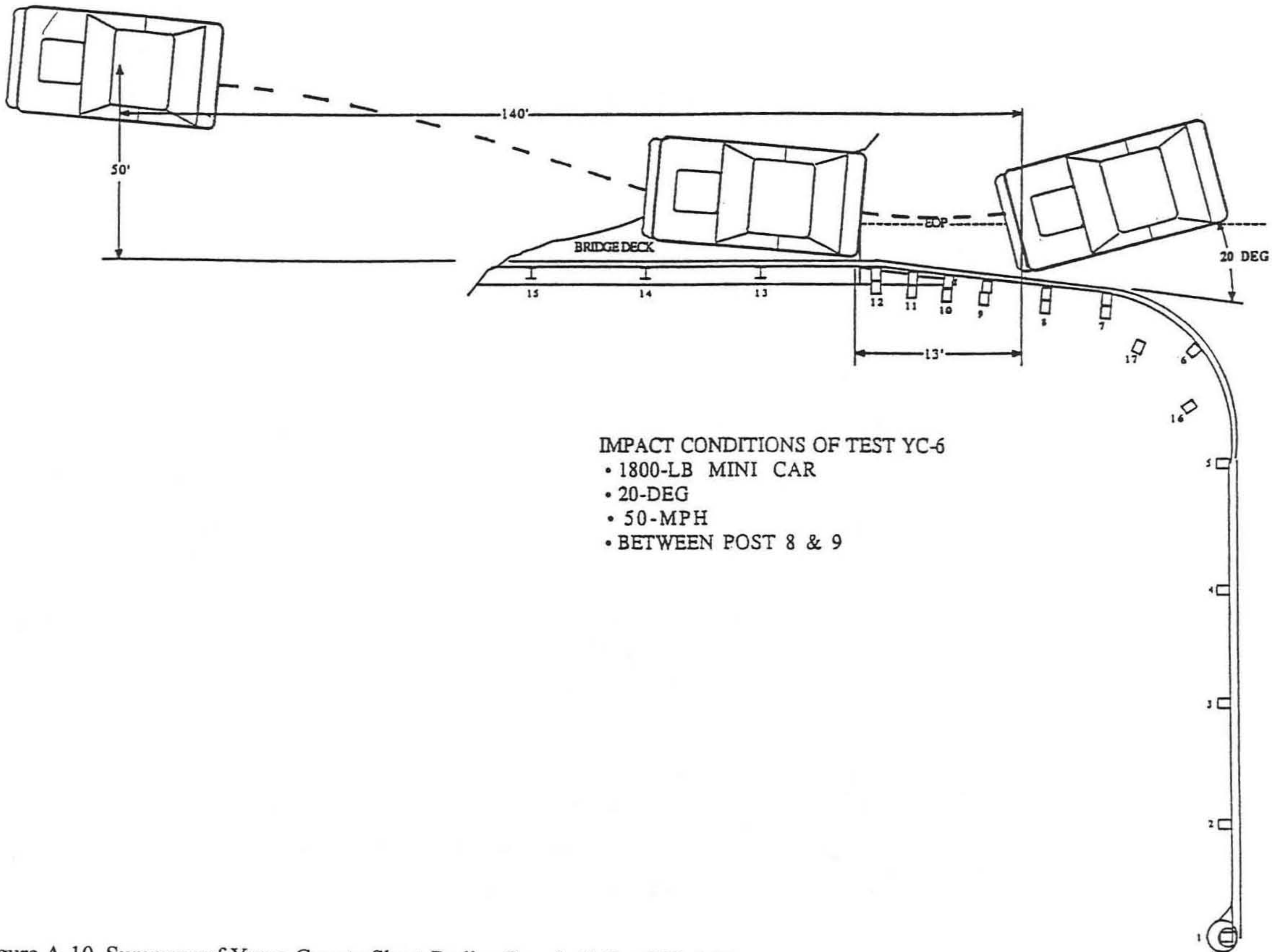


Figure A-10. Summary of Yuma County Short-Radius Guardrail Test YC-6 (5)

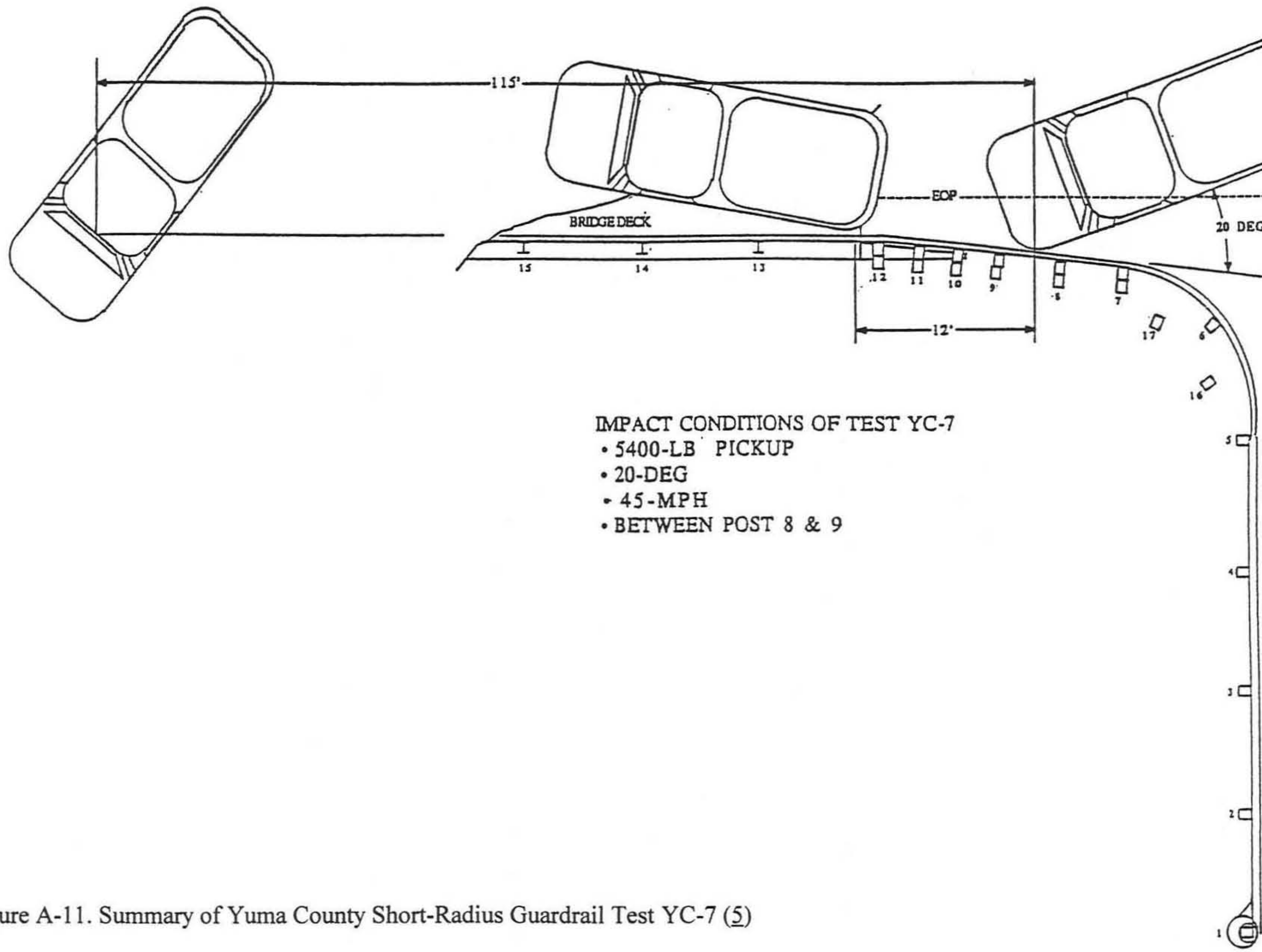


Figure A-11. Summary of Yuma County Short-Radius Guardrail Test YC-7 (5)

Table A-3. Summary of TTI's W-beam Short-Radius Study (7).

Test No.	Test Vehicle	Impact Specifications	System Configuration	Test Results
1263-1	1800 lb. small car	58.4 mph into the midpoint of curved section @ 20.5 degrees to primary roadway	14'-3" radius W-beam section supported by 7" diameter CRT posts at a height of 21.5" inches, remaining posts are standard 7" diameter wood, anchored by turndown.	-Posts did not fracture as intended causing high impact forces and occupant decelerations. **-test failed**
1263-2	1800 lb. small car	59.0 mph into the midpoint of curved section @ 20.4 degrees to primary roadway	Downstream BCT anchor was removed and CRT posts were lengthened to 6'-6".	-W-beam fractured at thre rail splice causing uncontrolled penetration of the vehicle. **-test failed**
1263-3	1800 lb. small car	60.2 mph into the midpoint of curved section @ 20.7 degrees to primary roadway	W-beam was nested in the curved sections.	-Vehicle was borught to a stop in approximately 14'. **-test passed**
1263-4	4500 lb. sedan	57.1 mph into the CIP of the transition section @ 24.7 degrees to primary roadway	Radius was enlarged to 16'-0" radius.	-Vehicle was redirected with minimal wheel snag. **-test passed**
1263-5	4500 lb. sedan	58.5 mph into the midpoint of curved section @ 26.8 degrees to primary roadway	Same a previous test.	- Guardrail overrode the front of the vehicle. Excessive occupant compartment damge and uncontrolled vehicle penetration resulted. **-test failed**
1263-6	4500 lb. sedan	58.3 mph into the curved section @ 2.0 degrees to primary roadway	Additional CRT post added upstream of the curved section of guardrail.	-The vehicle was smoothly redirected. **-test passed**

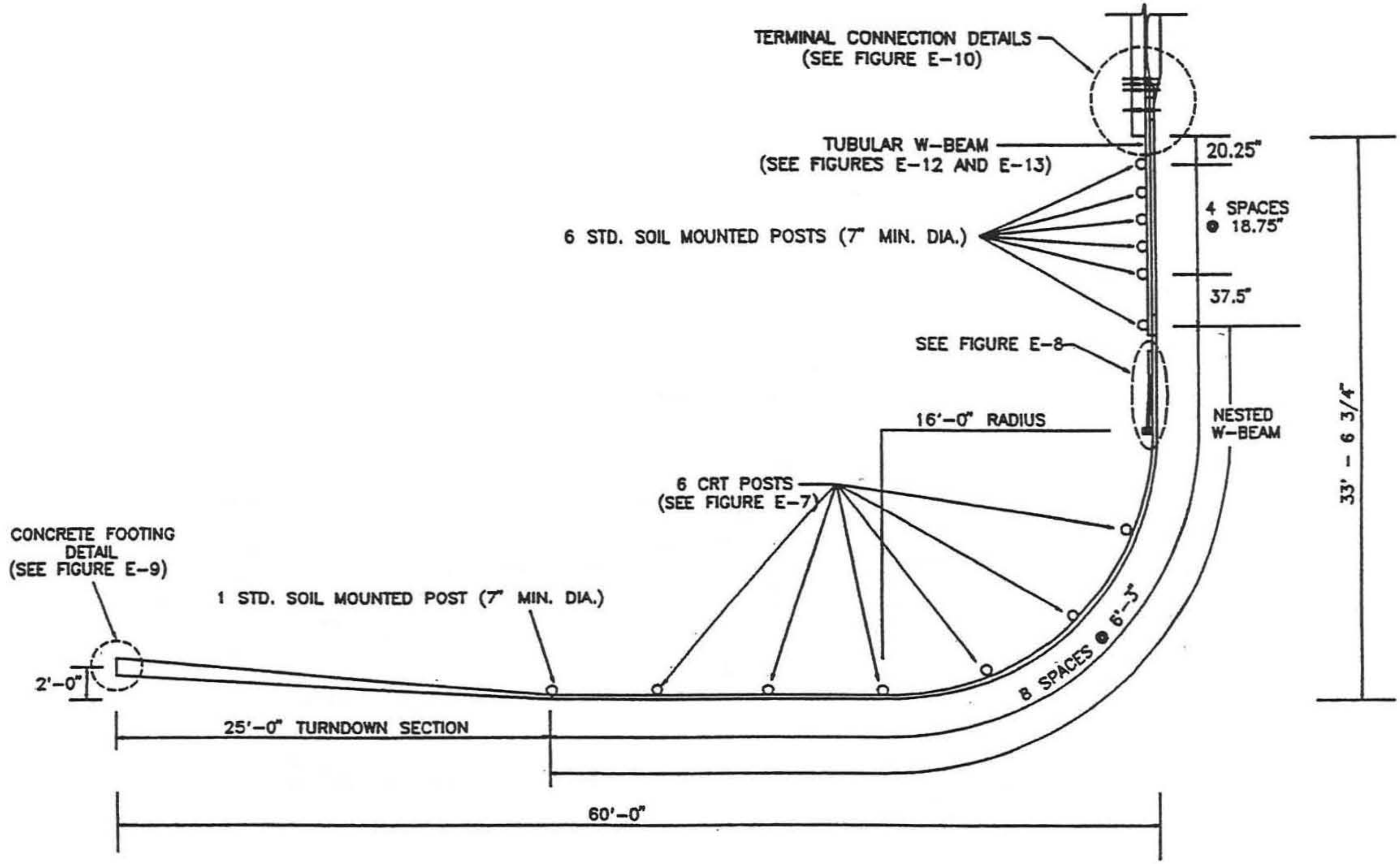


Figure A-12a. TTI W-beam Short Radius Design (7)

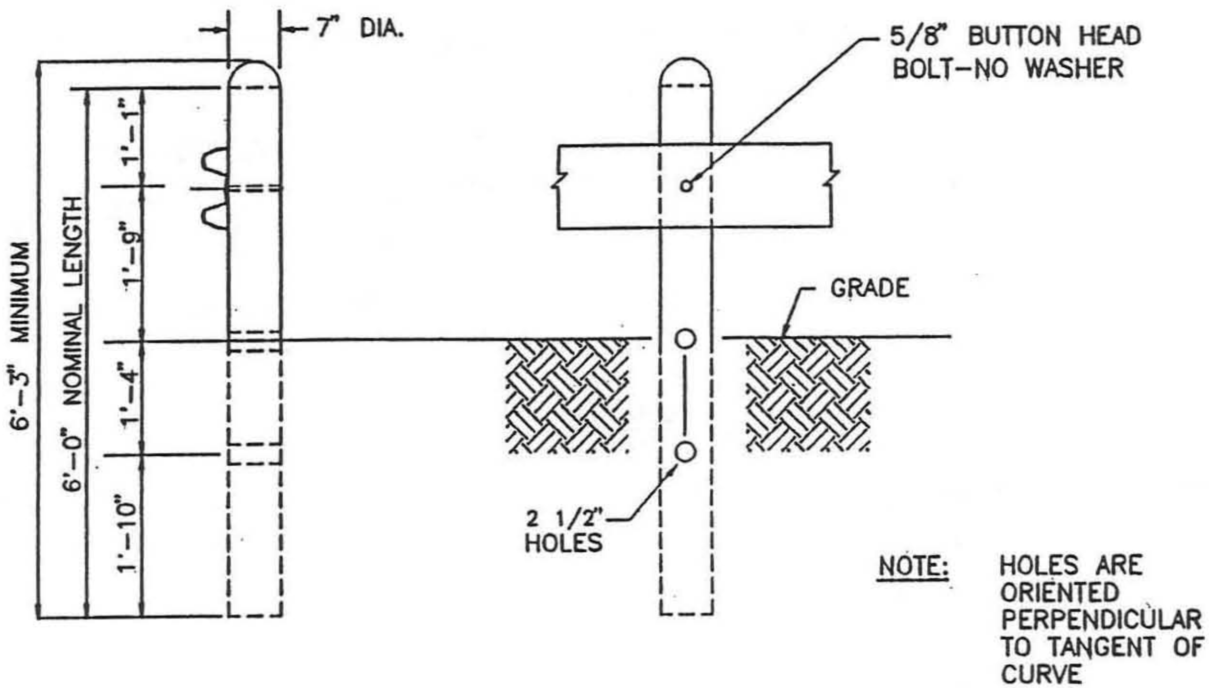


Figure A-12b. TTI W-beam Short Radius Design (7)

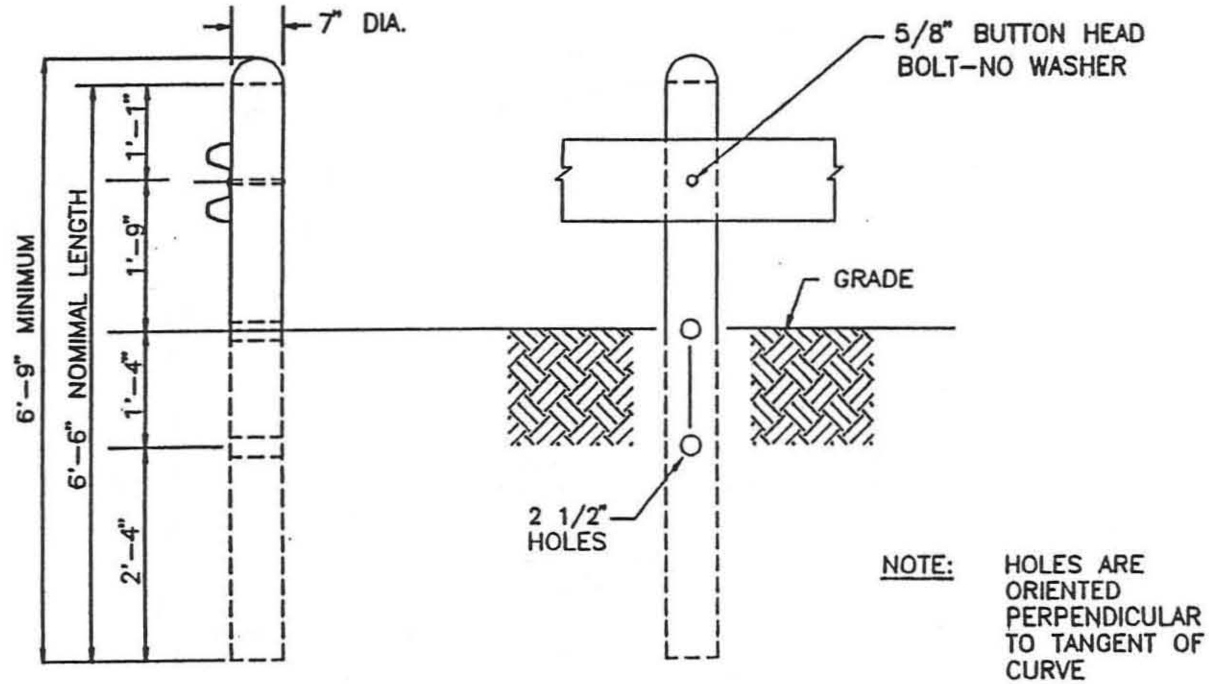


Figure A-12c. TTI W-beam Short Radius Design (7)

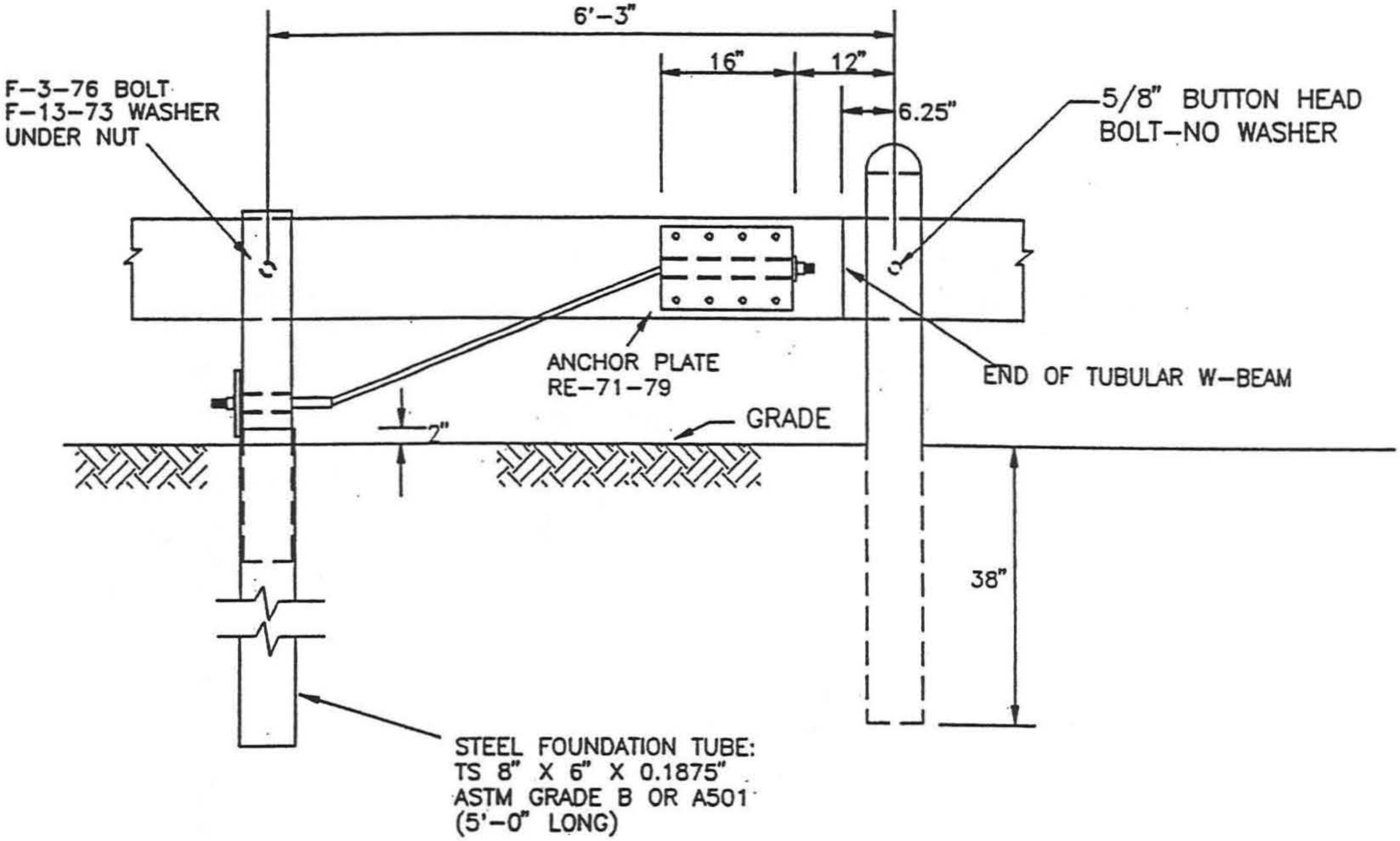


Figure A-12d. TTI W-beam Short Radius Design (7)

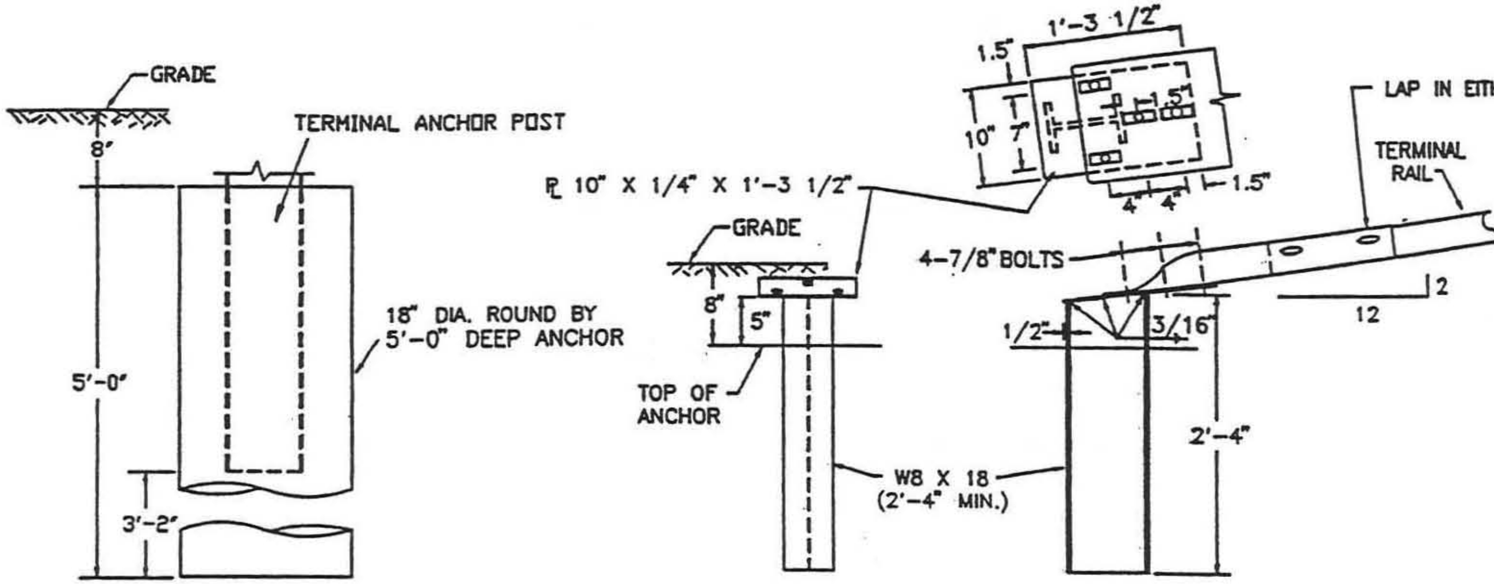


Figure A-12e. TTI W-beam Short Radius Design (7)

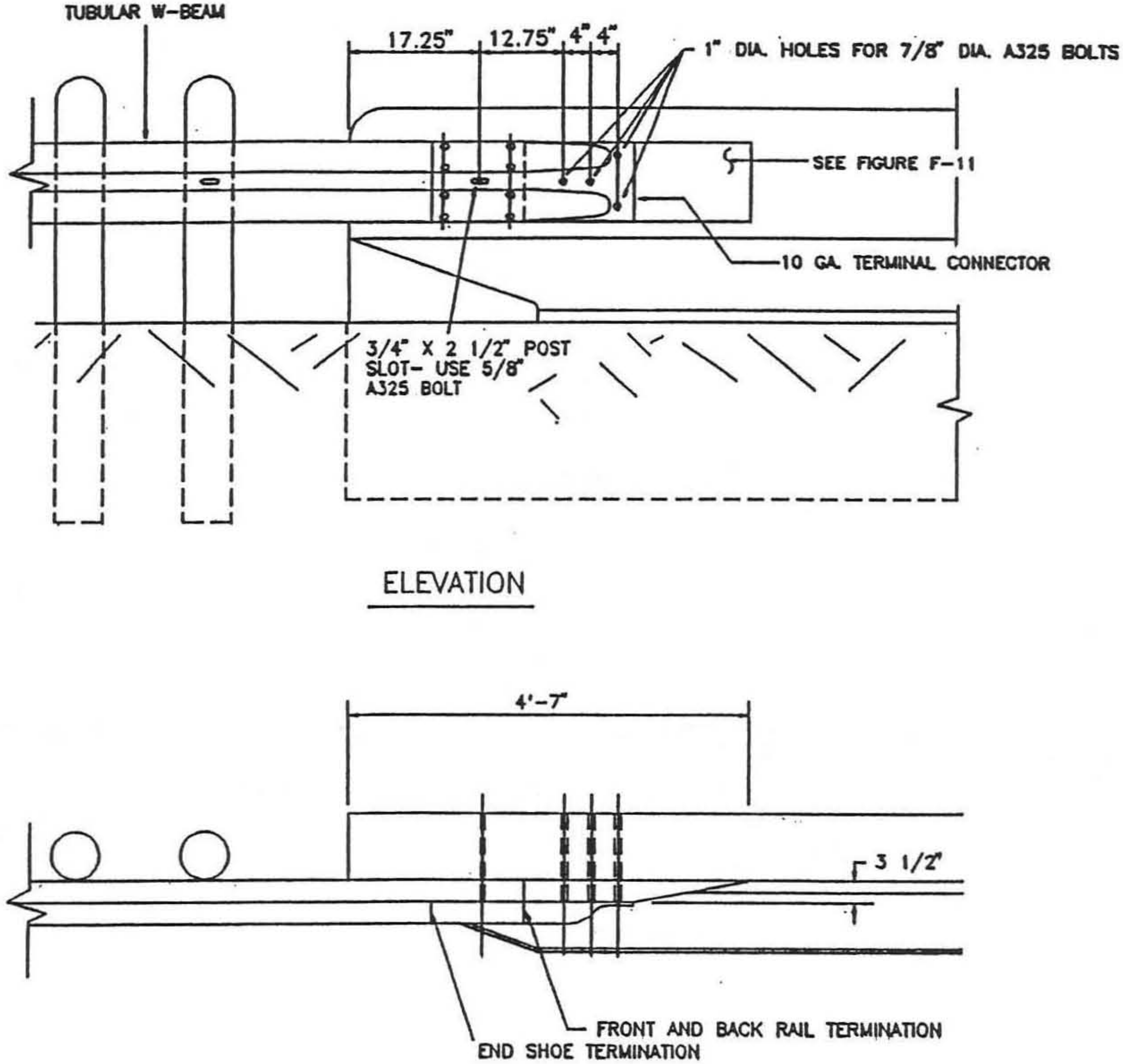


Figure A-12f. TTI W-beam Short Radius Design (7)

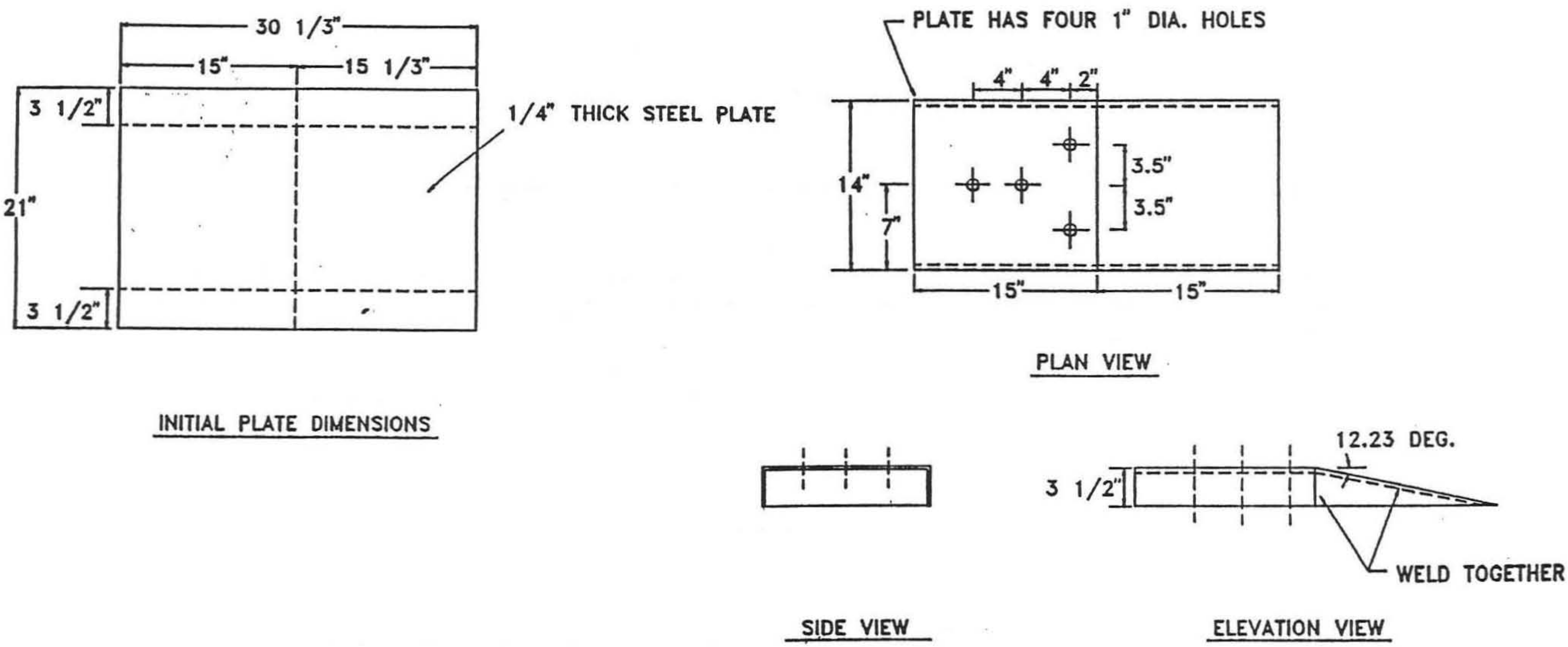


Figure A-12g. TTI W-beam Short Radius Design (7)

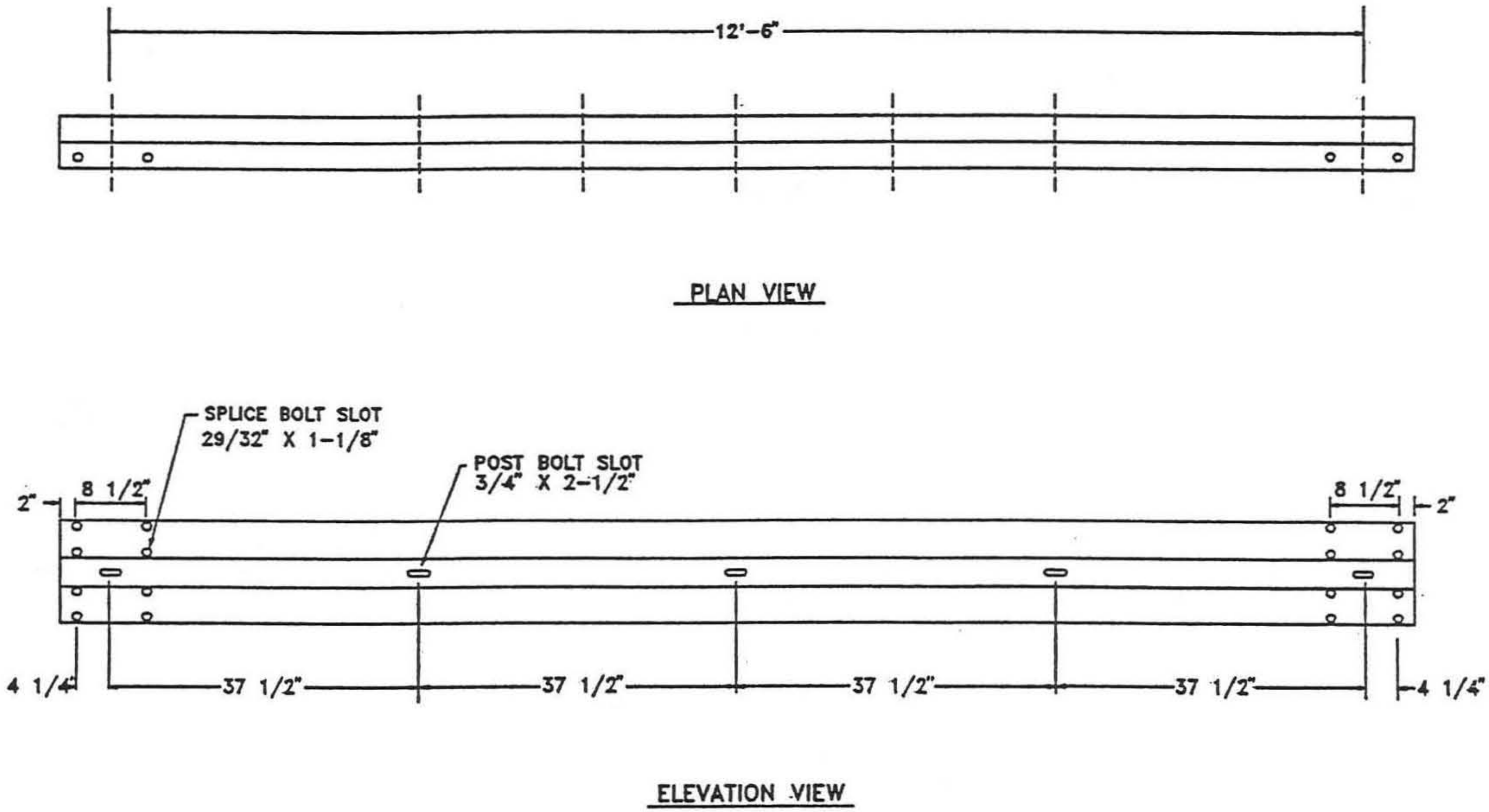
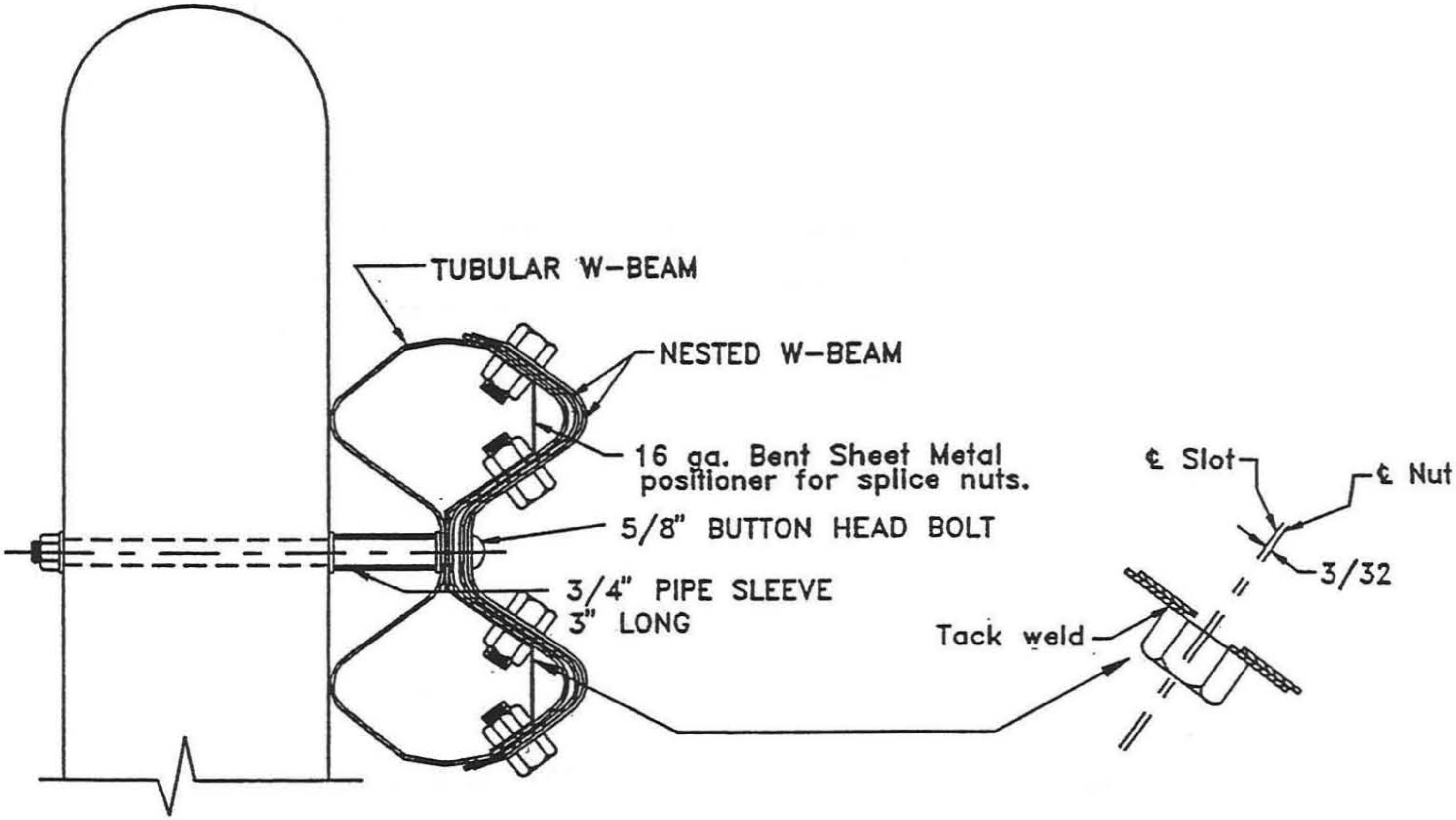


Figure A-12h. TTI W-beam Short Radius Design (7)



<u>NOTE</u>: 8~5/8" Splice nuts shall be tacked inside front rail of Tubular W-Beam. The nuts must be tacked approx. 3/32" off the center of the bolt slot toward the outside of the tube. Optionally, the nuts may be tacked to a bent sheet metal positioner as shown. Other suitable positioning methods or devices may be substituted. The complete splice shall have 8 bolts

Figure A-12i. TTI W-beam Short Radius Design (7)

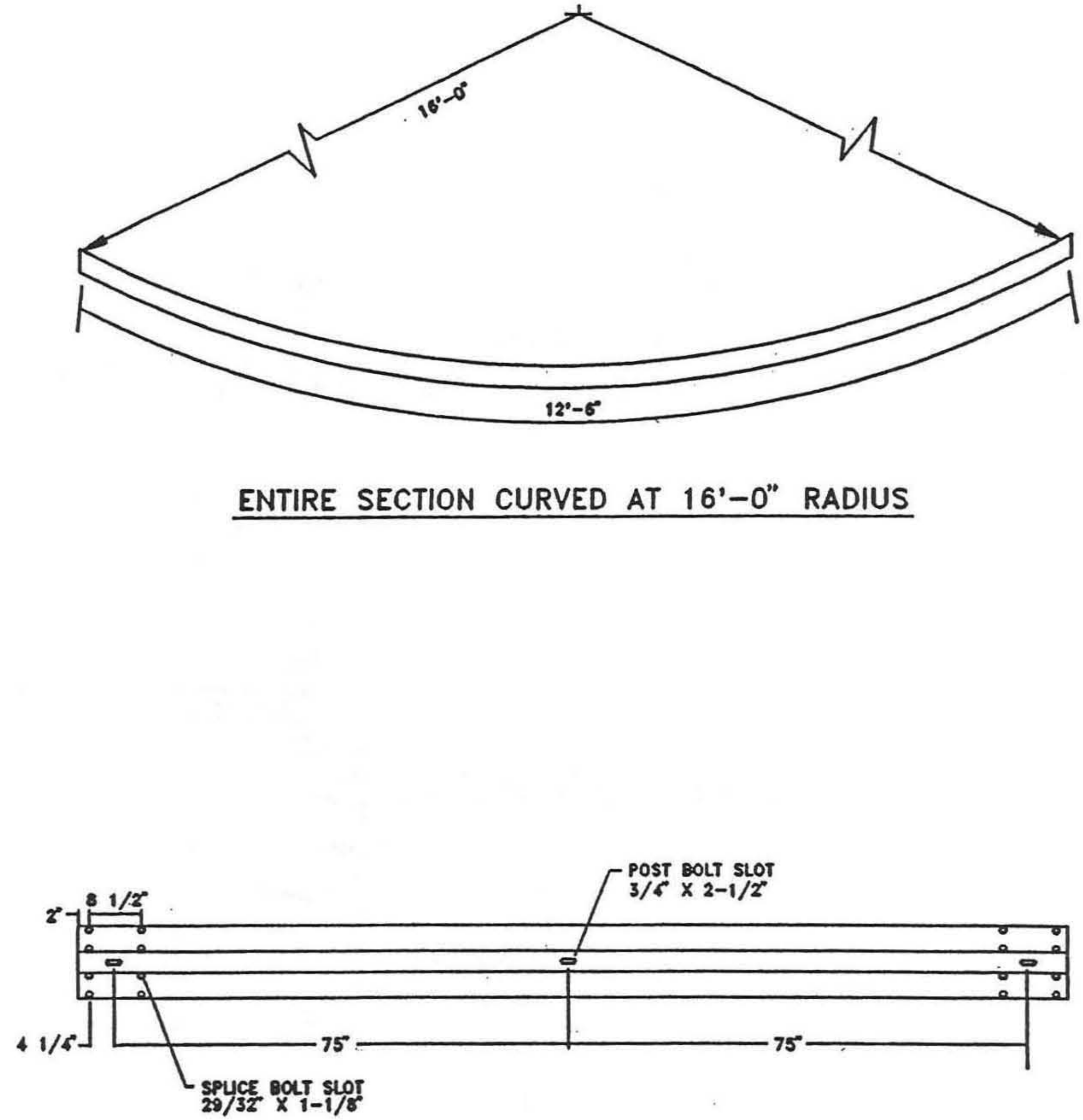


Figure A-12j. TTI W-beam Short Radius Design (7)

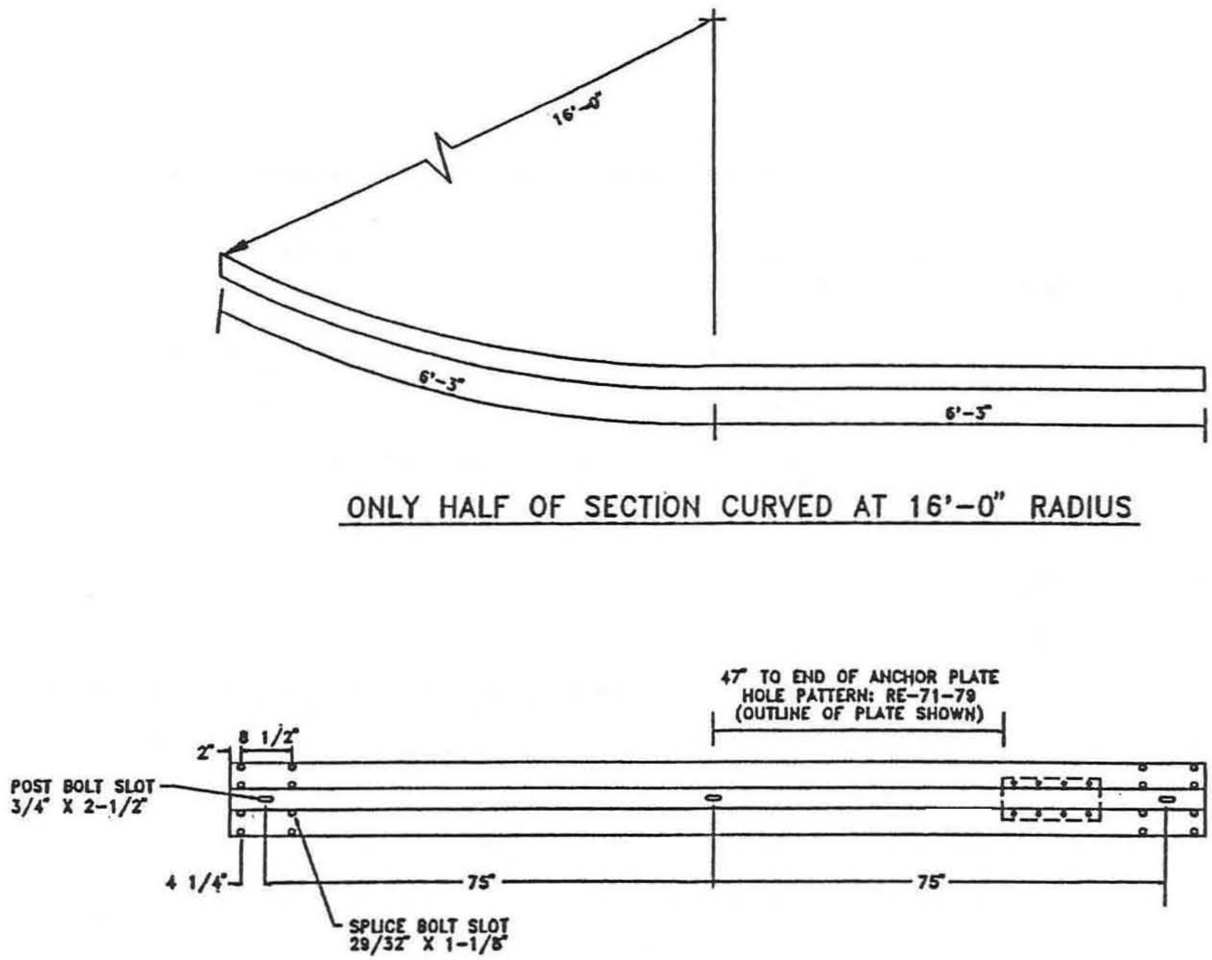
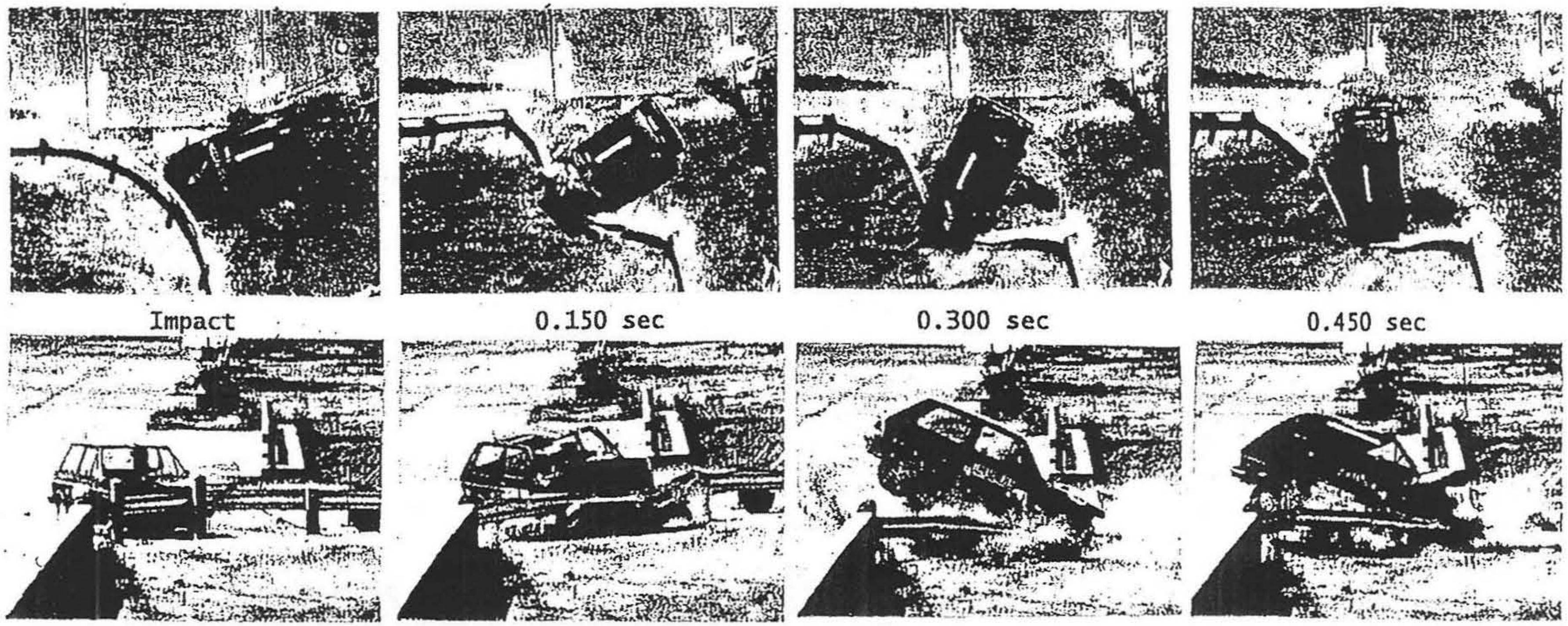


Figure A-12k. TTI W-beam Short Radius Design (7)

Test No.	1263-1	1263-2	1263-3	1263-4	1263-5	1263-6
Test Vehicle	1987 Yugo	1987 Yugo	1987 Yugo	1982 Cadillac	1982 Cadillac	1982 Cadillac
Gross Vehicle Weight, lb.	1970	1970	1968	4500	4500	4500
Impact Speed, mph	58.4	59.0	60.2	57.1	58.5	58.3
Impact Angle, deg	20.5	20.4	20.0	24.7	26.8	2.0
Exit Angle, deg	Did Not Exit	Did Not Exit	Did Not exit	9	Did Not Exit	16.6
Exit Speed, mph	Did Not Exit	Did Not Exit	Did Not Exit	42.2	Did Not Exit	52.8
Max. 50 msec Avg Accel Longitudinal - g's Lateral - g's	 -16.3 5.0	 -9.9 2.2	 -13.2 3.4	 -9.1 10.5	 -5.6 2.1	 -2.4 -4.8
Occupant Impact Velocity Longitudinal - fps Lateral - fps	 41.7 10.7	 27.4 4.2	 34.3 7.9	 27.6 25.4	 20.3 -6.2	 10.7 15.4
Ridedown Acceleration Longitudinal - g's Lateral - g's	 -12.8 2.5	 -10.5 0.8	 -8.9 -3.5	 -4.8 -7.7	 -7.5 2.3	 -1.6 -5.6
NCHRP Report 230 Evaluation Structural Adequacy (A,D) Occupant Risk (E) Vehicle Trajectory (H,I)	 Passed Failed Passed	 Failed Passed Failed	 Passed 40>Long. ΔV>30 Passed	 Passed 30>Lat. ΔV>20 Passed	 Failed Passed Failed	 Passed Passed Passed

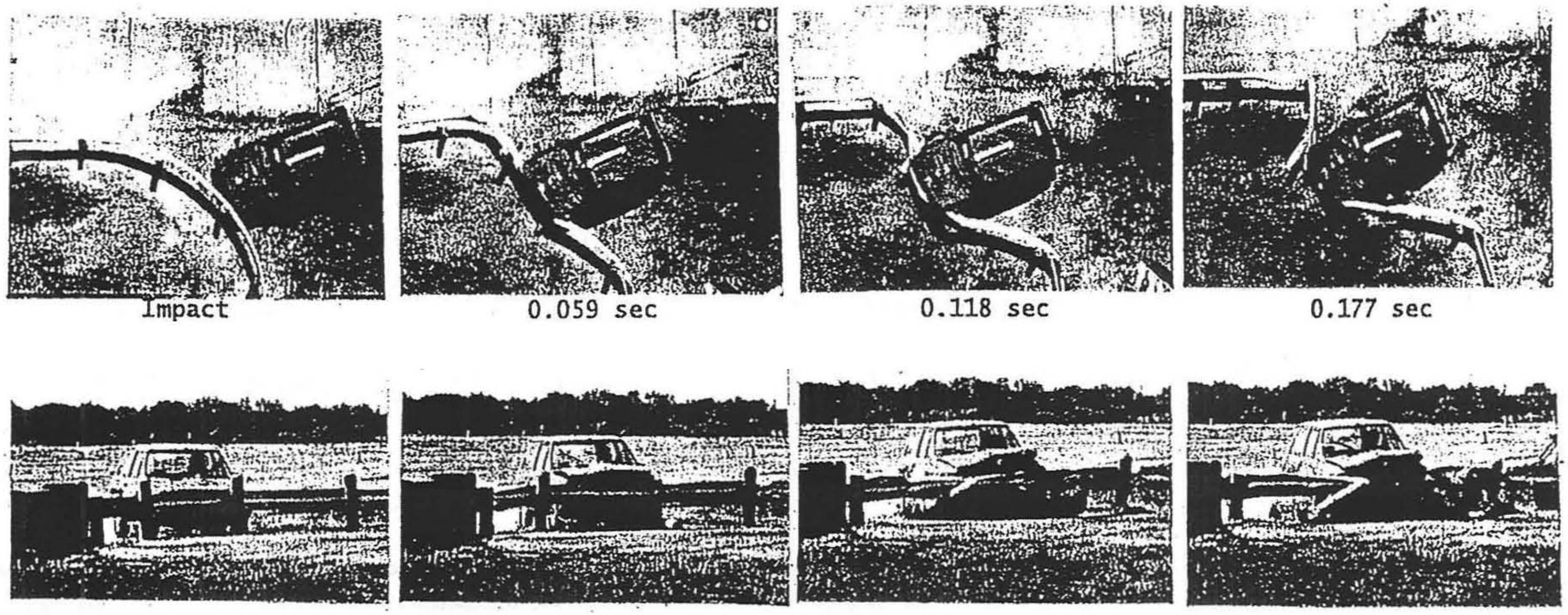
Figure A-13. Summary of TTI W-beam Short Radius Design Guardrail Testing (7)



Test No.	1263-1
Date	07/29/92
Test Installation . . .	Short-Radius Guardrail Treatment
Installation Length . .	100 ft (30 m)
Max. Dynamic Movement .	9.7 ft (3.0 m)
Max. Perm. Movement . .	6.0 ft (1.8 m)
Test Vehicle.	1987 Yugo GV
Vehicle Weight	
Test Inertia	1,800 lb (817 kg)
Gross Static	1,970 lb (894 kg)
Vehicle Damage Classification	
TAD	12FD6
CDC	12FDEW3
Maximum Vehicle Crush. .	15.5 in (39.4 cm)

Impact Speed.	58.4 mi/h (94.0 km/h)
Impact Angle.	20.5 deg
Speed at Parallel . .	N/A
Exit Speed	Vehicle landed on rail
Exit Trajectory . . .	N/A
Vehicle Accelerations at center-of-gravity (Max. 0.050-sec Average)	
Longitudinal. . . .	-16.3 g
Lateral	5.0 g
Occupant Impact Velocity at true c.g.	
Longitudinal. . . .	41.8 ft/s (12.7 m/s)
Lateral	10.7 ft/s (3.3 m/s)
Occupant Ridedown Accelerations	
Longitudinal . . .	-12.8 g
Lateral	2.5 g

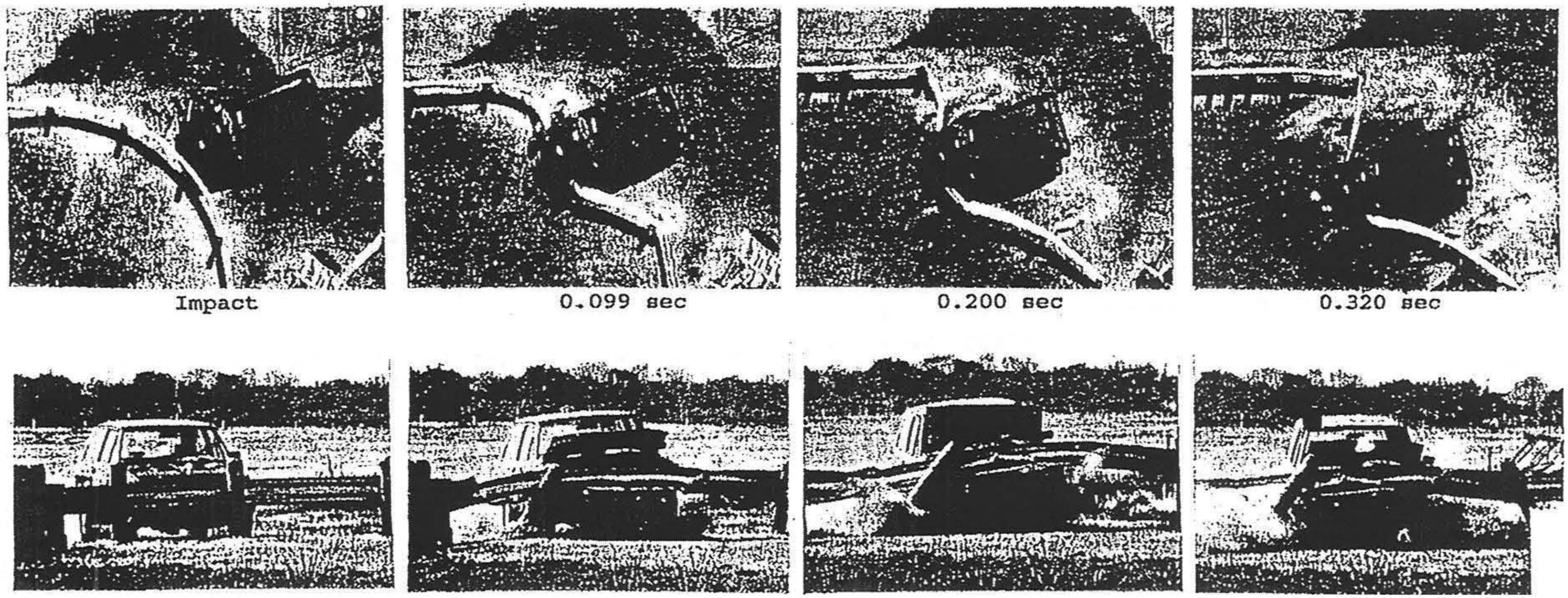
Figure A-14. Summary of TTI W-beam Short Radius Guardrail Test 1263-1 (7)



Test No. 1263-2
Date 08/07/92
Test Installation . . . Short-Radius Guardrail Treatment
Installation Length . . 100 ft (30 m)
Max. Dynamic Movement . Rail separated
Max. Perm. Movement . . Rail separated
Test Vehicle . . . . . . 1987 Yugo GV
Vehicle Weight
  Test Inertia . . . . . 1,800 lb (817 kg)
  Gross Static . . . . . 1,970 lb (894 kg)
Vehicle Damage Classification
  TAD 12FD5
  CDC 12FDEW3
Maximum Vehicle Crush. . 12.0 in (30.5 cm)

Impact Speed. . . . . 59.0 mi/h (94.9 km/h)
Impact Angle. . . . . 20.4 deg
Speed at Parallel . . N/A
Exit Speed . . . . . 35.8 mi/h (57.6 km/h)
Exit Trajectory . . . exited behind the rail
Vehicle Accelerations at center-of-gravity
 (Max. 0.050-sec Average)
  Longitudinal. . . . -9.9 g
  Lateral . . . . . . 2.2 g
Occupant Impact Velocity at true c.g.
  Longitudinal. . . . 27.4 ft/s (8.4 m/s)
  Lateral . . . . . . 4.2 ft/s (1.3 m/s)
Occupant Ridedown Accelerations
  Longitudinal . . . -10.5 g
  Lateral . . . . . . 0.8 g

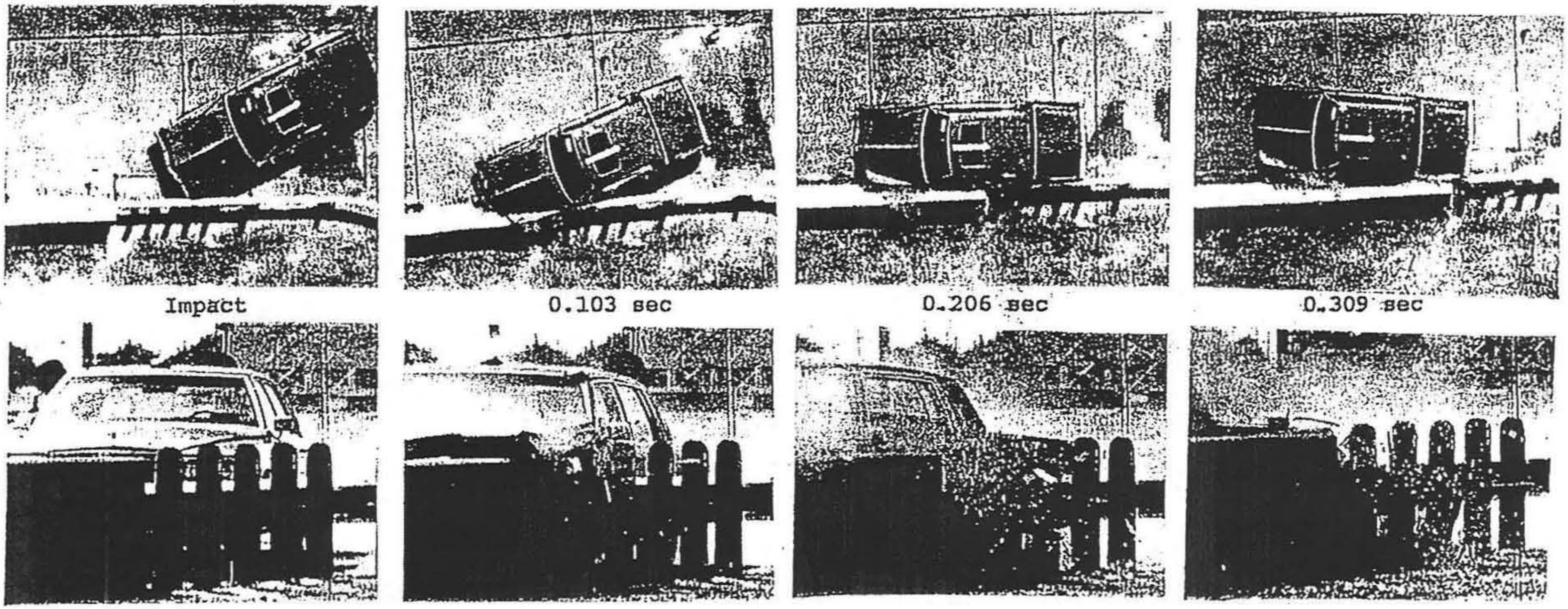
Figure A-15. Summary of TTI W-beam Short Radius Guardrail Test 1263-2 (7)



Test No.	1263-3
Date	08/17/92
Test Installation . . .	Short-Radius Guardrail Treatment
Installation Length . .	100 ft (30 m)
Max. Dynamic Movement .	14.1 ft (4.3 m)
Max. Perm. Movement . .	12.5 ft (3.8 m)
Test Vehicle	1987 Yugo GV
Vehicle Weight	
Test Inertia	1,800 lb (817 kg)
Gross Static	1,970 lb (894 kg)
Vehicle Damage Classification	
TAD	12FD6
CDC	12FCEW4
Maximum Vehicle Crush. .	21.0 in (53.3 cm)

Impact Speed.	60.2 mi/h (96.9 km/h)
Impact Angle.	20.7 deg
Speed at Parallel . .	N/A
Exit Speed	N/A
Exit Trajectory . . .	N/A
Vehicle Accelerations at center-of-gravity (Max. 0.050-sec Average)	
Longitudinal. . . .	-13.2 g
Lateral	3.4 g
Occupant Impact Velocity at true c.g.	
Longitudinal. . . .	34.3 ft/s (10.5 m/s)
Lateral	7.9 ft/s (2.4 m/s)
Occupant Ridedown Accelerations	
Longitudinal . . .	-8.9 g
Lateral	-3.5 g

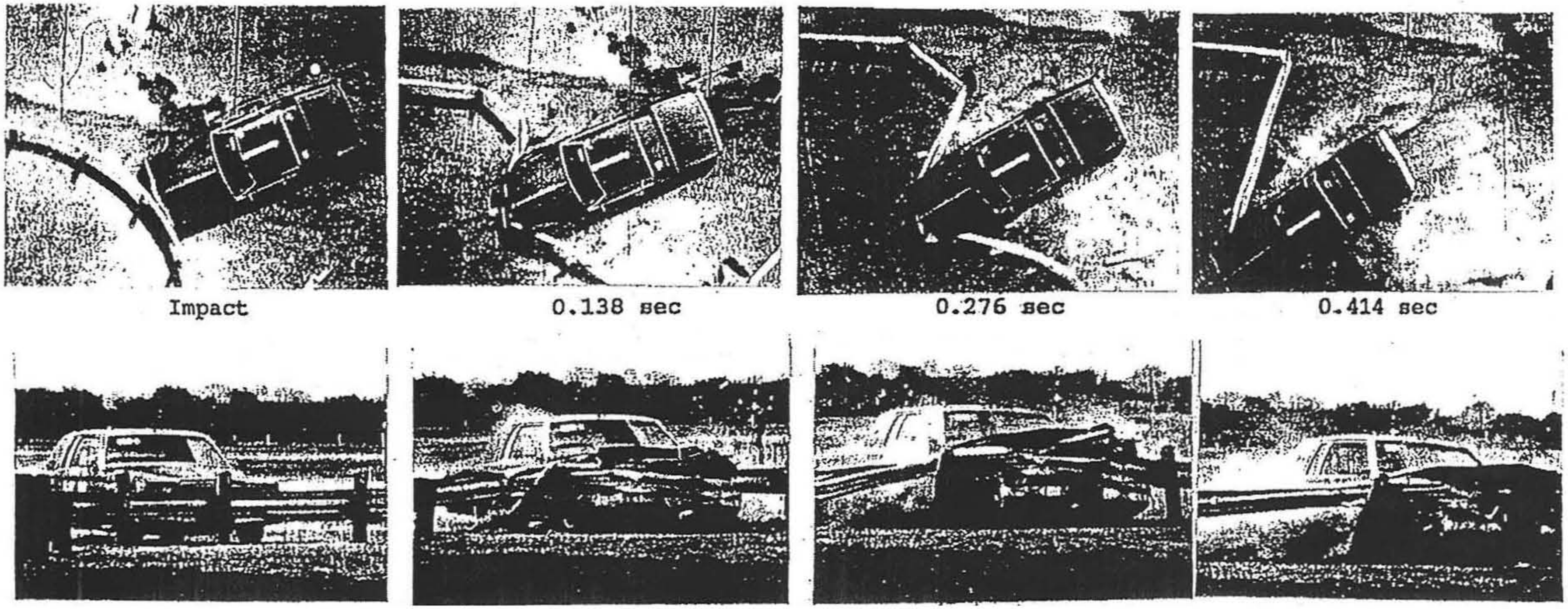
Figure A-16. Summary of TTI W-beam Short Radius Guardrail Test 1263-3 (7)



Test No.	1263-4
Date	08/27/92
Test Installation . . .	Short-Radius Guardrail Treatment
Installation Length . .	100 ft (30 m)
Max. Dynamic Movement .	Not Obtained
Max. Perm. Movement . .	2.0 in (5.1 cm)
Test Vehicle	1982 Cadillac Sedan
Vehicle Weight	
Test Inertia	4,500 lb (2,041 kg)
Gross Static	4,500 lb (2,014 kg)
Vehicle Damage Classification	
TAD	11FL7 11LD1
CDC	11FLEK5 11LDES1
Maximum Vehicle Crush. .	13.0 in (33.0 cm)

Impact Speed.	57.1 mi/h (91.9 km/h)
Impact Angle.	24.7 deg
Speed at Parallel . .	44.9 mi/h (72.2 km/h)
Exit Speed	42.2 mi/h (67.9 km/h)
Exit Trajectory	9.0 deg
Vehicle Accelerations at center-of-gravity	
(Max. 0.050-sec Average)	
Longitudinal.	-9.1 g
Lateral	10.5 g
Occupant Impact Velocity at true c.g.	
Longitudinal.	27.6 ft/s (8.4 m/s)
Lateral	25.4 ft/s (7.7 m/s)
Occupant Ridedown Accelerations	
Longitudinal	-4.8 g
Lateral	-7.7 g

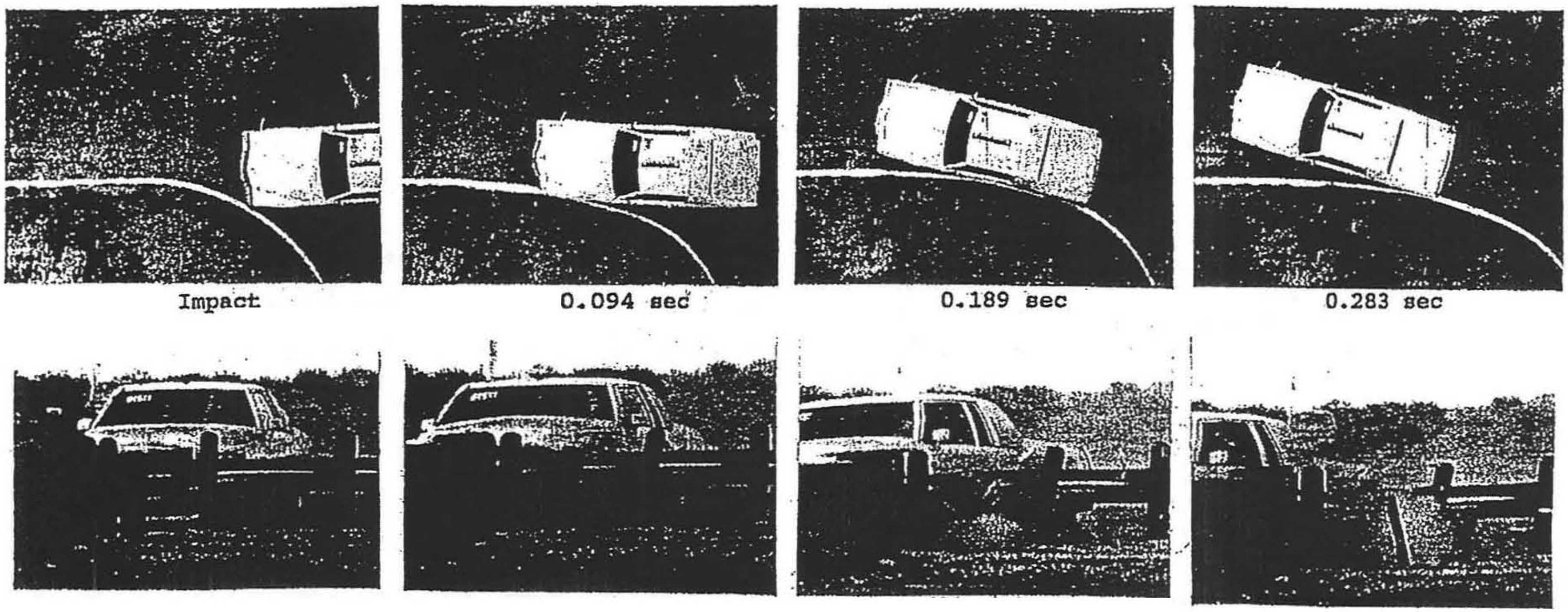
Figure A-17. Summary of TTI W-beam Short Radius Guardrail Test 1263-4 (7)



Test No. 1263-5
Date 08/25/92
Test Installation . . . Short-Radius
Guardrail Treatment
Installation Length . . 100 ft (30 m)
Max. Dynamic Movement . 28.3 ft (8.6 m)
Max. Perm. Movement . . 25.4 ft (7.7 m)
Test Vehicle . . . . . . 1982 Cadillac Coupe
Vehicle Weight
Test Inertia . . . . . . 4,500 lb (2,041 kg)
Gross Static . . . . . . 4,500 lb (2,041 kg)
Vehicle Damage Classification
TAD 12FD7
CDC 12FCAW7
Maximum Vehicle Crush. . 15.0 in (38.1 cm)

Impact Speed. . . . . 58.5 mi/h (94.1 km/h)
Impact Angle. . . . . 26.8 deg
Speed at Parallel . . N/A
Exit Speed . . . . . . 36.6 mi/h (58.9 km/h)
Exit Trajectory . . . Under the Guardrail
Vehicle Accelerations at center-of-gravity
(Max. 0.050-sec Average)
Longitudinal. . . . -5.6 g
Lateral . . . . 2.1 g
Occupant Impact Velocity at true c.g.
Longitudinal. . . . 20.3 ft/s (6.2 m/s)
Lateral . . . . . . -6.2 ft/s (-1.9 m/s)
Occupant Ridedown Accelerations
Longitudinal . . . -7.6 g
Lateral . . . . 2.3 g

Figure A-18. Summary of TTI W-beam Short Radius Guardrail Test 1263-5 (7)



Test No.	1263-6
Date	08/31/92
Test Installation . . .	Short-Radius Guardrail Treatment
Installation Length . .	100 ft (30 m)
Max. Dynamic Movement .	Not Obtained
Max. Perm. Movement . .	2 in (5.1 cm)
Test Vehicle	1983 Cadillac Coupe
Vehicle Weight	
Test Inertia	4,500 lb (2,041 kg)
Gross Static	4,500 lb (2,041 kg)
Vehicle Damage Classification	
TAD	10LD2
CDC	10LFEW2
Maximum Vehicle Crush. .	9.0 in (22.9 cm)

Impact Speed.	58.3 mi/h (93.8 km/h)
Impact Angle.	2.0 deg
Speed at Parallel . .	53.7 mi/h (86.4 km/h)
Exit Speed	52.8 mi/h (84.9 km/h)
Exit Trajectory . . .	16.6 deg
Vehicle Accelerations at center-of-gravity (Max. 0.050-sec Average)	
Longitudinal. . . .	-2.4 g
Lateral	-4.8 g
Occupant Impact Velocity at true c.g.	
Longitudinal. . . .	10.7 ft/s (3.3 m/s)
Lateral	15.4 ft/s (4.7 m/s)
Occupant Ridedown Accelerations	
Longitudinal	-1.6 g
Lateral	-5.6 g

Figure A-19. Summary of TTI W-beam Short Radius Guardrail Test 1263-6 (7)

Table A-4. Summary of TTI's Thrie beam Short-Radius Study (8).

Test No.	Test Vehicle	Impact Specifications	System Configuration	Test Results
1442-1	4409 lb. ¾ ton pickup	60.9 mph into transition section @ 26.0 degrees to the primary roadway	16 ft radius thrie-beam section supported by 7" diameter CRT posts at a height of 31 inches, remaining posts are standard 7" diameter wood, anchored by turndown.	-substantial deformation of occupant compartment, this was judged to not be critical, and the test was considered a success. **-test passed**
1442-2	4409 lb. ¾ ton pickup	63.0 mph into the midpoint of curved section @ 25.6 degrees to primary roadway	same as 1442-1 test configuration	-top edge of rail rotated downward allowing the vehicle to override the system **-test failed**
1442-3	4409 lb. ¾ ton pickup	63.0 mph into midpoint of curved section @ 24.6 degrees to primary roadway	same configuration as previous tests with several post bolts removed in the curved section in an attempt to keep the rail from being pulled down.	-top edge of rail rotated downward allowing the vehicle to override the system **-test failed**
1442-4	1808 lb. car	60.1 mph into midpoint of curved section @ 19.1 degrees to primary roadway	same as previous test	-rail began to override the vehicle before snagging on roof supports, no penetration into occupant compartment **-test passed**
1442-5	4500 lb. car	60.4 mph into midpoint of curved section @ 24.5 degrees to primary roadway	same as previous test	-the rail captured the vehicle, but the turndown anchor failed allowing the rail to "swing" away from the vehicle. -it was determined that the bolts installed at the turndown were smaller than specified. -the test was judged to be successful due to acceptable performance prior to anchorage failure **-test passed**

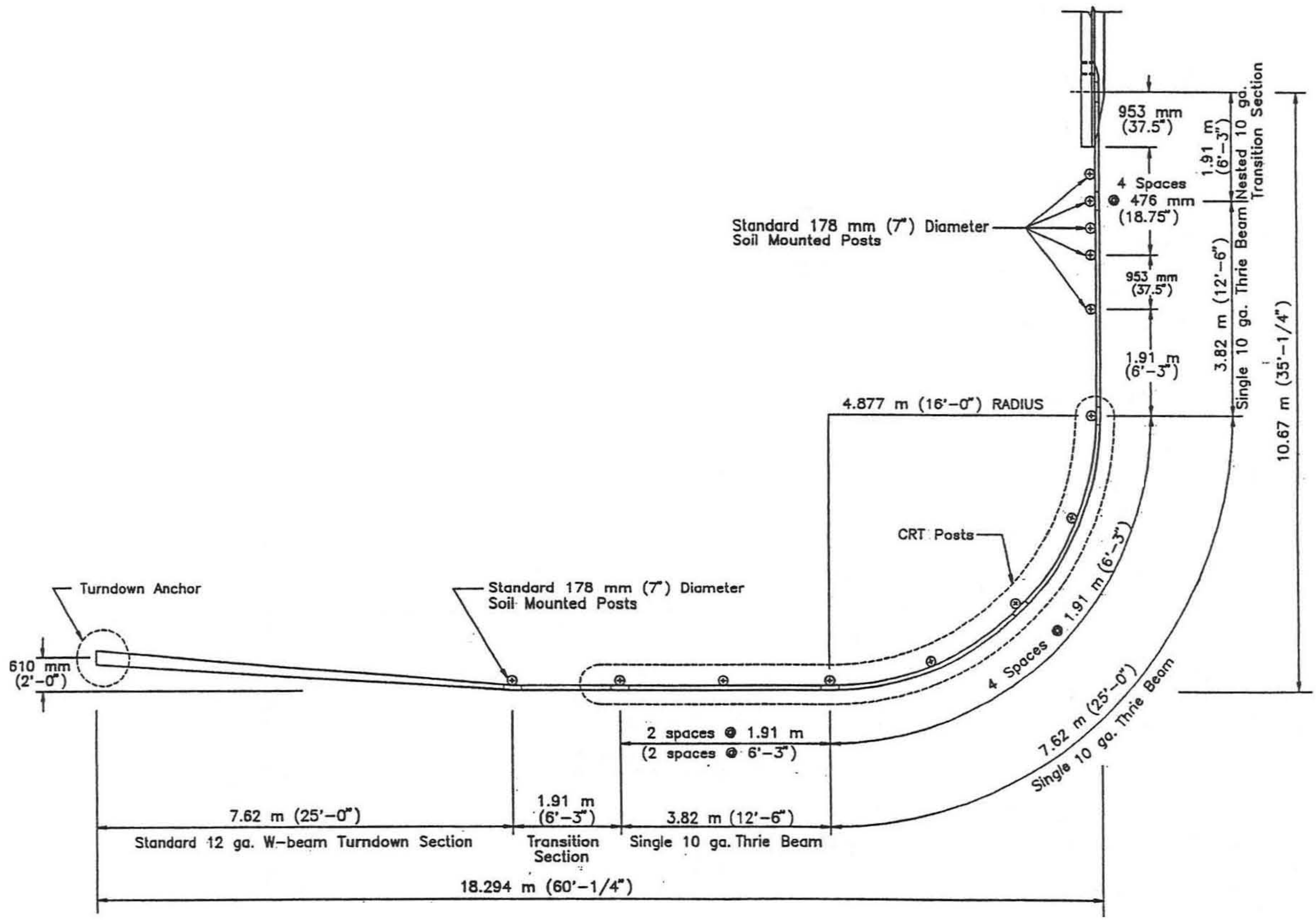


Figure A-20a. TTI Thrie Beam Short Radius Design (8)

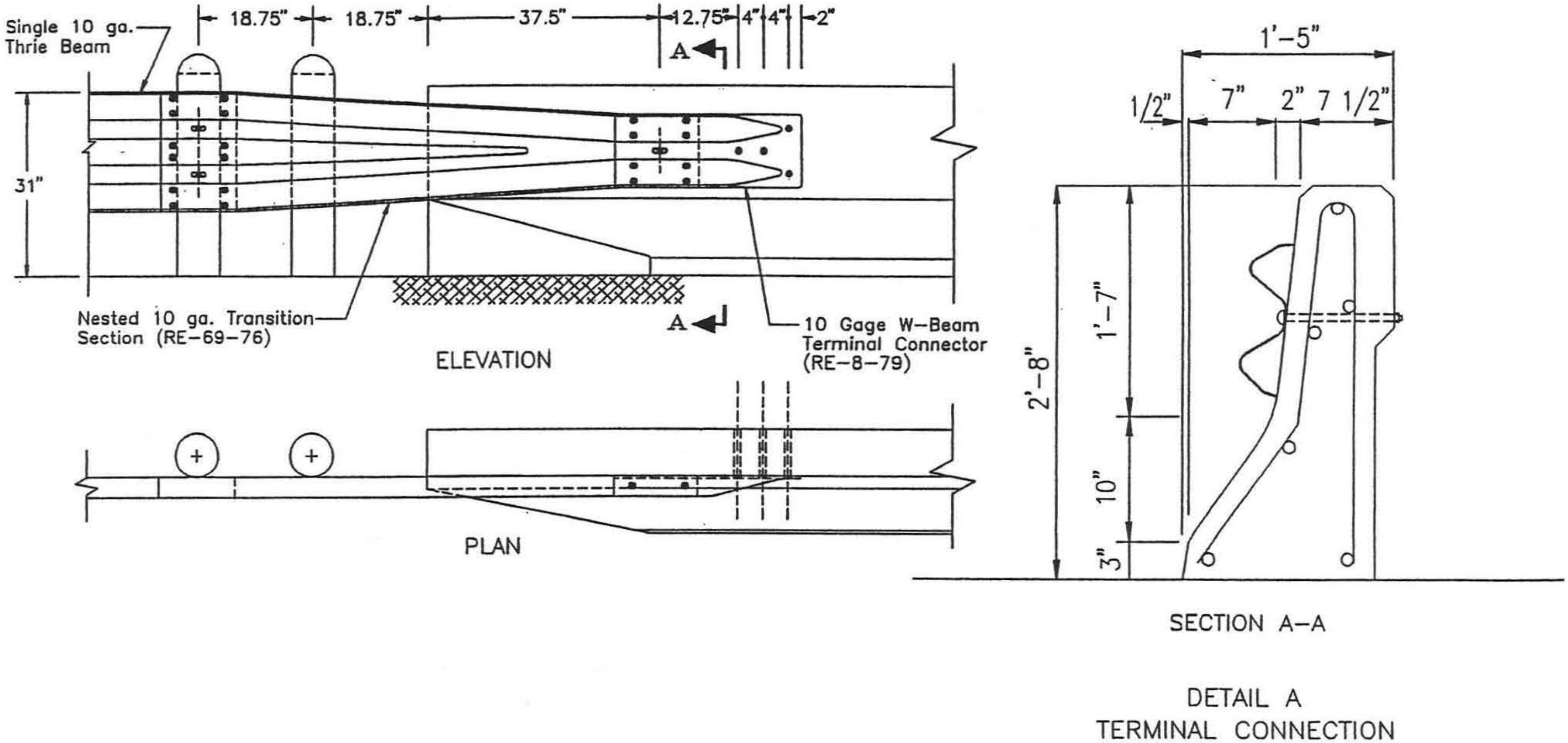
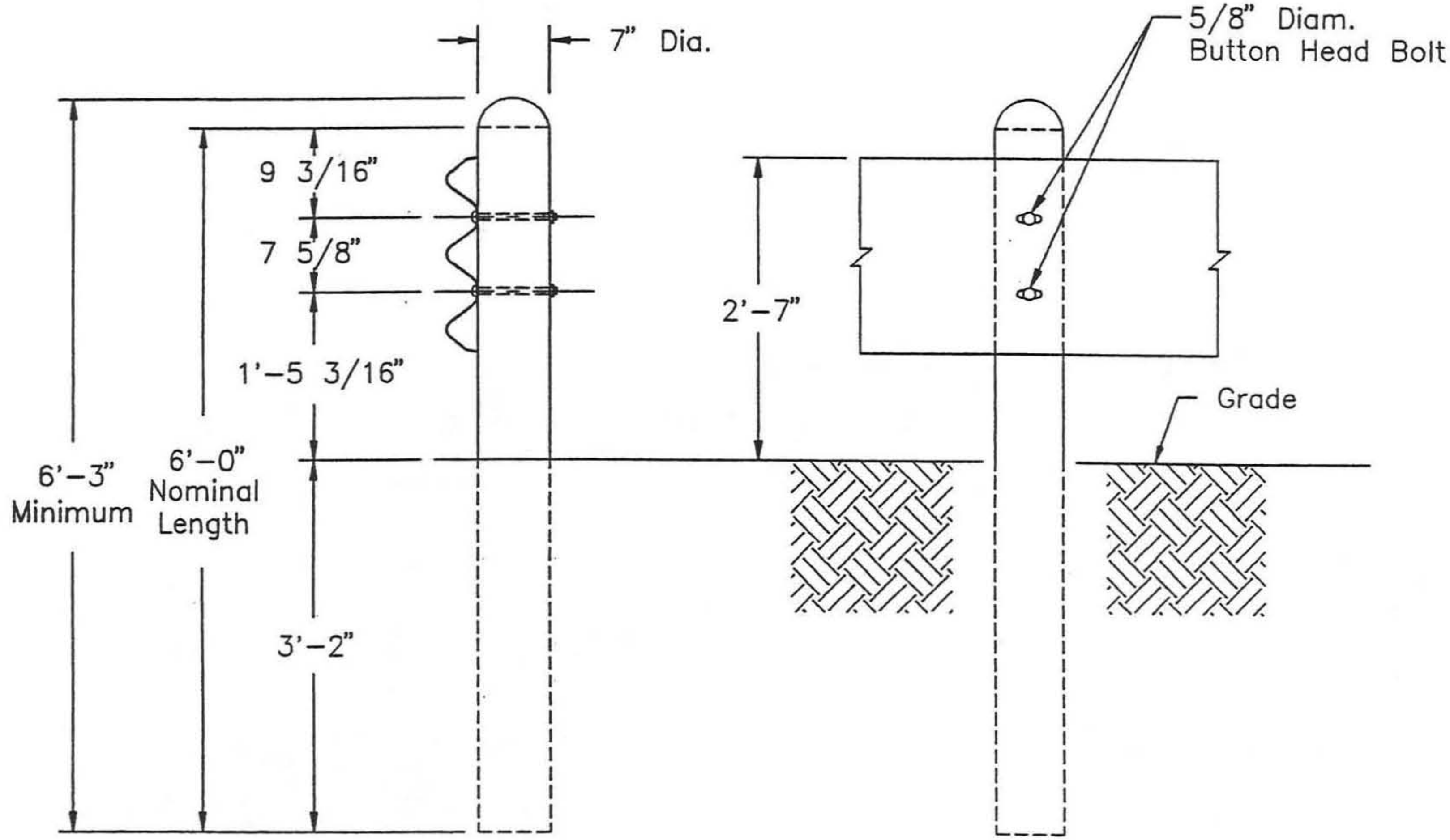


Figure A-20b. TTI Thrie Beam Short Radius Design (8)



DETAIL B
STANDARD POST

Figure A-20c. TTI Thrie Beam Short Radius Design (8)

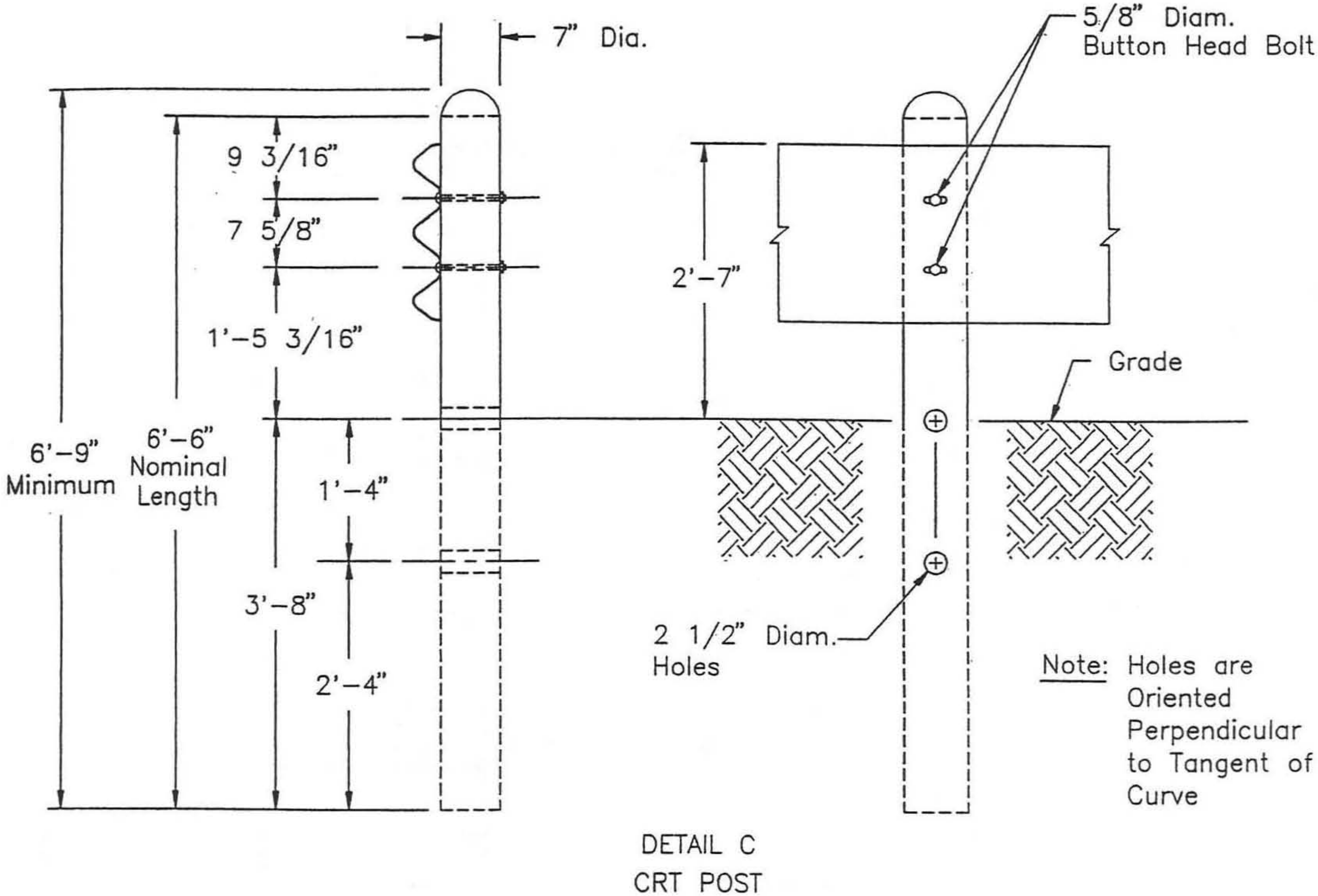
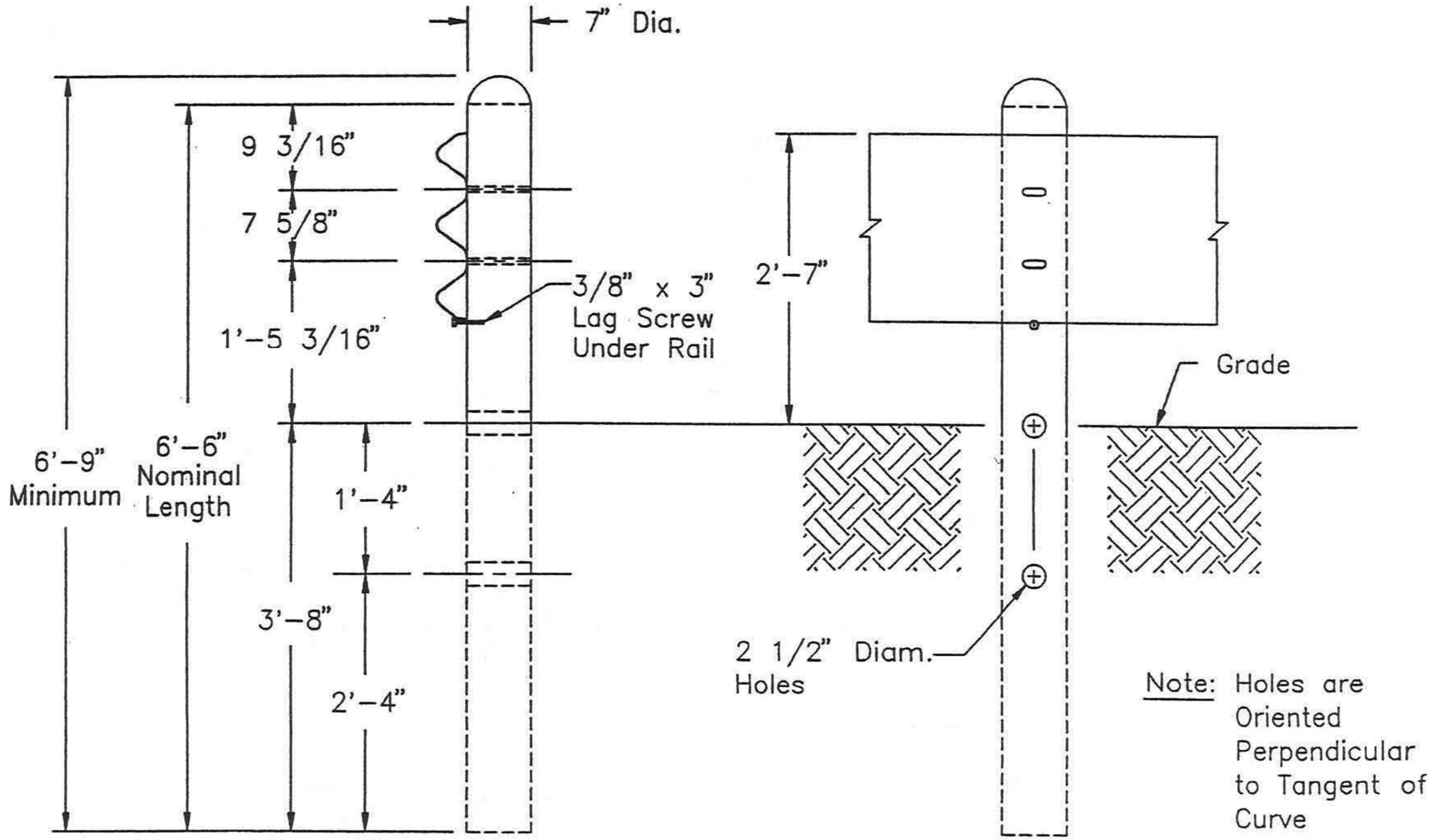
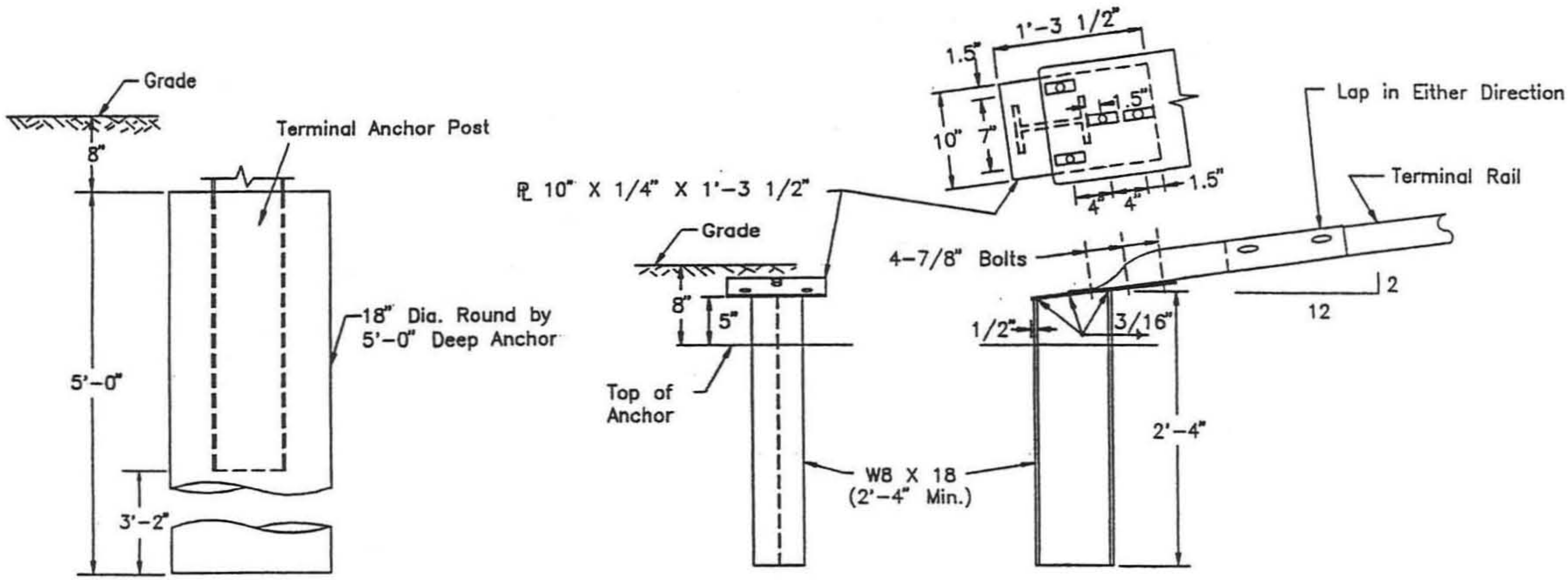


Figure A-20d. TTI Thrie Beam Short Radius Design (8)



DETAIL D
RAIL/POST CONNECTION IN CURVE

Figure A-20e. TTI Thrie Beam Short Radius Design (8)



DETAIL E
TURNDOWN ANCHOR

Figure A-20f. TTI Thrie Beam Short Radius Design (8)

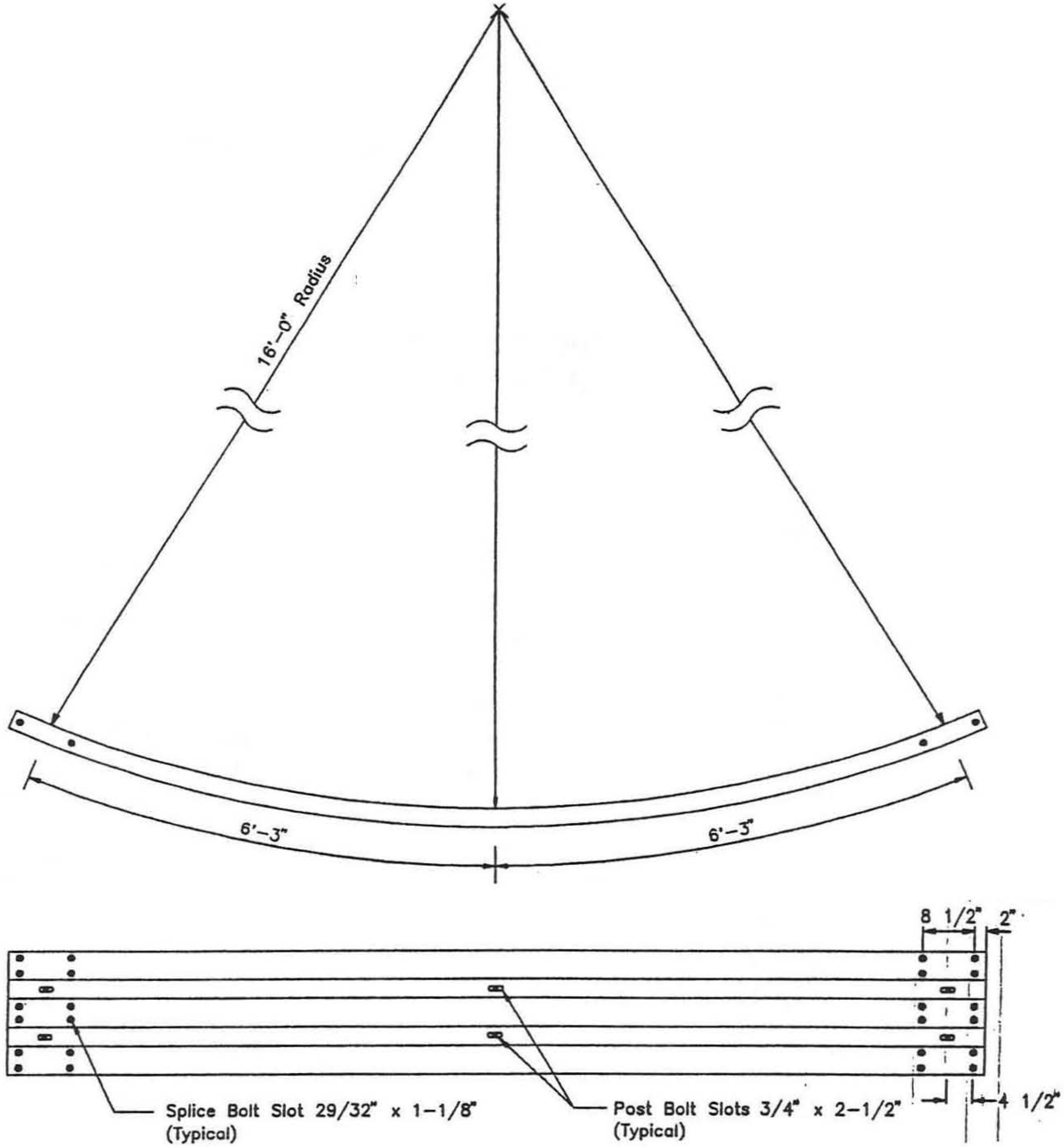
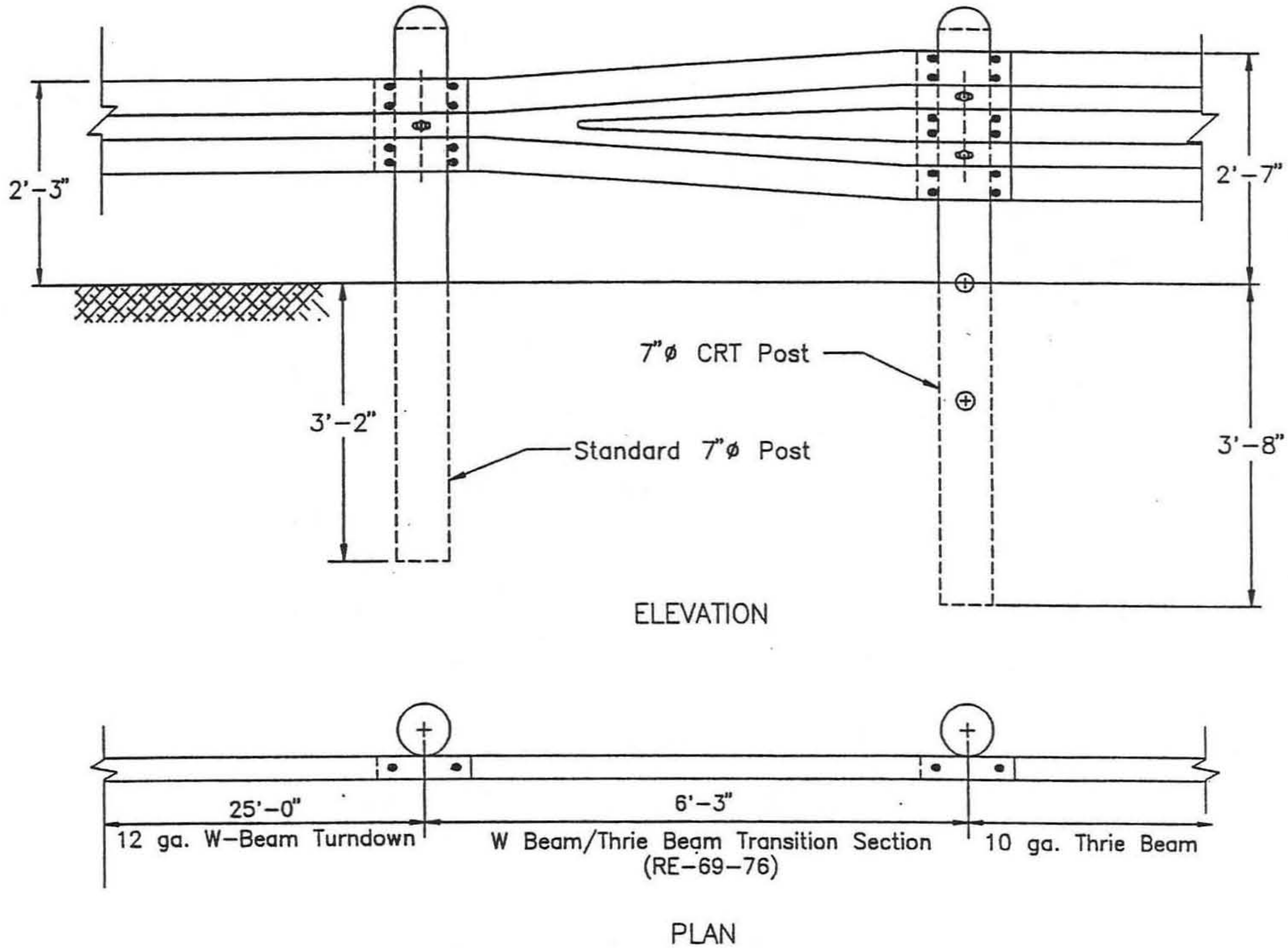
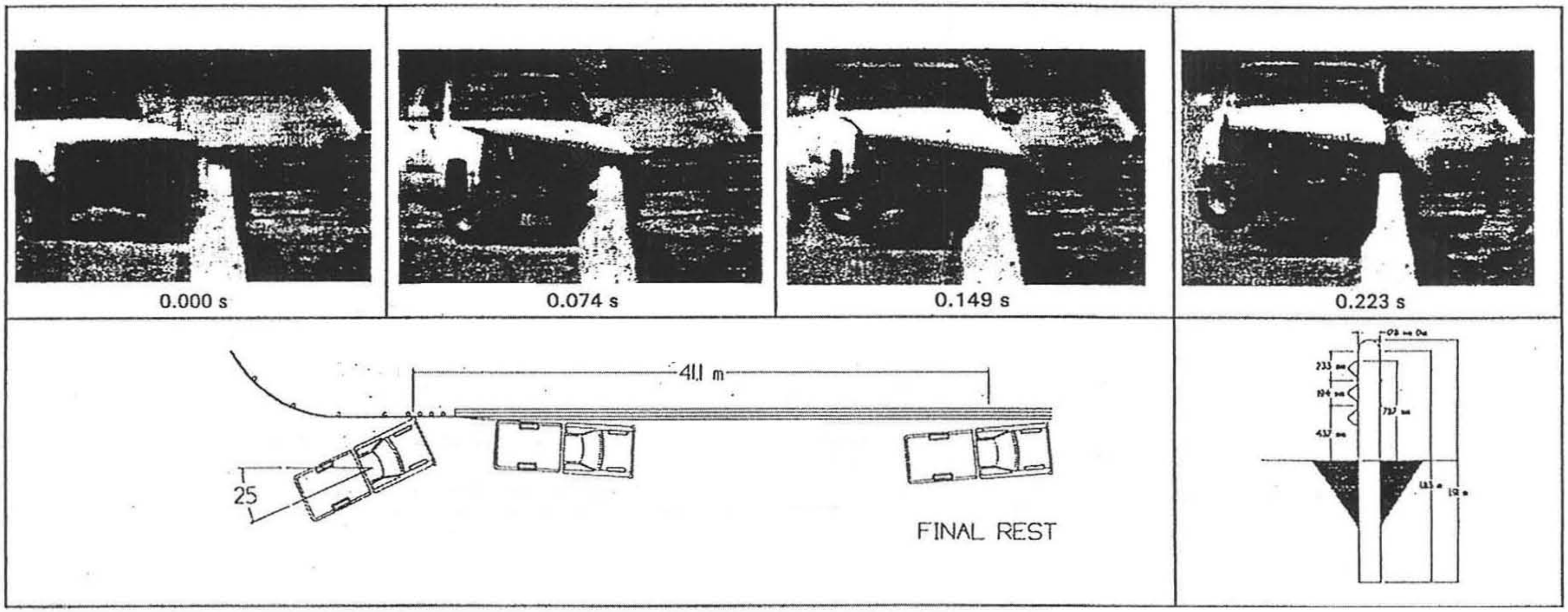


Figure A-20g. TTI Thrie Beam Short Radius Design (8)



DETAIL G
THRIE BEAM/W-BEAM TRANSITION

Figure A-20h. TTI Thrie Beam Short Radius Design (8)

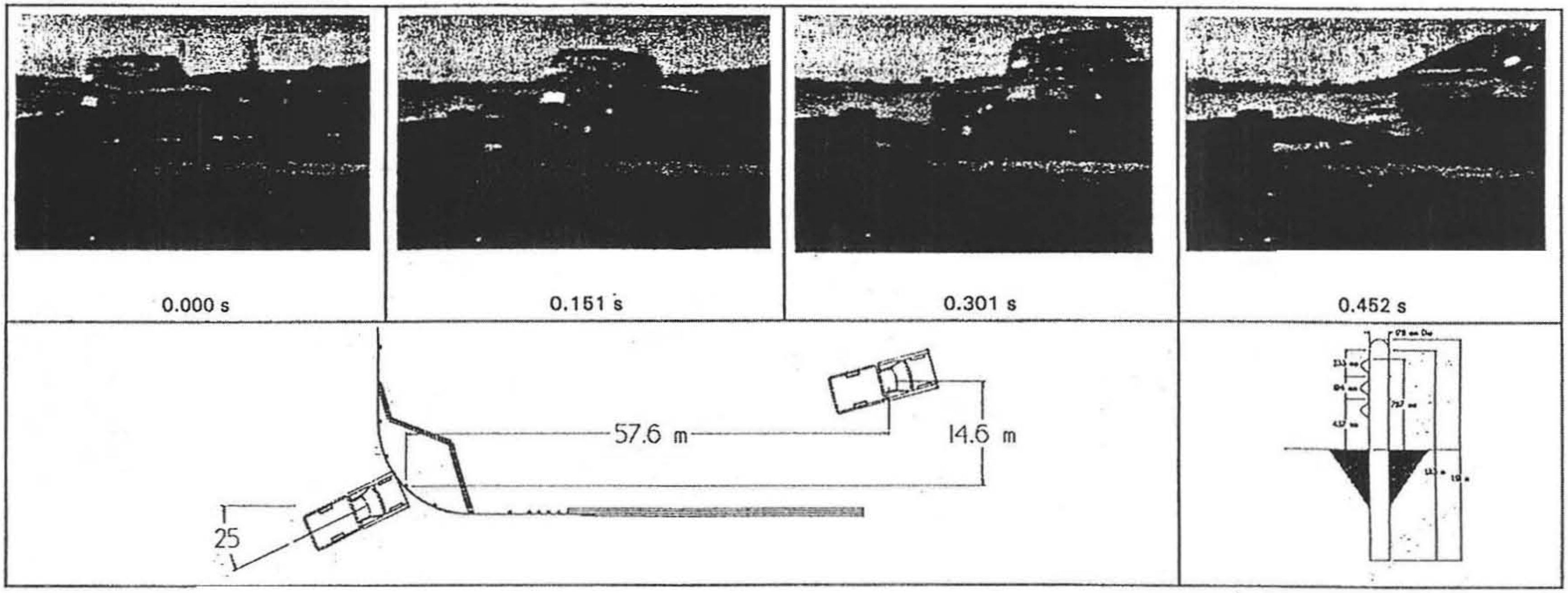


General Information	
Test Agency	Texas Transportation Institute
Test No.	414424-1
Date	07/27/94
Test Article	
Type	Short Radius Guardrail
Name or Manufacturer	TxDOT
Installation Length (m)	4.8 m (16.0 ft) Radius
Size and/or dimension and material of key elements	Thriebeam Guardrail 17.8 cm (7.0 in) Round Posts
Soil Type and Condition .	Strong soil, Dry
Test Vehicle	
Type	Production
Designation	2000P
Model	1986 Chevrolet Pickup
Mass (kg) Curb	2036 (4488 lb)
Test Inertial	2000 (4409 lb)
Dummy ..	
Gross Static	2000 (4409 lb)

Impact Conditions	
Speed (km/h)	98.1 (60.9 mi/h)
Angle (deg)	26.0
Exit Conditions	
Speed (km/h)	66.8 (41.5 mi/h)
Angle (deg)	2.5
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	7.3 (24.1 ft/s)
y-direction	8.0 (26.2 ft/s)
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-7.1
y-direction	11.7
PHD (optional)	
ASI (optional)	
Max. 0.050-sec Average (g's)	
x-direction	10.0
y-direction	10.6
z-direction	-12.5 (Floor Pan Bent)

Test Article Deflections (m)	
Dynamic	Unavailable
Permanent	0.09 (0.29 ft)
Vehicle Damage	
Exterior	
VDS	FL-6
CDC	11FLEW5
Interior	
OCDI	LF0115100
Maximum Exterior Vehicle Crush (mm) ..	705 (27.8 in)
Max. Occ. Compart. Deformation (mm) ...	95 (3.78 in)
Post-Impact Behavior	
Max. Roll Angle (deg)	-18.8
Max. Pitch Angle (deg)	5.8
Max. Yaw Angle (deg)	21.3

Figure A-21. Summary of TTI W-beam Short Radius Guardrail Test 1442-1 (8)

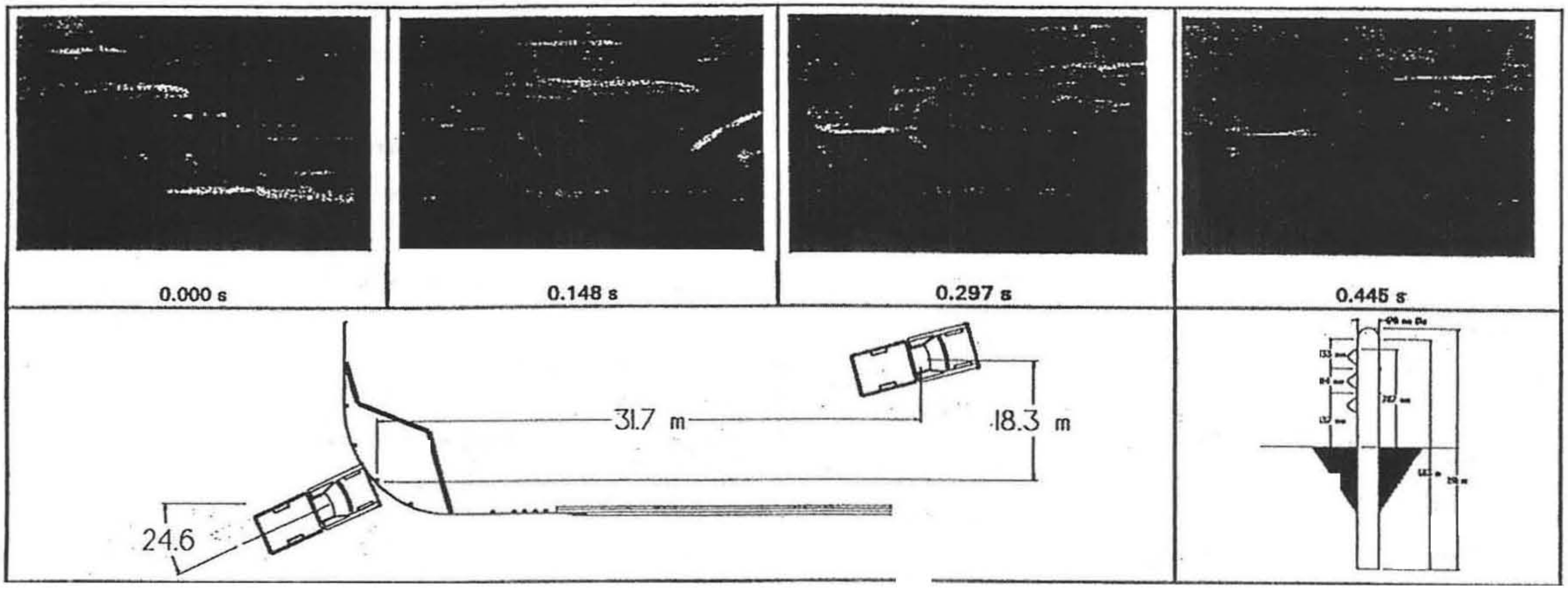


General Information	
Test Agency	Texas Transportation Institute
Test No.	414424-2
Date	07/29/94
Test Article	
Type	Short Radius Guardrail
Name or Manufacturer	TxDOT
Installation Length (m)	4.8 m (16.0 ft) Radius
Size and/or dimension and material of key elements	Thriebeam Guardrail 17.8 cm (7.0 in) Round Posts
Soil Type and Condition	Strong soil, Dry
Test Vehicle	
Type	Production
Designation	2000P
Model	1985 Chevrolet Pickup
Mass (kg) Curb	2094 (4616 lb)
Test Inertial	2000 (4409 lb)
Dummy	
Gross Static	2000 (4409 lb)

Impact Conditions	
Speed (km/h)	101.4 (63.0 mi/h)
Angle (deg)	25.6
Exit Conditions	
Speed (km/h)	75.9 (47.2 mi/h)
Angle (deg)	23.5
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	5.2 (17.2 ft/s)
y-direction	0.8 (2.6 ft/s)
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-10.4
y-direction	5.6
PHD (optional)	
ASI (optional)	
Max. 0.050-sec Average (g's)	
x-direction	-6.0
y-direction	-3.9
z-direction	-4.3

Test Article Deflections (m)	
Dynamic	3.05 (10.0 ft)
Permanent	2.84 (9.3 ft)
Vehicle Damage	
Exterior	
VDS	FD-2
CDC	12FDEW1
Interior	
OCDI	AS0000000
Maximum Exterior Vehicle Crush (mm)	280 (11.0in)
Max. Occ. Compart. Deformation (mm)	0
Post-Impact Behavior	
Max. Roll Angle (deg)	29.1
Max. Pitch Angle (deg)	7.3
Max. Yaw Angle (deg)	-12.6

Figure A-22. Summary of TTI W-beam Short Radius Guardrail Test 1442-2 (8)



General Information

Test Agency	Texas Transportation Institute
Test No.	414424-3
Date	08/16/94
Test Article	
Type	Short Radius Guardrail
Name or Manufacturer	TxDOT
Installation Length (m)	4.8 m (16.0 ft) Radius
Size and/or dimension and material of key elements	Thriebeam Guardrail 17.8 cm (7.0 in) Round Posts
Soil Type and Condition	Strong soil, Dry
Test Vehicle	
Type	Production
Designation	2000P
Model	1988 Ford F250 Pickup
Mass (kg) Curb	2059 (4539 lb)
Test Inertial	2000 (4409 lb)
Dummy	
Gross Static	2000 (4409 lb)

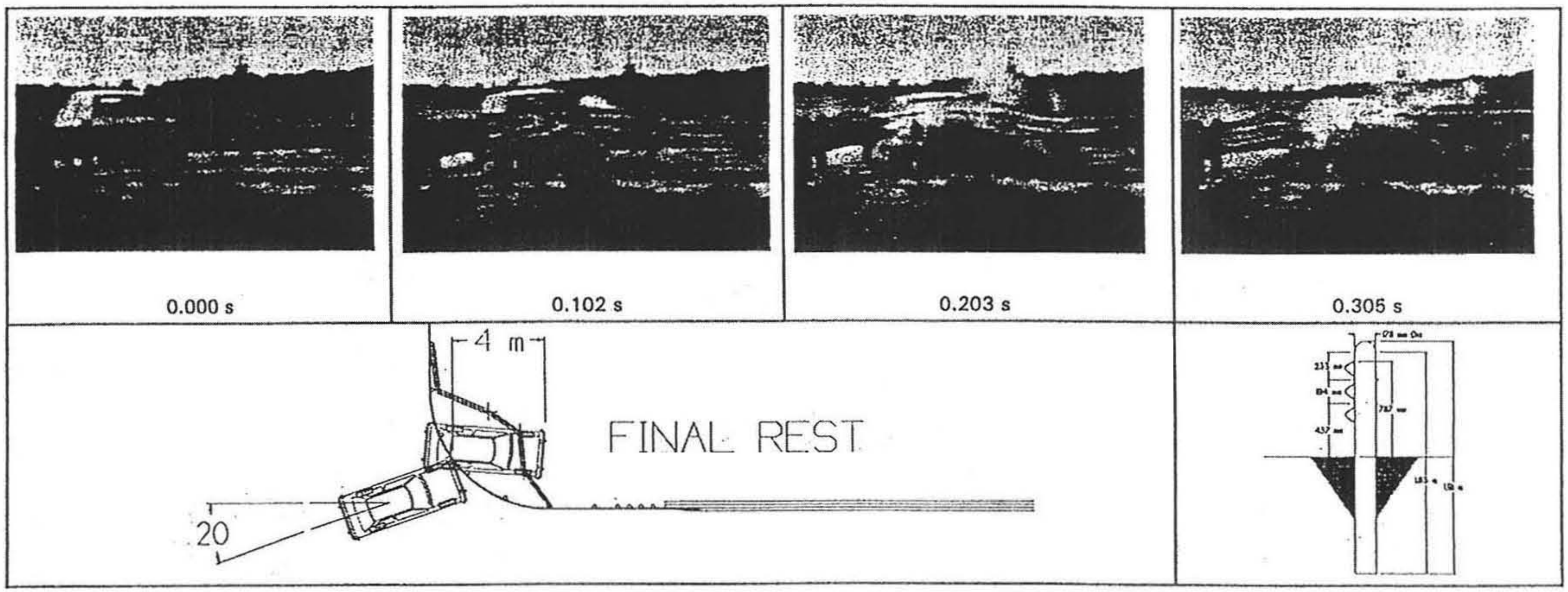
Impact Conditions

Speed (km/h)	101.4 (63.0 mi/h)
Angle (deg)	24.6
Exit Conditions	
Speed (km/h)	79.3 (49.3 mi/h)
Angle (deg)	22.9
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	5.0 (16.5 ft/s)
y-direction	1.0 (3.3 ft/s)
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-6.17
y-direction	-9.58
PHD (optional)	
ASI (optional)	
Max. 0.050-sec Average (g's)	
x-direction	-5.7
y-direction	-4.3
z-direction	-2.9

Test Article Deflections (m)

Dynamic	3.27 (10.7 ft)
Permanent	2.90 (9.5 ft)
Vehicle Damage	
Exterior	
VDS	FD-2 (EST.)
CDC	12FDEW1
Interior	
OCDI	AS0000000
Maximum Exterior Vehicle Crush (mm)	Unavailable (Tree impact)
Max. Occ. Compart. Deformation (mm)	0 (estimated)
Post-Impact Behavior	
Max. Roll Angle (deg)	15.7
Max. Pitch Angle (deg)	-9.8
Max. Yaw Angle (deg)	-4.3

Figure A-23. Summary of TTI W-beam Short Radius Guardrail Test 1442-3 (8)

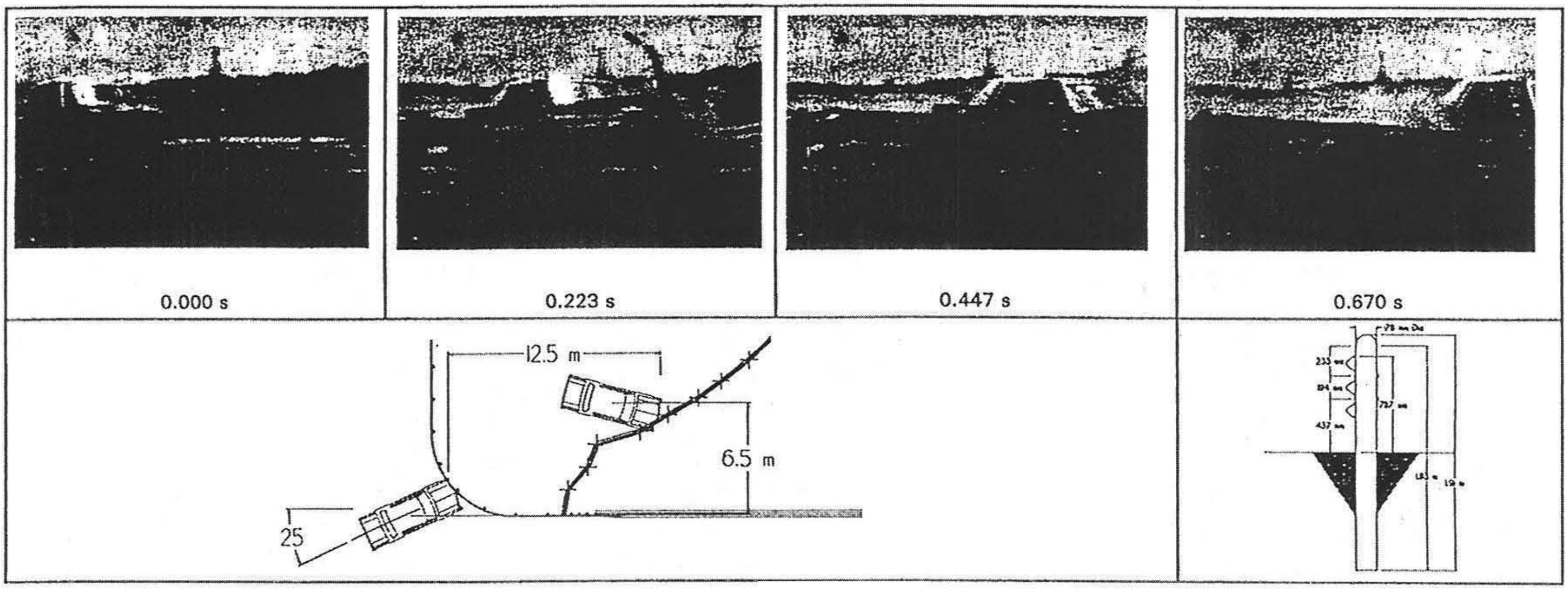


General Information	
Test Agency	Texas Transportation Institute
Test No.	414424-4
Date	08/26/94
Test Article	
Type	Short Radius Guardrail
Name or Manufacturer	TxDOT
Installation Length (m)	4.8 m (16.0 ft) Radius
Size and/or dimension and material of key elements	Thriebeam Guardrail 17.8 cm (7.0 in) Round Posts
Soil Type and Condition	Strong soil, Dry
Test Vehicle	
Type	Production
Designation	820C
Model	1988 Chevrolet Sprint
Mass (kg) Curb	720 (1587 lb)
Test Inertial	820 (1808 lb)
Dummy	77 (170 lb)
Gross Static	897 (1978 lb)

Impact Conditions	
Speed (km/h)	96.7 (60.1 mi/h)
Angle (deg)	19.1
Exit Conditions	
Speed (km/h)	Vehicle Contained
Angle (deg)	N/A
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	10.6 (34.7 ft/s)
y-direction	2.4 (7.8 ft/s)
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-8.59
y-direction	-3.02
PHD (optional)	
ASI (optional)	
Max. 0.050-sec Average (g's)	
x-direction	-14.0
y-direction	-2.2
z-direction	-4.3

Test Article Deflections (m)	
Dynamic	3.22 (10.6 ft)
Permanent	2.90 (9.5 ft)
Vehicle Damage	
Exterior	
VDS	FD-3
CDC	11FDEW4
Interior	
OCDI	AS1011000
Maximum Exterior Vehicle Crush (mm)	570 (22.4 in)
Max. Occ. Compart. Deformation (mm)	86 (3.4 in)
Post-Impact Behavior	
Max. Roll Angle (deg)	4.5
Max. Pitch Angle (deg)	-4.6
Max. Yaw Angle (deg)	-7.2

Figure A-24. Summary of TTI W-beam Short Radius Guardrail Test 1442-4 (8)



General Information	
Test Agency	Texas Transportation Institute
Test No.	414424-5
Date	08/29/94
Test Article	
Type	Short Radius Guardrail
Name or Manufacturer	TxDOT
Installation Length (m)	4.8 m (16.0 ft) Radius
Size and/or dimension and material of key elements	Thriebeam Guardrail 17.8 cm (7.0 in) Round Posts
Soil Type and Condition	Strong soil, Dry
Test Vehicle	
Type	Production
Designation	Full Size Automobile
Model	1984 Lincoln Town Car
Mass (kg) Curb	1820 (4012 lb)
Test Inertial	2041 (4500 lb)
Dummy	
Gross Static	2041 (4500 lb)

Impact Conditions	
Speed (km/h)	97.2 (60.4 mi/h)
Angle (deg)	24.5
Exit Conditions	
Speed (km/h)	Vehicle Contained
Angle (deg)	N/A
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	6.1 (20.0 ft/s)
y-direction	2.5 (8.0 ft/s)
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-5.24
y-direction	-2.75
PHD (optional)	
ASI (optional)	
Max. 0.050-sec Average (g's)	
x-direction	-7.2
y-direction	-2.5
z-direction	-2.3

Test Article Deflections (m)	At Post 8
Dynamic	13.2 (43.2 ft)
Permanent	11.3 (37.2 ft)
Vehicle Damage	
Exterior	
VDS	FD-2
CDC	11FDEW3
Interior	
OCDI	AS0000000
Maximum Exterior Vehicle Crush (mm)	460 (18.1 in)
Max. Occ. Compart. Deformation (mm)	0
Post-Impact Behavior	
Max. Roll Angle (deg)	12.04
Max. Pitch Angle (deg)	-2.95
Max. Yaw Angle (deg)	19.07

Figure A-25. Summary of TTI W-beam Short Radius Guardrail Test 1442-5 (8)

APPENDIX B - DETAILS OF FHWA TECHNICAL ADVISORY DRAWINGS

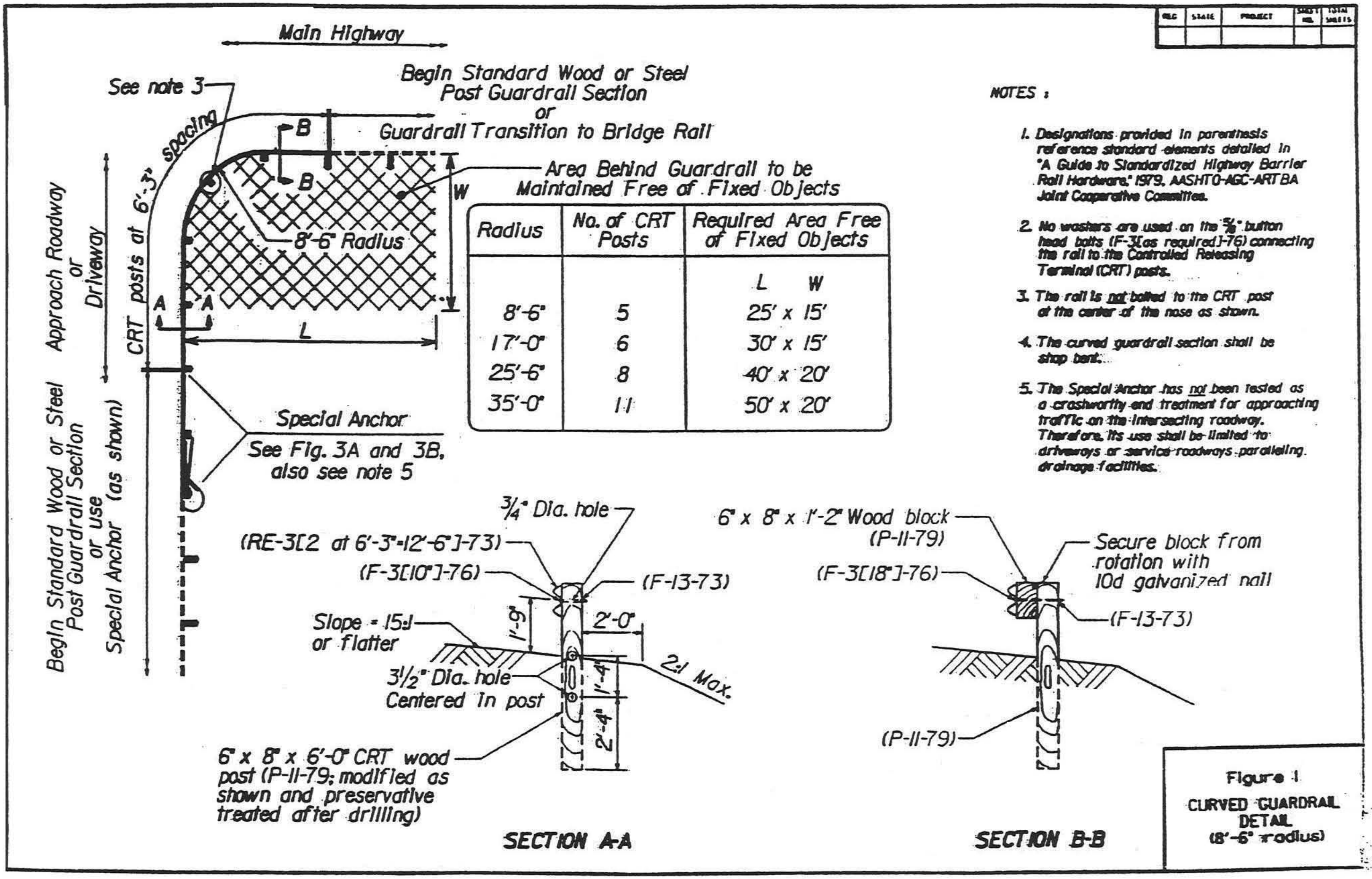


Figure B-1. FHWA Technical Advisory Drawings for Short Radius Guardrail Designs (9)

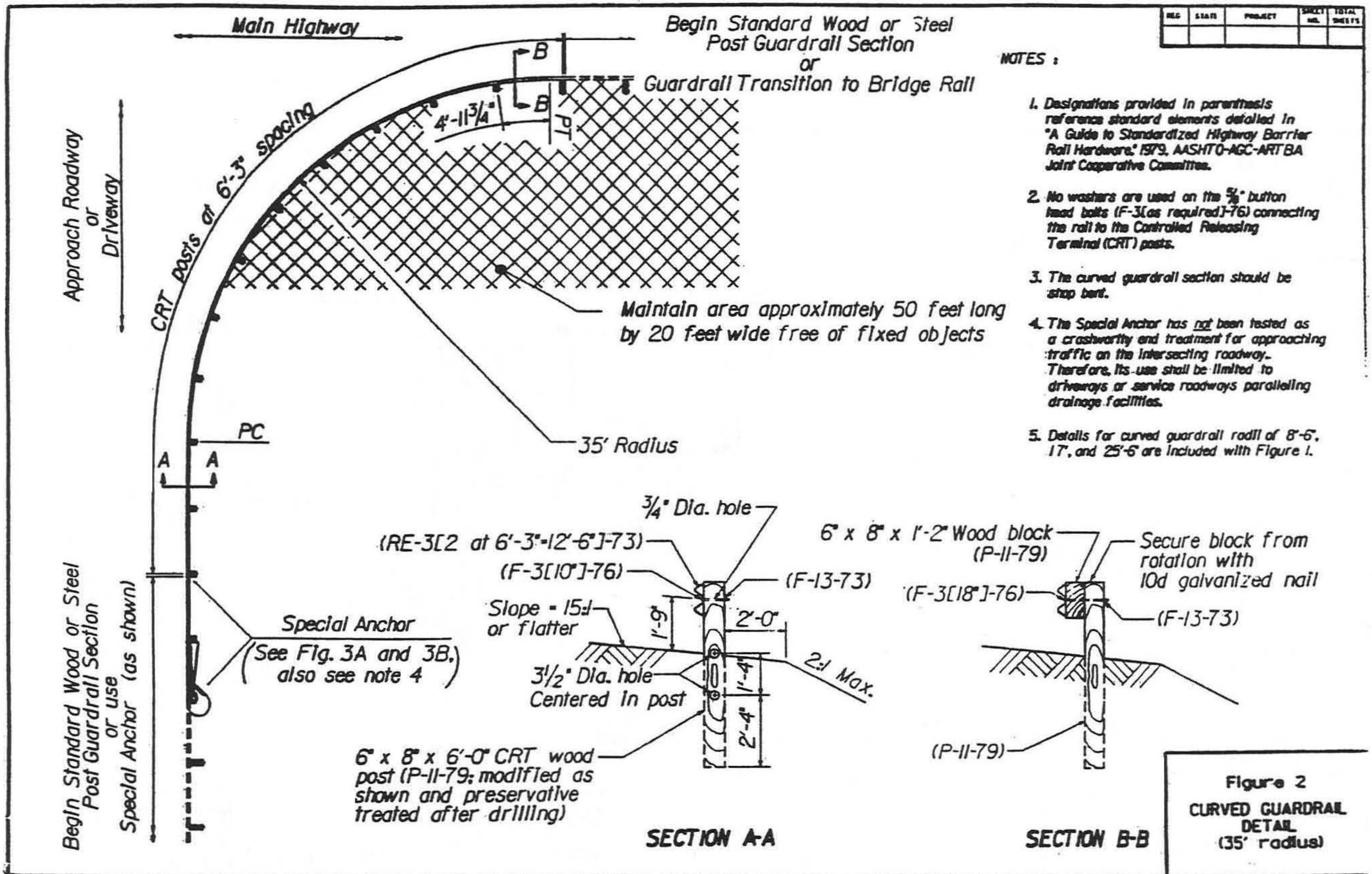


Figure B-2. FHWA Technical Advisory Drawings for Short Radius Guardrail Designs (9)

ATTACHMENT 3

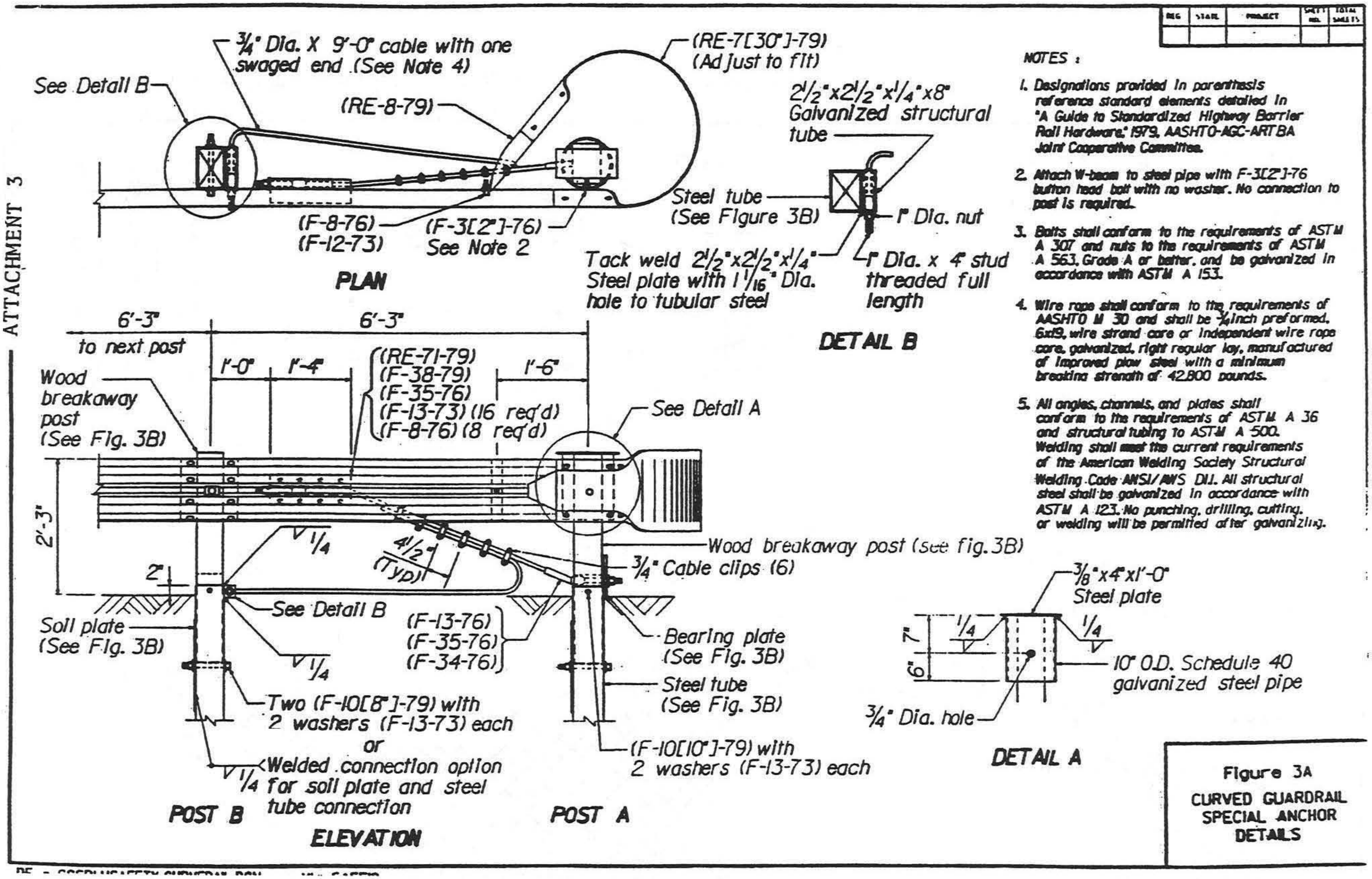


Figure B-3. FHWA Technical Advisory Drawings for Short Radius Guardrail Designs (9)

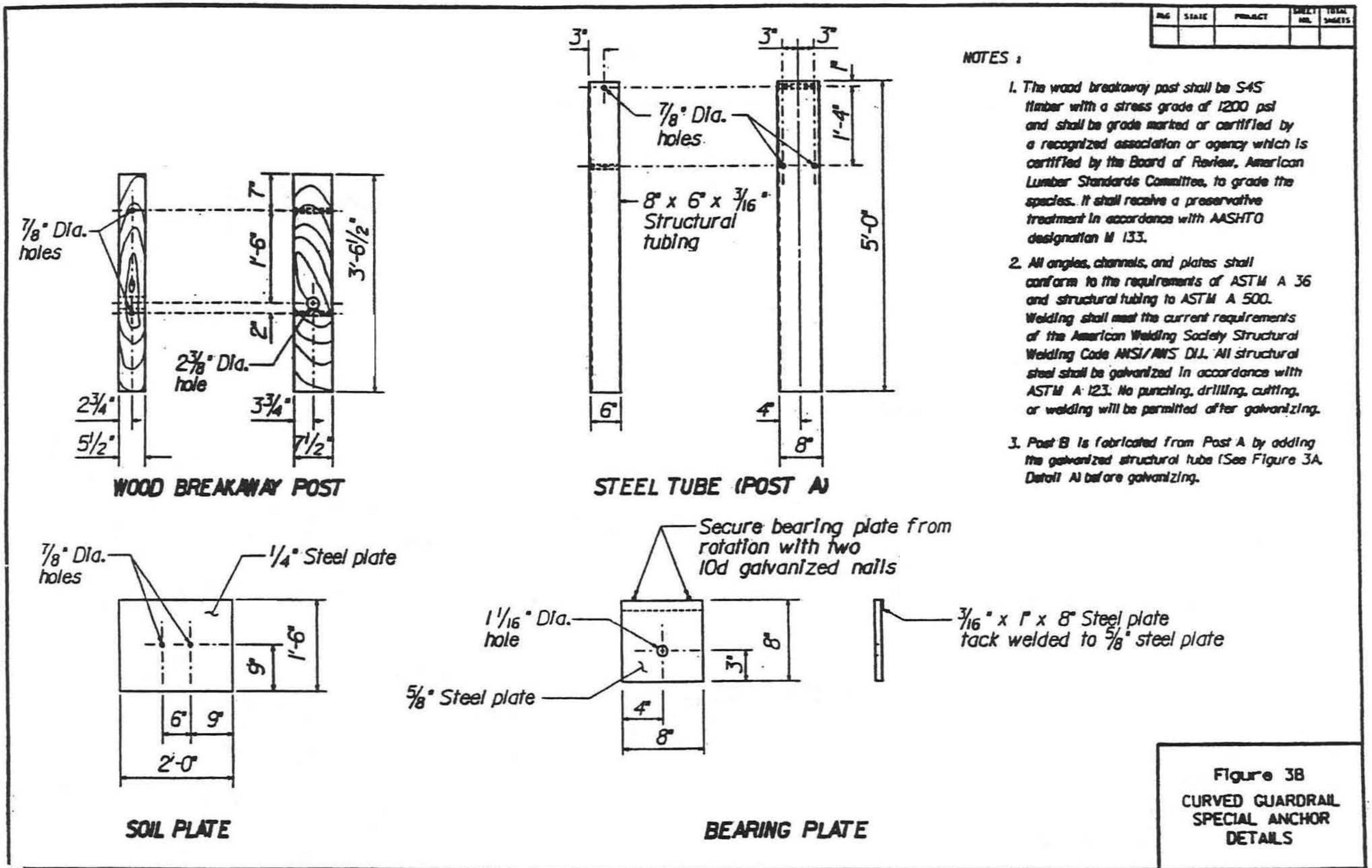


Figure B-4. FHWA Technical Advisory Drawings for Short Radius Guardrail Designs (9)

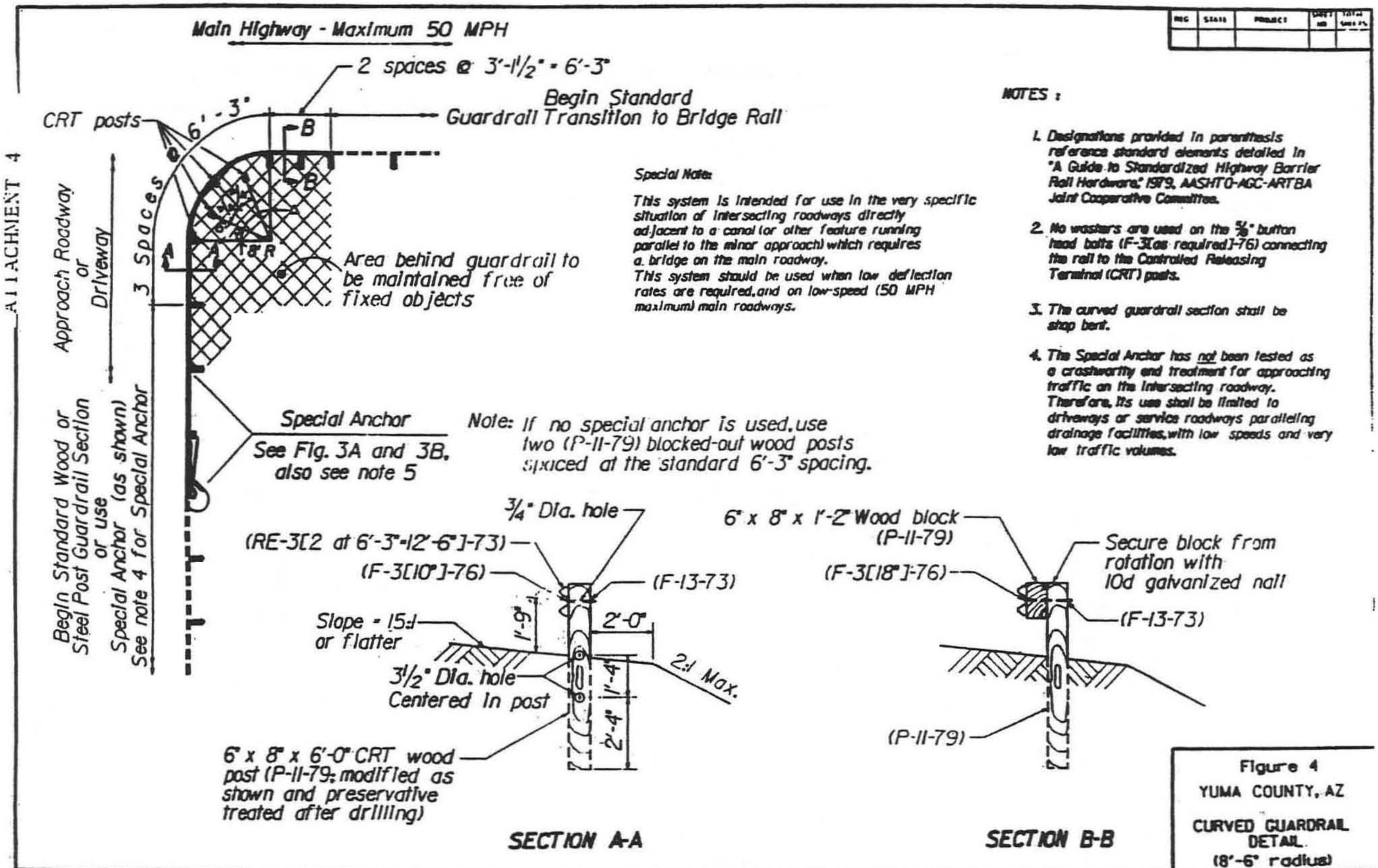


Figure B-5. FHWA Technical Advisory Drawings for Short Radius Guardrail Designs (9)

APPENDIX C - CURRENT STATE STANDARDS

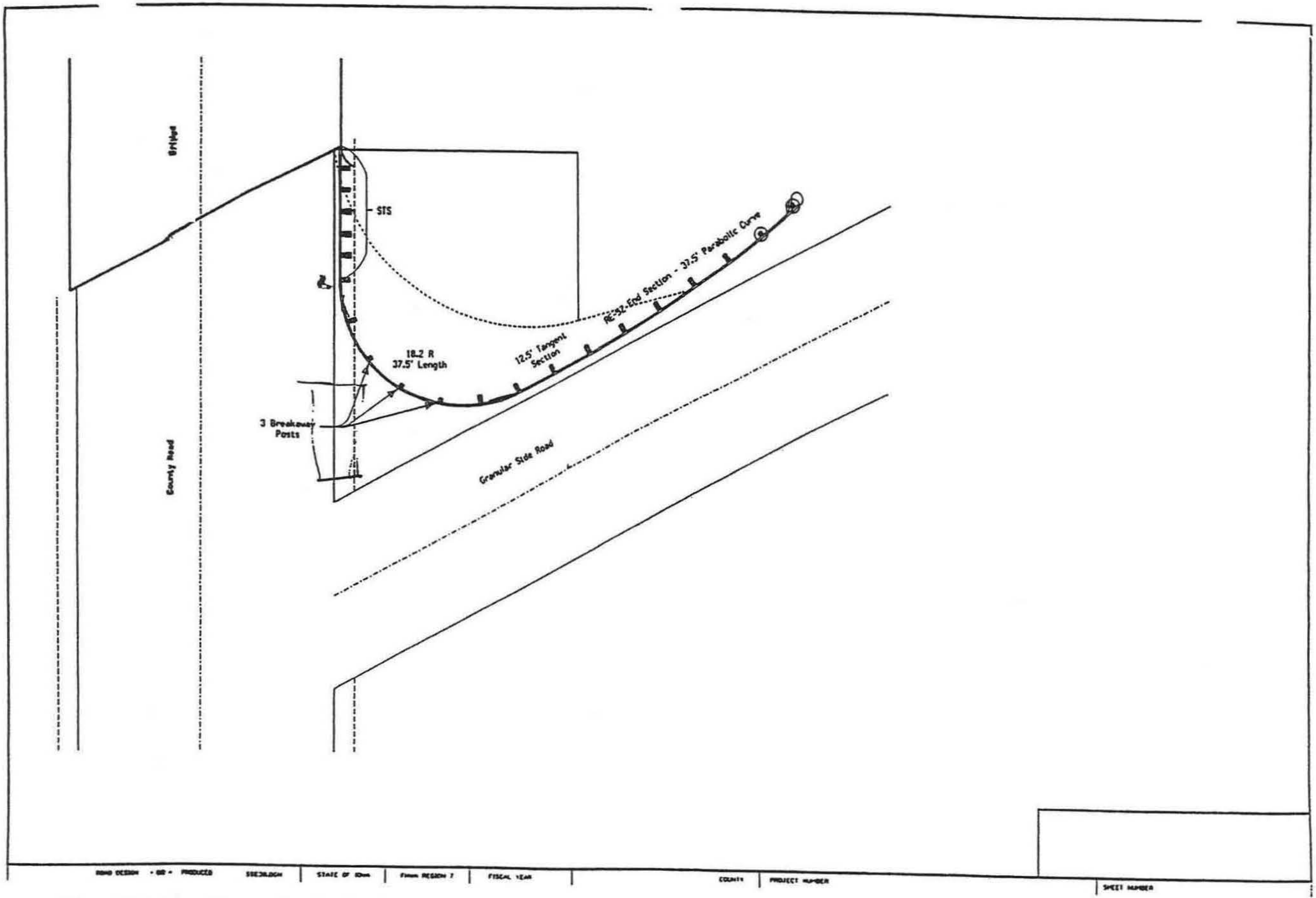
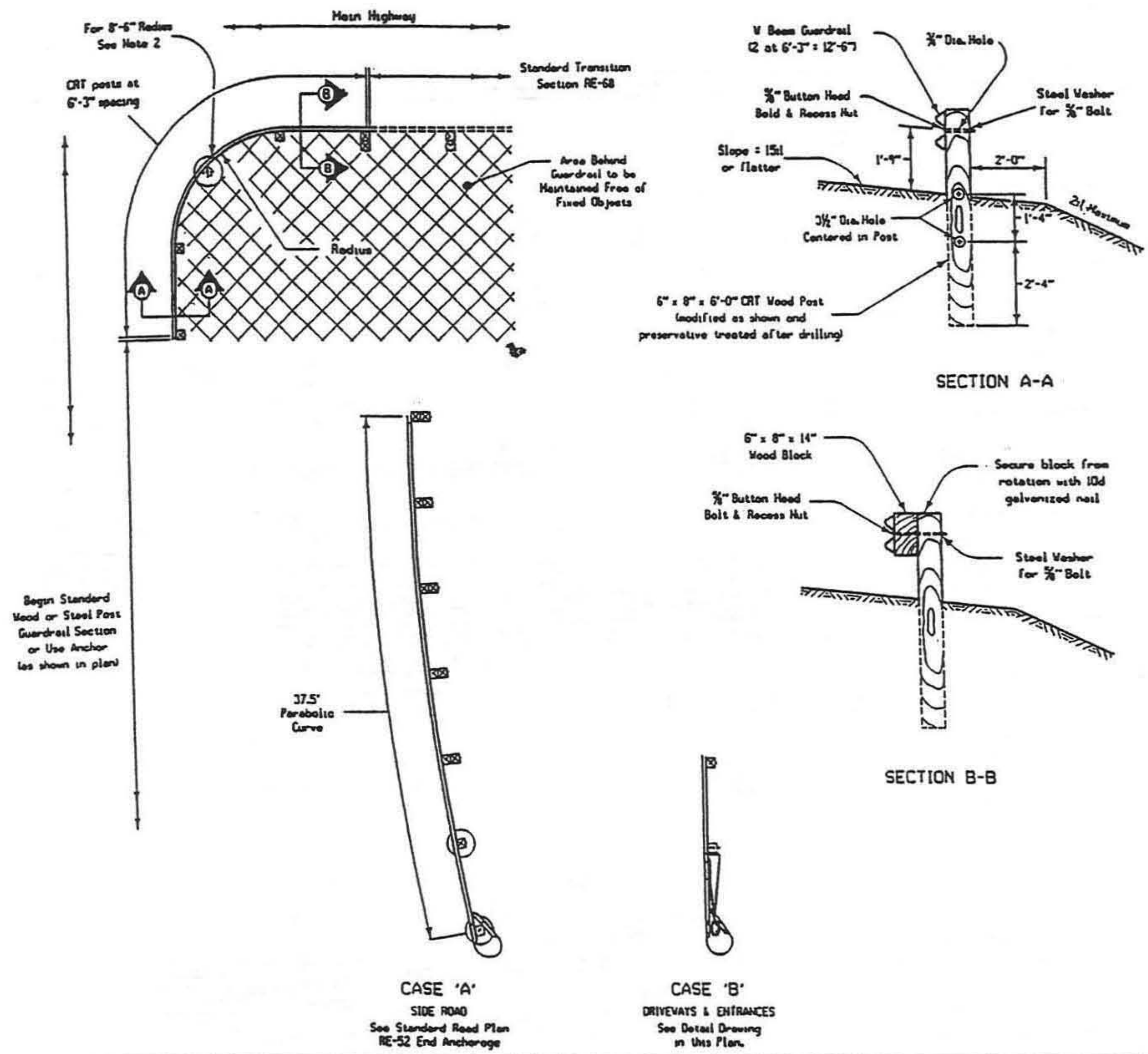


Figure C-1. Iowa Short-radius Design No. 1



GENERAL NOTES:

Details indicated hereon are for installation of formed steel beam guardrail for locations where sideroads or driveways are close to the end of a bridge or other restrictive feature.

1. No washers are used on the 5/8" button head bolts and recess nuts connecting the rail to the Cable Release Terminal (CRT) posts.
2. The rail is not bolted to the CRT post at the center of the nose as shown when 8'-6" radius is used.
3. The curved guardrail section shall be shop bent.
4. Use of the Special End Anchor shall be limited to private driveways or service roadways. An RE-52 end anchorage shall be used for intersecting roadways where the end anchorage is exposed to approaching traffic.

Price bid for contract items shall be considered full compensation for furnishing all materials and constructing guardrail essentially as indicated hereon.

Contract items for guardrail construction are:
- Formed Steel Beam Guardrail
- Beam Guardrail Posts
- Beam Guardrail End Anchorages (By Type)

Radius	Required Area Free of Fixed Objects
8.5' - 13'	25' x 15'
13' - 17'	30' x 15'
17' - 21'	40' x 20'
21' - 35'	50' x 20'

CURVED GUARDRAIL INSTALLATION

ROAD DESIGN • CADD • PRODUCED SSE-16	STATE OF IOWA	FHWA REGION 7	FISCAL YEAR	COUNTY	PROJECT NUMBER	SHEET NUMBER

Figure C-2a. Iowa Short-radius Design No. 2

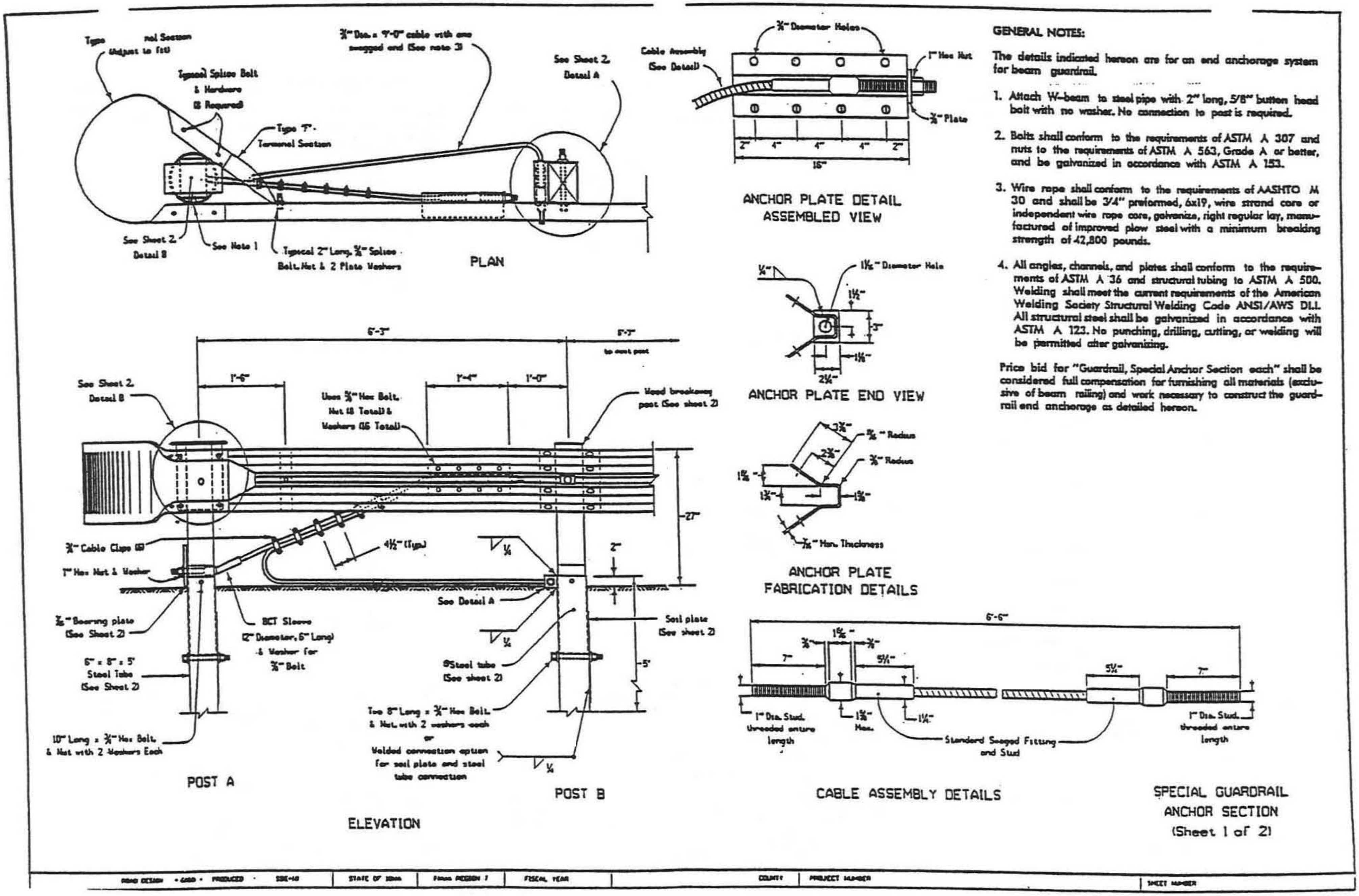


Figure C-2b. Iowa Short-radius Design No. 2.

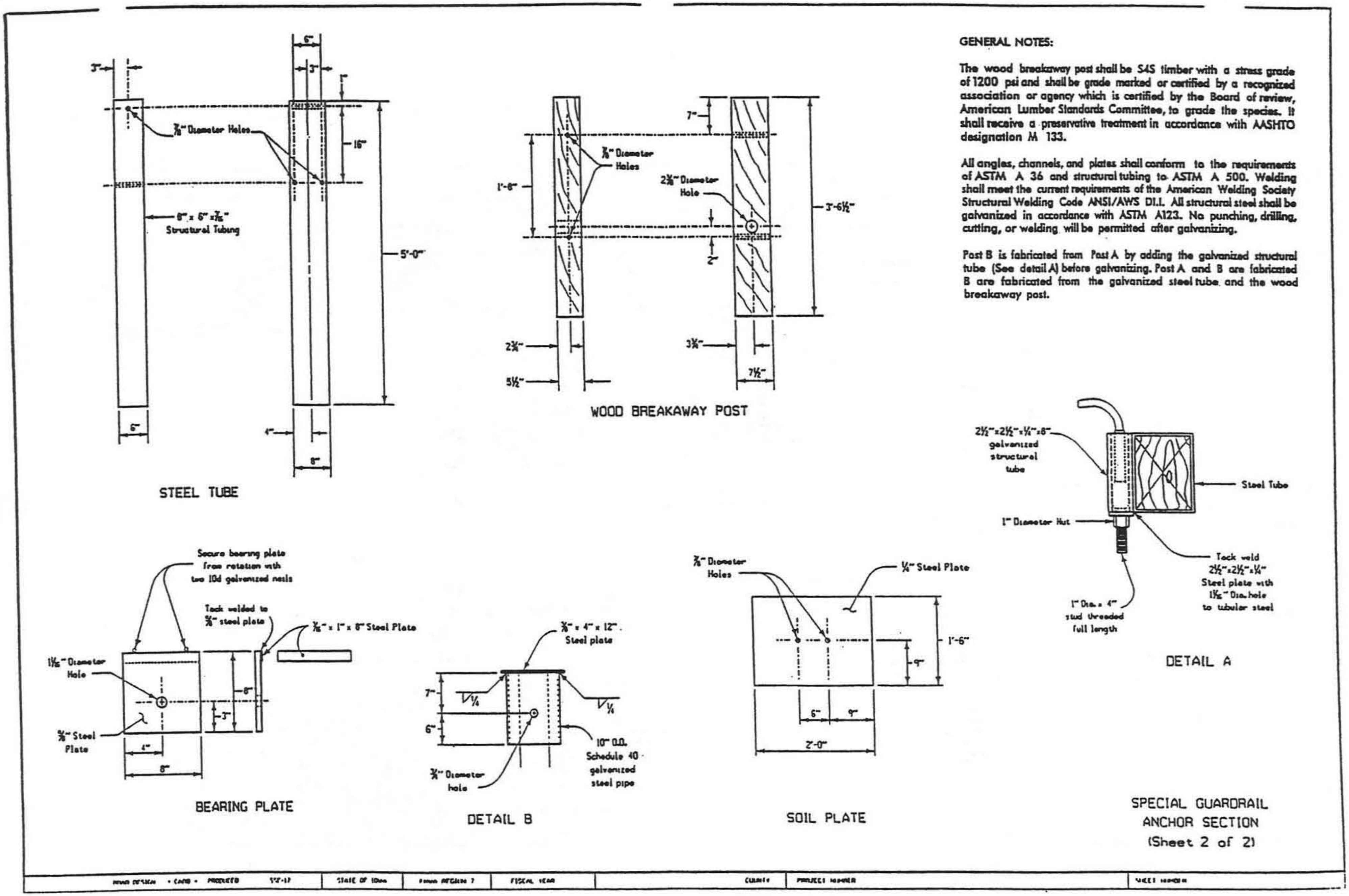


Figure C-2c. Iowa Short-radius Design No. 2.

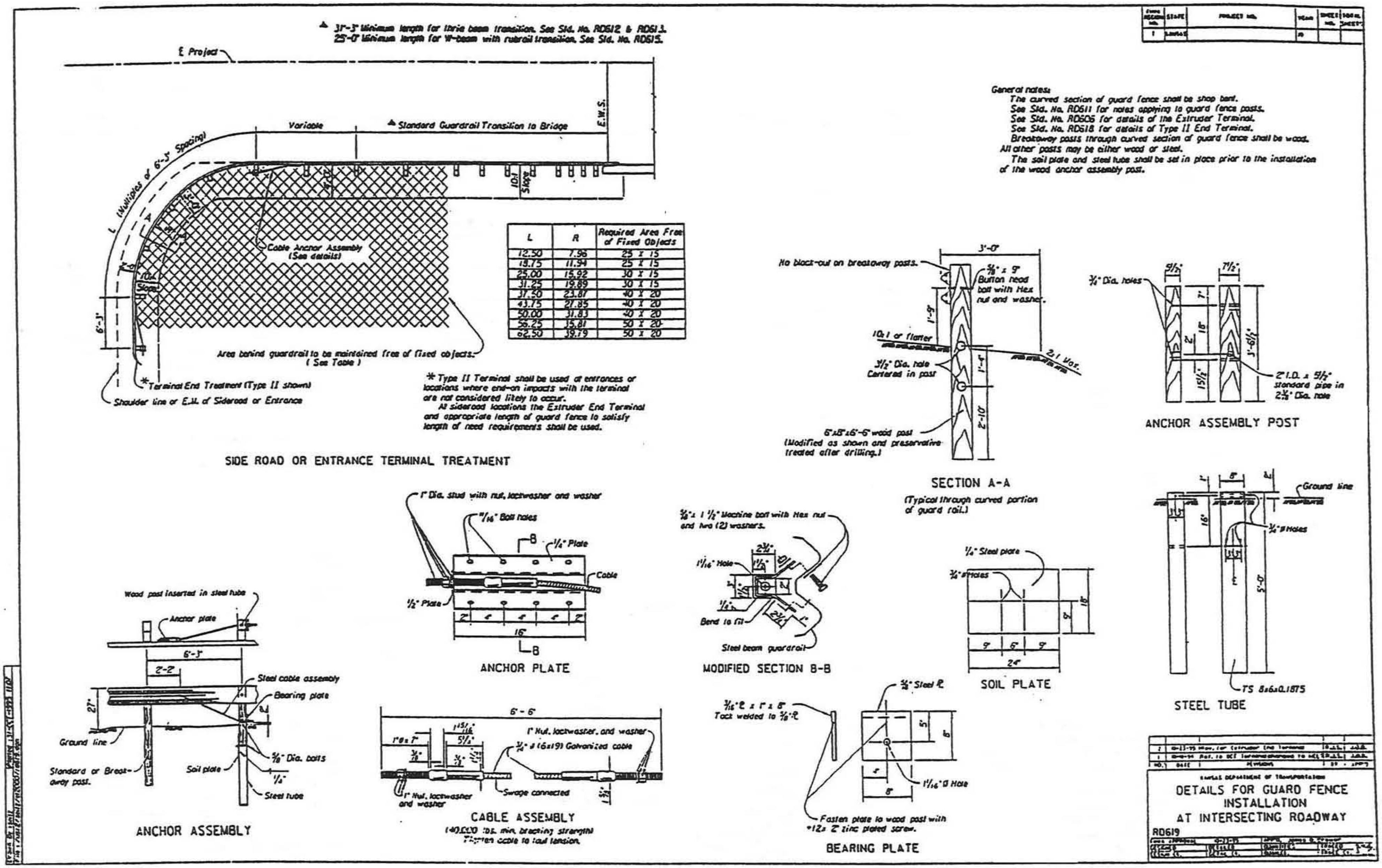


Figure C-3. Kansas Short-Radius Guardrail Details

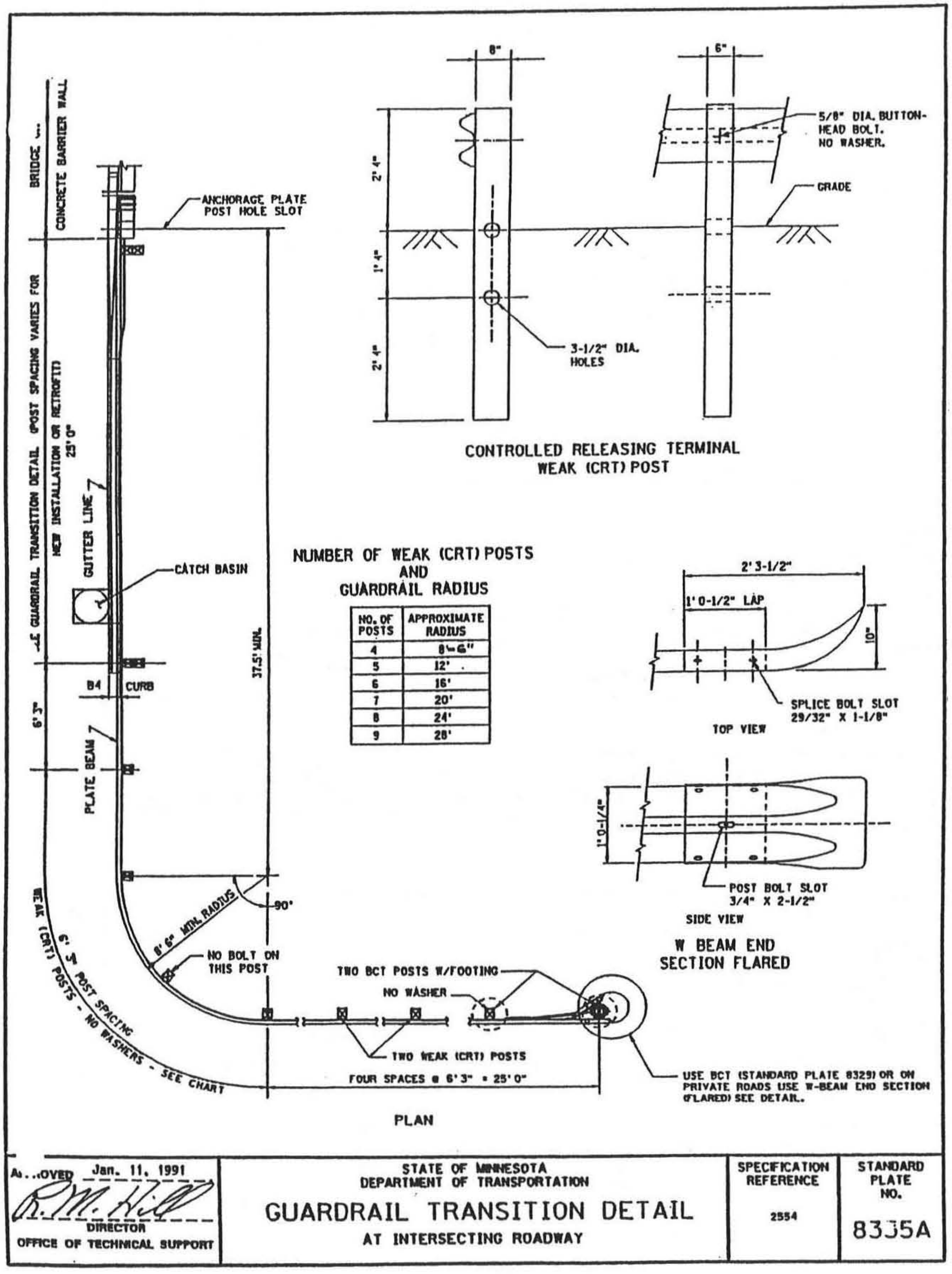


Figure C-4. Minnesota Short-radius Design Standard

DRIVE AND SIDE ROAD GUARDRAIL OPENINGS

601-9

REFERENCE SECTION 601.7

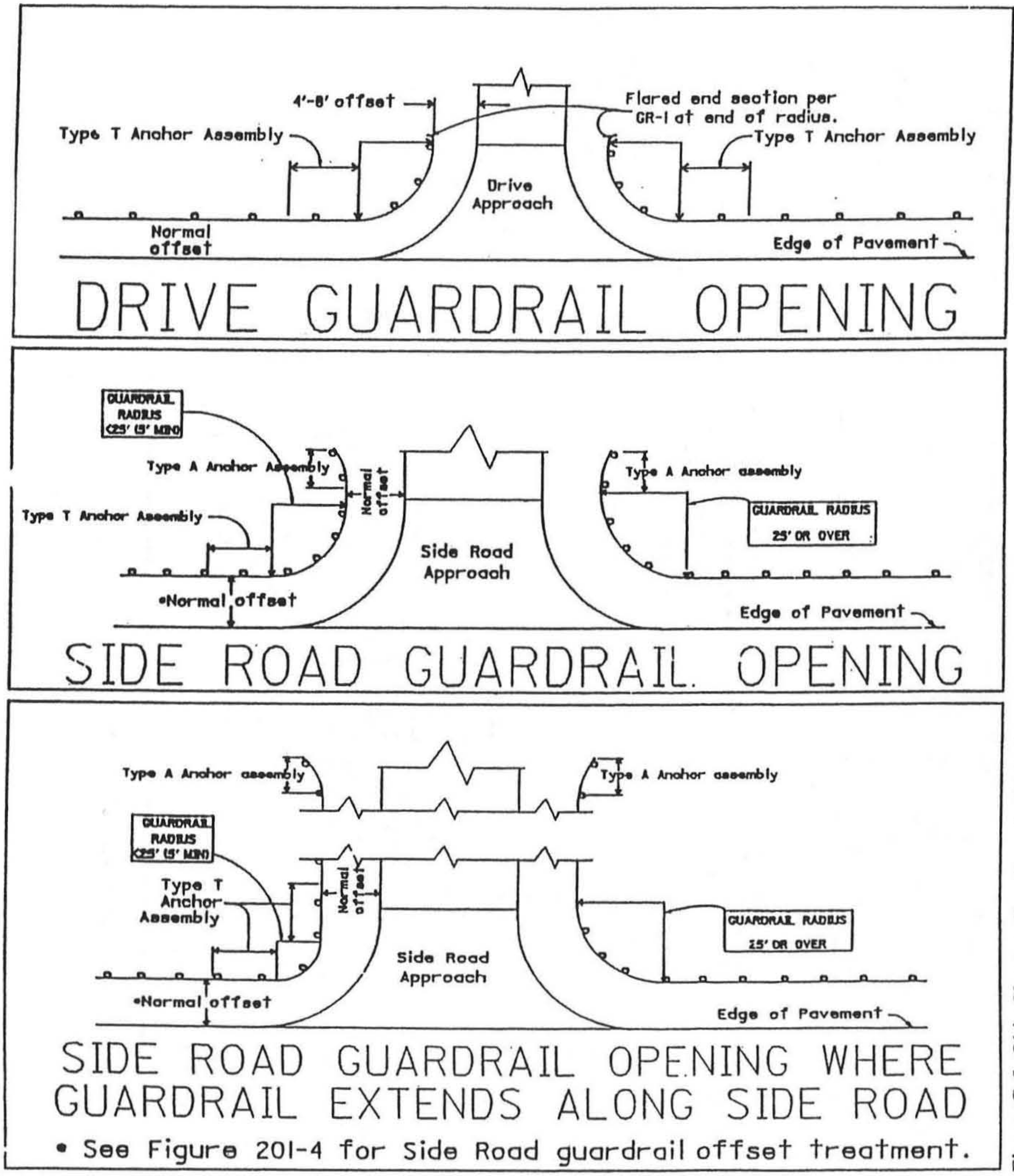


Figure C-5. Ohio Short-radius Guardrail No.1

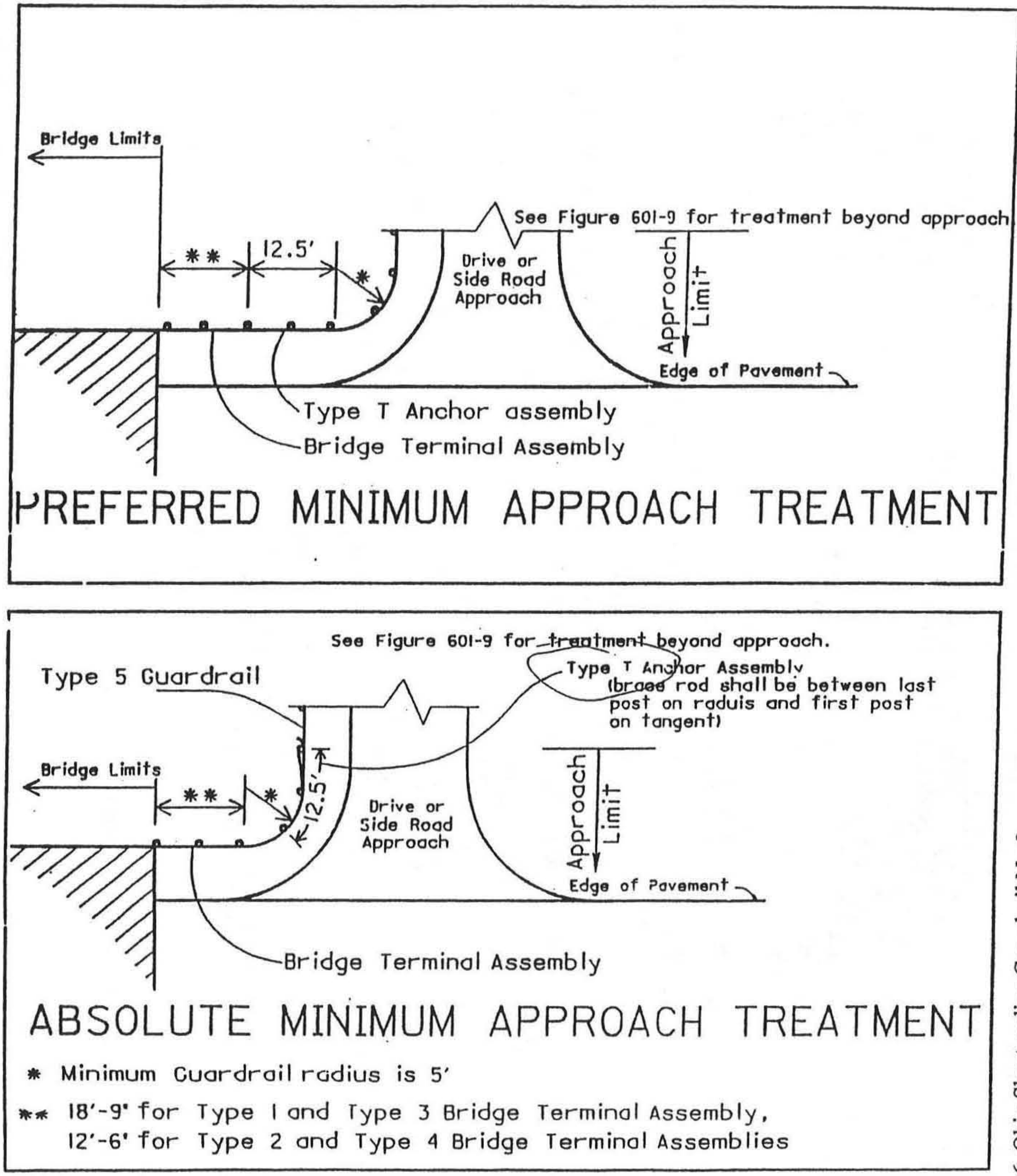


Figure C-6. Ohio Short-radius Guardrail No.2

SPECIFICATION REFERENCE NO. 630

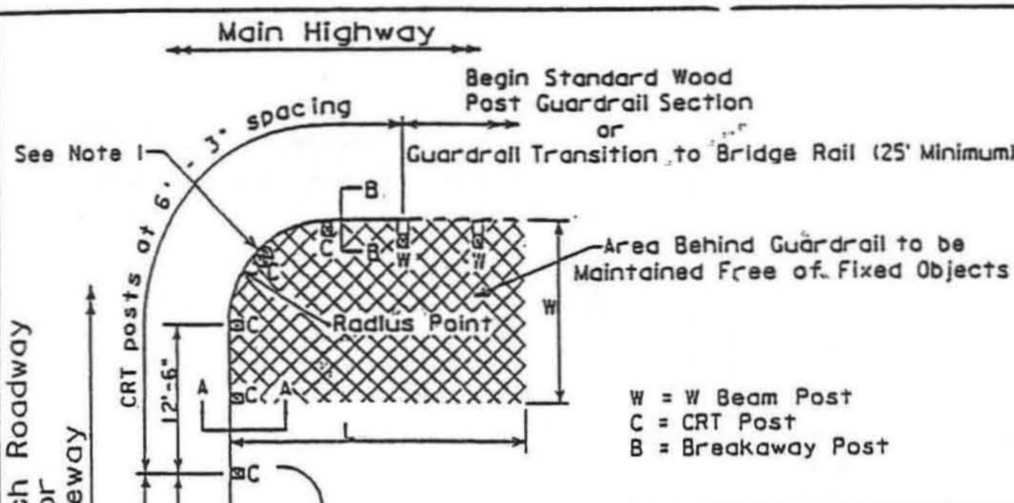
STATE OF SOUTH DAKOTA DEPARTMENT OF TRANSPORTATION

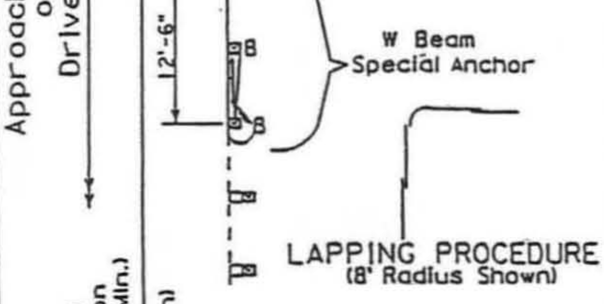
CURVED W BEAM RADIUS TERMINAL

PLATE NUMBER 630.16

1 of 4

July 8, 1994





NOTES:

1. The rail is not bolted to the CRT post at the center of the 8' radius nose only.
2. No washers are used on the face of the rail under the ⅝" button head bolts connecting the rail to the Controlled Releasing Terminal (CRT) posts.
3. The curved guardrail sections shall be shop bent.
4. The W Beam Special Anchor has not been tested as a crashworthy end treatment for approaching traffic on the intersecting roadway. Therefore, its use shall be limited to driveways or service roadways paralleling drainage facilities.

Radius	No. of CRT Posts	*No. and Length of Curved Rails	Required Area Free of Fixed Objects
			L x W
8'	5	1 @ 12.5'	25' x 15'
16'	7	1 @ 25'	30' x 15'
24'	9	1 @ 25' & 1 @ 12.5'	40' x 20'
32'	11	2 @ 25'	50' x 20'

*Number of rails is based on a 90° intersection

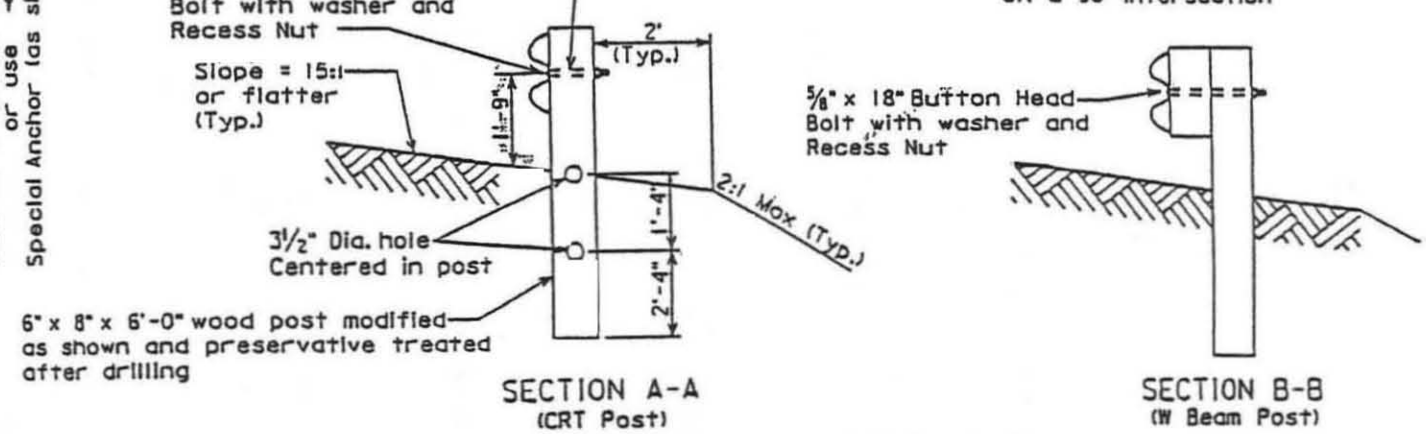


Figure C-7a. South Dakota Short-Radius Guardrail Details

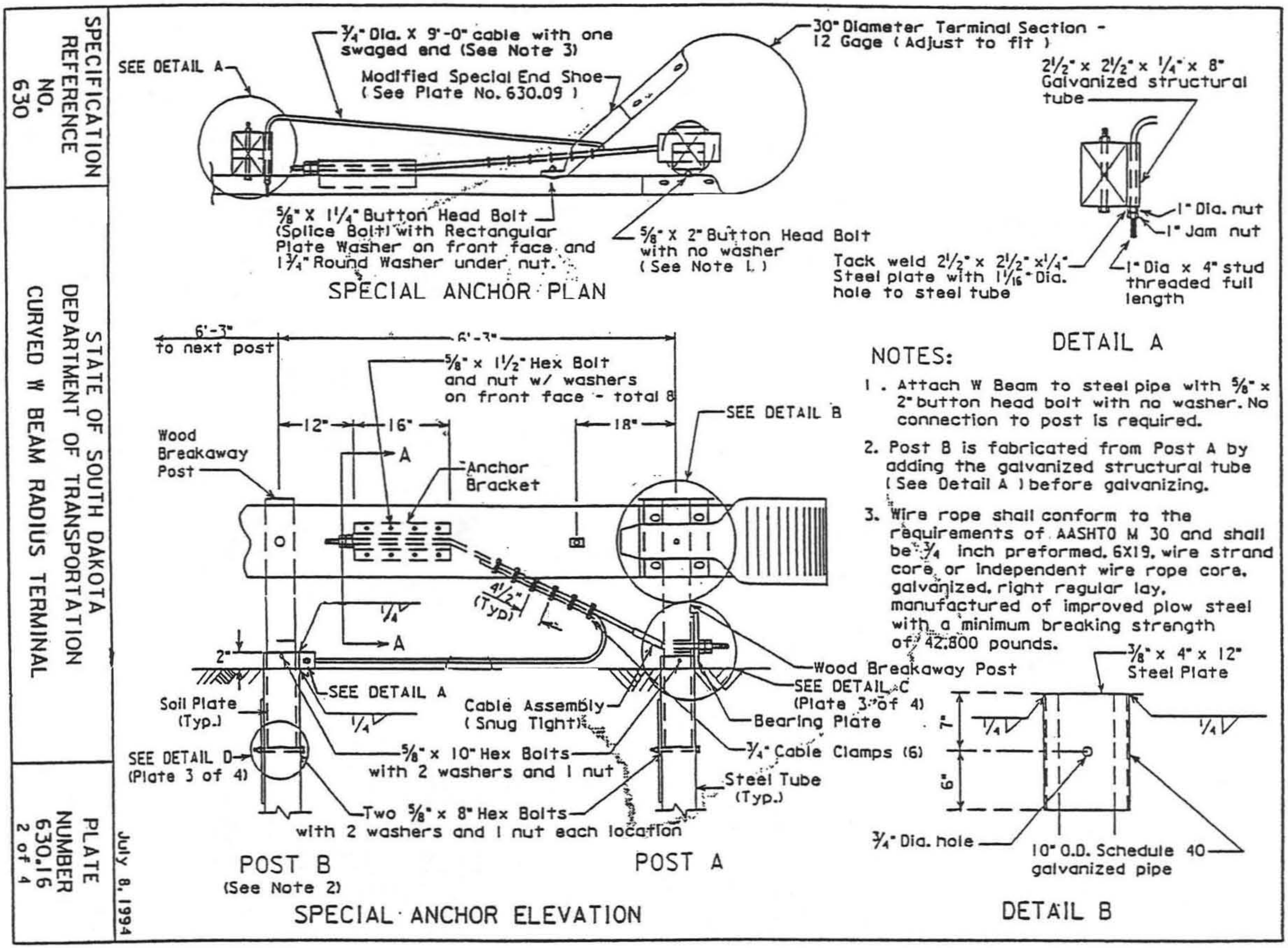


Figure C-7b. South Dakota Short-Radius Guardrail Details

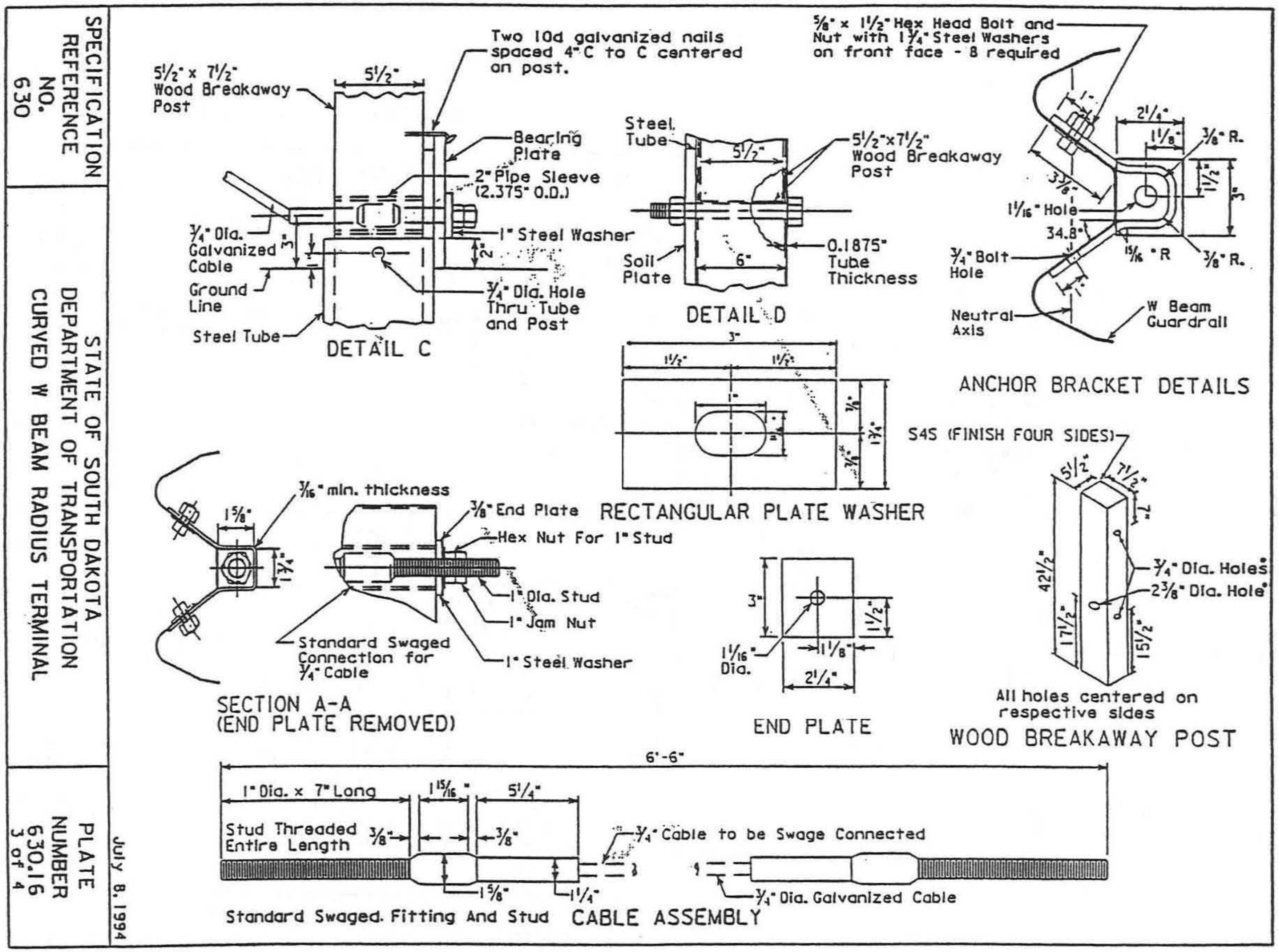
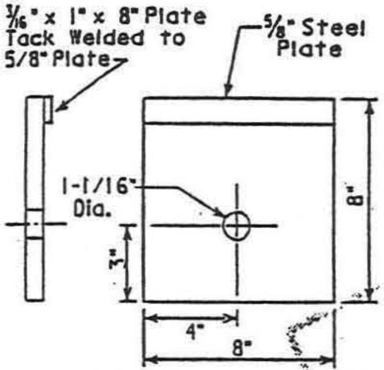
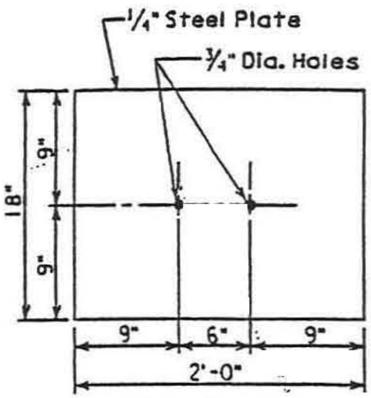


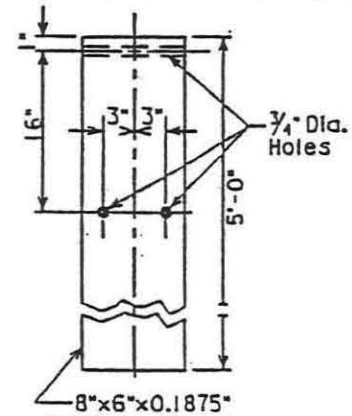
Figure C-7c. South Dakota Short-Radius Guardrail Details



BEARING PLATE DETAILS



SOIL PLATE



STEEL TUBE

GENERAL NOTES:

1. The wood breakaway post shall be S4S timber with a stress grade of 1200 psi and shall be grade marked or certified by a recognized association or agency which is certified by the Board of Review, American Lumber Standard Committee, to grade the species. It shall receive a preservative treatment in accordance with AASHTO designation M 133.

2. Bolts shall conform to the requirements of ASTM A 307 and nuts to the requirements of ASTM A 563. Grade A or better, and be galvanized in accordance with ASTM A 153.

3. All angles, channels, and plates shall conform to the requirements of ASTM A36 and structural tubing to ASTM A 500. Welding shall meet the current requirements of the American Welding Society Structural Welding Code ANSI/AWS D1.1. All structural steel shall be galvanized in accordance with ASTM A 123. No punching, drilling, cutting or welding will be permitted after galvanizing.

4. The Curved W Beam Radius Terminal is made up of the following bid items:

   1. W Beam Guardrail Curved Class A - Controlled Releasing Posts.
   2. W Beam Guardrail Straight Class A - Controlled Releasing Posts.
   3. W Beam Guardrail Special Anchor.

5. The Bid Item W Beam Guardrail Special Anchor is to include all material, including the 12'-6" length of rail and with the exception of the first post (CRT).

SPECIFICATION REFERENCE NO. 630

STATE OF SOUTH DAKOTA
DEPARTMENT OF TRANSPORTATION
CURVED W BEAM RADIUS TERMINAL

PLATE NUMBER 630.16
4 of 4

July 8, 1994

Figure C-7d. South Dakota Short-Radius Guardrail Details

APPENDIX D

SIMPLIFIED SHORT-RADIUS GUARDRAIL SYSTEM

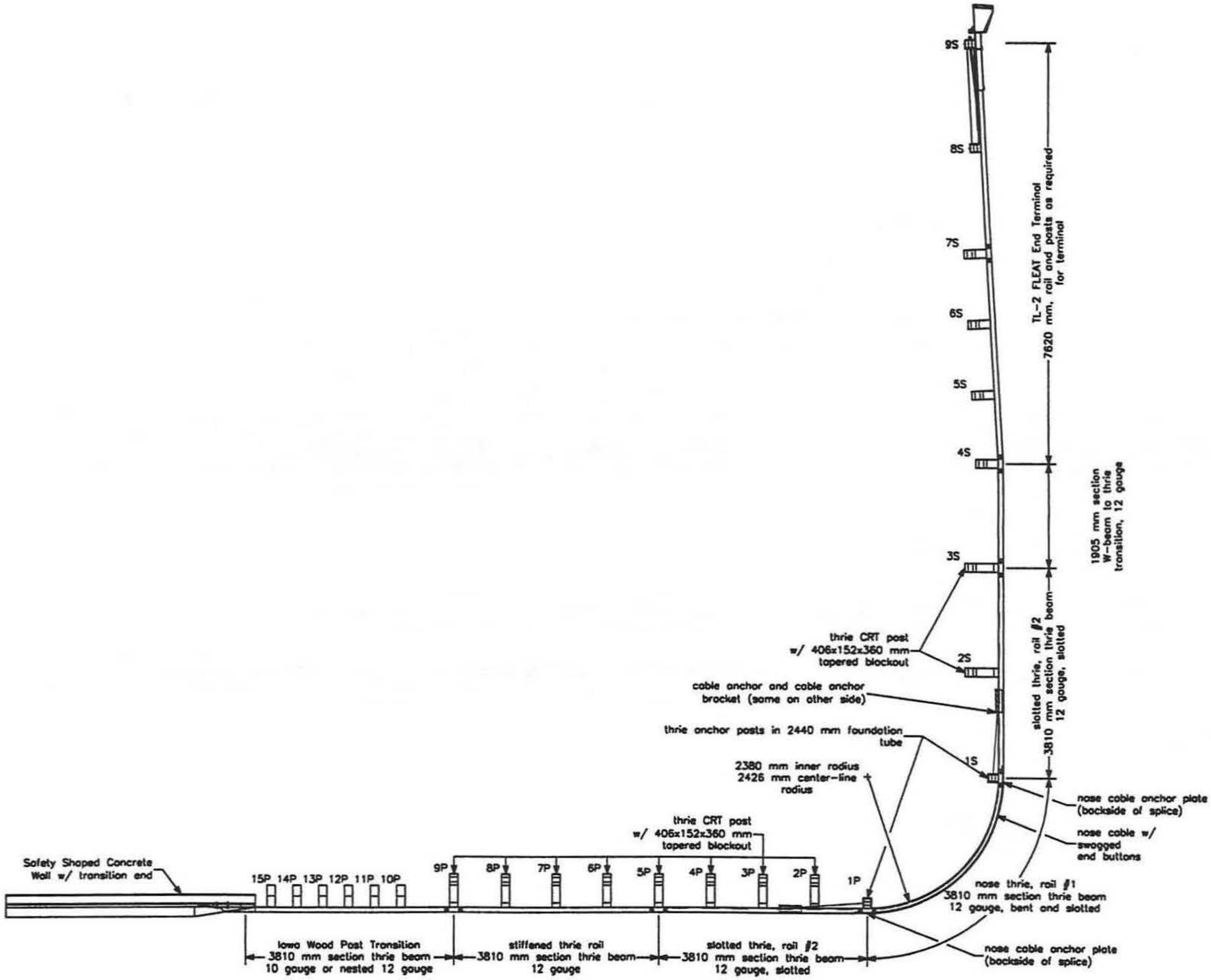


Figure D-1. Simplified Short-Radius Guardrail System

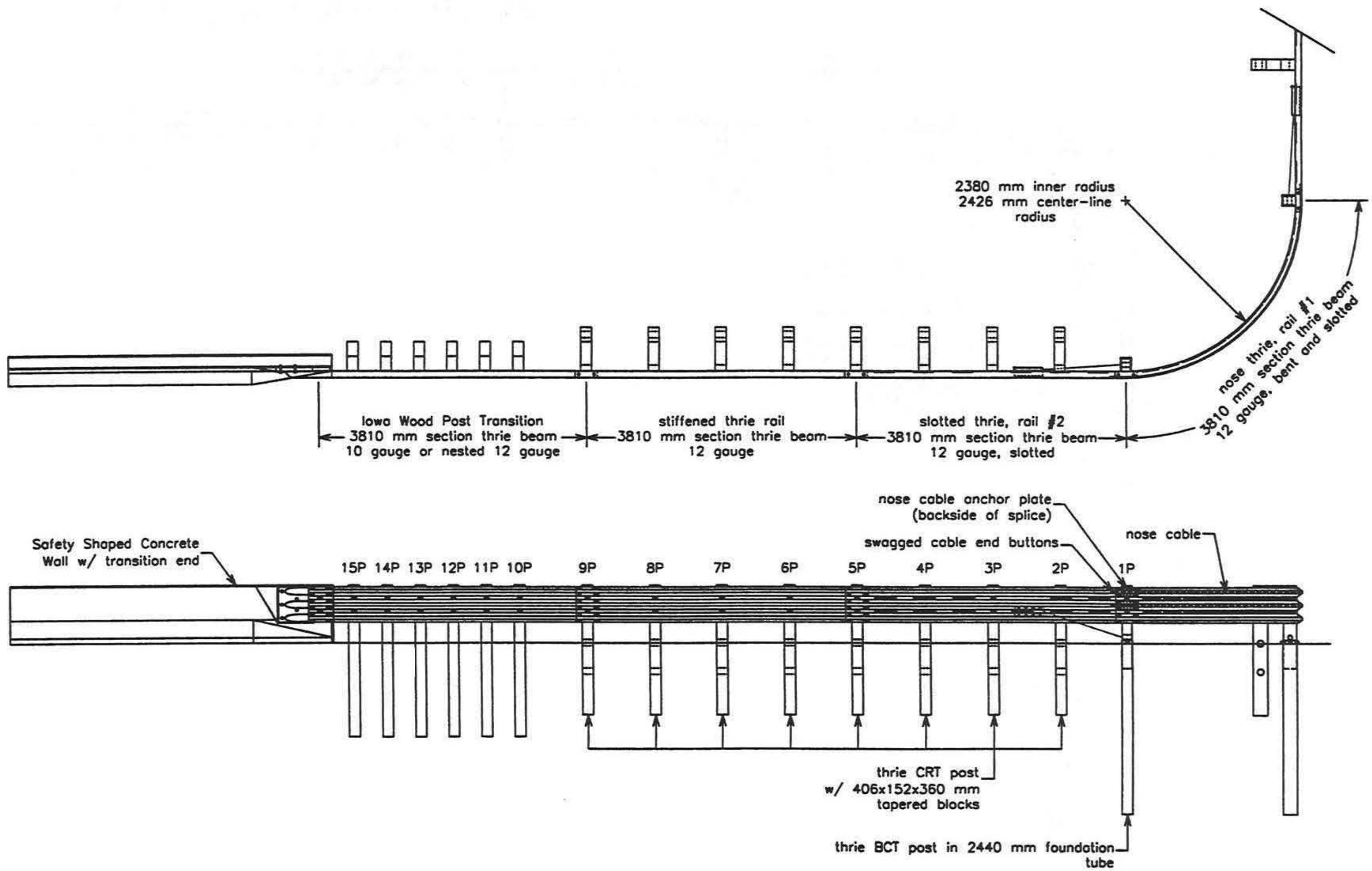


Figure D-2. TL-4 Side View, Simplified Short-Radius Guardrail System

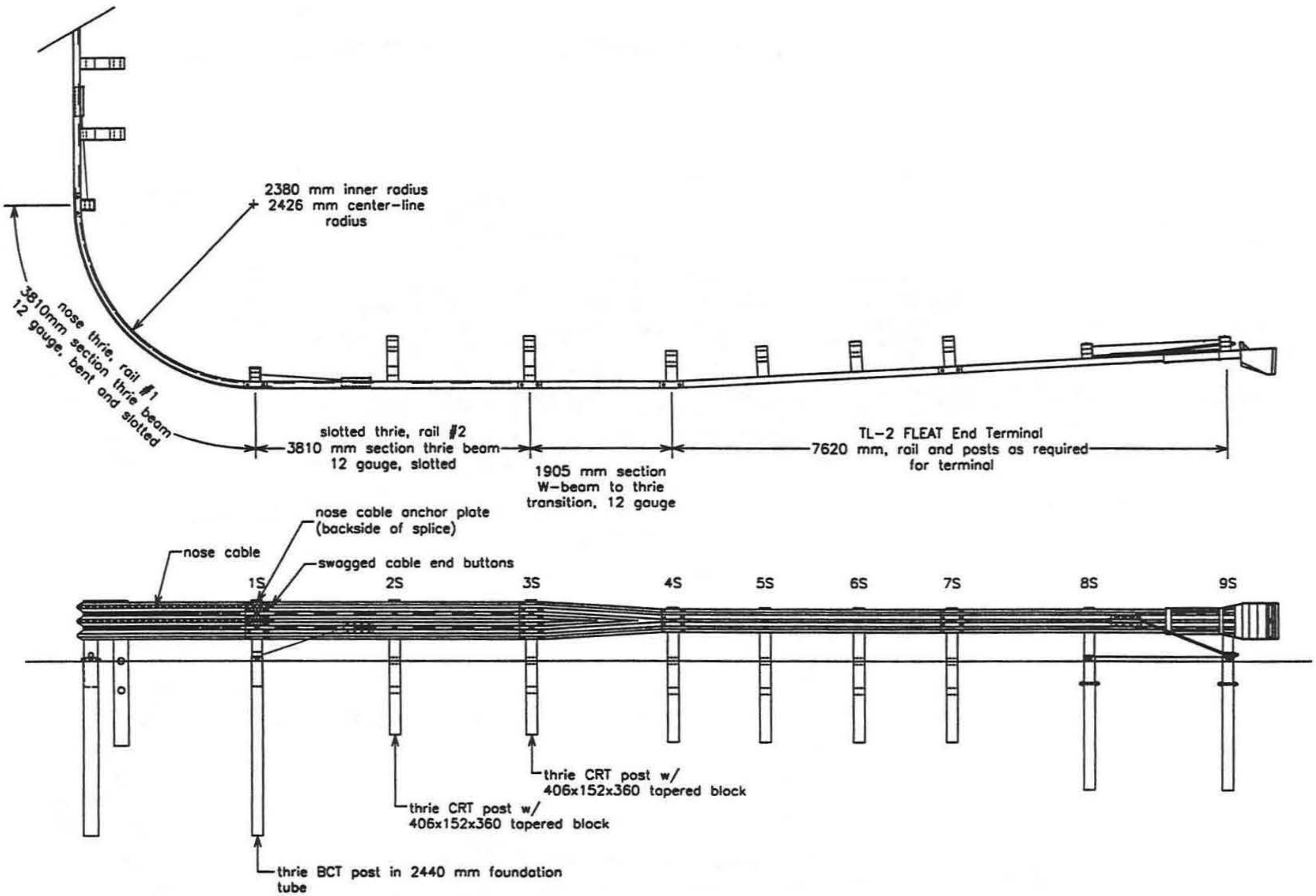


Figure D-3. TL-2 Side View, Simplified Short-Radius Guardrail System

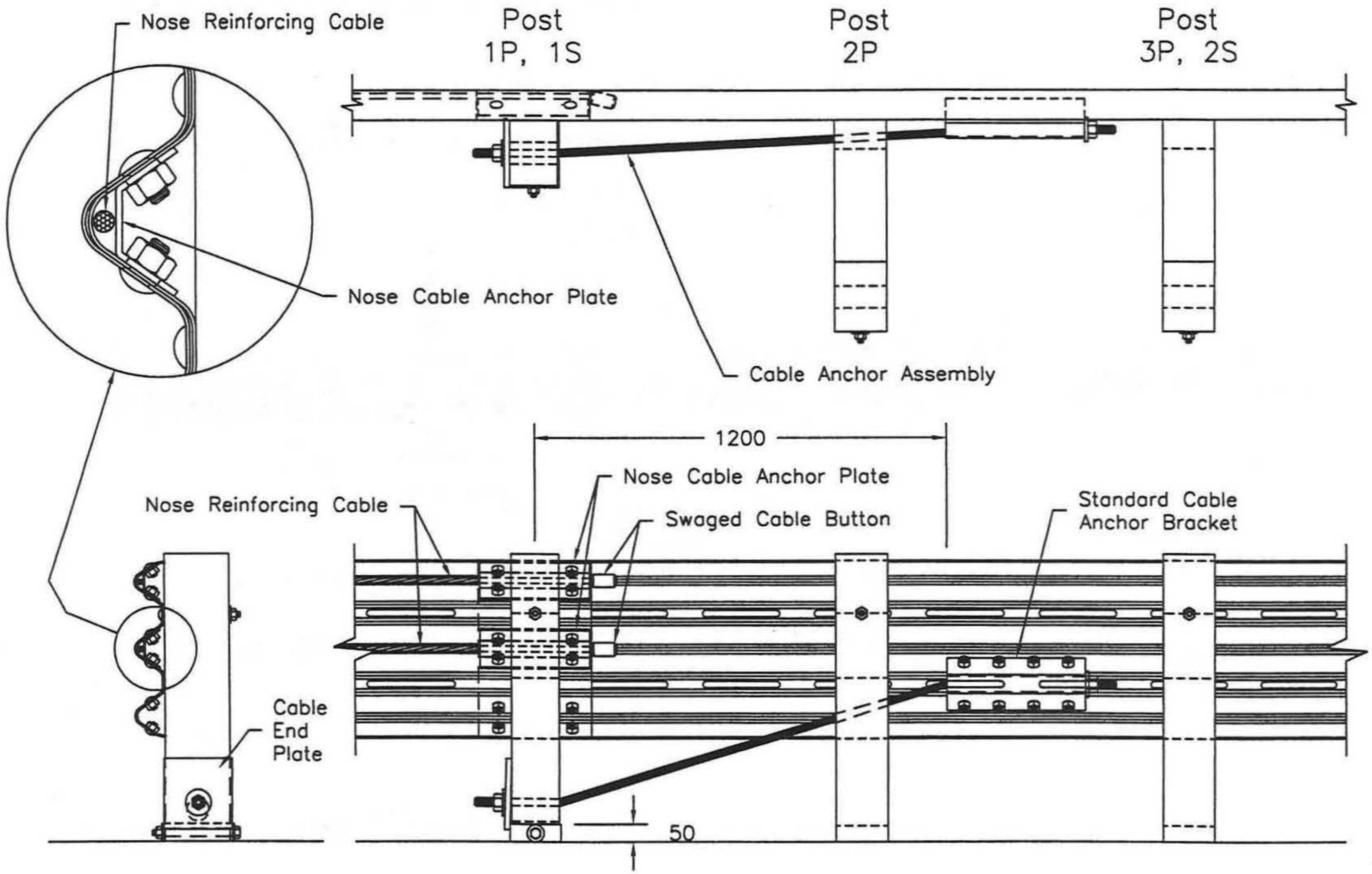


Figure D-4. Cable Assembly Detail, Simplified Short-Radius Guardrail System

Short–Radius Design Concept
Post Details

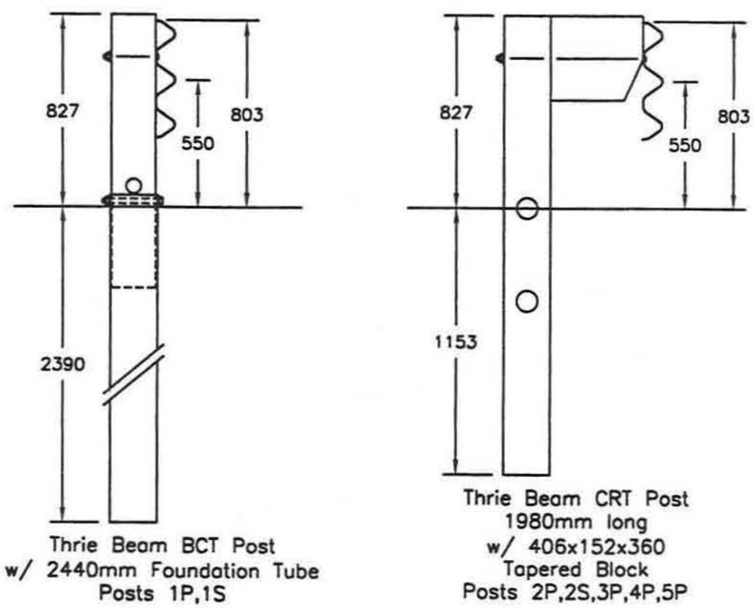


Figure D-5. Post Assembly Detail, Simplified Short-Radius Guardrail System

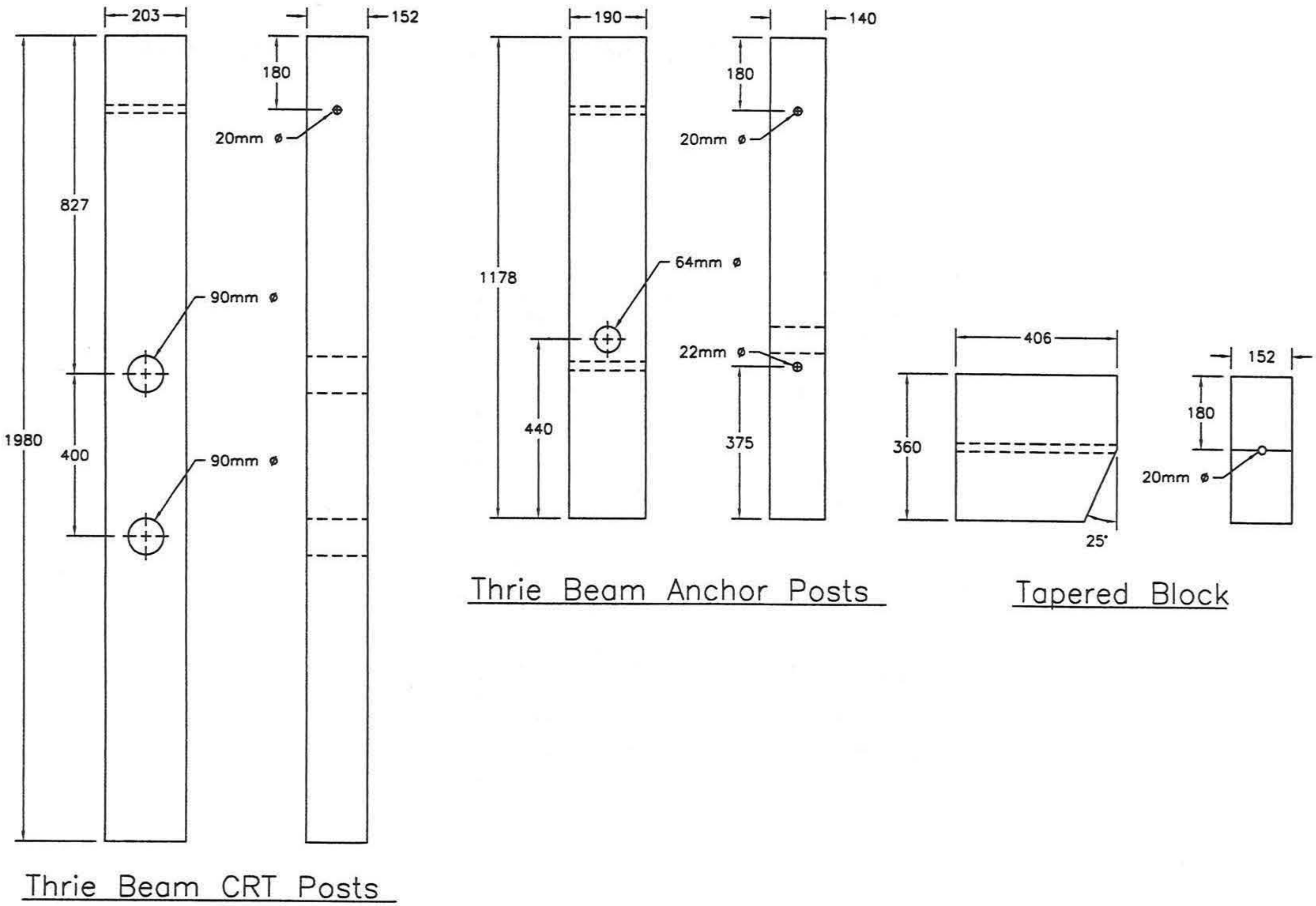
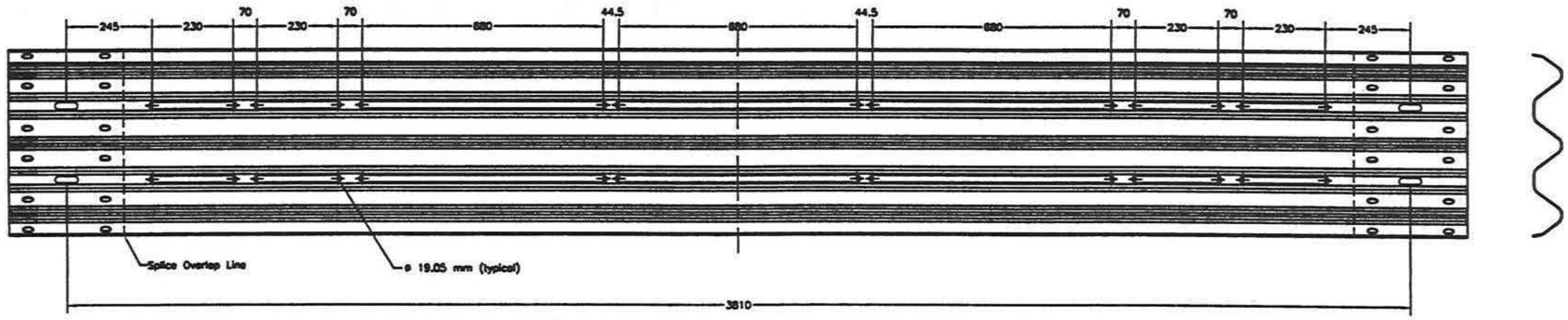
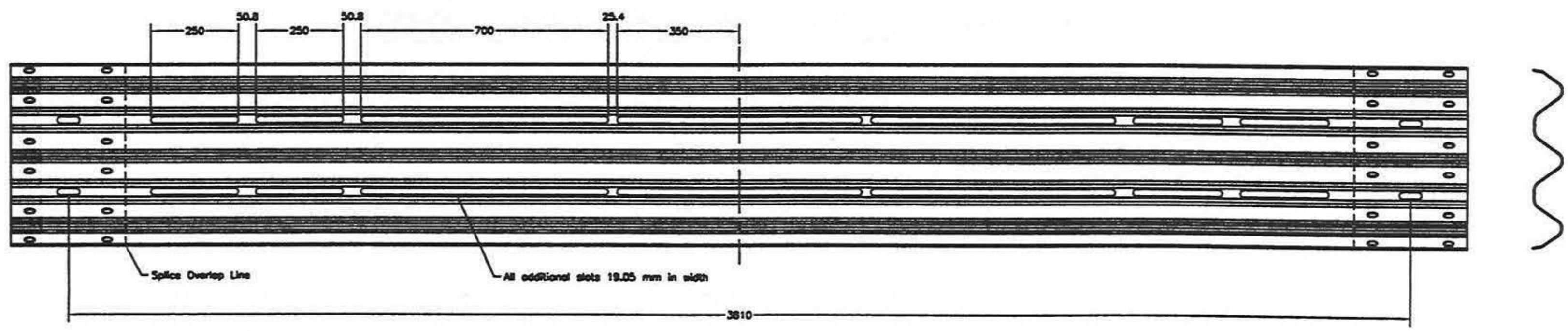


Figure D-6. Post Detail, Simplified Short-Radius Guardrail System



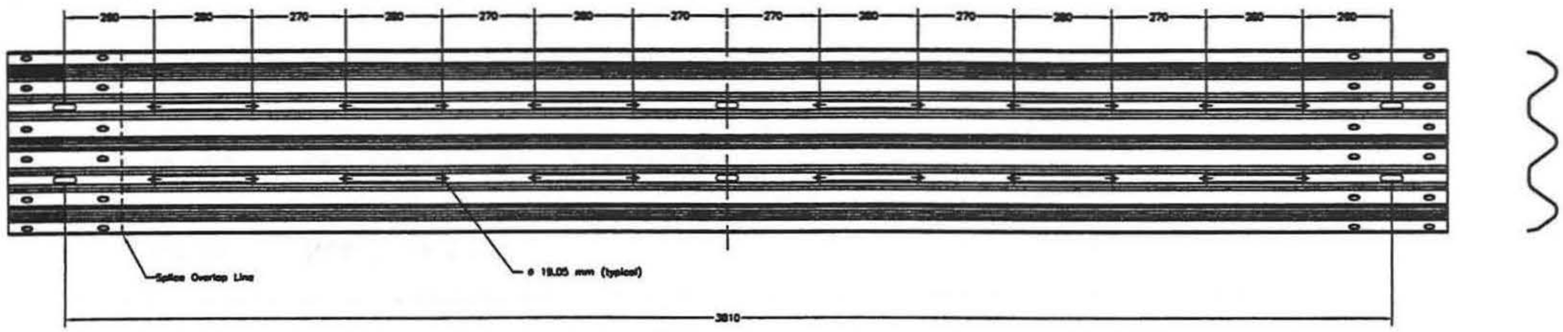
Rail Section 1 ("Nose" Section)



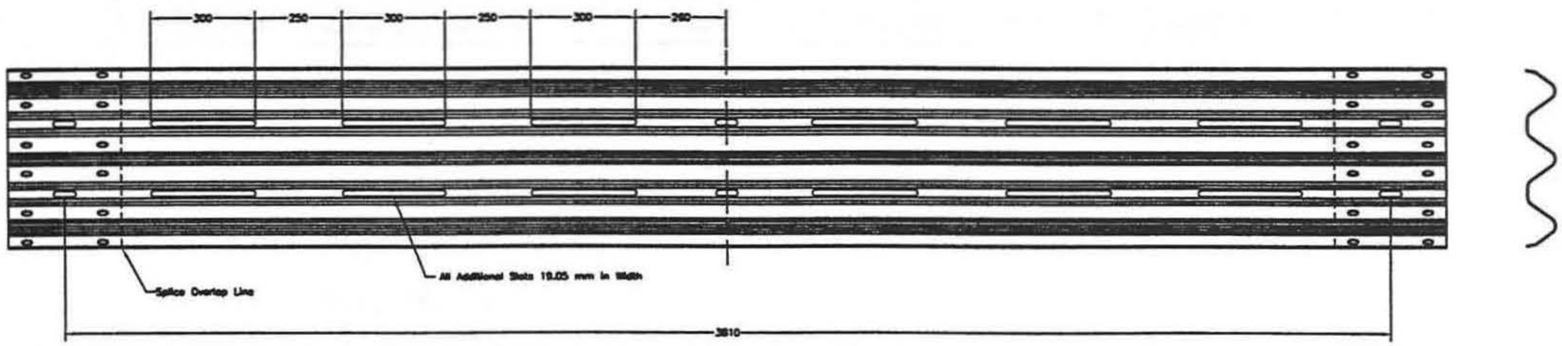
Rail Section 1 ("Nose" Section)

Note: All units are in mm unless specifed otherwise

Figure D-7. Rail Section No. 1, Simplified Short-Radius Guardrail System



Rail Section 2



Rail Section 2

Note: All units are in mm unless specified otherwise

Figure D-8. Rail Section No. 2, Simplified Short-Radius Guardrail System

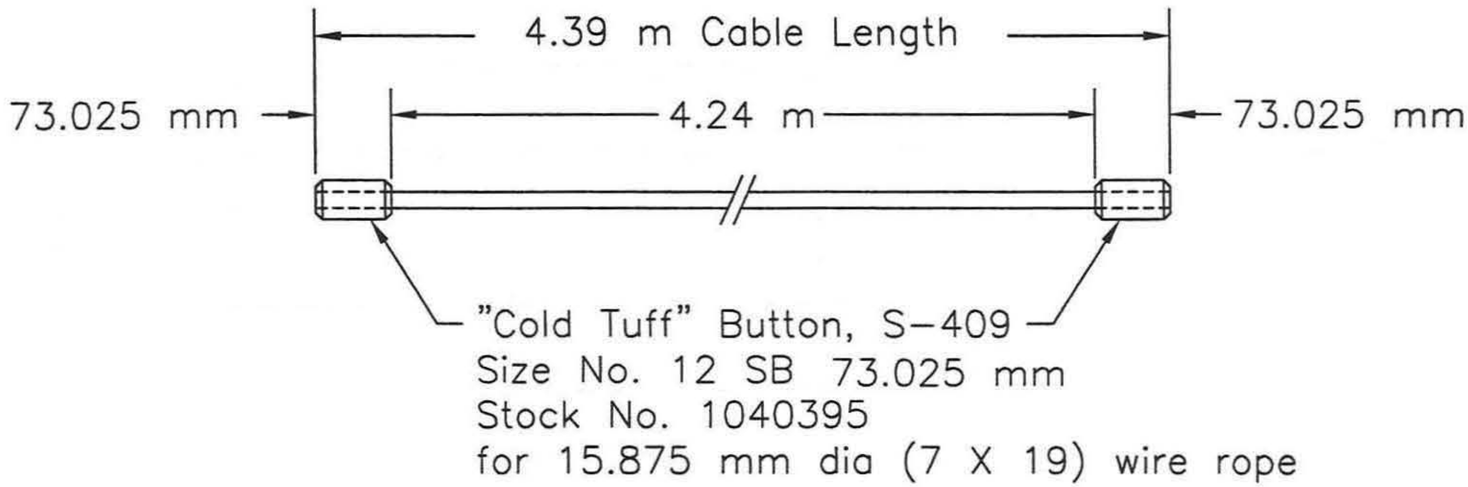


Figure D-9. Cable Detail, Simplified Short-Radius Guardrail System

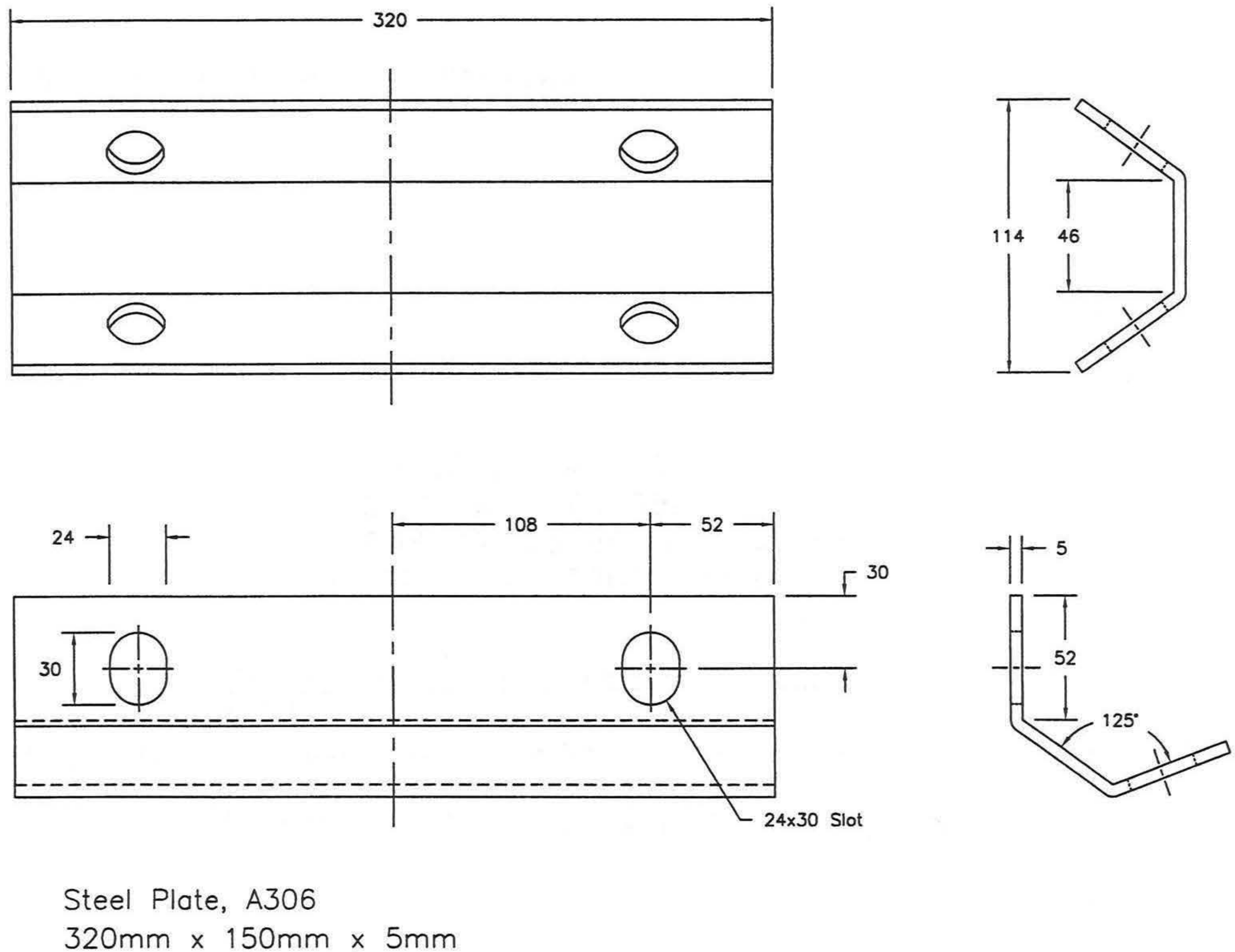


Figure D-10. Cable Plate Detail, Simplified Short-Radius Guardrail System