Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TX-94/1992-1		

4. Title and Subtitle	5. Report Date
DEVELOPMENT OF LOW-PROFILE TO SAFETY-SHAPE TRANSITION SECTIONS	November 1994
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
W. Lynn Beason, Don L. Ivey, and Barry Anderson	Research Report 1992-1
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	11. Contract or Grant No. Study No. 7-1992, Task 2
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080	Final: April 1994-August 1994
	14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation.
Research Study Title: Develop Design Policies, Procedures, and Guidelines under the Guidance of TxDOT Engineers

16. Abstract

This report presents recommendations for the development of two different low-profile to safety-shape transitions. The first transition involves the use of a special concrete barrier section which connects directly to the low-profile and safety-shape barrier sections. In the other transition scheme, the low-profile and safety-shape barriers are butted together and then connected through the use of special steel hardware. Preliminary design details presented allow either concept to be fabricated. Also, recommendations for the use and deployment of the safety-shape transitions are presented. Finally, recommendations are presented for evaluation of the two different transition concepts through full-scale crash testing.

17. Key Words	18. Distribution Statement
Concrete Median Barrier, Transition, Portable Concrete Barrier, Crash Testing, Construction, Safety	No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif.(of this report)	20. Security Classif.(of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	50	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

DEVELOPMENT OF LOW-PROFILE TO SAFETY-SHAPE TRANSITION SECTIONS

by

W. Lynn Beason
Associate Research Engineer
Texas Transportation Institute

Don L. Ivey
Research Engineer
Texas Transportation Institute

and

Barry Anderson
Graduate Assistant Engineer
Texas Transportation Institute

Research Report 1992-1
Research Study Number 7-1992
Research Study Title: Develop Design Policies, Procedures, and Guidelines Under the Guidance of TxDOT Engineers

Sponsored by the
Texas Department of Transportation

November 1994

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, Texas 77843-3135

IMPLEMENTATION STATEMENT

Two barrier transition sections have been developed. Further, recommendations have been presented for the use of the new transition sections.

A full-scale testing program has been recommended to validate the two barrier transitions. Once the full-scale testing has been accomplished, the barrier transitions should be ready for immediate implementation in low-speed work zones.

DISCLAIMER

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 view or policies of the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation and is not intended for construction, bidding or permit purposes. The engineer in charge of the project was W. Lynn Beason, P.E., #55905.

ACKNOWLEDGMENT

This research study was conducted under the sponsorship of the Texas Department of Transportation. Mark A. Marek, William D. Dillon, and Van M. McElroy of TxDOT worked closely with the researchers. Their comments, suggestions, and cooperative spirits were greatly appreciated.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

This report presents results of a six-month study to develop transition sections that can be used to connect low-profile barriers to safety-shape barriers for low-speed applications. This study was conducted for the Texas Department of Transportation.

INTRODUCTION

A new low-profile portable concrete barrier (PCB) system has recently been developed by researchers at the Texas Transportation Institute (TTI) in cooperation with engineers of the Texas Department of Transportation (TxDOT). The low-profile PCB is a 51 cm (20 in.) tall longitudinal barrier which is produced in 6.1 m (20 ft) segments (1). In addition, a new low-profile sloped end-treatment has been developed for use with the low-profile PCB (2). Together, these two elements result in a low-profile barrier system which has been successfully implemented in field applications. The primary advantage of the low-profile PCB system is that it provides a reasonable amount of redirective capability for low-speed applications while greatly enhancing work zone visibility when compared to 81 cm (32 in.) tall safety-shape barriers (1,2).

The increased work zone visibility is of most benefit near intersections where it is necessary to interrupt the longitudinal barrier to allow cross traffic to enter the flow of traffic as shown in Figure 1. In such situations it can be extremely difficult for the driver of the cross-traffic vehicle to see oncoming traffic unless the low-profile barrier system is used. The height of the low-profile barrier system was established through research which considered all relevant factors.

The problem addressed in the current research is that it is not economically feasible to discard all existing safety-shape PCB's which are stockpiled around the state in favor of the new low-profile barrier system. Therefore, a need exists to develop a system that allows the low-profile barrier and the existing safety-shape PCB's to be mixed in a continuous longitudinal barrier. The low-profile PCB's should be used adjacent to intersections to improve the sight distance problem, with the taller safety-shape PCB's used away from the intersections where the 81 cm (32 in.) height does not create a sight-distance problem.

Differences in connection schemes prevent a direct connection of the two types of barrier segments. Even if this problem could be overcome, the differences in the shapes of

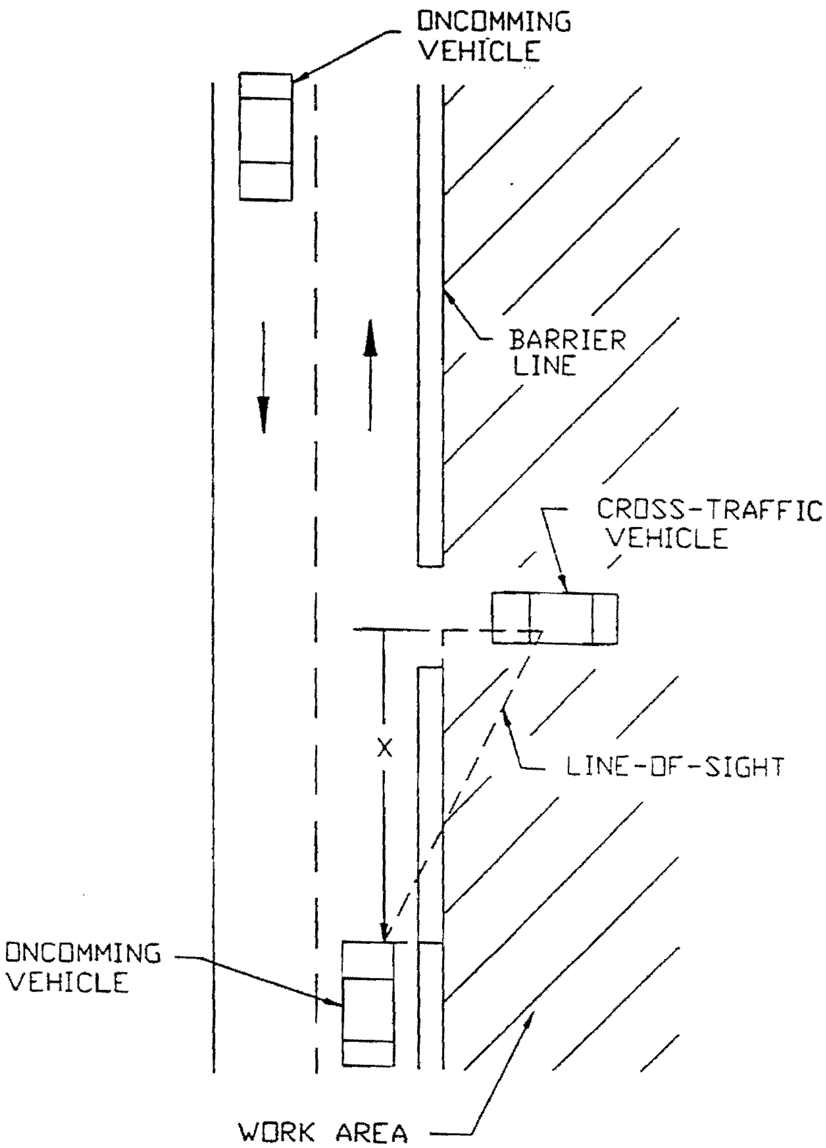

Figure 1: Geometry of Sight-Distance Problem.

the barrier cross-sections would most likely cause an errant vehicle to snag on the blunt end of the low-profile barrier that would protrude past the safety-shape barrier. Therefore, it is necessary to develop a new transition scheme which allows the two types of barriers to be connected.

The purpose of the research presented in this report was to develop economical transitions to connect low-profile barriers to the more traditional safety-shape barriers. Two different schemes have been developed for this task. In one scheme, the two different barrier segments are simply butted together, and a metal saddle is attached to the ends of the barrier. The metal saddle serves as a structural connection between the dissimilar barrier segments. In addition, its shape minimizes snagging of errant vehicles. In the other scheme, a special concrete transition segment is devised. The special transition segment is fabricated so that one end of the segment connects directly to a low-profile barrier and the other end of the transition segment connects directly to a safety-shape barrier.

The remainder of this report is divided into five major sections. The next section presents a discussion of the design requirements and expectations for the new low-profile to safety-shape barrier transition. This is followed by a section which describes the development of the two different transitions that are proposed. The next section presents general guidelines for the validation of the low-profile to safety-shape transition based on recommended full-scale crash tests. This is followed by a section which presents guidelines for the use of the barrier transitions once they have been validated through full-scale testing. The final section presents general conclusions and recommendations.

GENERAL DESIGN CONSTRAINTS

An ad hoc meeting was held at the Riverside Campus of Texas A&M University at the outset of the project. Attendence at this meeting included engineers and researchers associated with the Texas Department of Transportation (TxDOT) and the Texas Transportation Institute (TTI). The purpose of this meeting was to establish performance criteria for the development of the new low-profile to safety-shape transitions and to establish a more specific direction for the project.

The low-profile barrier system was developed for low-speed (73 km/h [45 mph]) applications. Since the original development and testing of the low-profile barrier, TTI testing has shown that the low-profile barrier is capable of smoothly redirecting a 2,043 kg (4,500 lb) automobile impacting with an angle of 25 degrees and a speed of 96.6 km/hr (60 mph). However, the effectiveness of the low-profile end-treatment has not been examined for high speed applications. Therefore, while it may be possible that the low-profile barrier system will function acceptably in high speed applications (96.6 km/hr[60 mph]), this cannot be certified without further testing.

After much discussion, the ad hoc research committee decided to focus the current efforts on development of low-speed (73 km/h [45 mph]) transitions. In addition, engineers and researchers decided to explore the development of two different barrier transition concepts. One concept involves the use of a special steel saddle which allows the two types of barrier segments to be butted together. The other concept employs a specially shaped concrete barrier segment which allows the two different types of barriers to be connnected together using their existing connection schemes.

Both barrier transition concepts have pros and cons. The purpose of this report is simply to described both concepts and to provide sufficient information to allow the TxDOT to make a rational decision as to which concept to develop.

DEVELOPMENT OF BARRIER TRANSITIONS

The objective of the proposed project was to develop two different types of transition techniques which will allow low-profile and safety-shape barriers to be connected into a continuous longitudinal barrier. The primary obstacle to this objective is the radical differences in the cross-sections of the two different types of barrier segments. Figure 2 presents sketches of the cross-sections of the two different types of barrier segments for comparision.

The effects of the two different barrier cross-sections on errant vehciles are significantly different. The safety-shape barrier is designed with a positive slope on the impact face. This results in an upward force being imparted to the errant vehicle. As the vehicle is forced upward energy associated with the impact is stored in potential associated with the increase in elevation of the vehicular center of mass. This results in a slight reduction in lateral accelerations experienced by the vehicle during the impact.

In the case of the low-profile barrier, the primary objective was to develop a low height barrier cross-section which would provide a minimal sight-distance obstruction. Thus, the upward movement of the errant vehicle during the impact could not be tolerated. Therefore, the barrier was constructed with a negative slope on the impact face so that the errant vehicle would not rise during the impact. As such the performance characteristics of the two different barriers are different.

The two considerations used in the development of the transition involved the performance of vehicles which first impact the low-profile barrier and move through the transition to the safety-shape barrier, and the performance of vehicles which first impact the safety-shape barrier and move through the transition ot the low-profile barrier. Both cases must be treated if the transitions are to be successful.

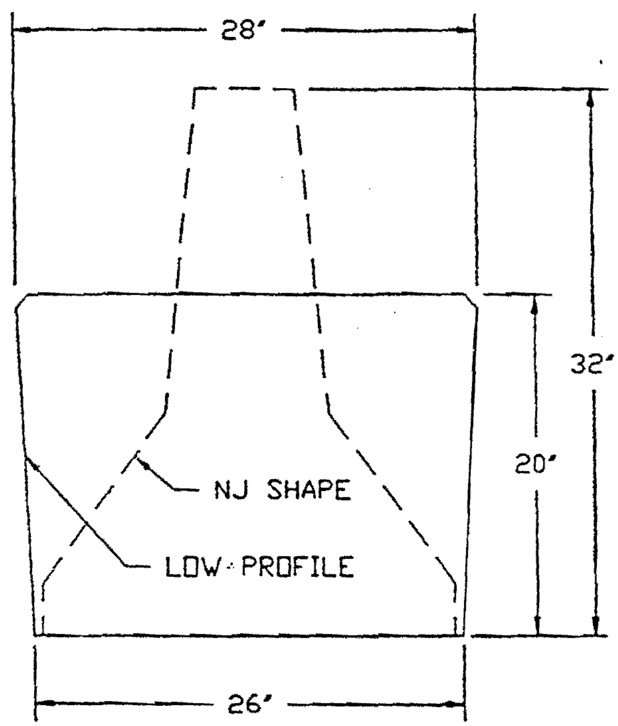

Figure 2: Comparison of Low-Profile and Safety-Shape Cross-Sections.

In the first case, it was decided that the transitions should be designed so that they do not facilitate an upward force being transferred to the errant vehicle as it impacts from the low-profile end. In a typical impact with a low-profile barrier, the vehicle first makes contact with the upper edge of the low-profile barrier. The upper edge of the low-profile barrier forces a groove to be formed in the contacting sheet metal of the errant vehicle, thus preventing the errant vehicle from gaining elevation. If this trend is to be maintained in a transition section, it is necessary for the transition to provide an impact edge which is of the same elevation as the upper edge of the low-profile barrier. Thus the grooved section of the errant vehicle will continue to prevent upward motion of the vehicle as the impact edge blends gently into the safety-shape barrier.

As stated previously, the positive slope of a safety-shape barrier is designed to force the errant vehicle to rise during the impact. Therefore, in this case, the objective is to provide a barrier transition that allows a vehicle, elevated as the result of contact with the safety-shape barrier, to return to its normal elevation without being destablized.

Details of the development of two types of barrier transitions are presented below.

Development of Concrete Transition

The concept of the concrete transition employs a specially shaped concrete barrier segment which allows the low-profile concrete barrier and the safety-shape barrier to be connected within the constraints of the two considerations discussed above. The design of the concrete transition segment is based on the results of a series of computer simulations and engineering judgments as discussed below.

To comply with the two design constraints discussed above, it was decided that the concrete transition should be divided into three zones. A safety-shape to stable zone, a stable zone, and a stable to low-profile zone as shown in Figure 3. In the safety-shape to stable zone, the barrier gently transitions from the safety-shape cross-section to a rectangular cross-section of the same height. Vehicles impacting in this zone will be subject to some amount

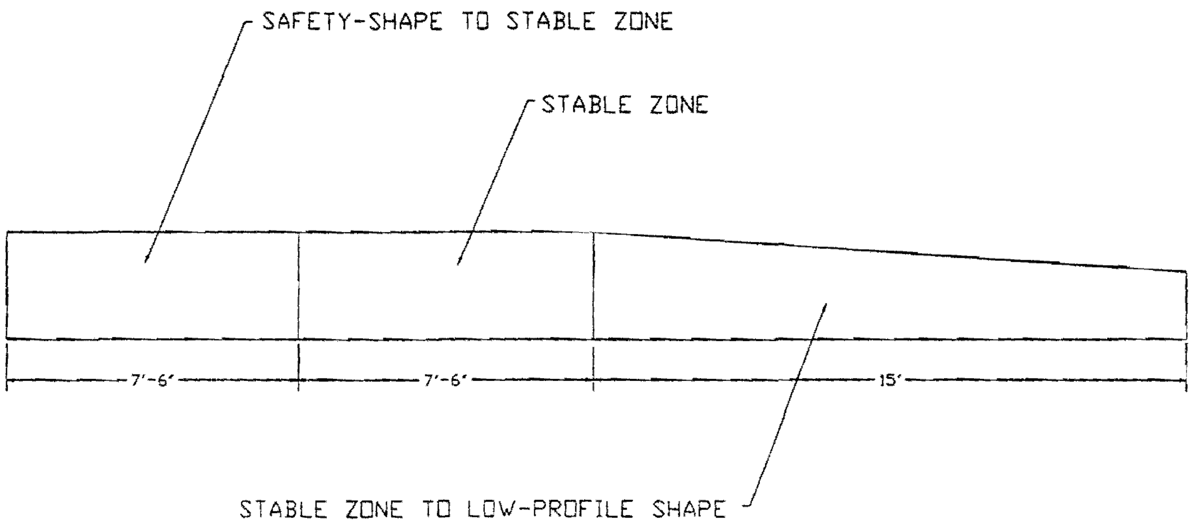

Figure 3: Different Zones for the Concrete Transition Section.

of uplift depending upon the impact point. The stable zone consists of vertical barrier face which will impart little to no uplift on an impacting vehcile. If an errant vehicle impacts in the stable to low-profile zone, there should be no uplift imparted to the vehicle. In addition, this zone provides for a convenient height transition between the height of the taller safety-shape barrier and the low-profile barier.

Computer simulations were used to study the effect of the transition barrier zones on the vehicle roll and vehicle height after impact. The computer program used to evaluate the performance of the concrete transition segment was HVOSM (highway-vehicle-object-simulation-model) (3,4). The version of HVOSM used in the study was the RD2 version which incorporates modifications developed by researchers at the TTI. The TTI modifications permit the structure of the vehicle to interact with the sloped faces of a multi-faced rigid barrier. Studies of rigid safety-shape barriers made with this modified version of HVOSM have met with reasonably good success (5,6).

The performance of the concrete transition segment is evaluated by the stability of the vehicle after impact and the uplift of the vehicle after impact. The objective of the computer simulation study was to select a sufficient length of the stable zone before height transition took place in order to prevent the vehicle from rising above the decreasing height of the barrier.

The HVOSM program was used to simulate the impact of a 2043 kg (4,500 lb) automobile and a 817 kg (1,800 lb) automobile traveling at 72 km/h (45 mph) with an angle of 25 degrees to evaluate the performance of the different zones.

Based on the above analysis and engineering judgment, it was determined to construct the concrete transition segment with a safety-shape to stable zone length of 2.286 m (7 ft 6 in.), a stable zone length of 2.286 m (7 ft 6 in.), and a stable to low-profile zone of length 4.572 m (15 ft). The safety-shape to stable zone has a height of 81.28 cm (32 in.) and a base width of 53.34 cm (21 in.) which decreases uniformly to a width of 38.1 cm (15 in.).

The stable zone has a constant rectangular cross-section with a height of 81.28 cm (32 in.) and a width of 38.1 cm (15 in.). The stable to low-profile transition zone has a height of 81.28 cm (32 in.) which decreases uniformly to a height of 50.8 cm (20 in.) while the base width of 38.1 cm (15 in.) increases uniformly to a maximum base width of 66.04 cm (26 in.). The weight of the concrete transition segment is estimated to be 7484 kg (16,500 lb).

Complete fabrication drawings for the concrete transition segment are presented in Appendix A. As shown in Appendix A, it is recommended that the concrete transition segment be fabricated in 9.14 m (30 ft) lengths.

The safety shape-end of the concrete transition segment is equipped with a TxDOT standard connection that involves the use of steel angles which are attached to the barrier segment ends with specially fabricated bolts as shown in the fabrication drawings presented in Appendix A. Figure 4 presents an isometric view of the concrete transition. This angle-splice connection is recommended for temporary connections. The low-profile end of the concrete transition segment is equipped with the same bolted connection used for the low-profile PCB (1).

Development of Steel Saddle Transition

The objective behind the steel saddle concept is to connect the two different barrier segments by simply butting them together and using a specially fabricated steel saddle as both a structural connection and a cross-section modifier. The design of the steel saddle is based primarily on engineering judgment.

The steel saddle will be bolted directly to the safety-shape barrier through holes that will have to be drilled through the barrier. The end of the steel saddle is specially fabricated so that a connection can be made to the low-profile barrier using the existing connection bolt holes that are fabricated into the low-profile barrier. The steel saddle is shaped so that it will minimize snagging of errant vehicles impact from either direction. Various sizes and shapes were considered during the development of the steel saddle transition.

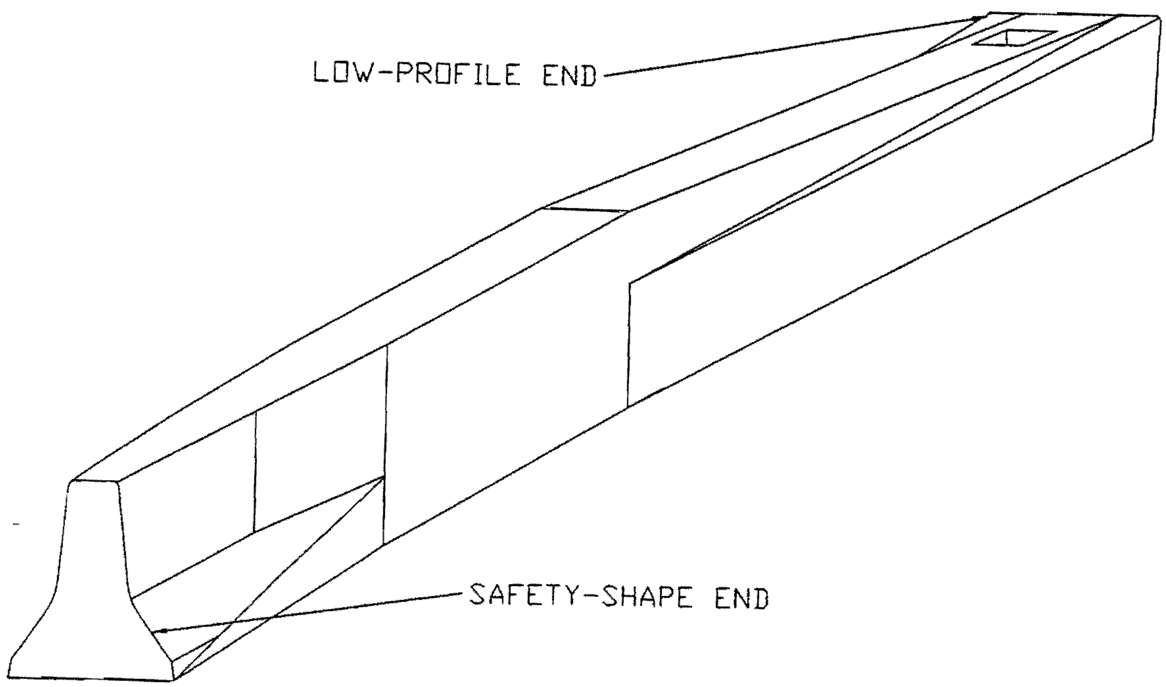

Figure 4: Isometric View of the Concrete Transition Section.

A steel saddle of length 3.048 m (10 ft) was chosen. The steel saddle allows the safety-shape barrier to conform to the shape of the low profile CMB at the connection between the two barriers. It then gradually transitions to the safety-shape CMB over the length of 3.048 m (10 ft). The steel saddle will be attached to the safety-shape CMB with specially fabricated bolts. The combined steel saddle and safety-shape will then be connected to the low profile CMB by means of an external steel plate, which will be bolted to both the low profile CMB and steel saddle.

As designed the steel saddle consists of three major elements: the connection plate, and the left and right cross-section modifiers. It is estimated that the connection plate will weigh less than 25 kg (55 lb) and that the weights of the left and right cross-section modifiers will be less than 80 kg (176 lb). Therefore, the complete steel saddle can be transported in the bed of a full-size pickup and the individual elements can be easily handled by two workers. It is estimated that a crew of three workers will be required to accomplish the installation of the steel saddle. Complete fabrication drawings for the steel saddle are presented in Appendix B. Figure 5 presents an isometric view of the steel saddle transition.

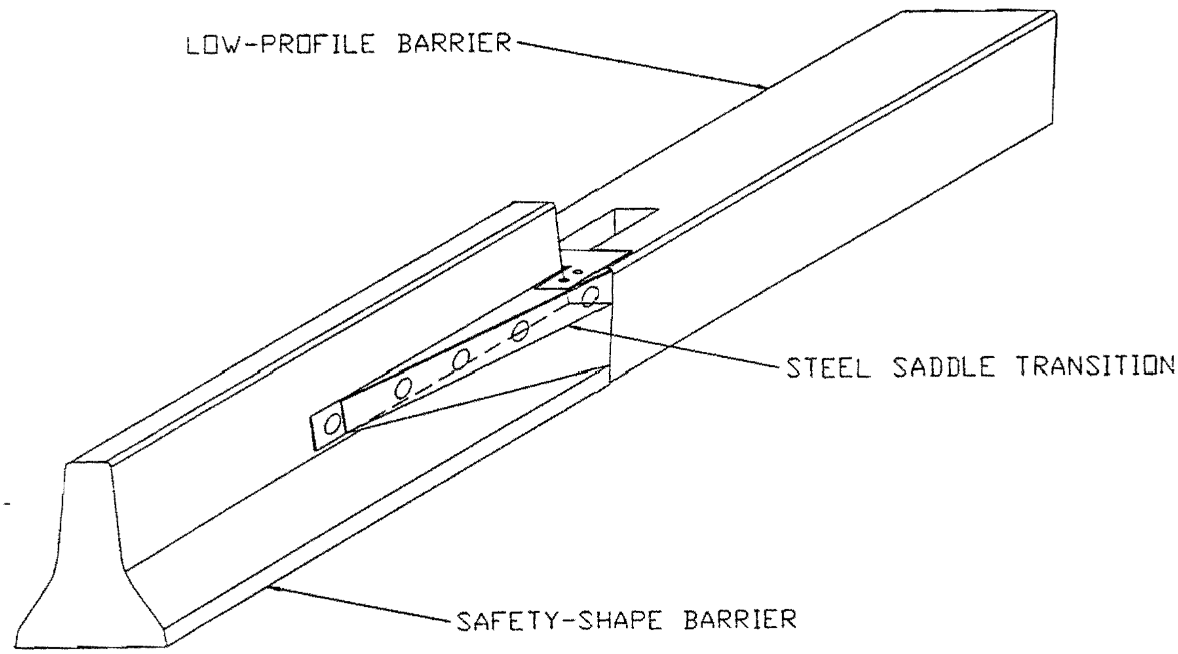

Figure 5: Isometric View of the Steel Saddle Transition Section.

GUIDELINES FOR VALIDATION FOR THE BARRIER TRANSITIONS

The previous section introduced two different concepts used to transition between the low-profile concrete barrier and the safety-shape concrete barrier. Both transition concepts were developed with the expectation that they can both be successfully fabricated and used. While it is believed that both concepts can be successfully employed, neither concept has been subjected to full-scale crash testing. Therefore, the purpose of this section is to recommend a set of crash tests that are consistent with recommendations presented in NCHRP 350 (7). These recommended crash tests can be used to evaluate the performance of the two different transition shapes.

Based upon definitions contained in NCHRP 350, the low-profile/safety-shape barrier system is properly classified as a longitudinal barrier. In addition, NCHRP 350 defines a transition as "that part of a longitudinal barrier system between and connecting sections of differing lateral stiffness and/or sections of differing design or geometry" (7). Therefore, the two connection schemes presented in this report are properly classified as transitions.

The low-profile and safety-shape barrier segments which make up most of the new barrier system have already been shown to meet or exceed NCHRP 350 Test Level 2 (TL2) criteria [70 km/h (43.5 mph) vehicle impacts](7). Based on discussions presented in NCHRP 350, longitudinal barriers that meet or exceed the TL2 criteria are deemed to be acceptable for most local and collector roads, and many work zones.

NCHRP 350 recommends three possible sets of test conditions for the evaluation of transition sections based on TL2 criteria as presented in Table 1. These test conditions are identified by designations 2-20, S2-20, and 2-21. Tests 2-20 and S2-20 are designed to evaluate the occupant risk and post-impact trajectory criteria associated with the impact of small automobiles [820 kg (1,808 lb) and 700 kg(1,543 lb)]. Test 2-21 is intended to evaluate the strength of the transition with respect to containing and redirecting the impact of a 2000 kg (4,409 lb) pickup(7).

Table 1: Test Matrix for Test Level 2 Longitudinal Barrier Transitions.

Barrier Section	Test Designation	Impact Conditions		
		Vehicle	Nominal Speed (km/h)	Nominal Angle (deg)
Transition	2-20	820C	70	20
	S2-20	700C	70	20
	2-21	2000P	70	25

Based upon recommendations presented in NCHRP 350, test S2-20 is listed as an optional test because it is conducted with a 700 kg (1,543 lb) small automobile. Further, it is stated in NCHRP 350 that test 2-20 may be optional. While test 2-21 is not identified as optional, it is clear in reading recommendations presented in NCHRP 350 that all three tests need be conducted only if there is reasonable uncertainty regarding the impact performance of the system associated with these three tests (7). Therefore, it is the writers' opinion that the proper group of tests to be conducted to evaluate the transition should be based on sound engineeing judgment in the case of all three tests.

Once it is determined which tests are required to demonstrate the adequacy of the transition, it is necessary to define the proper impact points for each test. The impact point is defined in NCHRP 350 as the initial point of contact between the test vehicle and the test article. The location of the critical impact point for each test to be conducted is to be based on the results of computer simulations, engineering judgment, and/or experience. It is suggested in NCHRP 350 that there may be two critical impact points for a given test article: one that results in the greatest potential for destabilizing the impacting vehicle through wheel snagging, vehicular pocketing, etc., and one that results in the critical loading on the weakest point of the barrier (7).

Recommended Evaluation Criteria for Steel Saddle Transition

With the steel saddle transition concept, a low-profile barrier and a safety-shape barrier are butted together as described in the previous section and connected through the use of specially frabricated steel hardware. It is recommended that the performance of this transition section be established with two full-scale impacts as described below.

First, it is recommended that the structural adequacy of the connection be established by subjecting the connection to test 2-21. In this test, it is recommended that the safety-shape barrier side of the connection be impacted with the 2000 kg (4,409 lb) pickup traveling with a speed of 70 km/hr (43.5 mph) and an impact angle of 25 degrees. It is the writers' opinion that the impact point that will cause the critical loading on the connection will correspond to a point which is located 1.524m (5 ft) upstream of the interface between the low-profile and the safety-shape barriers.

The second test that should be conducted is test 2-20. In this test, it is recommended that the safety-shape barrier side of the connection be impacted with the 820 kg (1,808 lb) small automobile traveling with a speed of 70 km/hr (43.5 mph) and impacting with an angle of 20 degrees. It is the writers' opinion that the impact point that will cause the critical instability of the vehicle will be associated with the small automobile impacting 1.524 m (5 ft) upstream of the tip of steel saddle on the safety-shape side of the connection. It is believed that this impact will result in the greatest possibility for destabilizing the small automobile.

It is recommended that test S2-20 be waived as it is not likely to generate additional information regarding the performance of the barrier transition.

Recommended Evaluation Criteria for the Concrete Barrier Transition

With the concrete barrier transition concept, the low-profile barrier and safety-shape barrier are connected with a specially fabricated concrete barrier transition segment as described in the previous section.

The concrete barrier transition segment connects to the low-profile and the safety-shape barrier segments using the conventional connection schemes. Because these connections have already been subjected to extensive testing, there is no need to subject the connections to further testing. Further, the structural properties of the transition section are equivalent to or greater than the other two barrier segments at all points, so there seems to be no reason to subject the transition barrier segment to a strength test. Therefore, it is the writers' opinion that test 2-21 can be waived.

To investigate the destabilizing effect of the transition segment, it is recommended that the concrete transition be subjected to test 2-20. In this test, it is recommended that the safety-shape barrier side of the connection be impacted with the 820 kg (1,808 lb) small automobile traveling with a speed of 70 km/hr (43.5 mph) and impacting with an angle of 20 degrees. It is the writers' opinion that the impact point that will cause the critical instability of the vehicle will be associated with the small automobile impacting at the point where the stable and low-profile to stable zones intersect. It is believed that this impact will result in the greatest possibility for destabilizing the small automobile.

It is recommended that test S2-20 be waived as it is not likely to generate additional information regarding the performance of the barrier transition.

GUIDELINES FOR USE OF BARRIER TRANSITIONS

The purpose for the development and use of the low-profile barrier system was to improve work zone visibility without significantly compromising the redirective capability of the longitudinal barrier system. In particular, the low-profile barrier system was designed to provide adequate stopping sight distances between cross-traffic vehicles and oncomming vehicles in the intersection condition depicted in Figure 1. Therefore, it seems reasonable that the same criteria used in development of the low-profile barrier system should be used in development of the low-profile/safety-shape barrier system.

The AASHTO design stopping sight distance for a vehicle travelling with a known speed is defined as the sum of the distance traveled during the brake reaction time and the distance traveled after the brakes are applied. This later distance is referred to as the braking distance (8).

The distance traveled during the brake reaction time is based on an assumed driver reaction time of 2.5 seconds. This assumed value of the brake reaction time is based upon interpretations of test data made by AASHTO (8). During the brake reaction time, the vehicle will have a constant forward speed of 73 km/h (45 mph) so that the vehicle will travel a total distance of 50 m (165 ft).

The distance traveled by the vehicle during the braking phase of stopping is computed using the following formula which was presented by AASHTO (8):

$$d=\frac{V^2}{30f} \tag{1}$$

where d is the braking distance in ft,

V is the initial speed of the vehicle in mph, and

f is the coefficient of friction between the tires and the roadway.

The only ambiguous term involved in equation (1) is f, the coefficient of friction between the tires and the roadway. According to AASHTO, the actual value of f depends upon a multitude of factors including air pressure of the tires, composition of the tires, the tire tread pattern and depth of tread, the type and condition of the pavement surface, the presence of moisture, mud, snow, or ice, etc. Based upon a review of relevant literature, a value of f = 0.31 was established by AASHTO for calculating conservative braking distances for 73 km/h (45 mph) design speeds (8). The maximum estimated braking distance on level terrain is thus found to be 66 m (217.7 ft).

The resulting total stopping distance for a vehicle traveling with a speed of 73 km/h (45 mph) on level terrain is found to be 116.6 m (382.7 ft). AASHTO rounds this value up to 122 m (400 ft) (8) for design purposes. Therefore, it is recommended by AASHTO that a total stopping distance of 122 m (400 ft) should be used for barrier systems deployed on a level roadway or one which has an upgrade (8).

If the barrier system is deployed on a downgrade, the brake stopping distance must be increased to account for the increased stopping distance associated with the downgrade. According to AASHTO, equation (1) can be modified as follows to account for the effects of the downgrade:

$$d=\frac{V^2}{30(f-\frac{g}{100})} \qquad (2)$$

where g is the percent of downgrade and all of the other terms are as previously defined (8).

The increase in stopping distance, Δd, as the result of a downgrade can then be determined by subtracting equation (1) from equation (2) resulting the following relationship:

$$\Delta d = \frac{V^2 \frac{g}{100}}{30(\frac{g}{100} f - f^2)} \tag{3}$$

where all of the variables are as previously defined. Equation (3) can be used to determine the increase in braking distance as a function of downgrade.

Values of the increase in braking distance, Δd, for downgrades ranging from 0 to 9 percent are presented in Table 2. Examinations of these data show that for downgrades up to 9 percent, the increase in breaking distance, Δd, can be conservatively estimated by increasing the stopping distance by 3.05 m (10 ft) for each percent of the downgrade. This relationship is much more convenient to use than equation (3). Thus the total stopping distance for a 73 km/h (45 mph) vehicle on a downgrade which does not exceed 9 percent can be conservatively given by the following relationship:

$$d = 400 + 10g \tag{4}$$

where g is the level of downgrade expressed in percent.

Table 2: Additional Barrier Length for Downgrade Requirements.

% Downgrade	Calculated Additional Barrier Length		Estimated Additional Barrier Length	
	(ft)	(m)	(ft)	(m)
1	7.258	2.21	10	3.05
2	15.017	4.58	20	6.10
3	23.330	7.08	30	9.14
4	32.258	9.83	40	12.19
5	41.873	12.76	50	15.24
6	52.258	15.93	60	18.29
7	63.508	19.36	70	21.34
8	75.736	23.08	80	24.38
9	89.076	27.15	90	27.43

Therefore, based on the above discussion, it is recommended that a typical installation involve at least one 6.1 m (20 ft) end treatment followed by nineteen 6.1 m (20 ft) low-profile barrier segments. This will provide a total of 121.9 m (400 ft) of low-profile barrier to assure adequate sight distance. Then, the transition segment presented in this report can be used to connect the low-profile barrier to the conventional safety-shape barrier. If the longitudinal barrier is installed on a downgrade, one additional 6.1 m (20 ft) low-profile barrier segment should be added for each 2 percent of downgrade.

CONCLUSIONS

In previous research, a low-profile barrier system was developed which greatly improves the site distance situation for drivers attempting to enter or exit a work zone which is delineated with concrete barriers. The purpose of the research presented in this report was to develop a longitudinal barrier transition which allows the low-profile barrier to be conveniently connected to the safety-shape barrier. In so doing the low-profile and safety-shape barriers can be arranged in a single barrier system which allows the advantages of the low-profile barrier system to be taken advantage of while at the same time utilizing existing safety-shape barriers. This should allow for an overall economy in the use of concrete barriers in work zones.

Two different barrier transition schemes have been developed. The steel saddle is a transition segment which allows the two types of barriers to be butted together and connected with a specially fabricated steel section which allows the system to function without adversely affecting an errant vehicle. The second system is a concrete barrier transition which allows the two types of barriers to be connected together using the traditional connection concepts.

While, it is believed by the writers that both concepts will function as designed, a sequence of full-scale crash tests have been recommended to fully evaluate the performance of both concepts based upon information contained within NCHRP 350 (7). Because, both barrier conepts are different, different crash test are recommended for their evaluation.

In addition, recommendations based upon information presented by AASHTO (8) have been used to develop a set of guidelines for the use of the low-profile/safety-shape barrier system. These guidelines incorporate existing AASHTO formulations along with simplifications developed by the writers to conservatively use the new barrier system.

The researchers recommend that TxDOT make a final decision on the preferred type of barrier transition to develop. Then based on this selection, the recommended full-scale crash testing should be conducted to verify that the selected system performs as designed.

REFERENCES

1. Guidry, T. R., and Beason, W. L., "Development of a Low-Profile Portable Concrete Barrier," Final Report No. 990-4F, Texas Department of Highways and Public Transportation, November 1991.

2. Beason, W. L., "Development of an End Treatment For a Low-Profile Concrete Barrier," Final Report No. TX-92/1949-2, Texas Department of Highways and Public Transportation, November 1992.

3. Segal, D. J., "Highway-Vehical-Object-Simulation-Model-1976," Report Numbers FHWA-RD-75-162 through 165, 4 volumes, Calspan Corporation, Buffalo, New York, 1976.

4. Ross, H. E., Krammes, R. A., Sicking, D. L., Tyer, K. D., and Perera, H. S., "Traffic Barriers and Control Treatments For Restricted Work Zones," Final Report, NCHRP Project 17-8, 3 volumes.

5. Perera, H. S., "Simulation of Vehicular Impacts with Safety Shaped Barrier," Ph.D. Dissertation, Department of Civil Engineering, Texas A&M University, College Station, Texas, 1987.

6. Ross, H. E., Perera, H. S., Sicking, D. L., and Bligh, R. P., "Roadside Safety Design for Small Vehicles," Final Report, NCHRP Project 22-6, 2 volumes.

7. Ross, H. E., Sicking, D. L., Zimmer, R. A., "Recommended Procedures for the Safety Performance Evaluation of Highway Features," NCHRP 350, Transportation Research Board, National Research Council, National Academy Press, Washington, D.C. 1993.

8. "AASHTO, A Policy on Geometric Design of Highways and Streets," 1990, American Association of State Highway and Transportation Officials, Washington, D.C.

APPENDIX A.
FABRICATION DETAILS FOR CONCRETE TRANSITION

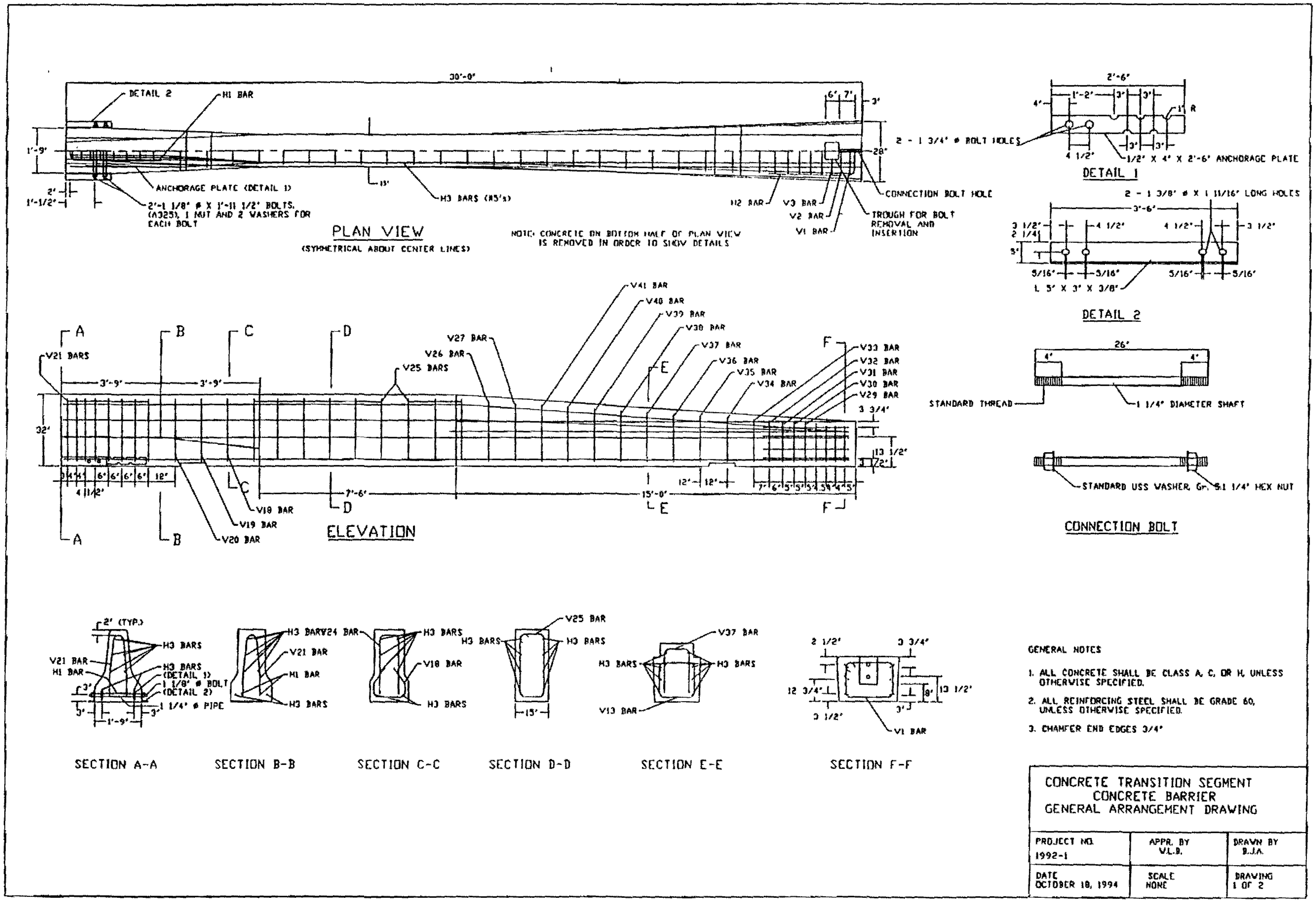

Figure 6. Fabrication Details for Concrete Transition.

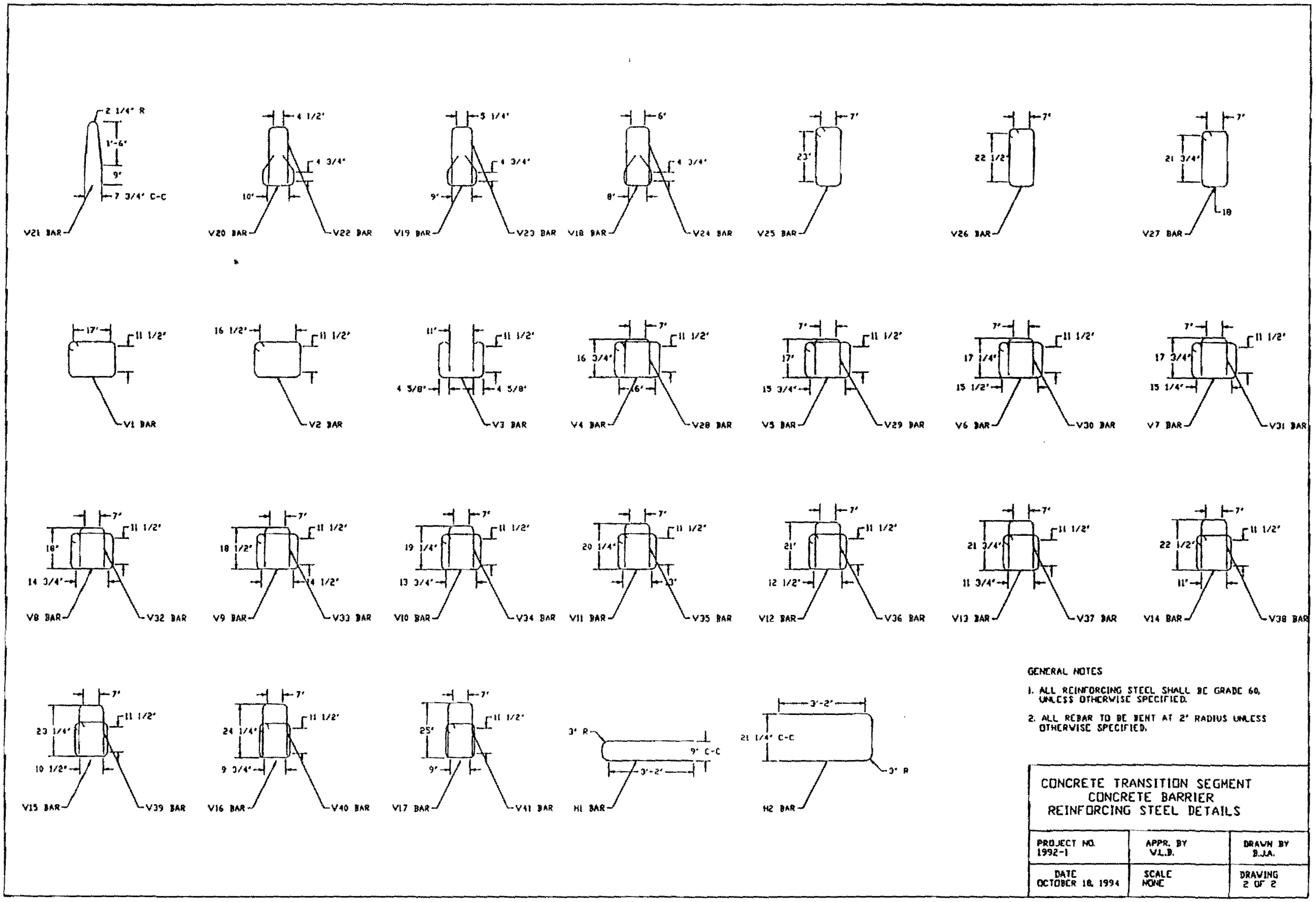

Figure 6. Fabrication Details for Concrete Transition (continued).

APPENDIX B.
FABRICATION DETAILS FOR STEEL SADDLE TRANSITION

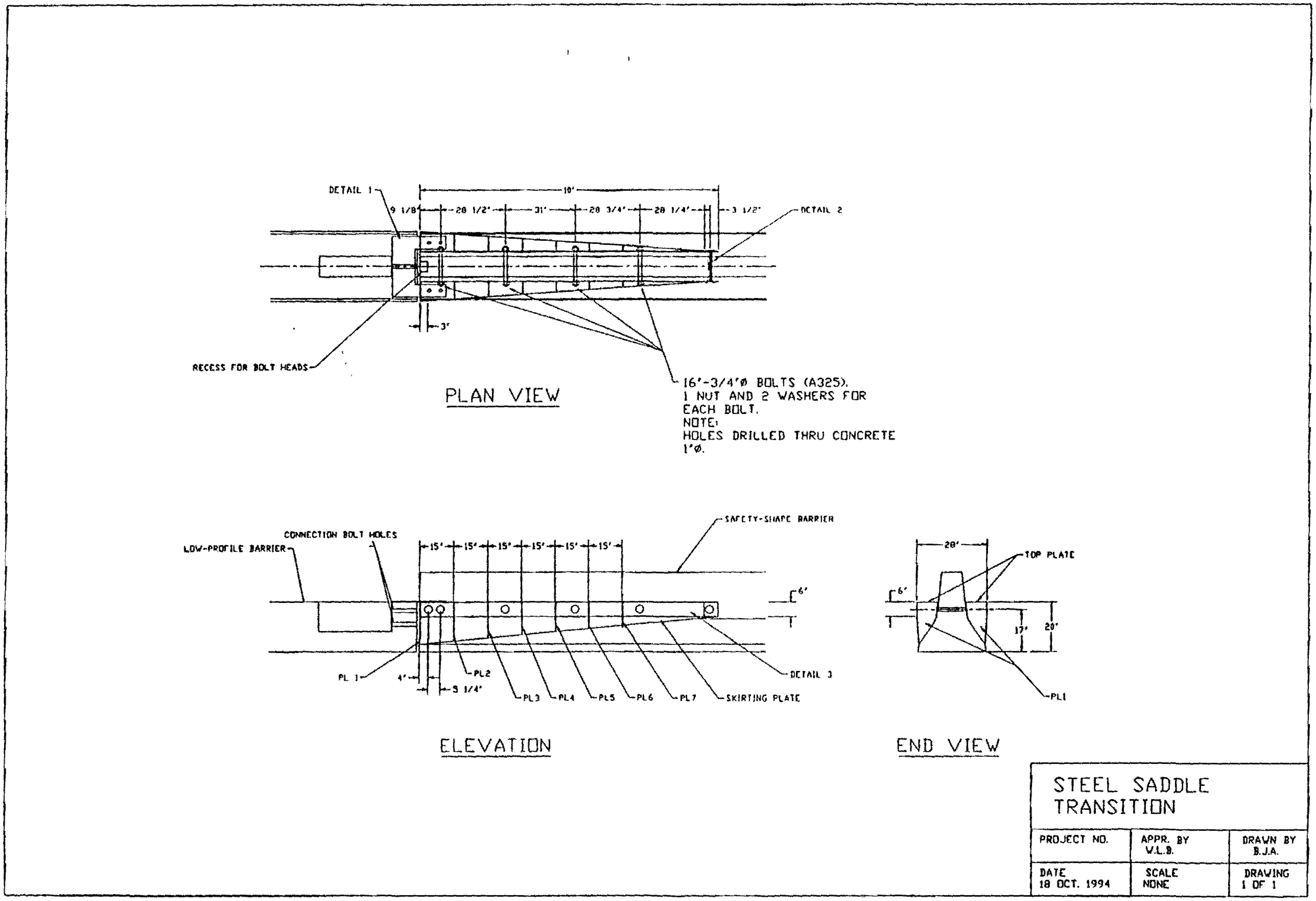

Figure 7. Fabrication Details for Steel Saddle Transition.

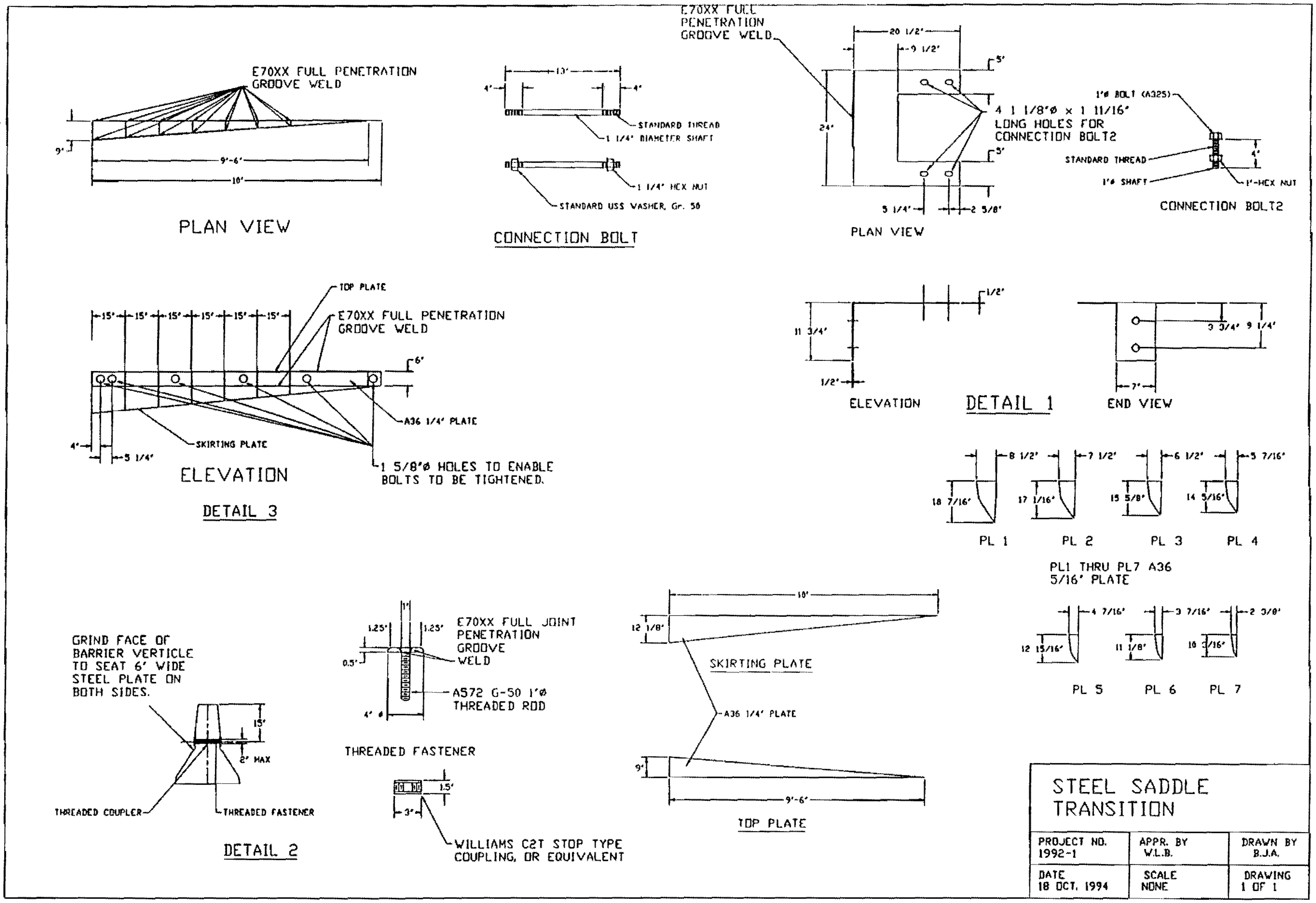

Figure 7. Fabrication Details for Steel Saddle Transition (continued).