TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TX-84/105-1F		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
EMERGENCY OPENING SYSTEM FOR AN AUTHORIZED VEHICLE LANE	5. Report Date: March 1984 6. Performing Organization Code:
7. Author(s) John W. Strybos, James R. Morgan, and Hayes E. Ross, Jr.	8. Performing Organization Report No. Research Report 105-1F
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843	10. Work Unit No. 11. Contract or Grant No. IAC(84-85)-0664
12. Sponsoring Agency Name and Address Houston Urban Project State Department of Highways and Public Transportation P.O. Box 187; Houston, Texas 77001	13. Type of Report and Period Covered Final Report Mar. 1983 - Apr. 1984 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

An emergency opening system (EOS) for an authorized vehicle lane was developed and crash tested. The design consisted of two steel box tubes mounted on top of each other. The beams were supported by pins at the ends that were connected to modified concrete median barrier sections. Factors considered in the development of the system were ease of operation and ability to redirect errant vehicles.

Three full-scale crash tests were conducted to evaluate the impact behavior of the design. All of the occupant risk values as well as the vehicle trajectory hazard were below recommended values for all of the crash tests. In addition, the EOS was still operational after the first two tests. The system was not operational after the third test because the anchorage system for the downstream concrete median barrier failed. Several modifications in the design of the EOS were recommended to improve the operation of the system. These changes were a result of observations of the construction and crash testing of the system.

17. Key Words	18. Distribution Statement
Median Barriers, Authorized Vehicle Lanes, Emergency Opening System, Traffic Barriers, Crash Tests, Highway Safety	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	61	

Form DOT F 1700.7 (8-69)

EMERGENCY OPENING SYSTEM FOR AN AUTHORIZED VEHICLE LANE

by

John W. Strybos
James R. Morgan
and
Hayes E. Ross, Jr.

Research Report 105-1F
on
IAC(84-85)-0664
Emergency Opening System for Authorized Vehicle Lanes

Sponsored by
Houston Urban Project of the
Texas State Department of Highways and Public Transportation

Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843

March 1984

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Texas State Department of Highways and Public Transportation or the Houston Urban Expressway Office. This report does not constitute a standard, specification, or regulation.

KEY WORDS

Median Barriers, Authorized Vehicle Lanes, Emergency Opening System, Traffic Barriers, Crash Tests, Highway Safety

ACKNOWLEDGMENTS

This research study was conducted by the Texas Transportation Institute (TTI) for the Texas State Department of Highways and Public Transportation (SDHPT). Technical liaison and guidance was provided by William V. Ward, Engineer-Manager and James G. Darden,III, Associate Designing Engineer of the Houston Urban Project of SDHPT. The crash tests were carried out by personnel of the Highway Safety Research Center of TTI. This report is based on a Master of Engineering report by John W. Strybos.

IMPLEMENTATION STATEMENT

At the writing of this report the concepts and designs presented herein are being implemented on the I-45 Authorized Vehicle Lane project in Houston, Texas.

ABSTRACT

An emergency opening system (EOS) for an authorized vehicle lane was developed and crash tested. The design consisted of two steel box tubes mounted on top of each other. The beams were supported by pins at the ends that were connected to modified concrete median barrier sections. Factors considered in the development of the system were ease of operation and ability to redirect errant vehicles.

Three full-scale crash tests were conducted to evaluate the impact behavior of the design. All of the occupant risk values as well as the vehicle trajectory hazard were below recommended values for all of the crash tests. In addition, the EOS was still operational after the first two tests. The system was not operational after the third test because the anchorage system for the downstream concrete median barrier failed. Several modifications in the design of the EOS were recommended to improve the operation of the system. These changes were a result of observations of the construction and crash testing of the system.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

INTRODUCTION

A $52 million project is underway in Houston to install an authorized vehicle lane (AVL) down the center of Interstate 45. This AVL will provide buses, van pools, and other authorized traffic with an expressway free from normal traffic congestion over a distance of 13.1 miles (21.1 km). Concrete median barriers (CMBs) will be used to separate traffic within the AVL from the normal I-45 traffic. Limited access to the AVL will insure smooth flow uninterrupted by unauthorized vehicles. However, in the event of a mechanical problem, minor breakdown (e.g., flat tire, etc.), accident or other emergency, this limited access also will impede the wrecker or other emergency equipment, causing major traffic congestion. Such eventualities make the implementation of a gate or emergency opening system (EOS) for the AVL essential.

The design of an EOS for a CMB involves several key parameters. The EOS must function as a median barrier in its ability to safely redirect errant vehicles and stop them from entering adjacent traffic lanes. This should be achieved without endangering the driver during vehicle redirection. At the same time, the EOS must be opened and closed by the operator of the emergency vehicle. This requires that the EOS either be lightweight or include provision for mechanical or electrical devices to aid in its operation. Futhermore, it would be desirable to have an EOS that would remain operational following moderate impacts with little or no maintenance. Guidelines and designs also are needed to properly transition the CMB both on the upstream and downstream ends of the EOS.

ANALYSIS

The EOS is designed to safely redirect errant vehicles and stop them from entering adjacent traffic lanes. The general configuration of the gate system is a steel beam 30 ft. (8.9 m) long that is connected to modified CMB sections at each end. A square tube was selected for the beam section based on a preliminary analysis of the system. The beam was pinned at the ends so that the gate could be opened and closed by an emergency vehicle operator.

When impacted by an errant vehicle, the EOS should behave similarly to a guardrail system. Both barriers can be modelled as a series of rigid beams connected together at joints. The EOS was therefore analyzed with a computer program developed to analyze the behavior of an automobile striking a deformable barrier of general configuration (1). For a description of the computer model the reader should refer to the referenced report.

In the computer program, a dynamic, inelastic large displacement structural analysis problem in two dimensions is solved using a step-by-step method. The automobile is modelled as a plane body of arbitrary shape surrounded by inelastic springs. During impact, the automobile slides along the barrier. Forces between the automobile tires and the pavement are taken into account, as well as the interaction forces between the automobile and the barrier. The barrier is an arbitrary assemblage of beams, posts, springs, and damping devices. Loads are applied to the barrier only at the nodes.

Impact with a large, 4500 lb (2040 kg) vehicle travelling at 60 mph (96.6 km/h) and 25 degrees was investigated. The joint loads and deflections from this simulation were used to design all of the appurtenances of the EOS. Impact with an 1800 lb (815 kg) vehicle travelling at 60 mph (96.6 km/h) and 15 degrees was also investigated. This simulation gave smaller loads and deflections than the impact with the large vehicle.

The EOS was modelled as a system of 20 beams. Each beam was 16.7 in. (42.4 cm) long with a centerline height of 19 in. (48.3 cm) above the pavement surface. In addition, there were two support posts in the model. The posts were placed at the initial node and at the terminal node of the model. The posts were given arbitrarily high values for the stiffness, base moment at failure, shear force at failure and deflection at failure because the computer simulation was performed to test the strength of the barrier itself, not the strength of the support posts. This accurately models the situation of a rigid CMB support.

EMERGENCY OPENING SYSTEM

The EOS must perform as a median barrier in its ability to safely redirect errant vehicles and stop them from entering adjacent traffic lanes. Futhermore, the EOS must be opened and closed by the operator of the emergency vehicle. Finally, the barrier should be relatively inexpensive to build and maintain, and it should not be too difficult to install in place.

Design of a system to satisfy these requirements presents special problems. Consultation with several state highway departments found that there was not a system presently in operation that would satisfy all of these requirements. The first function of the EOS was achieved by using two square steel tubes mounted on top of each other, but separated by 1.38 in. (3.5 cm) vertically. The size and orientation of the steel members was selected based on information from the computer analysis. The tubes were mounted between two 30 ft (8.9 m) long modified concrete median barrier sections that were separated by 30 ft (8.9 m). The emergency opening system is described in detail by Figures 1 and 2. Figure 3 shows the system in operation.

The other parts of the EOS were designed, using the applicable standards (2,3), from peak loads taken from the computer simulation. These loads were 250 kips (34.6 kN) axial and 50 kips (6.9 kN) lateral shear. The steel members transferred these forces to one 3.25 in. (8.3 cm) diameter pin at each end of the tubes. The pins were sized to carry the loads in

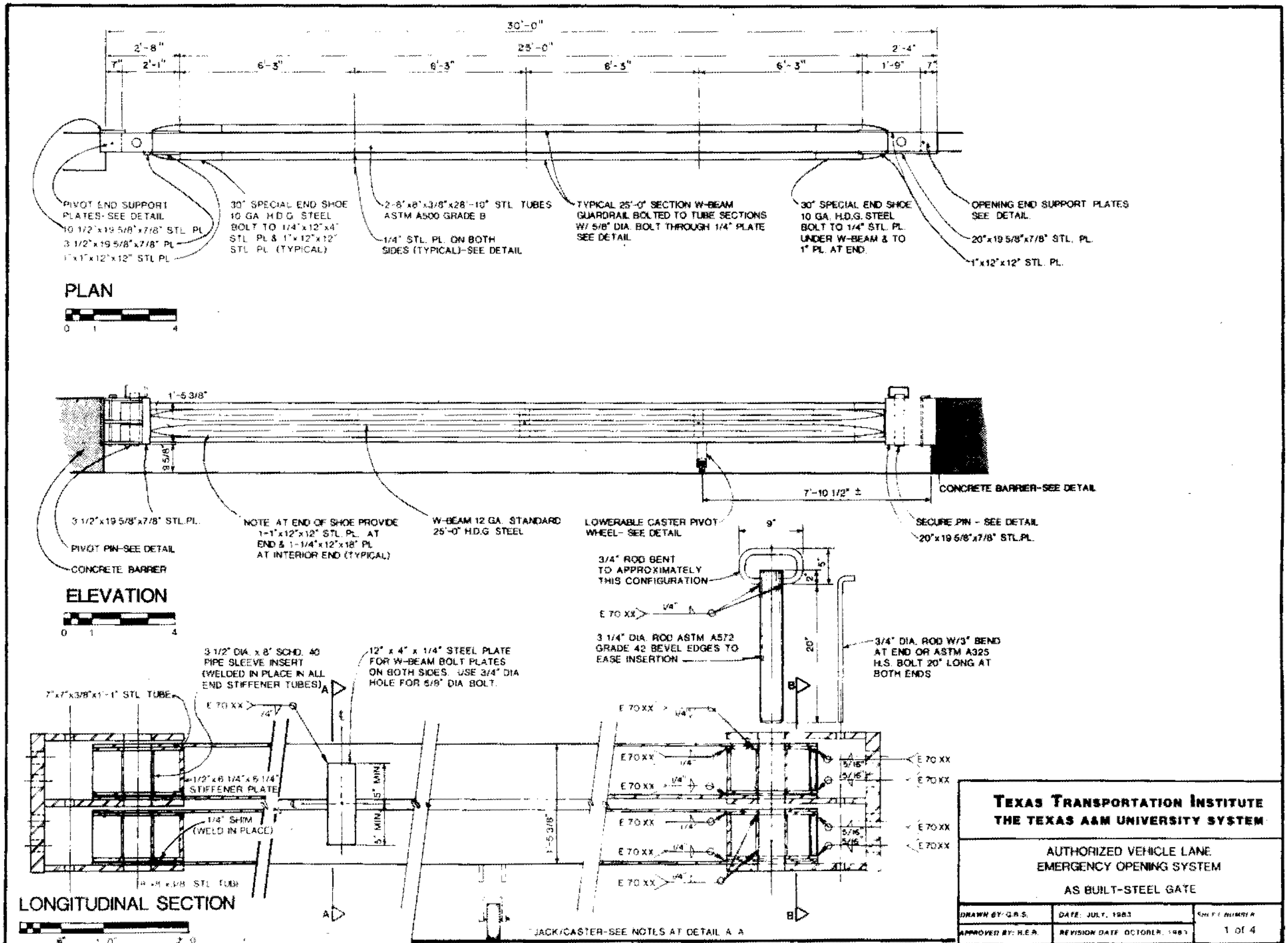


Figure 1. Emergency Opening System for Authorized Vehicle Lane.

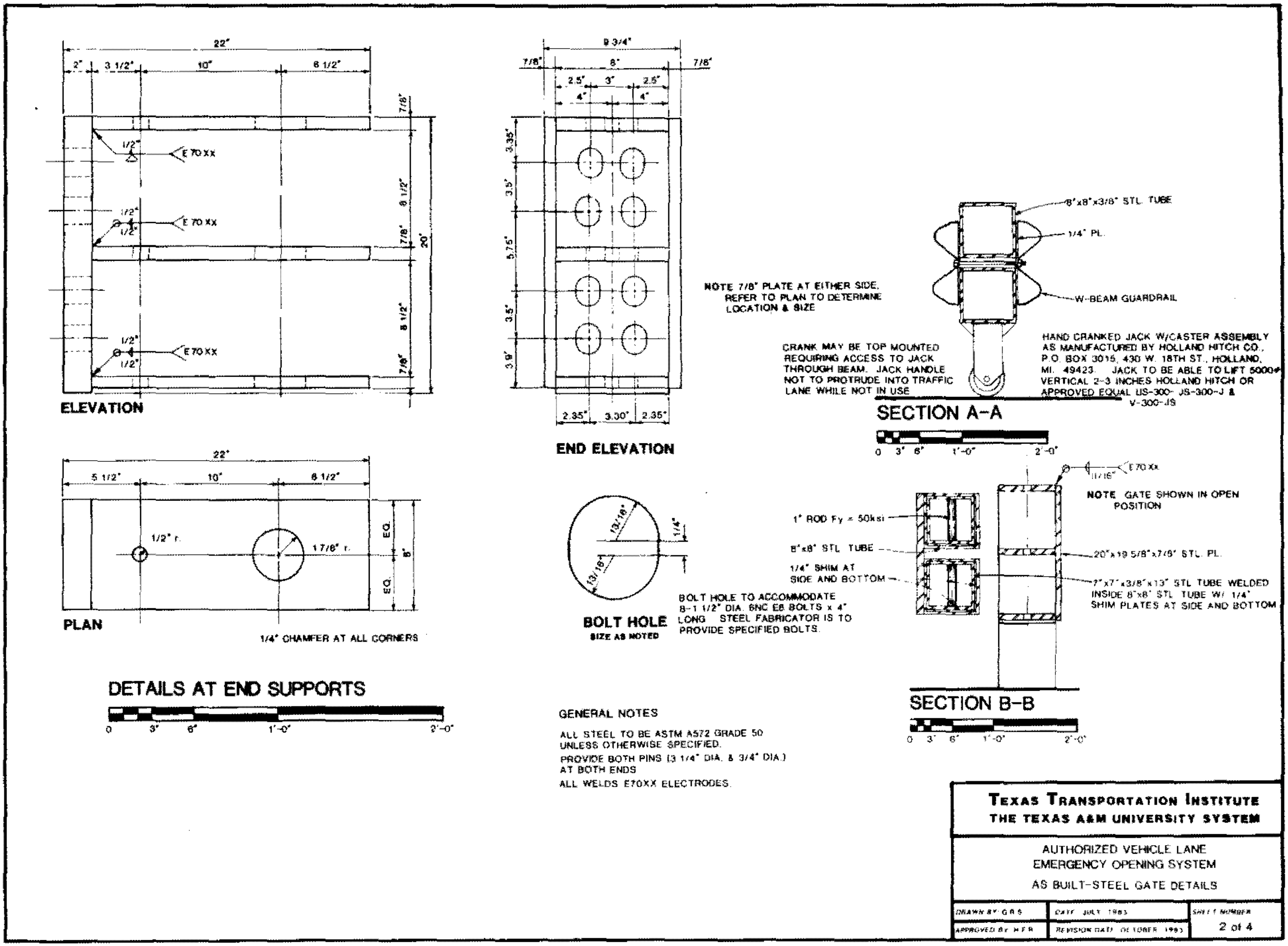


Figure 1. Emergency Opening System for Authorized Vehicle Lane. (continued)

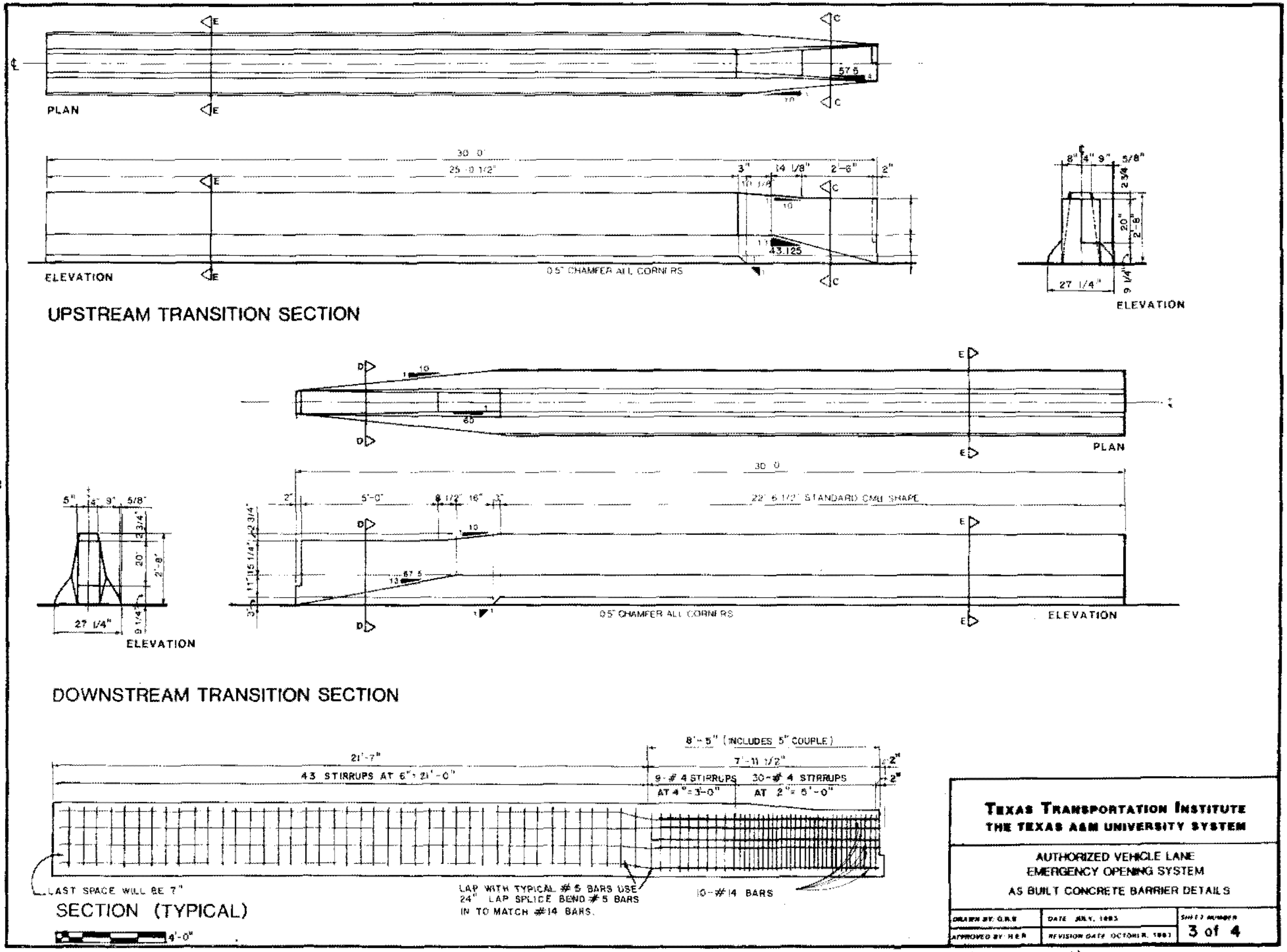


Figure 1. Emergency Opening System for Authorized Vehicle Lane. (continued)

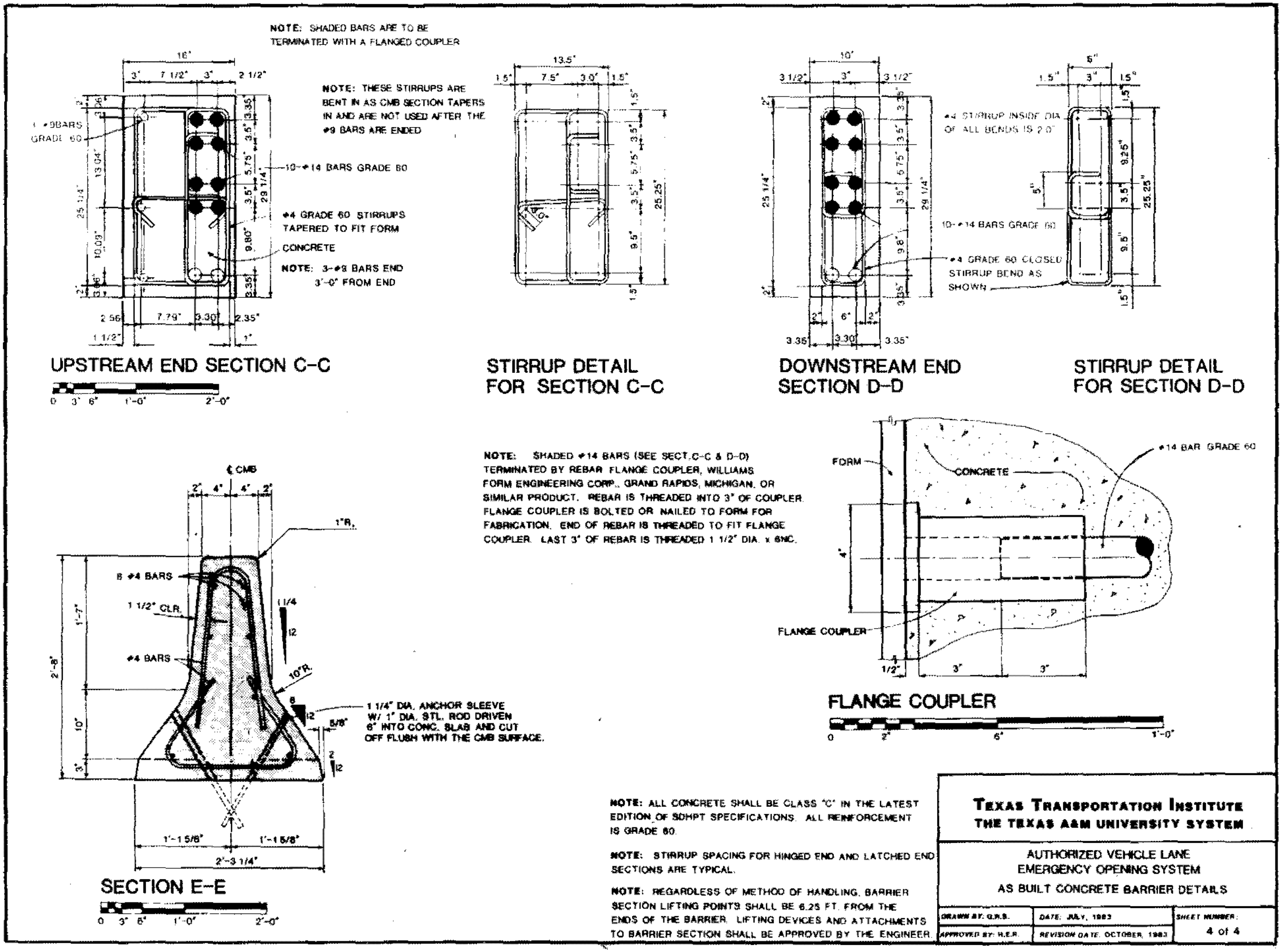
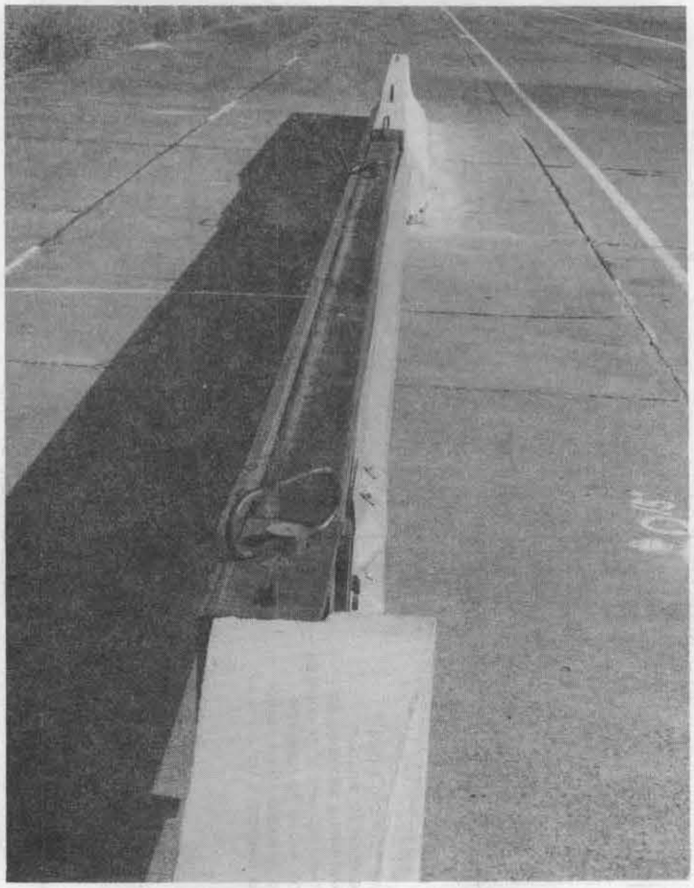


Figure 1. Emergency Opening System for Authorized Vehicle Lane. (continued)



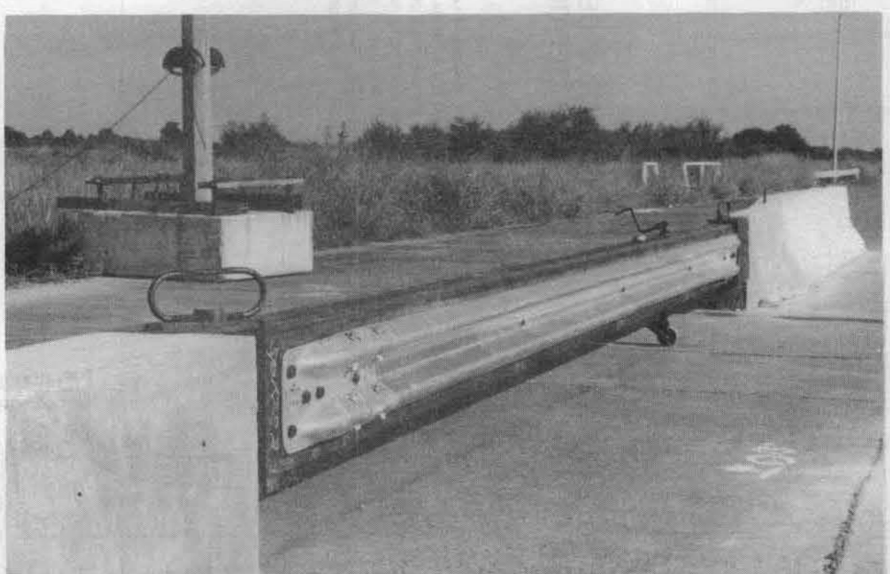


Figure 2. Emergency Opening System.

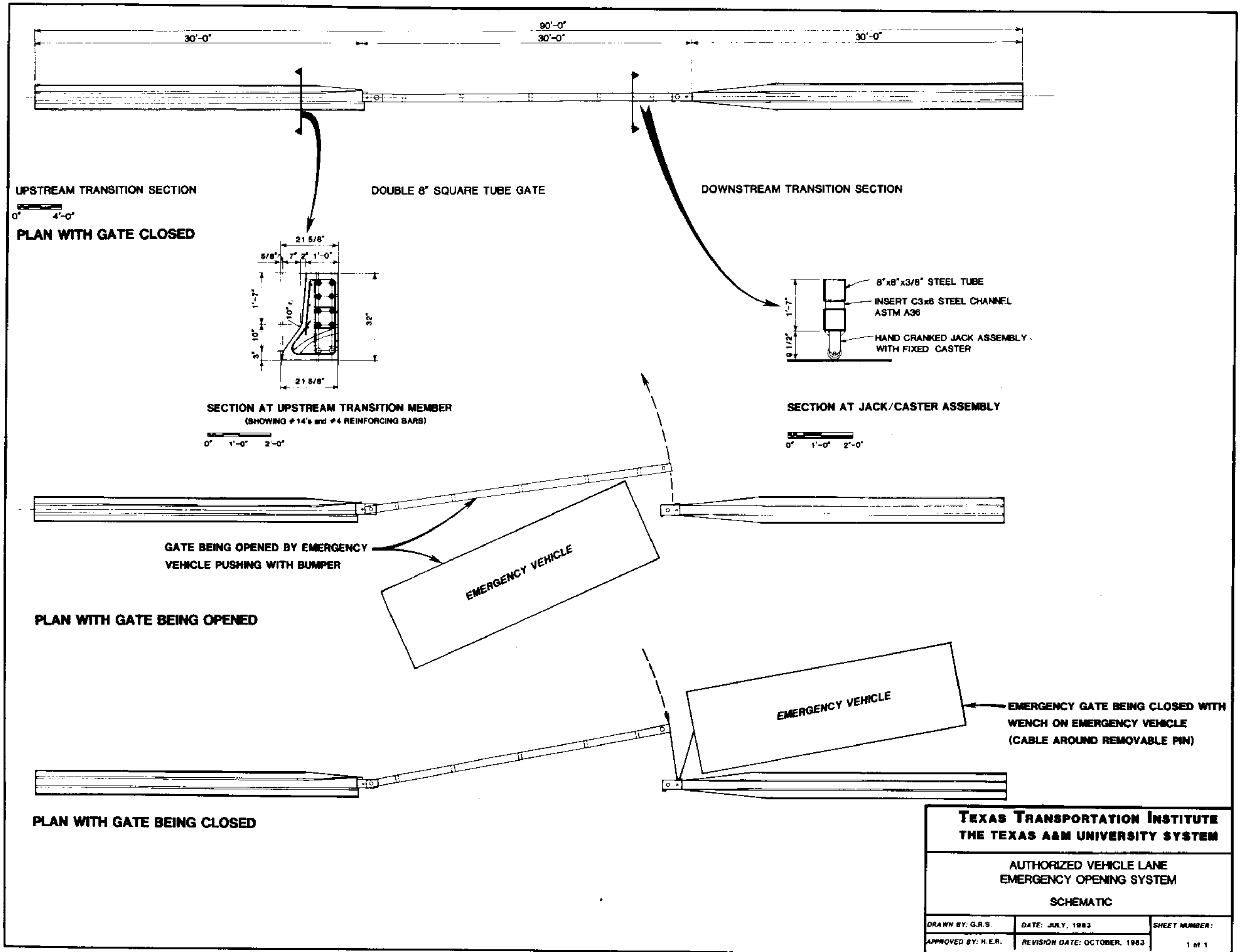


Figure 3. Emergency Opening System in Operation.

quadruple shear. The pins transferred the load to three tongue plates. The tongue plates were welded to a base plate that was attached to the concrete median barrier section by eight 1.5 in. (3.8 cm) diameter anchor bolts. The anchor bolts were screwed into rebar flange couplers manufactured by Williams Form Engineering Corporation of Grand Rapids, Michigan. Ten #14 reinforcement bars 8 ft (3.1 m) long were used in each CMB section to transfer the design loads from the steel gate to the CMB section. The #14 reinforcement bars were located in the part of the CMB section that was closest to the steel gate. The last 3 in. (7.6 cm) of the top eight #14 bars was threaded so that the reinforcement bars could screw into the rebar flange couplers. The last 8 ft (3.1 m) of the concrete median barrier before the gate had different shaped stirrups and a different cross-sectional geometry from that used in the standard CMB cross-section.

The steel tubes had a 3.5 in. (8.9 cm) diameter hole cut in them at each end for the pins. Both of these holes were reinforced with a 3.5 in. (8.9 cm) diameter schedule 40 steel pipe sleeve insert. The main tubes also had a short steel tube insert welded inside them at each end. The inserts were designed to reduce the potential for the pins to fail the tubes. The 1.38 in. (3.5 cm) vertical gap between the beams was kept constant over the length of the tubes by steel straps that were welded onto both sides of the tubes. These straps helped the two separate tubes to act as one unit and facilitated the mounting of the W-beam on both sides of the tubes. End shoes were used with the W-beams to reduce the snagging potential of the system. The CMB part of the system was held in place by 1.25 in. (3.2 cm) diameter anchor rods driven 6 to 8 in. (15.2 to 20.3 cm) into the pavement. There were eight anchor rods in each CMB section. The rods were separated by a center-to-center spacing of 6.5 ft (2.0 m) and the rods were angled toward the center of the CMB at approximately 45 degrees.

There were three features included in the design of the EOS to facilitate the opening and closing of the gate by the emergency vehicle operator. The first feature was a top mounted jack and caster assembly manufactured as a single unit by Holland Hitch Inc. of Holland, Michigan. The system was designed to open into the bus lane at one end only, thus requiring one jack and caster mechanism. The second feature consisted of two sets of vertical 1 in. (2.5 cm) diameter rods. One rod was welded in the end of the tubes and the other rod was inserted through a hole cut in the tongue plates. The emergency vehicle operator could then wrap a cable or chain around the rods and pull the gate shut with the emergency vehicle. The final feature was the vertical clearance between the beams and the tongue plates, and the slotted holes cut in the tongue plates.

Tests were conducted after the EOS was fabricated to demonstrate the amount of time required to open and close the steel gate by an emergency vehicle operator. The complete EOS tested was 90 ft (27.4 m) long and cost approximately $19,300. The cost included two 30 ft (9.1 m) long modified CMB sections. At a cost of $215/ft ($705./m), the barrier is reasonably priced when compared to other alternatives. The average cost of repairing the EOS after three full-scale crash tests was approximately $2440. This value includes the cost to replace the downstream CMB section after the third test.

CRASH TEST RESULTS

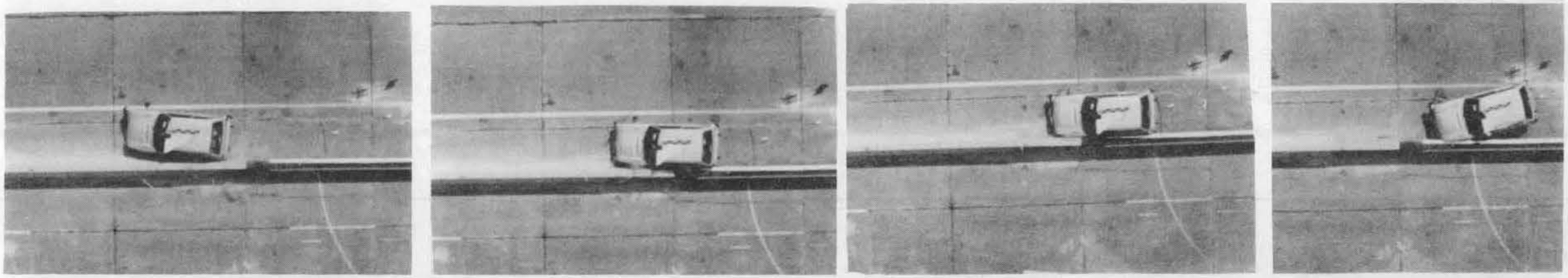
Three full-scale crash tests were conducted on the EOS as shown in Figures 1 and 2. The tests conducted were designed to evaluate the limits of performance of the barrier. The vehicle impact point for test 1 and for test 3 was 6 ft (1.8 m) upstream from the downstream end of the gate system. This point of impact should cause the maximum forces on the CMB anchorage system, and the maximum forces on the steel gate to the CMB section connection. In addition, this impact point should give the greatest possibility of vehicle snag on the barrier. The impact point for test 2 was 6 ft (1.8 m) upstream from the midpoint of the gate. This point of impact should cause maximum beam deflections and maximum forces in the beam. The tests are summarized in Table 1. Data acquisition systems are described in Appendix A. Sequential photographs of the tests are given in Appendix B. Appendix C shows accelerometer traces and plots of roll, pitch, and yaw angles.

Test 1

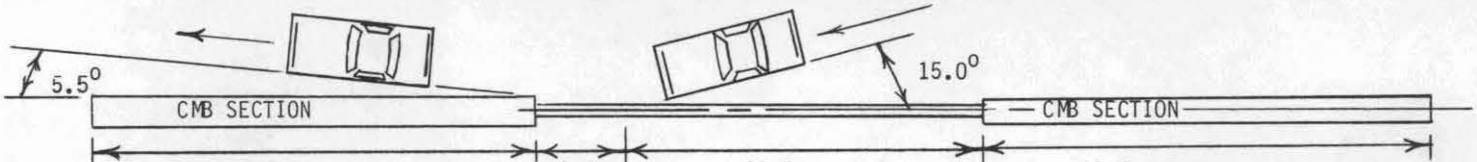
In the first test, an 1800 lb (815 kg) Honda Civic 1200 (1977) impacted the EOS 6 ft (1.8 m) upstream from the downstream end of the steel gate system at 55.2 mph (88.8 km/h) and 15 degrees. Figure 4 contains a summary of this test. The test vehicle was smoothly redirected. The vehicle exit angle and speed were 5.5 degrees and 48.0 mph (77.3 km/h), respectively. The occupant impact velocities were 14.15 ft/sec (4.31 m/s) longitudinal and 16.42 ft/sec (5.00 m/s) lateral. The peak 50 ms

TABLE 1. SUMMARY OF CRASH TESTS

Test	1	2	3
Vehicle Weight, lbs (kg)	1800 (815)	4500 (2040)	4500 (2040)
Impact Speed, mph (km/h)	55.2 (88.8)	60.7 (97.7)	60.04 (96.6)
Impact Angle, degrees	15.0	25.25	25.5
Exit Speed, mph (km/h)	48.0 (77.3)	47.96 (77.2)	39.01 (62.8)
Exit Angle, degrees	5.5	4.0	1.75
Maximum Beam Deflection, Dynamic, in. (cm)	3.36 (8.53)	17.16 (43.59)	30.84 (78.33)
Permanent, in. (cm)	0.0	1.63 (4.14)	23.88 (60.66)
Maximum CMB Movement Dynamic, in. (cm)	2.04 (5.18)	15.12 (38.40)	31.68 (80.47)
Permanent, in. (cm)	0.0	3.75 (9.53)	24.00 (60.96)
Maximum CMB Roll, degrees	0.0	3.5	9.0
Maximum CMB Yaw, degrees	0.0	0.0	5.5
Occupant Impact Velocity Longitudinal,ft/sec (m/s)	14.15 (4.32)	18.89 (5.76)	25.62 (7.81)
Lateral, ft/sec (m/s)	16.42 (5.00)	22.77 (6.94)	20.54 (6.26)
Vehicle Accelerations, g's Occupant Ride Down			
Longitudinal	1.49	8.21	4.11
Lateral	10.83	7.78	6.99
Peak 50 ms Average, g's			
Longitudinal	4.27	5.77	8.59
Lateral	7.52	9.32	8.32
Vehicle Damage Classification			
TAD	10LFQ4	11LFQ5	11FL6
VDI	10LFEW3	11LDEW4	11FDAW6



0.288 sec | 0.193 sec | 0.0143 sec | 0.048 sec



Test Number	0999-1
Test Date	9-5-83
Vehicle	
Model	Honda Civic 1200 (1977)
Mass, lb (kg)	1800 (815)
Speed, mph (km/h)	
Impact	55.2 (88.8)
Exit	48.0 (77.3)
Angle, degrees	
Impact	15.0
Exit	5.5
Maximum Beam Deflection	
Dynamic, in (cm)	3.36 (8.53)
Maximum CMB Movement	
Dynamic, in. (cm)	2.04 (5.18)

Occupant Impact Velocity, ft/s (m/s)	
Longitudinal	14.15 (4.32)
Lateral	16.42 (5.00)
Vehicle Accelerations, g's	
Occupant Ride Down	
Longitudinal	1.49
Lateral	10.83
Peak 50 ms Average	
Longitudinal	4.27
Lateral	7.52
Vehicle Damage Classification	
TAD	10LFQ4
VDI	10LFEW3

Figure 4. Summary of Test 1.

average acceleration was 4.27 g's longitudinal and 7.52 g's lateral. All of the occupant risk values as well as the vehicle trajectory hazard are below recommended values (4) for this type of test.

The test vehicle before and after the test is shown in Figure 5. Figure 6 shows the test installation before and after the test. Damage to the vehicle occured when the W-beam corrugation dragged the front bumper down and the left front tire snagged on one corner of the downstream CMB section. The vehicle damage consisted of sheet metal damage to the left front fender, the left front tire was flattened and the left front tire rim was bent from the impact with the CMB. Damage to the EOS consisted of the paint being scraped off the W-beam at the impact point and some surface cracking in the downstream end of the CMB. The only repairs to the gate were repainting the W-beam at the impact point. The EOS was still operational after this test. This test was considered a success based on the barrier safety performance and the relatively light damage incurred by the system.

Test 2

Test 2 examined the strength of the gate system. In this test a 4500 lb (2040 kg) Plymouth Grand Fury (1977) impacted the EOS 6 ft (1.8 m) upstream from the midpoint of the steel gate at 60.7 mph (97.7 km/h) and 25.25 degrees. Figure 7 contains a summary of this test. The test vehicle was smoothly redirected. The occupant impact velocities were 18.89 ft/sec (5.76 m/s) longitudinal and 22.77 ft/sec (6.94 m/s) lateral. The vehicle exit angle was 4 degrees and the vehicle exit velocity was 47.96 mph (77.2 km/h). The peak 50 ms average acceleration was 5.77 g's longitudinal and 9.32 g's lateral. The vehicle accelerations were within acceptable limits (4) for this type of test. The longitudinal occupant impact velocity was also within acceptable

Figure 5. Test Vehicle Before and After Test 1.

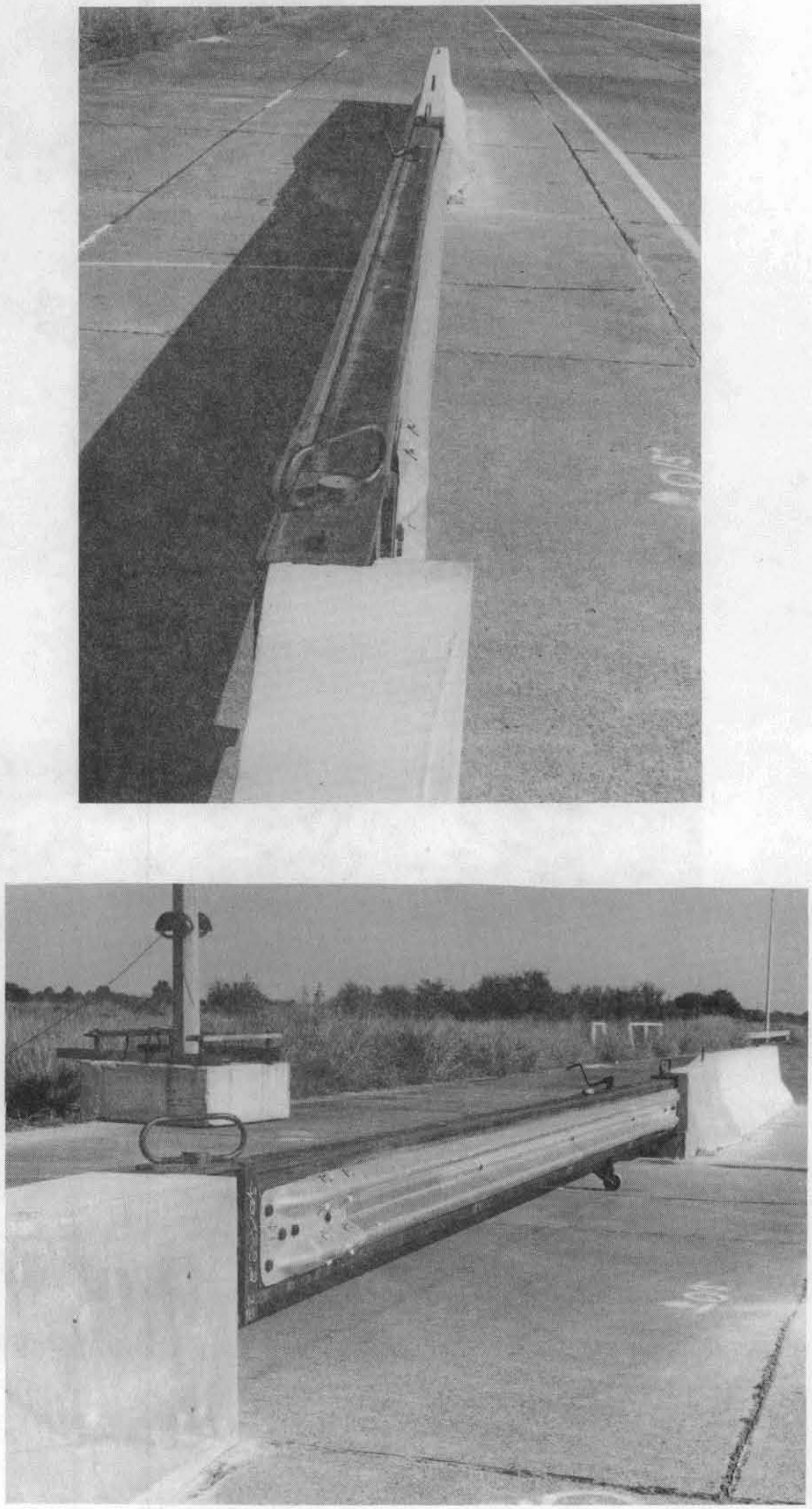
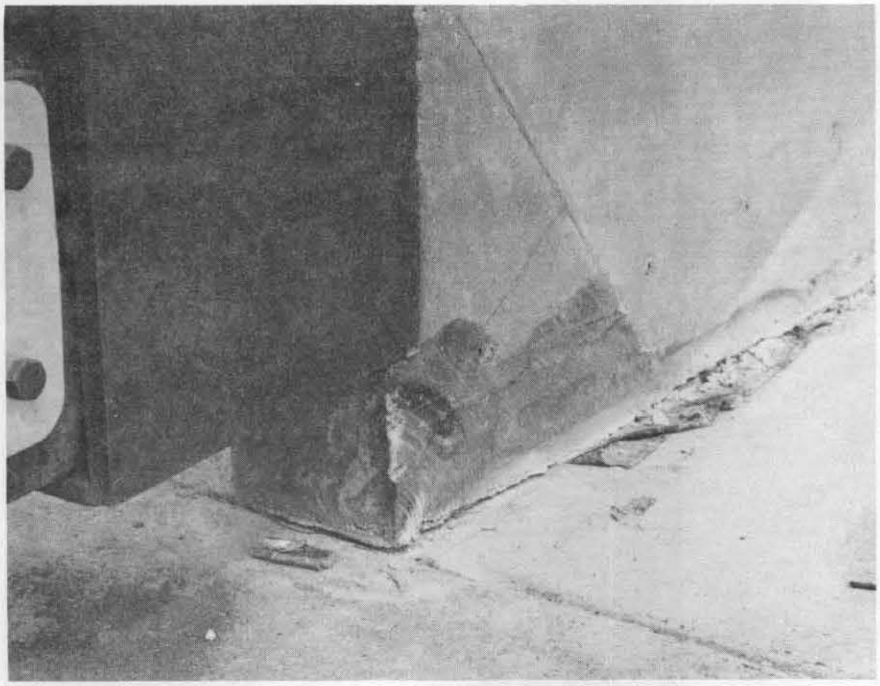


Figure 6. Test Installation Before and After Test 1.



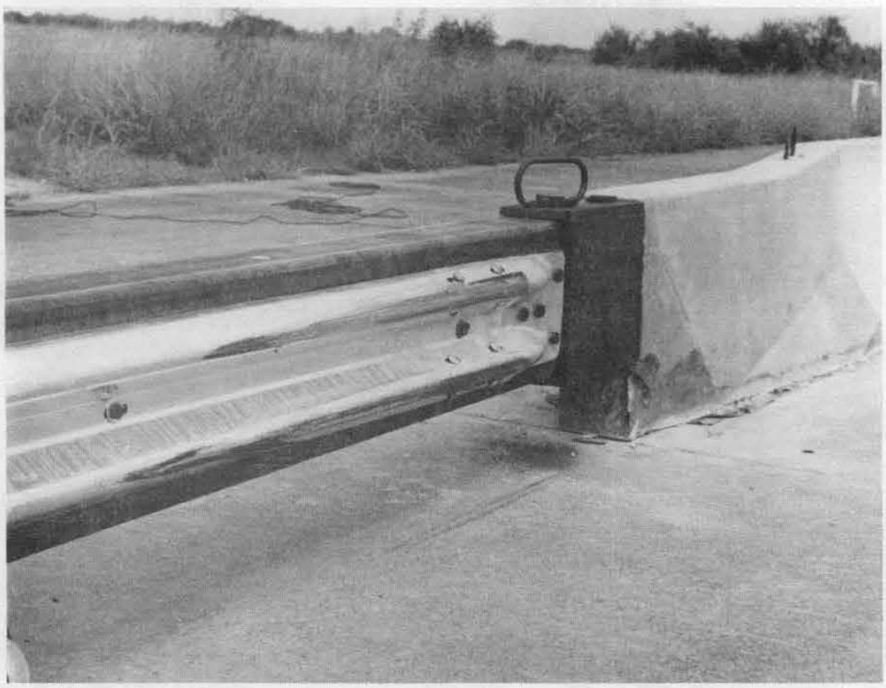
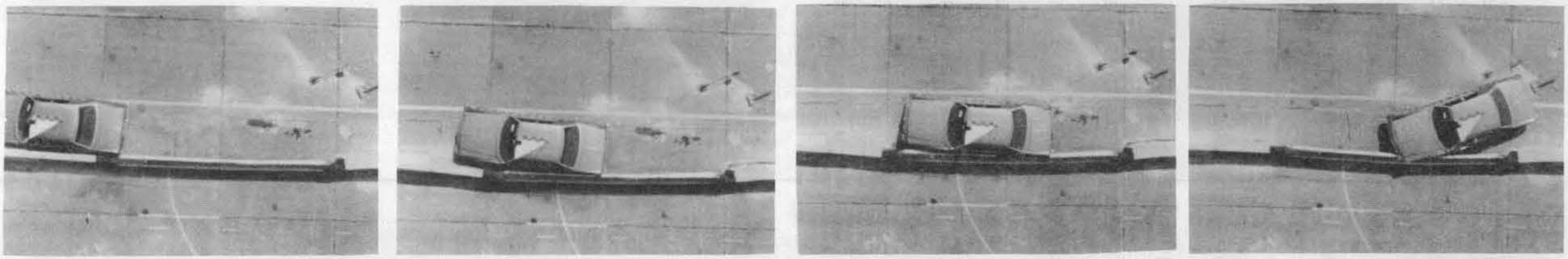
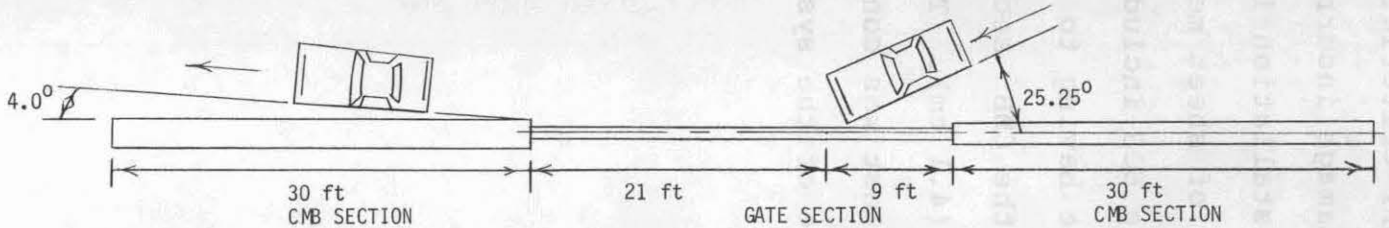


Figure 6. Test Installation Before and After Test 1 (continued).



0.491 sec | 0.328 sec | 0.246 sec | 0.083 sec



Test Number	0999-2
Test Date	9-7-83
Vehicle	
Model	Plymouth Grand Fury (1977)
Mass, lb (kg)	4500 (2040)
Speed, mph (km/h)	
Impact	60.7 (97.7)
Exit	47.96 (77.2)
Angle, degrees	
Impact	25.25
Exit	4.0
Maximum Beam Deflection, in. (cm)	
Dynamic	17.16 (43.59)
Permanent	1.63 (4.14)
Maximum CMB Roll, degrees	3.5

Maximum CMB Movement, in. (cm)	
Dynamic	15.12 (38.40)
Permanent	3.75 (9.53)
Occupant Impact Velocity, ft/s (m/s)	
Longitudinal	18.89 (5.76)
Lateral	22.77 (6.94)
Vehicle Accelerations, g's	
Occupant Ride Down	
Longitudinal	8.21
Lateral	7.78
Peak 50 ms Average	
Longitudinal	5.77
Lateral	9.32
Vehicle Damage Classification	
TAD	11LFQ5
VDI	11LDEW4

Figure 7. Summary of Test 2.

limits, but the lateral occupant impact velocity exceeded the recommended value. Although the lateral occupant impact velocity for this test exceeded the recommended value, it was less than the limiting value. In addition, this type of test was not required to meet the NCHRP criteria.

Figure 8 shows the damage incurred by the test vehicle. The damage to the test installation is shown in Figure 9. The vehicle damage consisted of sheet metal damage to the left front fender. Damage to the EOS included the W-beam on the vehicle impact side of the gate having to be replaced and noticeable flexural cracking in the CMB sections. The permanent beam deflection was 1.63 in. (4.1 cm). The gate could still be opened after this test. This test was considered very successful based on the safety performance of the system.

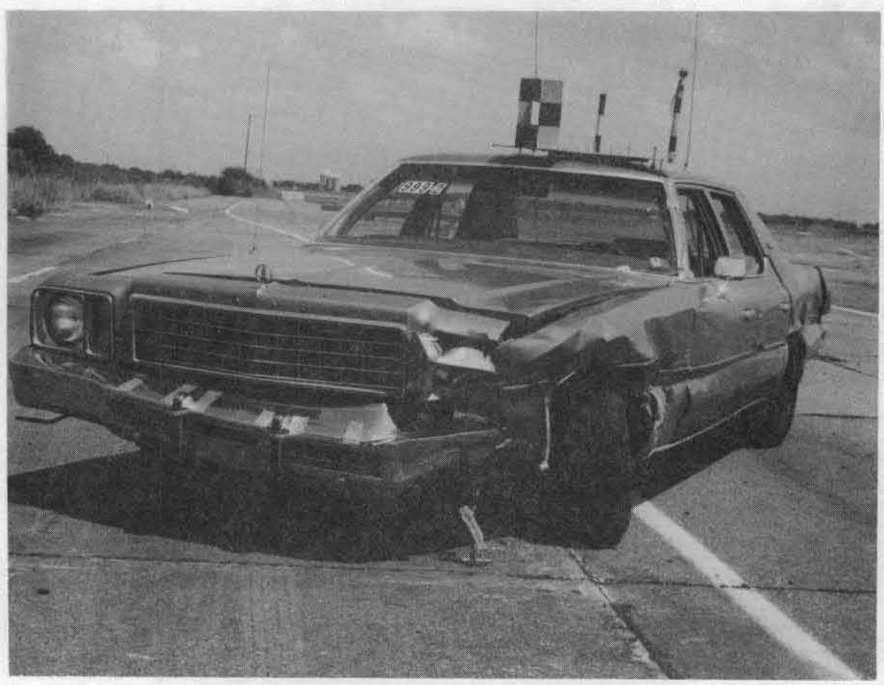


Figure 8. Test Vehicle Before and After Test 2.

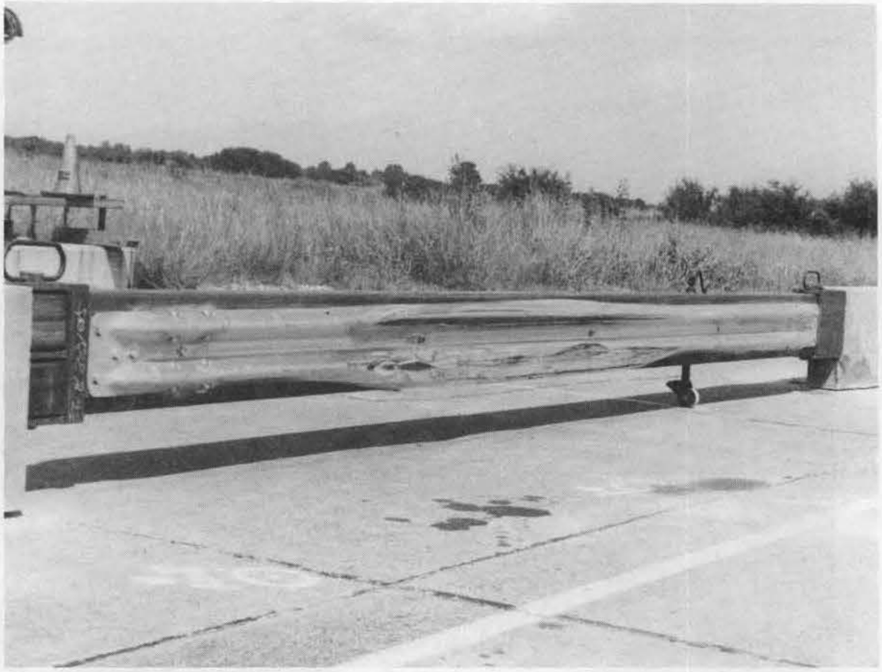


Figure 9. Test Installation Before and After Test 2.

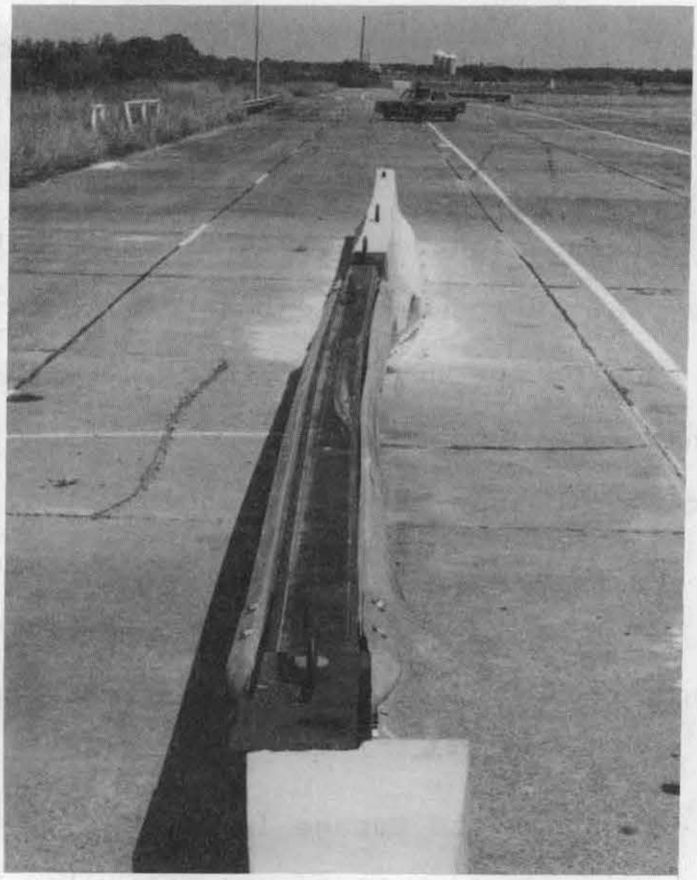
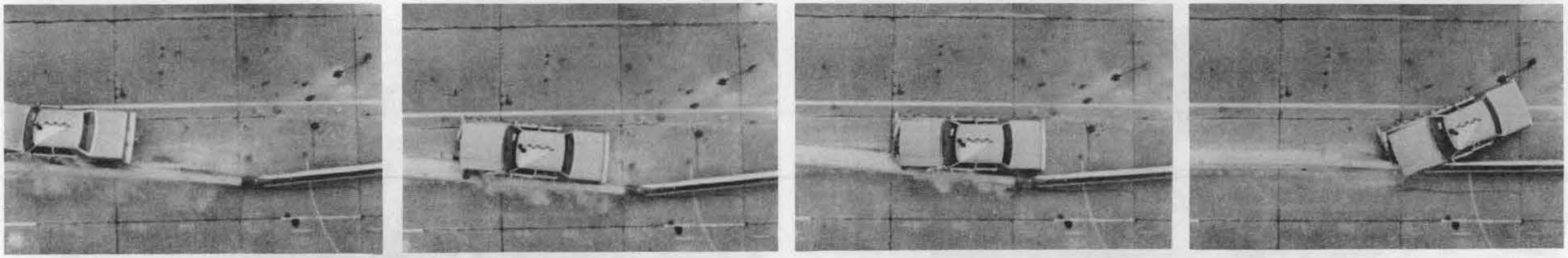


Figure 9. Test Installation Before and After Test 2 (Continued).

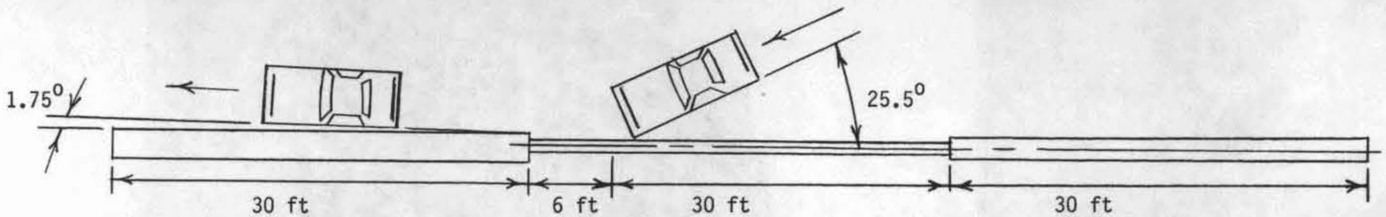
Test 3

Test 3 examined the strength of the beam to CMB connection. In this test a 4500 lb (2040 kg) Plymouth Grand Fury (1977) impacted the EOS 6 ft (1.8 m) upstream from the downstream end of the steel gate system at 60.04 mph (96.6 km/h) and 25.5 degrees. Figure 10 contains a summary of this test. The test vehicle was smoothly redirected. The vehicle exit angle was 1.75 degrees and the vehicle exit speed was 39.01 mph (62.8 km/h). The occupant impact velocities were 25.62 ft/sec (7.81 m/s) longitudinal and 20.54 ft/sec (6.26 m/s) lateral. The peak 50 ms average acceleration was 8.59 g's longitudinal and 8.32 g's lateral. The vehicle accelerations were within acceptable limits (4) for this type of test. The lateral occupant impact velocity was also within recommended limits, but the longitudinal occupant impact velocity exceeded the recommended value. Although the longitudinal occupant impact velocity for this test exceeded the recommended value, it was less than the limiting value. In addition, this type of test was not required to meet this criteria.

Figure 11 shows the damage incurred by the test vehicle. The damage to the test installation is shown in Figure 12. The test vehicle was severely damaged in this test when the vehicle snagged on the downstream CMB section. The permanent deflection of the gate was 23.88 in. (60.66 cm). Damage to the gate section consisted of the W-beam on the impact side of the tubes having to be replaced. The downstream CMB section was severely damaged due to flexure cracking and when one of the anchor rods failed the concrete. The upstream CMB section was also severely damaged due



0.573 sec 0.382 sec 0.285 sec 0.094 sec



Test Number	0999-3
Test Date	9-9-83
Vehicle	
Model	Plymouth Grand Fury (1977)
Mass, lb (kg)	4500 (2040)
Speed, mph (km/h)	
Impact	60.04 (96.6)
Exit	39.01 (62.8)
Anlge, degrees	
Impact	25.5
Exit	1.75
Maximum CMB Roll, degrees	9.0
Maximum CMB Yaw, degrees	5.5
Maximum Beam Deflection, in. (cm)	
Dynamic	30.84 (78.33)
Permanent	23.88 (60.66)

Maximum CMB Movement, in. (cm)	
Dynamic	31.68 (80.47)
Permanent	24.00 (60.96)
Occupant Impact Velocity, ft/s (m/s)	
Longitudinal	25.62 (7.81)
Lateral	20.54 (6.26)
Vehicle Accelerations, g's	
Occupant Ride Down	
Longitudinal	4.11
Lateral	6.99
Peak 50 ms Average	
Longitudinal	8.59
Lateral	8.32
Vehicle Damage Classification	
TAD	11FL6
VDI	11FDAW6

Figure 10. Summary of Test 3.

Figure 11. Test Vehicle Before and After Test 3.

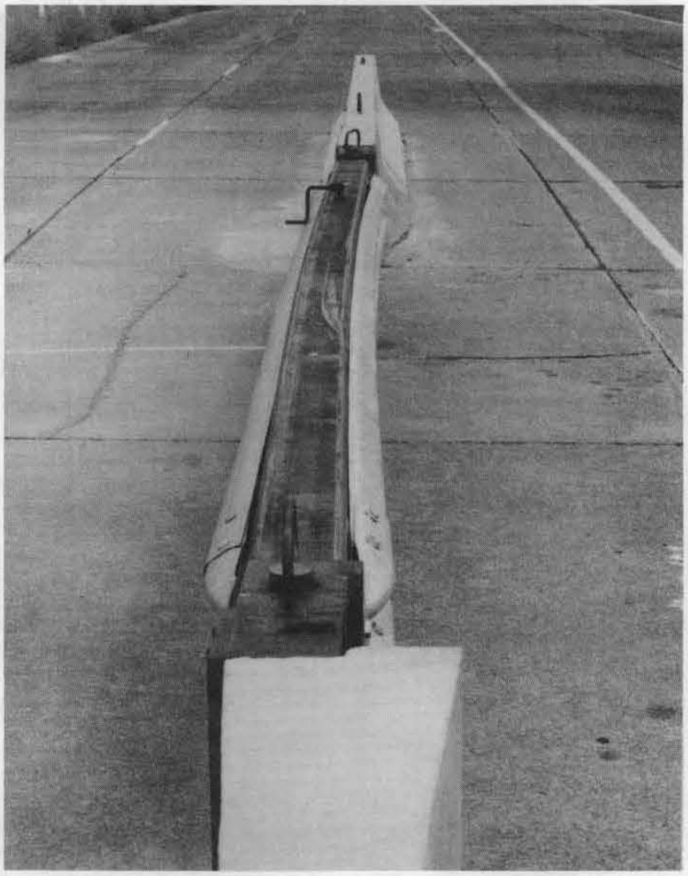


Figure 12. Test Installation Before and After Test 3.

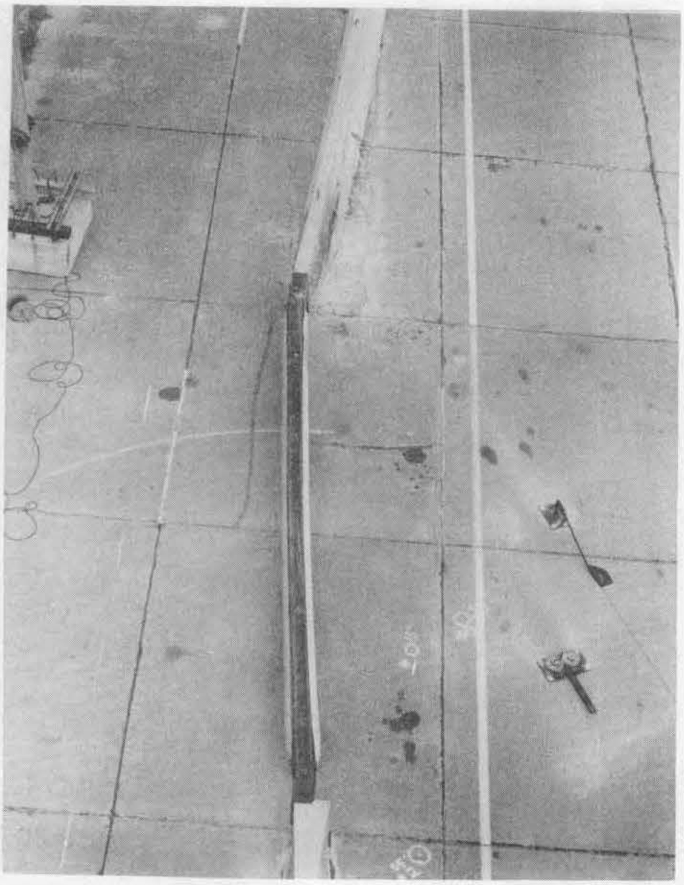


Figure 12. Test Installation Before and After Test 3 (Continued).

Figure 12. Test Installation Before and After Test 3 (Continued).

to flexural cracking. In addition, the gate could not be opened due to the metal tubes binding about the pin connections. However, this test was still considered a success based on the barrier's safety performance and because the vehicle did not penetrate the barrier.

SUMMARY AND CONCLUSIONS

An emergency opening system (EOS) for an authorized vehicle lane (AVL) was developed and crash tested. The system, as shown in Figures 1 and 2, consisted of two steel box tubes mounted on top of each other. The beams were supported by pins at the ends that were connected to modified concrete median barrier sections. Factors considered in its development were ease of operation and ability to redirect errant vehicles.

Three full-scale crash tests were conducted to evaluate the impact behavior of the design. In the first test, a small vehicle was smoothly redirected. In test 2, a large vehicle was smoothly redirected. In the third test a large vehicle was redirected. All of the vehicle accelerations were below recommended values for all of the crash tests. In addition, all of the occupant impact velocities were within acceptable limits for all of the crash tests except for the lateral occupant impact velocities for tests 2 and 3. Although the lateral occupant impact velocities for tests 2 and 3 exceeded the recommended value, they were less than the limiting value. Futhermore, this type of test was not required to meet this criteria. In addition, the EOS was still operational after the first two tests. The system was not operational after the third test because the anchorage system for the downstream concrete median barrier failed.

Several modifications in the design of the EOS were recommended to improve the operation of the system. These changes resulting from observations of the construction and crash testing of the system can be seen in Figure 13. The differences in the designs are listed as follows:

1. The concrete in the CMB below the steel mounting plates should be rounded to reduce the snagging potential of the EOS.
2. The stirrups in the transition section of the CMB should be increased in size from #4 reinforcement bars to #5 reinforcement bars, and the spacing between the stirrups should be increased to 3 in. (7.62 cm) center-to-center. The #14 reinforcement bars should have more horizontal clearance between them. This increased clearance will allow State Department of Highways and Public Transportation (SDHPT) Class-C concrete (5) to be used in the fabrication of the CMB.
3. The height of the concrete median barrier should be kept constant at 32 in. (81.3 cm) to accommodate the increased gap between the steel tubes.
4. The #14 reinforcement bars should be extended further into the standard CMB shape to transfer more of the load past the anchorage system. These reinforcement bars should not all be cut off at the same location.
5. The fabricator of the concrete median barrier must place the flange couplers exactly where the plans dictate, and he must be certain that the concrete face used to mount the base plate is vertical with respect to the horizontal ledge.

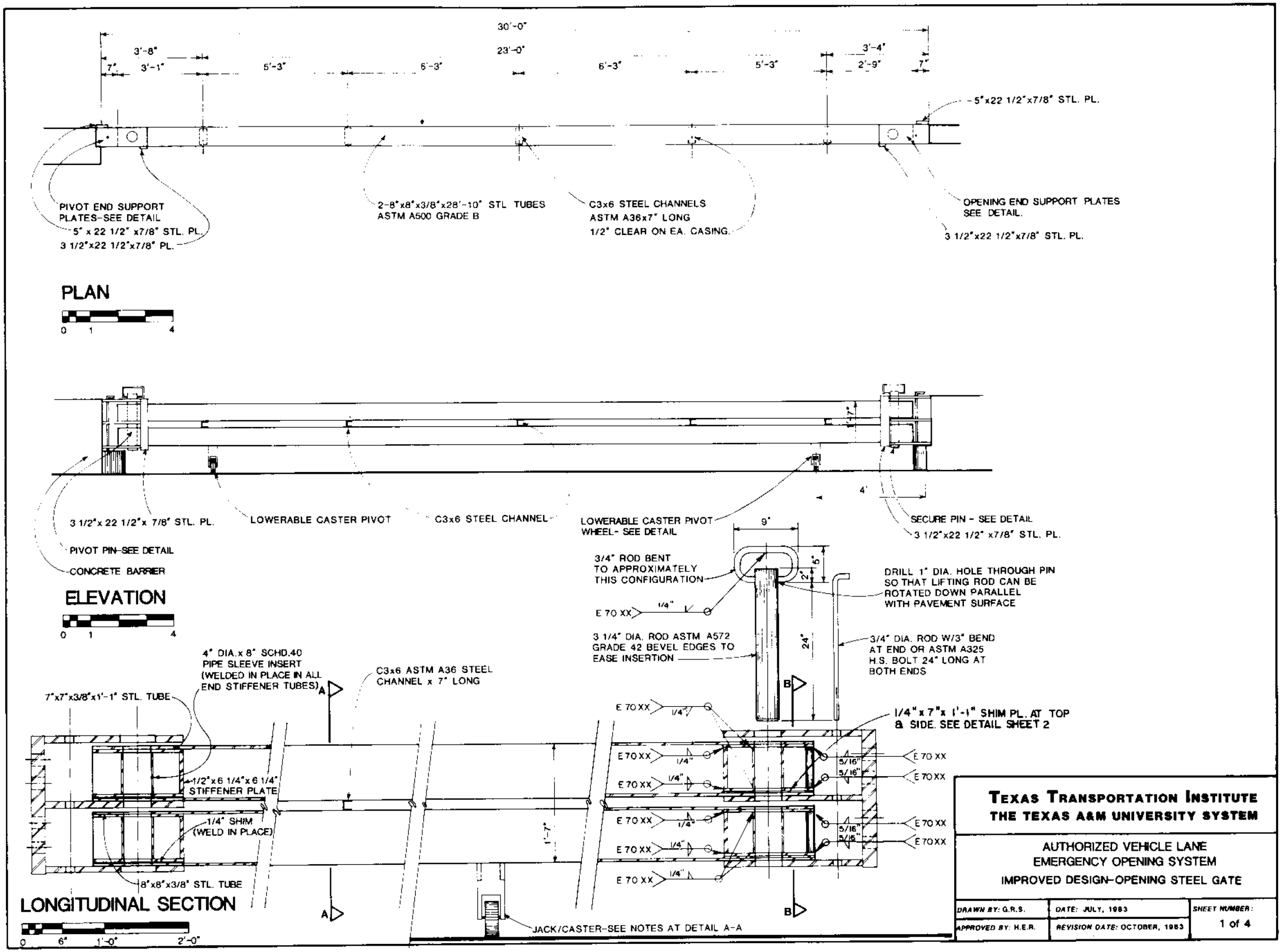


Figure 13. Design Modifications for Emergency Opening System.

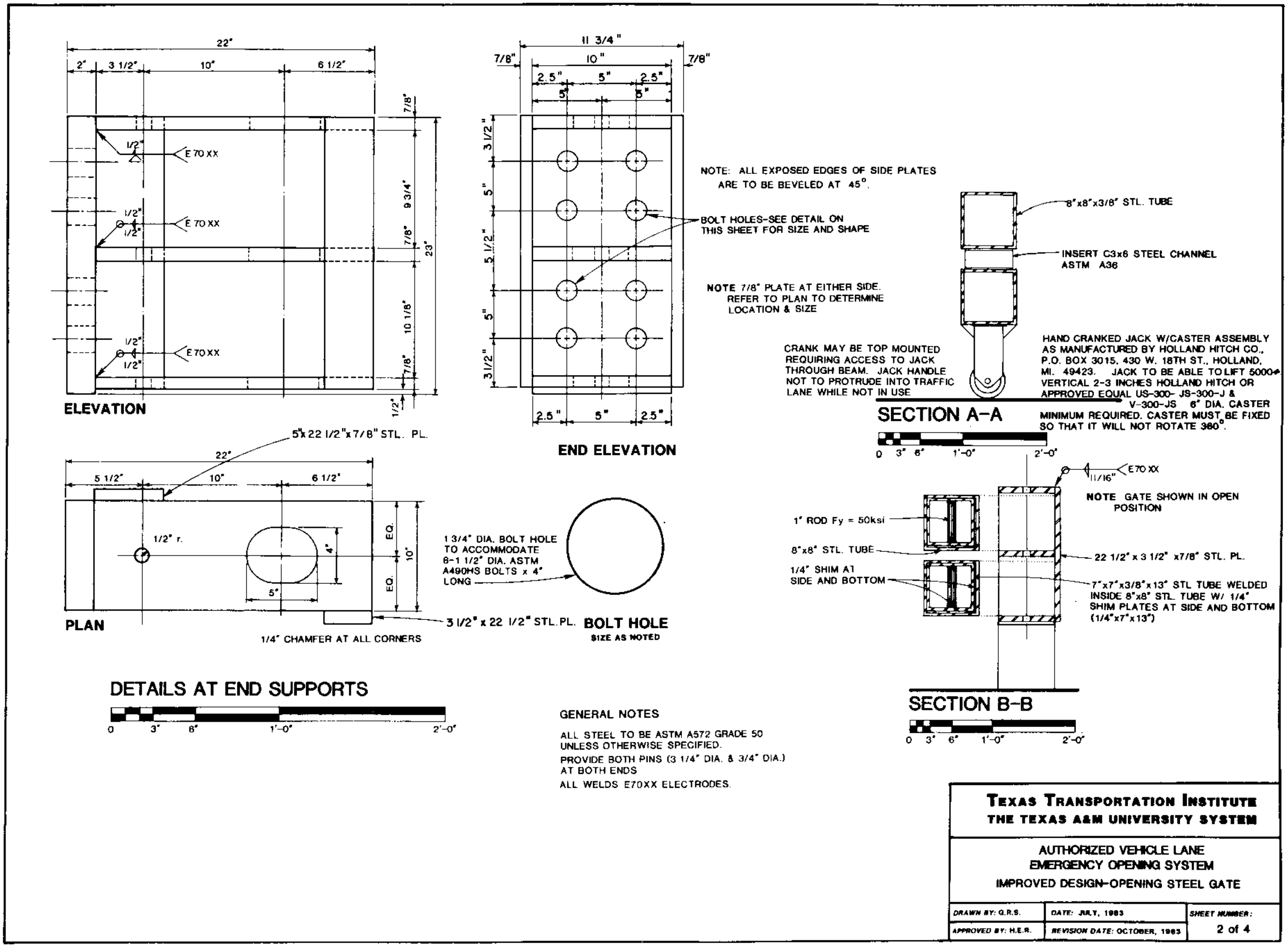


Figure 13. Design Modifications for Emergency Opening System. (continued)

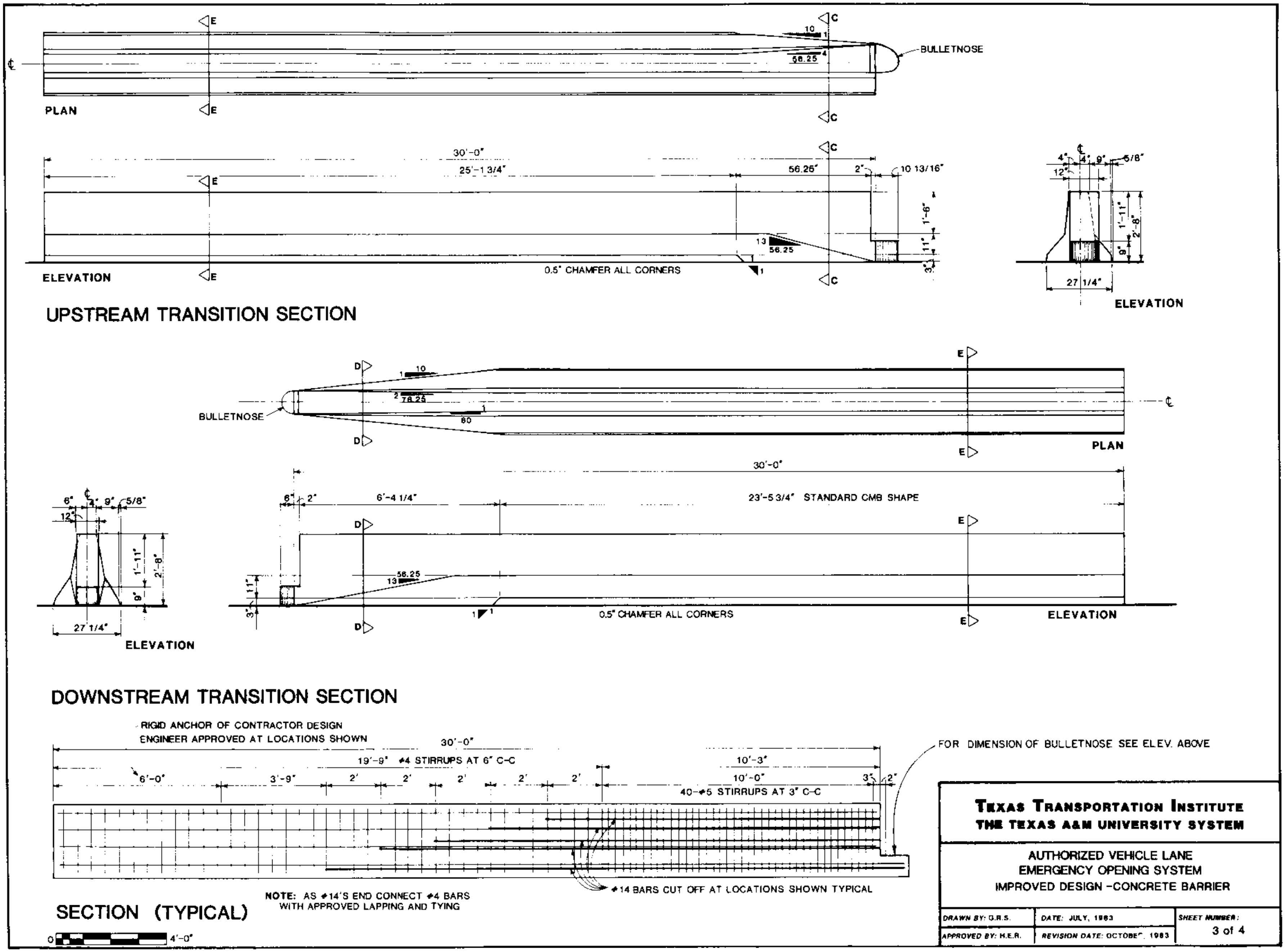


Figure 13. Design Modifications for Emergency Opening System. (continued)

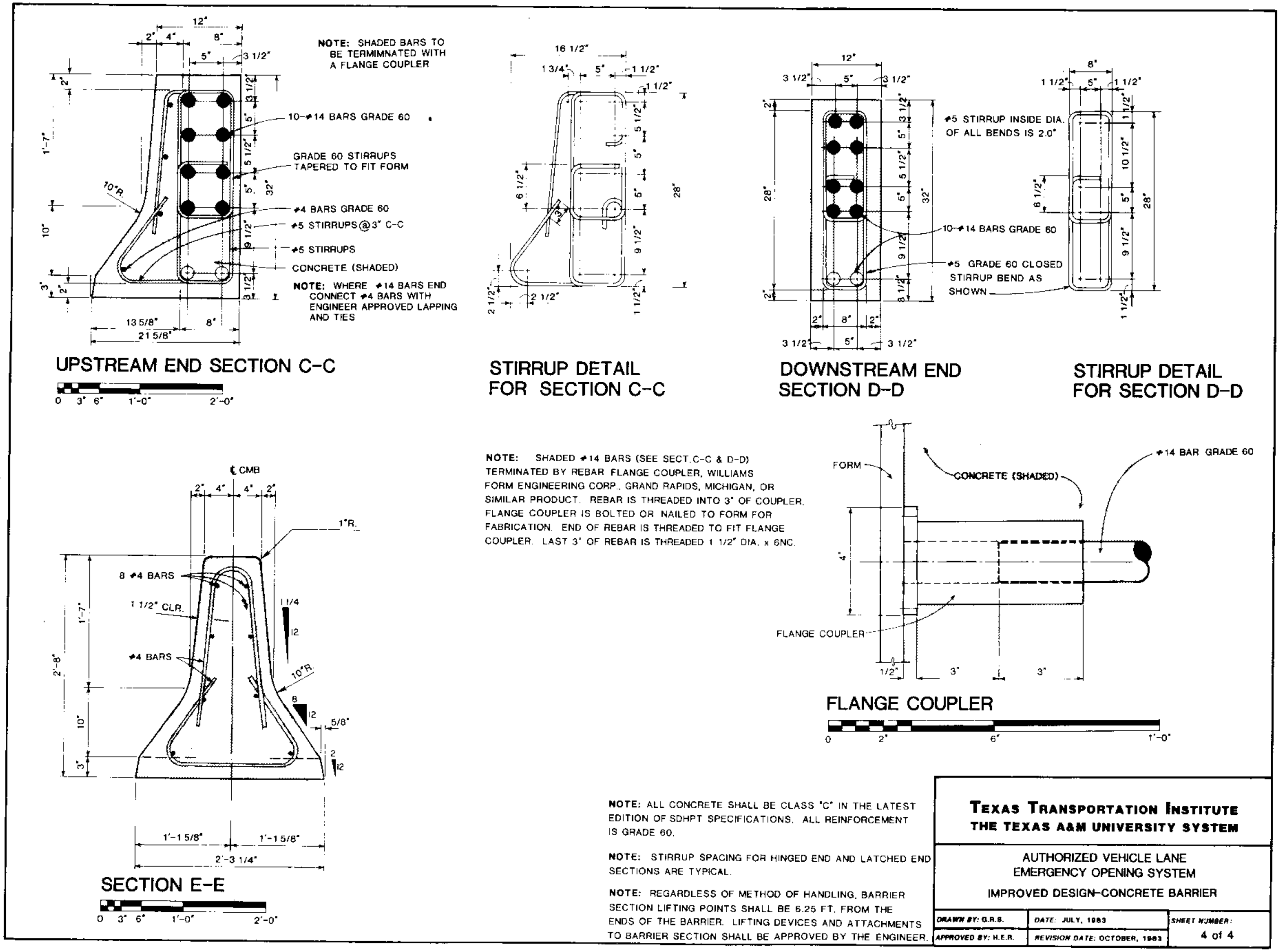


Figure 13. Design Modifications for Emergency Opening System. (continued)

6. The vertical concrete face used to mount the tongue plates should have its width increased from 10 in. (25.4 cm) to 12 in. (29.5 cm).
7. The traffic side of the upstream concrete median barrier should keep the same shape and reinforcement as the typical CMB section in the transition part of the EOS.
8. A different anchorage system should be used to anchor the CMB sections to the roadway surface.
9. The W-beams, end shoes and the side straps used to mount them should be left off the side of the box beams to reduce the snagging potential of the EOS. C3X6 steel channels should be used between the tubes in place of the steel side straps to keep the vertical clearance between the beams constant.
10. A larger diameter and wider caster should be used with the jacks to facilitate opening and closing the EOS. The caster should be fixed so that it will not rotate 360 degrees but will roll only back and forth across the roadway.
11. The pin holes in the tongue plates should be increased to 4 in. (10.2 cm) wide by 5 in. (12.7 cm) long to make it easier to open and close the gate.
12. The holes in the base plates for the anchor bolts that screw into the rebar flange couplers should be changed from slotted holes to 1.75 in. (4.4 cm) diameter holes. The bolt holes should be located as shown in Figure 13.
13. The vertical clearance between the steel tubes should be

increased to 3 in. (7.6 cm) to make it easier to open and close the EOS.

14. The pipe sleeve inserts in the tubes should be increased in size to 4 in. (10.2 cm) diameter schedule 40 steel pipe.
15. The pins used to operate the system will have to be longer to take into account the increased distance between the tubes.
16. A jack and caster mechanism should be used at both ends of the tubes so that the gate can be opened at either end.
17. The side mounted plates on the tongue plates will have to be arranged differently so that the gate can open into the authorized vehicle lane from either end, yet not open into the freeway traffic lanes. In addition, the tongue plates and the base plate that the tongue plates are welded to should have their width increased from 8 in. (20.3 cm) to 10 in. (25.4 cm).
18. The handles on the pins should be built so that they can be laid flat rather than sticking up in the air when they are not needed to raise or lower the pin.

The full-scale crash tests showed that the system tested can be used by an emergency vehicle to gain immediate access to an authorized vehicle lane. In addition, the tests showed the barrier's safety performance characteristics. Finally, the ability of the steel gate to be opened and closed from either end will allow the EOS to be used on any highway system that is separated by concrete median barriers.

APPENDIX A

DATA ACQUISITION SYSTEMS

Instrumentation

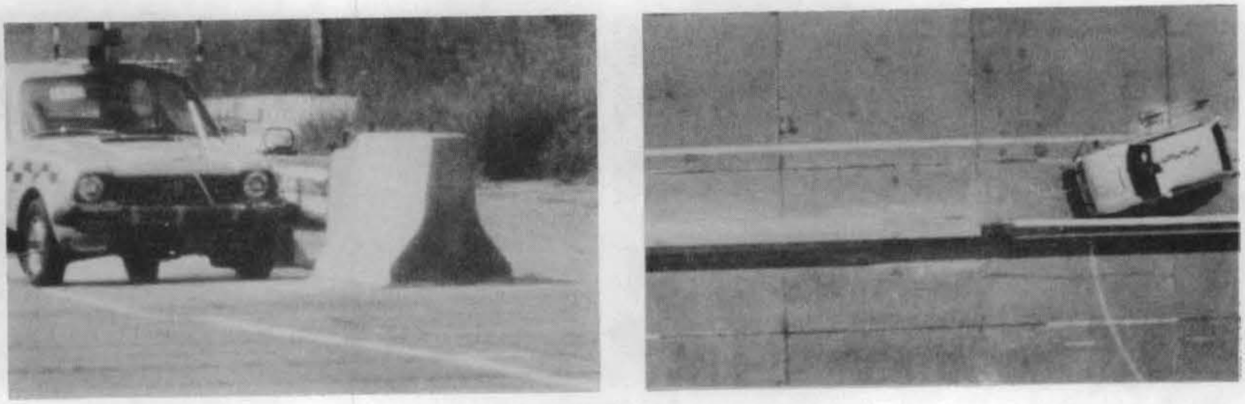
Test vehicles were equipped with triaxial accelerometers mounted near the center of gravity. Yaw, pitch and roll were sensed by on-board gyroscopic instruments. The analog signals were telemetered to a base station for recording on magnetic tape and display on real-time strip chart. Provision was made for transmission of calibration signals before and after the test, and an accurate time reference signal was simultaneously recorded with the data.

Tape switches near the impact area were actuated by the vehicle to indicate elapsed time over a known distance to provide a quick check of impact speed. The initial contact also produced an "event" mark on the data record to establish the instant of impact.

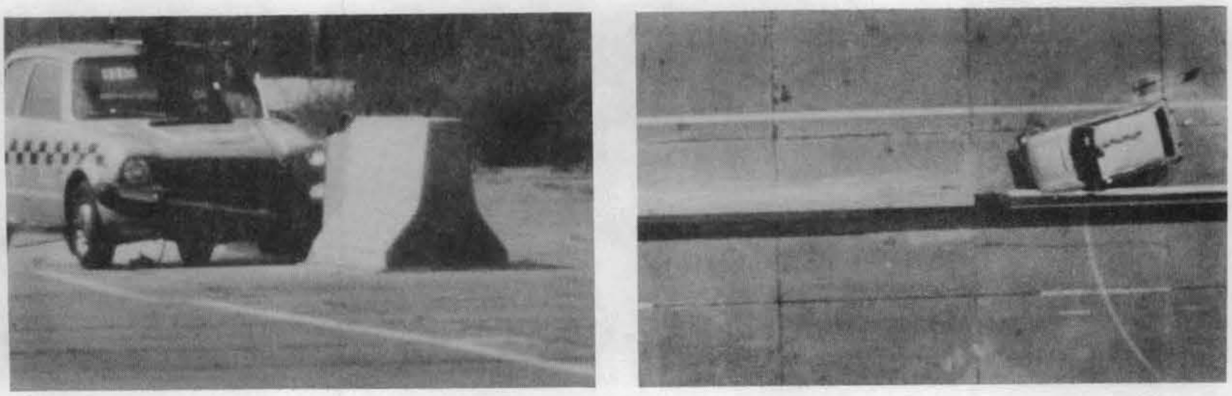
High-speed motion pictures were obtained from various locations, including overhead, to document the events and provide a time-displacement history. Film and electronic data were synchronized through a visual/ electronic event signal at initial contact.

APPENDIX B

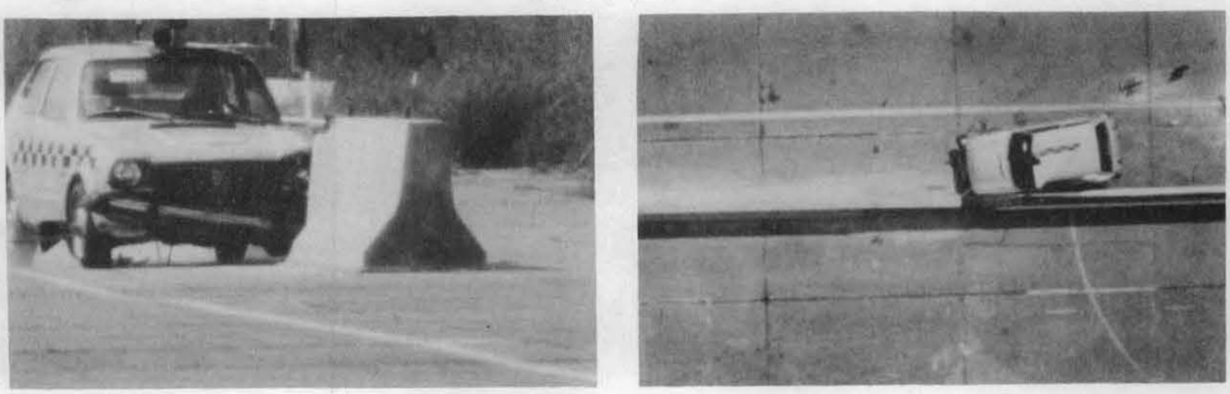
SEQUENTIAL PHOTOGRAPHS



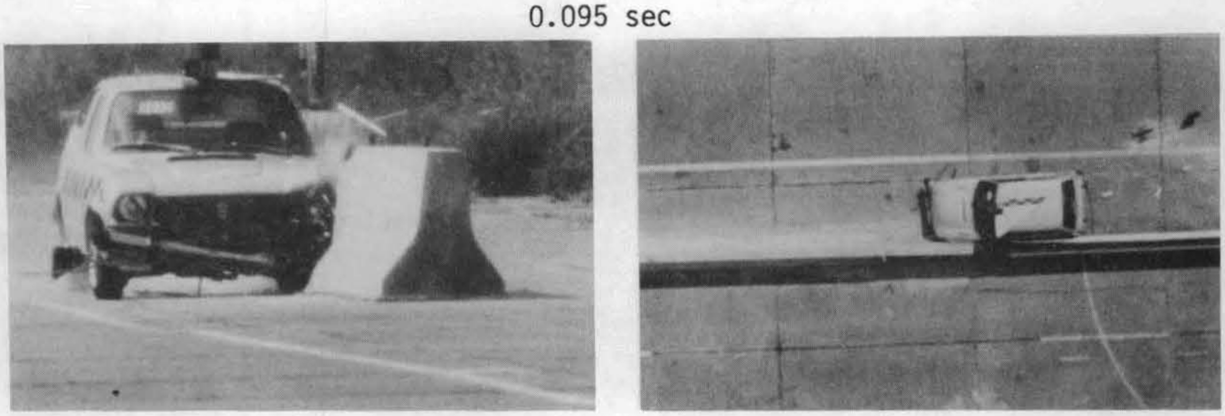
0.000 sec



0.048 sec

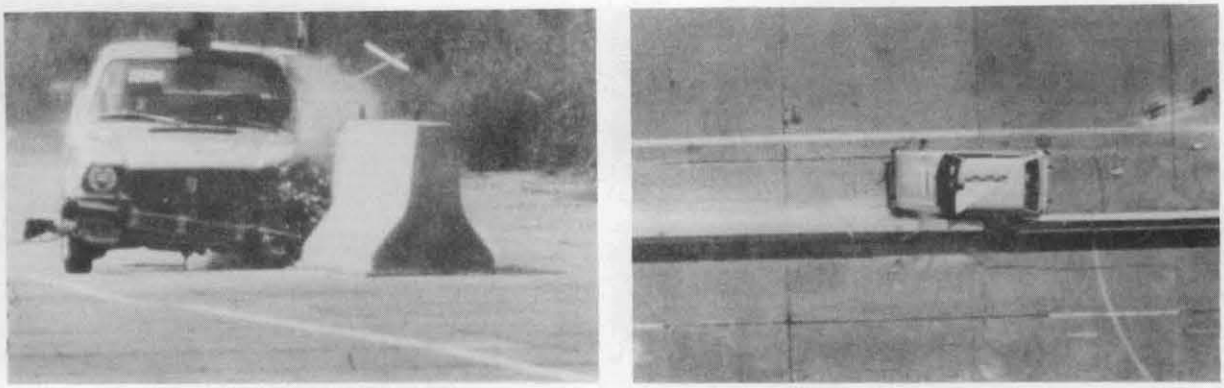


0.095 sec

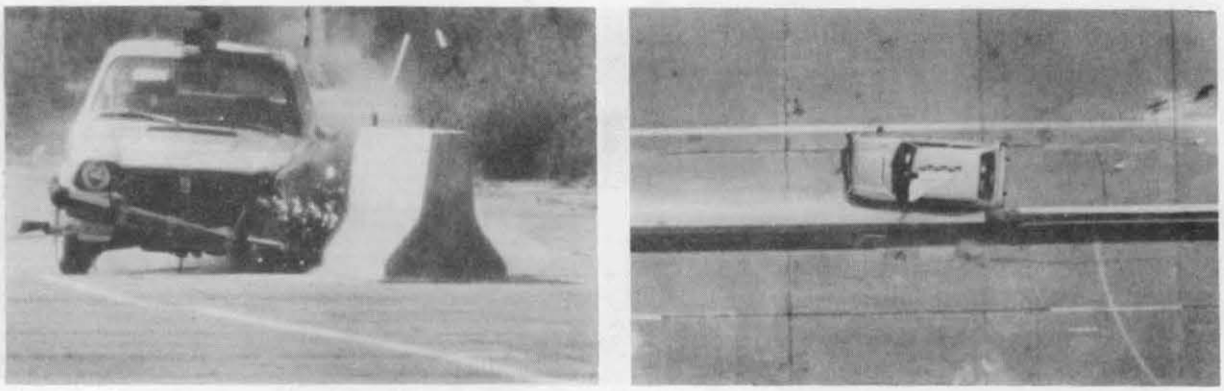


0.0143 sec

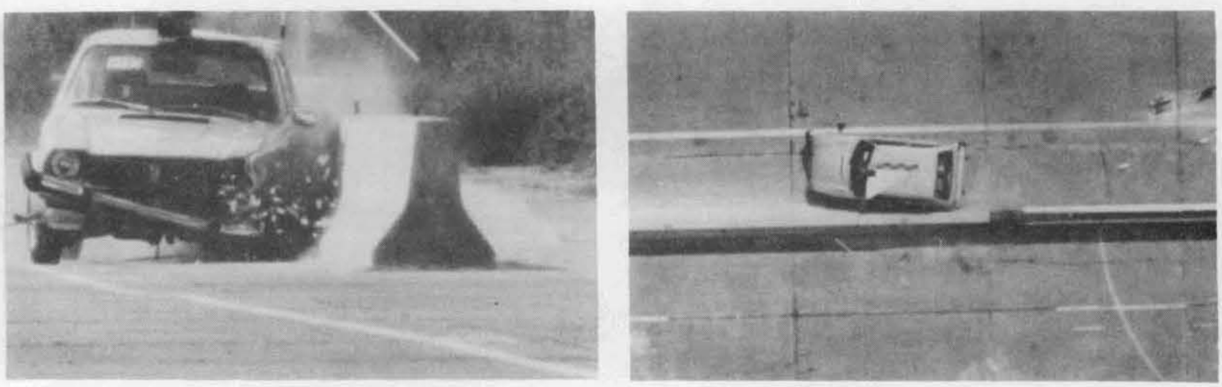
Figure 14. Sequential Photographs for Test 1.



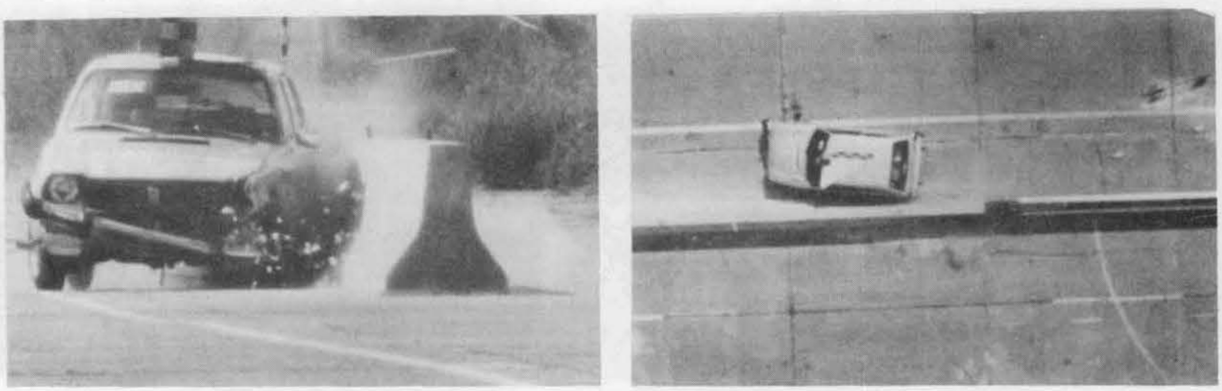
0.193 sec



0.240 sec

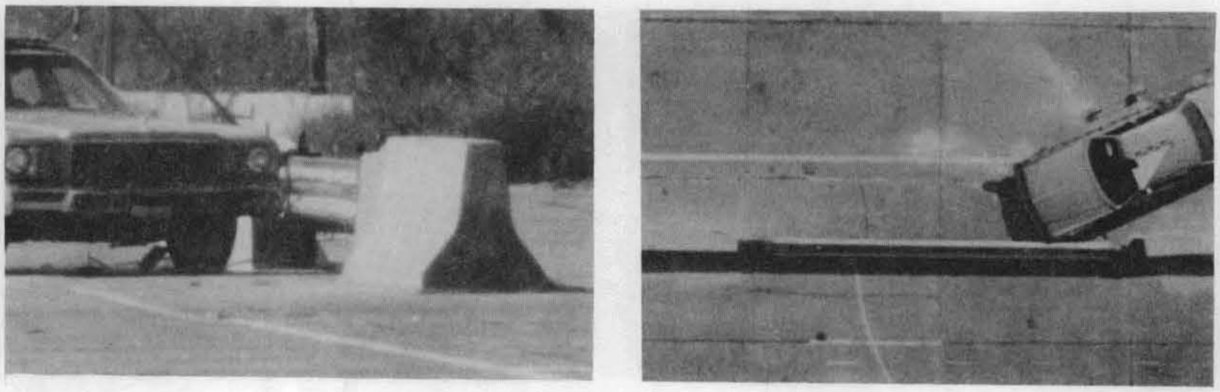


0.288 sec

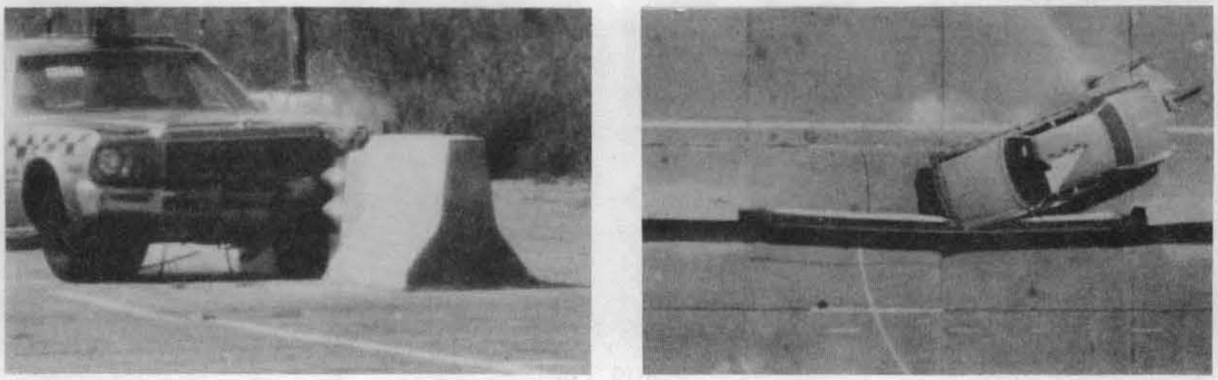


0.328 sec

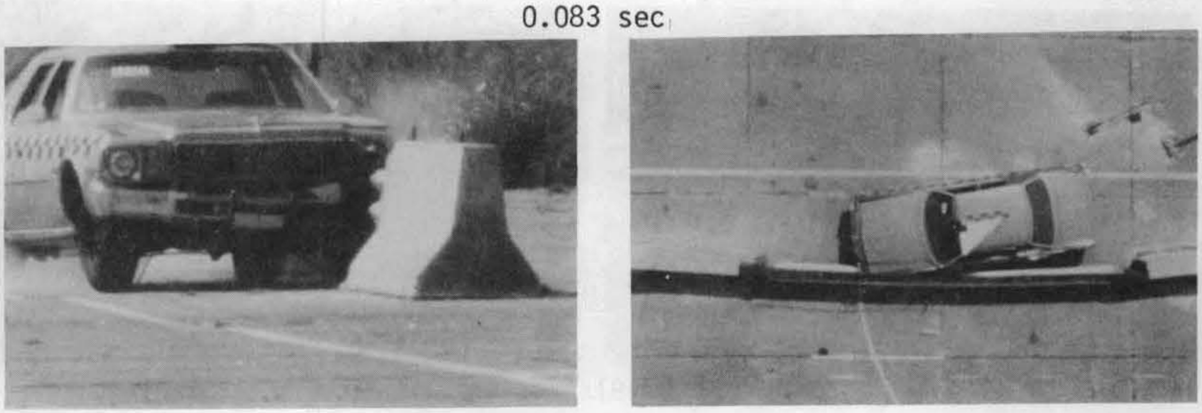
Figure 14. Sequential Photographs for Test 1. (Continued)



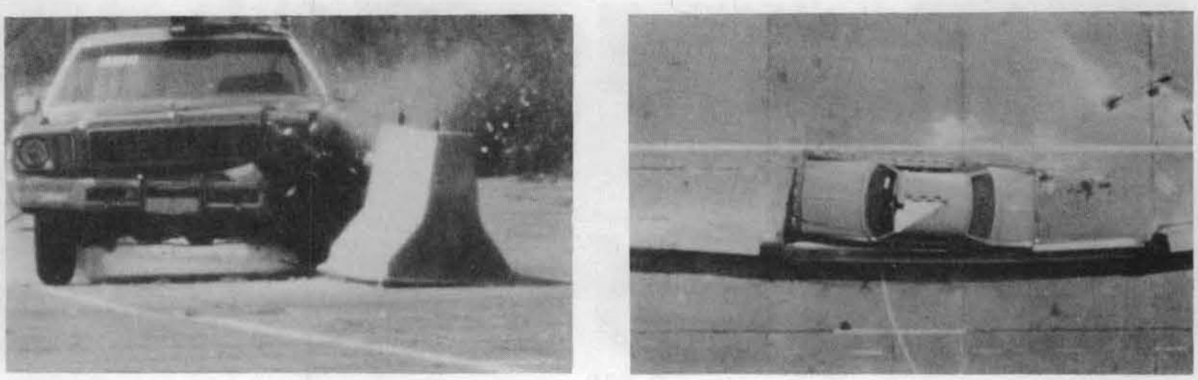
0.000 sec



0.083 sec

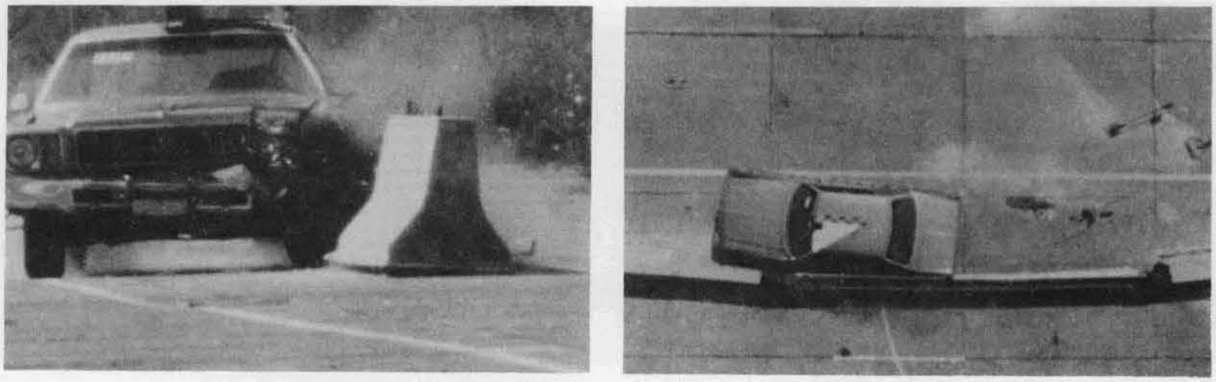


0.163 sec

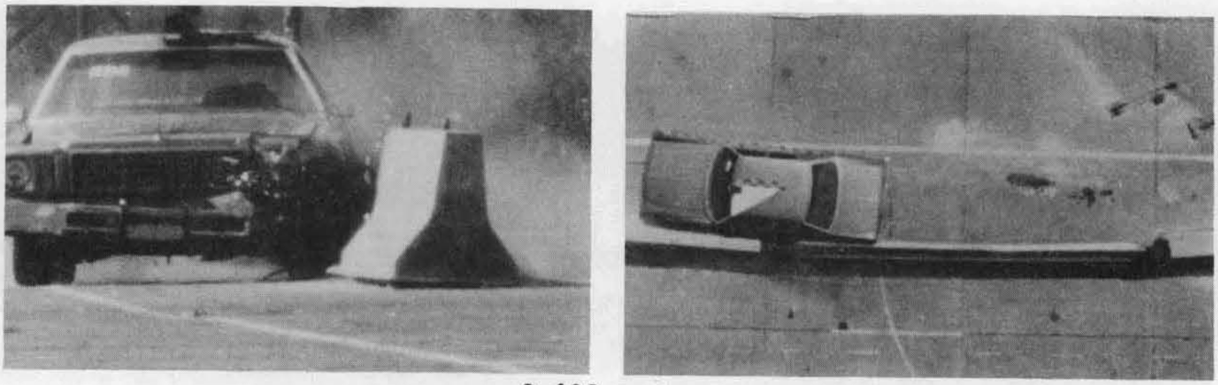


0.246 sec

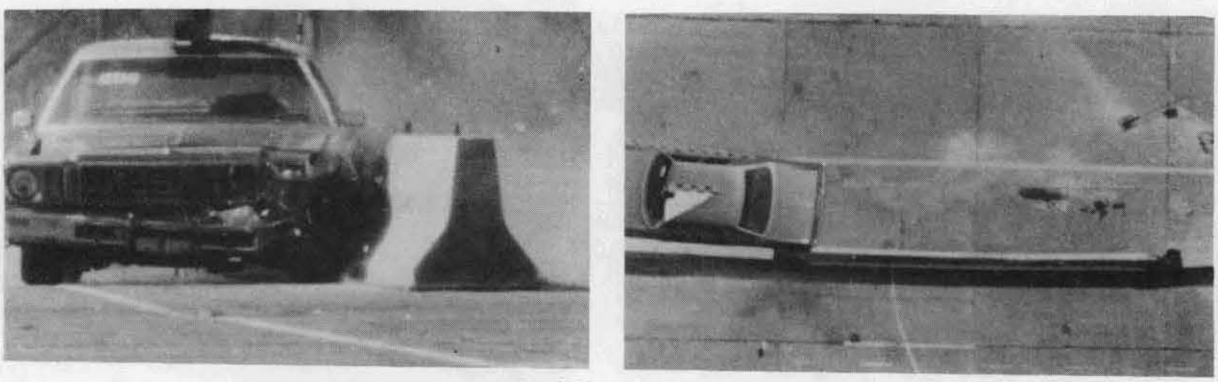
Figure 15. Sequential Photographs for Test 2.



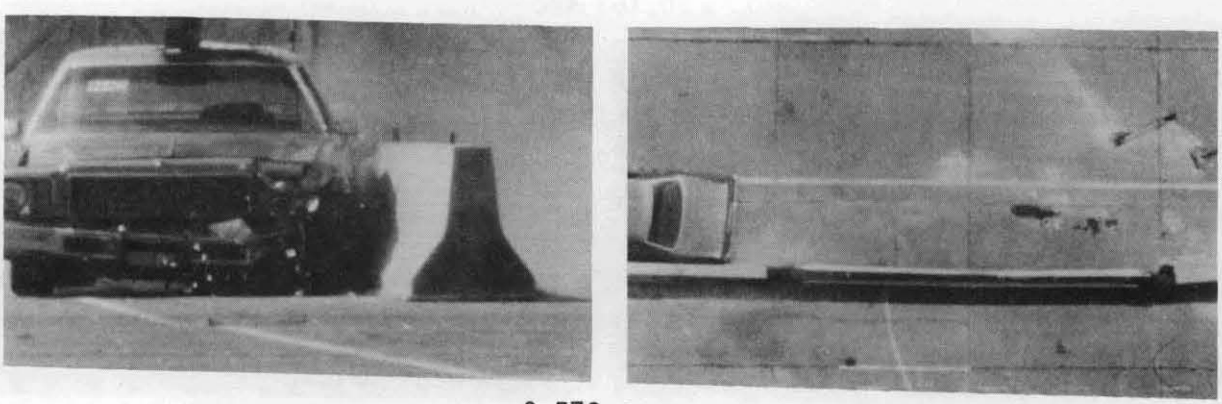
0.328 sec



0.409 sec

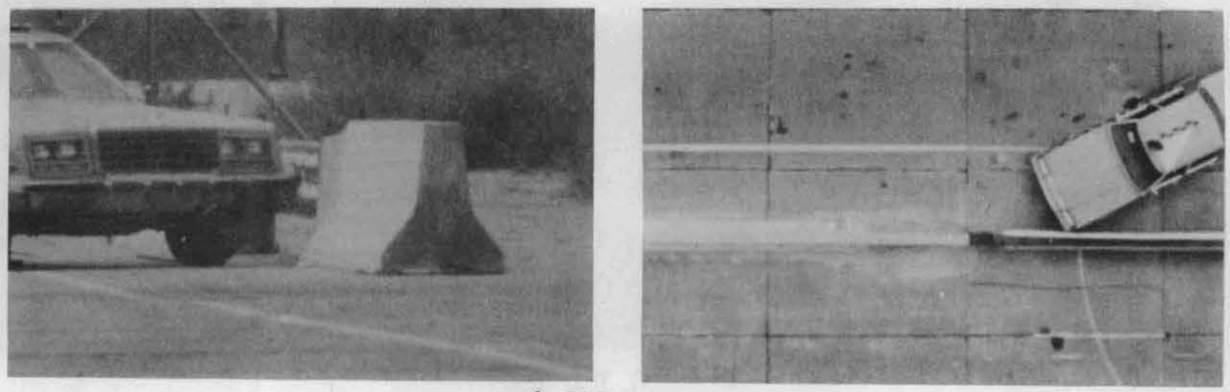


0.491 sec

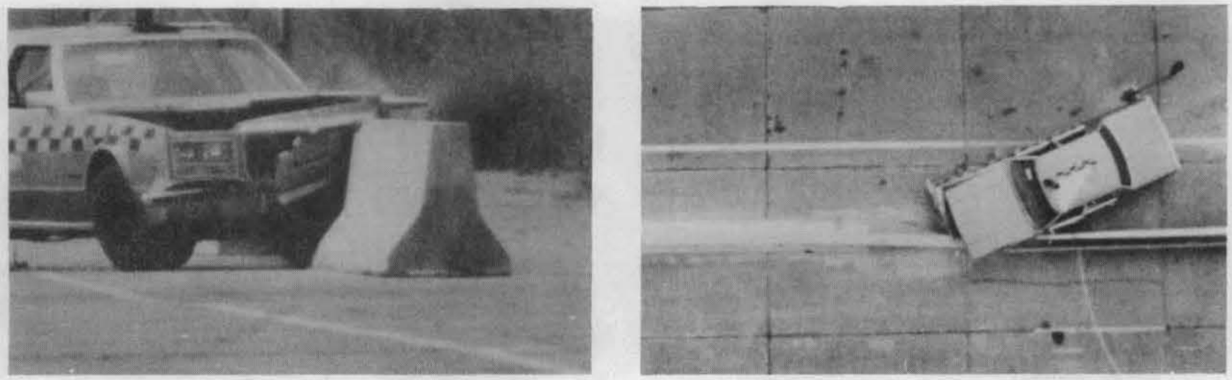


0.579 sec

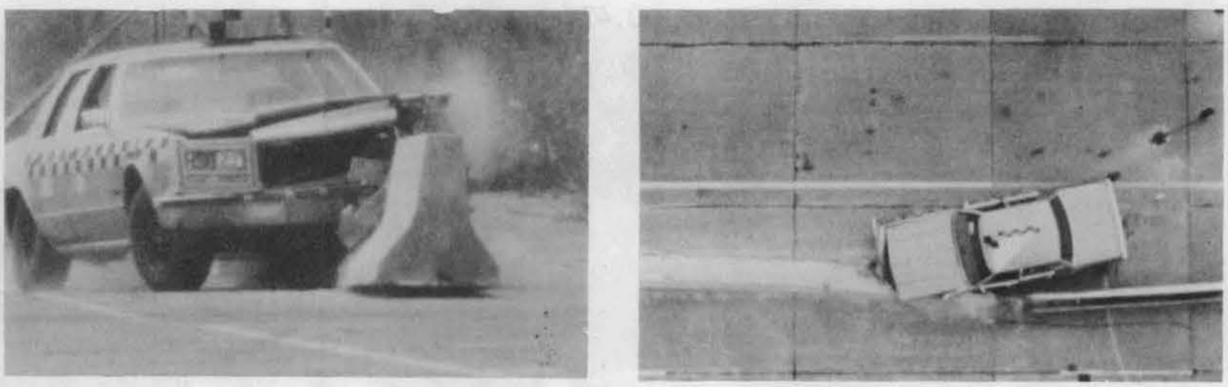
Figure 15. Sequential Photographs for Test 2. (continued)



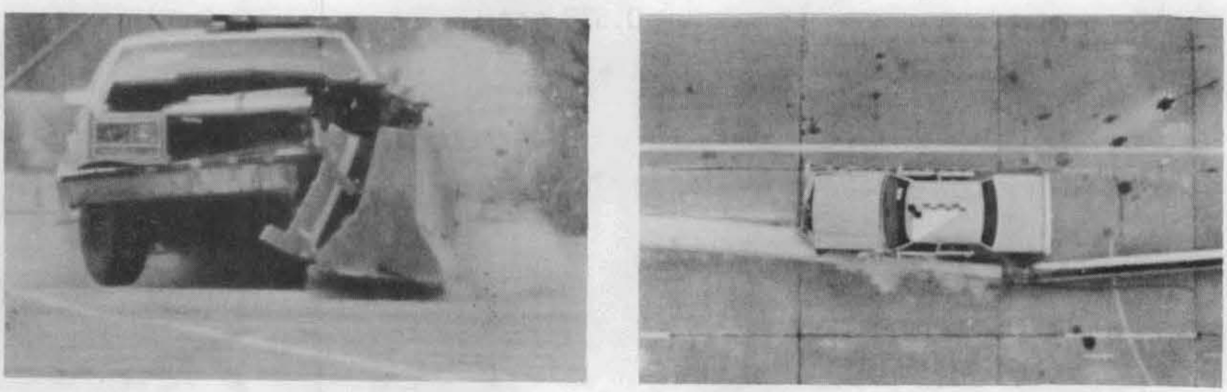
0.000 sec



0.094 sec

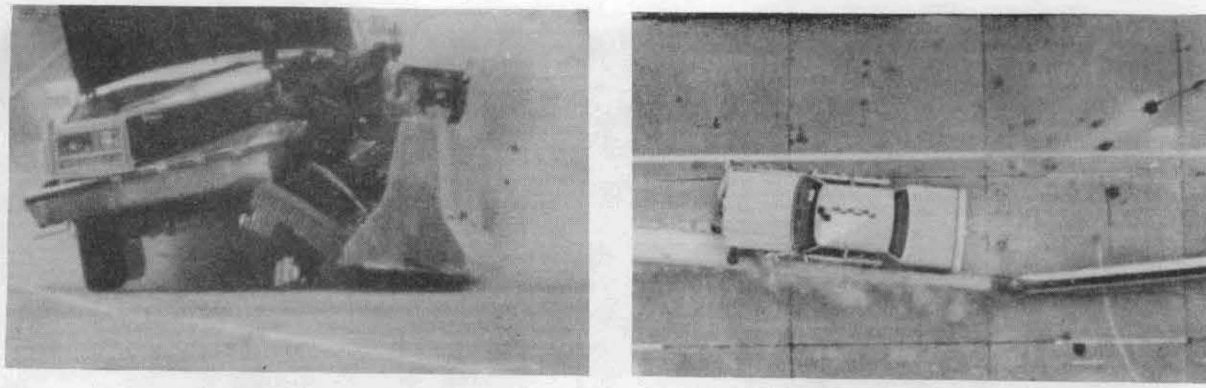


0.191 sec

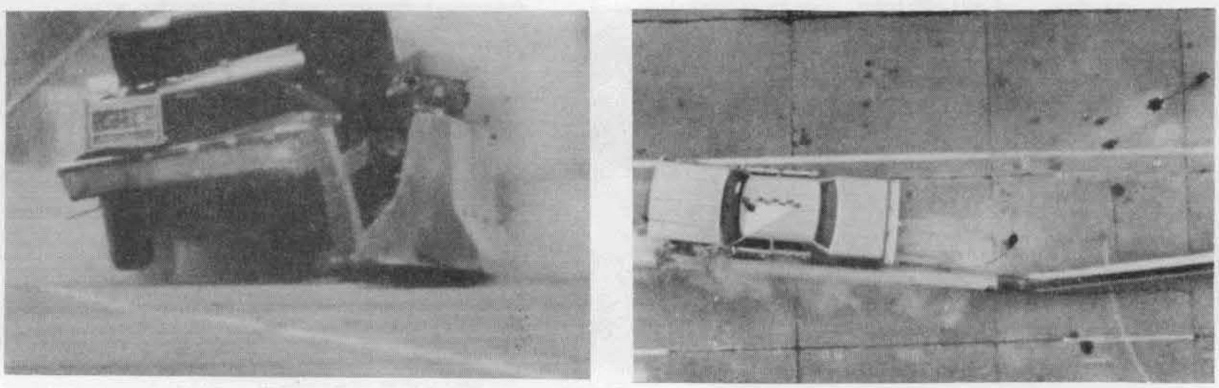


0.285 sec

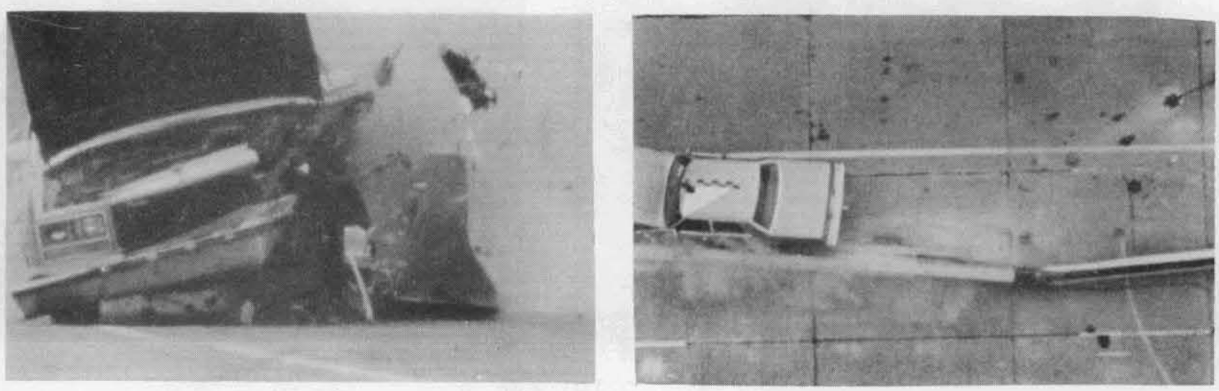
Figure 16. Sequential Photographs for Test 3.



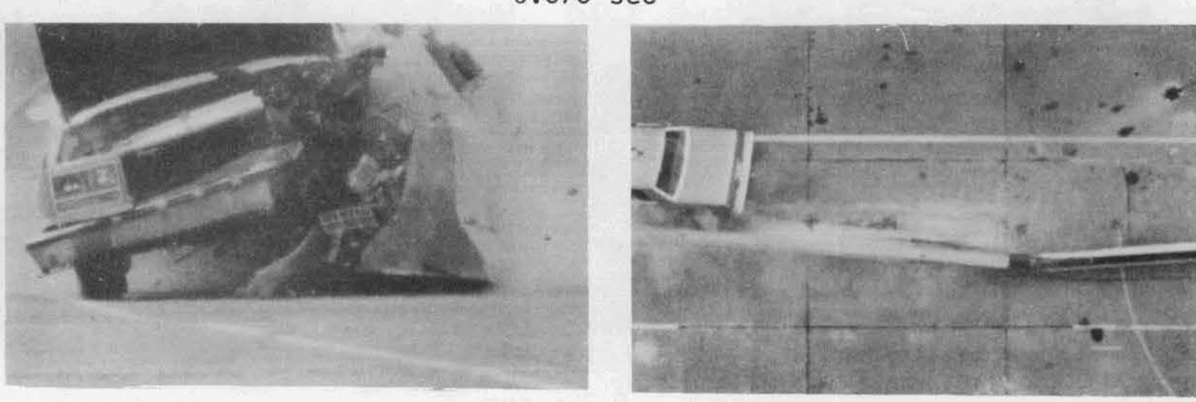
0.382 sec



0.476 sec



0.573 sec



0.690 sec

Figure 16. Sequential Photographs for Test 3. (Continued)

APPENDIX C

ACCELEROMETER TRACES
AND
PLOTS OF ROLL, PITCH, AND YAW RATES

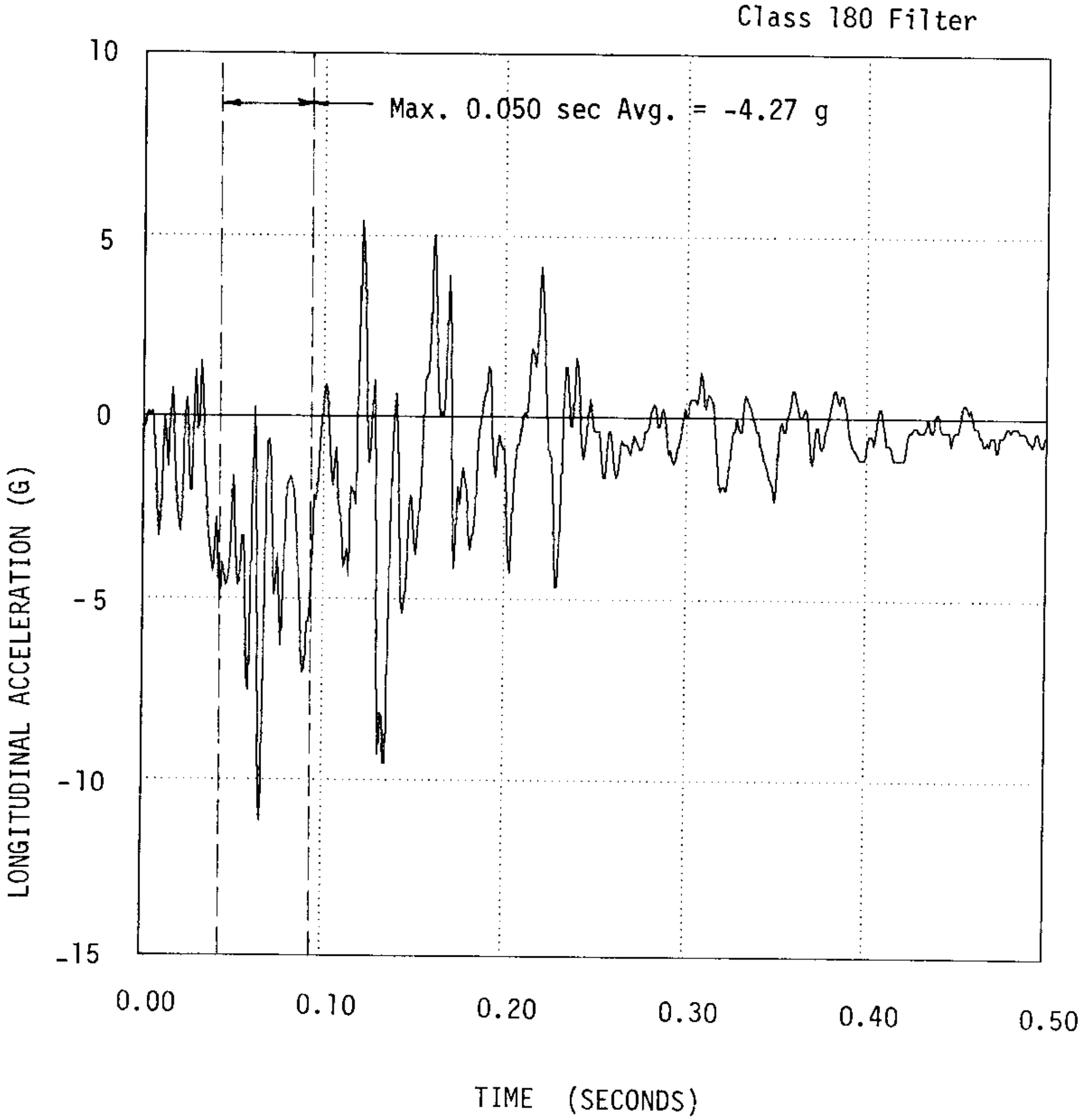


Figure 17. Vehicle Longitudinal Accelerometer Trace for Test 1.

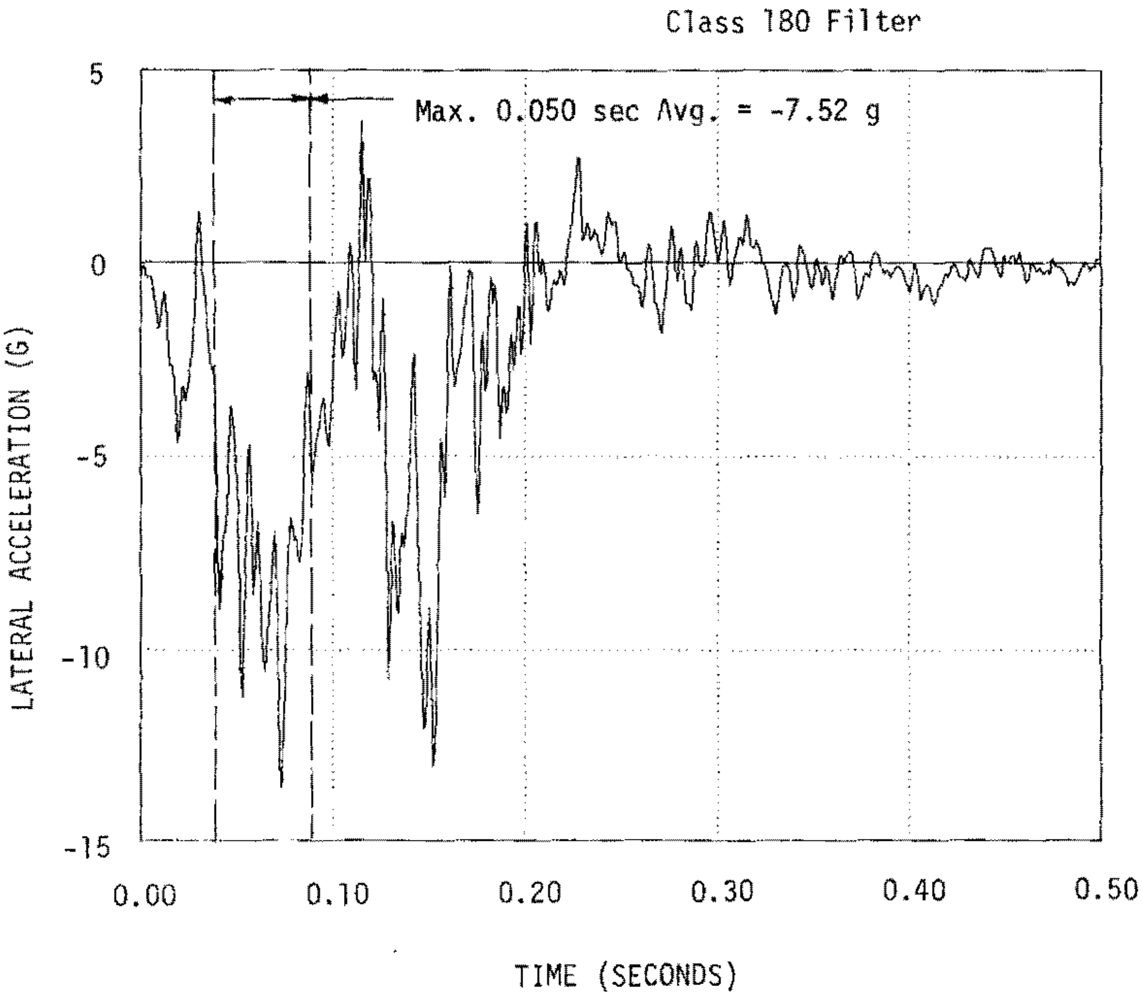
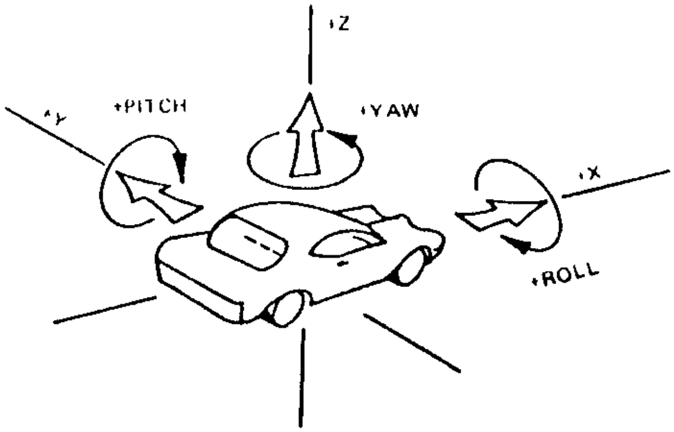


Figure 18. Vehicle Lateral Accelerometer Trace for Test 1.



Axes are vehicle fixed.
Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

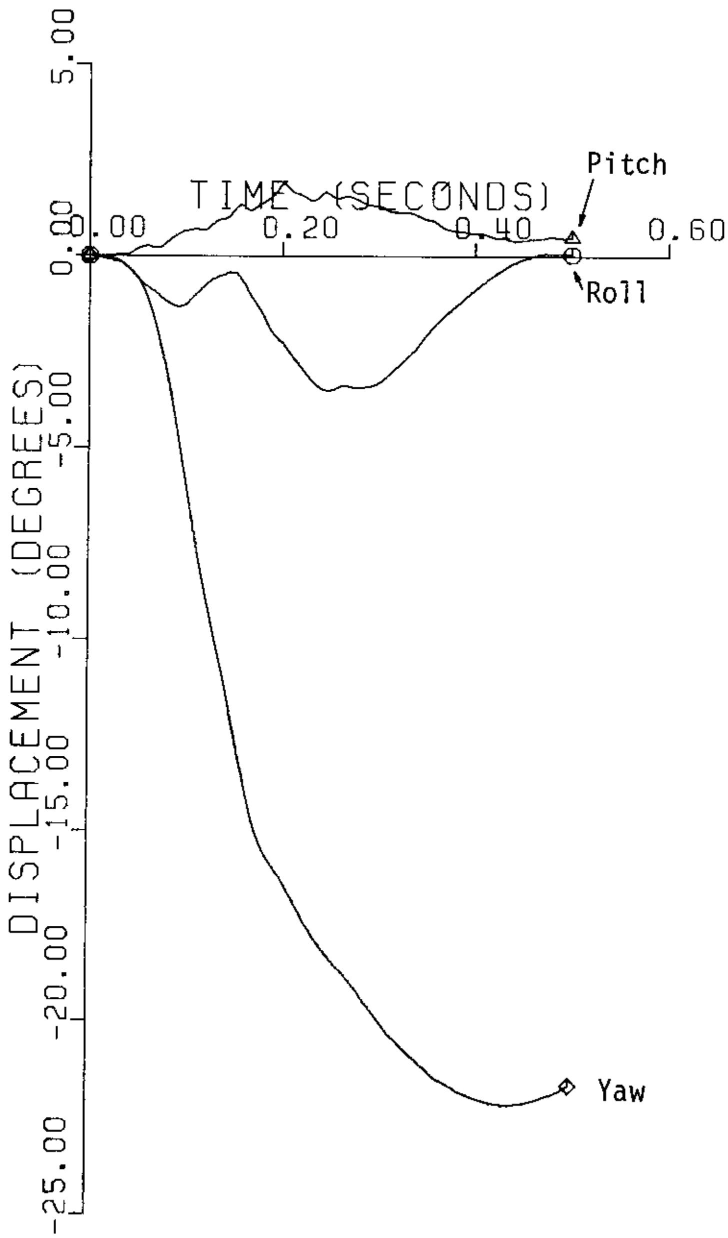


Figure 19. Vehicle Angular Displacement for Test 1.

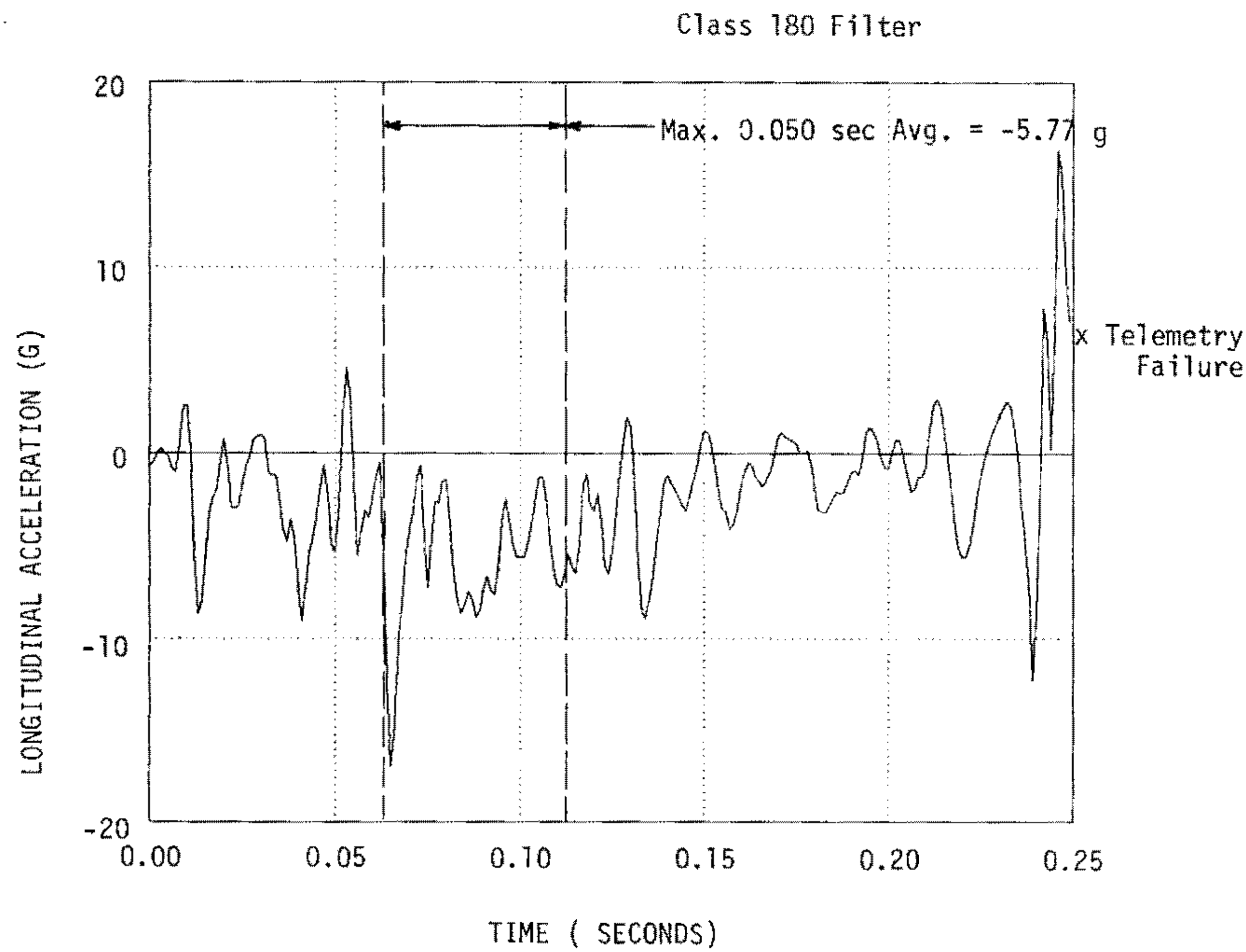


Figure 20. Vehicle Longitudinal Accelerometer Trace for Test 2.

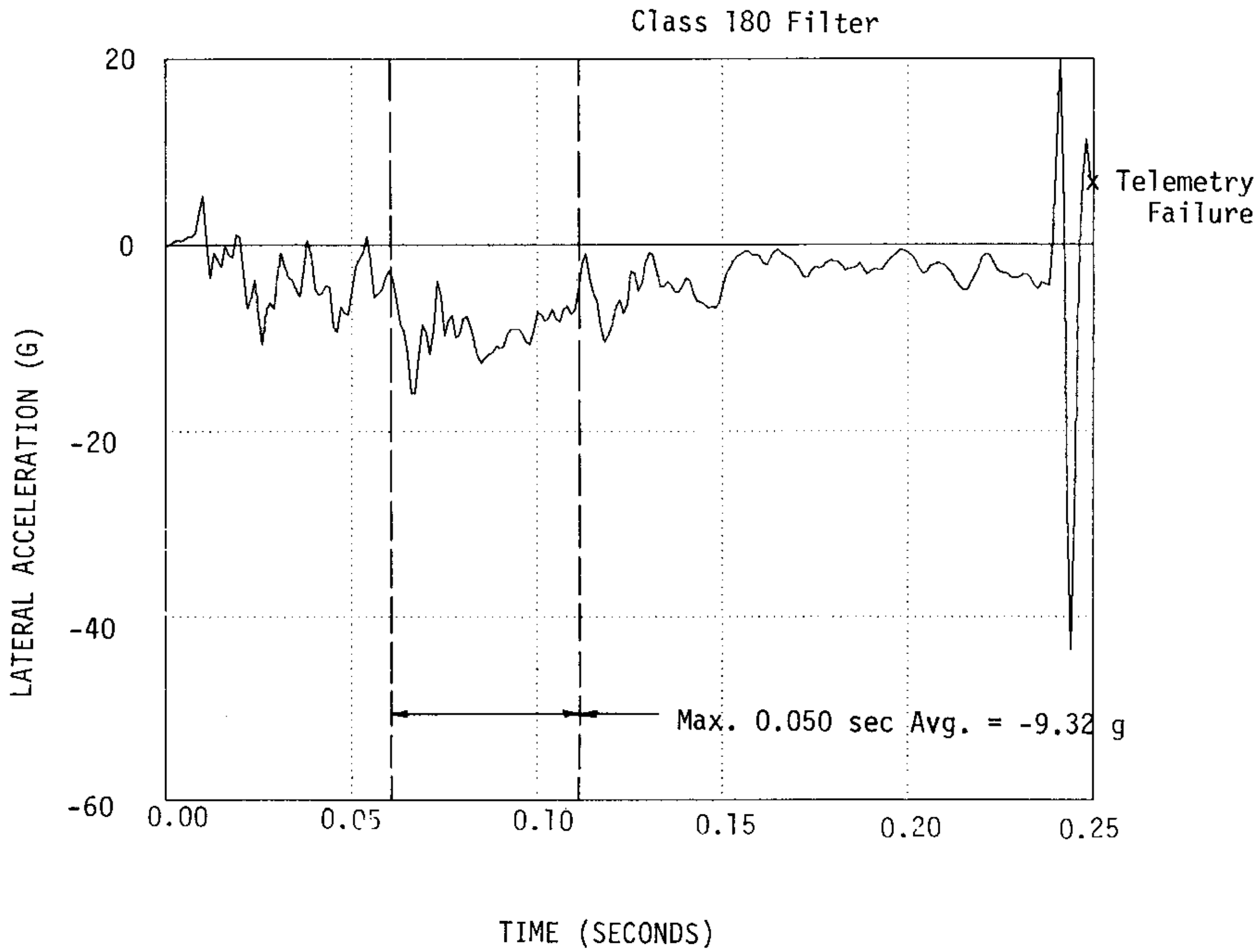
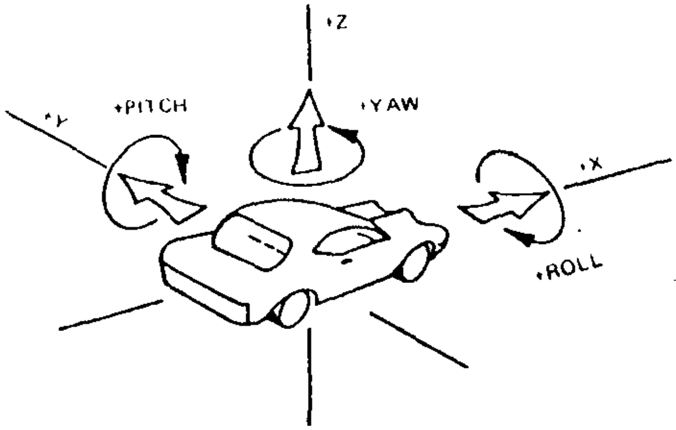


Figure 21. Vehicle Lateral Accelerometer Trace for Test 2.



Axes are vehicle fixed.
Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

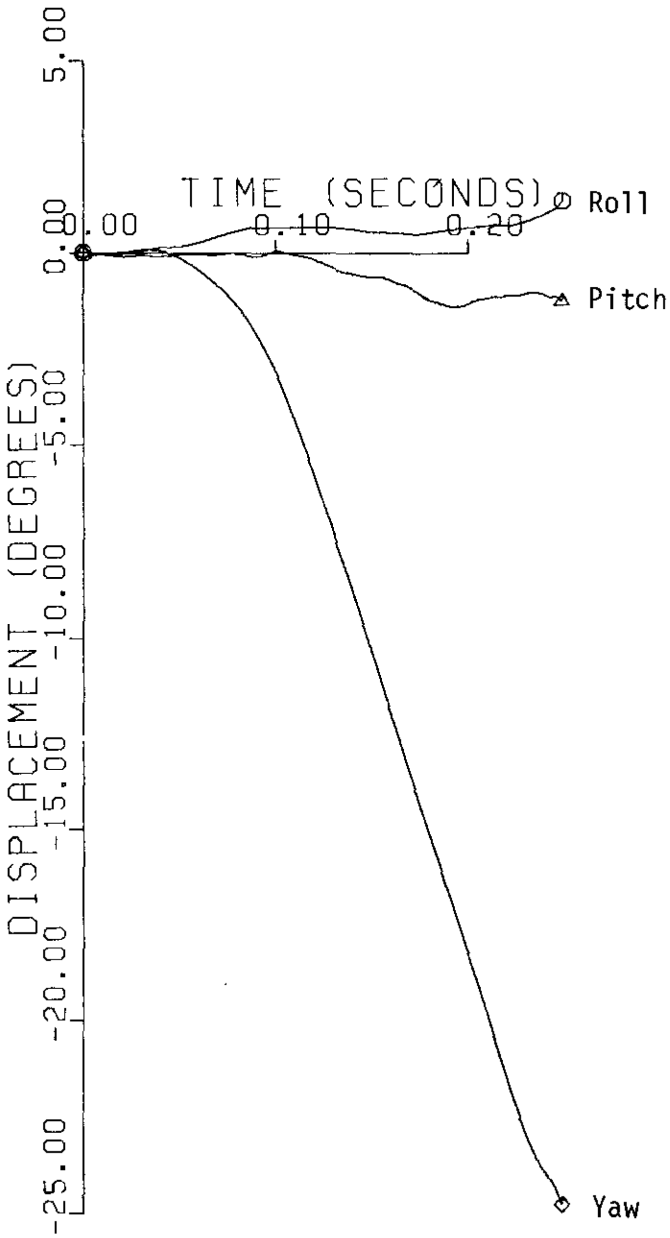


Figure 22. Vehicle Angular Displacements for Test 2.

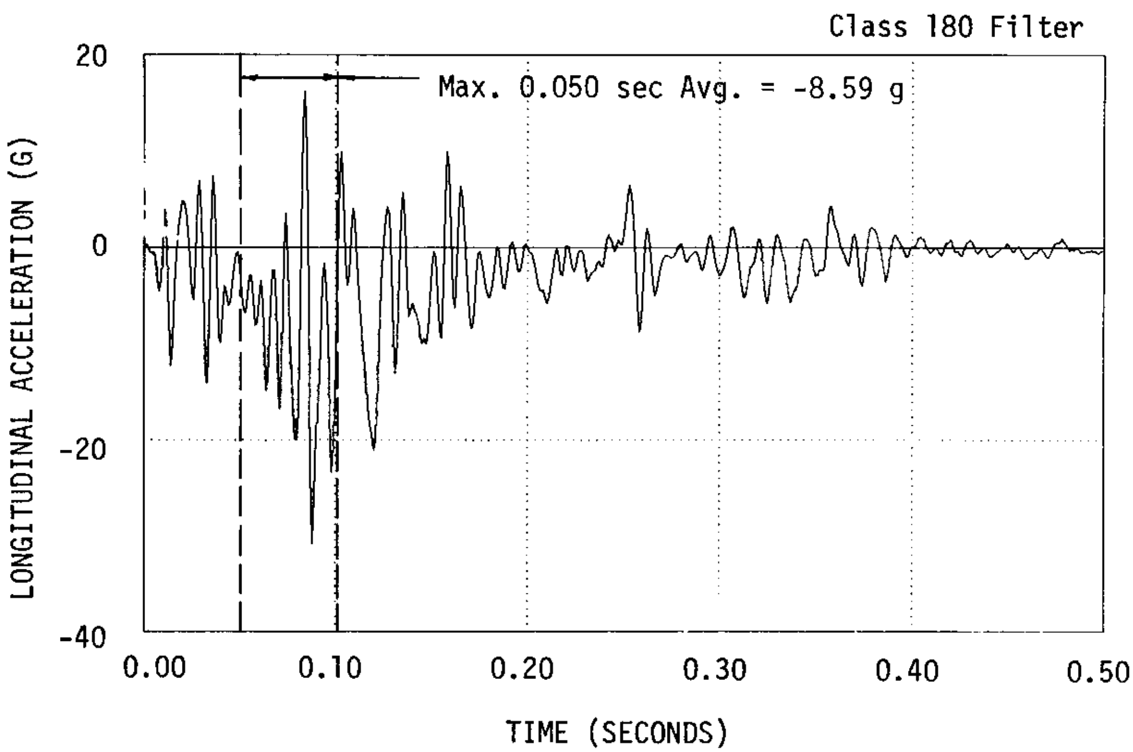


Figure 23. Vehicle Longitudinal Accelerometer Trace for Test 3.

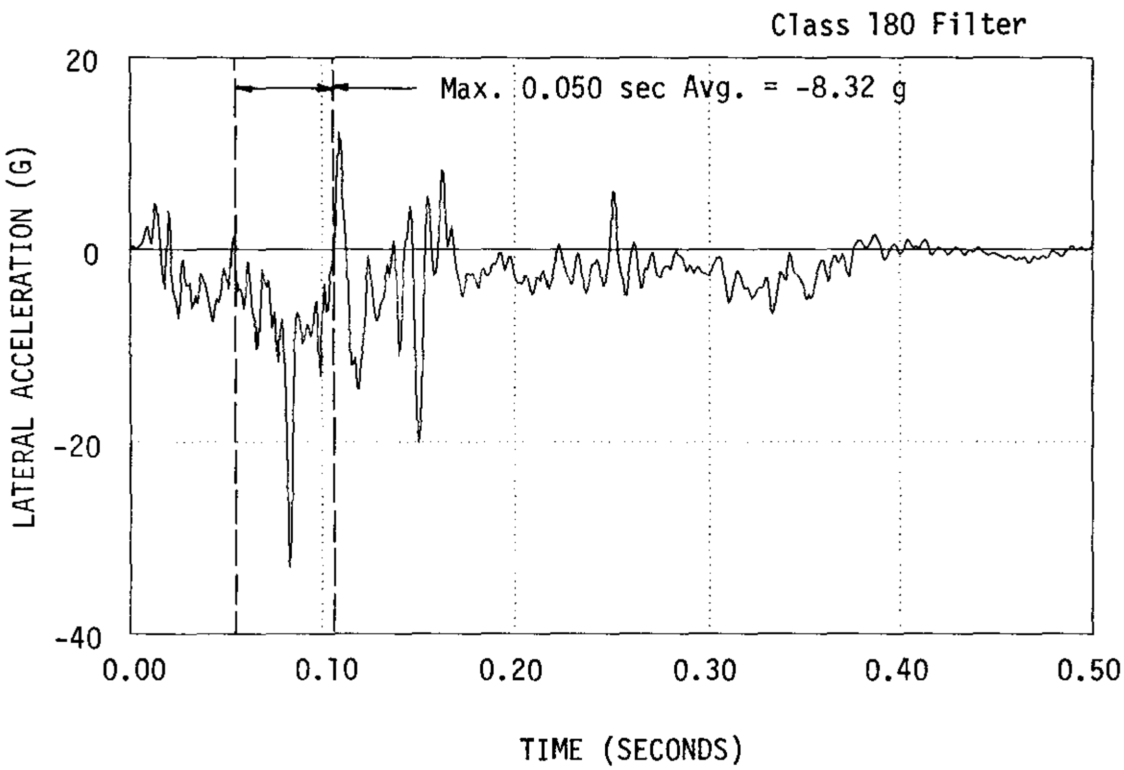
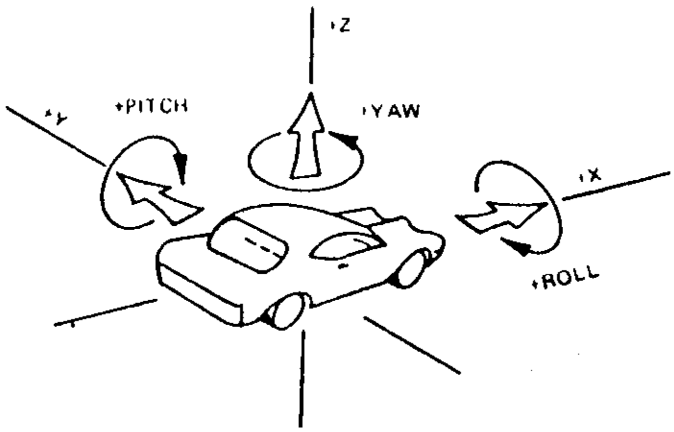


Figure 24. Vehicle Lateral Accelerometer Trace for Test 3.



Axes are vehicle fixed.
Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

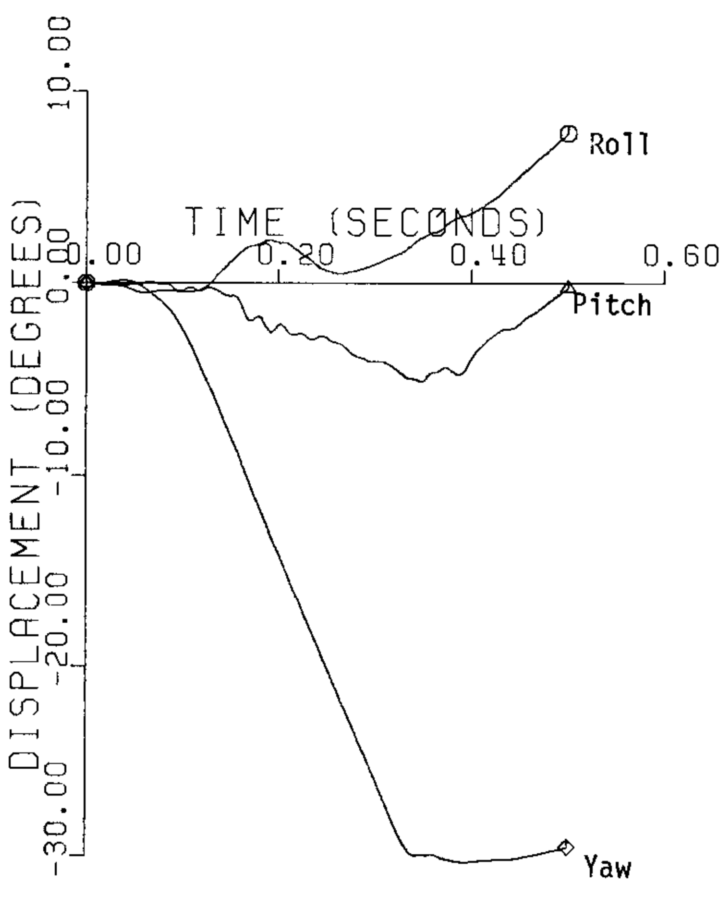


Figure 25. Vehicle Angular Displacements for Test 3.

REFERENCES

1. Powell, Graham H., "Barrier VII: A Computer Program for Evaluation of Automobile Barrier Systems," Federal Highway Administration, Washington, D. C., April, 1973.

2. "Building Code Requirements for Reinforced Concrete," ACI 318-77, American Concrete Institute, Detroit, Michigan, 1977.

3. "Manual of Steel Construction," American Institute of Steel Construction, Chicago, Illinois, May, 1981.

4. Michie, Jarvis D., "Recommended Procedure for the Safety Performance Evaluation of Highway Appurtenances," NCHRP Report 230, March, 1981.

5. "Standard Specifications for Construction of Highways, Streets and Bridges," Texas State Department of Highways and Public Transportation, Austin, Texas, September 1, 1982.