

# **Safety Performance Evaluation of the Steel Backed Wood Rail to Bridge Rail Transition**

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## **DISCLAIMER STATEMENT**

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 Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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## ABSTRACT

The safety performance of the Steel Backed Wood Rail to Bridge Rail Transition was evaluated as part of the federally sponsored Guardrail Testing Program II. During this evaluation, which included 5 full-scale vehicle crash tests, a number of modifications were made to improve the safety of the system.

The tests were conducted, reported, and evaluated in accordance with requirements specified for guardrail to bridge rail transitions in the National Cooperative Highway Research Program (NCHRP) Report No. 230, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*. Upon implementation of the design changes described herein, the performance of the Steel Backed Wood Rail to Bridge Rail Transition was determined to be acceptable according to these guidelines.



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## **1. INTRODUCTION**

### **1.1 Background**

The Coordinated Federal Lands Highways Technology Improvement Program (CTIP) was developed with the purpose of serving the immediate needs of those who design and construct Federal Lands Highways, including Indian Reservation roads, National Park roads and parkways, and forest highways. A wide assortment of guardrails, bridge rails and transitions are being used on roads under the jurisdiction of the National Park Service and other Federal agencies. These guardrails, bridge rails and transitions are intended to blend in with the roadside in order to preserve the visual integrity of the parks and parkways. However, many of them have never been crash tested (1,2). A testing program was developed in order to ensure that the safety hardware used in these areas are safe for the traveling public. The Steel Backed Wood Rail to Bridge Rail Transition (SBT) was included in the second Federal Highway Administration (FHWA) testing program - Guardrail Testing Program II.

### **1.2 Test Installation**

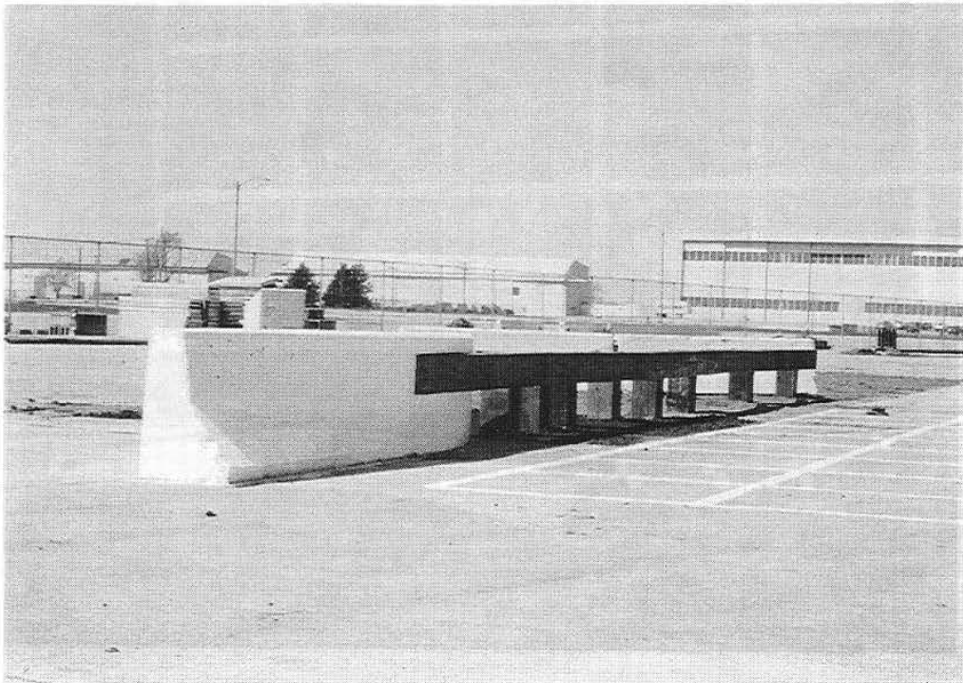
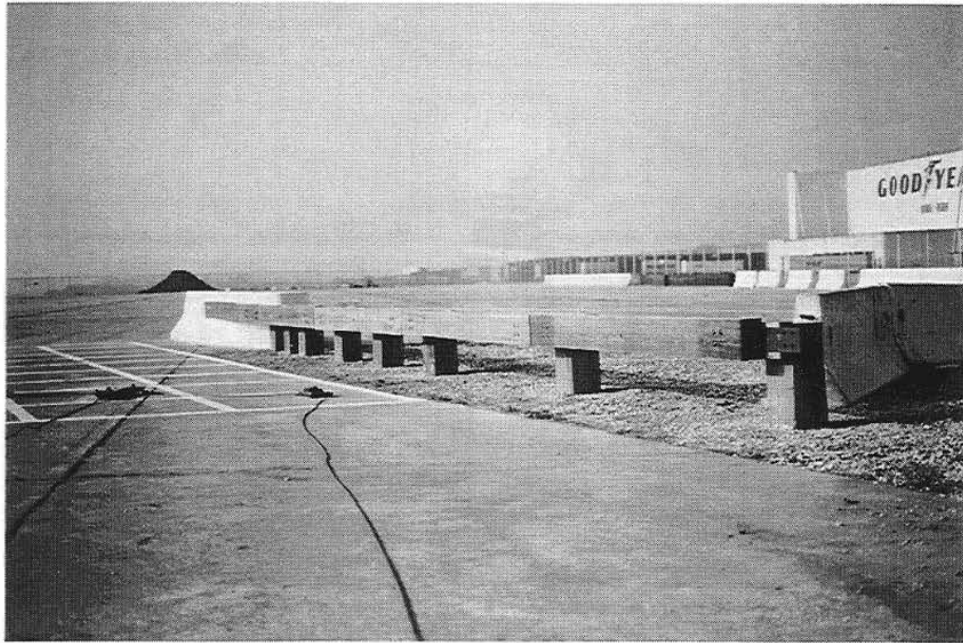
Photographs of the Steel Backed Wood Rail to Bridge Rail Transition are shown in Figures 1 and 2. Plan drawings of the original system, as well as the subsequently modified systems, are presented in Appendix A. The approach rail consists of 6 in. x 10 in. x 9 ft. - 11 in. (152 mm x 254 mm x 3.04 m) timber, backed with 3/8 in. (10 mm) ASTM A588 steel plate. This plate is attached to the back of the timber rail with 5/8 in. x 4 in. (16 mm x 102 mm) ASTM A588 lag screws. The splice details vary as shown in the plan drawings. One of the major design changes throughout the evolution of this system was the stiffening of the first splice location. This splice originally consisted of a number of 3/8" (10 mm) plates fastening the rails together, and was eventually

modified to include a 6 in. x 4 in. x ½ in. (152 mm x 102 mm x 13 mm) structural tube.

The rail was blocked out and mounted on 10 in. x 12 in. x 7 ft (254 mm x 305 mm x 2.13 m) timber posts for the first test, but the length of the first 3 posts were increased to 8 ft (2.44 m) for the remaining tests. The rail was attached to the flared concrete abutment with four ¾ in. x 2 ft A588 carriage bolts and a 3/8 in. (10 mm) bearing plate.

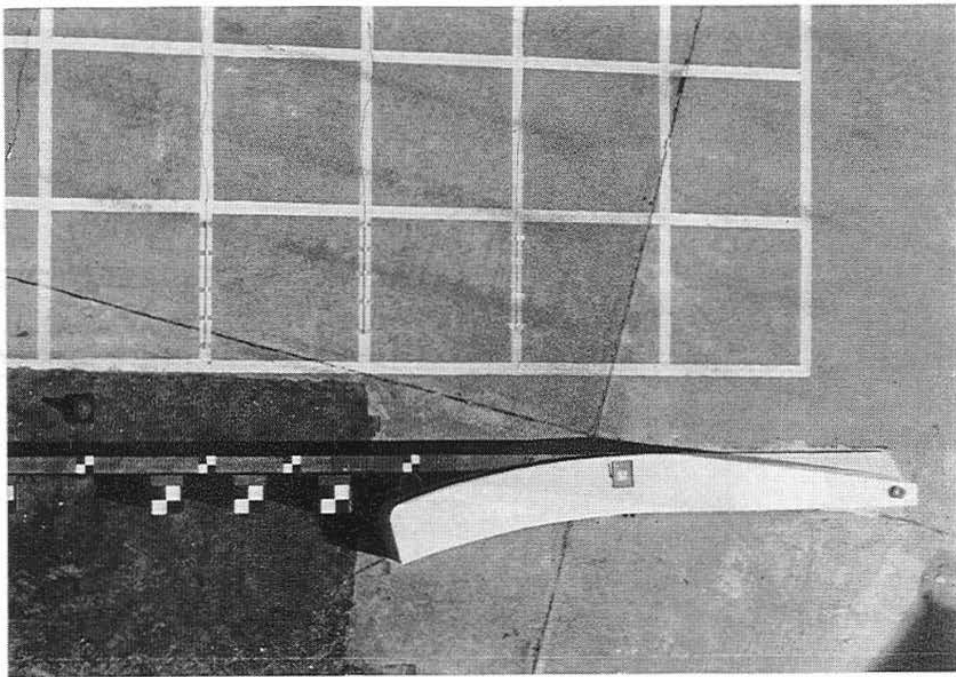
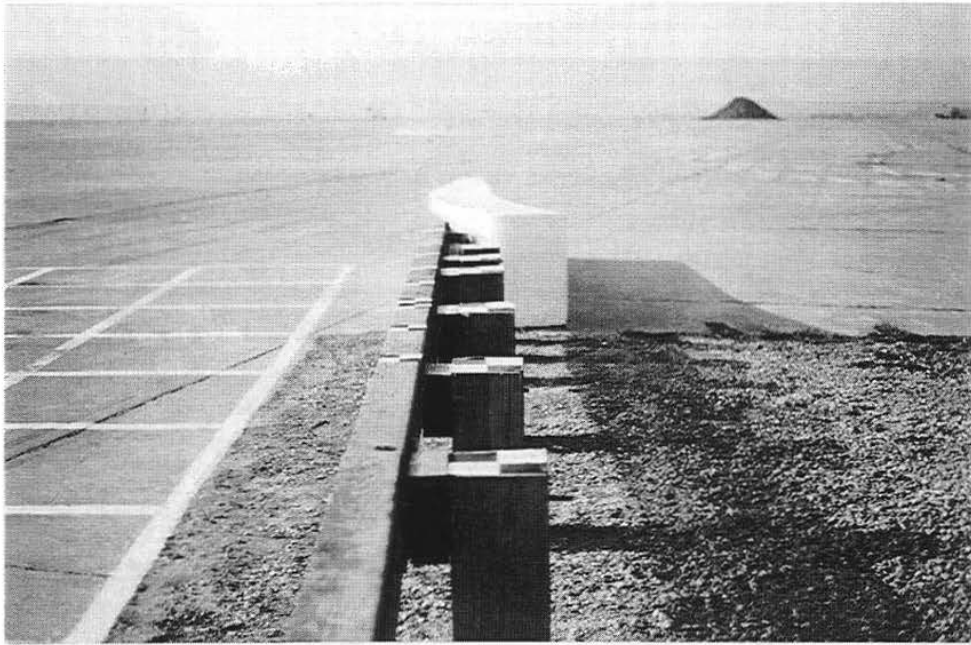
### **1.3 Test Criteria**

The tests performed on this system were conducted, reported, and evaluated in accordance with requirements for guardrail to bridge rail transitions specified in the National Cooperative Highway Research Program (NCHRP) Report No. 230 (3), *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*. This criteria requires that a 4500 lb sedan impact the transition at 60 mph (96.6 km/h) and 25 degrees. Barrier VII computer simulation was used to determine that the critical impact point was midway between the 3rd and 4th posts from the concrete bridge abutment.



**Figure 1.** The Steel Backed Wood Rail to Bridge Rail Transition.





**Figure 2.** The Steel Backed Wood Rail to Bridge Rail Transition (cont.).



## 2. TEST CONDITIONS

### 2.1 Test Vehicles

The test vehicles used in the evaluation of this system are summarized in Table 1. The pretest vehicle dimension and photos can be seen in Appendix B.

**Table 1. Test Vehicle Summary**

Test No.	Vehicle	Gross Static Weight	
		(lbs)	(kg)
SBT-1	1985 Ford LTD	4300	1950
SBT-2	1984 Buick LeSabre	4456	2021
SBT-3	1985 Ford LTD	4496	2039
SBT-4	1985 Mercury Grand Marquis	4668	2117
SBT-5	1985 Ford LTD	4500	2043

Black and white-checkered targets were placed on the test vehicle for use in the high-speed film analysis. Two targets were located on the center of gravity, one on the top and one on the driver's side of the test vehicle. Additional targets, visible from all three external high speed cameras, were located for reference. The front wheels of the test vehicle were aligned for camber, caster, and toe-in values of zero so that the vehicle would track properly along the guide cable. Two 5B flash bulbs, fired by a pressure tape switch on the front bumper, were mounted on the roof of each vehicle to establish the time of impact on the high-speed film.

## **2.2 Data Acquisition Systems**

### **2.2.1 Accelerometers**

Two triaxial piezoresistive accelerometer systems with a range of  $\pm 200$  g's (Endevco Model 7264) were used to measure vehicle accelerations. The accelerometers were rigidly attached to an aluminum block mounted near the vehicle's center of gravity. Accelerometer signals were received and conditioned by an onboard Series 300 Multiplexed FM Data System built by Metraplex Corporation. The multiplexed signal was then transmitted to a Honeywell 101 Analog Tape Recorder.

For tests SBT-2 through SBT-5, one backup triaxial piezoresistive accelerometer system with a range of  $\pm 200$  G's was used to measure the acceleration in the longitudinal, lateral, and vertical directions at a sample rate of 3,200 Hz. The environmental shock and vibration sensor/recorder system, Model EDR-3, was configured with 256 Kb of RAM memory and a 1,120 Hz filter. Computer software, "DynaMax 1 (DM-1)" and "DADiSP" were used to digitize, analyze, and plot the accelerometer data.

### **2.2.2 Rate Gyro**

A Humphrey 3-axis rate transducer with a range of 250 deg/sec in each of the three directions (pitch, roll, and yaw) was used to measure the rotational rates of the test vehicle in tests SBT-3,4, and 5.

### **2.2.3 High Speed Photography**

Four to five high-speed 16-mm cameras operating at 500 frames/sec were used to film the crash tests. A Red Lake Locam with a 12.5 mm lens was placed above the test installation to provide a field of view perpendicular to the ground. A Photec IV, with an 80-mm lens, was placed

downstream from the impact point and had a field of view parallel to the barrier. A second Photec IV, with a 55-mm lens, was placed on the traffic side of the bridge rail and had a field of view perpendicular to the barrier. A Hi-G Red Lake Locam with a 5.7-mm lens was placed onboard the vehicle to record dummy motions during the test. Additional high speed cameras were placed behind the rail in the later tests to better evaluate the vehicle/rail interaction. A white-colored 5-ft by 5-ft (1.52 m by 1.52 m) grid was painted on the concrete in front of the rail in view of the overhead camera. This grid provided a visible reference system to use in the analysis of the overhead high-speed film. The film was analyzed using a Vanguard Motion Analyzer.

### **2.2.3 Speed Trap**

Seven tape pressure switches spaced at 5-ft (1.52 m) intervals were used to determine the speed of the vehicle before impact. Each tape switch fired a strobe light and sent an electronic timing mark to the data acquisition system as the left front tire of the test vehicle passed over it. Test vehicle speeds were determined from electronic timing mark data recorded on "Computerscope" software. Strobe lights and high speed film analysis are used only as a backup in the event that vehicle speeds cannot be determined from the electronic data.

### 3. TEST RESULTS

#### 3.1 Test SBT-1

The 1985 Ford LTD was directed into the Steel Backed Wood Rail to Bridge Rail Transition using a reverse tow and cable guidance system (4). The vehicle was released from the tow cable and guidance system and was free wheeling at impact. The speed of the vehicle at impact was 61.7 mph (99.3 km/h) and the angle of impact was 25.0 degrees. As shown in Figure 3, the target impact point was located midway between the 3rd and 4th posts from the concrete bridge abutment. A summary of the test results and sequential photographs are shown in Figure 4, and additional sequential photos are presented in Figure 5.

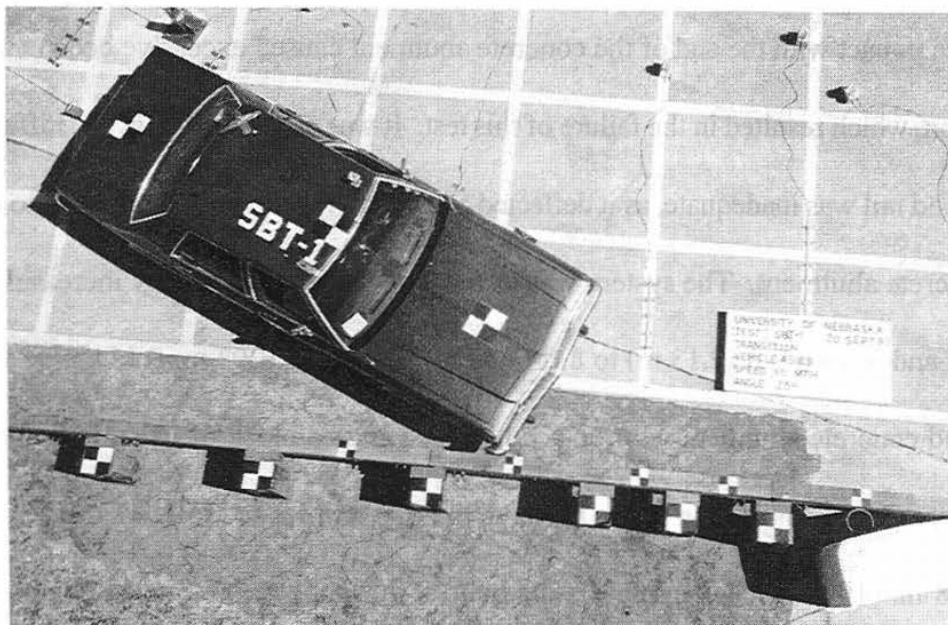
Upon impact with the steel backed wood rail, the right front corner of the vehicle began to crush inward. As the collision continued, the wood rail deflected considerably, with the maximum dynamic deflection of 13 in. (130 mm) occurring at post 1 at 130 ms. Immediately after this, at 133 ms, the vehicle impacted the end of the concrete abutment resulting in major damage to the vehicle. Approximately 167 ms after impact the buckling of the vehicle roof became very evident. At 204 ms after impact the vehicle became parallel to the system, and it exited the barrier at 439 ms at an angle of 17.5 degrees. The vehicle came to rest downstream and behind the rail as shown in Figure 5.

Damage to the vehicle, which can be seen in Figures 7 and 8, included major crushing and deformation of the right front corner of the vehicle, as well as buckling of the vehicle roof. The entire front half of the vehicle was bent slightly toward the drivers side. Interior compartment damage included buckling of the floorboard on the passenger side, as well as buckling of the dash. The maximum crush deformation of 17 in. (492 mm) is shown in Figure 9.

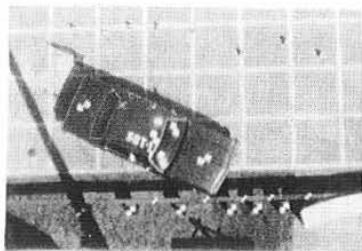
The damage to the system, shown in Figures 10 through 12, consisted of a maximum permanent set deformation of 11.25 in. (286 mm) at post No. 1. A bending failure occurred in the first rail, approximately 4.5 ft (1.37 m) from the downstream end of the rail. The 8 in. (203 mm) I.D. pipe located between the first rail and the concrete abutment was completely flattened. There was evidence of vehicle snagging at the splice between rail Nos. 1 and 2, as sheet metal from the vehicle was embedded in the end of rail No. 1. There were continuous scrape marks along the face of the rail from the point of impact to exit, as well as impact markings on the concrete abutment.

The normalized longitudinal and lateral occupant impact velocities, as determined from the accelerometer data, were 33.3 fps (10.1 m/s) and 20.4 fps (6.2 m/s), respectively. The maximum occupant ridedown decelerations were 13.8 g's (longitudinal), and 16.2 g's (lateral). The accelerometer data from this test is presented in Appendix C, and the results of this analysis are summarized in Figure 4.

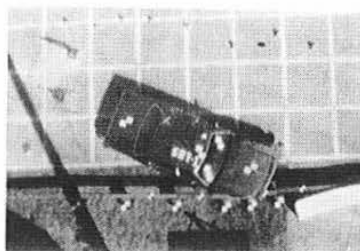
The impact with the end of the concrete abutment caused excessive occupant compartment deformation, which resulted in the failure of this test. It was determined that the stiffness of the steel backed wood rail was inadequate, as it deflected considerably, allowing the vehicle to impact the end of the concrete abutment. The system was redesigned for the next test by increasing the length of posts 1, 2, and 3 from 7 ft (2.13 m) to 8 ft (2.44 m). The 8 in. (203 mm) I.D. pipe spacer between the rail and concrete abutment was replaced with an angled block of wood in order to restrict the deflection of the first rail. The splice between the first and second rails was stiffened by adding a second 3/8 in. (10 mm) backup plate. The bolts at this splice were moved closer to the post and increased in number from 8 to 12. The details of these design changes are presented in the plan drawings in Appendix A.



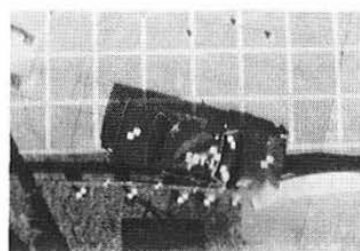
**Figure 3.** Impact Location, Test SBT-1.



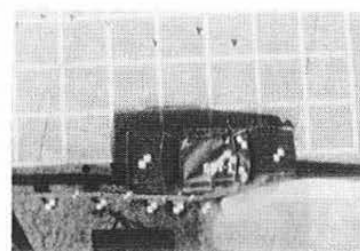
Impact



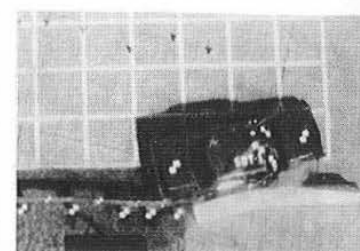
61 ms



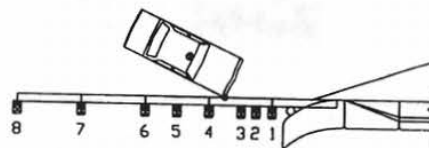
153 ms



204 ms



306 ms



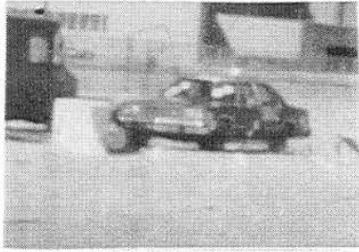
Test Number	SBT-1
Federal Contract No.	DTFH71-90-C-00035
Date	9/20/91
Installation	Steel Backed Wood Rail to Bridge Rail Transition
Approach Guardrail	
Length	50 ft
Height	2 ft- 3 in.
Material	
Post	10 in. x 12 in. x 7 ft rough sawn timber
Rail	6 in. x 10 in. x 9 ft- 11.5 in. rough sawn timber
Vehicle Model	1985 Ford LTD Crown Victoria
Vehicle Weight	
Curb	3880 lb
Test Inertia	4460 lb
Gross Static	4300 lb

Speed	
Impact	61.7 mph
Exit	25.6 mph
Angle	
Impact	25.0 deg
Exit	17.5 deg
Change in Velocity	36.1 mph
Normalized Occupant Impact Velocity	
Longitudinal	33.3 fps
Lateral	20.4 fps
Occupant Ridedown Deceleration	
Longitudinal	13.8 g's
Lateral	16.2 g's
Vehicle Damage	
TAD	1-RFQ-5
VDI	01RFES7
Vehicle Rebound Distance	16 ft- 7 in. @ 70 ft
Bridge Rail Damage	Minor
Maximum Deflections	
Permanent Set	11.25 in. @ post No. 1
Dynamic	13 in. @ post No. 1

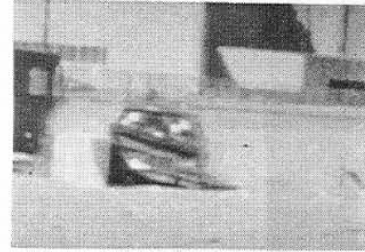
Figure 4. Summary of Test SBT-1.

Conversion Factors: 1 in.= 2.54 cm; 1 lb= 0.454 kg





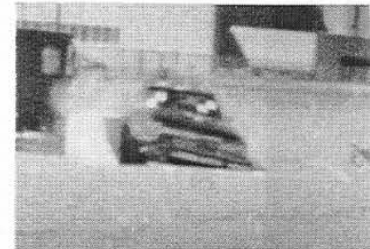
Impact



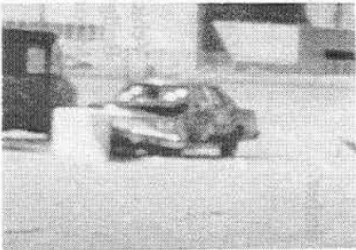
100 ms



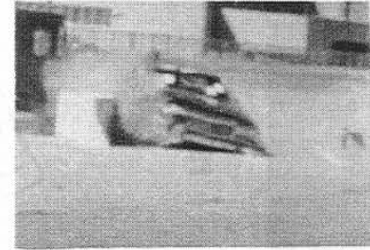
30 ms



130 ms



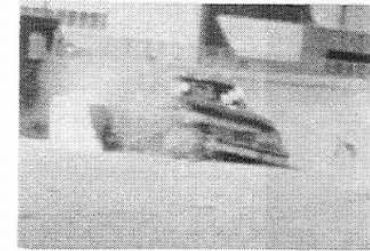
45 ms



160 ms



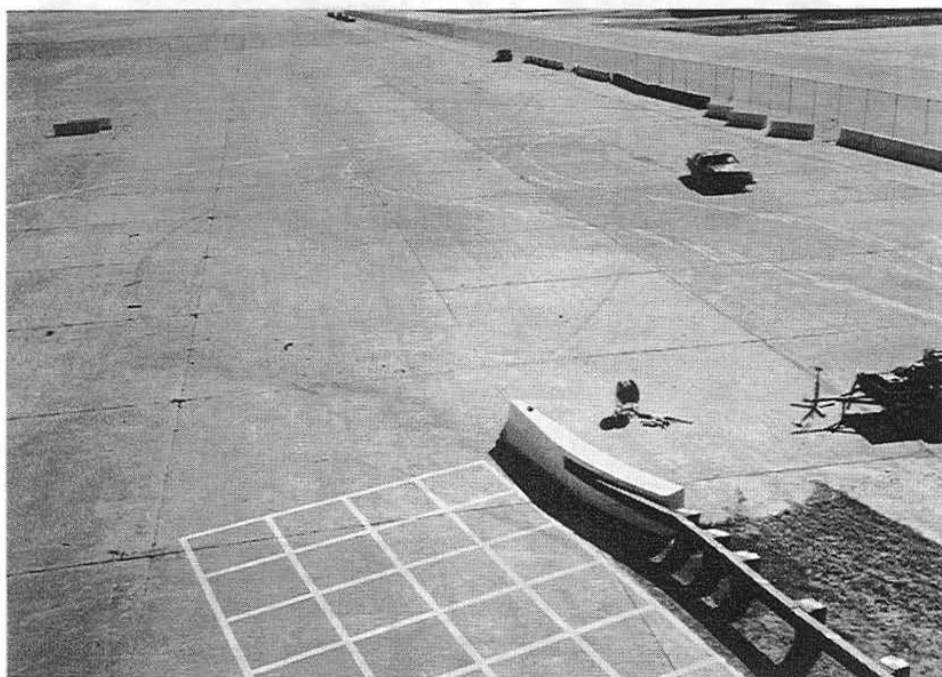
70 ms



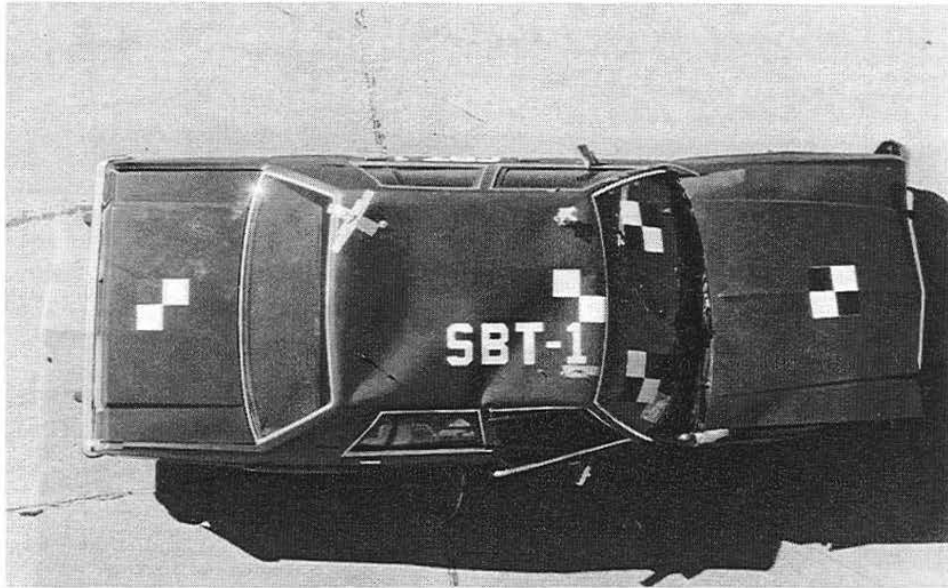
200 ms

**Figure 5.** Downstream Sequential Photographs, Test SBT-1.

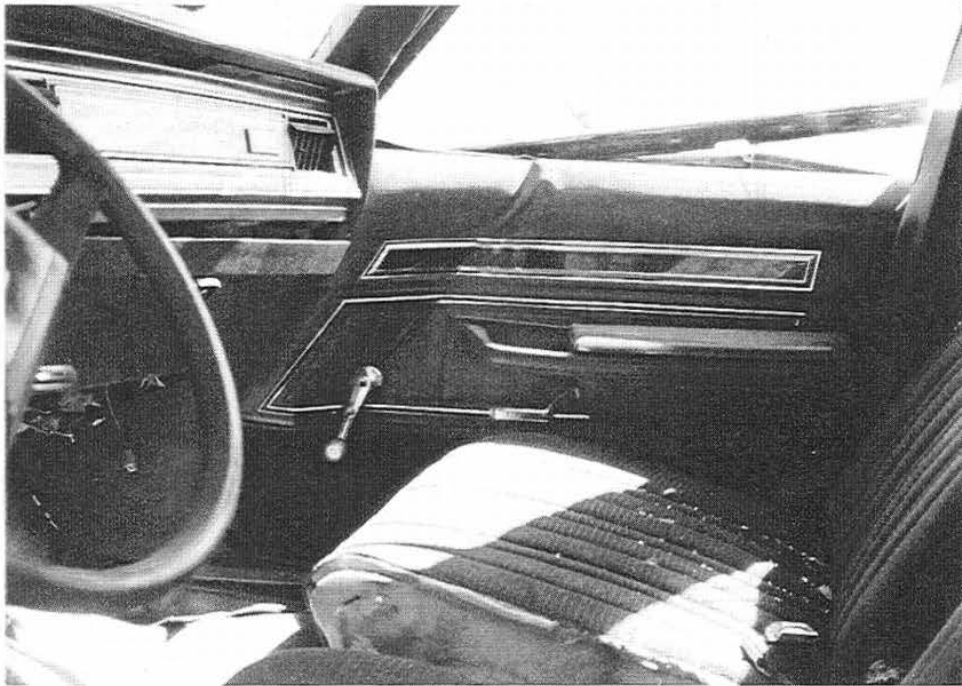
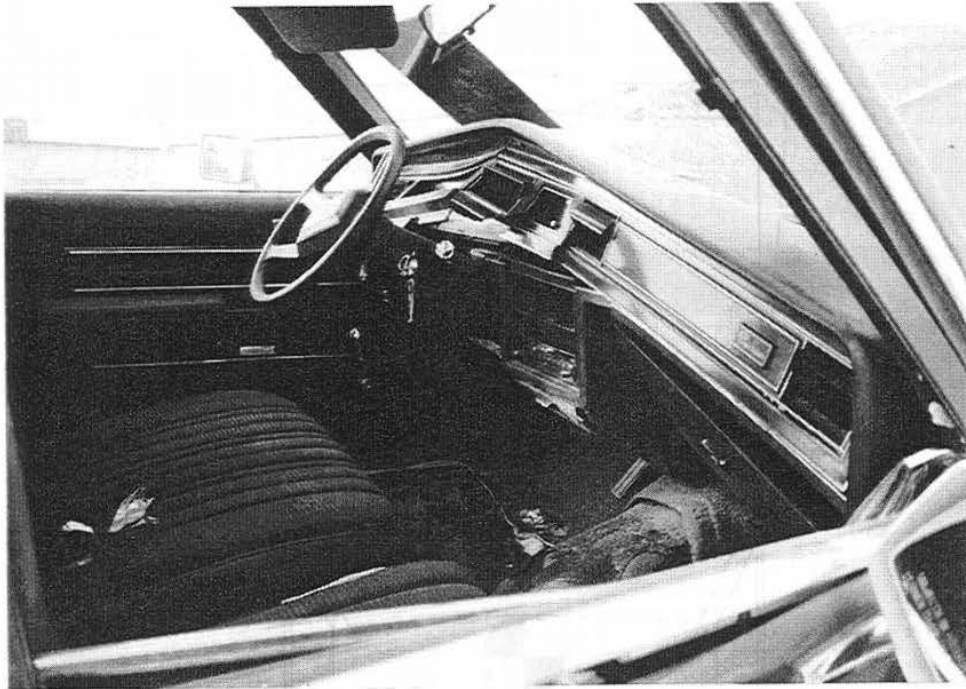




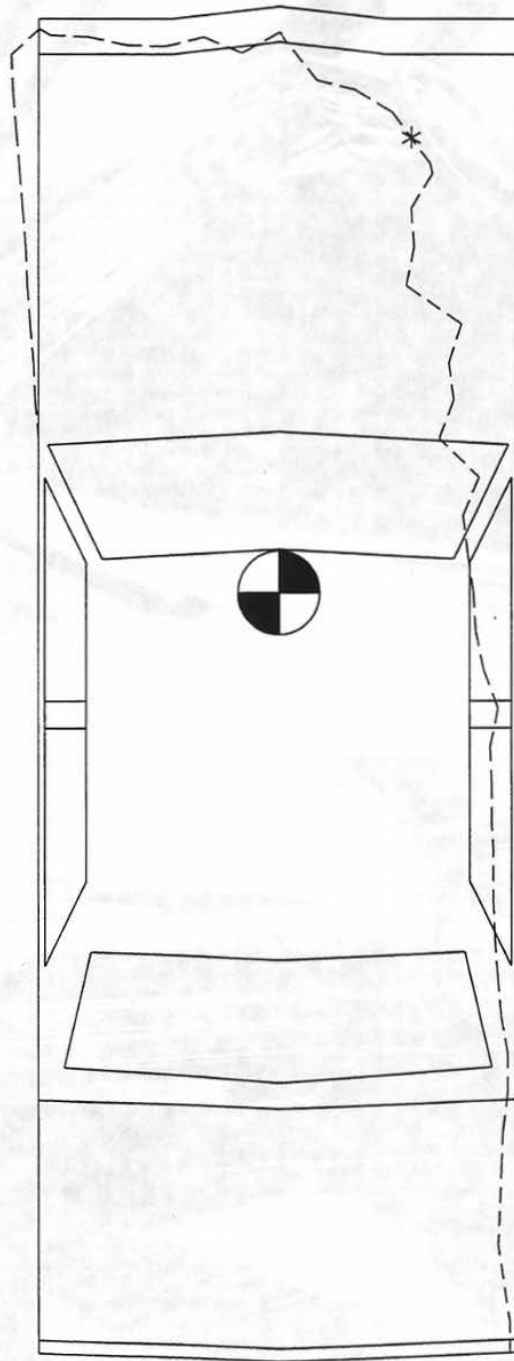
**Figure 6.** Vehicle Trajectory, Test SBT-1.



**Figure 7.** Vehicle Damage, Test SBT-1.

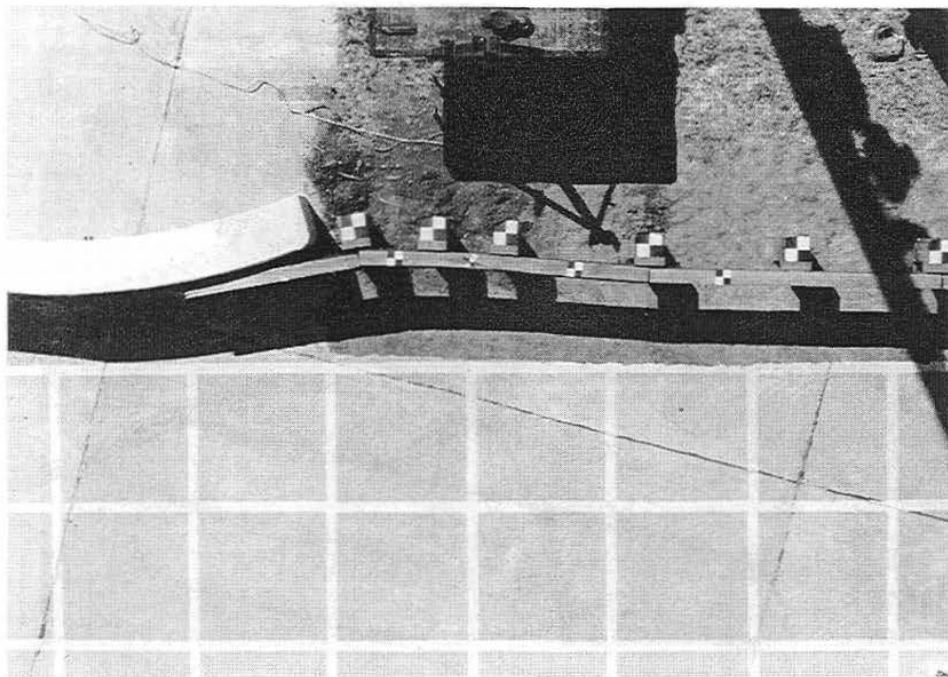
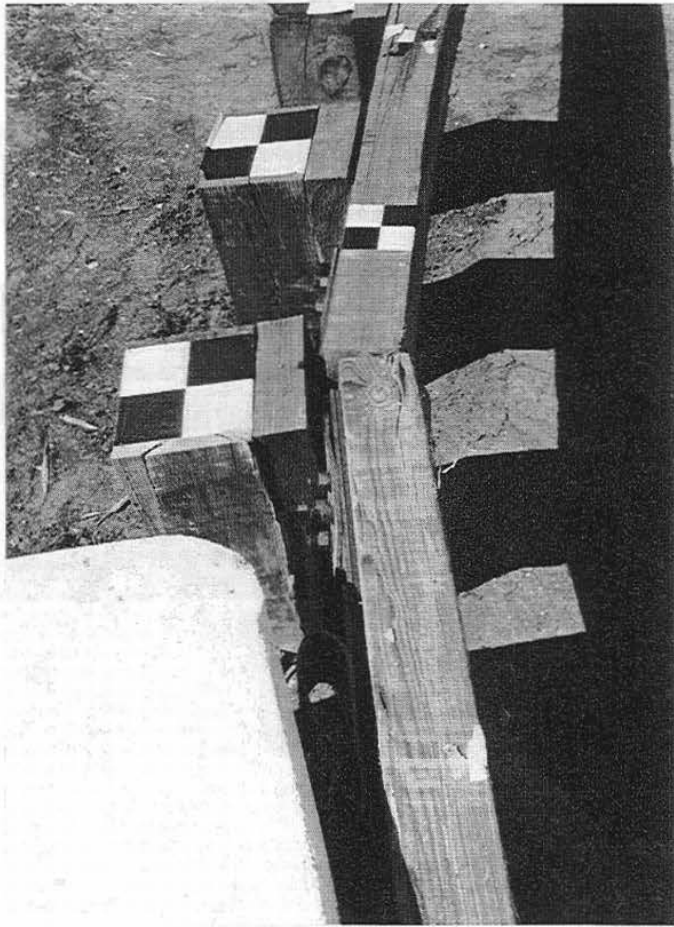


**Figure 8.** Vehicle Damage, Test SBT-1 (cont.).



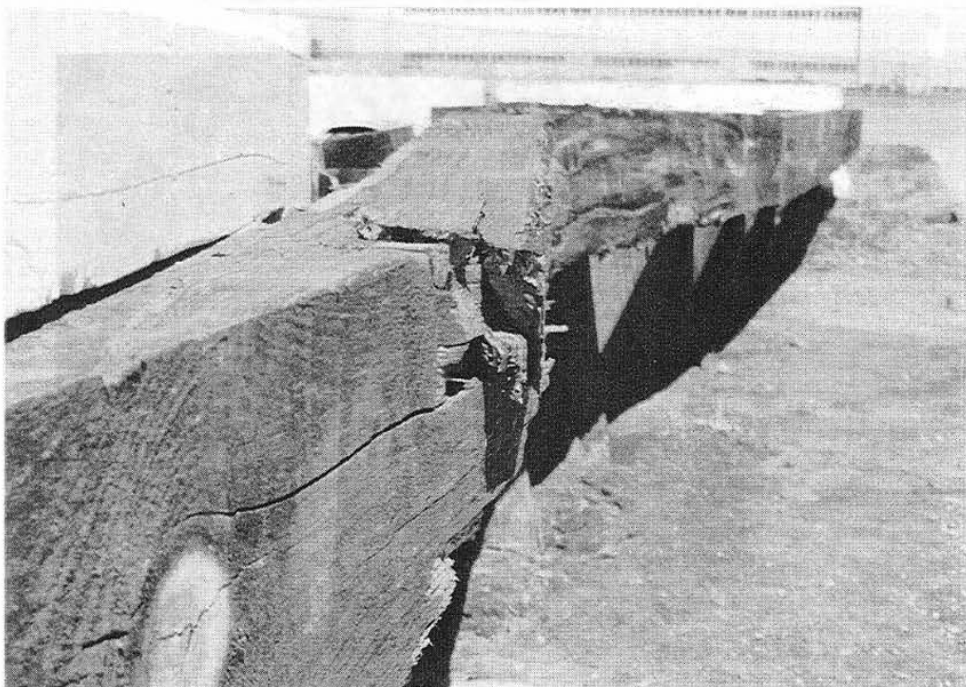
\*Maximum Crush=17in. (492mm)

**Figure 9.** Crush Depth Diagram, Test SBT-1.

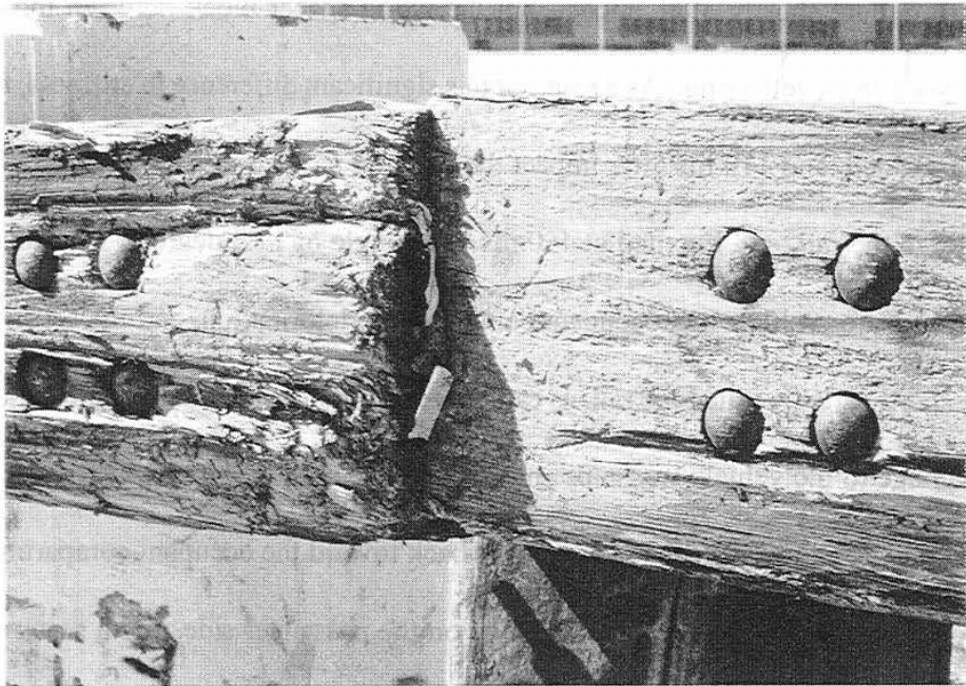
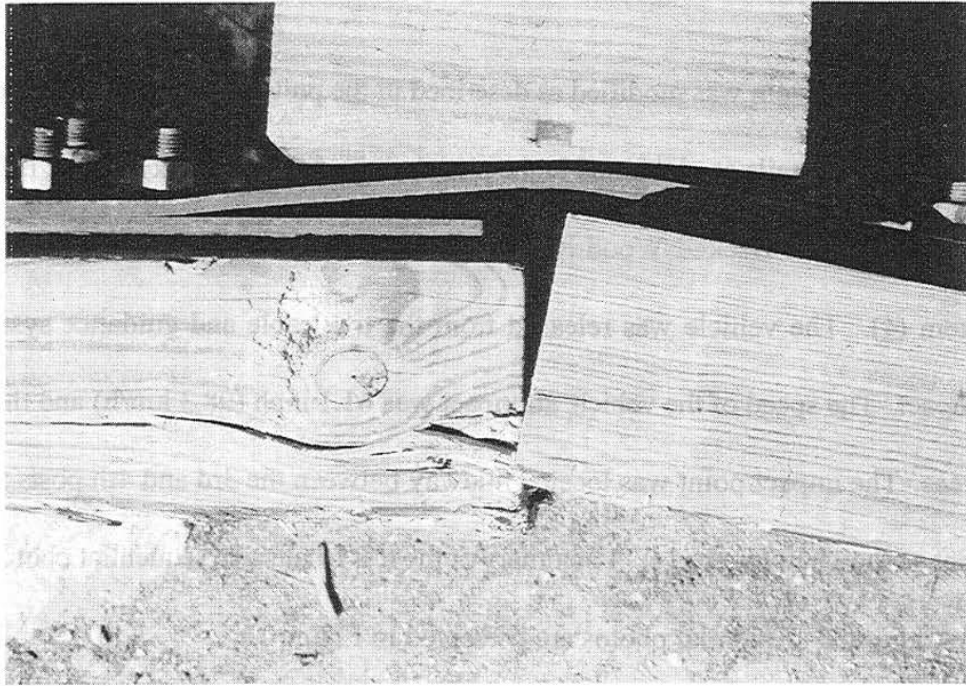


**Figure 10.** System Damage, Test SBT-1.





**Figure 11.** System Damage, Test SBT-1 (cont.).



**Figure 12.** Damage at first splice, Test SBT-1.

### 3.2 Test SBT-2

For this test the system was modified as described in the previous section. These modifications are shown in Figure 13, and details can be found in the plan drawings of Appendix A. The 1984 Buick LeSabre was directed into the Steel Backed Wood Rail to Bridge Rail Transition using a reverse tow and cable guidance system (4). The vehicle was released from the tow cable and guidance system and was free wheeling at impact. The speed of the vehicle at impact was 61.1 mph (98.3 km/h) and the angle of impact was 26.5 degrees. The impact point was located midway between the 3rd and 4th posts from the concrete bridge abutment as shown in Figure 14. A summary of the test results and sequential photographs are shown in Figure 15. Additional sequential photos are presented in Figure 16.

Upon impact with the wood rail, the right front corner of the test vehicle began to crush inward. Rail No. 2 began to deflect shortly after impact, but the wood spacer block between the concrete and rail prevented rail No. 1 from deflecting. As a result of this significant difference in stiffness, the splice between these two rails yielded, and 110 ms after impact the first rail speared into the vehicle. The vehicle never became parallel to the rail, and it exited at 450 ms at an angle of 17.3 degrees. The snagging at the first splice resulted in major vehicle and occupant compartment deformation, and the sedan was brought to a complete stop shortly after it exited the rail, as can be seen by its final resting position shown in Figure 17.

The damage to the vehicle was substantial, as can be seen in Figures 18 and 19. The entire front right portion of the vehicle was crushed and pushed back toward the occupant compartment considerably. The firewall and floorboard were pushed up and in on the passenger side, and a section of the wood rail penetrated the firewall on the extreme right hand side. The windshield was broken and the roof of the vehicle was buckled considerably. The maximum vehicle crush of 31.5 (800 mm) inches is shown schematically in Figure 20.

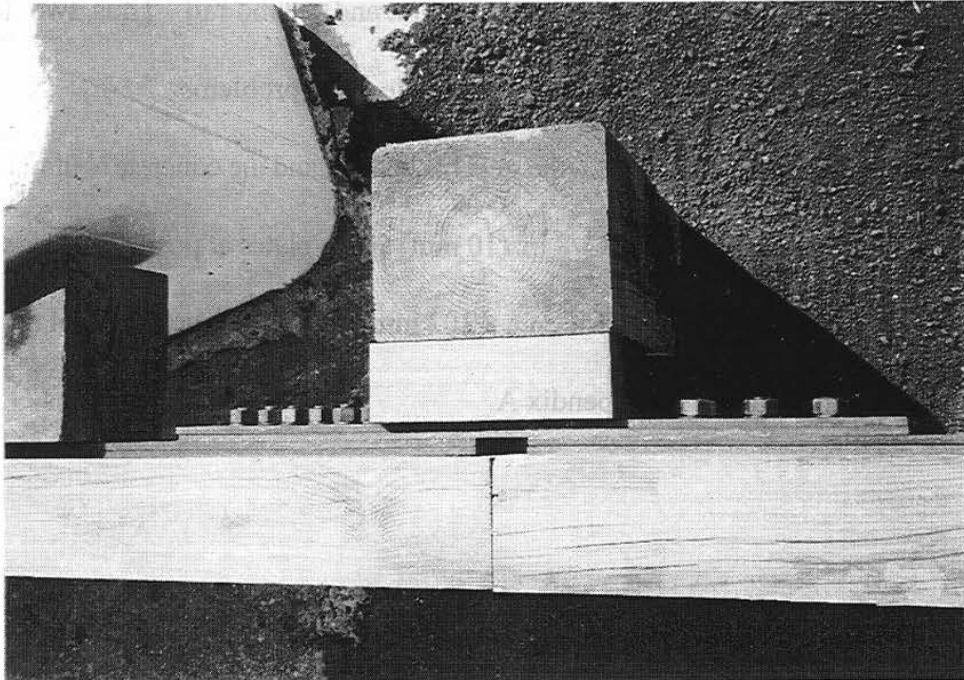
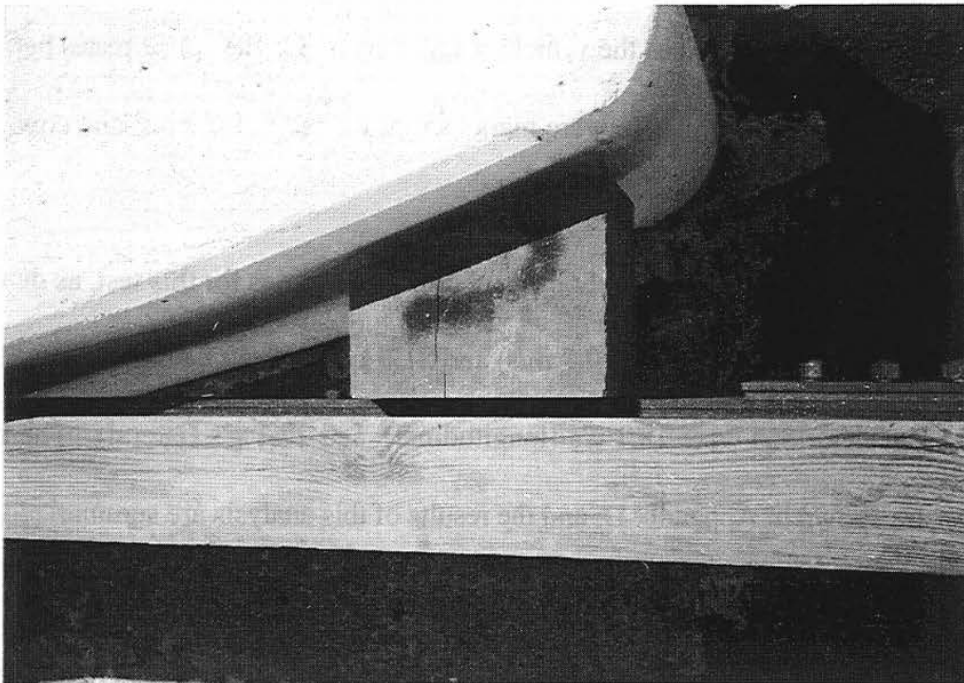


Damage to the steel backed wood rail was considerable, as can be seen in Figures 21 and 22. The upstream end of rail No. 1 was damaged as the vehicle snagged on it, and the splice plates between rails No. 1 and No. 2 were bent significantly. There were marks along the face of the rail and concrete abutment throughout the length of contact.

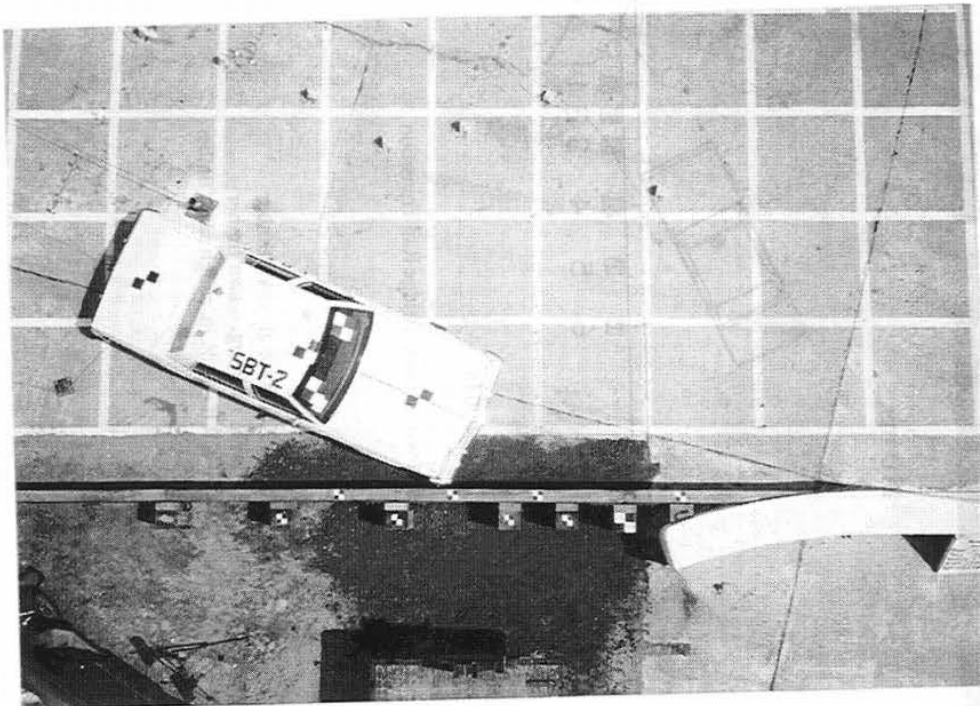
The normalized longitudinal and lateral occupant impact velocities for this test, as determined from accelerometer data analysis, were 35.1 fps (10.7 m/s) and 21.0 fps (6.4 m/s), respectively. The maximum occupant ridedown decelerations were 18.1 g's (longitudinal), and 22.1 g's (lateral). The accelerometer traces from this test are shown in Appendix D, and the results of this analysis are summarized in Figure 15.

Two of the systems design flaws became apparent as a result of this test. The first was that the wood blockout between the wood rail and concrete abutment made the first rail section much too stiff, which resulted in the snagging problem at splice No. 1. The second observation was that the steel splice plates did not provide adequate strength for the splice between the first and second rail. Thus, two design changes were incorporated into the next design in an effort to alleviate these problems.

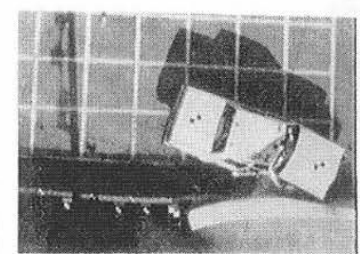
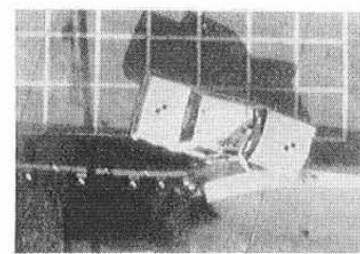
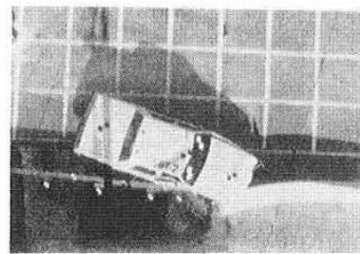
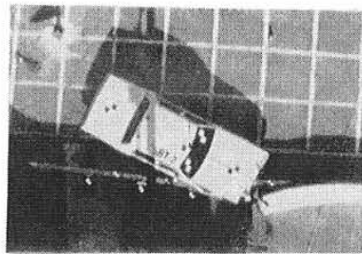
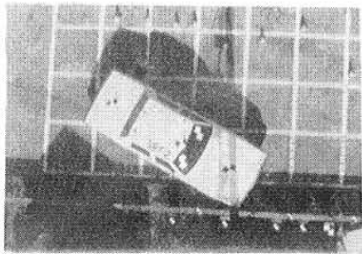
First, the angled wood blockout between the steel backed rail and the concrete abutment was replaced with a 6 in. diameter pipe. Secondly, the two 3/8 in. (10 mm) splice plates at post No. 1 were replaced with a 3 ft (0.91 m) length of 6 in. x 4 in. x 1/2 in. (152 mm x 102 mm x 13 mm) structural steel tube. The details of these design changes can be found in Appendix A.



**Figure 13.** Design Modifications, Test SBT-2.



**Figure 14.** Impact Location, Test SBT-2.



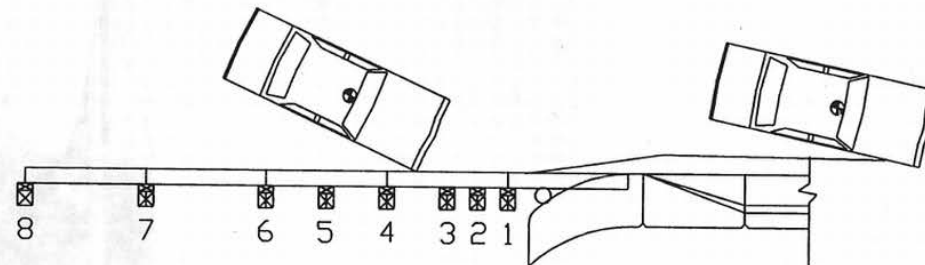
Impact

110 ms

170 ms

400 ms

600 ms



Speed

Impact ..... 61.1 mph  
Exit ..... 8.4 mph

Angle

Impact ..... 26.5 deg  
Exit ..... 17.3 deg

Change in Velocity ..... 52.7 mph

Normalized Occupant Impact Velocity

Longitudinal ..... 35.1 fps  
Lateral ..... 21.0 fps

Occupant Ridedown Deceleration

Longitudinal ..... 18.1 g's  
Lateral ..... 22.1 g's

Vehicle Damage

TAD ..... 1-RFQ-7  
VDI ..... 01FZES5

Vehicle Rebound Distance ..... 4 ft - 6 in. @ 15 ft

Bridge Rail Damage ..... Substantial

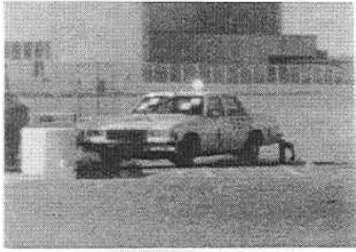
Maximum Deflections

Permanent Set ..... 4.75 in. midspan between posts 2 & 3  
Dynamic ..... 10.4 in. @ post No. 3

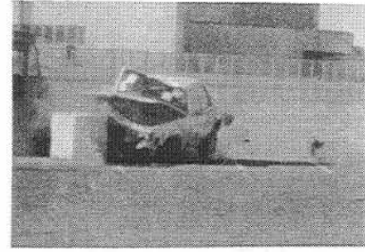
Conversion Factors: 1 in.= 2.54 cm; 1 lb=0.454 kg

Test Number ..... SBT-2  
Federal Contract No. .... DTFH71-90-C-00035  
Date ..... 4/3/92  
Installation ..... Steel Backed Wood Rail to Bridge Rail Transition  
Approach Guardrail  
Length ..... 50 ft  
Height ..... 2 ft- 3 in.  
Material  
Posts 1-3 ..... 10 in. X 12 in. X 8 ft rough sawn timber  
Posts 4-8 ..... 10 in. X 12 in. X 7 ft rough sawn timber  
Rail ..... 6 in. X 10 in. X 9 ft - 11 ½ in. rough sawn timber  
Vehicle Model ..... 1984 Buick LeSabre  
Vehicle Weight  
Curb ..... 3770 lb  
Test Inertia ..... 4616 lb  
Gross Static ..... 4456 lb

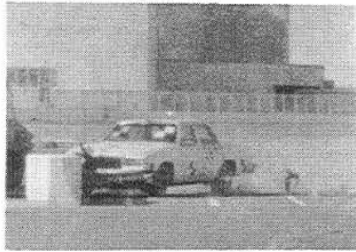
Figure 15. Summary of Test SBT-2.



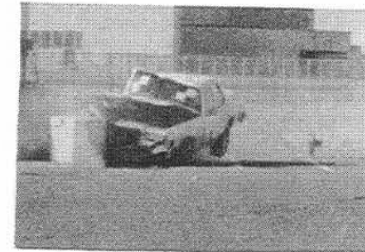
Impact



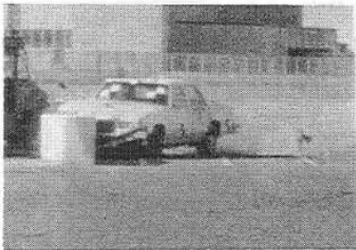
280 ms



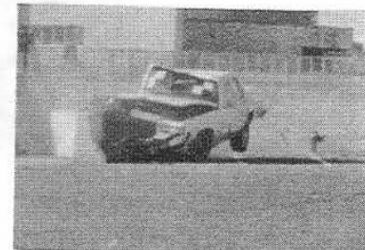
60 ms



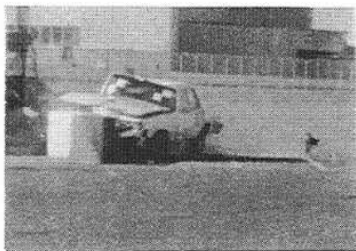
380 ms



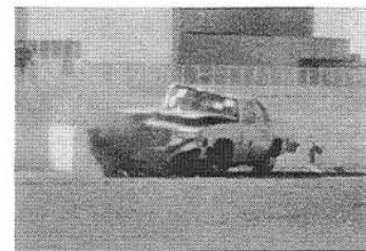
120 ms



500 ms



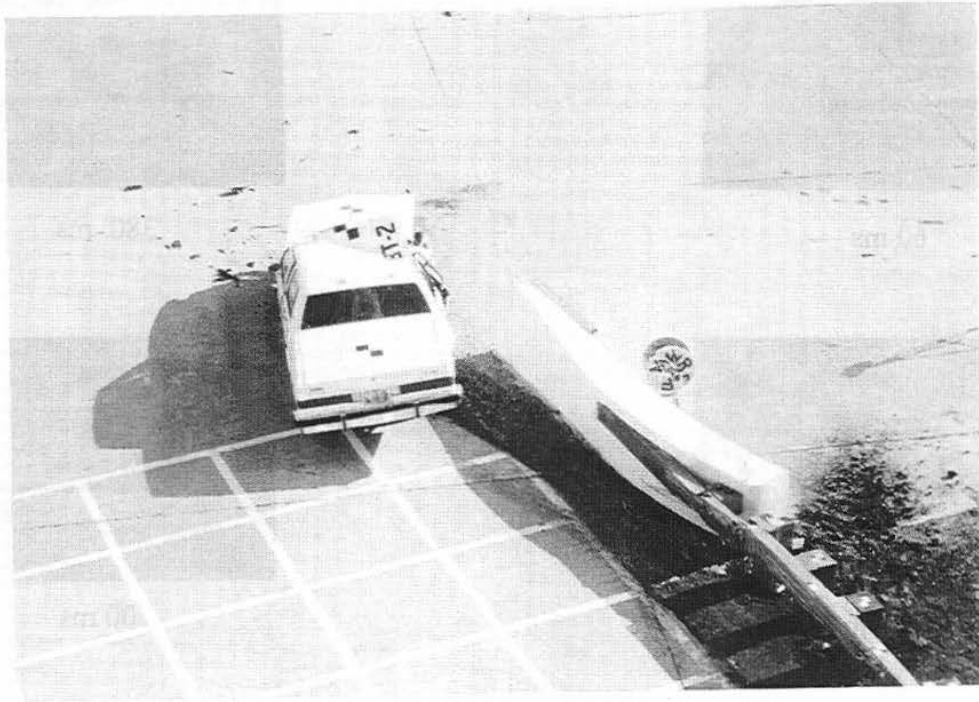
200 ms



700 ms

**Figure 16.** Downstream Sequential Photographs, Test SBT-2.

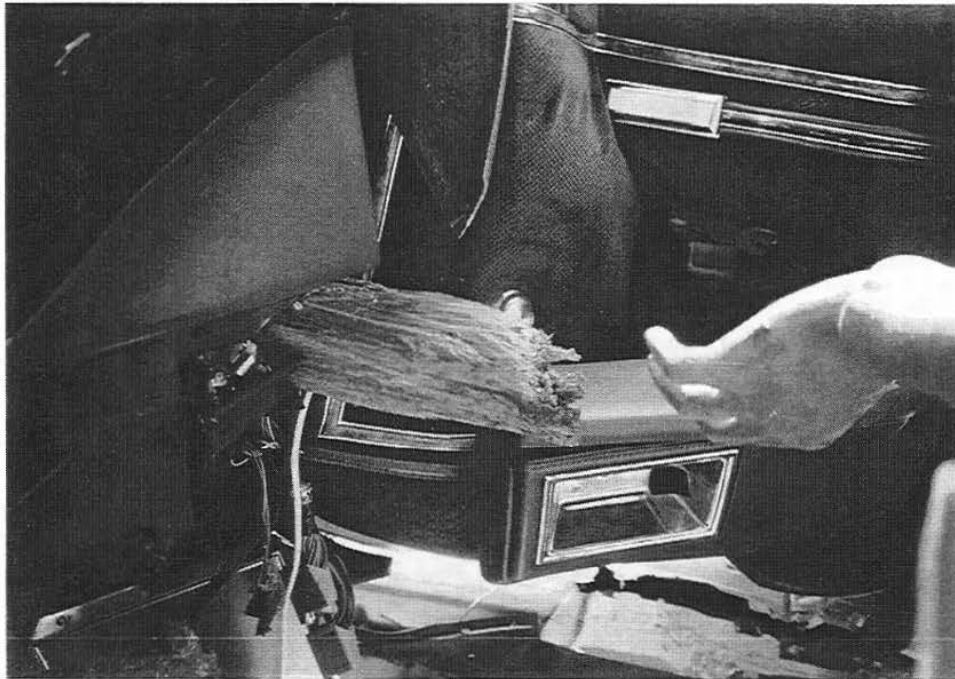
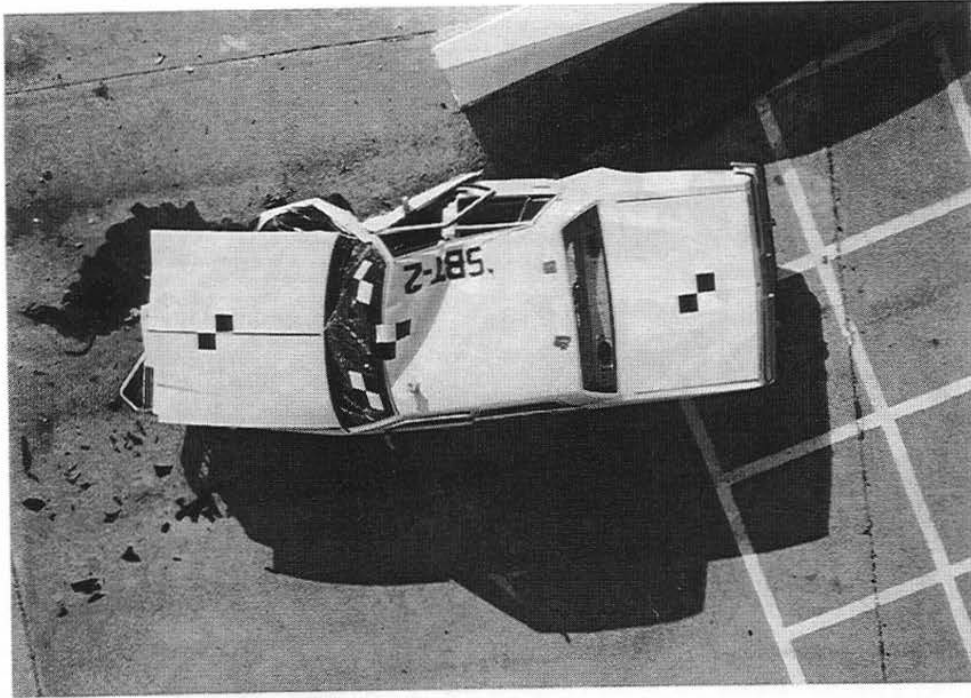




**Figure 17.** Vehicle Trajectory, Test SBT-2.

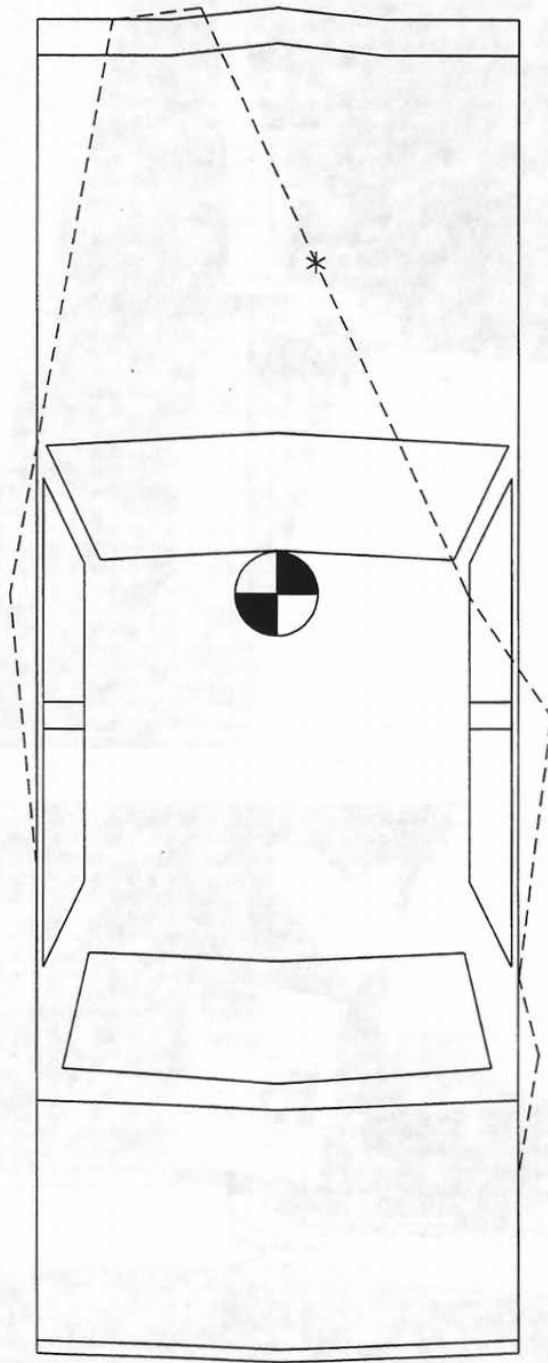


**Figure 18.** Vehicle Damage, Test SBT-2.



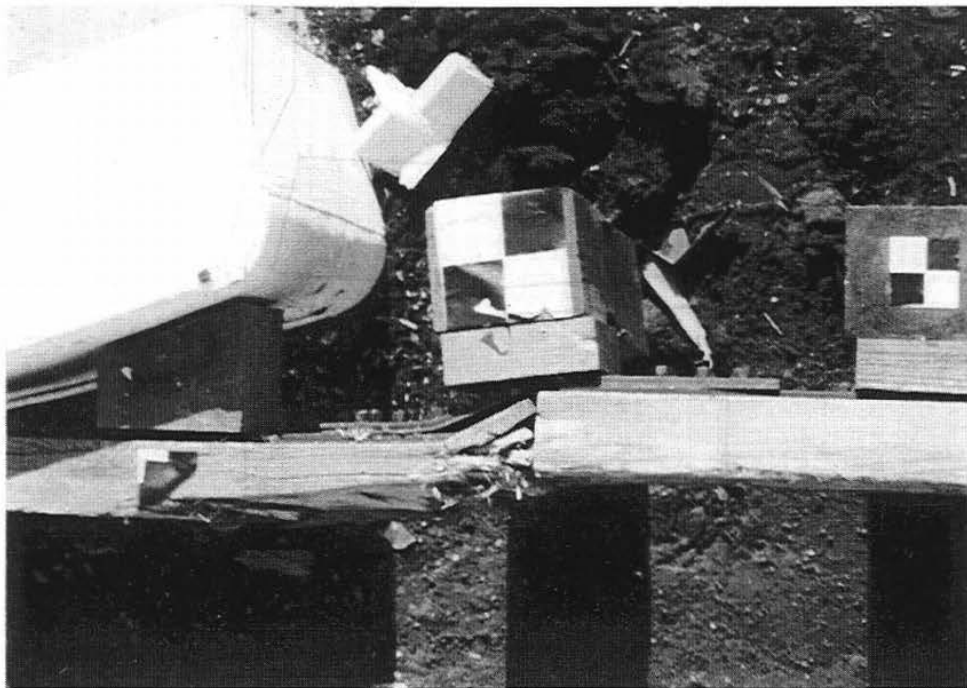
**Figure 19.** Vehicle Damage, Test SBT-2 (cont.).





\*Maximum Crush=31.5in. (800mm)

**Figure 20.** Crush depth diagram, Test SBT-2.



**Figure 21.** System Damage, Test SBT-2.



**Figure 22.** System Damage, Test SBT-2 (cont.).

### 3.3 Test SBT-3

The design changes discussed in the previous section are shown in Figure 23, and were implemented for this next test. The design details for the system tested here can be seen in Appendix A. For this test a 1985 Ford LTD was directed into the Steel Backed Wood Rail to Bridge Rail Transition using a reverse tow and cable guidance system (4). The vehicle was released from the tow cable and guidance system and was free wheeling at impact. The speed of the vehicle at impact was 62.0 mph (99.8 km/h) and the angle of impact was 25.8 degrees. The impact point was located midway between the 3rd and 4th posts from the concrete bridge abutment as shown in Figure 24. A summary of the test results and sequential photographs is shown in Figure 25. Additional sequential photos are presented in Figure 26.

Upon impact with the wood rail, the right front corner of the test vehicle was crushed inward, and the wheel was forced under the rail and back to the post. This resulted in considerable tire snagging on posts Nos. 1 and 2, which pushed the wheel back against the firewall and resulted in deformation of the occupant compartment. The vehicle became parallel to the system at 212 ms, and exited at 343 ms and 5.8 degrees. The maximum dynamic deflection of this system was limited to 6.4 in. (163 mm) at post No. 3, and there was no problem with the vehicle impacting the end of the concrete abutment. The final resting position of the vehicle was downstream and behind the rail, as seen in Figure 27.

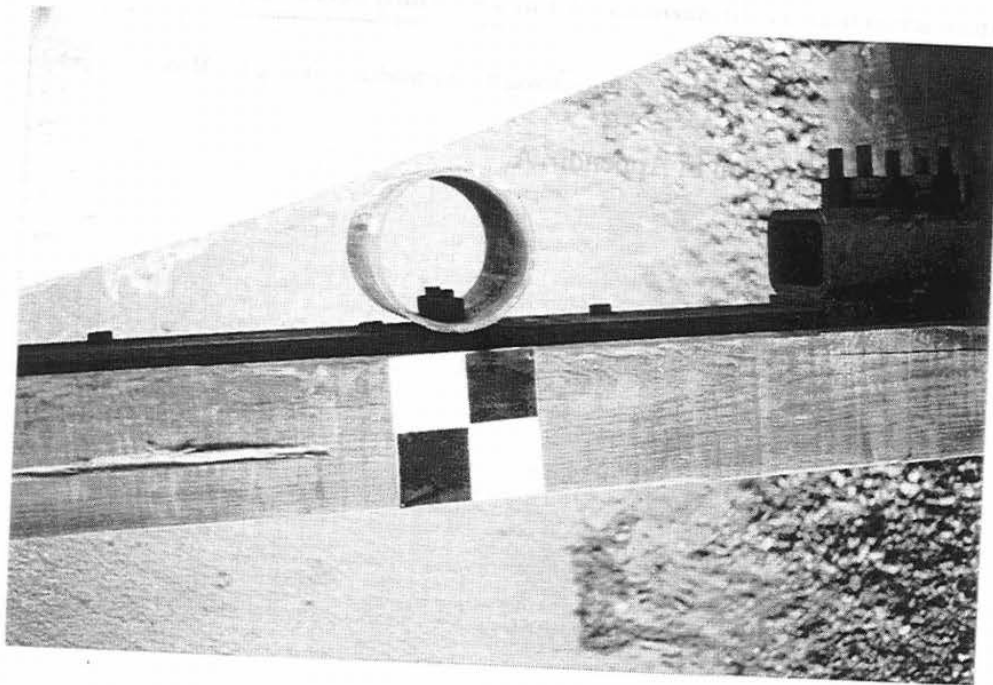
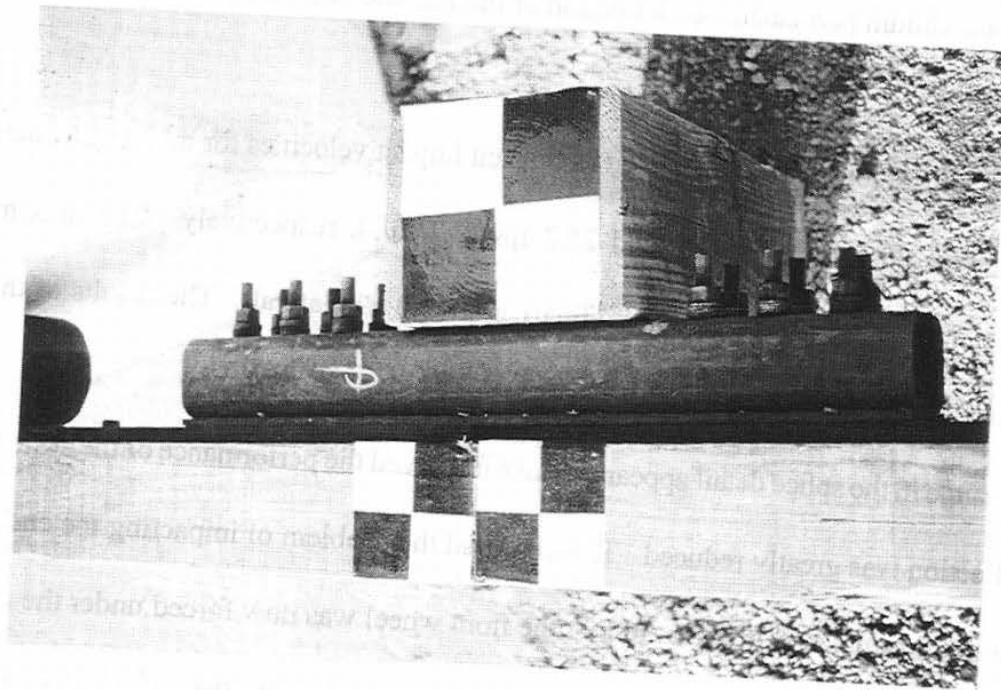
The vehicle damage, shown in Figures 28 and 29, consisted of the crushing of the front right corner of the vehicle, as well as scrapes and dents continuing down the side to the rear wheel well. The tire was torn off the front right wheel, and the rim was bent. Occupant compartment damage included buckling of the floor on the passenger side of the vehicle, as well as buckling of the dashboard. The maximum crush deformation of 13.75 in. (349 mm) is shown schematically in Figure 30.

Damage to the system, shown in Figure 31 and 32, consisted of minor scrapes along the face of the

rail, and significant gouges in post Nos. 1 and 2. There were only minor tire marks evident on the concrete abutment. The maximum permanent set deflection of the rail was 2.5 in. (64 mm), which occurred at post No. 2.

The normalized longitudinal and lateral occupant impact velocities for this test, as determined from film analysis, were 23.1 fps (7.0 m/s) and 25.2 fps (7.7 m/s), respectively. The maximum occupant ridedown decelerations were 2.5 g's (longitudinal), and 15.0 g's (lateral). The results of this analysis are summarized in Figure 25.

The change in the splice detail appears to have improved the performance of the system considerably, as the rail deflection was greatly reduced. This resolved the problem of impacting the end of the concrete abutment, but produced a new problem in that the front wheel was now forced under the rail and snagged on post Nos. 1 and 2. Tire marks on the posts indicated that a maximum snag of 5.5 in. (140 mm) occurred at post No. 2. In order to remedy this problem, a 4 in. (102 mm) deep blockout was added to post No. 1 and the 4 in. (102 mm) blockout at posts Nos. 2 and 3 were increased to a depth of 8 in. (203 mm). The details of these design changes can be seen in Appendix A.



**Figure 23.** Design Modifications, Test SBT-3.



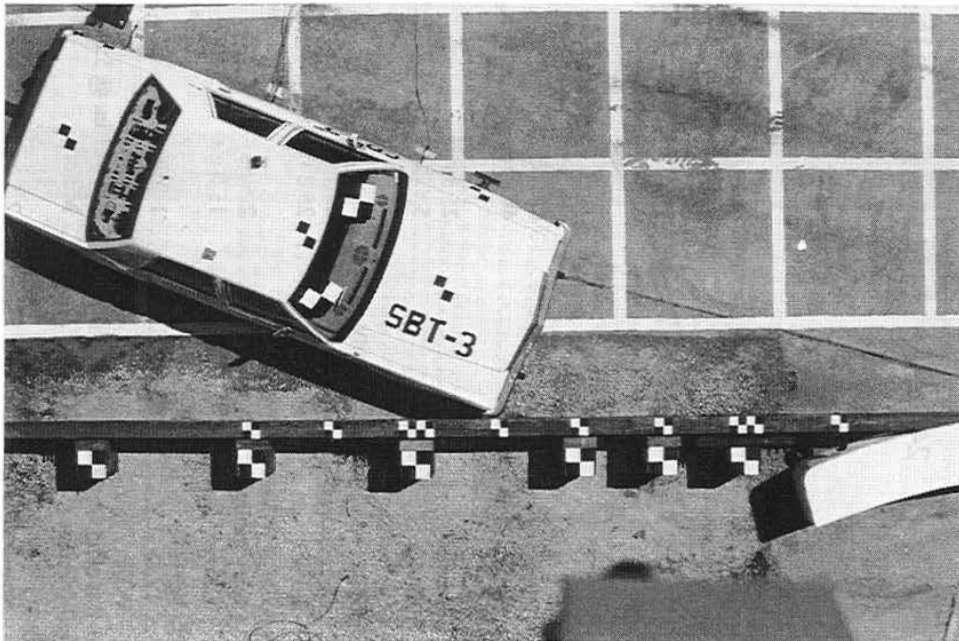
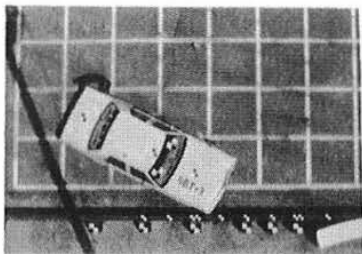
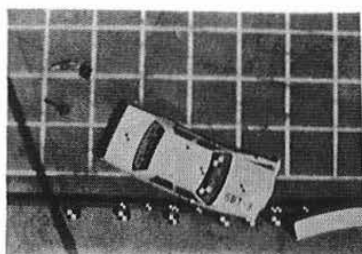


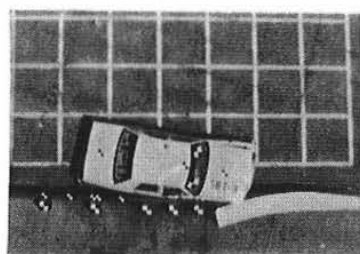
Figure 24. Impact Location, Test SBT-3.



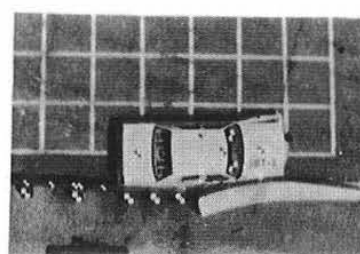
Impact



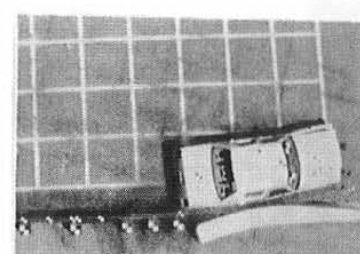
80 ms



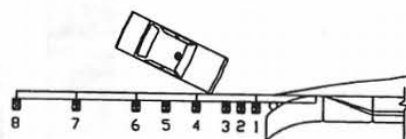
160 ms



240 ms



340 ms



#### Speed

Impact	62.0 mph
Exit	40.8 mph

#### Angle

Impact	25.8 deg
Exit	5.8 deg

#### Change in Velocity

Change in Velocity	21.2 mph
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#### Normalized Occupant Impact Velocity

Longitudinal	23.1 fps
Lateral	25.2 fps

#### Occupant Ridedown Deceleration

Longitudinal	2.5 g's
Lateral	15.0 g's

#### Vehicle Damage

TAD	1-RFQ-5
VDI	01RYES2

#### Vehicle Rebound Distance

Vehicle Rebound Distance	4 ft - 11 in. @ 55 ft
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#### Guardrail Damage

Guardrail Damage	Minor
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#### Maximum Deflections

Permanent Set	2.5 in. @ post No. 2
Dynamic	6.4 in. @ post No. 3

Conversion Factors: 1 in.= 2.54 cm; 1 lb= 0.454 kg

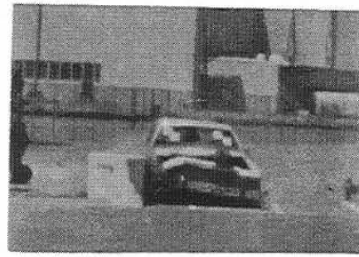
Test Number	SBT-3
Federal Contract No.	DTFH71-90-C-00035
Date	5/4/93
Installation	Steel Backed Wood Rail to Bridge Rail Transition
Approach Guardrail	
Length	50 ft
Height	2 ft- 3 in.
Material	
Posts 1-3	10 in. X 12 in. X 8 ft rough sawn timber
Posts 4-8	10 in. X 12 in. X 7 ft rough sawn timber
Rail	6 in. X 10 in. X 9 ft - 11 1/2 in. rough sawn timber
Vehicle Model	1985 Ford LTD
Vehicle Weight	
Curb	3940 lb
Test Inertia	4496 lb
Gross Static	4656 lb

Figure 25. Summary of Test SBT-3.





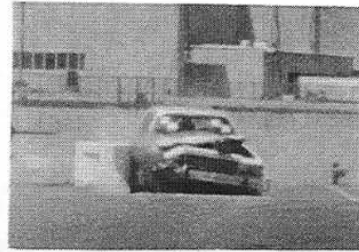
Impact



240 ms



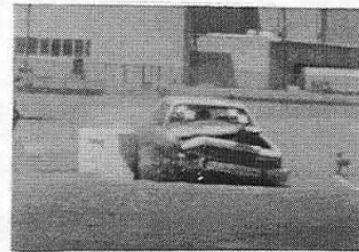
60 ms



300 ms



120 ms



360 ms

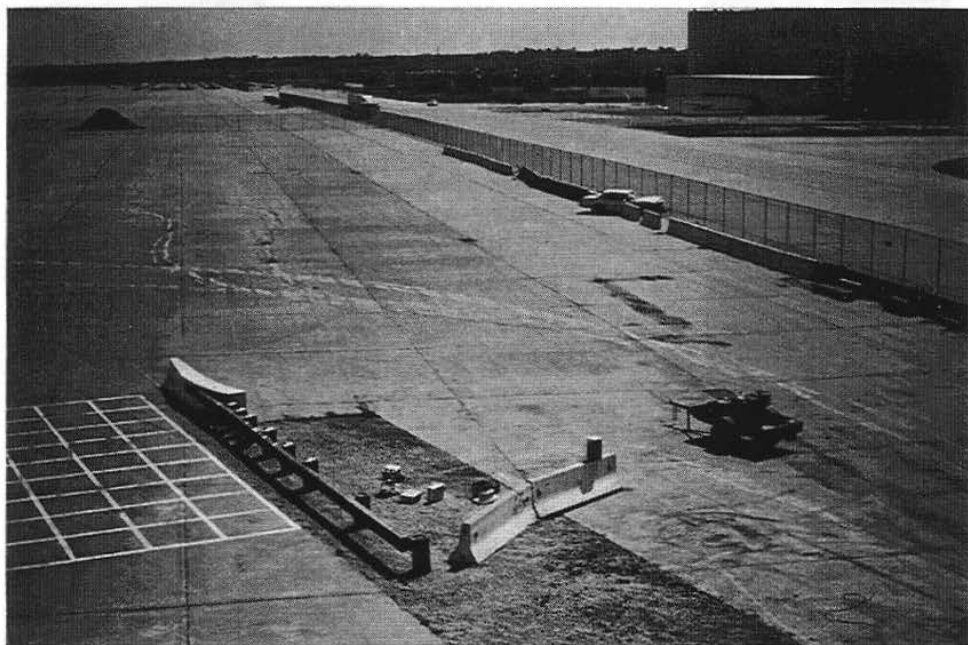


180 ms

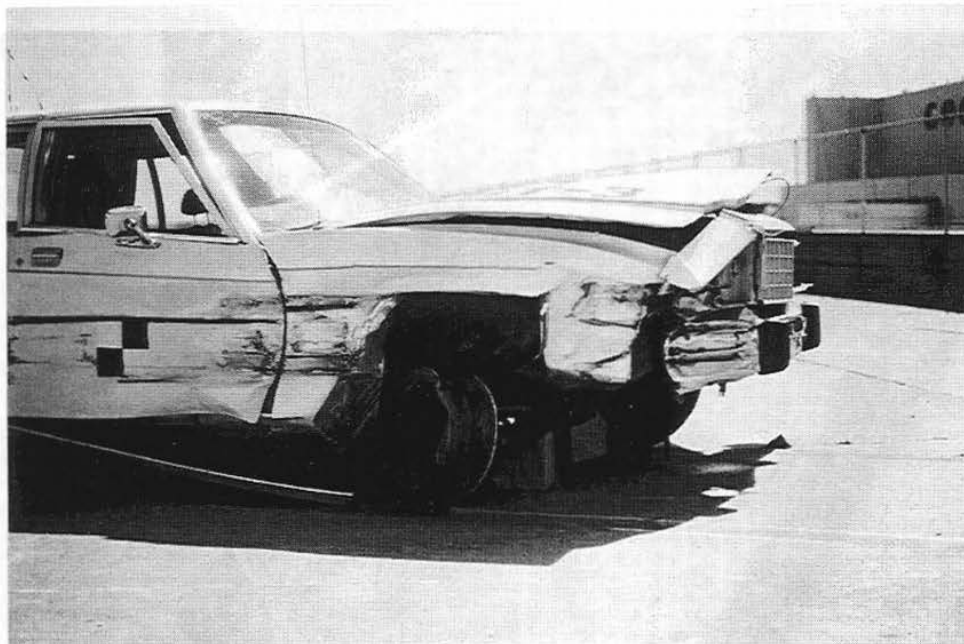


440 ms

**Figure 26.** Downstream Sequential Photographs, Test SBT-3.



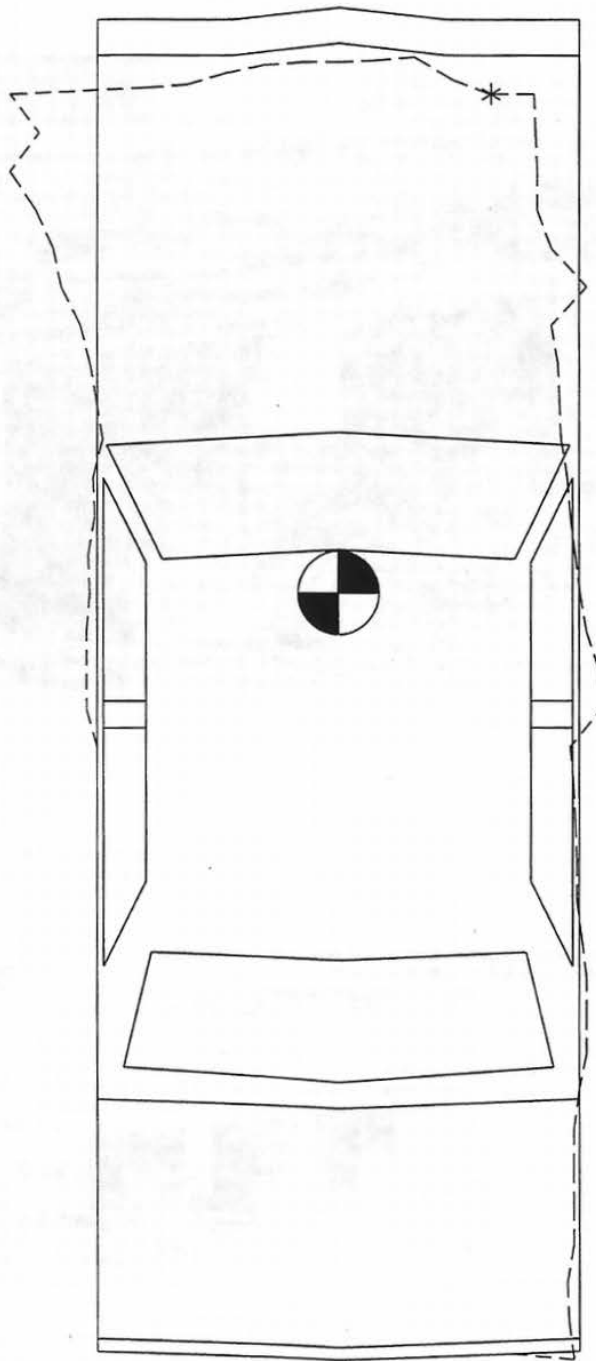
**Figure 27.** Vehicle Trajectory, Test SBT-3.



**Figure 28.** Vehicle Damage, Test SBT-3.



**Figure 29.** Vehicle Damage, Test SBT-3 (cont.).



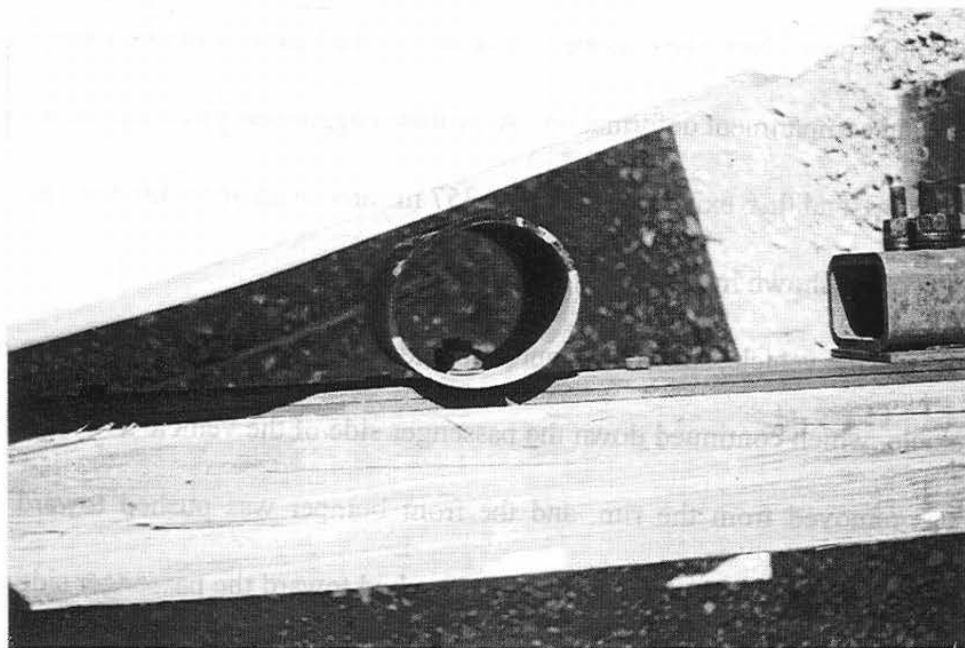
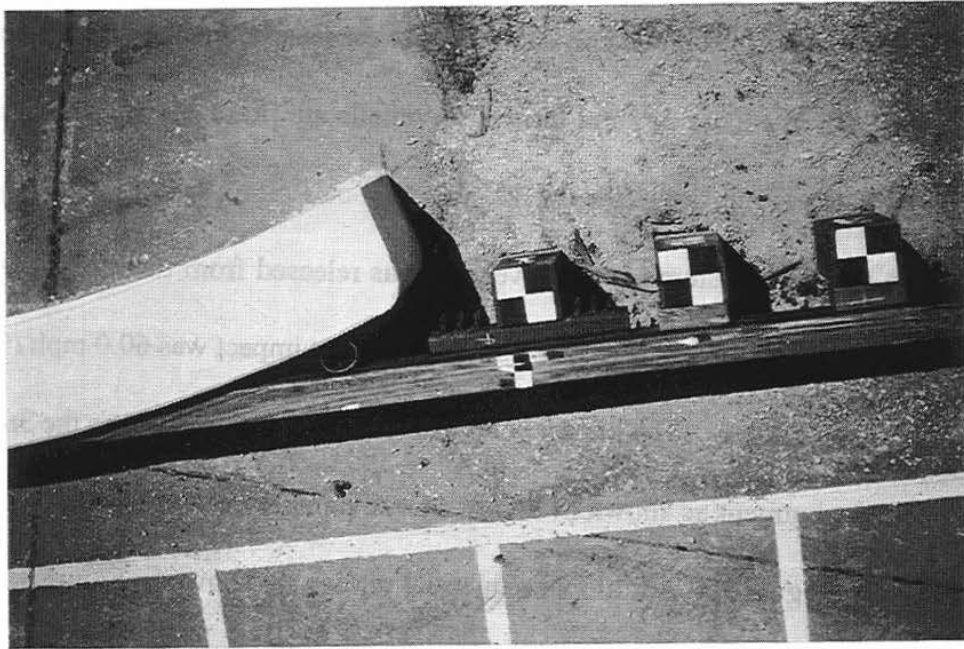
\*Maximum Crush=13.75in. (349mm)

**Figure 30.** Crush Depth Diagram, Test SBT-3.



**Figure 31.** System Damage, Test SBT-3.





**Figure 32.** System Damage, Test SBT-3 (cont.).



### 3.4 Test SBT-4

The design changes discussed in the previous section were incorporated into the system for this test. These changes can be seen in Figure 33, and the design details are presented in Appendix A. A 1984 Mercury Grand Marquis was directed into the Steel Backed Wood Rail to Bridge Rail Transition using a reverse tow and cable guidance system (4). The vehicle was released from the tow cable and guidance system and was free wheeling at impact. The speed of the vehicle at impact was 60.0 mph (96.5 km/h) and the angle of impact was 26.2 degrees. The impact point was located midway between the 3rd and 4th posts from the concrete bridge abutment as shown in Figure 34. A summary of the test results and sequential photographs are shown in Figure 35. Additional sequential photos are shown in Figure 36.

This test performed similar to Test SBT-3 in that as the right front corner of the vehicle was crushed upon impact, the wheel was forced under the rail and contacted the posts. This snagging occurred even though the first three posts had been moved back 4 in. (102 mm) with blockouts, and resulted in considerable occupant compartment deformation. After this snagging occurred, the vehicle became parallel to the system at 246 ms, and then exited the system at 357 ms and an angle of 4.0 degrees. The final resting position of the vehicle is shown in Figure 37.

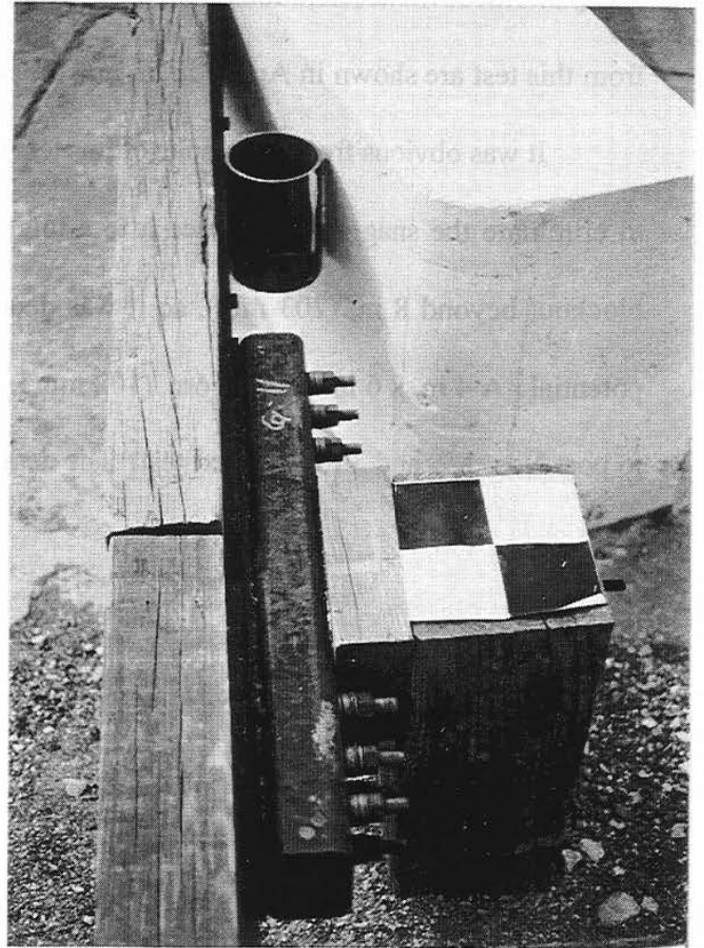
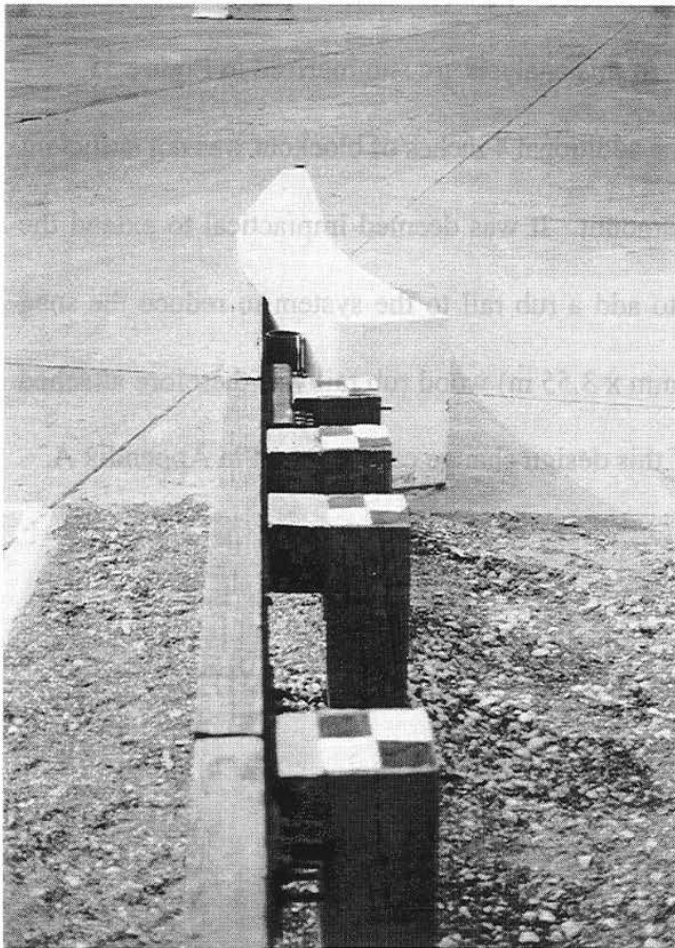
The damage to the vehicle, shown in Figures 38 and 39, consisted of deformation of the front right corner of the vehicle, which continued down the passenger side of the vehicle as scrapes and dents. The front left tire was removed from the rim, and the front bumper was pushed toward the drivers side considerably. The entire front end of the vehicle was pushed toward the passenger side and the roof was buckled. Interior compartment damage consisted of buckling of the floorboard on the passenger side and of the dash. The maximum crush deformation of 13.75 in. (349 mm) is shown schematically in Figure 40.

Damage to the system, shown in Figure 41 and 42, consisted of scrapes and gouges along the face

of the rail from the impact point to the midspan of the first rail. The spacer pipe between the rail and concrete abutment was deformed slightly, and the soil was gouged considerably in front of post Nos. 1,2, and 3. Markings on the posts indicated that the vehicle snagged on posts Nos. 1 and 2.

The normalized longitudinal and lateral occupant impact velocities for this test, as determined from accelerometer data analysis, were 18.8 fps (5.7 m/s) and 23.9 fps (7.3 m/s), respectively. The maximum occupant ridedown decelerations were 6.2 g's (longitudinal), and 16.7 g's (lateral). The accelerometer traces from this test are shown in Appendix E, and the results of this analysis are summarized in Figure 35.

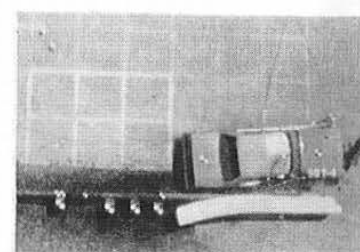
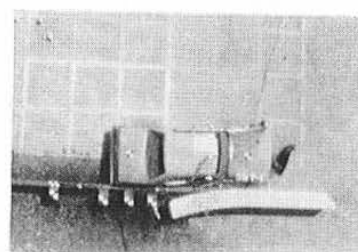
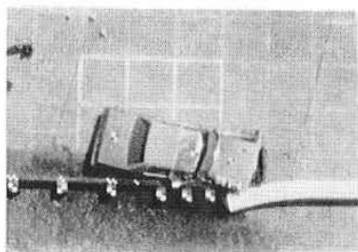
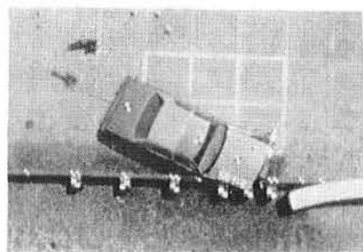
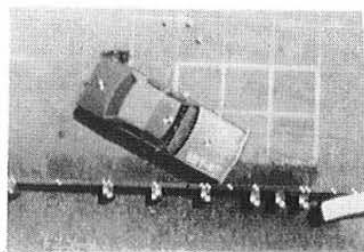
It was obvious from the results of this test that the additional 4 inches of blackout was not sufficient to eliminate the snagging or reduce it to a tolerable amount. It was deemed impractical to extend the blackout beyond 8 in. (203 mm), so it was decided to add a rub rail to the system to reduce the snag potential. A 4 in. x 6 in. x 11ft - 6in. (102 mm x 152 mm x 3.55 m) wood rub rail was therefore attached to post Nos. 1,2, and 3 for the next test. The details of this design change can be found in Appendix A.



**Figure 33.** Design Modifications, Test SBT-4.



**Figure 34.** Impact Location, Test SBT-4.



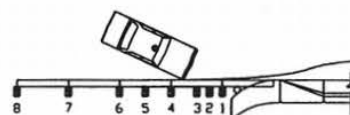
Impact

80 ms

160 ms

280 ms

400 ms



Speed

Impact ..... 60.0 mph  
Exit ..... 43.3 mph

Angle

Impact ..... 26.2 deg  
Exit ..... 4.0 deg

Change in Velocity ..... 16.7 mph

Normalized Occupant Impact Velocity

Longitudinal ..... 18.8 fps  
Lateral ..... 23.9 fps

Occupant Ridedown Deceleration

Longitudinal ..... 6.2 g's  
Lateral ..... 16.7 g's

Vehicle Damage

TAD ..... 1-RFQ-5  
VDI ..... 01RYES2

Vehicle Rebound Distance ..... 5 ft - 7 in. @ 55 ft

Guardrail Damage ..... Minor

Maximum Deflections

Permanent Set ..... 1.5 in. @ post No. 3  
Dynamic ..... 8.9 in. @ post No. 3

Conversion Factors: 1 in.= 2.54 cm; 1 lb= 0.454 kg

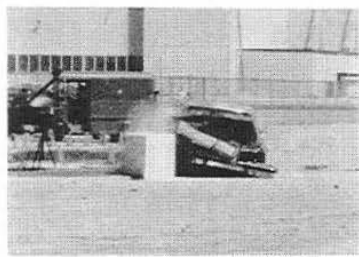
Test Number ..... SBT-4  
Federal Contract No. .... DTFH71-90-C-00035  
Date ..... 5/27/94  
Installation ..... Steel Backed Wood Rail to Bridge Rail Transition  
Approach Guardrail  
Length ..... 50 ft  
Height ..... 2 ft- 3 in.  
Material  
Posts 1-3 ..... 10 in. X 12 in. X 8 ft rough sawn timber  
Posts 4-8 ..... 10 in. X 12 in. X 7 ft rough sawn timber  
Rail ..... 6 in. X 10 in. X 9 ft - 11 1/2 in. rough sawn timber  
Vehicle Model ..... 1984 Mercury Grand Marquis  
Vehicle Weight  
Curb ..... 3910 lb  
Test Inertia ..... 4668 lb  
Gross Static ..... 4508 lb

Figure 35. Summary of Test SBT-4.





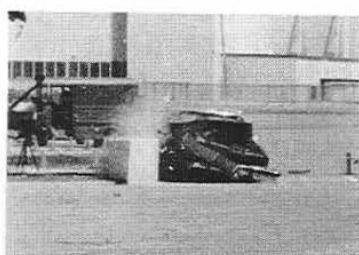
Impact



240 ms



60 ms



300 ms



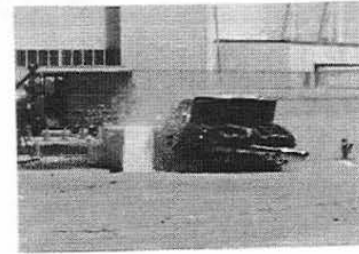
120 ms



360 ms

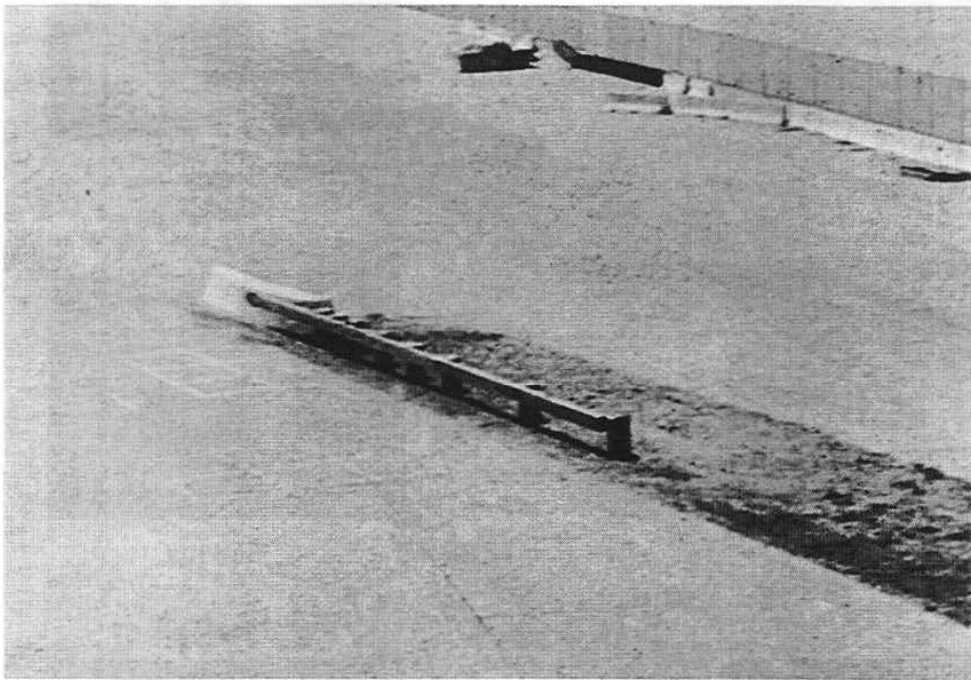


180 ms



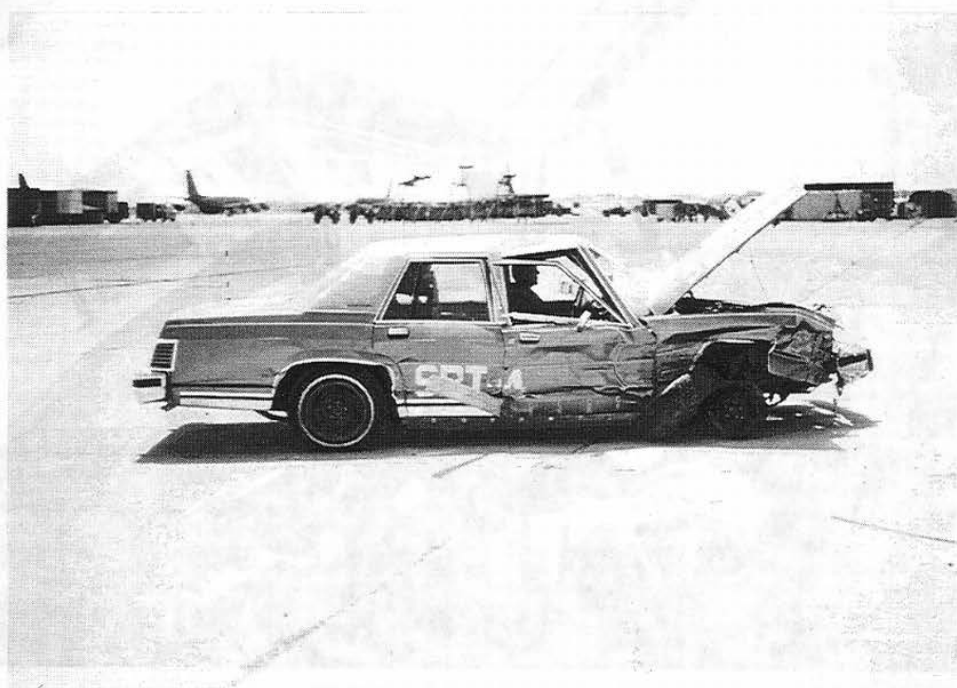
420 ms

**Figure 36.** Downstream Sequential Photographs, Test SBT-4.

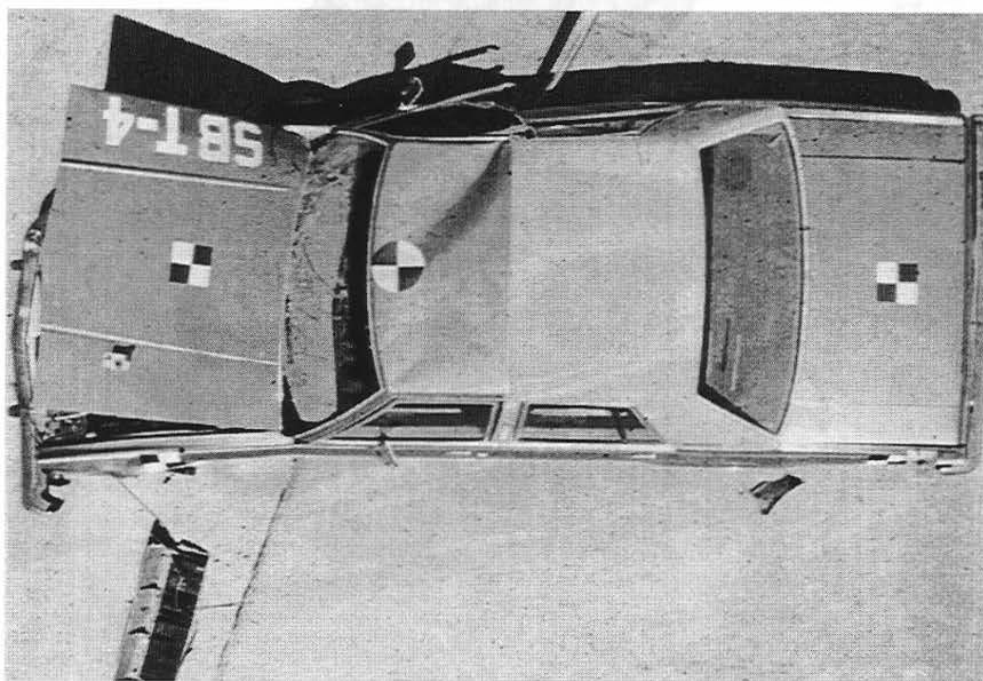


**Figure 37.** Vehicle Trajectory, Test SBT-4.

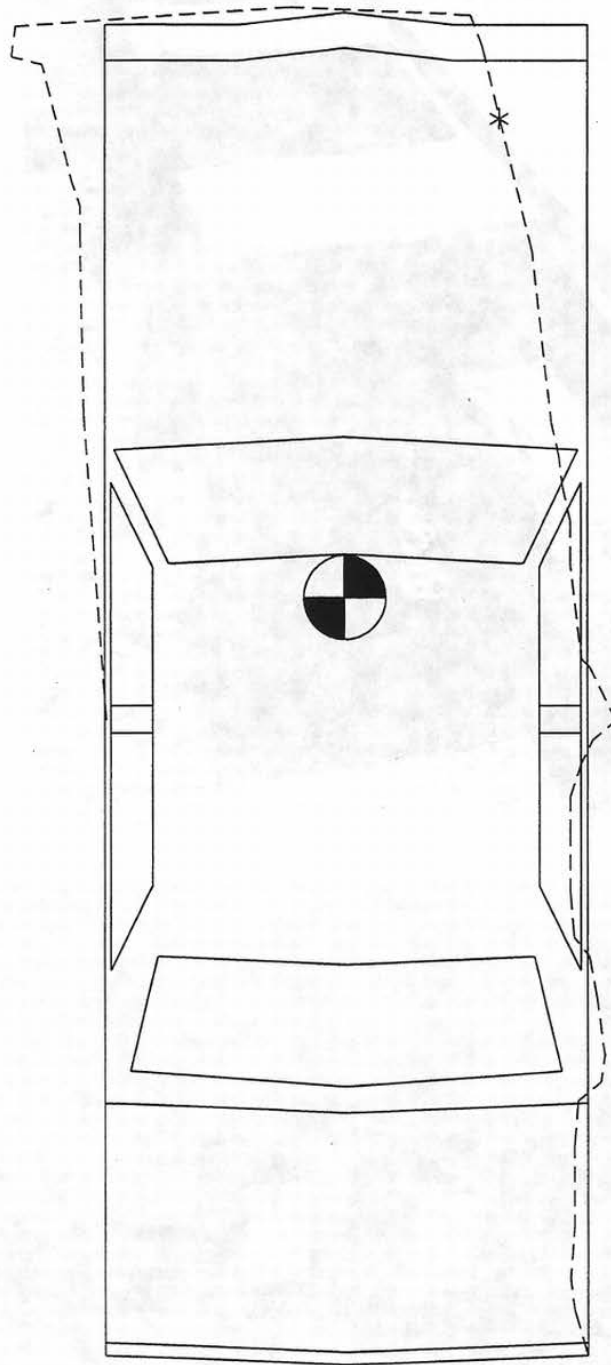




**Figure 38.** Vehicle Damage, Test SBT-4.

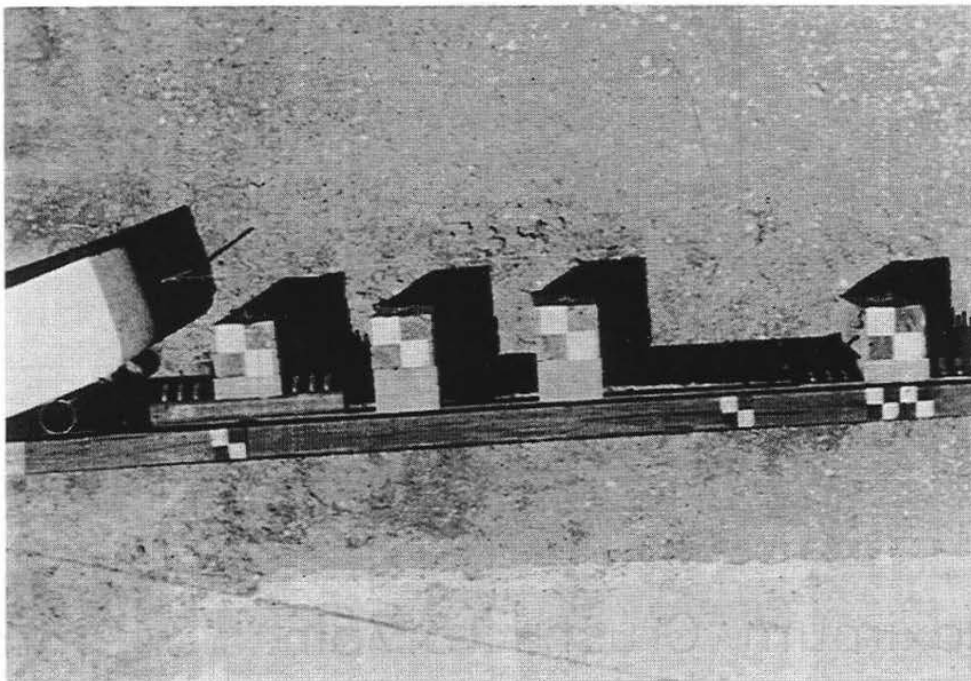
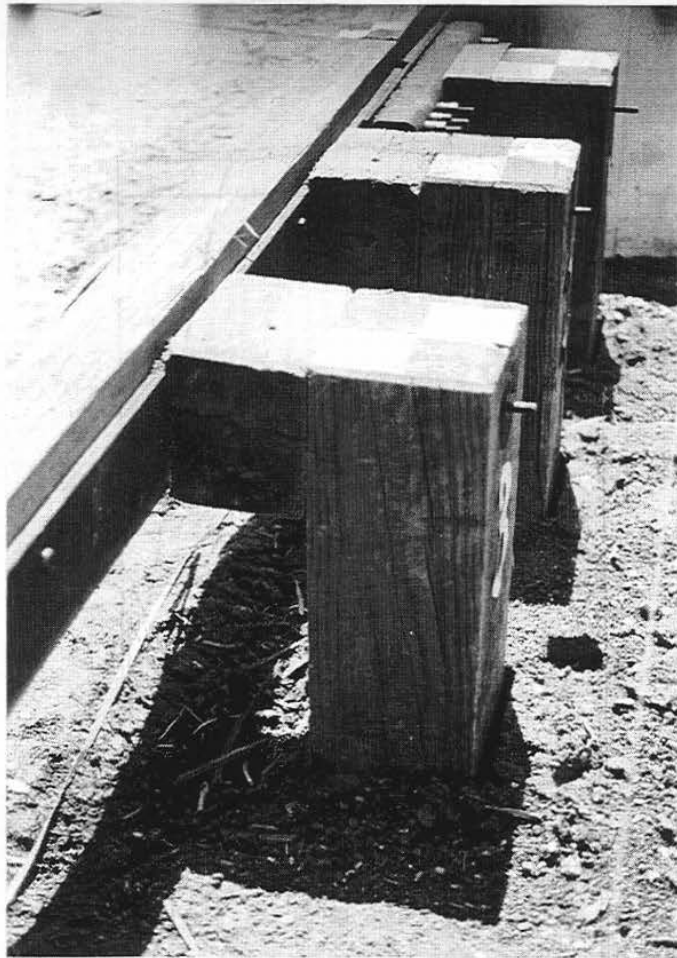


**Figure 39.** Vehicle Damage, Test SBT-4 (cont.).



\*Maximum Crush=13.75in. (349mm)

**Figure 40.** Crush Depth Diagram, Test SBT-4.



**Figure 41.** System Damage, Test SBT-4.



**Figure 42.** System Damage, Test SBT-4 (cont.).



### 3.5 Test SBT-5

A rub rail was added to the previous system for this test, as shown in Figure 43 and Appendix A. The 1984 Ford LTD was directed into the Steel Backed Wood Rail to Bridge Rail Transition using a reverse tow and cable guidance system (4). The vehicle was released from the tow cable and guidance system and was free wheeling at impact. The speed of the vehicle at impact was 58.6 mph (94.3 km/h) and the angle of impact was 24.8 degrees. The impact point was located midway between the 3rd and 4th posts from the concrete bridge abutment as shown in Figure 44. A summary of the test results and sequential photographs are shown in Figure 45. Additional sequential photographs are shown in Figure 46.

Upon impact with the wood rail, the front right corner of the vehicle was crushed inward, and the front tire contacted the rub rail approximately 10.5 in. (267 mm) downstream of post No. 3. This contact continued to the end of the rub rail. The vehicle became parallel to the rail 206 ms after impact. It was smoothly redirected and exited the system at 367 ms and at an angle of 7.3 degrees. The vehicle came to rest downstream and behind the rail as shown in Figure 47.

Damage to the vehicle, shown in Figures 48 and 49, included deformation of the front right corner, continuing along the length of the vehicle to the rear wheel well. There was no evidence of snagging, and the occupant compartment remained intact with the exception of minor deformation of the floorboard on the passenger side. The maximum crush deformation of 19.4 in. (492 mm) is shown schematically in Figure 50.

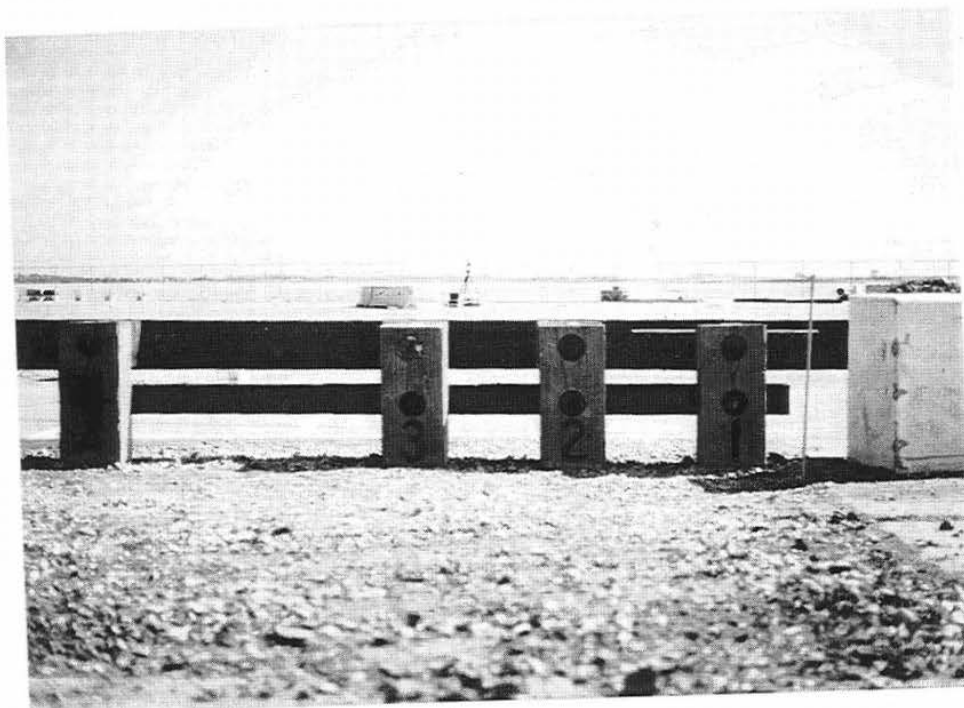
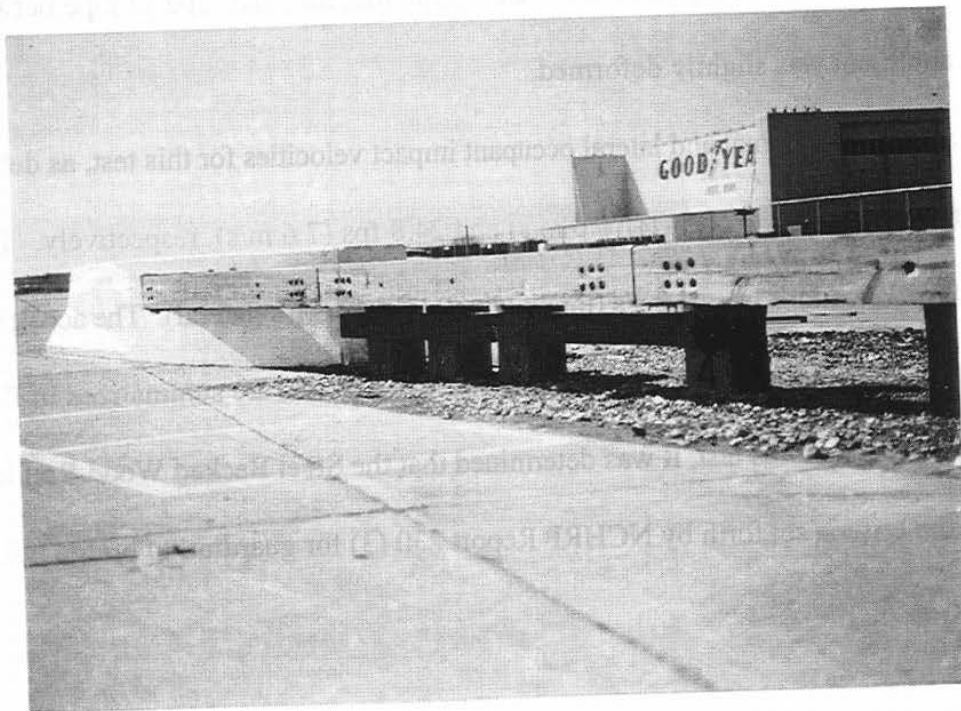
As can be seen in Figures 51 and 52, the wood rail sustained minor scraping and gouging along its face. The rub rail showed signs of tire contact starting 10.5 in. (267 mm) downstream of post No. 3 and continuing to the end of the rail. A 4 in. (102 mm) trench was dug by the vehicle starting and post No. 3 and continuing to post No. 1. Full tire contact was evident on the concrete abutment starting at its upstream



end and continuing until 3 in. (76 mm) before the end of the first rail. The spacer pipe between the wood rail and concrete abutment was slightly deformed.

The normalized longitudinal and lateral occupant impact velocities for this test, as determined from accelerometer data analysis, were 21.5 fps (6.6 m/s) and 24.8 fps (7.6 m/s), respectively. The maximum occupant ridedown decelerations were 4.0 g's (longitudinal), and 17.8 g's (lateral). The accelerometer traces from this test are shown in Appendix F, and the results of this analysis are summarized in Figure 45.

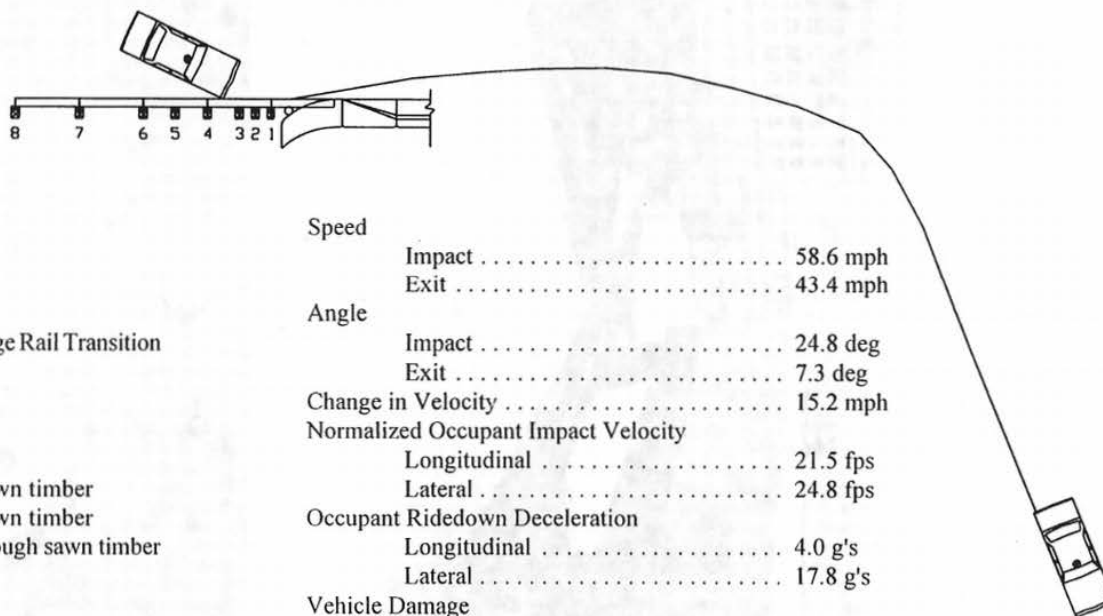
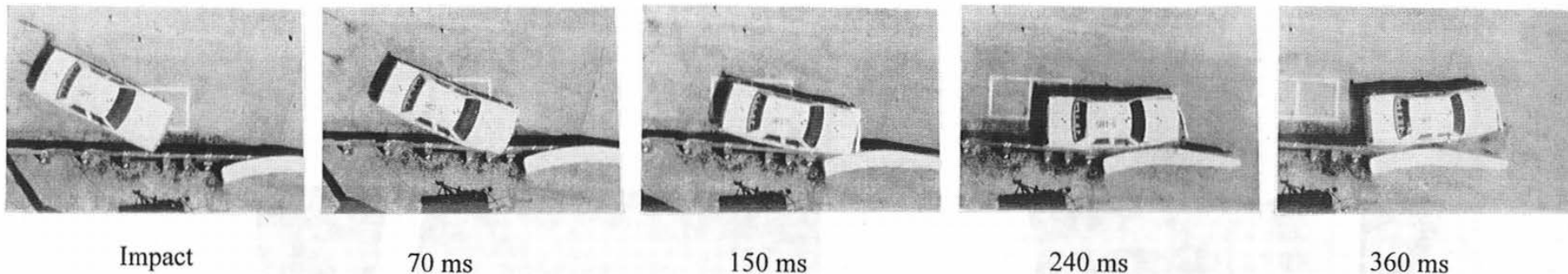
Based on the results of this test, it was determined that the Steel Backed Wood Rail to Bridge Rail Transition passed the criteria set forth by NCHRP Report 230 (3) for guardrail to bridge rail transitions.



**Figure 43.** Design Modifications, Test SBT-5.



**Figure 44.** Impact Location, Test SBT-5.



Test Number ..... SBT-5  
 Federal Contract No. .... DTFH71-90-C-00035  
 Date ..... 3/23/95  
 Installation ..... Steel Backed Wood Rail to Bridge Rail Transition  
 Approach Guardrail  
     Length ..... 50 ft  
     Height ..... 2 ft- 3 in.  
     Material  
         Posts 1-3 ..... 10 in. X 12 in. X 8 ft rough sawn timber  
         Posts 4-8 ..... 10 in. X 12 in. X 7 ft rough sawn timber  
         Rail ..... 6 in. X 10 in. X 9 ft - 11 ½ in. rough sawn timber  
 Vehicle Model ..... 1984 Ford LTD  
 Vehicle Weight  
     Curb ..... 3860 lb  
     Test Inertia ..... 4500 lb  
     Gross Static ..... 4660 lb

Speed  
     Impact ..... 58.6 mph  
     Exit ..... 43.4 mph  
 Angle  
     Impact ..... 24.8 deg  
     Exit ..... 7.3 deg  
 Change in Velocity ..... 15.2 mph  
 Normalized Occupant Impact Velocity  
     Longitudinal ..... 21.5 fps  
     Lateral ..... 24.8 fps  
 Occupant Ridedown Deceleration  
     Longitudinal ..... 4.0 g's  
     Lateral ..... 17.8 g's  
 Vehicle Damage  
     TAD ..... 1-RFQ-3  
     VDI ..... 01RYES2  
 Vehicle Rebound Distance ..... 5 ft @ 60 ft  
 Guardrail Damage ..... Minor  
 Maximum Deflections  
     Permanent Set ..... 1.3 in. @ post No. 2  
     Dynamic ..... 6.25 in. @ post No. 2

**Figure 45.** Summary of Test SBT-5.

Conversion Factors: 1 in.= 2.54 cm; 1 lb= 0.454 kg



Impact



200 ms



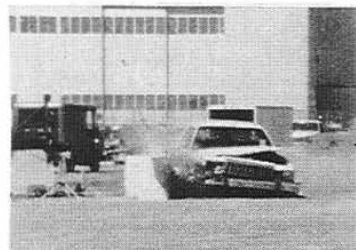
50 ms



250 ms



100 ms



300 ms

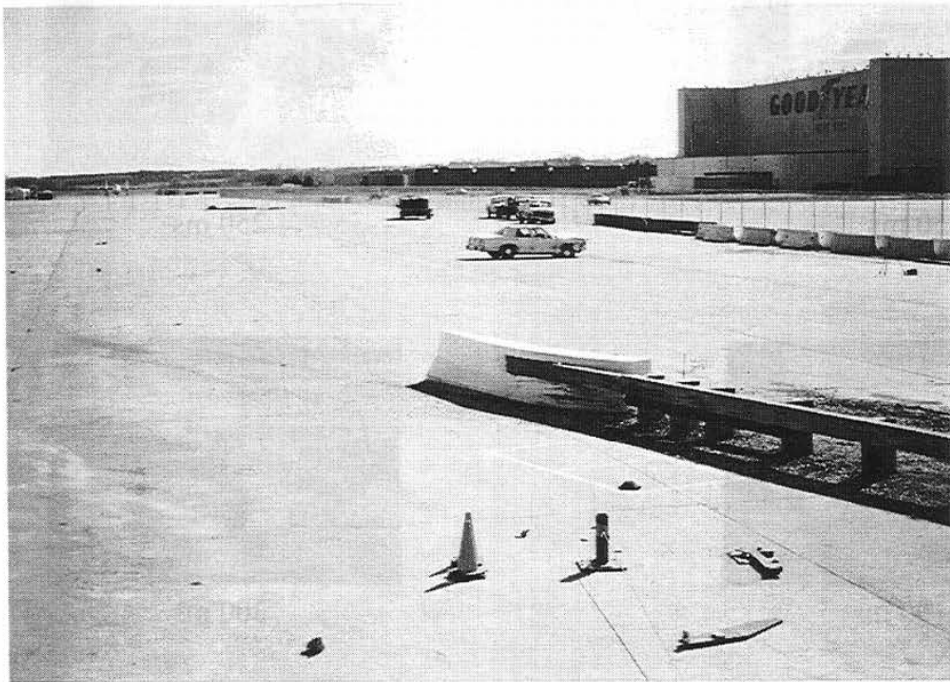


150 ms



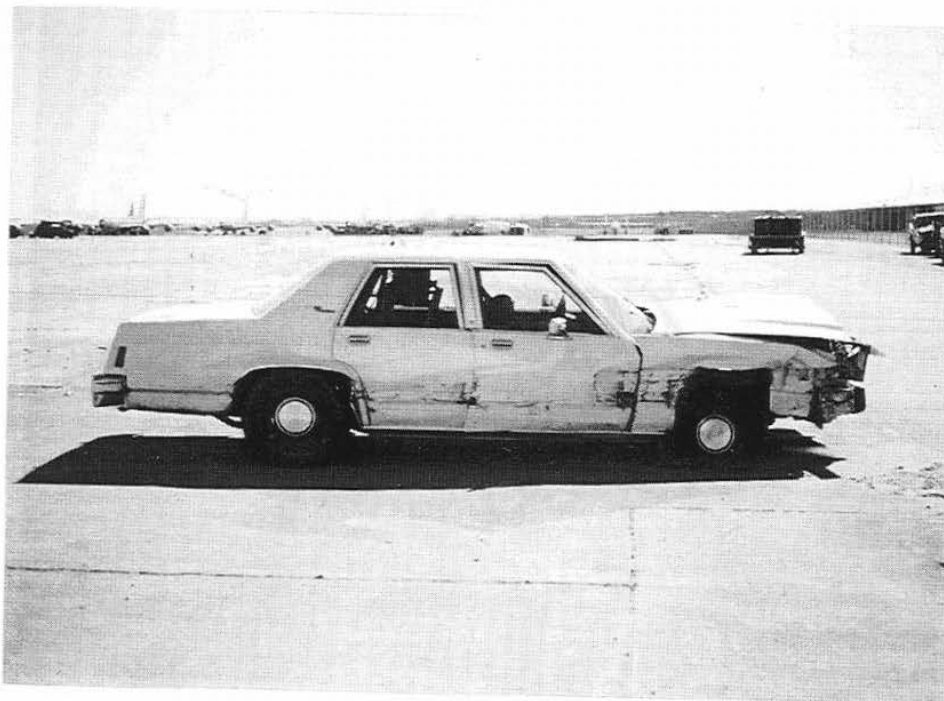
400 ms

**Figure 46.** Downstream Sequential Photographs, Test SBT-5.



**Figure 47.** Vehicle Trajectory, Test SBT-5.

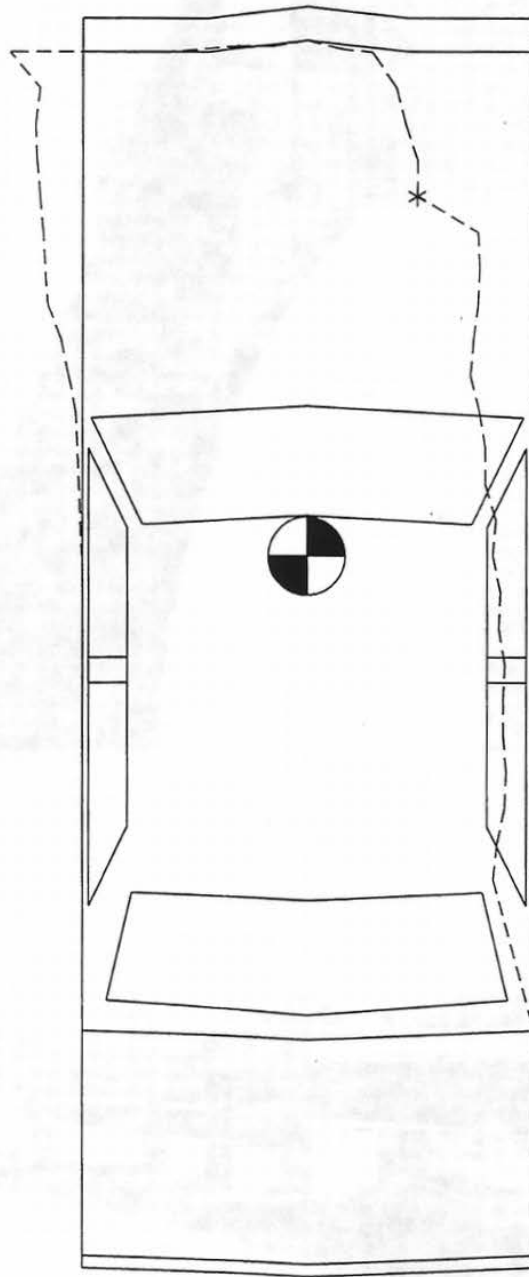




**Figure 48.** Vehicle Damage, Test SBT-5.

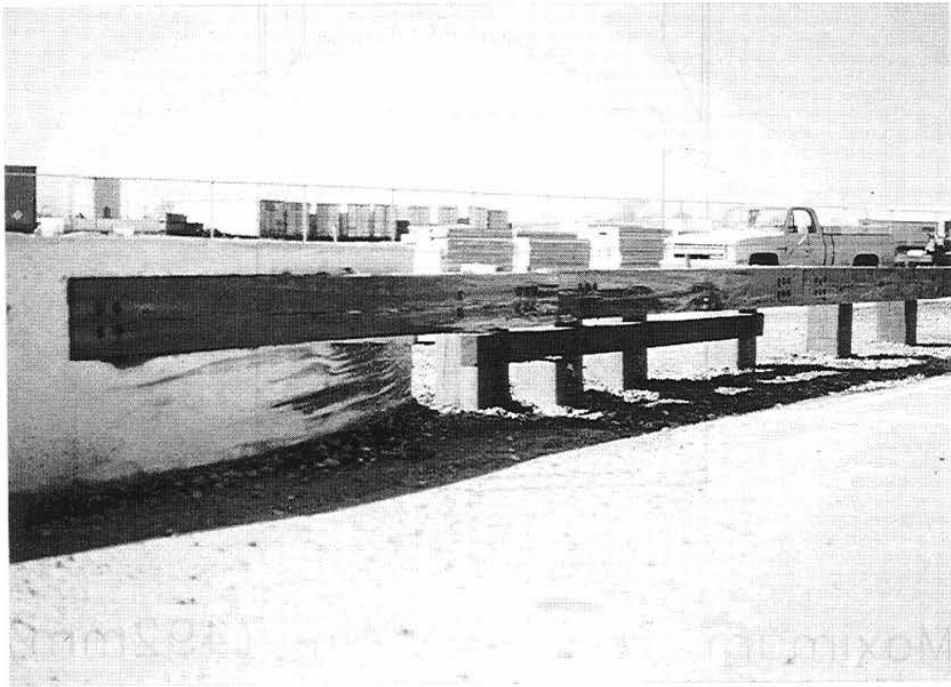
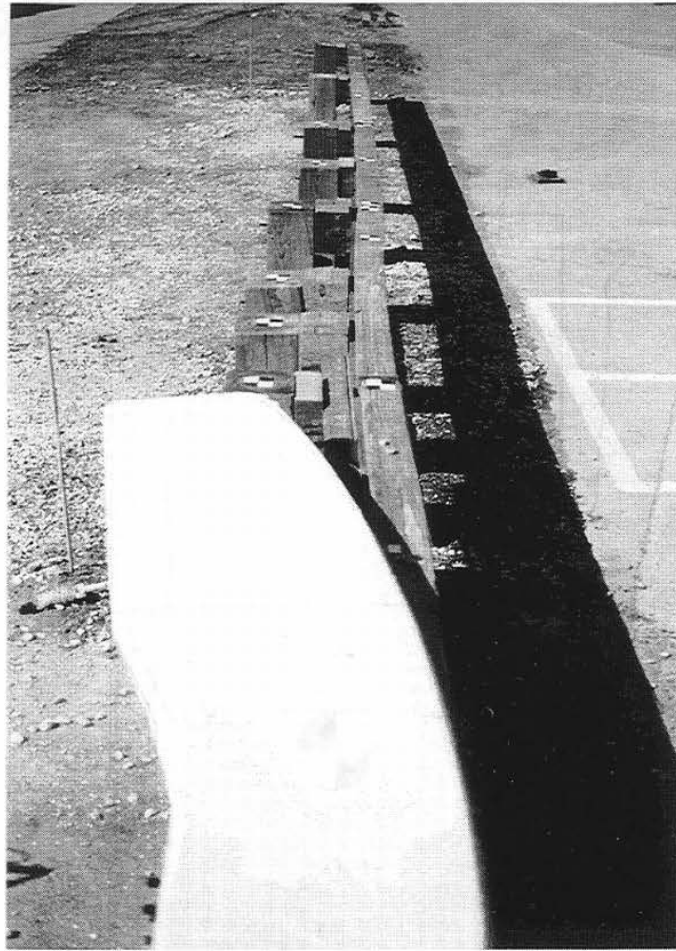


Figure 49. Vehicle Damage, Test SBT-5 (cont.).



\*Maximum Crush=19.4in. (492mm)

**Figure 50.** Crush Depth Diagram, Test SBT-5.



**Figure 51.** System Damage, Test SBT-5.



**Figure 52.** System Damage, Test SBT-5 (cont.).

#### 4. CONCLUSIONS

Five full-scale vehicle crash tests were performed on the Steel Backed Wood Rail to Bridge Rail Transition. These tests were evaluated, conducted, and reported in accordance with the criteria and requirements for guardrail to bridge rail transitions stated in NCHRP Report 230 (3). Table 2 summarizes the relevant evaluation criteria, as well as the findings from the five tests reported herein. As shown in this table, the final design of the Steel Backed Wood Rail to Bridge Rail Transition successfully passed all of the requirements for guardrail to bridge rail transitions.

**Table 2. Summary of Safety Performance Results**

Evaluation Factors	Evaluation Criteria	Test SBT-1	Test SBT-2	Test SBT-3	Test SBT-4	Test SBT-5
Structural Adequacy	A. The test article shall smoothly redirect the vehicle; the vehicle shall not penetrate or go over the installation although controlled lateral deflection of the test article is acceptable.	U	U	U	U	S
	D. Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	S	U	S	S	S
Occupant Risk	E. The vehicle shall remain upright during and after collision although moderate roll, pitching and yawing are acceptable. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.	U	U	U	U	S
Vehicle Trajectory	H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.	S	S	S	S	S
	I. In tests where the vehicle is judged to be redirected into or stopped while in adjacent traffic lanes, vehicle speed change during test article collision should be less than 15 mph and the exit angle from the test article should be less than 60 percent of test impact angle, both measured at time of vehicle loss of contact with test device.	U	U	U	U	S

S Satisfactory  
M Marginal  
U Unsatisfactory  
NA Not Applicable



## 5. REFERENCES

1. Hancock, K.L., Hansen, A.G., Mayer, J.B., *Aesthetic Bridge Rails, Transitions, and Terminals for Park Roads and Parkways*, Federal Highway Administration, Report No. FHWA-RD-90-052, May 1990.
2. Stout, D., Hinch, J., Sawyer, D., *Guardrail Testing Program*, Federal Highway Administration, Report No. FHWA-RD-90-087, June 1990.
3. *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, National Cooperative Highway Research Program Report No. 230, Transportation Research Board, Washington, D.C., March 1981.
4. Hinch, J., Yang, T-L, and Owings, R., *Guidance Systems for Vehicle Testing*, ENSCO, Inc., Springfield, VA, 1986.

## 6. APPENDICES

**APPENDIX A**  
**DESIGN DETAILS**

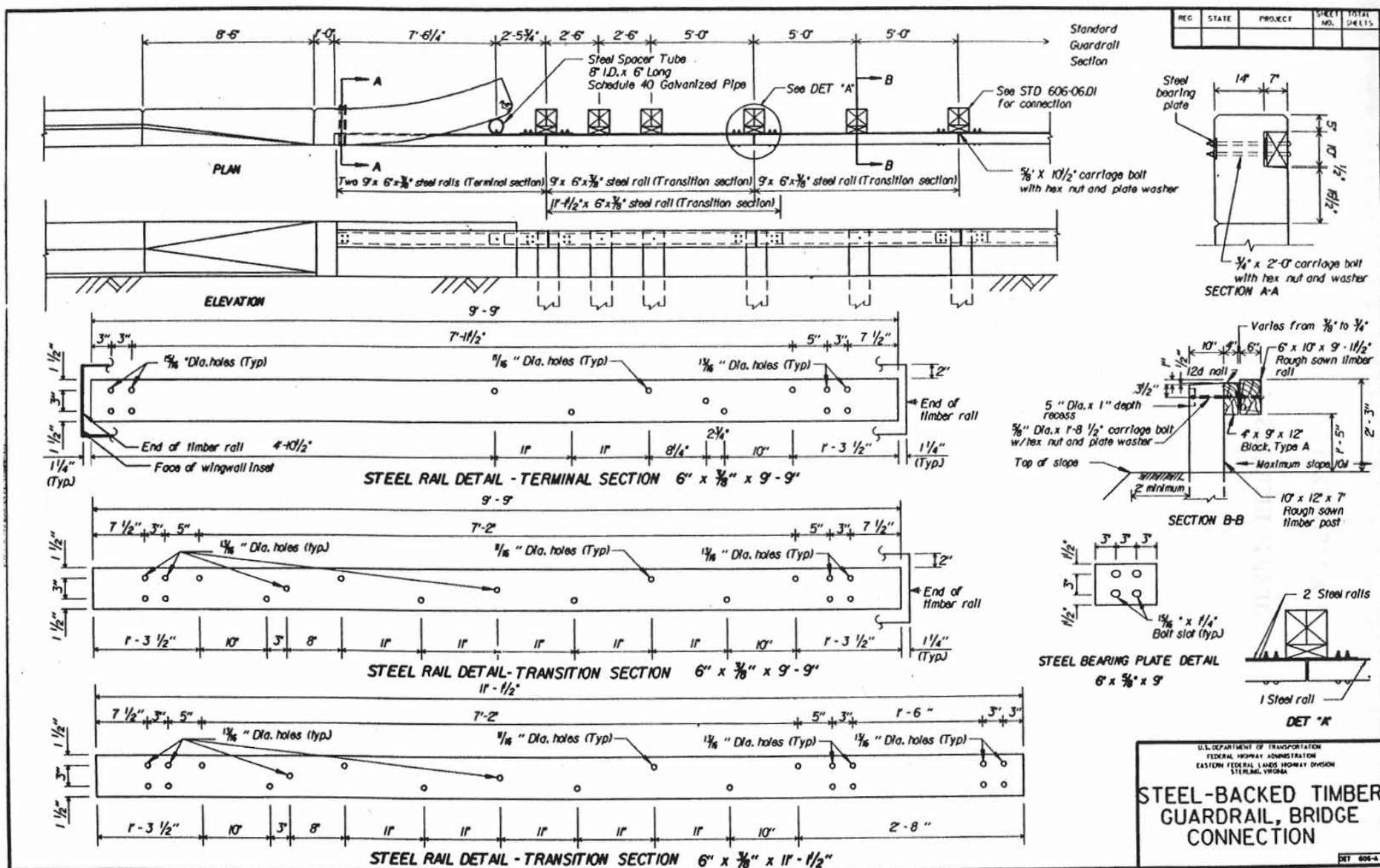
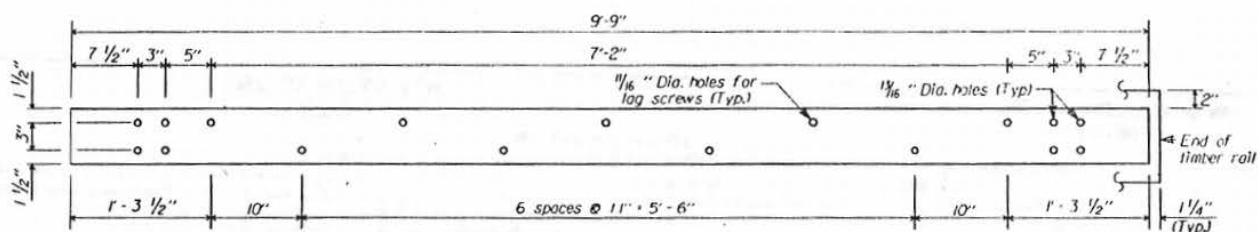


Figure A-1. Design Details of the SBT for Test SBT-1.

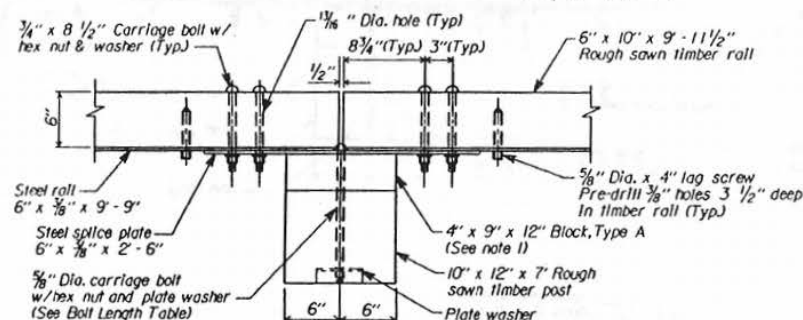
1. The Type A, blocked-out, system or the Type B, non blocked-out, system shall be used as specified.
2. All structural steel and fastener hardware shall be weathering steel as specified.

Type A (Block-out)	Type B (No Block-out)
$r-3^*$	$lf$

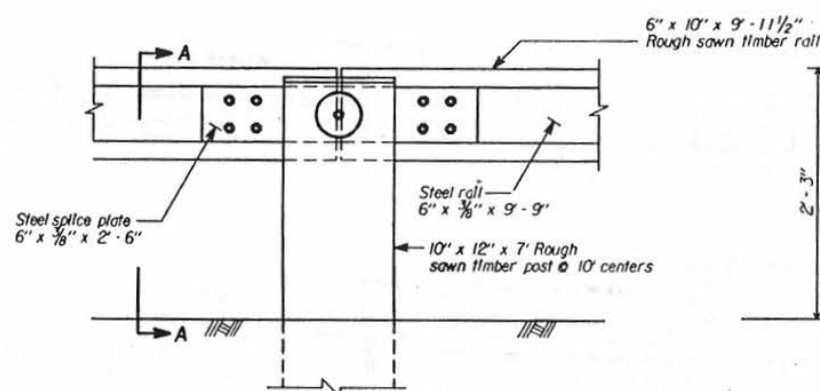
### Bolt Lengths for Rail/Post Connection



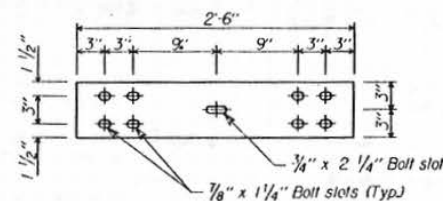
STEEL RAIL DETAIL  
6" x  $\frac{3}{8}$ " x 9'-9"



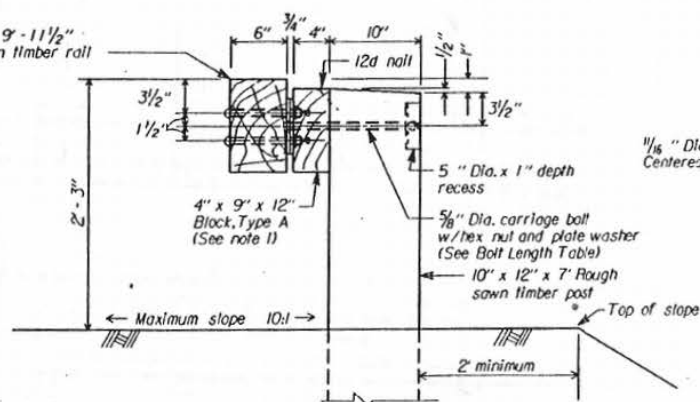
### POST CONNECTION PLAN



### POST CONNECTION ELEVATION



STEEL SPLICE PLATE DETAIL  
6" x  $\frac{3}{8}$ " x 2'-6"



SECTION A-A



PLATE WASHER DETAIL  
4 3/4" Dia. x 1/4"

U.S. DEPARTMENT OF TRANSPORTATION FEDERAL HIGHWAY ADMINISTRATION FEDERAL LINES HIGHWAY OFFICE	
<b>STANDARD</b> <b>STEEL-BACKED TIMBER</b> <b>GUARDRAIL, TYPE A &amp; TYPE B</b>	
STANDARD APPROVED FOR USE 3/90 REELED TO FILE	DRAWING NO. 606-6

No Scale

**Figure A-2. Design Details of the SBT for Test SBT-1 (cont.).**

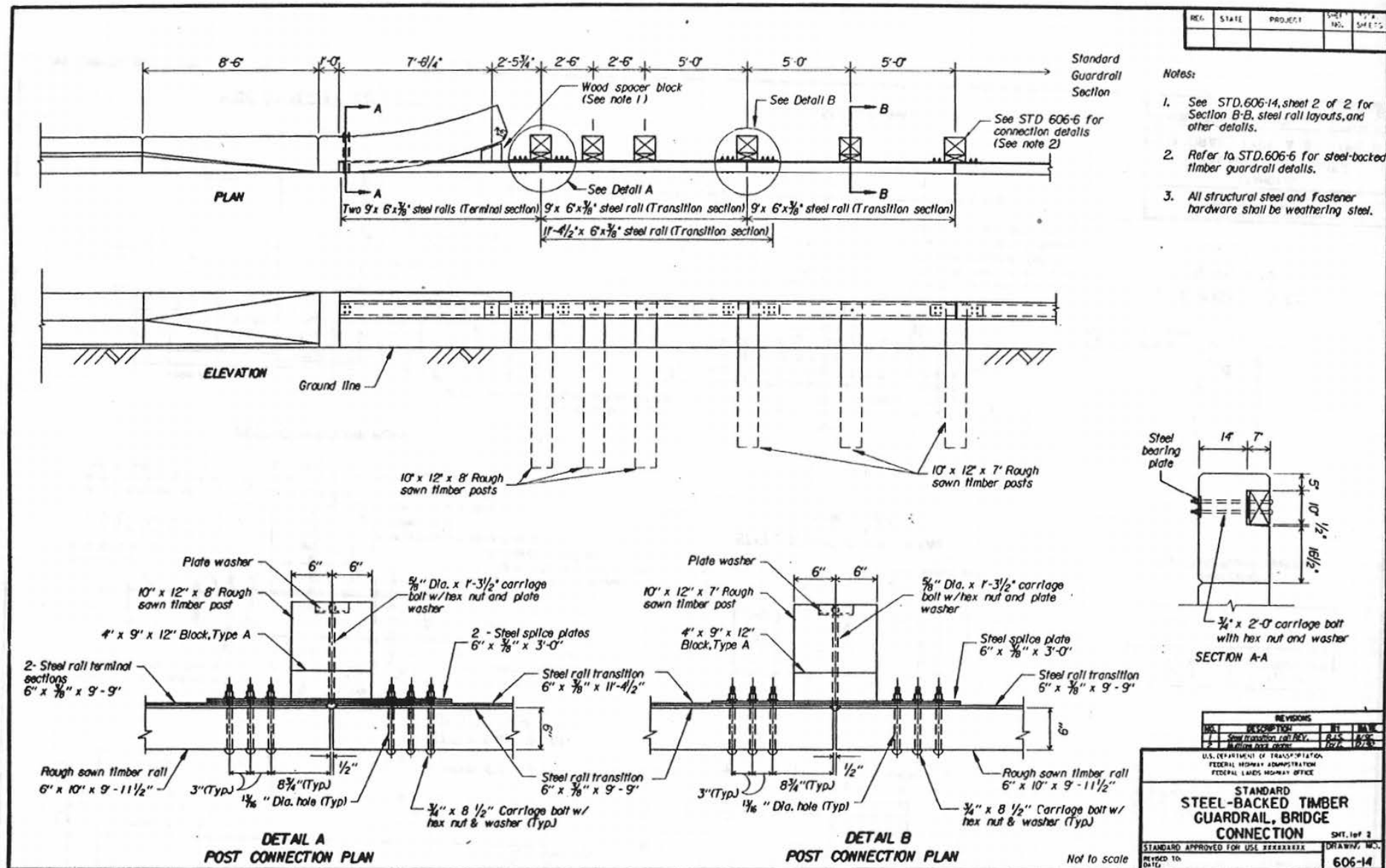


Figure A-3. Design Details of the SBT for Test SBT-2.



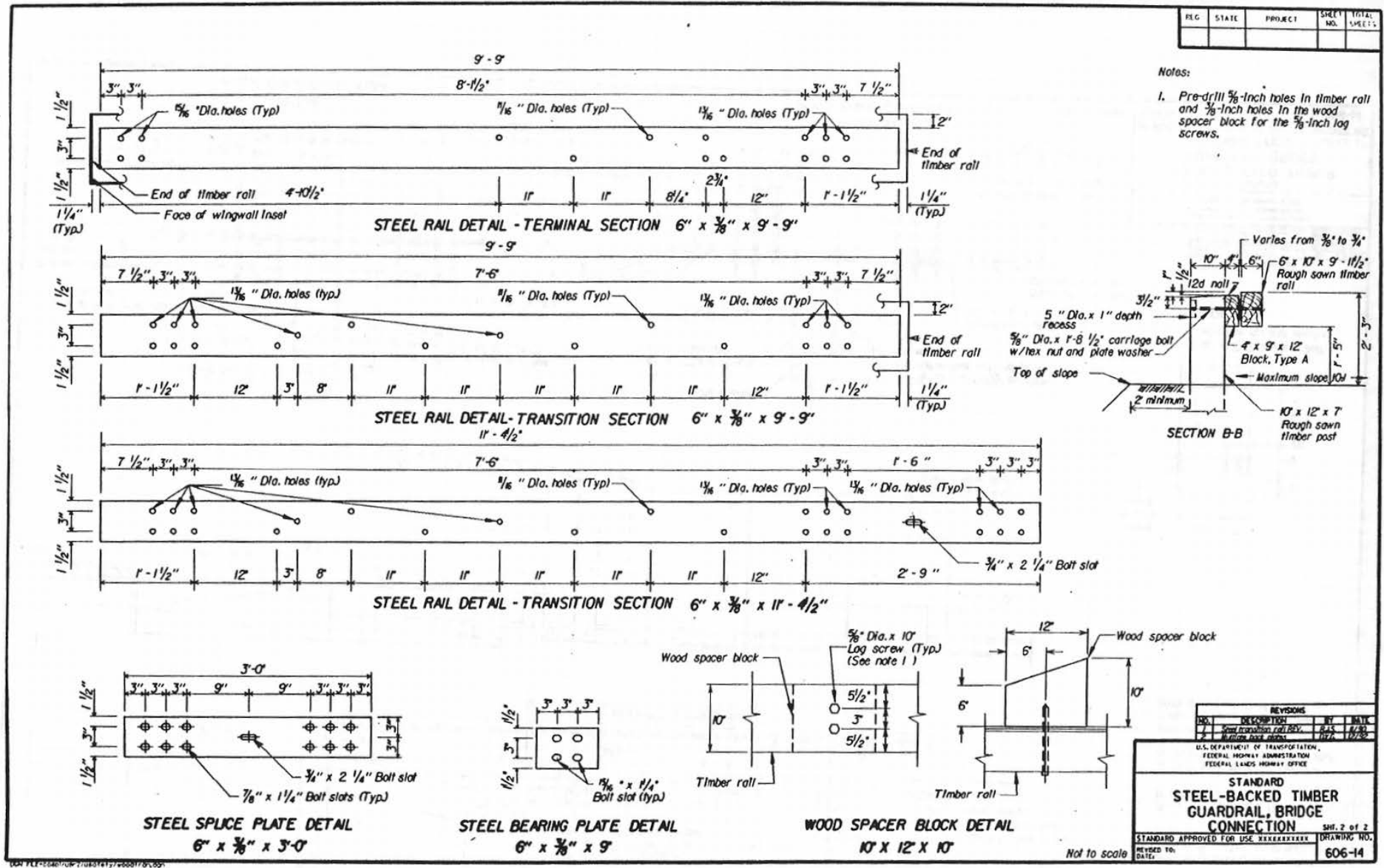


Figure A-4. Design Details of the SBT for Test SBT-2 (cont.).

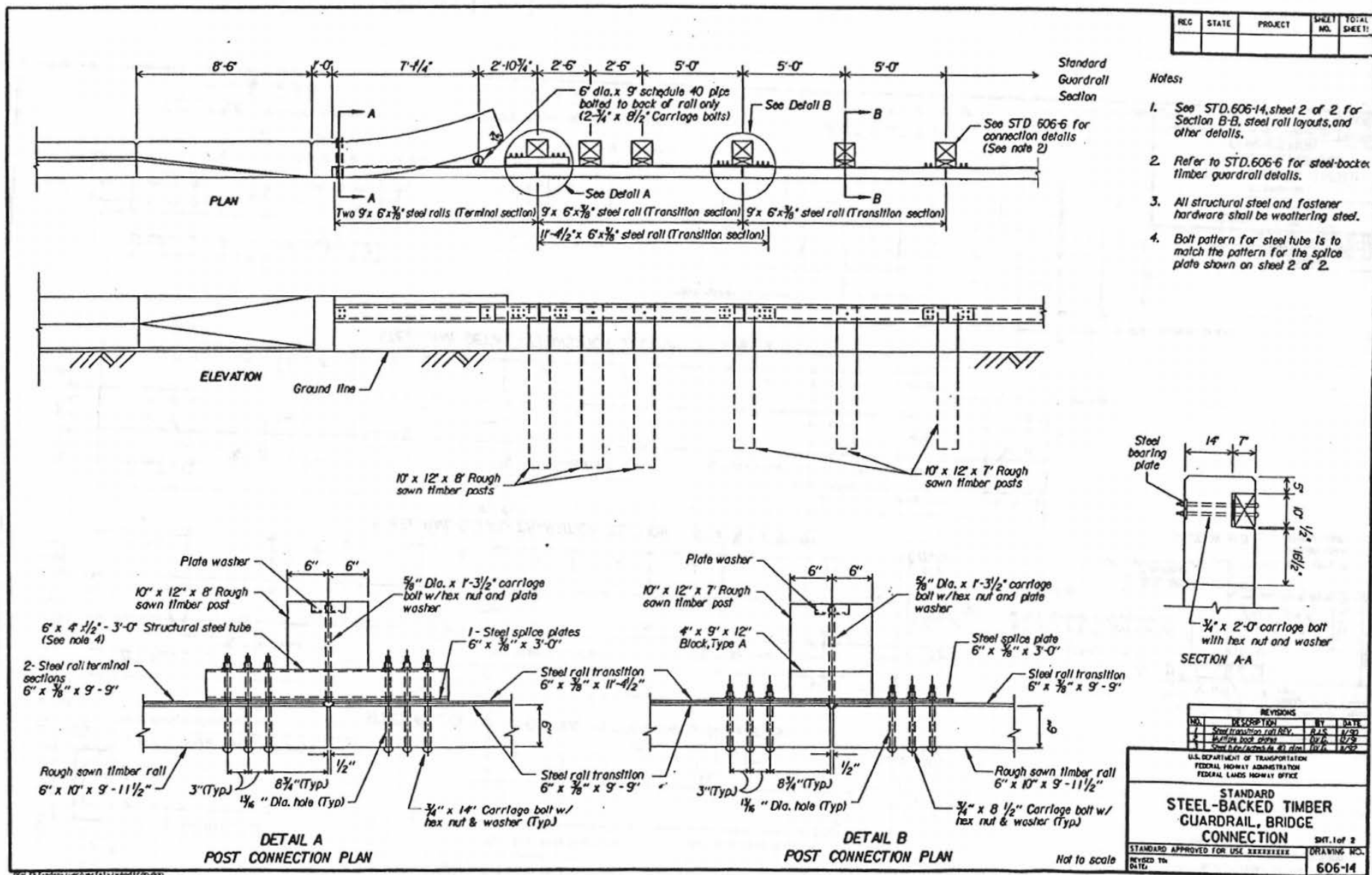
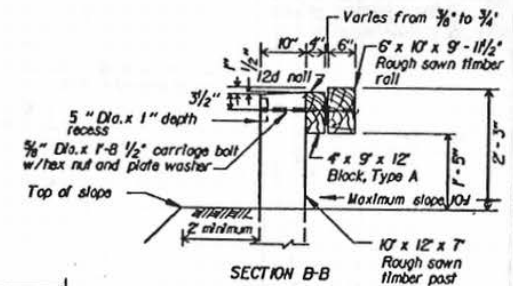


Figure A-5. Design Details of the SBT for Test SBT-3.



REVISIONS			
NO.	DESCRIPTION	BY	DATE
1	Steel transition rail R/R.	R/S	8/97
2	Welding base above	DZ/L	12/99
	Steel h/ds / webbed d. 40" dia	DZ/L	8/00

U.S. DEPARTMENT OF TRANSPORTATION  
FEDERAL HIGHWAY ADMINISTRATION  
FEDERAL LANDS HIGHWAY OFFICE

STANDARD  
STEEL-BACKED TIMBER  
GUARDRAIL, BRIDGE  
CONNECTION

CONNECTION		SHEET 2 OF 2
STANDARD APPROVED FOR USE XXXXXXXXXXXX		DRAWING NO.

REVISED TO: DATE:	606-14
----------------------	--------

*Not to scale*

SHT. 2 of 2  
DRAWING NO.  
606-14

**Figure A-6. Design Details of the SBT for Test SBT-3 (cont.).**

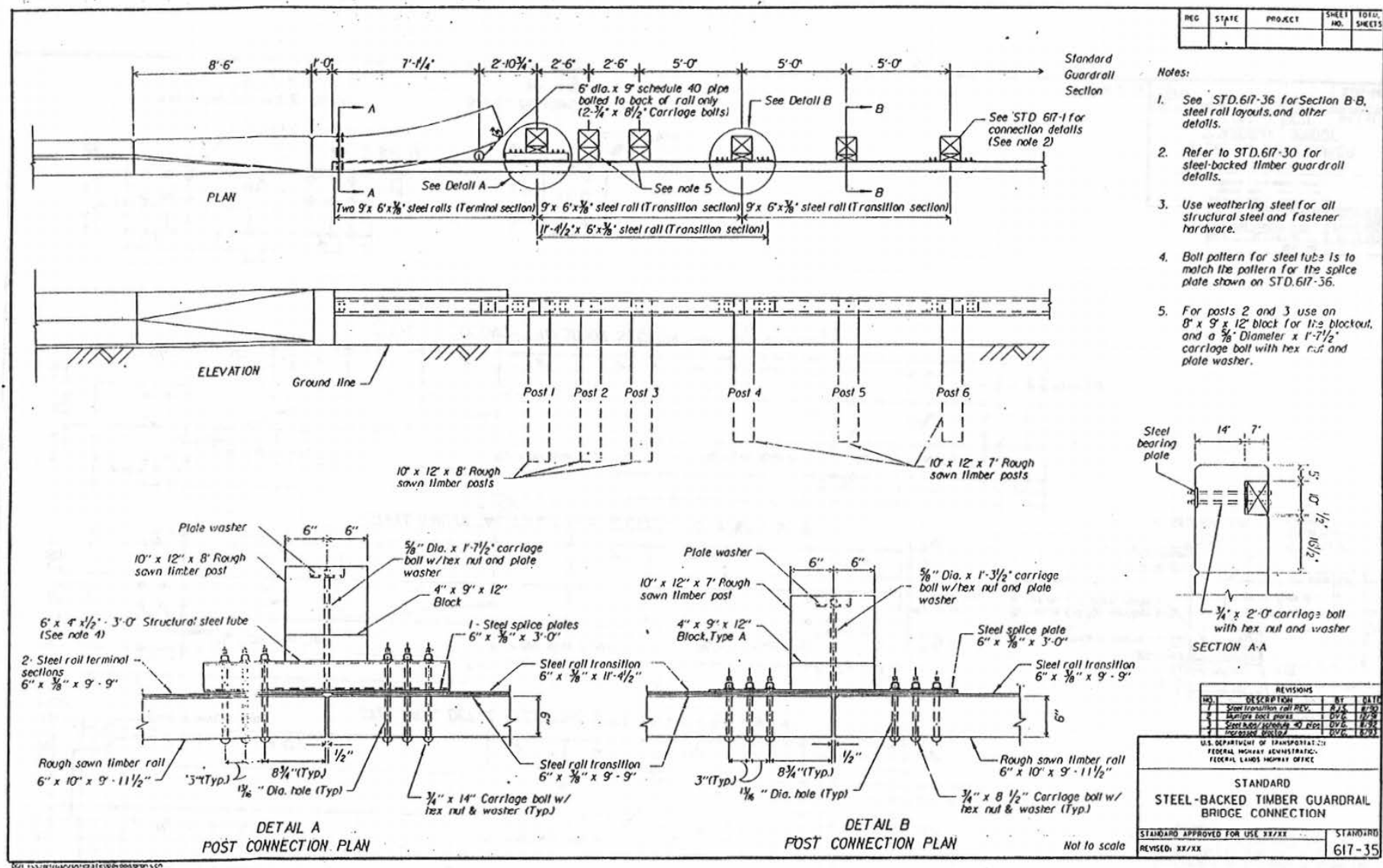
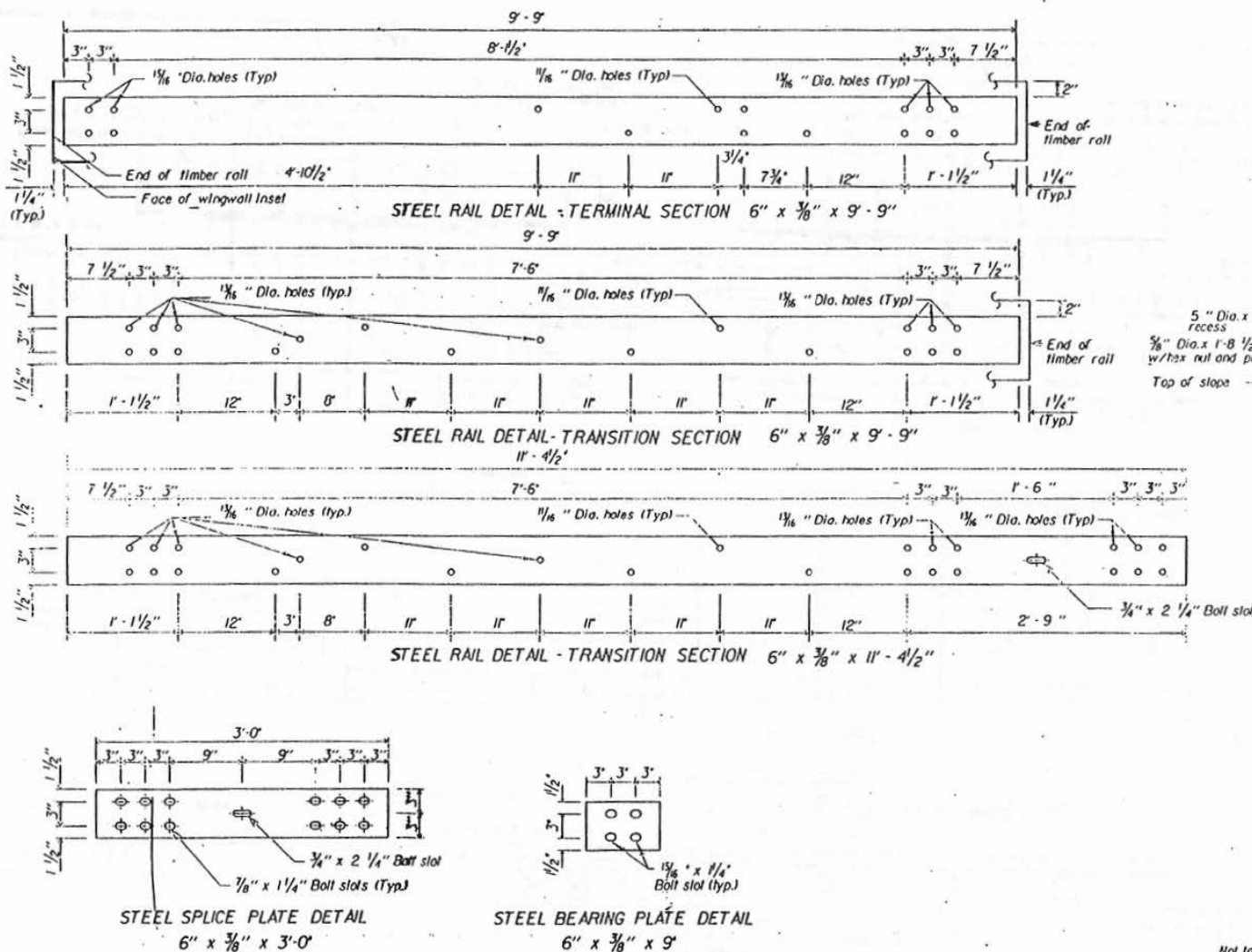


Figure A-7. Design Details of the SBT for Test SBT-4.

1. Pre-drill  $\frac{5}{8}$ -inch holes in timber rail and  $\frac{3}{8}$ -inch holes in the wood spacer block for the  $\frac{5}{8}$ -inch lag screws.



REVISIONS			
NO.	DESCRIPTION	BY	DA
1	Steel transition rail REV.	AJS	8/9
2	Multiple bolt plates	DZG	12/7
3	Steel base/anchorage @ pipe	JVG	8/9
4	Increased thickness	DZG	6/9

U.S. DEPARTMENT OF TRANSPORTATION  
FEDERAL HIGHWAY ADMINISTRATION  
FEDERAL LANDS HIGHWAY OFFICE

STANDARD  
STEEL-BACKED TIMBER GUARDRAIL  
BRIDGE CONNECTION

STANDARD APPROVED FOR USE XX/XX	STANDARD
REVISED: XX/XX	617-3

**Figure A-8.** Design Details of the SBT for Test SBT-4 (cont.).

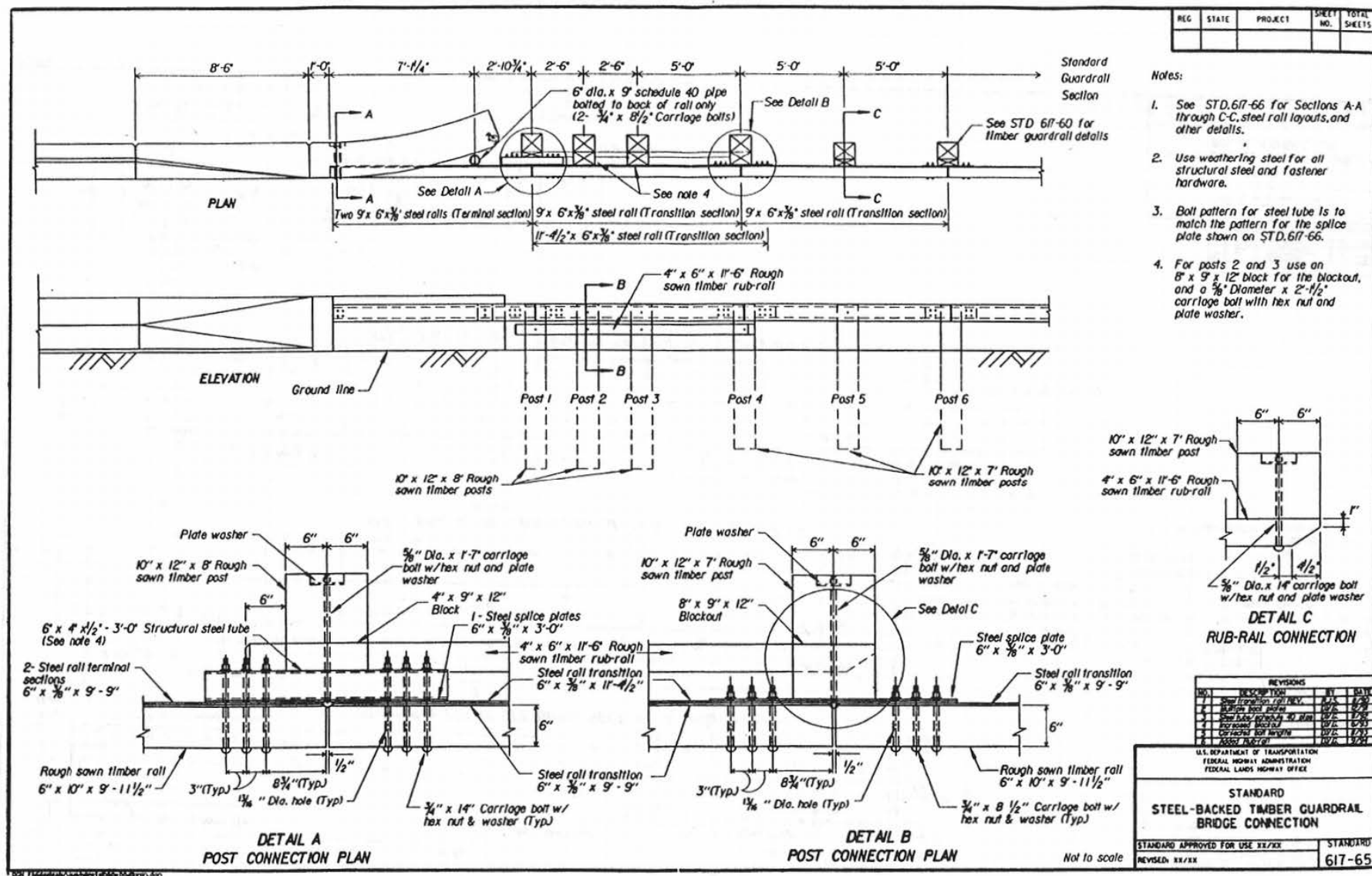


Figure A-9. Design Details of the SBT for Test SBT-5.



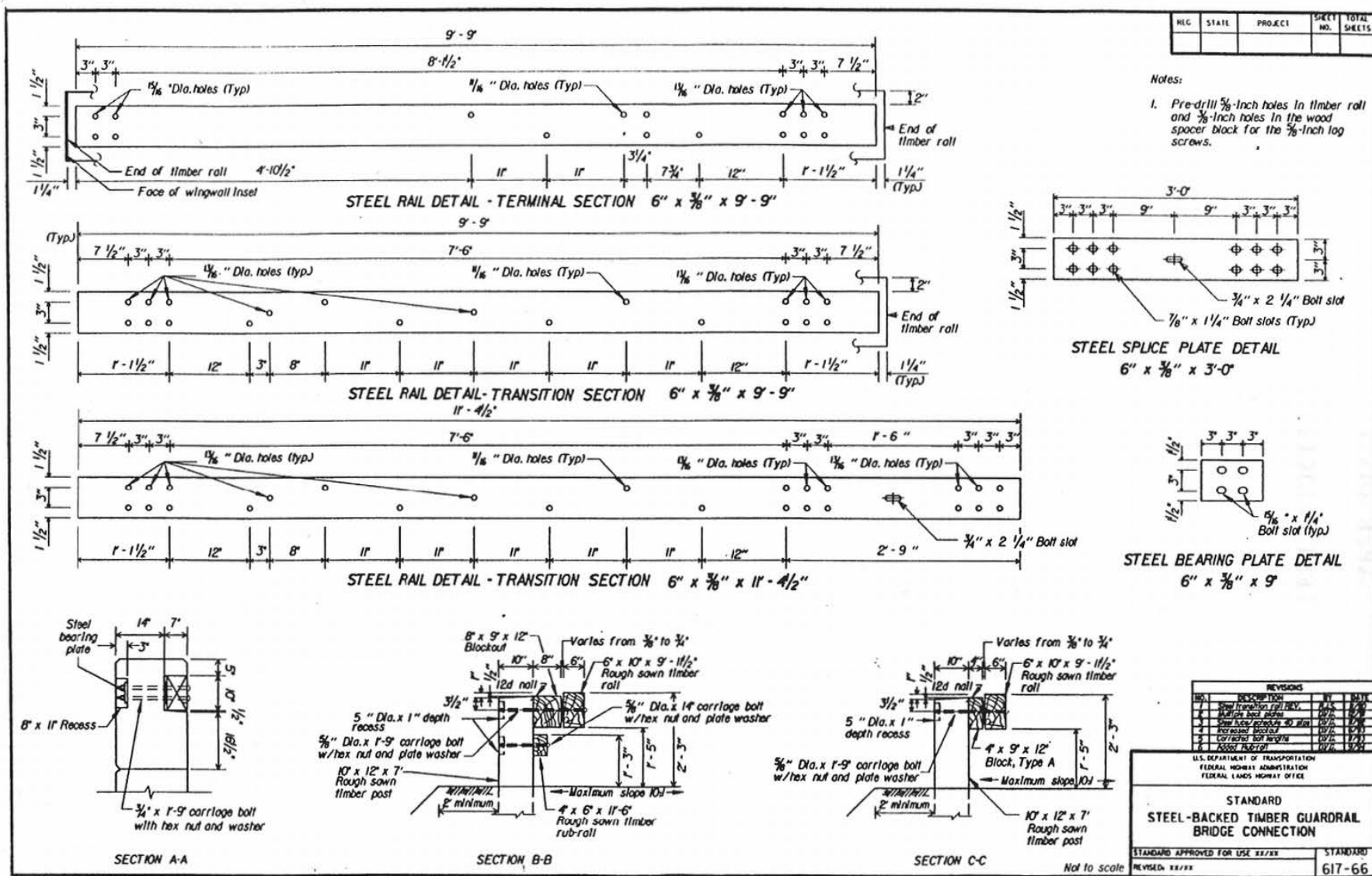


Figure A-10. Design Details of the SBT for Test SBT-5 (cont.).

**APPENDIX B**  
**TEST VEHICLES**



**Figure B-1.** Test Vehicle, Test SBT-1.

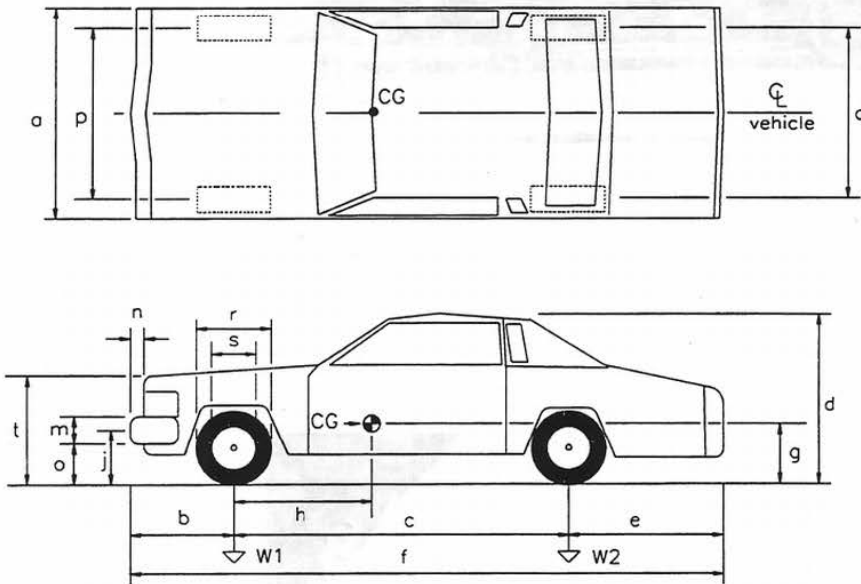
Make: Ford Test No.: SBT-1

Model: LTD Crown Victoria Tire Size: P205-75R15

Year: 1985 VIN: 1FABP43F6FZ109889

Vehicle Geometry  
Inches

a — 76.75 b — 39.0  
c — 114.0 d — 57.0  
e — 55.5 f — 208.5  
g — 20.5 h — 52.6  
j — 18.5 m — 8.0  
n — 4.5 o — 14.5  
p — 62.25 q — NA  
r — 27.0 s — 16.25  
t — NA



Engine Size: 5.0 liter

Transmission: Automatic

Weight (lbs)	Curb	Test Inertial	Gross Static
W1	<u>2190</u>	<u>2400</u>	<u>2315</u>
W2	<u>1690</u>	<u>2060</u>	<u>1985</u>
Wtotal	<u>3880</u>	<u>4460</u>	<u>4300</u>

Damage prior to test: None

**Figure B-2.** Test Vehicle Dimensions, Test SBT-1.

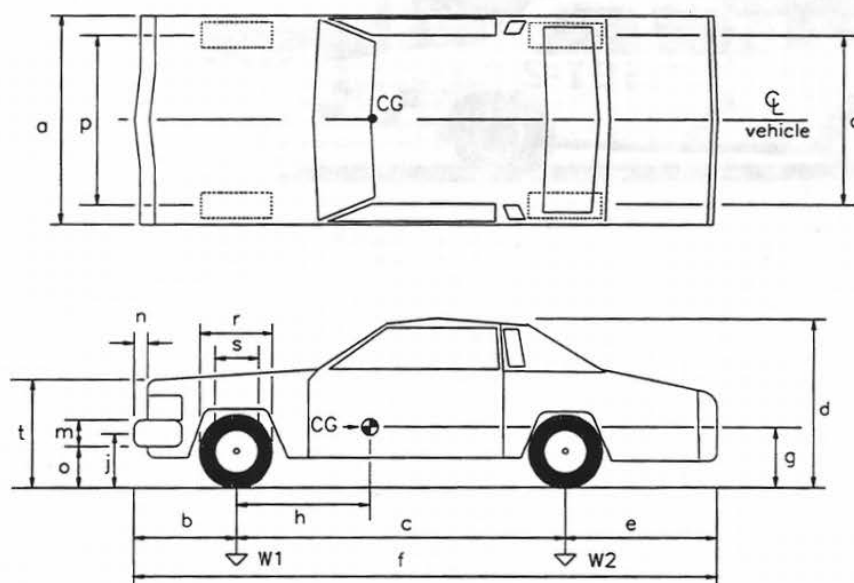


**Figure B-3.** Test Vehicle, Test SBT-2.

Make: Buick Test No.: SBT-2  
 Model: LeSabre Tire Size: P215-75R15  
 Year: 1984 VIN: 1G4AN6948EX424358

Vehicle Geometry  
Inches

a — 77.0 b — 41.5  
 c — 116.0 d — NA  
 e — 56.5 f — 214.0  
 g — 22.0 h — 51.0  
 j — 18.0 m — 8.0  
 n — 5.0 o — 14.0  
 p — 61.5 q — 63.0  
 r — 26.5 s — 16.25  
 t — NA



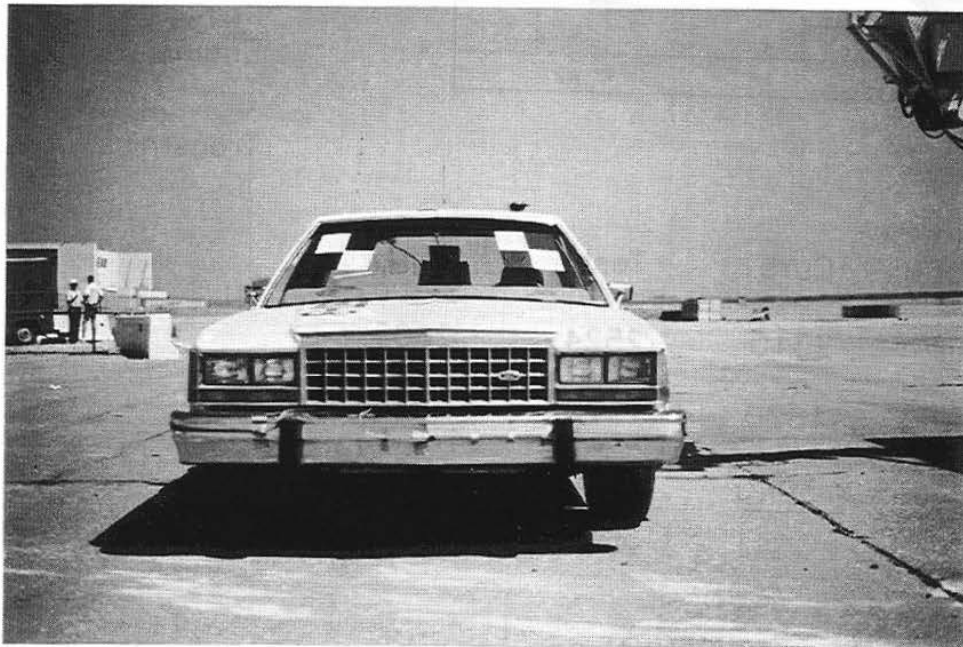
Engine Size: 5.0 liter  
 Transmission: Automatic

Weight (lbs)	Curb	Test Inertial	Gross Static
W1	<u>2210</u>	<u>2683</u>	<u>2598</u>
W2	<u>1560</u>	<u>1933</u>	<u>1858</u>
Wtotal	<u>3770</u>	<u>4616</u>	<u>4456</u>

Damage prior to test: None

Figure B-4. Test Vehicle Dimensions, Test SBT-2.





**Figure B-5.** Test Vehicle, Test SBT-3.

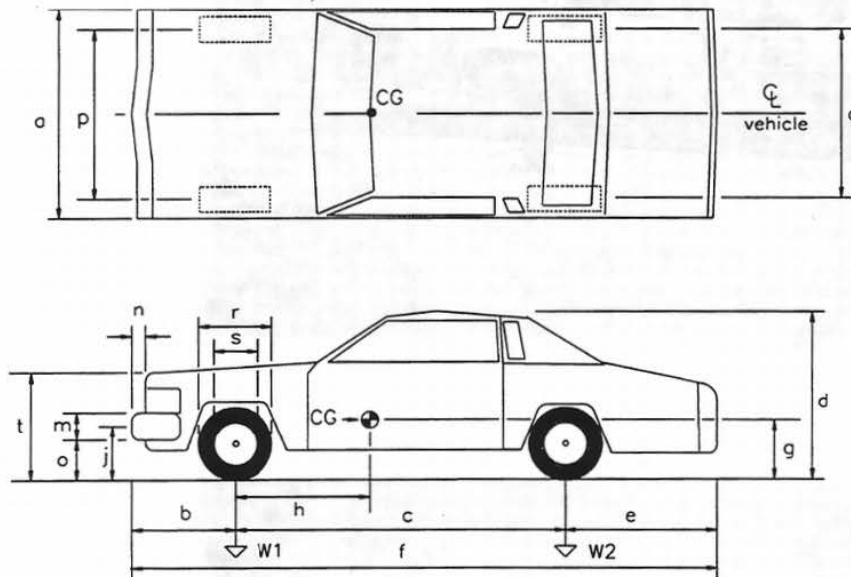
Make: Ford Test No.: SBT-3

Model: LTD Crown Victoria Tire Size: P205-75R15

Year: 1985 VIN: 2FABP43GAFX207998

Vehicle Geometry  
Inches

a — 77.0 b — 37.0  
c — 114.0 d — 55.5  
e — 52.5 f — 205.0  
g — 22.0 h — 50.0  
j — 18.0 m — 8.25  
n — 4.0 o — 12.5  
p — 62.5 q — NA  
r — 27.0 s — 16.25  
t — NA



Engine Size: 351 cu. in.

Transmission: Automatic

Weight (lbs)	Curb	Test Inertial	Gross Static
W1	<u>2310</u>	<u>2524</u>	<u>2609</u>
W2	<u>1630</u>	<u>1972</u>	<u>2047</u>
Wtotal	<u>3940</u>	<u>4496</u>	<u>4656</u>

Damage prior to test: None

Figure B-6. Test Vehicle Dimensions, Test SBT-3.



**Figure B-7.** Test Vehicle, Test SBT-4.

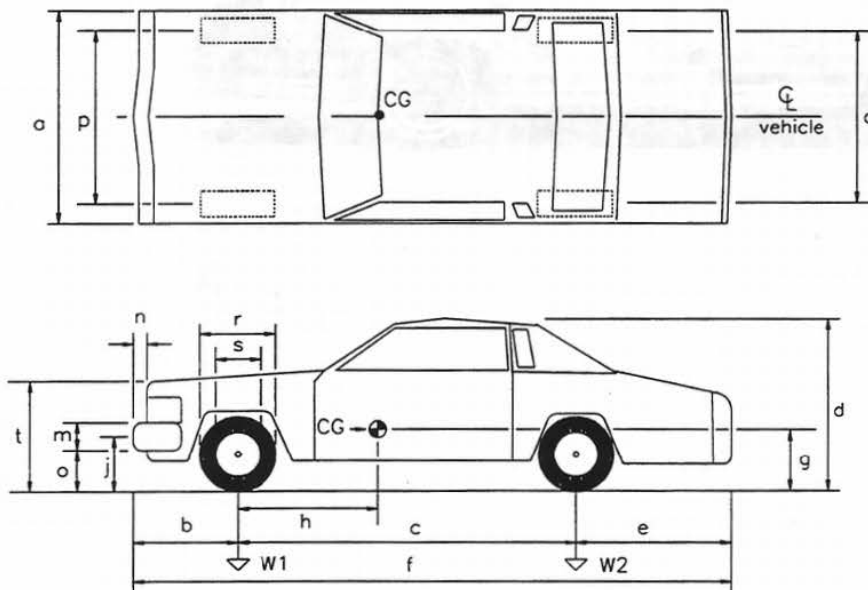
Make: Mercury Test No.: SBT-4

Model: Grand Marquis Tire Size: P215-75R15

Year: 1984 VIN: 1MEBP95F1EZ623182

Vehicle Geometry  
Inches

a — 76.0 b — 40.0  
c — 114.0 d — 56.0  
e — 55.0 f — 210.0  
g — 20.0 h — 51.0  
j — 20.0 m — 8.0  
n — 5.0 o — 14.0  
p — 63.0 q — 63.0  
r — 26.5 s — 16.5  
t — 33.5



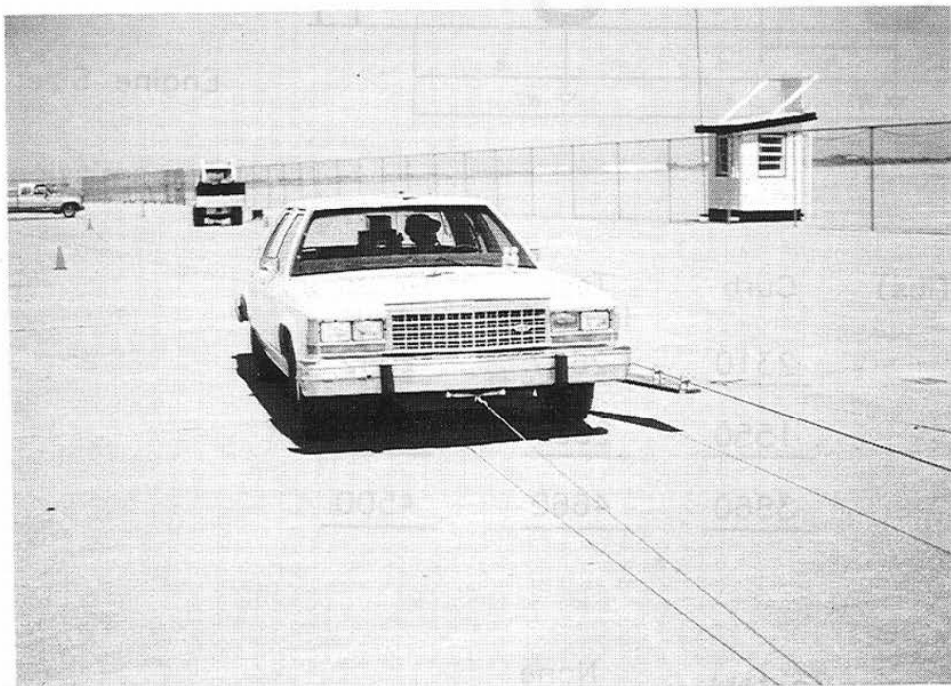
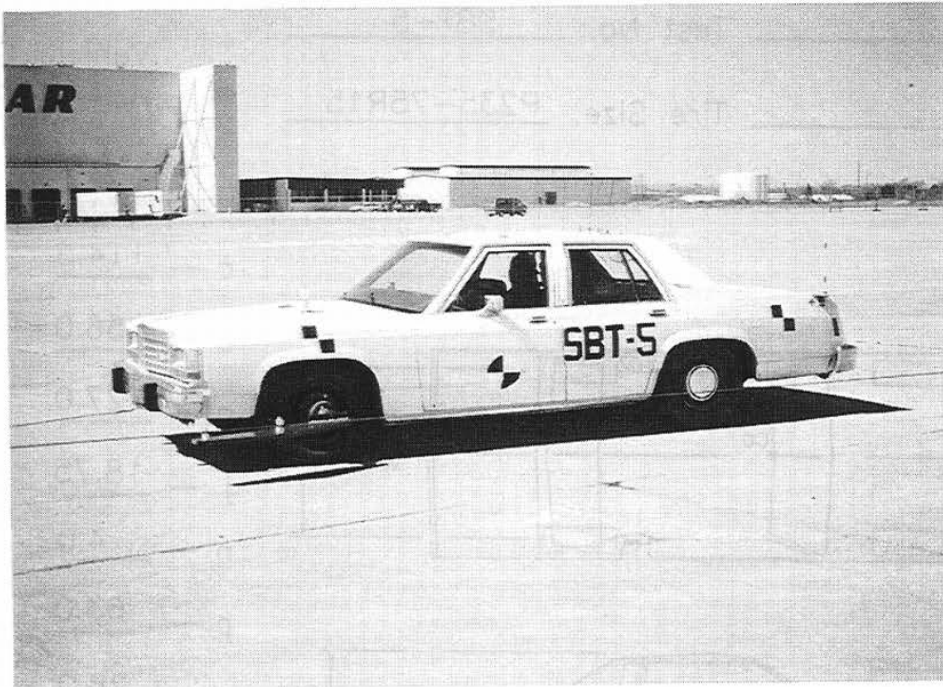
Engine Size: 5.0 liter

Transmission: Automatic

Weight (lbs)	Curb	Test Inertial	Gross Static
W1	<u>2250</u>	<u>2661</u>	<u>2576</u>
W2	<u>1660</u>	<u>2007</u>	<u>1932</u>
Wtotal	<u>3910</u>	<u>4668</u>	<u>4508</u>

Damage prior to test: None

Figure B-8. Test Vehicle Dimensions, Test SBT-4.



**Figure B-9.** Test Vehicle, Test SBT-5.

Make: Ford Test No.: SBT-5

Model: LTD Tire Size: P235-75R15

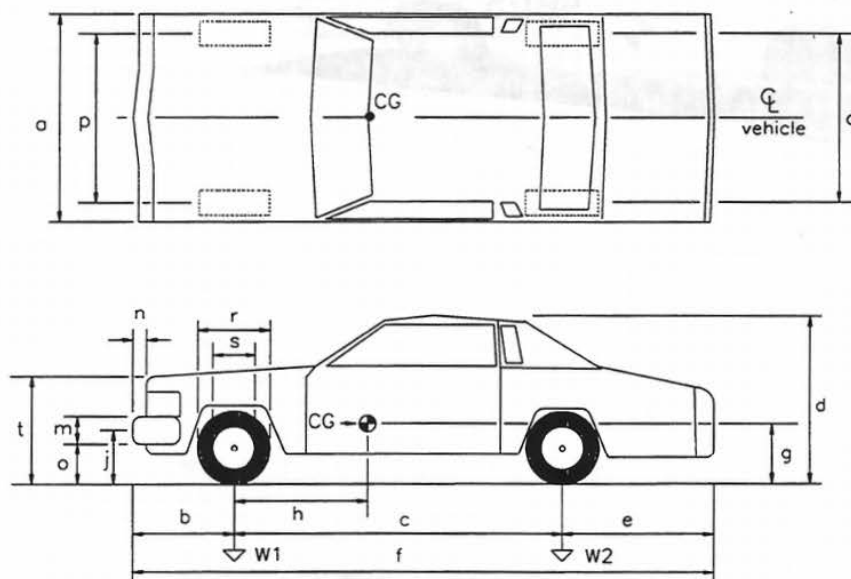
Year: 1984 VIN: 1FABP43G3EZ2182161

Vehicle Geometry  
Inches

a — 76.5 b — 41.0  
c — 114.5 d — 57.5  
e — 56.0 f — 211.0  
g — 27.0 h — 49.8  
j — 18.75 m — 22.5  
n — 4.0 o — 15.0  
p — 63.0 q — 63.0  
r — 28.0 s — 16.0  
t — 34.5

Engine Size: 351 V8

Transmission: Automatic



Weight (lbs)	Curb	Test Inertial	Gross Static
W1	<u>2310</u>	<u>2627</u>	<u>2542</u>
W2	<u>1550</u>	<u>2033</u>	<u>1958</u>
Wtotal	<u>3860</u>	<u>4660</u>	<u>4500</u>

Damage prior to test: None

Figure B-10. Test Vehicle Dimensions, Test SBT-5.



## **APPENDIX C.**

### **ACCELEROMETER DATA ANALYSIS, TEST SBT-1**

Figure C-1. Graph of Longitudinal Deceleration, Test SBT-1.

Figure C-2. Graph of Longitudinal Change in Velocity, Test SBT-1.

Figure C-3. Graph of Longitudinal Occupant Displacement, Test SBT-1.

Figure C-4. Graph of Lateral Deceleration, Test SBT-1.

Figure C-5. Graph of Lateral Change in Velocity, Test SBT-1.

Figure C-6. Graph of Lateral Occupant Displacement, Test SBT-1.

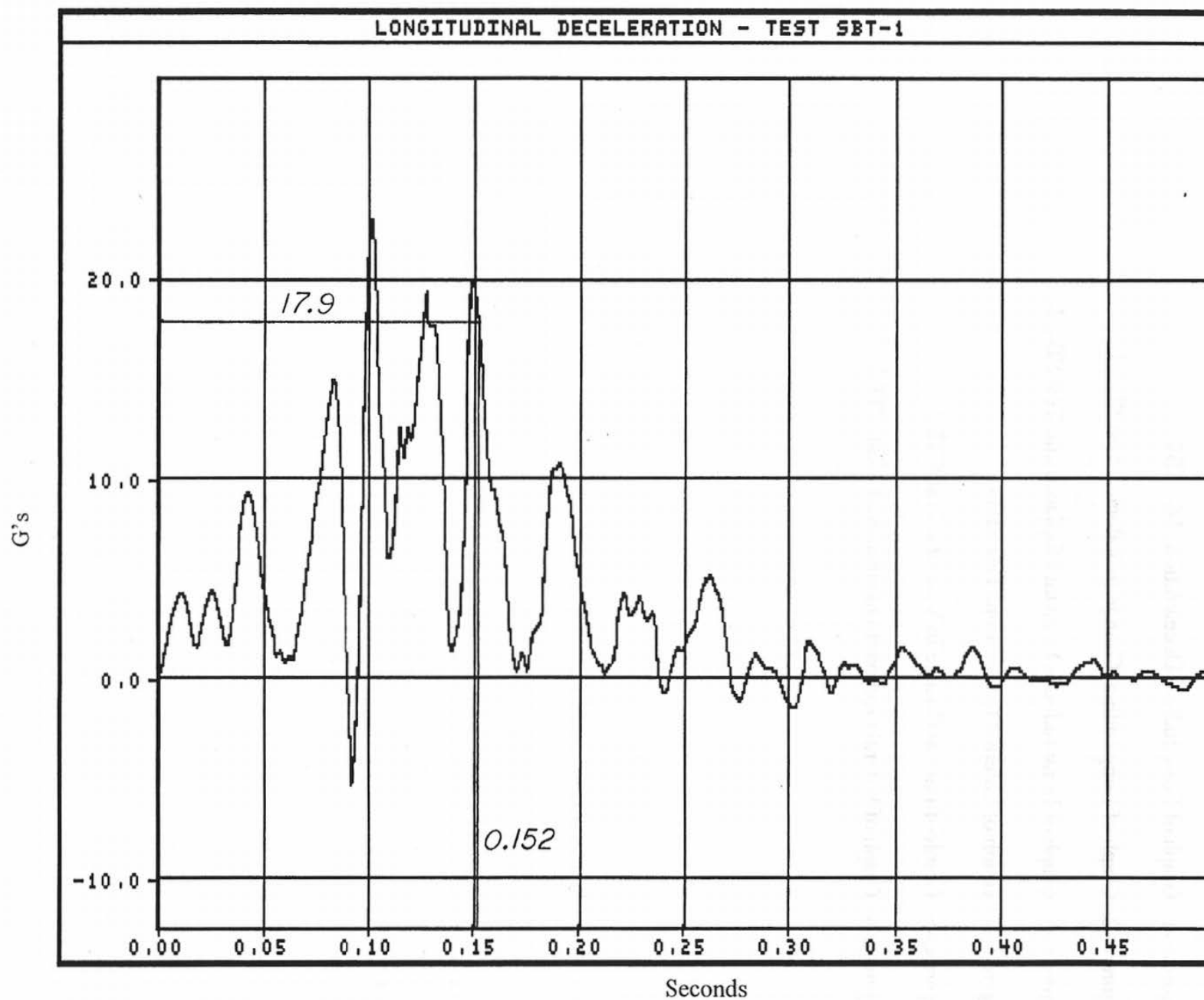


Figure C-1. Graph of Longitudinal Deceleration, Test SBT-1.

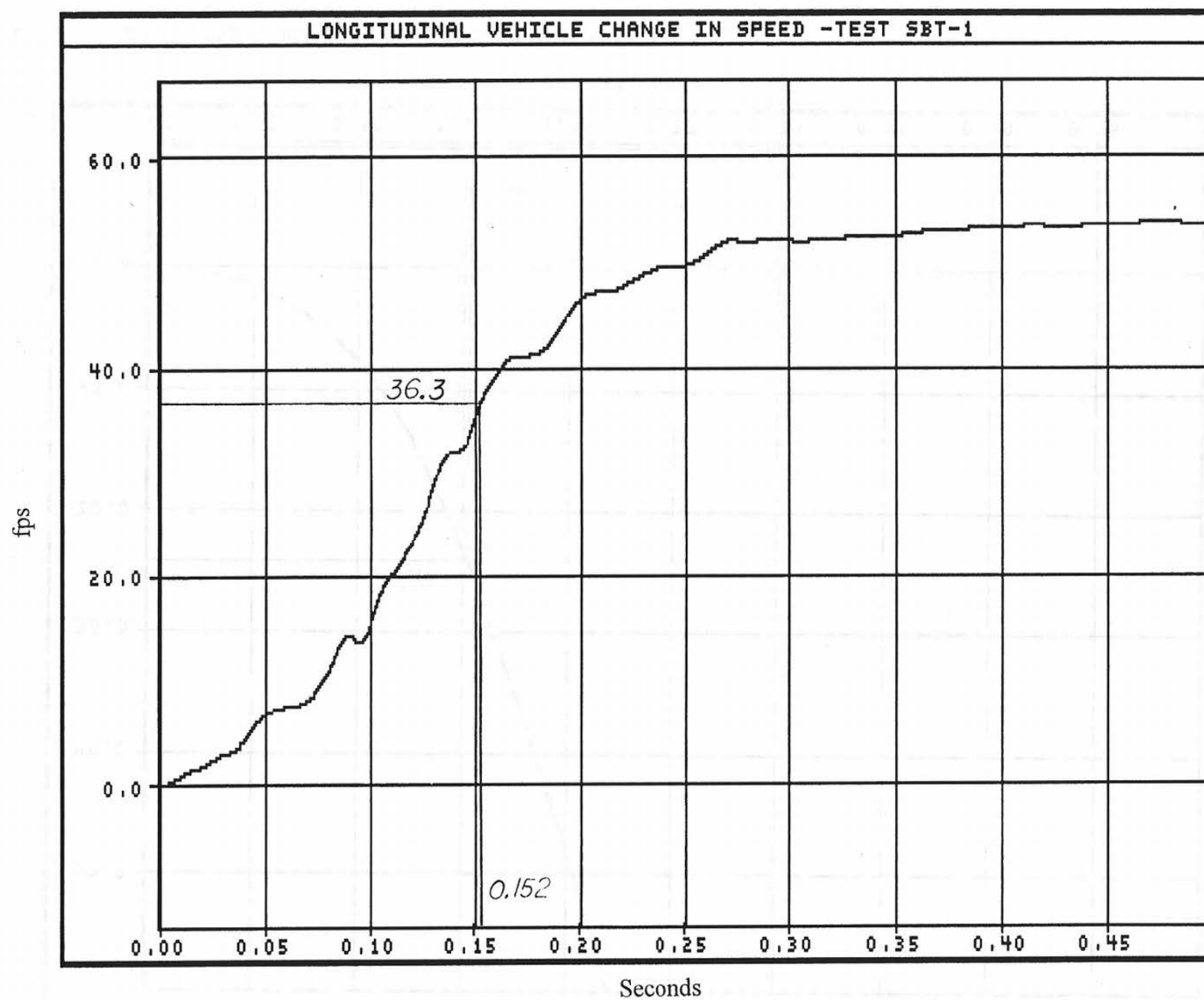
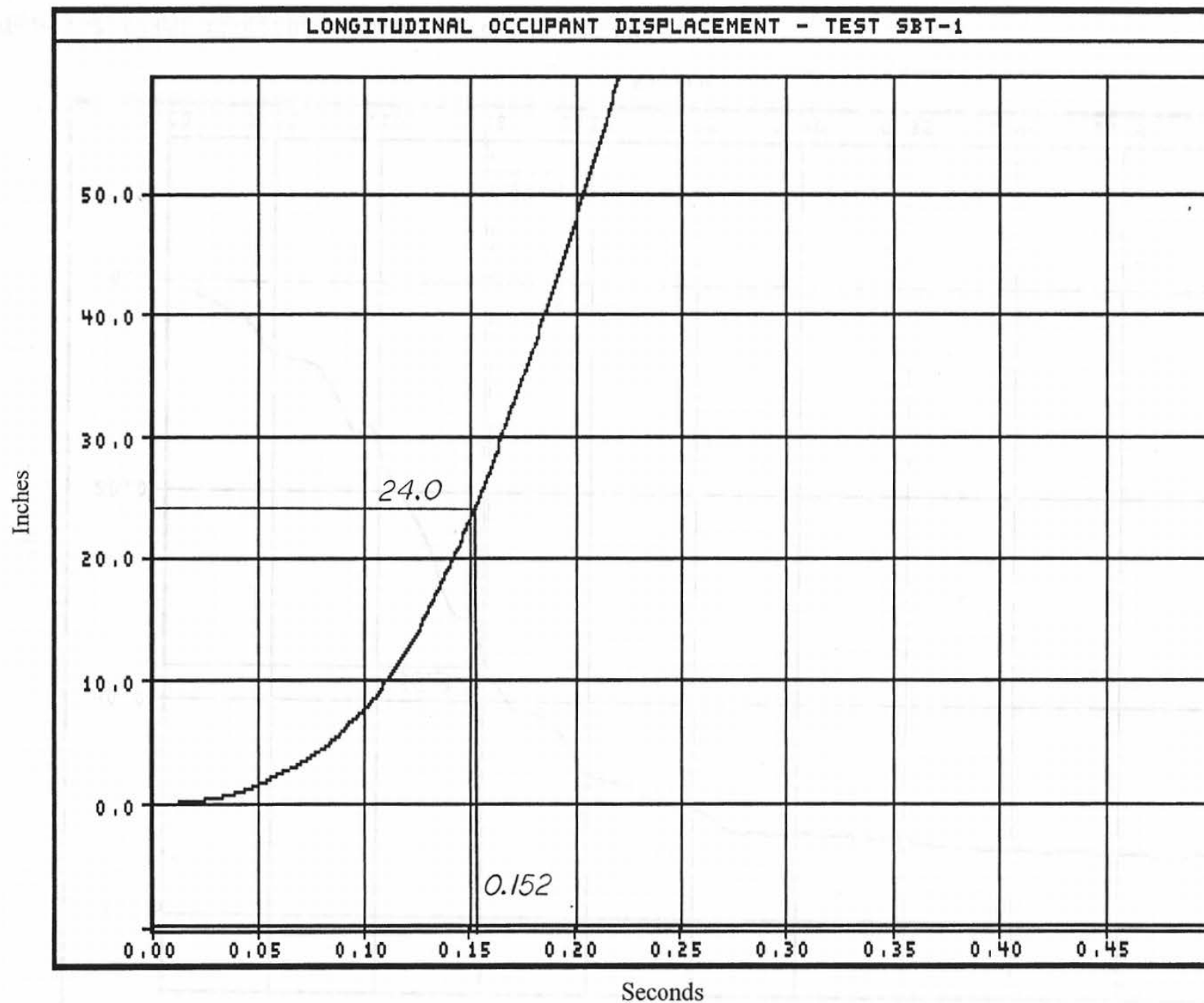


Figure C-2. Graph of Longitudinal Change in Velocity, Test SBT-1.



**Figure C-3.** Graph of Longitudinal Occupant Displacement, Test SBT-1.

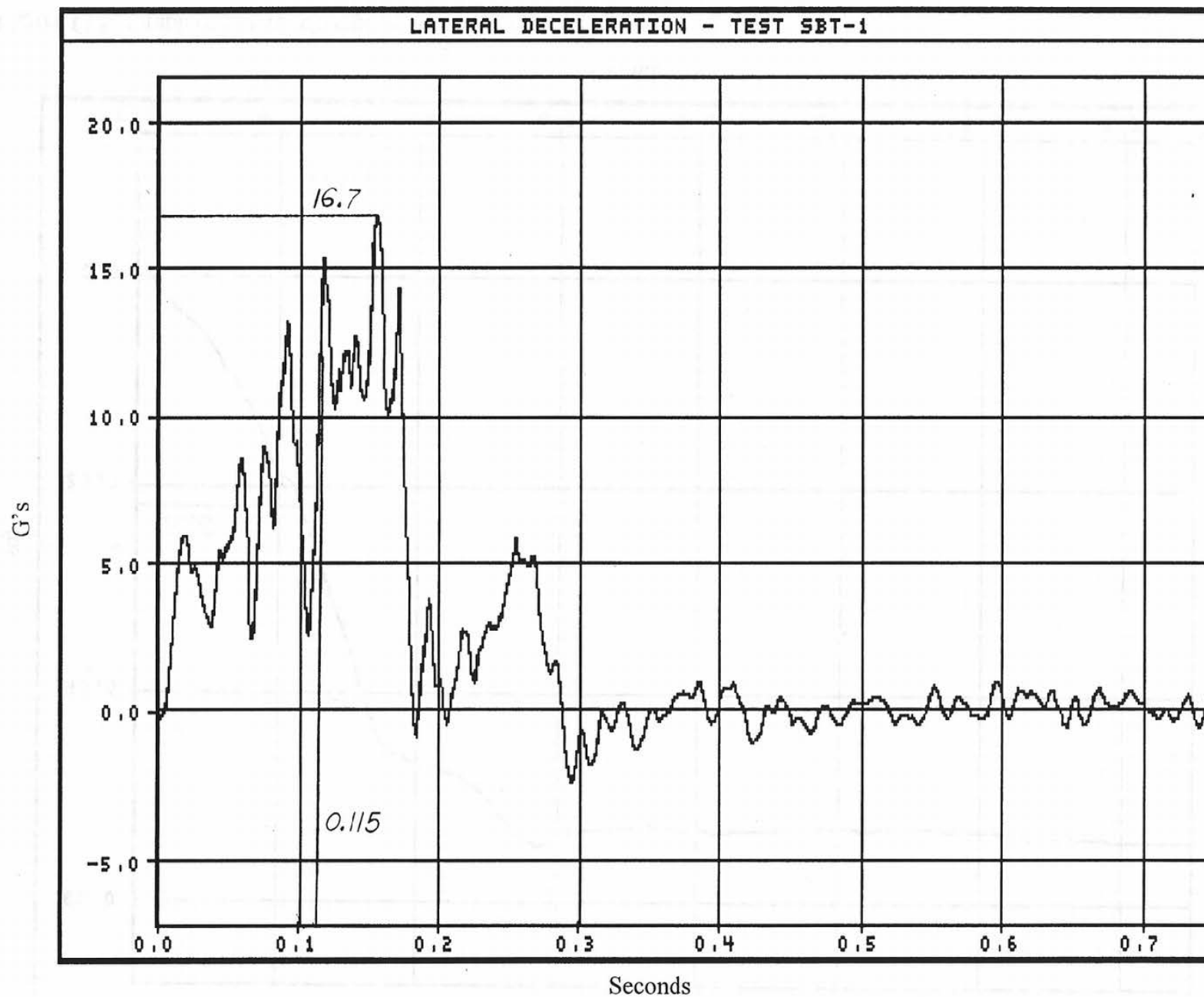
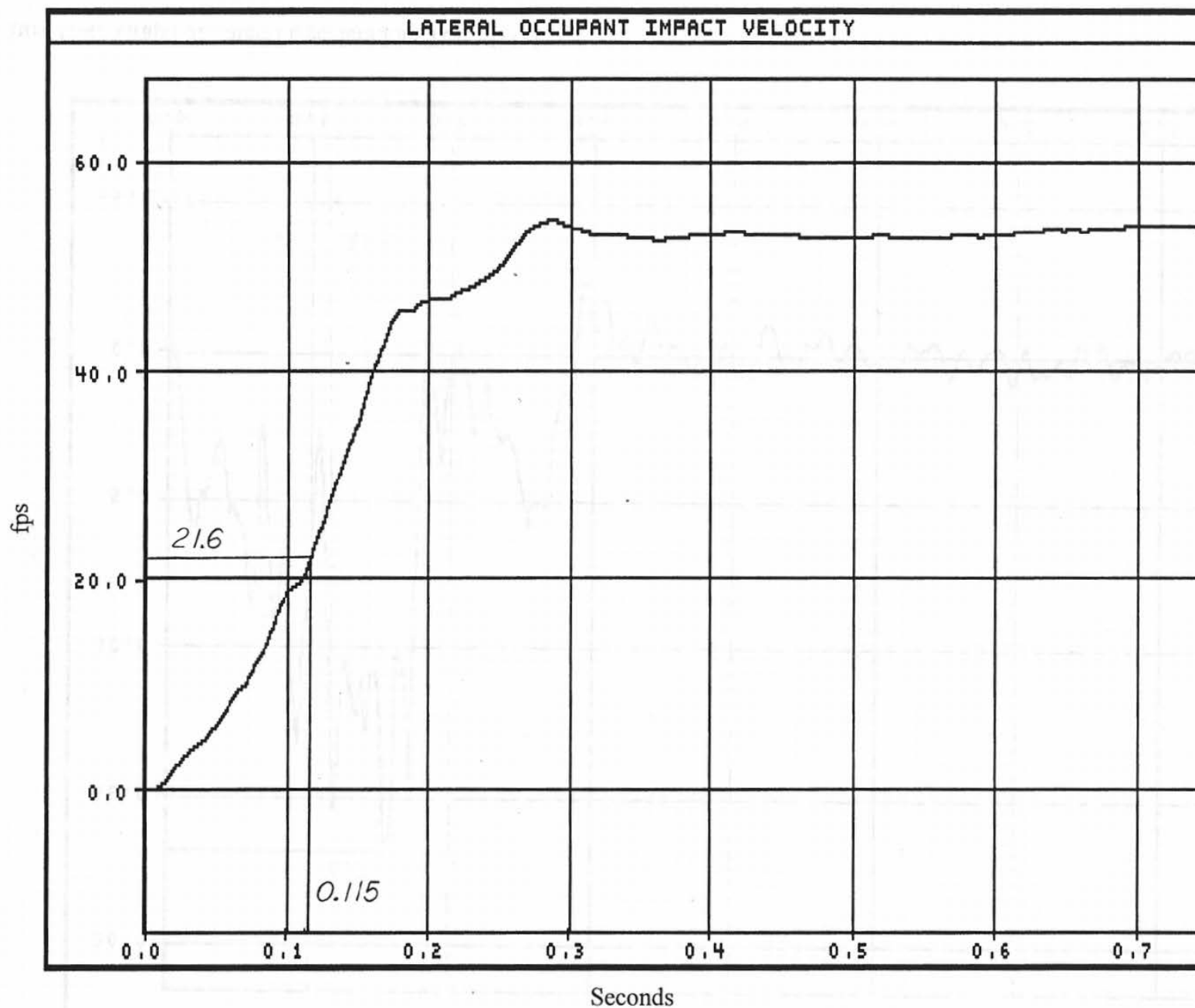
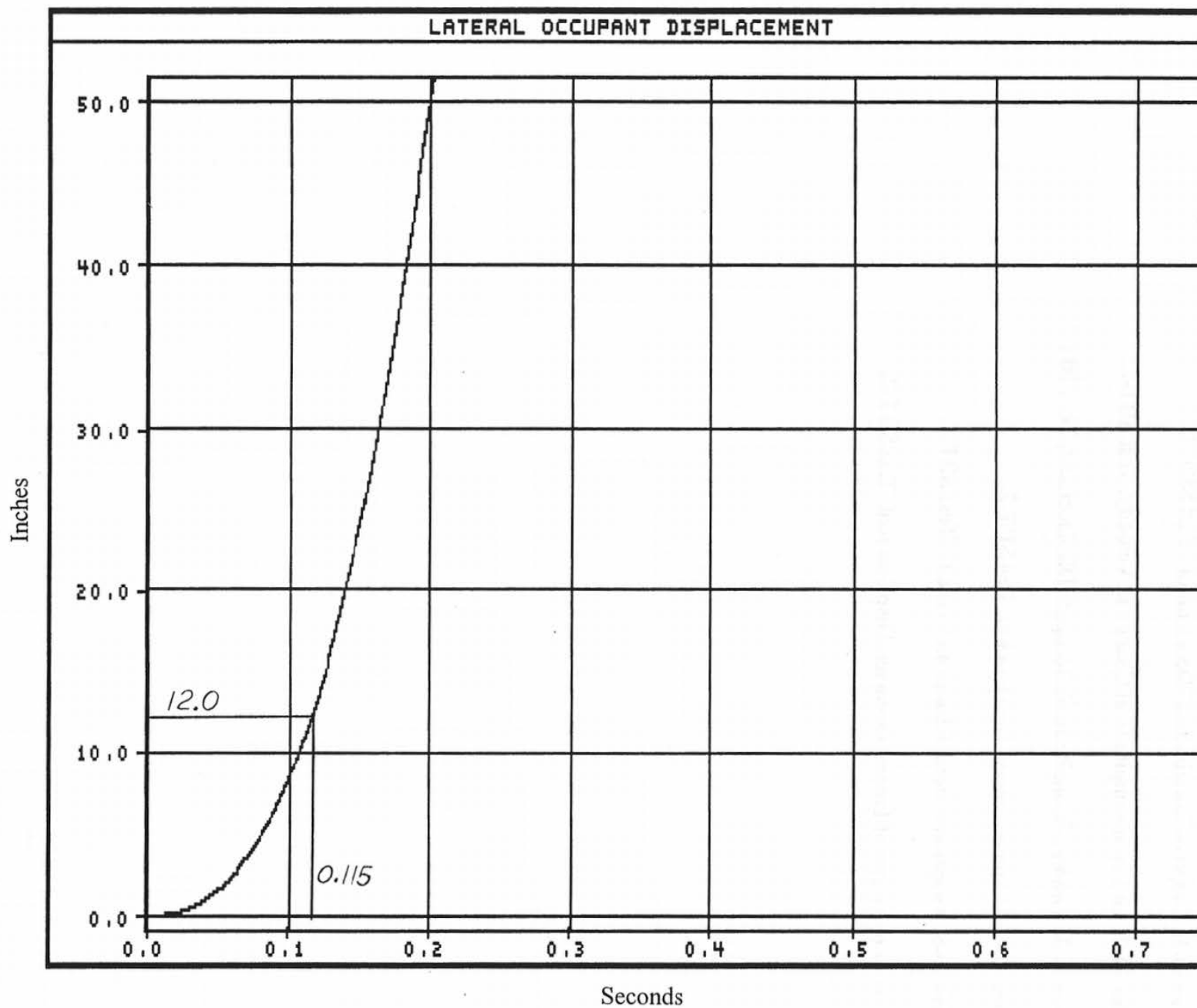


Figure C-4. Graph of Lateral Deceleration, Test SBT-1.



**Figure C-5.** Graph of Lateral Change in Velocity, Test SBT-1.





**Figure C-6.** Graph of Lateral Occupant Displacement, Test SBT-1.

## APPENDIX D.

### ACCELEROMETER DATA ANALYSIS, TEST SBT-2

Figure D-1. Graph of Longitudinal Deceleration, Test SBT-2.

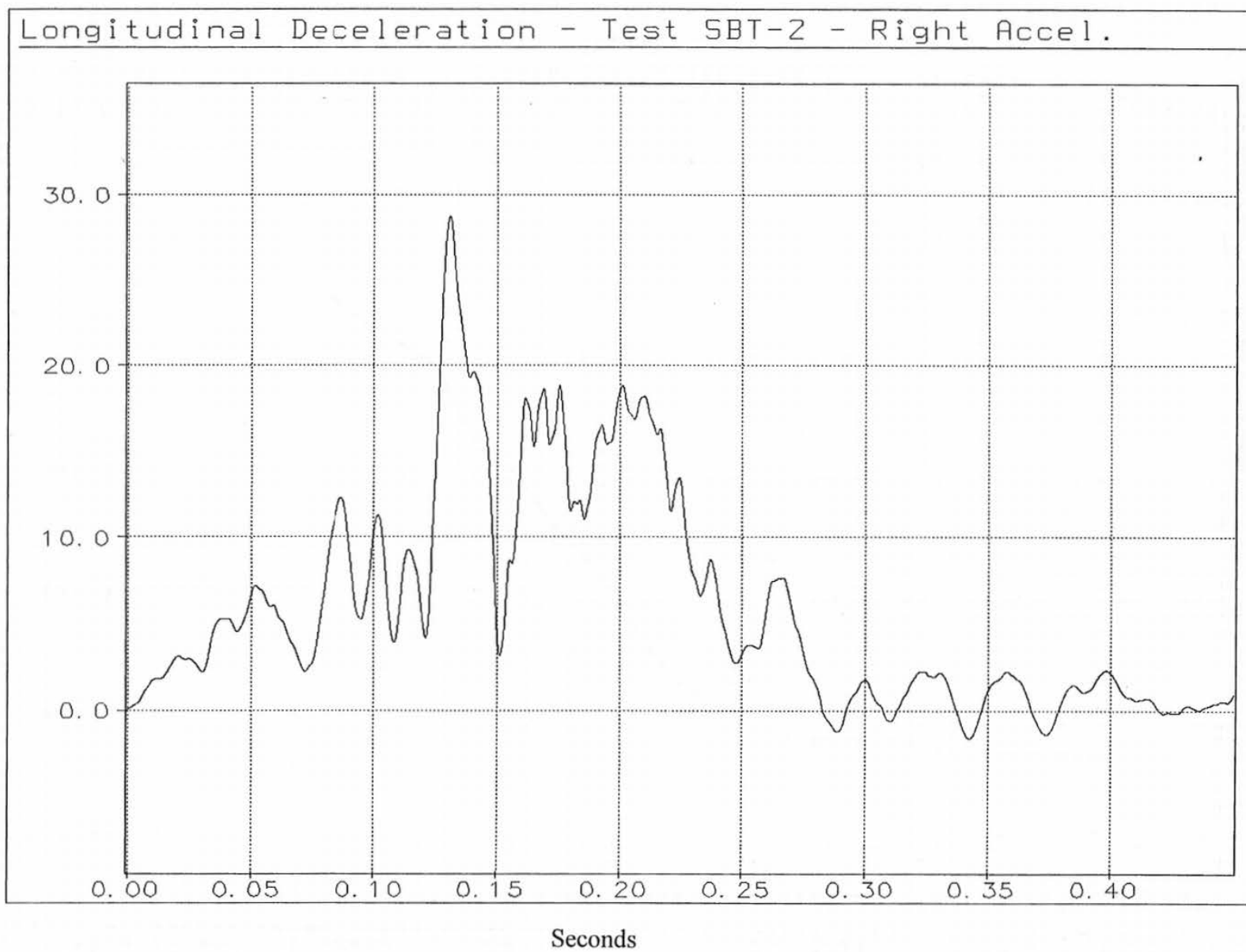
Figure D-2. Graph of Longitudinal Change in Velocity, Test SBT-2.

Figure D-3. Graph of Longitudinal Occupant Displacement, Test SBT-2.

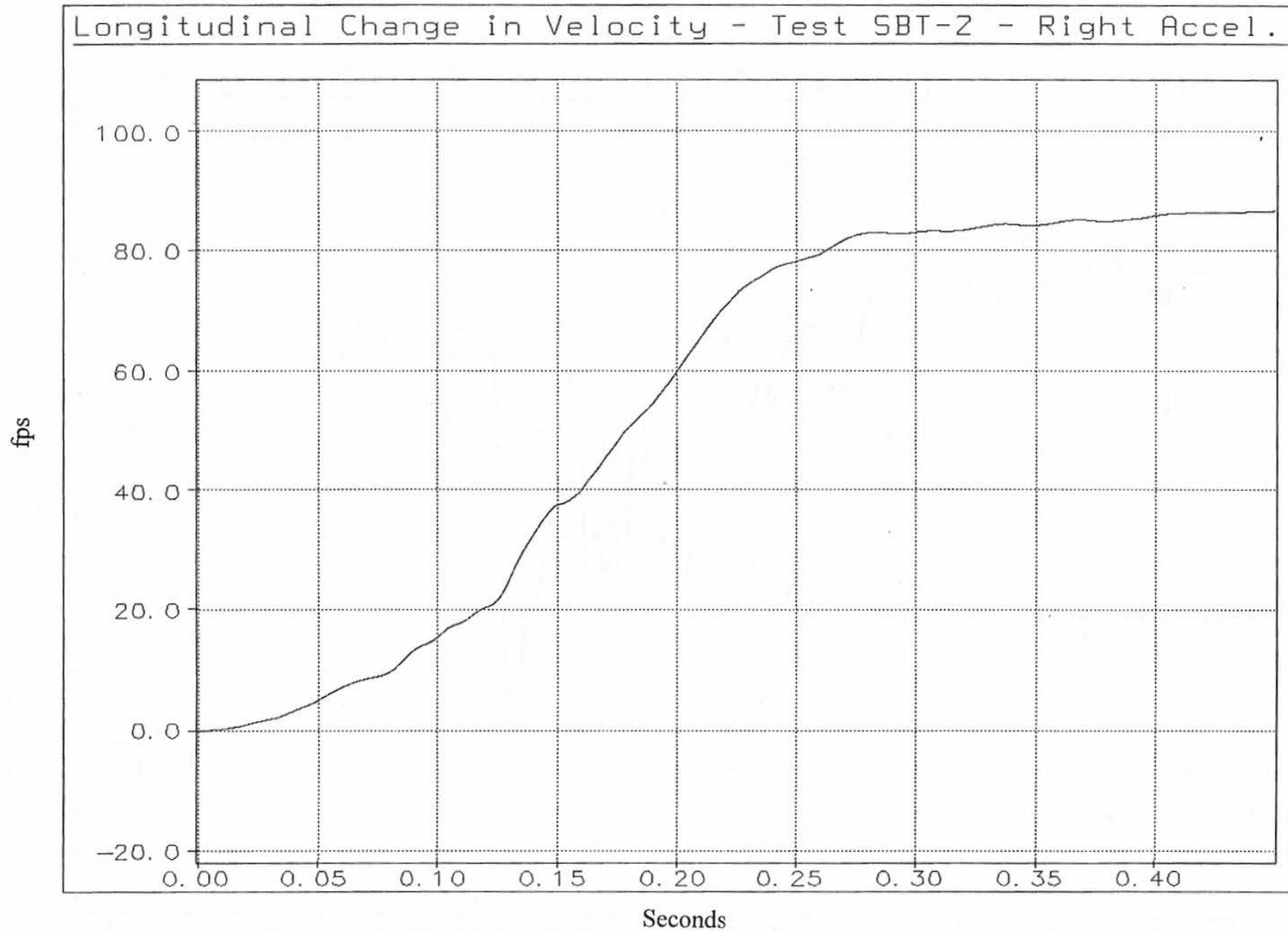
Figure D-4. Graph of Lateral Deceleration, Test SBT-2.

Figure D-5. Graph of Lateral Change in Velocity, Test SBT-2.

Figure D-6. Graph of Lateral Occupant Displacement, Test SBT-2.



**Figure D-1.** Graph of Longitudinal Deceleration, Test SBT-2.



**Figure D-2.** Graph of Longitudinal Change in Velocity, Test SBT-2.

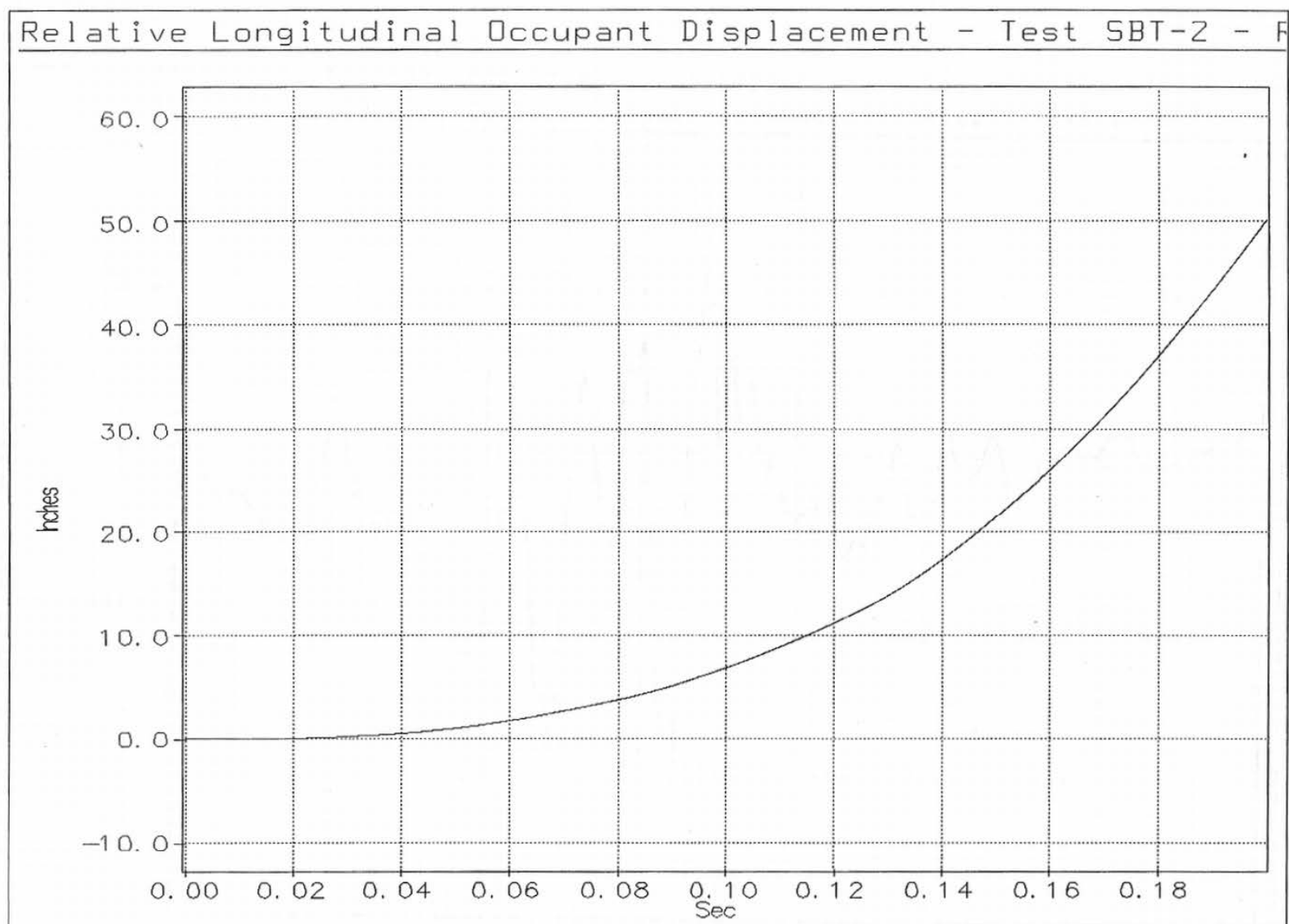


Figure D-3. Graph of Longitudinal Occupant Displacement, Test SBT-2.

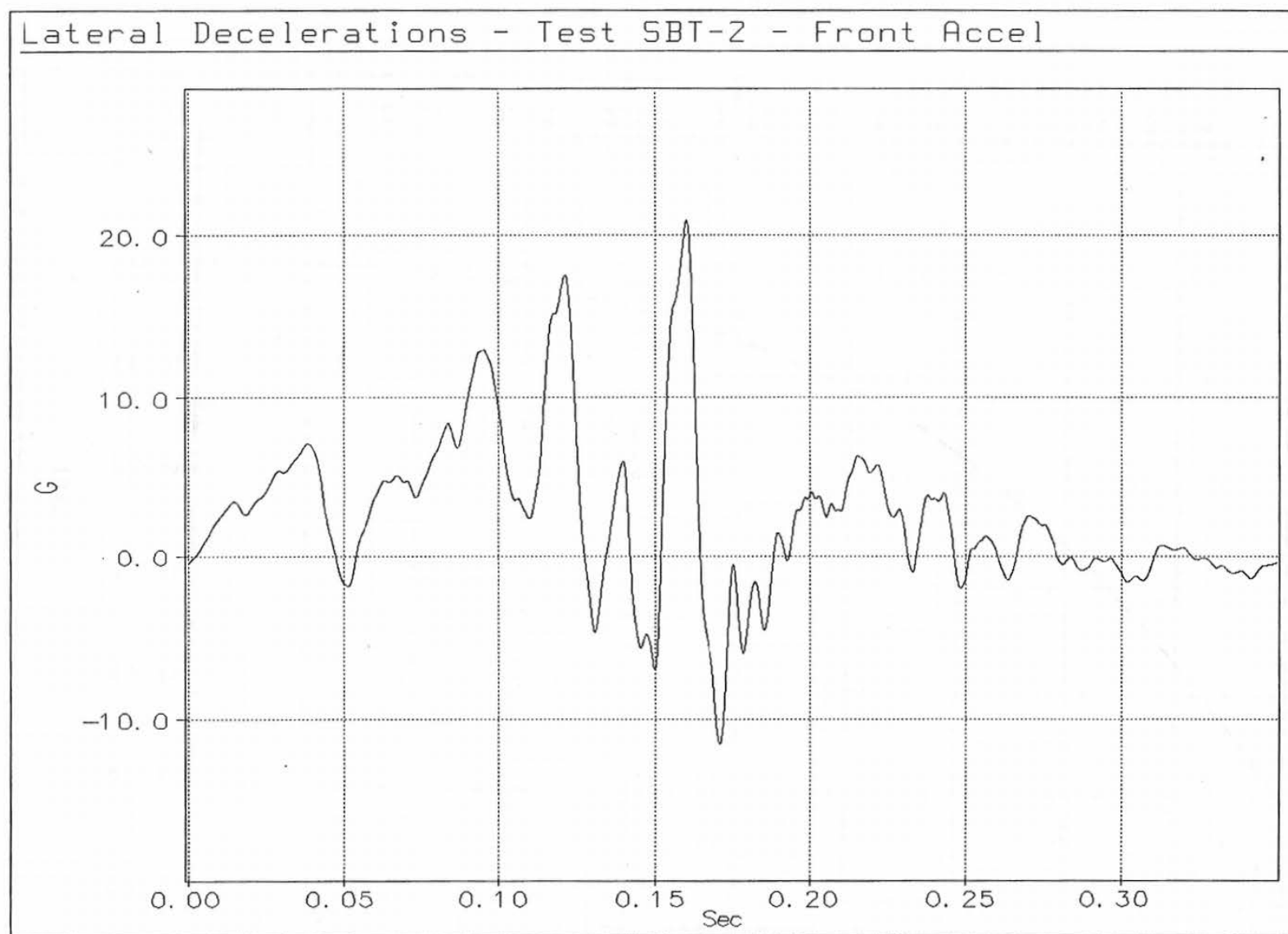
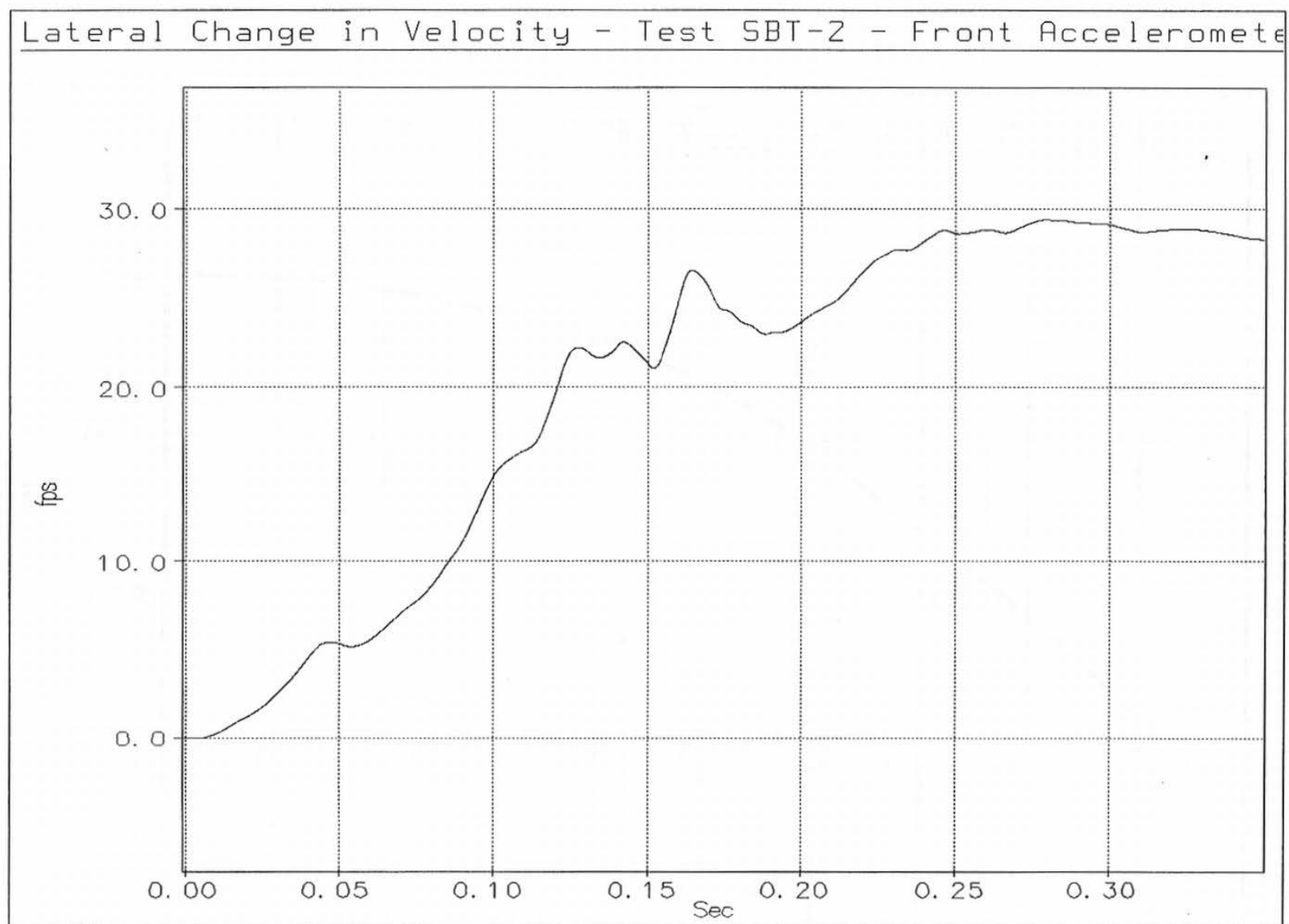
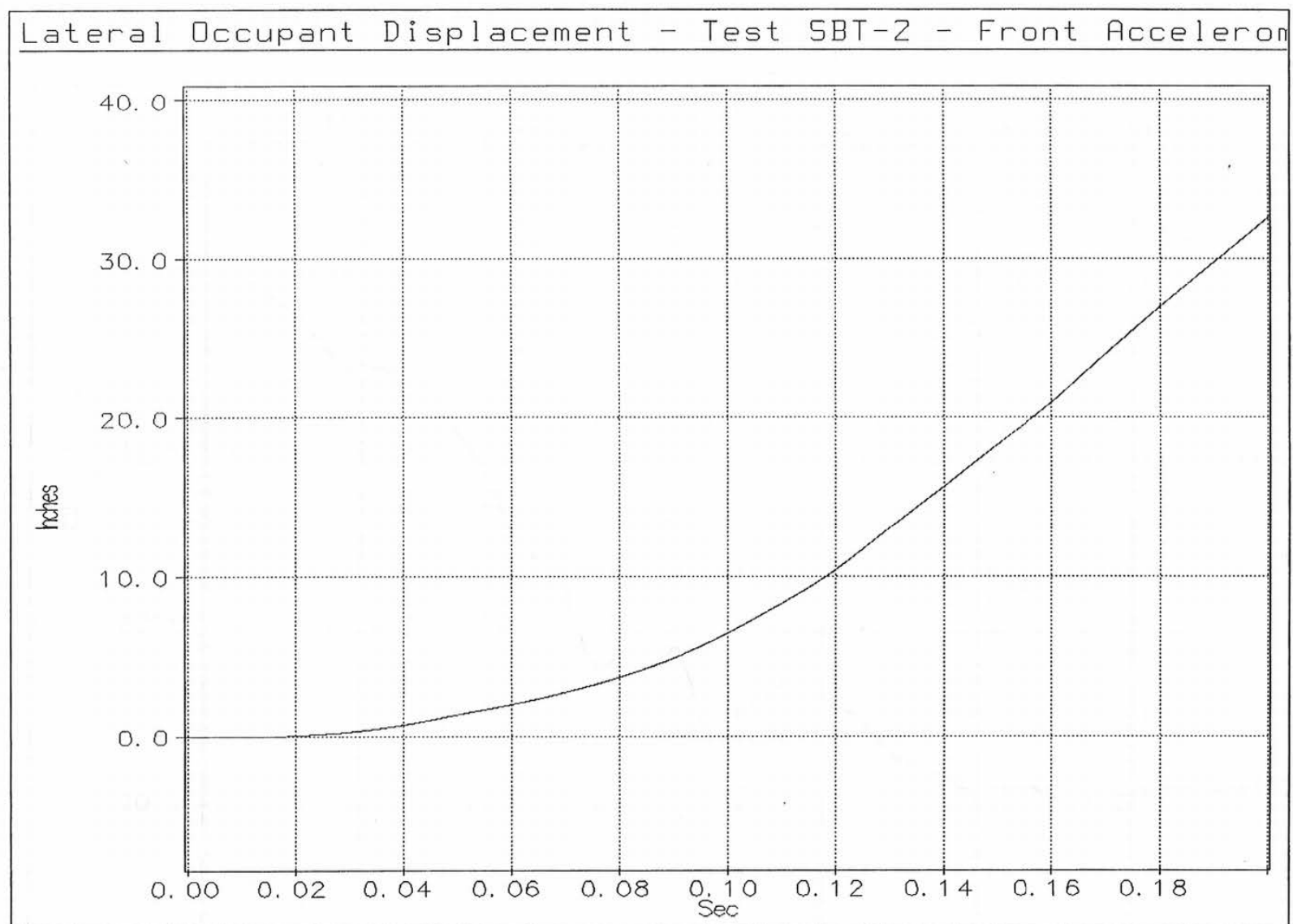


Figure D-4. Graph of Lateral Deceleration, Test SBT-2.





**Figure D-5.** Graph of Lateral Change in Velocity, Test SBT-2.



**Figure D-6.** Graph of Lateral Occupant Displacement, Test SBT-2.

## **APPENDIX E.**

### **ACCELEROMETER DATA ANALYSIS, TEST SBT-4**

Figure E-1. Graph of Longitudinal Deceleration, Test SBT-4.

Figure E-2. Graph of Longitudinal Change in Velocity, Test SBT-4.

Figure E-3. Graph of Longitudinal Occupant Displacement, Test SBT-4.

Figure E-4. Graph of Lateral Deceleration, Test SBT-4.

Figure E-5. Graph of Lateral Change in Velocity, Test SBT-4.

Figure E-6. Graph of Lateral Occupant Displacement, Test SBT-4.

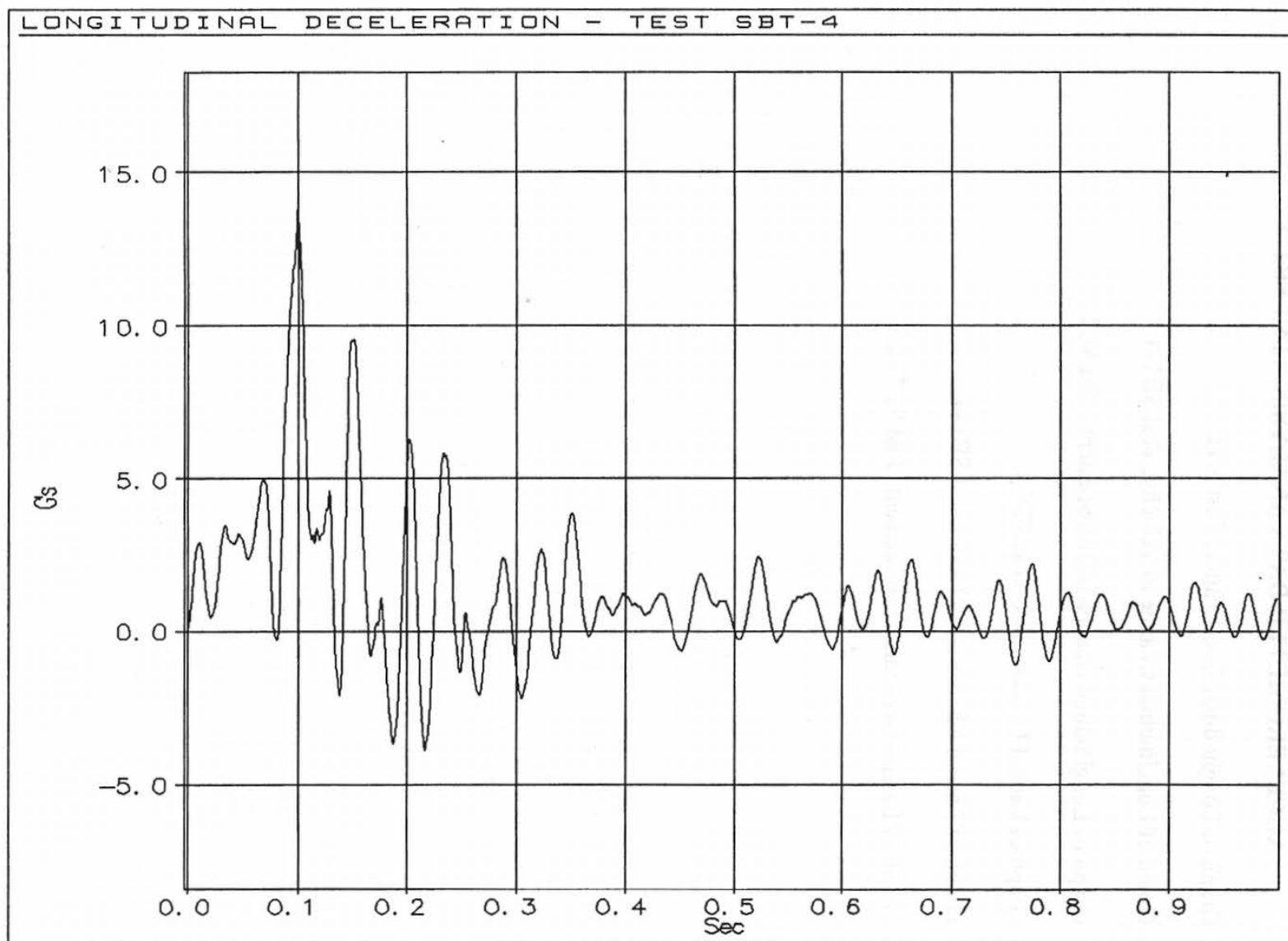


Figure E-1. Graph of Longitudinal Deceleration, Test SBT-4.

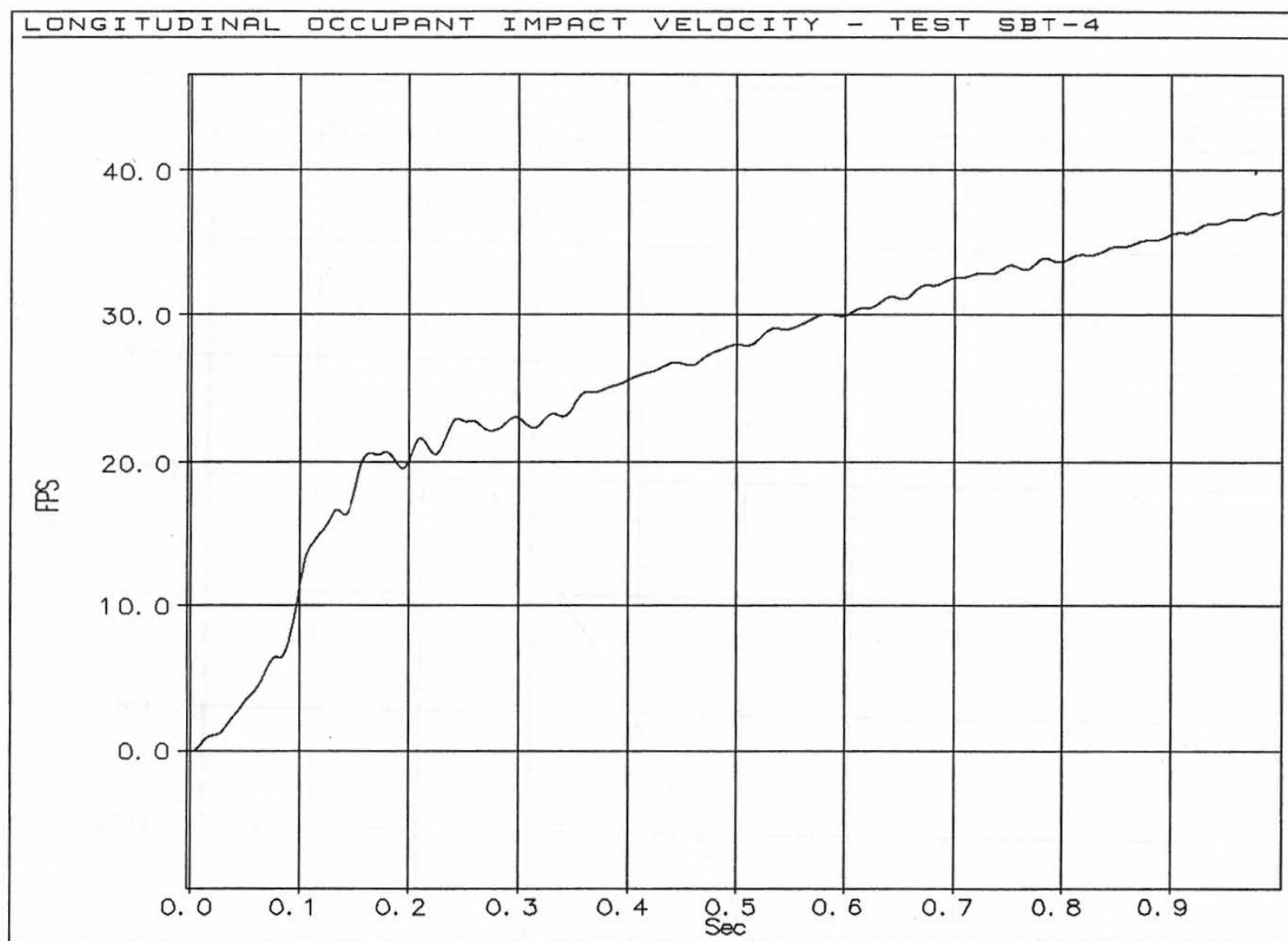


Figure E-2. Graph of Longitudinal Change in Velocity, Test SBT-4.

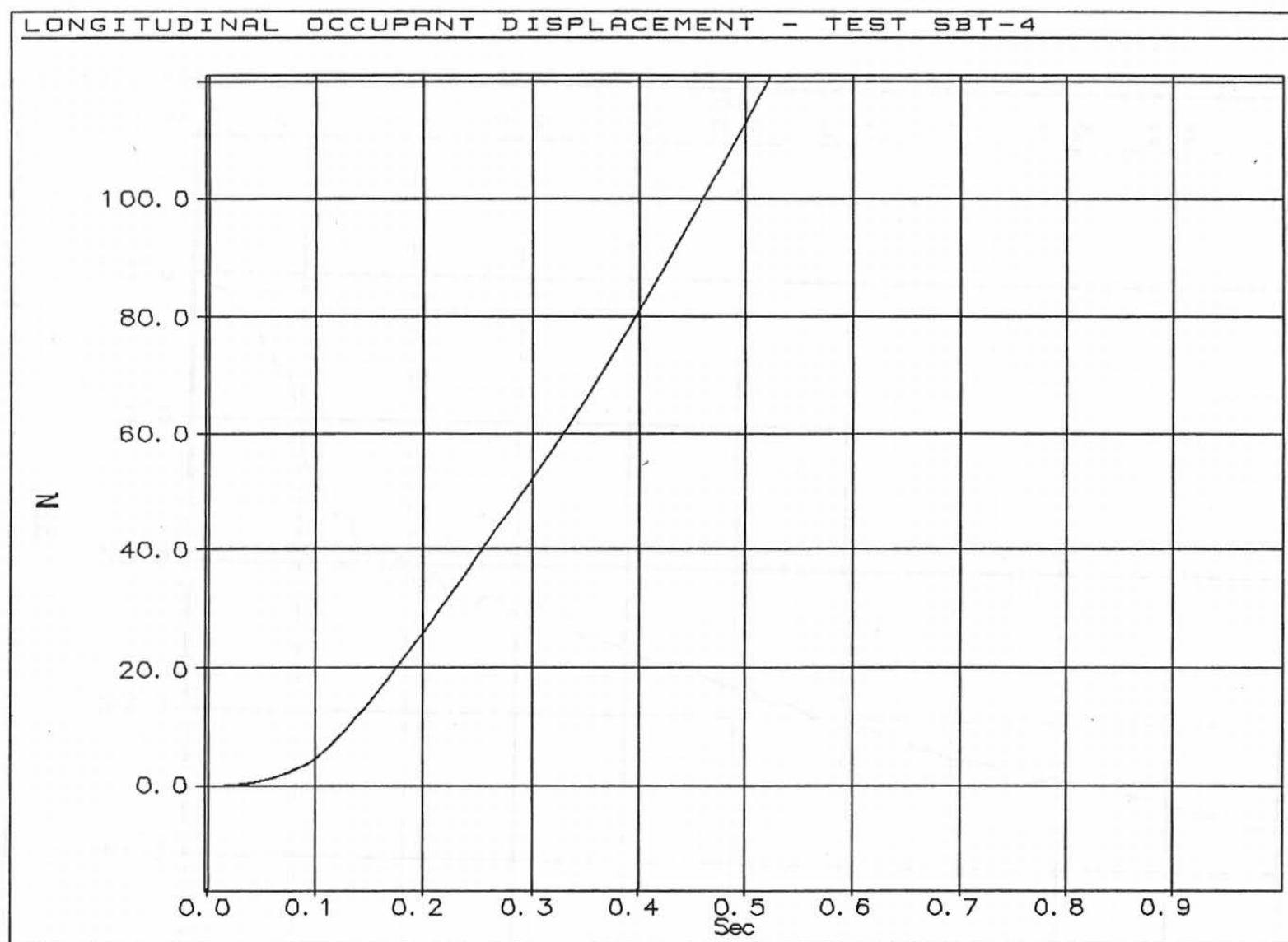


Figure E-3. Graph of Longitudinal Occupant Displacement, Test SBT-4.



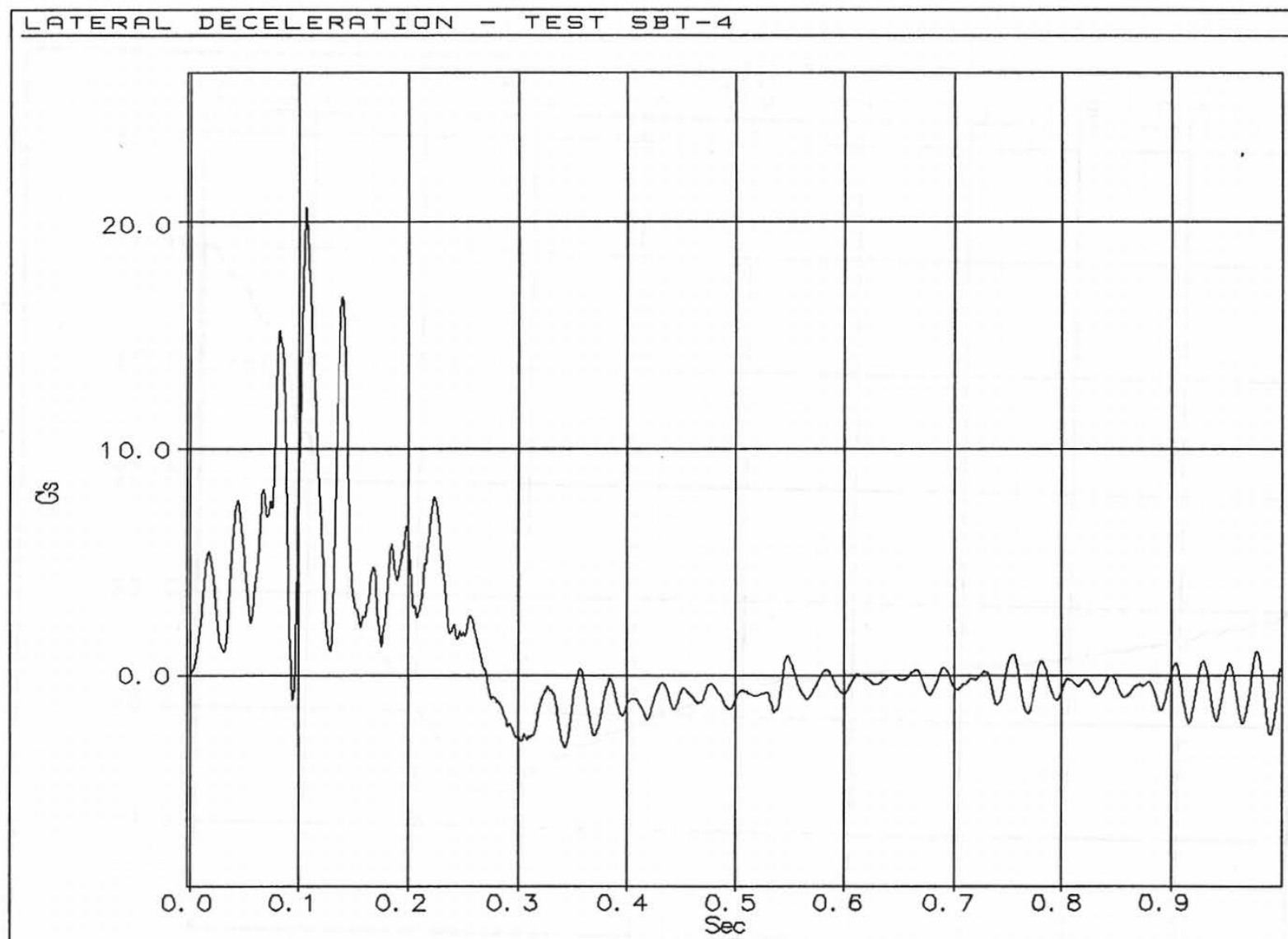


Figure E-4. Graph of Lateral Deceleration, Test SBT-4.

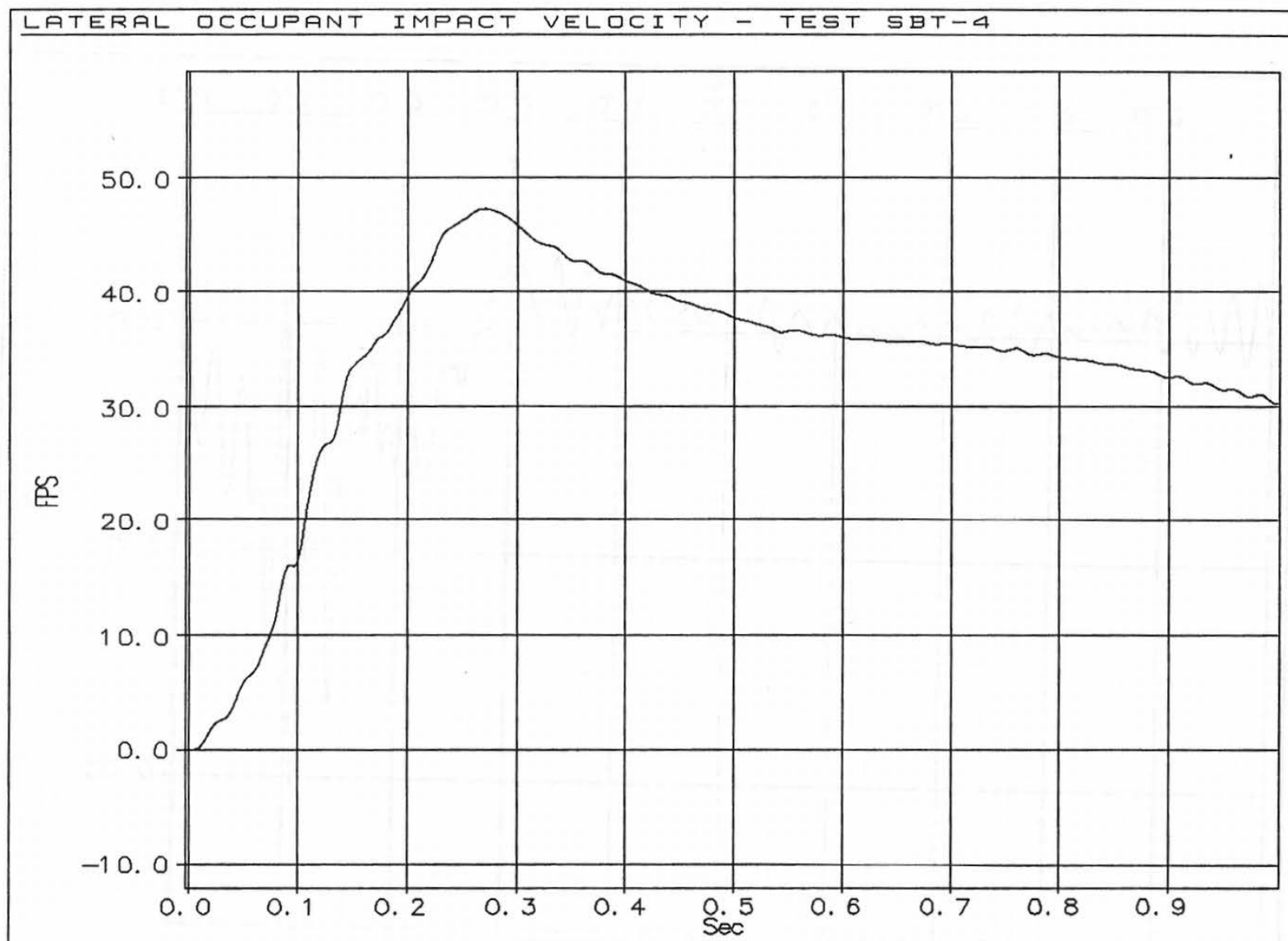


Figure E-5. Graph of Lateral Change in Velocity, Test SBT-4.

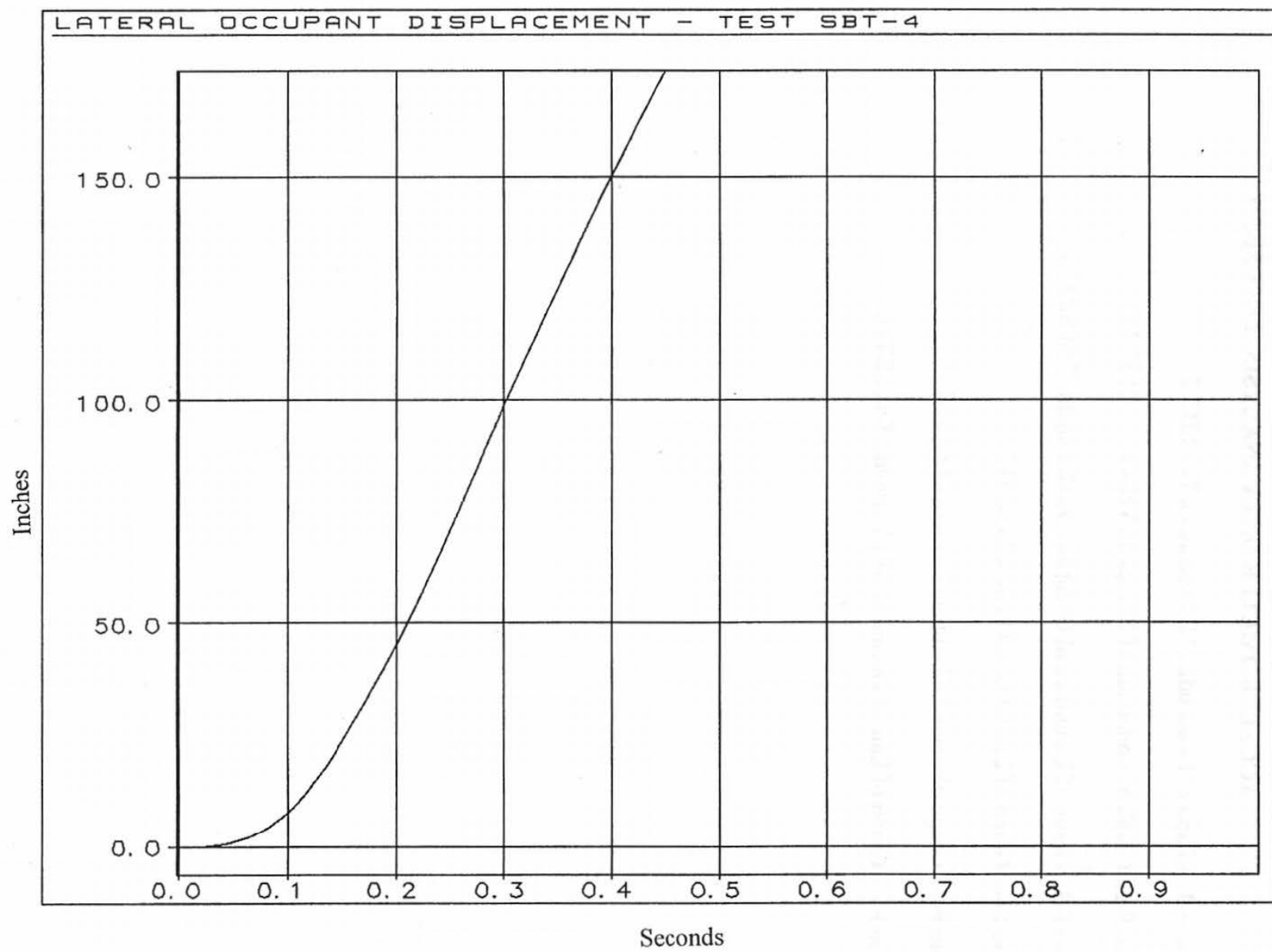


Figure E-6. Graph of Lateral Occupant Displacement, Test SBT-4.

## APPENDIX F.

### ACCELEROMETER DATA ANALYSIS, TEST SBT-5

Figure F-1. Graph of Longitudinal Deceleration, Test SBT-5.

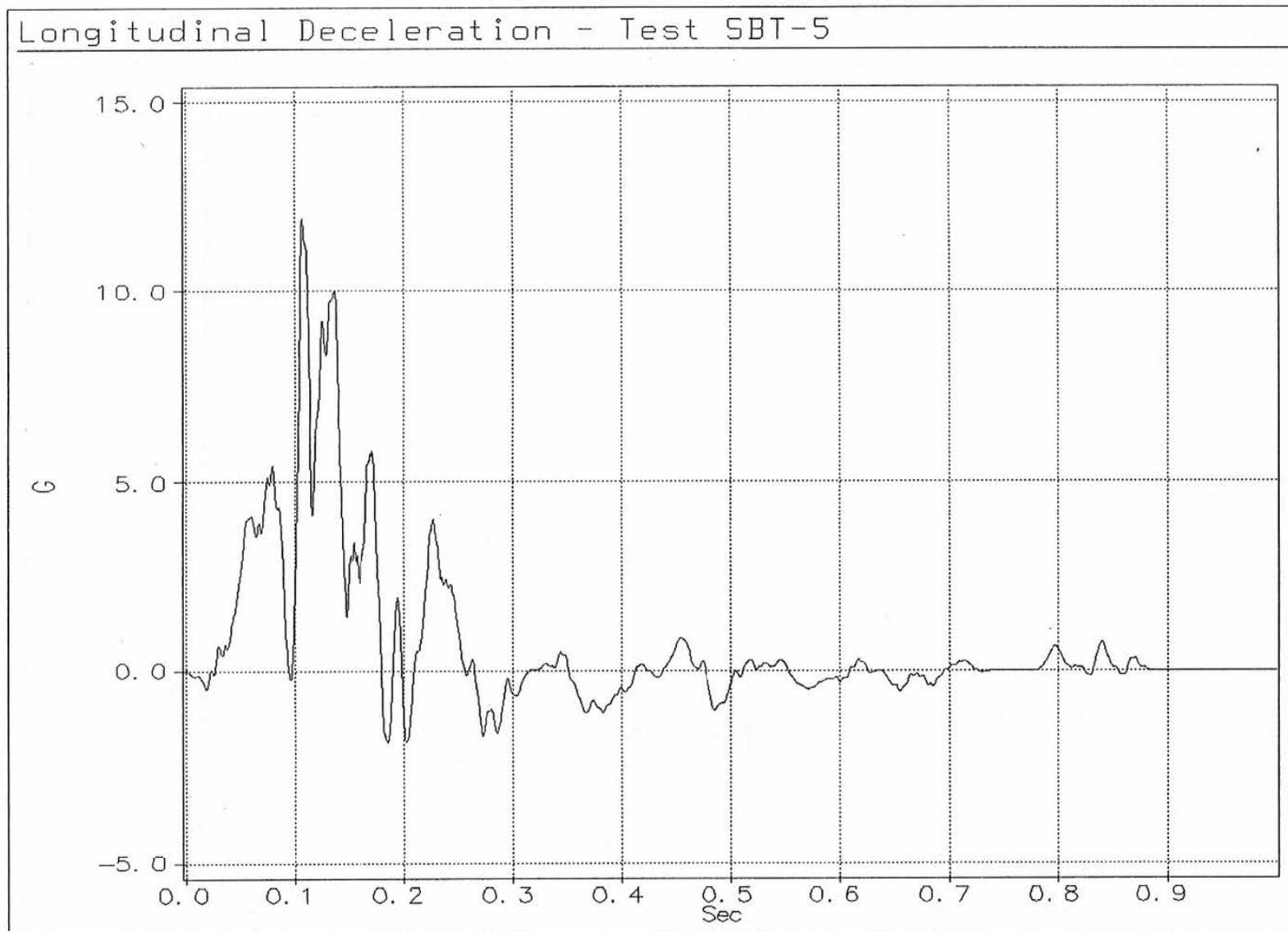
Figure F-2. Graph of Longitudinal Change in Velocity, Test SBT-5.

Figure F-3. Graph of Longitudinal Occupant Displacement, Test SBT-5.

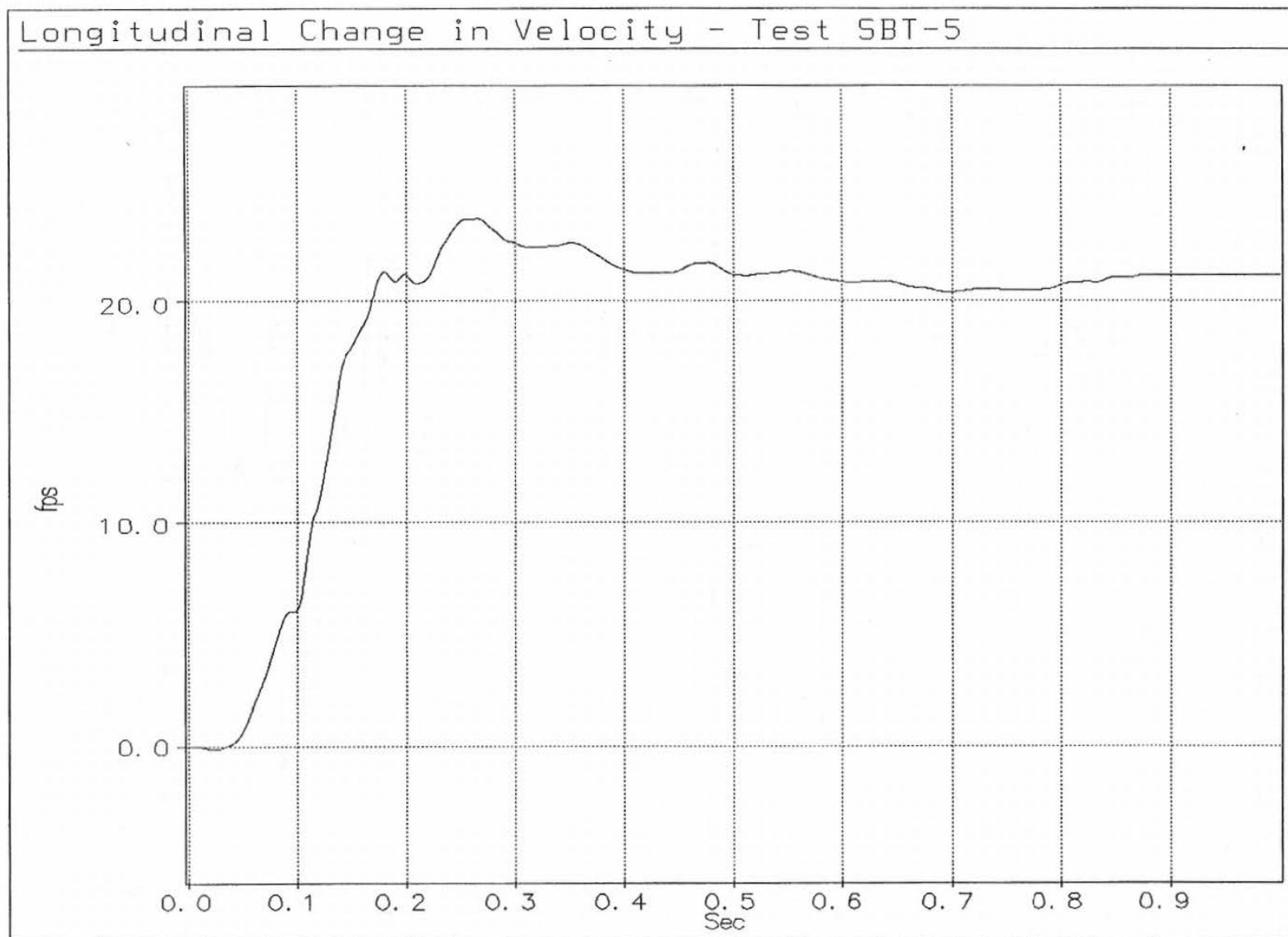
Figure F-4. Graph of Lateral Deceleration, Test SBT-5.

Figure F-5. Graph of Lateral Change in Velocity, Test SBT-5.

Figure F-6. Graph of Lateral Occupant Displacement, Test SBT-5.

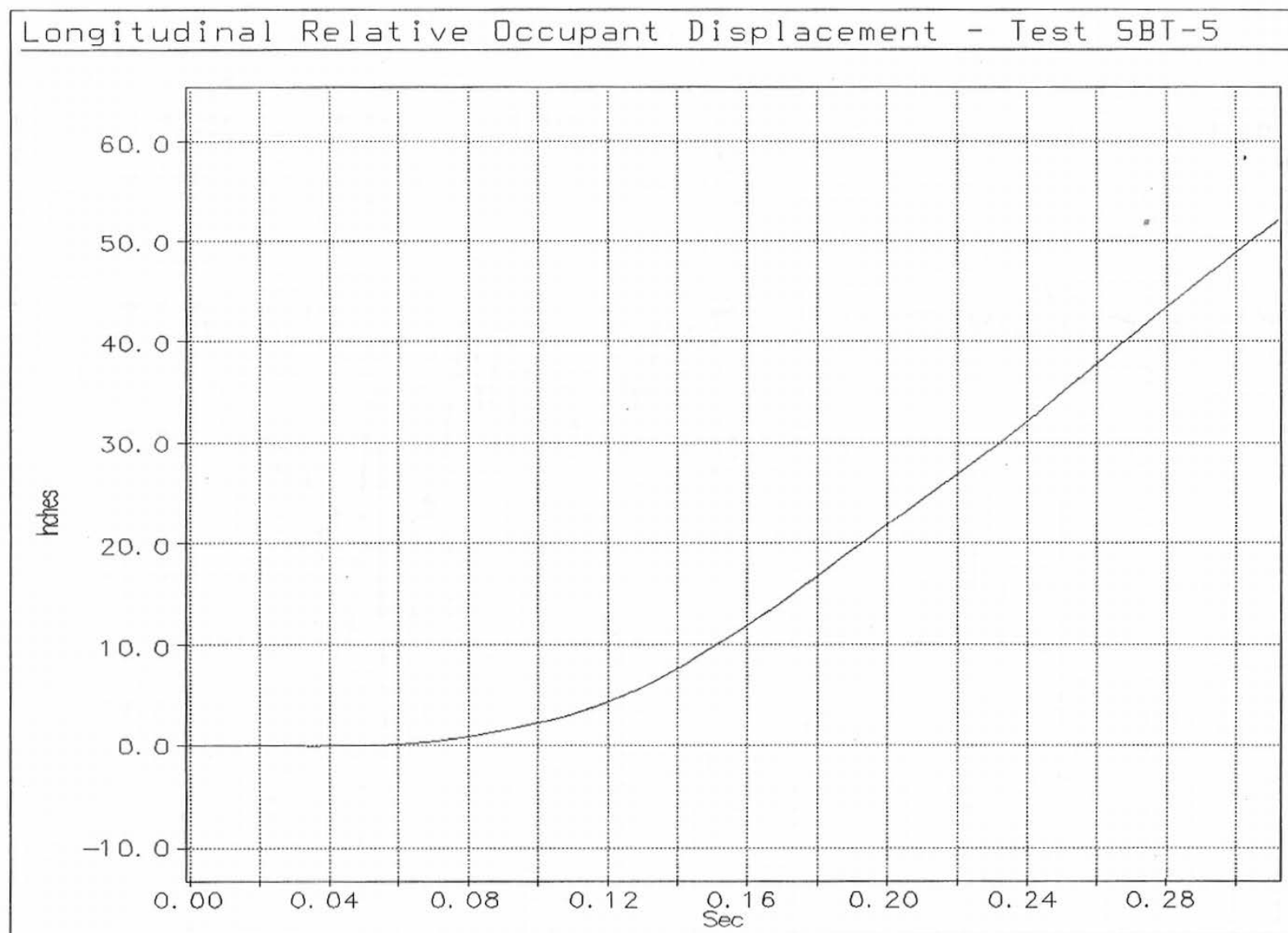


**Figure F-1.** Graph of Longitudinal Deceleration, Test SBT-5.



**Figure F-2.** Graph of Longitudinal Change in Velocity, Test SBT-5.





**Figure F-3.** Graph of Longitudinal Occupant Displacement, Test SBT-5.

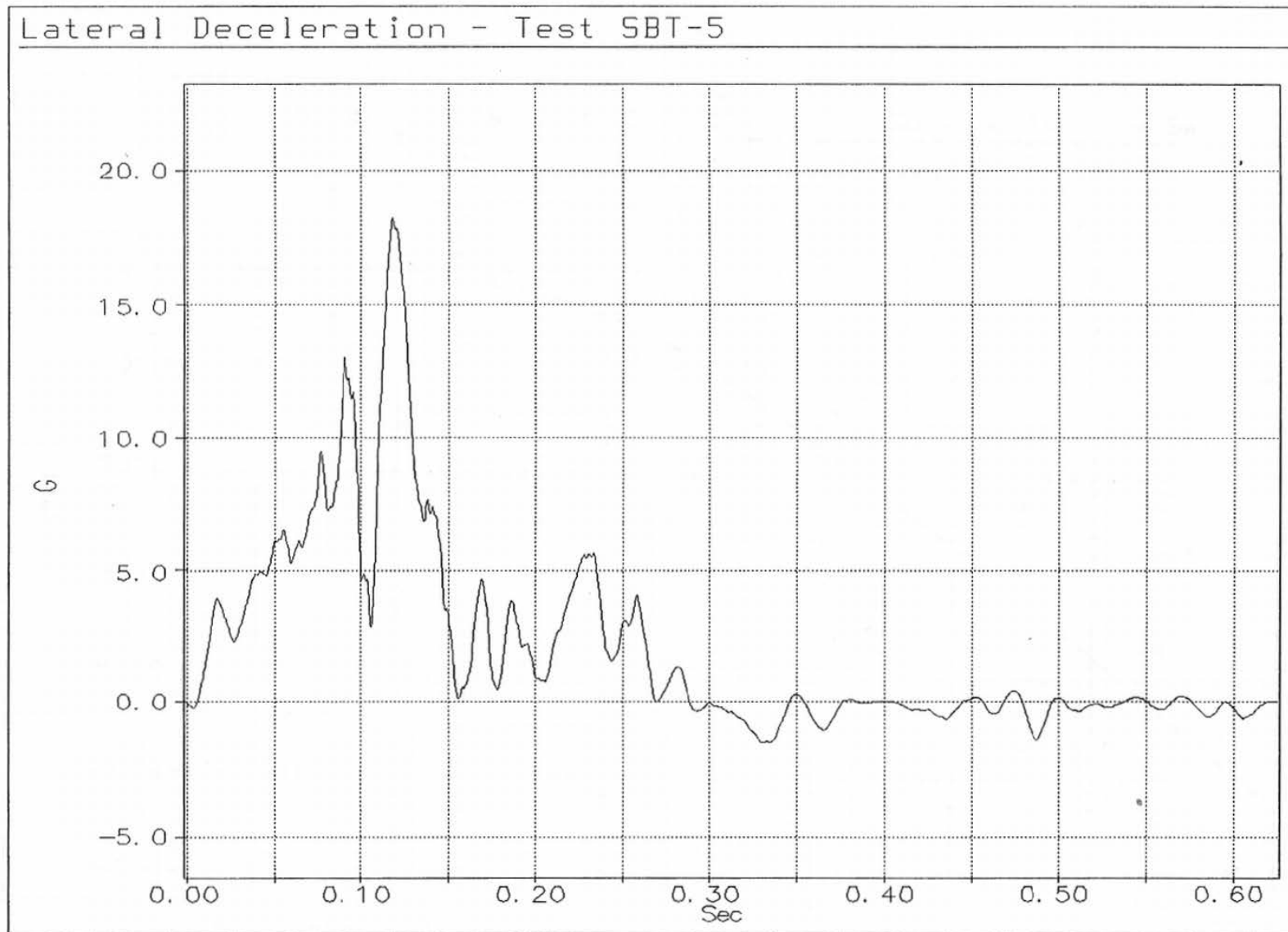
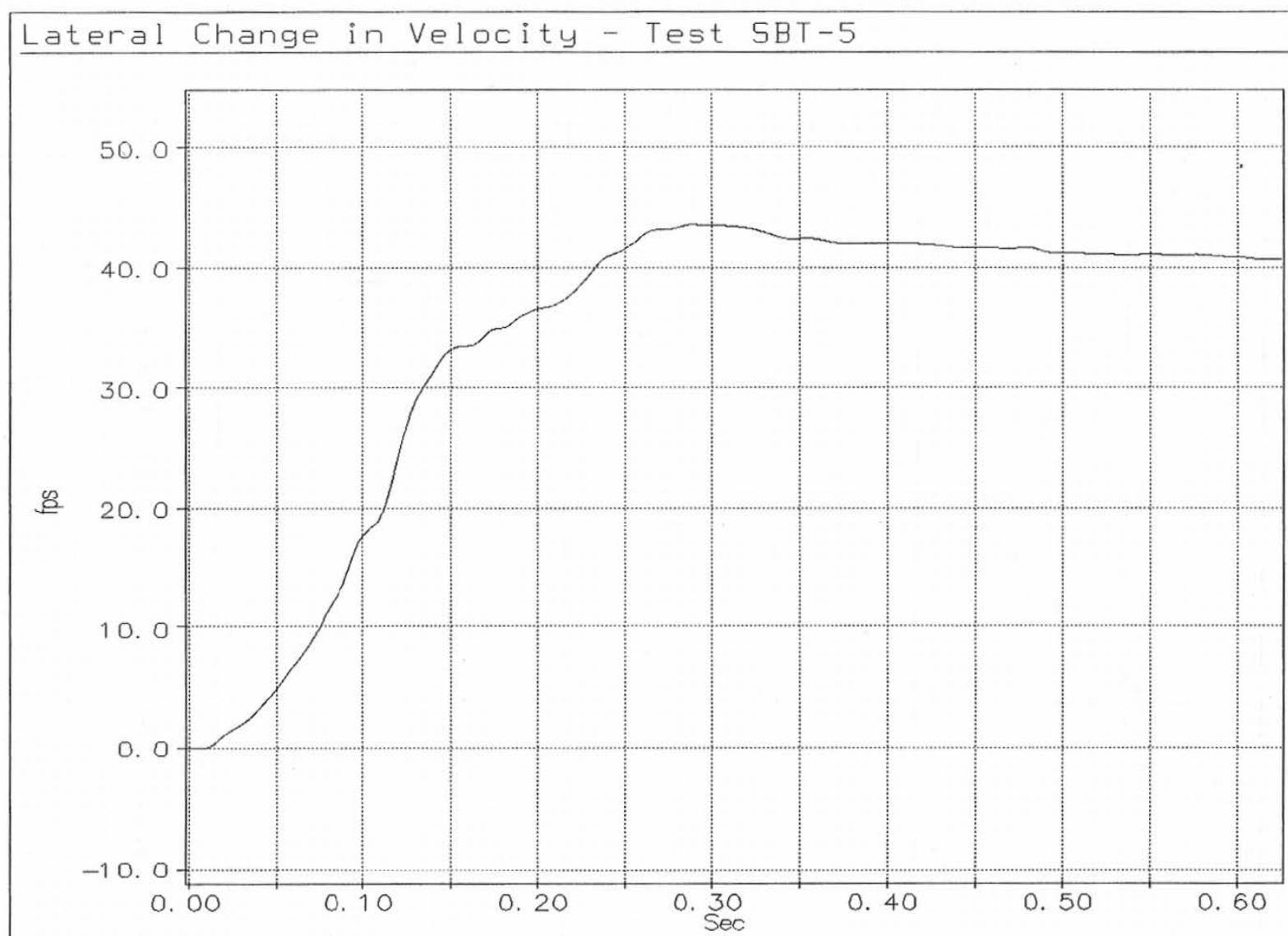


Figure F-4. Graph of Lateral Deceleration, Test SBT-5.



**Figure F-5.** Graph of Lateral Change in Velocity, Test SBT-5.