Improved Guardrail Terminal

Development of a BEST Terminal to Comply with NCHRP 350 Requirements

December 1998
Final Report

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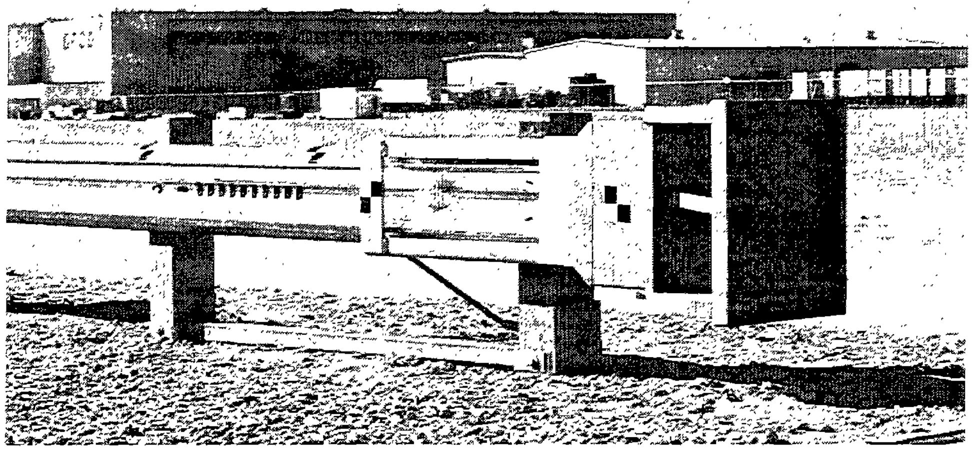

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13. ABSTRACT ***(Maximum 200 words)***

An energy absorbing guardrail terminal was developed at the Midwest Roadside Safety Facility in 1994 which met the safety criteria set forth in NCHRP Report 230. This terminal, known as the ***B***eam ***E***ating ***S***teel ***T***erminal, or ***BEST***, relies on the cutting of steel W-beam to absorb the energy of impacting vehicles. Since this time, a new set of safety standards has been developed to replace those set forth in NCHRP Report 230. This new criteria is published in NCHRP Report 350, with the most significant change being the replacement of the 4500 lb sedan test vehicle with a 2000 kg 3/4 ton pickup. The new criteria reflects the increase in popularity of pickups, vans, and sport utility vehicles which have a significantly higher center of gravity than the sedans and small cars which have been the standard for crash testing until now.

In order to insure that the ***BEST*** system would perform well, under these new and more stringent criteria, the system was subjected to the matrix of full-scale vehicle crash tests required by NCHRP Report 350. The results of this successful program are reported here.

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TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

2 INTRODUCTION

An energy absorbing guardrail terminal was developed at the Midwest Roadside Safety Facility in 1994 (1) which met the safety criteria set forth in NCHRP Report 230 (2). This terminal, known as the *B*eam *E*ating *S*teel *T*erminal, or ***BEST***, relies on the cutting of the steel W-beam to absorb the energy of impacting vehicles. Since this time, a new set of safety standards has been adopted to replace those set forth in NCHRP Report 230. This new criteria is published in NCHRP Report 350 (3), with the most significant change being the replacement of the 4500 lb sedan test vehicle with a 2000 kg 3/4 ton pickup. The new criteria reflects the increase in popularity of pickups, vans, and sport utility vehicles which have a significantly higher center of gravity than the sedans and small cars which have been the standard for crash testing until now.

In order to insure that the ***BEST*** system would perform well under these new, and more stringent criteria the system was subjected to the matrix of full-scale vehicle crash tests required by NCHRP Report 350 (3). The results of this series of tests are reported here.

3 SYSTEM DETAILS

The ***BEST*** system is an energy absorbing guardrail terminal which consists of an impact head mounted on the end of a standard wood post W-beam system. The concept behind this system is that when the impact head is struck by a vehicle, three cutter teeth within the head cut the W-beam along the peaks and valley. The W-beam is cut into four relatively flat plates that are subsequently bent out of the path of the impacting vehicle.

Photographs of the system used in the initial crash tests are shown in Figures 1 and 2, and a schematic of the design is shown in Figure 3. Details of the impact head used for tests BEST-2,3, and 4 are shown in Figures 4 and 5. After a preliminary evaluation of the performance of the original BEST system several design changes were made with the hope of improving its impact performance. Most notable of these changes involved shortening the first rail element. The W-beam rail in the previous system was 9.84 m (32 ft - 3½ in.) long and spanned over 5 post spacings. Testing showed that this length could be reduced by one post spacing without compromising the safety of the system. The rail was then extended by 152 mm (6 in.) on the upstream end in order to allow a greater distance between the end of the chute and the cable anchor box. This was done to ensure that the first post was broken and the cable released before the chute impacted the anchor box. Note that if the first post is not completely fractured when the feeder chute contacts the cable anchor bracket, the anchor cable will be loaded in tension and impart high decelerations on the impacting vehicle. Further, the cable will produce a downward force on the rail element that can deform the rail and induce premature buckling of the W-beam. In order to increase the time between fracturing post 1 and the feeder chute impacting the cable anchor bracket, it was also necessary to move the post breaker 152 mm (6 in.) toward post no. 1.

Another change involved removing the internal wedges on the inside of the end of the chute on the previous design and adding outward flares to the chute as shown in Figures 4 and 5. This modification increased the clearance between the W-beam and the top and bottom of the feeder chute and was incorporated for tests BEST-2 through BEST-7. It was thought that this change would allow greater rotation of the head relative to the W-beam prior to buckling the rail element. Component tests of the impact head demonstrated that this design change did not achieve the desired result and the wedges were returned to the design for tests BEST-8 through BEST-11.

During the process of crash testing the BEST system, several additional design changes were also incorporated. The first of these involved reducing the embedment depth of the CRT posts from 1120 mm (44 in.) to 1070 mm (42 in.). This change was incorporated to improve the energy management of the guardrail system and allow the posts to rotate in the soil rather than fracture in a brittle mode.

Although test BEST-4 was successful, there was a concern that the observed deformations of the post breaker block could slow the process of breaking the leading post and allow the feeder chute to strike the cable anchor bracket before the other end of the cable was released. Therefore, the impact head was modified after test BEST-4 by adding a brace to the post breaker to prevent it from being bent back upon impact with a post.

Following test BEST-5, the front of the head was redesigned to change the geometry of the outlet for the cut strips of W-beam. The revised outlet was necessary to eliminate the possibility of the bumper of an impacting vehicle from wrapping around the head and obstructing the outlet region. This design, shown in Figures 6 and 7, was used for the remainder of the tests.

The final change in design was a return to the original feeder chute end design after test BEST-7. As mentioned previously, bogie vehicle tests were used to explore the two feeder chute end configurations and the original design was found to offer slightly better performance than the revised configuration.

The cutting teeth are fabricated from AR250 abrasion resistant steel, and their dimensions are shown in Figure 8. The end of the W-beam is notched as shown in Figure 9 and the cutters are placed inside these notches to ensure that the cutting process is initiated in the correct location. The cutting action produces a force which brings the vehicle to a controlled stop in which the occupant ridedown accelerations and impact velocities are within the range required by NCHRP 350 (3). Post Nos. 1 and 2 were 1143 mm (3 ft - 9 in.) long and had a 140 mm x 191 mm (5.5 in. x 7.5 in.) cross section and post Nos. 3,4,5,6, and 7 had a reduced length of 1780 mm (5 ft -10 in.) and a full 152 mm x 203 mm (6 in. x 8 in.) cross section. Post nos. 1 and 2 had 64 mm

(2 ½ in.) diameter holes parallel to the rail near the ground line, and post nos. 3 through 7 incorporated CRT post weakening mechanisms with 89 mm (3 ½ in.) diameter holes at the ground line and 406 mm (16 in.) below. These holes weaken the posts for end on impacts, but allow the posts to retain most of their strength in the direction perpendicular to the rail.

In addition to head-on impacts, the guardrail terminal must also be capable of redirecting a 2000 kg (4409 lb) pickup impacting at the beginning of the length of need at a speed of 100 km/h (62.1 mph) and 20 degrees. Thus, the connection between anchor cable and the W-beam needs to develop the tensile force necessary for redirection of a vehicle and release during an end on impact. This was accomplished by cutting tabs in the W-beam, then bending them out to fit in slots of a cable anchor box. Photos of this anchoring system are shown in Figure 10 and the final design is shown in Figures 11 and 12. Note that the only change in this anchor mechanism from the original BEST design was the angling of the plate on the upstream end.

The W-beam used for this terminal is 8.09 m (26 ft - 6 ½ in.) long instead of the standard 7.94 m (26 ft - ½ in.) section. As mentioned previously, the additional 152 mm (6 in.) extends beyond the first post so that this post is completely broken and the cable released before the impact head reaches the cable box. The layout of this rail is shown in Figure 13.

In the event of a redirectional type impact downstream of the terminal, tensile forces in the rail are transferred through the anchor cable and into the first post and foundation tube. In order to distribute this load between the first and second foundation tubes, a strut was installed between the first and second posts to distribute the cable anchor loads between these posts. The location of this strut can be seen in Figure 3 and details are shown in Figure 14.

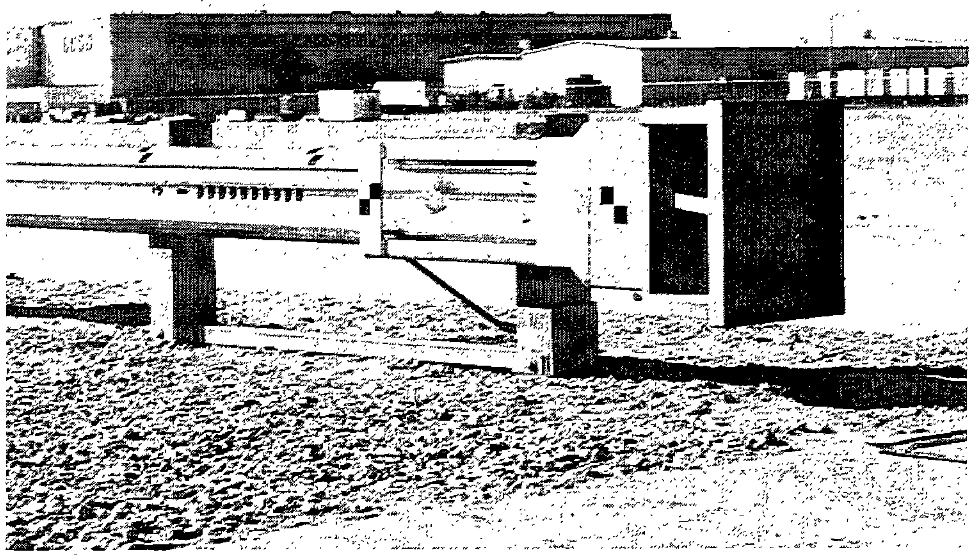


Figure 1. Photographs of the BEST system.

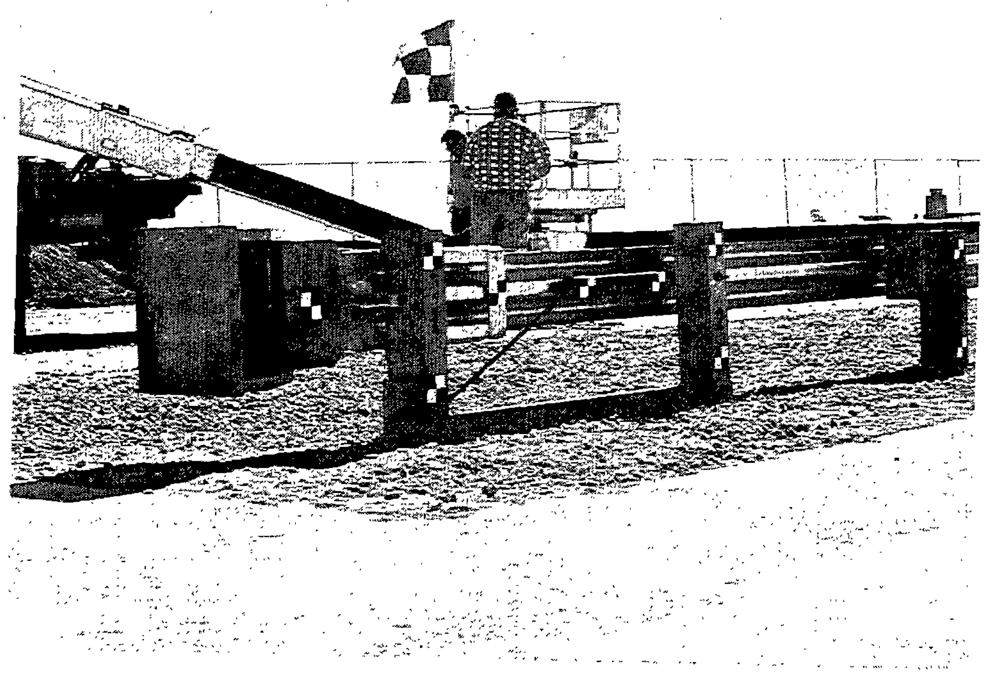


Figure 2. Photographs of BEST system (continued).

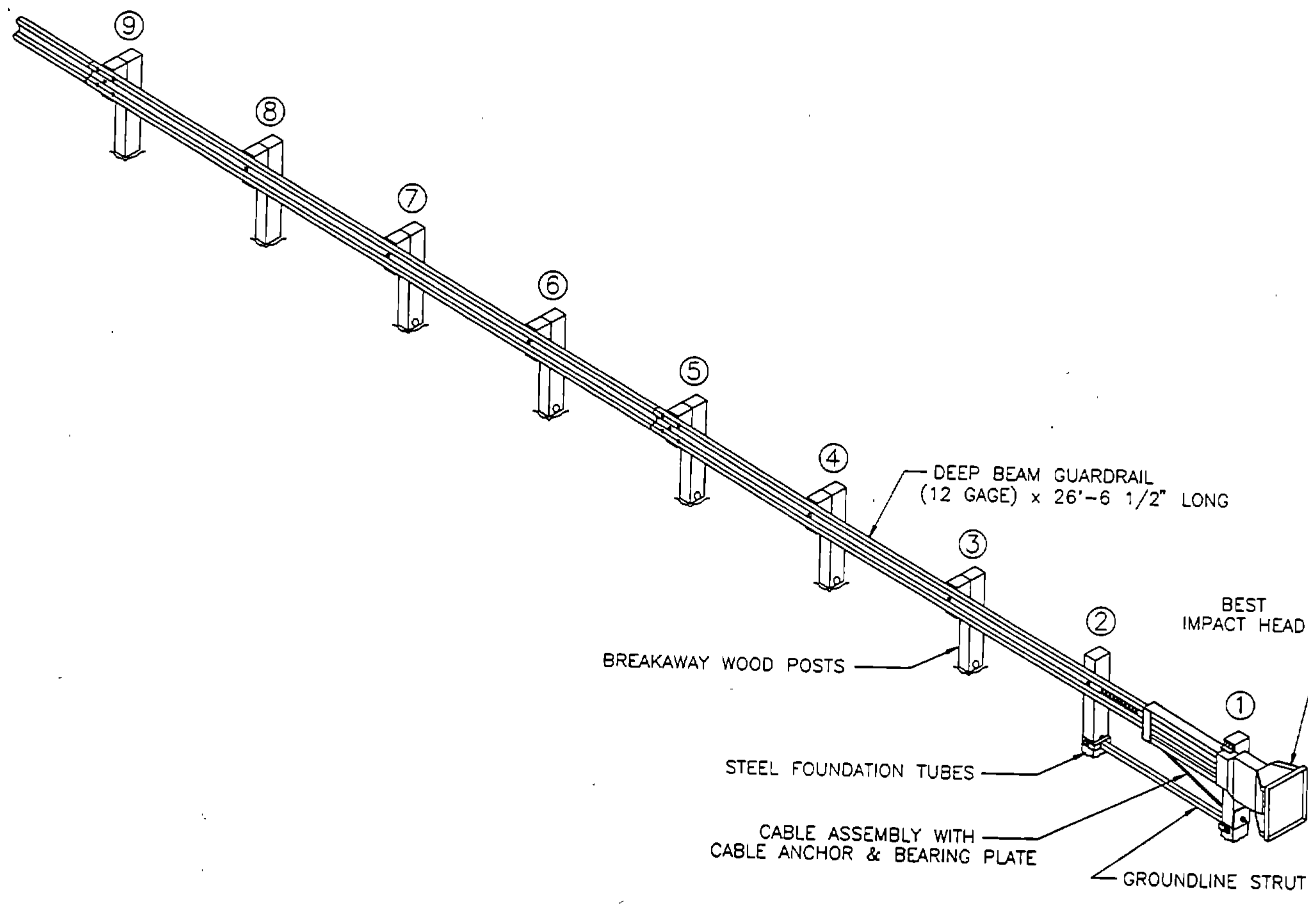


Figure 3. Schematic of the BEST system.

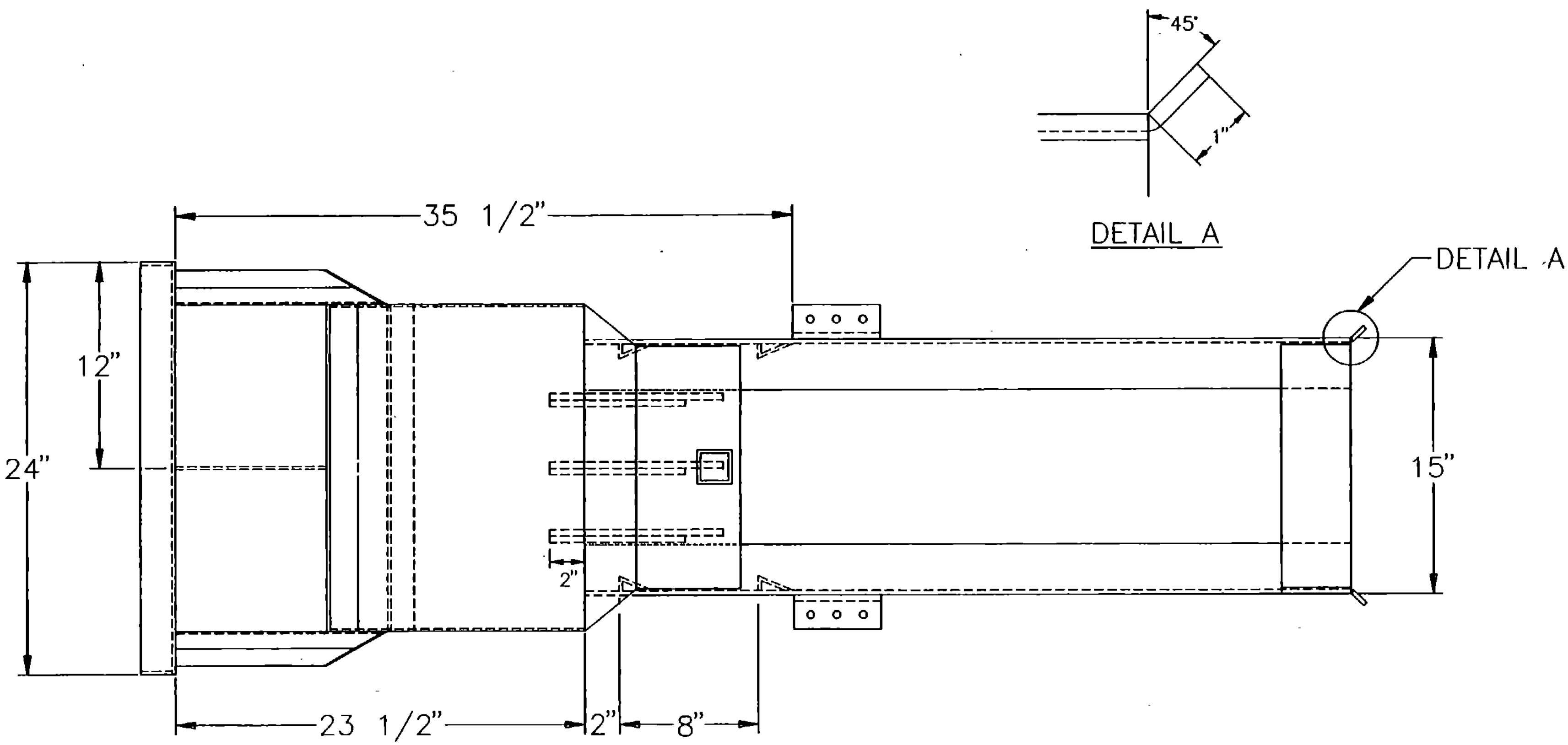


Figure 4. Side View of the BEST Impact Head for Tests BEST-2,3, and 4.

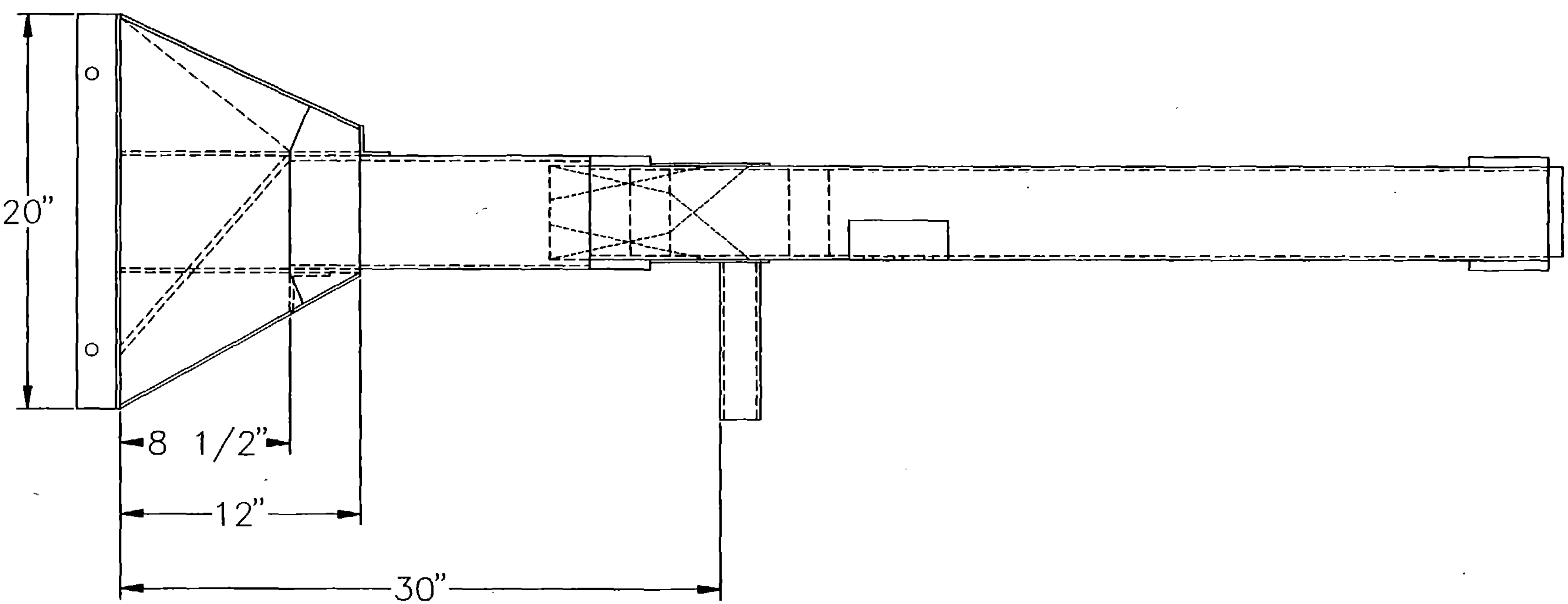


Figure 5. Top View of BEST Impact Head for Tests BEST-2,3, and 4.

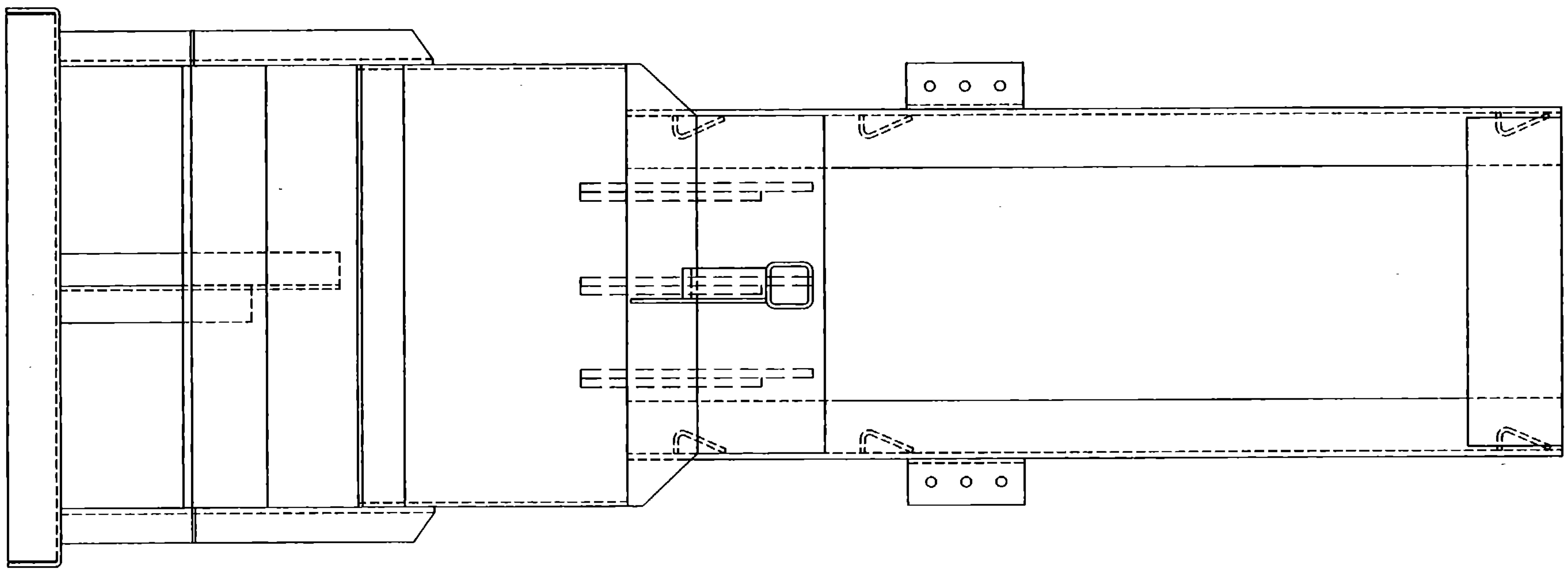


Figure 6. Side View of the BEST Impact Head for Tests BEST-8 through BEST-11.

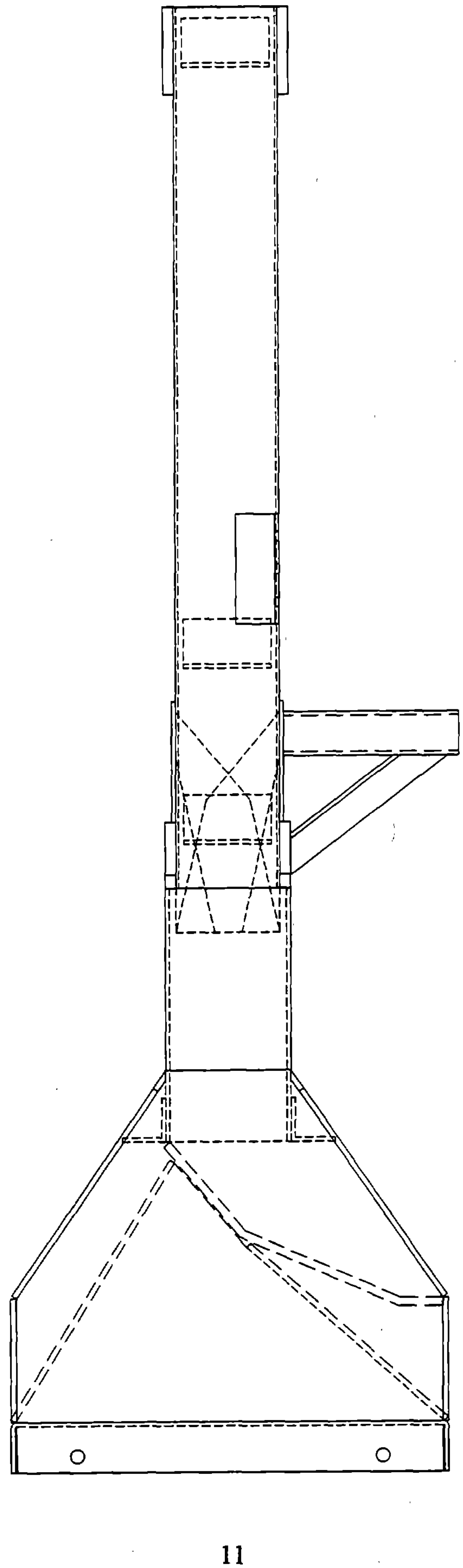


Figure 7. Top View of BEST Impact Head for Tests BEST-8 through BEST-11.

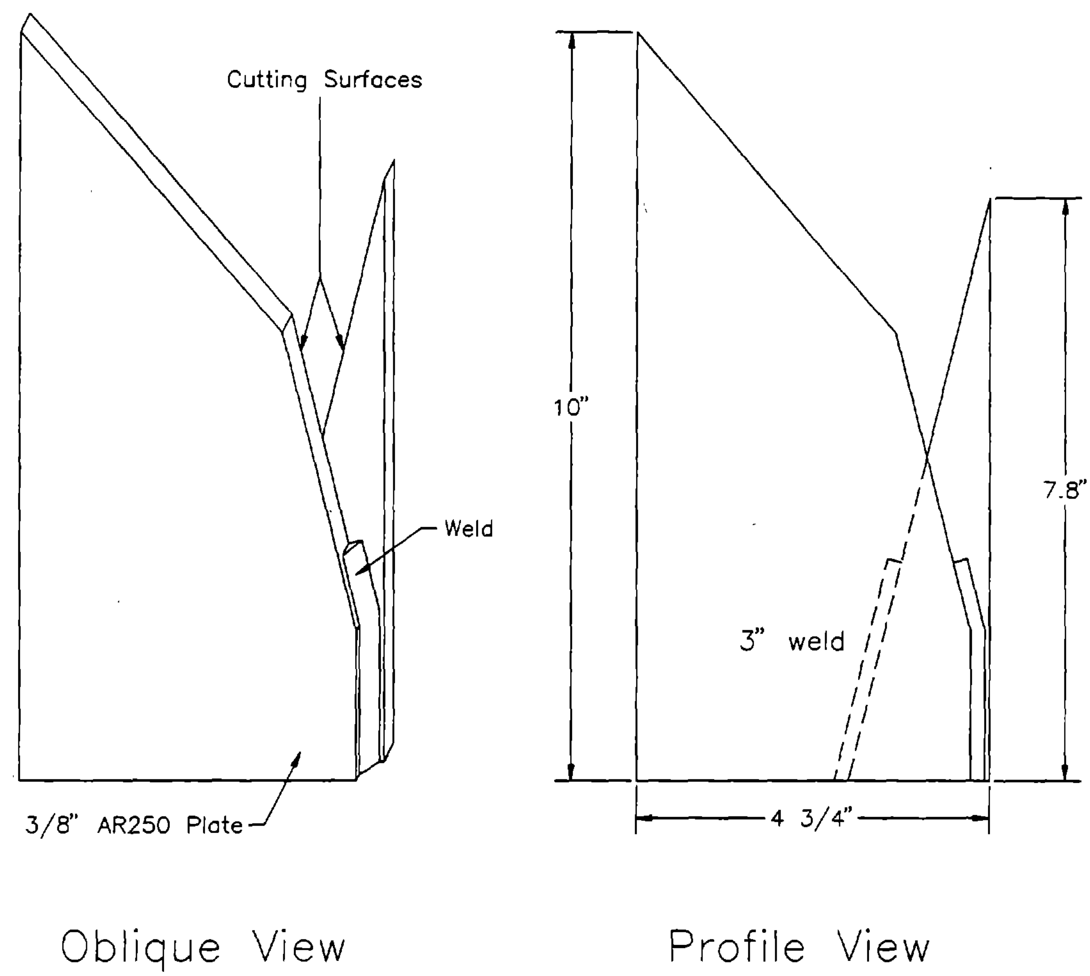


Figure 8. Details of BEST Cutting Teeth.

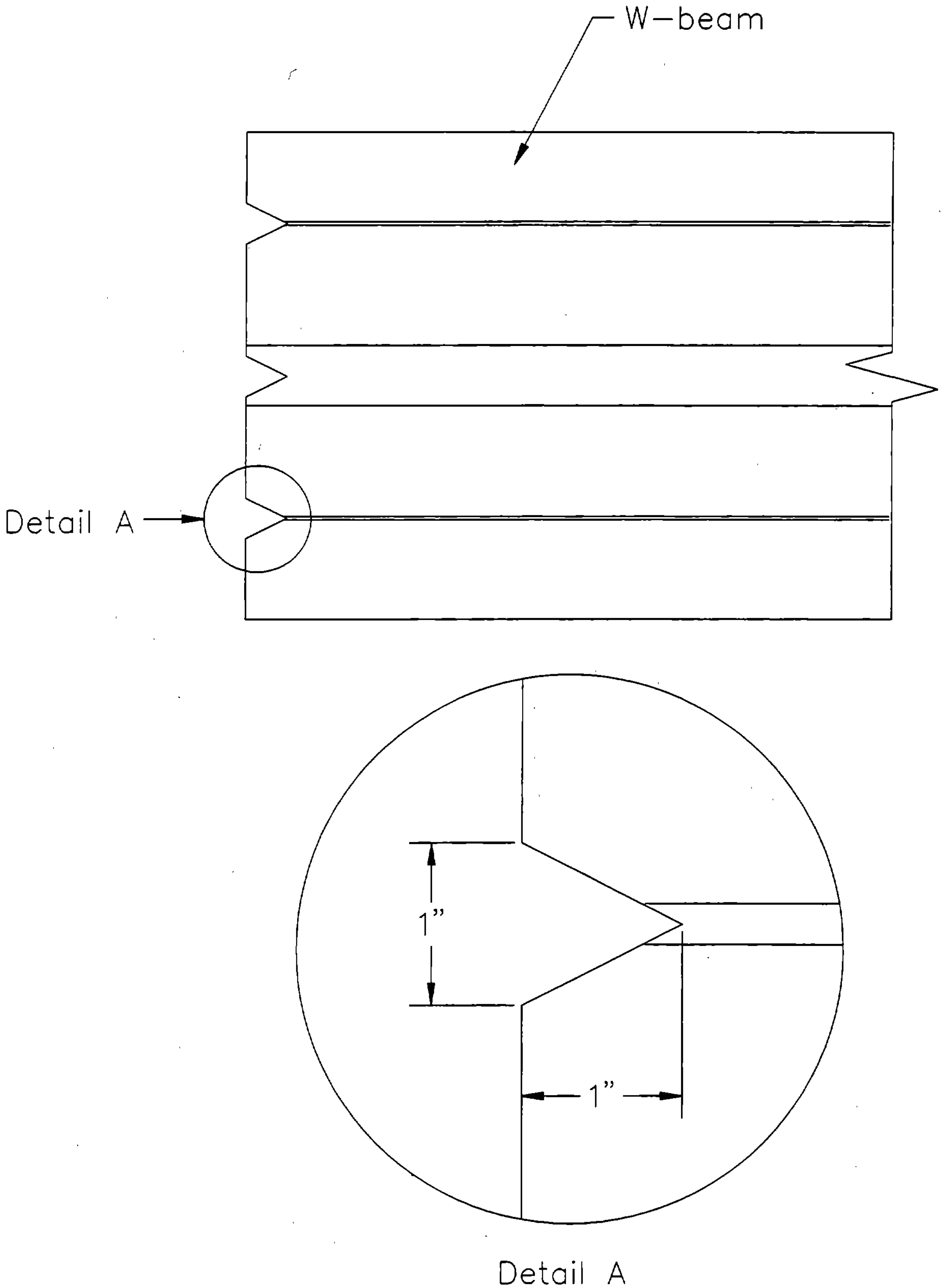


Figure 9. Details of W-beam Notches.

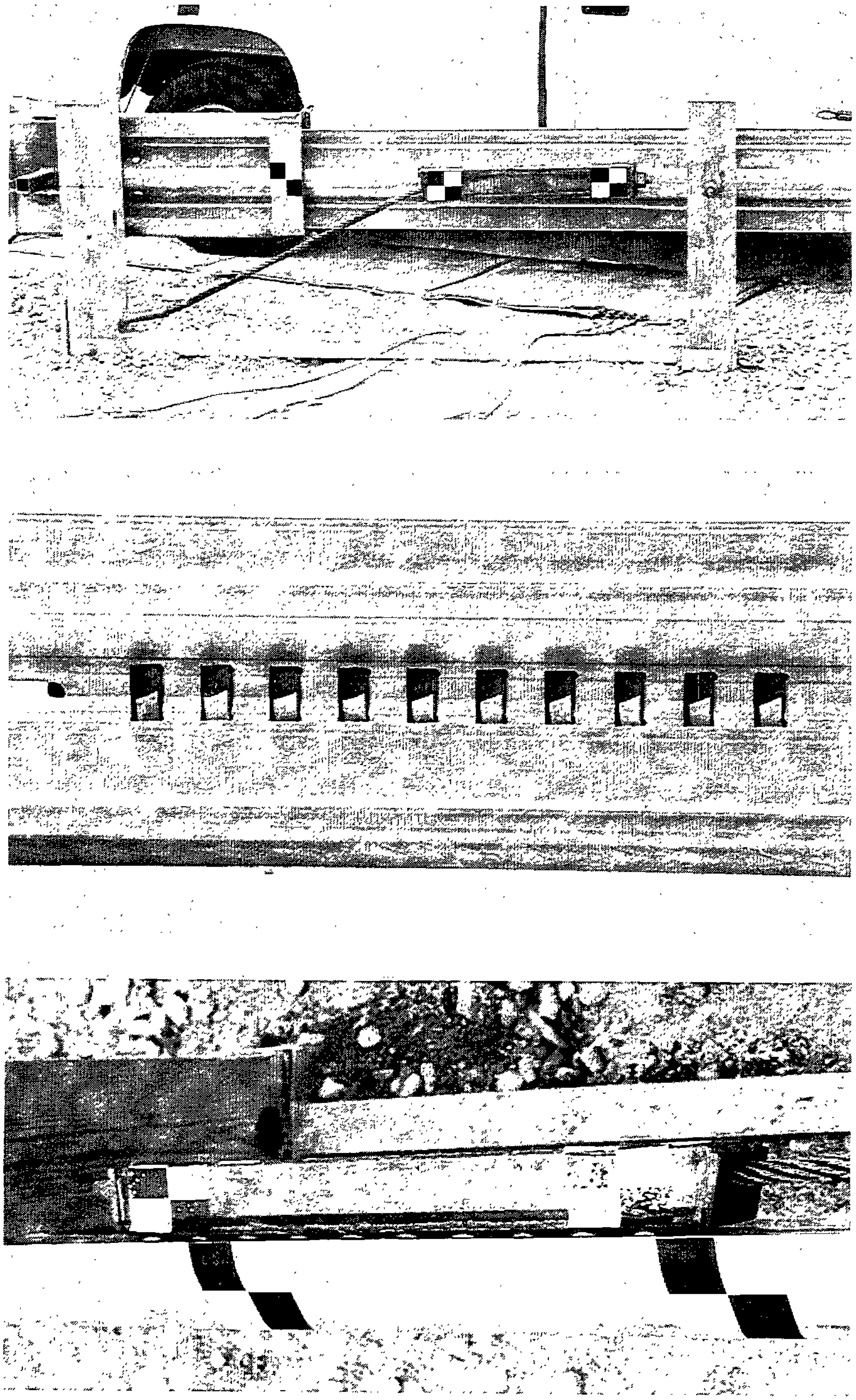


Figure 10. Photographs of Cable Anchor System.

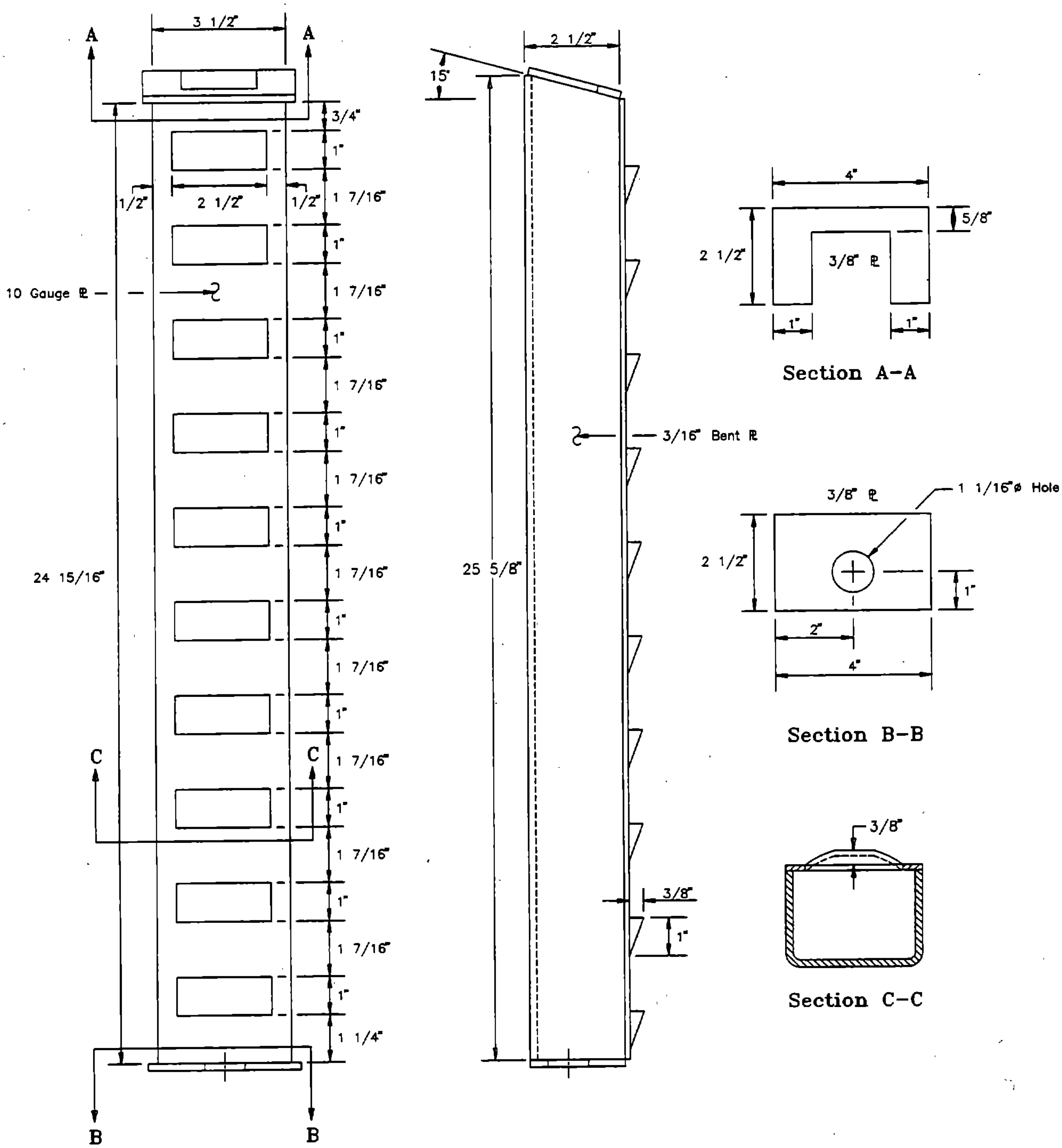


Figure 11. Breakaway Cable Anchor Box Details.

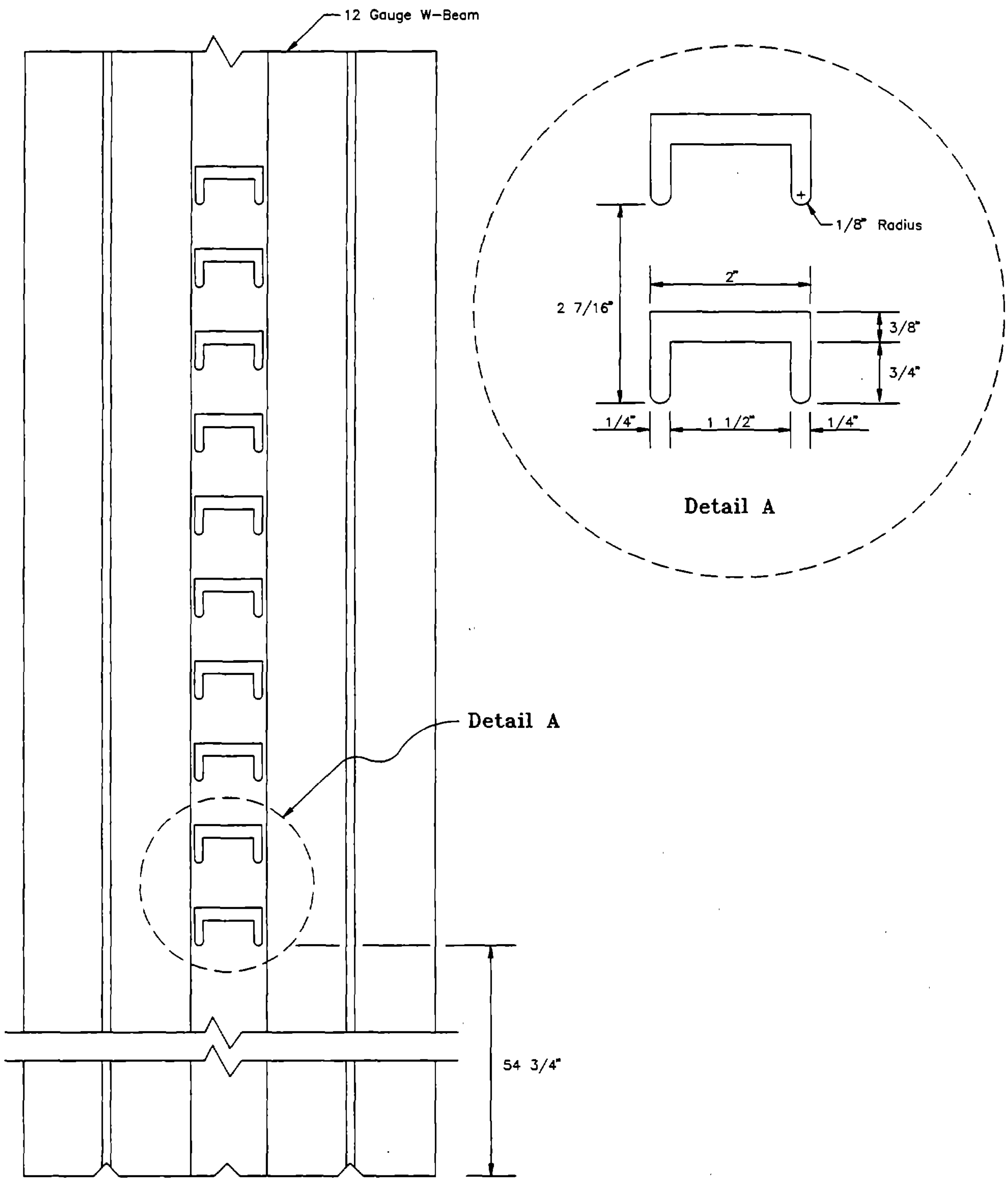


Figure 12. Breakaway Cable Anchor W-beam Attachment Details.

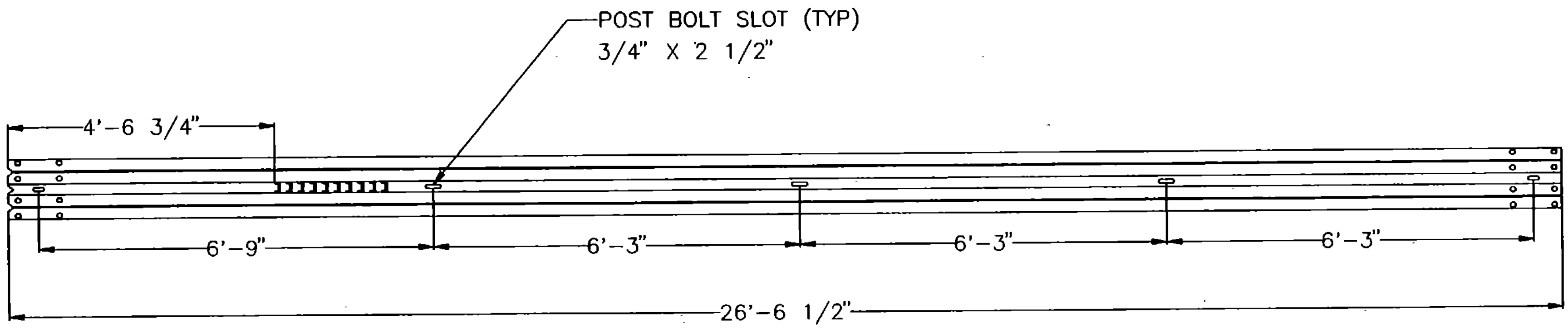


Figure 13. Terminal W-beam Details.

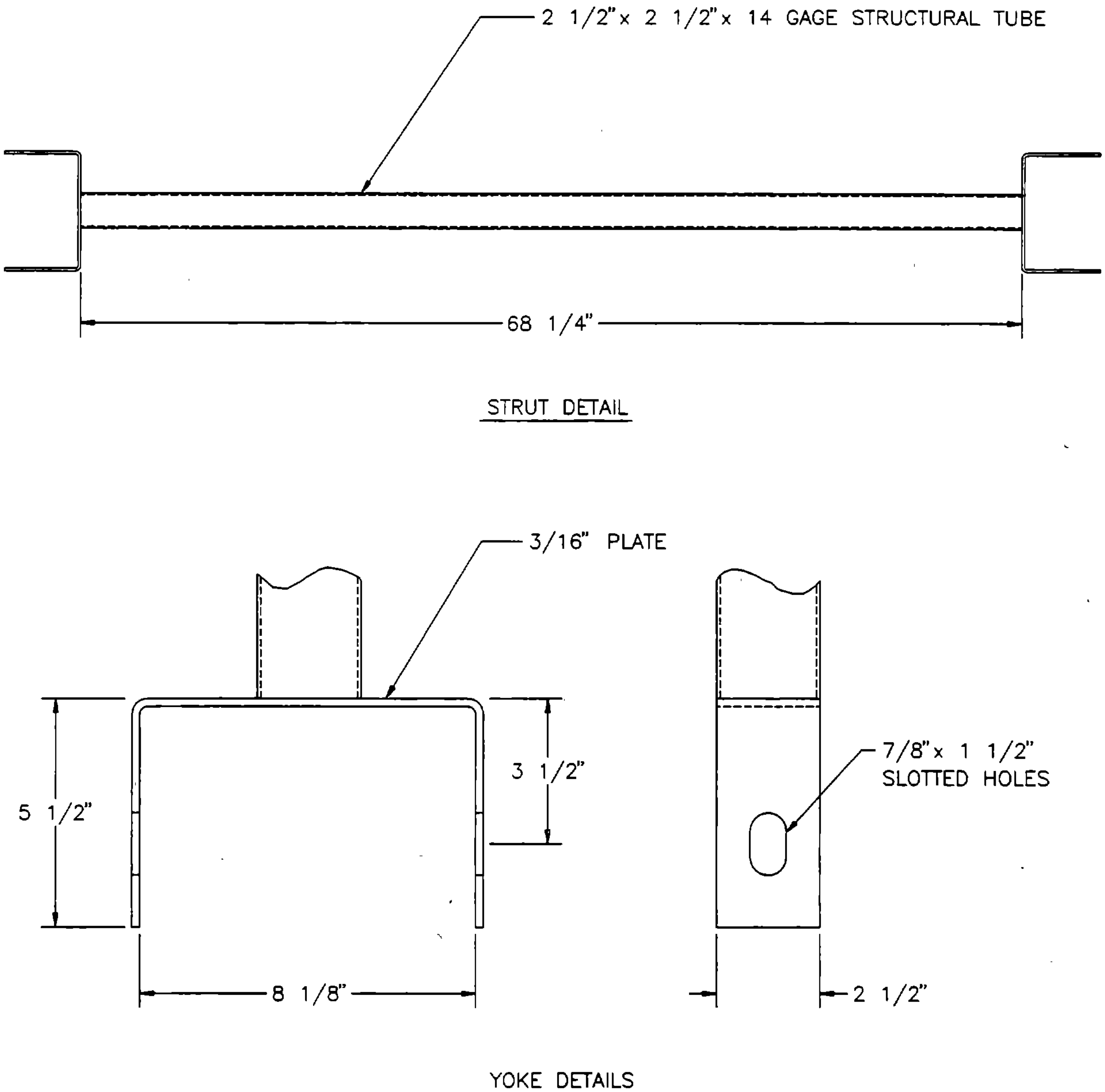


Figure 14. Groundline Strut Details.

4 TEST CONDITIONS

4.1 Test Vehicles

The vehicles used in this series of full-scale vehicle crash tests are summarized in Table 1. Photographs and data sheets of the test vehicles from the successful tests are presented in Appendix B.

Table 1. Test Vehicles

Test No.	Vehicle	Test Inertial Mass	
		(kg)	(lbs)
BEST-2	1991 Chevy ¾ ton pickup	2000	4408
BEST-3	1992 Chevy ¾ ton pickup	1996	4400
BEST-4	1991 Ford Festiva	820	1809
BEST-5	1991 Chevy ¾ ton pickup	2000	4410
BEST-6	1990 Chevy ¾ ton pickup	1997	4402
BEST-7	1990 Ford Festiva	821	1810
BEST-8	1990 Ford Festiva	817	1802
BEST-9	1990 Chevy ¾ ton pickup	2005	4421
BEST-10	1990 Chevy ¾ ton pickup	2003	4416
BEST-11	1990 GMC ¾ ton pickup	2000	4409

Black and white-checkered targets were placed on the test vehicles for use in high-speed film analysis. Two targets were located on the center of gravity, one on the top and one on the side of the test vehicle. Additional targets were located for reference so that they could be viewed from the high speed cameras. 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 the vehicle to establish the time of impact.

4.2 Data Acquisition Systems

4.2.1 Accelerometers

An Environmental Data Recorder (EDR-3) is used to record the accelerations during the full-scale vehicle compliance tests. This is a self contained unit which consists of a triaxial accelerometer system which triggers upon impact, records the data at 3200 samples/second, and stores the data on board. DynaMax software is then used to download the EDR-3 unit, filter the data, and convert it to an ASCII file. "DADiSP" software is then used to analyze and plot the data.

A similar data recorder, the EDR-4, was used as a backup system in tests BEST-3,4,5,7,8,9,10, and 11. This unit is the next generation of the EDR-3, and is set to record data at a rate of 10,000 samples/second.

4.2.2 High Speed Photography

Four to five high-speed 16-mm cameras, with operating speeds of 500 frames/sec, were used to film each crash test. The film was analyzed using a Vanguard Motion Analyzer. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed film.

4.2.3 Speed Trap

Five pressure tape switches spaced at 2 m (6.56 ft) 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 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.

4.3 Test Criteria

This system was evaluated according to the criteria in NCHRP Report 350 (3) for Test Level 3 gating terminals. The required test matrix for this testing program is presented in Table 2.

Table 2. Test Level 3 Crash Testing Matrix for Gating Terminals

Test Designation	Impact Conditions			Impact Point	Evaluation Criteria[1]
	Vehicle	Speed (km/h)	Angle (deg)		
3-30	820C	100	0	Head on, offset quarterpoint	C,D,F,H,I,(J),K,N
3-31	2000P	100	0	Head on, centered	C,D,F,H,I,(J),K,N
3-32	820C	100	15	Head on, 15 degree angle	C,D,F,H,I,(J),K,N
3-33	2000P	100	15	Head on, 15 degree angle	C,D,F,H,I,(J),K,N
3-34	820C	100	15	Redirectional, Critical Impact Point	C,D,F,H,I,(J),K,N
3-35	2000P	100	20	Redirectional, Beginning of length of need	A,D,F,K,L,M
3-39	2000P	100	20	Reverse direction, half the length of the terminal from the end	C,D,F,K,L,M,N

[1] Evaluation criteria is described in Table 3

Table 3. Relevant NCHRP 350 Evaluation Criteria

A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.
C.	Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.
D.	Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.
F.	The vehicle should remain upright during and after collision although moderate roll, pitching and yawing are acceptable.
H.	Longitudinal and lateral occupant impact velocities should fall below the preferred value of 9 m/s (29.5 fps), or at least below the maximum allowable value of 12 m/s (39.4 fps).
I.	Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15 Gs, or at least below the maximum allowable value of 20 Gs.
J.	(Optional) Hybrid III dummy. Response should conform to evaluation criteria of Part 571.208, Title 49 of Code of Federal Regulation, Chapter V.
K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.
L.	The occupant impact velocity in the longitudinal direction should not exceed 12 m/s (39.4 fps) and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 Gs.
M.	The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.
N.	Vehicle Trajectory behind the test article is acceptable.

4.4 Test Matrix

Although NCHRP Report 350 requires the seven full-scale crash tests shown in Table 2 for evaluation of a new guardrail terminal, Test 3-34 has been successfully completed on a very similar guardrail terminal system. This test involves an 820C vehicle impacting the terminal at the critical impact point at a speed of 100 km/h and an angle of 15 deg. The critical impact point for tangent, energy absorbing guardrail terminals of this type has been traditionally selected to be at post 2. This test was conducted on a guardrail extruding terminal system mounted on round wood posts under a study funded by the Texas Department of Transportation, (Test 9429A-1). Differences between the system tested under the TxDOT study and the BEST terminal include the cable anchor bracket, foundation system, and the guardrail posts. Test 9429A-1 incorporated a tangent guardrail terminal mounted on round wood posts without blockouts. In this test, the leading post was placed in a concrete anchor and the cable anchor bracket utilized a proprietary lug based bracket system to develop the necessary rail tension. The BEST guardrail terminal incorporates 152 mm x 203 mm (6 in. x 8 in.) wood posts and 152 mm x 203 mm (6 in. x 8 in.) wood blockouts. The BEST terminal also utilizes two steel foundation tubes and a ground line strut and a proprietary guardrail tab bracket to generate the required tensile loads in the guardrail system. By successfully passing Test 3-35, the BEST anchor system demonstrated that it can generate sufficient strength to contain and redirect a 2000 kg pick-up truck impacting at a speed of 100 km/hr and an angle of 20 deg. This impact generates much higher loads on the anchor than Test 3-34. Therefore, differences between the BEST anchor system and that used in Test 9429A-1 are irrelevant to the performance of this terminal under the Test 3-34 impact conditions.

Further, since the round wood guardrail posts used in Test 3-34 have approximately the same or less capacity than do the rectangular posts used in the BEST design, these differences cannot affect the terminals performance under this test. Finally, as shown in films of 9429A-1, (see crash test tape included in this package), the impacting vehicle did not contact post 2 and therefore snagging on the rectangular post used in the BEST design cannot be a concern. Therefore, Test 9429A-1 can be used as a demonstration of the performance of the BEST under Test 3-34 and this crash test was not repeated on the new terminal system.

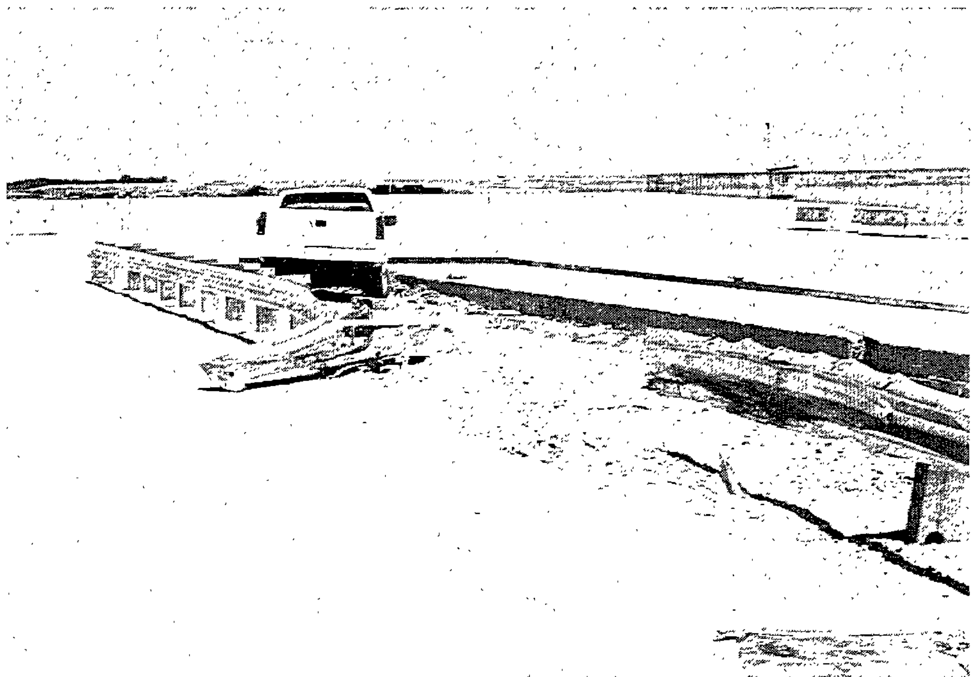
5 TEST RESULTS

5.1 Test BEST-2 (2000P, 100 km/h, 20 deg.)

This compliance test was performed to evaluate the redirectional capability of the guardrail terminal as specified in NCHRP Report 350 (3) test designation 3-35. It consisted of a 1991 Chevrolet ¾ ton pickup impacting the system at the beginning of the length of need, which was located at post No. 3. The pickup impacted the system at 101.8 km/h (63.2 mph) and at an angle of 20.1 degrees.

The cable anchor system performed well during this test, as the tab system supported the full load of the redirectional impact. However, the posts did not rotate normally, and broke off at the groundline before providing an adequate redirectional force to the vehicle. This behavior resulted in the pickup continuing into the system further than is normally observed, causing pocketing to occur, and ultimately resulting in the rupture of the W-beam guardrail. After this failure occurred, the vehicle continued through the system and came to rest behind the guardrail. Post-test photos of this system are presented in Figure 15.

After reviewing the high-speed film from this test, it was evident that the primary reason for the failure of the system was the fact that the posts fractured prematurely. This phenomenon was investigated through bogie testing of similar posts under comparable conditions, and several discoveries were made. The first and most significant finding was that the placement of the post next to the 610 cm (24 in.) deep concrete apron significantly affected the soil resistance and contributed to the early failure of the posts. A second contributing factor was that the CRT posts used for this system were 140 mm x 190 mm (5½ in. x 7½ in.) finished posts instead of the standard 152 mm x 203 mm (6 in. x 8 in.) rough cut. This resulted in a reduction in the post section modulus of approximately 22 percent. As a result of the bogie testing, a revised post design was developed that utilized 152 mm x 203 mm (6 in. x 8 in.) rough cut posts and a total length of 1778 mm (5 ft - 10 in.). The post's embedment depth was thereby cut to 1067 mm (42 in.) which was expected to reduce the soil forces on the post by approximately 10 percent in order to assure that the posts would rotate without fracturing, even under tight soil conditions. The problems associated with installing the guardrail adjacent to the concrete apron were also addressed moving the front face of an additional 1.5 m (5 ft) from the concrete.



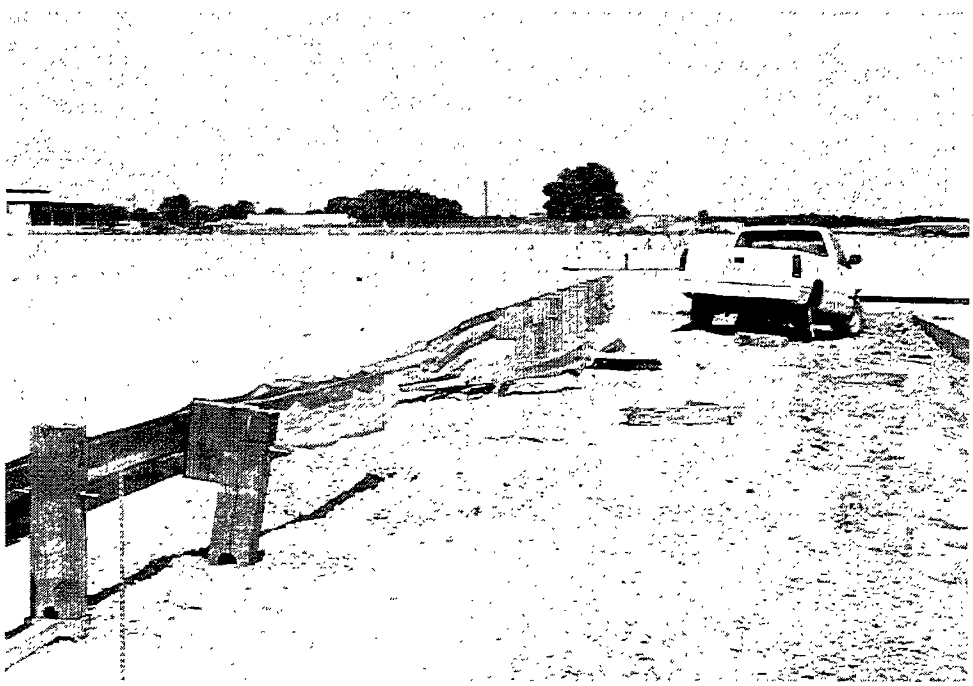


Figure 15. Post-test photographs of Test BEST-2.

5.2 Test BEST-3 (2000P, 100 km/h, 20 deg.)

The changes mentioned in the previous section were incorporated into the system for Test BEST-3, which was performed as a rerun of Test BEST-2. The 1992 Chevrolet ¾ ton pickup impacted the system 140 mm (5½ in.) upstream of post No. 3 at 102.7 km/h (63.8 mph) and 20.9 degrees. The impact location is shown in Figure 16. A summary of the test results is shown in Figure 17 and additional sequential photos are shown in Figure 18.

Upon impact with the guardrail, the bumper was captured by the W-beam and by 74 ms after impact it had reached post No. 4. The vehicle continued to be smoothly redirected as it reached post No. 5 at 152 ms and post No. 6 at 226 ms after impact. The right-rear tire blew out at 274 ms and the vehicle reached post No. 7 at 314 ms. The pickup became parallel to the rail 322 ms after impact, and the smooth redirection continued until it exited the rail and came to rest approximately 30 m (98.5 ft.) downstream from the point of impact as shown in Figures 17 and 19.

Damage to the vehicle was minor considering the severity of the impact conditions, as shown in Figure 20. The right-front corner of the vehicle was damaged and the wheel assembly was disengaged from the vehicle. Minor contact damage continued down the side of the vehicle and the right-rear tire was torn. There was only very minor deformation of the passenger compartment (13 mm (½in.) on the firewall on the passenger side) and the windshield remained undamaged.

Damage to the system, shown in Figure 21, included the rotation and subsequent fracture of post No. 3 at the top CRT hole. Post Nos. 4 and 5 rotated and fractured at the bottom hole, while post No. 6 rotated and was uprooted without breaking. Post No. 7 rotated and failed at an angle, with the fracture passing through both of the CRT holes. Post No. 8, which was not a CRT post, failed at the groundline, and there was no measurable damage to or deformation of the remaining posts. The total length of contact was approximately 11 m (36 ft), as the last point of contact was 610 mm (2 ft) upstream of post No. 9. There was no sign of damage to the cable anchor box, but a number of the W-beam tabs showed evidence of high loads. The maximum permanent deformation in the rail was 758 mm (29.8 in.) at post No. 6.

The analysis of the accelerometer data showed that the system passed the occupant risk criteria presented by NCHRP Report 350 (3). The normalized longitudinal occupant impact velocity was 6.5 m/s (21.3 fps), which is well below the design value of 9 m/s (29.5 fps). The maximum longitudinal ridedown acceleration of 10.5 Gs was well below the design value of 15 Gs. The lateral values for the occupant risk criteria were quite low, with a normalized lateral occupant impact velocity of 4.2 m/s (13.8 fps) and a lateral ridedown acceleration of 10.1 Gs. Plots of the accelerometer data from Test BEST-3 can be found in Appendix C. A summary of the safety performance assessment for this test is presented in Table 4.

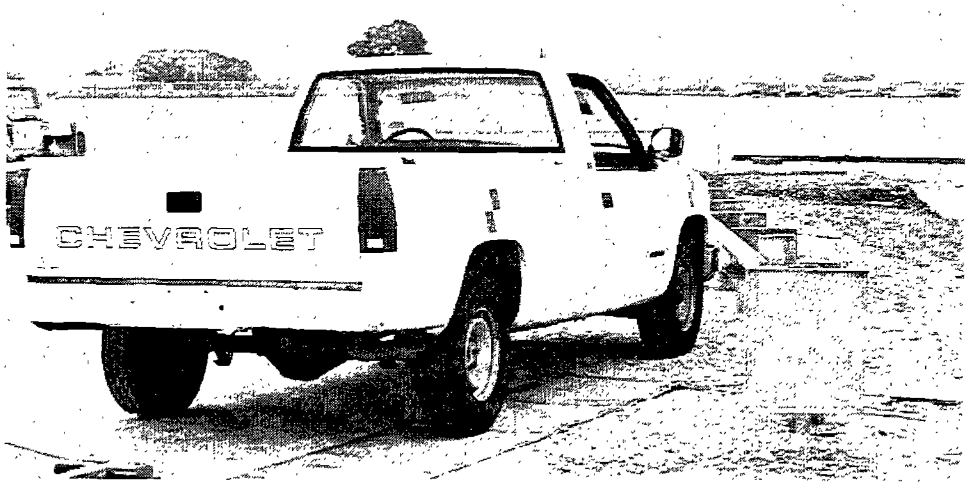


Figure 16. Impact Location, Test BEST-3.

Impact	60 ms	120 ms	180 ms	240 ms

Test Number	BEST-3
Date	7/30/96
Installation	BEST System
Length of Installation	30.5 m
Vehicle Model	1992 Chevy ¾ ton pickup
Vehicle Weight	
Curb	1905 kg
Test Inertial	2000 kg
Gross Static	2000 kg
Vehicle Impact Speed	102.7 km/h
Vehicle Impact Angle	20.9 deg

Vehicle Impact Location	Center of post no. 3
Normalized Occupant Impact Velocity	
Longitudinal	6.5 m/s
Lateral	4.2 m/s
Occupant Ridedown Accelerations	
Longitudinal	10.5 Gs
Lateral	10.1 Gs
Vehicle Damage Classification	
TAD	1-RFQ-5
VDI	01RFES2
Maximum rail deflection	
Dynamic	1097 mm @ midspan of post nos. 5 & 6
Permanent Set	758 mm @ post no. 6

Conversion Factor: 1 ft = 0.3048 m   1 lb = 0.4536 kg

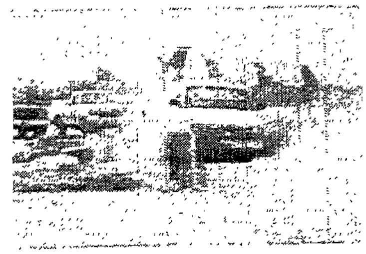
Figure 17. Summary of Test BEST-3.

Impact

60 ms

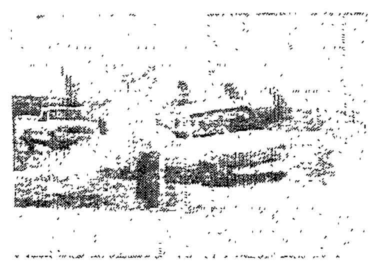
120 ms

180 ms

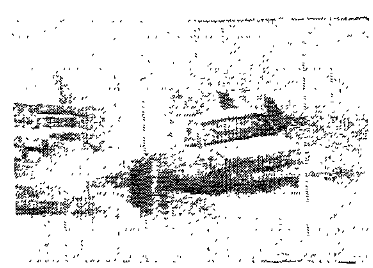


240 ms

300 ms



360 ms



420 ms

Figure 18. Sequential Photographs, Test BEST-3.

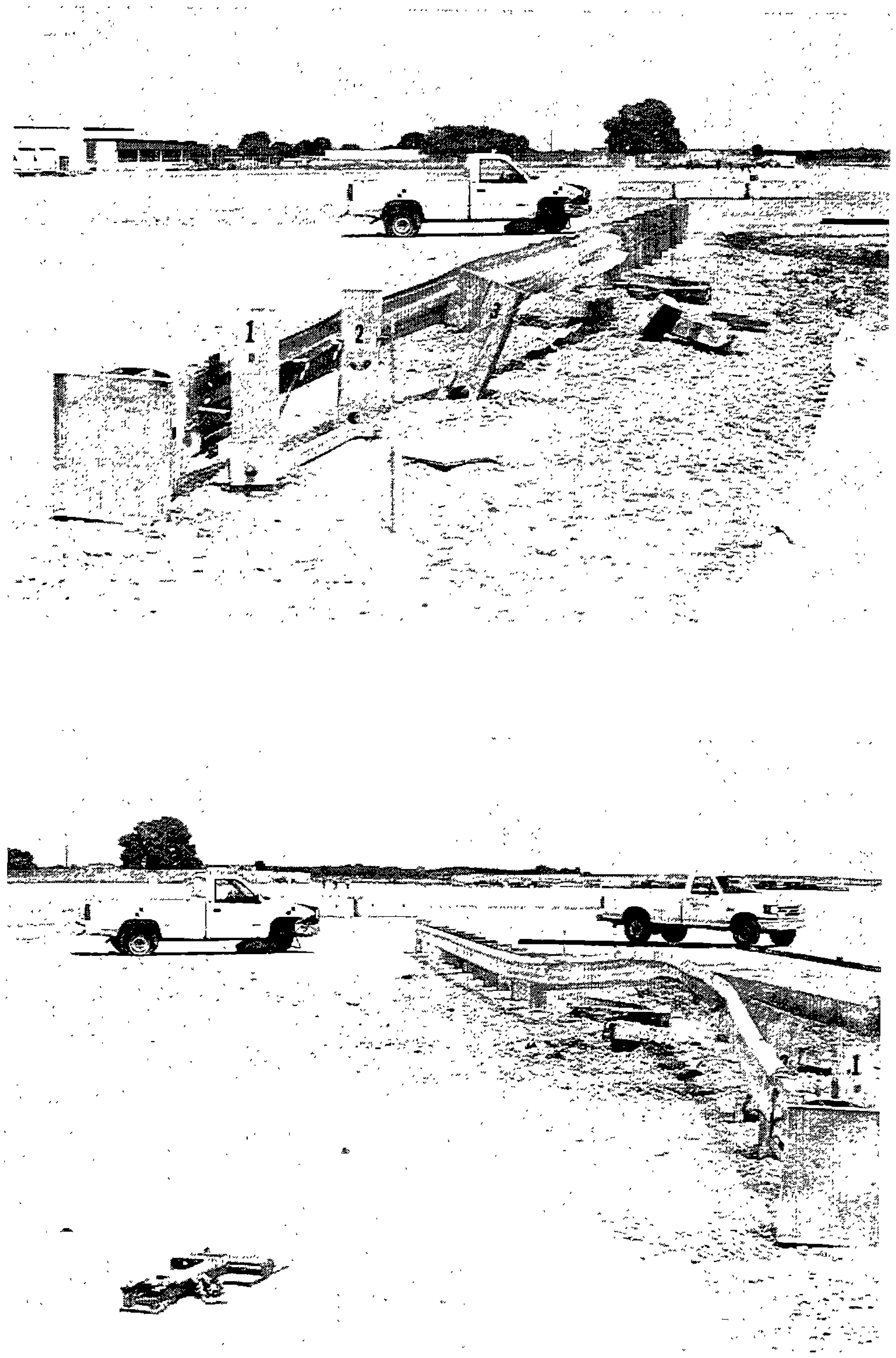
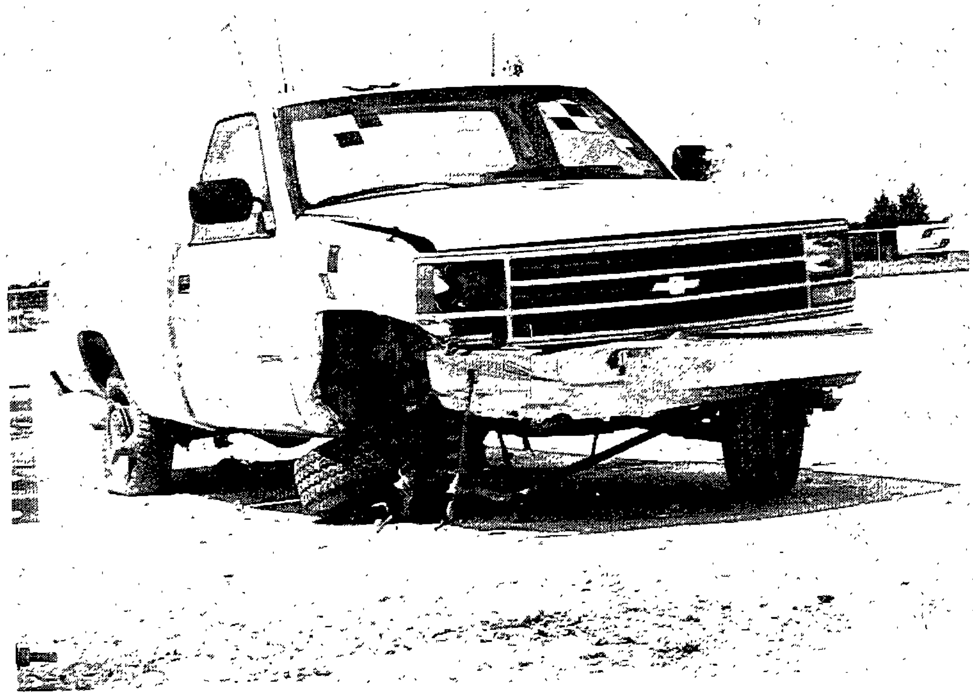


Figure 19. Vehicle Trajectory, Test BEST-3.



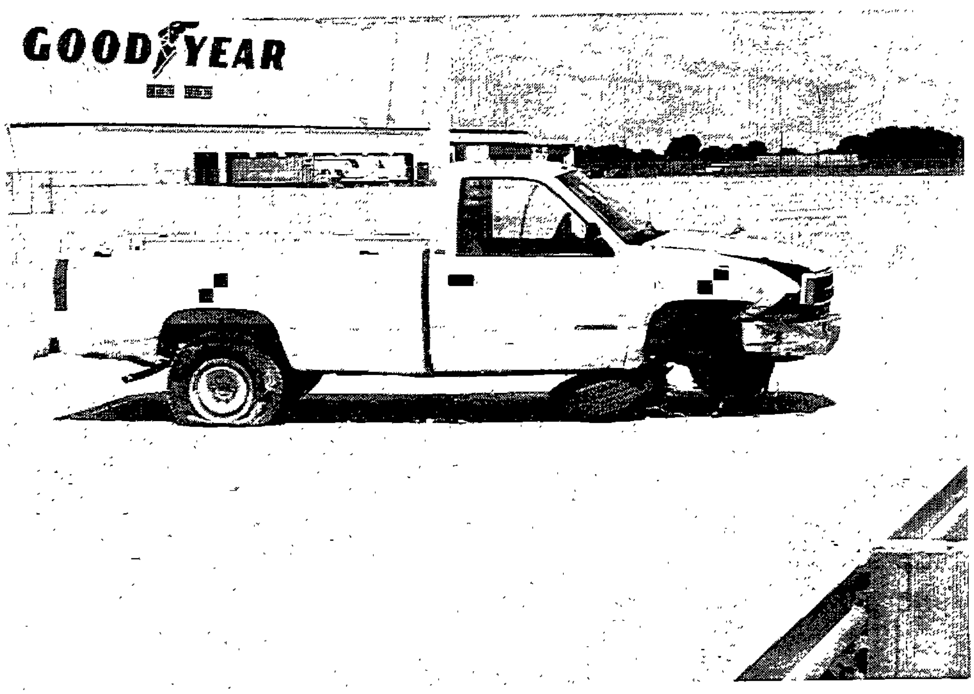
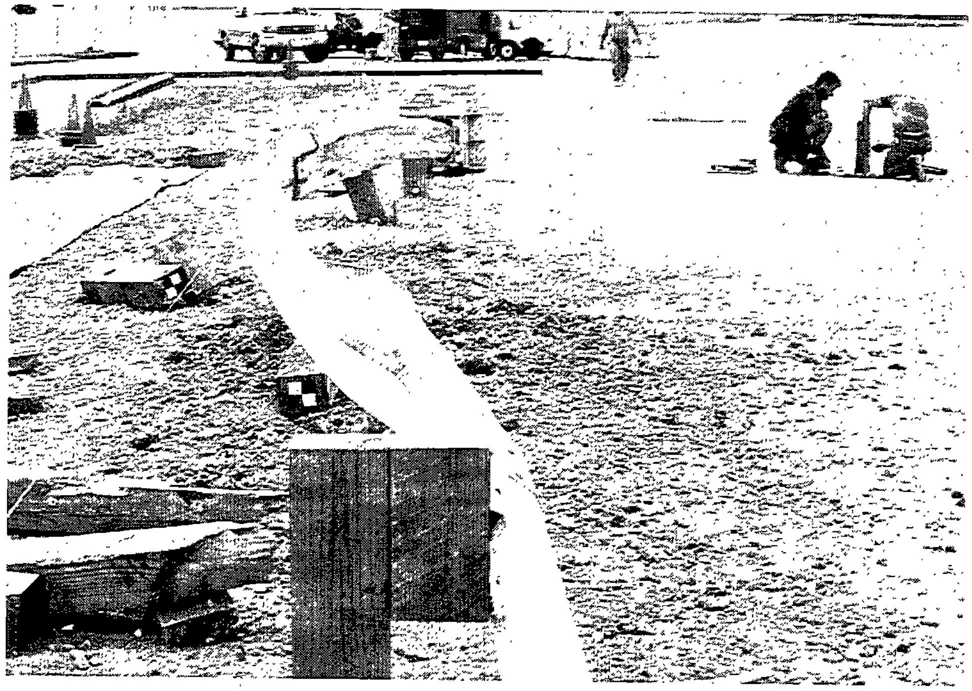


Figure 20. Vehicle Damage, Test BEST-3.



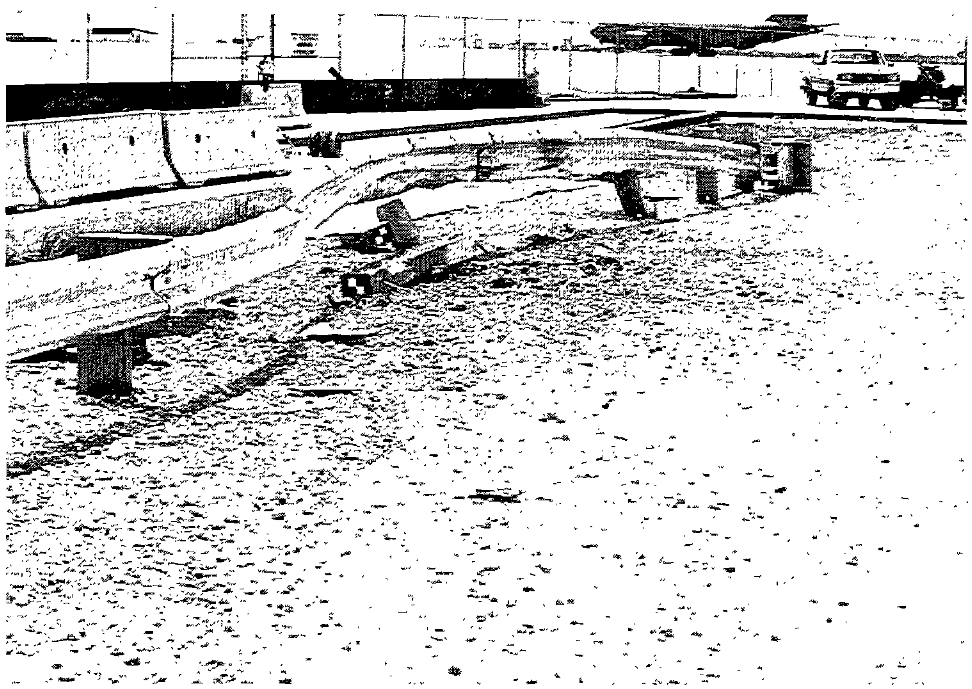


Figure 21. Installation damage, Test BEST-3.

5.3 Test BEST-4 (820C, 100 km/h, 15 deg)

The next compliance test was conducted to evaluate the performance of the BEST terminal during NCHRP Report 350 (3) test designation 3-32. For this test, as well as test BEST-5, the impact head geometry was virtually the same as the original terminal system tested under NCHRP Report 230 and described in reference 1. As mentioned previously, the only changes incorporated prior to initiation of compliance testing involved moving the post breaker 150 mm (6 in.) farther away from the impact plate and adjusting the end of the feeder chute. These changes are shown in Figures 4 and 5.

This test consisted of a 1991 Ford Festiva impacting the end of the terminal at 101.7 km/h (63.2 mph) and 13.6 degrees. The impact configuration is shown in Figure 22. A summary of the test results is shown in Figure 23 and additional sequential photos are shown in Figure 24.

Upon contact with the terminal, the vehicle interlocked with the impact head and began to push it down the rail. At approximately 12 ms after impact the first post began to break as a result of contact with the post breaker. At 28 ms after impact, the end of the chute contacted the cable anchor box after which it released immediately. By 68 ms the end of the chute had reached post No. 2, and by 74 ms a buckle in the rail was visible in the chute from the overhead view. This buckling continued and the impact head and W-beam was rotated around and out of the vehicle path. As the vehicle passed by the buckled rail, the drivers side door contacted a portion of the rail, causing it to deform slightly. The vehicle came to rest with the front-left tire 24.5 m (80 ft - 3 in.) downstream of impact and 11.1 m (36 ft - 4 in.) behind the rail as shown in Figures 23 and 25.

Damage to the vehicle, shown in Figure 26, included approximately 267 mm (10.5 in.) of front end crush resulting from the contact with the impact head. There was also approximately 76 mm (3 in.) of deformation on the outside of the drivers door resulting from contact with the W-Beam as the vehicle passed by it after losing contact with the head. This resulted in 25 mm (1 in.) of deformation on the inside of the driver's side door. There was only minor deformation of the vehicle floorboard, and the windshield was cracked on the lower driver's side corner.

The damage to the system is shown in Figure 27. The head cut through 1.28 m (4 ft - 2¼ in.) before the system buckled out of the path of the vehicle. Post Nos. 1 and 2 were fractured at the groundline, and post No. 3 rotated downstream slightly as a result of contact with the deformed W-Beam. The remainder of the posts were left virtually untouched.

The analysis of the accelerometer data showed that the system passed the occupant risk criteria presented by NCHRP Report 350 (3). The longitudinal occupant impact velocity was 10.0 m/s (32.7 fps), which is above the design value of 9 m/s (29.5 fps), but well below the maximum allowable limit of 12 m/s (39.4 fps). The maximum longitudinal ridedown acceleration of 12.0 Gs was below the design value of 15 Gs. As would be expected with this type of an impact, the lateral values for the occupant risk criteria were quite low, with a lateral occupant impact velocity of 1.2 m/s (4.1 fps) and a lateral ridedown acceleration of 4.7 Gs. Plots of the accelerometer data from Test BEST-4 can be found in Appendix C. A summary of the safety performance results is given in Table 4.

Figure 22. Impact Location, Test BEST-4.

Impact 22 ms 44 ms 80 ms 145 ms

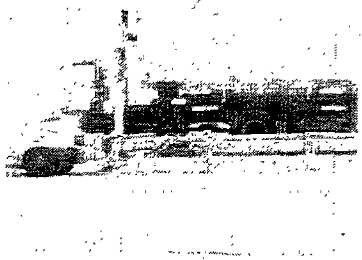
Test Number	BEST-4
Date	8/2/96
Installation	BEST System
Length of Installation	30.5 m
Vehicle Model	1991 Ford Festiva
Vehicle Weight	
Curb	819 kg
Test Inertial	820 kg
Gross Static	896 kg
Vehicle Impact Speed	101.7 km/h
Vehicle Impact Angle	13.6 deg

Vehicle Impact Location	Center of Impact Head
Occupant Impact Velocity	
Longitudinal	10.0 m/s
Lateral	1.2 m/s
Occupant Ridedown Accelerations	
Longitudinal	12.0 Gs
Lateral	4.7 Gs
Vehicle Damage Classification	
TAD	1-FC-4
VDI	12FCEN2
Amount of rail fed through cutter	1.28 m

Conversion Factor: 1 ft = 0.3048 m 1 lb = 0.4536 kg

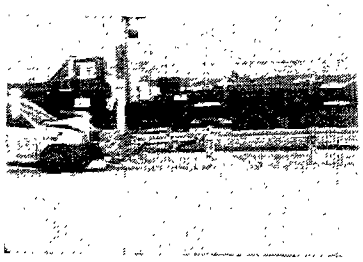
Figure 23. Summary of Test BEST-4.

Impact

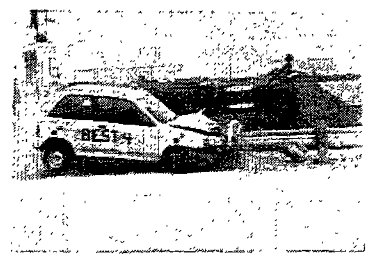


65 ms

10 ms



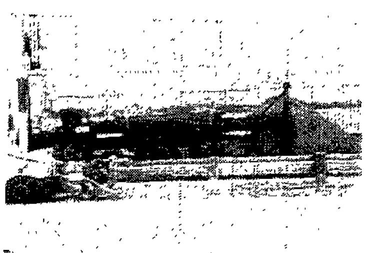
95 ms



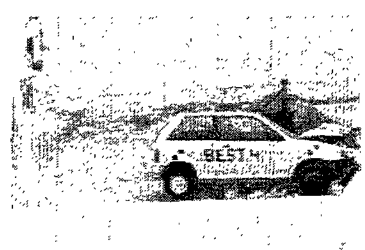
15 ms

125 ms

25 ms



160 ms



40 ms

205 ms

Figure 24. Sequential Photographs, Test BEST-4.

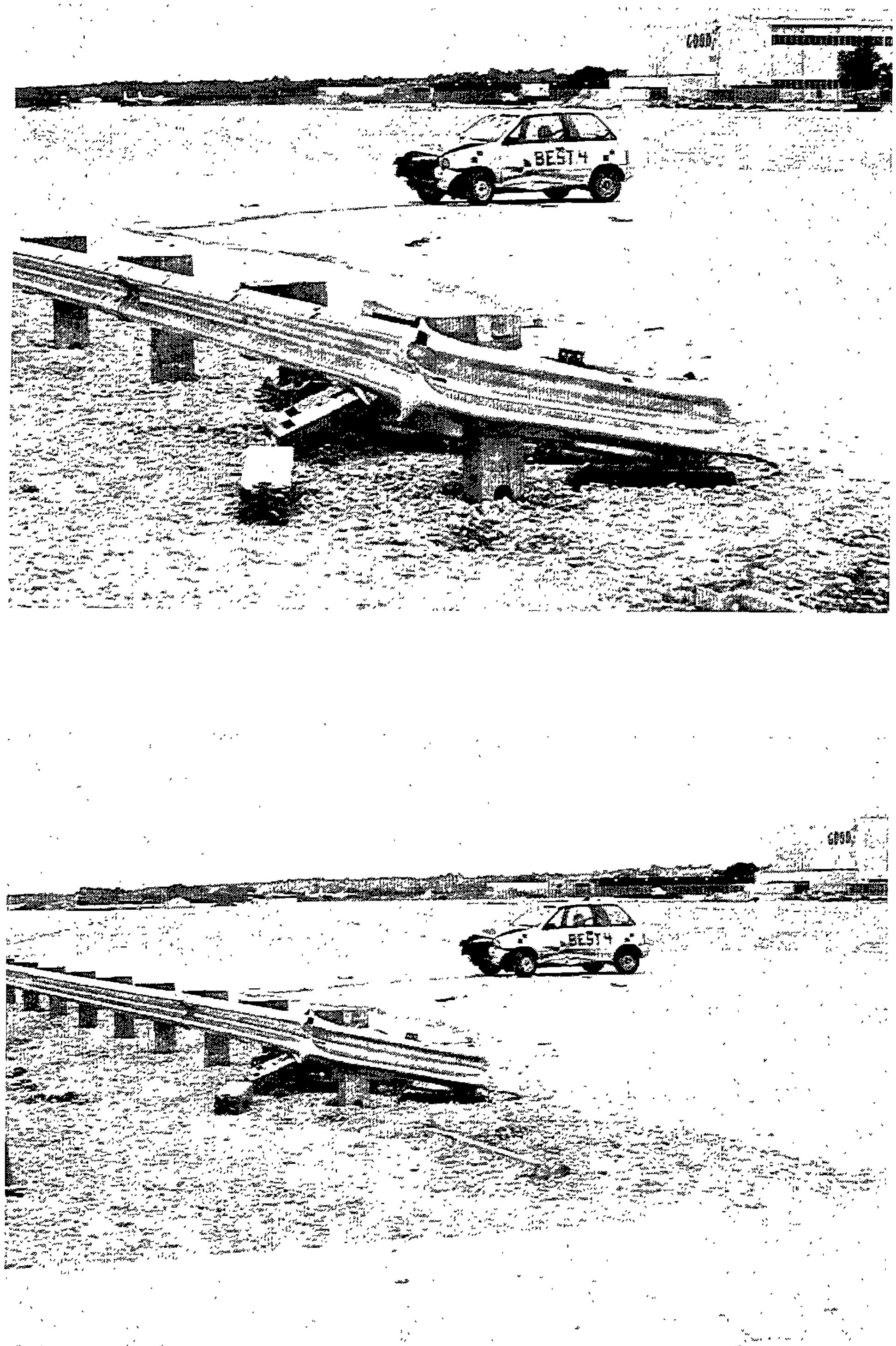


Figure 25. Vehicle Trajectory, Test BEST-4.

Figure 26. Vehicle Damage, Test BEST-4.

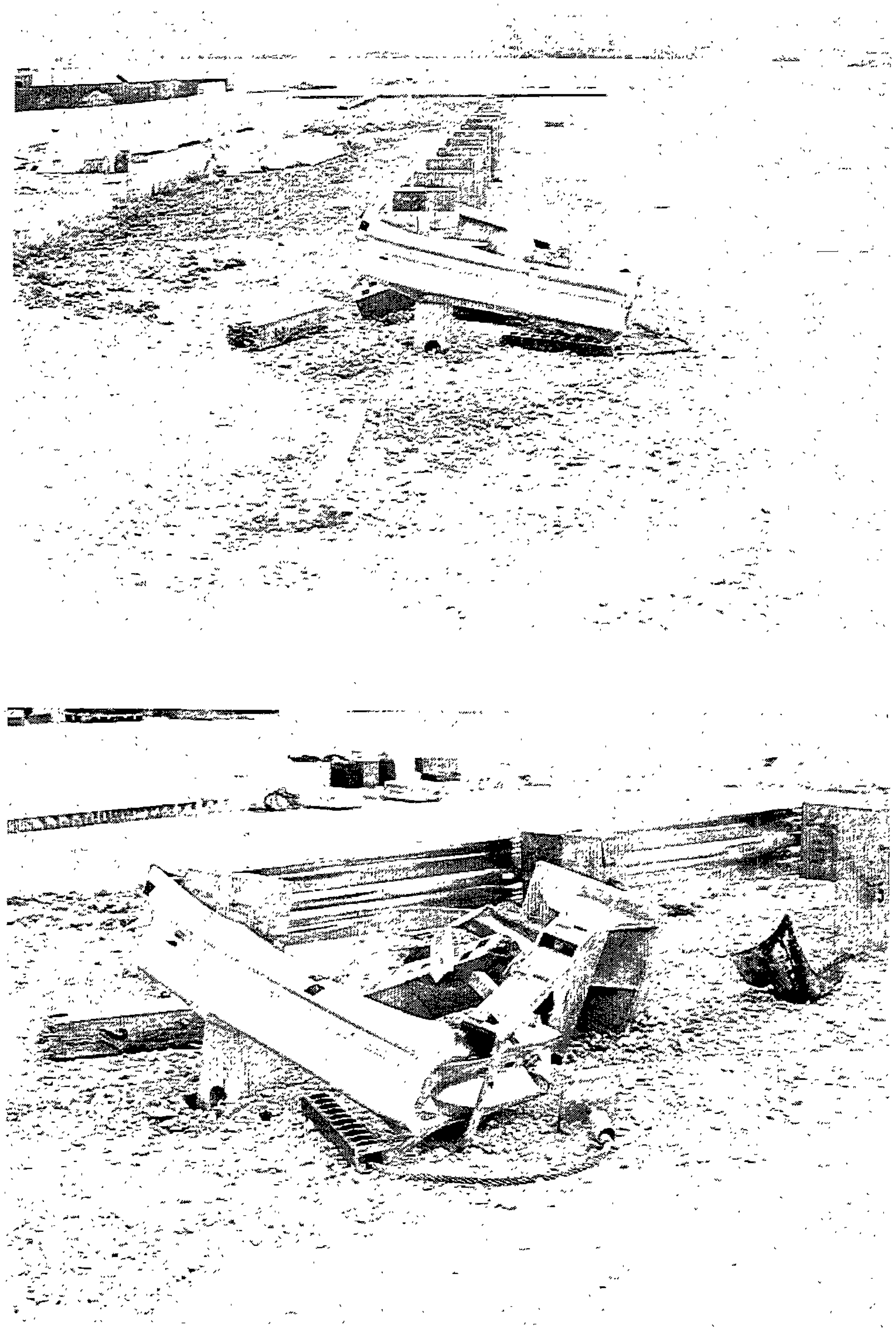


Figure 27. Installation damage, Test BEST-4.

5.4 Test BEST-5 (2000 kg, 100 km/h, 0 deg)

This test was conducted to fulfill the requirements of NCHRP Report 350 (3) test designation 3-31. It consisted of a 1991 Chevy ¾ ton pickup impacting the BEST system head at 0.5 degrees and 99.8 km/h (62.0 mph). Because of the non-standard size of the rail used in the terminal, it was necessary to have a special 8.09 m (26 ft - 6 ½ in.) rail made for this test. In the interest of time, this rail was tested black as it was thought that the behavior of the system would not be significantly affected by the galvanization of the rail.

Upon impact with the system, the front bumper of the pickup began to crush inward, interlocking with the head. This bumper deformed considerably, and the head became lodged between the two frame members which supported the bumper. The first post broke away cleanly, and the anchor box separated as designed. However, the test vehicle's bumper wrapped around the head sufficiently to occlude the outlet region where the cut strips of guardrail are pushed out of the system. The W-beam continued to feed through the cutting mechanism while the cut portions of the rail accumulated inside the head. After cutting 3.3 m (10 ft - 10 in.), the impact head was filled with cut strips of W-beam, causing the rail to buckle in front of the impact head. At this point the vehicle had already slowed to approximately 53 km/h (33 mph) and it began to move toward the traffic side of the system. As the vehicle began to push the rail away from the posts, the load in the rail caused a number of posts downstream to split in half, and the rail slipped off the bolts on the remaining posts. This resulted in the entire length of W-beam being separated from the posts and falling to the ground as the vehicle came to a stop. Post-test photographs of this test can be seen in Figure 28.

Despite the reduced feeding length resulting from the jamming at the outlet, the occupant risk criteria were still satisfied. The normalized longitudinal OIV and ridedown accelerations were determined to be 7.6 m/s (25.0 fps) and 10.7 Gs, respectively. There was no measurable occupant compartment deformation. Although this test did meet all of the safety criteria required by NCHRP Report 350 (3), it was decided to redesign the impact head to prevent this jamming phenomenon.

This redesigned head, shown in Figures 6 and 7, redirects the cut W-beam further away from the impacting vehicle, reducing the chance of the W-beam interacting with the vehicle. Moving the outlet farther from the impact plate has the added advantage of accommodating deformation of the impact plate that sometimes occurs during severe accidents without compromising the outlet geometry.

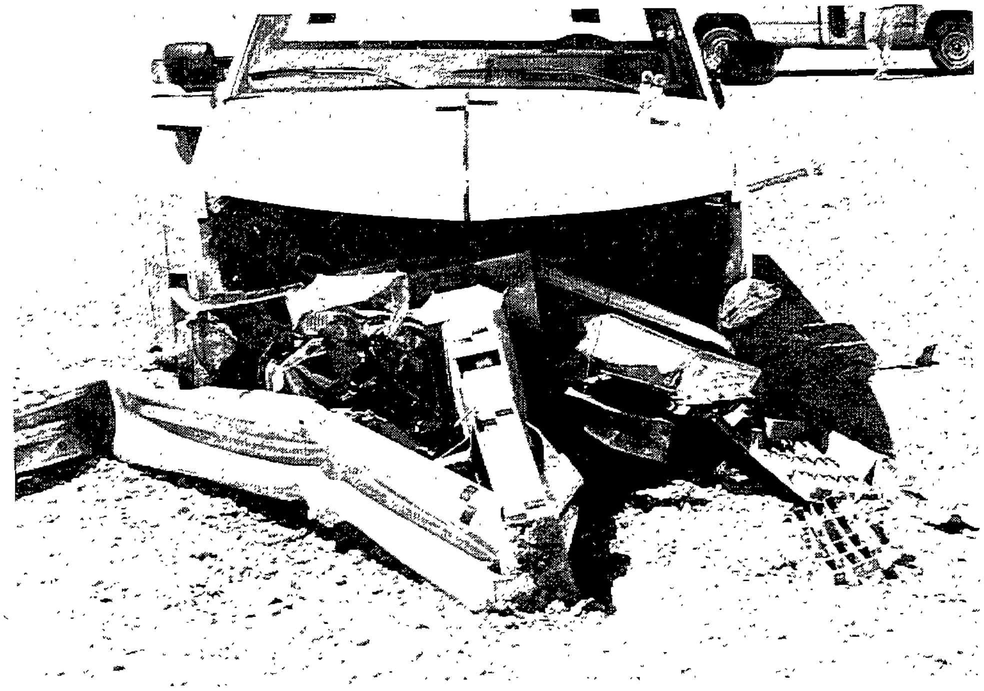


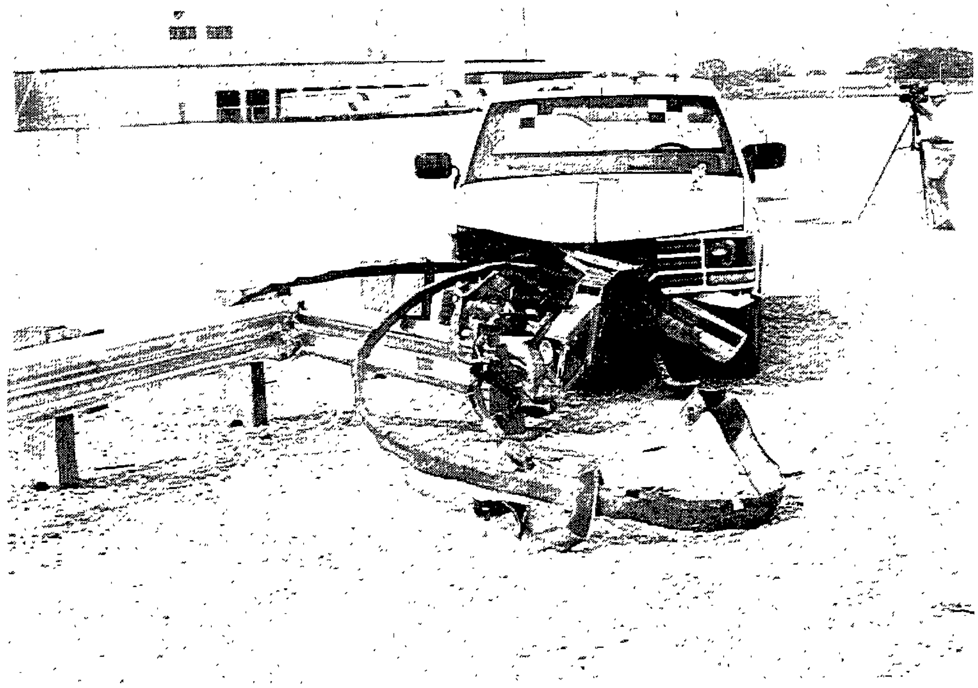
Figure 28. Post-test Photographs of Test BEST-5.

5.5 Test BEST-6 (2000 kg, 100 km/h, 0 deg)

This test was conducted as a rerun of test BEST-5. The modifications to the head were made and the length of the system was increased to 46 m (150 ft) to order to prevent the rail from becoming completely detached from the downstream posts as occurred during Test BEST-4. As in the previous test, the first length of rail was a special order specimen that was not galvanized because of the unusual length. At the time it was believed that the galvanization of the beam would have very little affect on the performance of the system.

The BEST system with the redesigned head was impacted with a 1990 Chevy ¾ ton pickup at 101.3 km/h (62.9 mph) and 0.2 degrees toward the back of the rail. The system performed very well, as shown in Figure 29. The pickup was brought to a controlled stop after cutting through 7.44 m (24 ft - 5 in.) of W-beam guardrail. All of the posts broke off cleanly, and the head cut evenly throughout the test. The damage to the test vehicle was minimal, considering the severity of the impact, with a maximum front end crush of 35.6 cm (14 in.). There was no measurable occupant compartment deformation. Although the bumper wrapped around the front of the head in a manner similar to that observed in BEST 4, the revised outlet geometry prevented the outlet from being obstructed in anyway.

The normalized longitudinal OIV and ridedown accelerations were determined to be 7.1 m/s (23.3 fps) and 8.4 Gs, respectively. As would be expected, the lateral occupant risk values were low, with a normalized lateral OIV of 1.3 m/s (4.3 fps) and lateral ridedown acceleration of 1.3 Gs.



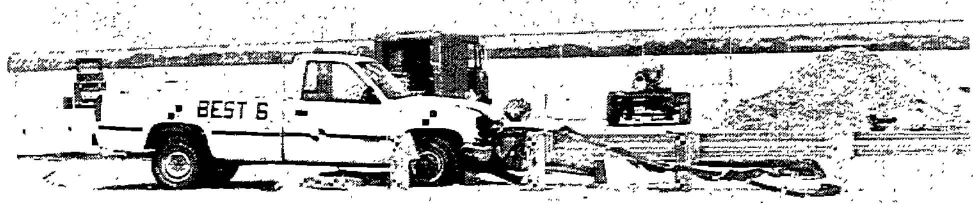


Figure 29. Post-test Photographs of Test BEST-6.

5.6 Test BEST-7 (820C, 100 km/hr, 0 degrees)

BEST-7 test was conducted to fulfill the requirements of NCHRP Report 350 (3) test designation 3-30. It consisted of a 1990 Ford Festiva impacting the terminal at 98.0 km/hr (60.9 mph), head-on and offset one-fourth the width of the vehicle toward the back of the rail. An uninstrumented dummy was restrained in the passenger seat. The first rail in the system was not galvanized, similar to the previous two tests.

Upon impact with the system, the front of the vehicle began to crush inward. The impact head began to pitch up immediately as a result of the low impact point provided by the small car. The pitching of the head resulted in the end of the chute deforming the bottom of the W-beam, and the eventual buckling of the rail. The system cut through 0.8 m (32 in.) of guardrail before the rail buckled and the vehicle began to yaw out. The vehicle continued to yaw out and began to roll over as it approached a yaw angle of 90 degrees. However, as the vehicle continued to yaw, the vehicle began to right itself. The vehicle eventually yawed 360 degrees before coming to rest on its wheels 20 m (65 ft) downstream of impact and 3.8 m (12.5 ft) behind the system.

Damage to the vehicle was acceptable, as shown in Figure 30, with 25 cm (10 in.) of crush in the front of the vehicle and a maximum of 73 mm (2⅞ in.) internal occupant compartment deformation occurring on the front floorboard.

There was significant deformation of the W-beam rail, as shown in Figure 30. The bottom of the rail was deformed from contact with the end of the chute. The cutting path showed that the blades started cutting in a sharply upward manner almost immediately after impact. When the head was removed from the rail, there was noticeable wear on the cutting blades. The first three posts broke away cleanly, and the rail buckled at the midspan between post nos. 2 and 3 and at post no. 4. There were also contact marks on the groundline strut and second foundation tube which indicated that the undercarriage of the vehicle had contacted these terminal components.

NCHRP Report 350 occupant risk criteria were met in this test as the normalized longitudinal OIV and ridedown accelerations were determined to be 11.3 m/s (37.1 fps) and 17.0 Gs, respectively. Lateral values of the occupant risk criteria were easily satisfied, with the normalized lateral OIV being 3.1 m/s (10.2 fps) and the lateral ridedown acceleration having a value of 8.8 Gs. Occupant compartment deformation was judged to be acceptable as well. However, because of the unexpected jamming and buckling of the rail which occurred, it was decided that this phenomenon was to be investigated, and any new information would be used to improve the performance in a repeat test.

Since this type of behavior had not been seen in any of the previous bogie or full-scale tests, which had all been conducted on galvanized W-beam, it was decided to perform a series of static and dynamic tests to determine the affect that galvanizing had on the behavior of the system. These tests showed that the system does perform differently on galvanized and non-galvanized W-beam. The bogie tests on galvanized W-beam produced a steady state cutting force of approximately 10 to 12 kips, while the tests on the non-galvanized rail produced a force which started out around 10 kips and climbed quickly to approximately 20 kips throughout the cutting process. This behavior was attributed to the wearing of the cutting blades which was evident after each bogie and full-scale test on ungalvanized beam. The cutters, which are fabricated from abrasion resistant steel and then galvanized, have shown no signs of wearing in all of the tests conducted previously with galvanized W-beam. It was also noted that the cutter teeth did not appear to track as well on the ungalvanized W-beam. These findings led the researchers to conclude that the poor performance observed in Test BEST-7 was a result of the use of ungalvanized W-beam. A special stock of lengthened galvanized W-beam was obtained for the remaining tests, and this test was conducted again as test BEST-8.

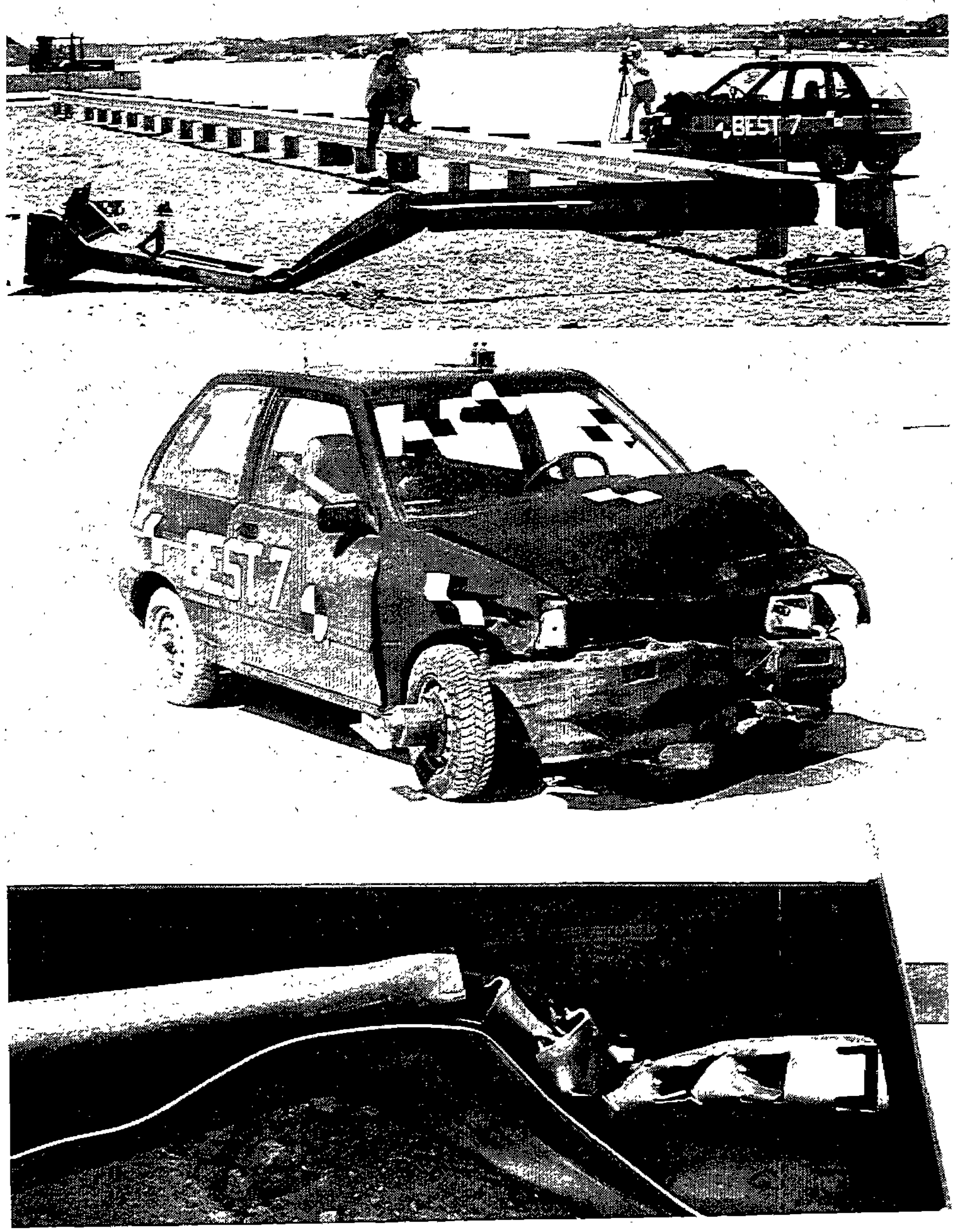


Figure 30. Post-test Photographs of Test BEST-7.

5.7 Test BEST-8 (820C, 100 km/hr, 0 degrees)

This test was conducted as a repeat of test BEST-7, with the only modification being the use of a galvanized W-beam rail for the terminal section. The test involved a 1990 Ford Festiva impacting the terminal at 100.4 km/hr (62.4 mph), head-on and offset one-fourth the width of the vehicle toward the back of the rail. An uninstrumented dummy was restrained in the passenger seat. The impact configuration is shown in Figure 31. A summary of the test results is shown in Figure 32 and additional sequential photos are shown in Figure 33.

The test vehicle impacted the system with an angle of 0.6 degrees toward the back of the guardrail system. At 22 ms after impact the post breaker on the impact head contacted the first post, and by 34 ms the end of the chute contacted the cable anchor box which released from the rail immediately thereafter. At 54 ms after impact the yawing of the impact head caused the W-beam rail to pull off of the bolt at the second post, and the end of the chute reached this point on the W-beam at approximately 72 ms. At approximately 112 ms after impact, after the system had cut 1.83 m (6 ft) of W-beam, the rail stopped feeding into the chute. When this feeding action stopped, the rail buckled out of the way and the vehicle yawed out slowly, coming to rest as shown in Figures 32 and 34.

Damage to the vehicle was minimal, as shown in Figure 35, with 25 cm (10 in.) of crush on the front of the vehicle. The only occupant compartment deformation occurred on the driver's side floorboard, and the maximum deformation was measured to be 76 mm (3 in.).

Damage to the system, shown in Figure 36, consisted of posts 1 and 2 breaking cleanly at the top of the foundation tubes. Post No. 3 was pushed downstream slightly, with a 19 mm (¾ in.) gap in the soil visible on the upstream side of the post at ground level. The W-beam rail was buckled at the end of the chute and at the post no. 3 location.

The results of this test confirmed that there is indeed a difference in the behavior of the system when a galvanized W-beam is used in place of an ungalvanized W-beam. The analysis of the accelerometer data showed that the system passed the occupant risk criteria presented by NCHRP Report 350 (3). The normalized longitudinal occupant impact velocity was 10.1 m/s (33.1 fps), which is above the design value of 9 m/s (29.5 fps), but well below the threshold value of 12 m/s (39.4 fps). The maximum longitudinal ridedown acceleration of 16.7 Gs was above the design value of 15 Gs, but well below the threshold value of 20 Gs. The lateral values for the occupant risk criteria were quite low, with a normalized lateral occupant impact velocity of 2.8 m/s (9.2 fps) and a lateral ridedown acceleration of 4.9 Gs. Plots of the accelerometer data from Test BEST-8 can be found in Appendix C. A summary of the safety performance results for all of the successful tests is presented in Table 4.

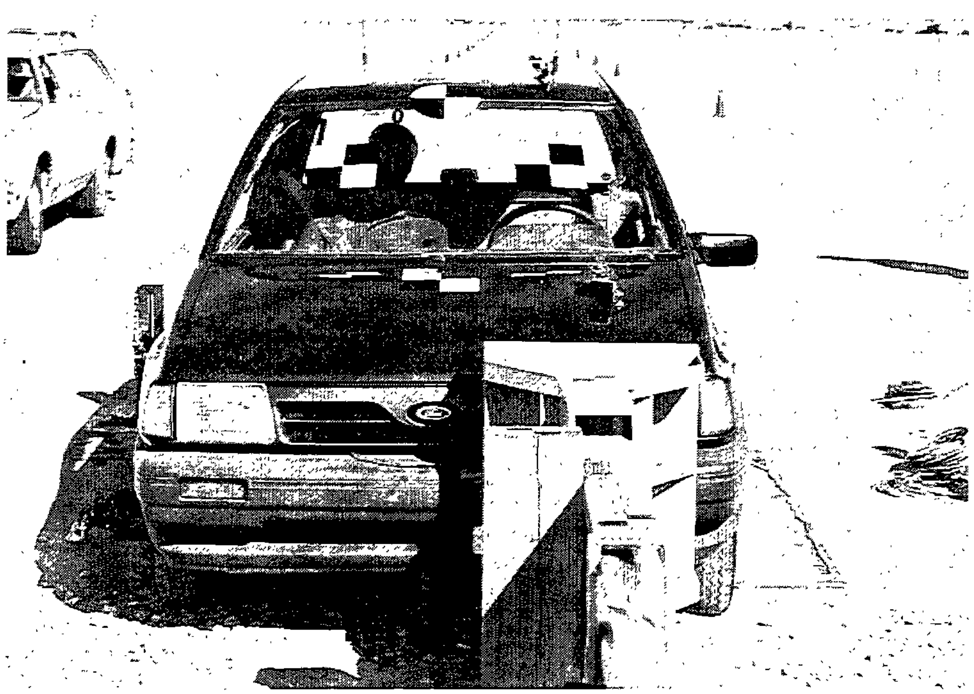


Figure 31. Impact Location, Test BEST-8.

Impact 50 ms 120 ms 240 ms 460 ms

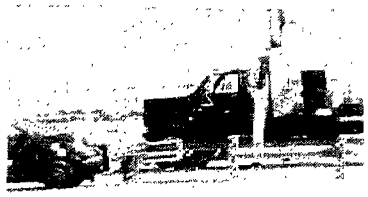
Test Number	BEST-8
Date	10/3/96
Installation	BEST System
Length of Installation	46 m
Vehicle Model	1990 Ford Festiva
Vehicle Weight	
Curb	781 kg
Test Inertial	817 kg
Gross Static	892 kg
Vehicle Impact Speed	100.4 km/h
Vehicle Impact Angle	0.6 deg

Vehicle Impact Location	Head-on, offset quarterpoint
Normalized Occupant Impact Velocity	
Longitudinal	10.1 m/s
Lateral	2.8 m/s
Occupant Ridedown Accelerations	
Longitudinal	16.7 Gs
Lateral	4.9 Gs
Vehicle Damage Classification	
TAD	12FYEN2
VDI	12-FL-3
Amount of rail fed through cutter	1.83 m

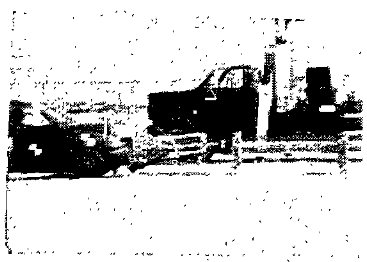
Conversion Factor: 1 ft = 0.3048 m 1 lb = 0.4536 kg

Figure 32. Summary of Test BEST-8.

Impact

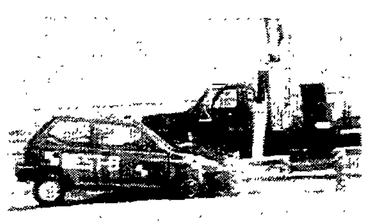


18 ms



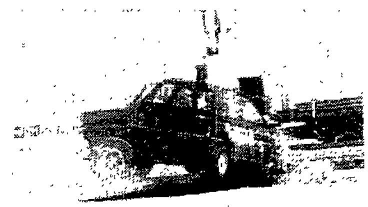
28 ms

40 ms



82 ms

140 ms



230 ms

280 ms

350 ms

490 ms

Figure 33. Sequential Photographs, Test BEST-8.

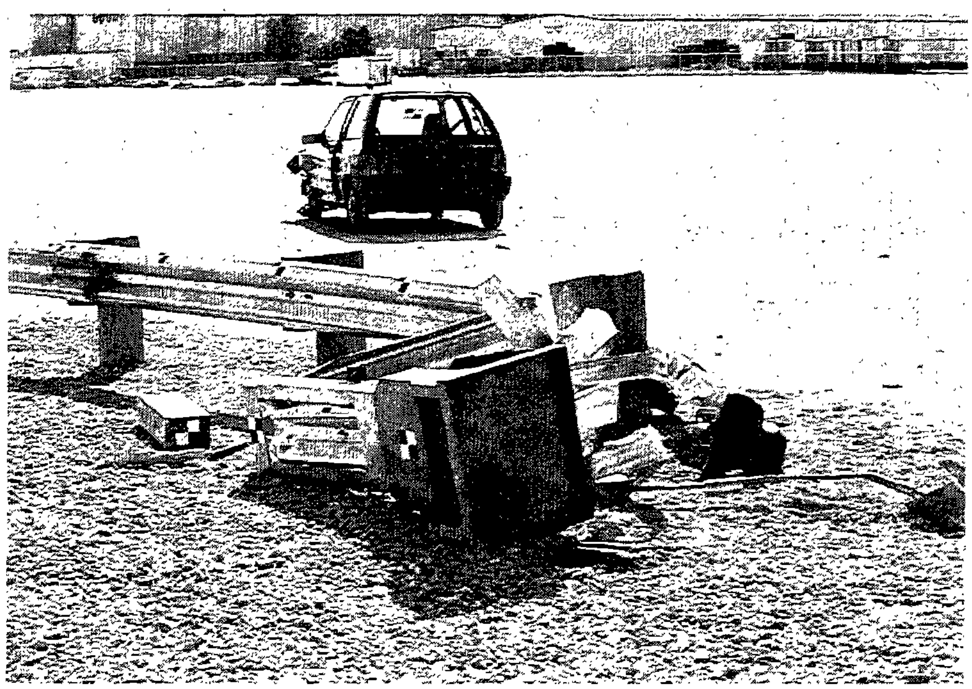


Figure 34. Vehicle Trajectory, Test BEST-8.

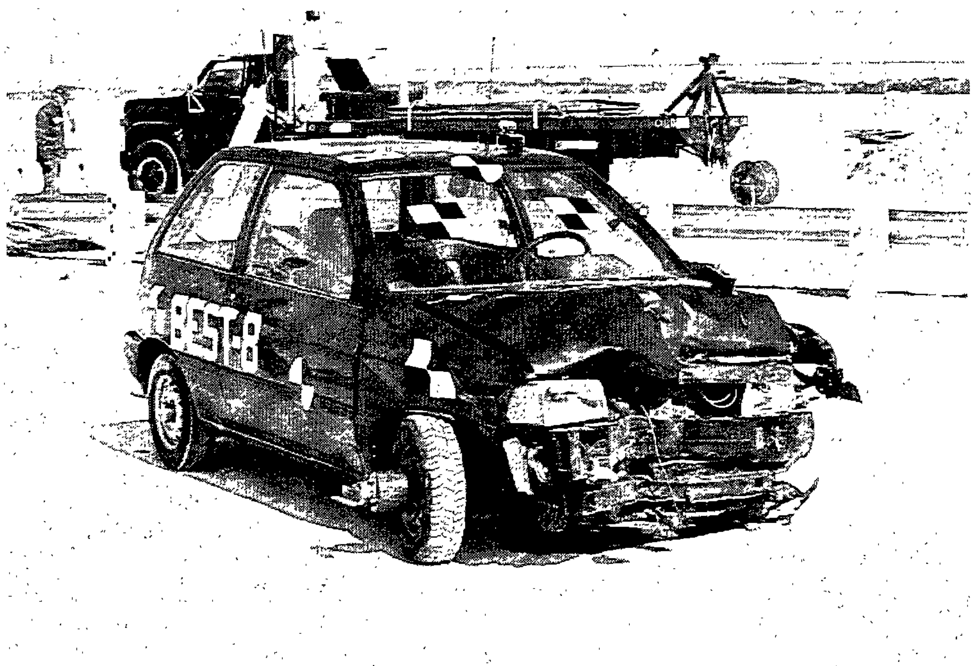


Figure 35. Vehicle Damage, Test BEST-8.

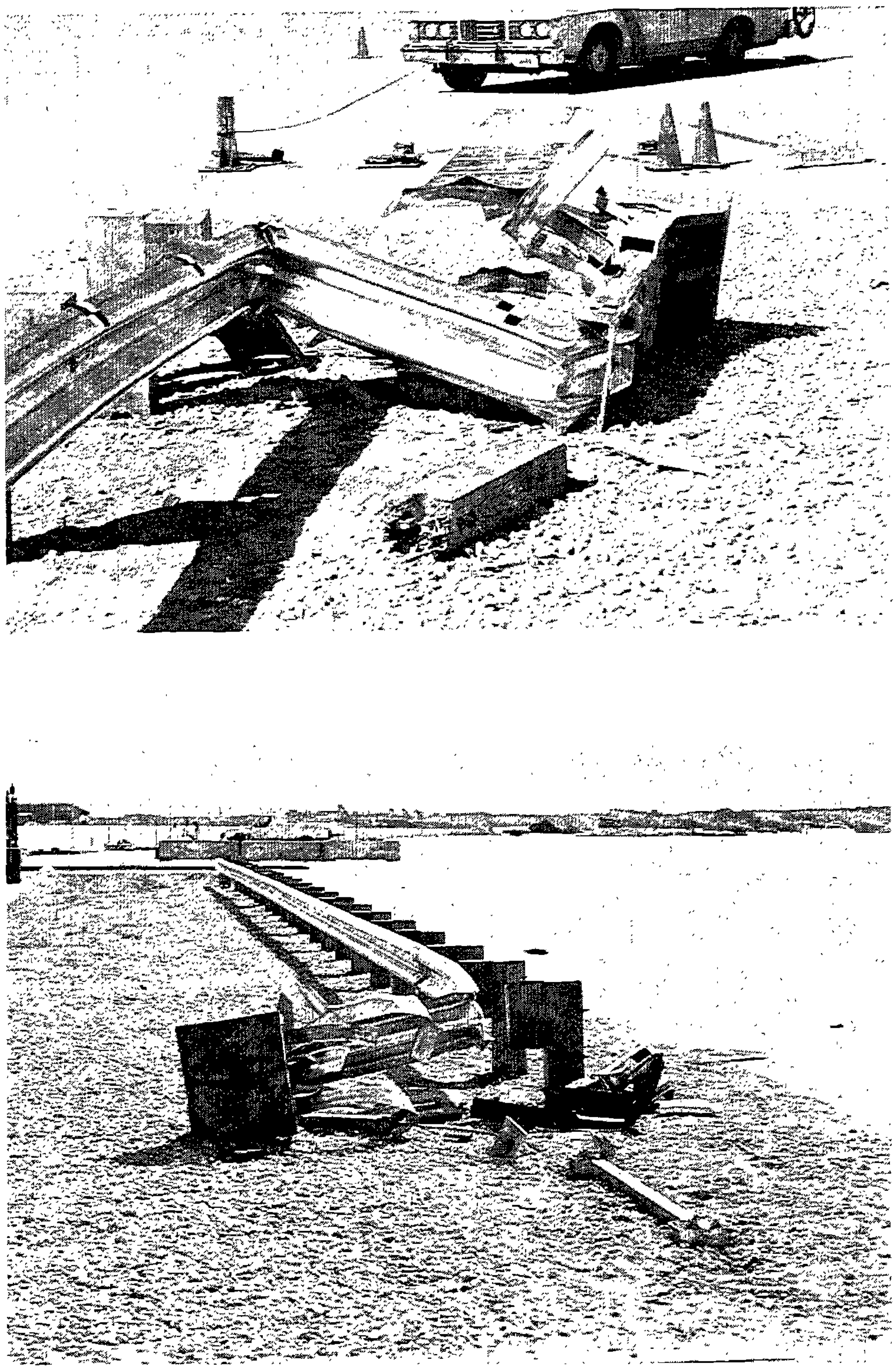


Figure 36. Installation damage, Test BEST-8.

5.8 Test BEST-9 (2000P, 100 km/hr, 0 deg)

The lower force levels produced by the galvanized rail resulted in a better performance with the small test vehicle. However, this behavior raised questions about the validity of the head-on test with the pickup which had been conducted successfully with a black rail. The concern was that with a lower cutting force, the pickup would travel further down the rail and the cutting blades would reach the first splice. There was some concern about what would happen when this occurred, since a splice has never been fed through the system. Therefore, the head-on test with the pickup (test designation 3-31) was conducted again with a galvanized W-beam as test BEST-9. The impact configuration for this test is shown in Figure 37. A summary of the test results is shown in Figure 38 and additional sequential photos are shown in Figure 39.

In this test a 1990 Chevrolet ¾ ton pickup was directed into the BEST impact head at 101.0 km/hr (62.8 mph) and at an angle of 1.2 degrees toward the back of the rail. The front of the vehicle began to deform immediately after contact, and the head began to cut the W-beam. At 18 ms after impact the post breaker contacted the first post and began to push it over. By 30 ms after impact the first post had failed and the end of the chute contacted the anchor box, causing it to release immediately. At 60 ms after impact the end of the chute contacted post no. 2, and by 64 ms the rail had released from the post. The impact head continued traveling down the rail, with the post breaker impacting post no. 2, 90 ms into the test. This sequence continued as the impact head was pushed down the system, with the end of the chute reaching post nos. 3, 4, and 5 at 148 ms, 248 ms, and 372 ms respectively. The W-beam splice at post no. 5 fed through the cutting blades and the impact head came to rest with the end of the chute resting against post no. 6. The total cutting distance for this test was 8.91 m (29 ft - 2¾ in.). The vehicle final resting position is shown in Figures 38 and 40.

Damage to the vehicle was minimal, as seen in Figure 41. There was no visible occupant compartment deformation, and there was 29.2 cm (11½ in.) of crush in the front of the vehicle where the impact head contacted the test vehicle.

The system damage can be seen in Figure 42. The cable system released properly and post nos. 1 through 4 were broken cleanly at ground level. Post No. 5 was split longitudinally and partially broken at the base. The head cut cleanly through the splice, with the first and third strips from the top becoming detached at the point of the splice, while the other two strips remained attached. The impact head was deformed slightly on the front face at the point where the test vehicle's bumper contacted it upon impact. The cutters contacted several of the splice bolts as they cut through the splice and, even though one of these bolts became wedged between two blades, the rail continued to be cut smoothly.

The analysis of the accelerometer data showed that the system passed the occupant risk criteria presented by NCHRP Report 350 (3). The normalized longitudinal occupant impact velocity was 6.9 m/s (22.6 fps), which is well below the design value of 9 m/s (29.5 fps). The maximum longitudinal ridedown acceleration of 13.3 Gs was below the design value of 15 Gs. The lateral values for the occupant risk criteria were quite low, with a normalized lateral occupant impact velocity of 1.0 m/s (3.3 fps) and a lateral ridedown acceleration of 2.8 Gs. Plots of the accelerometer data from Test BEST-9 can be found in Appendix C. A summary of the safety performance results for all of the successful tests is given in Table 4.

Figure 37. Impact Location, Test BEST-9.

Impact 64 ms 190 ms 320 ms 620 ms

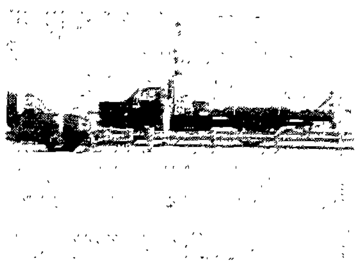
Test Number	BEST-9
Date	10/8/96
Installation	BEST System
Length of Installation	46 m
Vehicle Model	1990 Chevy ¾ ton pickup
Vehicle Weight	
Curb	1960 kg
Test Inertial	2005 kg
Gross Static	2005 kg
Vehicle Impact Speed	101.0 km/h
Vehicle Impact Angle	1.2 deg

Vehicle Impact Location	Center of Impact Head
Normalized Occupant Impact Velocity	
Longitudinal	6.9 m/s
Lateral	1.0 m/s
Occupant Ridedown Accelerations	
Longitudinal	13.3 Gs
Lateral	2.8 Gs
Vehicle Damage Classification	
TAD	12FCEN2
VDI	12-FC-4
Amount of rail fed through cutter	8.91 m

Conversion Factor: 1 ft = 0.3048 m 1 lb = 0.4536 kg

Figure 38. Summary of Test BEST-9.

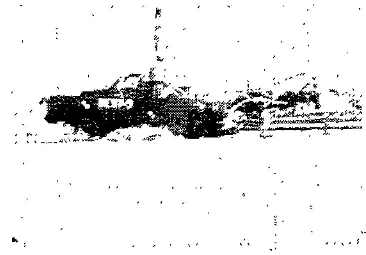
Impact



30 ms

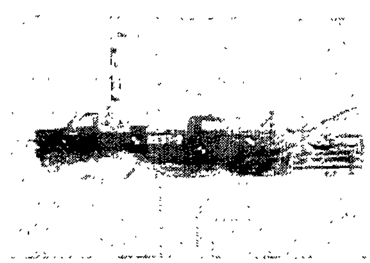
58 ms

140 ms



250 ms

380 ms



460 ms

700 ms

Figure 39. Sequential Photographs, Test BEST-9.

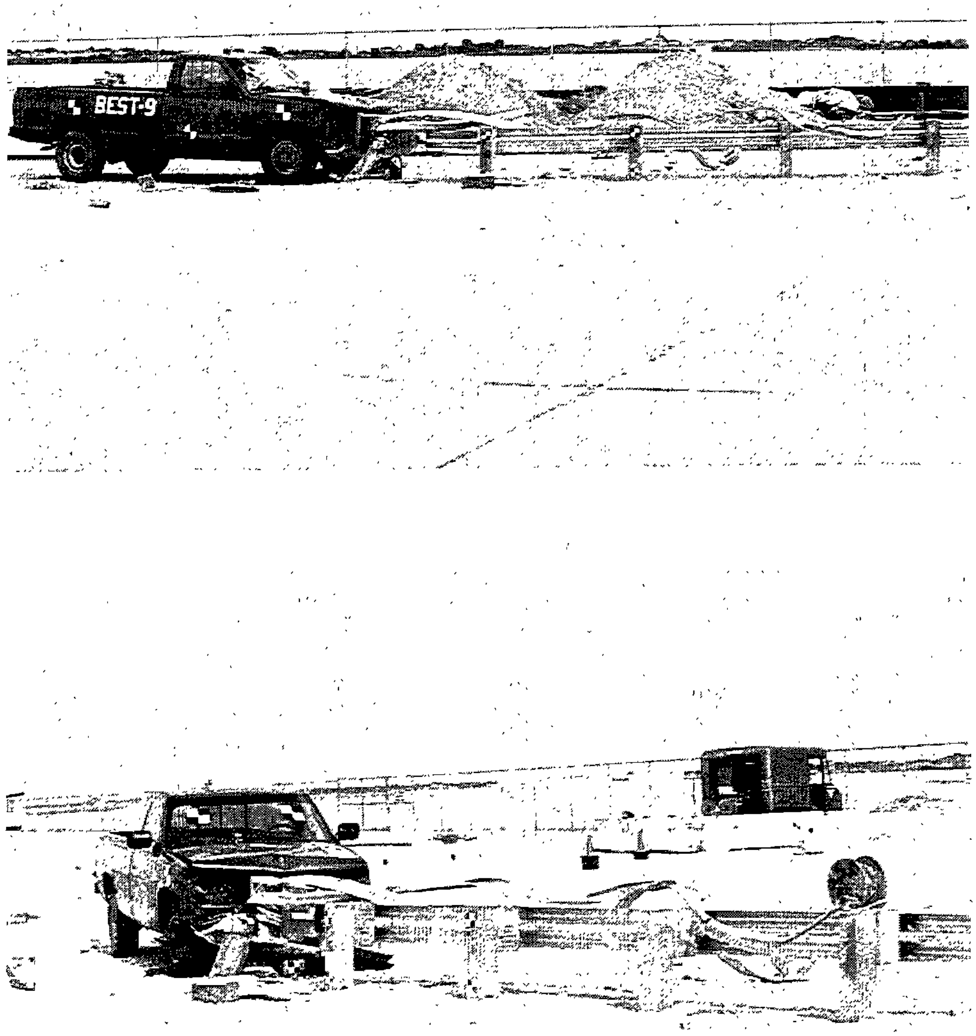


Figure 40. Vehicle Trajectory, Test BEST-9.

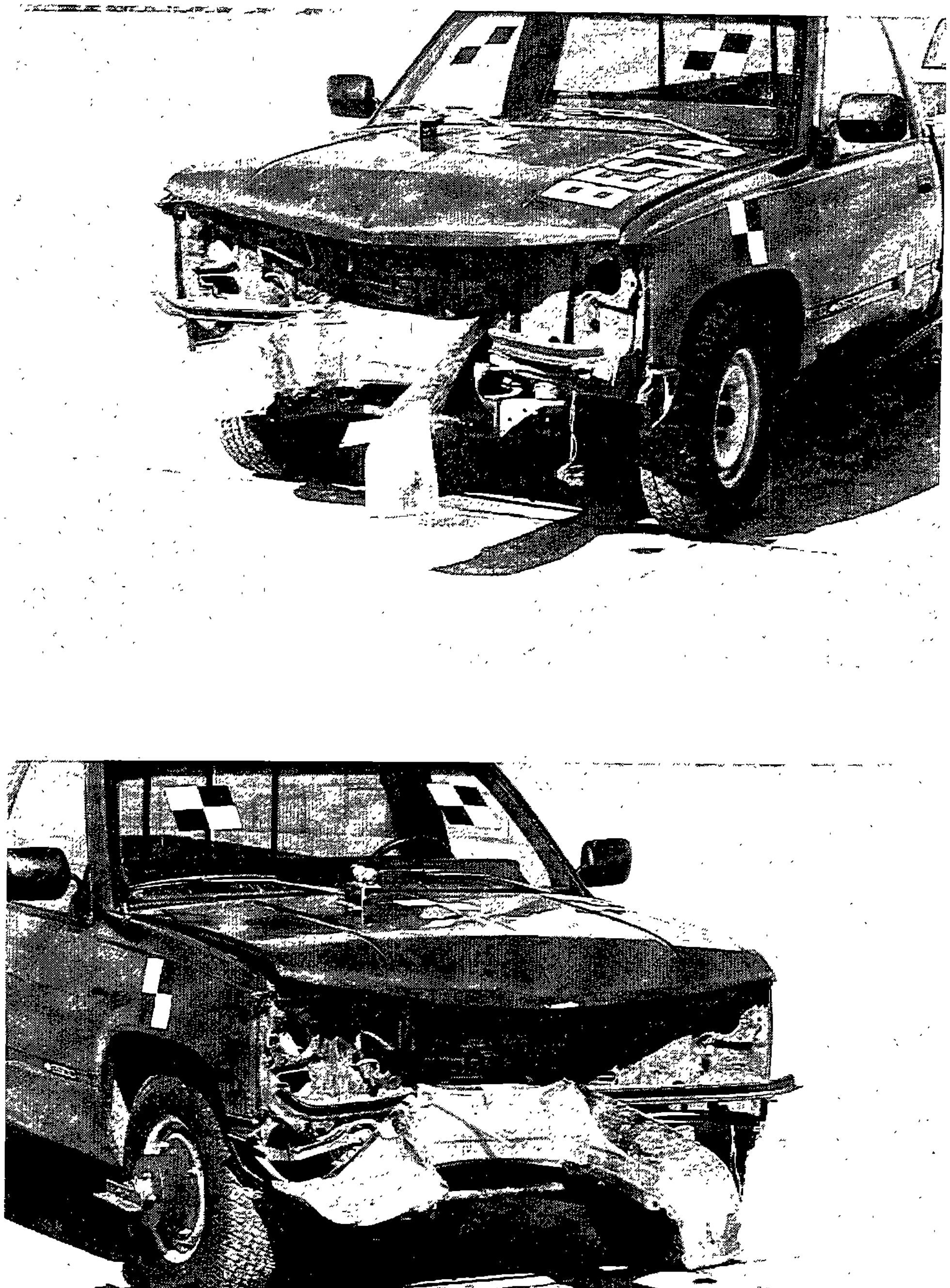


Figure 41. Vehicle Damage, Test BEST-9.

Figure 42. Installation damage, Test BEST-9.

5.9 Test BEST-10 (2000P, 100 km/h, head-on at 15 deg)

NCHRP Report 350 (3) test 3-33 was conducted with a 1990 Chevy ¾ ton pickup impacting the system head-on at 102.1 km/hr (63.4 mph) and 14.3 degrees toward the traffic side of the system. The impact configuration for this test is shown in Figure 43. A summary of the test results is shown in Figure 44 and additional sequential photos are shown in Figure 45.

Upon impact with the system, the front of the vehicle began to crush inward and then push the head down the W-beam. At 12 ms after impact the post breaker contacted post no. 1, and by 34 ms the end of the chute contacted the anchor box, causing it to release and drop to the ground. At 66 ms after impact the end of the chute reached post no. 2 and at 106 ms, after feeding 2.16 m (7 ft - 1 in.), the W-beam buckled at the end of the chute and the impact head began to rotate around with the vehicle. The vehicle continued to travel through the system and as the impact head rotated around, the end of the chute contacted the driver's side door at approximately 226 ms after impact. The vehicle continued through the system and was braked to a stop approximately 120 ft downstream of impact and 70 ft behind the rail, as shown in Figure 44 and 46.

Damage to the vehicle was relatively minor, with 34.3 cm (13.5 in.) of crush in the front and no visible undercarriage damage. The driver's side door was damaged from contact with the impact head as the vehicle passed by it. This damage, shown in Figure 47, consisted of the tearing of the outer sheet metal and approximately 229 mm (9 in.) of crush on the outside of the door. This resulted in approximately 114 mm (4.5 in.) of deformation on the inside of the driver's door. There was no other occupant compartment deformation.

Damage to the system can be seen in Figure 48. Post nos. 1 and 2 were broken cleanly at the top of the foundation tube. Post No. 3 broke at the groundline CRT hole, while post No. 4 rotated more and broke at the bottom CRT hole. The system cut for a total distance of 2.16 m (7 ft - 1 in.), with buckling occurring at the end of the chute when it was 0.97 m (3 ft - 2 in.) upstream of post no. 3. The W-beam also buckled at post locations 3 and 4. Damage to the impact head consisted of deformation of the front plate where the initial contact with the test vehicle occurred.

The analysis of the accelerometer data showed that the system passed the occupant risk criteria presented by NCHRP Report 350 (3). The normalized longitudinal occupant impact velocity was 6.2 m/s (20.3 fps), which is well below the design value of 9 m/s (29.5 fps). The maximum longitudinal ridedown acceleration of 17.5 Gs was above the design value of 15 Gs, but well below the threshold limit of 20 Gs. As expected, the lateral values for the occupant risk criteria were quite low, with a normalized lateral occupant impact velocity of 2.3 m/s (7.5 fps) and a lateral ridedown acceleration of 10.0 Gs. Plots of the accelerometer data from Test BEST-10 can be found in Appendix C. A summary of the safety performance results for all of the successful tests is given in Table 4.

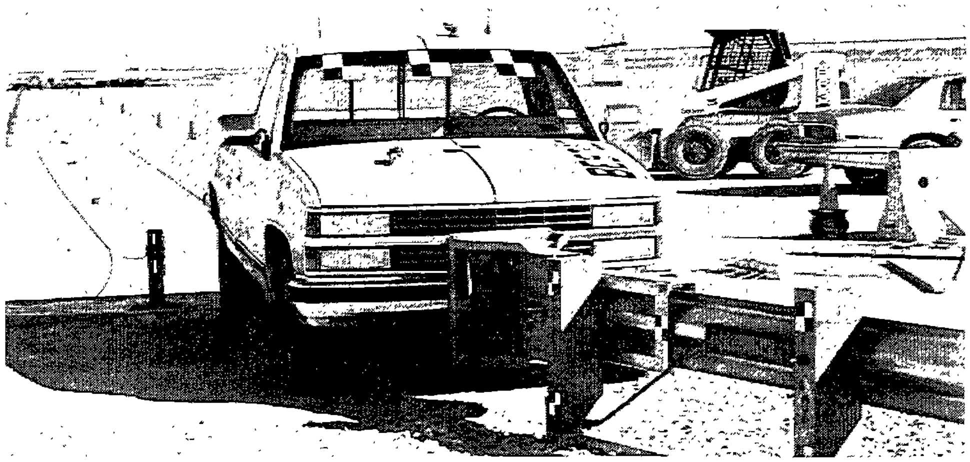


Figure 43. Impact Location, Test BEST-10.

Impact 64 ms 156 ms 266 ms 434 ms

Test Number	BEST-10
Date	10/11/96
Installation	BEST System
Length of Installation	46 m
Vehicle Model	1990 Chevy ¾ ton pickup
Vehicle Weight	
Curb	1924 kg
Test Inertial	2003 kg
Gross Static	2003 kg
Vehicle Impact Speed	102.1 km/h
Vehicle Impact Angle	14.3 deg

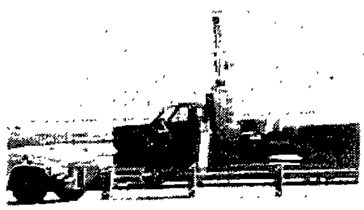
Vehicle Impact Location	Center of Impact Head
Normalized Occupant Impact Velocity	
Longitudinal	6.2 m/s
Lateral	2.3 m/s
Occupant Ridedown Accelerations	
Longitudinal	17.5 Gs
Lateral	10.0 Gs
Vehicle Damage Classification	
TAD	01FCEN1
VDI	1-FC-3
Amount of rail fed through cutter	2.16 m

Conversion Factor: 1 ft = 0.3048 m 1 lb = 0.4536 kg

Figure 44. Summary of Test BEST-10.

Impact

146 ms

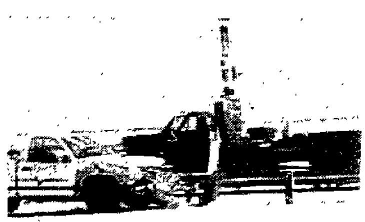


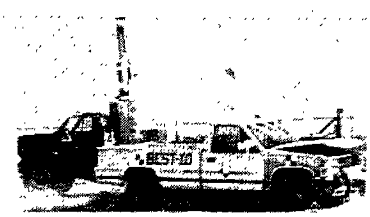
34 ms

200 ms

60 ms

270 ms





90 ms

420 ms

Figure 45. Sequential Photographs, Test BEST-10.

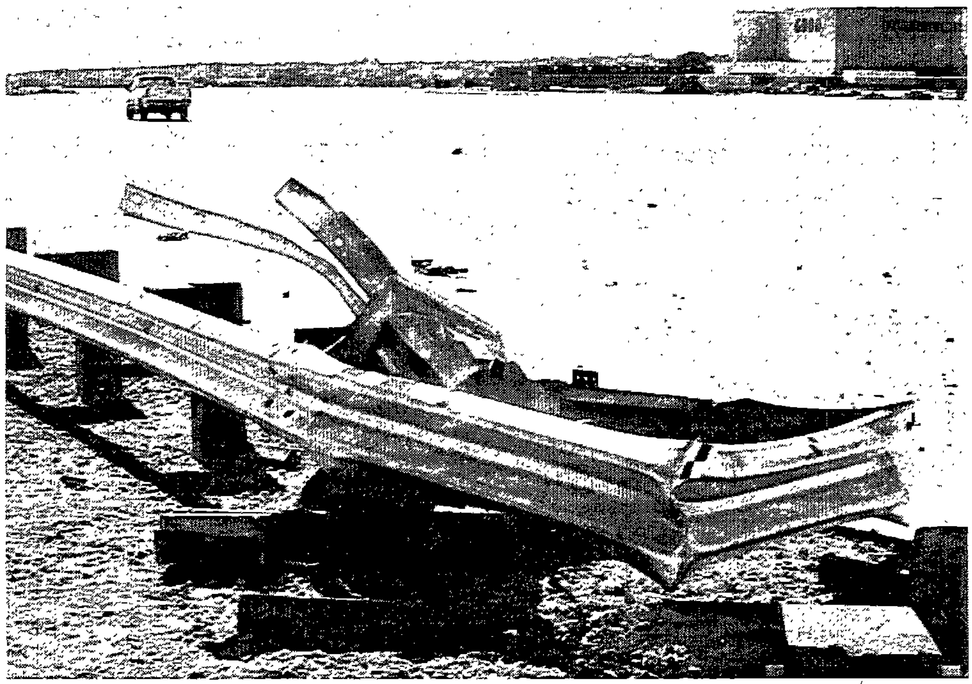


Figure 46. Vehicle Trajectory, Test BEST-10.

Figure 47. Vehicle Damage, Test BEST-10.

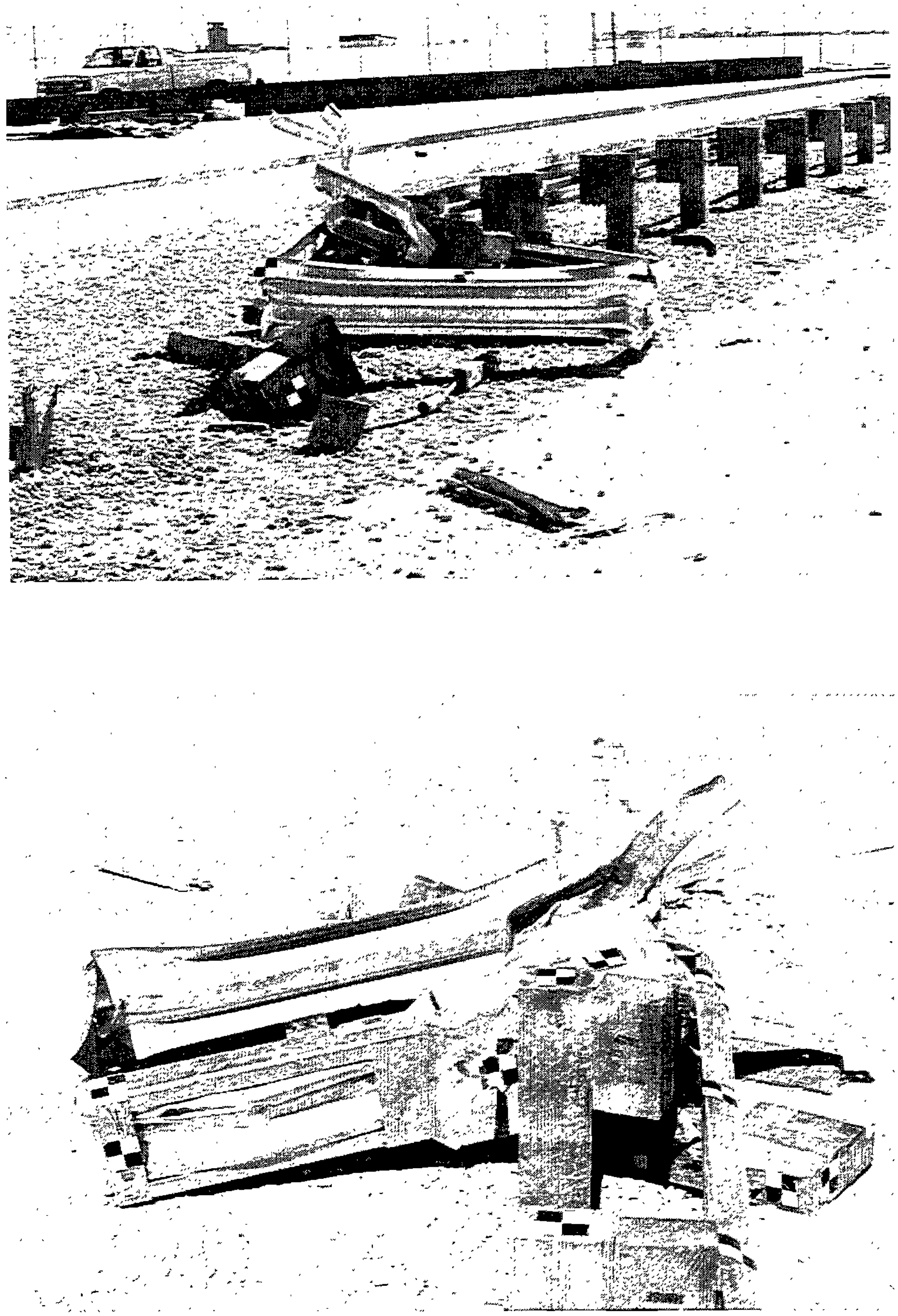


Figure 48. Installation damage, Test BEST-10.

5.10 Test BEST-11 (2000P, 100 km/hr, 20 deg reverse hit)

This test was conducted to satisfy the requirements of NCHRP Report 350 (3) test 3-39 which requires that the terminal be impacted from the reverse direction at the midpoint of the terminal length with a ¾ ton pickup impacting at 20 degrees and 100 km/hr (62.1 mph). The test vehicle impacted the guardrail at the midpoint between post nos. 3 and 4 at 101.6 km/hr (63.1 mph) and 20.5 degrees. The impact configuration for this test is shown in Figure 49. A summary of the test results is shown in Figure 50 and additional sequential photos are shown in Figure 51.

Upon impact with the W-beam the right-front corner of the vehicle began to crush inward. The vehicle reached post no. 3 at 30 ms after impact and by 94 ms it reached post no. 2. The pickup reached the beginning of the cable anchor box at 104 ms after impact, causing it to become detached at 126 ms. At 136 ms after impact the vehicle impacted the end of the chute, followed at 168 ms by the vehicle impacting post no. 1. The impact head was pushed free of the system and came to rest 55 m (180 ft) downstream of its initial location on a line parallel to the guardrail. The vehicle came to rest 19 m (62 ft - 9 in.) downstream and 19 m (62 ft - 9 in.) behind the system from a line parallel to the W-beam guardrail, as shown in Figures 50 and 52.

Damage to the vehicle, shown in Figure 53, consisted of crushing of the right-front quarter panel and failure of the front-right tie-rod which allowed the tire to rotate freely outward. All four tires remained inflated throughout the crash test and there were only minor contact marks along the passenger side of the vehicle. The manual transmission shifted as a result of the impact and caused slight damage to the center of the floorboard where the gear selector is located. There was no damage to the driver's side floorboard, but the passenger's side floorboard was deformed slightly, with a maximum deformation of 64 mm (2.5 in.). There was no damage to any of the glass on the test vehicle.

Damage to the system, shown in Figure 54, consisted of post nos. 1, 2, and 3 breaking at the groundline and post no. 4 rotating slightly so that there was a 25 mm (1 in.) gap in the soil at the front of the post. The impact head was undamaged and there was some noticeable deformation of the cable anchor box. There was a 229 mm (9 in.) long tear approximately 51 mm (2 in.) from the bottom of the W-beam just below the bolt hole location for post no. 2.

The analysis of the accelerometer data showed that the system passed the occupant risk criteria presented by NCHRP Report 350 (3). The normalized longitudinal occupant impact velocity was 7.2 m/s (23.6 fps), which is well below the design value of 9 m/s (29.5 fps). The maximum longitudinal ridedown acceleration of 10.5 Gs was well below the design value of 15 Gs. The lateral values for the occupant risk criteria were also acceptable, with a normalized lateral occupant impact velocity of 4.1 m/s (13.5 fps) and a lateral ridedown acceleration of 13.5 Gs. Plots of the accelerometer data from Test BEST-11 can be found in Appendix C. A summary of the safety performance results for all of the successful tests is given in Table 4.

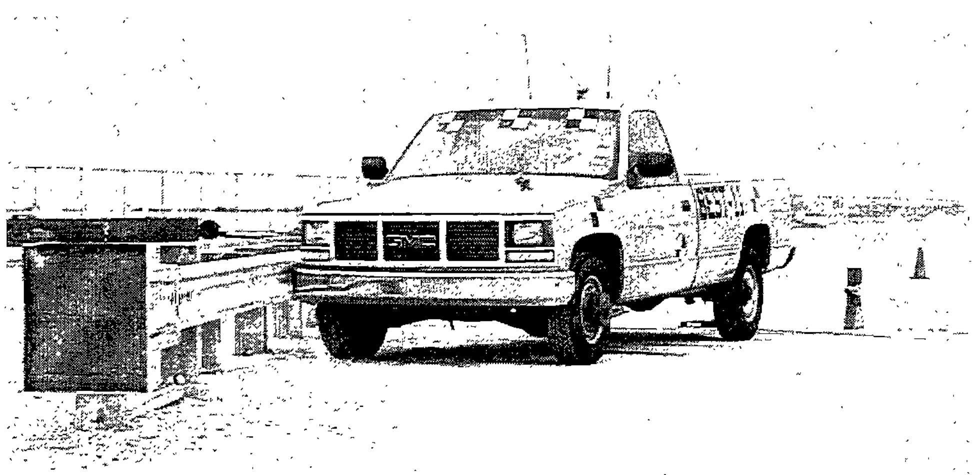


Figure 49. Impact Location, Test BEST-11.

Impact 70 ms 130 ms 200 ms 320 ms

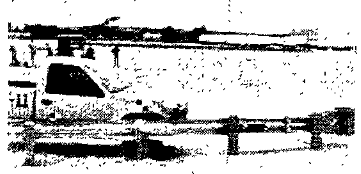
Test Number	BEST-11
Date	10/17/96
Installation	BEST System
Length of Installation	46 m
Vehicle Model	1990 GMC ¾ ton pickup
Vehicle Weight	
Curb	1780 kg
Test Inertial	2000 kg
Gross Static	2000 kg
Vehicle Impact Speed	101.6 km/h
Vehicle Impact Angle	20.5 deg

Vehicle Impact Location	midspan of posts 3 and 4
Normalized Occupant Impact Velocity	
Longitudinal	7.2 m/s
Lateral	4.1 m/s
Occupant Ridedown Accelerations	
Longitudinal	10.5 Gs
Lateral	4.1 Gs
Vehicle Damage Classification	
TAD	01RFES2
VDI	1-RFQ-4

Figure 50. Summary of Test BEST-11.

Conversion Factor: 1 ft = 0.3048 m 1 lb = 0.4536 kg

Impact

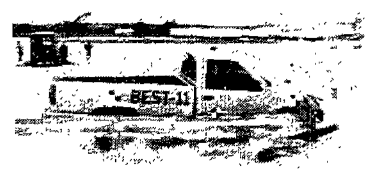


60 ms

90 ms

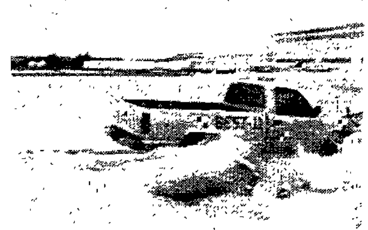
124 ms

152 ms



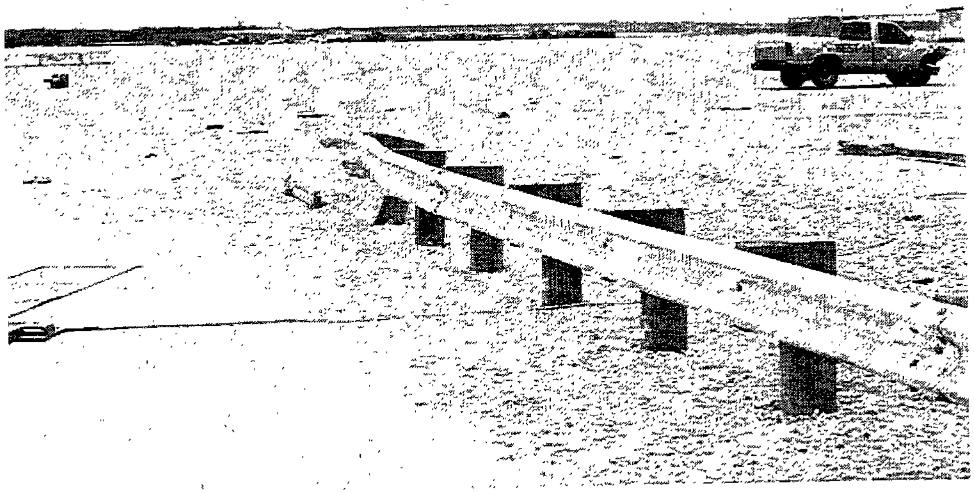
188 ms

240 ms



340 ms

Figure 51. Sequential Photographs, Test BEST-11.



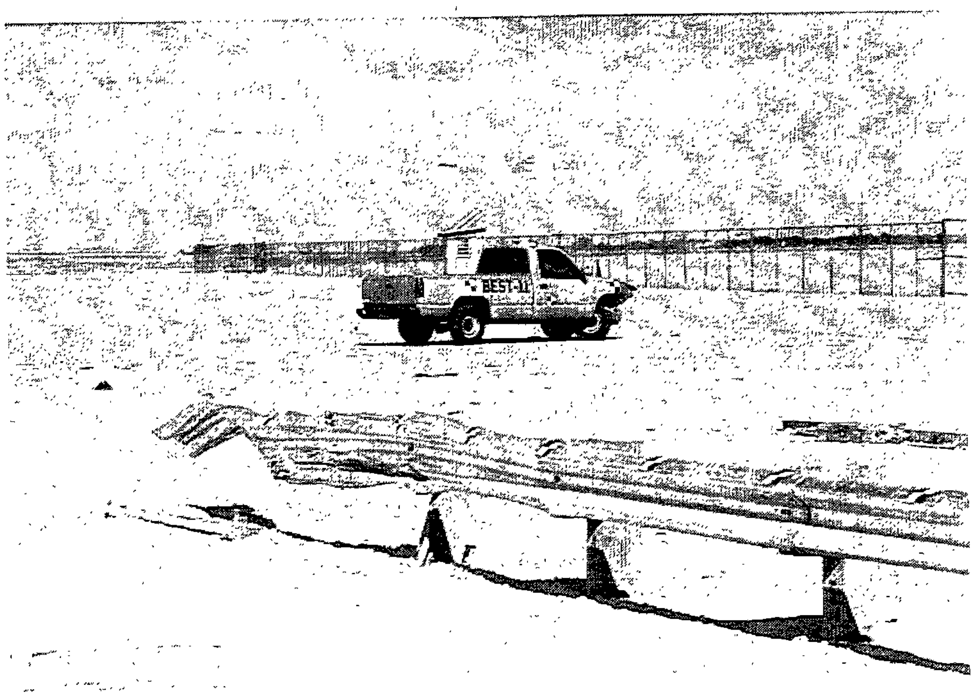


Figure 52. Vehicle Trajectory, Test BEST-11.

Figure 53. Vehicle Damage, Test BEST-11.

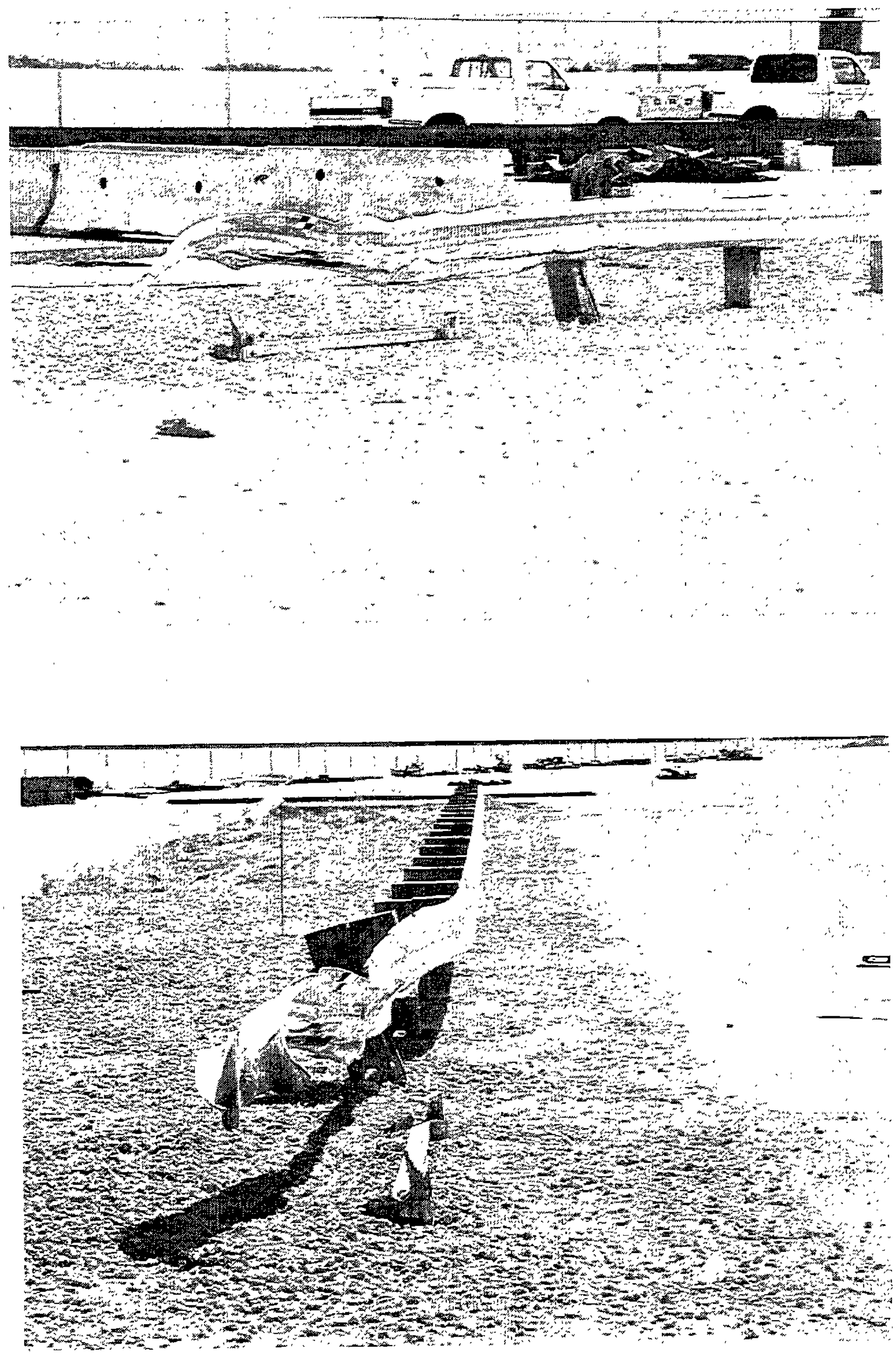


Figure 54. Installation damage, Test BEST-11.

Table 4. Performance Evaluation Results

Evaluation Criteria		Test BEST-3	Test BEST-4	Test BEST-8	Test BEST-9	Test BEST-10	Test BEST-11
A.	The test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	S	NA	NA	NA	NA	NA
C.	Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.	NA	S	S	S	S	S
D.	Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the occupant compartment or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.	S	S	S	S	S	S
F.	The vehicle should remain upright during and after collision although moderate roll, pitching and yawing are acceptable.	S	S	S	S	S	S
H.	The longitudinal and lateral occupant impact velocity shall preferably be below 9 m/s, with a maximum allowable value of 12 m/s	NA	S	S	S	S	NA
I.	The longitudinal and lateral occupant ridedown accelerations shall preferrably be below 15 Gs, with a maximum allowable value of 20 Gs.	NA	S	S	S	S	NA
K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	S	S	S	S	S	S
L.	The occupant impact velocity in the longitudinal direction should not exceed 12 m/s and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 Gs.	S	NA	NA	NA	NA	S
M.	The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.	S	NA	NA	NA	NA	S
N.	Vehicle trajectory behind the test article is acceptable.	NA	S	S	S	S	S

S - Satisfactory M - Marginal U - Unsatisfactory NA - Not Applicable

6 CONCLUSIONS

A series of full-scale crash tests was performed on the energy absorbing guardrail terminal known as the BEST system. Of the seven crash tests required by NCHRP Report 350 (3), five tests were successfully conducted on the final system design, while one test was performed on the same system with a slightly different head outlet geometry as described in this report. BEST-4 involved a small car impacting the system head on at an angle of 15 degrees (test 3-32). Although, the rail outlet geometry was changed after this test had been completed, the changes were found to cause not difference in the dynamic cutting forces measured during bogie tests and BEST-8 involving a small car impacting the system head-on (test 3-30). It is the opinion of the authors that the changes incorporated into the impact head will not affect the results of test BEST-4 and it is requested that this test be accepted for NCHRP Report 350 test designation 3-32.

The final test required by NCHRP Report 350 (3) is test designation 3-34 which requires that an 820C vehicle be directed into the critical impact point at 100 km/h (62.1 mph) and 15 degrees. As discussed in section 4.3 of this report, a test very similar to this was conducted previously on a system with the same geometry as the BEST guardrail terminal. Therefore, Test 9429A-1 is offered as evidence that the BEST guardrail terminal meets the requirements of NCHRP Report 350 Test 3-34.

The BEST guardrail terminal can bring competition to the tangent energy absorbing guardrail terminal market. Competition will not only drive the costs of guardrail terminals down, but it will also allow some states that are precluded from making sole source purchases to begin to use NCHRP 350 terminals. Therefore, the BEST system is believed to offer the potential for significantly improving the safety of guardrail ends across the nation.

7 REFERENCES

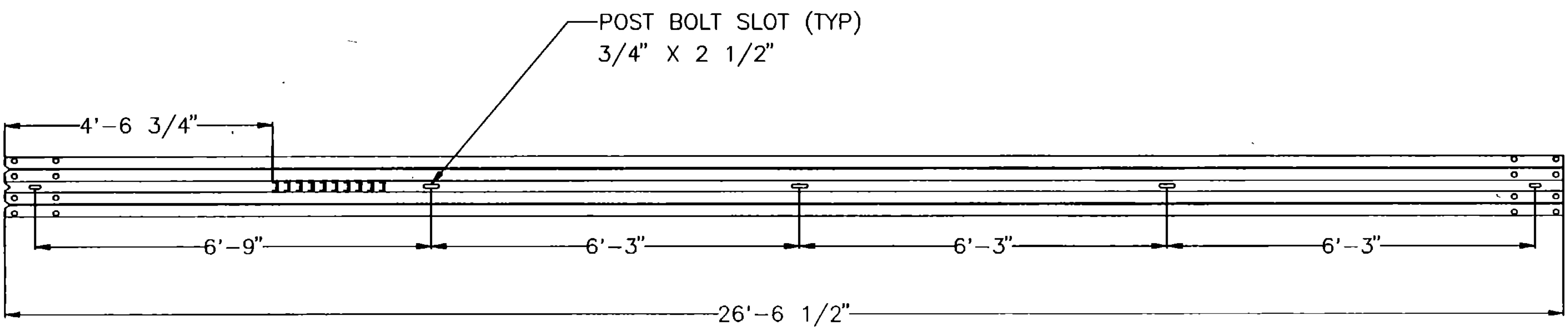
1. B.G. Pfeifer and D.L. Sicking, *Development of a Metal Cutting W-Beam Guardrail Terminal*, Report TRP-03-43-94, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Ne., September 1994.

2. *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.

3. *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Highway Research Program Report No. 350, Transportation Research Board, Washington, D.C., 1993.

8 APPENDIX A - System Drawings

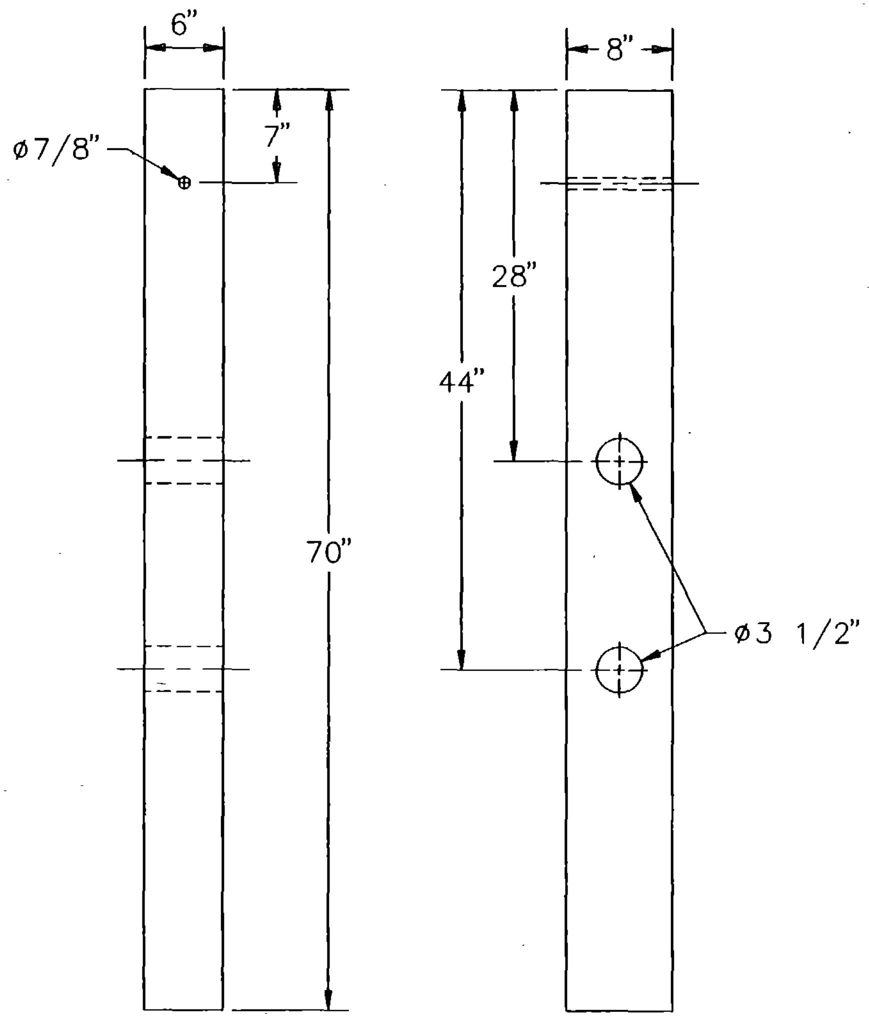
94



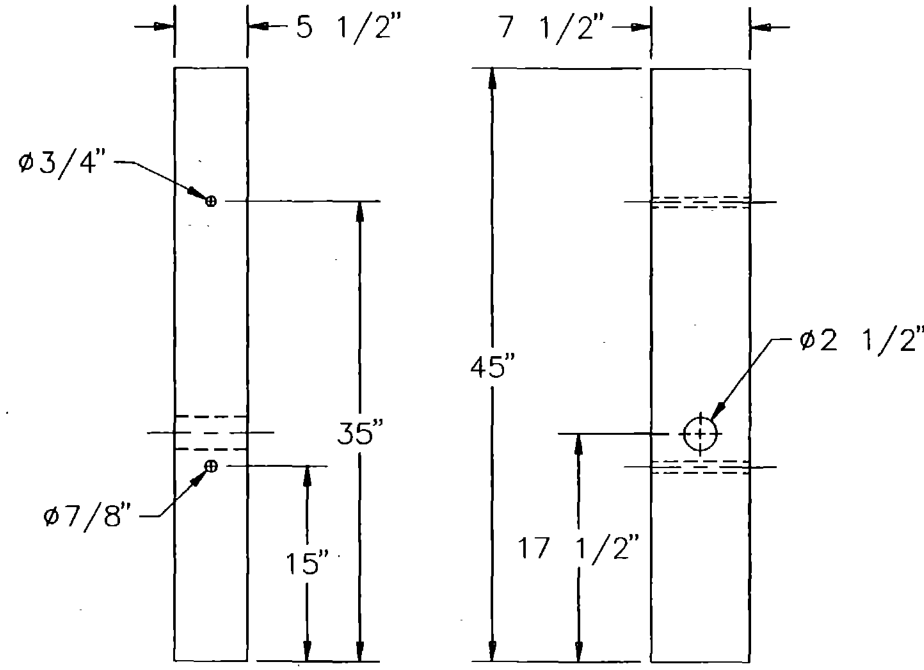
MwRSF University of Nebraska C.E. Department

BEST

DATE: 9-16-96		
SCALE: none		BPRAIL
DR'N: BWB		



Post Nos. 3–7



Post Nos. 1&2

MwRSF University of Nebraska C.E. Department

BEST

DATE: 10–23–96		
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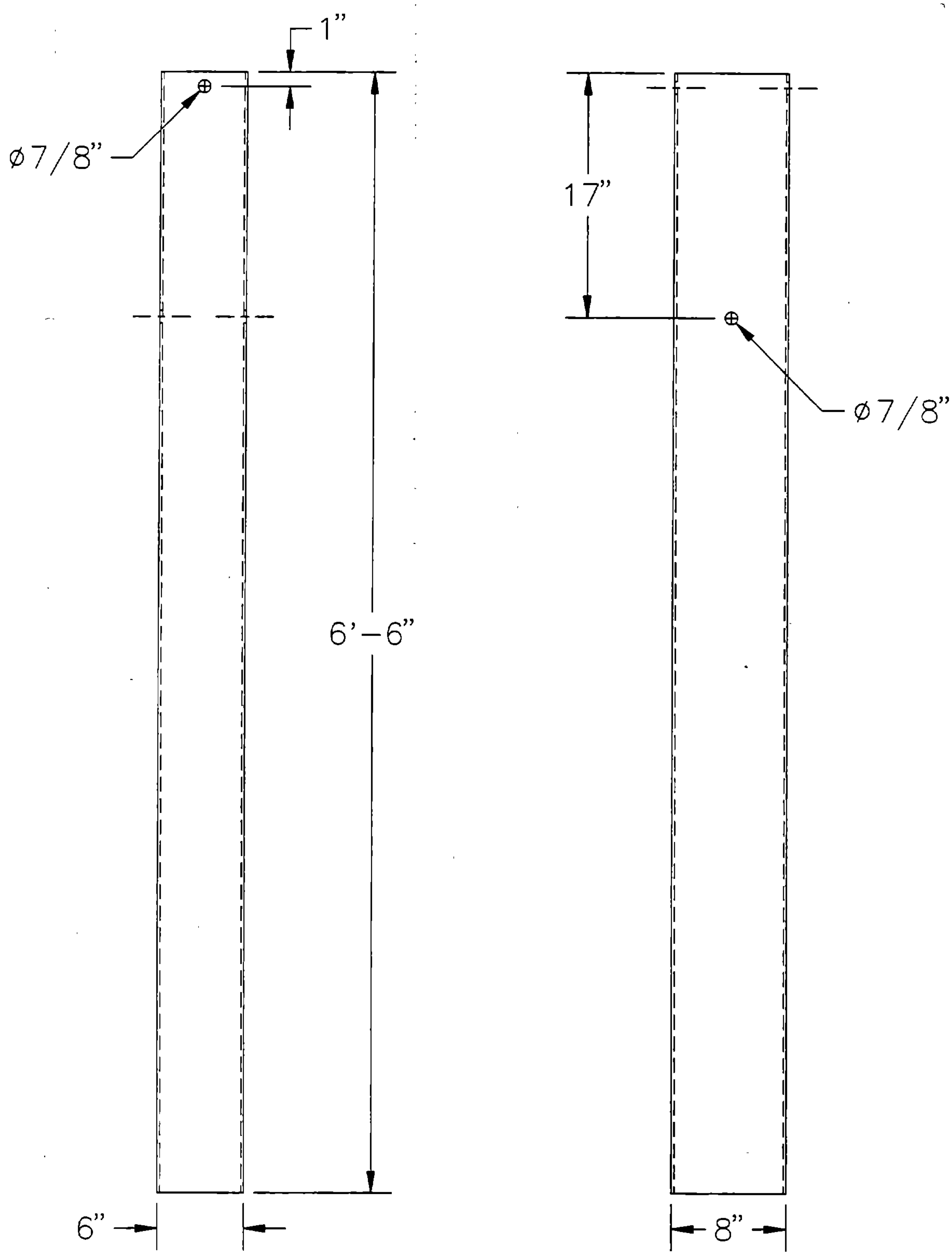
DR'N: EAK		

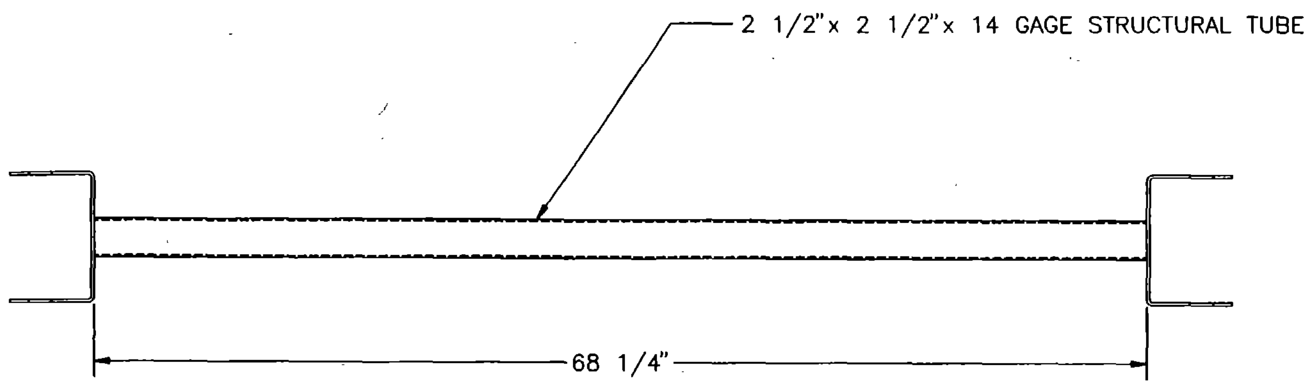


Foundation Tube
TS 8"x6"x3/16"

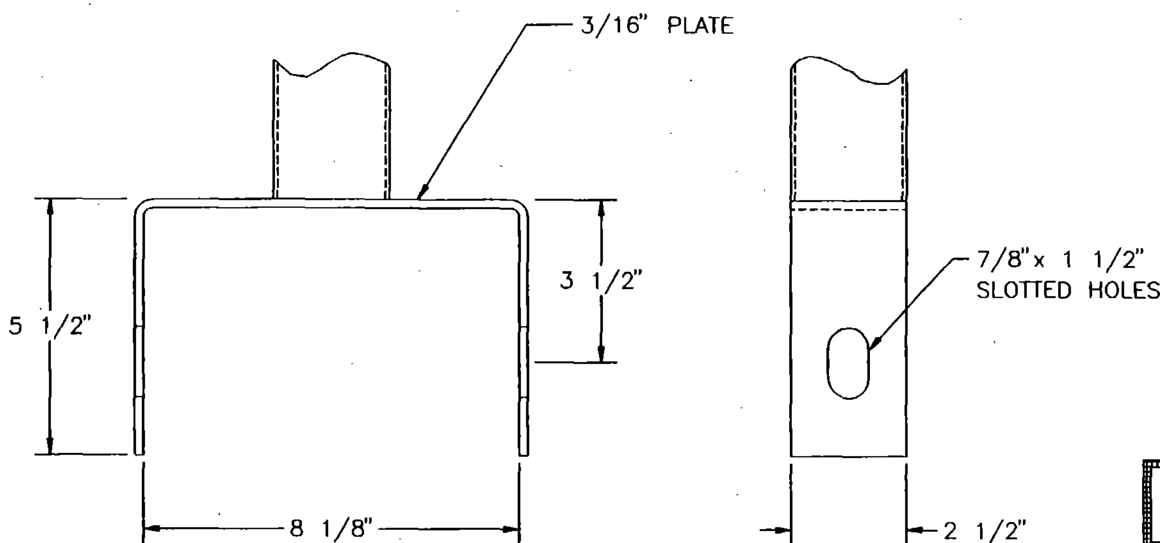
MwRSF University of Nebraska C.E. Department

BEST

DATE: 10-23-96		
SCALE: none		ftube
DR'N: EAK		



STRUT DETAIL



YOKE DETAILS

MwRSF University of Nebraska C.E. Department

BEST

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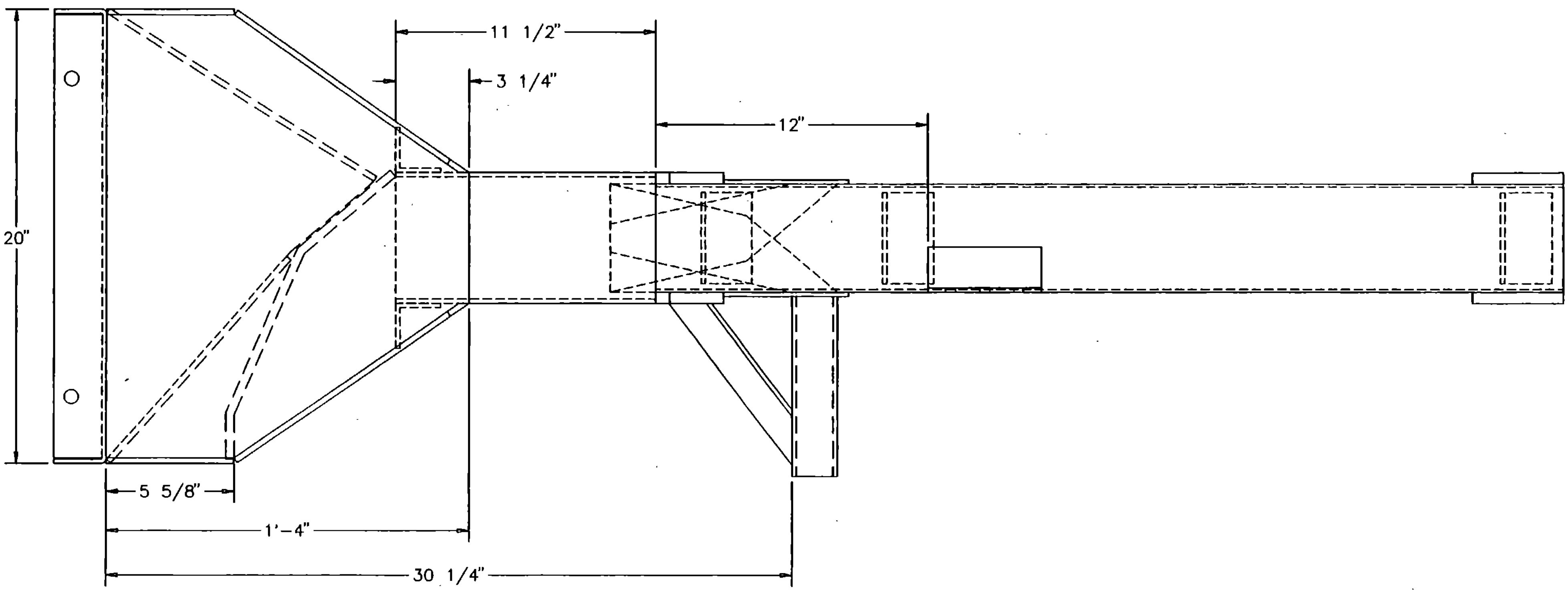

MwRSF University of Nebraska C.E. Department

BEST

DATE: 10-22-96		
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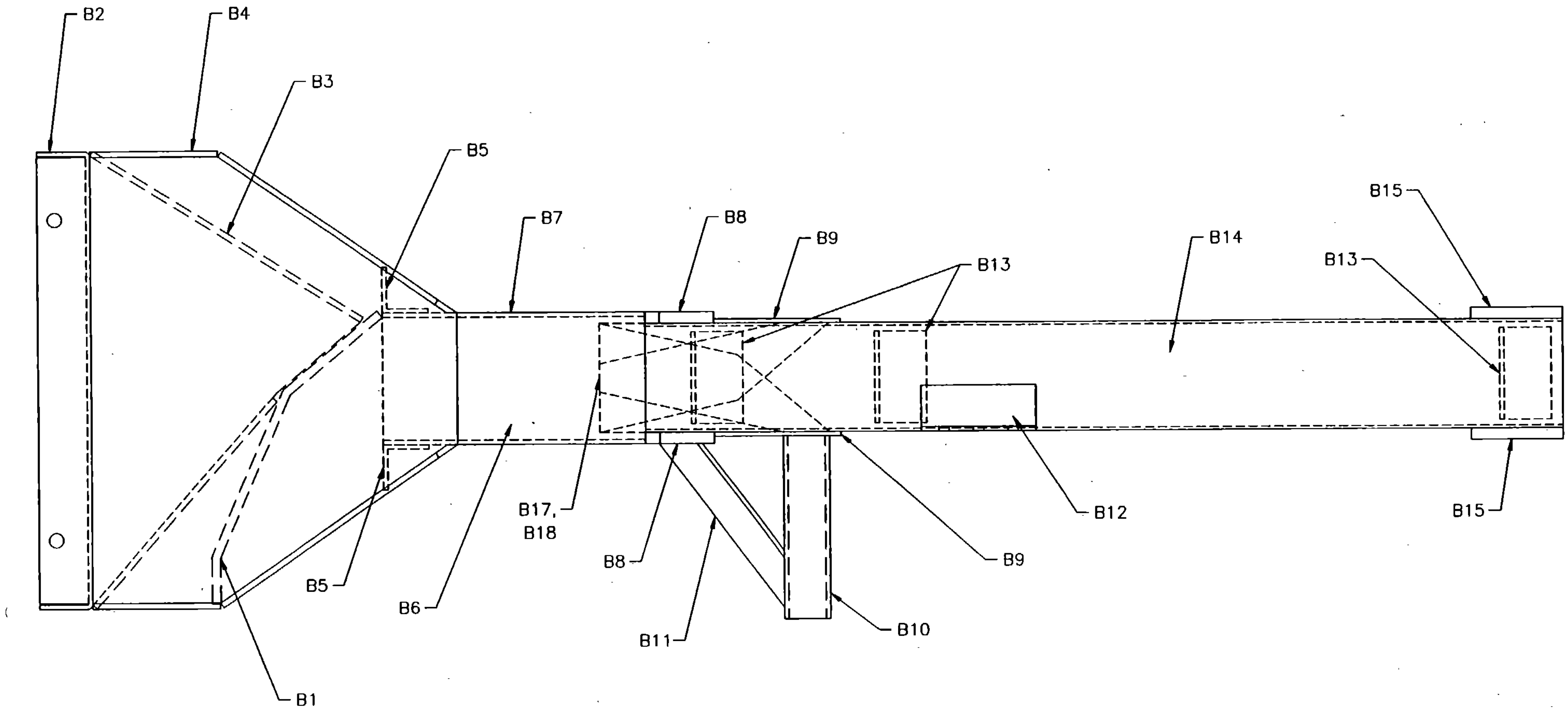
DR'N: EAK		



MwRSF University of Nebraska C.E. Department

BEST

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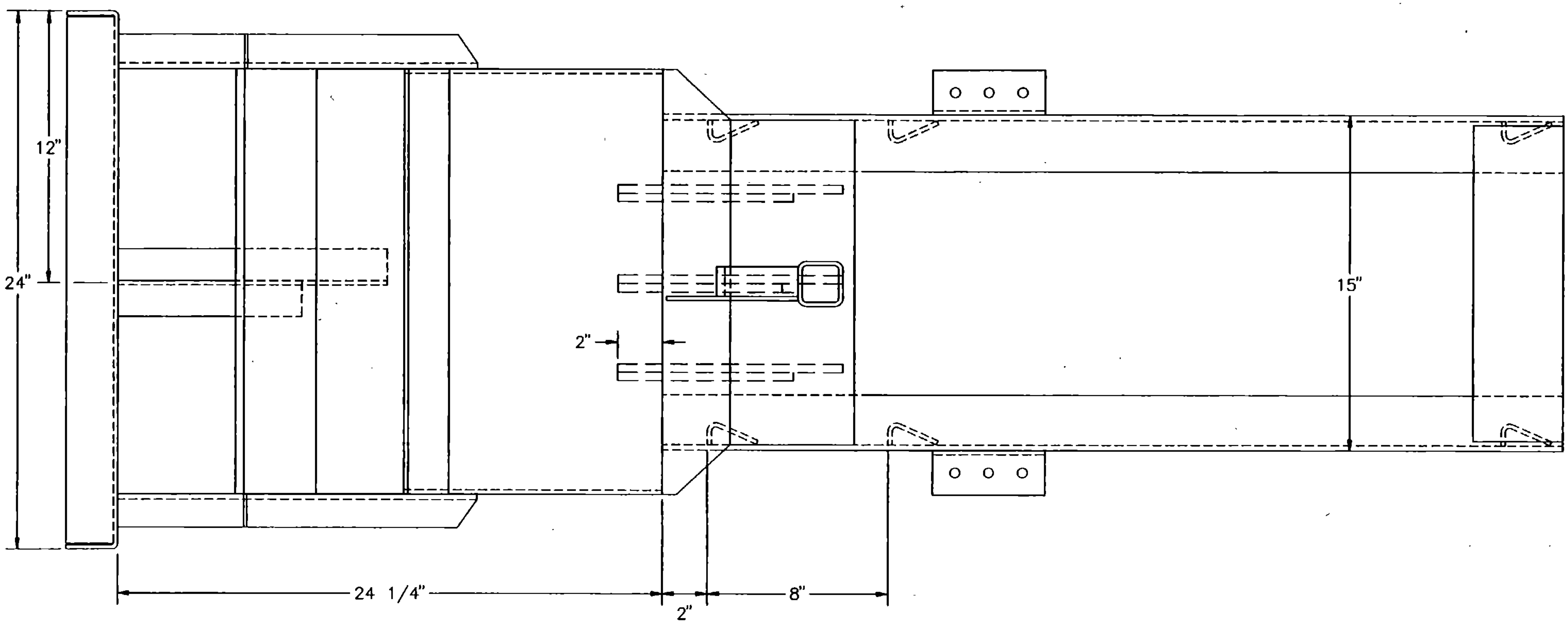
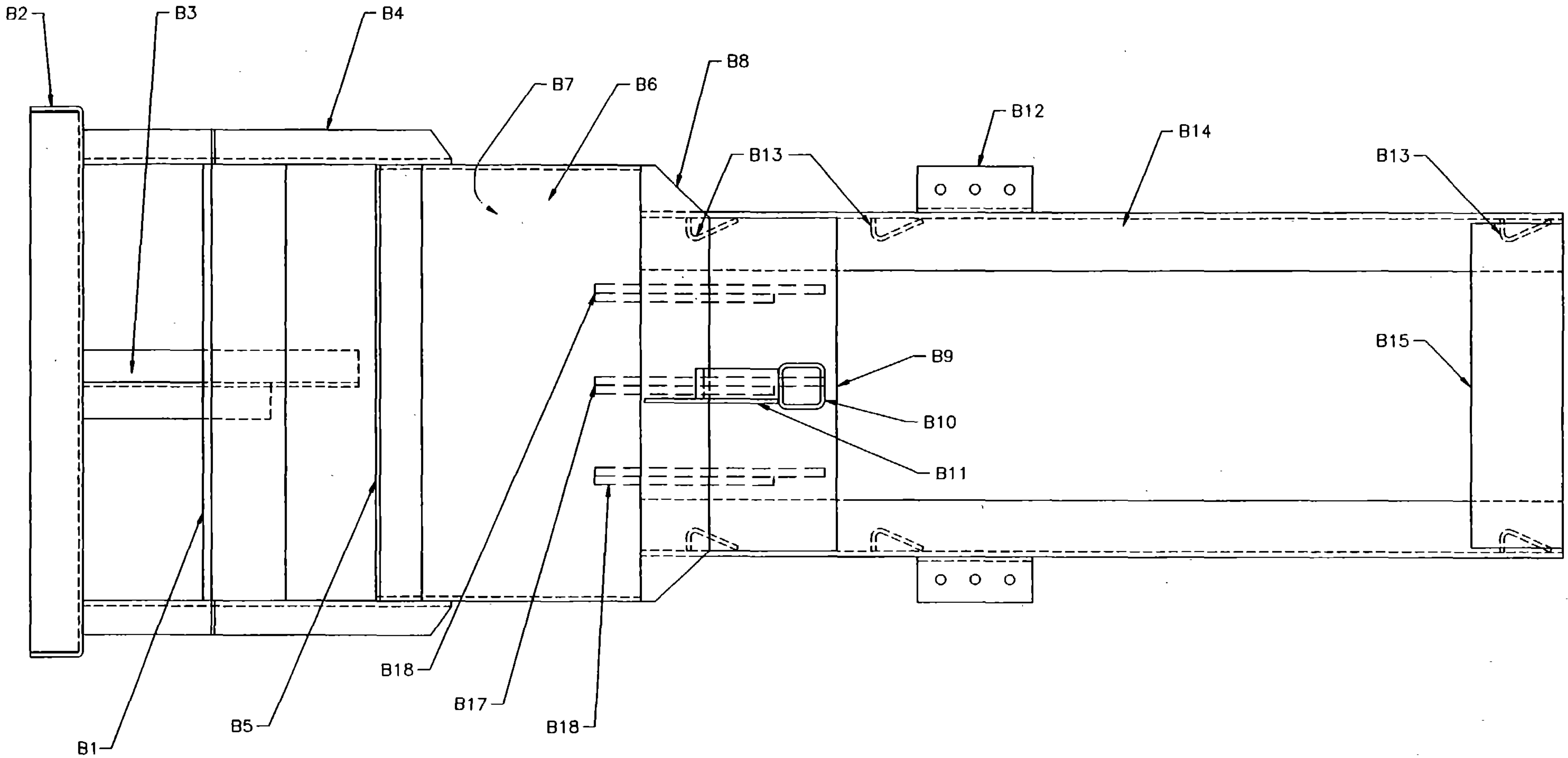


MwRSF University of Nebraska C.E. Department

BEST

DATE: 10-22-96		
SCALE: none		350side1
DR'N: EAK		



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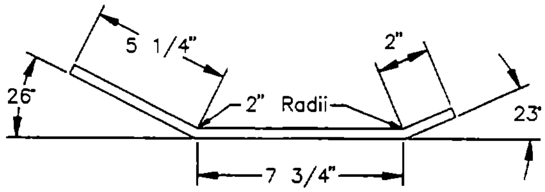
BEST

DATE:	10-22-96		
SCALE:	none		350side2
DR'N:	EAK		

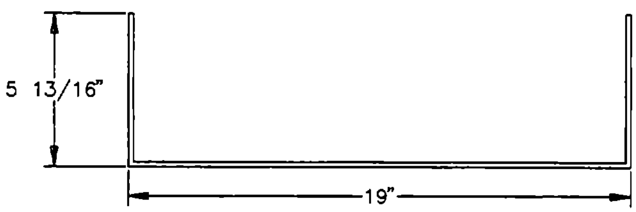


B1

15"x19"x3/8" Bent PL

Quantity = 1

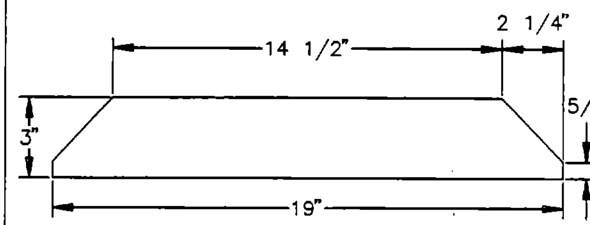
		Quantity
B5	19"x2"x2"x3/16" ∠	2
B10	8"x2"x2"x3/16" struct. tube	1
B7	19"x11 1/2"x3/16" PL	1
B9	5 1/2"x14 1/2"x3/16" PL	2
B15	4"x14 1/8"x1/2" PL	2



B6

30 5/8"x11 1/2"x3/16" Bent PL

Quantity = 1



B8

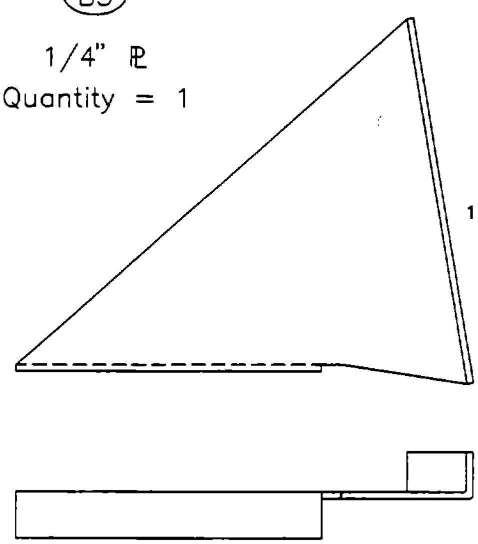
1/2" PL

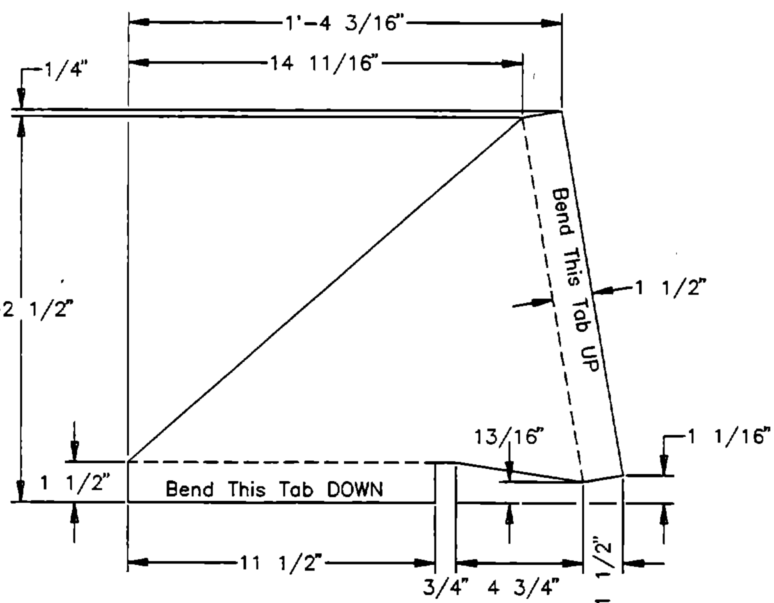
Quantity = 2

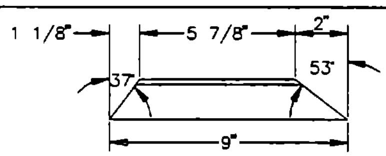
B3

1/4" PL

Quantity = 1







B11 1 1/2"x1 1/2"x3/16" ∠

Quantity = 1

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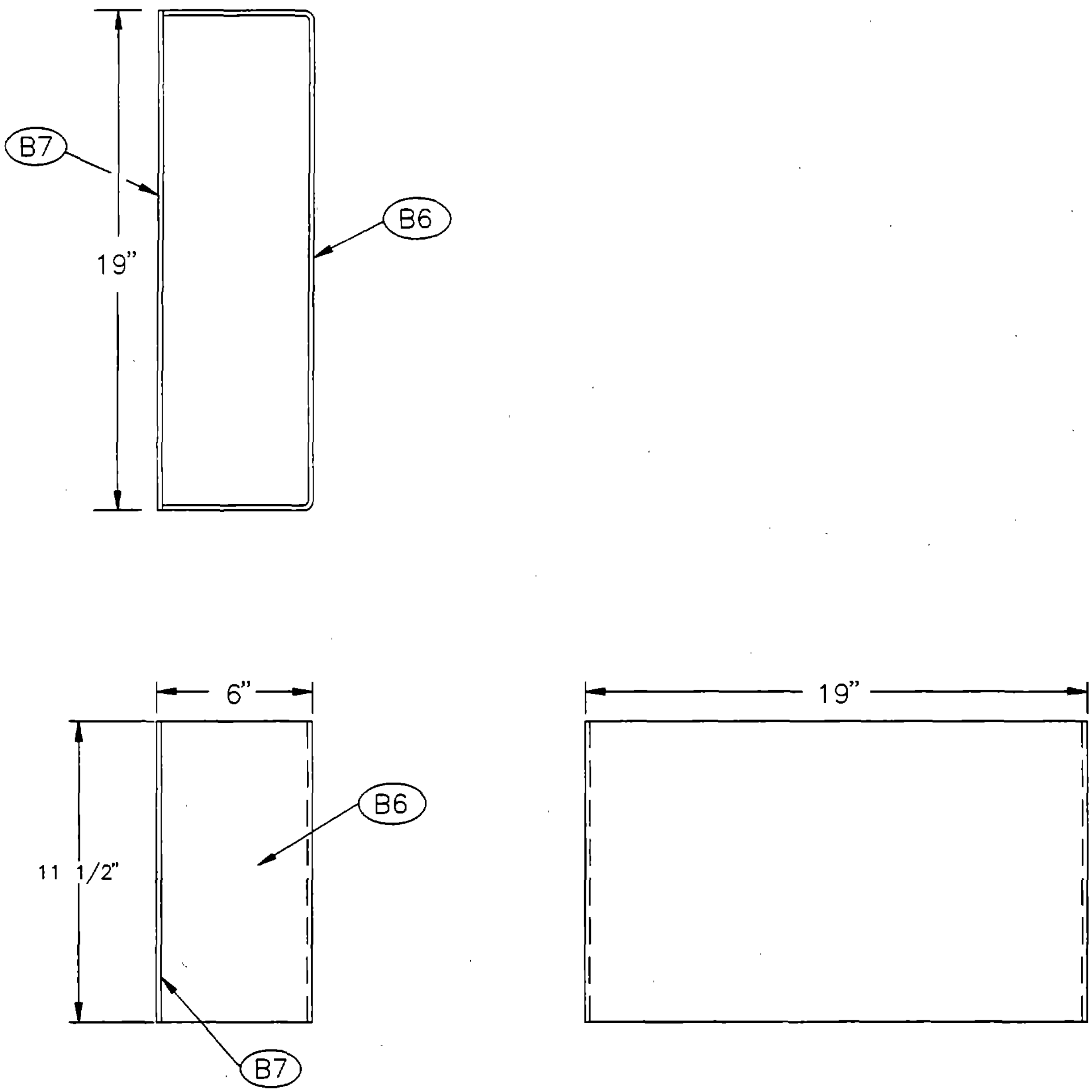
BEST–Head Components

DATE:	10-22-96		
SCALE:	none		partsa
DR'N:	KPR		

93



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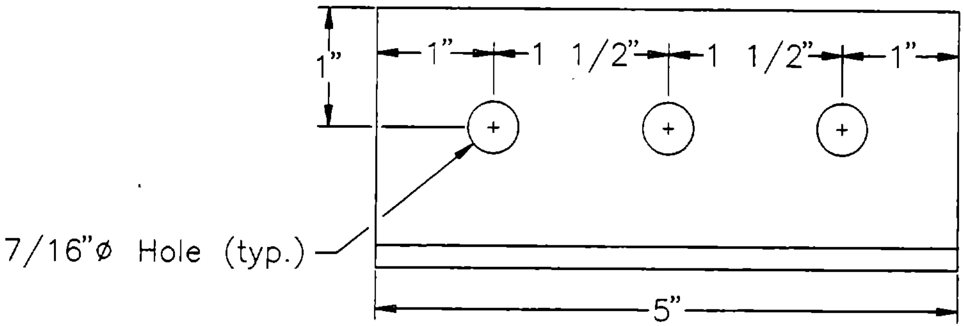
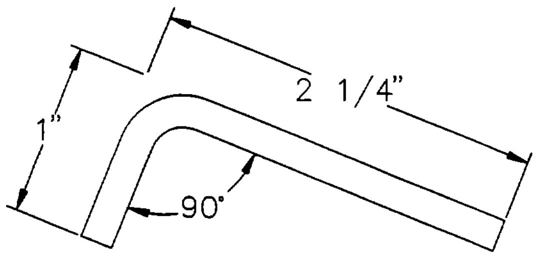
BEST

DATE:	10-22-96		
SCALE:	none		assem
DR'N:	BSP		



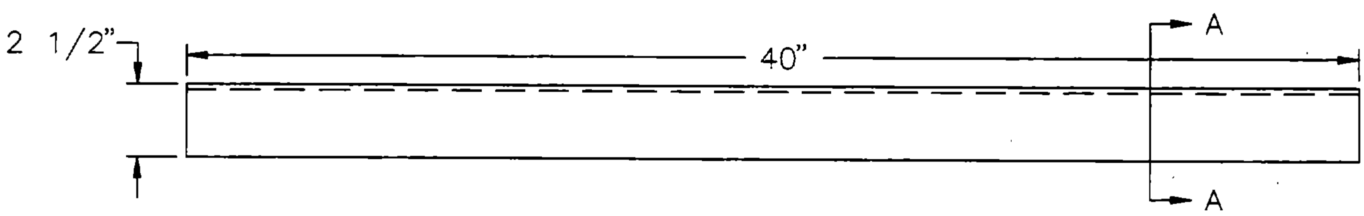
(B12)

2"x2"x3/16" ∠
Quantity = 2



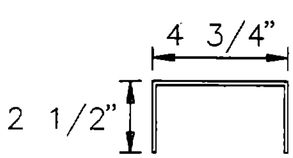
(B13)

3 1/4"x4"x3/16" Bent PL
Quantity = 6



(B14)

9 3/4"x40"x1/4" Bent PL
Quantity = 2



Section A–A

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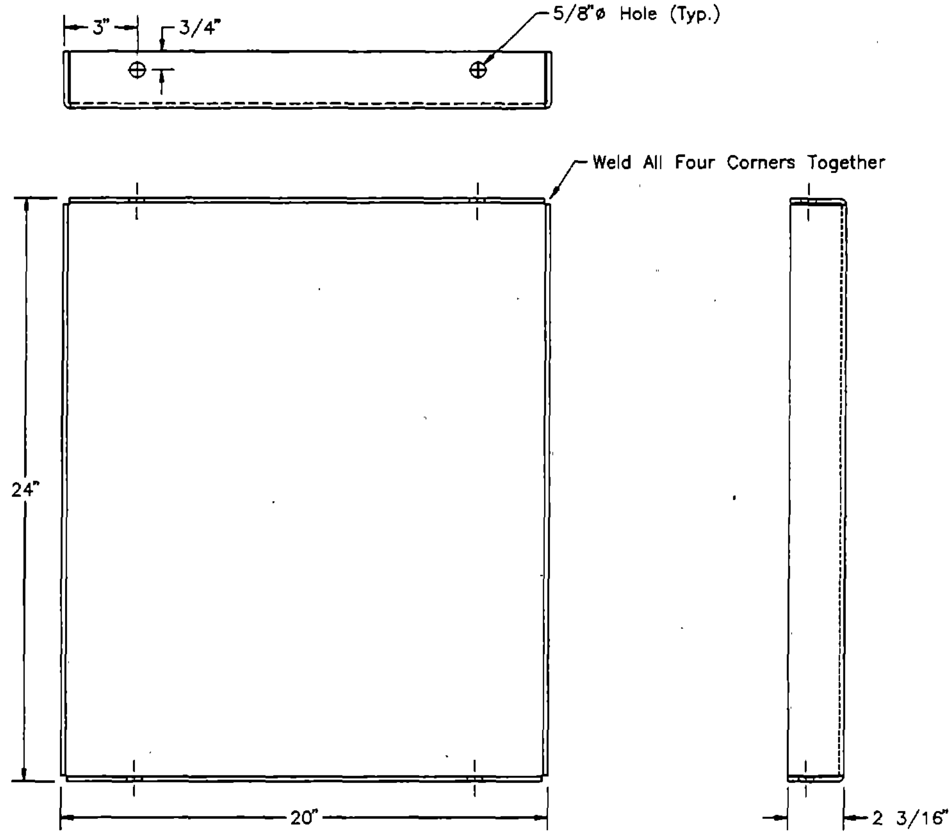
BEST–Head Components

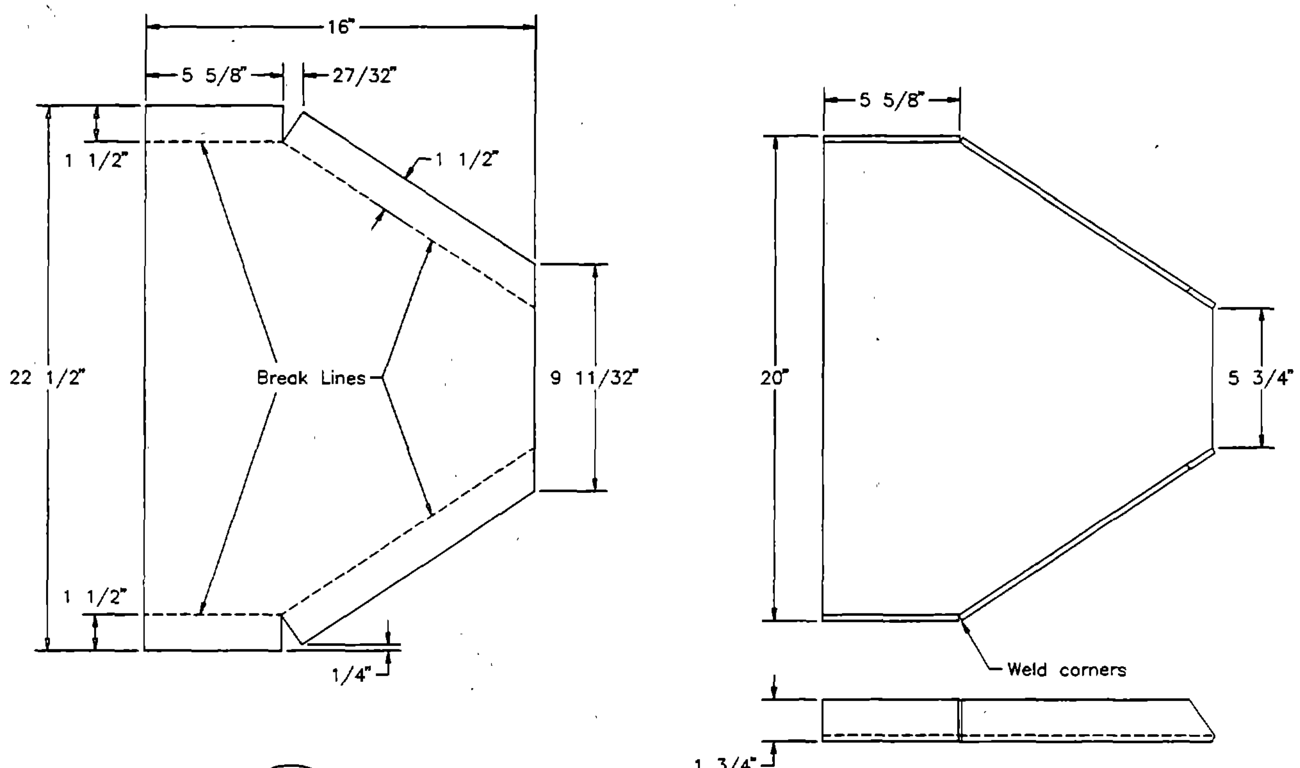
DATE: 10–22–96		
SCALE: none		partsb
DR'N: KPR		



B2

3/16" ℙ
Quantity = 1

Note: Break edges at 90° and weld corners



B4

1/4" ℙ
Quantity = 2

Break edges at 90°

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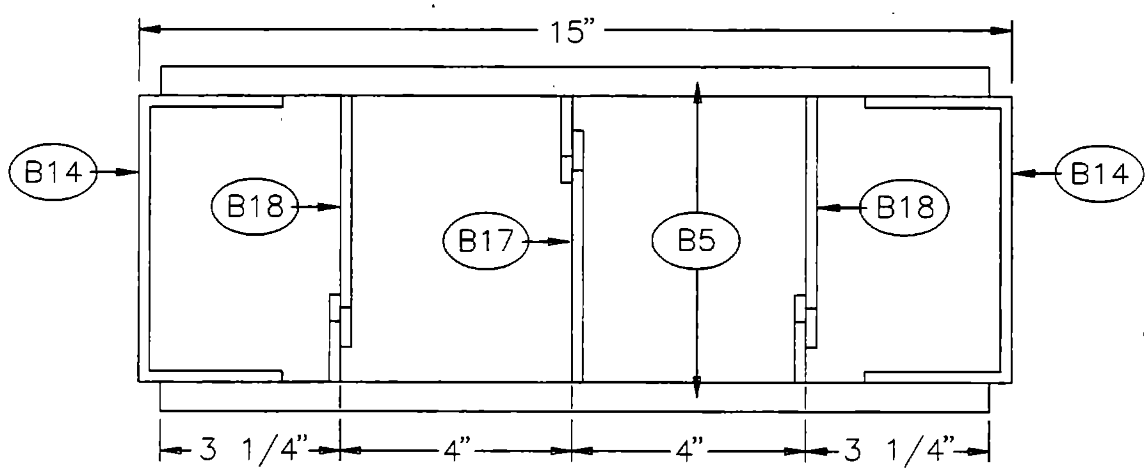
C.E. Department

BEST-Head Components

DATE: 10-22-96		
SCALE: none		partsc
DR'N: EAK		

Protruding Square Tube on This Side



Cutting Blade Orientation
As viewed from right hand side of head drawings.

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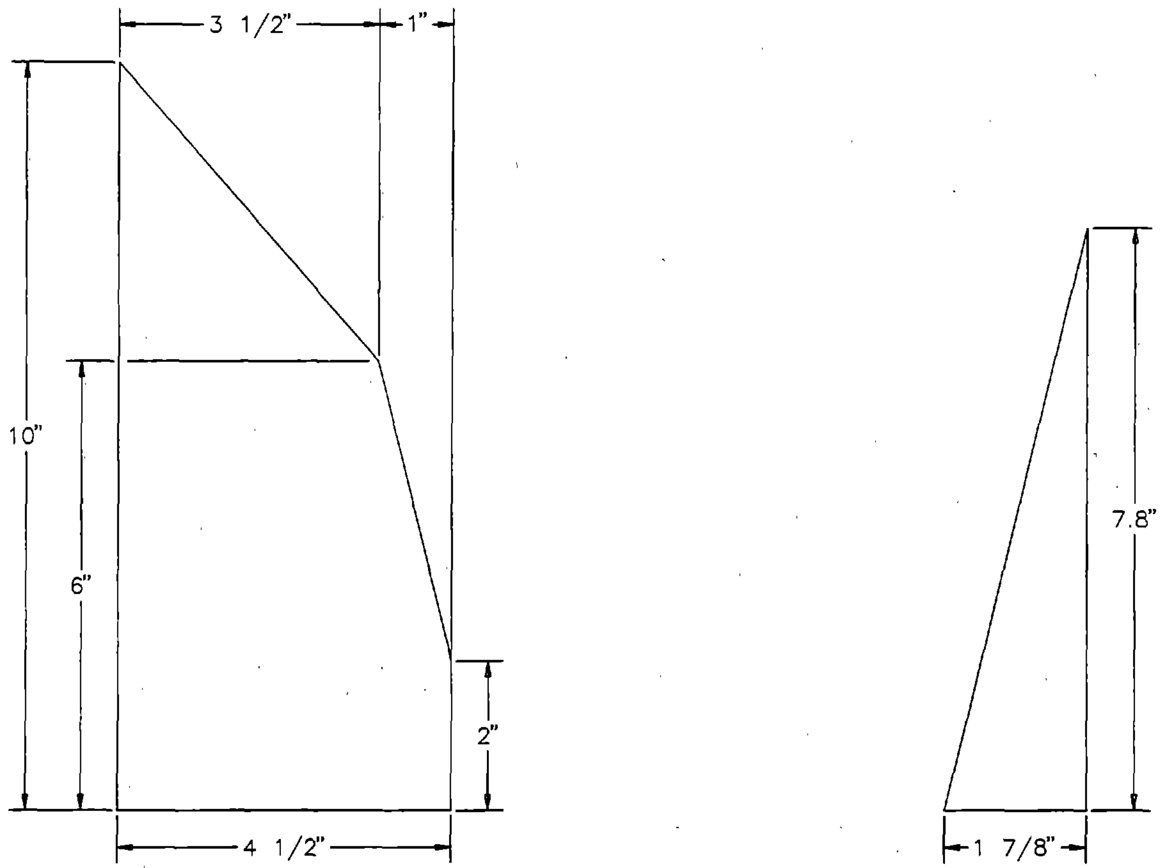
C.E. Department

BEST–Head Components

DATE:	10–22–96		
SCALE:	none		partsd
DR'N:	KPR		



3/8" AR250 PL

Components for B17 and B18

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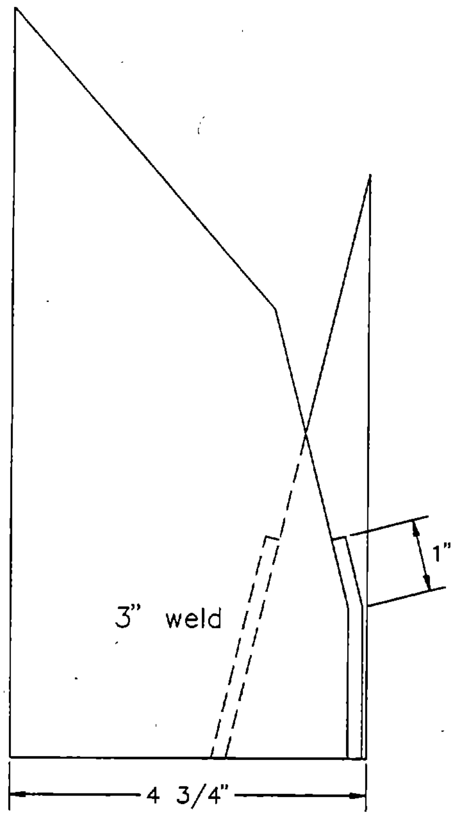
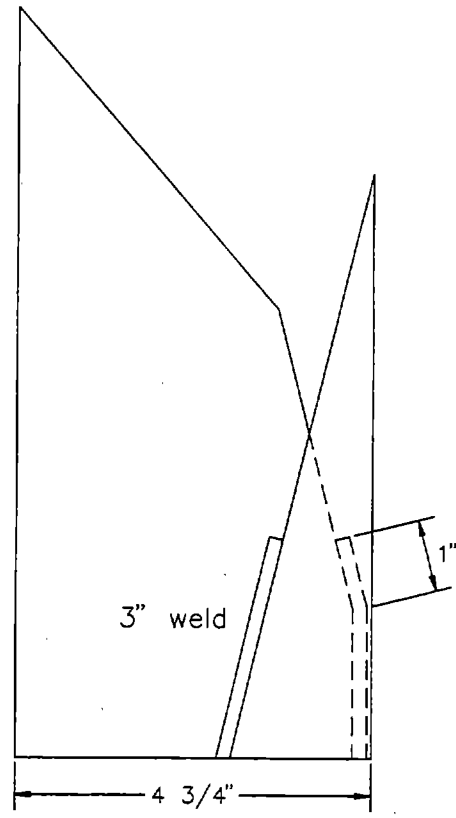
BEST

DATE:	10-22-96	SCISSORS	
SCALE:	none		blades
DR'N:	KPR		



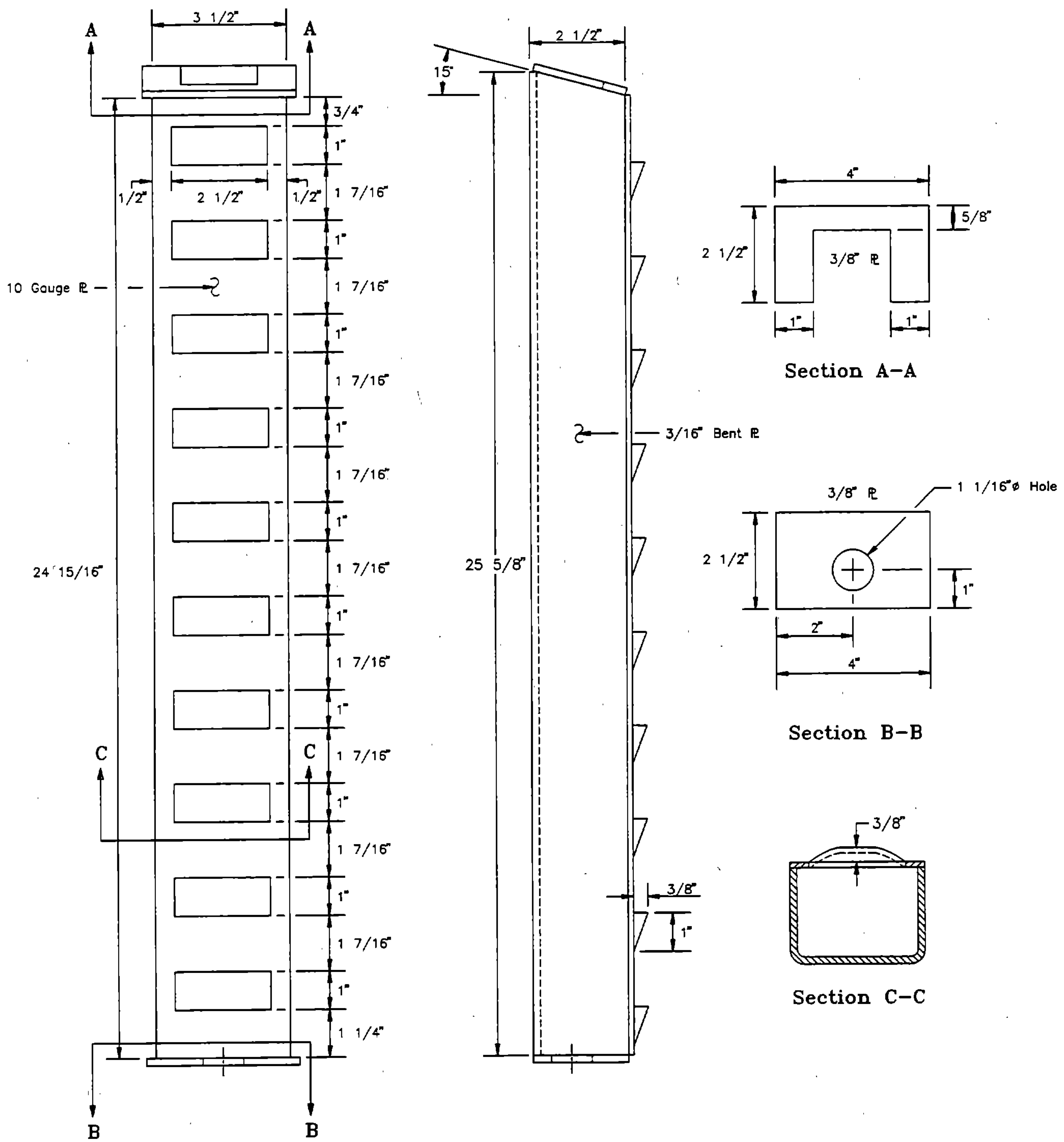
Middle Cutter
B17



Side Cutter
B18

3/8" AR250 PL

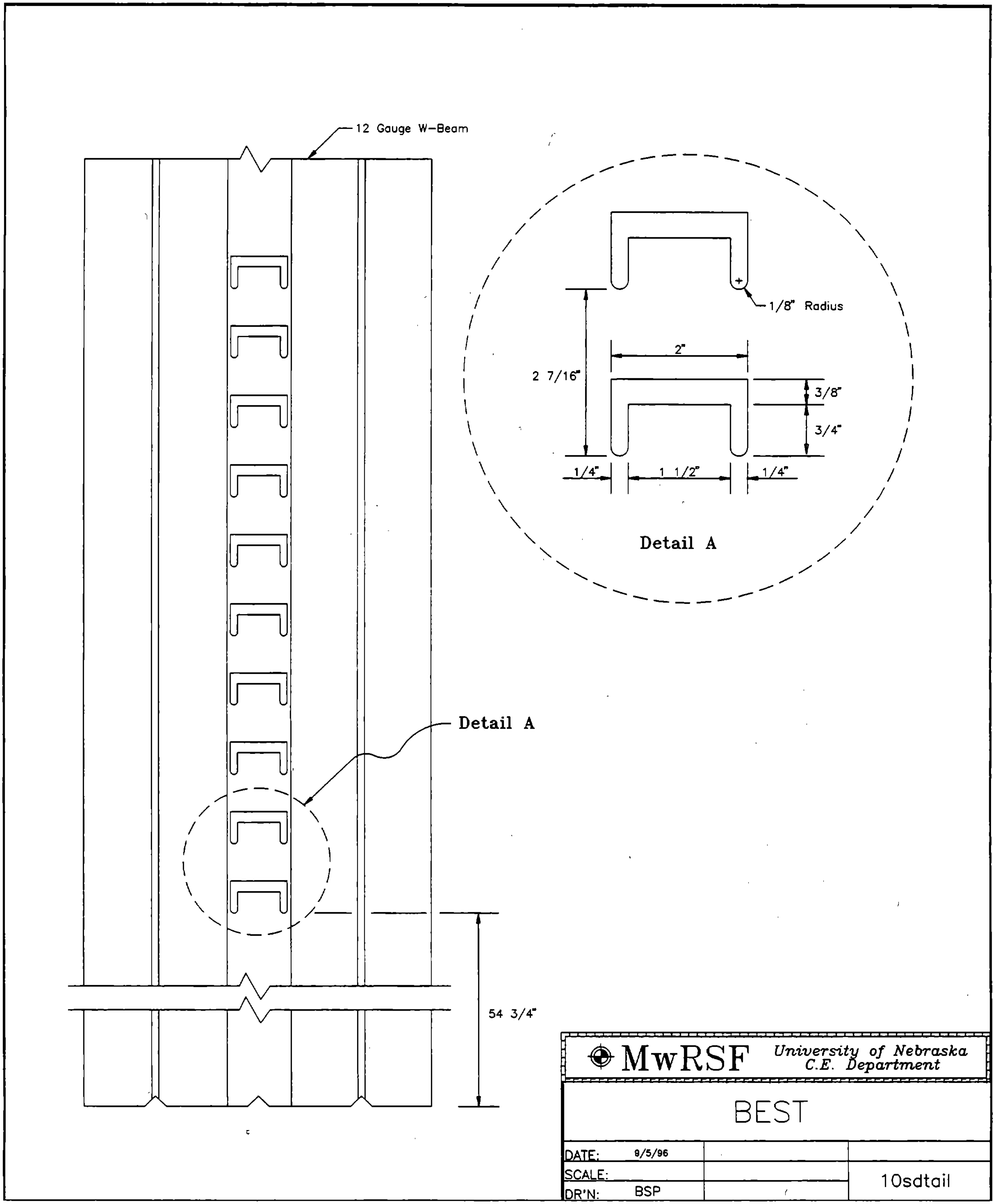
MwRSF	University of Nebraska C.E. Department	
BEST		
DATE: 10-22-96	SCISSORS	
SCALE: none		blades
DR'N: KPR		

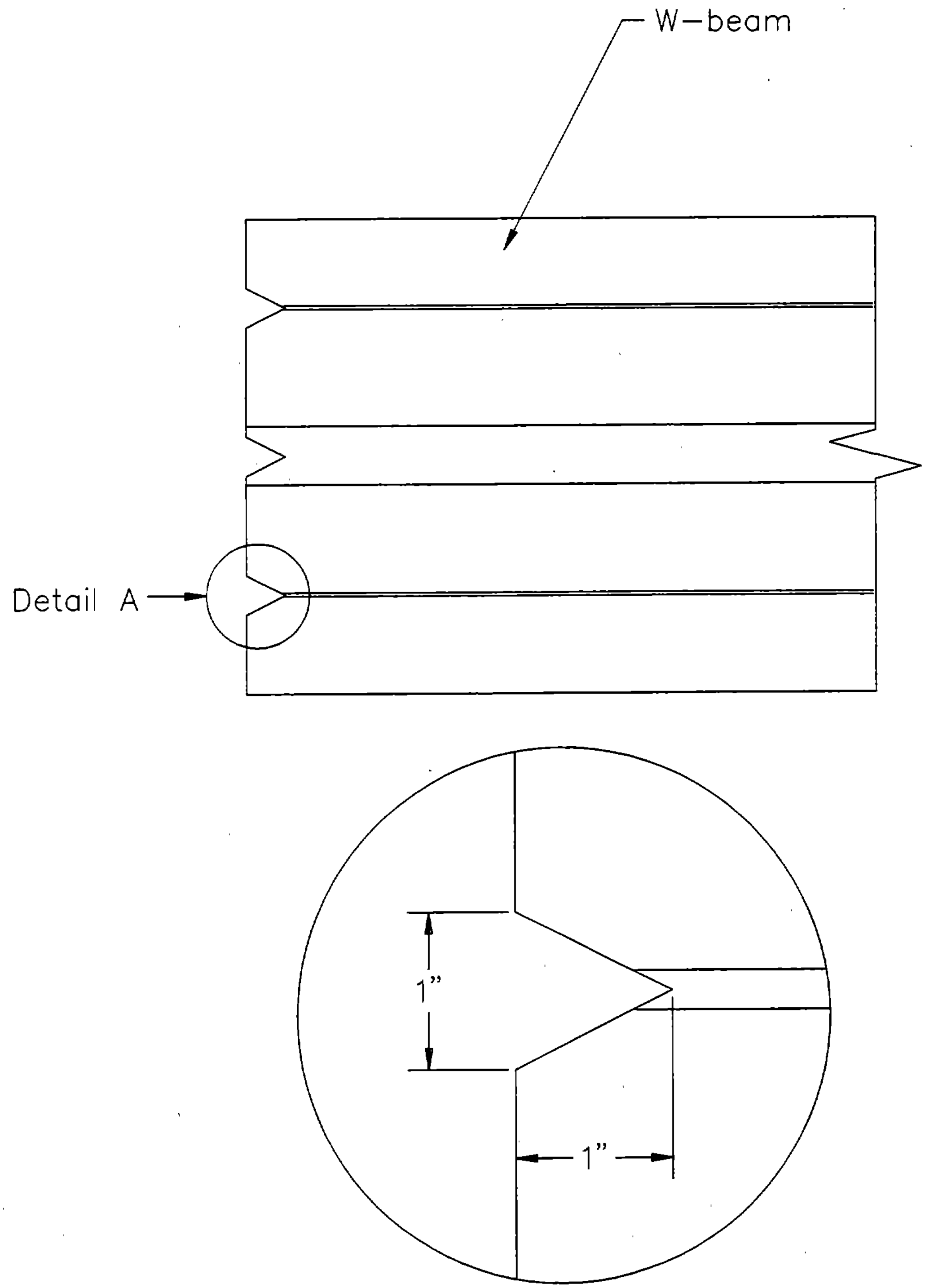


MwRSF University of Nebraska C.E. Department

BEST

DATE:	10-22-96	
SCALE:	none	10slot
DR'N:	BSP	


12 Gauge W-Beam
1/8" Radius
2"
2 7/16"
3/8"
3/4"
1/4"
1 1/2"
1/4"
Detail A
Detail A
54 3/4"
MwRSF
University of Nebraska
C.E. Department
BEST
DATE: 9/5/96
SCALE:
DR'N: BSP
10sdtail



Detail A

MwRSF University of Nebraska C.E. Department

BEST

DATE:	10-22-96		
SCALE:			wbeamend
DR'N:	KPR		

9 APPENDIX B - Test Vehicle Information

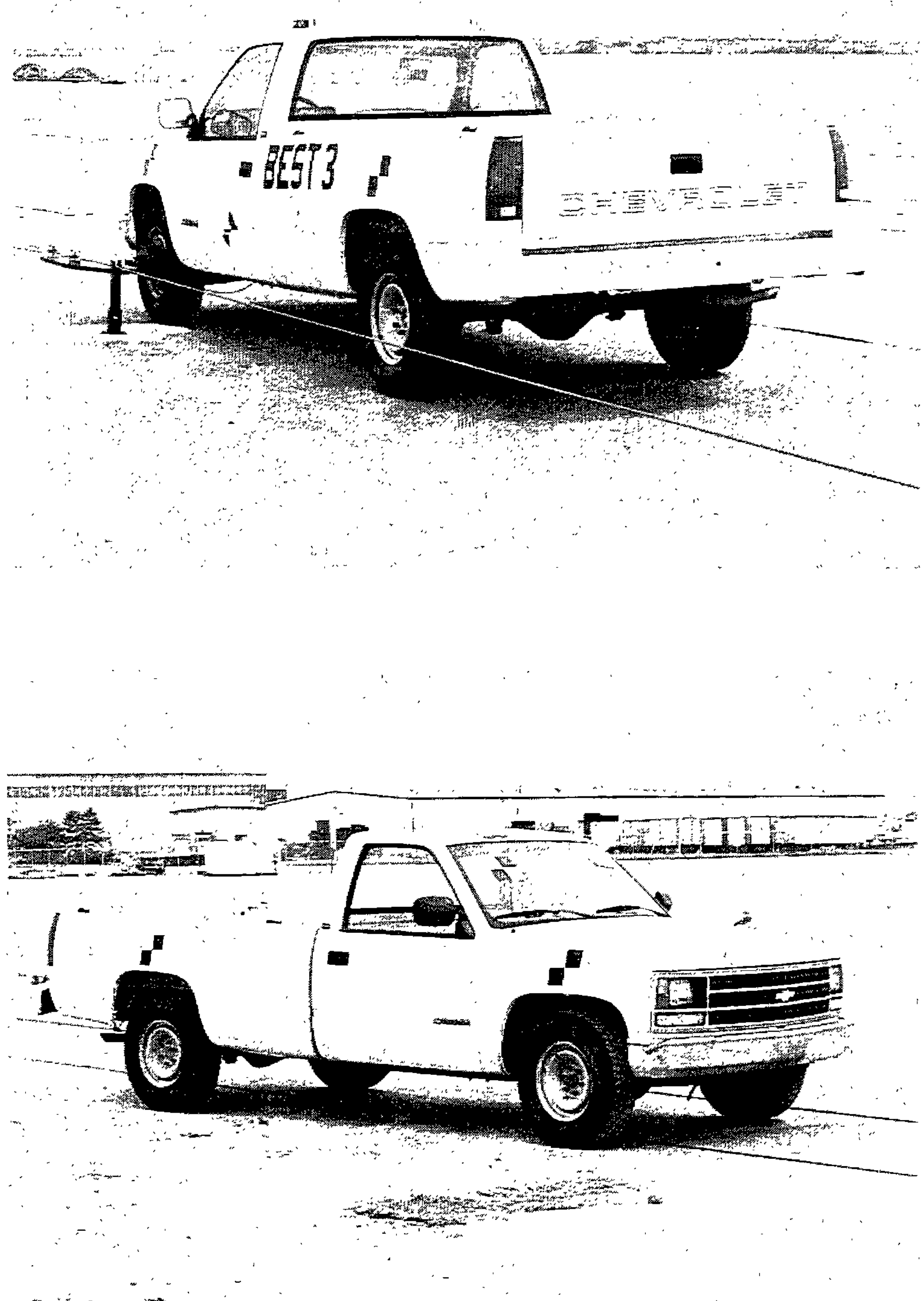


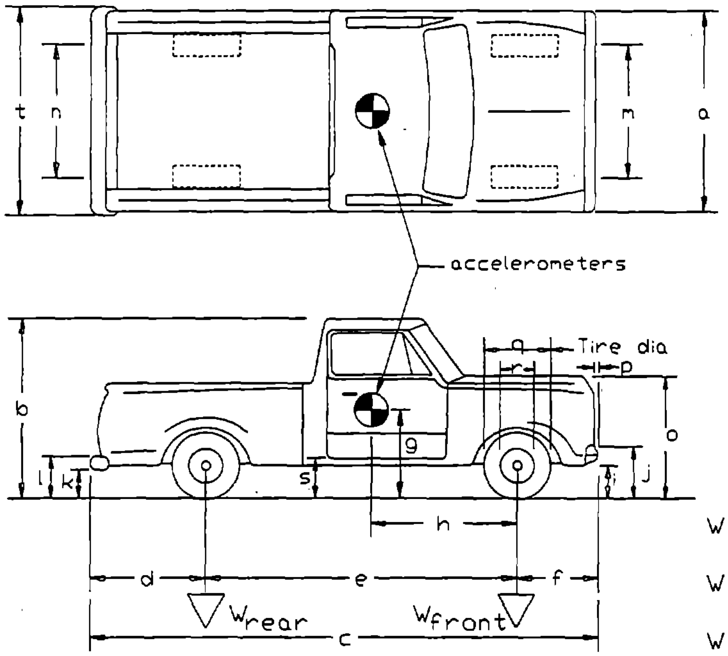
Figure B-1. Test Vehicle, Test BEST-3.

Date: 7/30/96 Test Number: BEST-3 Model: 2500

Make: Chevrolet Vehicle I.D.#: 1GCF24K4JE189961

Tire Size: 245/75-16 Year: 1992 Odometer: 153090

*(All Measurements Refer to Impacting Side)



Vehicle Geometry - in

a 74	b 70
c 215.5	d 41.5
e 132.25	f 33.5
g 26.20	h 58.5
i 16	j 24.5
k 22.75	l 21.25
m 62.5	n 63.25
o 40	p 3.25
q 30	r 17.5
s 16.25	t 73.75

Wheel Center Height Front 14.5

Wheel Center Height Rear 14.75

Wheel Well Clearance (FR) 33.5

Wheel Well Clearance (RR) 35.5

Engine Type V-6

Engine Size 4.3 Liter

Transmission Type:

Automatic or Manual

FWD or RWD or 4WD

Weights - lbs	Curb	Test Inertial	Gross Static
W_{front}	2370	2463	2463
W_{rear}	1830	1956	1956
W_{total}	4200	4419	4419

Conversion Factor: 1 lb = 0.4536 kg
1 in = 25.4 mm

Note any damage prior to test: ____________________

Figure B-2. Test Vehicle Dimensions, Test BEST-3.

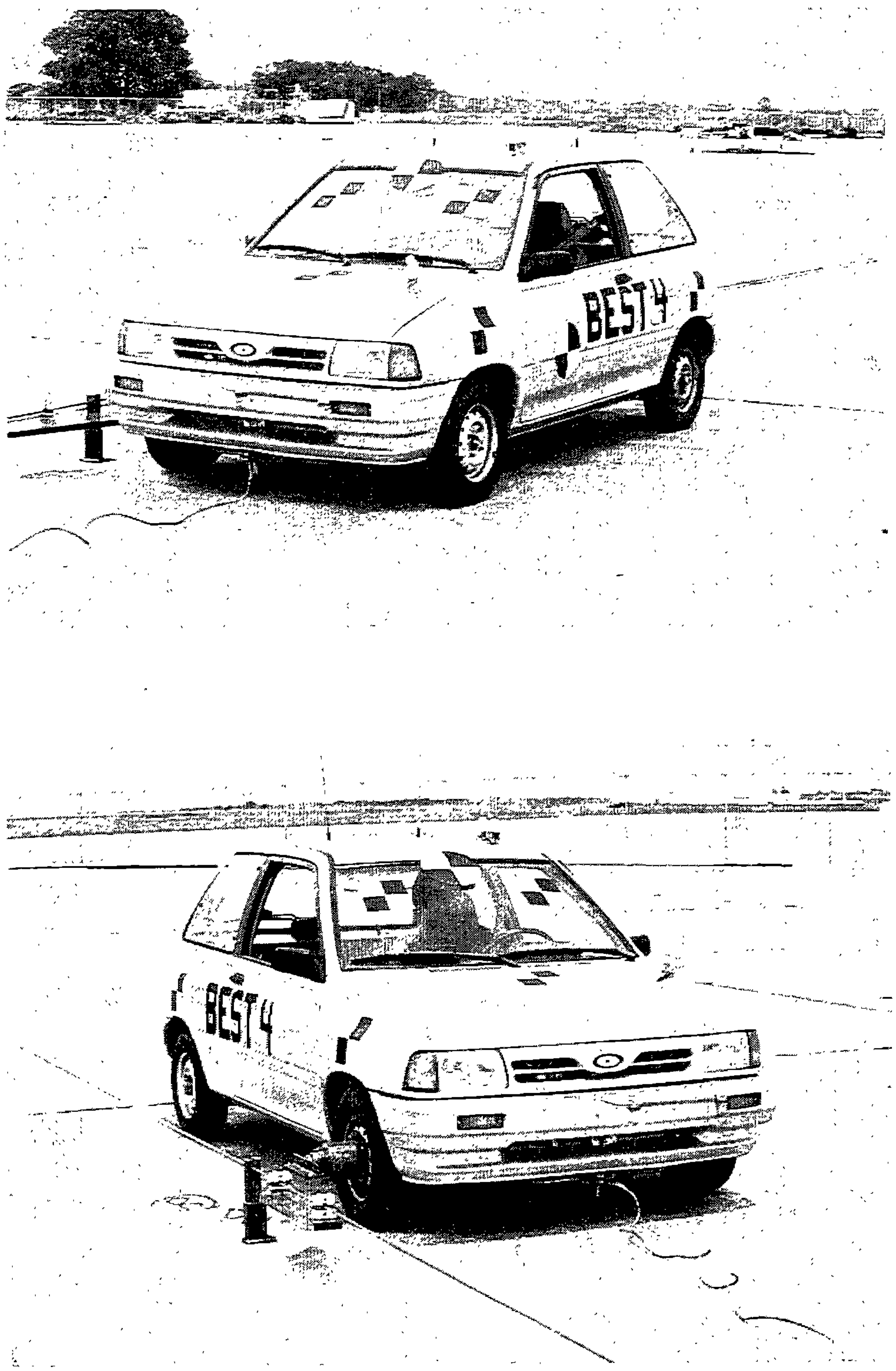
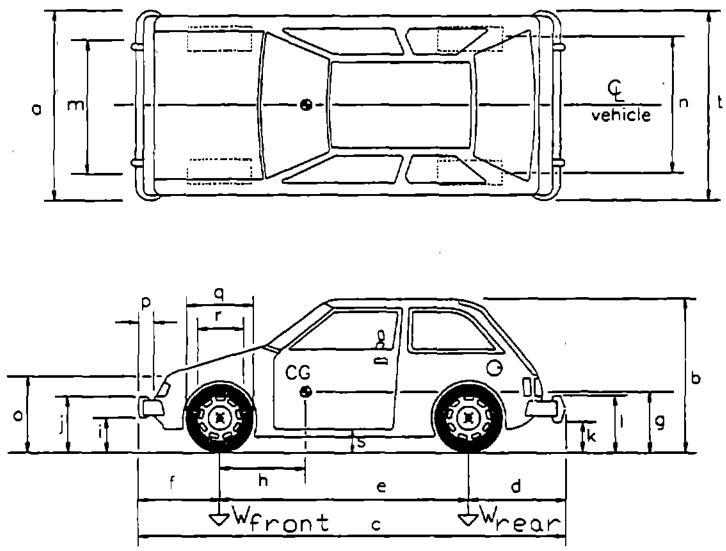


Figure B-3. Test Vehicle, Test BEST-4.

Date: 8/2/96 Test Number: BEST-4 Model: Festiva

Make: Ford Vehicle I.D.#: KNJPT06H6M6142114

Tire Size: 115-R12 Year: 1991 Odometer: 45524



Vehicle Geometry - in

a	63.5	b	57.0
c	139.0	d	22.5
e	90.375	f	26.0
g	22.0	h	31.39
i	14.5	j	21.5
k	15.5	l	22.5
m	55.5	n	55.0
o	29.5	p	3.25
q	21.5	r	13.0
s	11.5	t	61.0

height of wheel center 10.25

Engine Type 4 cylinder

Engine size 2.8 Liter

Transmission Type:

Automatic or Manual

FWD or RWD or 4WD

Weight - lbs	Curb	Test Inertial	Gross Static
W_{front}	1166	1168	1251
W_{rear}	639	641	724
W_{total}	1805	1809	1975

Conversion Factor : 1 lb = 0.4536 kg
1 in = 25.4 mm

Damage prior to test: None

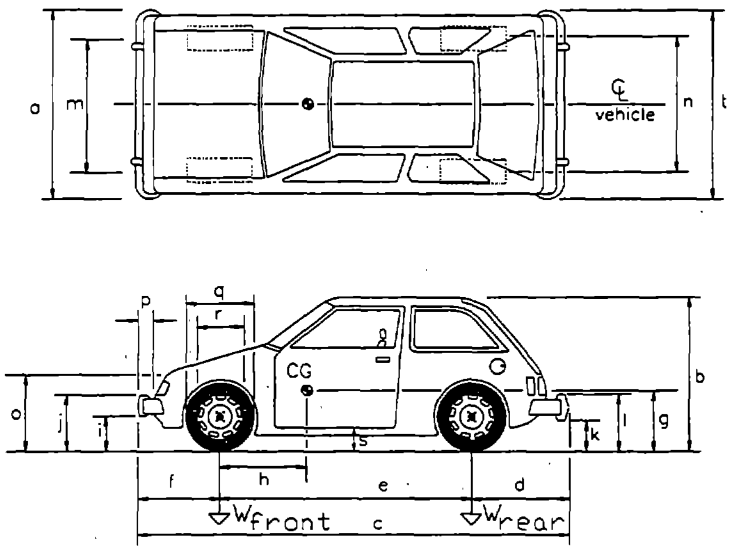
Figure B-4. Test Vehicle Dimensions, Test BEST-4.

Figure B-5. Test Vehicle, Test BEST-8.

Date: 10/3/96 Test Number: BEST-8 Model: Festiva

Make: Ford Vehicle I.D.#: KNJPT05HXL6143220

Tire Size: 145-S-R12 Year: 1990 Odometer: 69988



Vehicle Geometry - in

a	62	b	56.875
c	139.5	d	24
e	90.25	f	26.875
g	21.5	h	33.625
i	14.75	j	20
k	14.5	l	21.375
m	55.125	n	54.5
o	29	p	3.5625
q	21.125	r	13
s	11.125	t	62.5

height of wheel center 9.875

Engine Type ________

Engine size 4

Transmission Type:

Automatic or Manual

FWD or RWD or 4WD

Weight - lbs	Curb	Test Inertial	Gross Static
W_{front}	1101	1141	1224
W_{rear}	620	661	743
W_{total}	1721	1802	1967

Conversion Factor : 1 lb = 0.4536 kg
1 in = 25.4 mm

Damage prior to test: None

Figure B-6. Test Vehicle Dimensions, Test BEST-8.

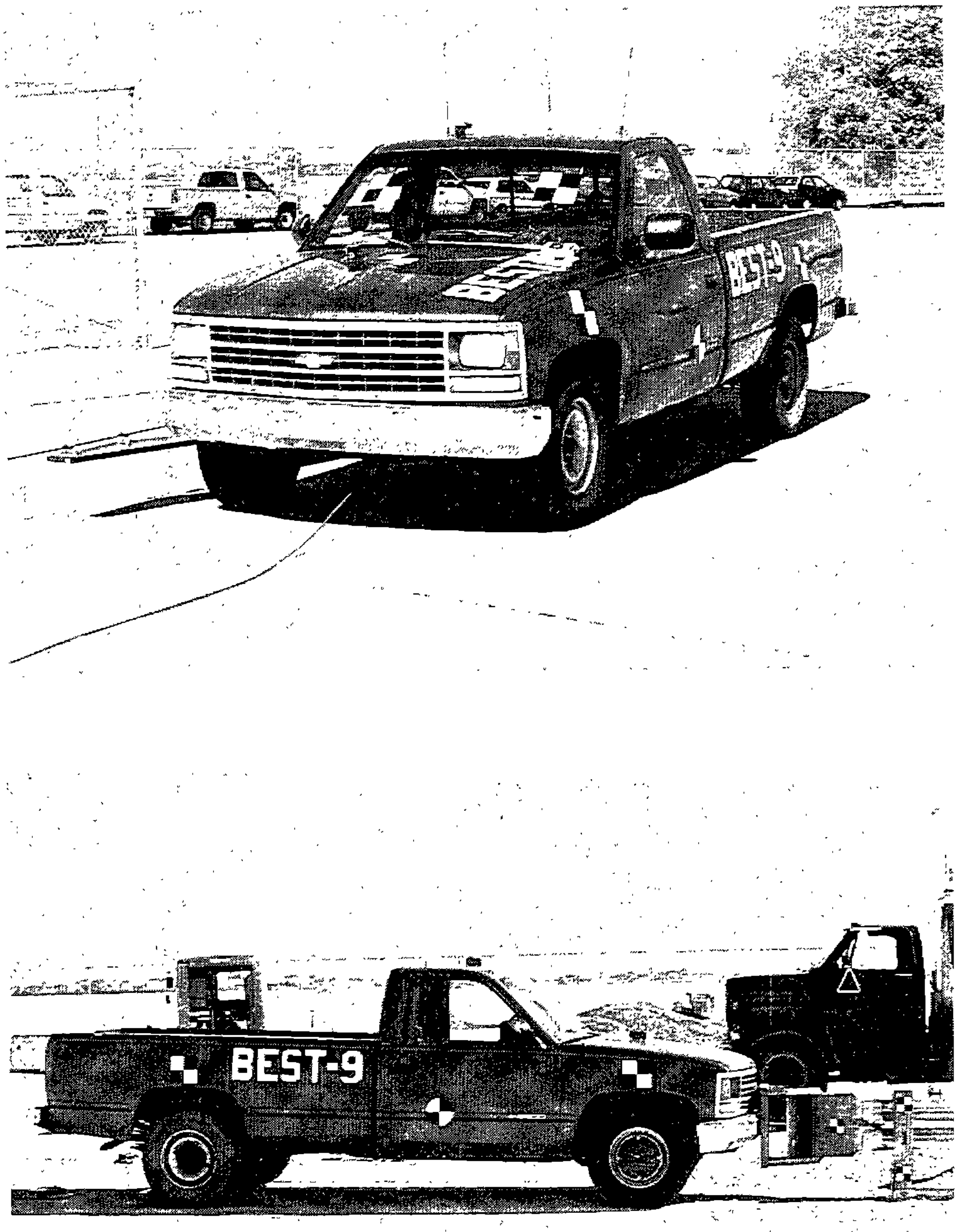


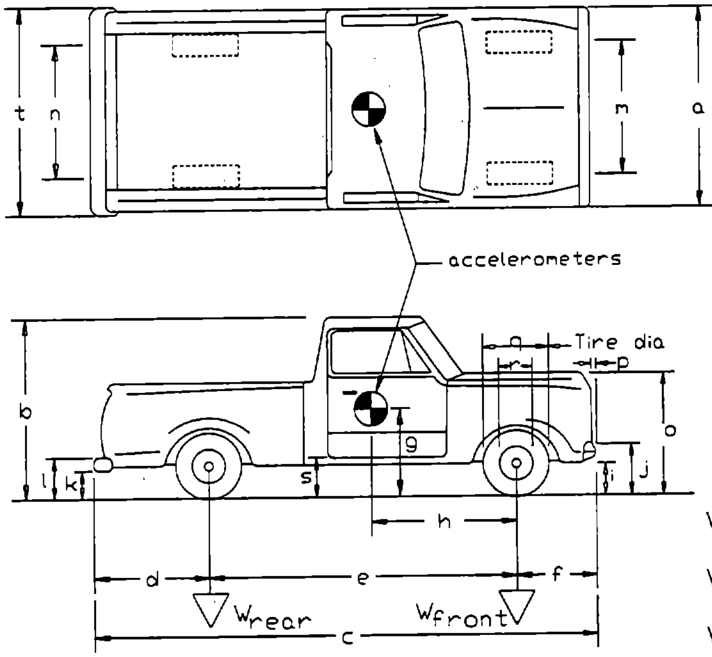
Figure B-7. Test Vehicle, Test BEST-9.

Date: 10/8/96 Test Number: BEST-9 Model: 2500

Make: Chevrolet Vehicle I.D.#: 1GCFC24K3L2255086

Tire Size: 245/75-R16 Year: 1990 Odometer: 132915

*(All Measurements Refer to Impacting Side)



Vehicle Geometry - in

a	74	b	71
c	214	d	48.75
e	131.5	f	33.625
g	28	h	56.5
i	15.5	j	24.5
k	20.25	l	30
m	62.75	n	63.75
o	40	p	2.75
q	30	r	17
s	16	t	73.5

Wheel Center Height Front 14.5

Wheel Center Height Rear 14.25

Wheel Well Clearance (FR) 33.125

Wheel Well Clearance (RR) 36.25

Engine Type 350 V-8

Engine Size 5.7 liter V-8

Transmission Type:

Automatic or Manual

FWD or RWD or 4WD

Weights - lbs	Curb	Test Inertial	Gross Static
W_{front}	2468	2463	2463
W_{rear}	1853	1956	1956
W_{total}	4321	4421	4421

Conversion Factor: 1 lb = 0.4536 kg
1 in = 25.4 mm

Note any damage prior to test: ______

Figure B-8. Test Vehicle Dimensions, Test BEST-9.

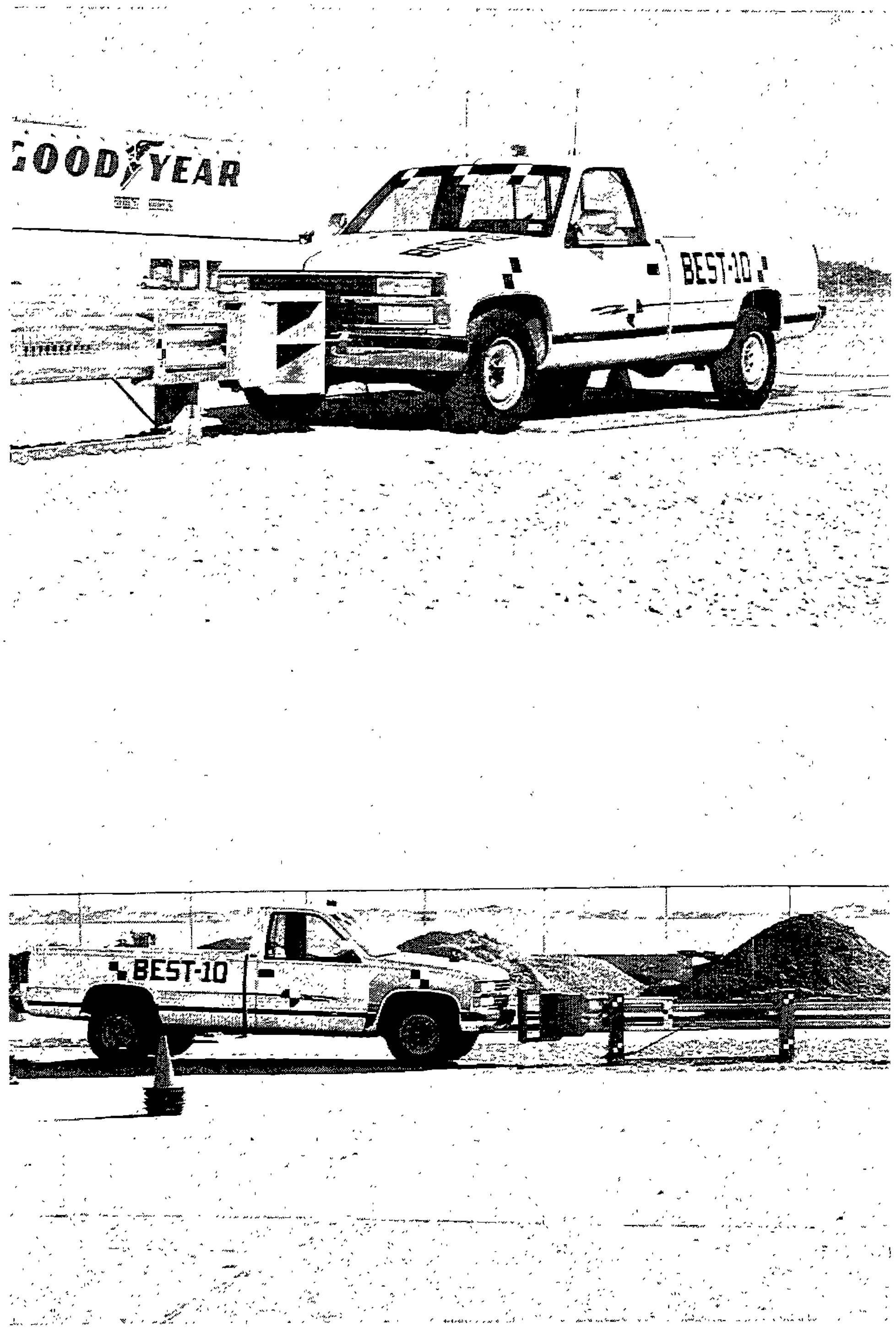


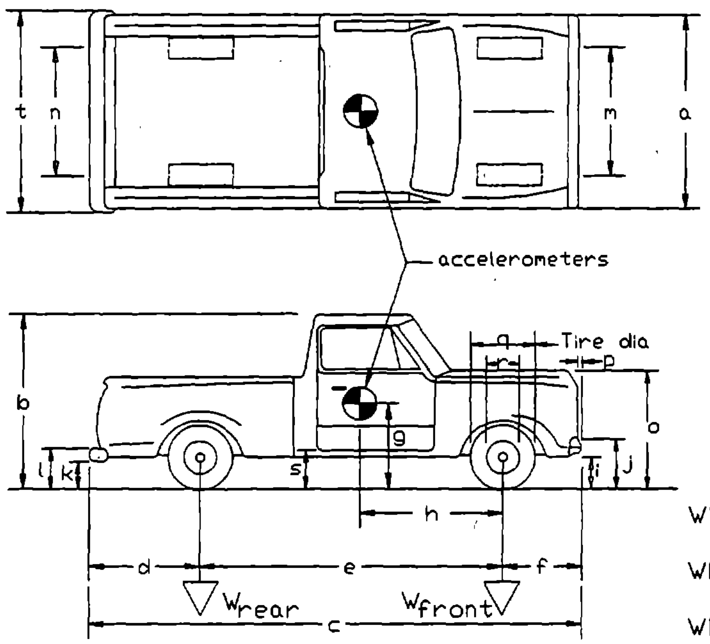
Figure B-9. Test Vehicle, Test BEST-10.

Date: 10/11/96 Test Number: BEST-10 Model: 2500

Make: Chevy Vehicle I.D.#: 1GCFC24KXLE103250

Tire Size: 245/75 R16 Year: 1990 Odometer: 75456

*(All Measurements Refer to Impacting Side)



Vehicle Geometry - inches

a	74	b	69
c	217	d	52.5
e	133.5	f	33
g	29.5	h	55.5
i	16	j	24.5
k	22.5	l	30.5
m	62.5	n	63.5
o	40.5	p	3.25
q	30.5	r	17.5
s	16.75	t	74

Wheel Center Height Front 14.5

Wheel Center Height Rear 15

Wheel Well Clearance (FR) 33

Wheel Well Clearance (RR) 36.25

Engine Type V-8

Engine Size 350 5.7L

Transmission Type:

Automatic or Manual

FWD or RWD or 4WD

Weights - lbs	Curb	Test Inertial	Gross Static
W_{front}	2482	2463	2463
W_{rear}	1760	1956	1956
W_{total}	4242	4419	4419

Conversion Factor: 1 lb = 0.4536 kg
1 in = 25.4 mm

Note any damage prior to test: Cracked & Gouged Windshield

Figure B-10. Test Vehicle Dimensions, Test BEST-10.

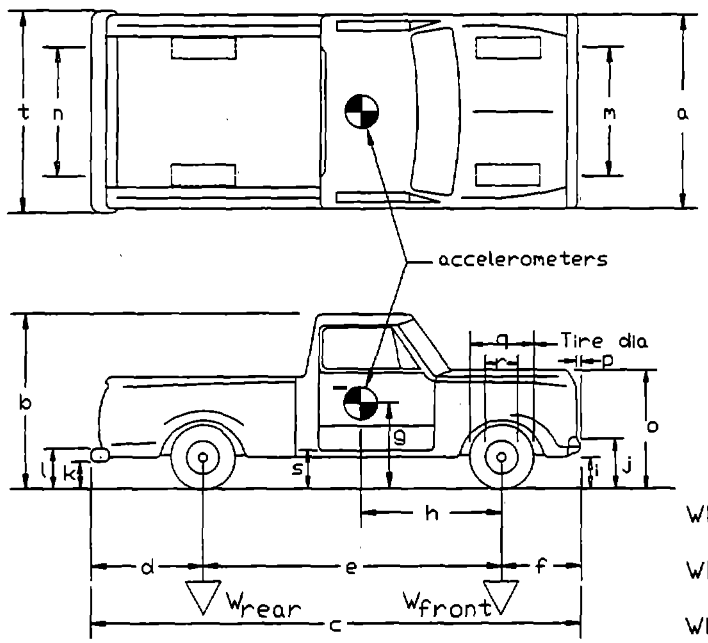
Figure B-11. Test Vehicle, Test BEST-11.

Date: 10/17/96 Test Number: BEST-11 Model: 2500

Make: GMC Vehicle I.D.#: 1GTFC24Z9ME514587

Tire Size: 255/75 R16 Year: 1990 Odometer: 24526

*(All Measurements Refer to Impacting Side)



Vehicle Geometry - inches

a	73	b	69
c	225.25	d	51.75
e	131.5	f	33
g	28.5	h	29.5
i	16	j	24
k	19.25	l	26.75
m	62.125	n	3.25
o	40.5	p	3.25
q	29.75	r	17.5
s	15.75	t	72.5

Wheel Center Height Front 13.5

Wheel Center Height Rear 14

Wheel Well Clearance (FR) 32.25

Wheel Well Clearance (RR) 34.75

Engine Type V-6

Engine Size 4.3L

Transmission Type:

Automatic or Manual

FWD or RWD or 4WD

Weights - lbs	Curb	Test Inertial	Gross Static
W_{front}	2247	2463	2463
W_{rear}	1677	1956	1956
W_{total}	3924	4419	4419

Conversion Factor: 1 lb = 0.4536 kg
1 in = 25.4 mm

Note any damage prior to test: ______

Figure B-12. Test Vehicle Dimensions, Test BEST-11.

10 APPENDIX C - Accelerometer Data Analysis

Longitudinal Deceleration - Test BEST-3

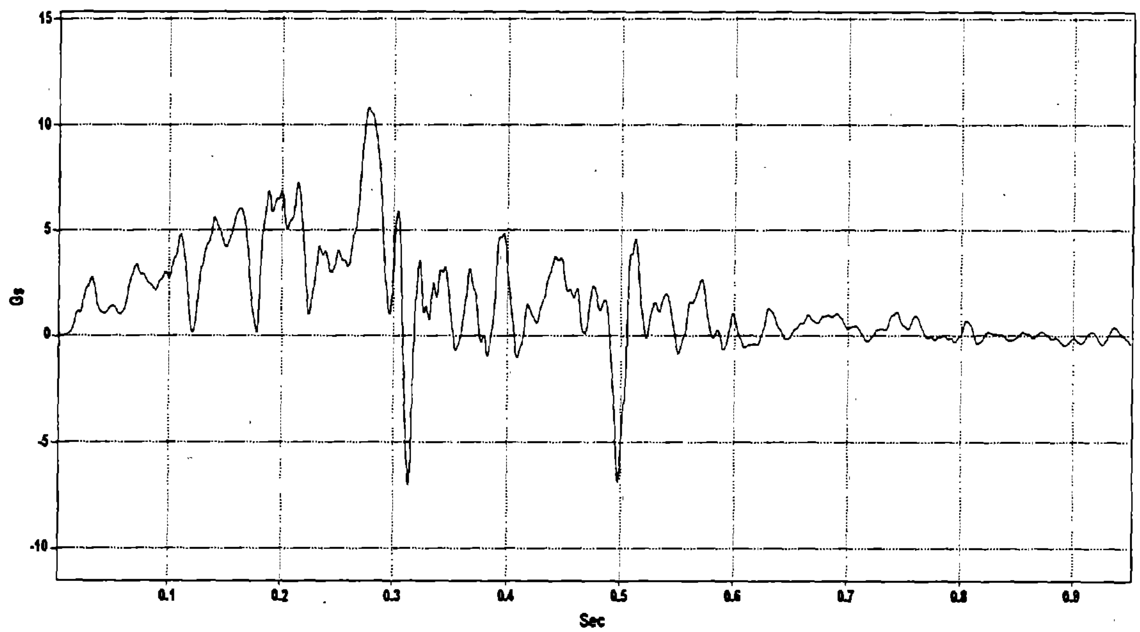


Figure C-1. Longitudinal Deceleration, Test BEST-3.

Relative Long. Occup. Velocity - Test BEST-3

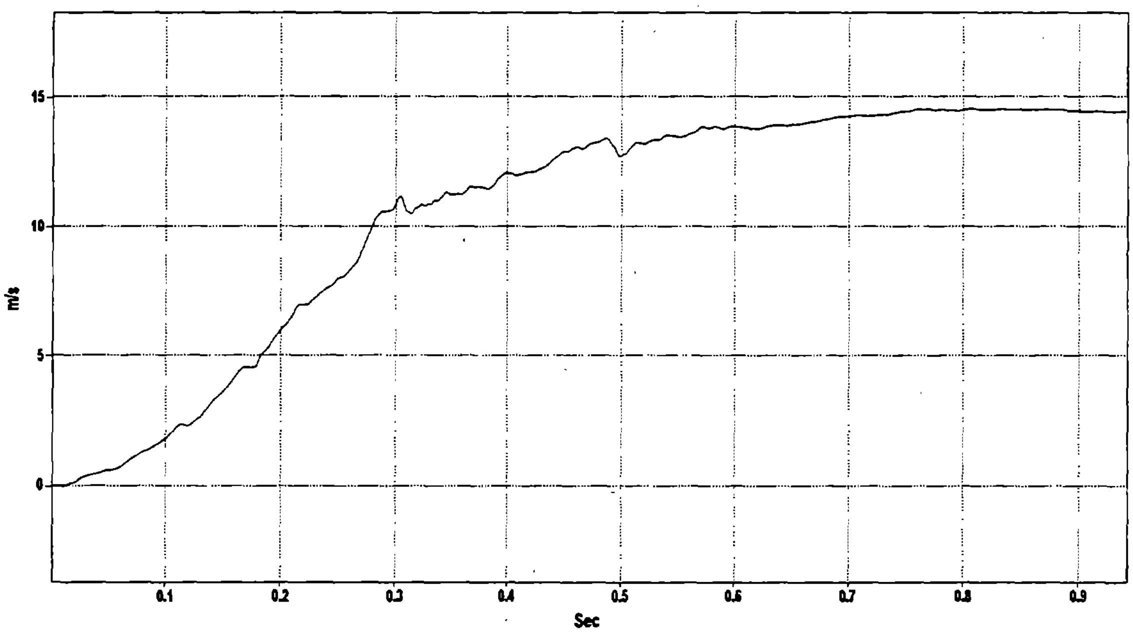


Figure C-2. Longitudinal Change in Velocity, Test BEST-3.

Relative Longitudinal Occ. Disp. - Test BEST-3

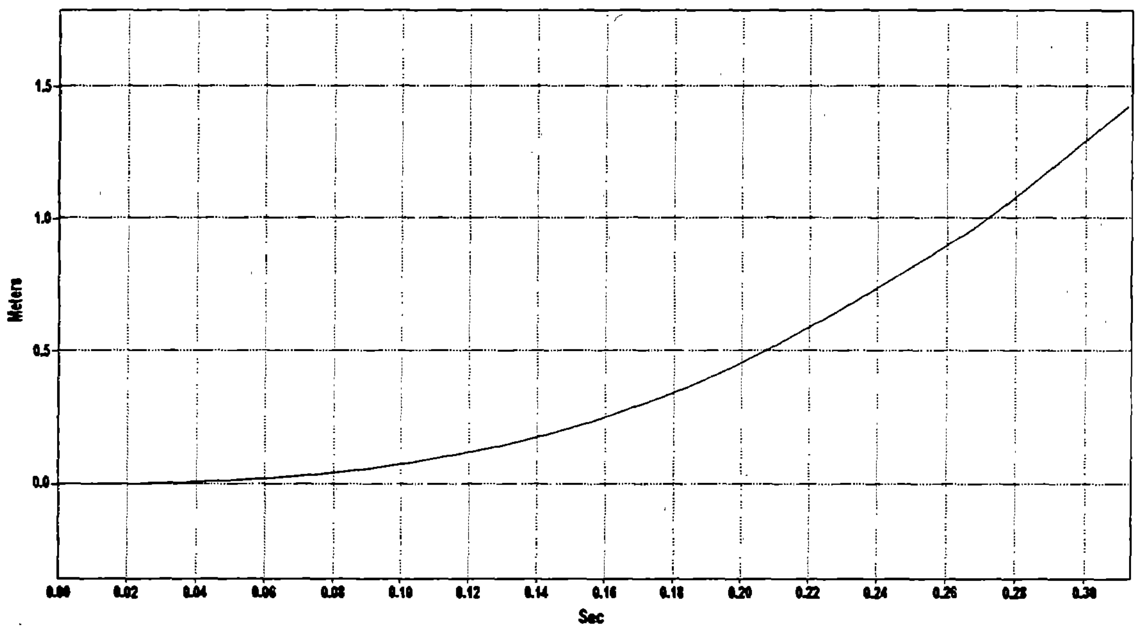


Figure C-3. Relative Longitudinal Occupant Displacement, Test BEST-3.

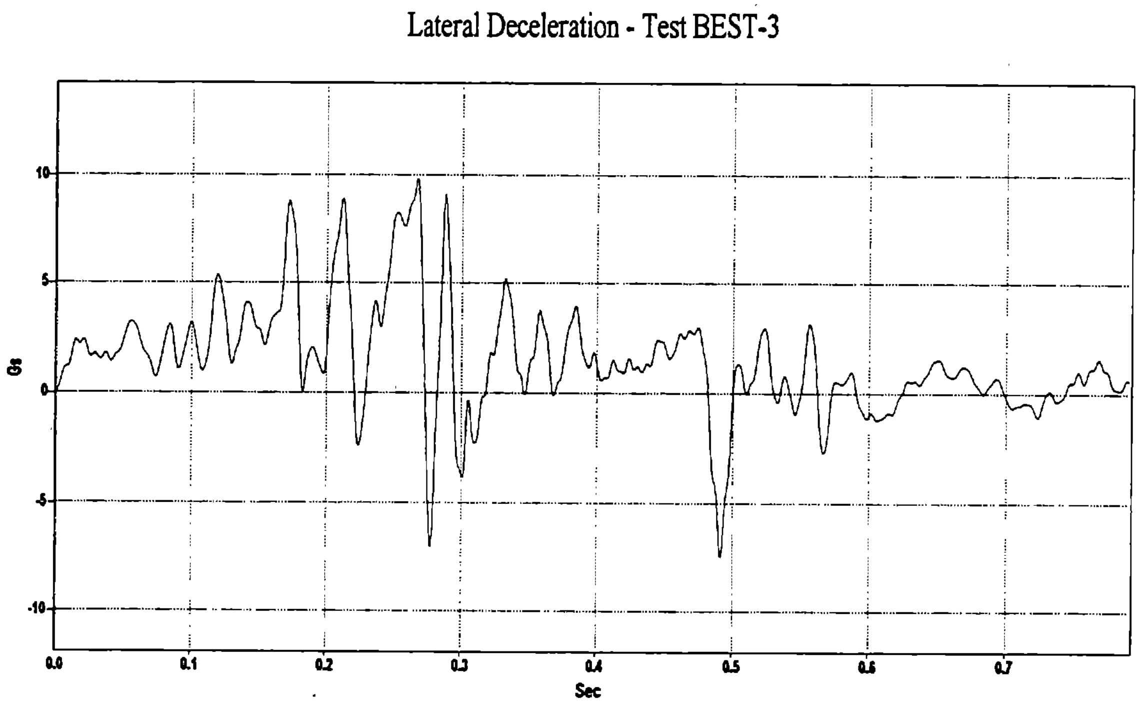


Figure C-4. Lateral Deceleration, Test BEST-3.

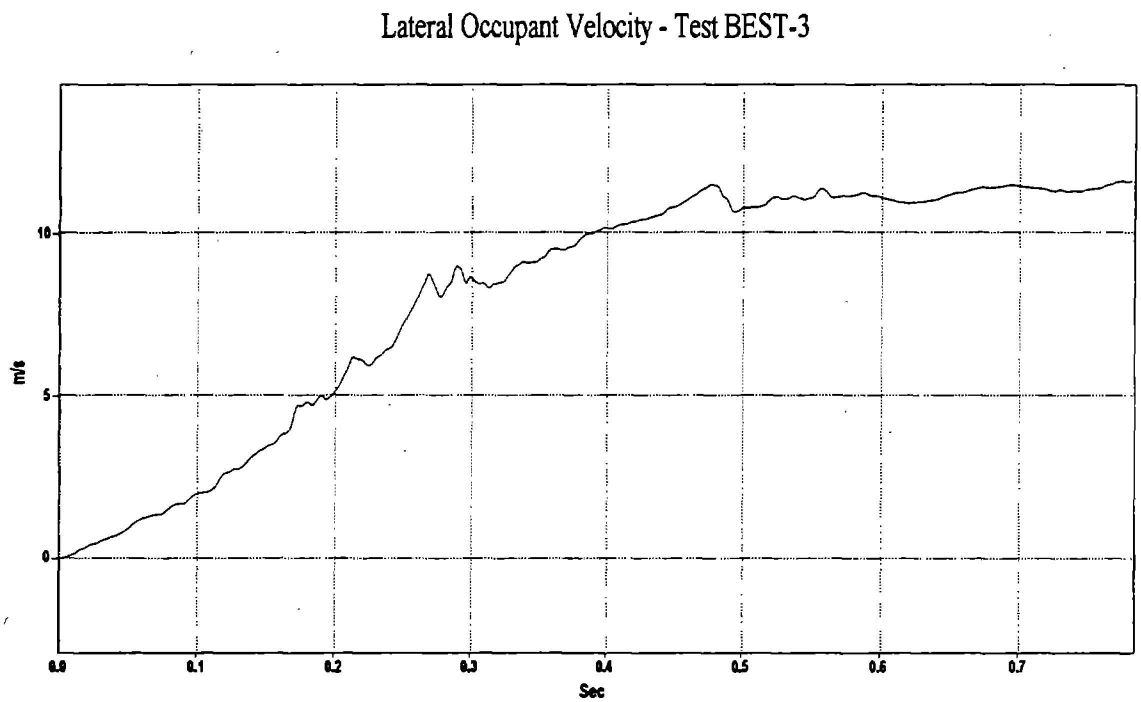


Figure C-5. Lateral Change in Velocity, Test BEST-3.

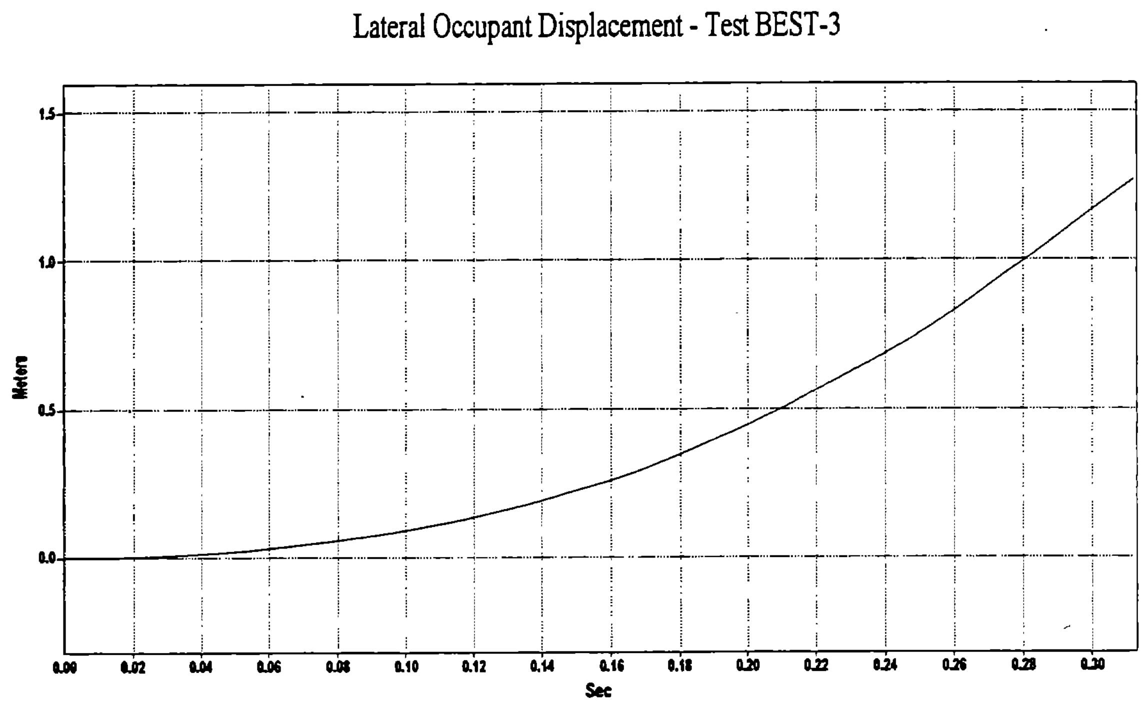


Figure C-6. Relative Lateral Occupant Displacement, Test BEST-3.

Longitudinal Deceleration - Test BEST-4

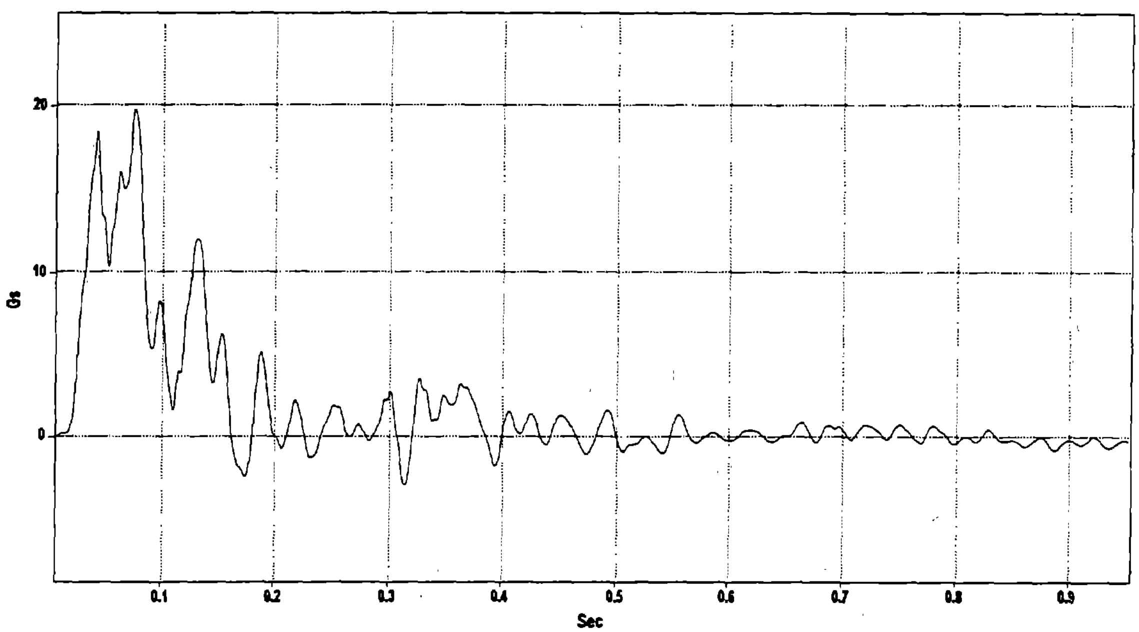


Figure C-7. Longitudinal Deceleration, Test BEST-4.

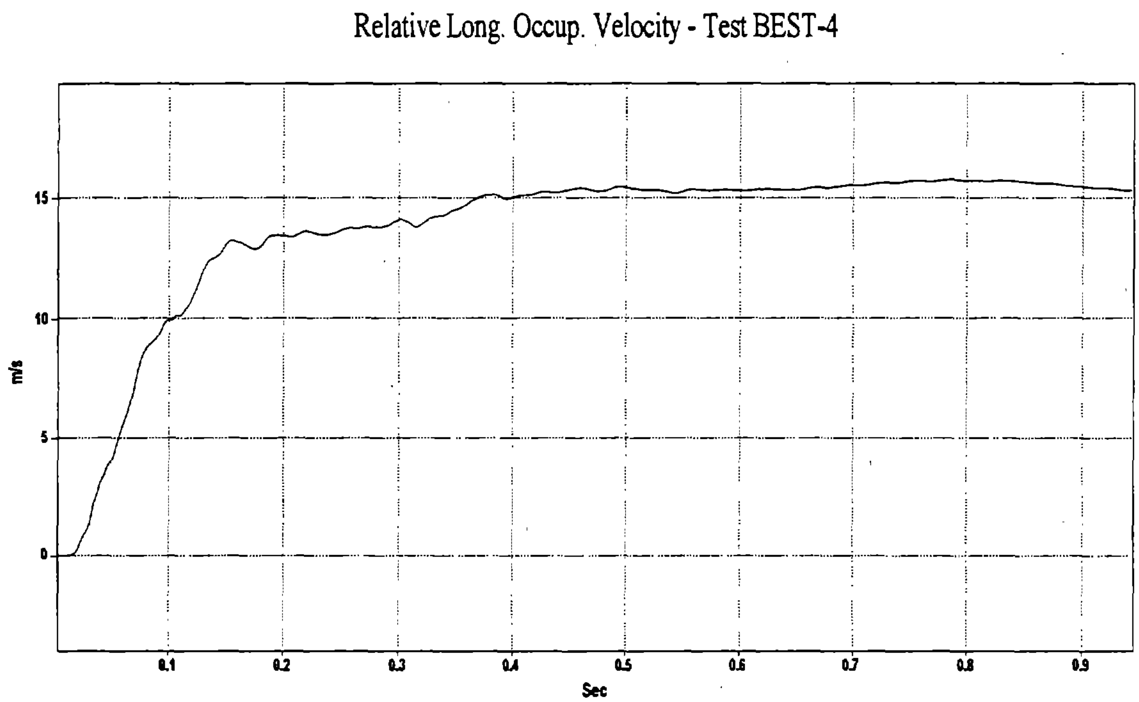


Figure C-8. Longitudinal Change in Velocity, Test BEST-4.

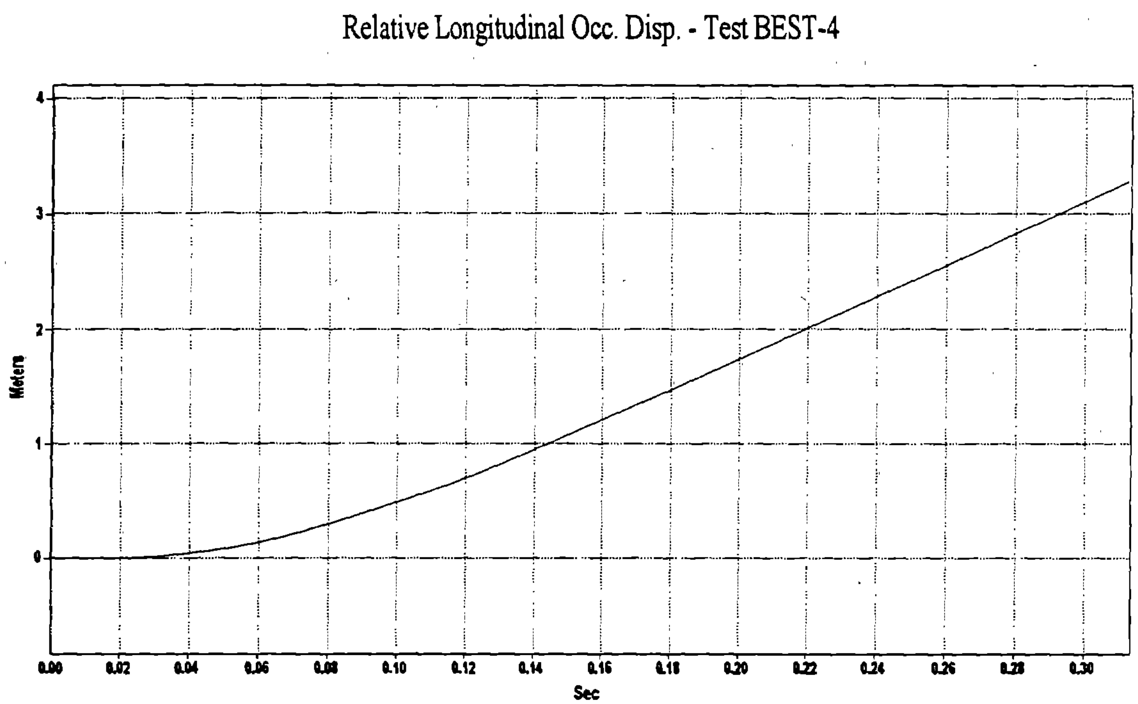


Figure C-9. Relative Longitudinal Occupant Displacement, Test BEST-4.

Lateral Deceleration - Test BEST-4

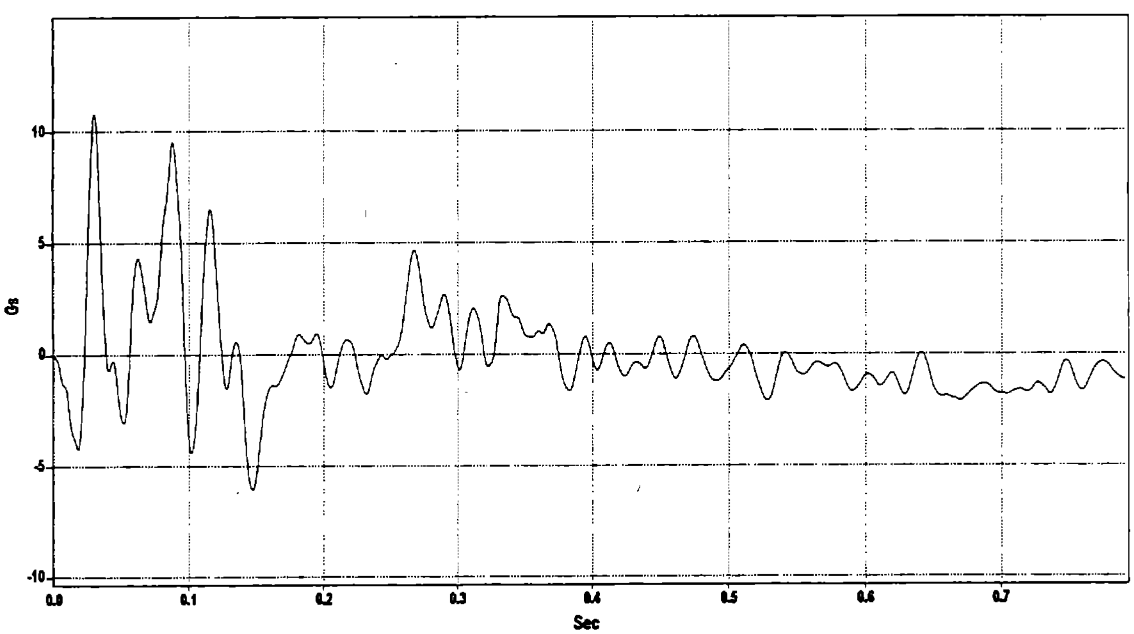


Figure C-10. Lateral Deceleration, Test BEST-4.

Lateral Occupant Velocity - Test BEST-4

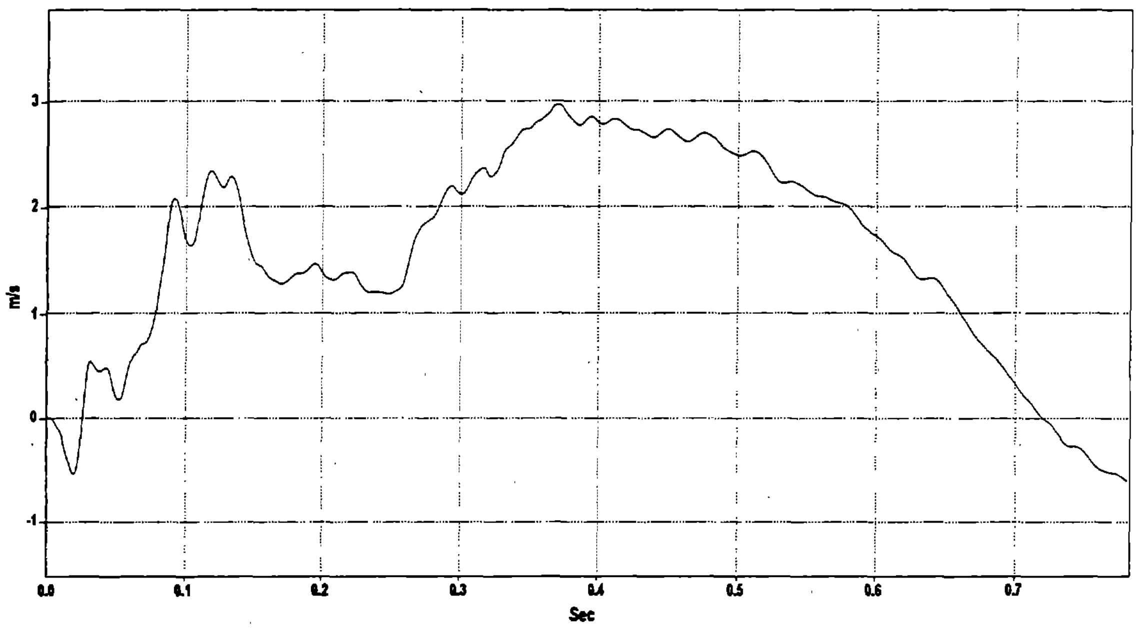


Figure C-11. Lateral Change in Velocity, Test BEST-4.

Lateral Occupant Displacement - Test BEST-4

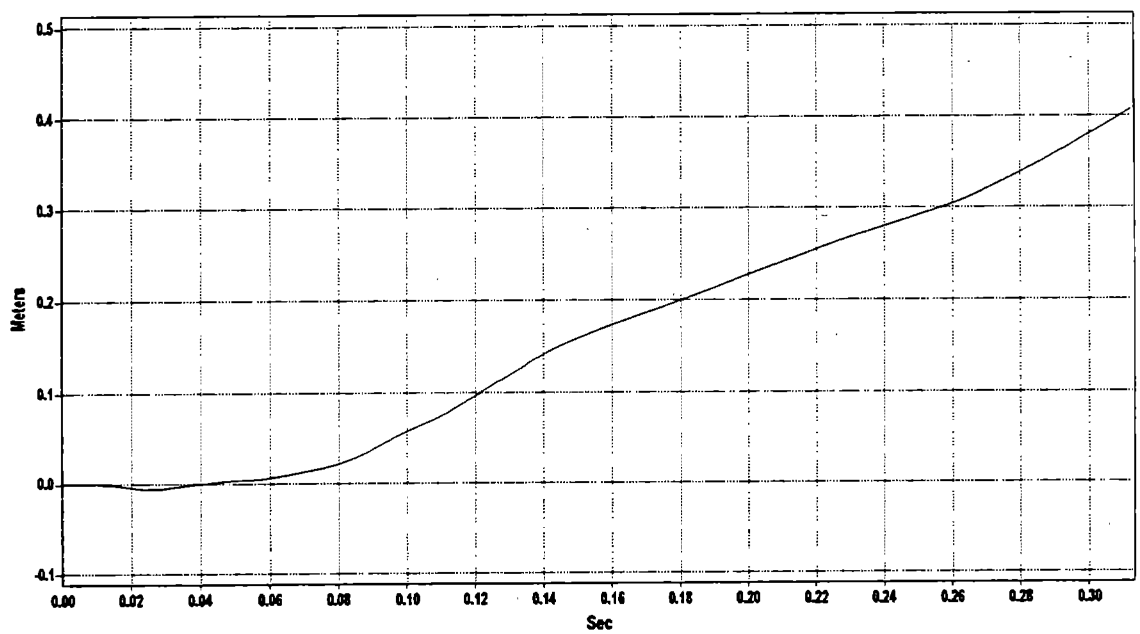


Figure C-12. Relative Lateral Occupant Displacement, Test BEST-4.

Longitudinal Deceleration - Test BEST-8

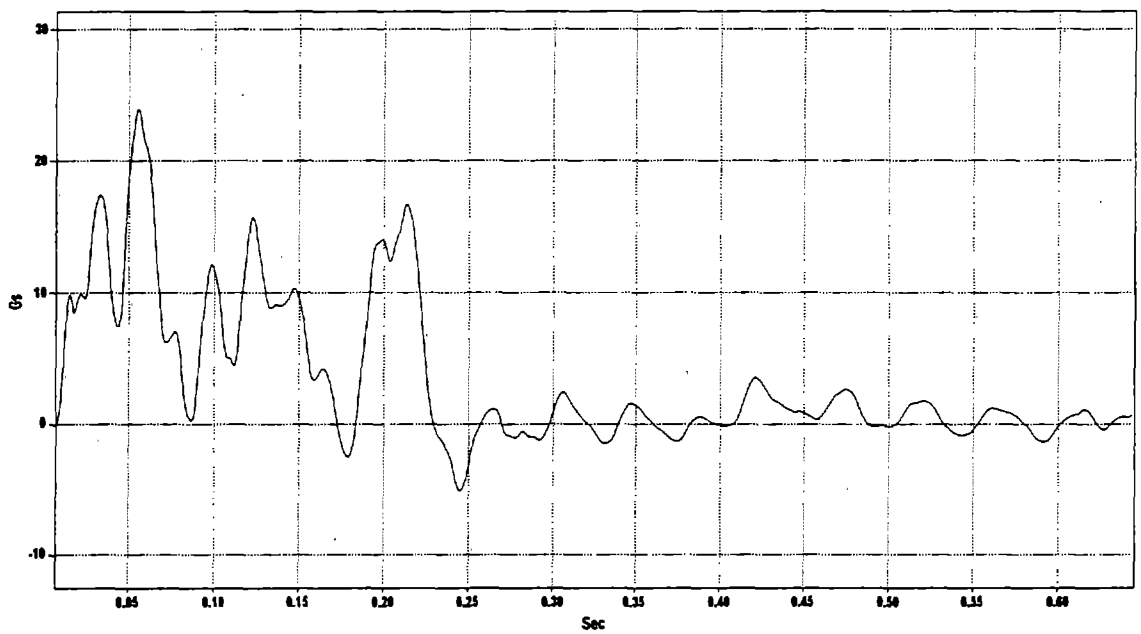


Figure C-13. Longitudinal Deceleration, Test BEST-8.

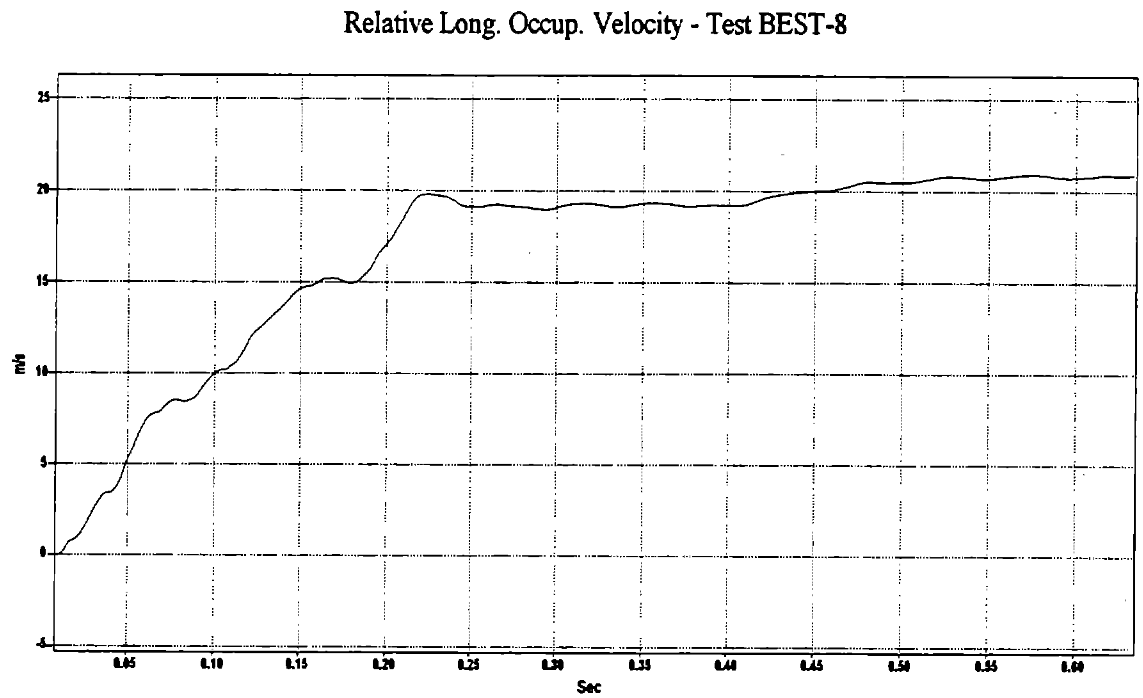


Figure C-14. Longitudinal Change in Velocity, Test BEST-8.

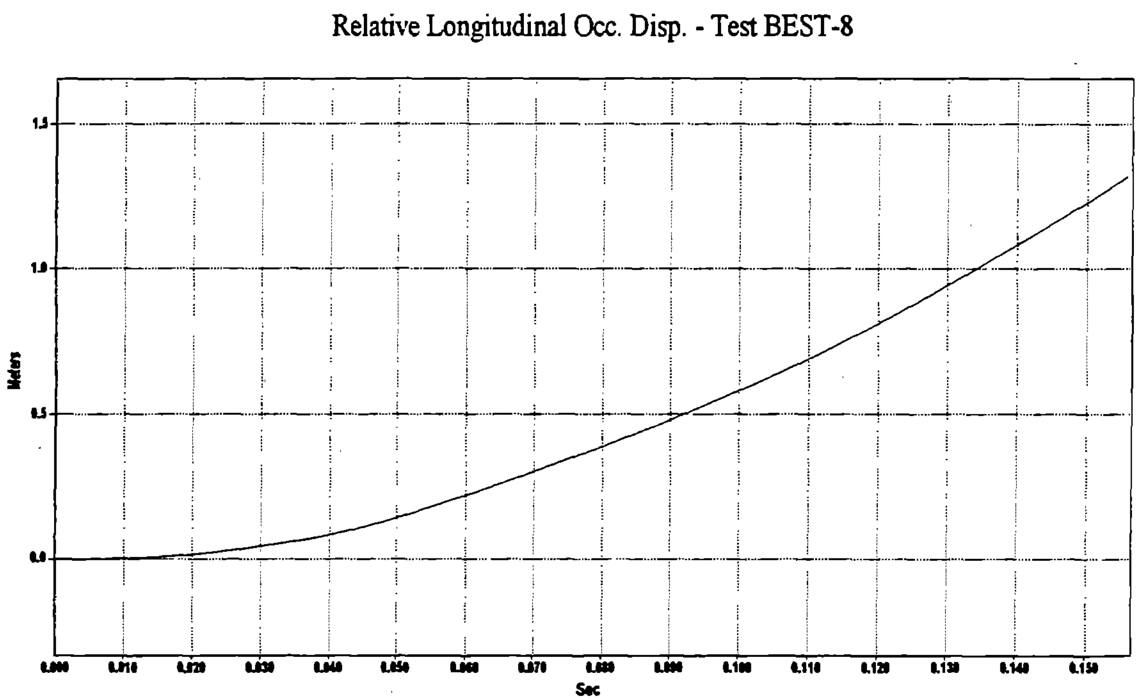


Figure C-15. Relative Longitudinal Occupant Displacement, Test BEST-8.

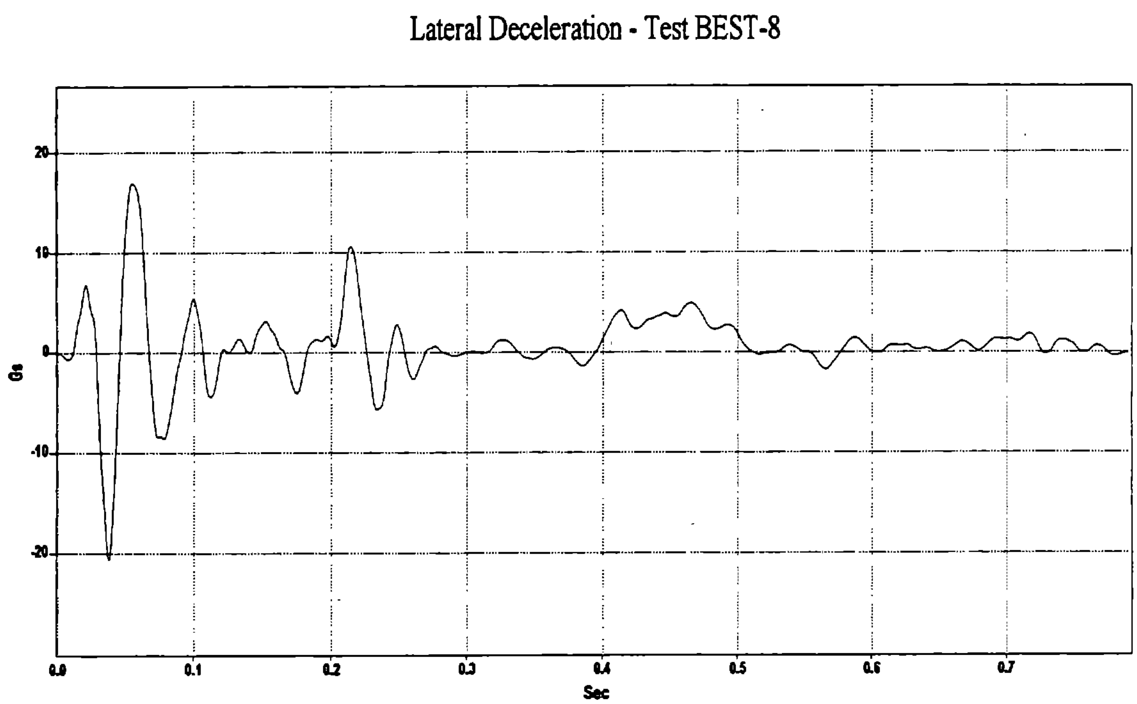


Figure C-16. Lateral Deceleration, Test BEST-8.

Lateral Occupant Velocity - Test BEST-8

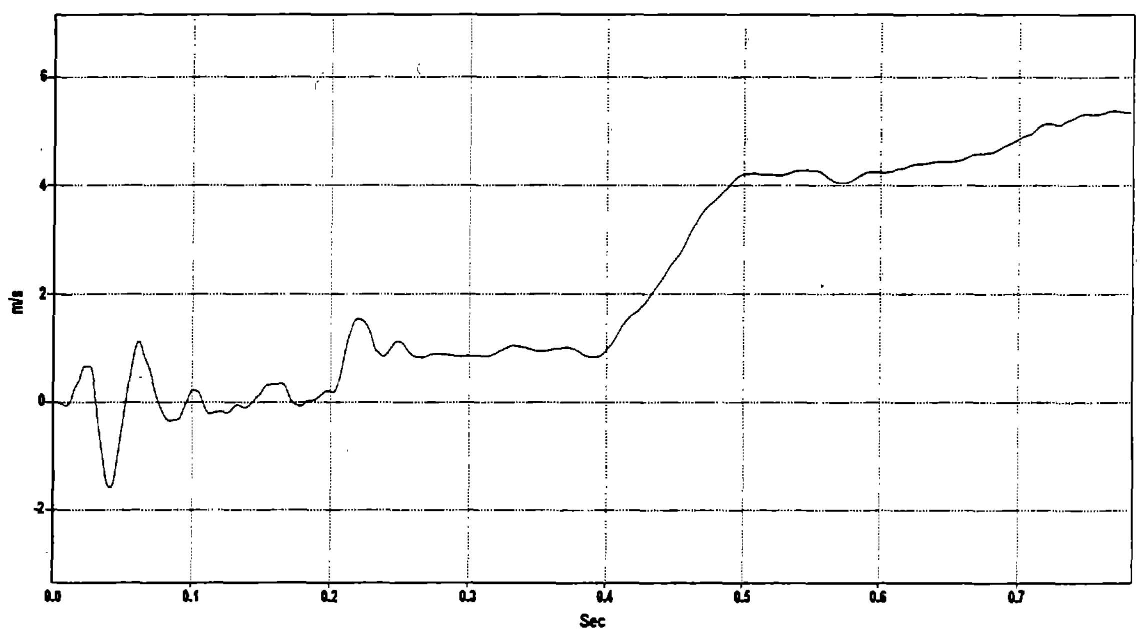


Figure C-17. Lateral Change in Velocity, Test BEST-8.

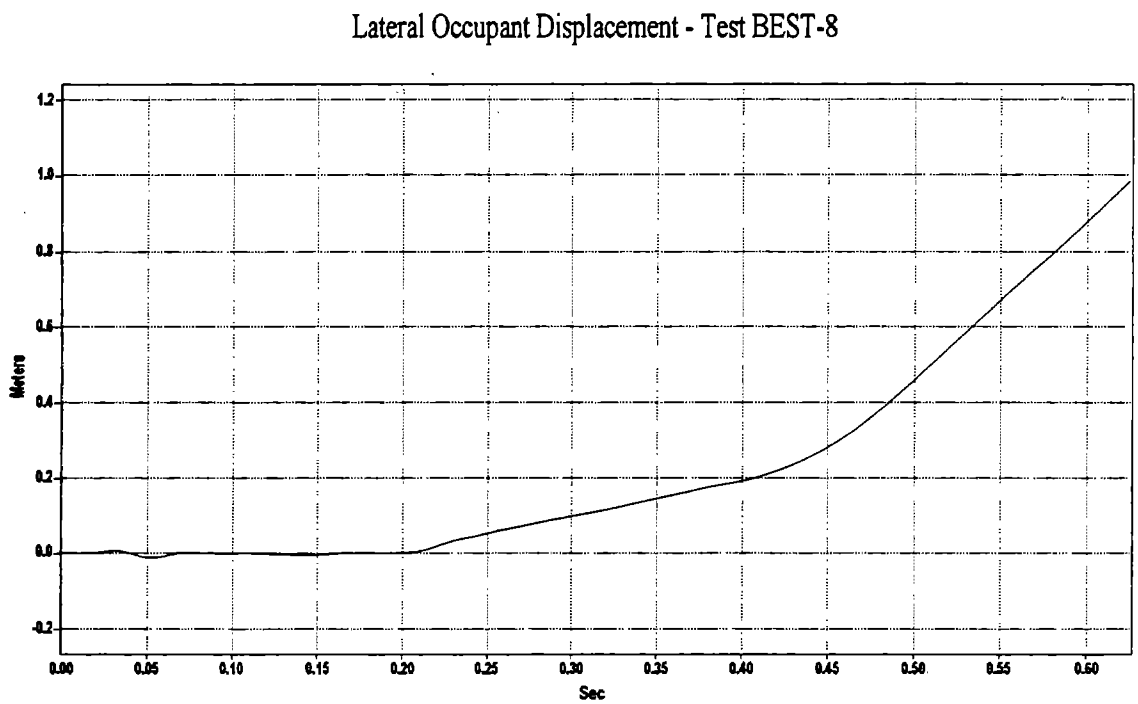


Figure C-18. Relative Lateral Occupant Displacement, Test BEST-8.

Longitudinal Deceleration - Test BEST-9

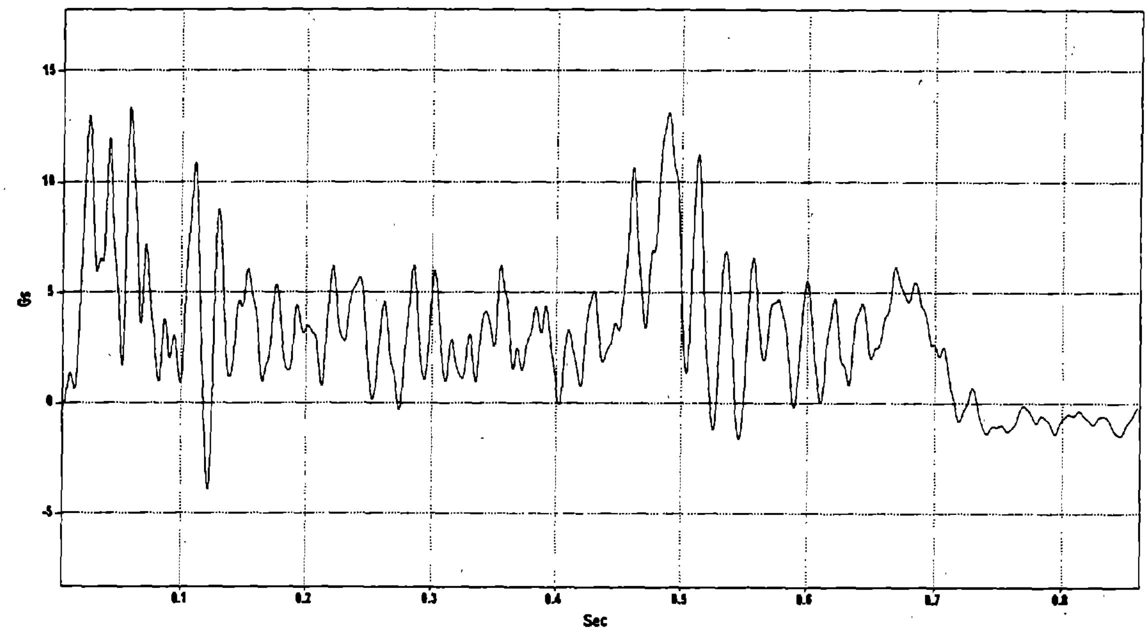


Figure C-19. Longitudinal Deceleration, Test BEST-9.

Relative Long. Occup. Velocity - Test BEST-9

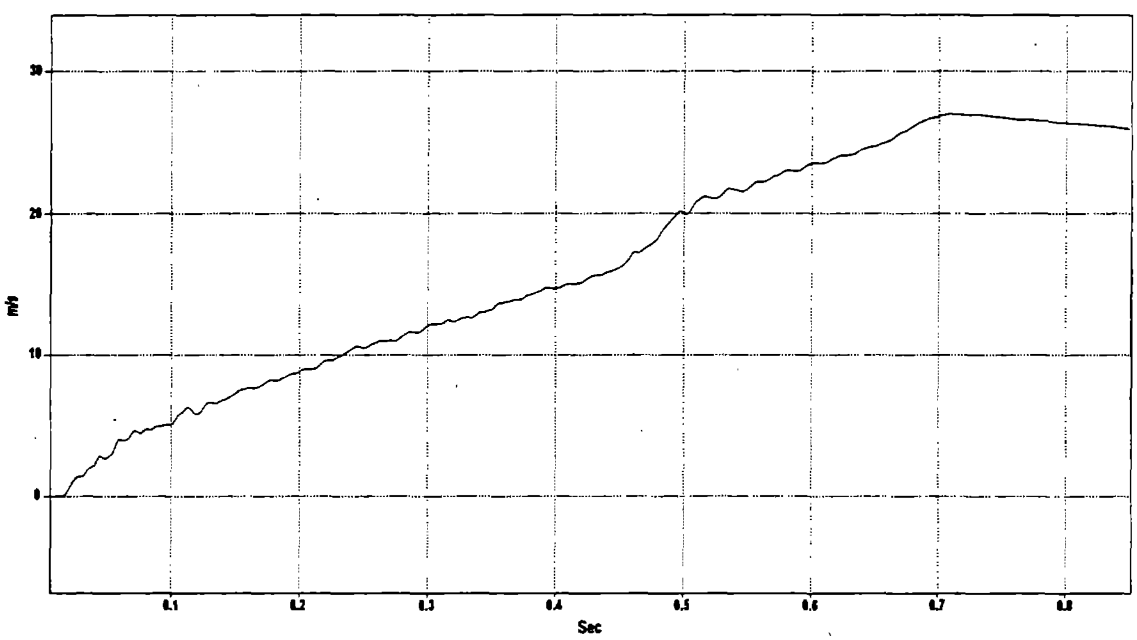


Figure C-20. Longitudinal Change in Velocity, Test BEST-9.

Relative Longitudinal Occ. Disp. - Test BEST-9

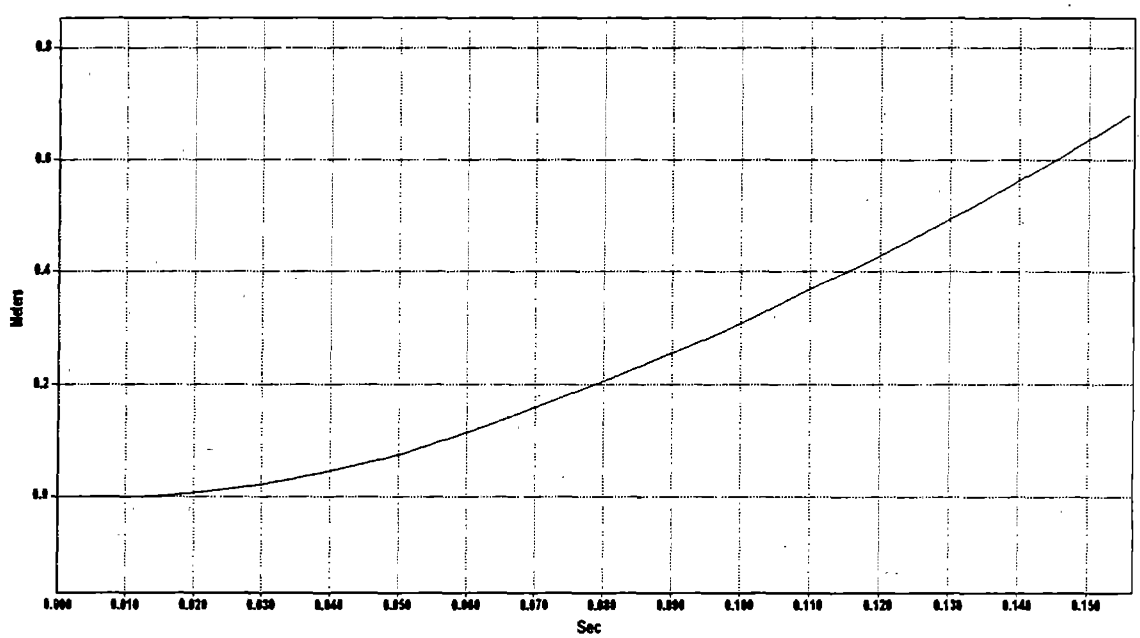


Figure C-21. Relative Longitudinal Occupant Displacement, Test BEST-9.

Lateral Deceleration - Test BEST-9

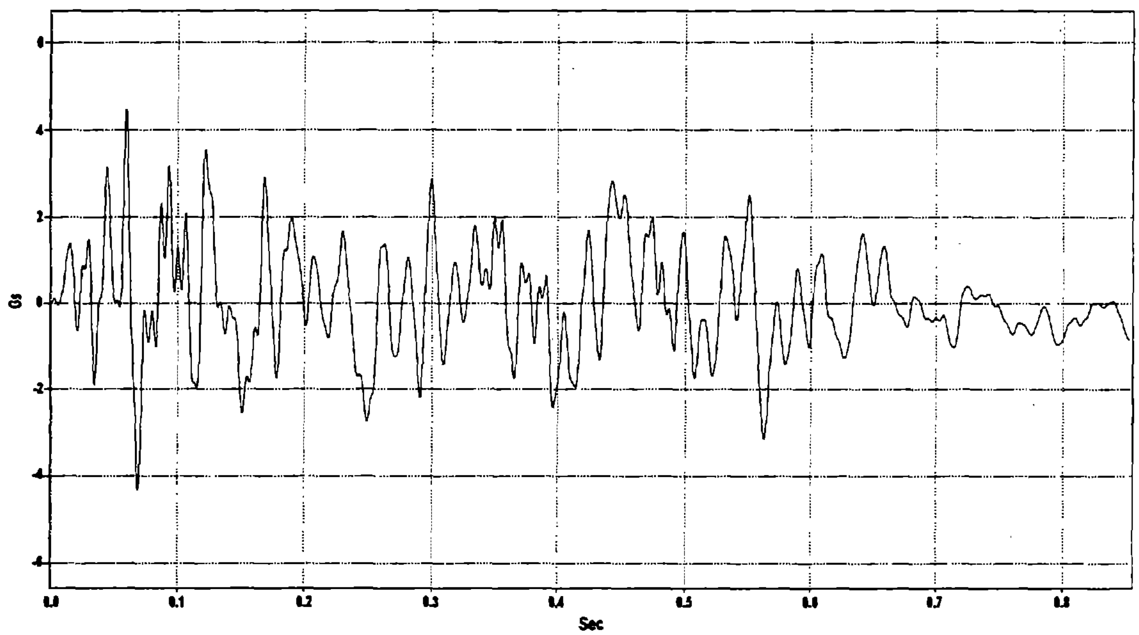


Figure C-22. Lateral Deceleration, Test BEST-9.

Lateral Occupant Velocity - Test BEST-9

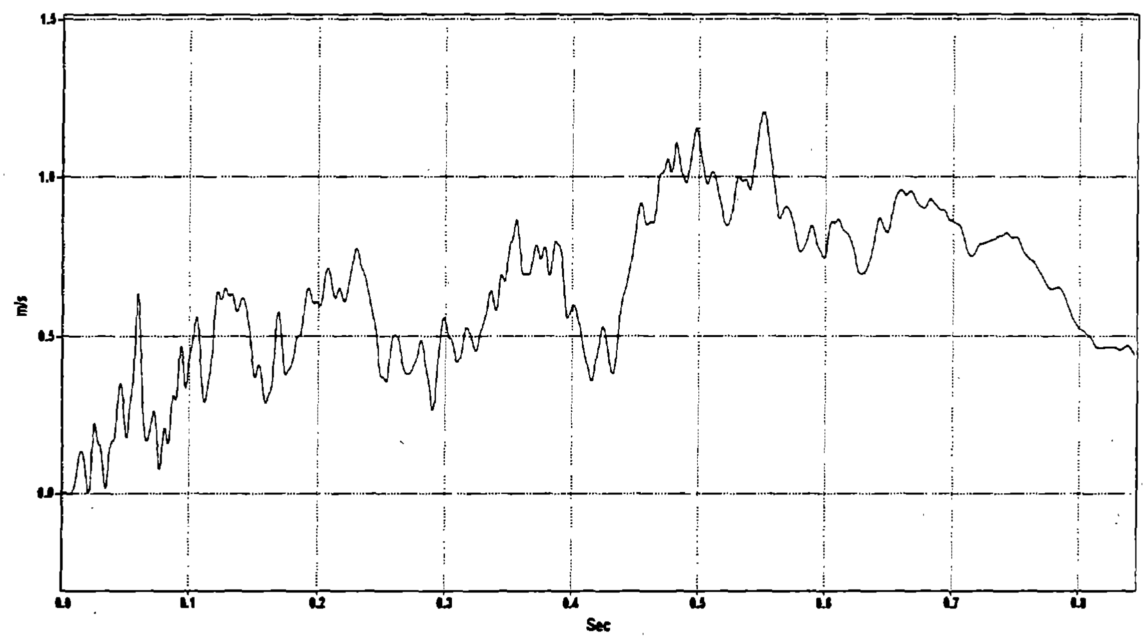


Figure C-23. Lateral Change in Velocity, Test BEST-9.

Lateral Occupant Displacement - Test BEST-9

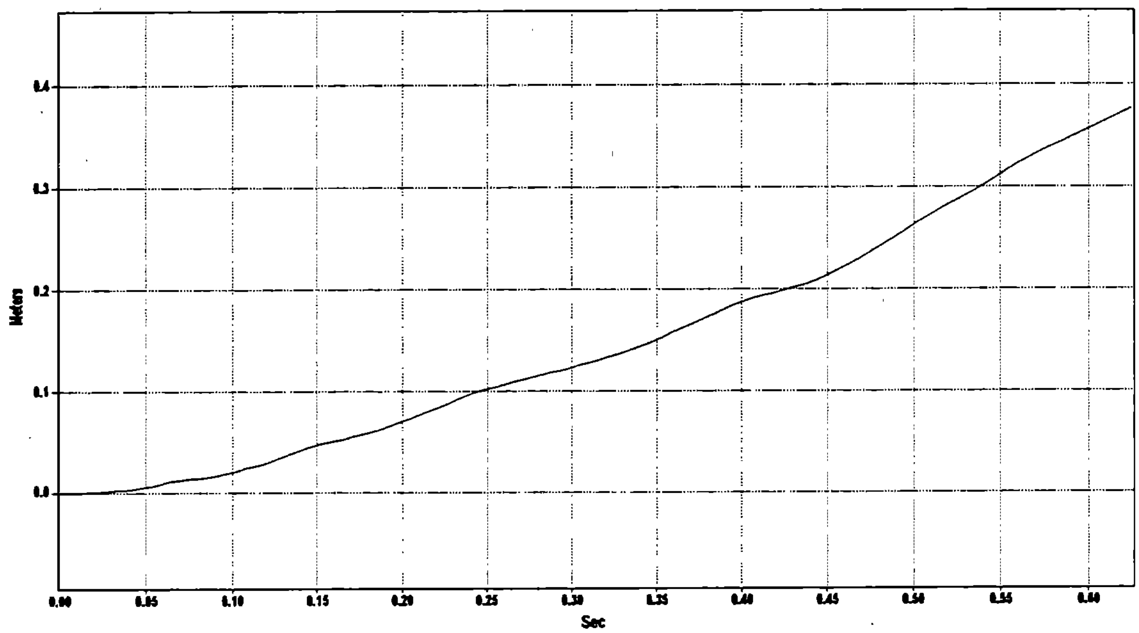


Figure C-24. Relative Lateral Occupant Displacement, Test BEST-9.

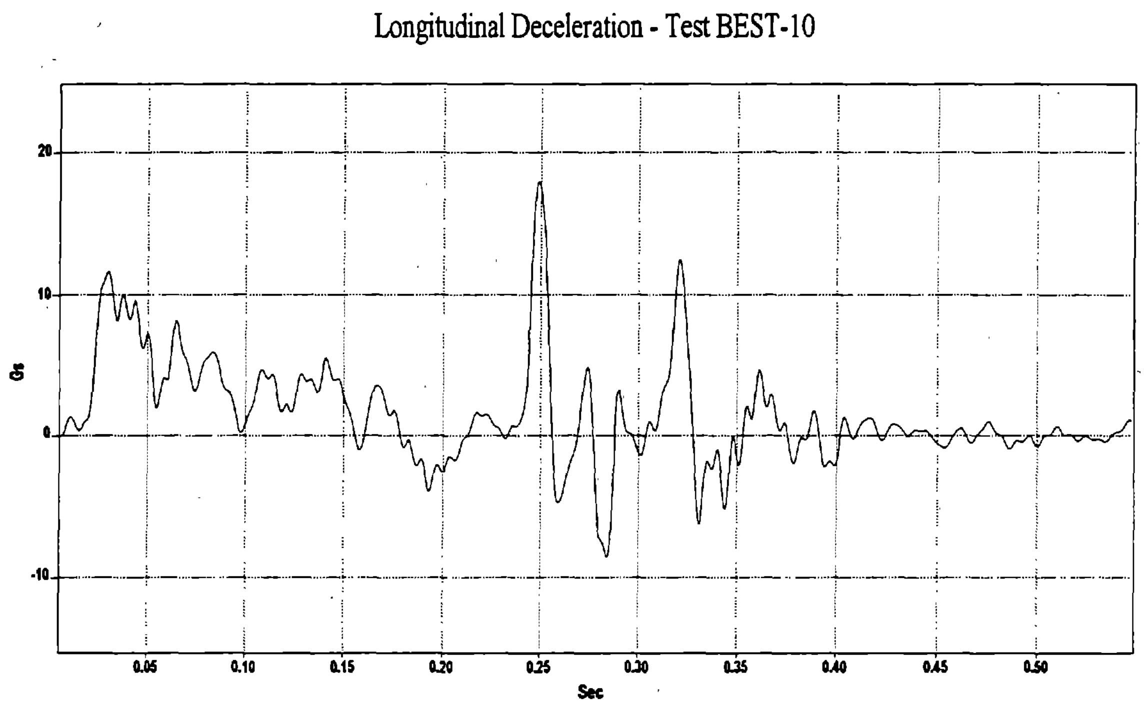


Figure C-25. Longitudinal Deceleration, Test BEST-10.

Relative Long. Occup. Velocity - Test BEST-10

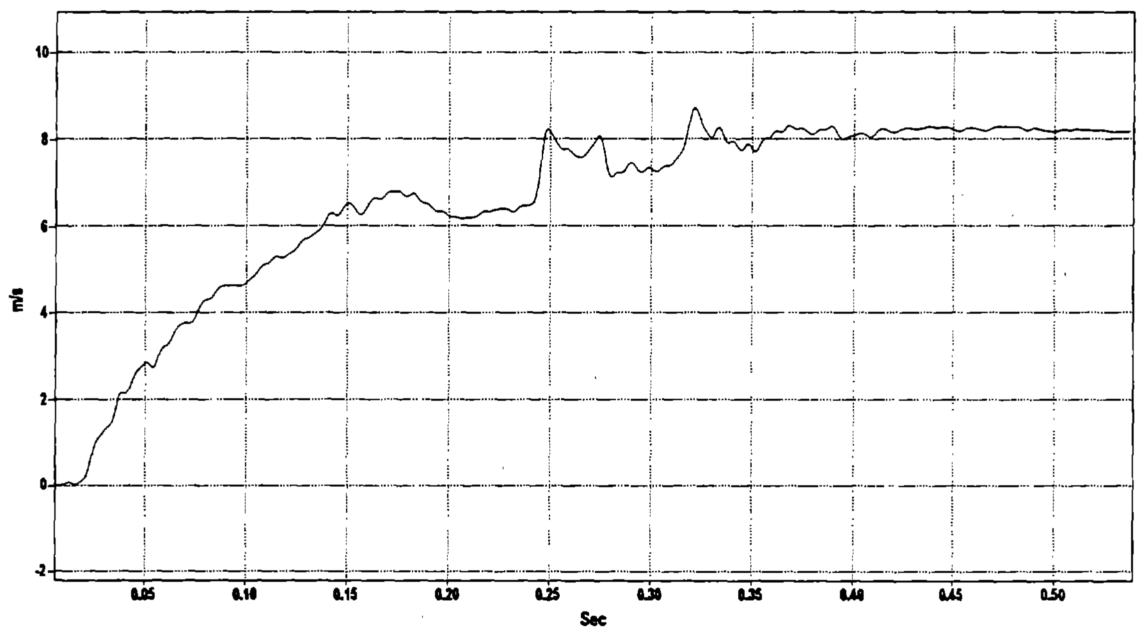


Figure C-26. Longitudinal Change in Velocity, Test BEST-10.

Relative Longitudinal Occ. Disp. - Test BEST-10

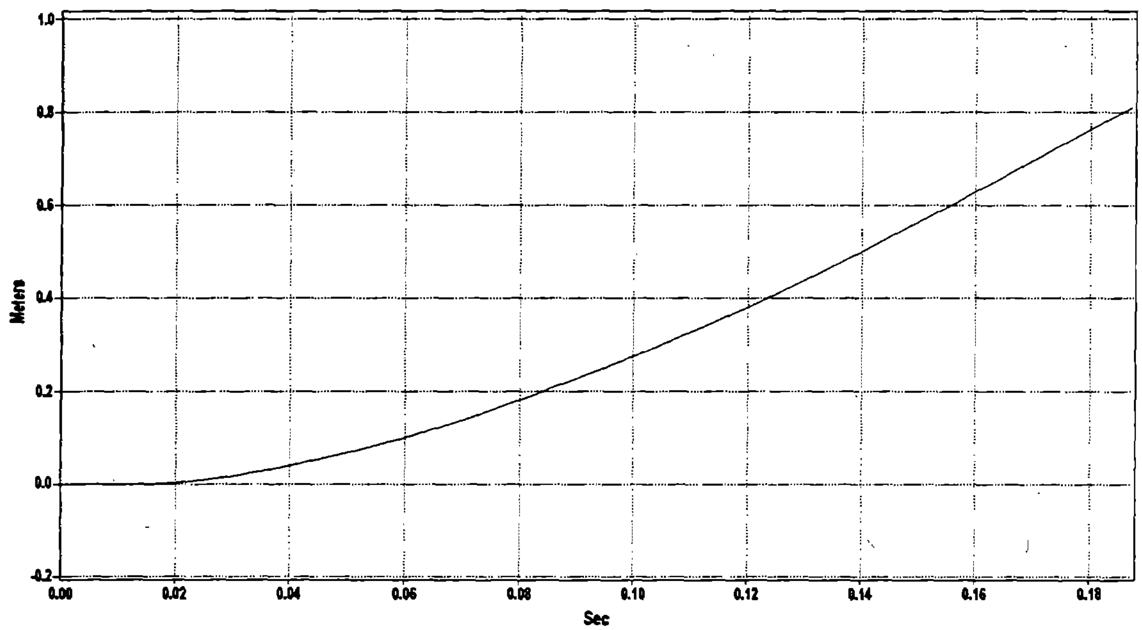


Figure C-27. Relative Longitudinal Occupant Displacement, Test BEST-10.

Lateral Deceleration - Test BEST-10

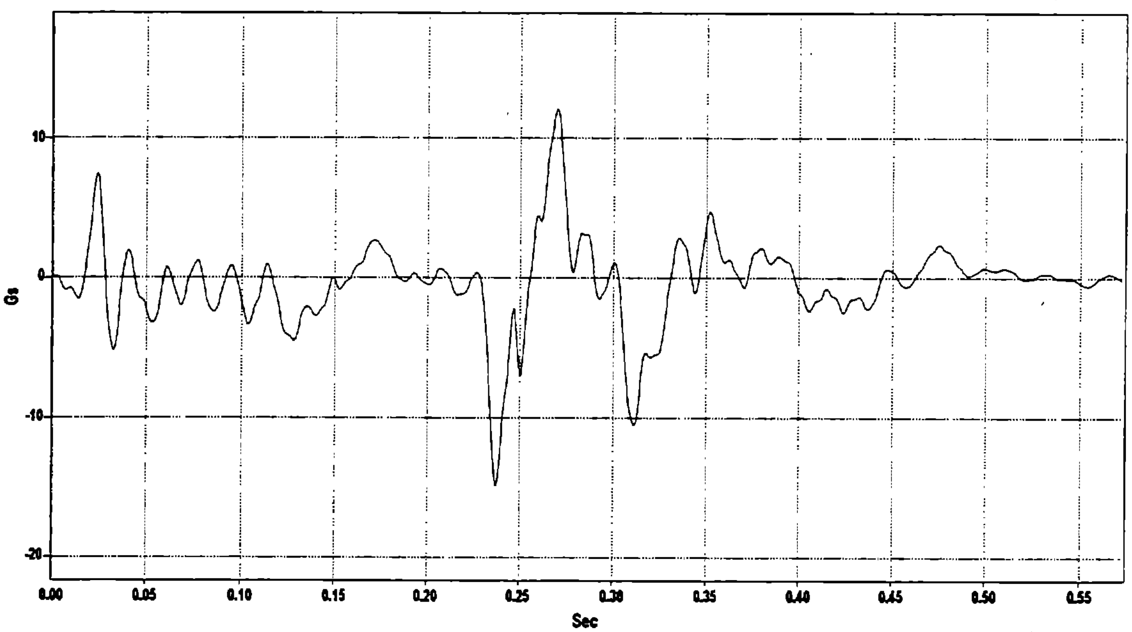


Figure C-28. Lateral Deceleration, Test BEST-10.

Lateral Occupant Velocity - Test BEST-10

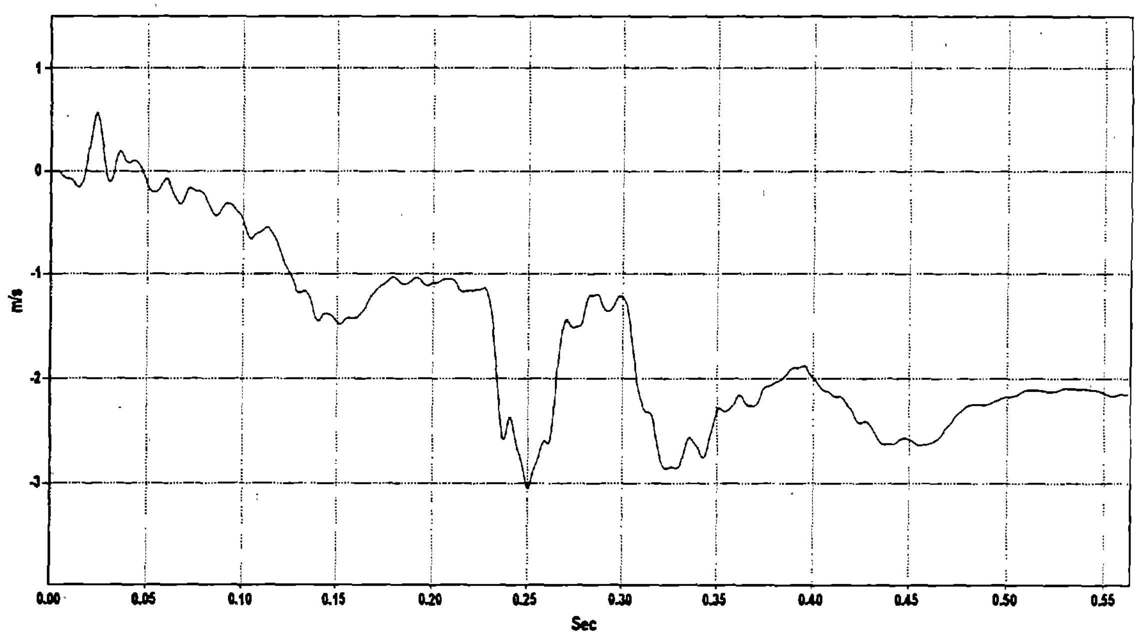


Figure C-29. Lateral Change in Velocity, Test BEST-10.

Lateral Occupant Displacement - Test BEST-10

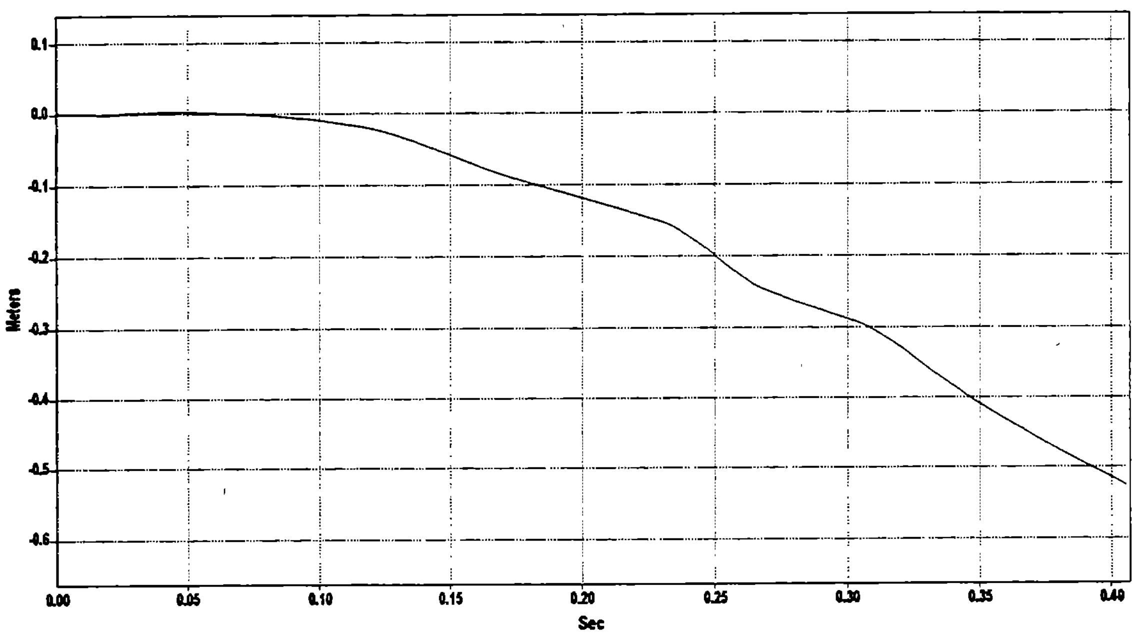


Figure C-30. Relative Lateral Occupant Displacement, Test BEST-10.

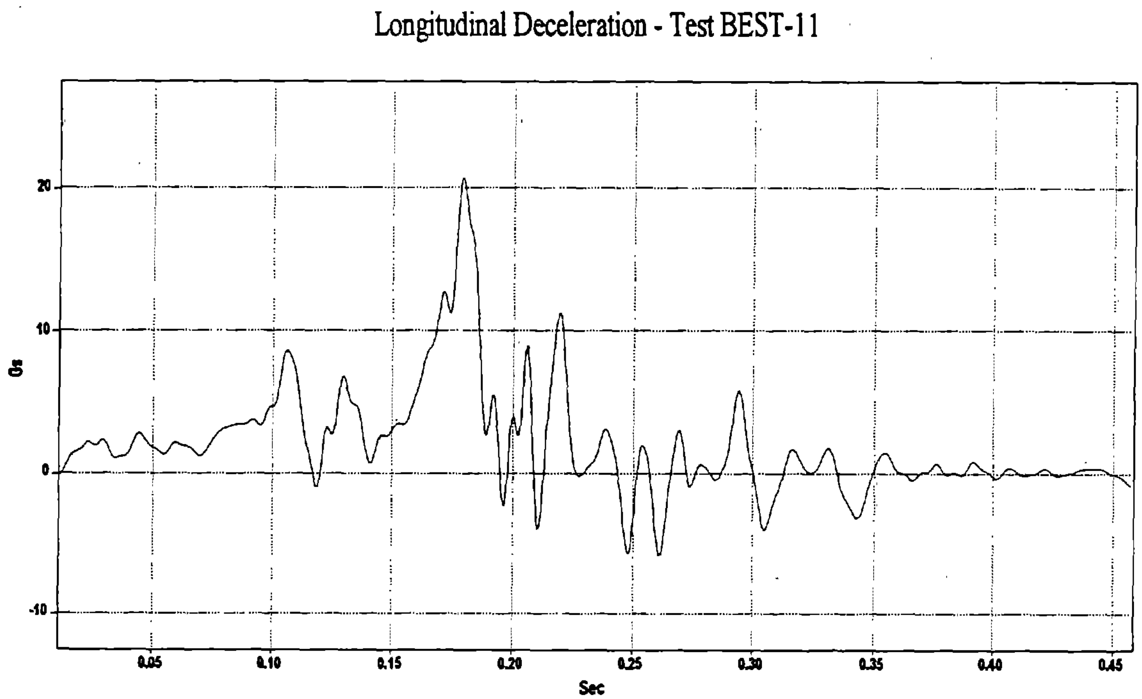


Figure C-31. Longitudinal Deceleration, Test BEST-11.

Relative Long. Occup. Velocity - Test BEST-11

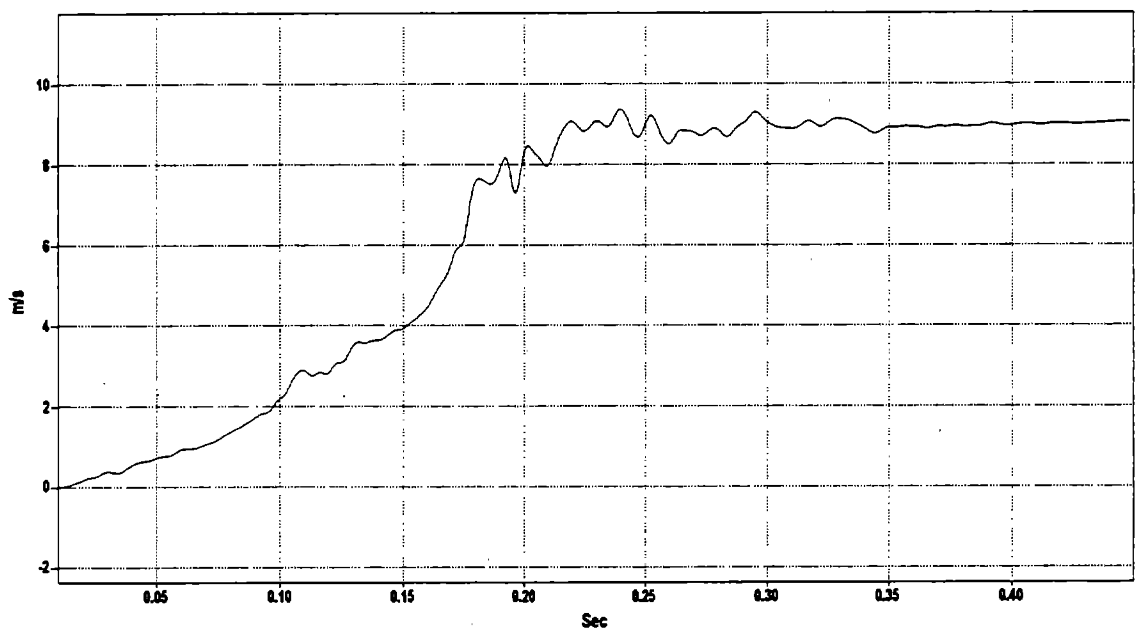


Figure C-32. Longitudinal Change in Velocity, Test BEST-11.

Relative Longitudinal Occ. Disp. - Test BEST-11

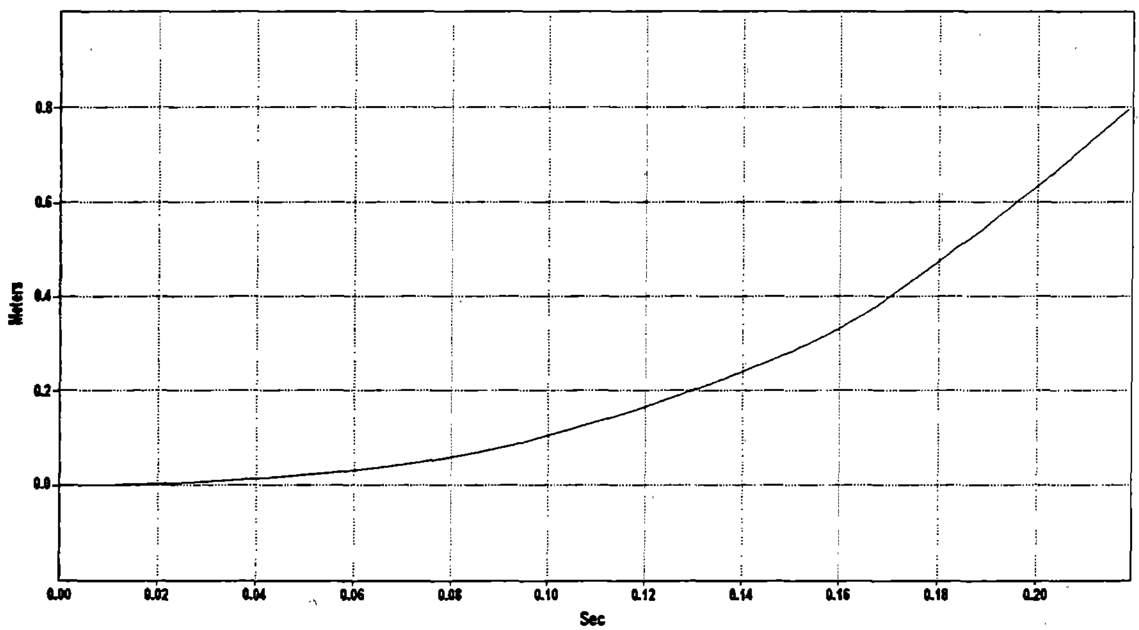


Figure C-33. Relative Longitudinal Occupant Displacement, Test BEST-11.

Lateral Deceleration - Test BEST-11

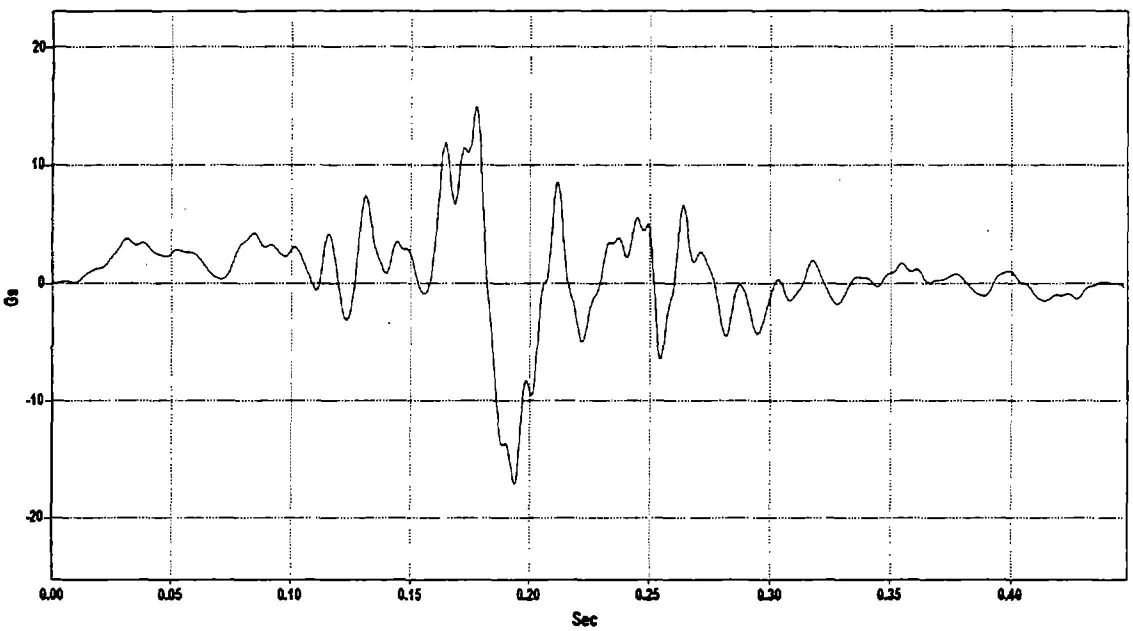


Figure C-34. Lateral Deceleration, Test BEST-11.

Lateral Occupant Velocity - Test BEST-11

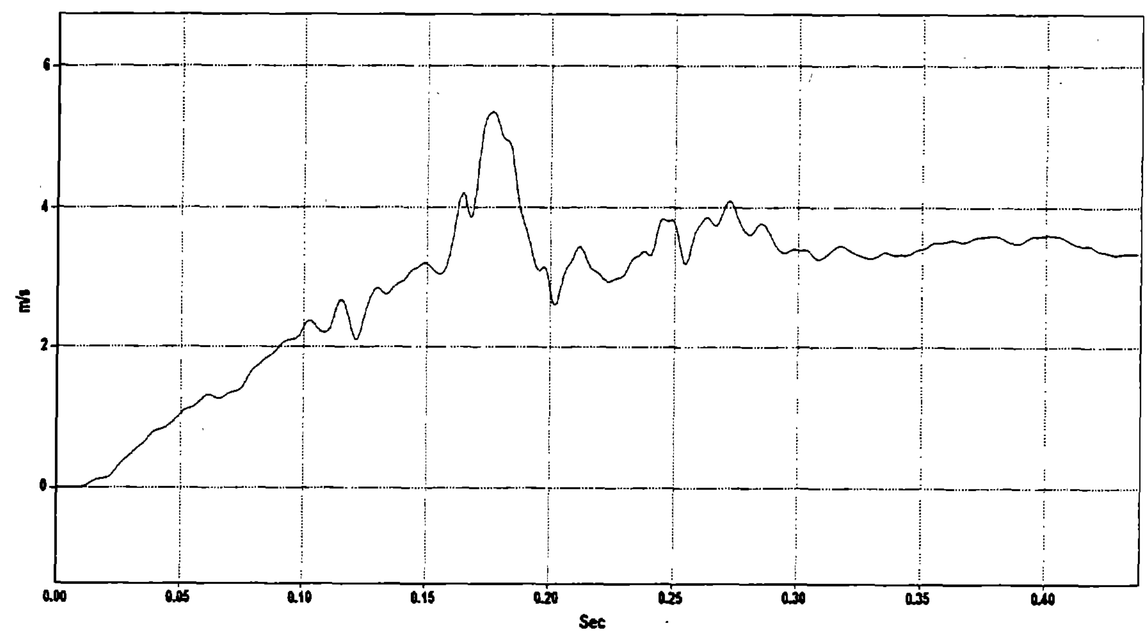


Figure C-35. Lateral Change in Velocity, Test BEST-11.

Lateral Occupant Displacement - Test BEST-11

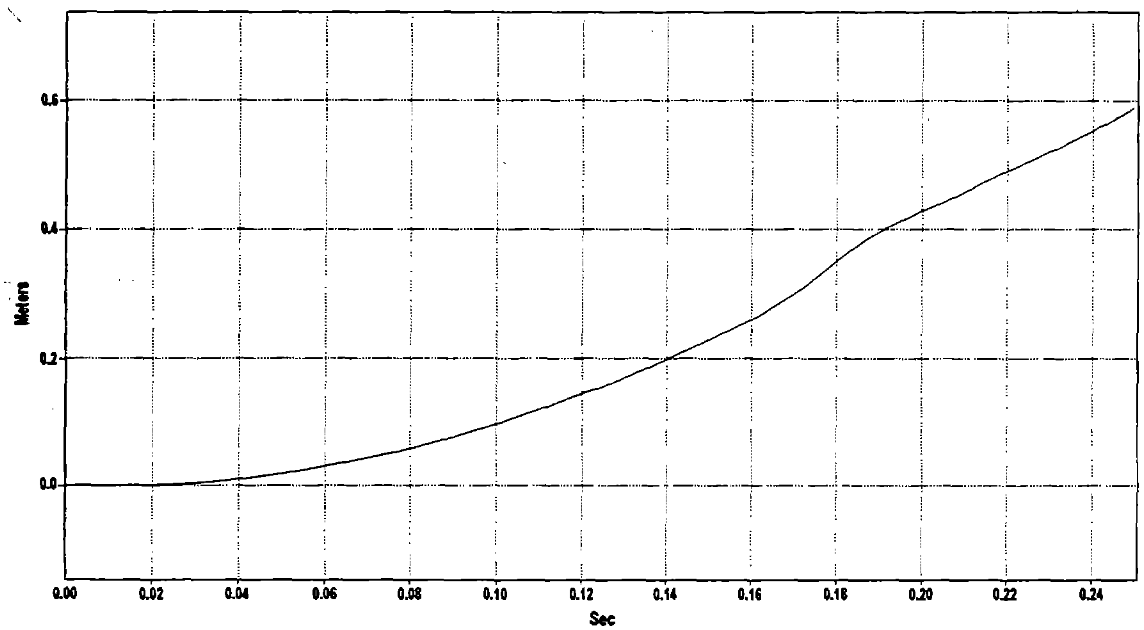


Figure C-36. Relative Lateral Occupant Displacement, Test BEST-11.