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TEST AND EVALUATION OF TRAFFIC BARRIERS

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
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16. Abstract

A series of crash tests were conducted to evaluate several types of guardrails and bridge rails.

Two bridge rail designs were tested and showed acceptable performance when evaluated in accordance with NCHRP 230.

A three-cable guardrail was modified, and an end terminal was redesigned to obtain good performance. The guardrail safely redirected a large and small vehicle traveling at 60 mi/h and impacting at 25 and 20 degrees, respectively. The terminal design was tested for snagging by directly impacting the downstream end. Although the device released, the vehicle rolled over.

A new PL3 median barrier was designed and tested in accordance with the new AASHTO bridge rail test criteria. A 50,000-lb tractor-trailer impacted the median barrier at 50 mi/h and 15 degrees. The truck was redirected and contained, but rolled over producing undesirable occupant compartment intrusion.

An 18,000-lb truck test was conducted on the modified thrie beam median barrier. The results indicated good performance.

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Three-cable rails	PL3 testing	
Full-scale testing	PL3	

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METRIC (SI*) CONVERSION FACTORS

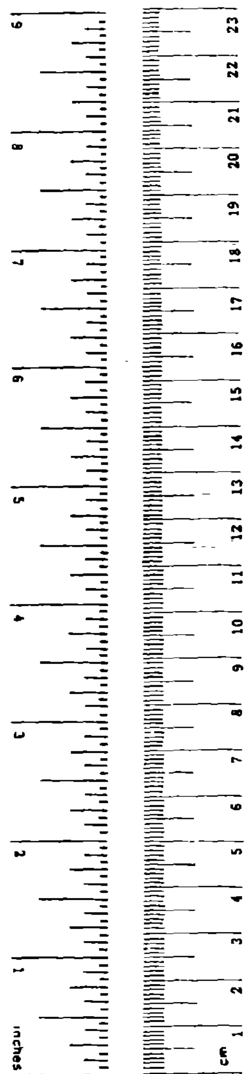
APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

TEMPERATURE (exact)

°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

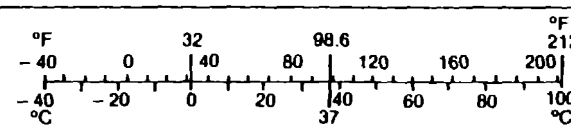


APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectores (10 000 m²)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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INTRODUCTION

This project consisted of design work and testing of several guardrail and bridge rail systems. The project started with a review of past work in the areas of the Minnesota three-cable guardrail and high-performance level median barriers.[1,6] The review of the data directed the research on these two systems. The review is discussed in the first section of this report.

A drawing package was developed for the redesigned guardrail systems. These drawings were submitted to the Federal Highway Administration (FHWA) for review. The remainder, and largest portion, of the contract consisted of full-scale and pendulum testing. Tests were conducted on:

- Minnesota three-cable guardrail system.
- Quad beam and modified thrie beam system.
- Iowa bridge rail system.
- Nebraska bridge rail system.

This testing is discussed in the following sections of this report. Each test is discussed in detail. Photographs, drawings, data plots and descriptions of the test setup and results are presented for each test. The last two sections of the report contain conclusions and recommendations, which summarize the results of this research project. This report follows the task outline of the contract.

BARRIER ANALYSIS, LABORATORY TESTING AND BARRIER DRAWINGS

This contract used a standard approach to barrier design of systems which have proved inadequate through past testing. The first step was to understand the problem causing the undesirable rail performance. A solution was then formulated and analyzed using simple analytical techniques. The most promising ideas were then evaluated through the use of laboratory tests. Drawings of the new designs were made prior to full-scale testing. The full-scale tests are discussed in the following chapters.

For the Minnesota three-cable guardrail system, the analysis and laboratory testing were intermixed. This occurred because analytical results and actual measured results did not agree well during the early tests. A discussion of this process is contained in the section one of this chapter. Several modifications to the standard post were tested and the results are reported. An end terminal for the three-cable guardrail was developed and tested. This is also discussed in section one. Section two contains a discussion of the design of a new median barrier system. Drawings for these systems are contained in section three.

1. <u>MINNESOTA THREE-CABLE SYSTEM</u>

a. Redesign of Three-cable Guardrail Post

A Minnesota three-cable guardrail was tested under a previous FHWA contract.[1] Under this project, a three-cable system was tested and proved successful for a large vehicle impacting at 60 mi/h and 25 degrees. During the small vehicle test, the vehicle overturned. This occurred when the vehicle impacted several posts along the length of need (LON), which caused the vehicle to roll.

A post modification developed for the controlled releasing terminal (CRT) was adapted for this contract.[2] This modification consists of a hole drilled through the post to make the post break more easily in the direction of vehicle travel, while maintaining nearly all of the post's strength in the lateral direction. The hole and typical post section is shown in figure 1.

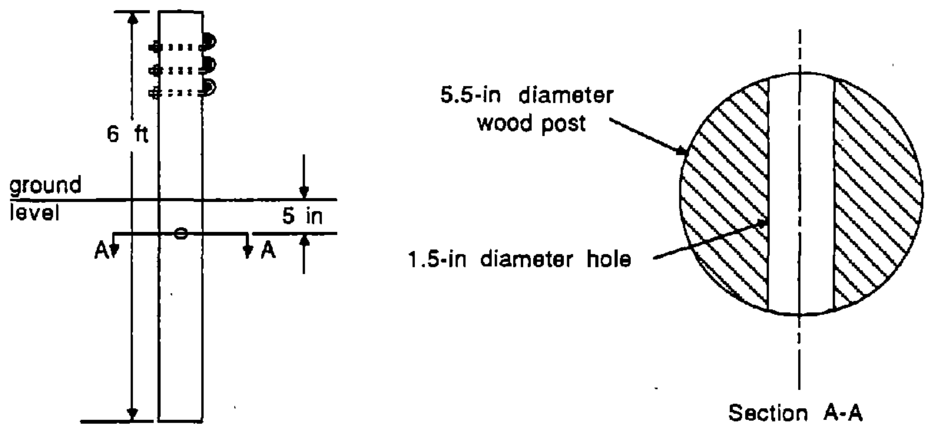


Figure 1. Hole modification for Minnesota three-cable guardrail posts.

The area moment of inertia for the nominal diameter post (diameter = 5.5 in) is 44.9 in^4. With a 1.5-in hole drilled through the post, the moment of inertia in the direction of vehicle travel is reduced by 45 percent, while in the lateral direction it is reduced by only 3 percent. A plot of lateral and longitudinal percent of area moment of inertia for varying hole diameters is shown in figure 2.

b. Pendulum Tests of the Minnesota Three-cable Post

A total of 39 pendulum tests were conducted at the FHWA Federal Outdoor Impact Laboratory (FOIL) in McLean, VA. All posts had a nominal diameter of 5.5 in and a length of 6 ft. The posts were purchased directly from a guardrail supplier in Minnesota which supplies installation crews in the State. The impact point was 24 in above the ground which is the center

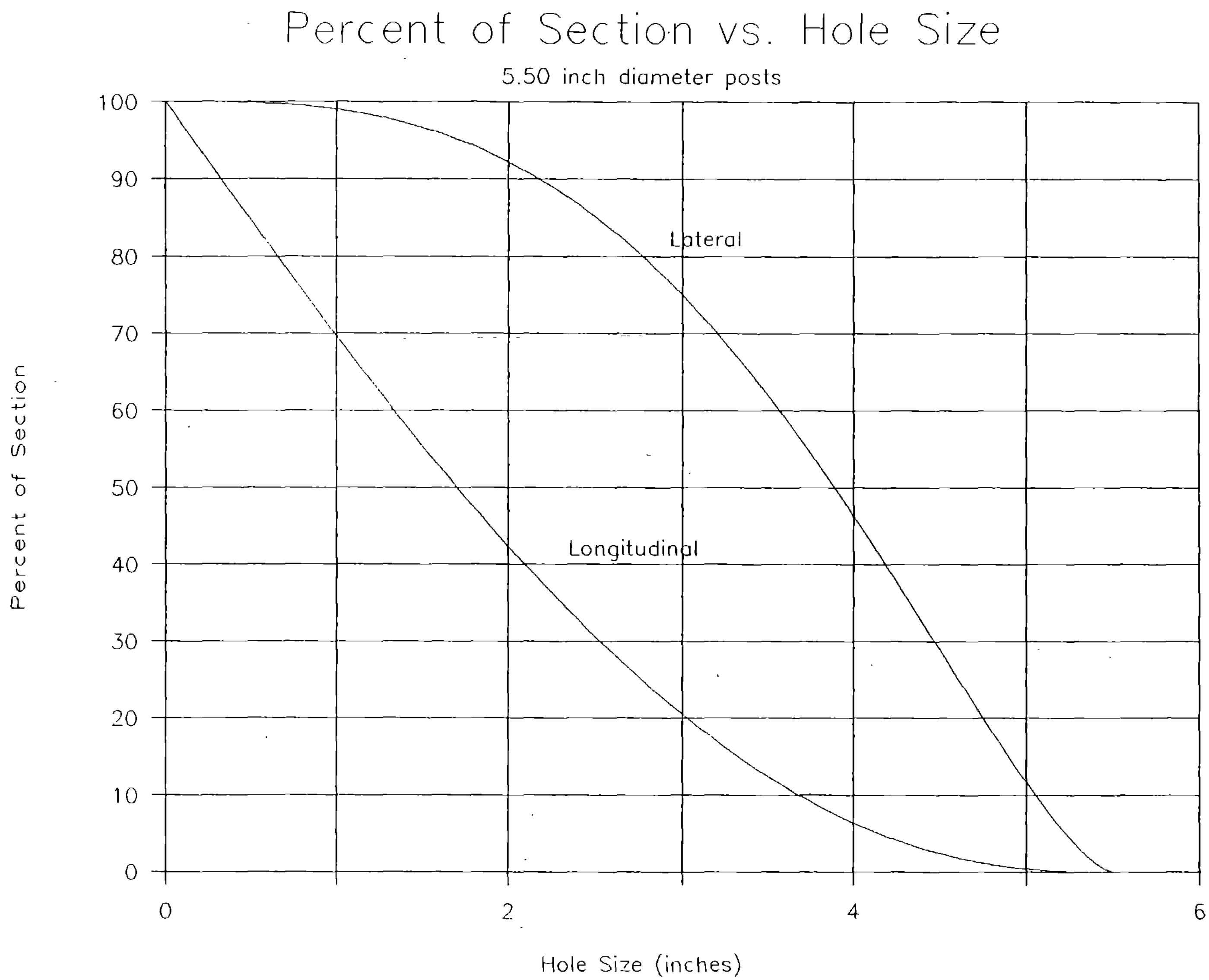


Figure 2. Percent of section vs. hole size.

cable height for the system. The overall test matrix and results are shown in table 1.

Standard posts are those which were not modified, i.e., tested as they are currently installed. The lateral impact direction is perpendicular to the cable direction. In this direction, the post maintains most of the strength that is needed for redirection of the vehicle. In the longitudinal direction, the post is hit parallel to the hole direction, in line with the LON. In this direction, the post has been weakened and should break more easily than the unmodified post.

Testing was conducted in several series of tests. The first series was conducted with the post modification located at ground level. A second series was conducted with a two-hole modification (one at grade and one below grade). A final series was conducted with a single hole located below grade. The following sections discuss each of these test series.

(1). <u>Single Hole Above Grade Test Series</u>

The one hole above ground modification had two service benefits. First, since the hole would be just above ground level, it would be an easy retrofit and second, the above ground hole was a visible indication of correct installation. Table 2 shows the average results for these tests. Since the posts varied slightly in actual diameter, the peak forces were scaled by the ratio of average diameter of the set to the diameter of each post to get the adjusted peak forces. Both sets of final data are presented in table 2. The ratios of the breakaway force level for posts with lateral and longitudinal holes to the standard post are presented in table 3. The theoretical ratios based on the reduction in area moment of inertia are also presented.

Table 1. Minnesota three-cable guardrail post pendulum tests.

Date	Test Number	Modification			ID #	Diameter	Breakaway Force
2/3/87	87P005	None			16	4.85	3995
	87P006	None			11	4.77	3581
	87P007	None			13	4.93	3211
	87P008	1 hole	Lat		4	5.01	4000
	87P009	1 hole	Lat		2	5.01	2558
	87P010	2 hole	Lon/Lat		8	4.62	1774
	87P011	2 hole	Lon/Lat		9	4.70	2100
2/10/87	87P015	2 hole	Lon/Lat		7	4.81	1996
	87P016	1 hole	Lat		3	4.93	2637
	87P017	1 hole	Lon		6	4.89	2252
	87P018	1 hole	Lon		1	4.85	4756
	87P019	1 hole	Lon		5	5.17	5119
2/19/87	87P024	None			15	4.89	2980
	87P025	None			12	4.66	9835
	87P026	1 hole	Lat		19	4.93	2696
	87P027	1 hole	Lat		18	4.62	3912
	87P028	1 hole	Lon		14	5.25	3580
	87P029	1 hole	Lon		10	5.01	3978
					Avg Diam	4.88	
4/2/87	87P042	2 hole	Lat		2-5	4.81	3194
	87P043	2 hole	Lon		2-8	4.97	2476
	87P044	None			2-3	4.93	4495
	87P045	2 hole	Lat		2-1	4.77	4414
	87P046	2 hole	Lon		2-7	4.93	2579
	87P047	1 hole	Lat	12" bg	2-9	5.33	4776
	87P048	None			2-6	5.01	3623
	87P049	2 hole	Lat		2-2	4.91	3481
	87P050	2 hole	Lon		2-4	4.93	3546
					Avg Diam	4.95	
4/20/87	87P056	1 hole	Lat	5" bg	3-1	5.01	3195
	87P057	1 hole	Lon	5" bg	3-2	5.17	3181
	87P058	None			3-7	5.09	4010
	87P059	1 hole	Lat	5" bg	3-4	5.21	3984
	87P060	1 hole	Lon	5" bg	3-6	5.05	2653
	87P061	None			3-10	4.85	3820
	87P062	1 hole	Lat	5" bg	3-5	5.05	3068
	87P063	1 hole	Lon	5" bg	3-8	4.93	2391
	87P064	None			3-12	4.97	3178
	87P065	1 hole	Lat	5" bg	3-9	5.09	3654
	87P066	1 hole	Lon	5" bg	3-3	5.05	2549
	87P067	None			3-11	5.09	3247
					Avg Diam	5.05	

Table 2.

Ground hole modification results.

Post Type	No. of Tests	Avg Peak Force (lb)	Standard Deviation (lb)	Average Adjusted Peak Force (lb)	Adjusted Standard Deviation (lb)
Standard	5	4720	2580	4945	2953
Lateral	5	3161	652	3167	775
Longitudinal	5	3937	1004	3702	948
Crossed Holes	3	1957	136	2102	120

Table 3.

Ground hole force ratios.

Post Hole Direction	Measured Force	Adjusted Peak Force	Theoretical Ratios
Longitudinal	.83	.75	.50
Lateral	.67	.64	.95

Note: Ratio equals force with modification divided by standard post force level.

As can be seen, the posts did not produce results as expected. The longitudinal type impacts produced force levels higher then expected while the lateral impacts produced force levels lower then expected. In fact, the posts tended to be stronger in the weaker impacted direction. Both modifications did produce a lower force level than the standard post. It was felt that the shear force through the post may have contributed to the test results not being as predicted when using bending moment theory to predict the performance of the posts. This modification did not produce the results of strength reduction in one direction while maintaining strength in the other direction, as desired, and thus was dropped.

(2). Two-Hole Test Series

In these tests, two holes were drilled at two different depths. One was maintained at the ground level, while the second was located below grade. In previous work conducted for the FHWA, it was demonstrated that the maximum moment in a post-bending situation occurred at .375 of the embedment depth down from the surface.[2] For these Minnesota posts, the embedment depth is 38.5 in. The maximum moment would occur at 14.4 in. This value was developed for the noncohesive soil case where the post is much stronger than the post. The post tests had been conducted in very strong soil. The actual breakaway location data from the unmodified tests showed the break location was occurring at 9.6 in below ground. These points (14.4 and 9.6 in) were weighed equally and the appropriate location for a second hole was determined to be 12 in below ground.

Posts were modified and pendulum tests were conducted. Table 4 shows the average results for these tests. The first six tests were conducted by dropping the post into the hole that remained after removing the post from the previous test. As seen in table 5, the data and ratios from these tests showed good correlation with theory. However, placing the posts into the previous hole may have created a three-point loading situation and it was felt that this was not representative of actual conditions. A three-point loading occurs when the post is loaded at the top by the impact and the impact load is resisted by two local loading areas below ground, instead of the uniform loading of a typical post in uniform soil. This is shown in figure 3.

Table 4. Two-hole modification results, set 1.

Post Type	Number of Tests	Peak Force	Adjusted Peak Force
Standard	2	4636	4333
Lateral	2	3808	4076
Longitudinal	2	2528	2533

Note: Post loading may not have been uniform (three-point loading may have occurred)

Table 5. Force ratios for two-hole modification.

Direction	Peak	Adjusted	Theory
Lateral	.82	.94	.95
Longitudinal	.55	.58	.50

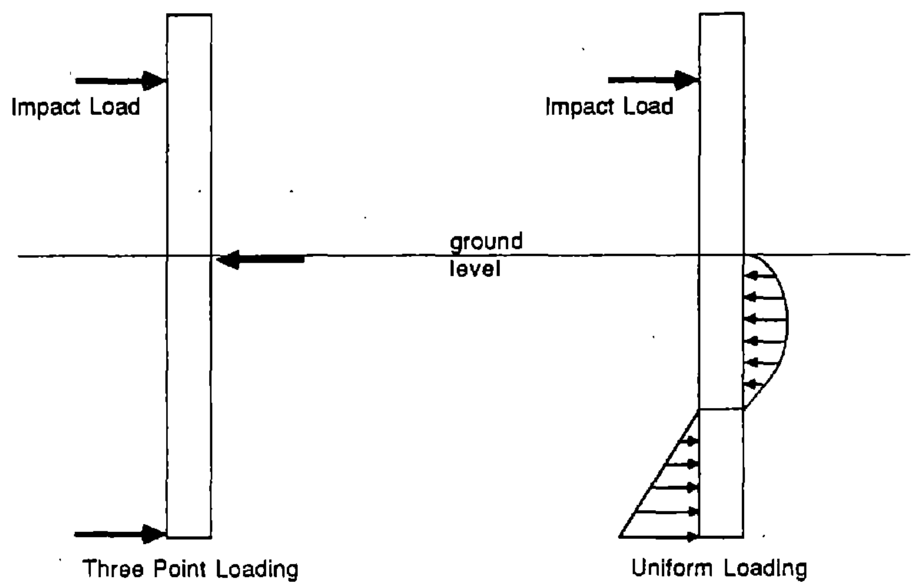


Figure 3. Post loading diagrams.

The second set of three tests was run in well disturbed soil to determine if the three-point loading was affecting the results. The peak force values for these three tests were very similar, thus indicating a heavy relationship between post performance and soil condition. The results of these three tests, and the ratios of the modified posts to the standard posts are presented in tables 6 and 7.

Table 6. Two-hole modification results, set 2.

Post Type	Number of Tests	Peak Force	Adjusted Peak Force
Standard	1	3623	3543
Lateral	1	3481	3544
Longitudinal	1	3546	3582

Table 7. Force ratios for two-hole modification, set 2.

Direction	Peak	Adjusted	Theory
Two Lat Holes	.96	1.00	.95
Two Long Holes	.98	1.01	.50

An analysis was conducted to understand why the two-hole modification that had previously worked very well, was not working for the Minnesota posts.(2) The first major difference between the CRT posts and the Minnesota posts was that the CRT posts were constant in cross-sectional area with depth while the Minnesota posts varied with depth. Due to the changing diameter of the posts (taper due to wood), the modulus of elasticity (E)-area moment of inertia (I) product was changing. A plot of moment and stress vs. depth for a noncohesive soil, shown in figure 4, shows the shift upward in maximum stress location. The location of the maximum moment is approximately 11 in while the maximum stress occurs at approximately 9.5 in or a 1.5 in shift upward due entirely to the taper in the post. This soil/post model represents cases where the post is strong in relation to the soil.

For the Minnesota weak wood posts set in strong soil, the soil and post are similar in strength, and a new soil model was needed to analyze the action of the post in the soil. The "beam on elastic foundation" model is more representative of wood posts in this soil environment. A moment and stress vs.

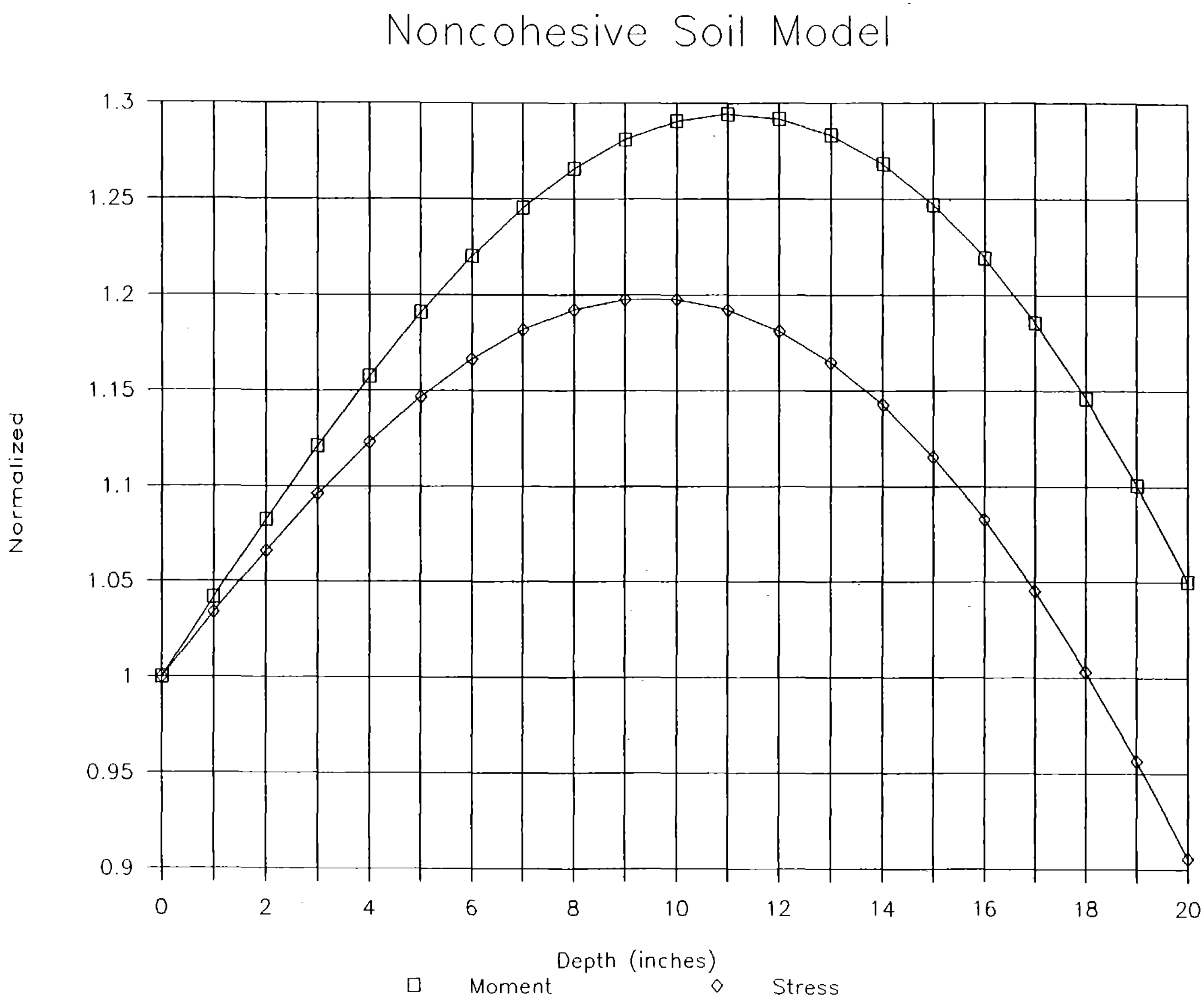


Figure 4. Noncohesive soil model.

depth plot for this model is shown in figure 5. The soil strength characteristic, k, was set at 250,000 ($lb/ft^2/ft$), which is typical for this soil. Using this model, the maximum moment is predicted to be at 7 in below grade while the maximum stress is at 5 in.

Using this model, the two-hole modification was reviewed. Figures 6 and 7 show moment and stress for the post with two holes, from the longitudinal and lateral directions, respectively. (Note: the ground hole is centered at 1-in below ground to eliminate the zero depth from the numeric calculations.)

For the longitudinal case, the stress is high (approximately two times the stress at ground level) at both hole locations. This would indicate that the post could break through either hole. In the lateral direction, from ground level to the hole at 12 in, the stress is no more than 10 percent greater than at ground level. In this direction, the post could break at any location from ground to the hole 12 in below ground. Test results validated the above explanation. The lateral impacted post broke between the holes and through the bottom hole.

(3). <u>One Hole Below Grade</u>

A more effective modification was required and different possibilities were investigated. The best was to locate a single hole 5 in below ground. This modification was chosen because it placed the stress peak due to the hole at the maximum stress location. Figures 8 and 9 show plots for longitudinal and lateral directions. As compared to the two hole modification, it is clear that the hole at 5 in creates stresses that should not allow the post to break at other locations. The last set of tests are given in table 8. The ratios of the modified posts tested in the two directions compared to the standard post is presented in table 9. Based on the good test

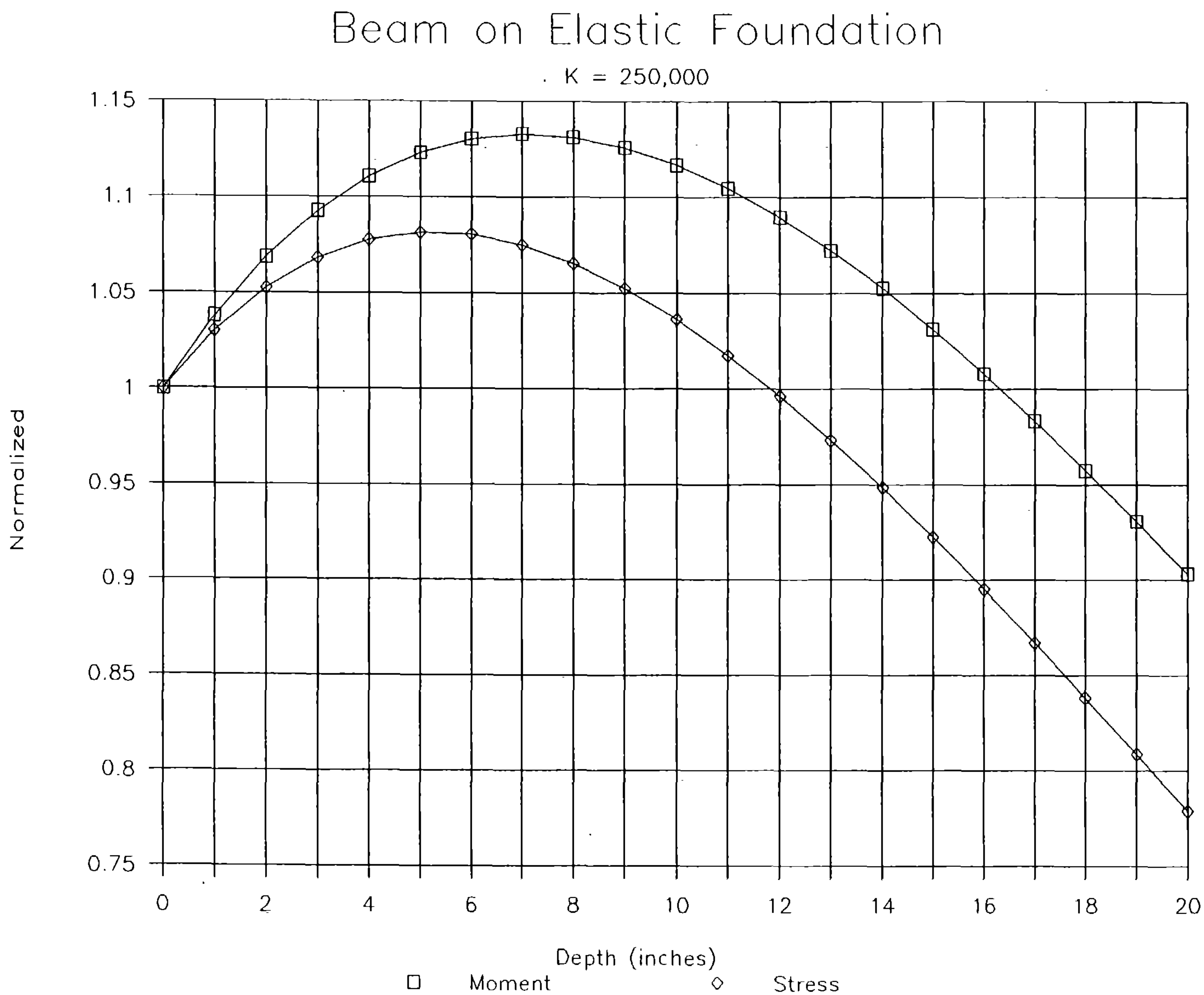


Figure 5. Beam on elastic foundation model.

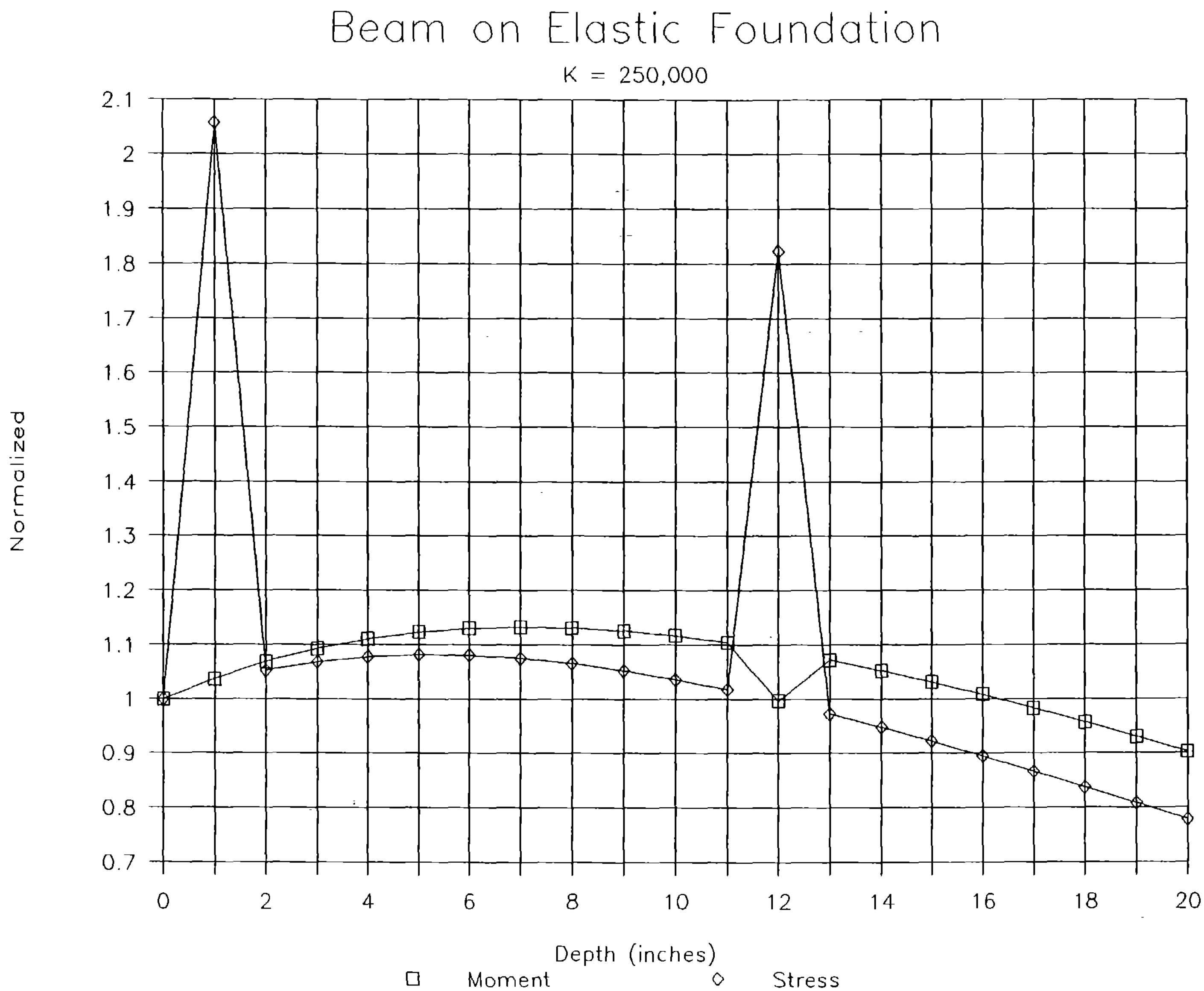


Figure 6. Two-hole longitudinal.

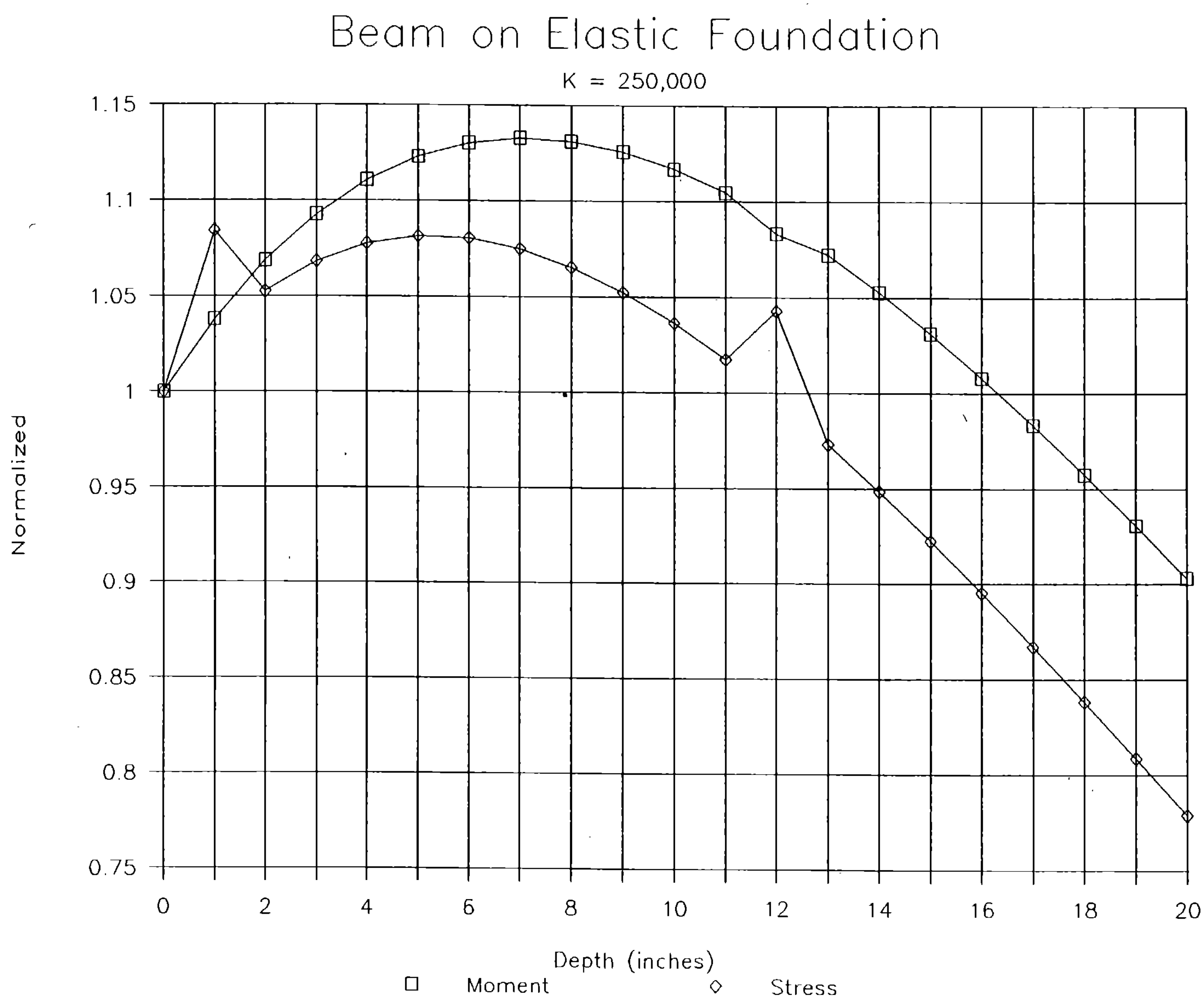


Figure 7. Two-hole lateral.

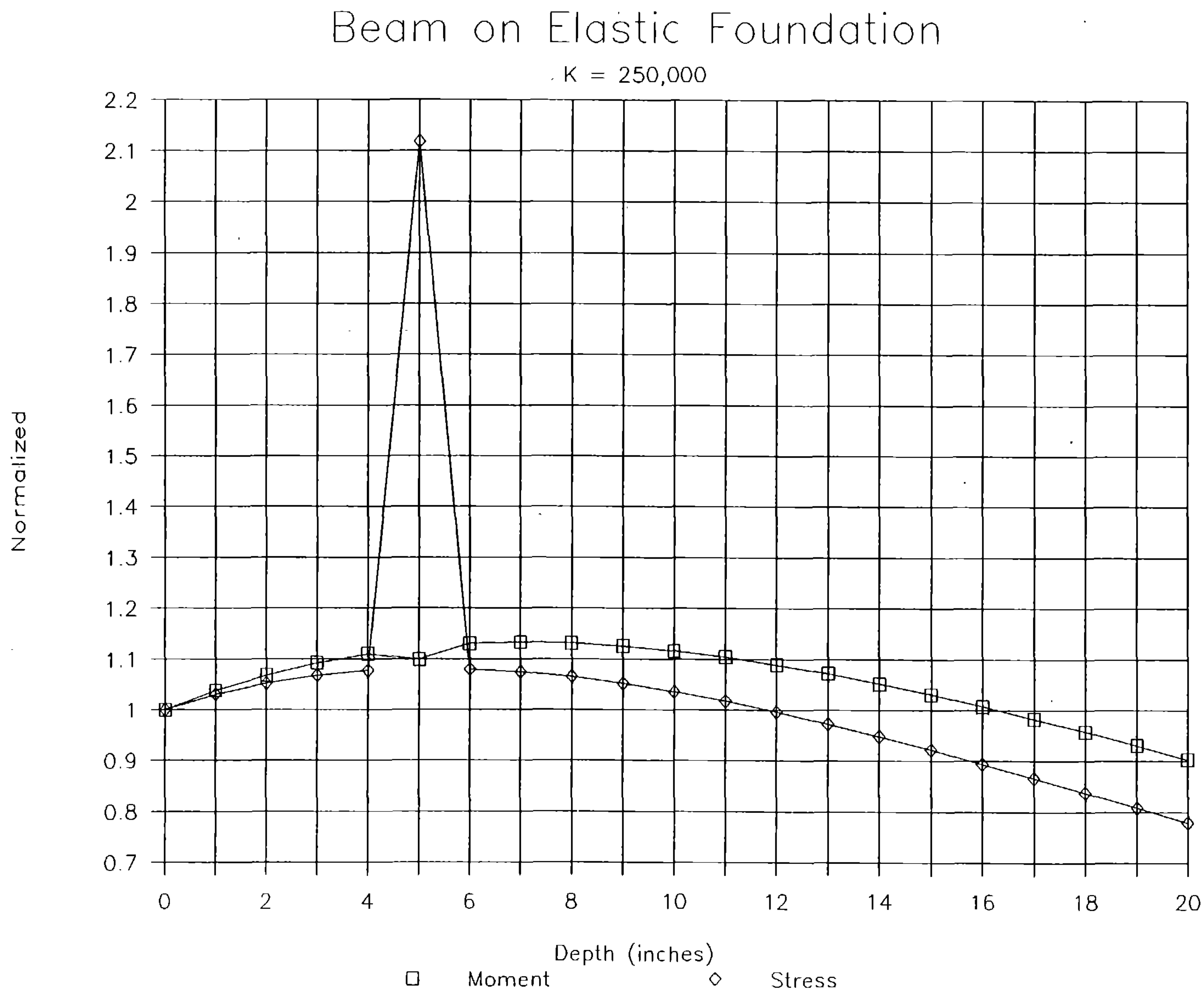


Figure 8. One-hole longitudinal.

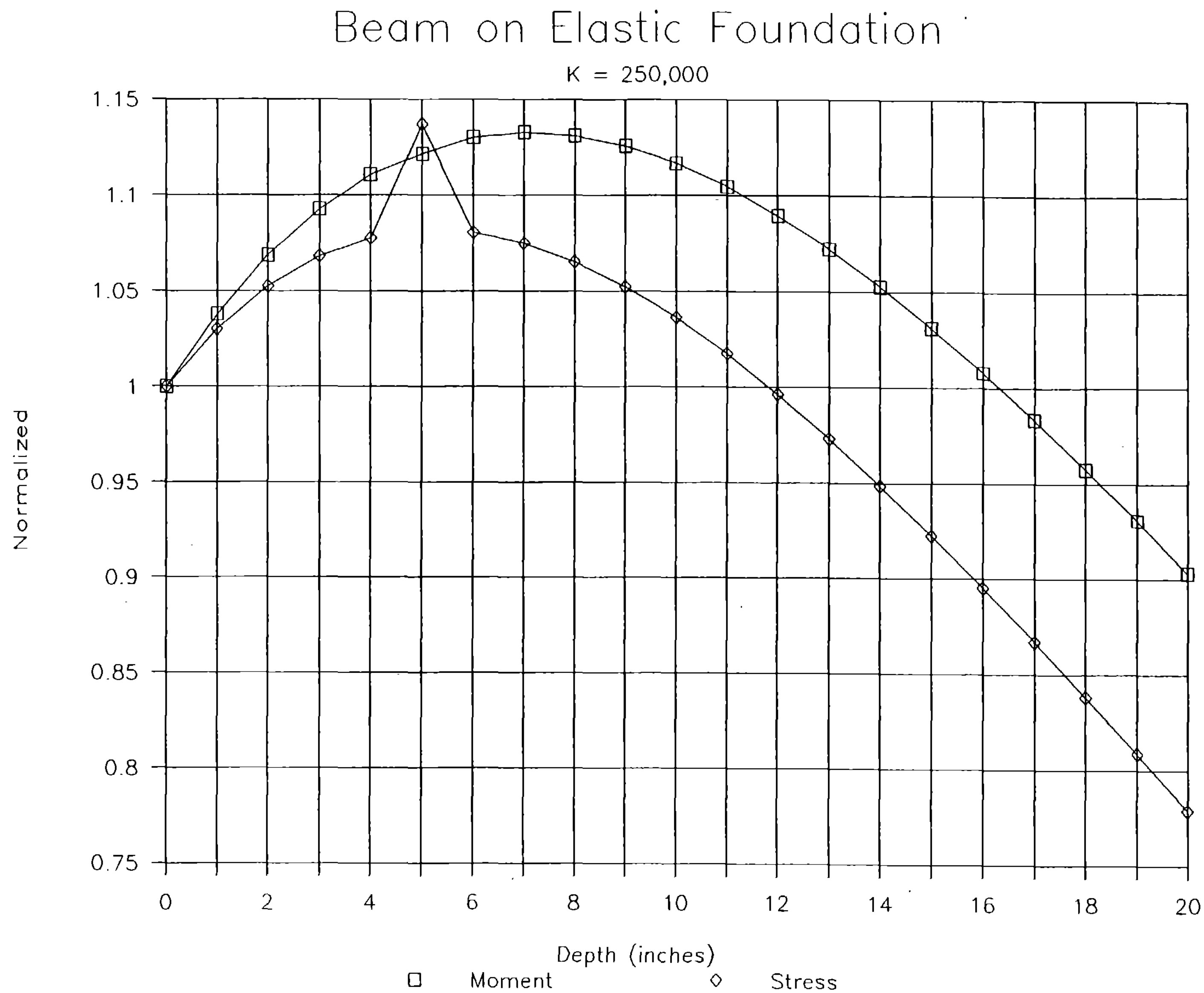


Figure 9. One-hole lateral.

Table 8.
One-hole modification results.

Post Type	No. of Tests	Avg Peak Force (lb)	Standard Deviation (lb)	Average Adjusted Peak Force (lb)	Adjusted Standard Deviation (lb)
Standard	4	3564	3564	3637	472
Lateral	4	3475	422	3409	310
Longitudinal	4	2694	342	2683	240

Table 9.
One-hole modification force ratio.

Direction	Peak Force	Adjusted Peak	Theory (5.05 in post)
Lateral	.98	.94	.96
Longitudinal	.76	.74	.52

results and the validation of the post/soil model, the single hole located 5 in below grade was selected as the design for testing. This post design was depicted in figure 1, shown previously. This post was used in the full scale tests. Its performance was validated in that it did not cause the 1800-lb vehicle to roll over during the NCHRP Report 230 test type S13.[3] This test uses an 1800-lb vehicle impacting at 60 mi/h and 20 degrees. The vehicle was redirected smoothly. See full-scale tests of Minnesota three-cable guardrail for details.

c. Design of Minnesota Three-cable End Terminal

The standard terminal for the Minnesota three-cable guardrail system consists of a concrete anchor block, end post and attachment hardware. The end block is 30 in by 30 in by 8 in deep. It is set approximately 8 ft away from the end post. A 1.25-in anchor rod connects the anchor block to the end post through a turnbuckle. The anchor rod is attached to the end post through a set of connector plates and secured with a nut. The three cables are also connected to the same plates, thus providing for a path for the rail forces to be transmitted to the block. The standard configuration is shown in figure 10.

This anchor assembly was used in test C-1. The strength was adequate in that the vehicle was contained, but the vehicle continued down the rail and impacted the end terminal. The terminal captured the front corner of the vehicle causing it to yaw and rollover.

Based on the results of test C-1, a weaker link was needed to facilitate release of the anchor from the cables to prevent vehicle snag. Also some uplift of the foundation was observed, thus the foundation was moved back and deeper by adding 4 ft to the anchor rod. One additional problem was observed in that the end post collapsed under the compressive load from the anchor rod. This occurs when the rail tension is transmitted down the angled anchor rod. A portion of the tension in the rod is resolved into a vertical force which is reacted against the end anchor post.

The new design consisted of a dual end post with two saddle brackets which spanned the two posts. One bracket held the end anchor rod while the second held the three-cable anchor rods. The load path for the rail tension was into one bracket, then through the wood posts and into the second bracket which was attached to the anchor rod. This system is shown in figure 11.

This design was tested in test C-2 with an 1800-lb vehicle. During the test the end anchor assembly failed to transmit the load to the end anchor block. Review of the results indicated that posts failed in the area between the two brackets.

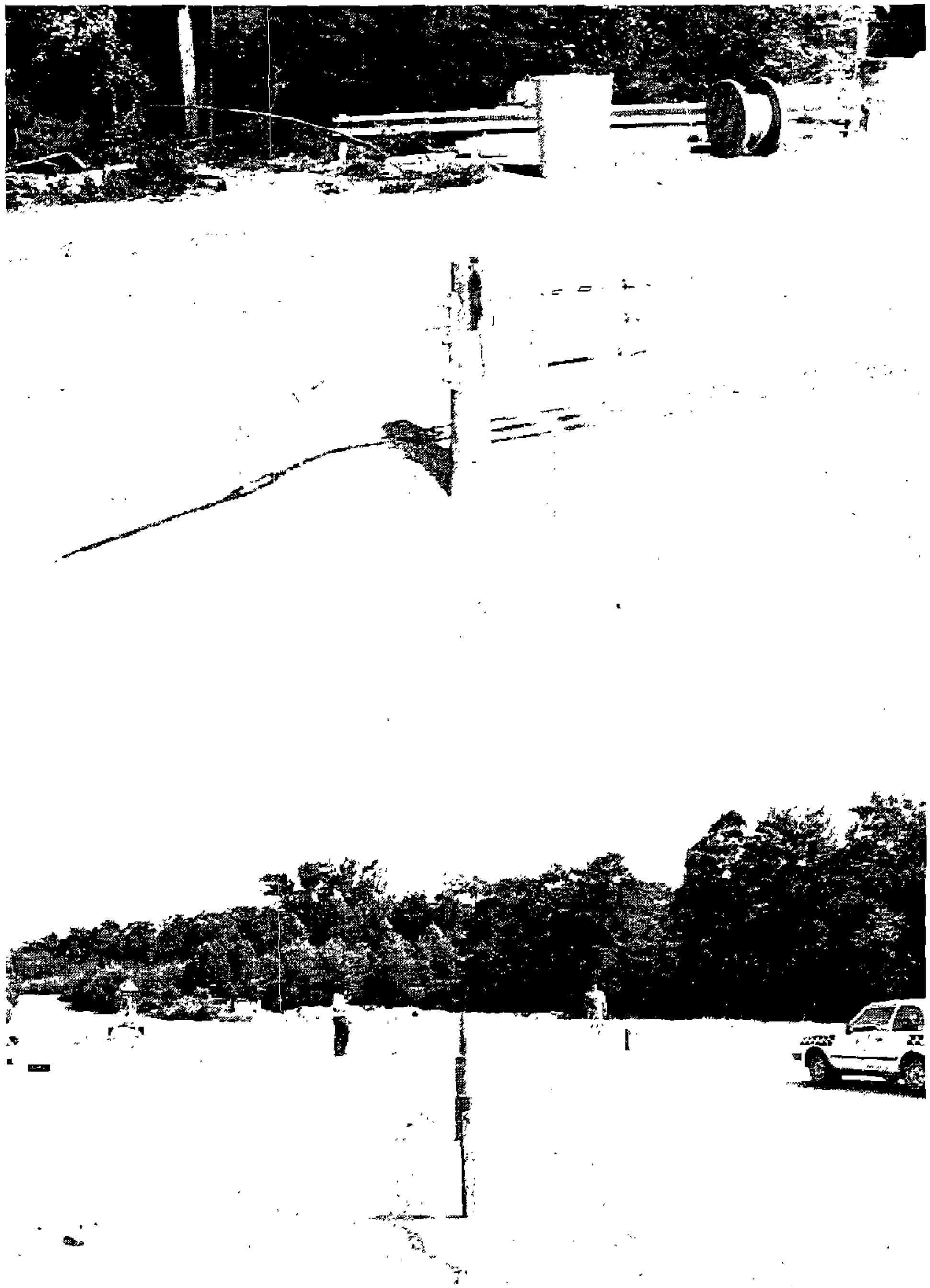


Figure 10. Standard terminal design for Minnesota three-cable guardrail system.

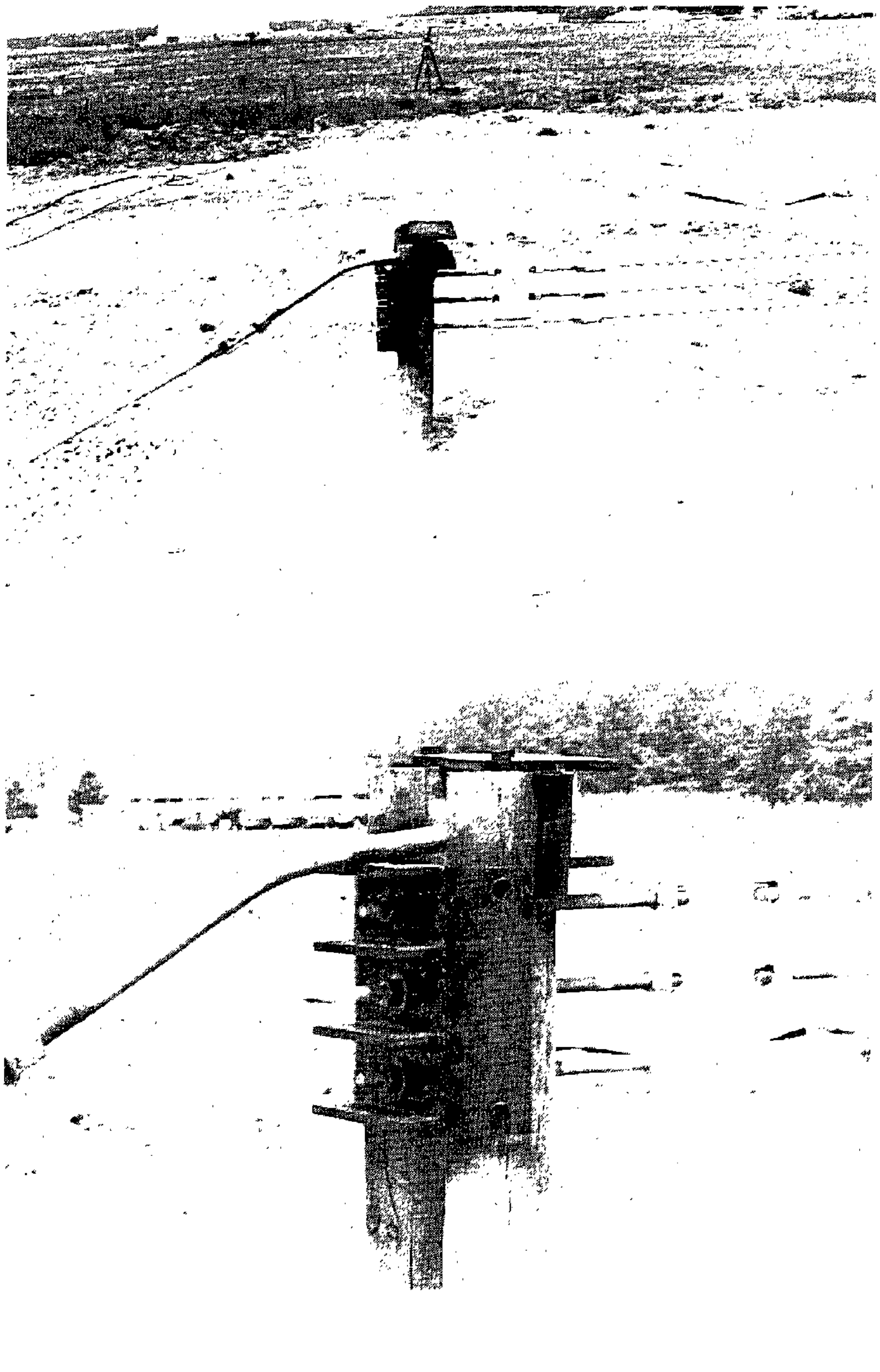


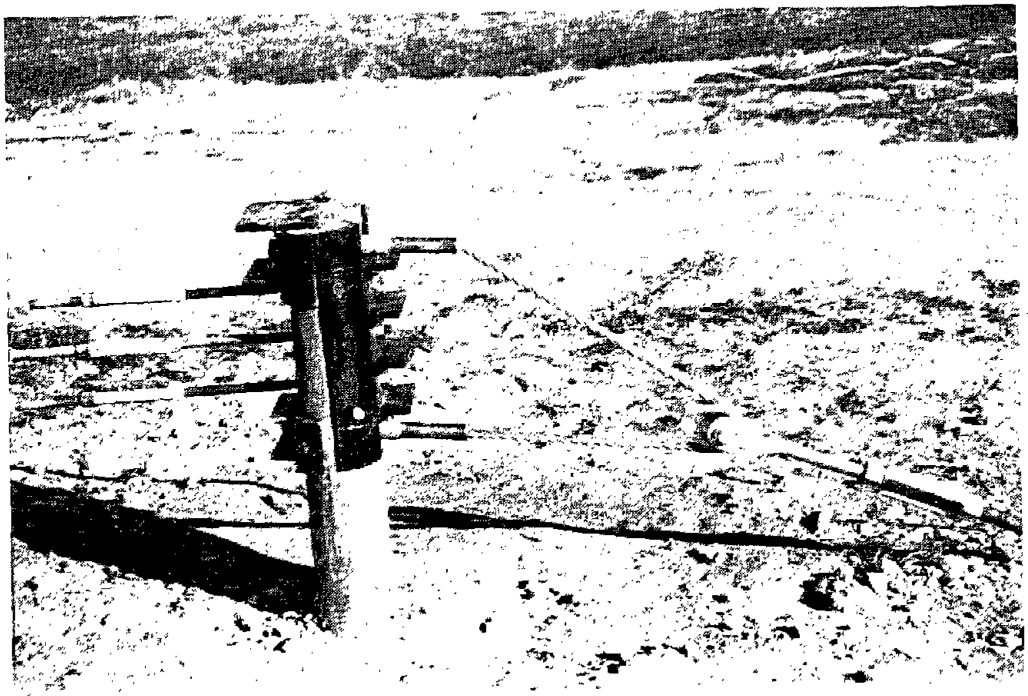
Figure 11. First modification to Minnesota three-cable terminal.

A new bracket assembly was designed featuring a third bracket added below the bracket which held the three cables. The two brackets were attached to the anchor rod using a standard BCT cable. The cable was held by one end of the anchor rod turnbuckle assembly. The cable allowed the load to adjust between the brackets to maintain an even load. This assembly is shown in figure 12.

This modification was crash tested with a small and a large vehicle in tests C-3 and C-4, respectively. During test C-4, with the large vehicle, the vehicle was redirected away from the rail in the area of the end terminal. This resulted in a direct impact with the end terminal, causing considerable damage to the vehicle. After review of the test, it was determined the three brackets did not separate as designed which would allow release of the end anchor from the three cables.

During the final test (C-5), an 1800-lb vehicle impacted directly at the trailing end of the system to test the release of the anchor. To facilitate release, the lag bolts which were used to hold the system together were removed and small shelves were added to hold the parts in vertical alignment. During the test, the end anchor released but the vehicle yawed resulting in a rollover.

Based on these tests, the original plates attached to a single post may work, but the vertical post strength is not adequate. The redesign, which uses two posts, improves this but adds three large steel brackets to the design to span between the posts. During the final test, the improved design caused the vehicle to roll over, the same results as the original design.



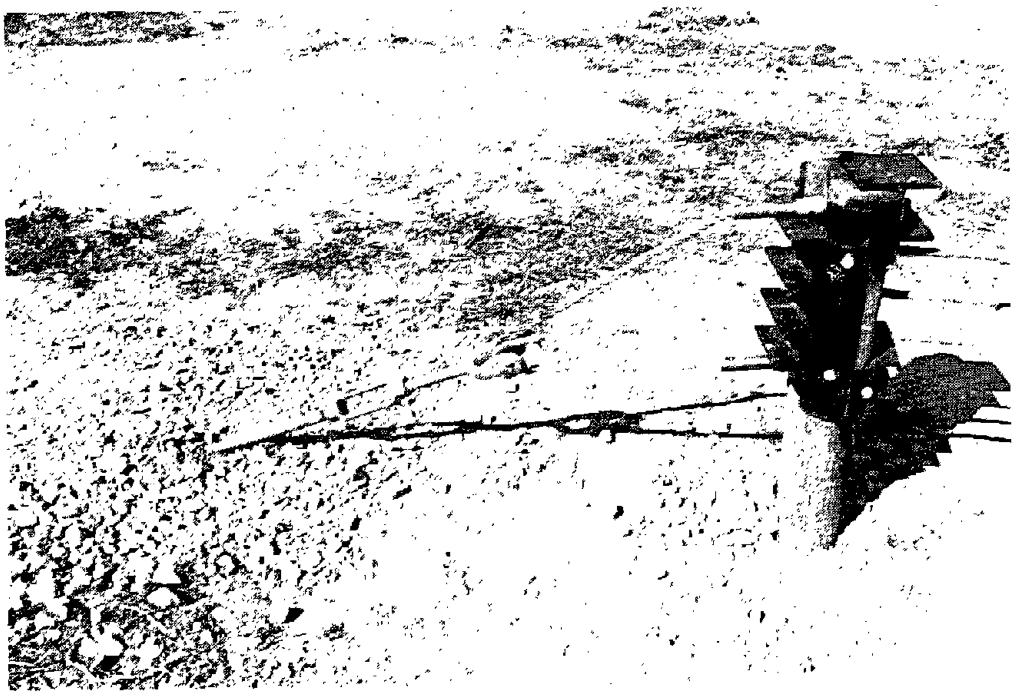


Figure 12. Final modification to Minnesota 3-cable terminal.

2. DESIGN OF QUAD BEAM MEDIAN BARRIER

The quad beam median barrier was designed to be a heavy duty, steel median barrier which would be capable of redirecting 50,000-lb tractor-trailers. The design was based on a an extension of the improved thrie beam median barrier developed for the FHWA.(1)

In tests of the improved thrie beam median barrier, the 40,000-lb intercity bus rolled over although it was contained. An improvement was needed to increase this barrier's performance level. During the same period of time, the test vehicles were being changed. The new AASHTO bridge rail test matrix had been developed which divided rail systems into performance levels.(5) The high performance for standard roadways was PL3, which called for three test vehicles: (1) 1800-lb vehicle, (2) 5400-lb pickup and (3) 50,000-lb tractor-trailer. With the new bridge rail standard in existence, it was decided that similar test vehicles should be used for this heavy median barrier, hence the selection of the 50,000-lb tractor-trailer.

The quad beam rail system received its name from its silhouette of four humps in the rail panel. In actuality, the system was built around the improved thrie beam median barrier, in that the posts and blocks were extended upward 6 in. This allowed a W beam panel to be nested over the top hump of the thrie beam and bolted to the lengthened post. The blockouts incorporated the notch cut in the lower outside portion, as was done in the improved thrie beam design. Photographs and a profile drawing of the system are presented in figure 13.

The system was terminated on the upstream end with a BCT eccentric loader terminal. The W beam was transitioned to a thrie beam using a standard transition, RE-69-76.(4) From the thrie beam to the quad beam, a transition was constructed

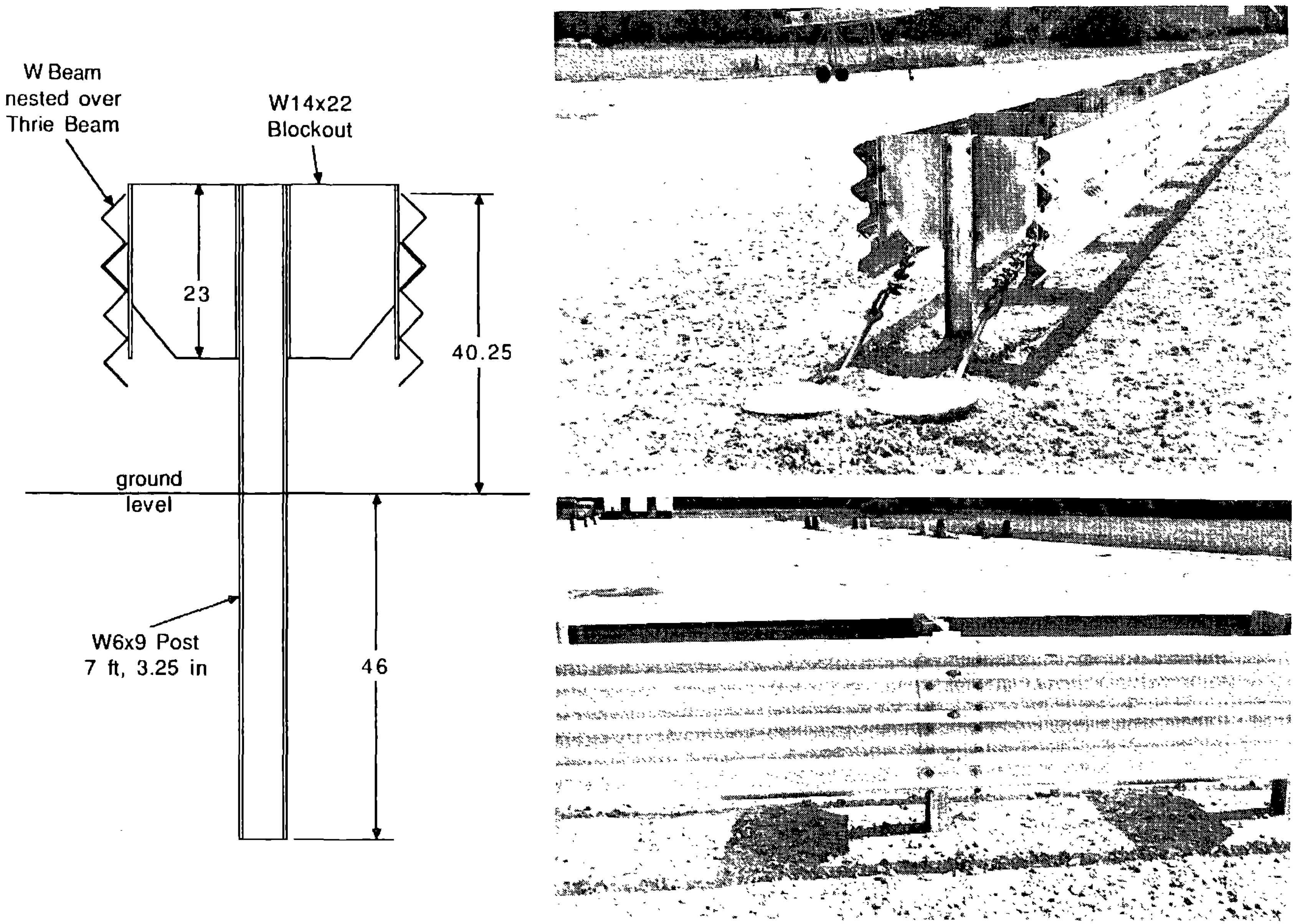


Figure 13. Quad beam rail system.

which included a steel angle spanning the end of the quad beam's top hump to the top of the thrie beam section. A BCT cable was also used to help transmit load between the quad beam and the thrie beam. The back side of the upstream end was anchored using a 18-in diameter by 5 ft-deep foundation attached to the rail through a 1.25-in hook rod and 0.75-in cable. On the downstream end of the system, both sides of the rail were anchored with a concrete foundation type anchor.

This system was tested with a 50,000-lb tractor-trailer at 50 mi/h and 15 degrees. The tractor was redirected followed by the redirection of the trailer. As the trailer redirected, it rolled onto the rail. The connection between the trailer and tractor pulled the tractor over onto the rail. The vehicle came to a rest on the rail. The results were unacceptable.

3. PREPARATION OF DRAWINGS

Design drawings were made for the changes to guardrail systems or components which were used during this project. Some changes were very simple and thus only the new component was designed. These drawings are included in this section. However, one system was completely redesigned and a complete set of report sized drawings were generated and are included. The following text details the design packages which were drawn and included.

a. Minnesota Three-cable Guardrail Post

A replacement post for the standard Minnesota three-cable rail system was designed and discussions of this design were presented in the previous chapter of this report. The drawing of this system is presented in figure 14. The modification consists of a 1.5-in hole through a standard post, 5 in below grade.

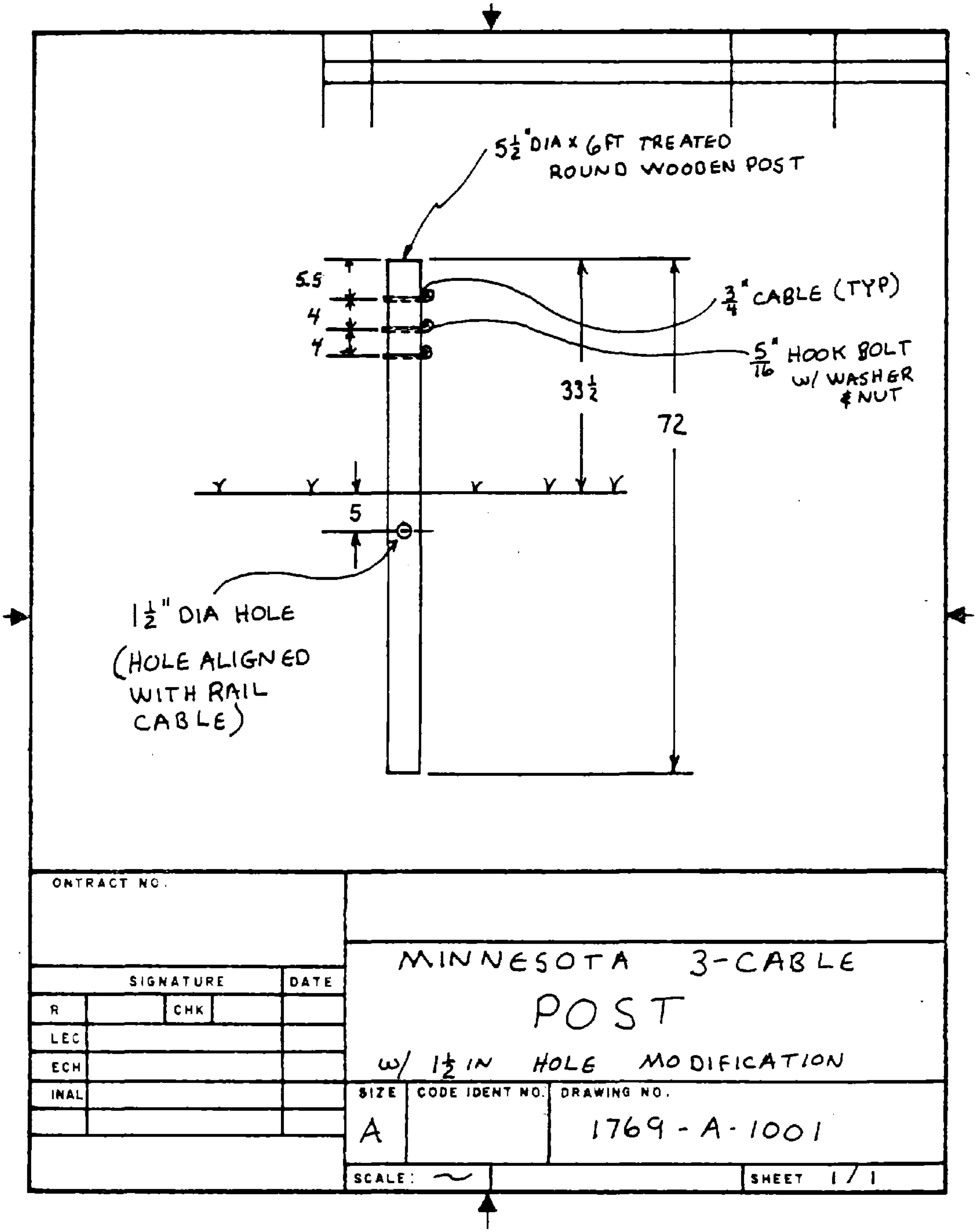


Figure 14. Minnesota three-cable guardrail post redesign.

b. Minnesota Three-cable Guardrail End Anchor System

A new end anchor assembly for the three-cable system was designed and tested. The drawings for this terminal are presented in figure 15. The first drawing in this figure depicts the overall terminal system. The major components are the dual end post, the rail attachment bracket, the end anchor attachment brackets, a BCT cable, the anchor rod, and the anchor block.

The dual end post consists of two standard line posts modified with the 1.5-in hole drilled 5 in below grade. The posts are set 8 in apart and rest on the standard concrete support block at the bottom of the posts. The three cables are attached to the posts through a saddle-type steel bracket which supports the cables in the center of the posts. There are two anchor attachment brackets. Both brackets span the two posts. The top bracket has a plate which rests on top of the posts to support it vertically. The lower device is a simple saddle which supports the lower anchor cable. The anchor rod is a 1.25-in diameter steel rod approximately 10 ft long. It connects to the BCT cable through a 1.25-in turnbuckle, having a threaded rod on one end and a clevis on the other. The clevis supports the BCT cable with a 0.75-in thimble. The concrete anchor is the standard anchor detailed in the Minnesota three-cable plan, measuring 30 in square by 8 in deep. Details of these parts are also depicted in figure 15.

c. Quad Beam Rail System

The quad beam rail was designed under this project to be a heavy median barrier capable of safely redirecting large vehicles. The standard heavy test vehicle under NCHRP 230 for testing this rail was a 40,000-lb intercity bus.[3] This was the vehicle which rolled over during the previous testing of the improved thrie beam median barrier.[1] This data was

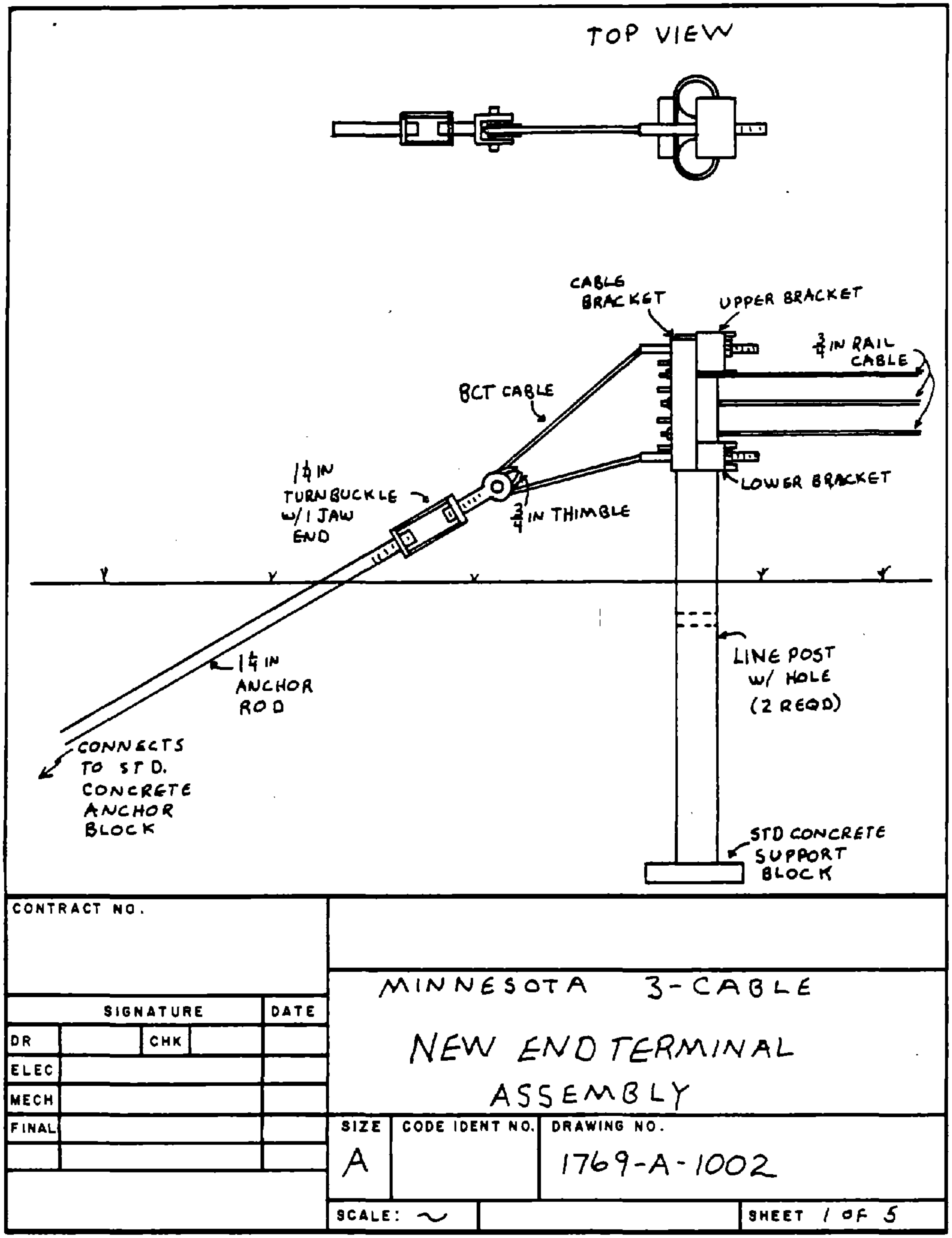


Figure 15. Minnesota three-cable end anchor system.

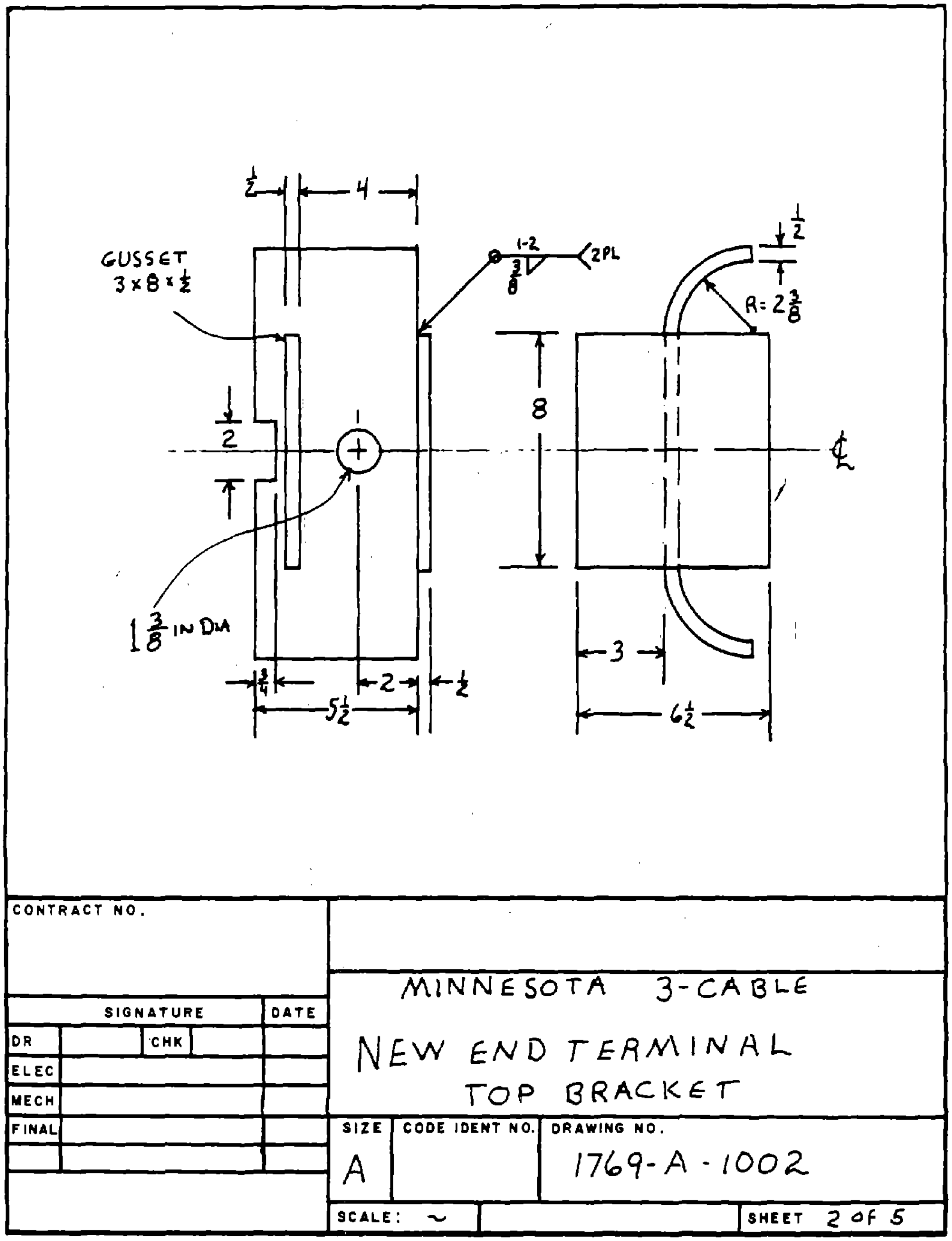


Figure 15. Minnesota three-cable end anchor system (continued).

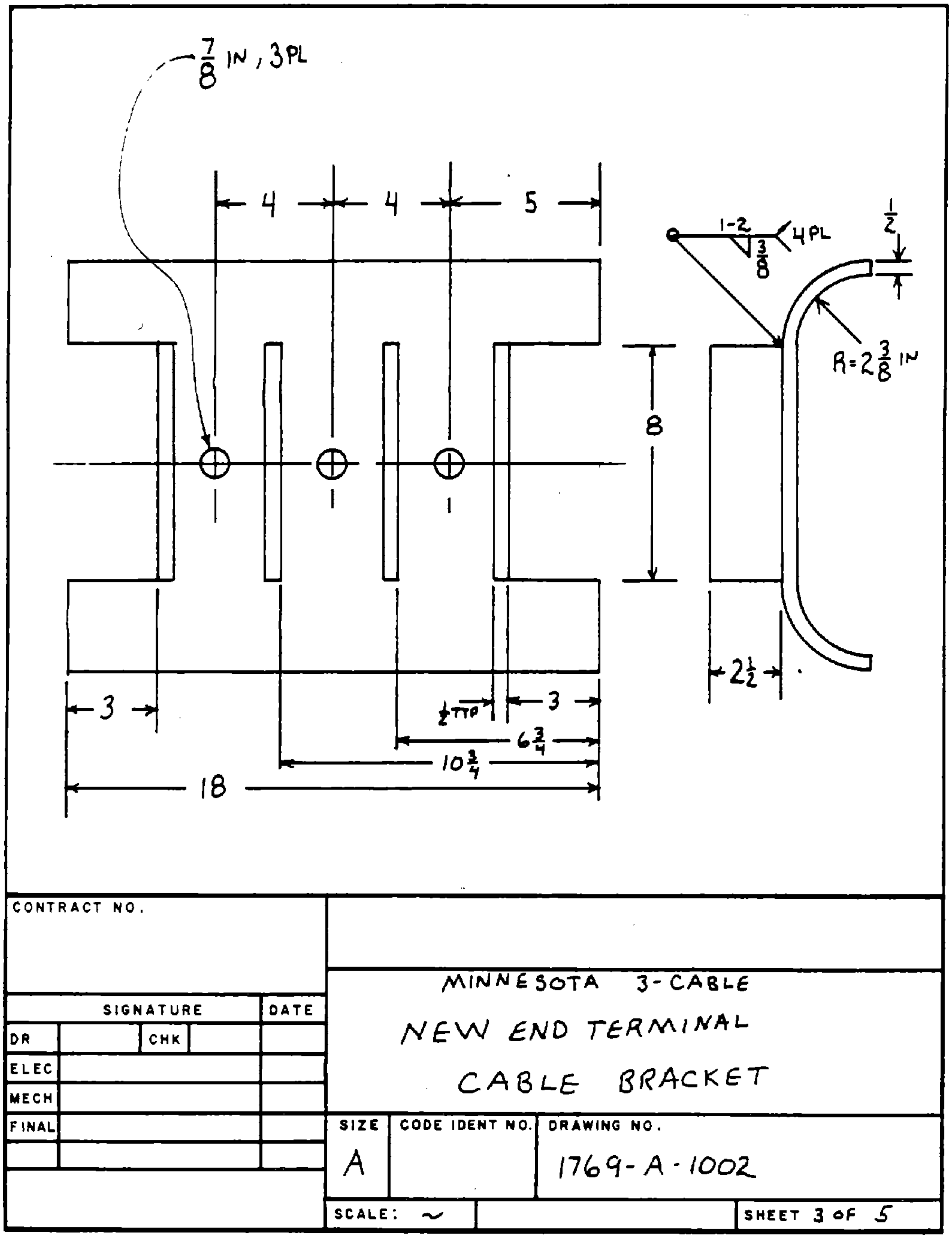


Figure 15. Minnesota three-cable end anchor system (continued).

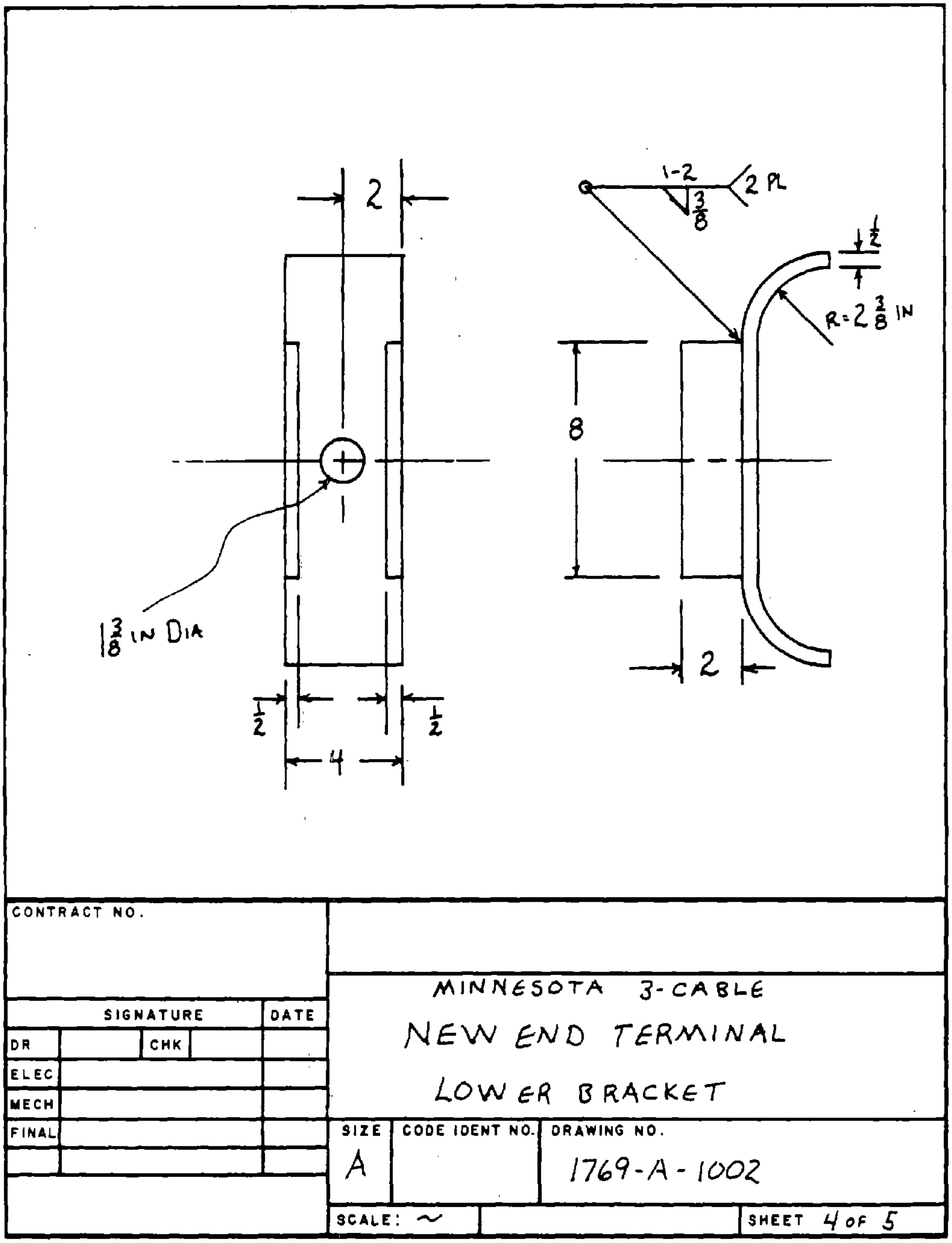


Figure 15. Minnesota three-cable end anchor system (continued).

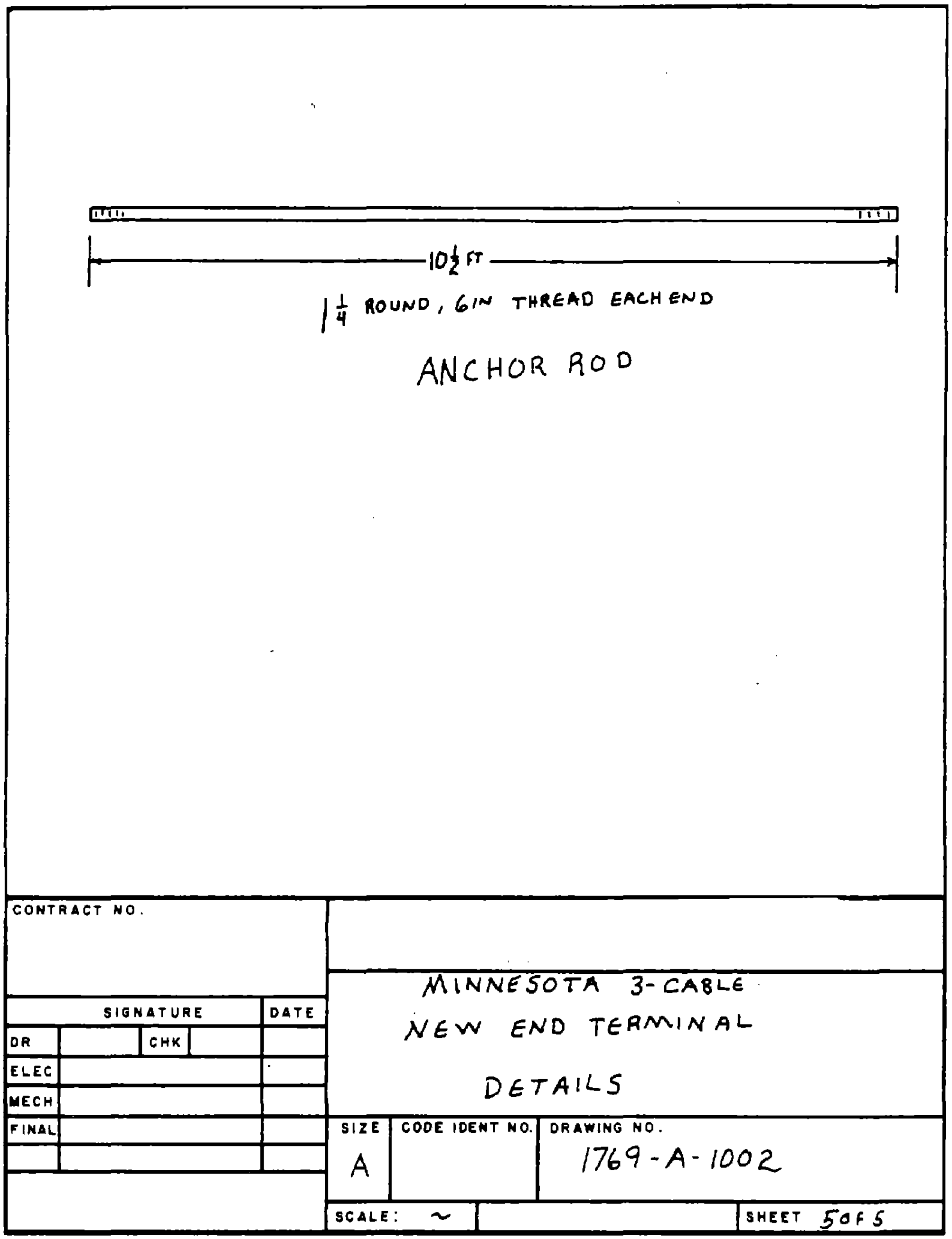


Figure 15. Minnesota three-cable end anchor system (continued).

reviewed and it was felt that raising the rail approximately 6 in would improve its performance. Around the time of this test, the new AASHTO bridge rail test matrix was being formulated and approved.[5] This called for a 50,000-tractor semitrailer to be used for the heavy vehicle. Based on this new test criteria, it was decided to test the quad beam rail with the 50,000-lb truck instead of the 40,000-lb intercity bus, for which the rail was actually designed

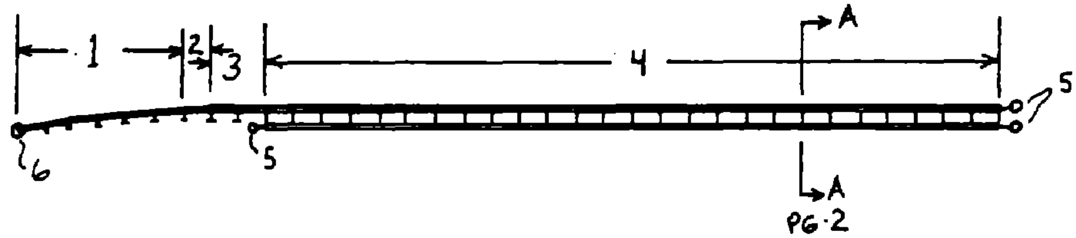
The test conditions were a 50,000-lb tractor semitrailer impacting at 50 mi/h and 15 degrees. To redirect a large truck, a rail height of 40 in or more was needed, along with sufficient strength to generate the rail tensile forces to obtain redirection. The quad beam system was based on the design of the modified thrie beam median barrier.

The quad beam rail has a mounting height of 40.25 in and uses thrie beam and W beam rail elements nested together to obtain a four-hump rail profile. Both rails are mounted to a modified blockout which incorporates a 6-in notch cut in the lower outside portion of the block. This modification is the same as the modified thrie beam median barrier. The posts are W6x9 steel posts set on 6.25-ft centers.

The terminals used in evaluation of this system consisted of an eccentric loader BCT, two transitions, and three 18-in round by 5-ft deep concrete footings. Details of this rail are shown in figure 16.

d. Iowa Bridge Rail Modifications

The Iowa bridge rail was tested successfully using a large sedan, but when tested with a small sedan (NCHRP Report 230 test type S13), the vehicle's front wheel snagged considerably.[3] The rail was redesigned by adding 4 in of depth to the bottom surface of the concrete rail. This produced a



		LENGTH (FT)
1	ECCENTRIC LOADER BCT	37.5
2	W-BEAM TO THRIE BEAM TRANSITION	6.25
3	THRIE BEAM TO QUAD BEAM TRANSITION	12.5
4	QUAD BEAM RAIL	AS NEEDED
5	ANCHOR ASSY	~
6	BCT ANCHOR	~

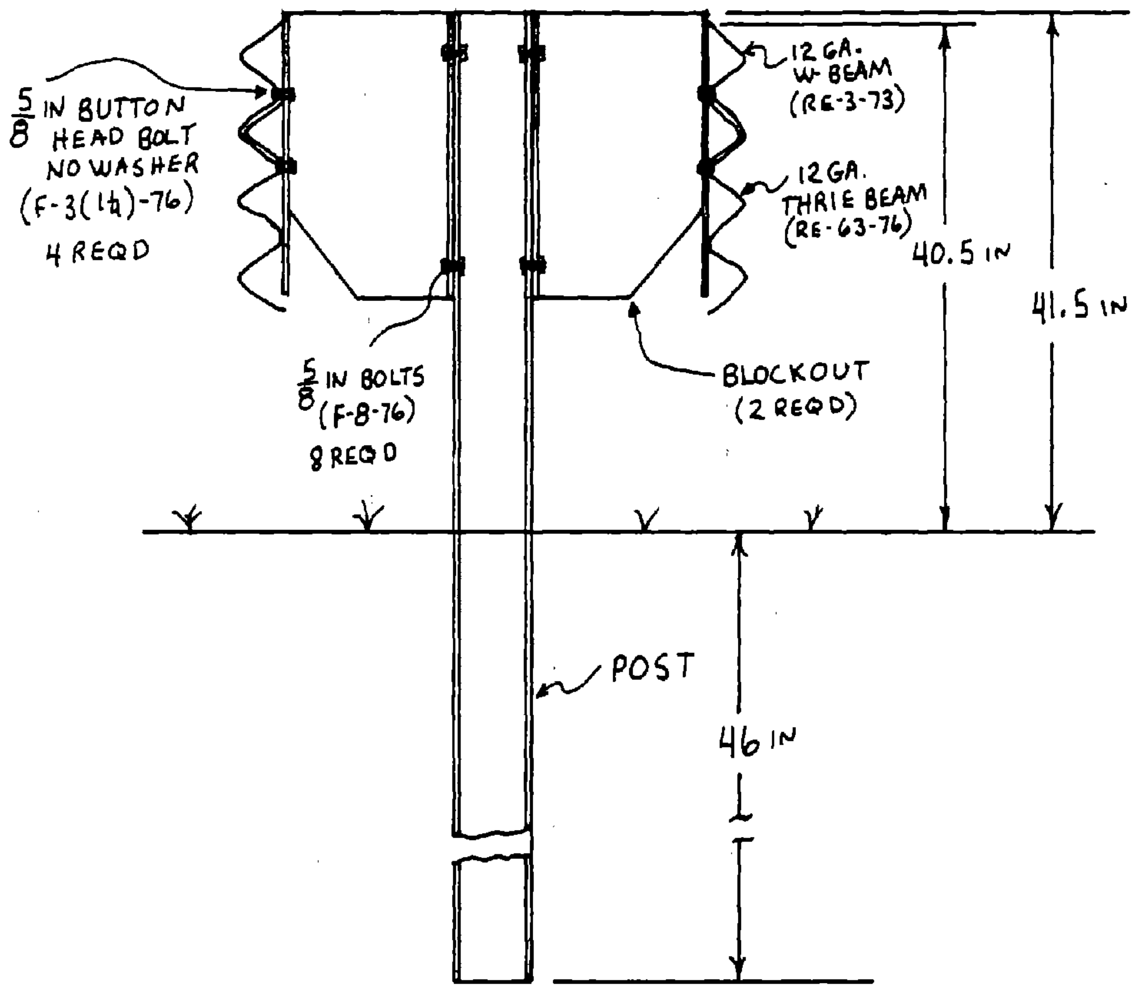
CONTRACT NO.				
SIGNATURE				DATE
DR		CHK		
ELEC				
MECH				
FINAL				

LAYOUT

QUAD BEAM

SIZE	CODE IDENT NO.	DRAWING NO.
A		1769-A-4000
SCALE: ~		SHEET 1 OF 6

Figure 16. Quad beam rail system.



CONTRACT NO.				
	SIGNATURE		DATE	SECTION A-A QUAD BEAM
DR		CHK		
ELEC				
MECH				
FINAL				SIZE: A · CODE IDENT NO.: · DRAWING NO.: 1769-A-4000
				SCALE: · SHEET 2 OF 6

Figure 16. Quad beam rail system (continued).

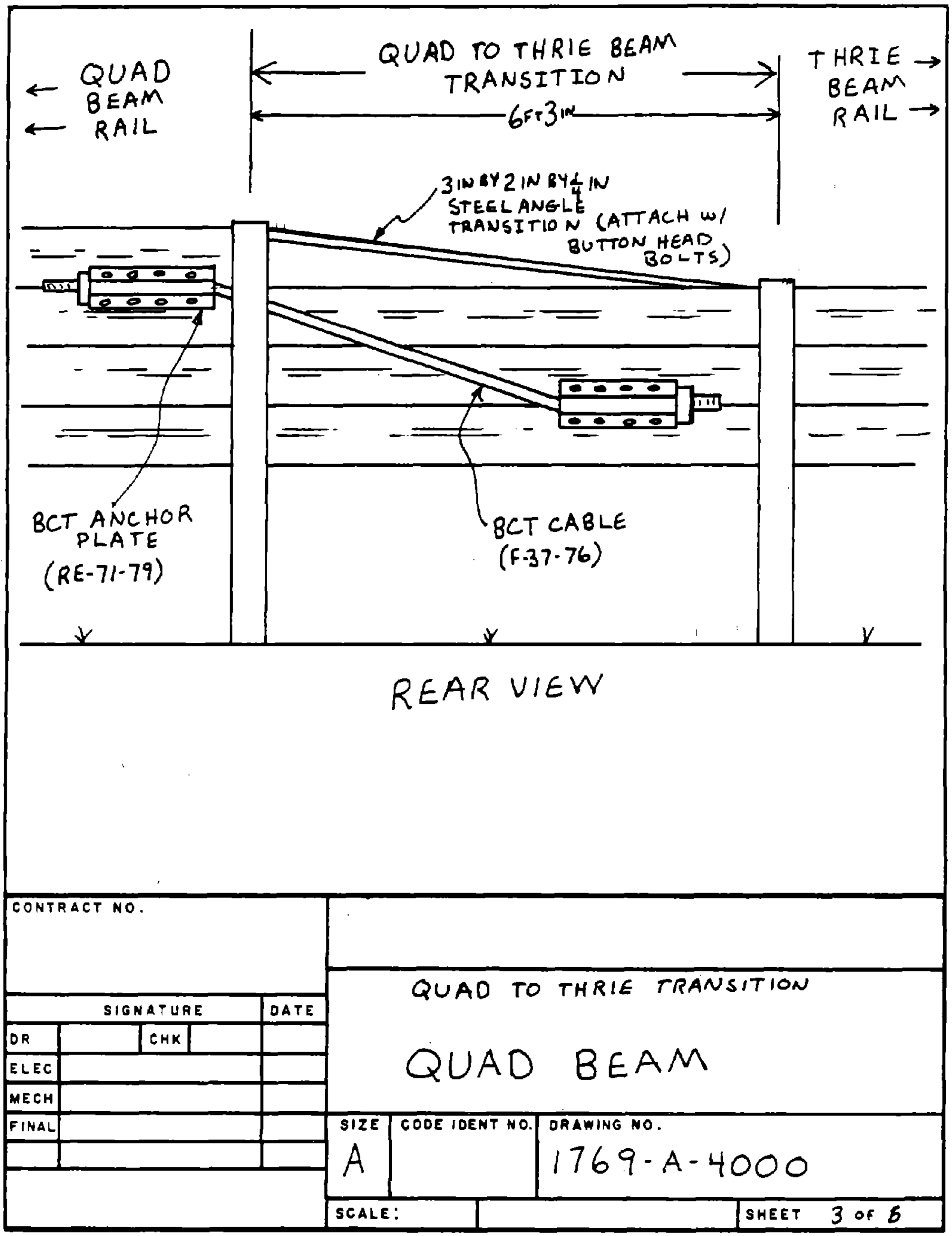


Figure 16. Quad beam rail system (continued).

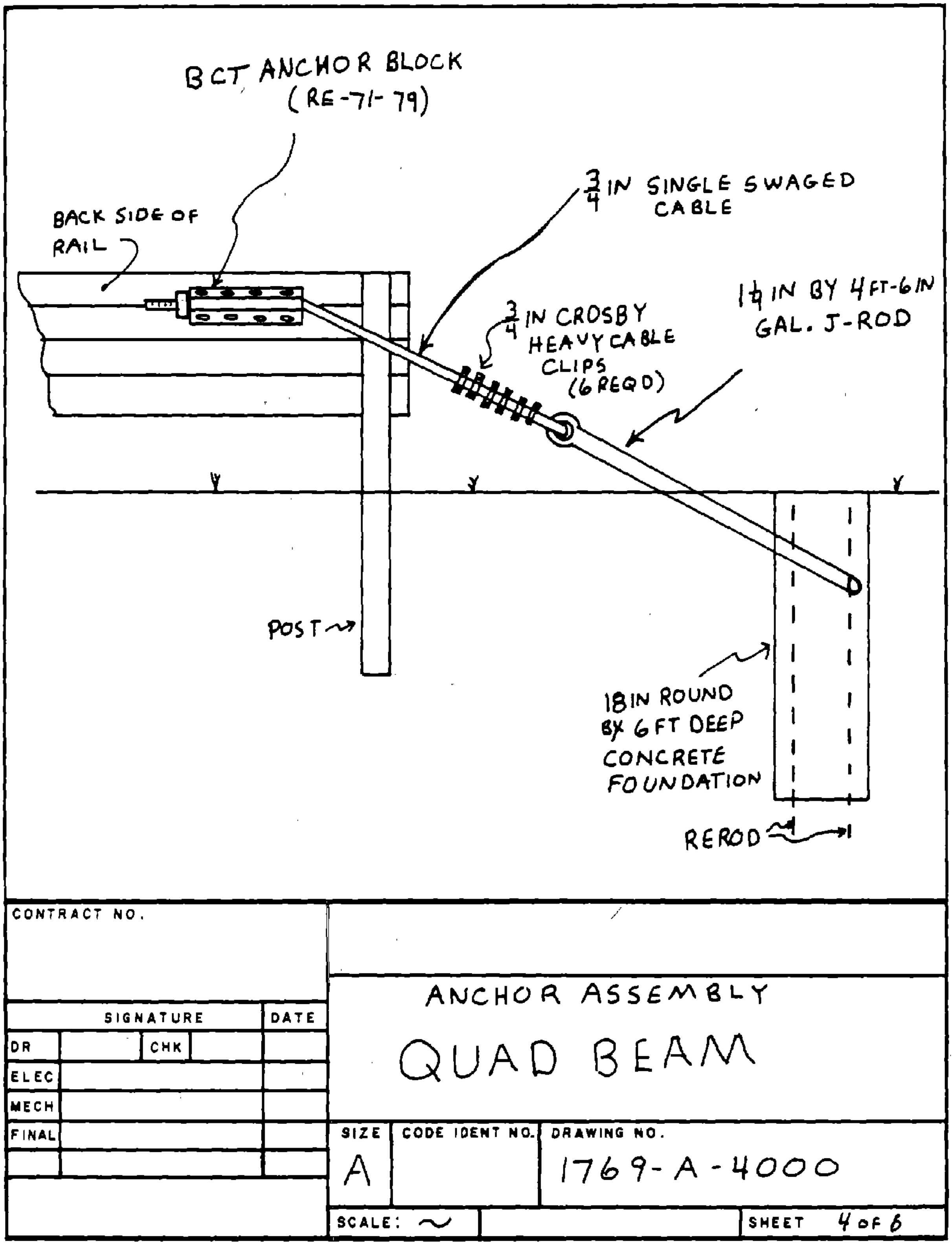


Figure 16. Quad beam rail system (continued).

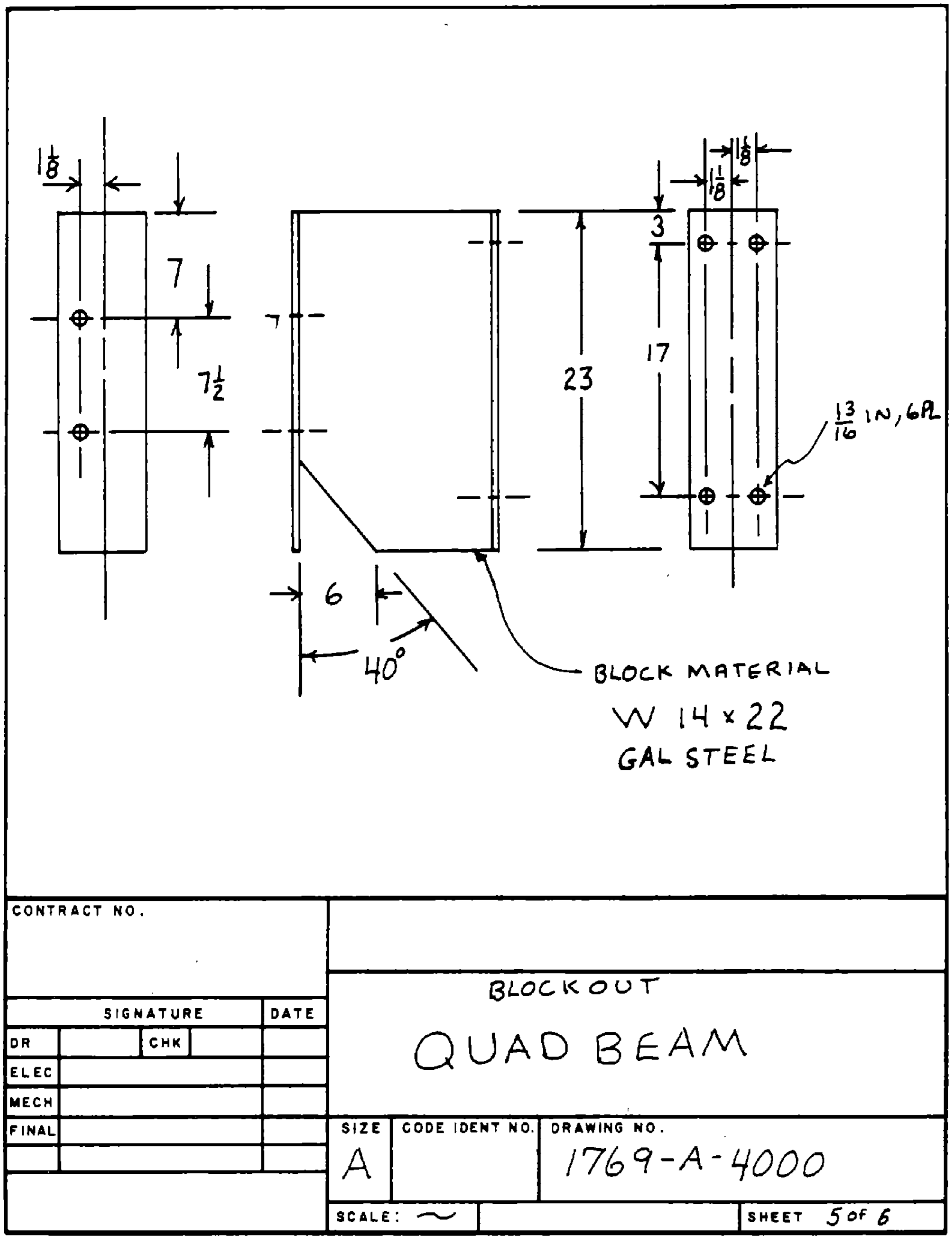


Figure 16. Quad beam rail system (continued).

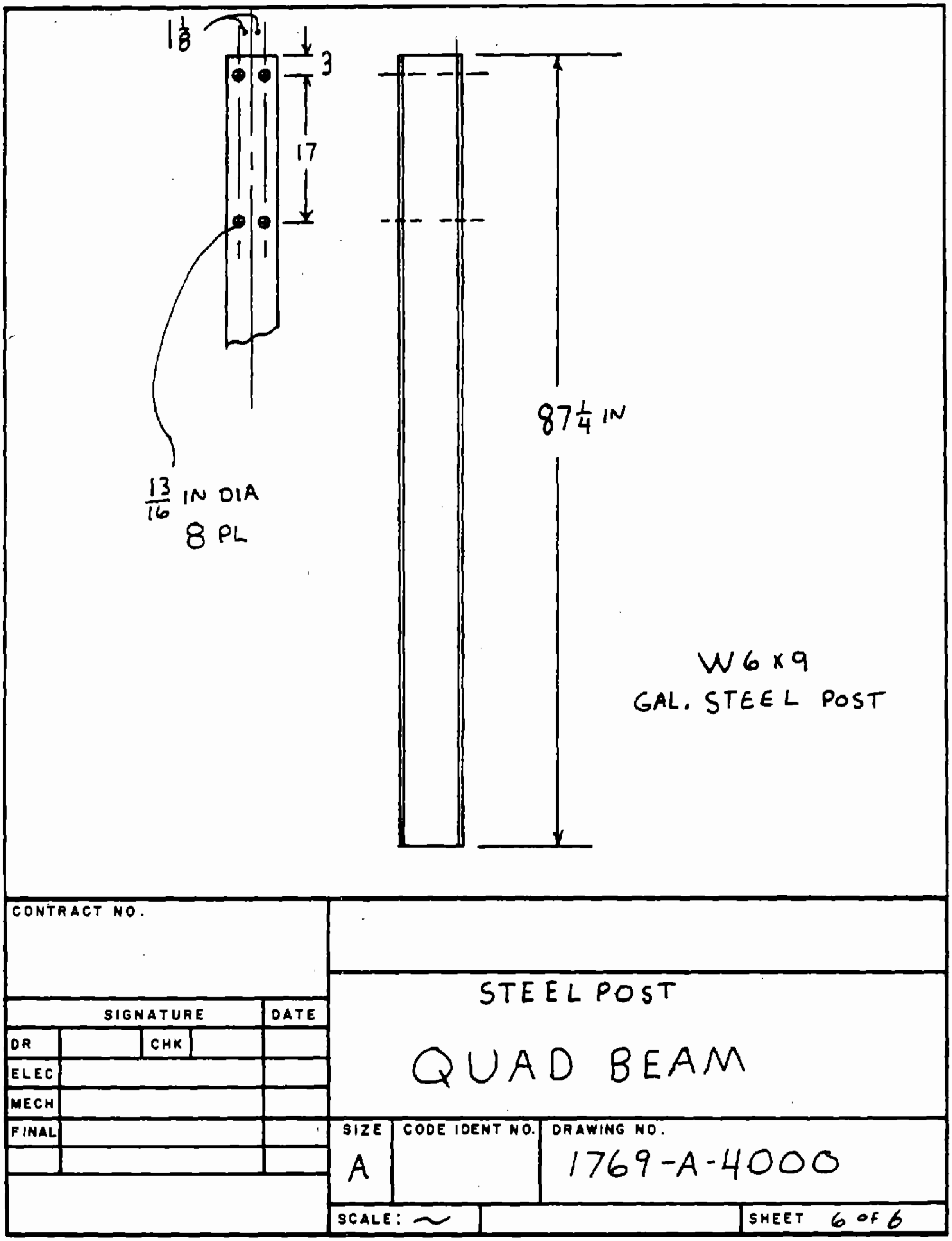


Figure 16. Quad beam rail system (continued).

10-in opening between the bottom of the rail and the road deck. The rail size was 15 in wide and 19 in tall for a mounting height of 29 in. The rail profile is shown in figure 17.

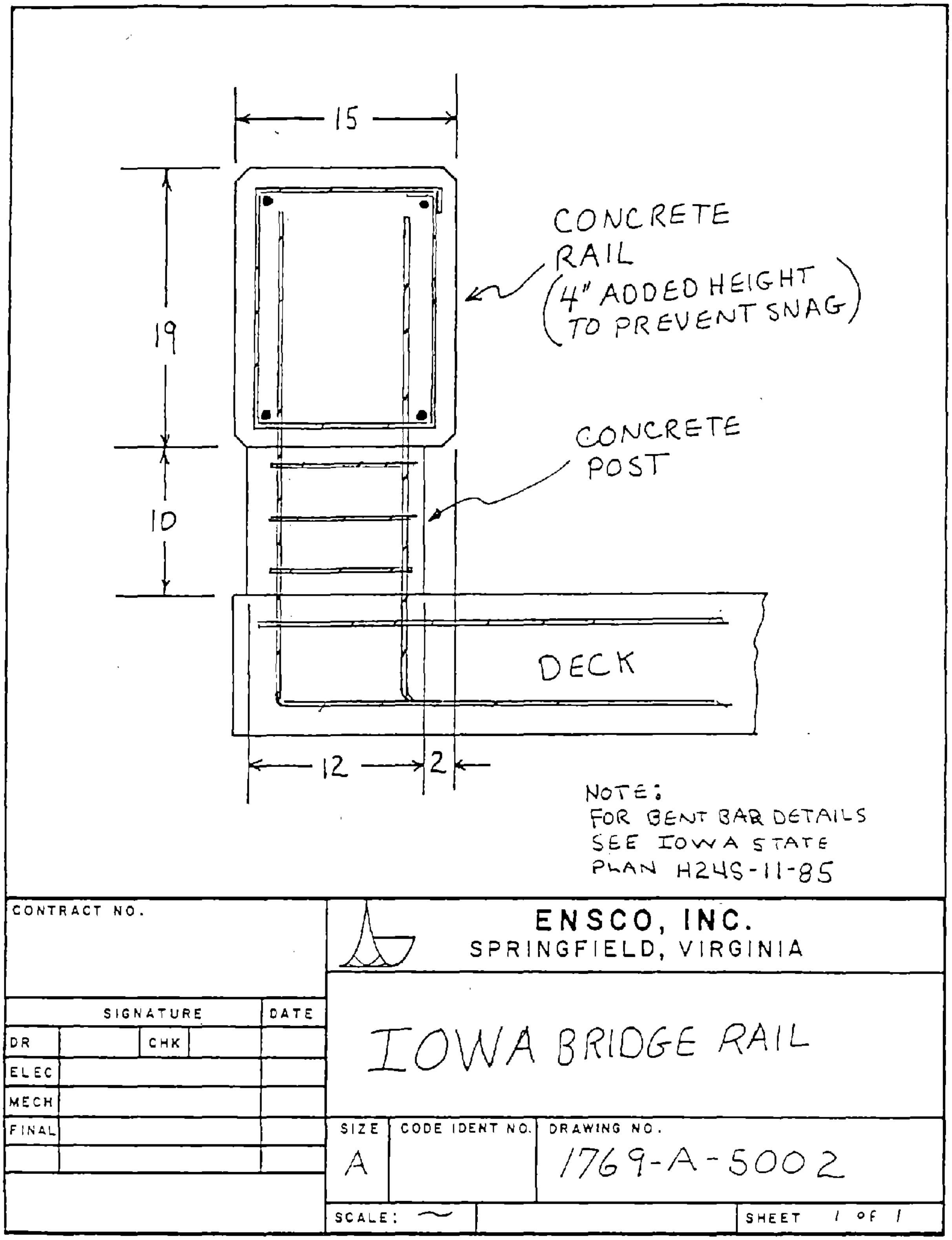


Figure 17. Iowa bridge rail modifications.

FULL-SCALE TESTING OF MINNESOTA THREE-CABLE GUARDRAIL

Based on the modified designs created in Task B and the results of the pendulum tests in Task A, three test types were formulated. The three test types were:

- 1800-lb, 20 degrees, 60 mi/h,
- 4500-lb, 25 degrees, 60 mi/h, and
- 1800-lb, 20 degrees, 60 mi/h - impacting on end post.

Five tests were actually conducted under this task. The five tests are listed in table 10.

Table 10.

Task C - Minnesota test matrix.

Test Number	Vehicle	Angle	Result
1769-C-1-87	1800-lb	20°	Test failed due to vehicle rollover
1769-C-2-87	1800-lb	20°	Test article did not redirect vehicle
1769-C-3-87	1800-lb	20°	Successful test
1769-C-4-87	4500-lb	25°	Successful test
1769-C-5-88	1800-lb	20°	Test failed due to vehicle rollover

Test 1 was conducted using a standard Minnesota three-cable guardrail system modified with the 1.5-in hole 5 in below grade. Because this test device did not pass, details of the end post and foundation were modified. This next test (test 2) also did not pass, leading to a further modification of the end brackets and the use of a BCT cable for attachment to the anchor foundation. This next test (test 3) passed leading to the 4500-lb vehicle test (test 4). Test 4 also passed and the reverse angle impact on the end post test (test 5) was conducted. This test failed.

The following text describes the tests conducted under this task.

1. <u>TEST 1769-C-1-87</u>

a. Test Device

The test device was the modified Minnesota three-cable guardrail system. This system consists of three strands of 0.75-in cable held in place by hook bolts through 5.5-in diameter wood posts. The posts have been modified by drilling a 1.5-in hole in the longitudinal direction, 5 in below ground level. The 6-ft long posts have 38.5-in embedment depth. The cables are 20, 24 and 28 in above the ground.

Figure 18 shows the test site and the test device. Figure 19 shows the Minnesota system in various views. Figures 20 and 21 show pretest photographs of the Minnesota three-cable guardrail system and the test vehicle.

b. Impact Description

Review of the high-speed films, fifth wheel and speed trap data indicated that the test vehicle impacted at 21 degrees and 60.6 mi/h. This review also indicated that the left corner of the vehicle impacted the rail at the desired point. The vehicle remained in contact with the rail throughout the impact event.

The vehicle penetrated into the rail approximately 66 in. The posts near the impact area were snapped off, breaking through the hole located below ground, due to the loads caused by cable deflection. The downstream end post began to break and

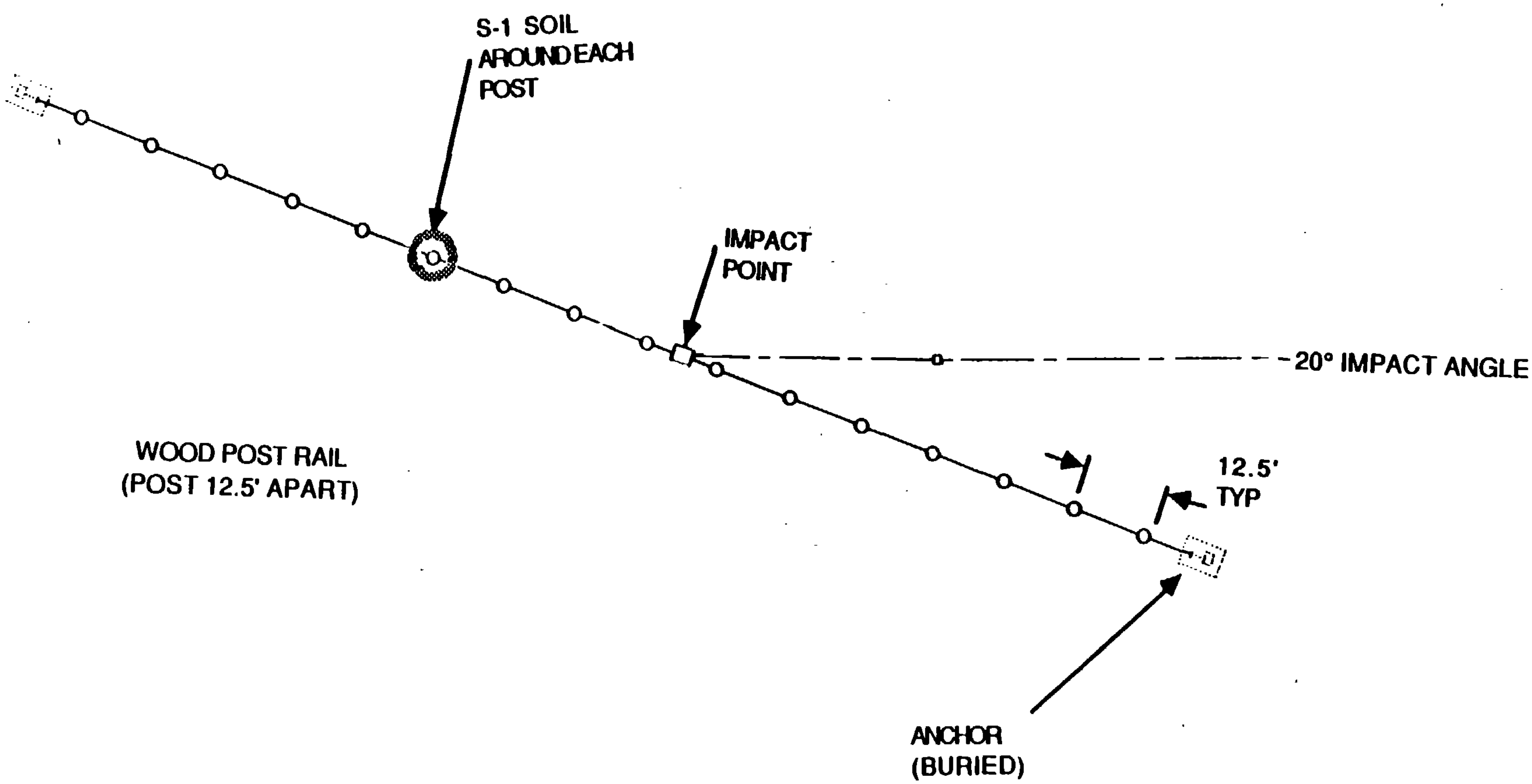


Figure 18. Test site layout, test 1769-C-1-87.

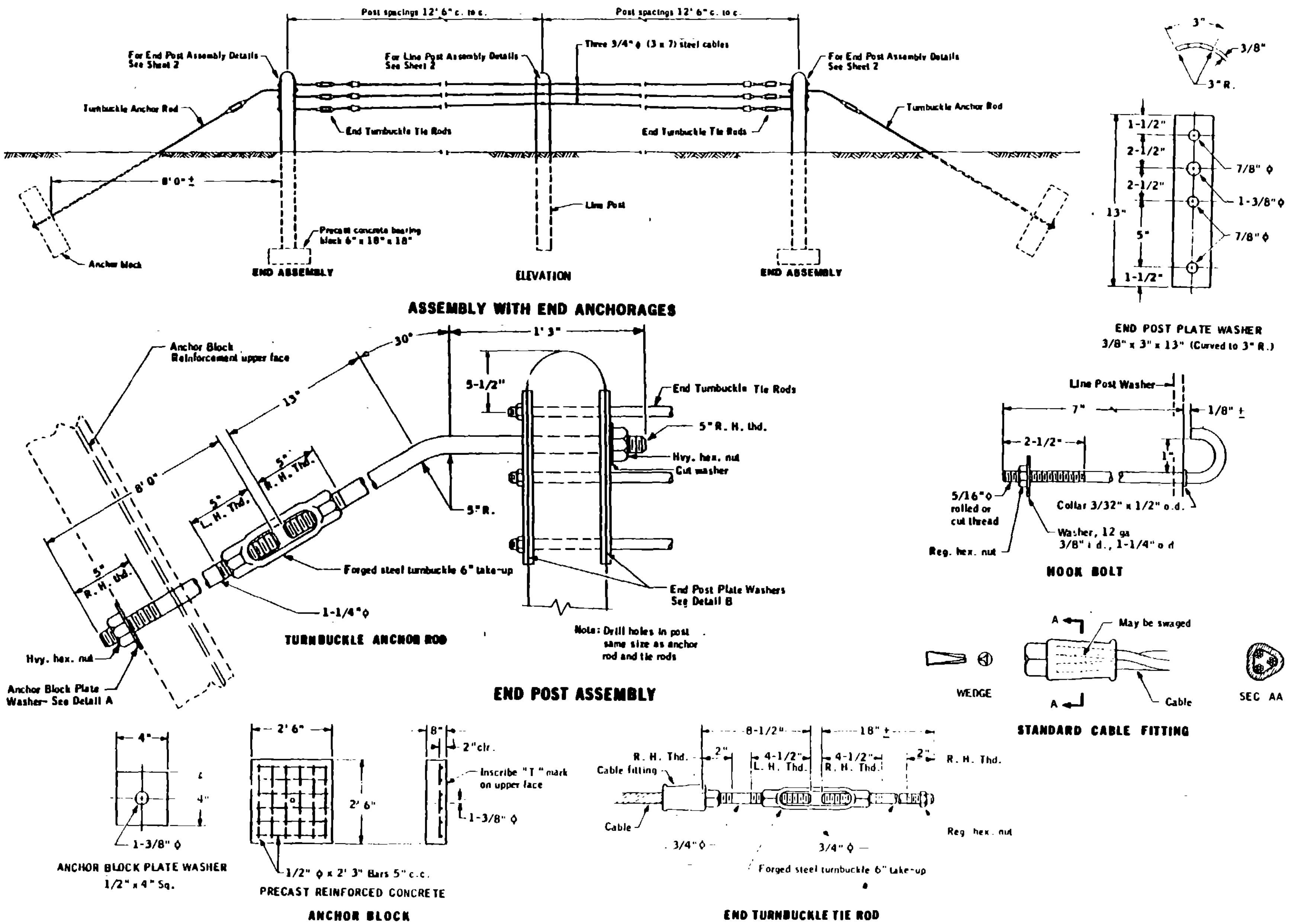


Figure 19. Minnesota 3-cable guardrail system.

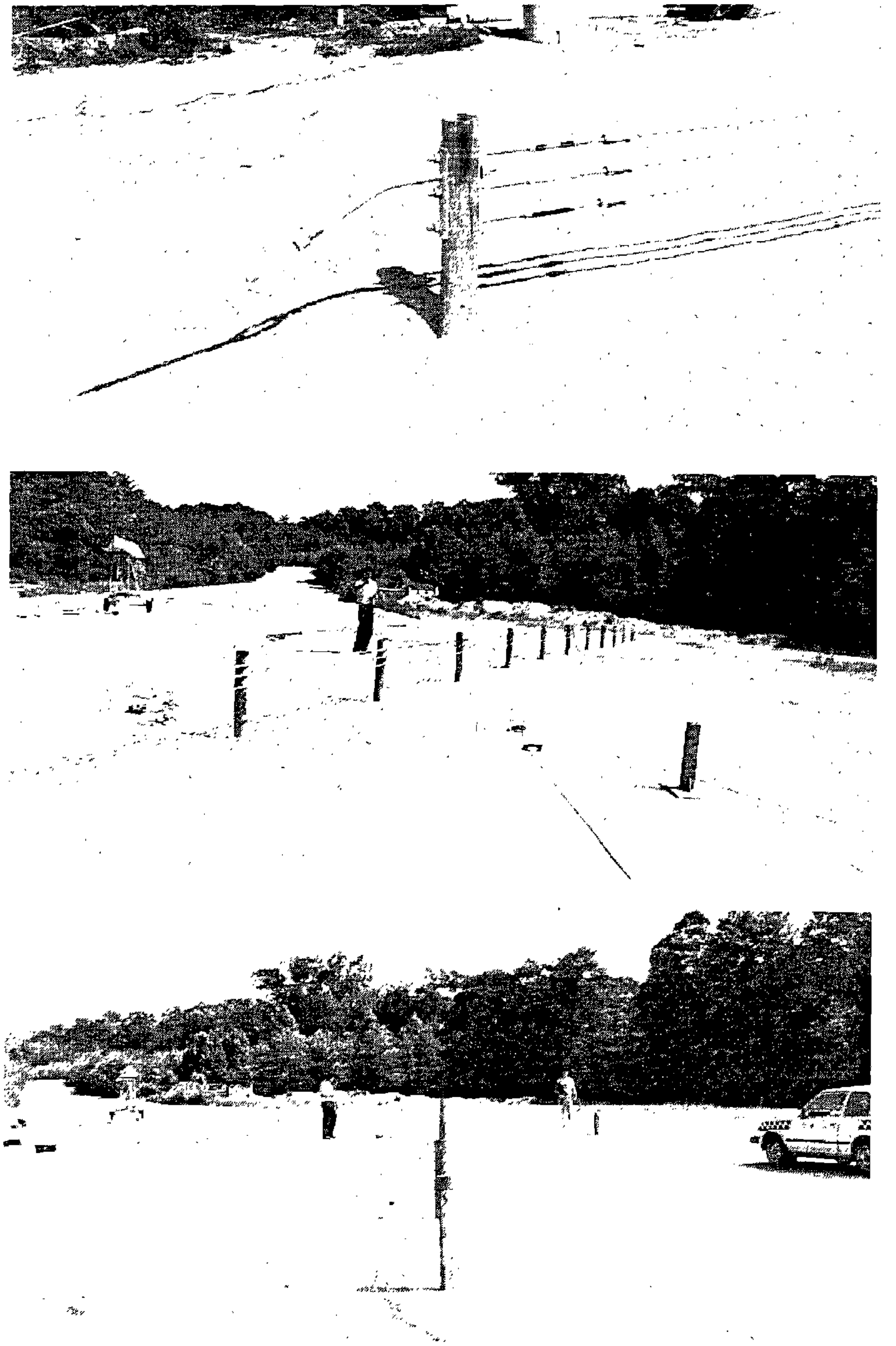


Figure 20. Pretest photographs of Minnesota three-cable guardrail system, test 1769-C-1-87.

Figure 21. Pretest photographs of test vehicle, test 1769-C-1-87.

the foundation began to move 0.25 seconds after impact. The vehicle continued downstream, rubbing along the cable and breaking off posts. Approximately 30 ft from the end post, the vehicle ran over the broken off post sections, causing the vehicle to steer to the left. The car contacted the end post 1.5 seconds after impact. The tie rod and turnbuckle assembly slid over the bumper, with the lower sections of the tie rod catching the bumper, which caused the vehicle to yaw counter-clockwise after which it rolled. The car came to rest on the passenger side perpendicular to the rail. A summary of the test conditions and results are given in figure 22.

Inside the vehicle, it was observed that the dummy slid into the drivers window, but the window did not break. The dummy rolled into the passenger seat and came to rest leaning on the passenger side window and windshield.

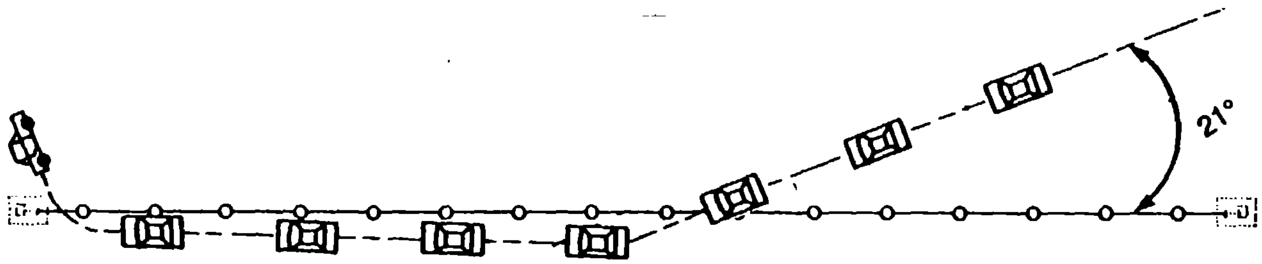
Data analysis was performed and the vehicle x-axis and y-axis, 100 Hz acceleration traces are shown in figure 23.

c. Vehicle Damage

Almost all of the left side of the vehicle was damaged, but damage occurred mainly to the left front fender, grill and bumper. Posttest photographs of the vehicle are shown in figure 24.

d. Traffic Barrier Damage

The Minnesota three-cable system performed as designed, with the exception of the secondary impact with the end post, which caused the vehicle to roll. The line post redesign performed as planned. Impacts with the line posts did not cause the vehicle to yaw or roll. No abrasions were evident in the cable. Posttest photographs are shown in figure 25.



Date: 11 June 1987
Weather: Sunny, 85° F

Test Vehicle: 1981 Honda Civic

Device Configuration: Minnesota 3-Cable Guardrail System, 200 ft long, 12.5-ft post spacing,
Post: Modified 5.5-in diameter wood
Rail: 0.75-in steel cable

1. Vehicle Weight:

	Test Inertial	Gross
Planned:	1800 ± 50	1950 ± 50
Actual:	1830	2000

2. Number of Occupants: One
3. Occupant Model: Anthropomorphic Dummy, 50th%, male
4. Occupant Location: Driver Seat, Unrestrained
5. Impact:

	Speed	Angle (a)	Location
Planned:	60.0 mi/h	20°	Midway between posts
Actual:	60.6 mi/h	21°	Midway between posts

6. Redirection Angle: 0 degrees
7. Redirection Speed: 50.3 mi/h (73.8 ft/s)
8. Total Speed Change: 10.3 mi/h (15.1 ft/s)
9. Total Momentum Change: 938 lb-s
10. Vehicle Damage Index: (SAE J224a) 10LFEW1
11. NCHRP 230 Test Number: S13
12. Impact Severity:

$\frac{m(V \sin a)^2}{2}$ 28.8 kip-ft (Spec: 23 to 29 kip-ft)

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-10.4 ft/s	30/40 ft/s
Ridedown Acceleration:	-4.9 g's	15/20 g's
Delta-V at 1.58 ft (actual):	-10.1 ft/s	30/40 ft/s
Ridedown Acceleration:	-4.9 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-12.9 ft/s	20/30 ft/s
Ridedown Acceleration:	-7.3 g's	15/20 g's
Delta-V at 0.83 ft (actual):	-11.9 ft/s	20/30 ft/s
Ridedown Acceleration:	-7.3 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-1.7 g's	
Lateral:	-4.3 g's	

14. Test Results Conclusion: Smooth redirection over length of need section. However, test fails due to vehicle rollover.

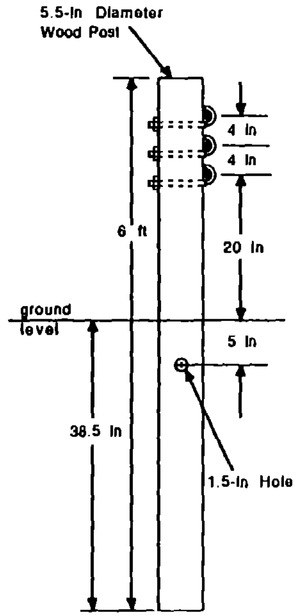
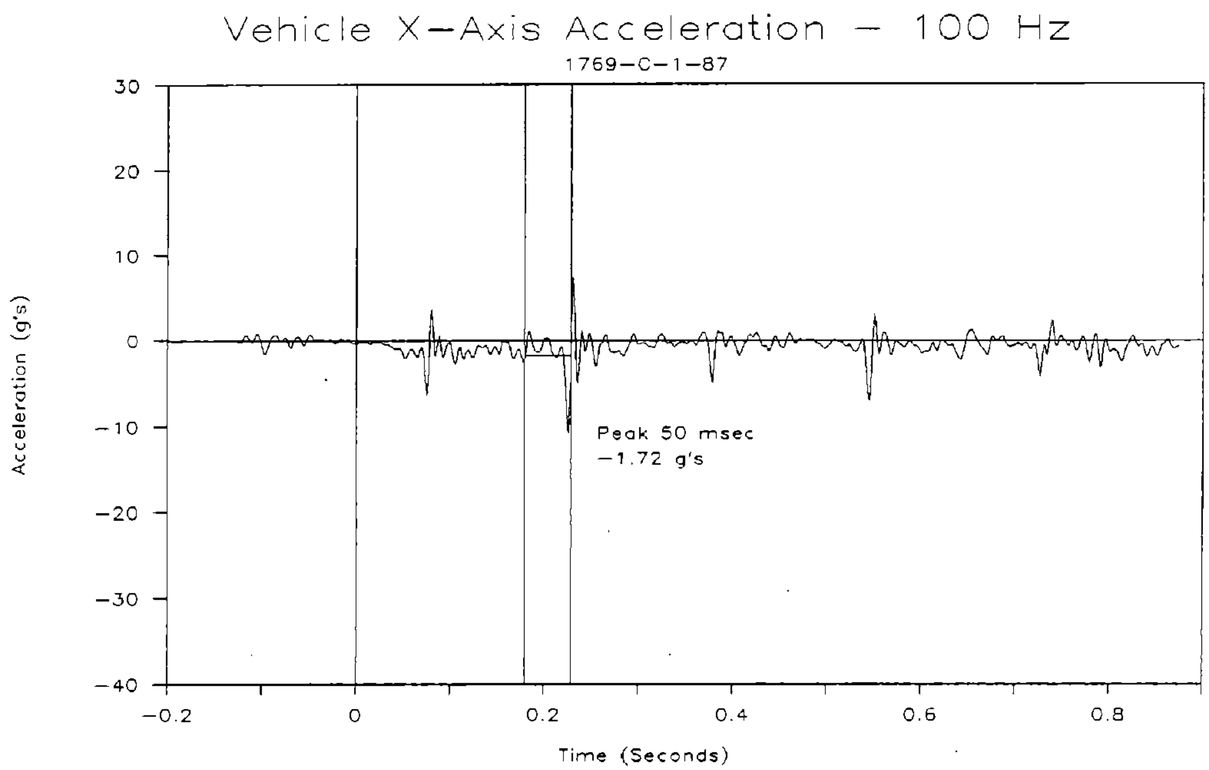


Figure 22. Test summary, test 1769-C-1-87.



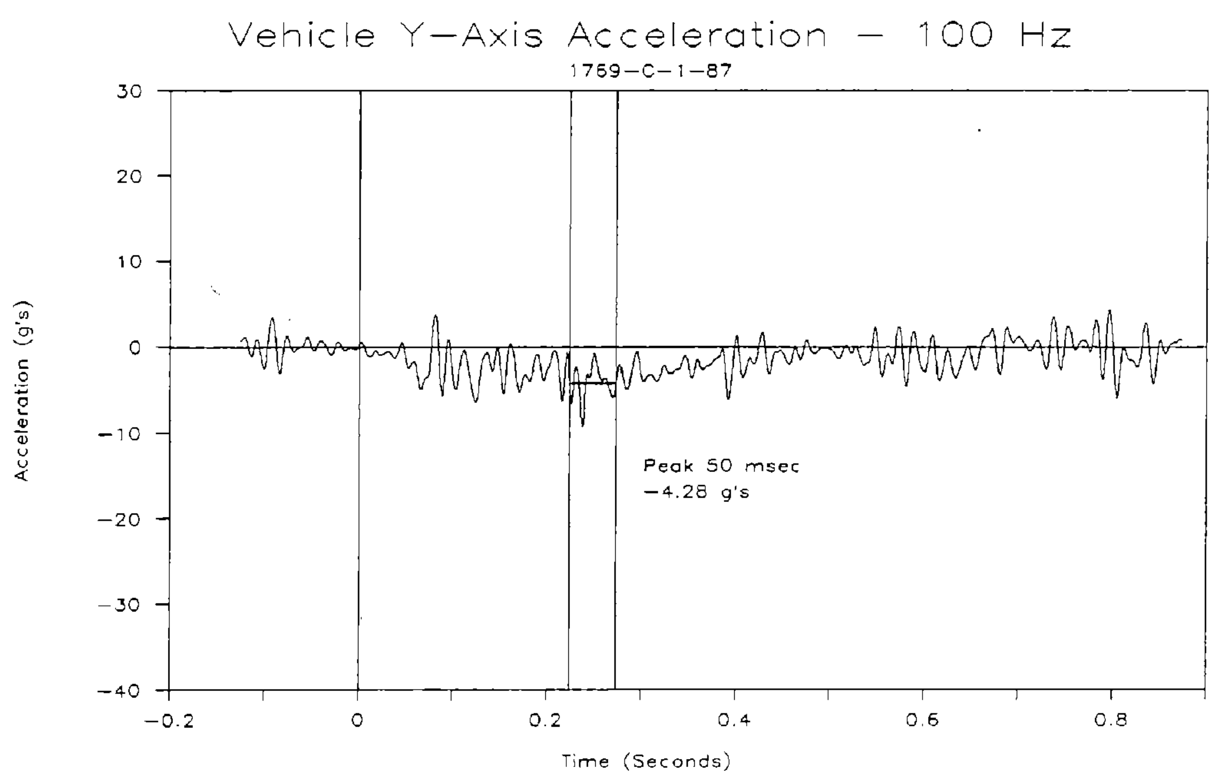
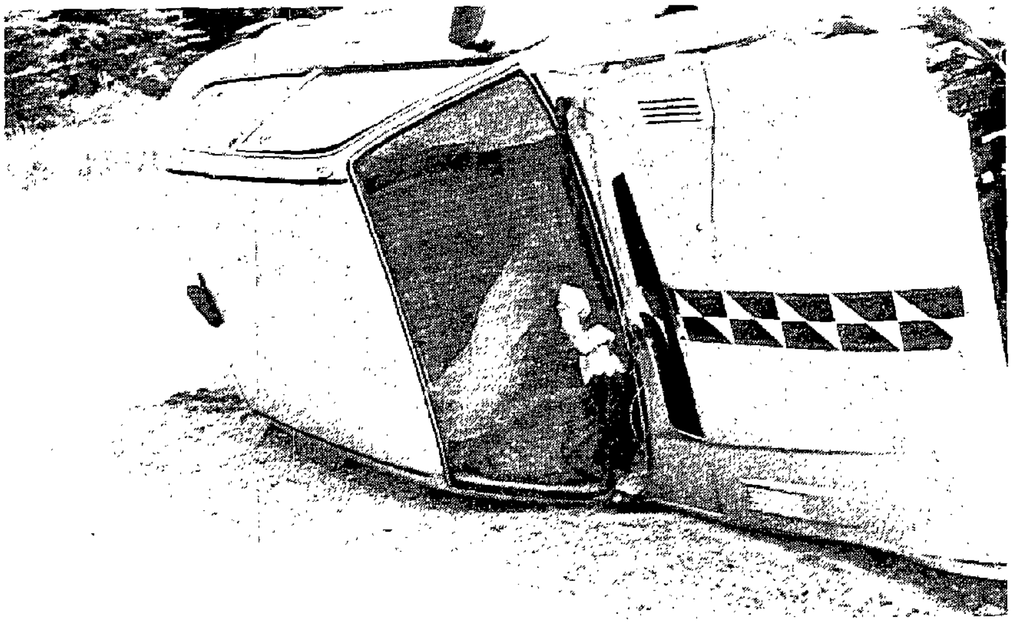


Figure 23. Vehicle acceleration, test 1769-C-1-87.



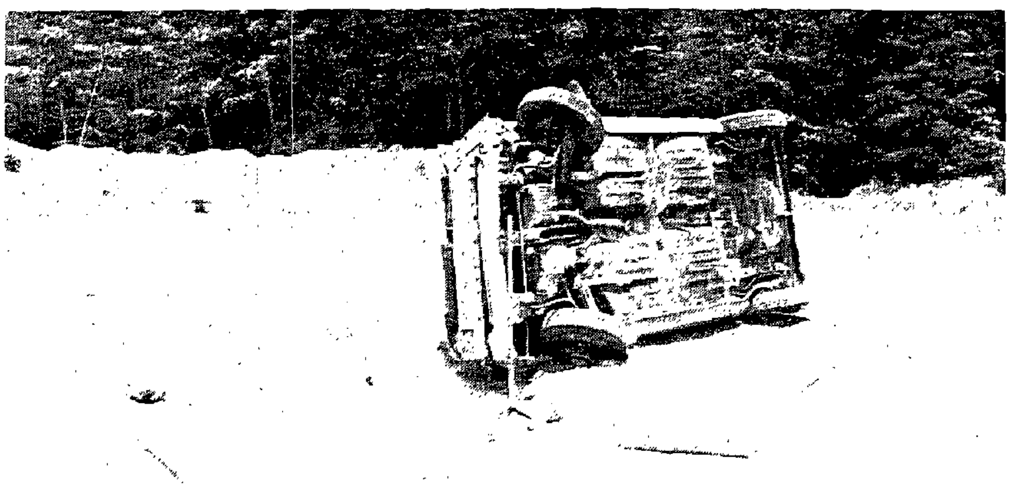


Figure 24. Posttest photographs of test vehicle, test 1769-C-1-87.

Figure 25. Posttest photographs of Minnesota three-cable guardrail system, test 1769-C-1-87.

2. <u>TEST 1769-C-2-87</u>

a. Test Device

The test device was the modified Minnesota three-cable guardrail system. The posts have been modified by drilling a 1.5-in hole in the longitudinal direction, 5 in below ground level.

The end post and foundation placement were modified from test C-1. Three features were included in the new design. They were:

- Prevent end anchor from pulling out.
- Provide method of detachment between rail and anchor.
- Provide additional vertical strength to end post to prevent buckling.

The end anchor rod was increased in length by 4 ft. This placed the anchor deeper. The end post was replaced by a dual end post. This doubled the vertical strength of this unit. A special assembly was fabricated to allow detachment of the rail from the end anchor. This was accomplished by a two piece bracket, one attached to the end anchor and the other to the cable. Each bracket loaded against the dual post with one bracket on each side of the end post.

Figure 26 shows the test site and test device. Figures 27 and 28 show pretest photographs of the Minnesota three-cable guardrail system including details of the end bracket assembly and the test vehicle.

b. Impact Description

Review of the high-speed films, fifth wheel and speed trap data indicated that the test vehicle impacted at 20 degrees

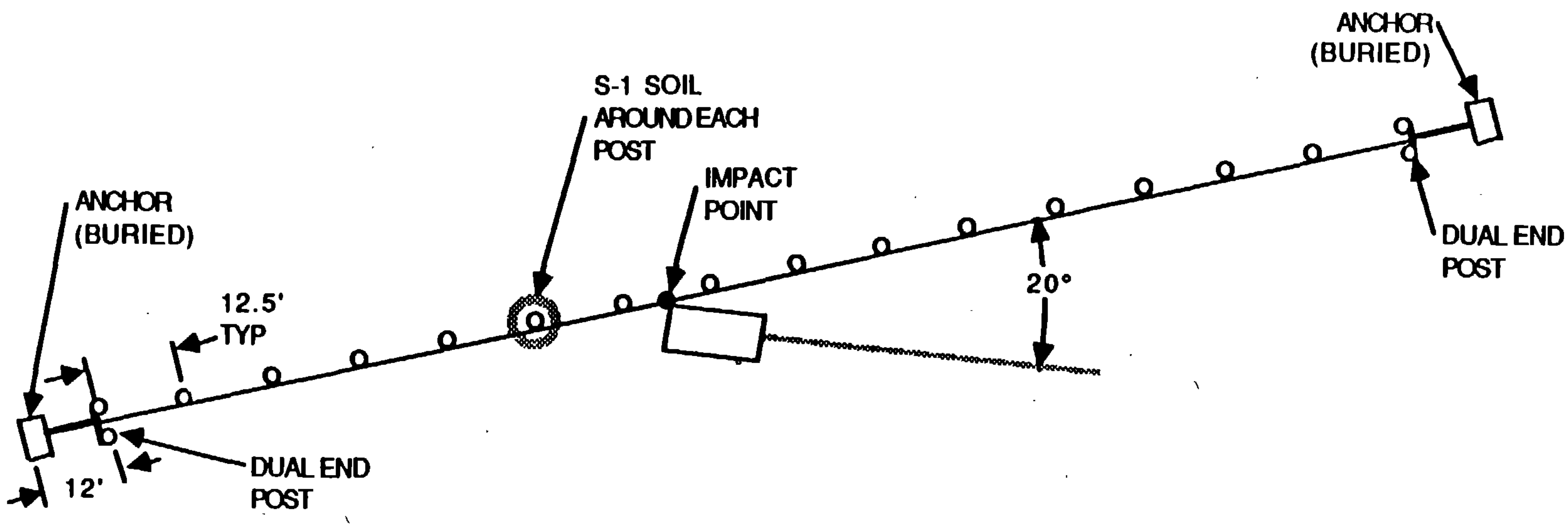


Figure 26. Test site layout, test 1769-C-2-87.

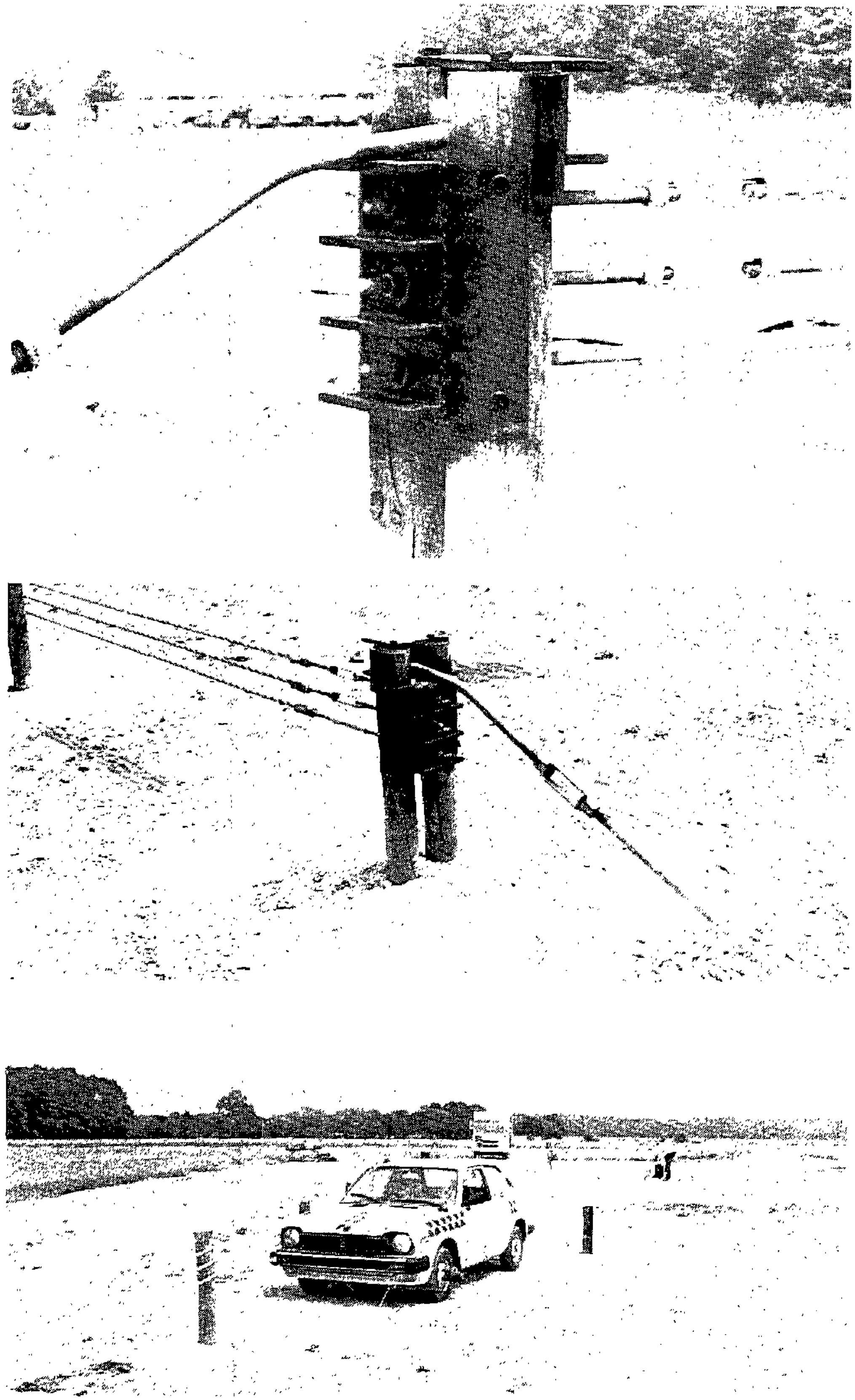


Figure 27. Pretest photographs of Minnesota three-cable guardrail system, test 1769-C-2-87.

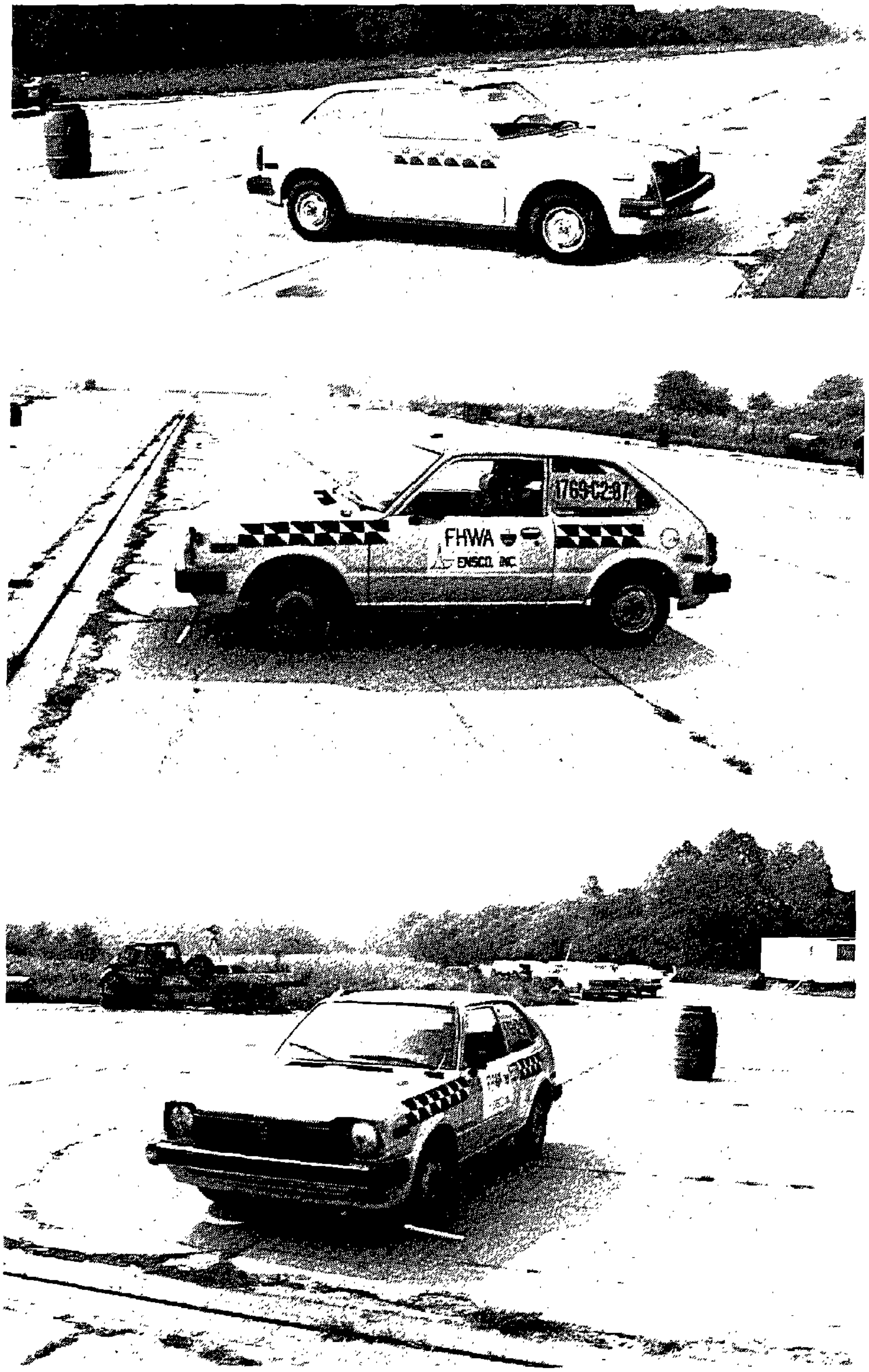


Figure 28. Pretest photographs of test vehicle, test 1769-C-2-87.

and 62.1 mi/h. This review also indicated that the left corner of the vehicle impacted the rail at the desired point.

As the vehicle penetrated into the rail it began to redirect slightly. At approximately 0.220 s, the upstream end post broke allowing the cable rail to become detached from the anchor block. With the loss of rail tension, there was no capability for the rail to redirect the test vehicle. The vehicle continued in almost a straight line through the rail system into the field side. Some of the cables were tangled with the vehicle causing it to be captured with a final result of the vehicle rolling over approximately 200 ft past the impact point. A summary of the test conditions and results are given in figure 29.

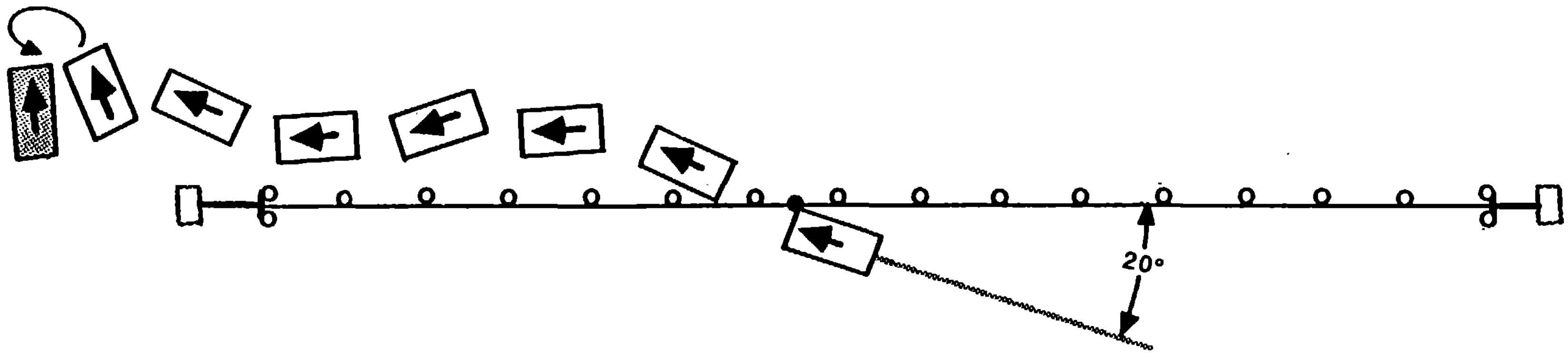
Review of the high-speed photography of the upstream end post indicate the post assembly failed due to the top bracket breaking away. This bracket attaches the anchor rod to the post. Failure seemed to occur when the bracket rotated up and over the top of the post.

Inside the vehicle, it was observed that the dummy fell into the passenger seat upon impact and remained there until the vehicle rolled. The dummy came to rest on the roof with the vehicle upside down.

Data analysis was performed and the vehicle x-axis and y-axis, 100 Hz acceleration traces are shown in figure 30.

c. Vehicle Damage

Almost all of the right side of the vehicle was damaged, but damage occurred mainly to the right front fender, grill and bumper. Some top damage occurred after the vehicle rolled on its roof. Posttest photographs of the vehicle are shown in figure 31.



Date: 27 August 1987
Weather: Sunny, 80° F

Test Vehicle: 1981 Honda Civic

Device Configuration: Minnesota 3-Cable Guardrail System, 200 ft long, 12.5-ft post spacing,
Post: Modified 5.5-in diameter wood
Rail: 0.75-in steel cable
End Post: Dual post with special anchor attachment bracket

1. Vehicle Weight:

	Test Inertial	Gross
Planned:	1800 ± 50	1950 ± 50
Actual:	1787	1957

2. Number of Occupants: One

3. Occupant Model: Anthropomorphic Dummy, 50th%, male

4. Occupant Location: Driver Seat, Unrestrained

5. Impact:

	Speed	Angle (a)	Location
Planned:	60.0 mi/h	20°	Midway between posts
Actual:	62.1 mi/h	20°	Midway between posts

6. Redirection Angle: None, vehicle passed through rail

7. Redirection Speed: n/a

8. Total Speed Change: n/a

9. Total Momentum Change: n/a

10. Vehicle Damage Index: (SAE J224a) 02RYAO2

11. NCHRP 230 Test Number: S13

12. Impact Severity:

$\frac{m(V \sin a)^2}{2}$ 26.9 kip-ft (Spec: 23 to 29 kip-ft)

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-10.6 ft/s	30/40 ft/s
Ridedown Acceleration:	-4.2 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-12.6 ft/s	20/30 ft/s
Ridedown Acceleration:	-7.0 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-2.0 g's	
Lateral:	-3.3 g's	

14. Test Results Conclusion: Smooth redirection until upstream anchor attachment separated from rail. Test fails due to vehicle passing through rail and rolling over.

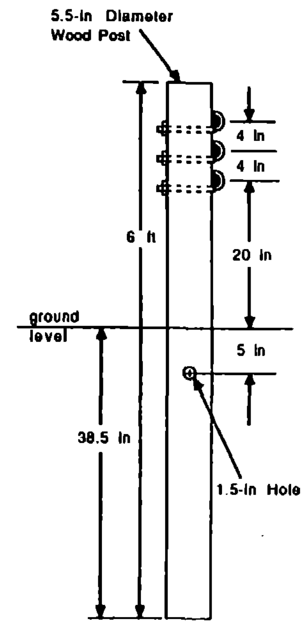
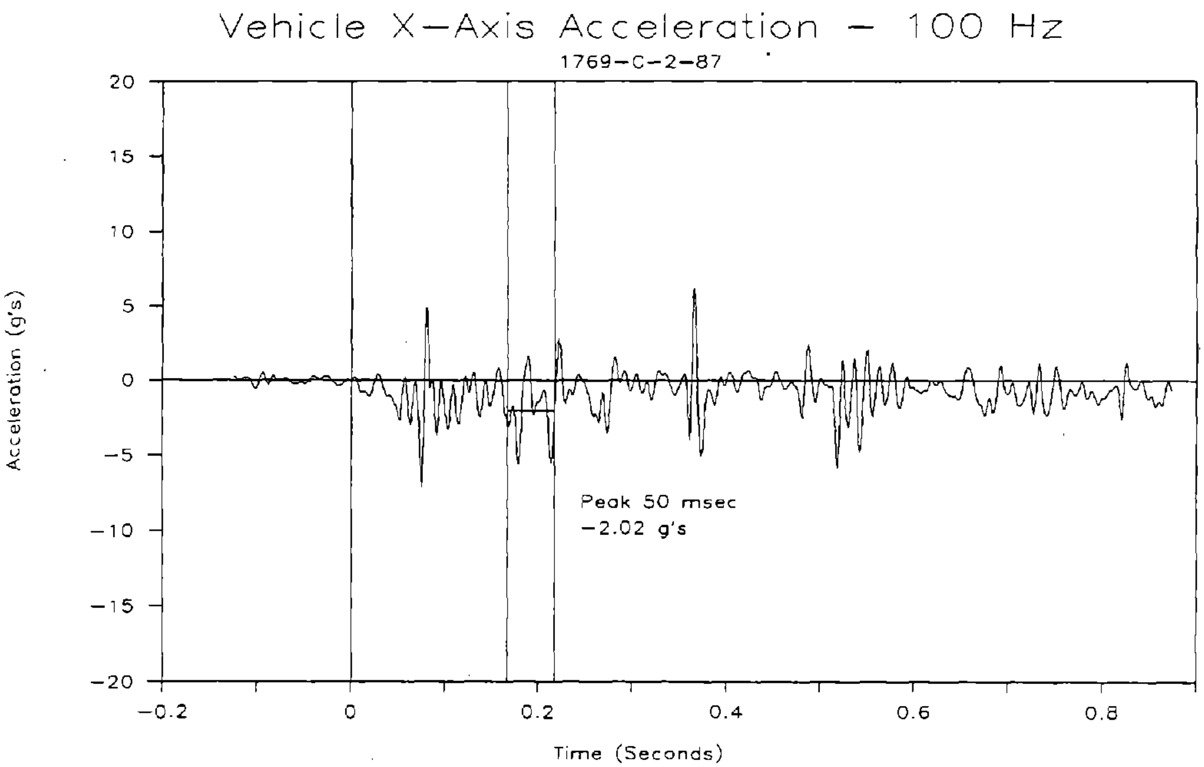


Figure 29. Test summary, test 1769-C-2-87.



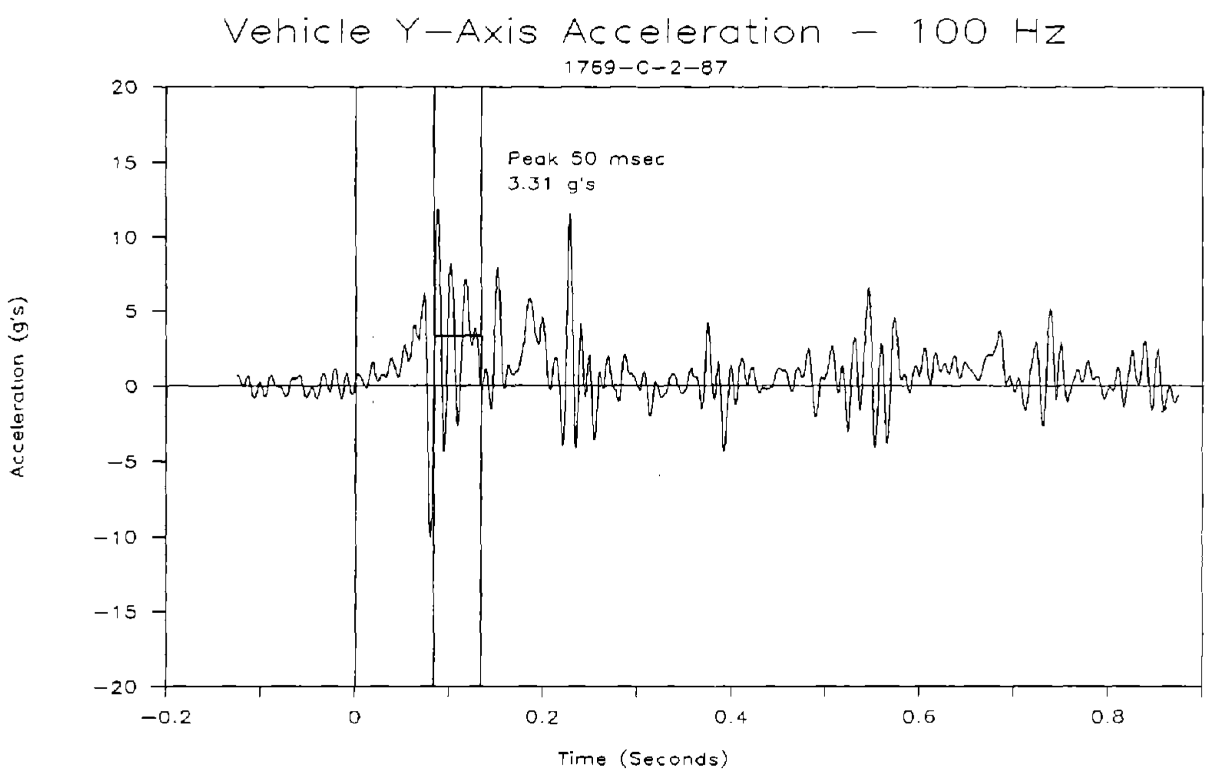


Figure 30. Vehicle acceleration, test 1769-C-2-87.

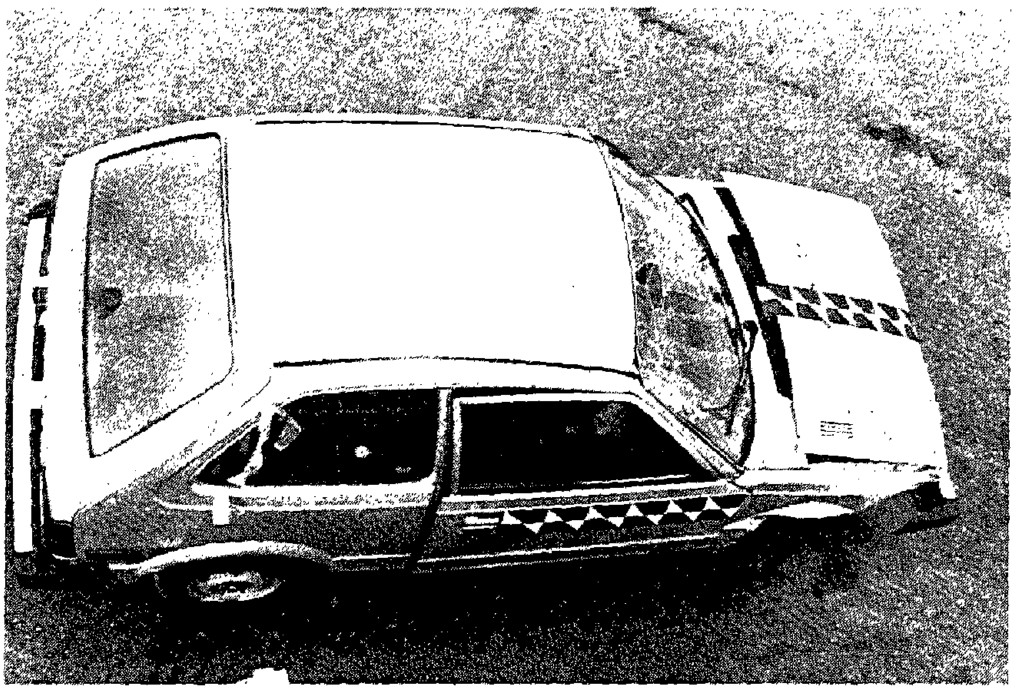


Figure 31. Posttest photographs of test vehicle, test 1769-C-2-87.

d. Traffic Barrier Damage

The Minnesota three-cable system did not perform as designed, with the release of the cable rail from the end foundation allowing the vehicle to pass through. Posttest photographs are shown in figure 32.

3. <u>TEST 1769-C-3-87</u>

a. Test Device

The test device was the modified Minnesota three-cable guardrail system. The posts have been modified by drilling a 1.5-in hole in the longitudinal direction, 5 in below ground level.

The end anchor attachment and attachment brackets have been modified from test C-2. An additional end anchor bracket has been added to facilitate the use of a standard BCT cable for the releasing anchor. The BCT cable anchors above and below the three-cable bracket. The end rod has been shortened 2 ft. The cable passes through a clevis end which attaches to the end anchor turnbuckle assembly. The three-cable bracket has been extended to provide greater overlap with the BCT cable brackets. All other features of test C-2 have been maintained.

Figure 33 shows the test site and test device. Figures 34 and 35 show pretest photographs of the Minnesota three-cable guardrail system including details of the end bracket assembly, and the test vehicle.

b. Impact Description

Review of the high-speed films, fifth wheel and speed trap data indicated that the test vehicle impacted at 20 degrees

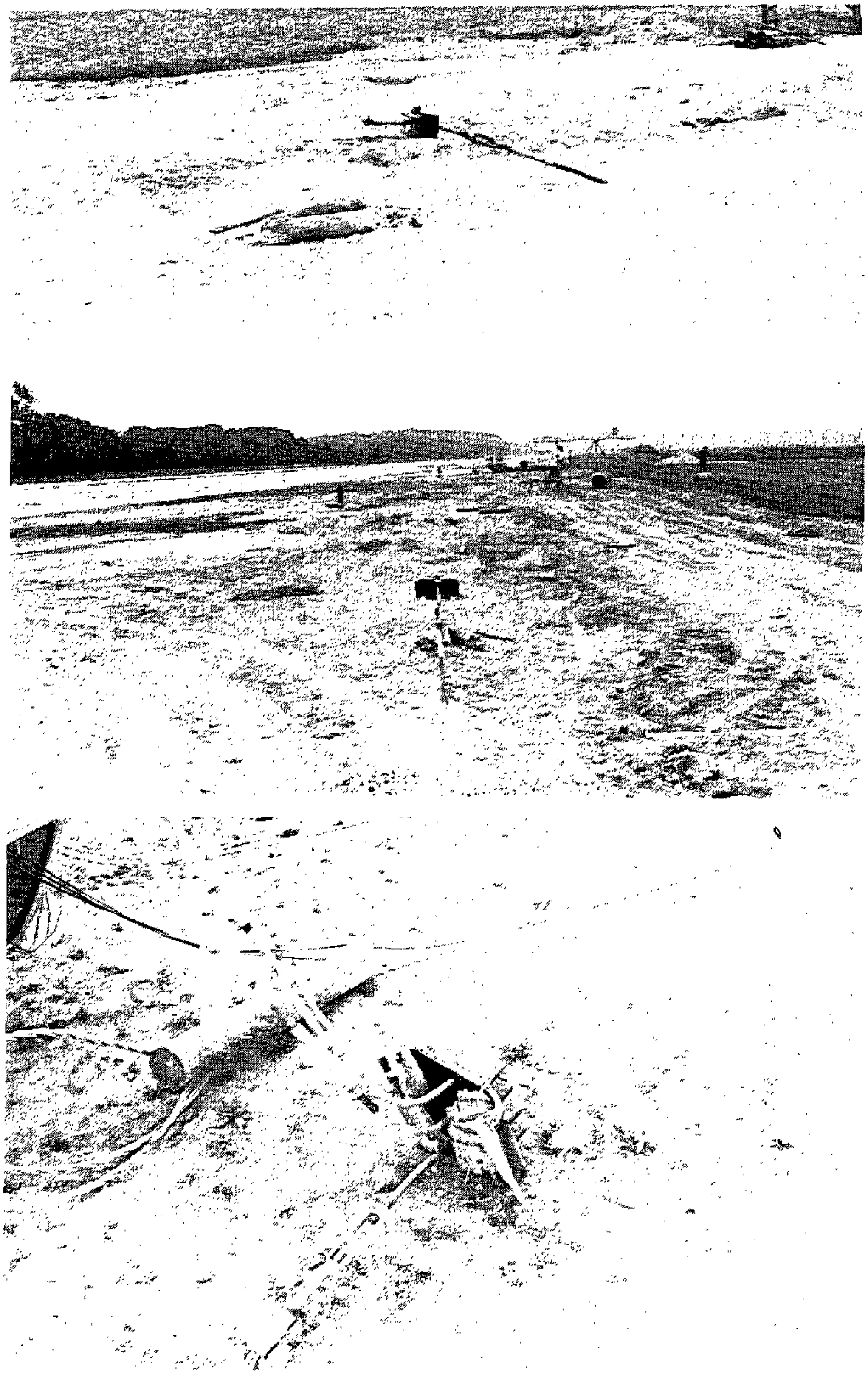


Figure 32. Posttest photographs of Minnesota three-cable guardrail system, test 1769-C-2-87.

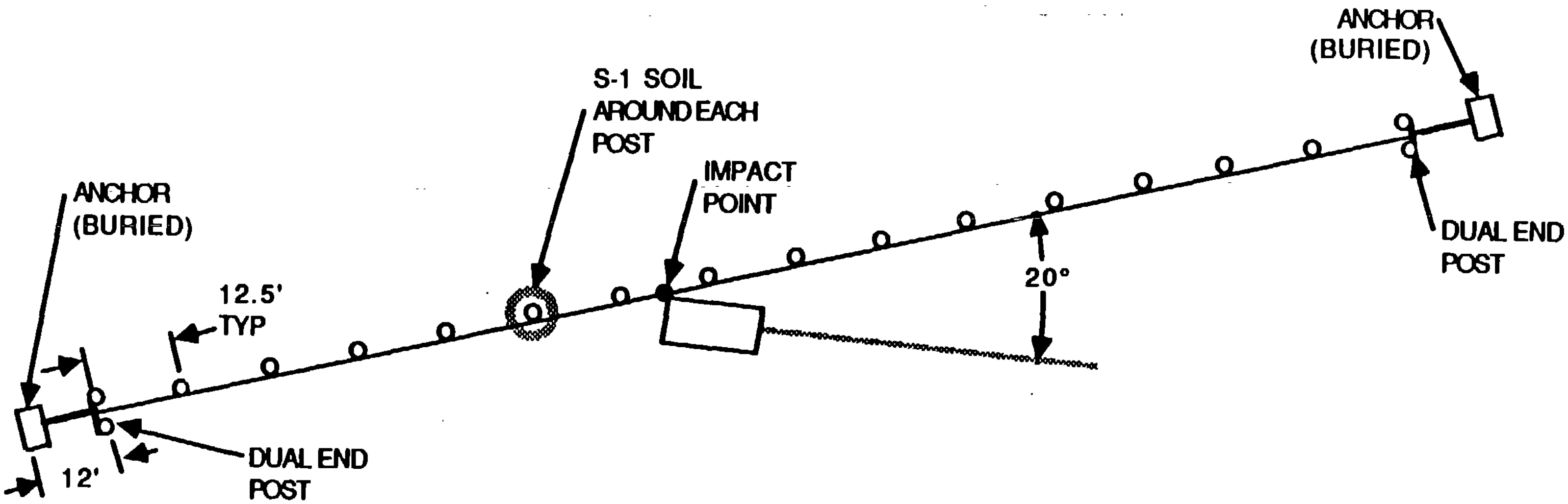


Figure 33. Test site layout, test 1769-C-3-87.

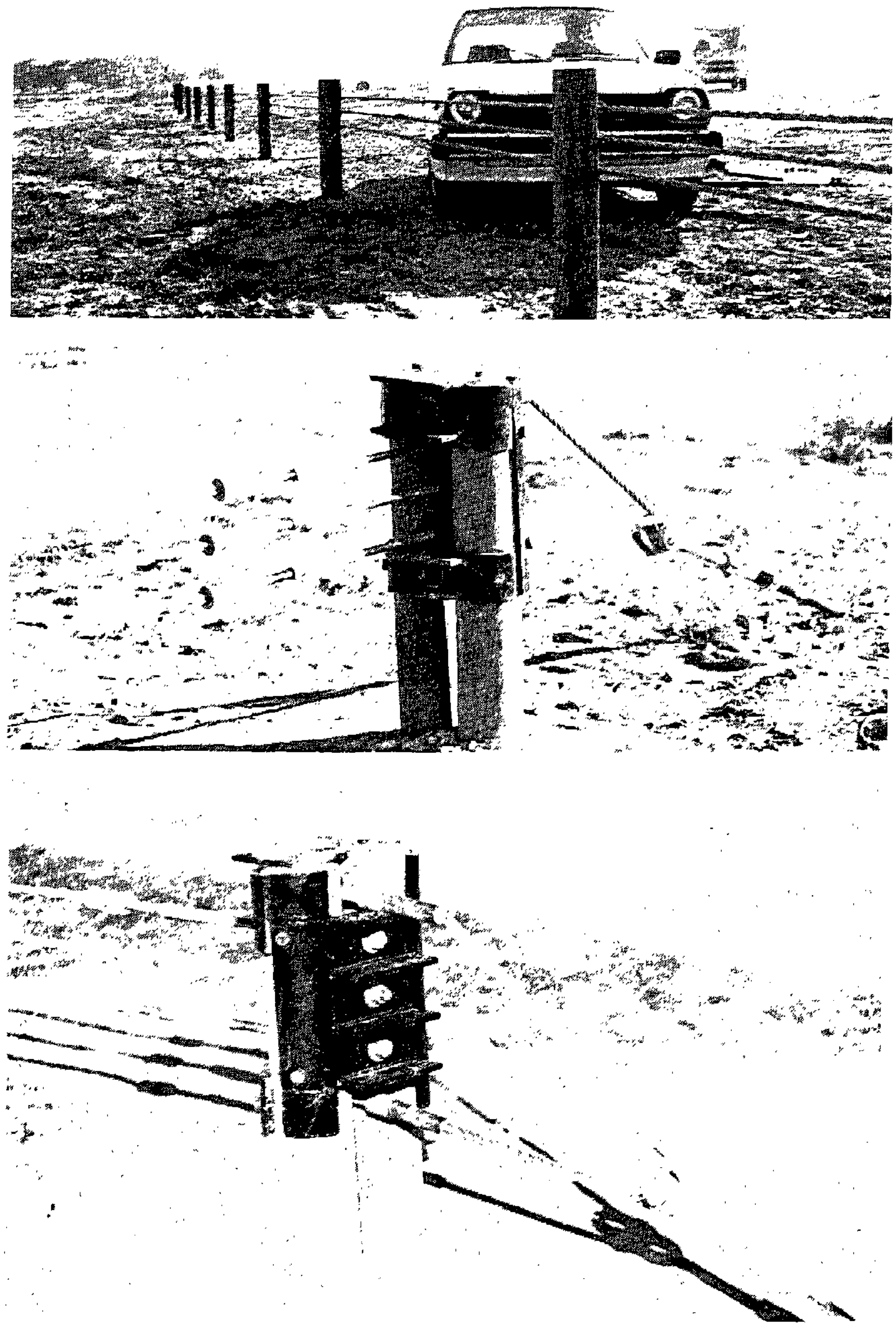


Figure 34. Pretest photographs of Minnesota three-cable guardrail system, test 1769-C-3-87.

Figure 35. Pretest photographs of test vehicle, test 1769-C-3-87.

and 61.0 mi/h. This review also indicated that the right corner of the vehicle impacted the rail at the desired point.

The vehicle penetrated into the rail approximately 4.5 ft and was redirected by the rail but did not exit from the rail. Ten posts were broken off through the hole below ground, including the downstream dual end post. The vehicle continued downstream breaking off posts. The vehicle squarely impacted the dual end post. The vehicle continued away downstream turning hard right. It came to rest 200 ft downstream of impact, 65 ft behind the rail, after turning 95 degrees clockwise to the rail. A summary of the test conditions and results are given in figure 36.

Inside the vehicle it was observed that the dummy fell into the passenger seat upon impact, and hit the door and window, breaking the window. The dummy came to rest in front of the passenger seat.

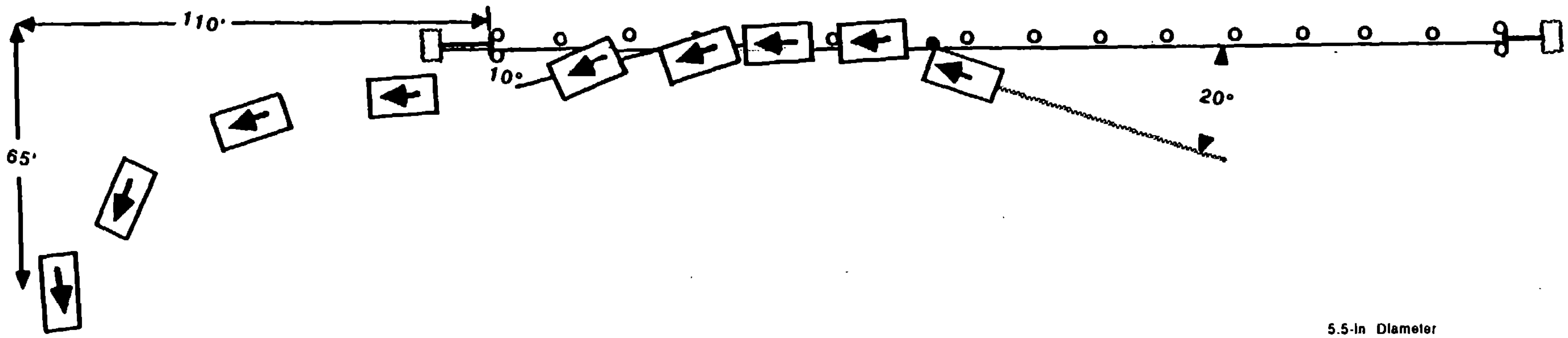
Data analysis was performed and the vehicle x-axis and y-axis, 100 Hz acceleration traces are shown in figure 37.

c. Vehicle Damage

Almost all of the right side of the vehicle was damaged, but damage occurred mainly to the right front fender, grill and bumper. Posttest photographs of the vehicle are shown in figure 38.

d. Traffic Barrier Damage

The Minnesota three-cable system performed as designed. The vehicle was redirected by the rail. Four posts were broken off. The end anchors showed no sign of movement. Posttest photographs are shown in figure 39.



Date: 16 October 1987
Weather: Sunny, 70° F

Test Vehicle: 1981 Honda Civic

Device Configuration: Minnesota 3-Cable Guardrail System, 200 ft long, 12.5-ft post spacing,
Post: Modified 5.5-in diameter wood
Rail: 0.75-in steel cable
End Post: Dual post with BCT cable anchor attachment brackets.

		Test Inertial	Gross
1.	Vehicle Weight:		
	Planned:	1800 ± 50	1950 ± 50
	Actual:	1794	1960

2. Number of Occupants: One

3. Occupant Model: Anthropomorphic Dummy, 50tht, male

4. Occupant Location: Driver Seat, Unrestrained

5. Impact:	Speed	Angle (a)	Location
Planned:	60.0 mi/h	20°	Midway between posts
Actual:	61.0 mi/h	20°	Midway between posts

6. Redirection Angle: 10 degrees

7. Redirection Speed: 47.8 mi/h (70.1 ft/s)

8. Total Speed Change: 13.2 mi/h (19.4 ft/s)

9. Total Momentum Change: 1181 lb-s

10. Vehicle Damage Index: (SAE J224a) 02RYEW1

11. NCHRP 230 Test Number: S13

12. Impact Severity:

$\frac{m(V \sin a)^2}{2}$ 26.1 kip-ft (Spec: 23 to 29 kip-ft)

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-12.7 ft/s	30/40 ft/s
Ridedown Acceleration:	-6.0 g's	15/20 g's
Delta-V at 1.38 ft (actual):	-11.3 ft/s	30/40 ft/s
Ridedown Acceleration:	-6.0 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-14.3 ft/s	20/30 ft/s
Ridedown Acceleration:	-10.2 g's	15/20 g's
Delta-V at 0.67 ft (actual):	-11.0 ft/s	20/30 ft/s
Ridedown Acceleration:	-10.2 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-2.3 g's	
Lateral:	-5.9 g's	

14. Test Results Conclusion: Smooth redirection by rail.

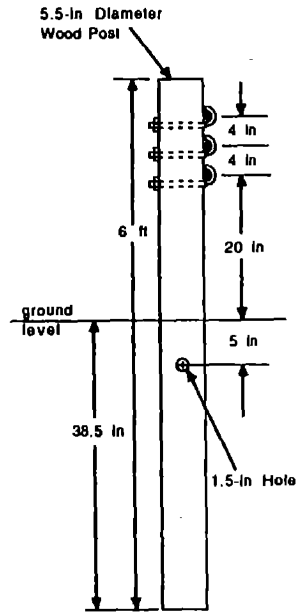
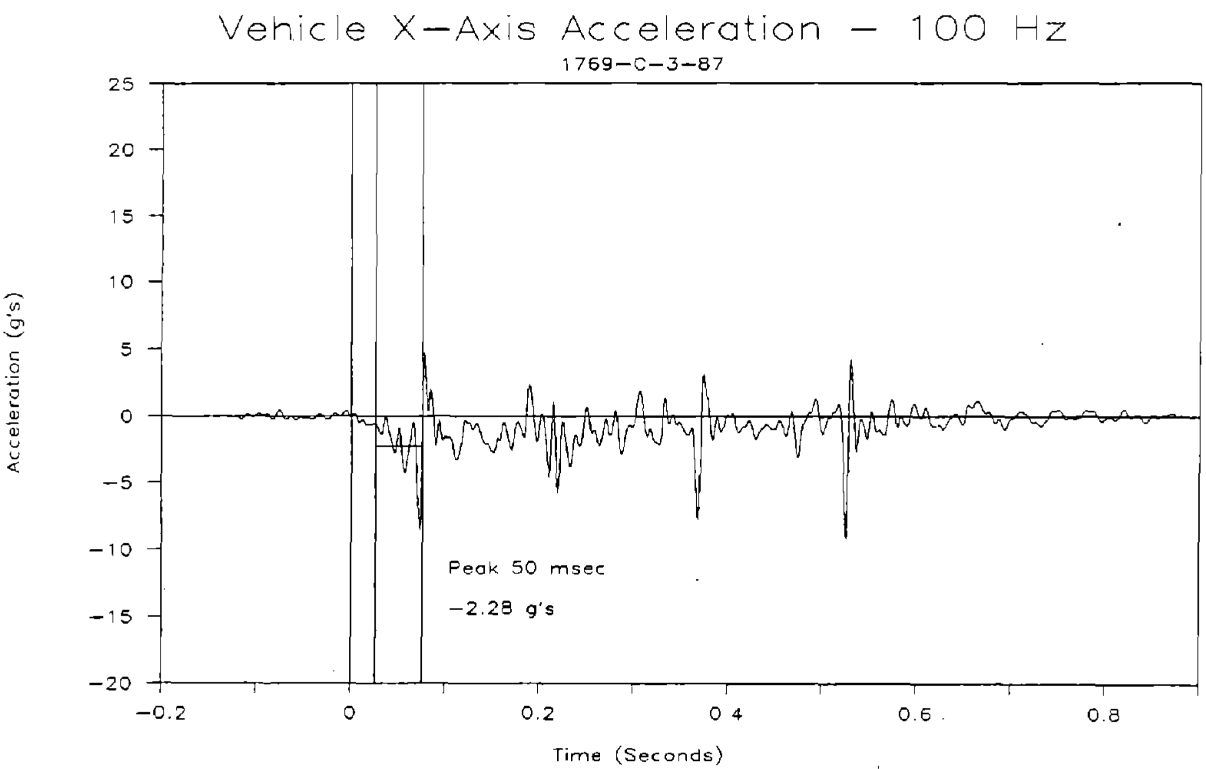


Figure 36. Test summary, test 1769-C-3-87.



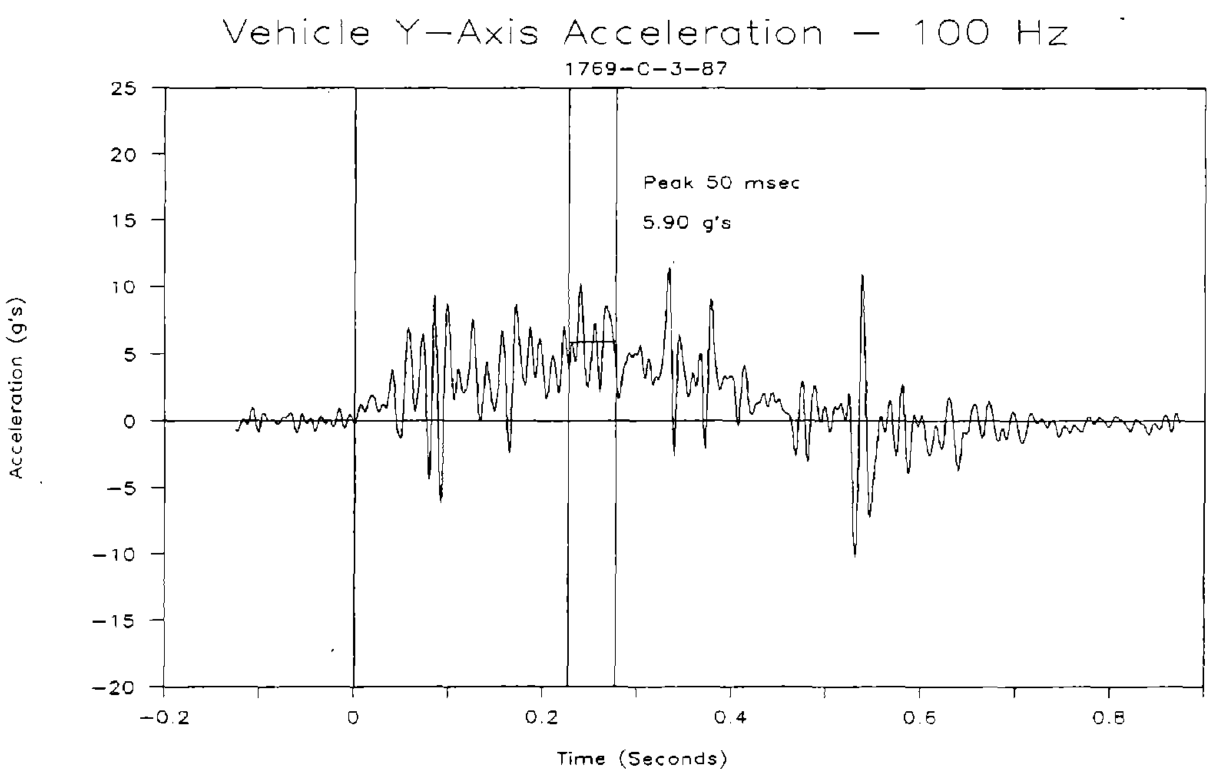


Figure 37. Vehicle acceleration, test 1769-C-3-87.

Figure 38. Posttest photographs of test vehicle, test 1769-C-3-87.

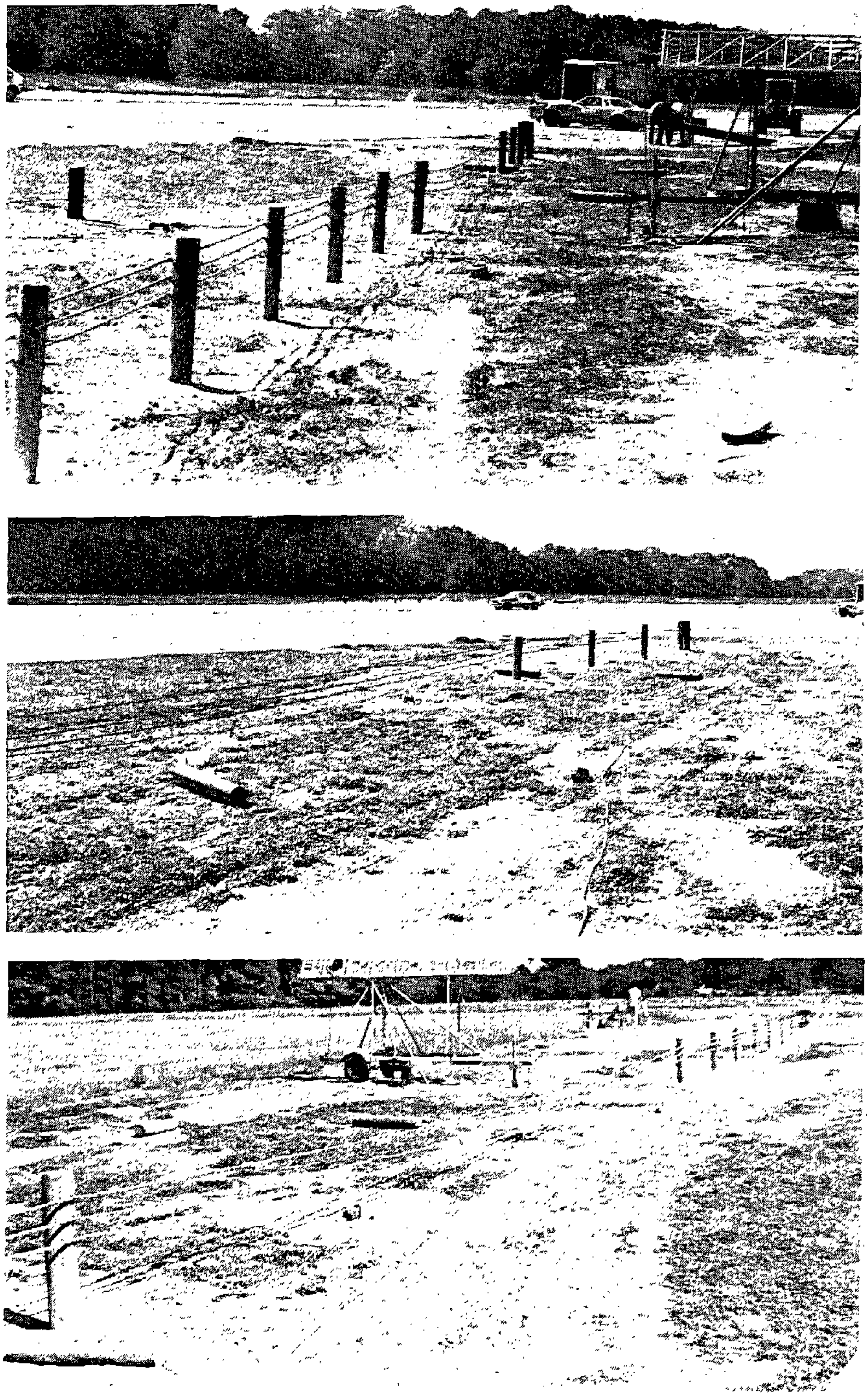


Figure 39. Posttest photographs of Minnesota three-cable guardrail system, test 1769-C-3-87.

4. TEST 1769-C-4-87

a. Test Device

The test device was the modified Minnesota three-cable guardrail system. The posts have been modified by drilling a 1.5-in hole in the longitudinal direction, 5 in below ground level.

This test utilizes the same end anchor attachment and attachment brackets as test C-3. All other features of test C-2 have been maintained.

Figure 40 shows the test site and test device. Figures 41 and 42 are show pretest photographs of the Minnesota three-cable guardrail system including details of the end bracket assembly, and the test vehicle.

b. Impact Description

Review of the high-speed films, fifth wheel and speed trap data indicated that the test vehicle impacted at 26 degrees and 62.7 mi/h. This review also indicated that the right corner of the vehicle impacted the rail at the desired point.

The vehicle penetrated into the rail approximately 8 ft and was redirected by the rail but did not exit from the rail. Ten posts were broken off through the hole below ground, including the downstream dual end post. The vehicle continued downstream breaking off posts and squarely impacted the dual end post. It continued away downstream turning hard right, coming to rest 160 ft downstream of impact, 25 ft behind the rail, after turning 110 degrees clockwise. A summary of the test conditions and results are given in figure 43.

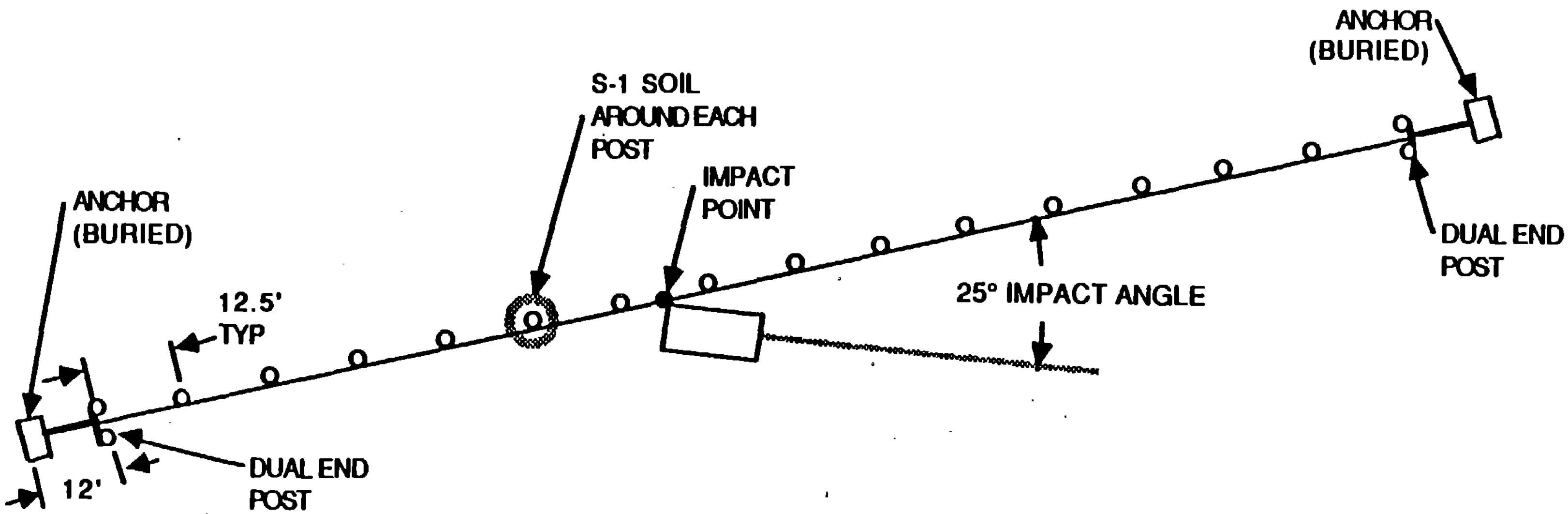


Figure 40. Test site layout, test 1769-C-4-87.

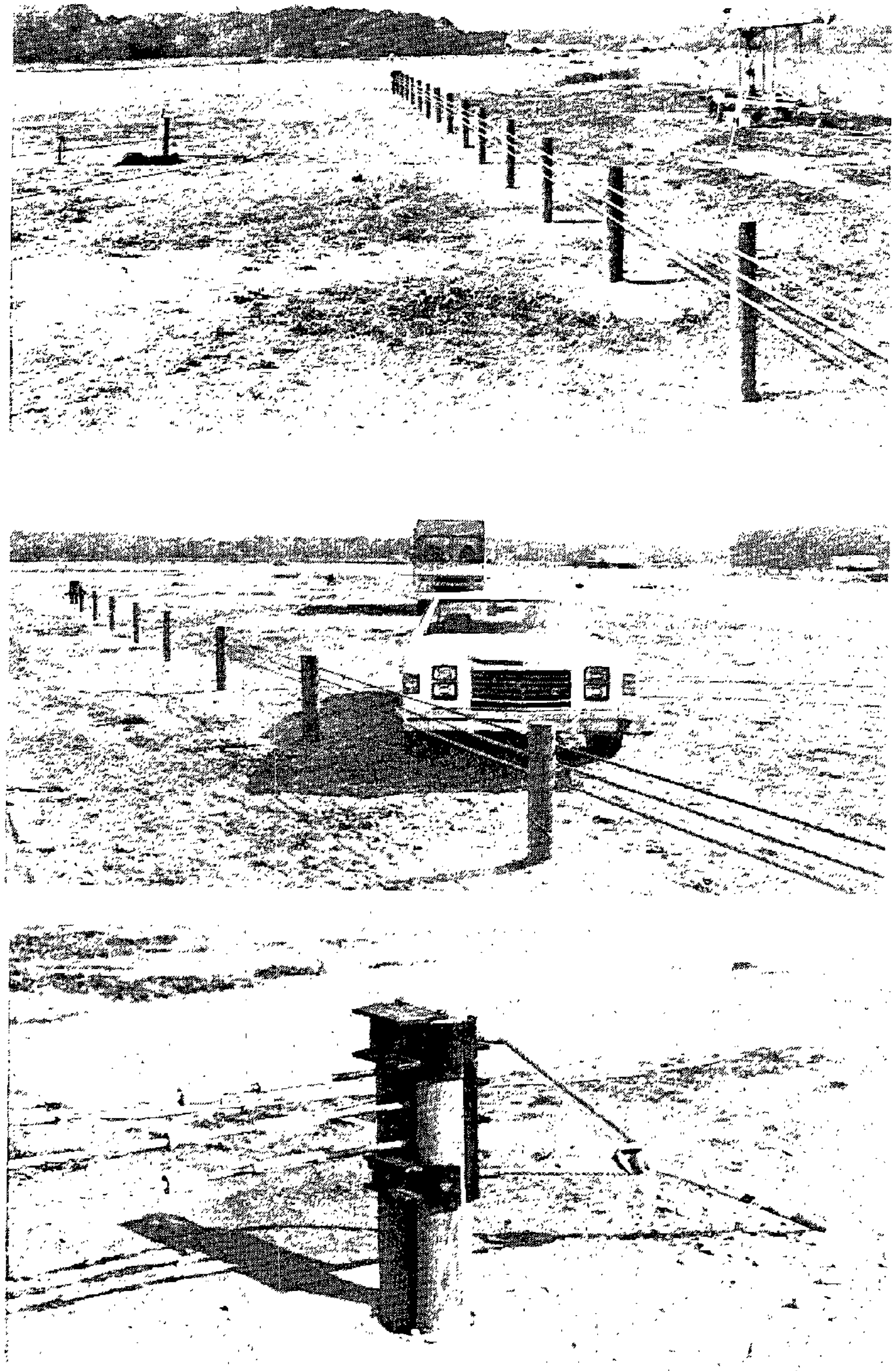


Figure 41. Pretest photographs of Minnesota three-cable guardrail system, test 1769-C-4-87.

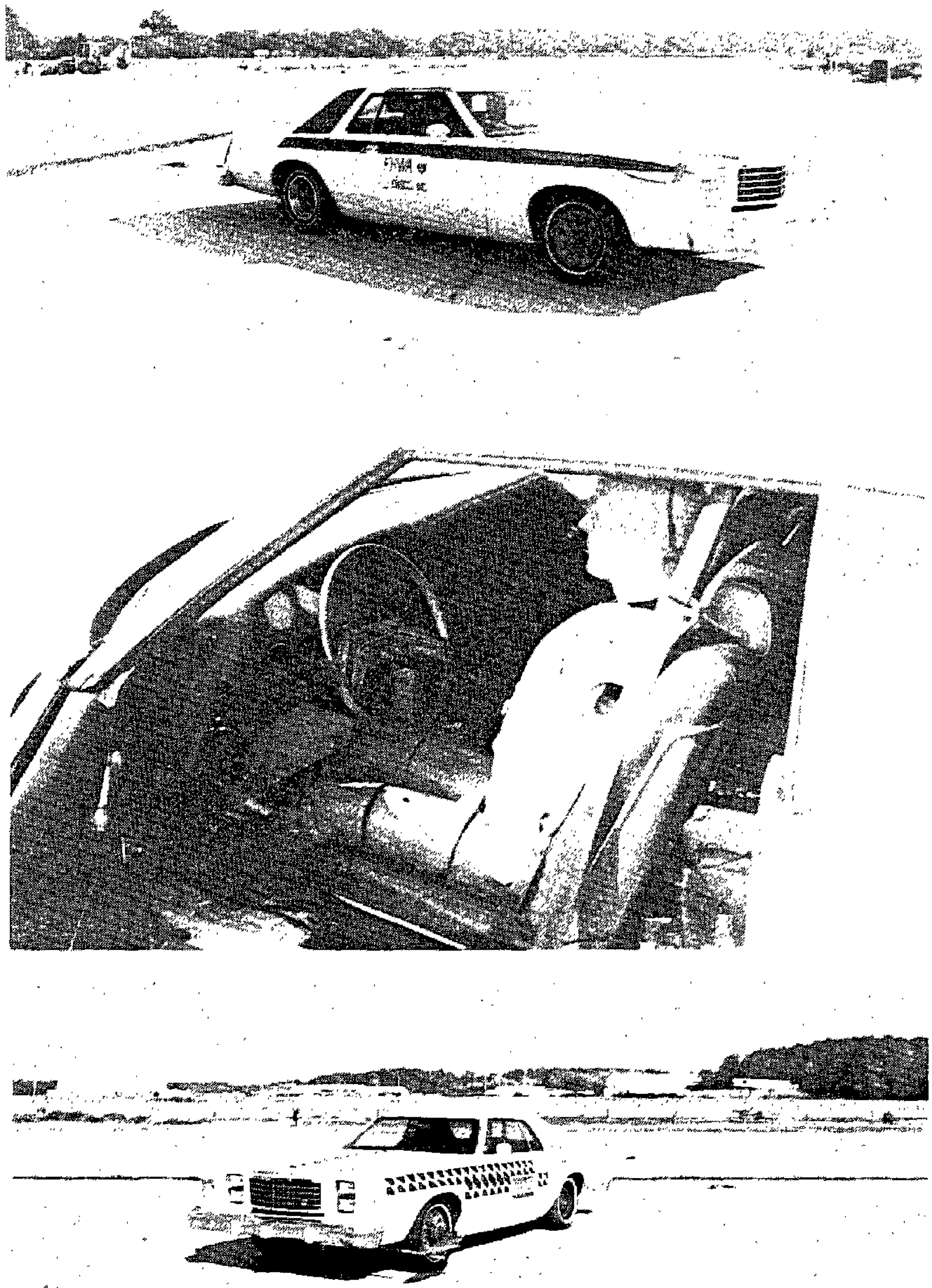
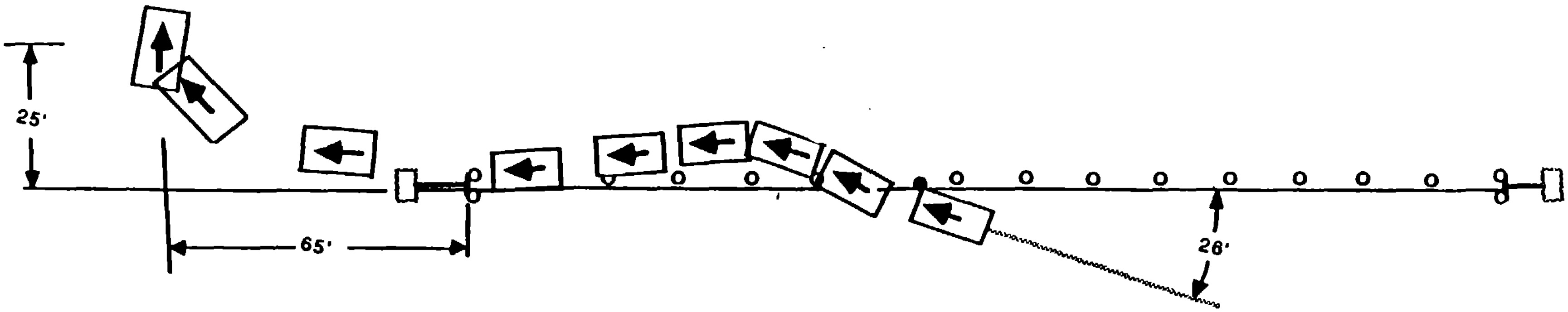


Figure 42. Pretest photographs of test vehicle, test 1769-C-4-87.



Date:	3 November 1987
Weather:	Sunny, 50° F
Test Vehicle:	1979 Ford LTD II
Device Configuration:	Minnesota 3-Cable Guardrail System, 200 ft long, 12.5-ft post spacing, Post: Modified 5.5-in diameter wood Rail: 0.75-in steel cable End Post: Dual post with BCT cable anchor attachment brackets.

1. Vehicle Weight:

	Test Inertial	Gross
Planned:	4500 ± 200	4500 ± 300
Actual:	4508	4680

2. Number of Occupants: One
3. Occupant Model: Anthropomorphic Dummy, 50th%, male
4. Occupant Location: Driver Seat, Unrestrained
5. Impact:

	Speed	Angle (a)	Location
Planned:	60.0 mi/h	25°	Midway between posts
Actual:	62.7 mi/h	26°	Midway between posts

6. Redirection Angle: 0 degrees
7. Redirection Speed: n/a (Vehicle did not exit rail)
8. Total Speed Change: n/a
9. Total Momentum Change: n/a
10. Vehicle Damage Index: (SAE J224a) 02RDEW2
11. NCHRP 230 Test Number: 10
12. Impact Severity:

$\frac{m(V \sin a)^2}{2}$ 113.9 kip-ft (Spec: 88 to 114 kip-ft)

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-13.0 ft/s	30/40 ft/s
Ridedown Acceleration:	-3.0 g's	15/20 g's
Delta-V at 1.67 ft (actual):	-12.4 ft/s	30/40 ft/s
Ridedown Acceleration:	-3.0 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-12.3 ft/s	20/30 ft/s
Ridedown Acceleration:	-6.1 g's	15/20 g's
Delta-V at 0.75 ft (actual):	-11.3 ft/s	20/30 ft/s
Ridedown Acceleration:	-6.1 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-2.0 g's	
Lateral:	-3.8 g's	

14. Test Results Conclusion: Smooth redirection by rail.

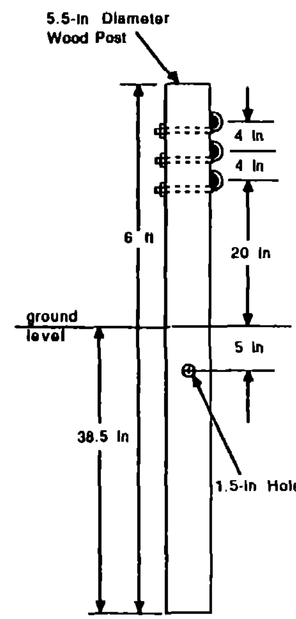


Figure 43. Test summary, test 1769-C-4-87.

Inside the vehicle, it was observed that the dummy fell into the passenger seat upon impact, and hit the door and window, breaking the window. The dummy came to rest over the hump with its knees under the steering wheel and head under the glove box.

Data analysis was performed and the vehicle x-axis and y-axis, 100 Hz acceleration traces are shown in figure 44.

c. Vehicle Damage

Almost all of the right side of the vehicle was damaged, but damage occurred mainly to the right front fender, grill and bumper. Posttest photographs of the vehicle are shown in figure 45.

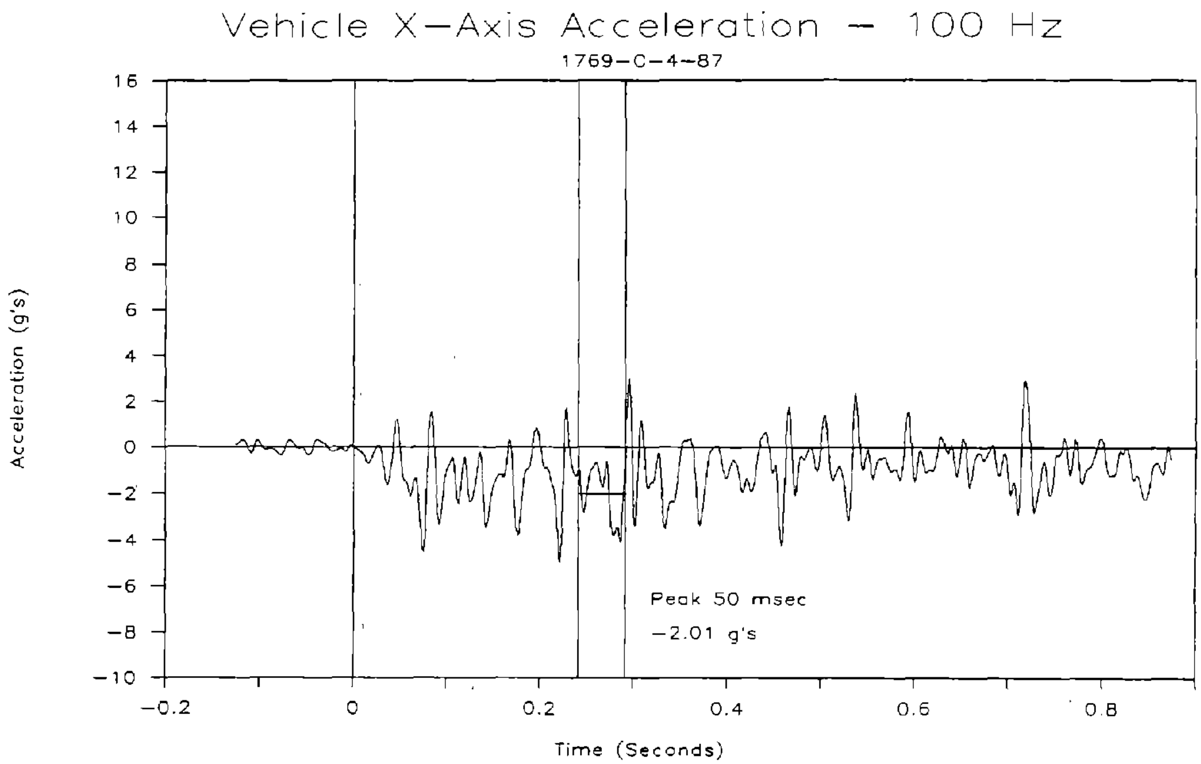
d. Traffic Barrier Damage

The Minnesota three-cable system performed as designed. The vehicle was redirected by the rail. The end anchors showed no sign of movement. However, one cable pulled out the fitting on the upstream end. Two pulled out on the downstream end with the third breaking at the threaded rod connection. The cables broke approximately 0.650 s after impact. The top bracket at the downstream end came off the post and the end anchor attachment rod broke at ground level. Posttest photographs are shown in figure 46.

5. <u>TEST 1769-C-5-88</u>

a. Test Device

The test device was the modified Minnesota three-cable guardrail system. The posts have been modified by drilling a 1.5-in hole in the longitudinal direction, 5 in below ground level.



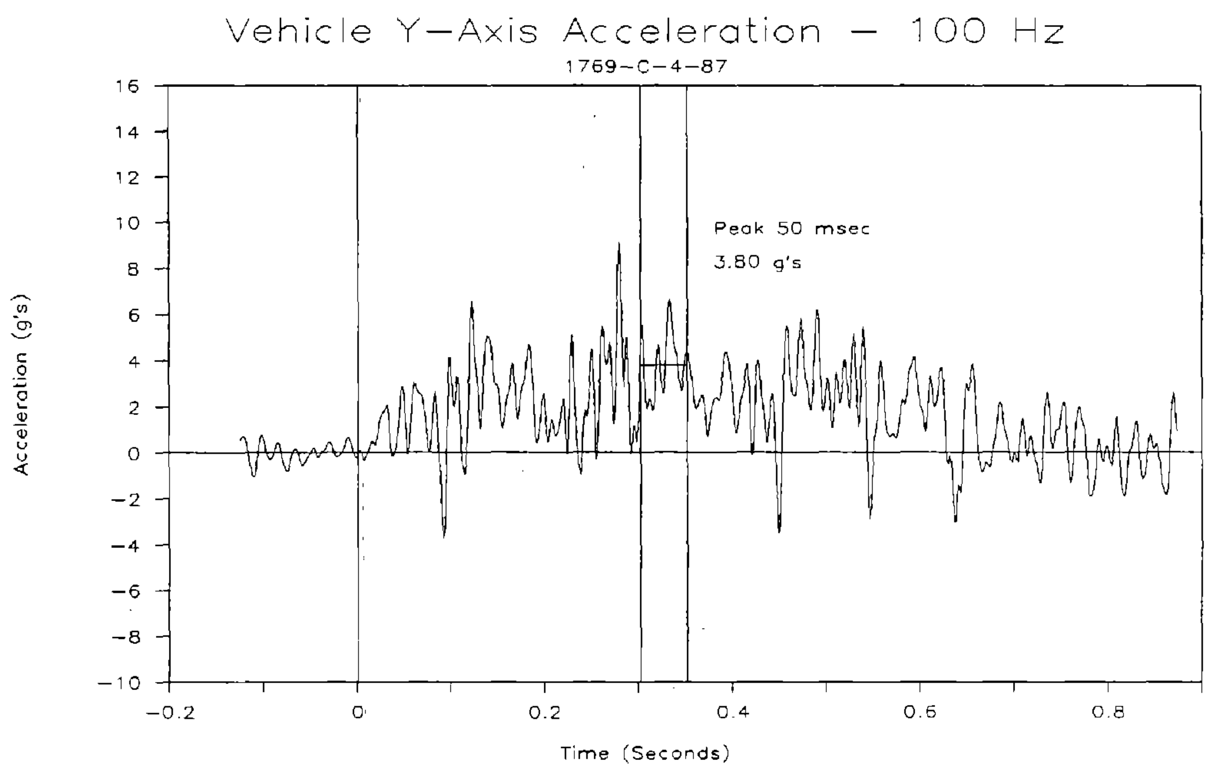


Figure 44. Vehicle acceleration, test 1769-C-4-87.

Figure 45. Posttest photographs of test vehicle, test 1769-C-4-87.

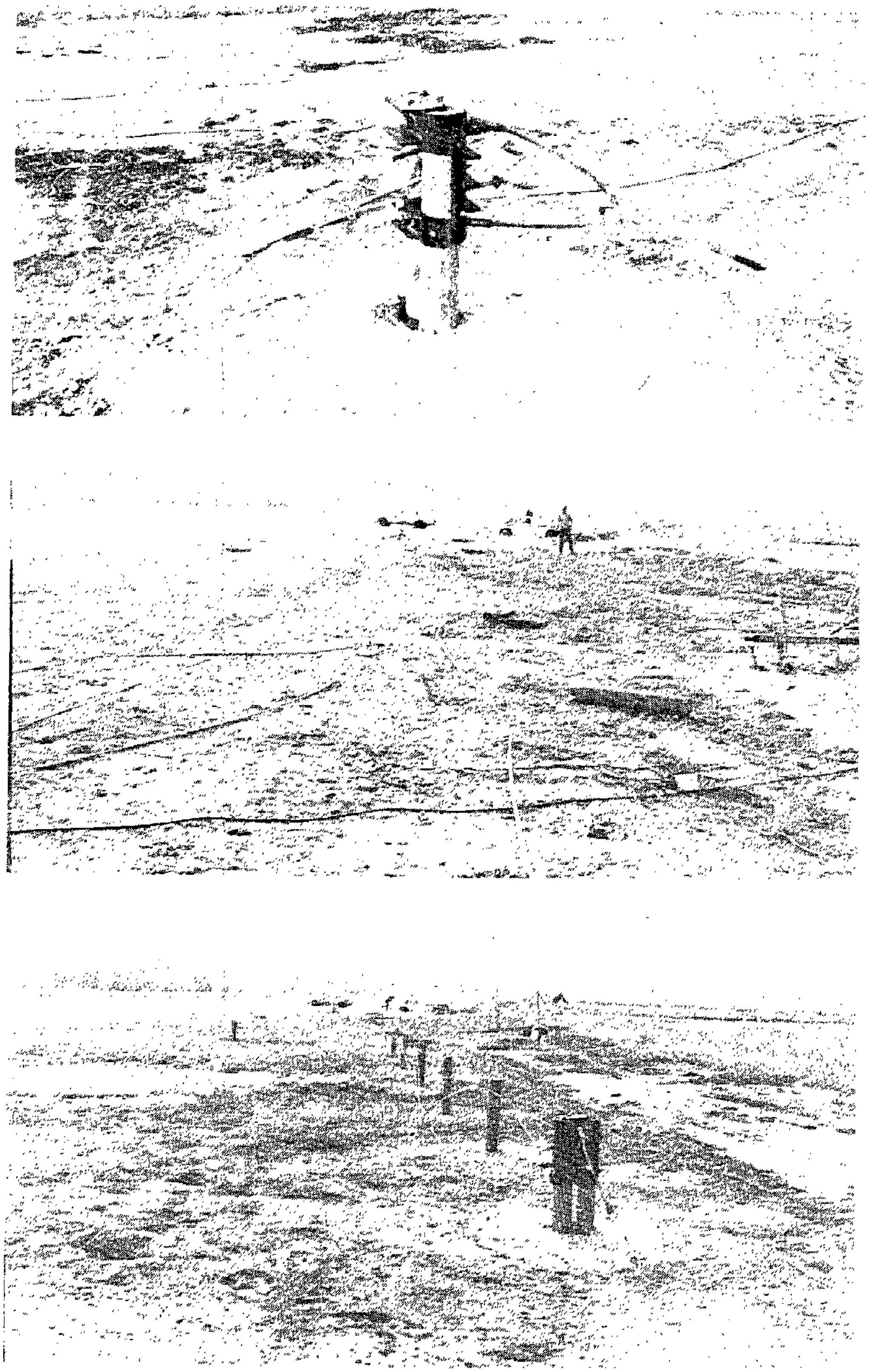


Figure 46. Posttest photographs of Minnesota three-cable guardrail system, test 1769-C-4-87.

This test utilizes the same end anchor attachment and attachment brackets as test C-3. The lag screws that had been used to attach the brackets to the end posts for tests C-3 and C-4, were only used to support the brackets for this test. All other features of test C-2 have been maintained.

Figure 47 shows the test site and test device. Figures 48 and 49 show pretest photographs of the Minnesota three-cable guardrail system and the test vehicle.

b. Impact Description

Review of the high-speed films, fifth wheel and speed trap data indicated that the test vehicle impacted at 60.6 mi/h and 21 degrees. This review also indicated that the center of the vehicle impacted the rail end post.

The vehicle squarely impacted the dual end post, breaking the posts off at ground level. The brackets on the post came apart cleanly. The impact, however, caused the vehicle to yaw clockwise. The yaw caused the vehicle to enter a continued yaw and roll coupling maneuver. The vehicle changed roll direction when it was on its roof. The vehicle came to rest on its tires after yawing 435 degrees and rolling 360 degrees. It stopped 75 ft past the end posts, 30 ft behind the line of the rail system. A summary of test conditions and results are shown in figure 50.

Inside the vehicle, it was observed that, upon impact, the dummy lunged forward into the windshield, punching it out. When the vehicle rolled over the dummy impacted the roof, coming to rest in the drivers seat.

Data analysis was performed and the vehicle x-axis and y-axis, 100 Hz data plots are shown in figure 51.

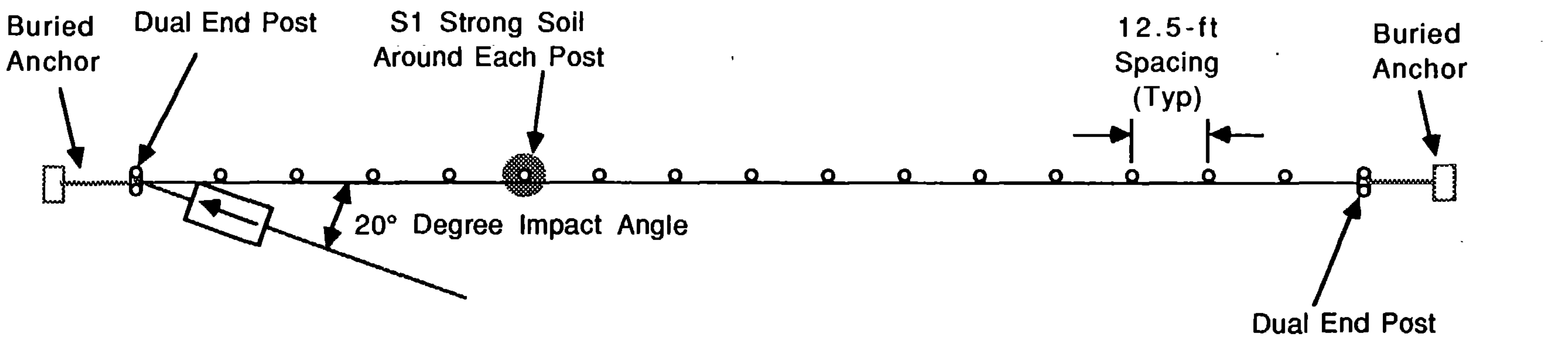


Figure 47. Test site layout, test 1769-C-5-88.

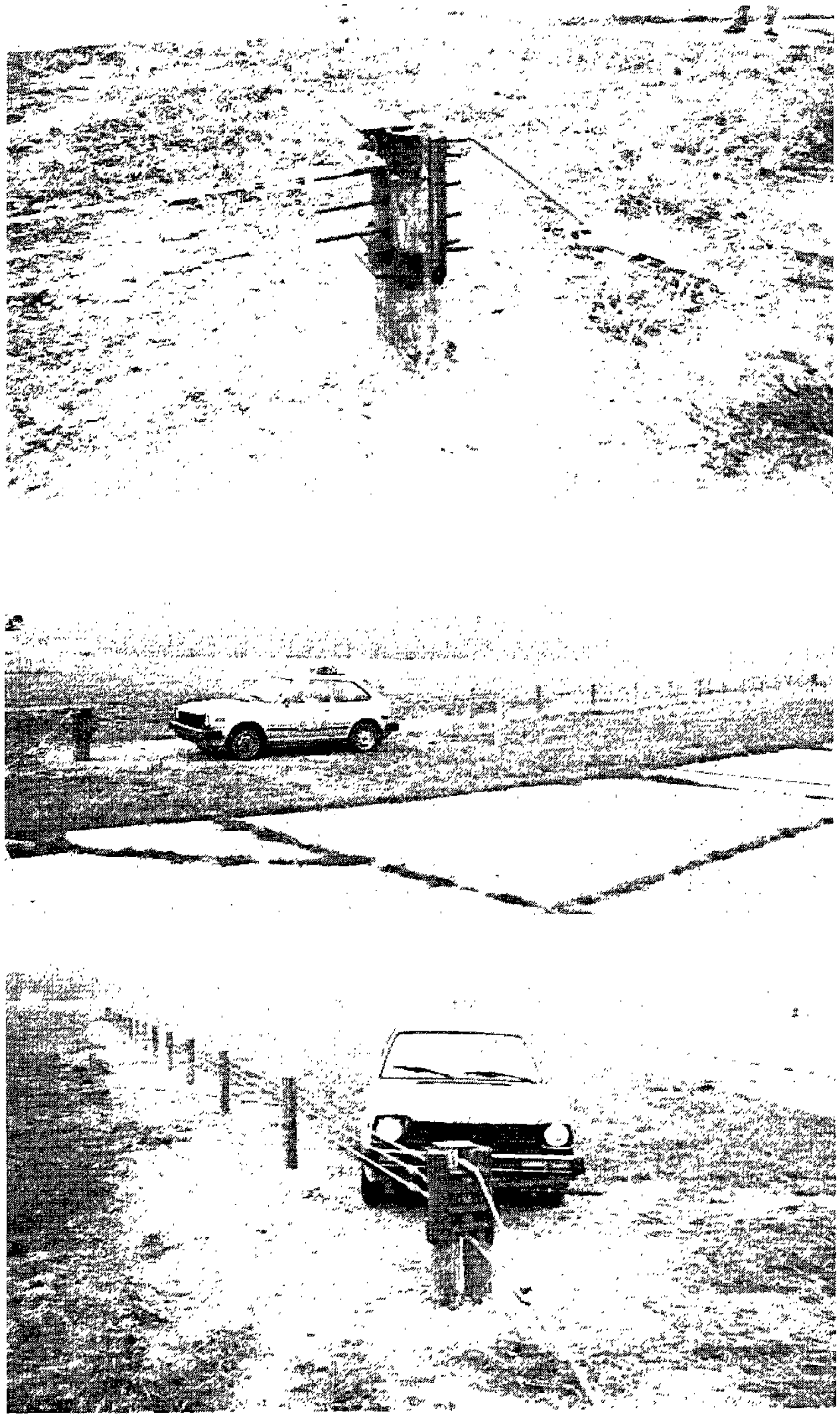
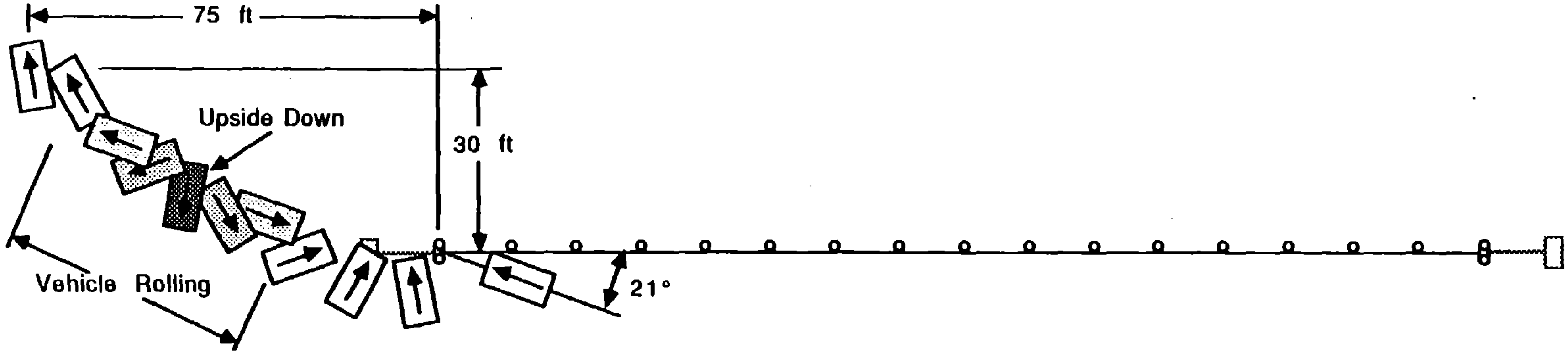


Figure 48. Pretest photographs of Minnesota three-cable guardrail system, test 1769-C-5-88.

Figure 49. Pretest photographs of test vehicle, test 1769-C-5-88.



Date:	9 September 1988
Weather:	Overcast, 70° F
Test Vehicle:	1981 Honda Civic
Device Configuration:	Minnesota 3-Cable Guardrail System, 200 ft long, 12.5-ft post spacing, Post: Modified 5.5-in diameter wood Rail: 0.75-in steel cable End Post: Dual post with BCT Cable anchor attachment brackets

1. Vehicle Weight:

	Test Inertial	Gross
Planned:	1800 ± 50	1950 ± 50
Actual:	1794	1940

2. Number of Occupants: One

3. Occupant Model: Anthropomorphic Dummy, 50th%, male

4. Occupant Location: Driver Seat, Unrestrained

5. Impact:

	Speed	Angle (a)	Location
Planned	60.0 mi/h	20°	Centered on end post
Actual	60.6 mi/h	21°	Centered on end post

6. Redirection Angle: n/a

7. Redirection Speed: n/a

8. Total Speed Change: n/a

9. Total Momentum Change: n/a

10. Vehicle Damage Index: (SAE J224a) 01FDEO2

11. NCHRP 230 Test Number: Special

12. Impact Severity: (evaluated for NCHRP 230 test number S13)

$\frac{m(V \sin a)^2}{2}$ 28.3 kip-ft (Spec: 23 to 29 kip-ft)

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-34.3 ft/s	30/40 ft/s
Ridedown Acceleration:	-3.6 g's	15/20 g's
Delta-V at 1.75 ft (actual):	-34.1 ft/s	30/40 ft/s
Ridedown Acceleration:	-3.6 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-8.6 ft/s	20/30 ft/s
Ridedown Acceleration:	-4.1 g's	15/20 g's
Delta-V at 0.46 ft (actual):	-4.9 ft/s	20/30 ft/s
Ridedown Acceleration:	-4.1 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-16.2 g's	
Lateral:	-5.1 g's	

14. Test Results Conclusion: (evaluated for NCHRP 230 test S13)

Vehicle rolled over after yawing. Integrity of the passenger compartment was not maintained due to rollover. Detached elements showed potential for penetrating passenger compartment.

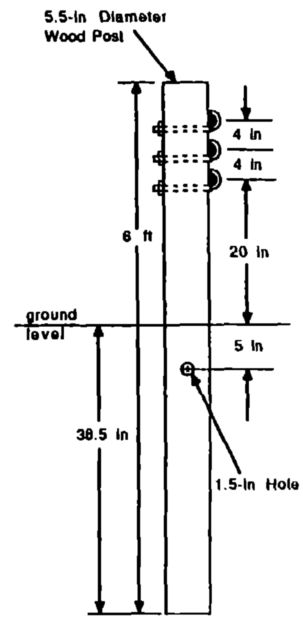


Figure 50. Test summary, test 1769-C-5-88.

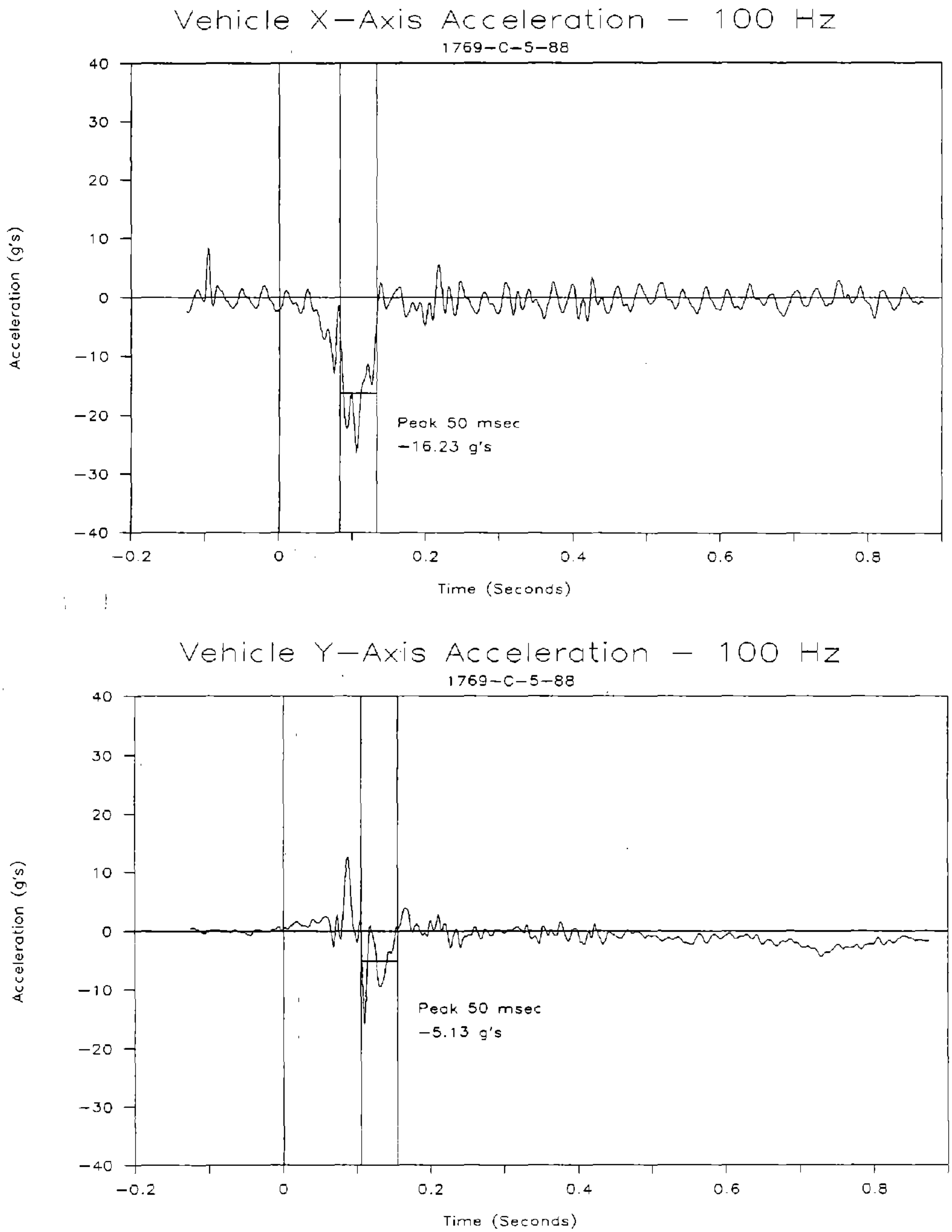


Figure 51. Vehicle acceleration, test 1769-C-5-88.

c. Vehicle Damage

All of the front of the vehicle was damaged, including the fenders on both sides. Posttest photographs of the vehicle are shown in figure 52.

d. Traffic Barrier Damage

The Minnesota three-cable system performed well, but because of the vehicle rollover the device did not pass this test. The vehicle traveled past the end posts (was not stopped or slowed greatly by the end post assembly). The upstream end anchor showed signs of slight movement. One cable pulled out of the fitting on the upstream end. On the downstream end, all three cables sheared off at the threaded rod connection. posttest photographs of the rail are shown in figure 53.

Figure 52. Posttest photographs of test vehicle, test 1769-C-5-88.

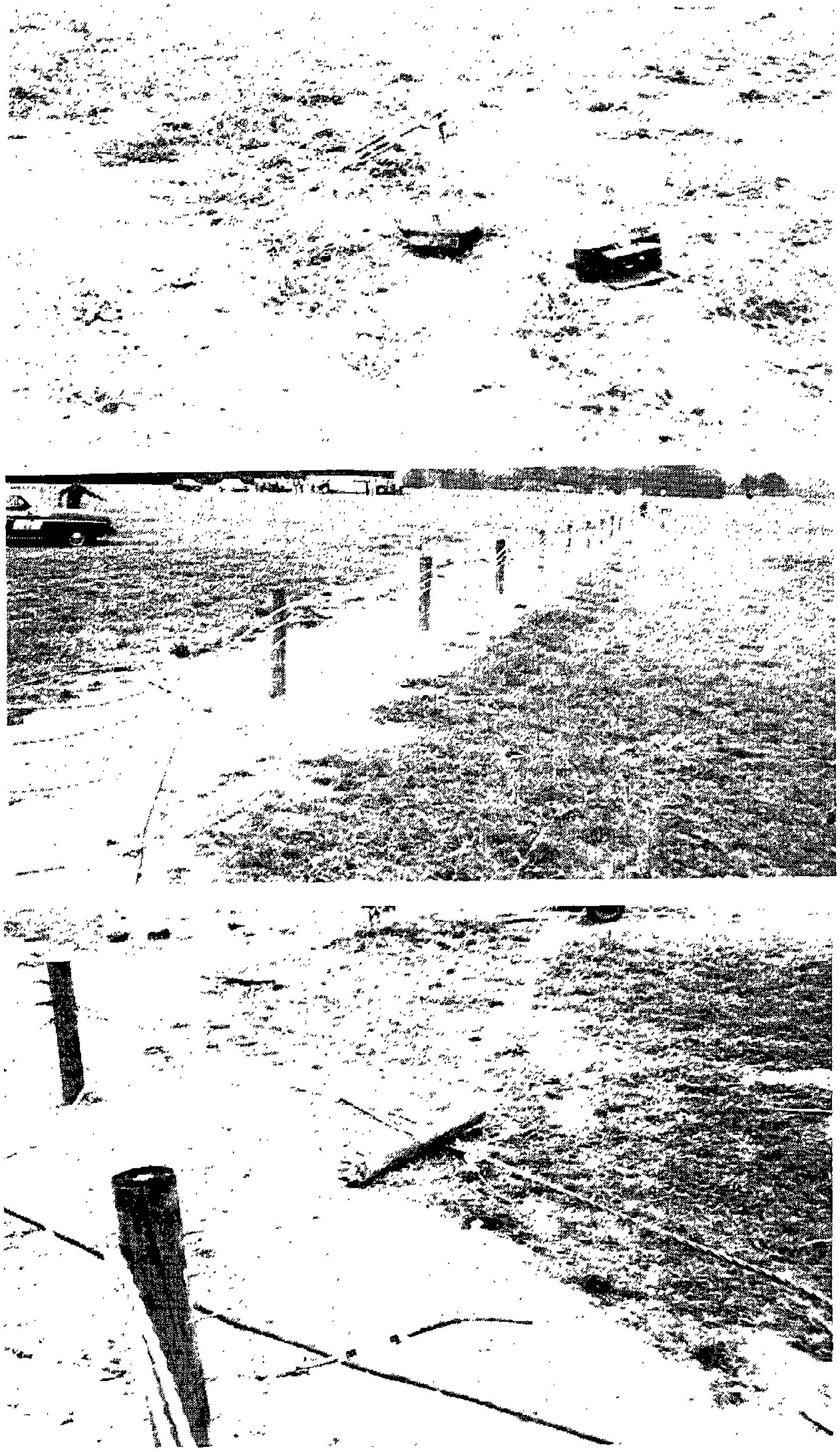


Figure 53. Posttest photographs of Minnesota three-cable guardrail system, test 1769-C-5-88.

FULL-SCALE TESTING OF THE REDESIGNED, MODIFIED THRIE BEAM MEDIAN BARRIER

The purpose of this task was to full-scale test a redesigned version of the modified thrie beam median barrier. Based on the drawings from the redesign effort, three tests were planned. Because of the results of the first test (50,000-lb tractor-trailer, 50 mi/h, 15 degrees), the proposed second and third tests were changed and consolidated into a single test. This one (18,000-lb truck, 50 mi/h, 15 degrees) tested the modified thrie beam median barrier under the new AASHTO bridge rail specifications. The following text describes the tests conducted under this task.

1. <u>TEST 1769-D-1-88</u>

a. Test Device

The test device was the quad beam median barrier. The quad beam (redesigned, modified, thrie beam) consists of a W beam nested over the top hump of the thrie beam, creating four humps. The rail is 40.25 in high and features a 7-ft, 3.25-in W6x9 post embedded 46 in and 23-in W14x22 blockouts. The rail is attached to the block with two bolts and the block to the post with four bolts. W beam and thrie beam backup plates are used at all nonsplice post locations. This rail maintains the modified thrie beam median barrier configuration from the ground to the top of the thrie beam and adds one-half of a W beam to the top.

The entire system was 218.75 ft long. The system consisted of 162.5 ft of quad beam, a 6.25-ft quad to thrie transition, 6.25 ft of thrie beam, a 6.25-ft thrie to W beam transition and a 37.5-ft eccentric loader BCT. Three cable anchor assemblies were used (two on the downstream ends, one on the backside upstream end). These feature a 1.5-ft diameter, 5-ft deep cast-in-place concrete foundation, a 4.5-ft, 1.25-in diameter hook eye rod and a single-swaged 0.75-in cable. The rod is cast in the foundation and the cable is attached to the eye with cable clips. The threaded end anchors to the guardrail with a BCT anchor plate. A double swaged cable assembly and a 2 by 3 by 0.25-in steel angle were utilized for the quad to thrie transition.

The entire system was installed in very well compacted (approximately 95%) NCHRP 230 S1 strong soil.

Figure 54 shows the test site and test device. Figure 55 shows pretest photographs of the quad system.

b. Test Vehicle

The test vehicle was a 1980 GMC Brigadier tractor with a 1970 Fruehauf trailer. The target vehicle weight was 50,000 lb. The vehicle weighed 27,972 lb empty. Straw and sand ballast weighing 22,175 lb was added. The ballasted weight of the truck was 50,147 lb. X-axis, y-axis and z-axis accelerometers were mounted in the cab of the tractor along with roll and yaw rate gyros. X-axis and y-axis accelerometers were also mounted on the rear of the tractor, the front of the trailer and the rear of the trailer. Pretest photographs of the test vehicle are shown in figure 56. Figure 57 shows a diagram of the truck along with a list of the important parameters.

c. Impact Description

Review of the high-speed films and speed trap data indicated that the test vehicle impacted at 50.0 mi/h and 15 degrees. This review also indicated that the right corner of the vehicle impacted the rail at the desired point.

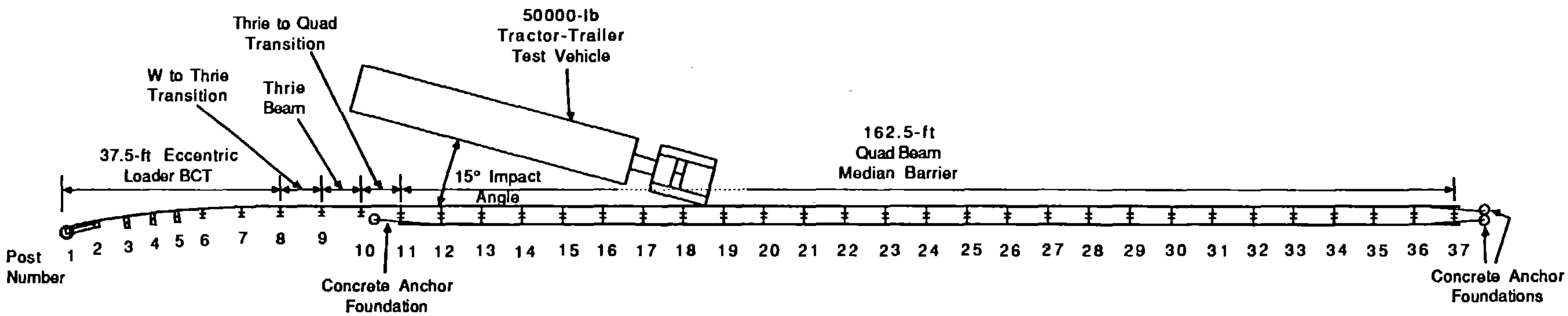


Figure 54. Test site layout, test 1769-D-1-88.

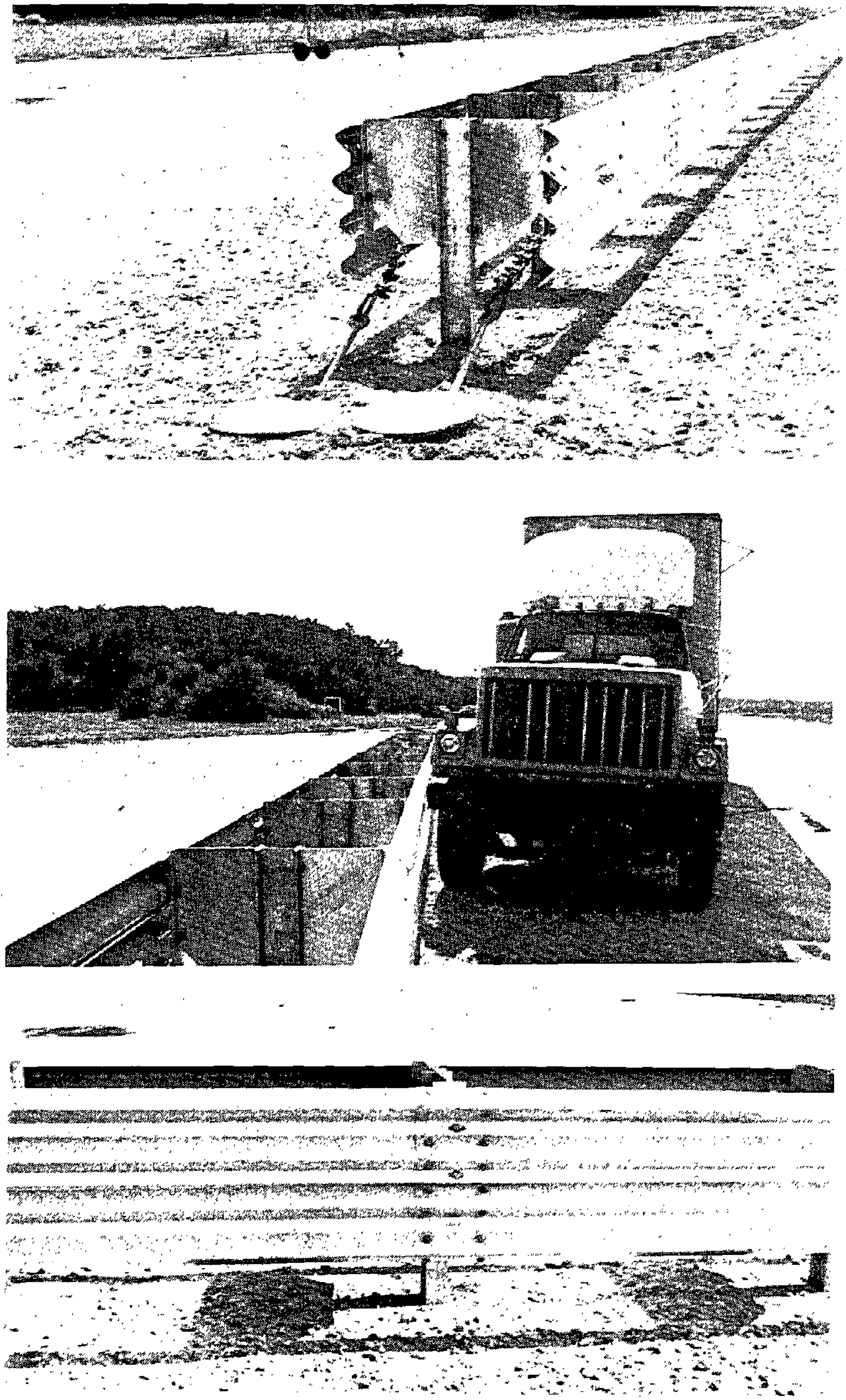
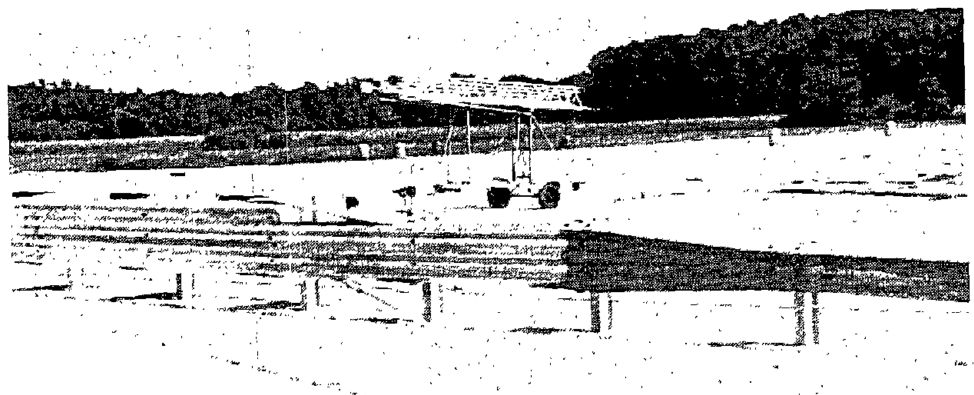


Figure 55. Pretest photographs of guardrail system, test 1769-D-1-88.



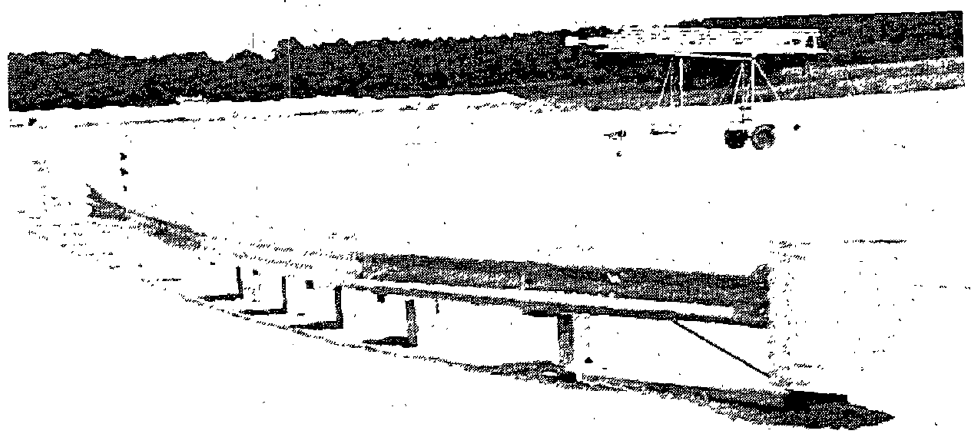


Figure 55. Pretest photographs of guardrail system, test 1769-D-1-88 (continued).

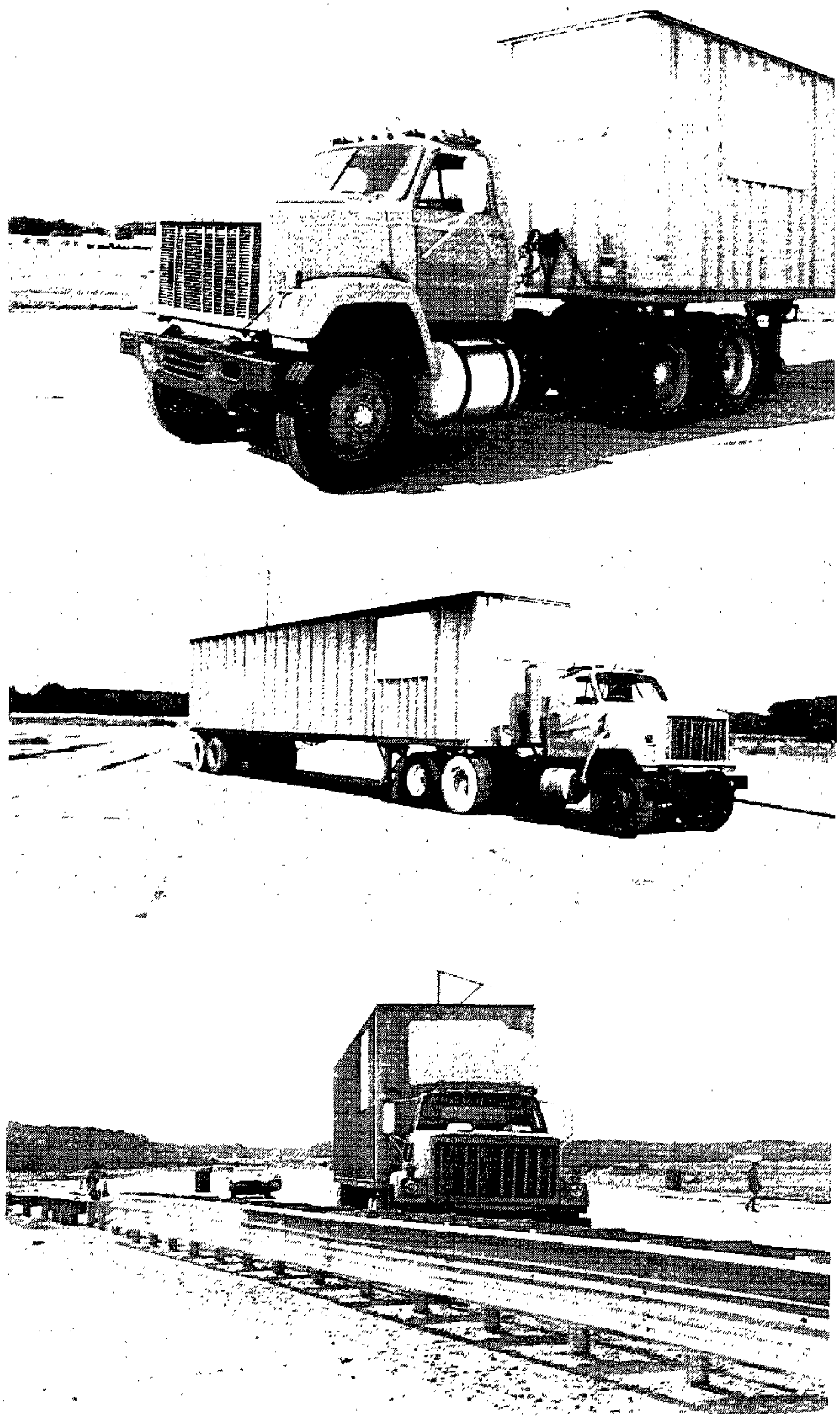
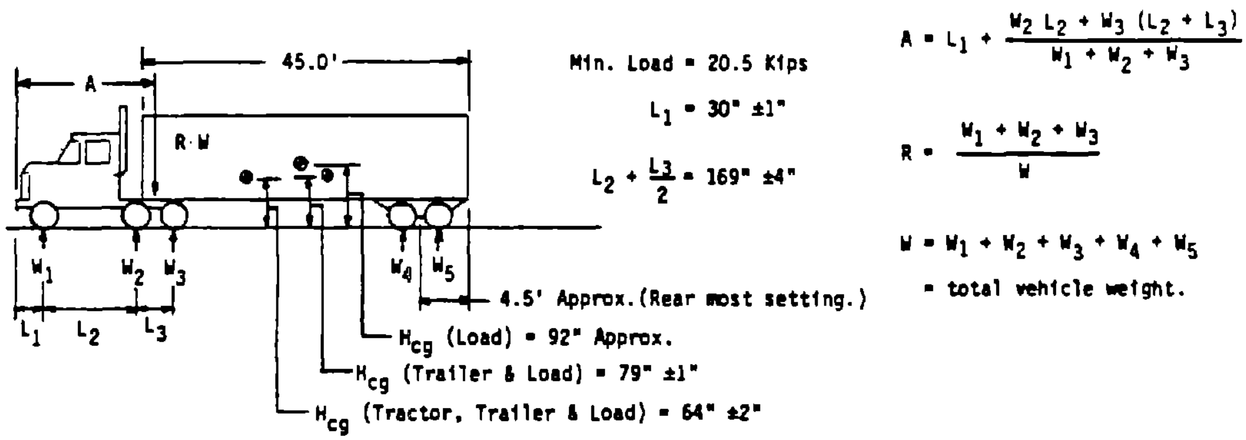


Figure 56. Pretest photographs of test vehicle, test 1769-D-1-88.



Truck Parameters

Item	Actual	Specification
Ballast	22,175 lb	>20,500 lb
L_1	30 in	30 ± 1 in
$L_2 + L_3/2$	171.5 in	169 ± 4 in
H_{cg} (Load)	92.3 in	92 in
H_{cg} (Trailer, Load)	78.0 in	79 ± 1 in
H_{cg} (Tractor, Trailer, Load)	63.5 in	64 ± 2 in
A	12.99 ft	12.5 ± .5 ft
R	.616	0.61 ± .01
Tractor Length	21 ft, 0.5 in	
Trailer Length	45 ft	45 ft
Overall Length	58 ft, 1 in	
Tractor Wheelbase (same as item 3 above)	171.5 in	169 ± 4 in
Wheel/Tire Size	11R24.5	
Trailer Box Height	155 in	

Figure 57. Test truck parameters, test 1769-D-1-88.

Upon impact, the vehicle penetrated into the rail approximately 3 ft. Posts in the impact area bent because of the penetration and the rail was pushed toward the back side. The tractor started to roll toward the rail as it was redirected. When the trailer impacted the rail (approximately 320 ms after impact) it started to yaw but also began to roll. The trailer continued to roll as the vehicle momentum carried it down the rail. The trailer rolled over in approximately 1.25 seconds (roll rate of approximately 72 degrees/second). The rolling of the trailer caused the tractor to roll over also. The vehicle came to rest on the passenger side at the end of the barrier system. A summary of test conditions and results are shown in figure 58.

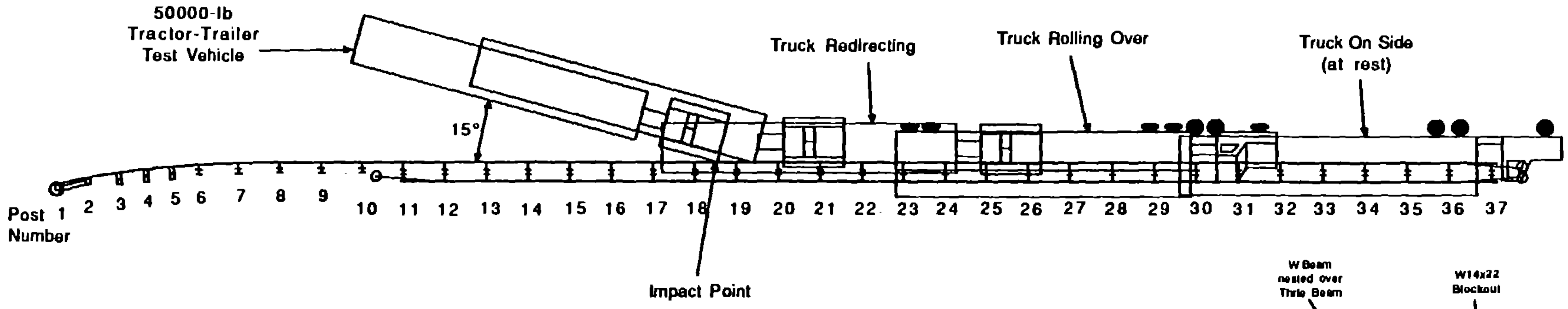
Data analysis was performed. The tractor front, tractor rear, trailer front and trailer rear x-axis and y-axis, 100 Hz data plots are shown in figures 59 through 62.

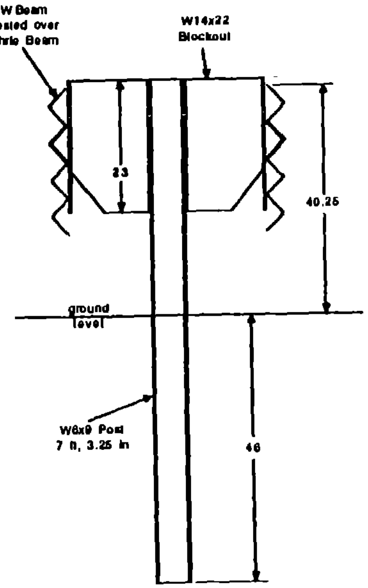
d. Vehicle Damage

The tractor was nearly destroyed. The cab was demolished and the front axle was torn from the frame. When the trailer rolled onto the barrier, the rail sliced open the side of the trailer. Posttest photographs of the tractor-trailer are shown in figure 63.

e. Traffic Barrier Damage

The barrier was severely damaged from the impact point to the downstream end. All posts in the area were bent over. The rail was detached from most posts. When the trailer rolled onto the barrier, it split the rail down the middle (posts were bent in the downstream direction, and the rail on both sides was splayed outwards). Posttest photographs of the rail are shown in figure 64.





Date:	10 August 1988
Weather:	Overcast, 80° F
Test Vehicle:	1980 GMC Brigadier Tractor with 1970 Fruehauf Trailer
Device Configuration:	Quad Beam Median Barrier, 219 ft total length, 40.25 in high, W-beam nested over top of Thrie beam, 162.5 ft of Quad beam, 18.75 ft of transition to W-beam, 37.5-ft Eccentric Loader BCT

1. Vehicle Weight:
   - Planned: 50000
   - Actual: 50147
2. Number of Occupants: None
3. Occupant Model: n/a
4. Occupant Location: n/a
5. Impact:

	Speed	Angle (a)	Location
Planned	50.0 mi/h	15°	Midspan posts 18 and 19
Actual	50.0 mi/h	15°	Midspan posts 18 and 19

6. Redirection Angle: n/a
7. Redirection Speed: n/a
8. Total Speed Change: n/a
9. Total Momentum Change: n/a
10. Vehicle Damage Index: (SAE J224a) n/a
11. NCHRP 230 Test Number: Special
12. Impact Severity:

$\frac{m(V \sin a)^2}{2}$ 280.5 kip-ft (Spec: 279.7 kip-ft)

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-11.3 ft/s	30/40 ft/s
Ridedown Acceleration:	-10.6 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	15.5 ft/s	20/30 ft/s
Ridedown Acceleration:	8.8 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-3.5 g's	
Lateral:	6.1 g's	

14. Vehicle-Railing Interaction Coefficient of Friction:

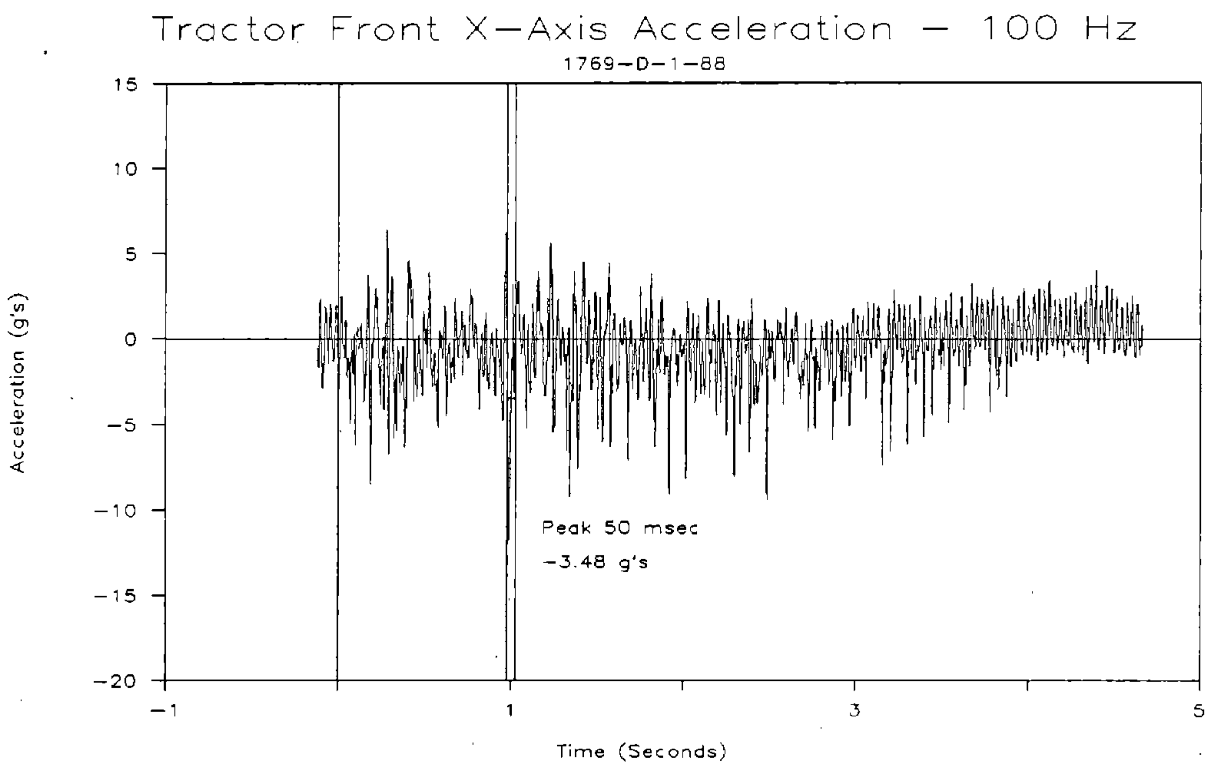
$$mu = \frac{\text{Cos theta} - V_P/V}{\text{Sin theta}}$$

mu	assessment
0.62	marginal

15. Test Results Conclusion: (evaluated using June 1, 1988 revision of "AASHTO Standard Specifications for Highway Bridges")

The vehicle was redirected. During redirection, the vehicle rolled onto the rail with one-half the trailer intruding into the other side of the rail. There were no detached elements. Due to the vehicle rollover, integrity of the passenger compartment was not maintained. The vehicle-railing interaction friction was calculated as 0.62. The vehicle did not exit from the rail.

Figure 58. Test summary, test 1769-D-1-88.



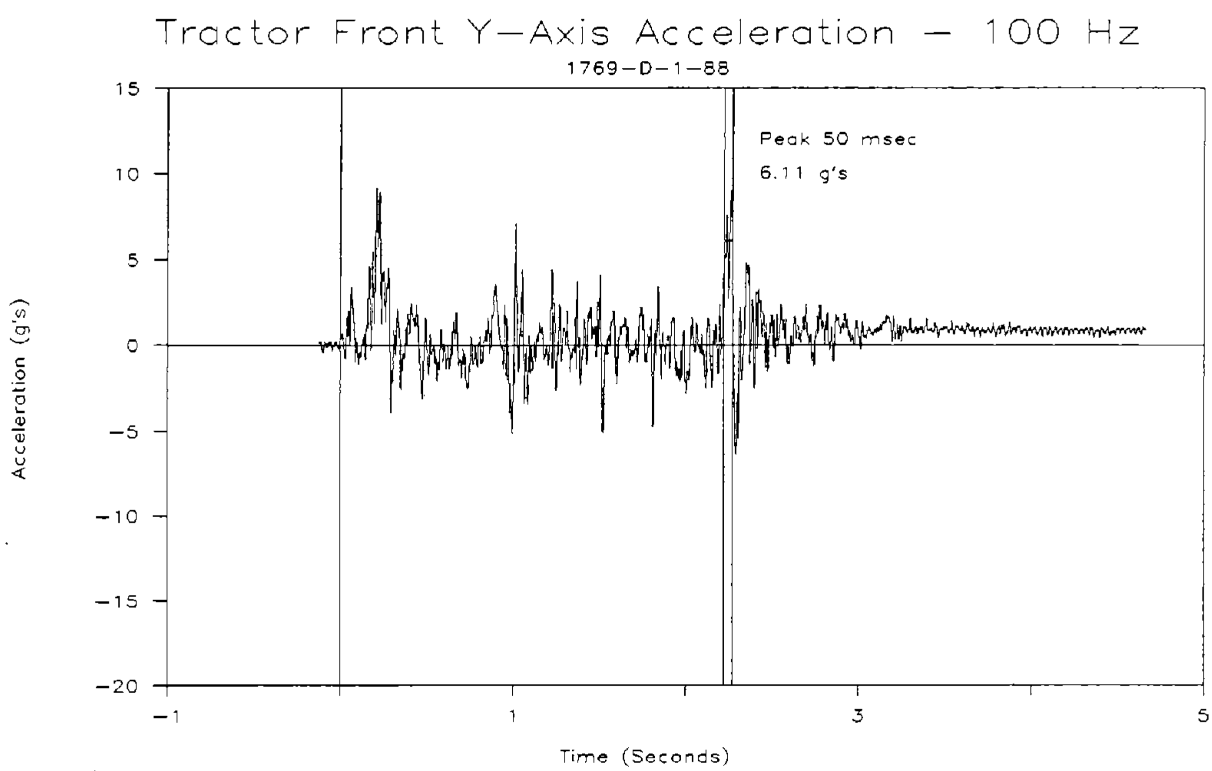
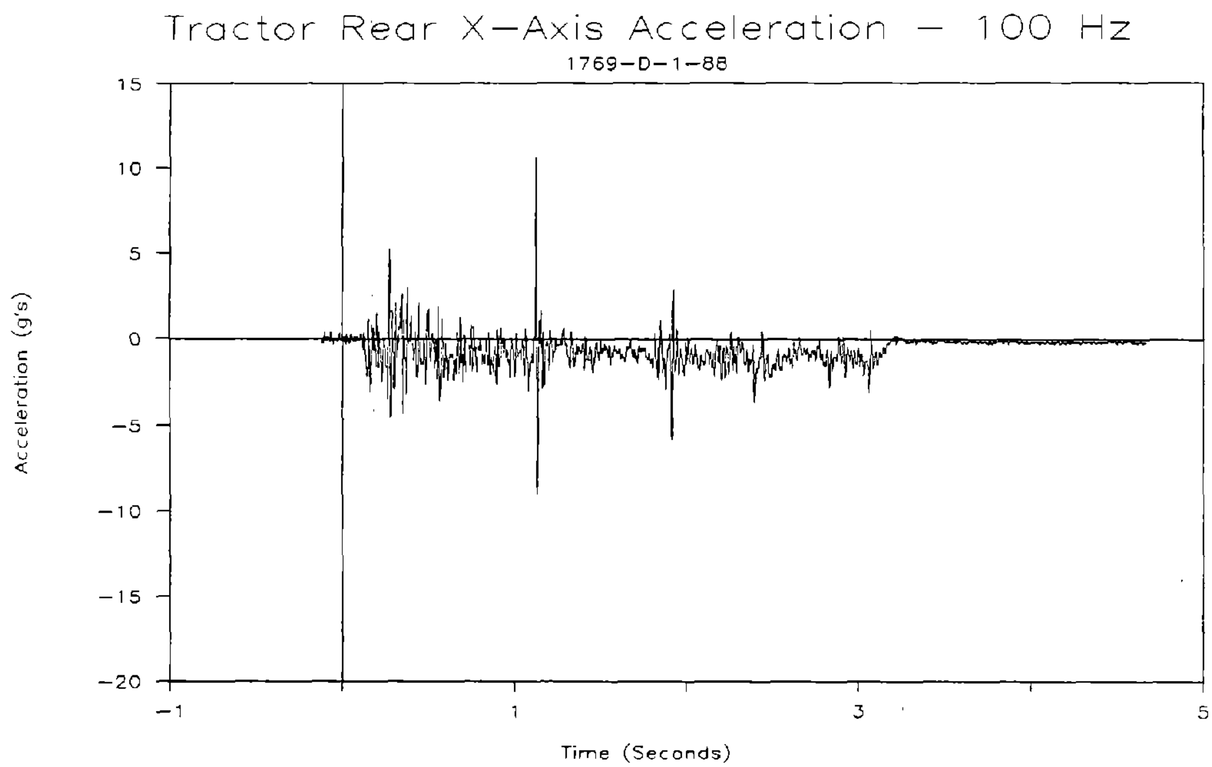


Figure 59. Tractor front acceleration, test 1769-D-1-88.



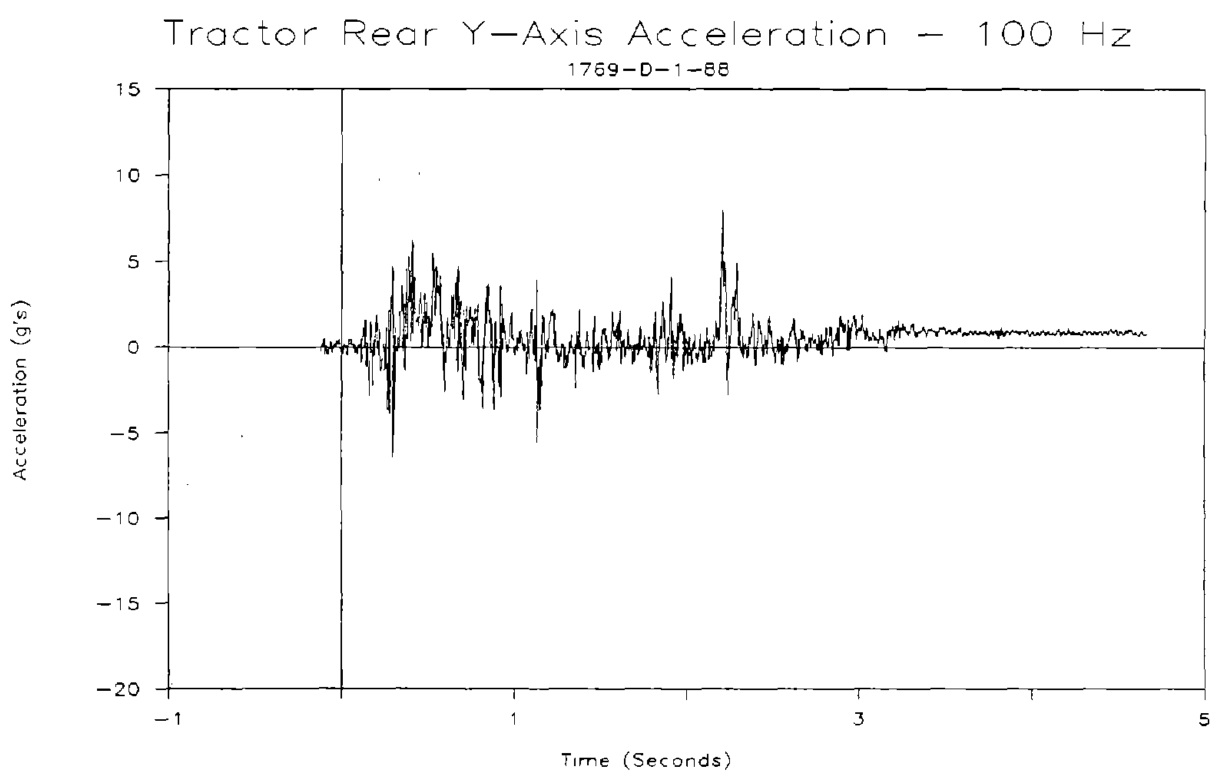


Figure 60. Tractor rear acceleration, test 1769-D-1-88.

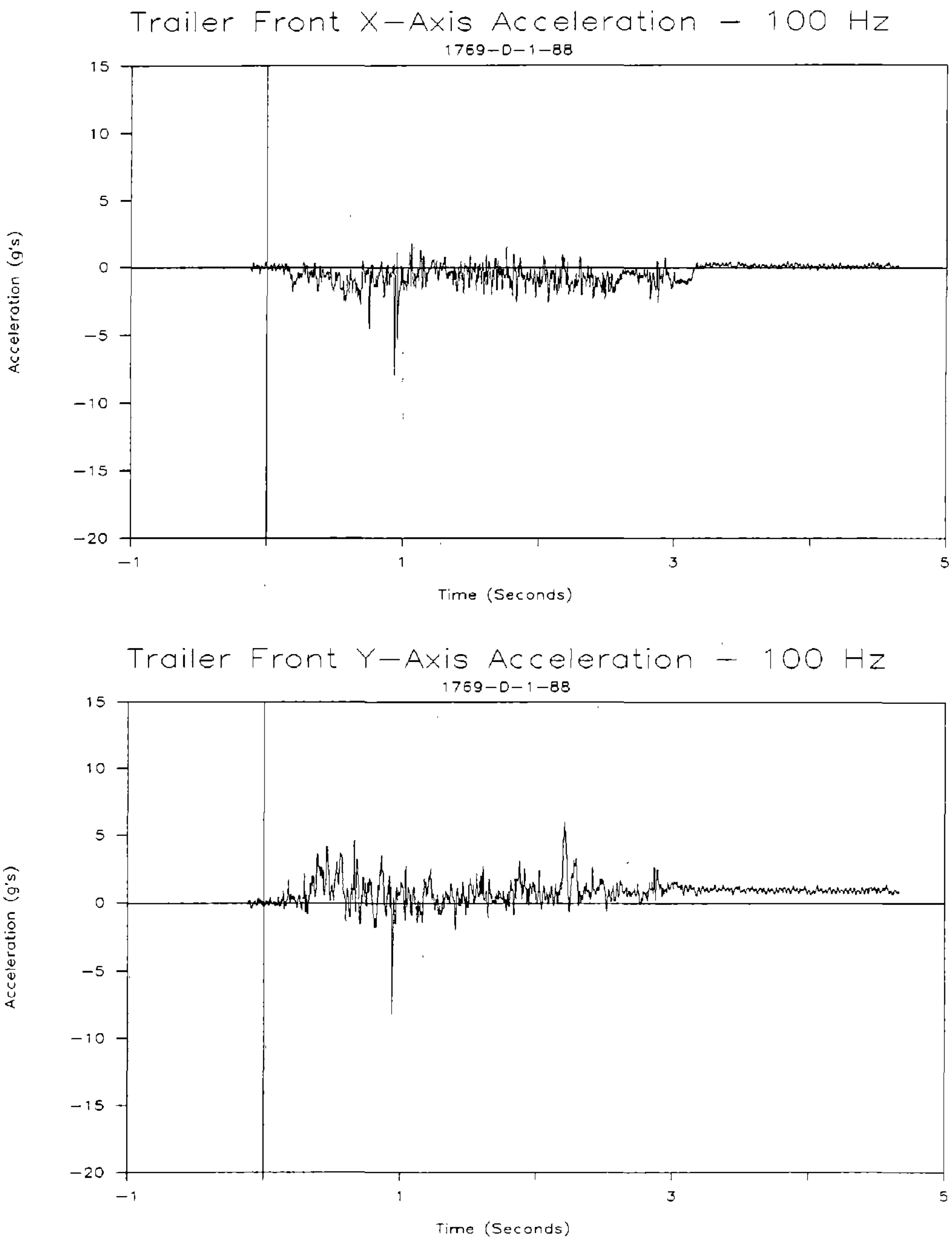
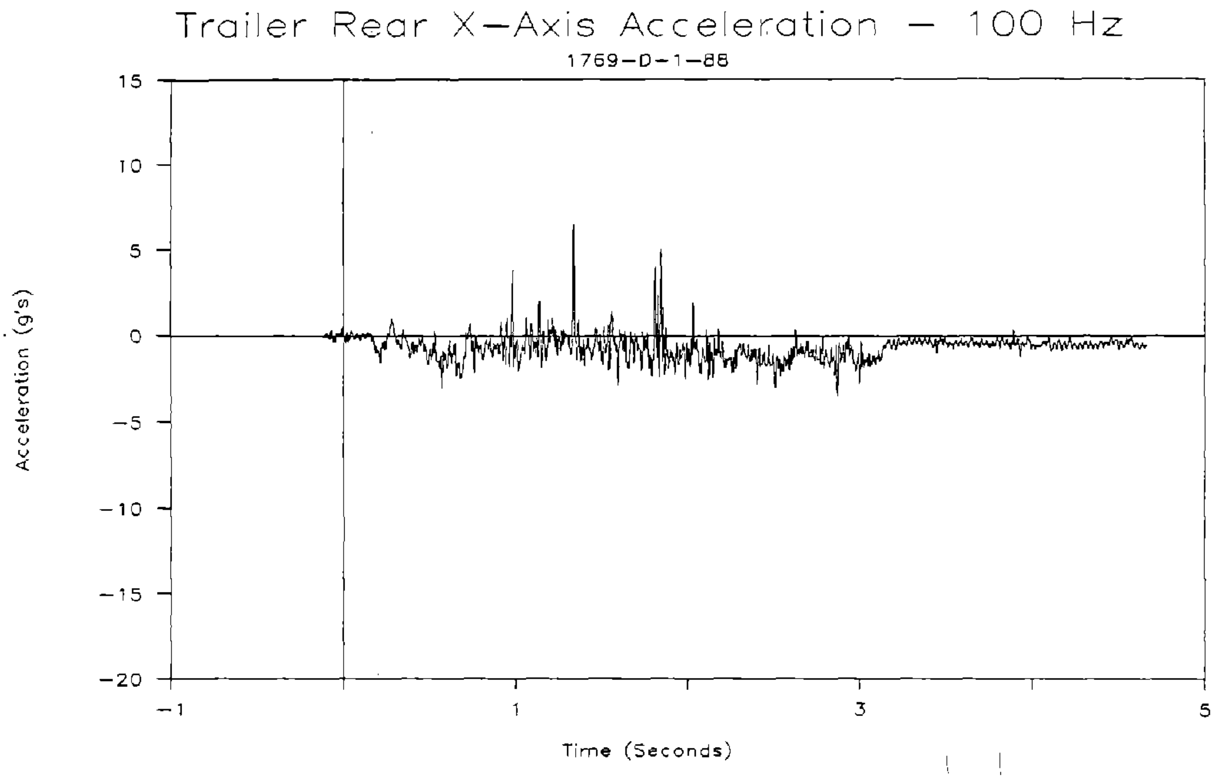


Figure 61. Trailer front acceleration, test 1769-D-1-88.



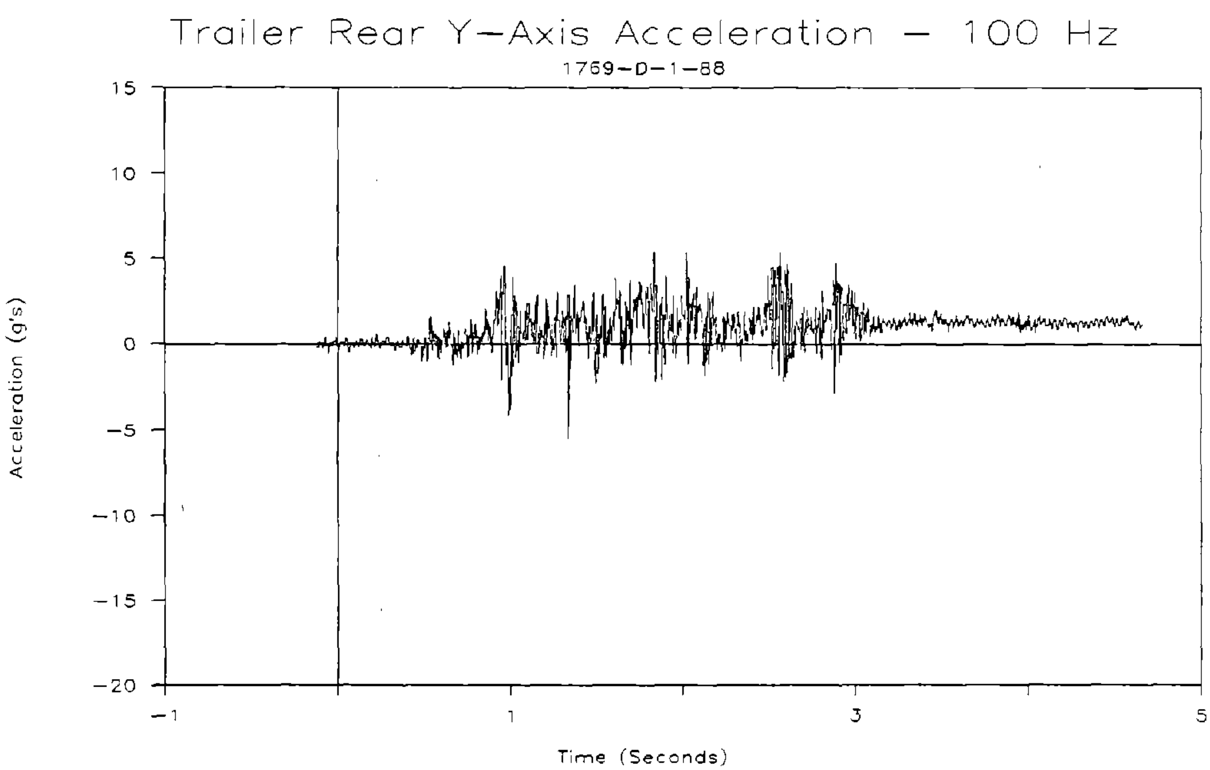


Figure 62. Trailer rear acceleration, test 1769-D-1-88.

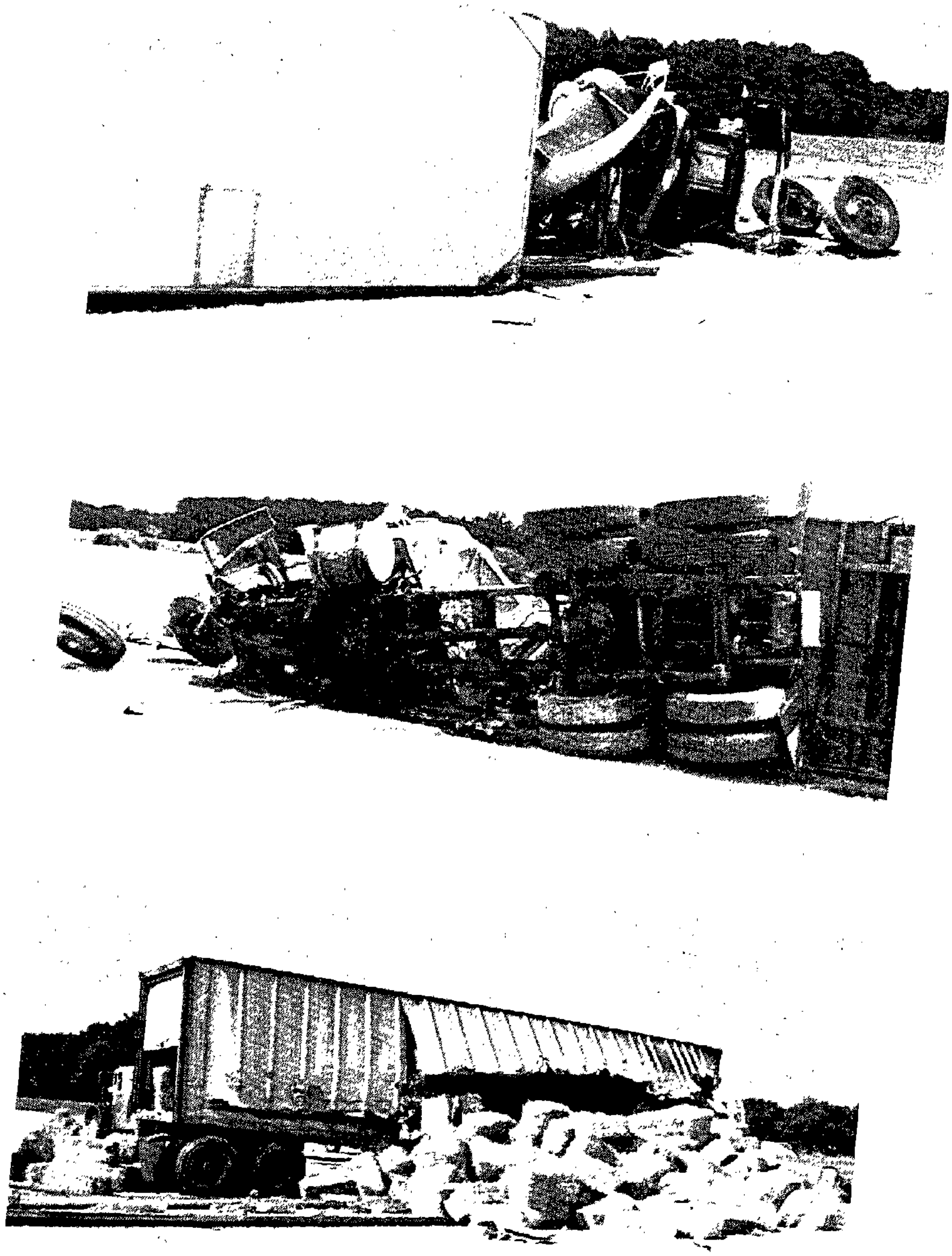


Figure 63. Posttest photographs of test vehicle, test 1769-D-1-88.

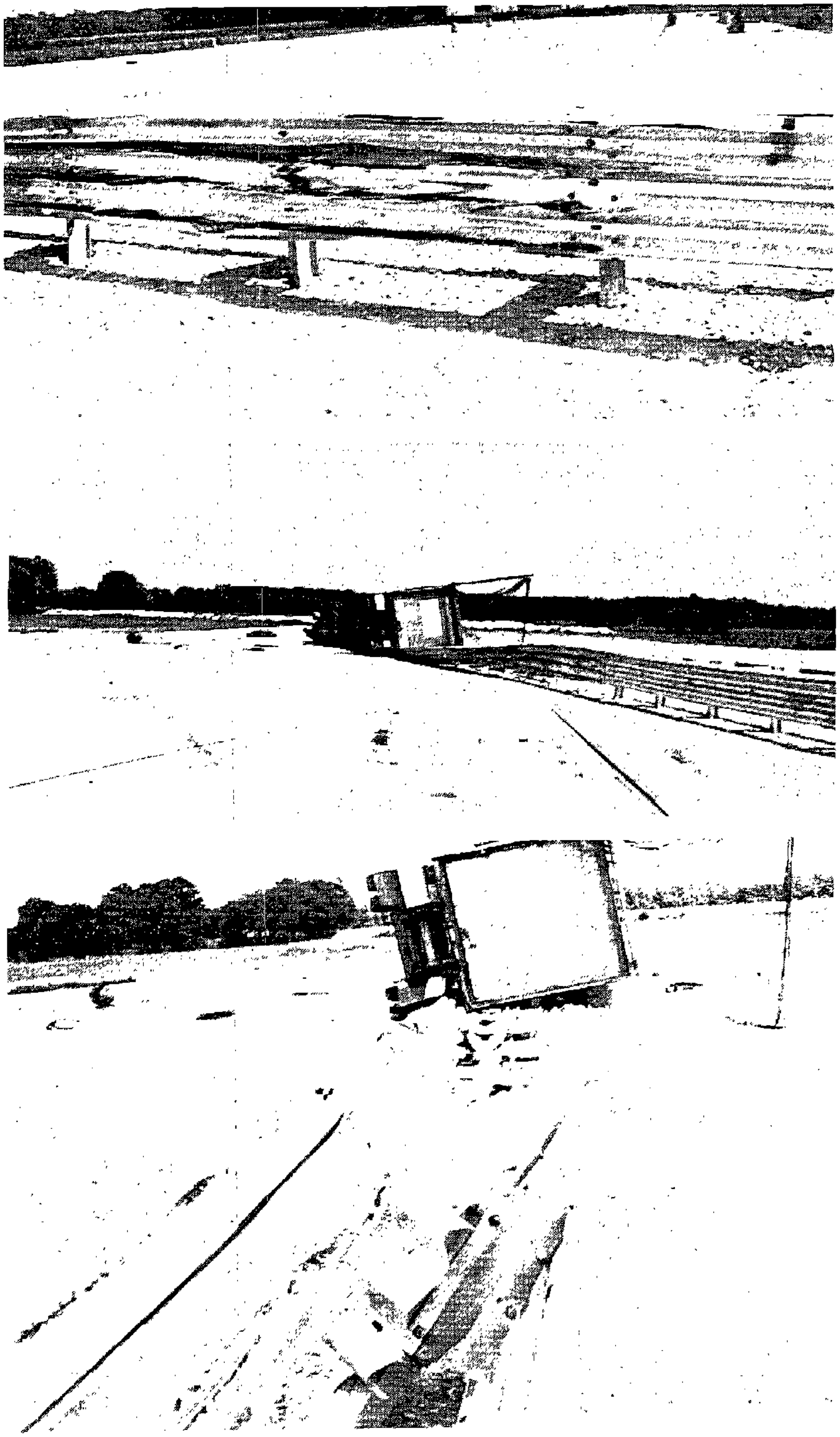


Figure 64. Posttest photographs of guardrail system, test 1769-D-1-88.

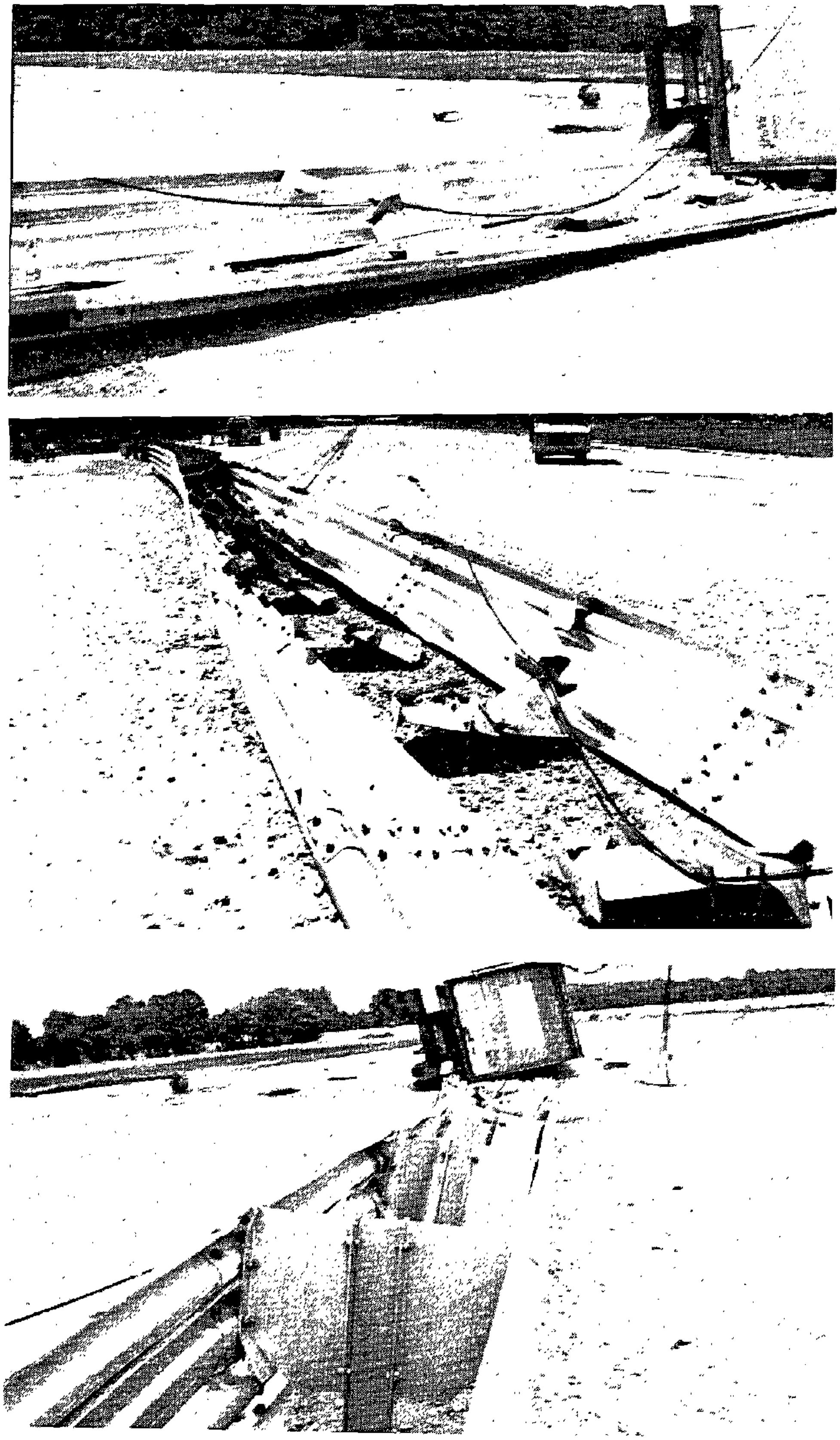


Figure 64. Posttest photographs of guardrail system, test 1769-D-1-88 (continued).

2. TEST 1769-D-2-88

a. Test Device

The test device was the modified thrie beam median barrier. The rail is 34 in high and features a 6-ft, 9.25-in W6x9 post embedded 46 in and 17-in W14x22 blockouts. The rail is attached to the block with one bolt and the block to the post with four bolts. Thrie beam backup plates are used at all nonsplice post locations. This rail is also known as the improved MB9 barrier.

The entire system was 218.75 ft long and consisted of 162.5 ft of modified thrie beam, 18.75 ft of transition to W beam and a 37.5-ft eccentric loader BCT. Three cable anchor assemblies were used (two on downstream ends, one on backside upstream end). These feature a 1.5-ft diameter, 5-ft deep cast-in-place concrete foundation, a 4.5-ft, 1.25-in diameter hook eye rod and a single-swaged 0.75-in cable. The rod is cast in the foundation and the cable is attached to the eye with cable clips. The threaded end anchors to the guardrail with a BCT anchor plate.

The entire system was installed in very well compacted (approximately 95%) NCHRP 230 S1 strong soil.

Figure 65 shows the test site and test device. Figure 66 shows pretest photographs of the modified thrie system.

b. Test Vehicle

The test vehicle was a 1975 International Loadstar 1600. The target vehicle weight was 18,000 lb. The vehicle weighed 11,971 lb empty. Straw and sand ballast weighing 6039 lb was added. The ballasted weight of the truck was 18,010 lb. X-axis, y-axis and z-axis accelerometers were mounted in the cab

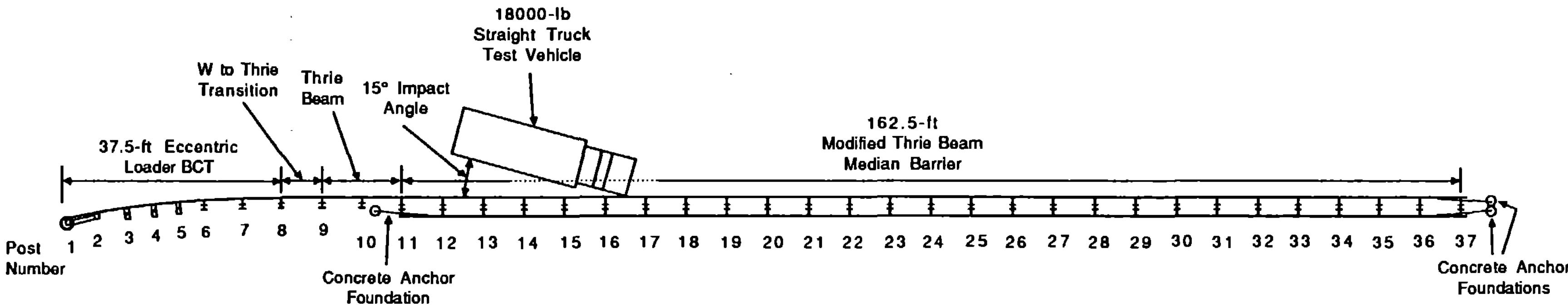


Figure 65. Test site layout, test 1769-D-2-88.

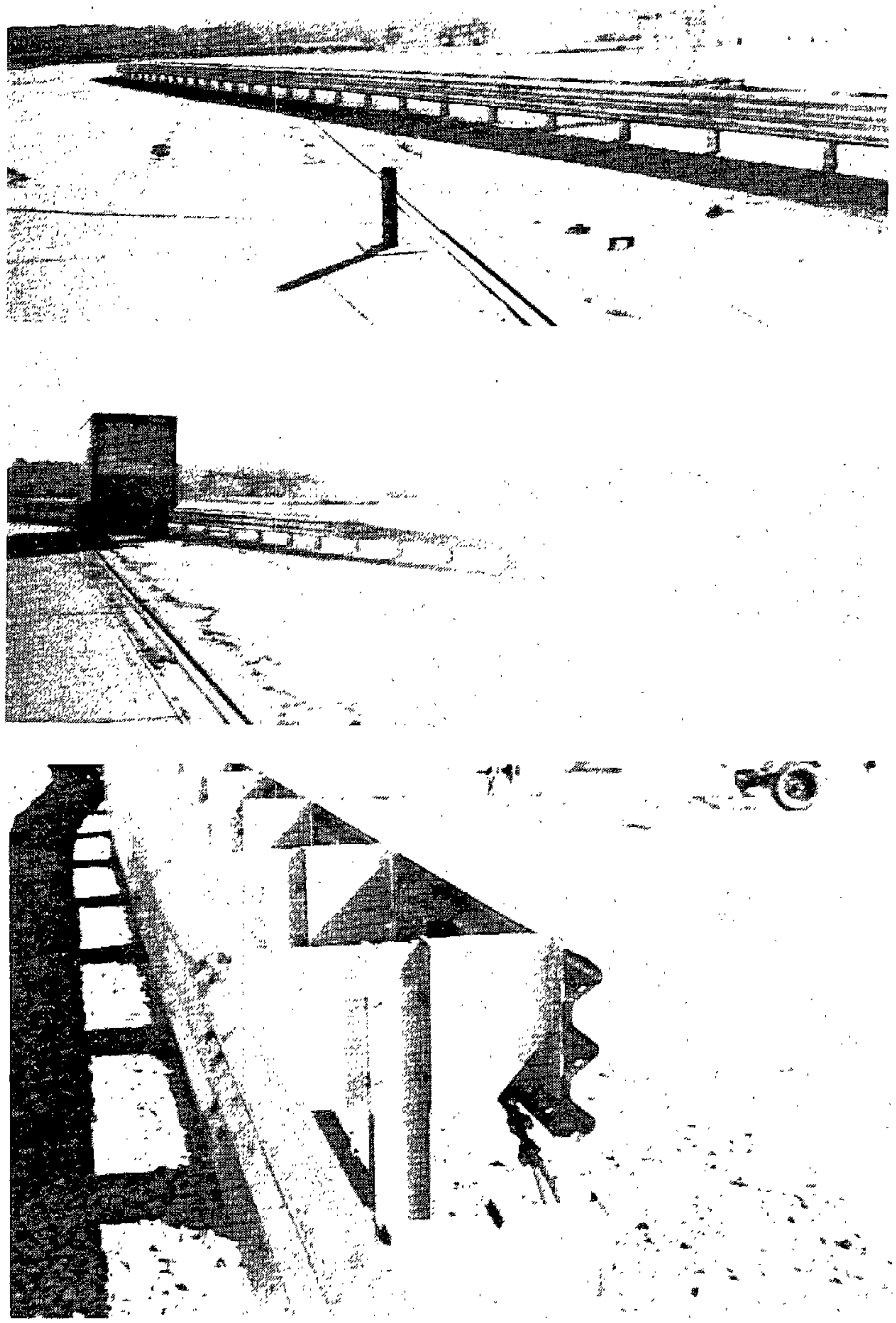


Figure 66. Pretest photographs of guardrail system, test 1769-D-2-88.

of the truck along with roll and yaw rate gyros. Pretest photographs of the test vehicle are shown in figure 67. Table 11 lists important parameters of the test truck.

Table 11. Truck parameters.

Item	Actual	Specification
Empty Weight	11,971 lb	n/a
Ballast	6039 lb	n/a
Total Weight	18,101 lb	18,000 lb
H_{cg}	49.3 in	49 ± 1 in
A (front to cg)	12.8 ft	12.8 ± 0.2 ft

Truck Length	29 ft, 8 in
Truck Wheelbase	18 ft, 1 in
Wheel/Tire Size	11R22.5
Truck Box Size	20 ft long by 8 ft high by 7.5 ft wide
Ground to top of box	11 ft, 6.5 in

c. Impact Description

Review of the high-speed films and speed trap data indicated that the test vehicle impacted at 51.0 mi/h and 15 degrees. This review also indicated that the right corner of the vehicle impacted the rail 6 in downstream of the desired point.

Upon impact, the vehicle penetrated into the rail approximately 2 ft. Posts in the impact area bent because of the penetration and the rail was pushed toward the back side. The truck started to roll toward the rail as it was redirected. It rolled over to approximately 45 degrees before rolling back to the upright position. The vehicle came to rest on all four tires 12.5 ft from the end of the barrier system. A summary of test conditions and results are shown in figure 68.

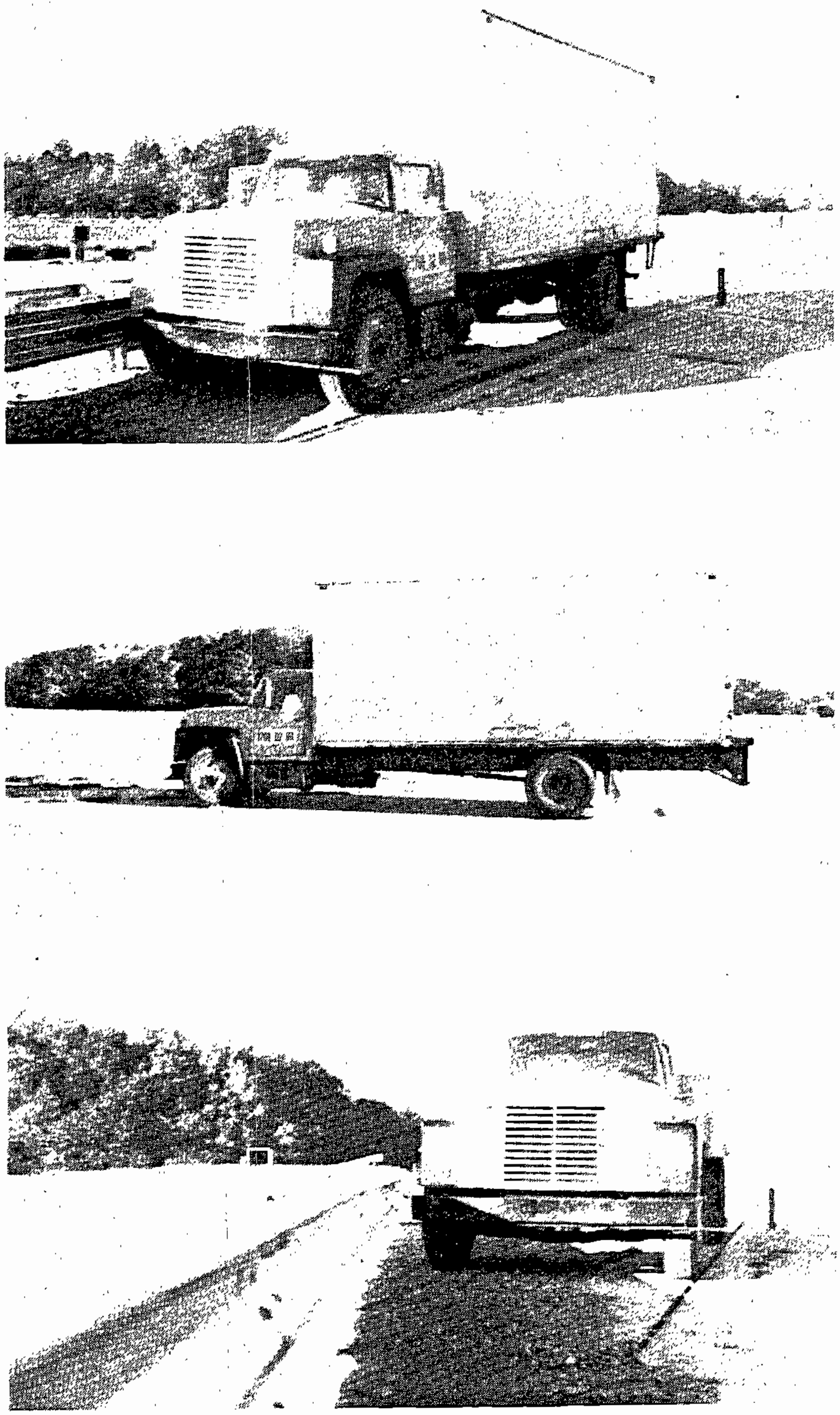
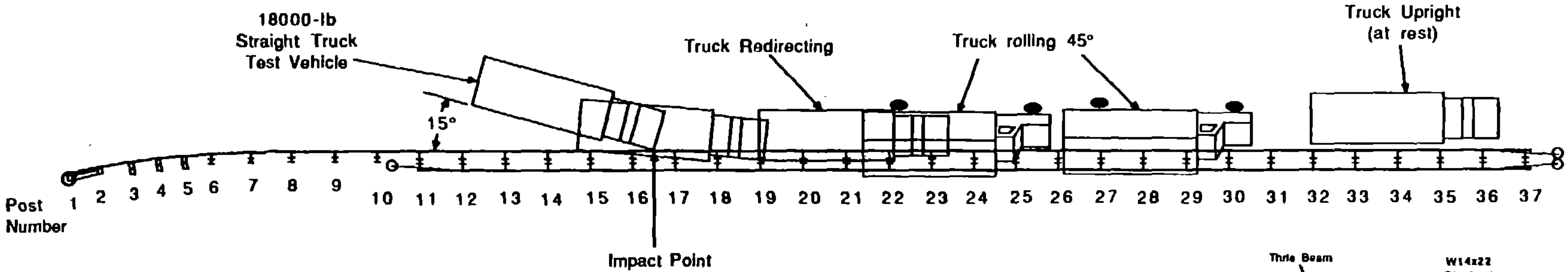
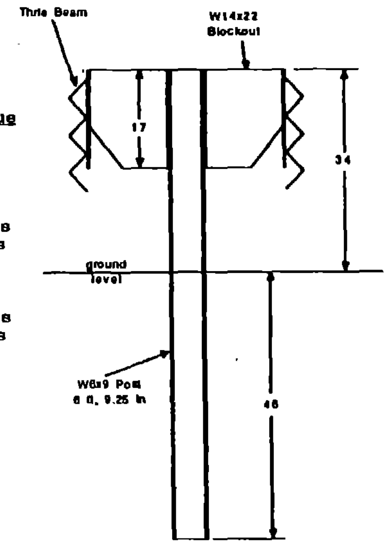


Figure 67. Pretest photographs of test vehicle, test 1769-D-2-88.





Date: 27 October 1988
Weather: Clear 60° F

Test Vehicle: 1975 International Loadstar 1600

Device Configuration: Modified Thrie Beam Median Barrier, 219 ft total length, 34 in high, Thrie beam on W14x22 blockouts, 162.5 ft of Modified Thrie beam, 18.75 ft of transition to W-beam, 37.5-ft Eccentric Loader BCT

1. Vehicle Weight:
   - Planned: 18000
   - Actual: 18010
2. Number of Occupants: None
3. Occupant Model: n/a
4. Occupant Location: n/a
5. Impact:

	Speed	Angle (a)	Location
Planned:	50.0 mi/h	15°	Midspan posts 16 and 17
Actual:	51.0 mi/h	15°	6 in downstream of desired point

   Tolerances: Speed: -1.0, +2.5 mi/h
   Angle: -1.0, +2.5 degrees

6. Redirection Angle: 1 degree
7. Redirection Speed: 20.9 mi/h (30.7 ft/s)
8. Total Speed Change: 30.1 mi/h (44.1 ft/s)
9. Total Momentum Change: 24,666 lb-sec
10. Vehicle Damage Index: (SAE J224a) n/a
11. NCHRP 230 Test Number: Special

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-13.6 ft/s	30/40 ft/s
Ridedown Acceleration:	-5.4 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	14.2 ft/s	20/30 ft/s
Ridedown Acceleration:	8.1 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-5.7 g's	
Lateral:	3.8 g's	

14. Vehicle-Railing Interaction Coefficient of Friction:

$$mu = \frac{\text{Cos theta} - V_p/V}{\text{Sin theta}}$$

mu	assessment
0.93	marginal

15. Test Results Conclusion: (evaluated using June 1, 1988 revision of "AASHTO Standard Specifications for Highway Bridges")

The vehicle was contained by the test article. There were no detached elements. Integrity of the passenger compartment was maintained. During redirection the vehicle rolled approximately 45 degrees before coming to rest on all four wheels. The vehicle was smoothly redirected. The vehicle-railing interaction friction was calculated as 0.93. The vehicle was redirected at an angle of 1 degree. The vehicle did not move 20 ft from the front face of the rail.

Figure 68. Test summary, test 1769-D-2-88.

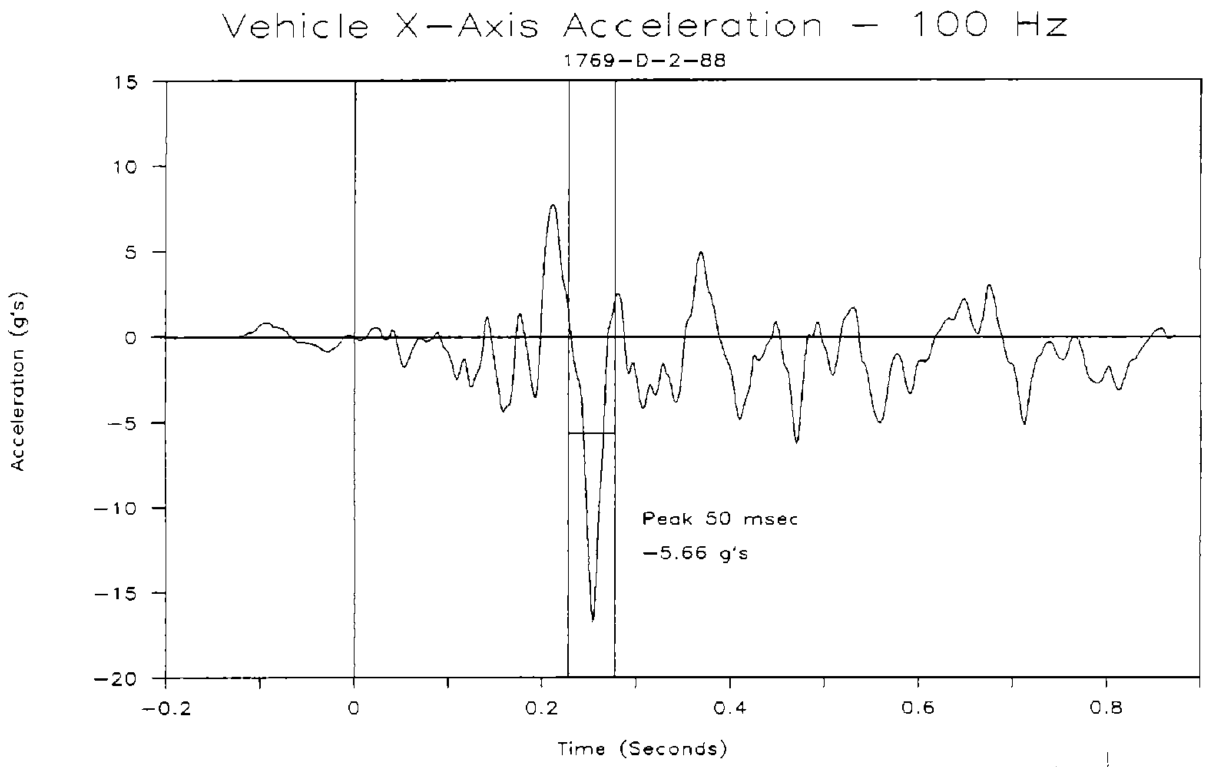
Data analysis was performed. The truck x-axis and y-axis, 100 Hz data plots are shown in figure 69.

d. Vehicle Damage

The chassis at the front of the truck was damaged and twisted. The hood came open and the front axle was torn from the frame and pushed into the truck. The rail side of the vehicle was damaged from impacting the rail, posts and blocks during the impact event. Posttest photographs of the truck are shown in figure 70.

e. Traffic Barrier Damage

The barrier was damaged from the impact point downstream six rail lengths (75 ft). Posts and blocks in this area were bent or deformed. The rail was detached from the blocks on the front side of the barrier for the 75 ft and pushed downward by the rolling truck. The rail was detached on the backside for 37.5 ft because of the bending and twisting of the posts and blocks. Posttest photographs of the rail are shown in figure 71.



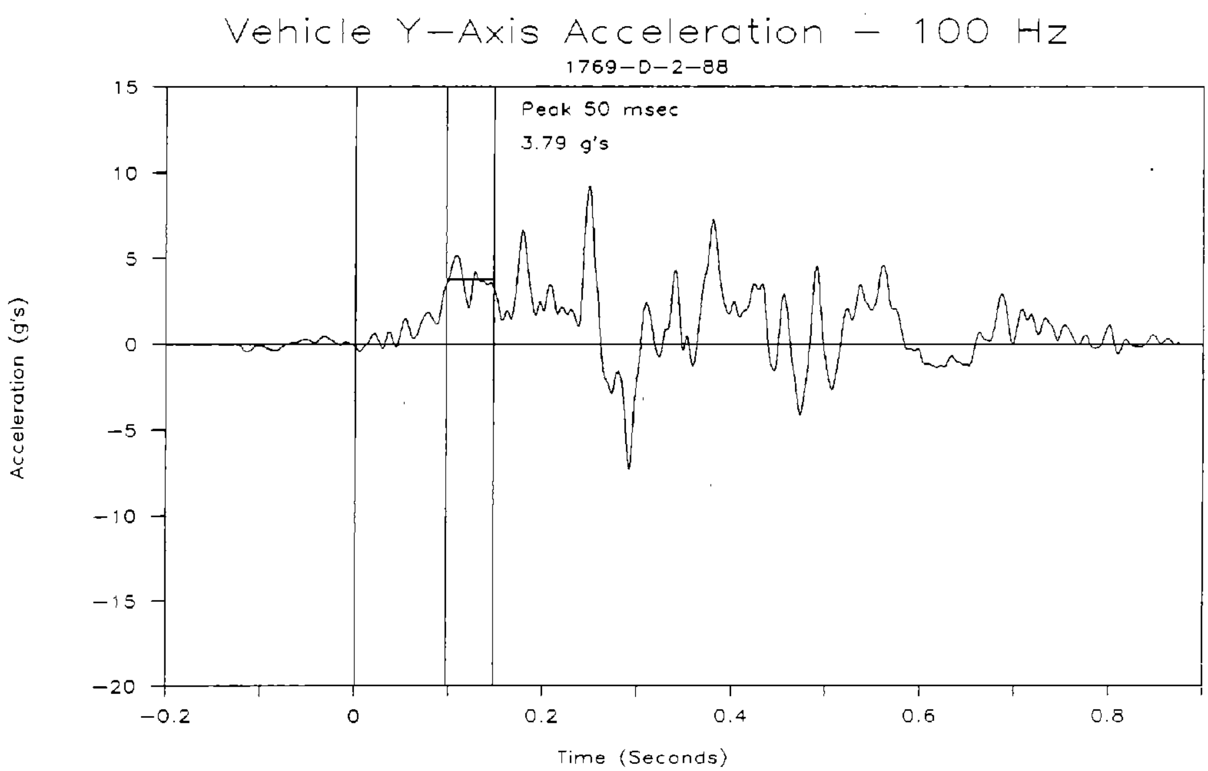


Figure 69. Vehicle acceleration, test 1769-D-2-88.

Figure 70. Posttest photographs of test vehicle, test 1769-D-2-88.

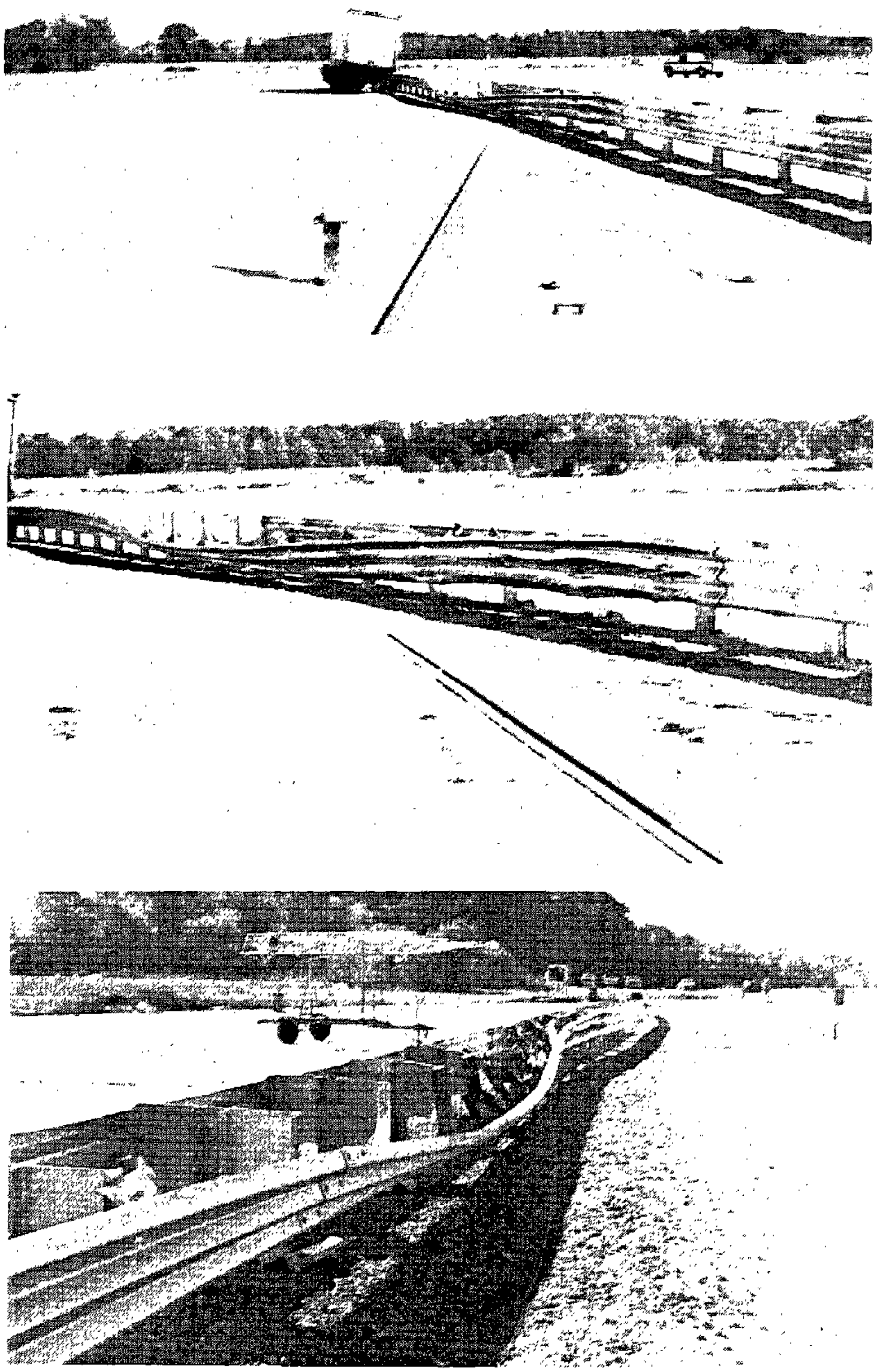


Figure 71. Posttest photographs of guardrail system, test 1769-D-2-88.

FULL-SCALE TESTS OF IOWA CONCRETE POST-RAIL SYSTEM

The purpose of this task was to full-scale test a bridge rail design from the State of Iowa. Two tests were originally planned. These tests were:

- 4500-lb, 60 mi/h, 25 degrees.
- 1800-lb, 60 mi/h, 20 degrees.

A third test was later added to test a modification designed to reduce snagging potential. This test was a rerun of the test 2. The following text describes the tests conducted under this task.

1. <u>TEST 1769-E-1-86</u>

a. Test Device

The test device was the Iowa bridge rail system. This system consists of two segments separated by an expansion joint. The half-deck and bridge rail were installed by a private contractor using 4200-lb/in^2 concrete throughout. Construction took place during August 1986. The deck was poured on August 6, 1986 and the rail was poured on August 7, 1986. Three test cylinders were poured. The crush strengths are given in table 12.

Table 12.
Crush strengths of test cylinders.

Crush Date	Strengths (lb/in^2)
August 21 (1 week)	4420
September 4 (4 weeks)	4510, 4420

Figure 72 shows the test site and test device. Figure 73 shows the Iowa system in various views. Figures 74 and 75

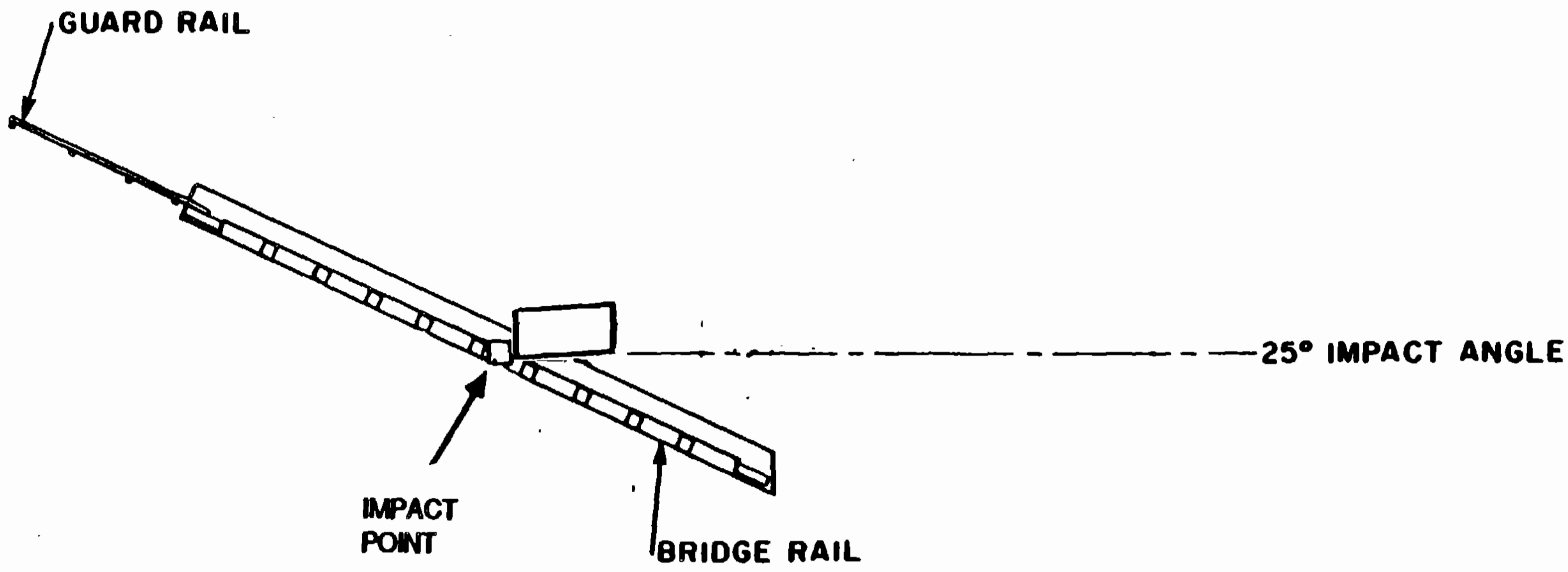


Figure 72. Test site layout, test 1769-E-1-86.

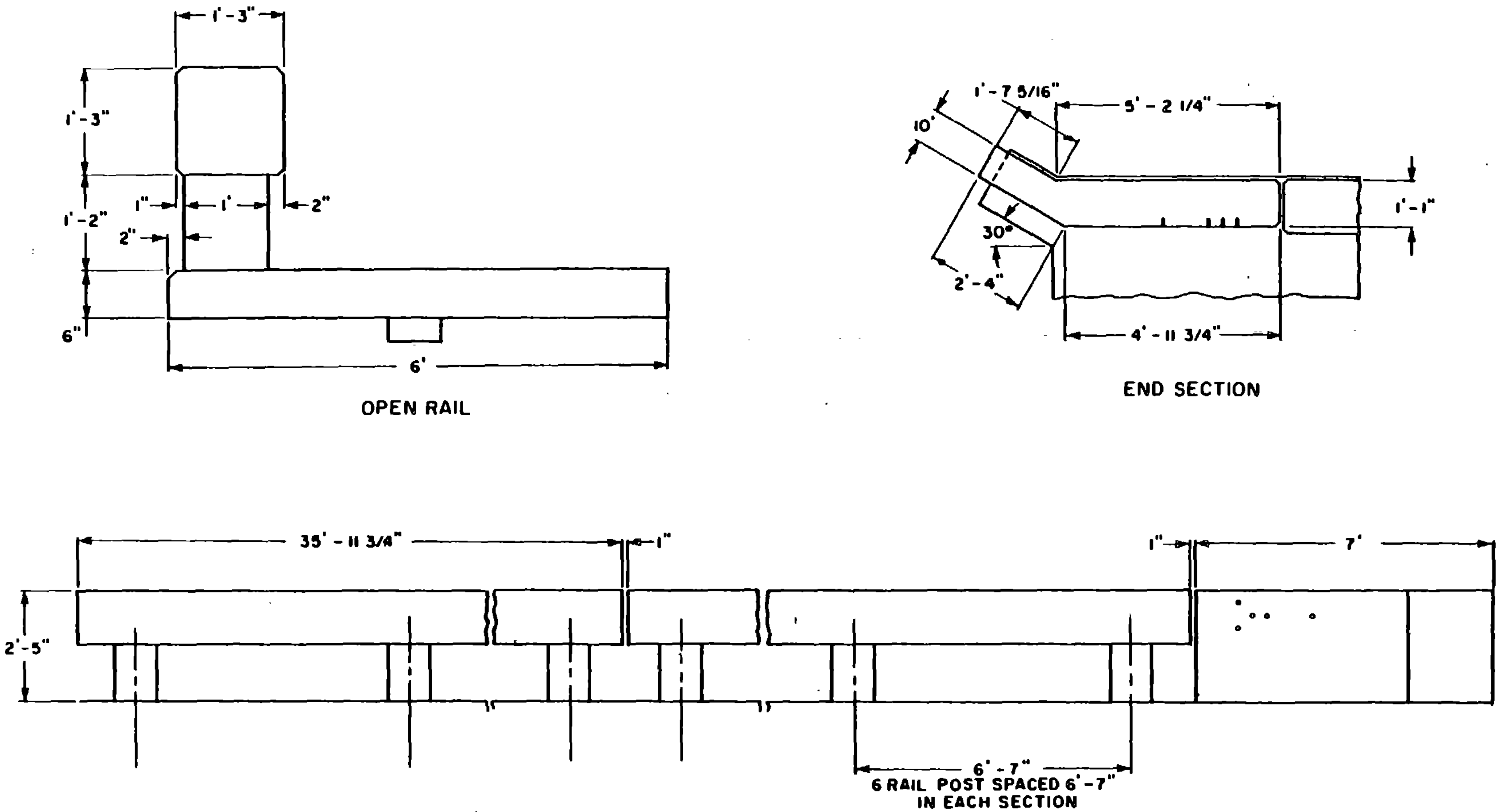


Figure 73. Iowa bridge rail system.

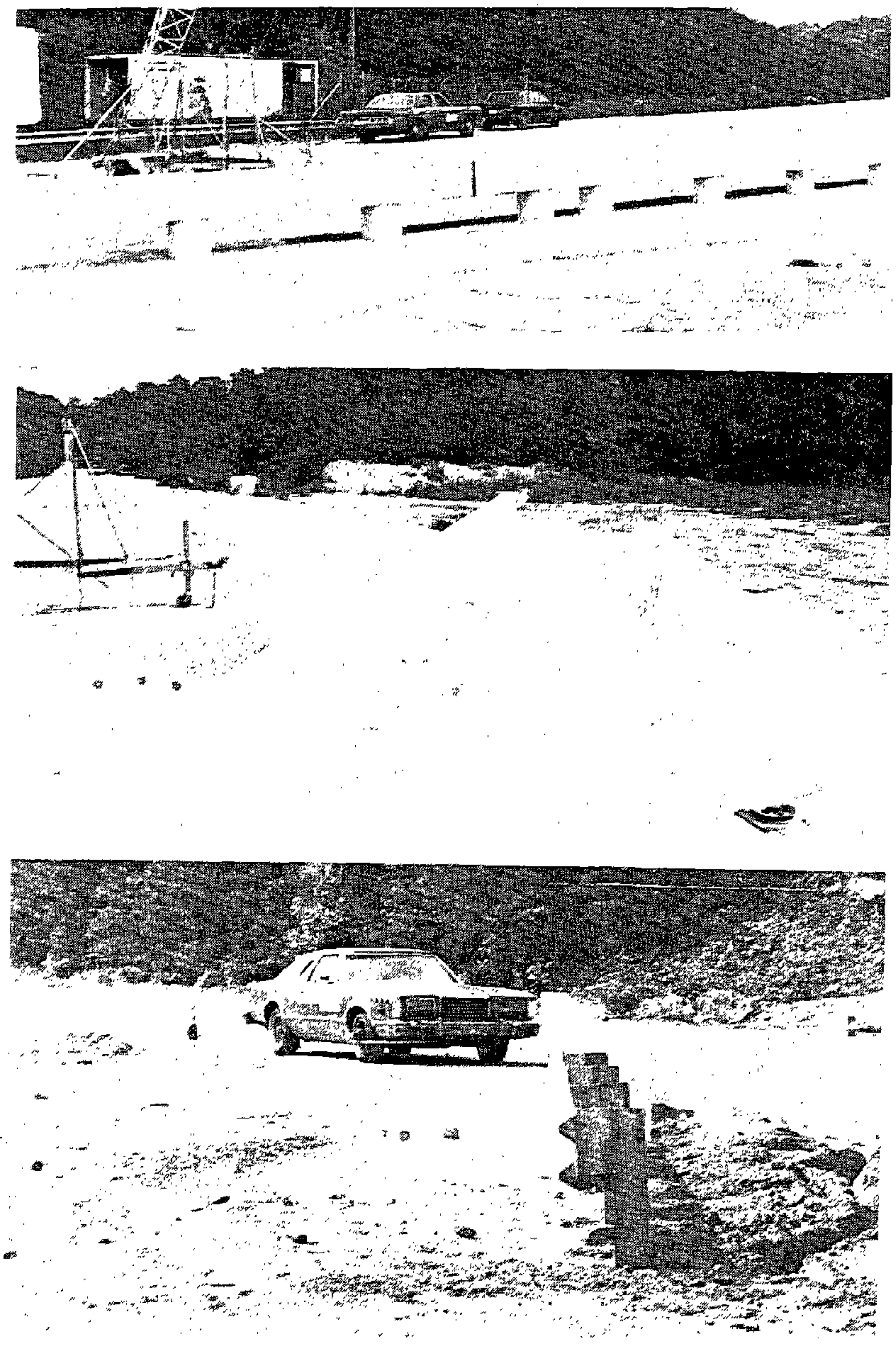


Figure 74. Pretest photographs of Iowa bridge rail system, test 1769-E-1-86.

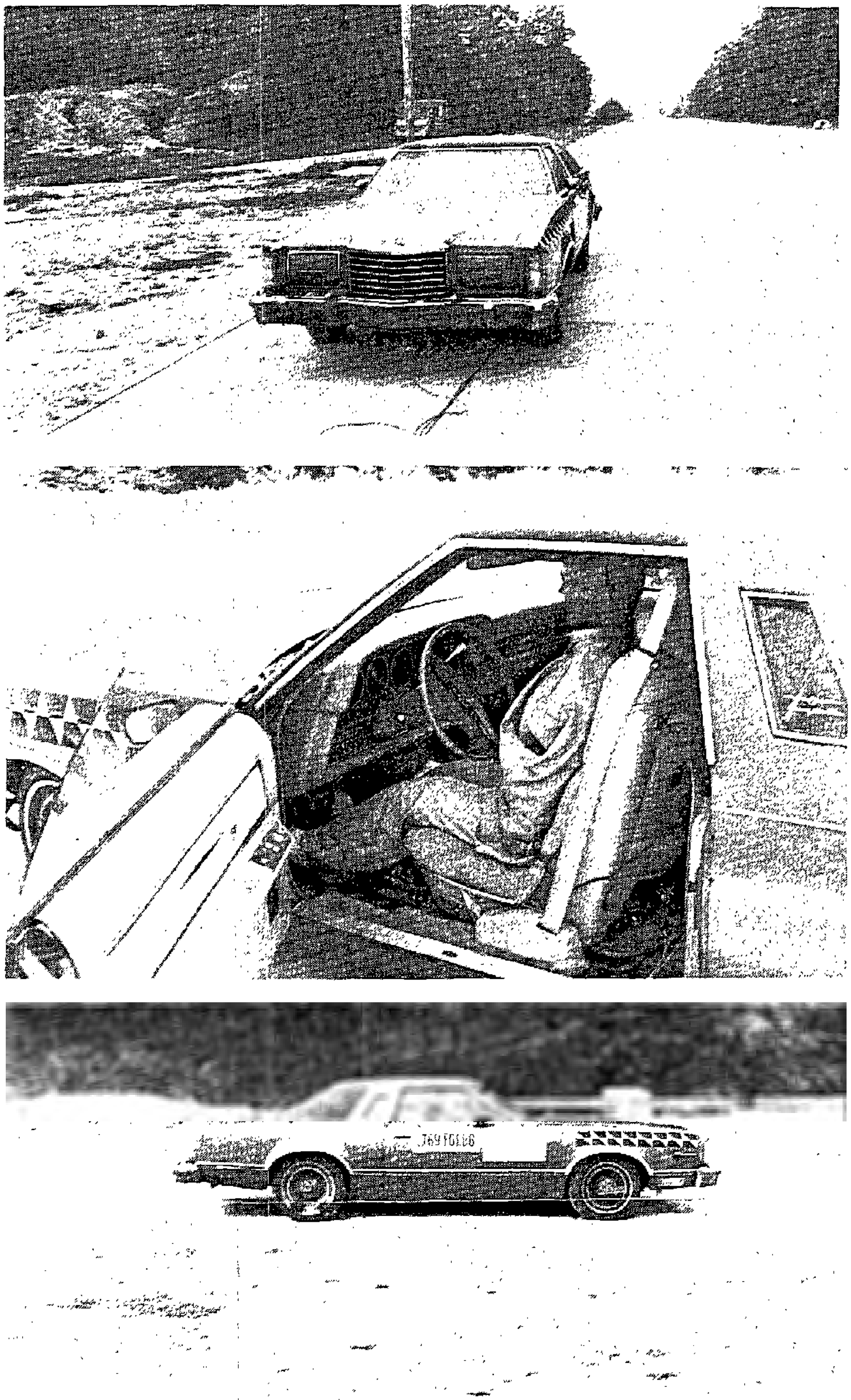


Figure 75. Pretest photographs of test vehicle, test 1769-E-1-86.

show pretest photographs of the Iowa bridge rail system and test vehicle.

b. Impact Description

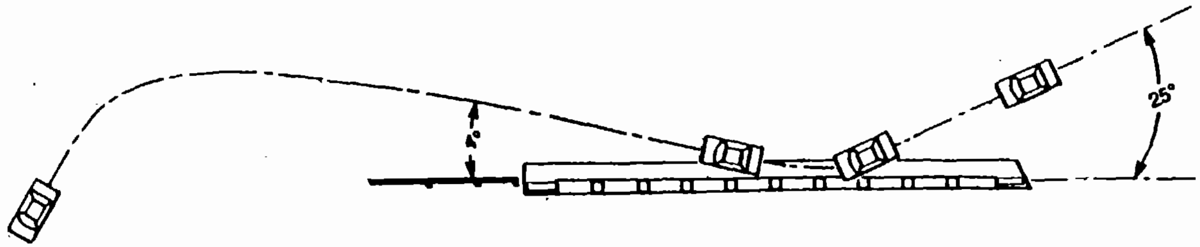
Review of the high-speed films, fifth wheel and speed trap data indicated that the test vehicle impacted at 25 degrees and 58.5 mi/h. This review also indicated that the left corner of the vehicle impacted the rail 5 in upstream of the desired point. The vehicle remained in contact with the rail for approximately 11 ft. The vehicle was redirected at 48.7 mi/h and 4 degrees.

Upon impact, the front of the vehicle was deformed and skewed toward the nonimpact side. The bumper detached from the nonimpact side of the vehicle. The hood came loose as the front of the car was skewed. The driver's side front tire blew out upon impact with the first downstream post. The vehicle rear-end slapped hard against the rail. The vehicle then continued downstream.

After the impact, the vehicle rolled slightly to the impact side and pitched forward. The rear passenger side wheel left the ground. After redirection, the vehicle continued downstream for 137 ft before stopping. The brakes were applied 70 ft after impact. A summary of test conditions and results is shown in figure 76.

Inside the vehicle, it was observed that the dummy slid and impacted the driver's side window. The dummy's upper body was out of the window and its nearly scraped the top of the rail. The dummy came to rest leaning on the driver's side door.

Data analysis was performed and the vehicle x-axis and y-axis, 100 Hz acceleration traces are shown in figure 77.



Date:	11 September 1986
Weather:	Overcast, 80° F
Test Vehicle:	1978 Ford Thunderbird
Device Configuration:	Iowa Bridge Rail, 75 ft long, 6 ft wide deck, 6 ft, 7 in post spacing Post: 12 in by 12 in Rail: 15 in by 15 in, 14 in from bottom of rail to deck

1. Vehicle Weight:

	Test Inertial	Gross
Planned:	4500 ± 200	4500 ± 300
Actual:	4506	4662

2. Number of Occupants: One
3. Occupant Model: Anthropomorphic Dummy, 50th%, male
4. Occupant Location: Driver Seat, Unrestrained
5. Impact:

	Speed	Angle (a)	Location
Planned:	60.0 mi/h	25°	Midway between posts
Actual:	58.5 mi/h	25°	Midway between posts

6. Redirection Angle: 4 degrees
7. Redirection Speed: 48.7 mi/h (71.4 ft/s)
8. Total Speed Change: 9.8 mi/h (14.4 ft/s)
9. Total Momentum Change: 2085 lb-s
10. Vehicle Damage Index: (SAE J224a) 10LFEW2
11. NCHRP 230 Test Number: 10
12. Impact Severity:

$$\frac{m(V \sin a)^2}{2}$$ 92.0 kip-ft (Spec: 88 to 114 kip-ft)

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-23.3 ft/s	30/40 ft/s
Ridedown Acceleration:	-3.4 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-34.7 ft/s	20/30 ft/s
Ridedown Acceleration:	-11.1 g's	15/20 g's
Delta-V at 0.67 ft (actual):	-24.4 ft/s	20/30 ft/s
Ridedown Acceleration:	-34.9 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-9.5 g's	
Lateral:	-18.0 g's	

14. Test Results Conclusion: Meets all NCHRP 230 criteria.

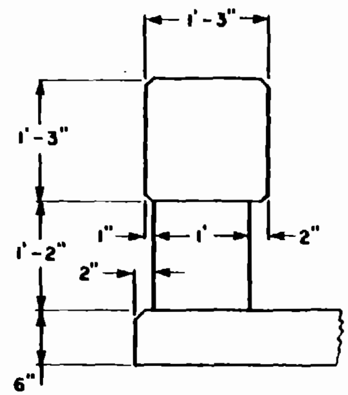
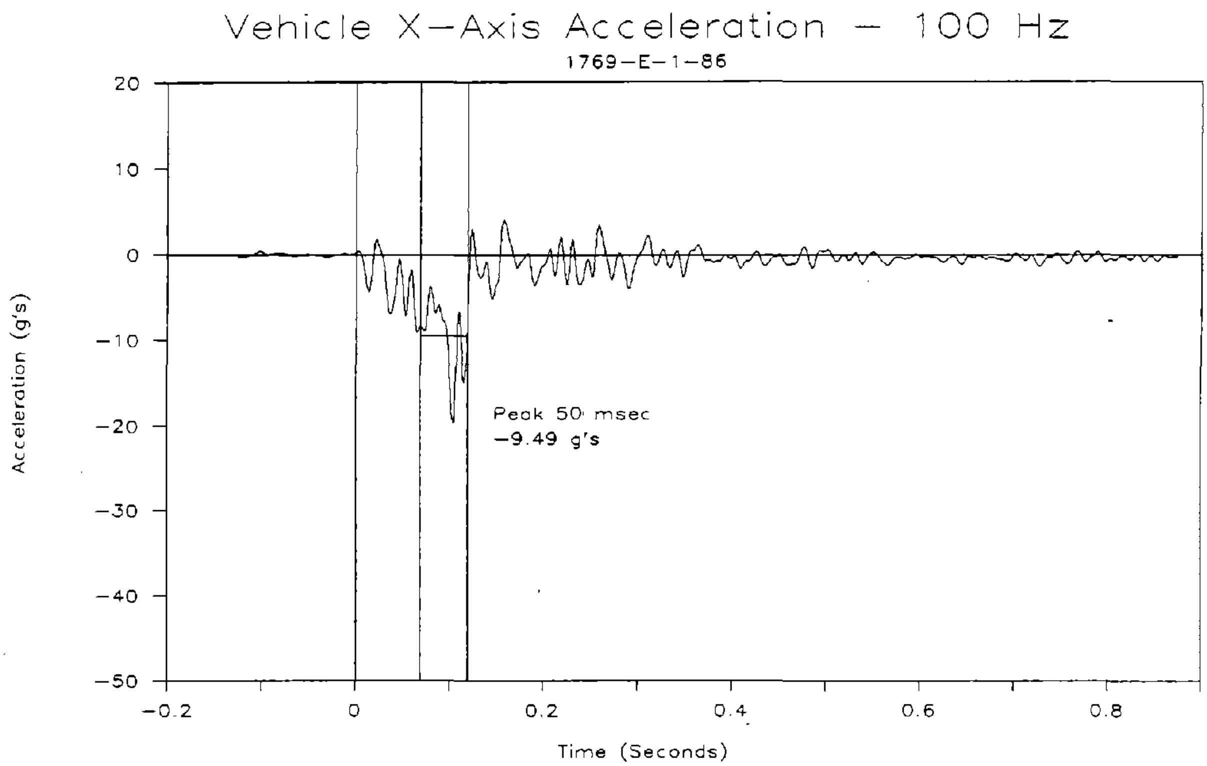


Figure 76. Test summary, test 1769-E-1-86.



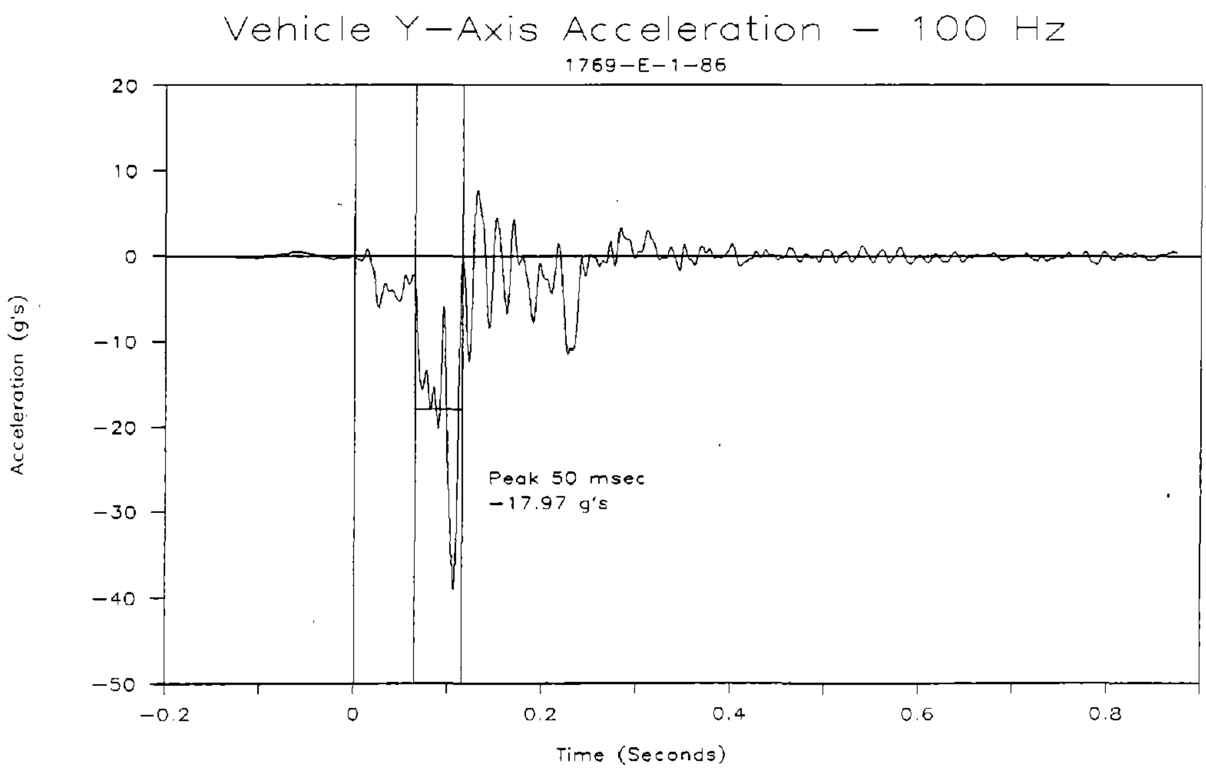


Figure 77. Vehicle acceleration, test 1769-E-1-86.

c. Vehicle Damage

The entire left side of the vehicle was damaged, but damage occurred mainly to the left front fender and left front wheel. Posttest photographs of the vehicle are shown in figure 78.

d. Traffic Barrier Damage

The Iowa bridge rail system performed as designed. No structural damage was observed. Hairline cracks were observed in two locations on the rail and in one location on the deck. The cracks on the deck were behind the last post in the first segment of the rail (the post next to the expansion joint). Minor abrasions were evident. Posttest photographs are shown in figure 79. Photographs of the cracks are shown on page 127. All the cracks have been highlighted with a magic marker.

2. TEST 1769-E-2-86

a. Test Device

The test device was the Iowa bridge rail system. Figure 80 shows the test site and test device. Figures 81 and 82 show pretest photographs of the Iowa bridge rail system and test vehicle.

b. Impact Description

Review of the high-speed films, fifth wheel and speed trap data indicated that the test vehicle impacted at 19 degrees and 60.4 mi/h. This review also indicated that the left corner of the vehicle impacted the rail at the desired point. The vehicle remained in contact with the rail for approximately 8 ft. The first two posts downstream of impact were hit very hard as evidenced by the tire scrub on the front

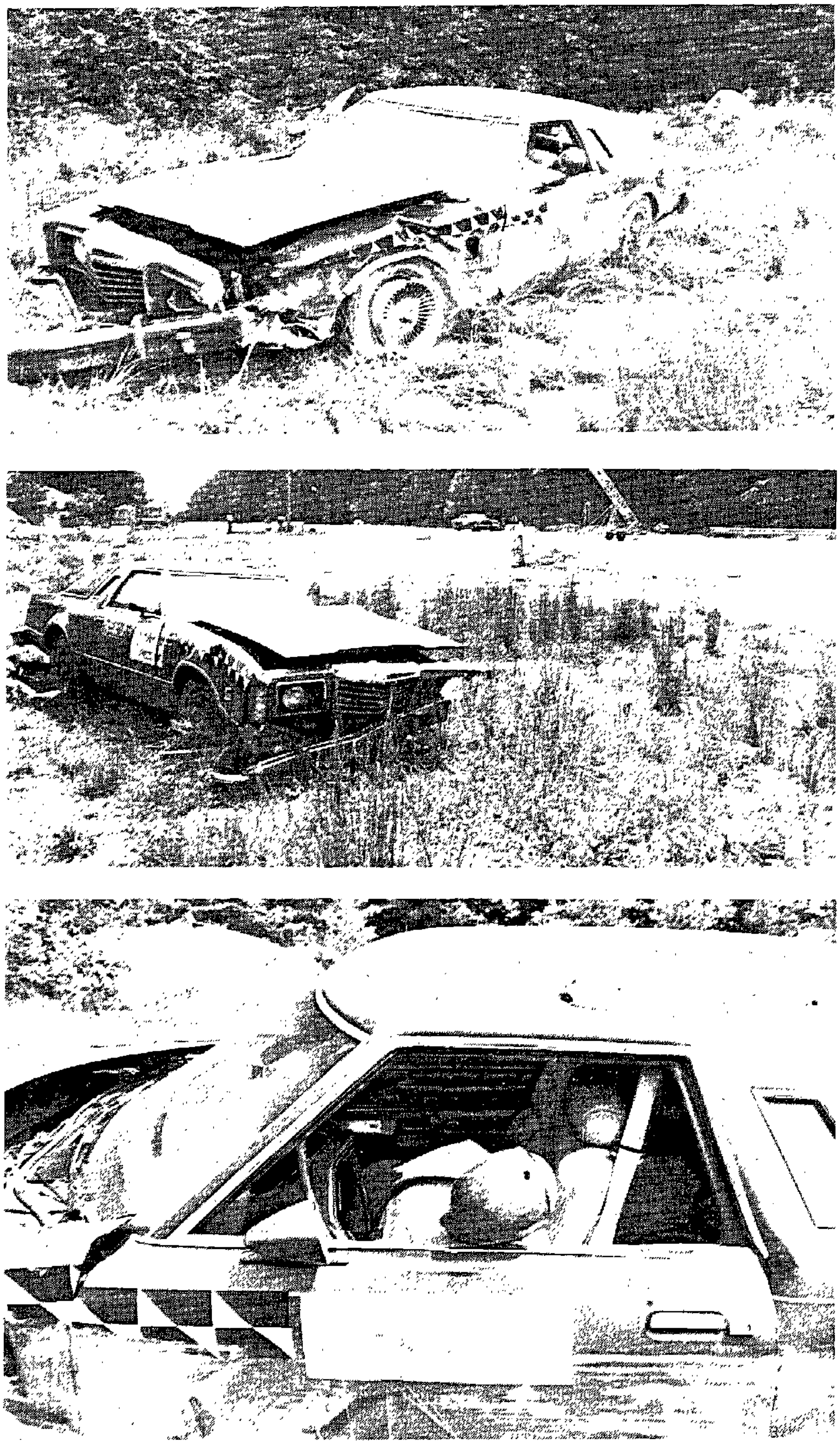


Figure 78. Posttest photographs of test vehicle, test 1769-E-1-86.

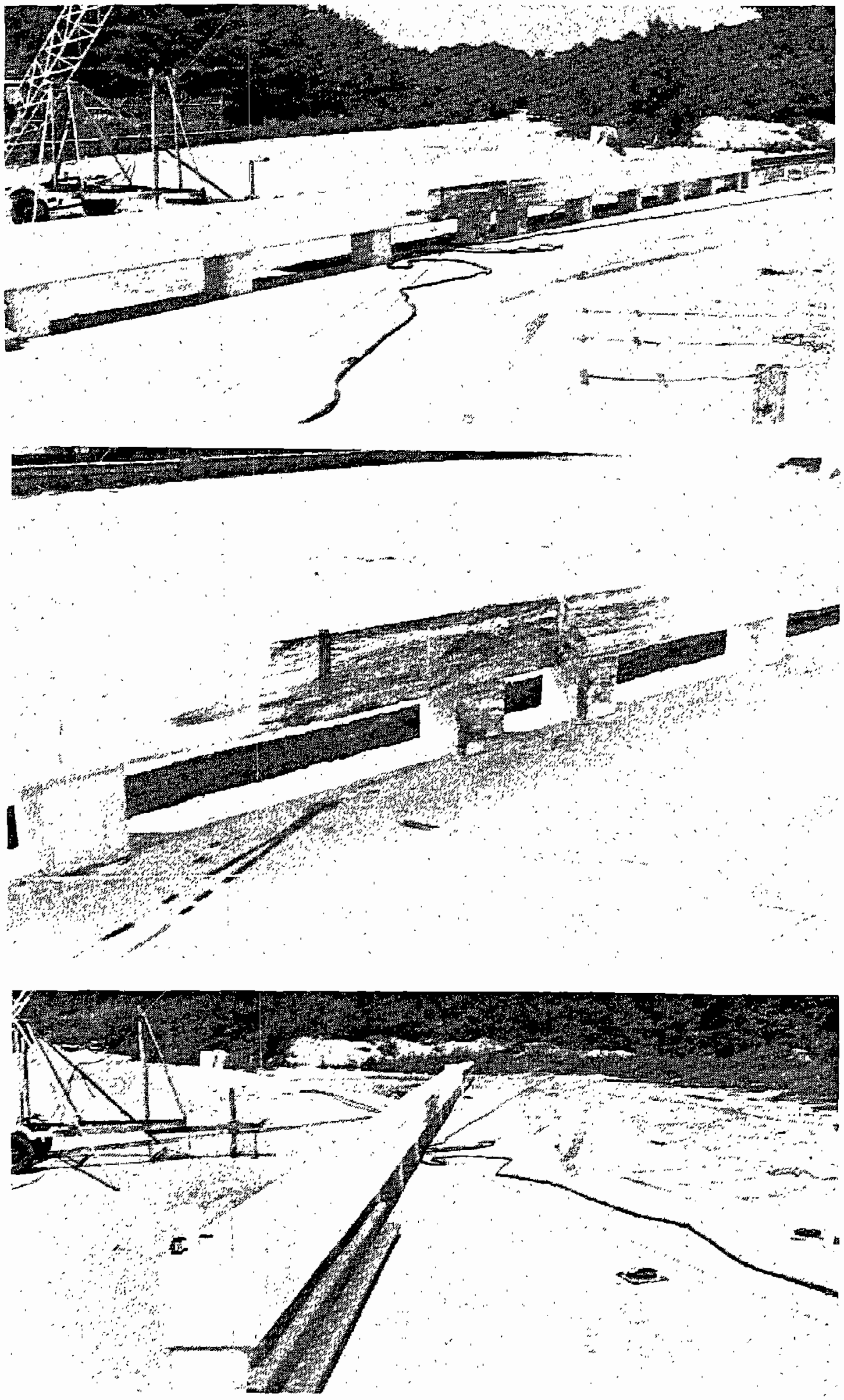


Figure 79. Posttest photographs of Iowa bridge rail system, test 1769-E-1-86.

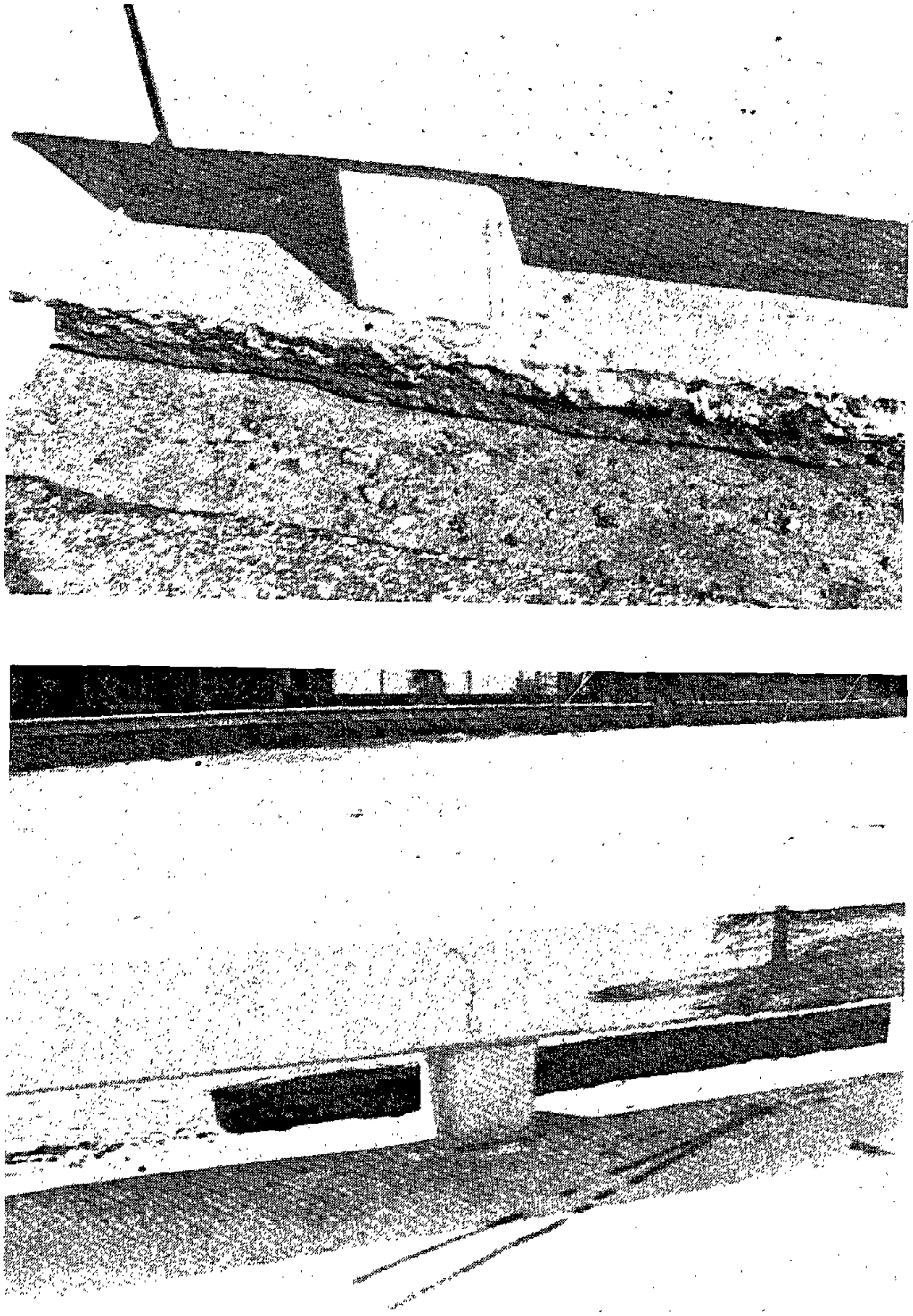


Figure 79. Posttest photographs of Iowa bridge rail system, test 1769-E-1-86 (continued).

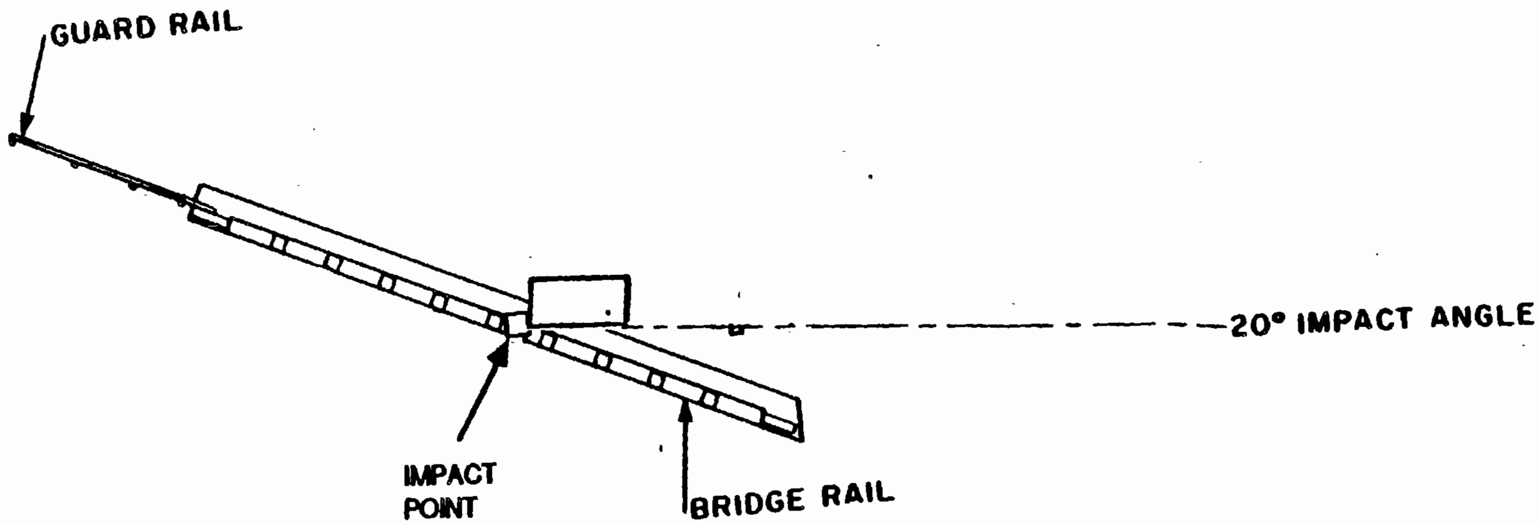


Figure 80. Test site layout, test 1769-E-2-86.

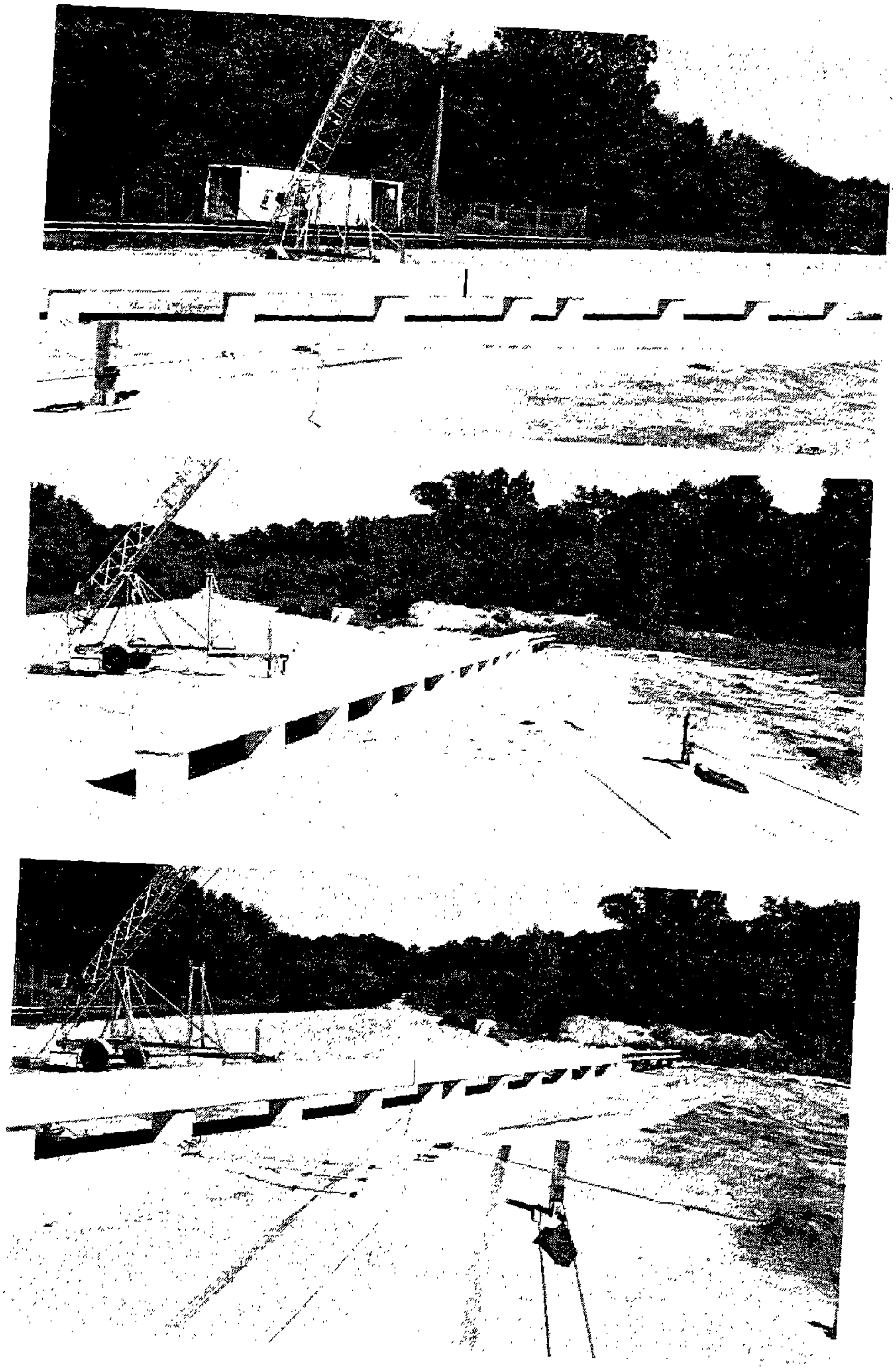


Figure 81. Pretest photographs of Iowa bridge rail system, test 1769-E-2-86.

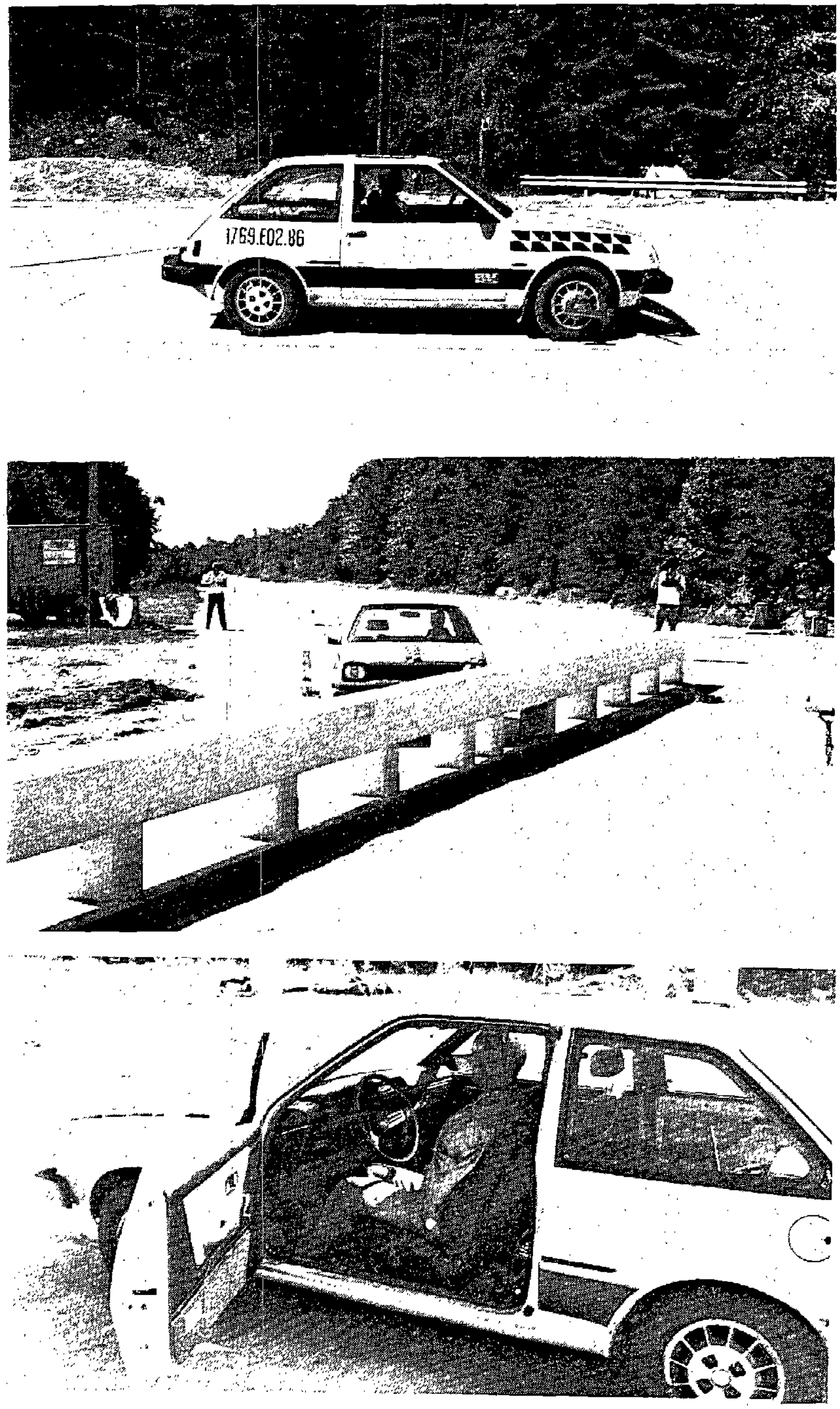


Figure 82. Pretest photographs of test vehicle, test 1769-E-2-86.

face of the posts. The vehicle was redirected at 48.7 mi/h and 6 degrees.

Upon impact, the front of the vehicle was deformed and skewed toward the nonimpact side. The driver's side front tire blew out upon impact with the first downstream post. The vehicle rear-end slapped against the rail and then continued downstream.

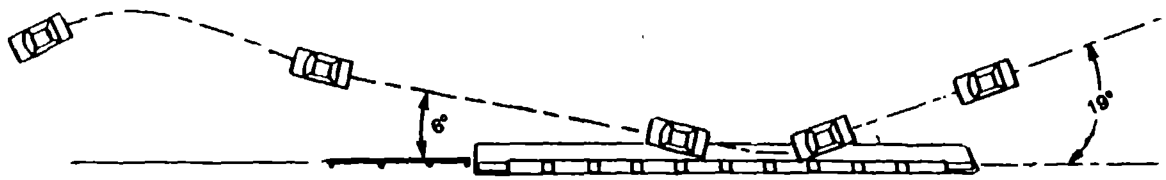
During the impact, the vehicle rolled toward the impact side and pitched forward. The rear wheels left the ground. After redirection, the vehicle continued downstream for 110 ft before stopping. The brakes were applied 70 ft after impact. A summary of the test conditions and results is given in figure 83.

Inside the vehicle it was observed that the dummy slid into the drivers door. The door buckled but did not come open. The dummy's head broke the driver's side window. During the impact the dummy had its upper body out of the window. The dummy came to rest leaning on the door with its head in the plane of the window.

Data analysis was performed and the vehicle x-axis and y-axis, 100 Hz acceleration traces are shown in figure 84.

c. Vehicle Damage

Almost all of the left side of the vehicle was damaged, but damage occurred mainly to the left front fender and left front wheel. Posttest photographs of the vehicle are shown in figure 85.



Date: 9 September 1986
Weather: Sunny, 75° F

Test Vehicle: 1980 Dodge Colt

Device Configuration: Iowa Bridge Rail, 75 ft long, 6 ft wide deck, 6 ft, 7 in post spacing
Post: 12 in by 12 in
Rail: 15 in by 15 in, 14 in from bottom of rail to deck

1. Vehicle Weight:

	Test Inertial	Gross
Planned:	1800 ± 50	1950 ± 50
Actual:	1842	2014

2. Number of Occupants: One

3. Occupant Model: Anthropomorphic Dummy, 50th%, male

4. Occupant Location: Driver Seat, Unrestrained

5. Impact:

	Speed	Angle (a)	Location
Planned:	60.0 mi/h	20°	Midway between posts
Actual:	60.4 mi/h	19°	Midway between posts

6. Redirection Angle: 6 degrees

7. Redirection Speed: 48.7 mi/h (71.4 ft/s)

8. Total Speed Change: 11.7 mi/h (17.2 ft/s)

9. Total Momentum Change: 1076 lb-s

10. Vehicle Damage Index: (SAE J224a) 10LFEW2

11. NCHRP 230 Test Number: S13

12. Impact Severity:

$\frac{m(V \sin a)^2}{2}$ 23.8 kip-ft (Spec: 23 to 29 kip-ft)

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-25.5 ft/s	30/40 ft/s
Ridedown Acceleration:	-4.0 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-31.9 ft/s	20/30 ft/s
Ridedown Acceleration:	-11.1 g's	15/20 g's
Delta-V at 0.54 ft (actual):	-28.2 ft/s	20/30 ft/s
Ridedown Acceleration:	-22.5 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-12.3 g's	
Lateral:	-18.3 g's	

14. Test Results Conclusion: Meets all NCHRP 230 criteria.

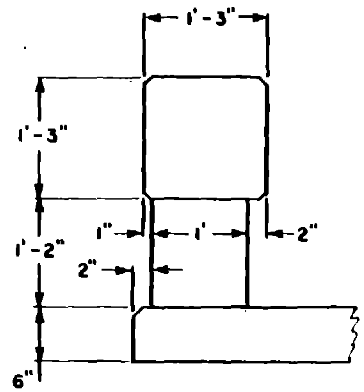


Figure 83. Test summary, test 1769-E-2-86.

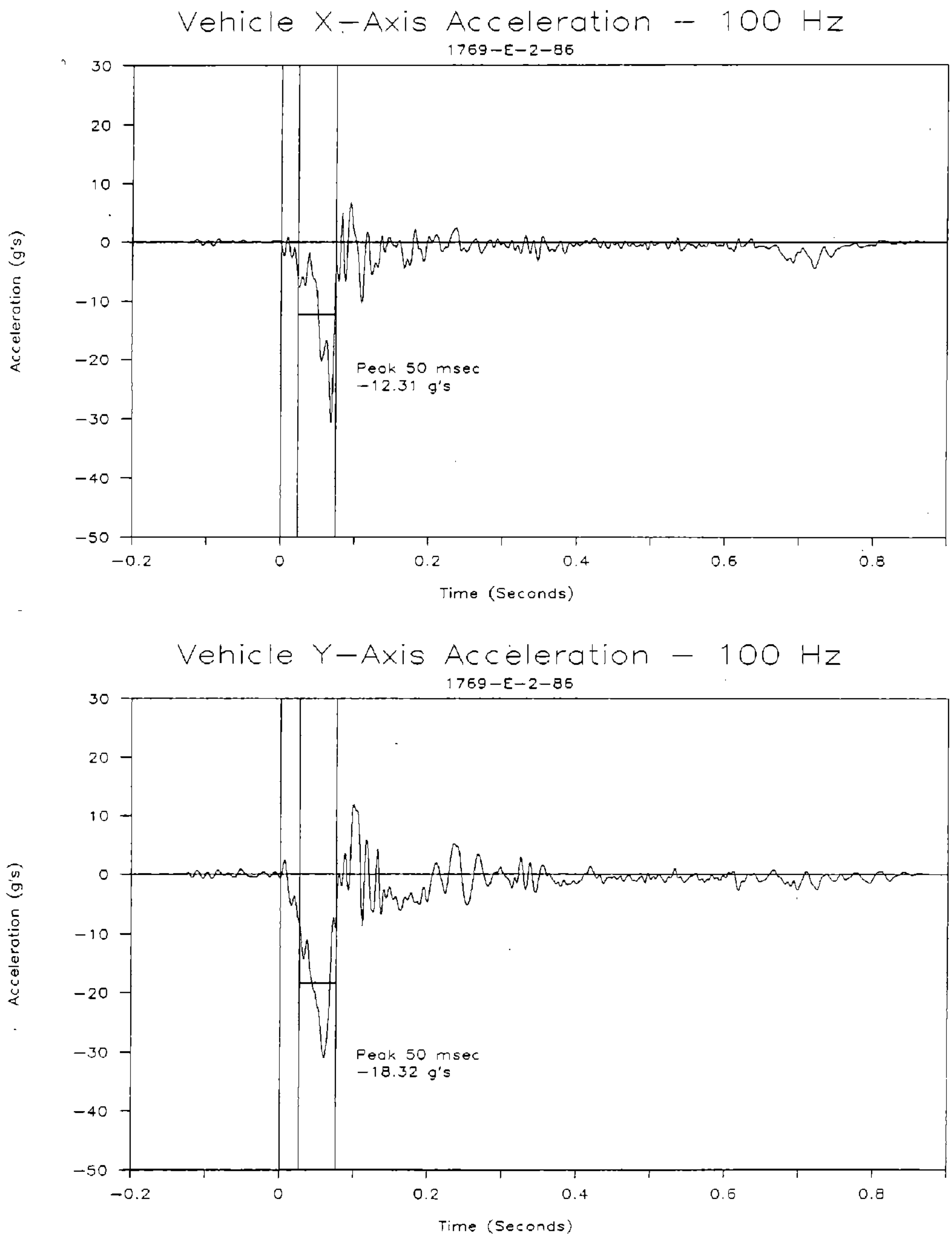


Figure 84. Vehicle acceleration, test 1769-E-2-86.

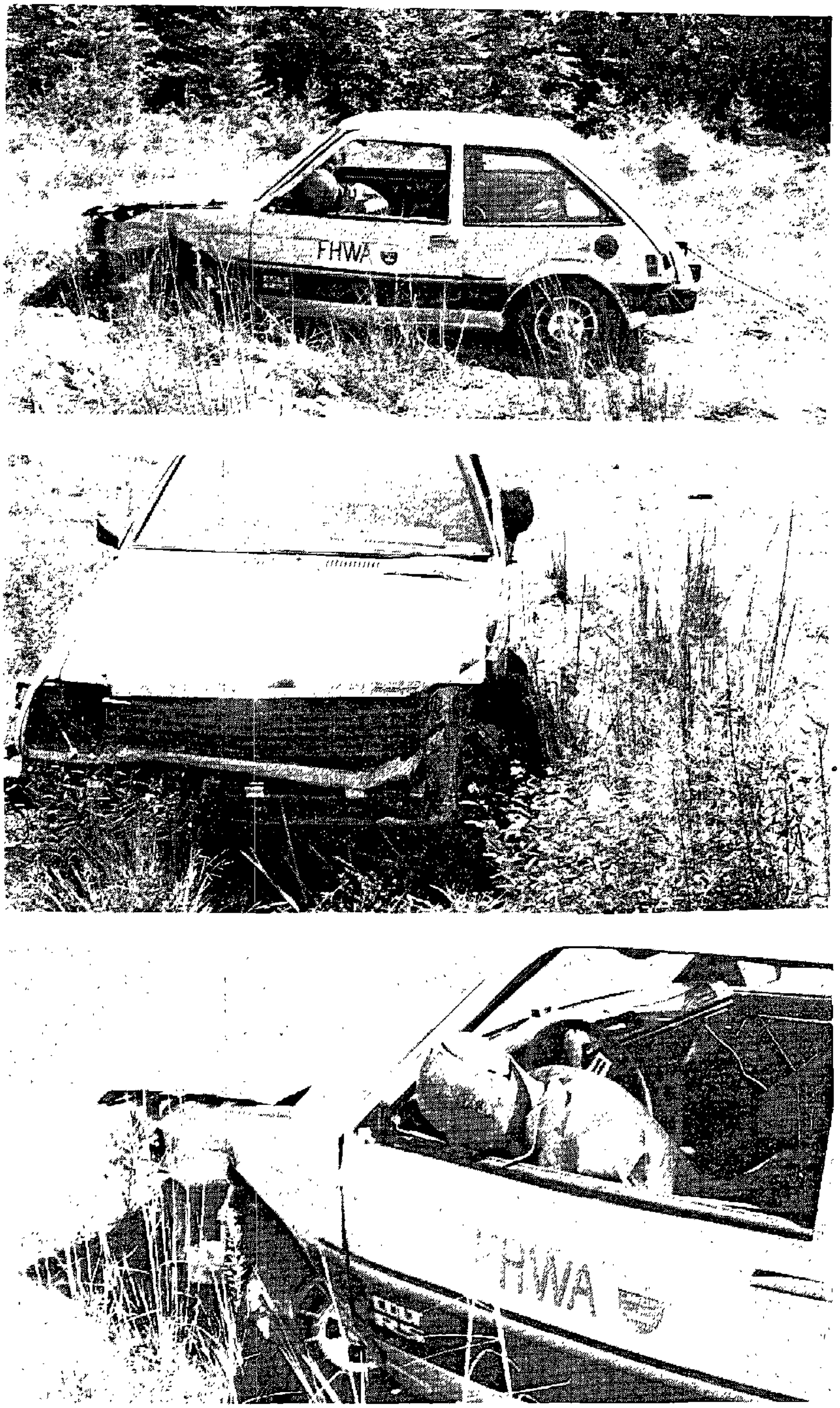


Figure 85. Posttest photographs of test vehicle, test 1769-E-2-86.

d. Traffic Barrier Damage

The Iowa bridge rail system performed as designed. No structural damage was observed. Only minor abrasions were evident. Posttest photographs are shown in figure 86.

3. TEST 1769-E-3-86

a. Test Device

The test device was the modified Iowa bridge rail system. The modification for this test consisted of the reduction of the gap between the bottom of the rail and the deck. This was accomplished by attaching 4-in by 8-in concrete lintels to the bottom of the rail in the rail span areas. Sand mix was used to fill in at the post locations. This modification was added in the area just upstream of impact to the downstream end of the rail.

Figure 87 shows the test site and test device. Figures 88 and 89 show pretest photographs of the Iowa bridge rail system and the test vehicle.

b. Impact Description

Review of the high-speed films, fifth wheel and speed trap data indicated that the test vehicle impacted at 20.5 degrees and 60.1 mi/h. This review also indicated that the left corner of the vehicle impacted the rail at the desired point. The vehicle remained in contact with the rail for approximately 9.5 ft. There was no evidence of tire scrub on any of the posts. The vehicle was redirected at 47.8 mi/h and 5 degrees.

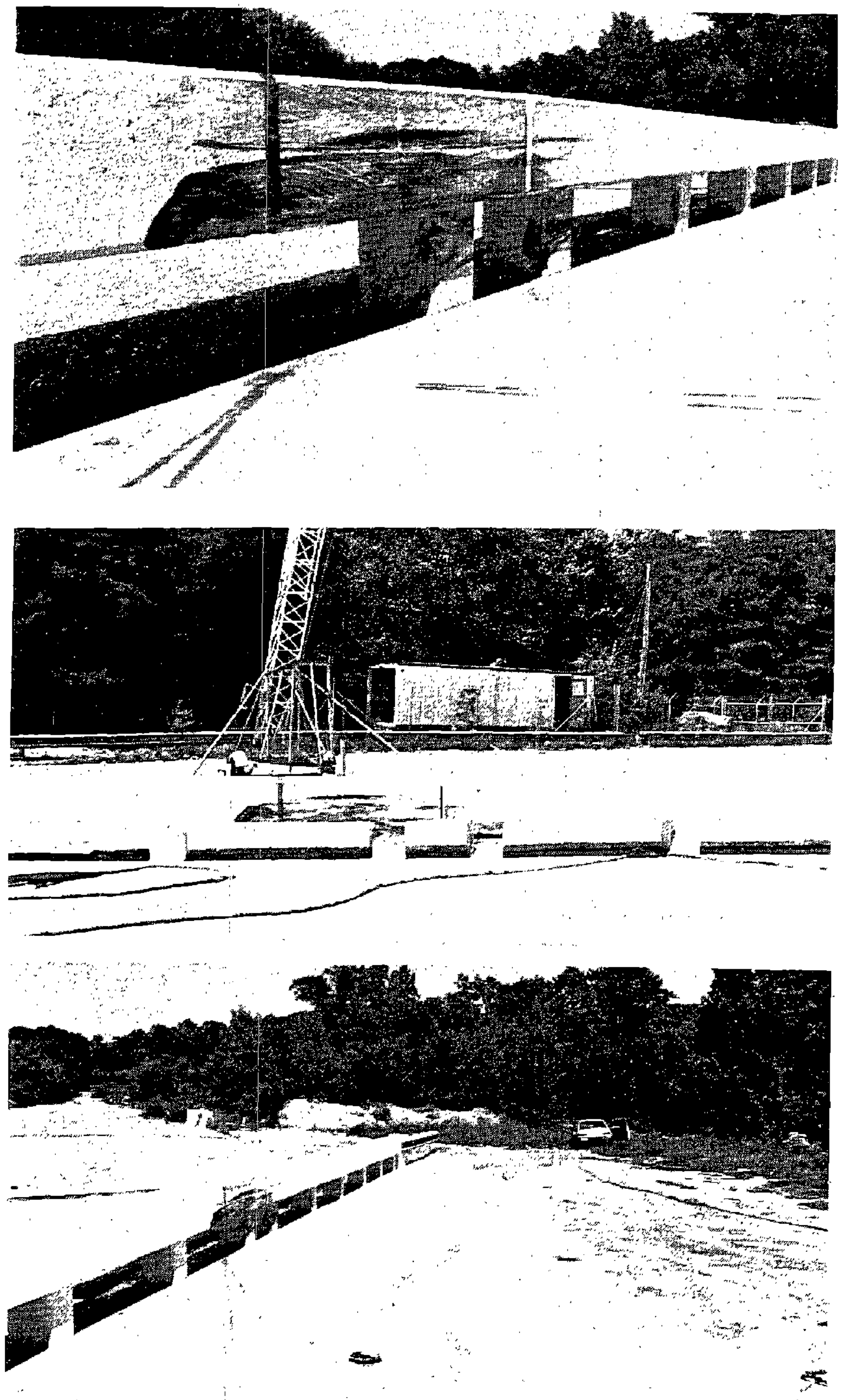


Figure 86. Posttest photographs of Iowa bridge rail system, test 1769-E-2-86.

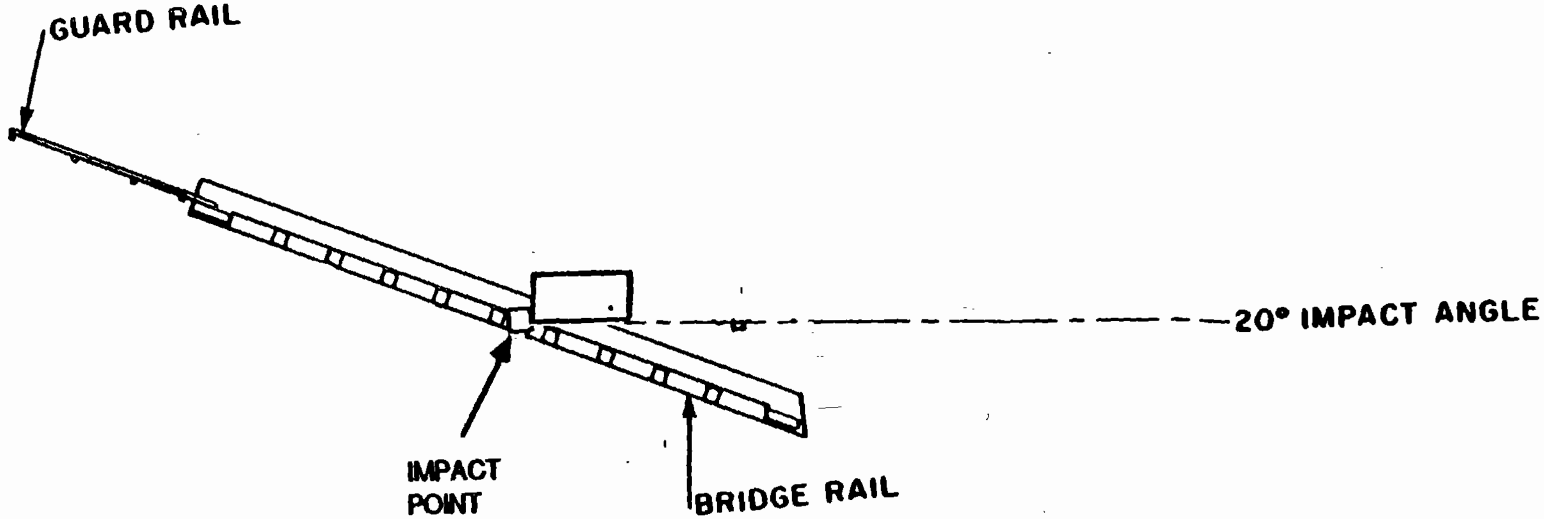


Figure 87. Test site layout, test 1769-E-3-86.

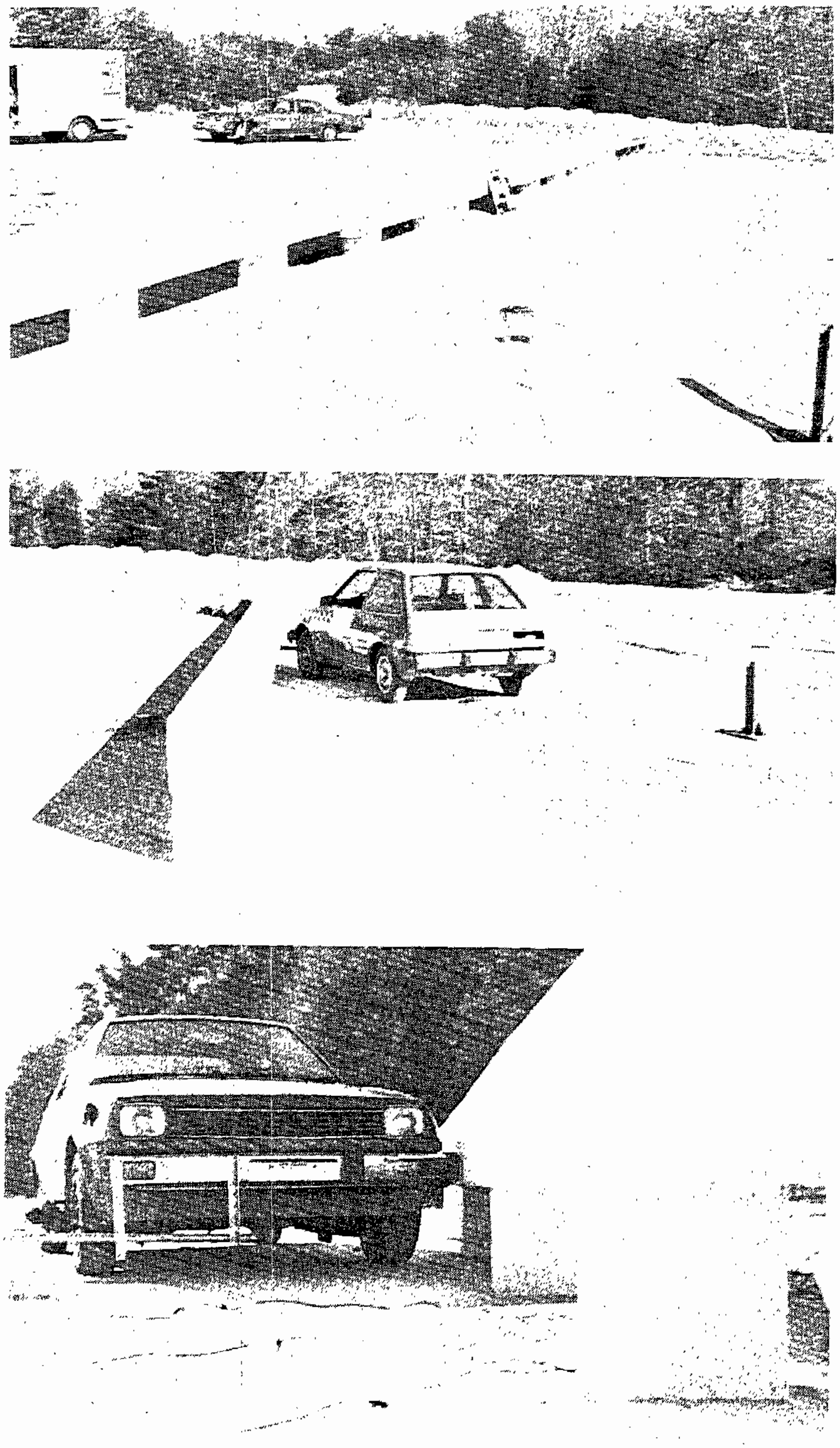


Figure 88. Pretest photographs of Iowa bridge rail system, test 1769-E-3-86.

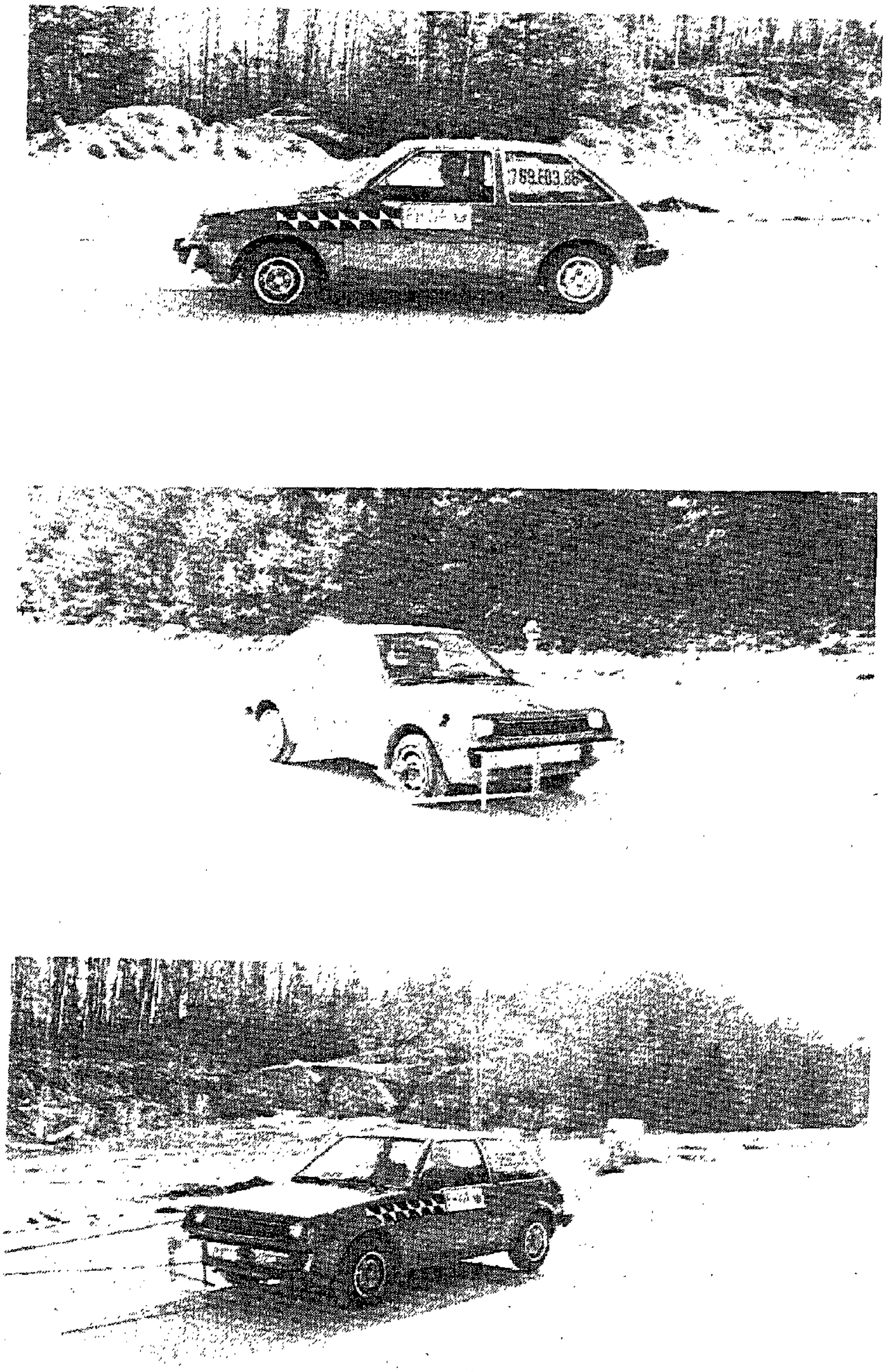


Figure 89. Pretest photographs of test vehicle, test 1769-E-3-86.

Upon impact, the front of the vehicle was deformed and skewed toward the nonimpact side. The vehicle rear-end slapped against the rail and then continued downstream.

During the impact, the vehicle rolled toward the impact side and pitched forward slightly. The passenger side wheels left the ground. After redirection, the vehicle continued downstream (on a curving trajectory) for 125 ft before stopping. A summary of the test conditions and results is given in figure 90.

Inside the vehicle it was observed that the dummy slid into the drivers door. The door buckled but did not come open. The dummy's head broke the driver's side window. During the impact, the dummy had its upper body out of the window. The dummy came to rest leaning on the door with its head in the plane of the window.

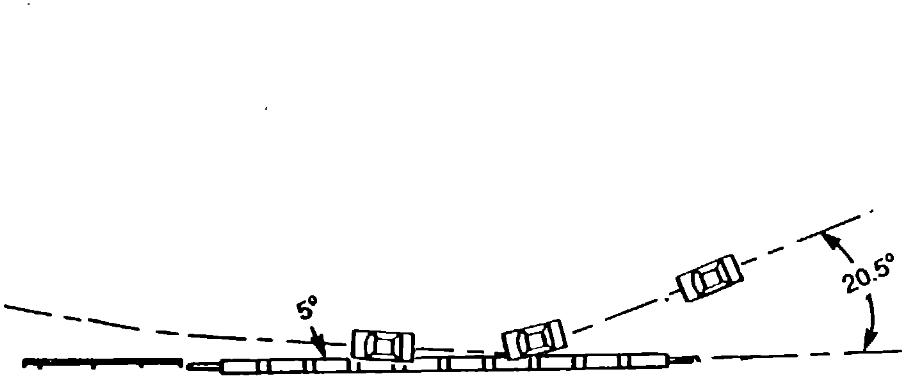
Data analysis was performed and the vehicle x-axis and y-axis, 100 Hz acceleration traces are shown in figure 91.

c. Vehicle Damage

Damage occurred mainly to the left front corner of the vehicle. Posttest photographs of the vehicle are shown in figure 92.

d. Traffic Barrier Damage

The Iowa bridge rail system performed as designed. No structural damage was observed. Only minor abrasions were evident. Posttest photographs are shown in figure 93.



Date: 5 December 1986
Weather: Sunny, 40° F

Test Vehicle: 1980 Dodge Colt

Device Configuration: Iowa Bridge Rail, 75 ft long, 6 ft wide deck, 6 ft, 7 in post spacing
Post: 12 in by 12 in
Rail: 15 in by 19 in, 10 in from bottom of rail to deck, 4 in by 8 in concrete lintel attached to bottom of rail to close gap from test 2

1. Vehicle Weight:

	Test Inertial	Gross
Planned:	1800 ± 50	1950 ± 50
Actual:	1779	1922

2. Number of Occupants: One

3. Occupant Model: Anthropomorphic Dummy, 50th%, male

4. Occupant Location: Driver Seat, Unrestrained

5. Impact:

	Speed	Angle (a)	Location
Planned:	60.0 mi/h	20°	Midway between posts
Actual:	60.1 mi/h	20.5°	Midway between posts

6. Redirection Angle: 5 degrees

7. Redirection Speed: 47.3 mi/h (69.4 ft/s)

8. Total Speed Change: 12.8 mi/h (18.7 ft/s)

9. Total Momentum Change: 1116 lb-s

10. Vehicle Damage Index: (SAE J224a) 10LFEW2

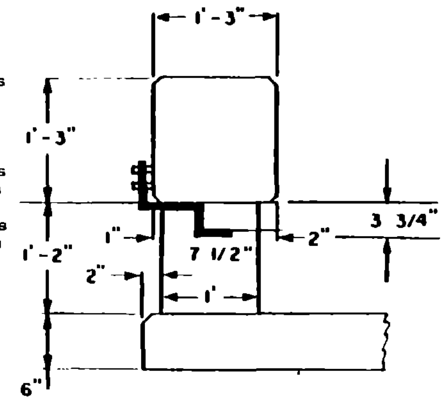
11. NCHRP 230 Test Number: S13

12. Impact Severity:

$\frac{m(V \sin a)^2}{2}$ 26.3 kip-ft (Spec: 23 to 29 kip-ft)

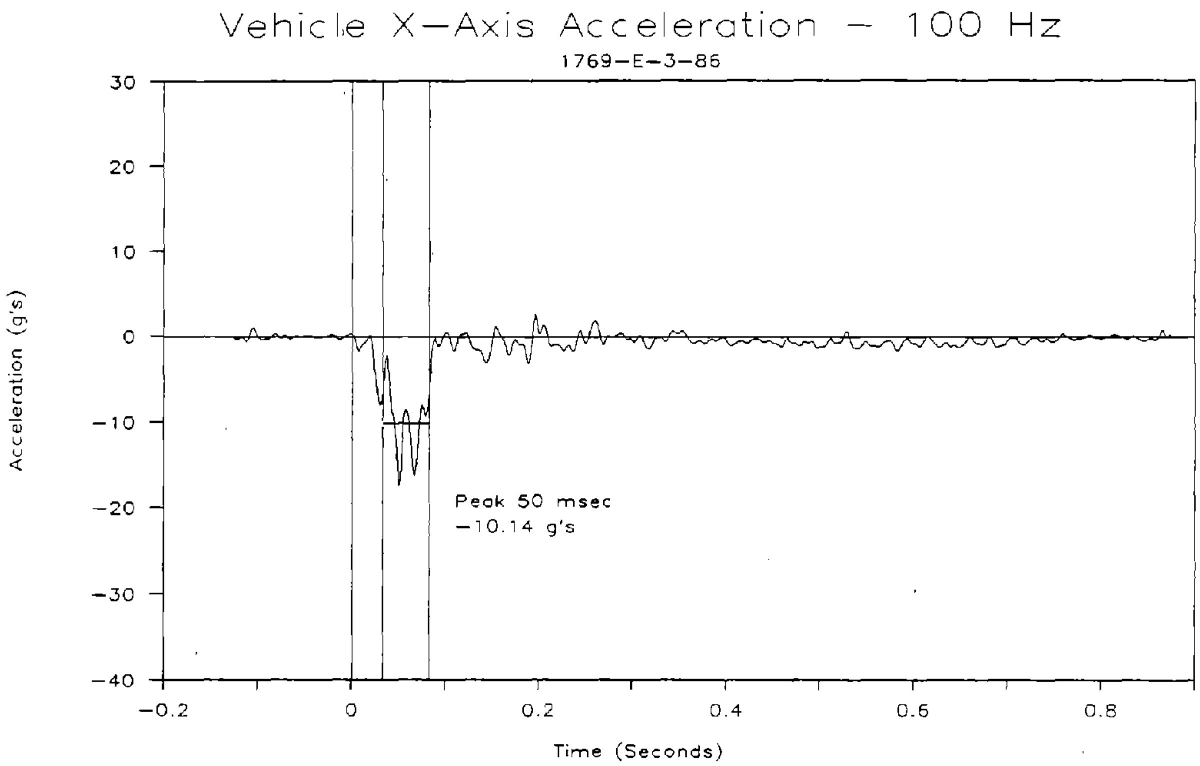
13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-20.8 ft/s	30/40 ft/s
Ridedown Acceleration:	-2.3 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-27.6 ft/s	20/30 ft/s
Ridedown Acceleration:	-5.9 g's	15/20 g's
Delta-V at 0.54 ft (actual):	-26.5 ft/s	20/30 ft/s
Ridedown Acceleration:	-20.2 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-10.1 g's	
Lateral:	-16.4 g's	



14. Test Results Conclusion: Meets all NCHRP 230 criteria.

Figure 90. Test summary, test 1769-E-3-86.



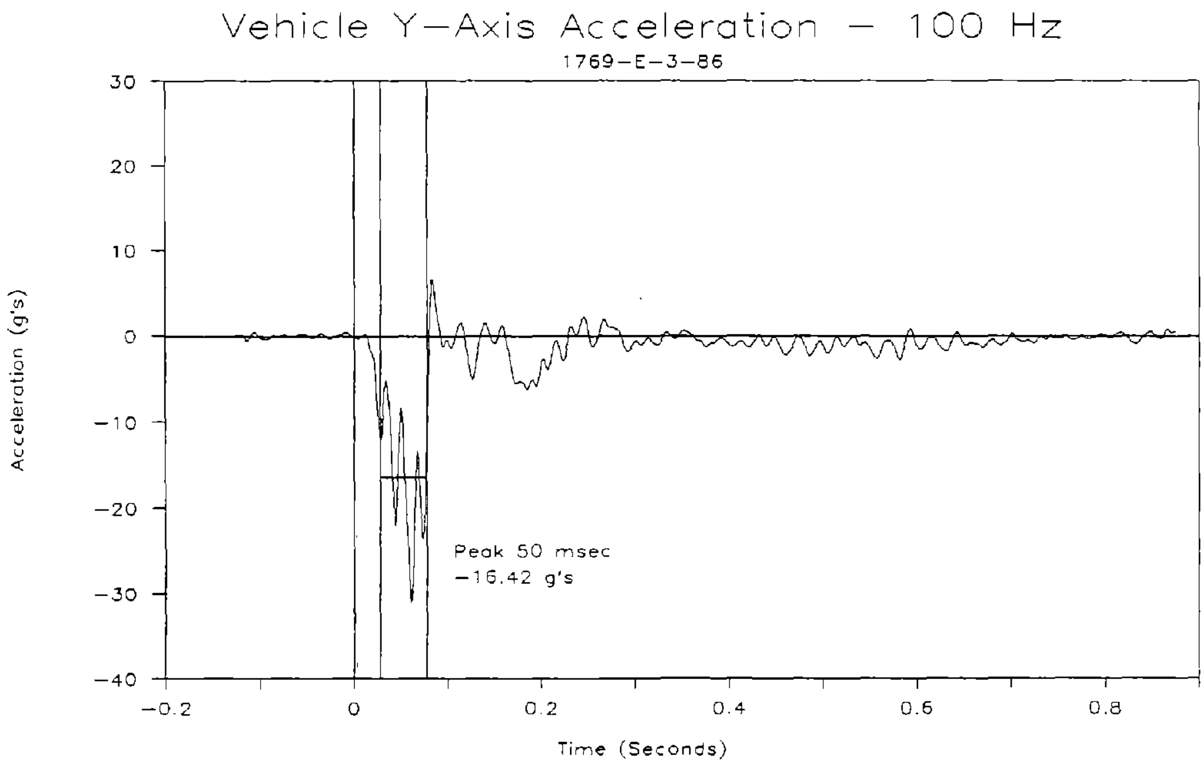


Figure 91. Vehicle acceleration, test 1769-E-3-86.

Figure 92. Posttest photographs of test vehicle, test 1769-E-3-86.

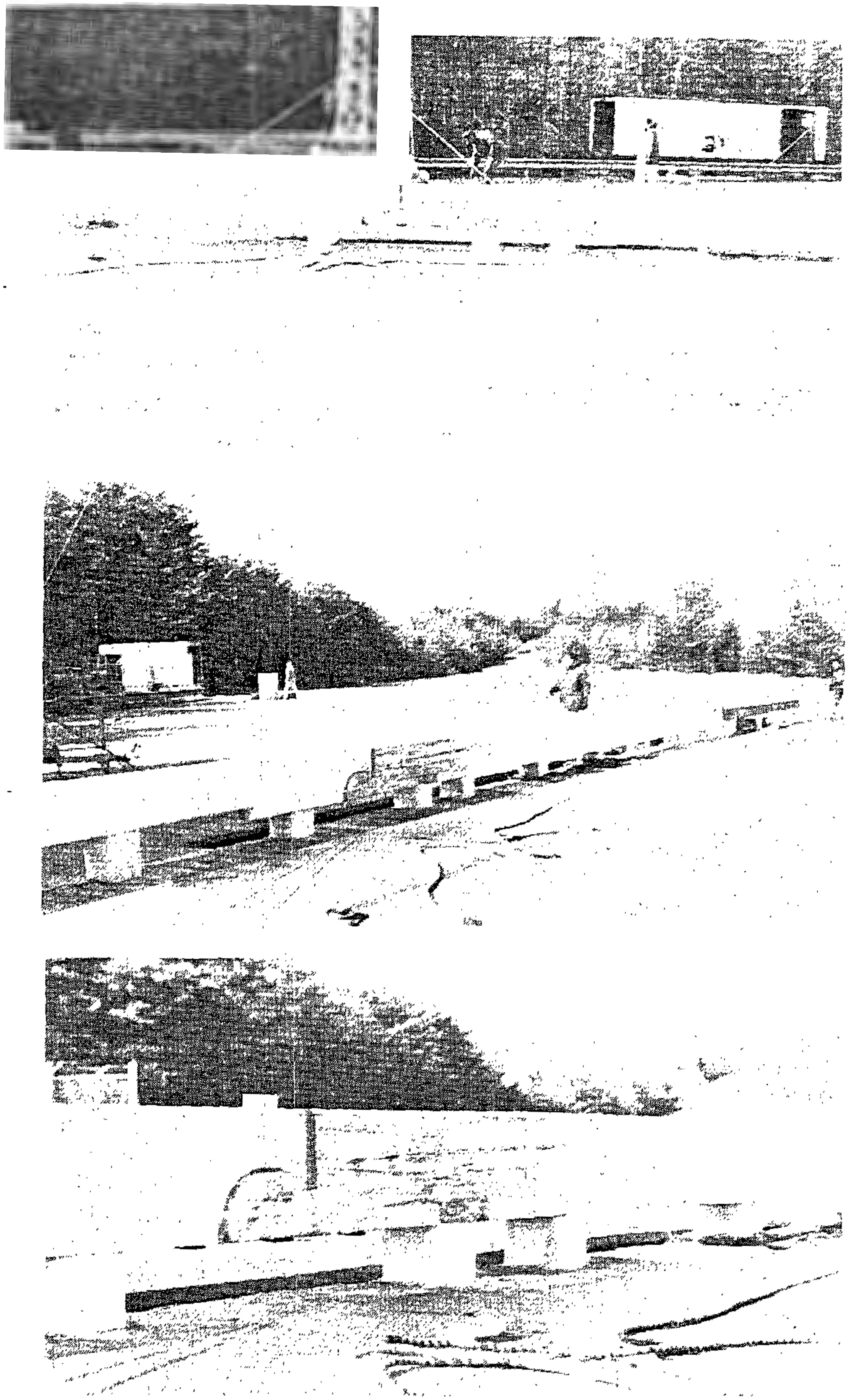


Figure 93. Posttest photographs of Iowa bridge rail system, test 1769-E-3-86.

FULL-SCALE TESTS OF NEBRASKA BRIDGE RAIL DESIGN

The purpose of this task was to full-scale test a bridge rail design from the State of Nebraska. Two tests were conducted. These tests were:

- 4500-lb, 60 mi/h, 25 degrees.
- 1800-lb, 60 mi/h, 20 degrees.

The following text describes the tests conducted under this task.

1. TEST 1769-F-1-86

a. Test Device

The test device was the Nebraska bridge rail system. The half-deck and bridge rail were installed by a private contractor using 3500-lb/in^2 concrete throughout. Construction took place during June 1986. The deck was poured on June 6, 1986 and the rail was poured on June 10, 1986. Four test cylinders were poured. The crush strengths are given in table 13.

Table 13.
Crush strengths of test cylinders.

Crush Date	Strengths (lb/in^2)
June 13 (1 week after deck)	3200, 3340
July 4 (4 weeks)	4240, 4510

Figure 94 shows the test site and test device. Figure 95 shows the Nebraska system in various views. Figures 96 and 97 shows pretest photographs of the Nebraska bridge rail system and test vehicle.

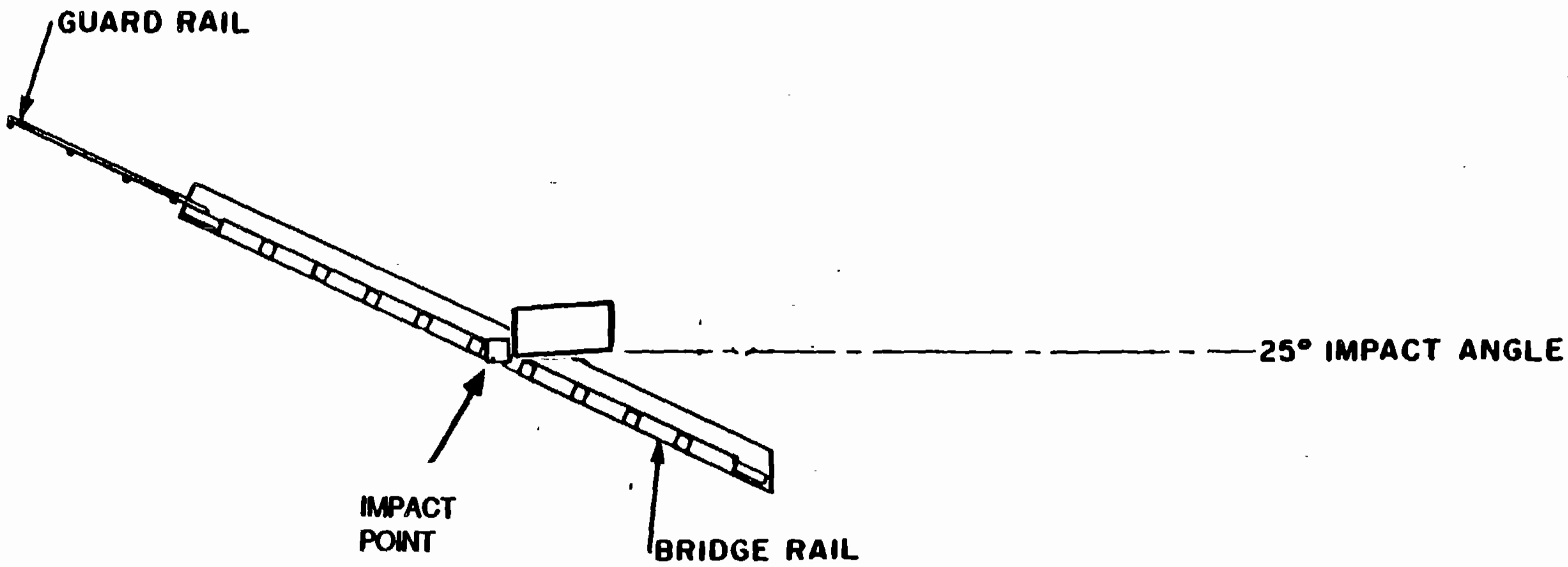


Figure 94. Test site layout, test 1769-F-1-86.

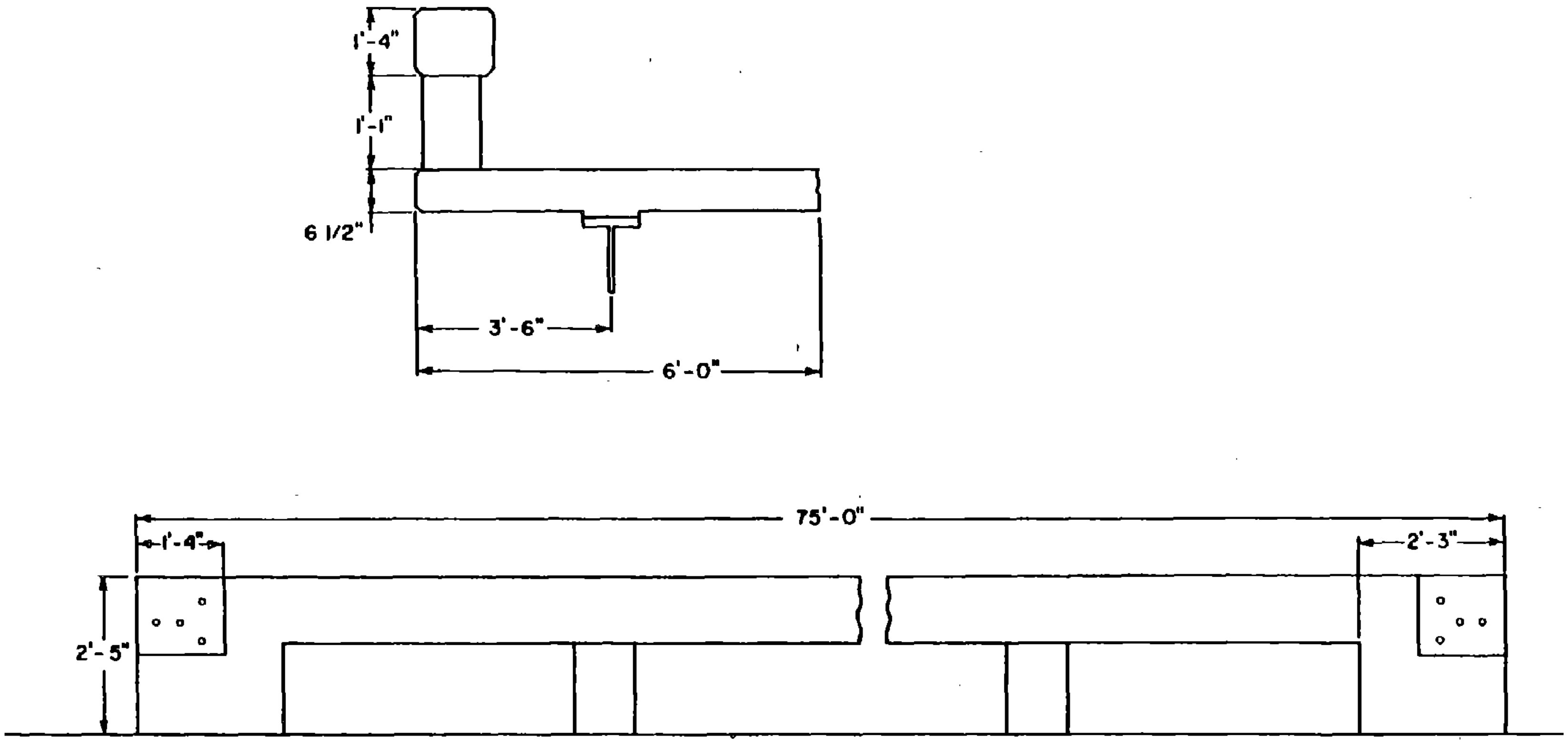


Figure 95. Nebraska bridge rail system.

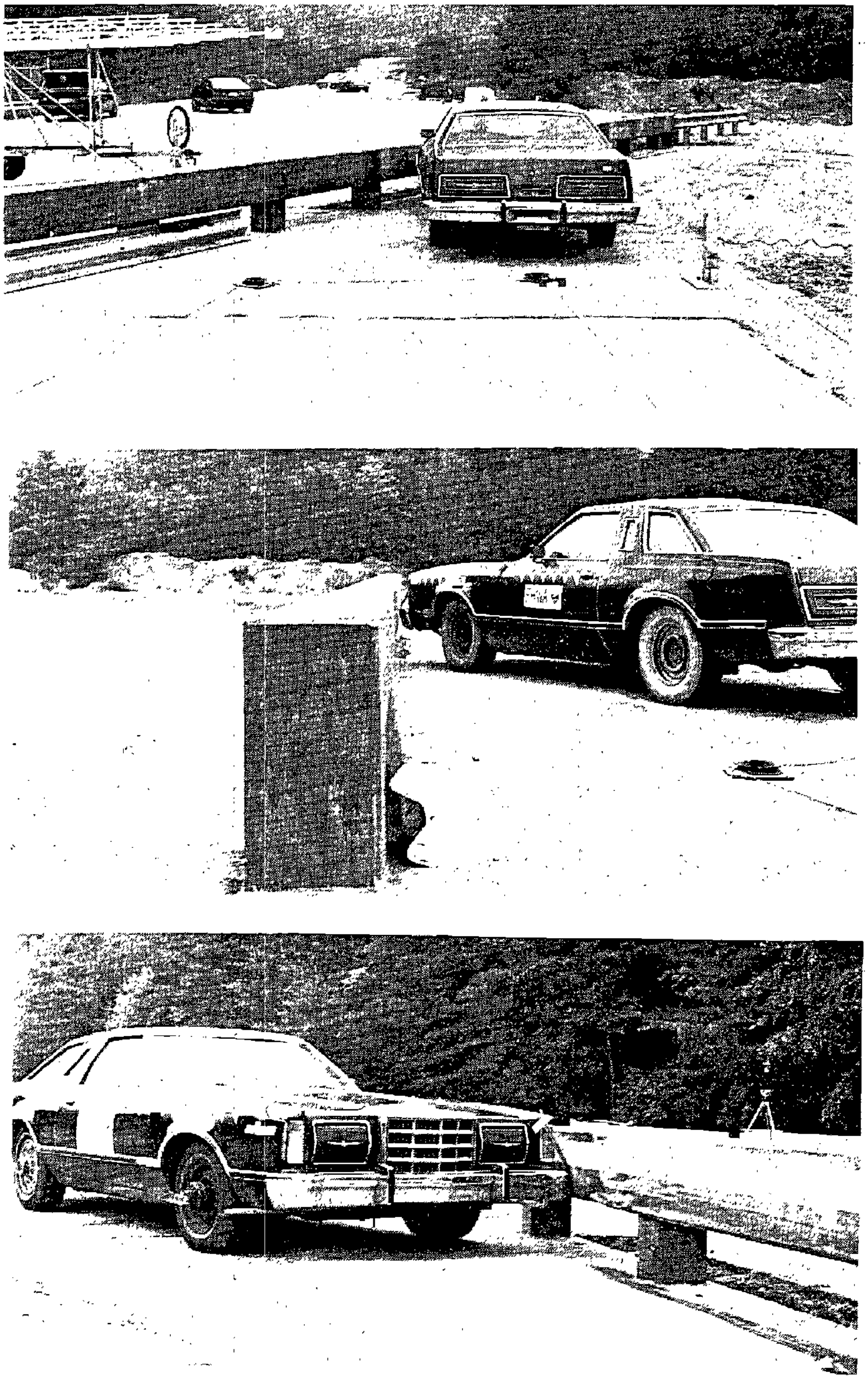


Figure 96. Pretest photographs of Nebraska bridge rail system, test 1769-F-1-86.

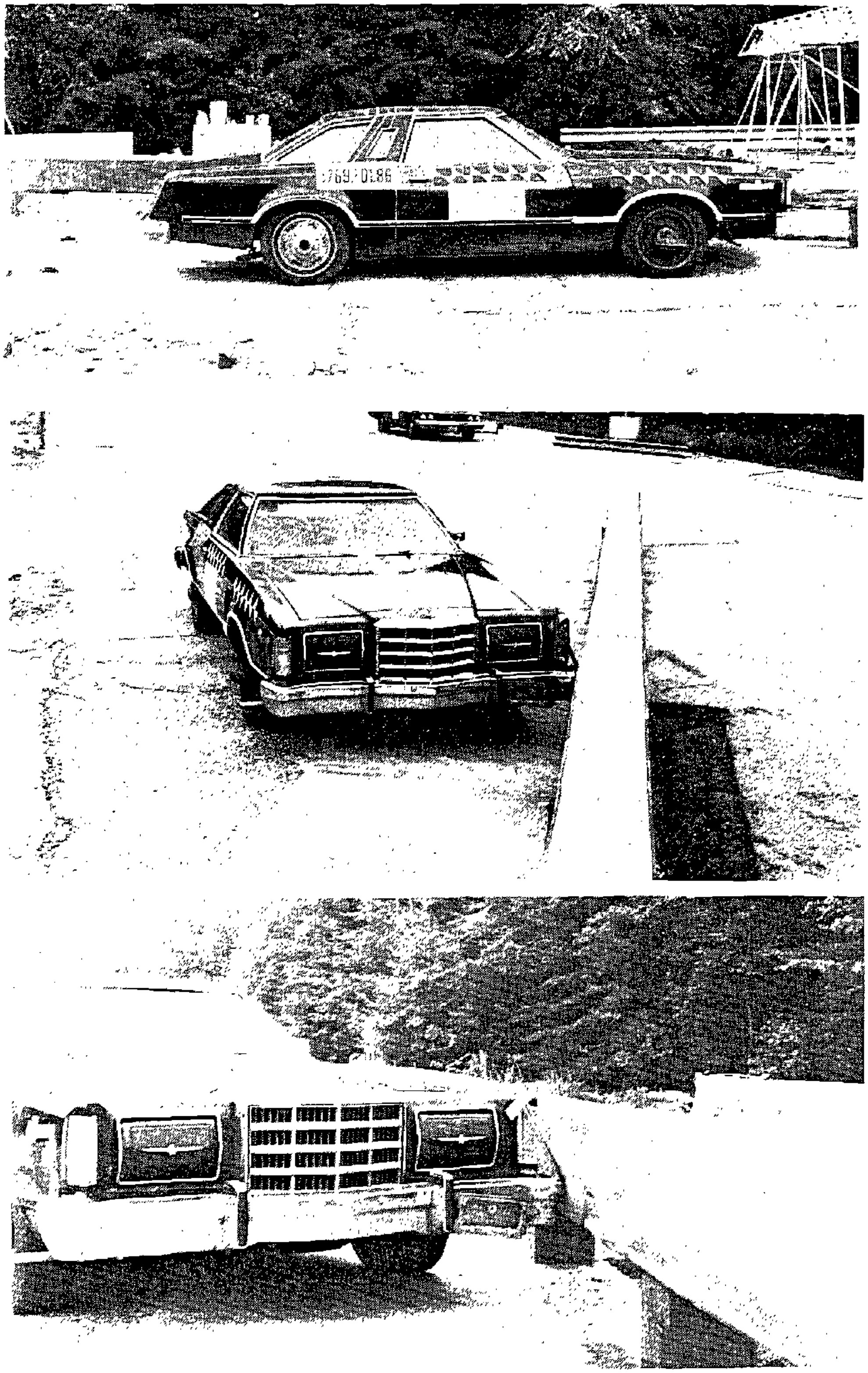


Figure 97. Pretest photographs of test vehicle, test 1769-F-1-86.

b. Impact Description

Review of the high-speed films, fifth wheel and speed trap data indicated that the test vehicle impacted at 26 degrees and 57.6 mi/h. This review also indicated that the left corner of the vehicle impacted the rail 11 in upstream of the desired point. The vehicle remained in contact with the rail for approximately 11 ft. The vehicle was redirected at 43.7 mi/h and 2 degrees.

Upon impact, the front of the vehicle was deformed and skewed toward the nonimpact side. The vehicle rear-end slapped hard against the rail. The vehicle then continued downstream.

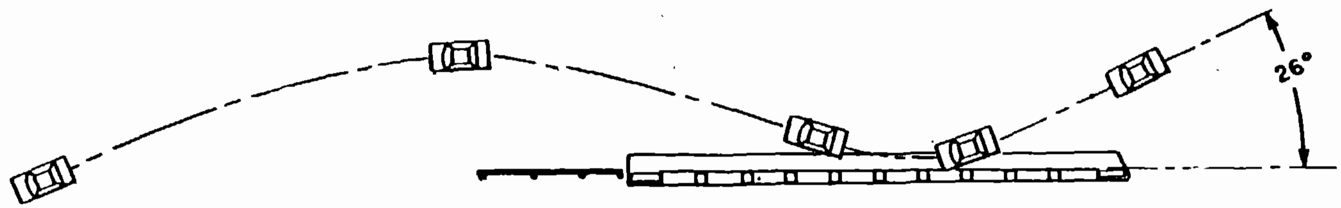
During the impact, the vehicle remained level and stable. After redirection, the vehicle continued downstream for 150 ft before stopping. The brakes were applied 95 ft after impact. A summary of test condition and results is shown in figure 98.

Inside the vehicle, it was observed that the dummy slid and impacted the driver's window. During the impact, the dummy had its upper body out of the window, nearly scraping its head on the top of the rail. The dummy came to rest leaning toward the passenger seat on the arm rest between seats.

Data analysis was performed and the vehicle x-axis and y-axis, 100 Hz acceleration traces are shown in figure 99.

c. Vehicle Damage

The entire left side of the vehicle was damaged, but damage occurred mainly to the left front fender and left front wheel. Posttest photographs of the vehicle are shown in figure 100.



Date: 17 July 1986
Weather: Overcast, 85° F

Test Vehicle: 1979 Ford Thunderbird

Device Configuration: Nebraska Bridge Rail, 75 ft long, 6 ft wide deck, 7 ft, 6 in post spacing
Post: 11 in by 11 in
Rail: 14 in ty 16 in, 13 in from bottom of rail to deck

1. Vehicle Weight:

	Test Inertial	Gross
Planned:	4500 ± 200	4500 ± 300
Actual:	4499	4669

2. Number of Occupants: One

3. Occupant Model: Anthropomorphic Dummy, 50th%, male

4. Occupant Location: Driver Seat, Unrestrained

5. Impact:

	Speed	Angle (a)	Location
Planned:	60.0 mi/h	25°	Midway between posts
Actual:	57.6 mi/h	26°	Midway between posts

6. Redirection Angle: 2 degrees

7. Redirection Speed: 43.7 mi/h (64.1 ft/s)

8. Total Speed Change: 13.8 mi/h (20.3 ft/s)

9. Total Momentum Change: 2944 lb-s

10. Vehicle Damage Index: (SAE J224a) 10LFEW2

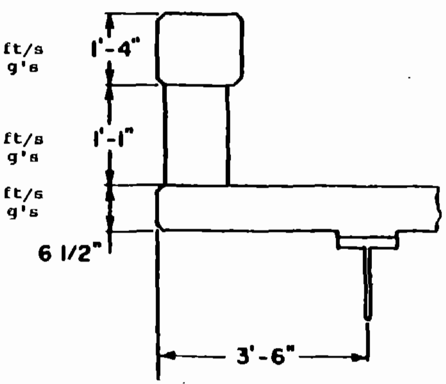
11. NCHRP 230 Test Number: 10

12. Impact Severity:

$\frac{m(V \sin a)^2}{2}$ 95.8 kip-ft (Spec: 88 to 114 kip-ft)

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-17.2 ft/s	30/40 ft/s
Ridedown Acceleration:	-2.8 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-31.2 ft/s	20/30 ft/s
Ridedown Acceleration:	-14.3 g's	15/20 g's
Delta-V at 0.67 ft (actual):	-23.9 ft/s	20/30 ft/s
Ridedown Acceleration:	-20.7 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-7.5 g's	
Lateral:	-15.3 g's	



14. Test Results Conclusion: Meets all NCHRP 230 criteria.

Figure 98. Test summary, test 1769-F-1-86.

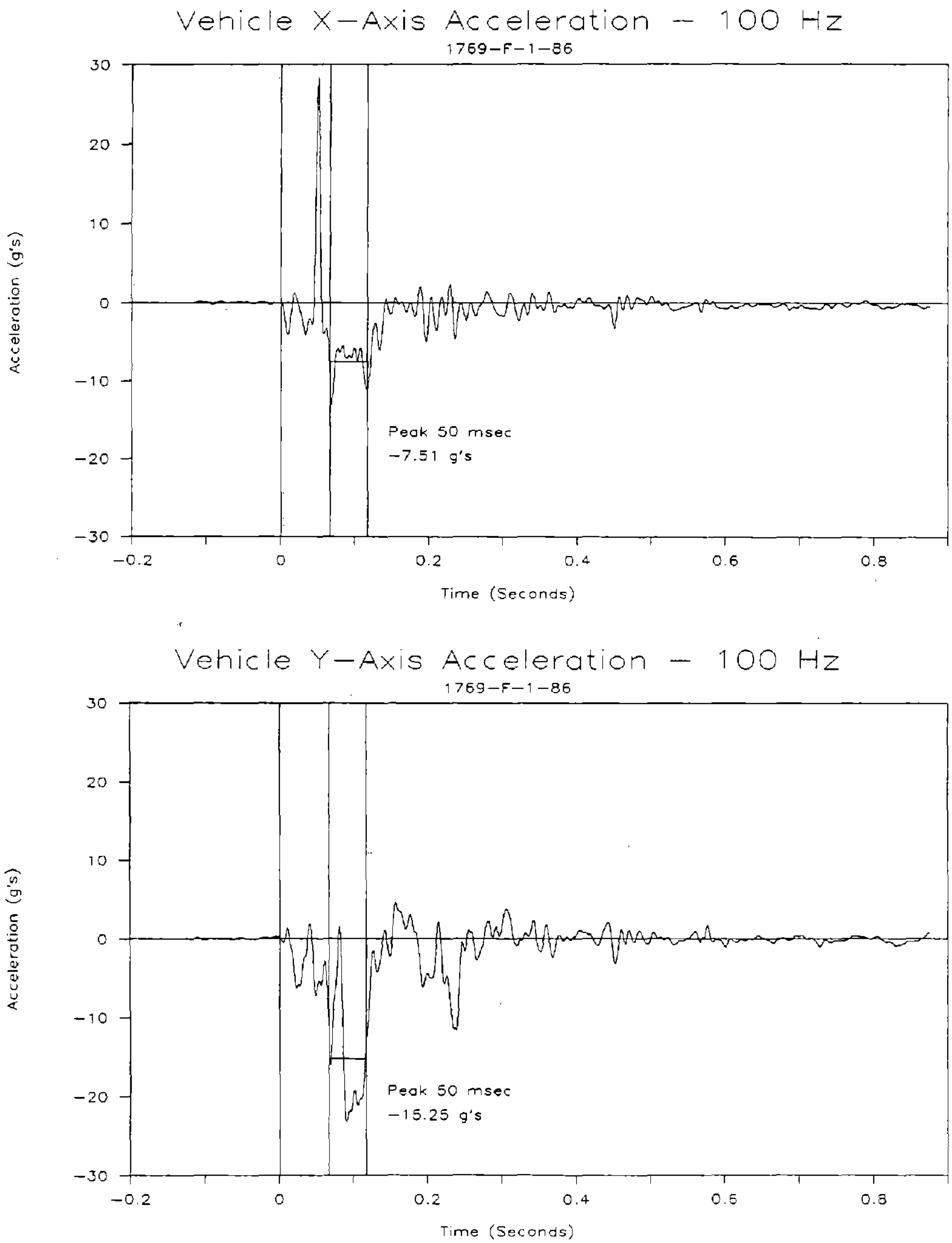
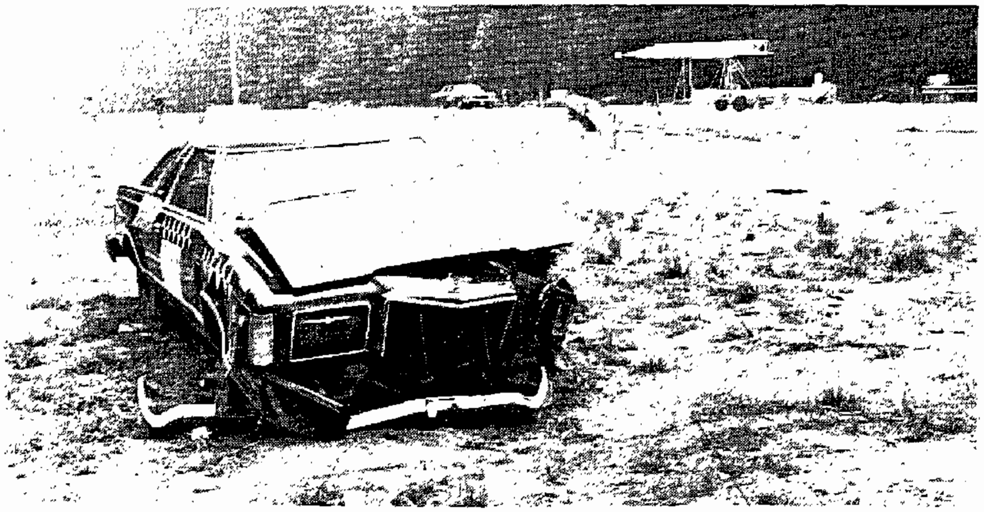


Figure 99. Vehicle acceleration, test 1769-F-1-86.



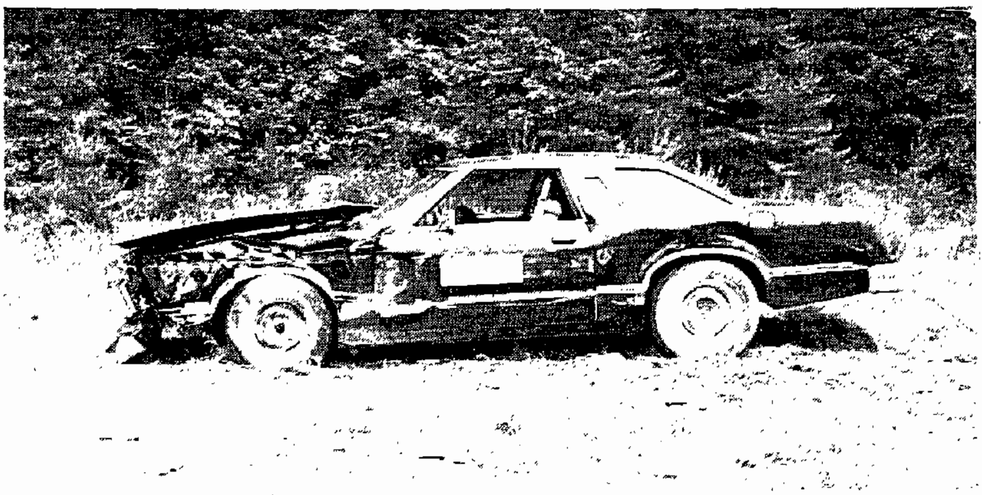


Figure 100. Posttest photographs of test vehicle, test 1769-F-1-86.

d. Traffic Barrier Damage

The Nebraska bridge rail system performed as designed. No structural damage was observed. Only minor abrasions were evident. Posttest photographs are shown in figure 101.

2. TEST 1769-F-2-86

a. Test Device

The test device was the Nebraska bridge rail system. Figure 102 shows the test site and test device. Figures 103 and 104 show pretest photographs of the Nebraska bridge rail system and test vehicle.

b. Impact Description

Review of the high-speed films, fifth wheel and speed trap data indicated that the test vehicle impacted at 21 degrees and 59.8 mi/h. This review also indicated that the left corner of the vehicle impacted the rail 11 in downstream of the desired point. The vehicle remained in contact with the rail for approximately 12 ft. The first two posts downstream of impact (post 5 and 6 were hit very hard as evidenced by the tire scrub on the front face of the posts. The vehicle was redirected at 48.7 mi/h and 1.5 degrees.

Upon impact, the driver side door came open and it remained open for the duration of the test. Also the front of the vehicle was deformed and skewed toward the nonimpact side. The vehicle rear-end slapped against the rail and then continued downstream.

During the impact, the vehicle remained level and stable. After redirection, the vehicle continued downstream for 250 ft before stopping upon hitting the sand berm. The brakes were

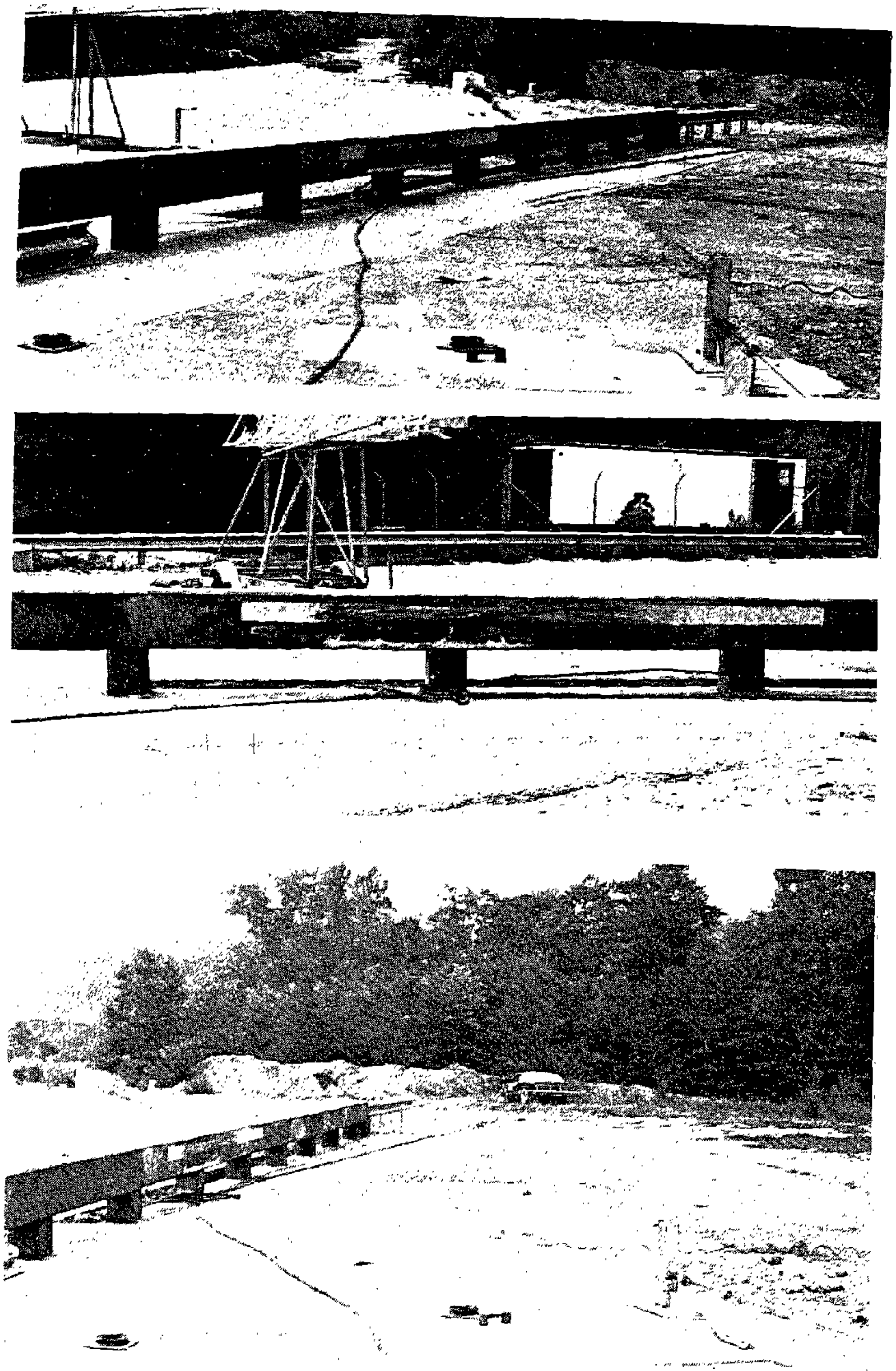


Figure 101. Posttest photographs of Nebraska bridge rail system, test 1769-F-1-86.

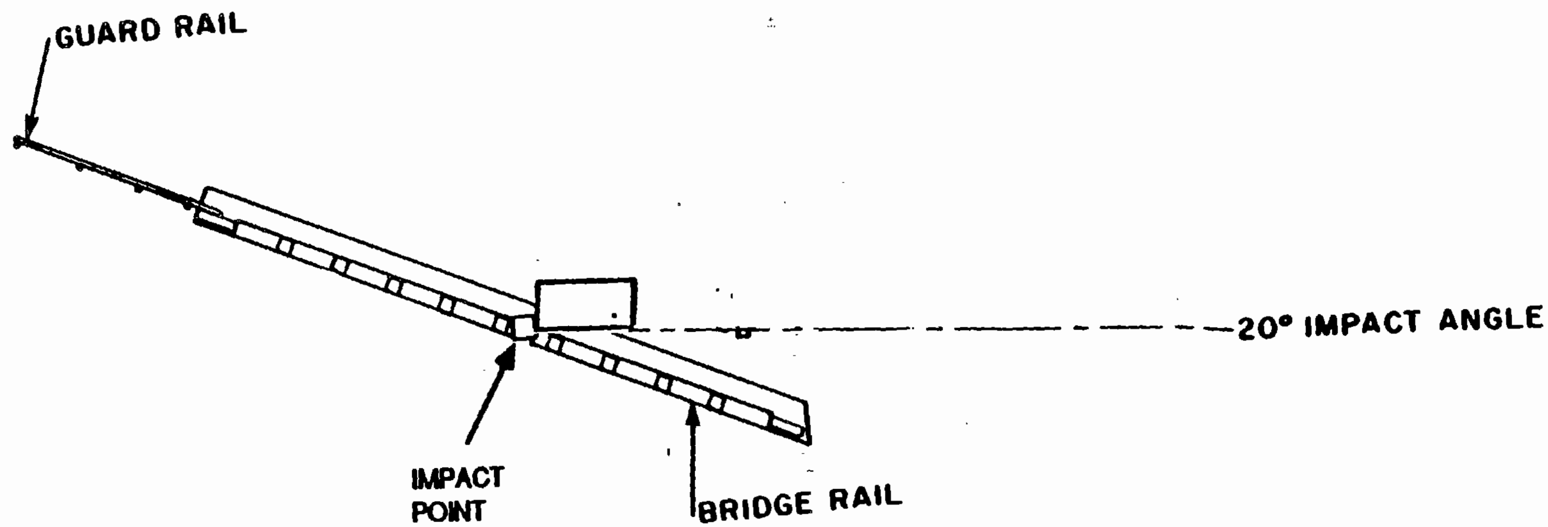


Figure 102. Test site layout, test 1769-F-2-86.

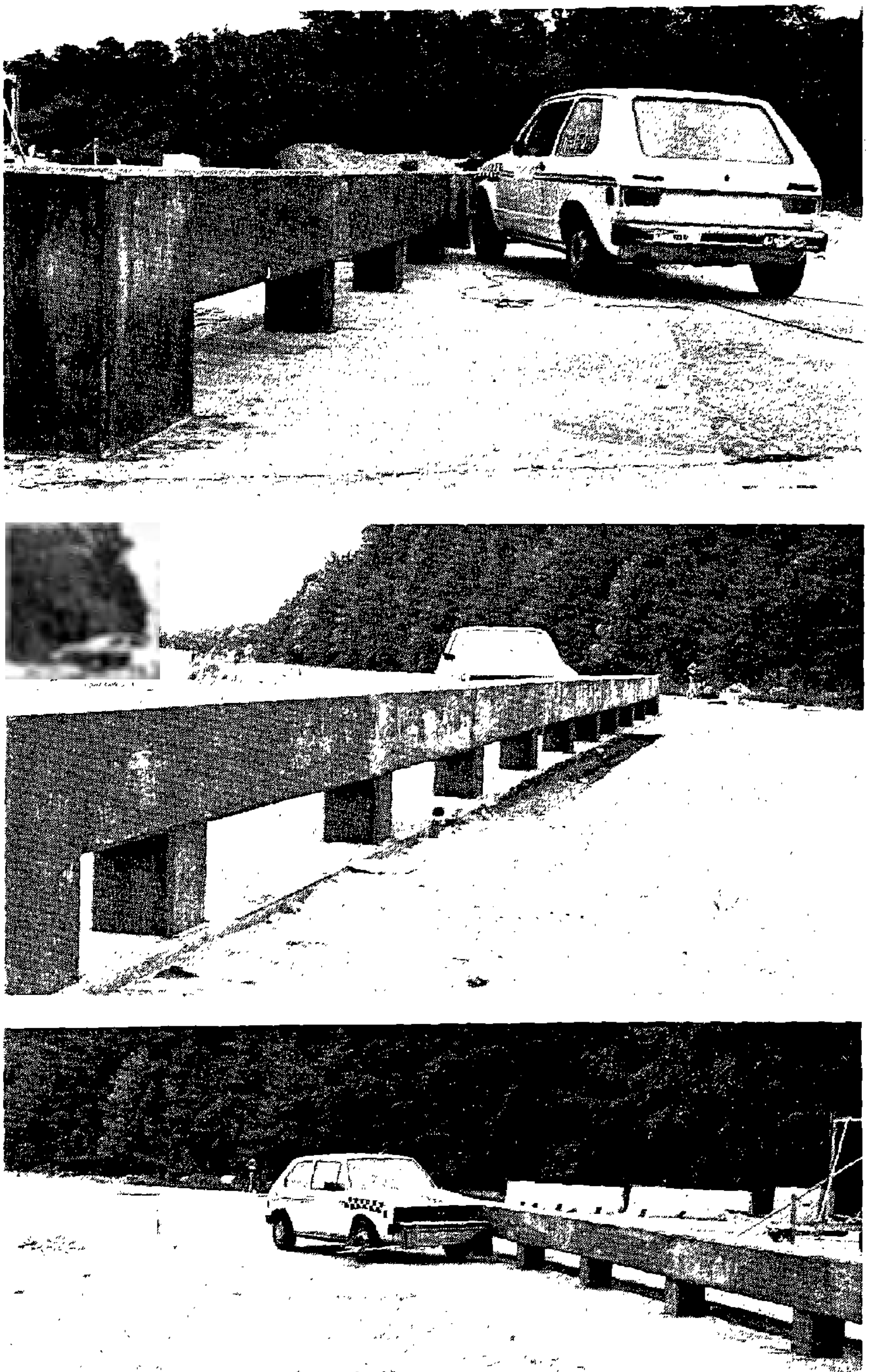


Figure 103. Pretest photographs of Nebraska bridge rail system, test 1769-F-2-86.

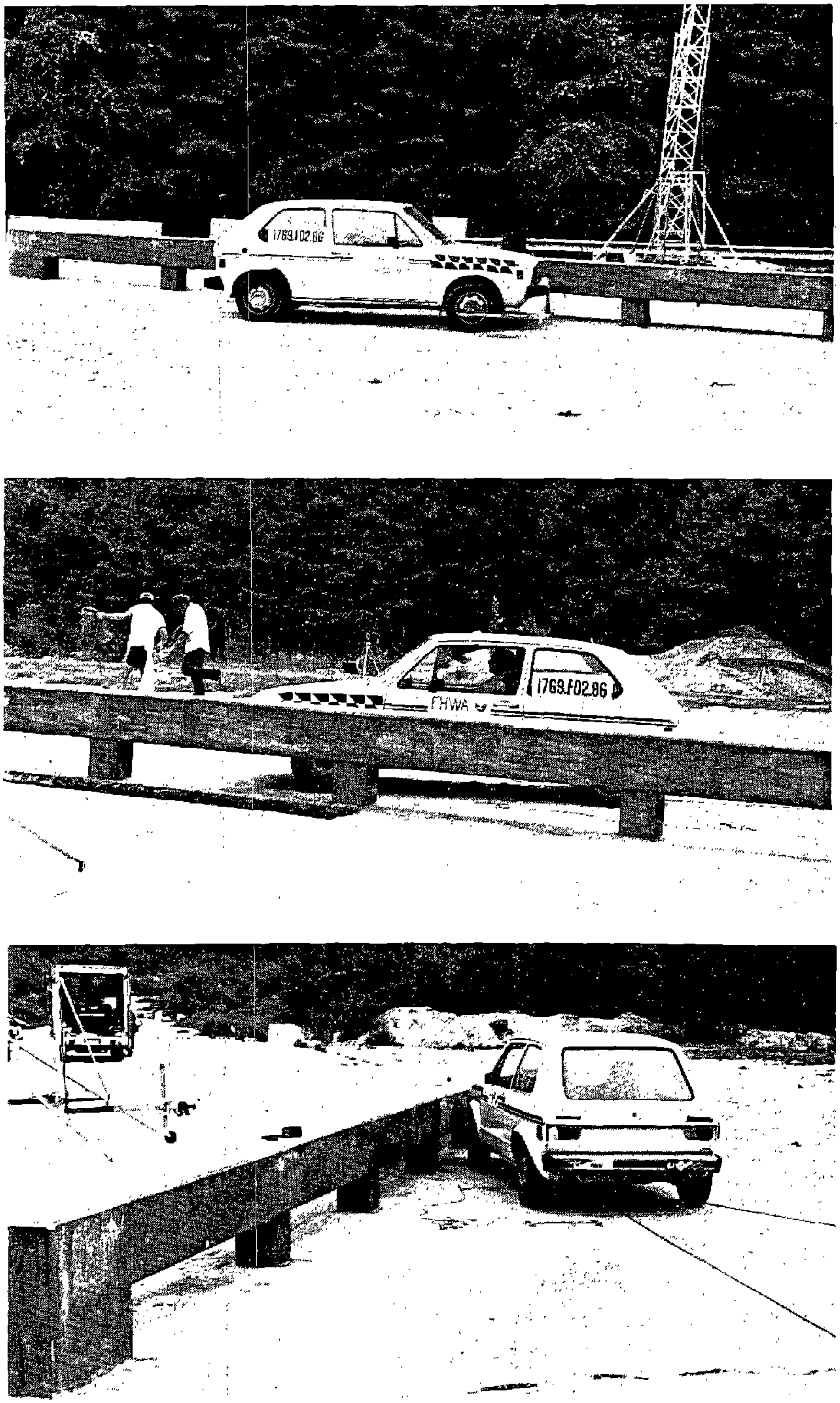


Figure 104. Pretest photographs of test vehicle, test 1769-F-2-86.

not applied. A summary of the test conditions and results is shown in figure 105.

Inside the vehicle, it was observed that the dummy had its upper body out of the window and its head nearly scraped on the top of the rail. As the vehicle left the rail, the dummy was leaning against the open door. When the vehicle came to rest (after hitting the safety berm) the door came completely open and the dummy fell out of the vehicle.

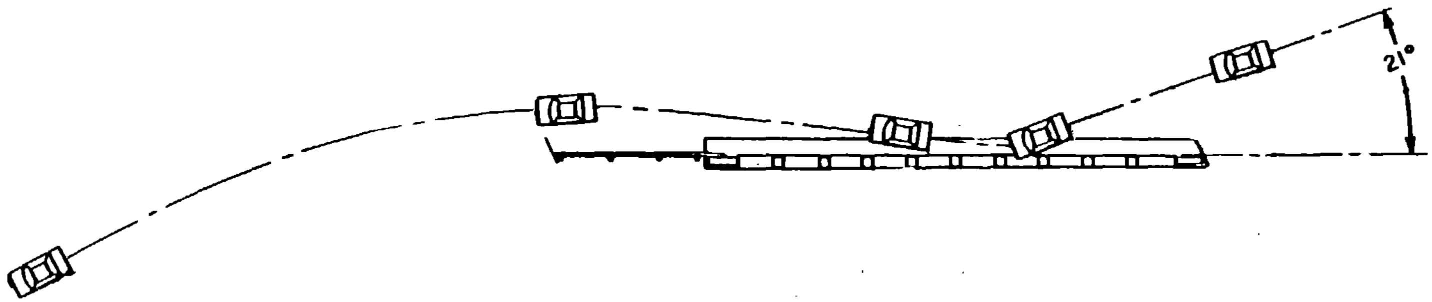
Data analysis was performed and the vehicle x-axis and y-axis, 100 Hz acceleration traces are shown in figure 106.

c. Vehicle Damage

Almost all of the left side of the vehicle was damaged, but damage occurred mainly to the left front fender and left front wheel. Posttest photographs of the vehicle are shown in figure 107.

d. Traffic Barrier Damage

The Nebraska bridge rail system performed as designed. No structural damage was observed. Only minor abrasions were evident. Posttest photographs are shown in figure 108.



Date:	15 July 1986
Weather:	Sunny, 85° F
Test Vehicle:	1980 VW Rabbit
Device Configuration:	Nebraska Bridge Rail, 75 ft long, 6 ft wide deck, 7 ft, 6 in post spacing Post: 11 in by 11 in Rail: 14 in by 16 in, 13 in from bottom of rail to deck

1. Vehicle Weight:

	Test Inertial	Gross
Planned:	1800 ± 50	1950 ± 50
Actual:	1812	1971

2. Number of Occupants: One
3. Occupant Model: Anthropomorphic Dummy, 50th%, male
4. Occupant Location: Driver Seat, Unrestrained
5. Impact:

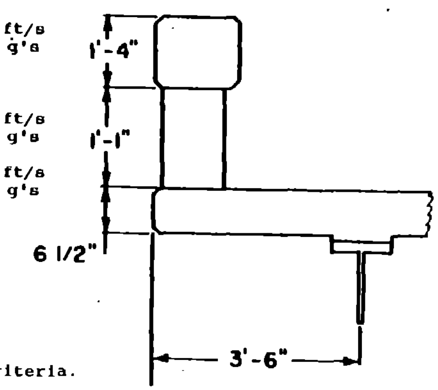
	Speed	Angle (a)	Location
Planned:	60.0 mi/h	20°	Midway between posts
Actual:	59.8 mi/h	21°	Midway between posts

6. Redirection Angle: 1.5 degrees
7. Redirection Speed: 48.7 mi/h (71.4 ft/s)
8. Total Speed Change: 11.1 mi/h (16.3 ft/s)
9. Total Momentum Change: 988 lb-s
10. Vehicle Damage Index: (SAE J224a) 10LFEW2
11. NCHRP 230 Test Number: S13
12. Impact Severity:

$\frac{m(V \sin a)^2}{2}$ 27.8 kip-ft (Spec: 23 to 29 kip-ft)

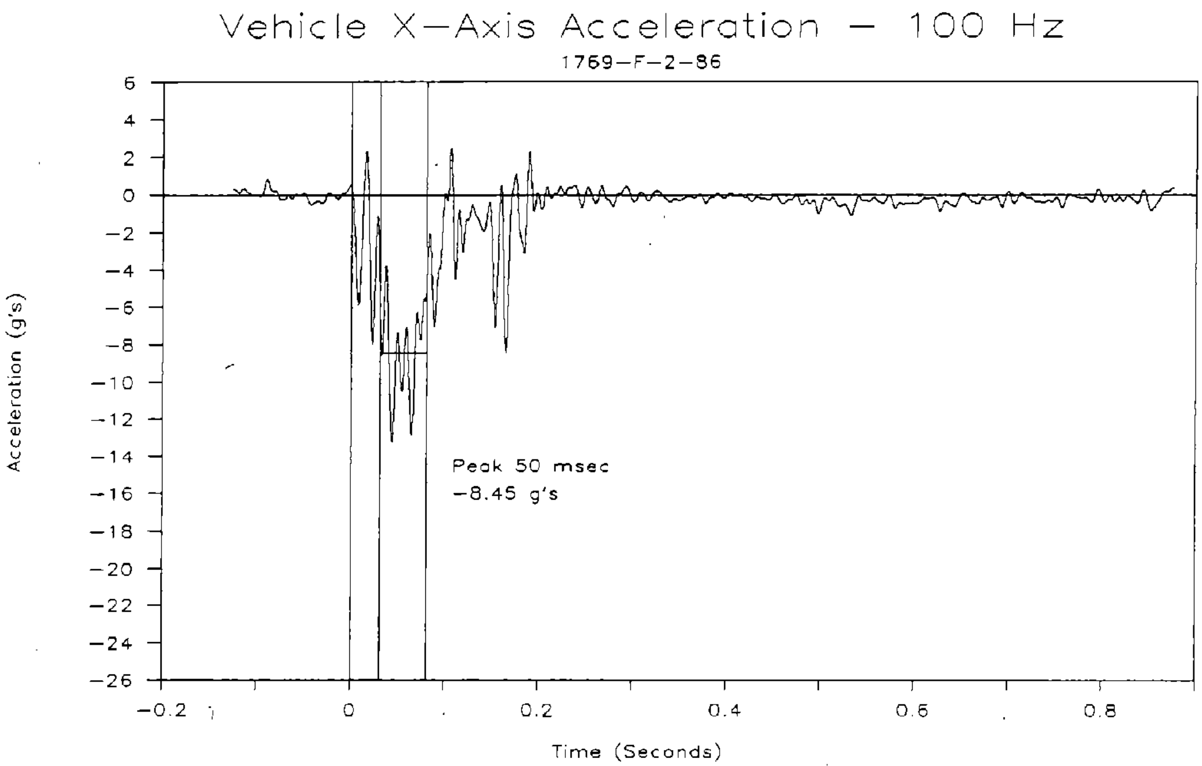
13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-21.8 ft/s	30/40 ft/s
Ridedown Acceleration:	-4.9 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-24.1 ft/s	20/30 ft/s
Ridedown Acceleration:	-10.5 g's	15/20 g's
Delta-V at 0.67 ft (actual):	-22.9 ft/s	20/30 ft/s
Ridedown Acceleration:	-10.5 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-8.5 g's	
Lateral:	-13.0 g's	



14. Test Results Conclusion: Meets all NCHRP 230 criteria.

Figure 105. Test summary, test 1769-F-2-86.



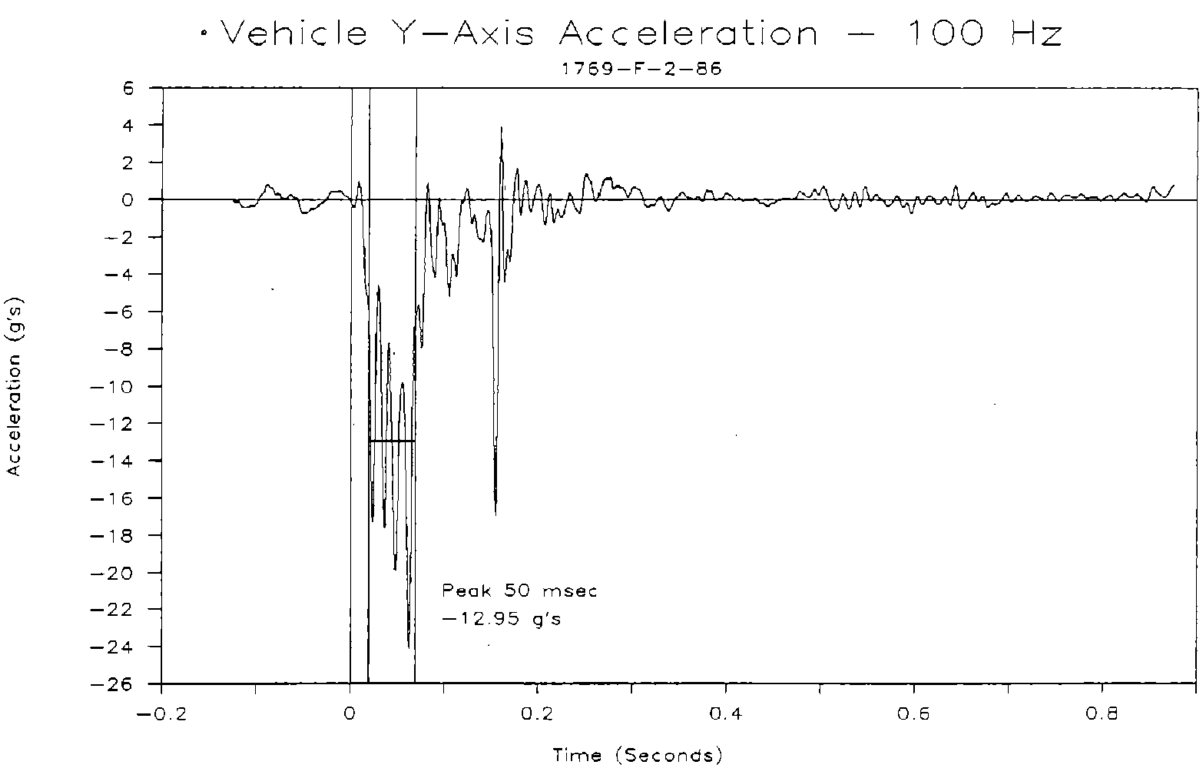


Figure 106. Vehicle acceleration, test 1769-F-2-86.

Figure 107. Posttest photographs of test vehicle, test 1769-F-2-86.

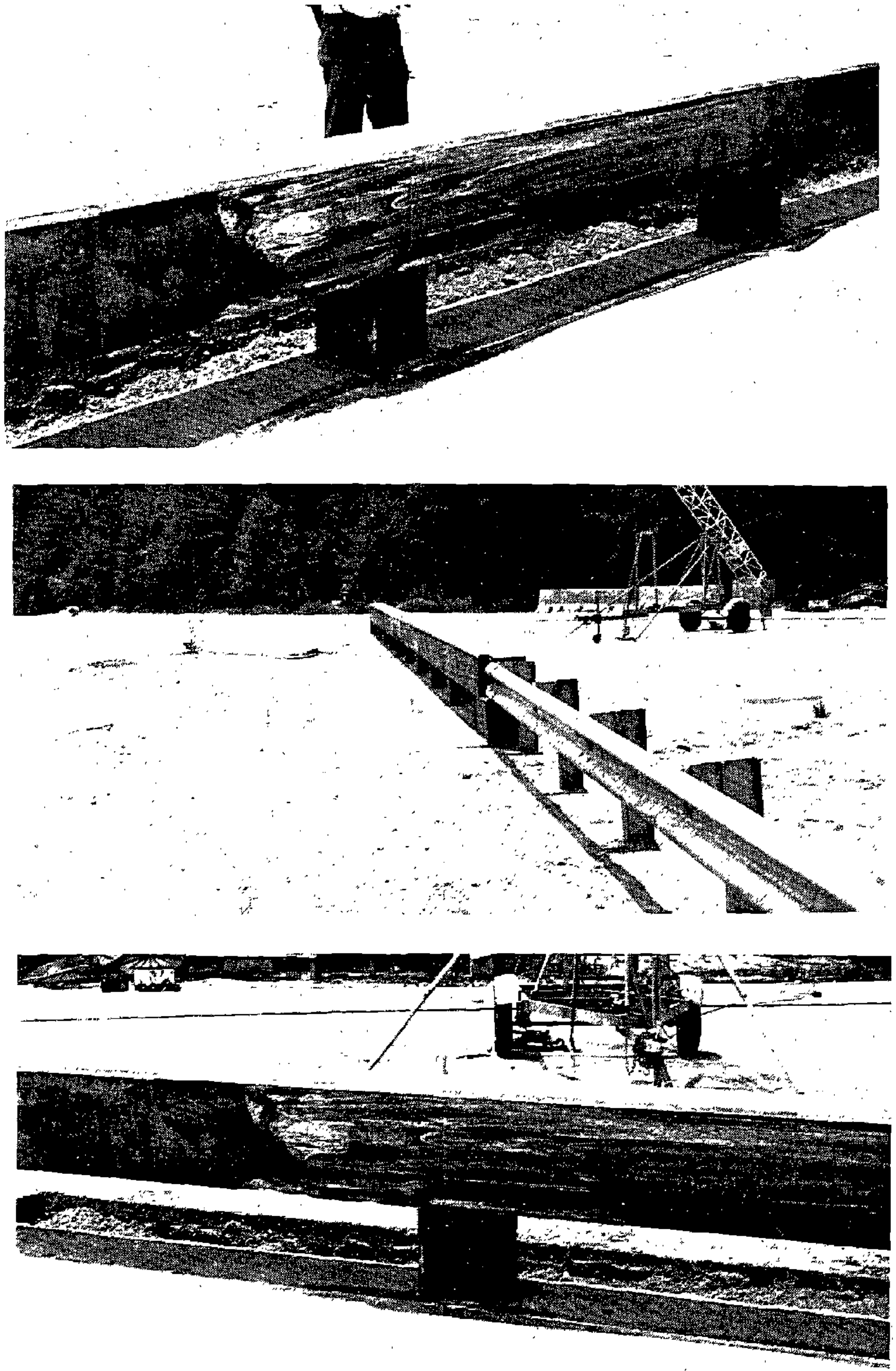


Figure 108. Posttest photographs of Nebraska bridge rail system, test 1769-F-2-86.

CONCLUSIONS

The following conclusions are based on the findings of this research project. They are divided by test article type.

1. MINNESOTA THREE-CABLE GUARDRAIL SYSTEM

a. The Minnesota three-cable guardrail system's performance was greatly enhanced for small vehicles with the addition of the modified line post. The modification consisted of a 1.5-in hole drilled through the post parallel to the cable, 5 in below ground level. With the modification, the rail had sufficient strength to redirect a large vehicle impacting at 60 mi/h and 25 degrees.

The modification of drilling the 1.5-in hole caused the area moment of inertia to be reduced approximately 50 percent in the longitudinal direction, while maintaining almost 95 percent of its strength laterally. This maintains post strength for redirection of errant vehicles, but lowers the post strength when impacted head on by the vehicle being redirected.

b. A design methodology of analyzing the weak Minnesota line post was developed and used to predict the performance of the post. The post soil model which proved successful was the 'beam on elastic foundation' approach. This model takes into account the fact that the post, like the soil, is flexible. Also investigated was the effect of the post taper on post strength and its associated effect on breaking location. For these posts, the location of the peak bending stress moves upward 2 to 3 in when compared to a post with no taper.

c. Thirty-nine pendulum tests were conducted to study the performance of round wooden posts with several modifications. The variability of these posts was shown to be high. The average breaking strength of unmodified posts was 4180 lb with a standard deviation of 1928 lb. This produces a variation of 46 percent [(1928/4180)*100].

In pendulum tests of the final design, the posts showed reductions in breaking strength which were close to the theoretical reductions. Also the location of break was in concert with that which was predicted.

d. A new terminal anchor assembly was designed to prevent vehicles which were directed down the rail from being captured by the connection between the rail cables and terminal anchor. The new anchor unit consisted of a dual end post and special steel brackets to pass the rail loads to the foundation. The design was tested successfully with a large vehicle impacting at 60 mi/h and at 25 degrees. The release device was then tested by conducting a special test where a small vehicle was directed at the trailing end of the anchor. Although the anchor released correctly, the small vehicle yawed about 90 degrees followed by a roll over of the vehicle. Additional work is needed to refine this design or develop a new one.

2. QUAD BEAM MEDIAN BARRIER

a. The quad beam rail system described in this report was tested with a 50,000-lb tractor-trailer vehicle at 50 mi/h and 15 degrees. The tractor was redirected along the rail, but the semitrailer rolled onto the rail system as it was redirected. The rollover of the semitrailer caused the tractor to also roll onto the rail, resulting in passenger compartment intrusion as the truck slid to a stop along the rail. The rail was completely demolished during the test, and the quad system was considered unacceptable.

3. **MODIFIED THRIE BEAM MEDIAN BARRIER**

a. The modified thrie beam median barrier was tested using an 18,000-lb straight truck impacting the rail at 50 mi/h and 15 degrees. The modified thrie beam median barrier was set up in accordance with the plans generated during its development. It used an eccentric loader BCT as a terminal on the upstream end and was anchored with concrete foundations elsewhere. The rail successfully redirected the vehicle without causing it to rollover.

b. The 18,000-lb truck test is the upper level test for a performance level 2 (PL2) barrier. The system had passed a small and large sedan test during previous tests. Although the pickup truck test was not conducted, the 4500-lb sedan had been conducted and this system could be thought of as an acceptable PL2 rail.

A PL2 rail is a typical rail used on highway systems and is capable of redirecting an 18,000-lb straight truck impacting at 50 mi/h and 15 degrees, a 5400-lb pickup and an 1800-lb small sedan both impacting at 60 mi/h and 20 degrees.

4. **IOWA BRIDGE RAIL**

a. The Iowa bridge rail system was successfully crash tested using a 4500-lb vehicle impacting at 60 mi/h and 25 degrees and an 1800-lb vehicle impacting at 60 mi/h and 20 degrees. Based on the results of these tests, the rail passed the requirements of NCHRP 230.

b. During the small vehicle test, the front wheel was snagged somewhat, causing higher accelerations than desired. Although the test was considered successful, the rail was redesigned by adding 4 in to the bottom side of the rail beam. In the retest, the involvement of the front wheels was almost eliminated, and no evidence of snagging was found. The new rail, which is 10 in from the deck to the bottom and 19 in high, worked well and should be considered for installation, considering that newer vehicles will have even smaller wheels and be subject to snagging.

5. NEBRASKA BRIDGE RAIL

a. The Nebraska bridge rail was tested using a 4500-lb sedan at 60 mi/h and 25 degrees and an 1800-lb sedan at 60 mi/h and 20 degrees. The results of the tests indicated the rail passed the requirements of NCHRP 230.

b. This rail exhibited characteristics similar to the Iowa bridge rail during the small vehicle test. The addition of the 4-in fill to the lower portion of the rail face could improve the performance.

RECOMMENDATIONS

1. MINNESOTA THREE-CABLE SYSTEM

a. The new end treatment which was designed and tested under this project requires additional design and testing to complete its development. The system developed showed improved performance in that it released upon impact, but it caused an 1800-lb vehicle to roll. This research should be given high priority since the problem has been identified.

b. Examine the possibility of adapting the New York three-cable end terminal to the Minnesota system. The New York system has been successfully crash tested.

c. The line post modification developed under this project should be used for new installations. The modification consists of drilling a 1.5-in hole 5 in below grade. The hole is aligned with the cable rail.

d. The existing anchor block should be deepened to obtain additional anchorage. This could be accomplished by adding 4 ft to the anchor rod. The current block location showed potential for pull out under extreme loads.

2. QUAD SYSTEM

a. The quad system should not be implemented in its current design. It did not demonstrate adequate performance.

b. Investigate the possibility of modifying the system by increasing the height and the strength of the posts. The height could be increased by changing the top W beam to a thrie beam, thus increasing the height by 6 in. The posts may need to be upgraded to a W6x12 post to achieve higher lateral strength.

3. **MODIFIED THRIE BEAM**

a. The modified thrie beam median barrier demonstrated performance at the high end for a PL2 rail. Since previous tests showed good performance with smaller vehicles, the rail could be considered a PL2 rail.

4. **IOWA BRIDGE RAIL**

a. The Iowa bridge rail showed acceptable performance. However, improved performance was shown when 4 in of depth was added to the lower side of the rail. This modification should be made to new rails to enhance their crash performance.

5. **NEBRASKA BRIDGE RAIL**

a. The modification made to the Iowa bridge rail should be considered to improve its performance.

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