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TRAFFIC BARRIERS ON CURVES, CURBS, AND SLOPES

FINAL REPORT - TECHNICAL

Prepared for:

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FOREWORD

This report presents the results of a series of crash tests to investigate potential safety problems with guardrail/curb combinations, horizontal curvature of guardrails, and guardrails installed on non-level terrain. It was found that vehicles can vault over guardrail/curb combinations under some impact conditions. Retrofit designs for solving this problem were developed. In general, horizontal curvature did not appear to degrade the performance of a guardrail. However, rollover and vaulting problems were observed when guardrails were installed on superelevated sections. It was shown that a high performance guardrail know as the Modified Thrie Beam guardrail was a solution for this problem.

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16. Abstract

A review of past research and accident databases, conduct of full-scale testing, and computer simulation and validation were conducted in an attempt to develop definitive guidelines for the placement of traffic barriers on curves, curbs, and slopes.

Initially, more extensive computer simulation and additional testing was to be conducted in order to develop the definitive guidelines. However, computer simulation and validation efforts were less than successful due to the inability of the computer software to model the complex vehicle/barrier interactions that occur in a full-scale crash test. Due to this problem, it was decided to redirect the remaining contract effort at solving geometric and hardware problems with barriers.

Seventeen full-scale tests were conducted on 15 different configurations of barriers on curves, curbs, and slopes.

Hardware modifications were developed and tested to improve the performance of a G4(1S) system in combination with a 6-in (152.4-mm) asphalt dike. A Modified Thrie Beam guardrail was used to improve barrier performance on superelevated terrain with a curved guardrail.

The following barriers demonstrated acceptable performance: a G4(1S) system with an 1192-ft (363.3-m) radius, a 27-in (685.8-mm) concrete wall with an 8-in (203.2-mm) brush curb, a G4(1S) system with a 4-in (101.6-mm) Type H curb, and a G4(1S) system installed on a downslope.

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INTRODUCTION

The purpose of this study, entitled Traffic Barriers on Curves, Curbs, and Slopes, was to analyze barrier systems used in conjunction with curves, curbs, and slopes and to identify the potential problems in these uses. The knowledge gained through full-scale testing and computer simulation would aid in the development of safer barrier designs and definitive guidelines for the proper usage and placement of barriers in the presence of curves, curbs, and slopes. The following is a breakdown of the contract objectives.

- Review Of Previous Research (Task A) - Previously conducted research of barrier testing on curves, with curbs, and on slopes was reviewed.
- Review of Accident Data (Task B) - Five databases were reviewed to identify accident-related problems associated with guardrails on curves, with curbs, and on slopes.
- Initial Full-Scale Tests (Task C) - Eight full-scale tests were planned to investigate problems with barriers on curves, with curbs, and on slopes. The results were to be used to validate a computer model.
- Program Validation (Task D) - Using the results from task C, the computer simulation program was to be validated.

The original contract contained two additional tasks, the aim of which was to develop definitive guidelines on the proper usage and placement of barriers in the presence of curves, curbs, and slopes.

However, due to problems encountered during the simulation work, the scope of the contract was altered to the identification of problems and geometric or hardware solutions to these problems. Seventeen total tests were conducted under task C.

Four sections describe tasks A through D. The task C section discusses each test in detail. 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 project.

1. BACKGROUND

Curves and sideslopes are present on a significant portion of the Nation's highway mileage. These areas present higher risk levels to vehicles in terms of accident and injury potential. Reviews of existing design guidelines for guardrails show that, in general, special provisions are not made to address these problems. Past studies have shown that barriers and guardrails designed and qualified for tangent conditions do not provide the same level of performance when installed in curves and non-level conditions. Previous studies have addressed individual aspects of the problems involving curves, curbs, and slopes. This project is the first major effort tasked with developing safer barrier designs and definitive guidelines for the proper usage and placement of barriers in the presence of curves, curbs, and slopes.

TASK A - REVIEW OF PREVIOUS RESEARCH

A literature search was conducted in task A as a review of previously conducted research. The results of studies of guardrails tested on curves, with curbs, and on slopes were reviewed. This review laid the foundation for this research project by discovering guardrail behavior on curves, curbs, and slopes.

The following reports were reviewed:

Guidelines for Placement of Longitudinal Barriers on Slopes, Effects of Changes in Effective Rail Height on Barrier Design, Hazardous Effects of Highway Features and Roadside Objects.[1,2,3] NCHRP and previous research studies have studied barriers on or near slopes and in conjunction with curbs and the effects of curb placement in terms of barrier performance.[4,5,6]

The reviewed studies indicated:

- The standard W-beam guardrail and thrie beam rails did not meet the evaluation criteria of NCHRP 230 for tests conducted with various offset distances, vehicle types, and impact angles on non-level terrain. The 3-cable rail met the same evaluation criteria.

- Various offset distances and rail heights could lead to conditions of underride or override. Tests were conducted to evaluate the performance of barriers located on sloping terrain. The test results were used to develop barrier containment criteria. Simulations were conducted by using HVOSM to model the impacting vehicle. At the point of contact with the rail, the bumper height was compared to the rail height and a determination of underride or override was performed using the developed barrier containment criteria.

- Vehicle behavior is greatly influenced by highway features and roadside objects. Guardrail performance and vehicle behavior is discussed in relation to highway features.

Furthermore, previously conducted contractor research has shown that barrier performance varies significantly in the presence of roadside slopes.

NCHRP 150 and previously conducted contractor research has shown that curb placement in relation to a barrier can greatly affect the performance of the barrier, causing override and underride, both unacceptable in terms of barrier performance.

TASK B - REVIEW OF ACCIDENT DATA

The objectives of task B were to identify problems associated with guardrails on curves, curbs, and slopes and to obtain insight into these problems.

A subcontractor was utilized to review available accident data from five databases in order to identify differences between accidents on tangential and curved roadway alignments, and the differences between accidents on level terrain and slopes. Photolog data and accident reports were also reviewed.

1. INTRODUCTION

a. Purpose

This section presents the findings of an analysis of accidents involving roadside barriers located on horizontal curves, behind curbs, and on side slopes beyond the hinge point. The purpose of this accident data review was to determine the difference in characteristics and the outcome of accidents involving roadside barriers. The objectives were to identify accident-related problems associated with guardrails in these situations and to obtain insight into those problems.

b. Background

Extensive research has been conducted in recent years to improve highway safety. A major emphasis has been on the elimination of hazardous roadside conditions and on the improvement of roadside barriers to shield those hazards that cannot be eliminated. Currently, there are no differences in the typical design for guardrail on horizontal curve compared to the typical design on tangents. The question has been raised if the design is adequate for guardrails on horizontal curves. Vehicles may impact a guardrail on a curve at a significantly different angle and speed than they normally would impact a guardrail on a tangent. Crash tests have shown that strong post guardrails need blockouts to prevent wheels and bumpers from snagging on the posts. Snagging problems are expected to be more severe at higher impact angles and higher speeds. Light posts guardrails do not have blockouts because it is expected that wheels and bumpers will be able to push these relatively weak posts over, or out of the way.

2. METHODOLOGY

a. Overview

The study concentrated on extracting relevant information from an analysis of accident databases. After a review of available databases and a series of inquiries, it was determined that there were two existing databases that could be used for this study.

As part of the National Accident Sampling System (NASS), the Longitudinal Barrier Special Study (LBSS) was conducted. Data collected by special teams throughout the country were codified and the resulting LBSS database contained extensive data on accidents involving collisions with traffic barriers. Consequently, the LBSS database was selected and used in this study.

The second available existing database selected was the one created by the New York State Department of Transportation, Bureau of Engineering Research. They developed the database and made available a copy for the purposes of this study.

To supplement these two databases, three additional databases were created from data obtained from the Alabama Highway Department, the Michigan Department of Transportation, and the Illinois State Toll Highway Authority. A description of each of these databases is presented in the next section.

b. Accident Databases

The five databases used in this study are identified in table 1. The LBSS database was recreated from computer listings pertaining to the accidents investigated in 1984, 1985, and 1986. The New York State Special Study database was developed by others. The three other databases were created for this study from data and information obtained from State agencies.

Unfortunately, none of the databases contained information on impact speed, one of the key factors for barrier accidents. Alabama does provide for the investigating officer to record the travelling speed on their accident report form. However, this was determined to be a unreliable estimate of impact speed. No values for impact speed were coded or entered for any accident record in the LBSS database, although the database structure was established to include impact speed.

(1) LBSS

Hard copy listings of the merged Longitudinal Barrier Study (LBSS) and National Accident Sampling System (NASS) data files for 1984, 1985, and 1986 were obtained from a computer consultants to the Federal Highway Administration (FHWA). The data related to accidents involving a variety of longitudinal barrier systems. However, for this study, accidents involving concrete shaped barriers, bridge rails, and the end or terminal section of guardrails were excluded.

The database consisted of 364 data elements for each accident record. A total of 95 data elements relevant to this study were selected for further analysis. A microcomputer-based database consisting of these 95 data elements was subsequently developed. In entering the data, it was determined that information related to 32 elements was missing for 58 accident cases. Consequently,

Table 1. Databases analyzed.

	Database	Primary Source of Information	Years in Which Accidents Occurred	Number of Hit Barrier Cases	Barrier Types
1.	LBSS[1]	Special reporting forms & field investigations by PSU teams	1984-86	287	Various
2.	Michigan	Individual State accident reports & State's computer database	1986	196	Various
3.	New York Special Study[2]	Field observations and individual State accident reports	1983	2,213	Various
4.	Alabama	Individual State accident reports, photologs, & limited field inspections	1986	189	Blocked-out W-beam, Steel Post only
5.	Illinois State Highway Toll	Individual State accident reports	1986-87	165	Blocked-out W-beam, Steel Post only

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1 NASS Longitudinal Barrier Special Study.

2 Database developed by NYSDOT's Engineering Research and Development Bureau.

the original data forms maintained by a contractor to the National Highway Traffic Safety Administration (NHTSA), were reviewed and the pertinent data obtained.

(2) New York

The Engineering Research and Development Bureau of the New York State Department of Transportation recently developed a database consisting of over 3,000 accidents reported in 1983 in New York State in which the first harmful event was collision with a traffic barrier. Extensive field investigations and reviews of the accident reports were conducted by NYSDOT personnel to gather information on the vehicle, the guardrail characteristics, environmental conditions, and site characteristics. The Bureau provided a copy of the database on diskette.

(3) Michigan

The Michigan database contained data obtained from the files provided by the Michigan Department of Transportation. These files were a guardrail inventory file, a segment file (geometric operational data), and an accident file. The accident file consisted of data from accidents occurring in 1986 in the four counties around Lansing (Ionia, Eaton, Ingham, and Clinton Counties). Subcontract personnel also made a field trip to Lansing to obtain missing geometric data from photologs. A total of 244 guardrail accidents were generated from photologs from the combination of the three files, and hard copies of police accident reports were obtained from the Michigan State Police for these accidents. The accident reports provided more insight into guardrail performance. After screening out guardrail end hit accidents and non-longitudinal barrier accidents, a total of 196 accident records were used in the analysis.

(4) Alabama

Hard copies of 1986 police accident reports involving roadside barriers were obtained with the assistance of the Alabama Highway Department and the Alabama Department of Public Safety. In addition, photologs of selected sections containing the barriers involved in these accidents were reviewed and a sample of site investigations were conducted. These accident reports and other information gathered were than coded into a microcomputer database for detailed analysis.

The database consisted of 30 data elements from accident reports and an additional 20 data elements from the photolog reviews and field investigation for 189 accidents for which the first harmful event was an impact with a longitudinal traffic barrier. Accidents with the end of the guardrail were screened out.

(5) Illinois

The Illinois State Toll Highway Authority provided a computer-generated listing and copies of the original police accident reports for accidents related to longitudinal barriers.

A database was developed on a microcomputer that included 13 data elements from the computer printout of the Illinois State database. Although computer printouts received from the State provided some data elements, the hard copy accident reports were reviewed to extract vital information contained in the report, narrative, and sketch. Information for 26 data elements were coded and entered for a total of 165 accidents reported in 1986 and 1987.

c. Primary Measures of Effectiveness

One of the purposes of traffic barriers is to reduce the severity of accidents. However, accident severity is affected by many other items such as seat belt usage, speed at impact, vehicle size and weight, environmental conditions, and geometric and cross-section factors. Because the emphasis of this study was on the design of the barrier, another factor was selected as the primary measure of effectiveness, namely, barrier performance. In this context, "good" barrier performance meant that the barrier performed adequately by safely redirecting the vehicle. The barrier performance was defined as "poor" if the vehicle impacting the barrier snagged, broke through, went over or went under the barrier, or if the barrier brought the vehicle to an abrupt stop.

An analysis was conducted to determine if there is a relationship between the two measures of effectiveness: accident severity distribution and barrier performance. Table 2 shows that there does indeed appear to be a strong relationship between these two variables. Accidents with poor barrier performance had a higher proportion of fatal and A-injury accidents than accidents with good barrier performance. It should be noted, though, that the type of barrier is not considered in the analysis.

3. FINDINGS

This section of the report presents the major findings of the accident analysis. Specifically, results are discussed with respect to guardrails on curves, guardrails placed behind curbs, and finally, guardrails placed down the side slope. In addition, data on impact angles, road surface conditions, and other accident characteristics are also discussed.

a. Horizontal Alignment

One of the major questions raised was whether the design for guardrails on horizontal curves is adequate. An analysis of the available accident data did not reveal evidence to suggest that

Table 2. Relationship between barrier performance and accident severity.

Accident Severity	Barrier Performance: Good No[1]	%	Poor No	%
Fatal	16	1%	19	5%
A-Injury	181	9%	68	18%
B-Injury	517	26%	123	32%
C-Injury	450	23%	96	25%
P.D.O[2]	800	41%	77	20%
TOTALS	1,964	100%	383	100%

NOTES:

- Databases: LBSS, New York, and Michigan.
- Computed Chi-Square Statistic = 100.10 with 4 degrees of freedom; probability <0.001.

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1 No. = Number of Accident Cases

2 P.D.O. = Property Damage Only

guardrails on horizontal curves performed worse than guardrails on tangents. Table 3 presents a summary comparing the portion of accident cases with poor barrier performance on curves versus tangents for various barrier types. The G1, G2, etc. barrier types are the designations that have been established and presented in the American Association of State Highway and Transportation Officials (AASHTO) Guide for Selecting, Locating and Designing Traffic Barriers. The C2 barrier listed in table 3 is an old cable on strong post barrier that is no longer used for new construction. There was insufficient evidence to suggest that curves had a greater proportion of poor performance compared to tangents, except for the blocked-out W-beam with heavy posts. However, the statistical analysis revealed that this difference was not statistically significant at $\alpha = 0.10$. On the contrary, the data indicates that blocked-out, steel post cable systems actually had better performance on curves than on tangents and this difference was found to be statistically significant at $\alpha = 0.10$.

Differences in terms of accident severity between tangents and curves were also investigated. Two measures of accident severity were employed. The percentage of all reported accidents that are fatal or A-injury accidents was the first. The results are summarized for the various barrier types in table 4. The blocked-out W-beam with heavy posts had a significantly higher proportion of severe accidents on tangents than on curves. As expected, the W-beam on heavy posts with no block-out present had a significantly higher proportion of severe accidents on curves than on tangents. This data suggests that W-beam traffic barriers should be designed with a block-out when they are placed on horizontal curves. Table 4 also indicates that Box-beam barrier systems with light posts on curves had a significantly higher proportion of fatal or A-injury accidents than similar barriers on tangents.

The second measure of accident severity was the proportion of all accidents that are fatal or injury accidents (i.e., A-injury, B-injury, or C-injury). Table 5 present the results, which contradict the findings previously discussed. There were no significant differences between no block-outs on tangents compared to W-beam with heavy posts and no block-outs on curves. There were no significant differences between box-beams with light posts on tangents compared to box-beams with light posts on curves. However, using this measure of severity, cable systems with light posts and W-beam barriers with light posts had significantly higher percentages of fatal and injury accidents on curves than on tangents.

In terms of frequency, slightly more hit-barrier accidents occurred on left curves than on right curves. An analysis of the New York State database revealed that 616 hit-barrier accidents occurred on left curves and 555 occurred on right curves. The combined LBSS and Michigan databases were consistent in this respect. A total of 86 accidents occurred on left curves,

Table 3. Performance comparison of tangents vs. curves by barrier type.

Barrier Type	Tangents No[1]	Tangents Prop. Poor[2]	Curves No	Curves Prop. Poor	Statistically Significant Difference (at α=0.10)
Cable, Light Post (G1)	186	.19	253	.20	No
Cable, Blocked-Out, Steel Post (C2)	80	.25	142	.16	Yes[3]
W-beam, Light Post (G2)	145	.14	201	.15	No
W-beam, Blocked-Out, Heavy Post (G4)	73	.18	57	.26	No
W-beam, Not Blocked-Out, Heavy Post (G6)	96	.30	130	.30	No
Box-Beam, Light Post (G3)	312	.04	354	.04	No

NOTE:

Databases: New York and LBSS.

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1 No. = Number of Accident Cases

2 Prop. Poor = Proportion of all accident cases on tangents (or on curves) in which the barrier performed poorly.

3 Computed Z - Statistic = 1.58, Probability = 0.06

Table 4. Comparison of tangents vs. curves by barrier type (fatal + A-injury).

Barrier Type	Tangents No[1]	Tangents Prop. F+A[2]	Curves No	Curves Prop. F+A	Statistically Significant Difference (at α=0.10)
Cable, Light Post (G1)	151	.09	214	.11	No
Cable, Blocked-Out, Steel Post (C2)	74	.12	128	.16	No
W-beam, Light Post (G2)	127	.12	187	.16	No
W-beam, Blocked-Out, Heavy Post (G4)	68	.21	53	.11	Yes[3]
W-beam, Not Blocked-Out, Heavy Post (G6)	88	.16	116	.23	Yes[4]
Box-Beam, Light Post (G3)	271	.08	319	.13	Yes[5]

NOTE:

Databases: New York and LBSS.

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1 No. = Number of Accident Cases

2 Prop. F+A = Proportion of all tangent accidents (or curve accidents) that resulted in fatalities and/or A-injuries.

3 Computed Z - Statistic = 1.34, Probability = 0.09

4 Computed Z - Statistic = 1.29, Probability = 0.10

5 Computed Z - Statistic = 1.84, Probability = 0.03

Table 5. Severity comparison of tangents vs. curves by barrier type (fatal + all injury).

Barrier Type	Tangents No[1]	Tangents Prop. F+I[2]	Curves No	Curves Prop. F+I	Statistically Significant Difference (at α=0.10)
Cable, Light Post (G1)	151	.56	214	.64	Yes[3]
Cable, Blocked-Out, Steel Post (C2)	74	.72	128	.75	No
W-beam, Light Post (G2)	127	.57	187	.66	Yes[4]
W-beam, Blocked-Out, Heavy Post (G4)	68	.71	53	.64	No
W-beam, Not Blocked-Out, Heavy Post (G6)	88	.69	116	.71	No
Box-Beam, Light Post (G3)	271	.70	319	.73	No

NOTE:

Databases: New York and LBSS.

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1 No. = Number of Accident Cases

2 Prop. F+I = Proportion of all accidents on tangent (or curves) that resulted in fatalities and/or personal injuries (A, B, or C type).

3 Computed Z - Statistic = 1.61, Probability = 0.05

4 Computed Z - Statistic = 1.58, Probability = 0.06

whereas only 66 accidents occurred on right curves. Unfortunately, for accident records in the New York State database it was not possible to determine if the traffic barrier was located on the right side or left side of the roadway. However, it was possible to make the determination for the combined LBSS and Michigan databases.

Figure 1 presents the distribution of hit-barrier accidents by departure location for left curves and right curves. For approximately 76 percent of the accidents reported on left curves, the vehicle ran off the road and struck a barrier on the right side of the road. For accidents on right curves, about half of the vehicles ran off the road and struck a barrier on the left side and the other half ran off the right side. These results are consistent with other studies. An accident analysis of breakaway and non-breakaway poles found 82 percent of hit-pole accidents in which a vehicle ran off the road on a left curve involved a pole on the right side of the road.[7] That study also found that 52.6 percent of the hit-pole accidents in which a vehicle ran off the road on a right curve involved a pole on the right side of the road. A 1974 study of run-off-road hit-fixed-objects accidents found that for 82 percent of run-off-road accidents on left curves on undivided roads, the vehicle ran off the road and hit a fixed object on the right side of the road. This 1974 study also found that approximately 42 percent of all accidents on right curves involved a vehicle running off and hitting an object on the right side of the road.

Overall, the databases provide evidence that there were more accidents involving barriers placed on the outside of the horizontal curve than with barriers placed on the inside of the curve.

b. Curbing

Another one of the major questions raised was whether the design for guardrails was adequate when the guardrails were placed behind a curb. An analysis of the combined New York and LBSS databases revealed that "observed" proportion of poor performance was, for most barrier systems, larger when the curbs were present. However, due to the limited sample sizes, these differences were determined not to be statistically significant, except for cable systems with light posts. Table 6 presents the results of this analysis.

It should be understood that even though the calculations indicate the difference is significant, it is based on a sample of only 12 accident cases for which curbs were present.

In terms of accident severity, the cable systems with light posts were found to have a higher proportion of fatal and A-injury accidents when curbs were present than when curbs were not present. Table 7 presents the results. Once again, it should be understood that although significant, this difference is based on

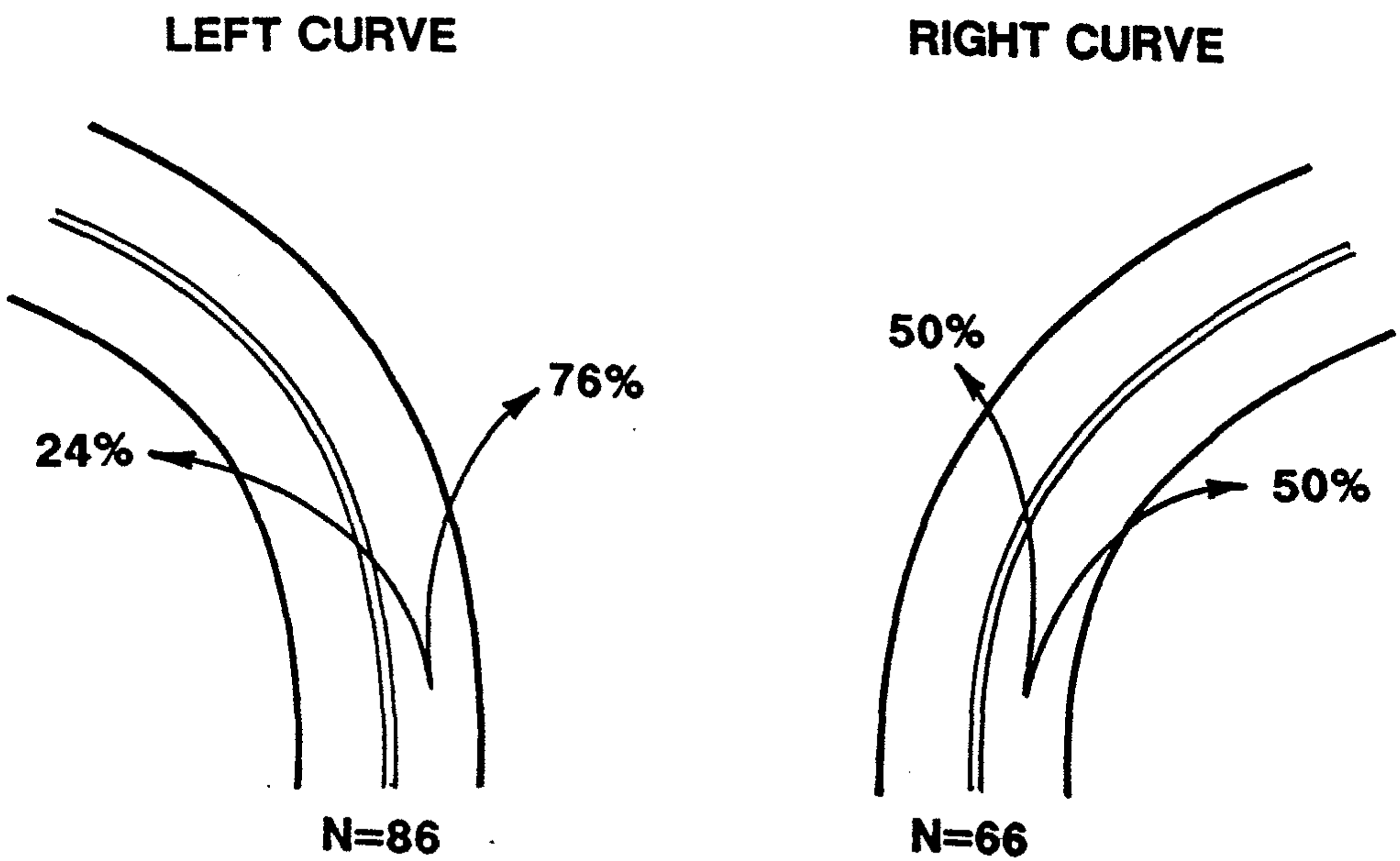

Figure 1. Distribution of hit barrier accidents by curve direction.

Table 6. Performance comparison by curb presence and guardrail type.

Barrier Type	No Curb: No[1]	No Curb: Prop. Poor[2]	Curb: No	Curb: Prop. Poor	Statistically Significant Difference (at α=0.10)
Cable, Light Post (G1)	421	.19	12	.42	Yes[3]
Cable, Blocked-Out, Steel Post (C2)	220	.19	6	.33	No
W-beam, Light Post (G2)	313	.14	33	.21	No
W-beam, Blocked-Out, Heavy Post (G4)	99	.19	32	.28	No
W-beam, Not Blocked-Out, Heavy Post (G6)	195	.30	35	.29	No
Box-Beam, Light Post (G3)	571	.04	58	.07	No

NOTE:

Databases: New York and LBSS.

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1 No. = Number of Accident Cases

2 Prop. Poor = Proportion of all accidents cases where curbs were not present (or were present) in which the barrier performed poorly.

3 Computed Z - Statistic = 1.84, Probability = 0.03

Table 7. Severity comparison by presence of guardrail and guardrail type (fatal + A-injury).

Barrier Type	No Curb No[1]	No Curb Prop. F+A[2]	Curb No	Curb Prop. F+A	Statistically Significant Difference (at α=0.10)
Cable, Light Post (G1)	355	.10	11	.27	Yes[3]
Cable, Blocked-Out, Steel Post (C2)	199	.15	6	.17	No
W-beam, Light Post (G2)	285	.13	29	.24	Yes[4]
W-beam, Blocked-Out, Heavy Post (G4)	92	.16	30	.17	No
W-beam, Not Blocked-Out, Heavy Post (G6)	174	.22	32	.09	Yes[5]
Box-Beam, Light Post (G3)	525	.11	86	.05	Yes[6]

NOTE:

Databases: New York and LBSS.

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1 No. = Number of Accident Cases

2 Prop. F+A = Proportion of all accidents cases where curbs were not present (or were present) in which a fatality and/or A-injury occurred.

3 Computed Z - Statistic = 1.71, Probability = 0.04

4 Computed Z - Statistic = 1.61, Probability = 0.05

5 Computed Z - Statistic = 1.56, Probability = 0.06

6 Computed Z - Statistic = 1.79, Probability = 0.04

a sample of only 11 accident cases with curbs. Table 7 also shows something very surprising. For box-beam barriers with light posts and for W-beams with heavy posts but no block-outs, a lower proportion of severe accidents was found with the presence of curbs.

An analysis was also conducted using the other severity measure, namely, proportion of fatal and all-injury accidents. These results, which are shown in table 8, also indicate potential problems when light post cable systems are placed behind curbs. The analysis also suggests that the severity of accidents involving box-beams on light posts is less when curbs are present. However, the difference for W-beams on heavy posts and no block-outs was not found to be statistically significant.

c. Roadside Slope

The LBSS database was the only one that contained sufficient data to investigate traffic barriers placed on side slopes. The situation of interest in this case was where the guardrail is placed beyond the hinge point and down on the side slope. Of the 287 accident cases, it was determined that 58 accidents involved guardrails placed beyond the hinge point.

An analysis of these 58 accident cases revealed that the side slope was relatively gentle (i.e., 4 to 1 or greater). This finding reflects AASHTO practices in that guardrails are recommended for slopes less than 4 to 1. Barrier performance of guardrails placed beyond the hinge point was found to be significantly worse than guardrails placed before the hinge point.

However, the sample sizes are too small to develop any relationship among slope, distance, and barrier performance or to draw firm conclusions about the effect of side slope.

d. Other Accident Characteristics

(1) Impact Angle

In addition to this comparative analysis of tangents versus curves and curbs versus curbs, the study attempted to gather information on the characteristics and outcomes of accidents involving traffic barriers. One of the research questions posed was what is the angle at which the vehicle impacts the guardrail. The LBSS database was found to be the only database that contained information on impact angle. Figure 2 presents the distribution of impact angles. Many have argued, rightfully so, that the impact speed must be considered with impact angle. However, no data was available for impact speed. Consequently, this is an attempt to present the available information. Figure 2 indicates that the 50th percentile impact angle is 16° and that the 85th percentile is 36°. Based on past research, physics

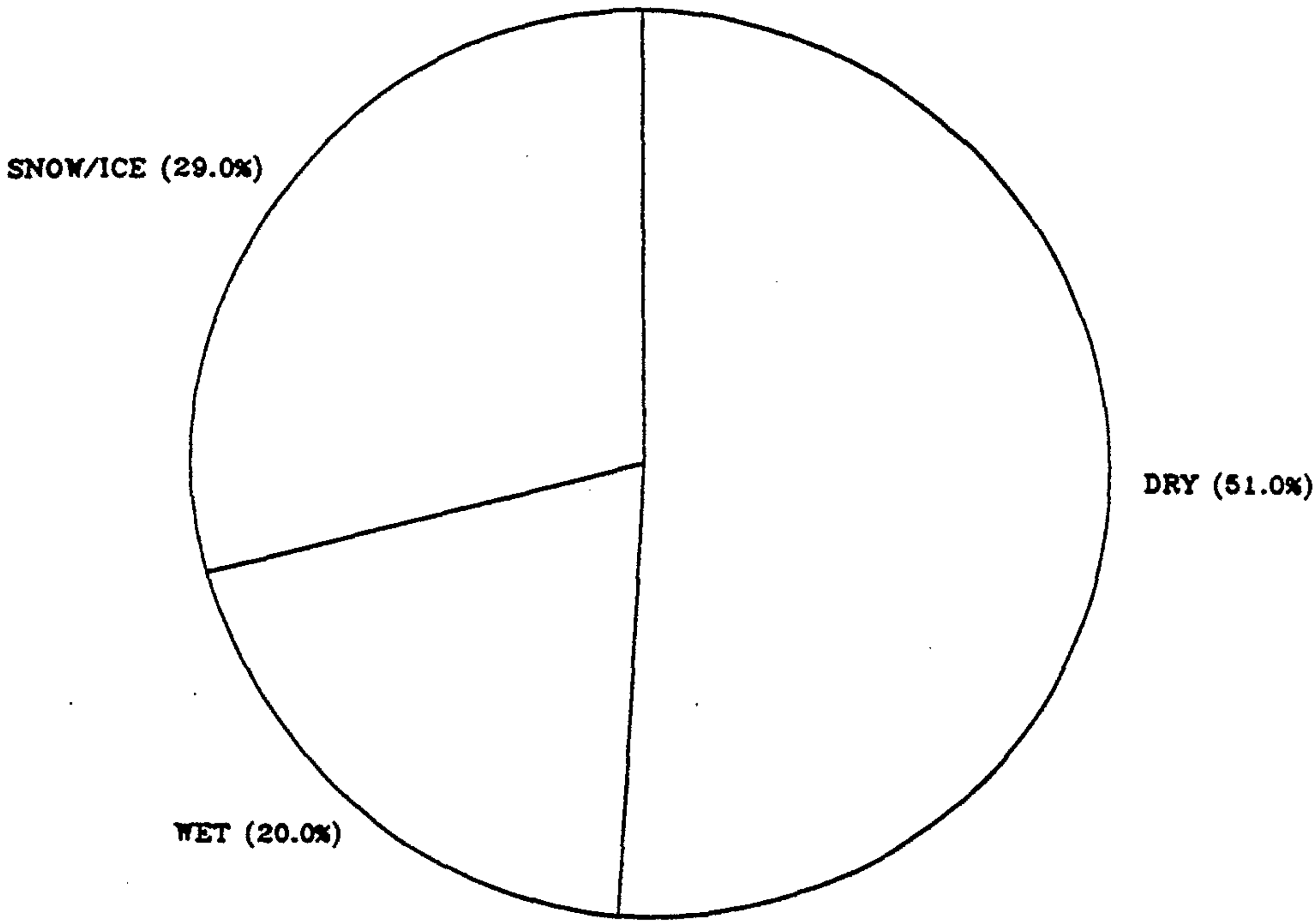

Figure 3. Distribution of accidents by pavement conditions.

Table 9. Performance comparison by surface conditions and guardrail type.

Barrier Type	Dry		Wet		Snow	
	No[1]	Prop. Poor[2]	No	Prop. Poor	No	Prop. Poor
Cable, Light Post (G1)	221	.23	61	.23	136	.13
Cable, Blocked-Out, Steel Post (C2)	104	.29	46	.13	61	.13
W-beam, Light Post (G2)	167	.19	63	.63	101	.37
W-beam, Blocked-Out, Heavy Post (G4)	86	.23	29	.17	13	.15
W-beam, Not Blocked-Out, Heavy Post (G6)	119	.32	45	.22	50	.22
Box-Beam, Light Post (G3)	119	.14	45	.09	62	.08

NOTE:

Databases: New York and LBSS.

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[1] No. = Number of Accident Cases

[2] Prop. Poor = Proportion of all accident cases reported on dry pavement (or on wet pavement or on snow-/ice-covered pavement).

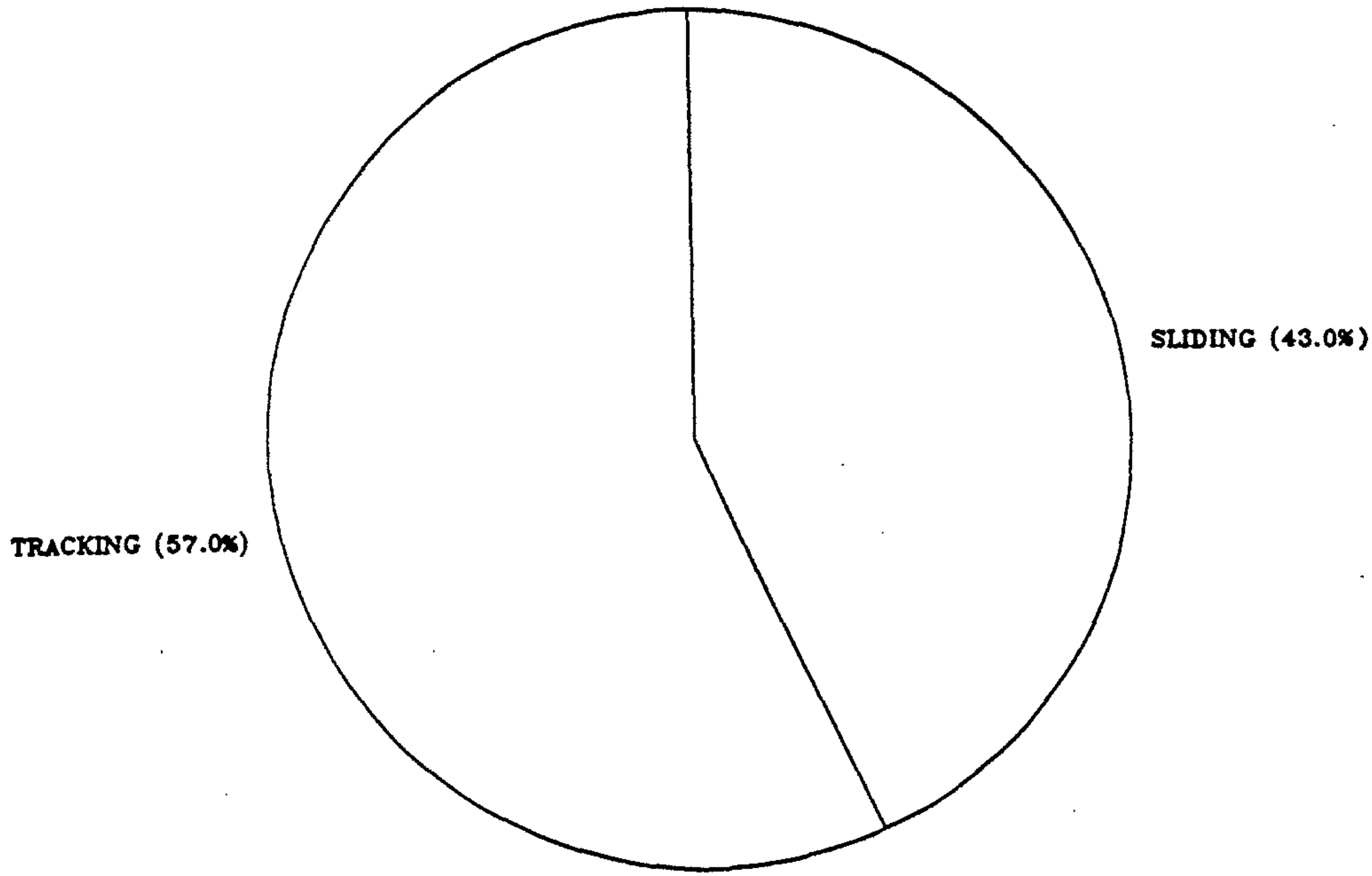


Figure 4. Distribution of accidents by sliding vs. tracking.

2. For guardrail accidents that occurred on curves:

   - 42 percent of the total of 152 ran off the right side on a left curve.
   - 22 percent of the total of 152 ran off to the right side on the right curve.
   - 22 percent of the total of 152 ran off to the left side of a right curve.
   - 14 percent of the total of 152 ran off to the left side of a left curve.

3. A curb was present for only 9 percent of the guardrail accidents analyzed. Again, without data on the presence of curbs in combination with guardrails, it cannot be determined if this reflects an over-representation.

4. Of the accidents analyzed, 20 percent involved wet pavement conditions and 29 percent involved snow or ice.

5. Of the accidents analyzed, 57 percent involved vehicles tracking as they hit the guardrail and 43 percent were sliding.

6. Based on the available data, the 15th, 50th, and 85th percentile impact angles were 5°, 16°, and 36°, respectively. Vehicles impacted the guardrail at a slightly larger angle on curves than on tangents (the median percentiles were 17° and 14°, respectively). The associated speed for these impacts was not available.

Regarding the outcomes of the guardrail accidents, the following findings are presented:

There was no evidence to suggest that barrier performance on curves is worse than barrier performance on tangents. When severity of the accident was analyzed, mixed results were found.

For cable barriers with light posts (G1), barrier performance and accident severity were found to be significantly worse when curbs were present. However, this finding is based on a small sample size. Similar findings were found for W-beam on light post (G2) guardrails.

For cable and W-beam type barrier systems, the performance of the barrier improved with increasing offset distance from the roadway.

TASK C - INITIAL FULL-SCALE TESTS

Task C was originally specified as the preparation of a test plan and the conduct of eight full-scale crash tests. These tests were designed to investigate potential problems with the performance of standard W-beam on strong post guardrails when located on curves or slopes, or when used in combination with curbs.

A test plan was created to investigate barrier performance in conjunction with curves, curbs, and slopes. The test plan contained various geometries for the tests.

Following two revisions, a final test plan was formulated. The tests contained in the final test plan were:

- 1800-lb vehicle, 20°, 60 mi/h, Curve.
- 5400-lb vehicle, 20°, 60 mi/h, Curve.
- 5400-lb vehicle, 20°, 60 mi/h, Curve.
- 5400-lb vehicle, 20°, 60 mi/h, Curb.
- 1800-lb vehicle, 20°, 60 mi/h, Curb.
- vehicle to be determined, 7 to 10°, 60 mi/h, curb.
- 5400-lb vehicle, 20°, 60 mi/h, slope.
- Open test (to be determined).

---

1 lb = 0.45 kg   1 mi/h = 1.61 km/h

Following the conduct of these tests, and using the computer program selected for the Task D validation work, these tests were to be validated against and used to improve the computer simulation program. Following unsuccessful results from the program and after investigation of the causes of the problems, it was discovered that the program code contained both simple errors and serious flaws.

It was decided that it would not be possible to use the computer program to create the desired simulations of varied geometries and barriers in order to expand the design envelope. At this point, it was decided to evaluate design and geometry changes by conducting additional full-scale tests. Seventeen tests were conducted in this task. Table 10 lists the tests conducted.

The following text describes the tests conducted under this task.

1. **TEST 1862-1-88**

a. **Test Device**

The test device was a standard G4(1S) W-beam rail with an AASHTO type A curb and gutter placed in front of the posts. The face of the curb was aligned with the face of the W-beam. Approximately 80 ft (24.4 m) of curb was installed along the rail system. The curb began between posts 14 and 15 or approximately 12 ft (3.7 m) upstream of the impact point.

The entire system was 218.75 ft (66.7 m) long. The system consisted of 181.25 ft (55.3 m) of W-beam and a 37.5-ft (11.4-m) standard Breakaway Cable Terminal (BCT). A cable anchor assembly was used on the downstream end. This assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 5 shows the test site and test device. Figure 6 shows pretest photographs of the guardrail system.

b. **Test Vehicle**

The test vehicle was a 1982 Chevrolet C20 pickup. The target inertial vehicle weight was 5400 lb (2452 kg). The vehicle weighed 4537 lb (2060 kg) empty. Ballast weighing 860 lb (390 kg) was added. The ballasted inertial weight of the truck was 5415 lb (2458 kg). The gross vehicle weight was 5742 lb (2607 kg).

Two dummies were placed in the vehicle. The driver was restrained while the passenger was unrestrained. X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the cab of the truck. Pretest photographs of the test vehicle are shown in figure 7. Table 11 lists important parameters of the test vehicle.

c. **Impact Description**

Review of the high-speed films and speed-trap data indicated that the test vehicle impacted at 61.3 mi/h (98.7 km/h) and 20°. This review also indicated that the right corner of the vehicle impacted the rail at the desired point.

Upon impact, the vehicle penetrated into the rail with little or no redirection prior to the right-front tire impacting the curb. The wheel hit the curb hard, gouging out a small portion of

Table 11. Test vehicle parameters, test 1862-1-88.

Item	Actual	Specification
Empty Weight	4537 lb	n/a
Ballast	860 lb	n/a
Total Weight, Inertial	5415 lb	5400 lb
Total Weight, Gross	5742 lb	n/a
H_{cg}	26 in	27 ± 1 in
A (front to cg), Inertial	8.58 ft	8.5 ± 0.1 ft
B (width)	6.58 ft	6.5 ft
Truck Length	217 in	
Truck Wheelbase	132 in	
Wheel/Tire Size	235 85R16	
Truck Box Size	8 ft long by 1.5 ft high by 5.5 ft wide	
Ground to Box Floor	27 in	

1 lb = 0.45 kg   1 ft = 0.31 m   1 in = 25.4 mm

concrete. Approximately 0.050 s after impact, the vehicle started to rise up, caused by the wheel overriding the curb. This allowed the bumper to get on top of the rail, and thus the vehicle rode over the rail with little or no redirection. The vehicle rolled counterclockwise approximately 45° before the left tires impacted the top of the rail. This stabilized the vehicle and caused it to roll back to an upright position. The vehicle was airborne for approximately 70 ft (21.4 m) and reached a height of 3 ft (0.9 m) from the ground to the bottom of the wheels. The vehicle then landed on all four wheels about 15 ft (4.6 m) behind the rail and continued away on the field side of the rail.

The driver dummy remained seated throughout the impact event. The passenger broke out the side window, turned around 180°, and landed on the driver. The final position of the passenger was under the dash and on the floor.

A summary of test conditions and results are shown in figure 8. Data analysis was performed. The x- and y-axis, 100-Hz data plots are shown in figure 9.

d. Vehicle Damage

The front of the truck was damaged and the right tire and wheel were broken. The rail side of the vehicle was damaged slightly from impacting the rail. Post-test photographs of the test vehicle are shown in figure 10.

e. Barrier Damage

The barrier was damaged from the impact point downstream 1.5 rail lengths [18 ft (5.5 m)]. Posts and blocks in this area were bent or deformed. The rail was not detached from the blocks. The curb was not damaged except for a local gouge where the right front tire and wheel impacted. Post-test photographs of the rail are shown in figure 11.

f. Test Evaluation

This test was evaluated using the AASHTO Guide Specifications for Bridge Railings. The following is an item-by-item evaluation using this guideline.

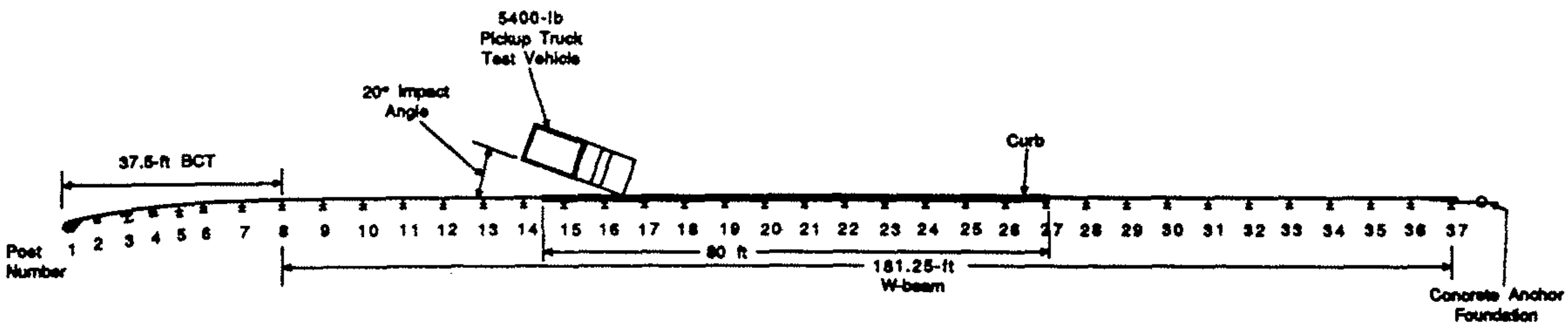
Required Criteria:

a. The vehicle was **NOT** contained by the test article.
b. There were no detached elements.
c. Integrity of the passenger compartment was maintained.
d. The vehicle remained upright.
g. Delta-V and Ridedown values were within limits.

Desirable Criteria:

e. The vehicle was **NOT** redirected.
f. Vehicle railing interaction:
mu = not evaluated, no assessment.
h. No exit angle. The vehicle exited on the field side of the rail.

TEST ARTICLE FAILS DUE TO VEHICLE PENETRATION AND VAULTING OF THE RAIL.



1 ft = 0.30 m   1 lb = 0.45 kg

Figure 5. Test site layout, test 1862-1-88.

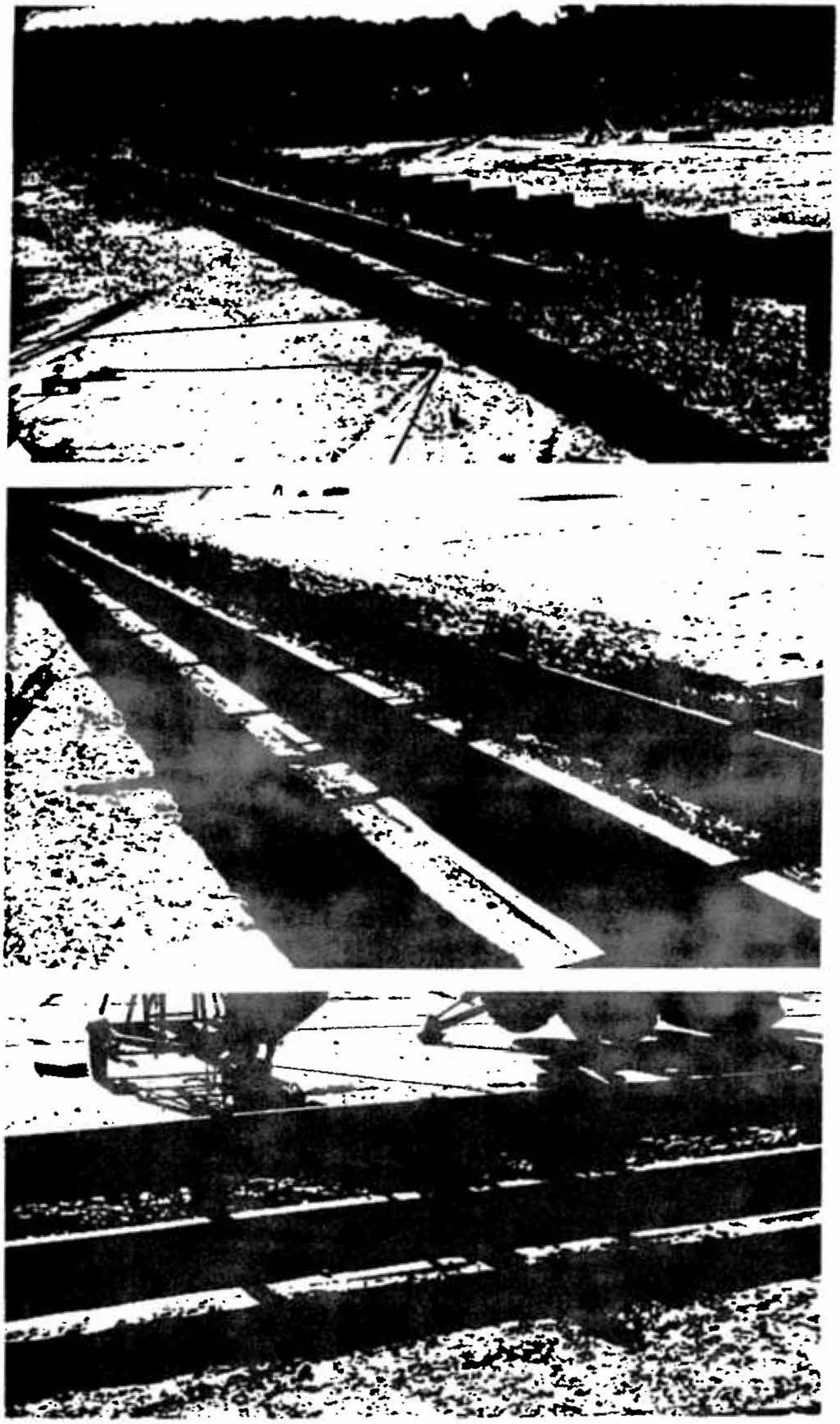


Figure 6. Pretest photographs of guardrail system, test 1862-1-88.

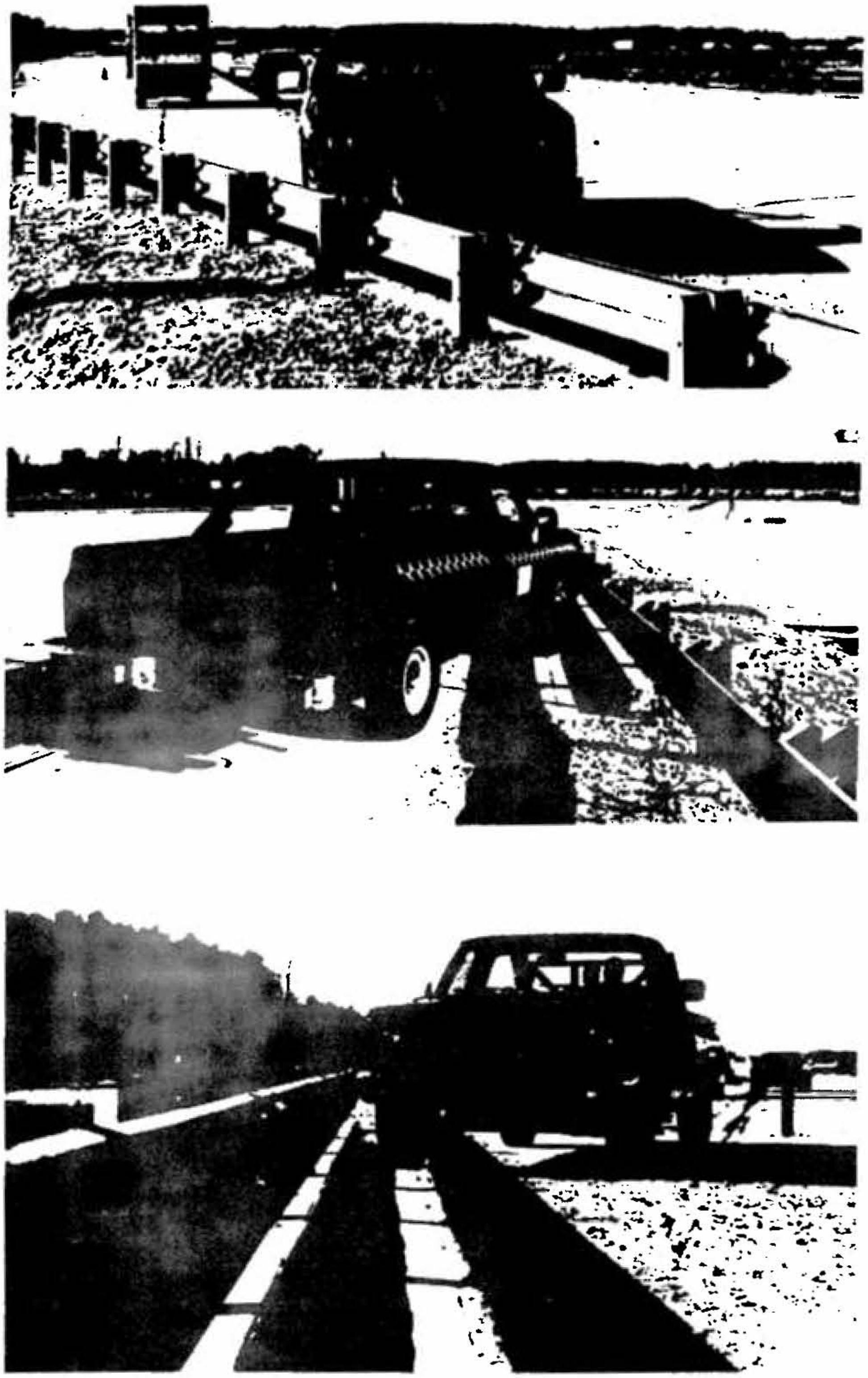
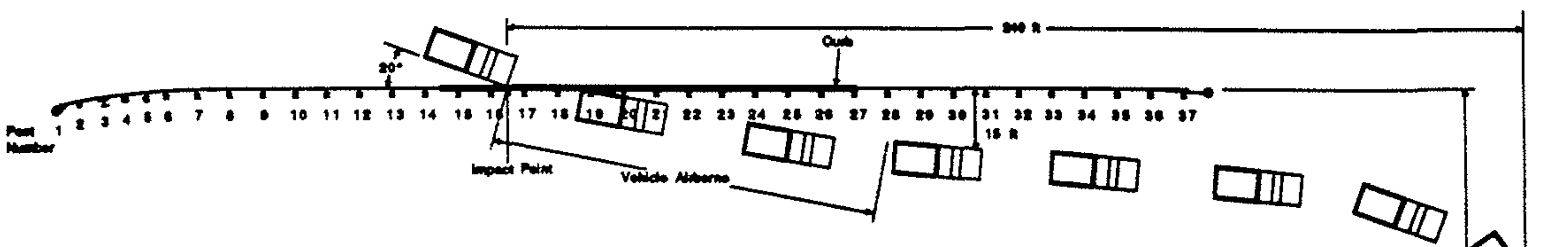
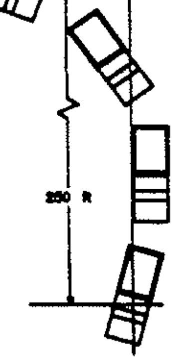


Figure 7. Pretest photographs of test vehicle, test 1862-1-88.





32°F = 0°C   1 ft = 0.30 m   1 lb = 0.45 kg   1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s   1 kip-ft = 1360 N-m   1 g = 9.8 m/s^2

Contract Number:	DTFH61-87-C-00126
Date:	6 December 1988
Weather:	Clear 60° F
Test Vehicle:	1982 Chevrolet C20 Pickup
Device Configuration:	G4(1S) W-Beam with AASHTO Type A curb in front of barrier, 219 ft total length, 37.5-ft BCT

1. Vehicle Weight:
   - Planned, Inertial: 5400
   - Actual, Inertial: 5417
   - Actual, Gross: 5742
2. Number of Occupants: Two
3. Occupant Model: Part 572, 50 percentile male
4. Occupant Locations: Driver Seat, Restrained; Passenger Seat, Unrestrained
5. Impact:

	Speed	Angle	Location
Planned:	60.0 mi/h	20°	Midspan posts 16 and 17
Actual:	61.3 mi/h	20°	Midspan posts 16 and 17

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

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) 01RFEE2
11. NCHRP 230 Test Number: Special; AASHTO Test Type: PL2

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-16.3 ft/s	30/40 ft/s
Ridedown Acceleration:	-2.9 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	10.2 ft/s	20/30 ft/s
Ridedown Acceleration:	5.5 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-5.2 g's	
Lateral:	3.8 g's	

14. Vehicle-Railing Interaction Coefficient of Friction:

$$mu = \frac{\cos theta - V_p/V}{\sin theta}$$

mu	assessment
n/a	n/a

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

a. The vehicle was NOT contained by the test article. b. There were no detached elements. c. Integrity of the passenger compartment was maintained. d. The vehicle remained upright. e. The vehicle was not redirected. f. Not evaluated. g. Not required, see above for data. h. No exit angle, vehicle exited on the field side of rail. THE TEST ARTICLE FAILED DUE TO VEHICLE PENETRATION AND VEHICLE VAULTING RAIL.

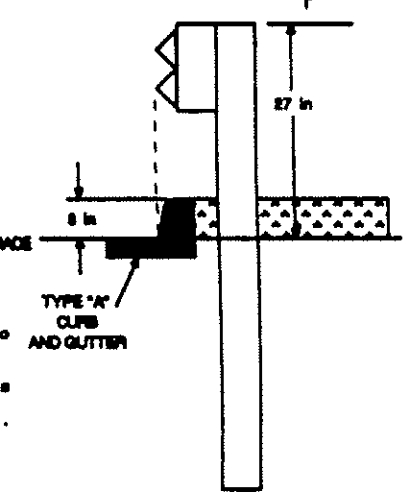
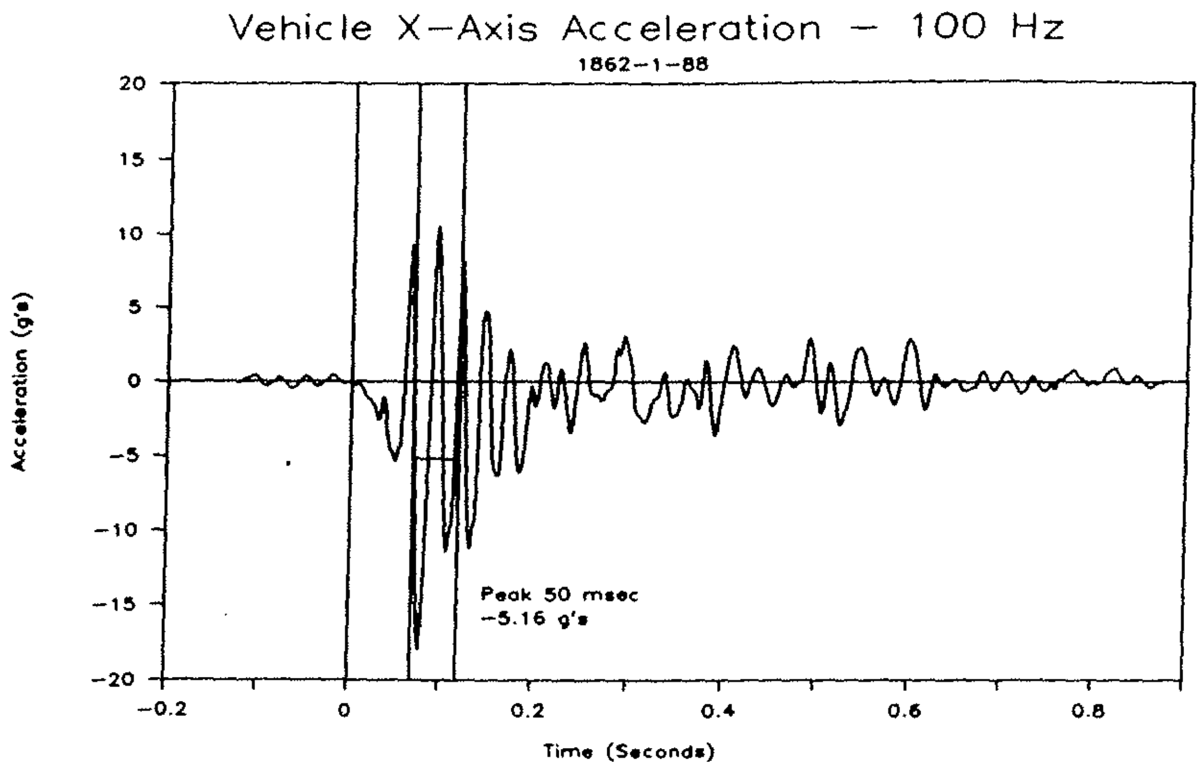


Figure 8. Test summary, test 1862-1-88.



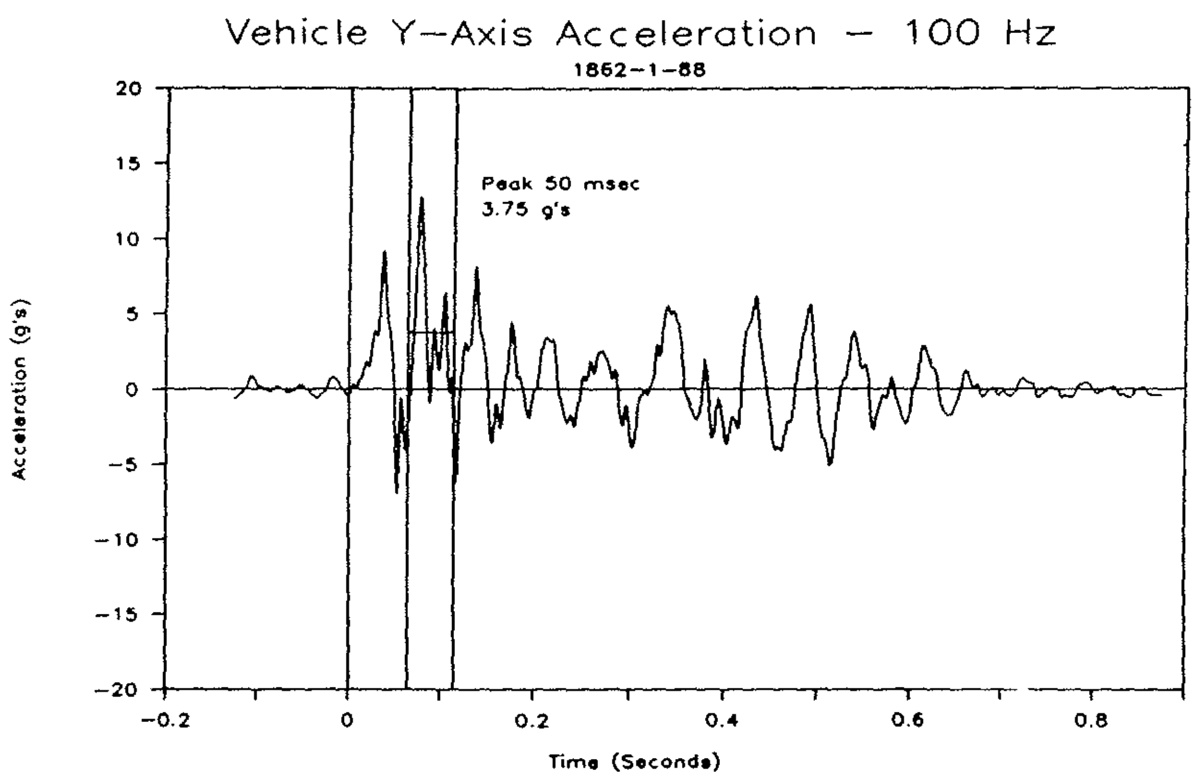


Figure 9. Vehicle accelerations, test 1862-1-88.

Figure 10. Post-test photographs of test vehicle, test 1862-1-88.

Figure 11. Post-test photographs of guardrail system, test 1862-1-88.

2. TEST 1862-2-89

a. Test Device

The test device was a standard G4(1S) W-beam rail installed with a 1192-ft (363.6-m) radius curve. The entire system was 262.5 ft (80.1 m) long. The system consisted of 150 ft (45.8 m) of W-beam in the curved section, 75 ft (22.9 m) of straight rail prior to the curve, and a 37.5-ft (11.4-m) standard BCT on the upstream end. The BCT used steel slipbase posts that incorporate large soil plates in lieu of the concrete anchor. A cable anchor assembly was used on the downstream end. This assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 12 shows the test site and test device. Figure 13 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1982 Honda Civic. The target inertial vehicle weight was 1800 lb (817 kg). The vehicle weighed 1764 lb (801 kg) empty. Ballast weighing 40 lb (18.2 kg) was added. The ballasted inertial weight of the vehicle was 1804 lb (819 kg). The gross vehicle weight was 1964 lb (891 kg).

X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the vehicle. One fully-instrumented dummy was placed in the vehicle in the driver's seat and was restrained. The dummy instrumentation consisted of x-, y-, and z-axis accelerometers in the head and chest, and load cells in the legs. Pretest photographs of the test vehicle are shown in figure 14. Table 12 lists important parameters of the test vehicle.

c. Impact Description

Review of the high speed films, fifth wheel data, and speed-trap data indicated that the test vehicle impacted at 62.2 mi/h (100.1 km/h) and 20°. This review also indicated that the right corner of the vehicle impacted the rail at the desired point.

Upon impact, the vehicle penetrated into the rail approximately 9 in (228.6 mm) before starting to be redirected. As the vehicle was redirected, it began to yaw and translate rather than roll. While yawing counterclockwise, the vehicle re-impacted the rail approximately 85 ft (25.9 m) downstream of the impact point. The

Table 12. Test vehicle parameters, test 1862-2-89.

Item	Actual	Specification
Empty Weight	1764 lb	n/a
Ballast	40 lb	n/a
Total Weight, Inertial	1804 lb	1800 lb
Total Weight, Gross	1964 lb	n/a
H_{cg}	20 in	20 ± 1 in
A (front to cg), Inertial	5.27 ft	5.4 ± 0.1 ft
B (width)	5.17 ft	5.5 ft
Vehicle Length	147.5 in	
Vehicle Wheelbase	89 in	
Wheel/Tire Size	155 R13	

1 lb = 0.45 kg   1 ft = 0.31 m   1 in = 25.4 mm

vehicle was again redirected. The vehicle then struck the end anchor and yawed counterclockwise approximately 100°. The vehicle came to rest in this position.

The dummy remained seated throughout the impact event. However, upon impact the dummy punched out the driver side window. The final position of the dummy was leaning toward the passenger seat held in its seatbelt.

A summary of test conditions and results is shown in figure 15. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 16.

d. Dummy Data Analysis

Dummy data analysis was performed. The dummy data was digitized at 4652 Hz and processed to compute the desired parameters. Table 13 lists the dummy head, chest, and femur parameters. Because the dummy was restrained, these values are well within the specified limits.

e. Vehicle Damage

The front and entire left side of the vehicle were damaged, but damage occurred mainly to the left front fender, grill, bumper, and driver's door. Post-test photographs of the vehicle are shown in figure 17.

Table 13. Dummy parameters, test 1862-2-89.

Head	
HIC	137.8
Start time	0.10814 s
End time	0.26853 s
Time duration	0.16039 s
Chest	
CSI	82.3
0.003 s Chest Acceleration	22.3 g's
Time	0.14878 s
Femur	
Right	355 lb
Left	412 lb

1 lb = 0.45 kg   1 g = 9.8 m/s^2

f. Barrier Damage

The barrier was damaged from the impact point downstream 1.5 rail lengths [18 ft (5.5 m)]. The posts in this area were pushed over or bent and the rail was slightly deformed. The rail was not detached from the blocks. Post-test photographs of the rail are shown in figure 18.

g. Test Evaluation

This test was evaluated using both the AASHTO Guide Specifications for Bridge Railings and NCHRP 230. The following is an item-by-item evaluation using these two guidelines.

- AASHTO Guide Specifications for Bridge Railings:

Required Criteria:

a. The vehicle was contained by the test article.
b. There were no detached elements.
c. Integrity of the passenger compartment was maintained.
d. The vehicle remained upright.
g. Delta-V and Ridedown values were within limits.

Desirable Criteria:

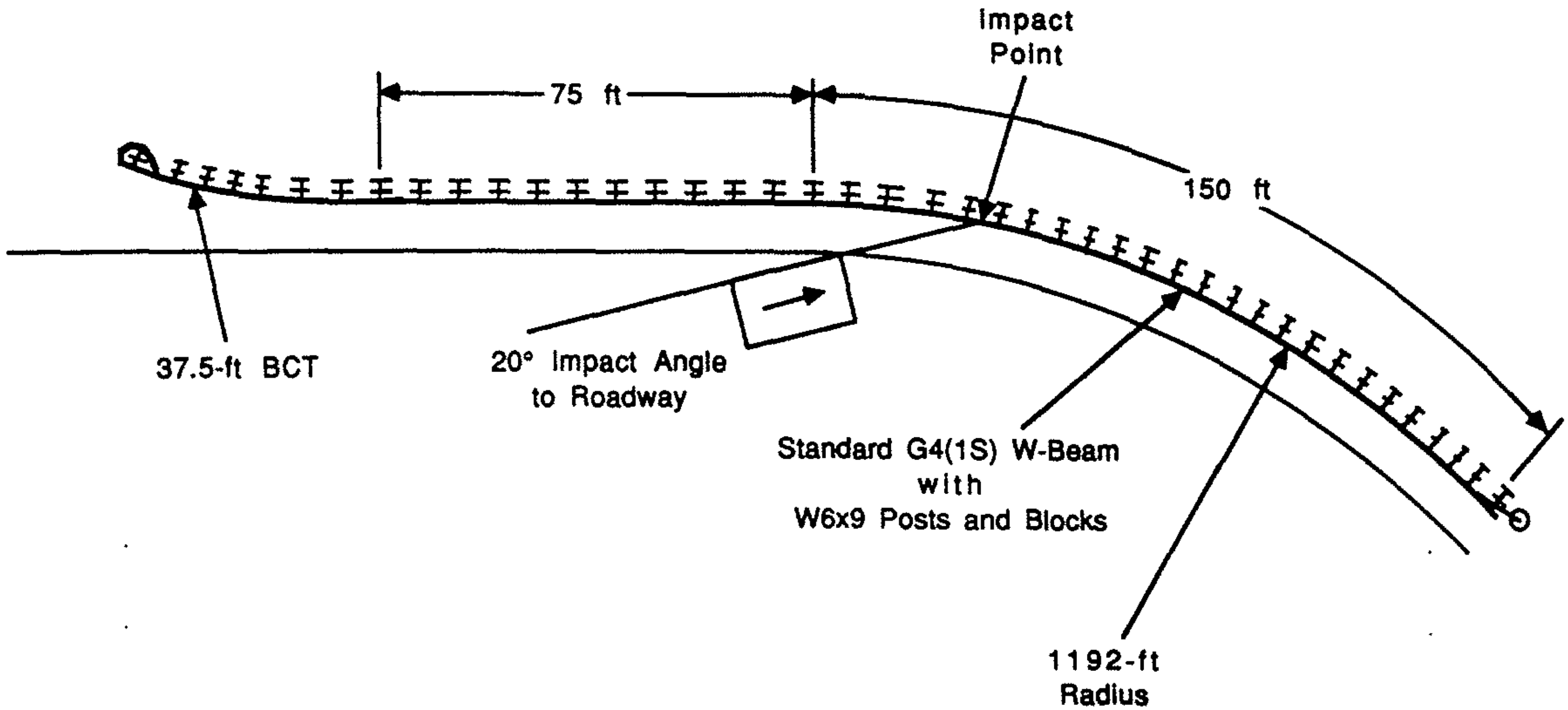
- e. The vehicle was smoothly redirected.
- f. Vehicle railing interaction: mu = 0.34, assessment: Fair.
- h. The exit angle was less than 12° (exit angle was 9°). Vehicle was within 20 ft (6.1 m) of the rail, 100 ft (30.5 m) downstream of the impact point.

MEETS ALL REQUIRED CRITERIA.

■ NCHRP 230:

- a. The test article smoothly redirected the vehicle.
- d. There were no detached elements.
- e. The vehicle remained upright during and after the collision. Integrity of the passenger compartment was maintained.
- h. Vehicle trajectory and stopping position did not intrude into adjacent traffic lanes.
- i. Because the vehicle trajectory and stopping position did not intrude into adjacent traffic lanes, vehicle speed change and exit angle criteria do not apply.

MEETS ALL CRITERIA.



1 ft = 0.30 m

Figure 12. Test site layout, test 1862-2-89.

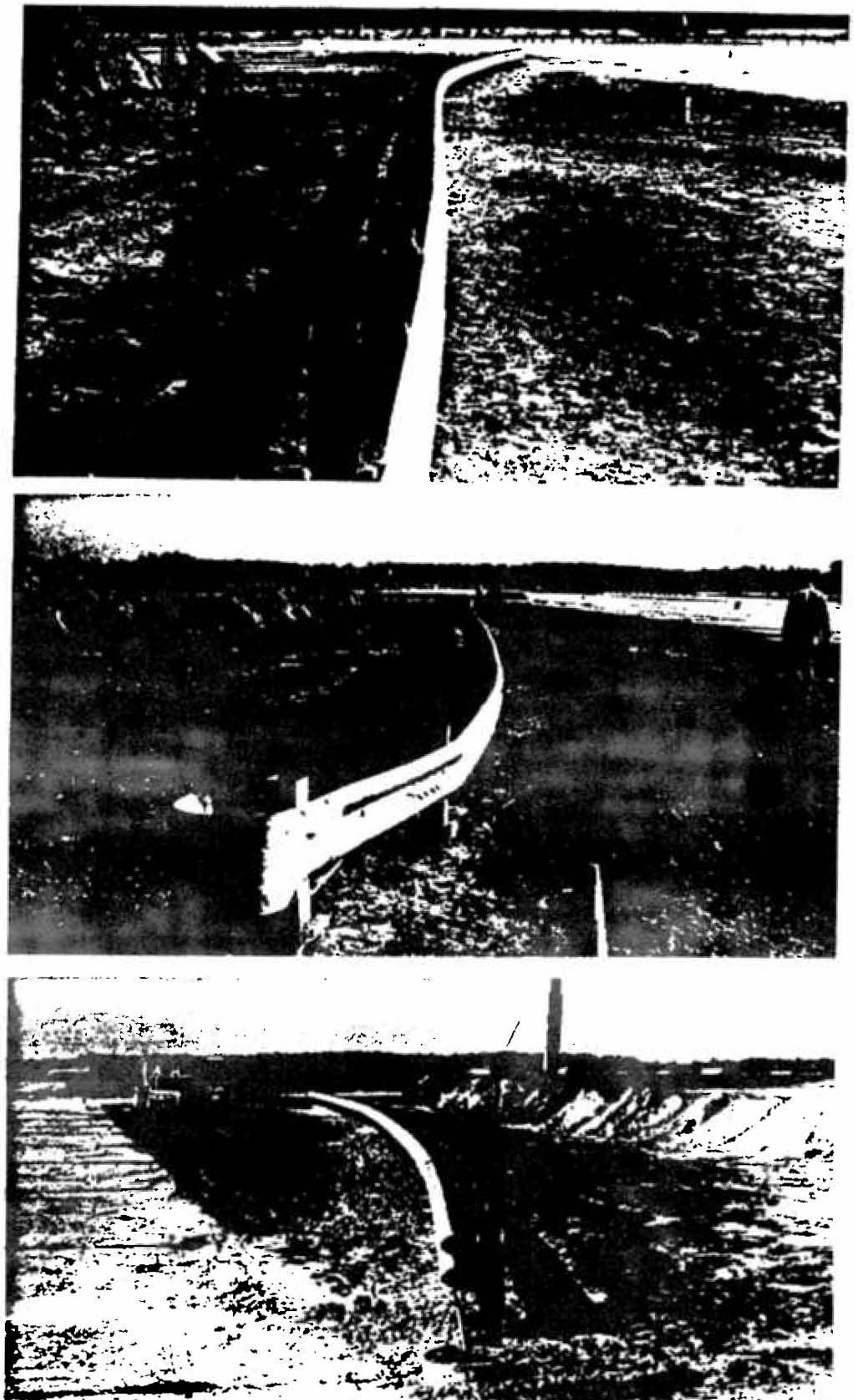


Figure 13. Pretest photographs of guardrail system, test 1862-2-89.

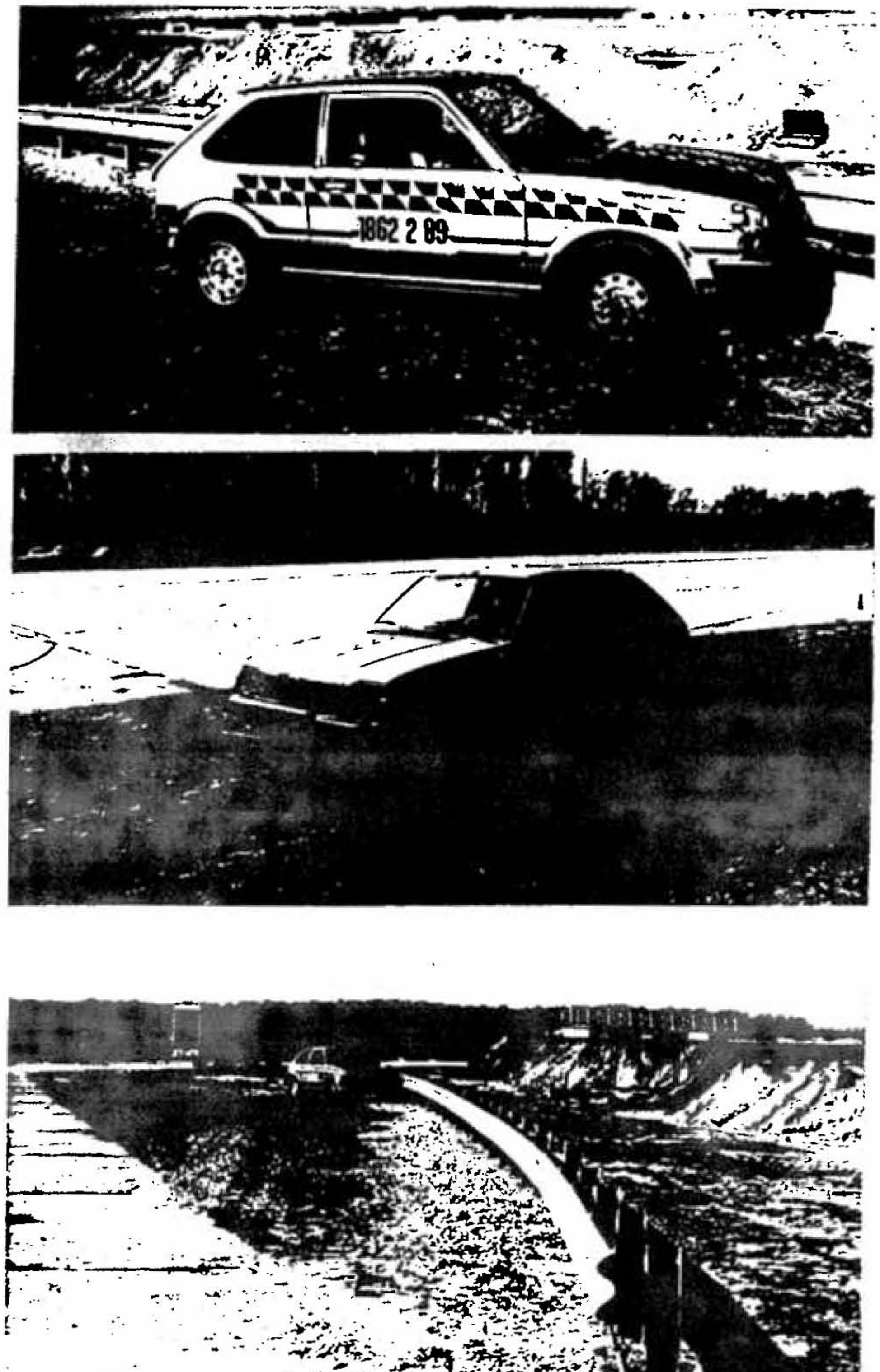
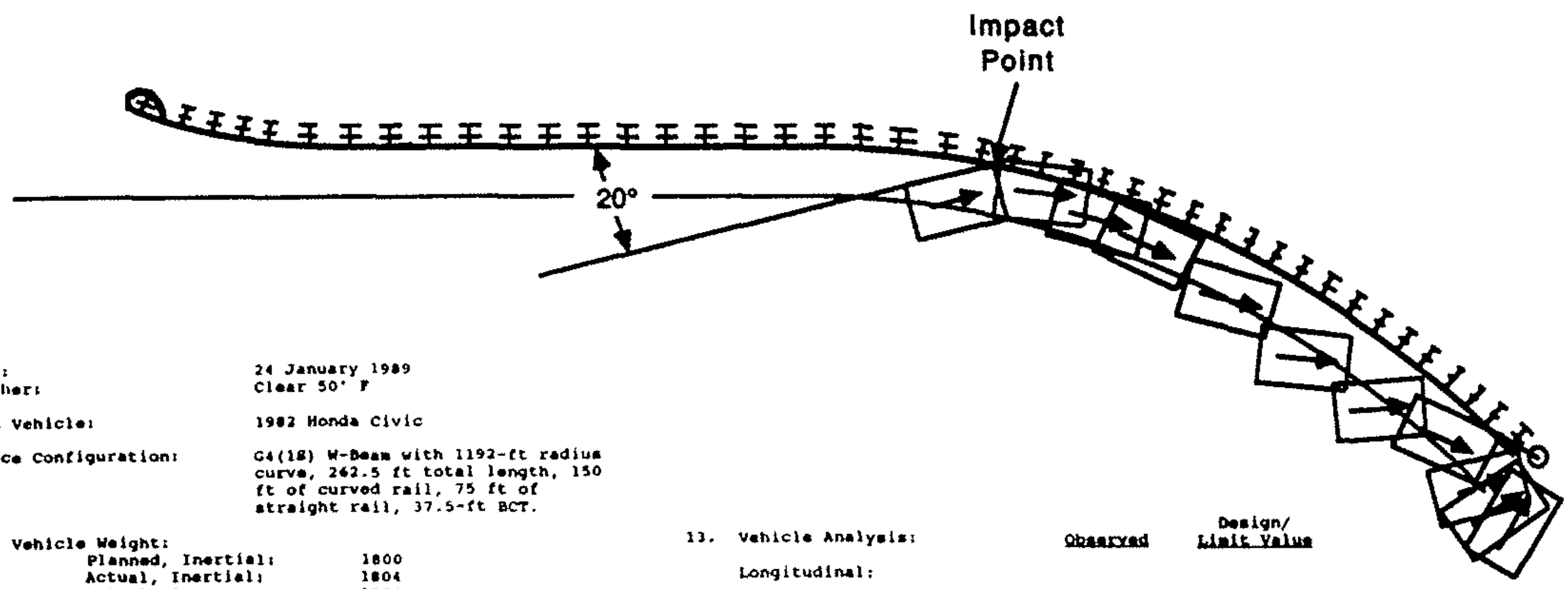


Figure 14. Pretest photographs of test vehicle, test 1862-2-89.



Date: 24 January 1989
Weather: Clear 50° F

Test Vehicle: 1982 Honda Civic

Device Configuration: G4(1S) W-Beam with 1192-ft radius curve, 262.5 ft total length, 150 ft of curved rail, 75 ft of straight rail, 37.5-ft BCT.

1. Vehicle Weight:
   - Planned, Inertial: 1800
   - Actual, Inertial: 1804
   - Actual, Gross: 1964

2. Number of Occupants: One

3. Occupant Model: Part 572, 50th percentile male, fully instrumented

4. Occupant Locations: Driver Seat, Restrained

5. Impact:

	Speed	Angle	Location
Planned:	60.0 mi/h	20°	Midspan posts 23 and 24
Actual:	62.2 mi/h	20°	Midspan posts 23 and 24

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

6. Redirection Angle: 9°

7. Redirection Speed: 49.8 mi/h (73.1 ft/s)

8. Total Speed Change: 12.4 mi/h (18.1 ft/s)

9. Total Momentum Change: 1104 lb-s

10. Vehicle Damage Index: (SAE J224a) 11LFEW2

11. NCHRP 230 Test Number: S13
    AASHTO Test Type: PL2

12. NCHRP 230 Impact Severity:

    $\frac{m(V \sin a)^2}{2}$ 27.3 kip-ft (Spec: 23 to 29 kip-ft)

13. Vehicle Analysis:

	Observed	Design/ Limit Value
Longitudinal:		
Delta-V at 2 ft:	-17.2 ft/s	30/40 ft/s
Ridedown Acceleration:	-2.7 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-21.6 ft/s	20/30 ft/s
Ridedown Acceleration:	-11.6 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-4.1 g's	
Lateral:	-8.6 g's	

14. Vehicle-Railing Interaction Coefficient of Friction:

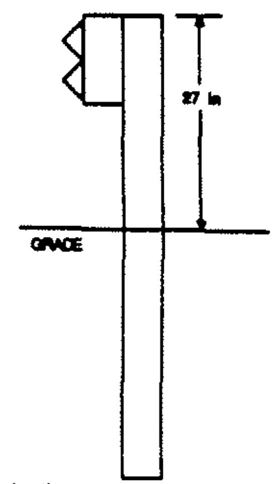
    $mu = \frac{\text{Cos theta} - V_p/V}{\text{Sin theta}}$ mu 0.34 Assessment Fair

    V_p = 51.3 mi/h (75.2 ft/s)

15. Test Results Conclusion:

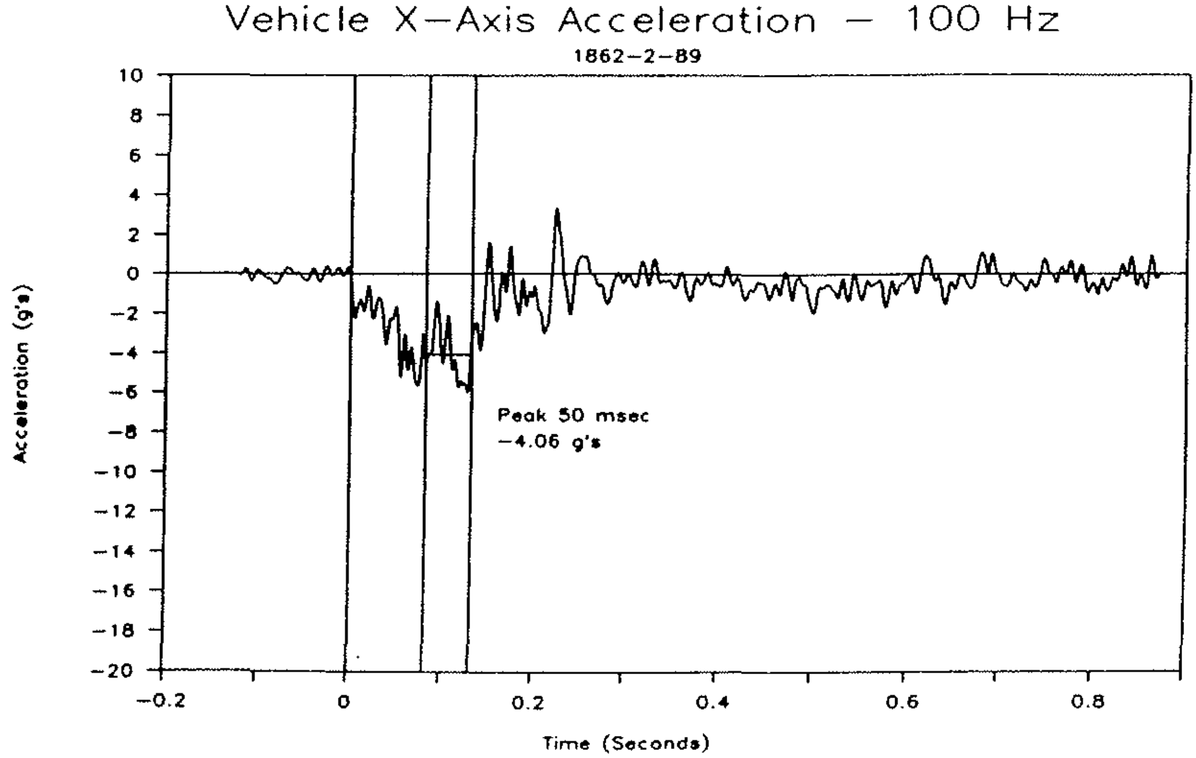
    AASHTO Bridge Rail Specification: MEETS ALL REQUIRED CRITERIA.

    NCHRP 230: MEETS ALL CRITERIA.



32°F = 0°C 1 ft = 0.30 m 1 lb = 0.45 kg 1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s 1 kip-ft = 1360 N-m 1 g = 9.8 m/s²

Figure 15. Test summary, test 1862-2-89.



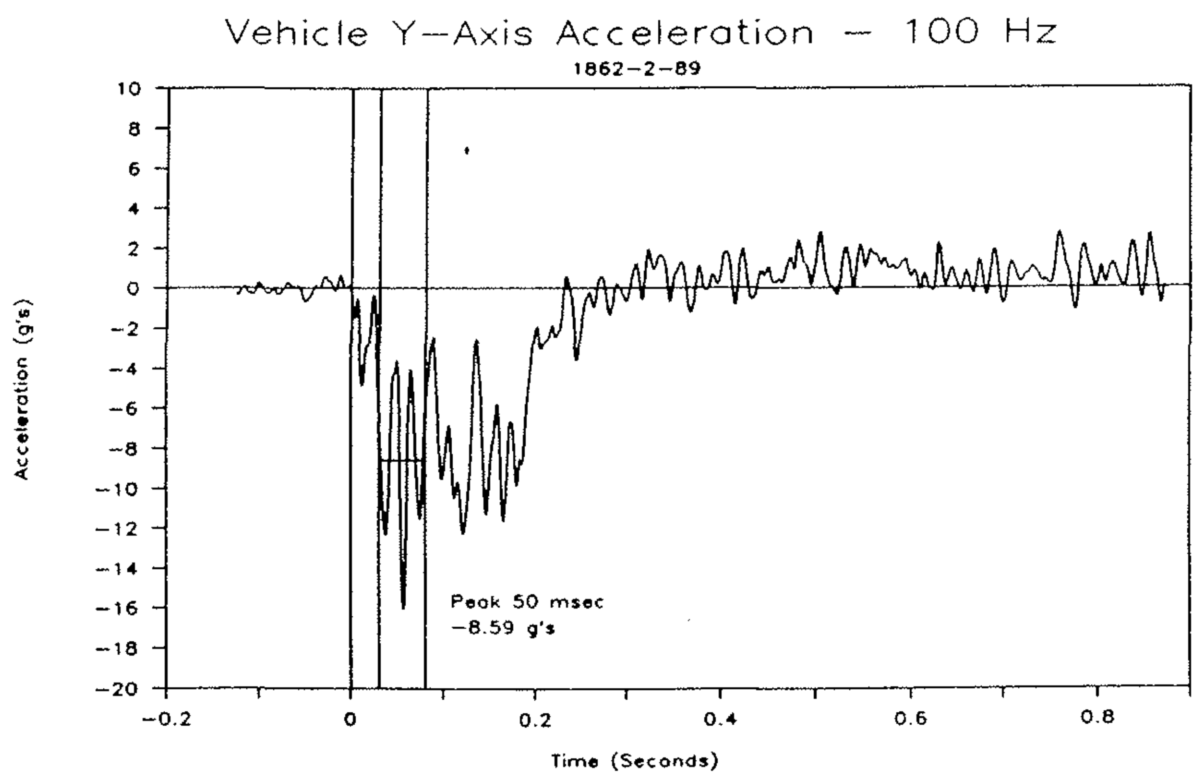


Figure 16. Vehicle accelerations, test 1862-2-88.

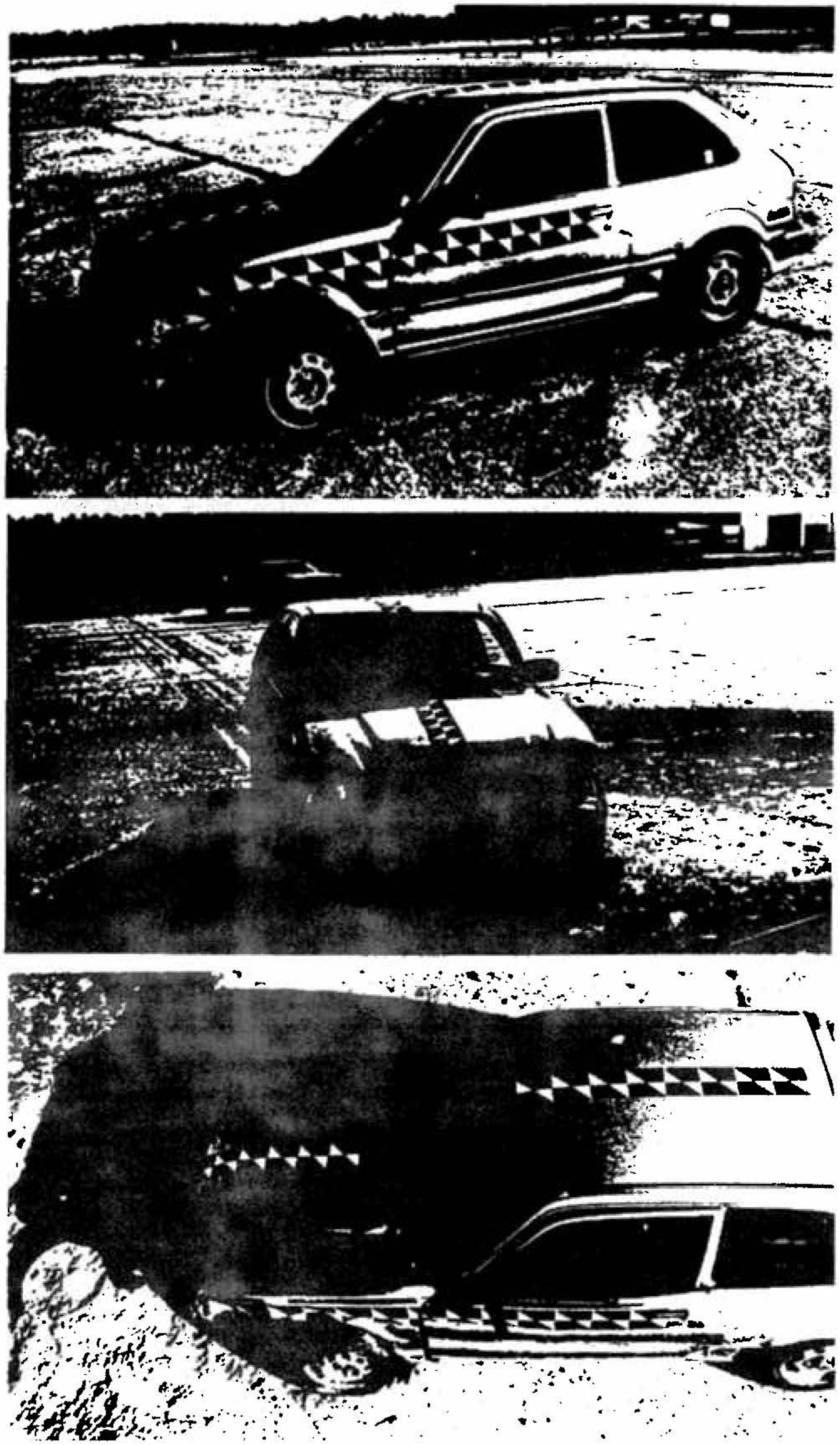


Figure 17. Post-test photographs of test vehicle, test 1862-2-89.

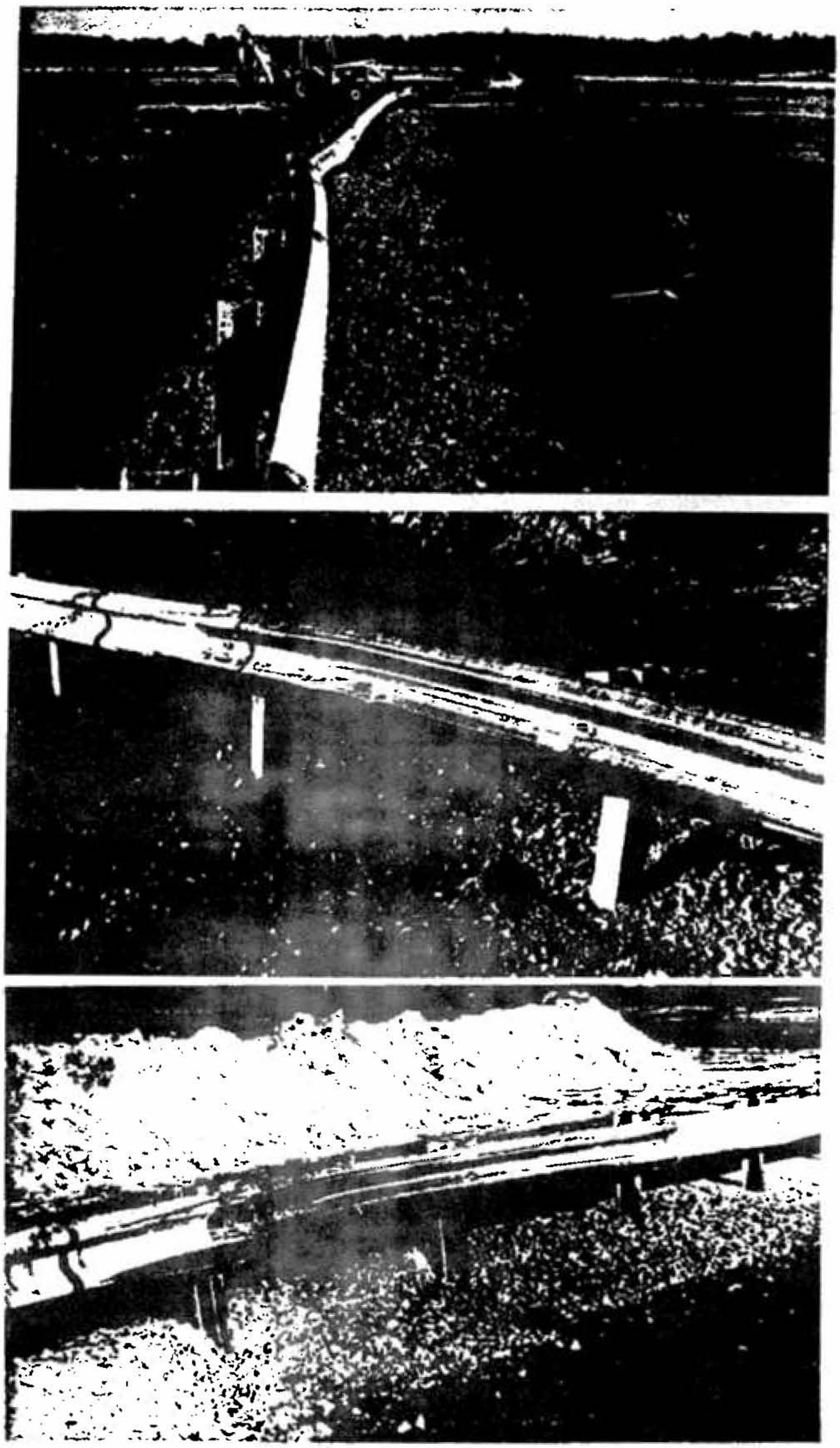


Figure 18. Post-test photographs of guardrail system, test 1862-2-89.

3. TEST 1862-3-89

a. Test Device

The test device was a standard G4(1S) W-beam rail installed with a 1192-ft (363.6-m) radius curve. The entire system was 262.5 ft (80.1 m) long. The system consisted of 150 ft (45.8 m) of W-beam in the curved section, 75 ft (22.9 m) of straight rail prior to the curve, and a 37.5-ft (11.4-m) standard BCT on the upstream end. The BCT used steel slipbase posts that incorporate large soil plates in lieu of the concrete anchor. A cable anchor assembly was used on the downstream end. This assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 19 shows the test site and test device. Figure 20 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1983 Chevrolet C20 pickup. The target inertial vehicle weight was 5400 lb (2452 kg). The vehicle weighed approximately 4500 lb (2043 kg) empty. Approximately 900 lb (409 kg) of ballast were added. The ballasted inertial weight of the truck was 5396 lb (2450 kg). The gross vehicle weight was 5712 lb (2593 kg).

Two dummies were placed in the vehicle. The driver was restrained while the passenger was unrestrained. X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the cab of the truck. Pretest photographs of the test vehicle are shown in figure 21. Table 14 lists important parameters of the test vehicle.

c. Impact Description

Review of the high speed films and fifth-wheel data indicated that the test vehicle impacted at 61.1 mi/h (98.3 km/h) and 20°. This review also indicated that the right corner of the vehicle impacted the rail at the desired point.

Upon impact, the vehicle penetrated into the rail 18 to 20 in (457.2 to 508.0 mm) before redirection. The vehicle remained in contact with the rail for approximately 32 ft (9.8 m). The vehicle was redirected and exited the rail at 7°. As the vehicle was redirected, it rolled to the driver's side approximately 20° and pitched forward approximately 10°.

Table 14. Test vehicle parameters, test 1862-3-89.

Item	Actual	Specification
Empty Weight	~4500 lb	n/a
Ballast	~900 lb	n/a
Total Weight, Inertial	5396 lb	5400 lb
Total Weight, Gross	5712 lb	n/a
H_{cg}	27 in	27 ± 1 in
A (front to cg), Inertial	8.60 ft	8.5 ± 0.1 ft
B (width)	6.58 ft	6.5 ft
Truck Length	217 in	
Truck Wheelbase	132 in	
Wheel/Tire Size	235 85R16	
Truck Box Size	8 ft long by 1.5 ft high by 5.5 ft wide	
Ground to Box Floor	27 in	

1 lb = 0.45 kg 1 ft = 0.31 m 1 in = 25.4 mm

Because of the damage to the left front of the vehicle, the vehicle steered to the left after redirection. The vehicle came to rest 35 ft (10.7 m) downstream of the end of the rail, 10 ft (3.1 m) behind the line of the rail after turning approximately 135°.

The driver dummy remained seated throughout the impact event. The passenger dummy violently impacted the driver dummy. The passenger came to rest under the dash, on the floor near the middle of the cab. The driver came to rest nearly horizontal on the seat, leaning toward the middle of the cab.

A summary of test conditions and results are shown in figure 22. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 23.

d. Vehicle Damage

The bumper, grill, and entire left side of the truck were damaged, but damage occurred mainly to the left front of the vehicle. Both tires on driver's side were damaged. The damage to the front left suspension and wheel caused the vehicle to steer to the left after redirection. Post-test photographs of the test vehicle are shown in figure 24.

e. Barrier Damage

The barrier was damaged from the impact point downstream three rail lengths [37 ft (11.3 m)]. Posts and blocks in this area were bent or deformed. The rail was detached from the block at post 23. Posts 23 and 24 had some local bending, indicating wheel snag. The downstream foundation was pulled toward the rail approximately 1.5 in (38.1 mm) by the lateral rail deflection. The maximum permanent rail deflection occurred at post 24 and was 17 in (431.8 mm). Post-test photographs of the rail are shown in figure 25.

f. Test Evaluation

This test was evaluated using the AASHTO Guide Specifications for Bridge Railings. The following is an item-by-item evaluation using this guideline.

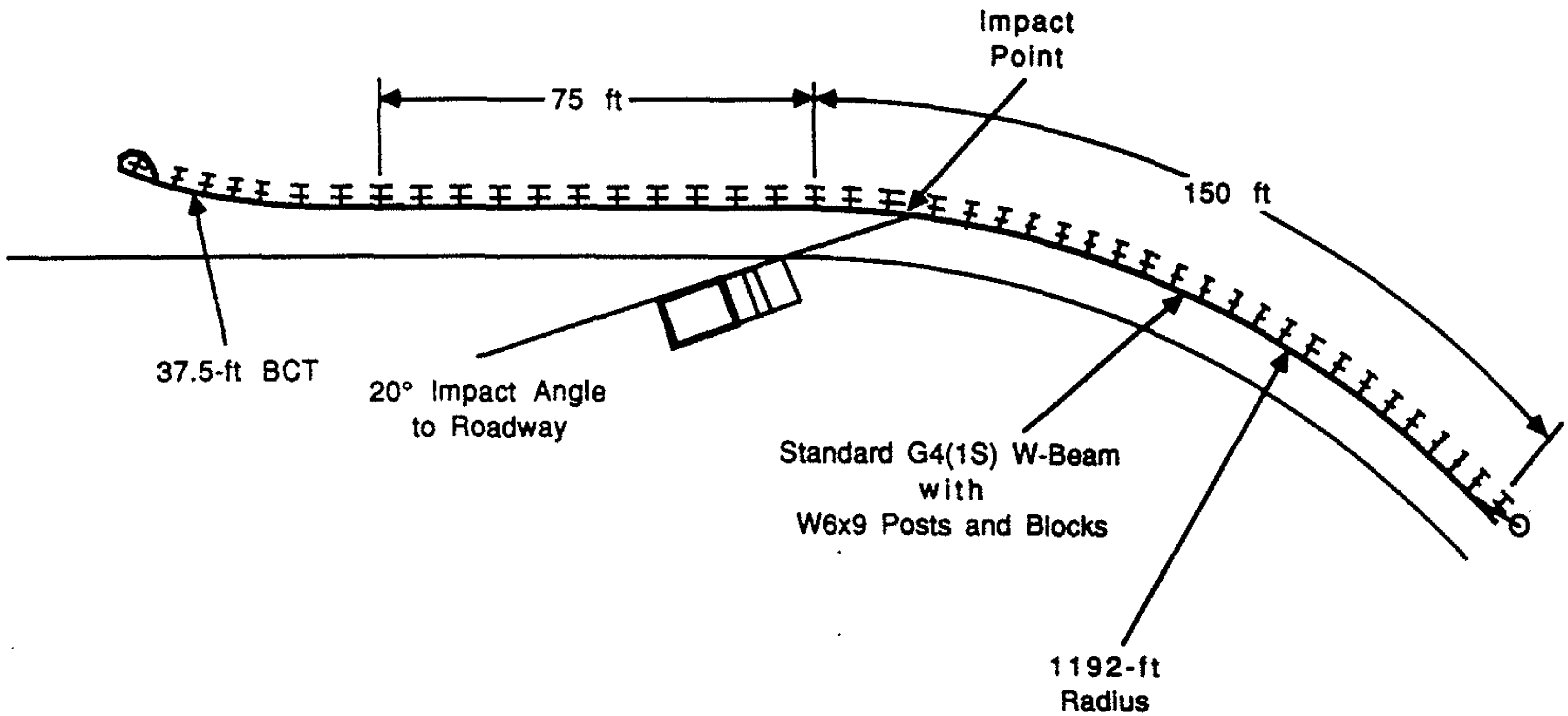
Required Criteria:

a. The vehicle was contained by the test article.
b. There were no detached elements.
c. Integrity of the passenger compartment was maintained.
d. The vehicle remained upright.

Desirable Criteria:

e. The vehicle was smoothly redirected.
f. Vehicle railing interaction: mu = 0.36, assessment: Marginal.
g. Delta-V and Ridedown values were within limits.
h. The exit angle was less than 12° (exit angle was 7°). Vehicle was within 20 ft (6.1 m) of the rail, 100 ft (30.5 m) downstream of the impact point.

MEETS ALL REQUIRED CRITERIA.



1 ft = 0.30 m

Figure 19. Test site layout, test 1862-3-89.

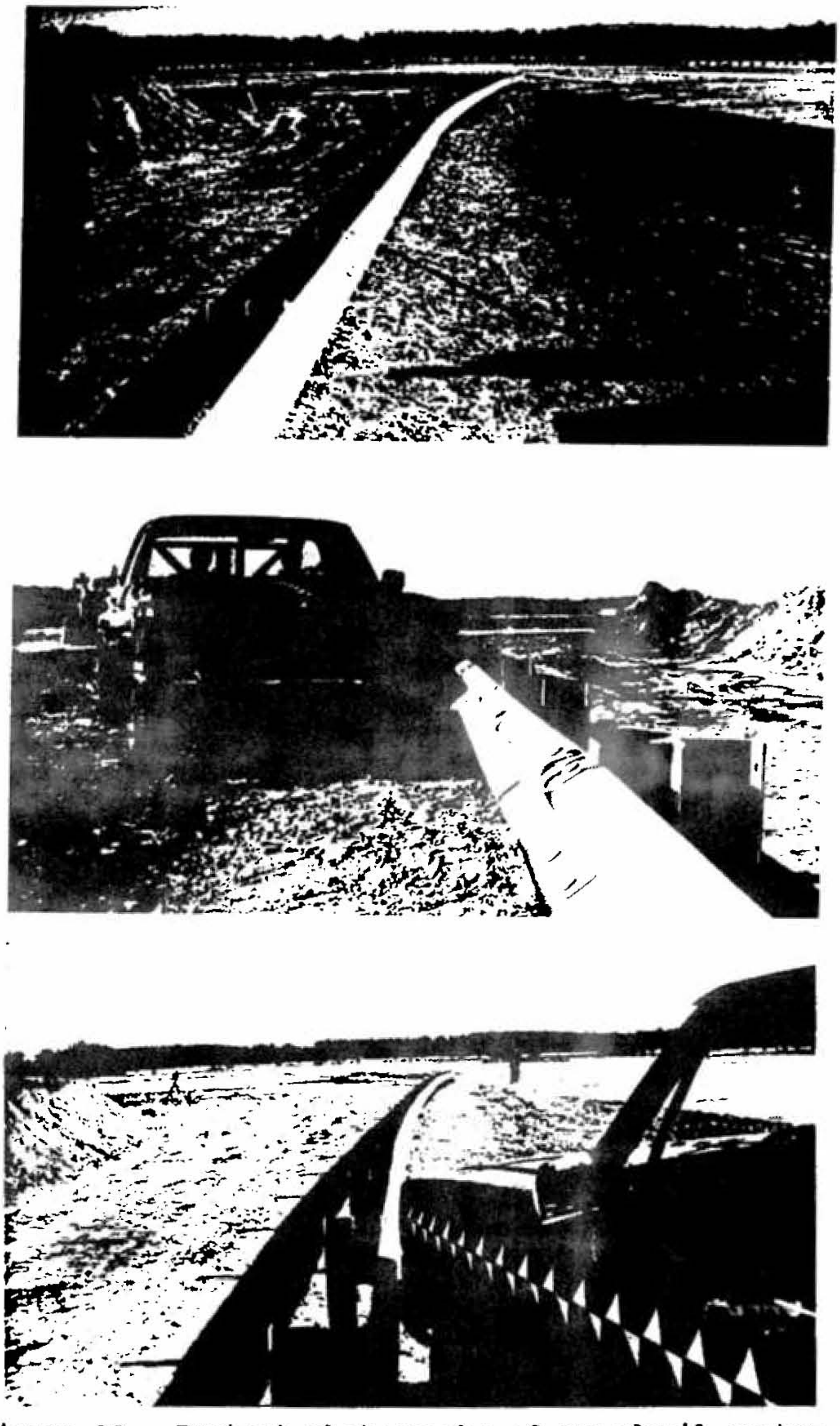


Figure 20. Pretest photographs of guardrail system, test 1862-3-89.

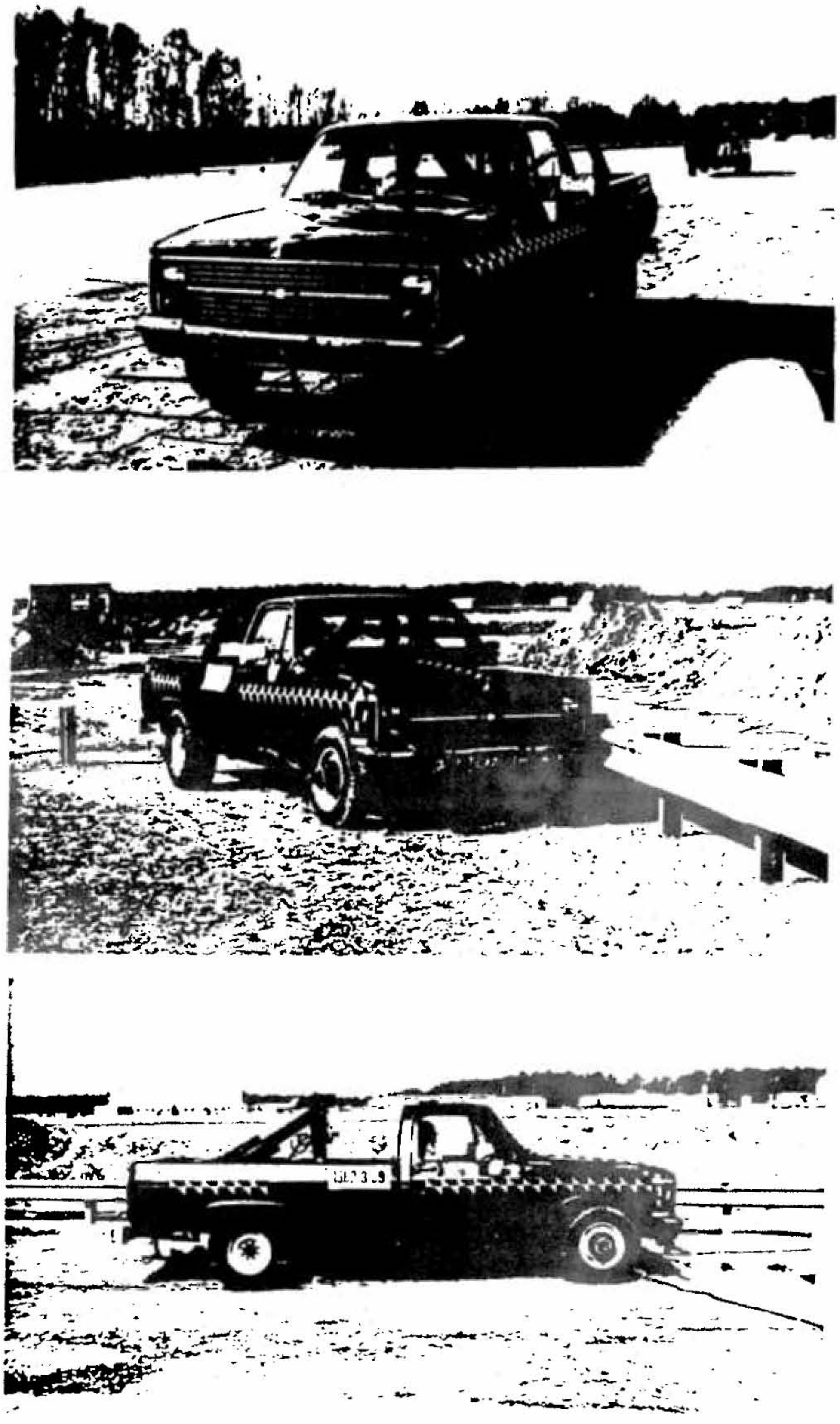
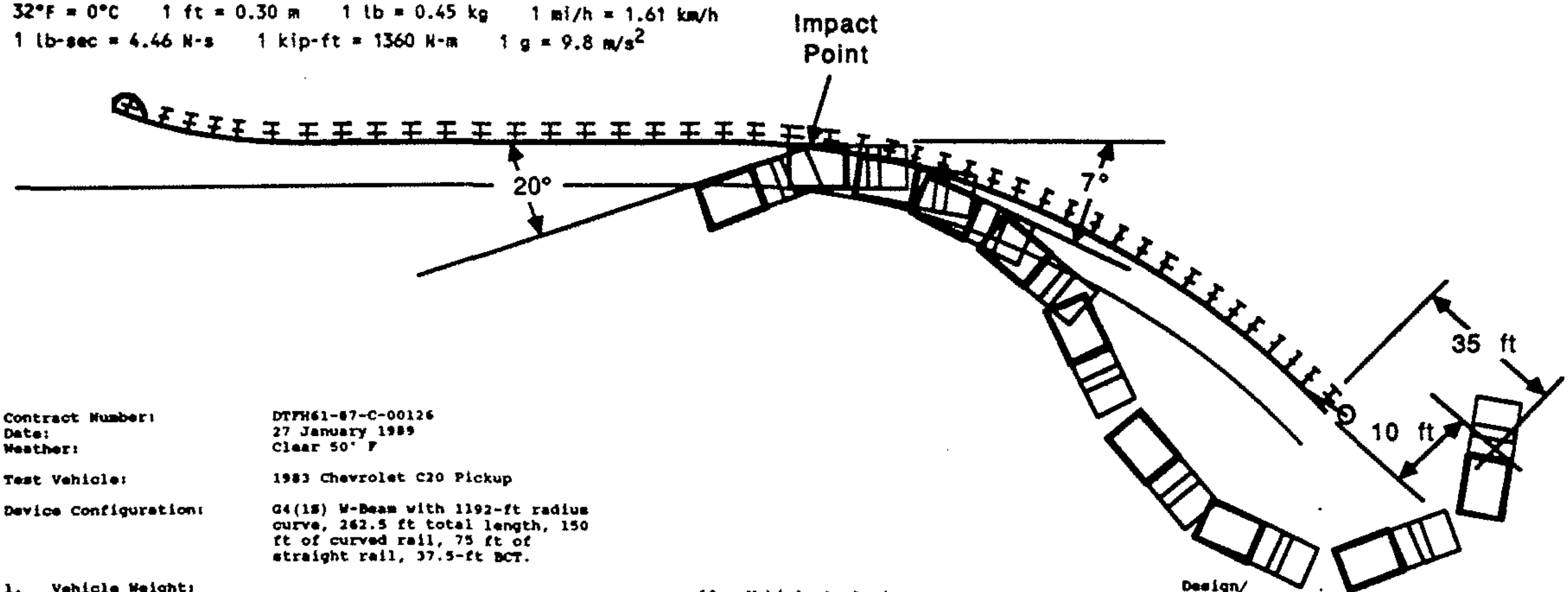


Figure 21. Pretest photographs of test vehicle, test 1862-3-89.

32°F = 0°C   1 ft = 0.30 m   1 lb = 0.45 kg   1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s   1 kip-ft = 1360 N-m   1 g = 9.8 m/s²



Contract Number:	DTFH61-87-C-00126
Date:	27 January 1989
Weather:	Clear 50° F
Test Vehicle:	1983 Chevrolet C20 Pickup
Device Configuration:	G4(1S) W-Beam with 1192-ft radius curve, 262.5 ft total length, 150 ft of curved rail, 75 ft of straight rail, 37.5-ft BCT.

1. Vehicle Weight:
   - Planned, Inertial: 5400
   - Actual, Inertial: 5396
   - Actual, Gross: 5712
2. Number of Occupants: Two
3. Occupant Model: Part 572, 50 percentile male
4. Occupant Locations: Driver Seat, Restrained; Passenger Seat, Unrestrained
5. Impact:

	Speed	Angle	Location
Planned:	60.0 mi/h	20°	Midspan posts 21 and 22
Actual:	61.1 mi/h	20°	Midspan posts 21 and 22

   Tolerances: Speed: -1.0, +2.5 mi/h; Angle: -1.0, +2.5 degrees
6. Redirection Angle: 7°
7. Redirection Speed: 47.2 mi/h (69.2 ft/s)
8. Total Speed Change: 13.9 mi/h (20.4 ft/s)
9. Total Momentum Change: 3619 lb-s
10. Vehicle Damage Index: (SAE J224a) 11LFEW2
11. NCHRP 230 Test Number: Special
    AASHTO Test Type: PL2
12. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-18.1 ft/s	30/40 ft/s
Ridedown Acceleration:	-6.1 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-15.1 ft/s	20/30 ft/s
Ridedown Acceleration:	-11.3 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-3.9 g's	
Lateral:	-6.4 g's	

13. Vehicle-Railing Interaction Coefficient of Friction:

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

mu	Assessment
0.36	Marginal

V_p = 49.9 mi/h (73.2 ft/s)

14. Test Results Conclusion:
    AASHTO Bridge Rail Specification: **MEETS ALL REQUIRED CRITERIA.**

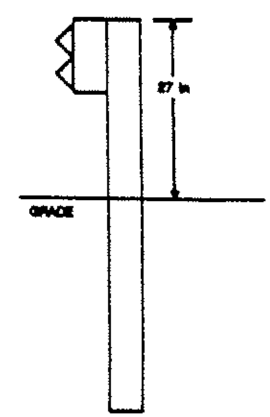
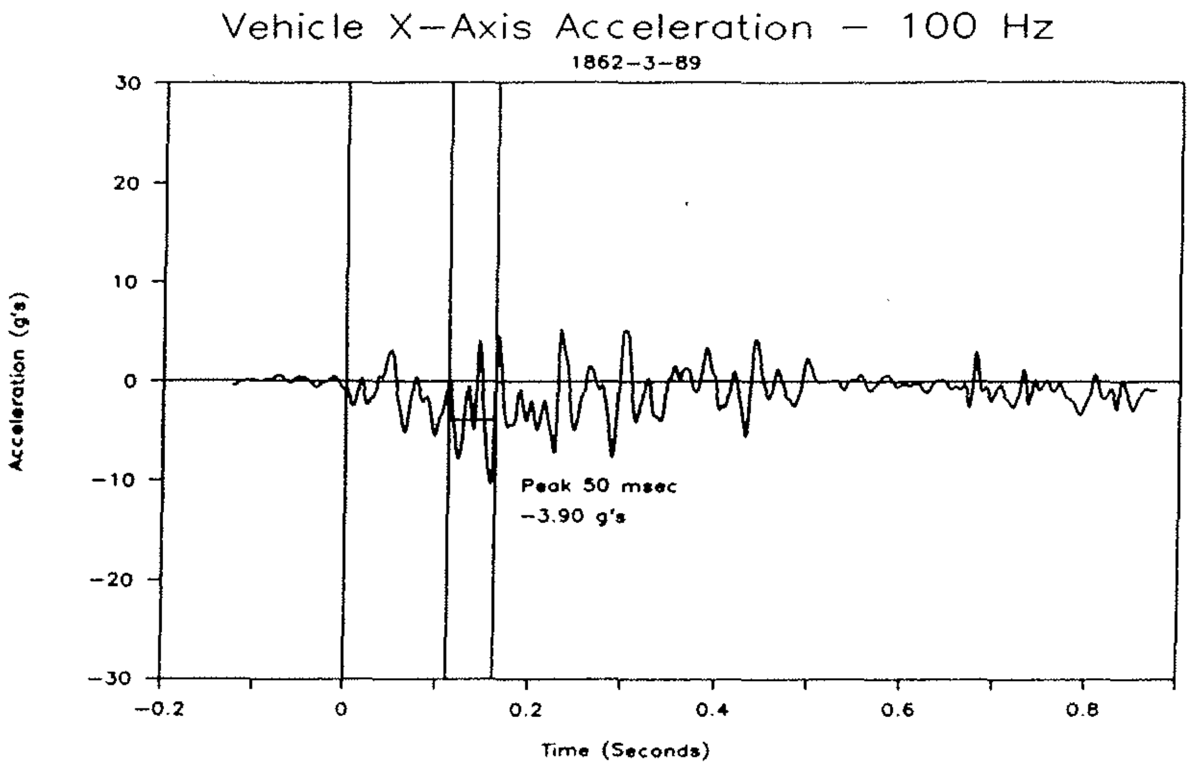


Figure 22. Test summary, test 1862-3-89.



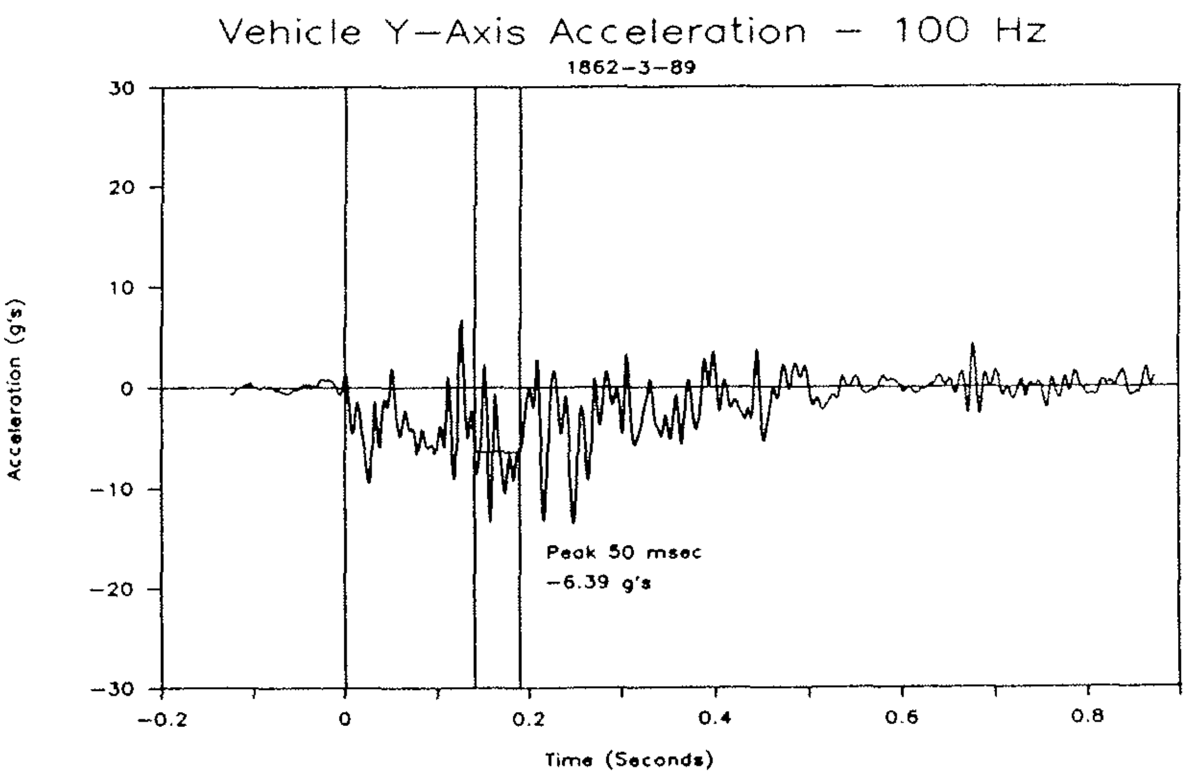


Figure 23. Vehicle accelerations, test 1862-3-89

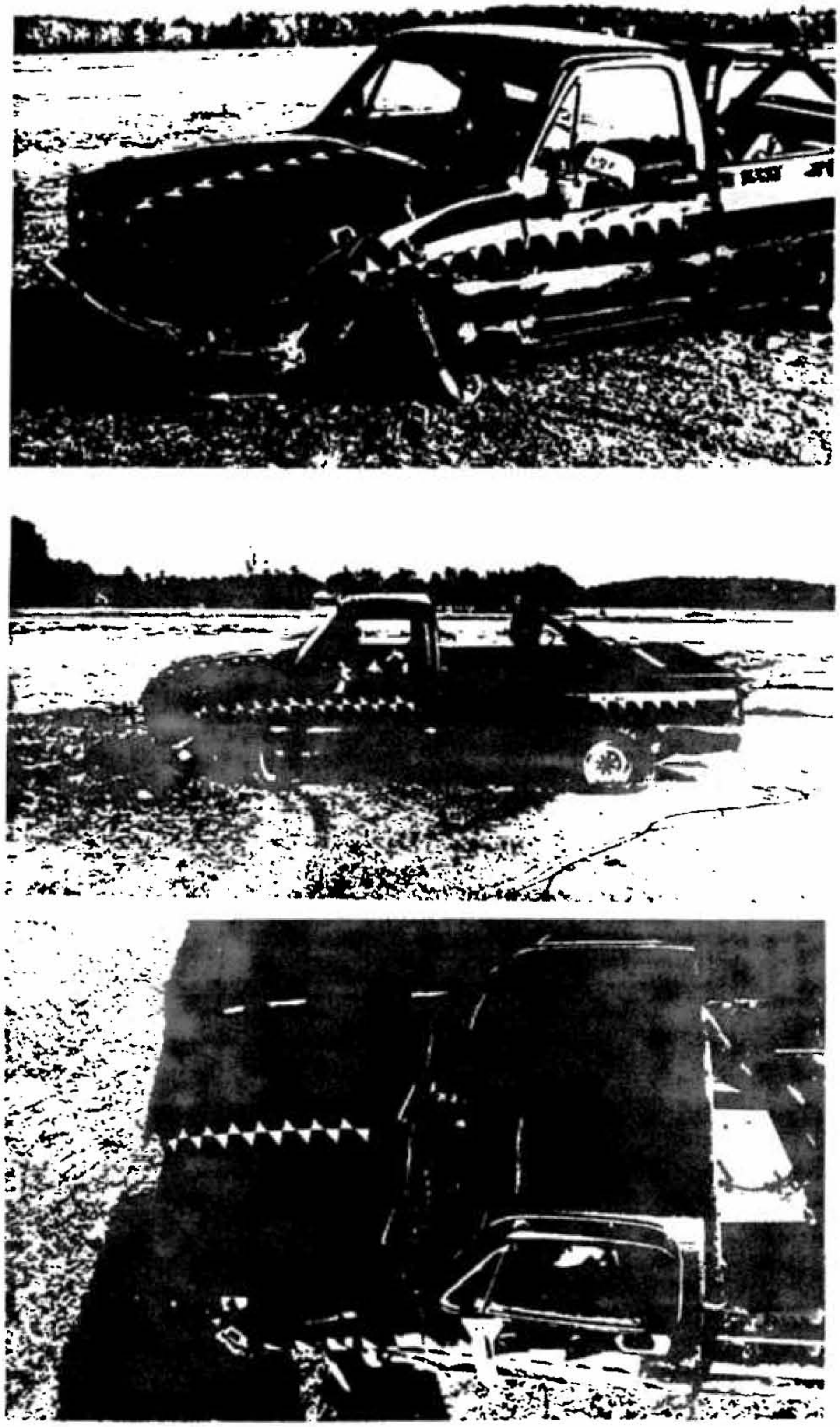


Figure 24. Post-test photographs of test vehicle, test 1862-3-89.

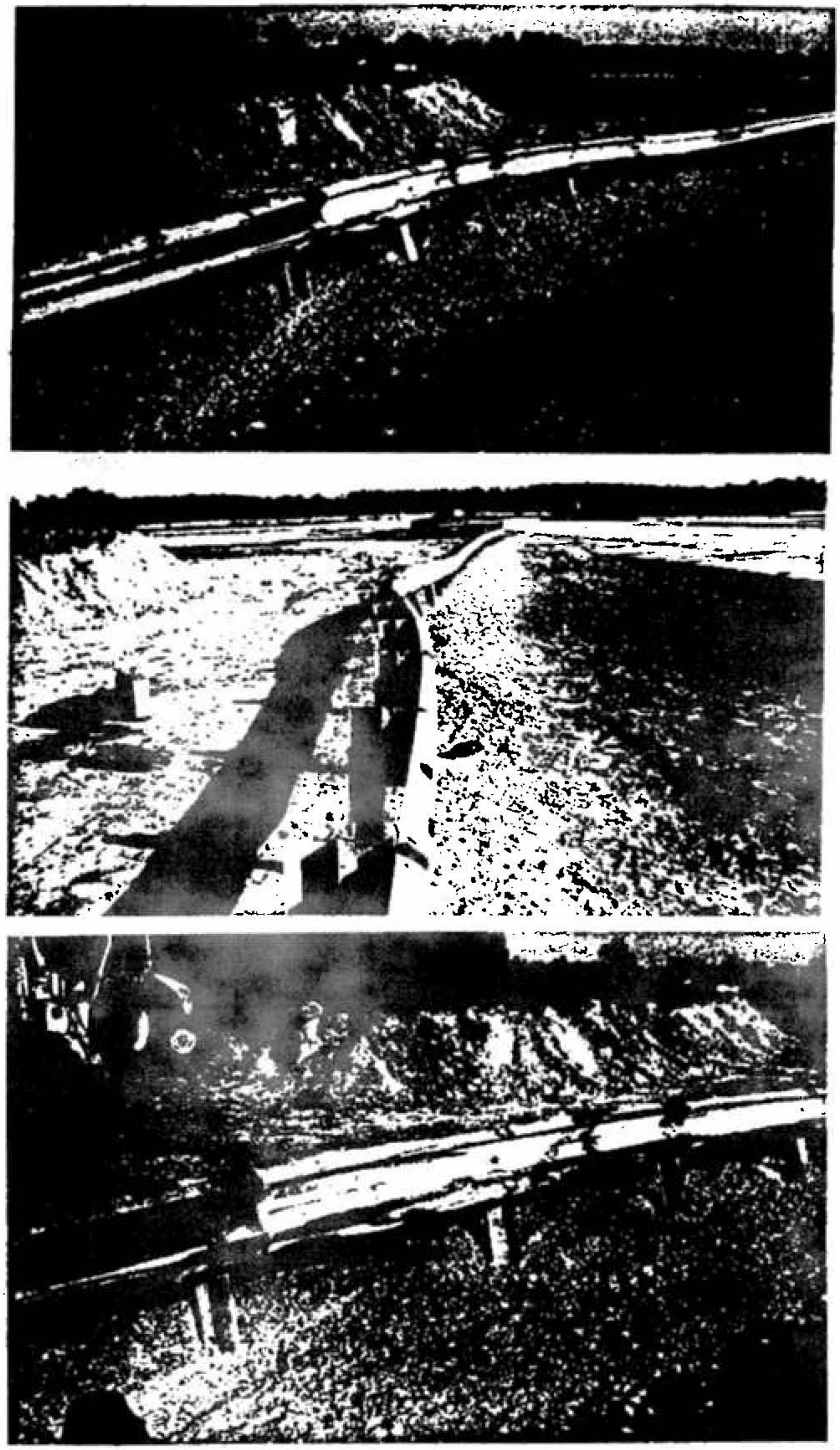


Figure 25. Post-test photographs of guardrail system, test 1862-3-89.

4. TEST 1862-4-89

a. Test Device

The test device was a standard G4(1S) W-beam rail with an AASHTO 6-in (152.4-mm) type G asphalt dike placed in front of the posts. The front of the dike was aligned with the face of the W-beam. The dike was formed on the top of a 2-in (50.8-mm) thick, 16-in (406.4-mm) wide asphalt layer. Approximately 80 ft (24.4 m) of curb was installed along the rail system. The curb began between posts 14 and 15 or approximately 12 ft (3.7 m) upstream of the impact point. The posts that were located in the area of the curb were driven through the 2-in (50.8-mm) asphalt layer.

The entire system was 218.75 ft (66.7 m) long. The system consisted of 181.25 ft (55.3 m) of W-beam and a 37.5-ft (11.4-m) standard BCT. A cable anchor assembly was used on the downstream end. This assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 26 shows the test site and test device. Figure 27 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1982 Honda Civic. The target inertial vehicle weight was 1800 lb (817 kg). The vehicle weighed approximately 1750 lb (795 kg) empty. With the instrumentation, no ballast was required. The inertial weight of the vehicle was 1799 lb (817 kg). The target gross vehicle weight was 1950 lb (885 kg). The gross vehicle weight was 1946 lb (883 kg).

X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the vehicle. One fully-instrumented dummy was placed in the vehicle in the driver's seat and was restrained. The dummy instrumentation consisted of x-, y-, and z-axis accelerometers in the head and chest, and load cells in the legs. Pretest photographs of the test vehicle are shown in figure 28. Table 15 lists important parameters of the test vehicle.

c. Impact Description

Review of the high speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 62.2 mi/h (100.1 km/h) and 20°. This review also indicated that the right corner of the vehicle impacted the rail at the desired point.

Table 15. Test vehicle parameters, test 1862-4-89.

Item	Actual	Specification
Empty Weight	~1750 lb	n/a
Ballast	0 lb	n/a
Total Weight, Inertial	1799 lb	1800 lb
Total Weight, Gross	1946 lb	1950 lb
H_{cg}	20 in	20 ± 1 in
A (front to cg), Inertial	5.3 ft	5.4 ± 0.1 ft
B (width)	5.2 ft	5.5 ft
Vehicle Length	147.5 in	
Vehicle Wheelbase	89 in	
Wheel/Tire Size	155 SR13	

1 lb = 0.45 kg   1 ft = 0.31 m   1 in = 25.4 mm

Upon impact, the vehicle penetrated into the rail approximately 9 in (228.6 mm). The right front tire deflated upon striking post 17. The passenger-side door came open during the impact. The vehicle was then redirected by the rail at 6°. The vehicle then began to turn back toward the rail and reimpacted at the end of the LON rail, approximately 130 ft (39.7 m) downstream of impact. At this point, the vehicle front bumper caught on the end foundation causing the vehicle to yaw clockwise approximately 90°. The vehicle came to rest 45 ft (13.7 m) past the end foundation, 15 ft (4.6 m) in front of the rail.

Upon impact, the driver dummy fell into the passenger seat, held by the seat belt. The driver dummy remained seated throughout the impact event.

A summary of test conditions and results are shown in figure 29. Data analysis was performed. The vehicle x- and y-axis 100 Hz data plots are shown in figure 30. Due to a data cable failure, it was not possible to process the dummy data.

d. Vehicle Damage

Damage occurred to the hood, bumper, and entire right side of the vehicle. The passenger-side door came open during the impact. Post-test photographs of the vehicle are shown in figure 31.

e. Barrier Damage

The only parts of the barrier that were damaged were the impact section rail and the first two posts downstream of impact. The rail was bent and the posts were pushed back and bent. The maximum permanent deflection of the rail occurred at the midspan between posts 17 and 18 and was 6.5 in (165.1 mm). The curb was not damaged except for a few gouges where the right front tire and wheel impacted. Post-test photographs of the rail are shown in figure 32.

f. Test Evaluation

This test was evaluated using both the AASHTO Guide Specifications for Bridge Railings and NCHRP 230. The following is an item-by-item evaluation using these two guidelines.

- AASHTO Guide Specifications for Bridge Railings:

Required Criteria:

a. The vehicle was contained by the test article.
b. There were no detached elements.
c. Integrity of the passenger compartment was maintained.
d. The vehicle remained upright.
g. Delta-V and Ridedown values were within limits.

Desirable Criteria:

e. The vehicle was smoothly redirected.
f. Vehicle railing interaction:
mu = 0.43, assessment: Marginal.
h. The exit angle was less than 12° (exit angle was 6°). Vehicle was within 20 ft (6.1 m) of the rail, 100 ft (30.5 m) downstream of the impact point.

MEETS ALL REQUIRED CRITERIA.

- NCHRP 230:

a. The test article smoothly redirected the vehicle.
d. There were no detached elements.
e. The vehicle remained upright during and after the collision. Integrity of the passenger compartment was maintained.
h. Vehicle trajectory and stopping position did not intrude into adjacent traffic lanes.
i. Because the vehicle trajectory and stopping position did not intrude into adjacent traffic lanes, vehicle speed change and exit angle criteria do not apply.

MEETS ALL CRITERIA.

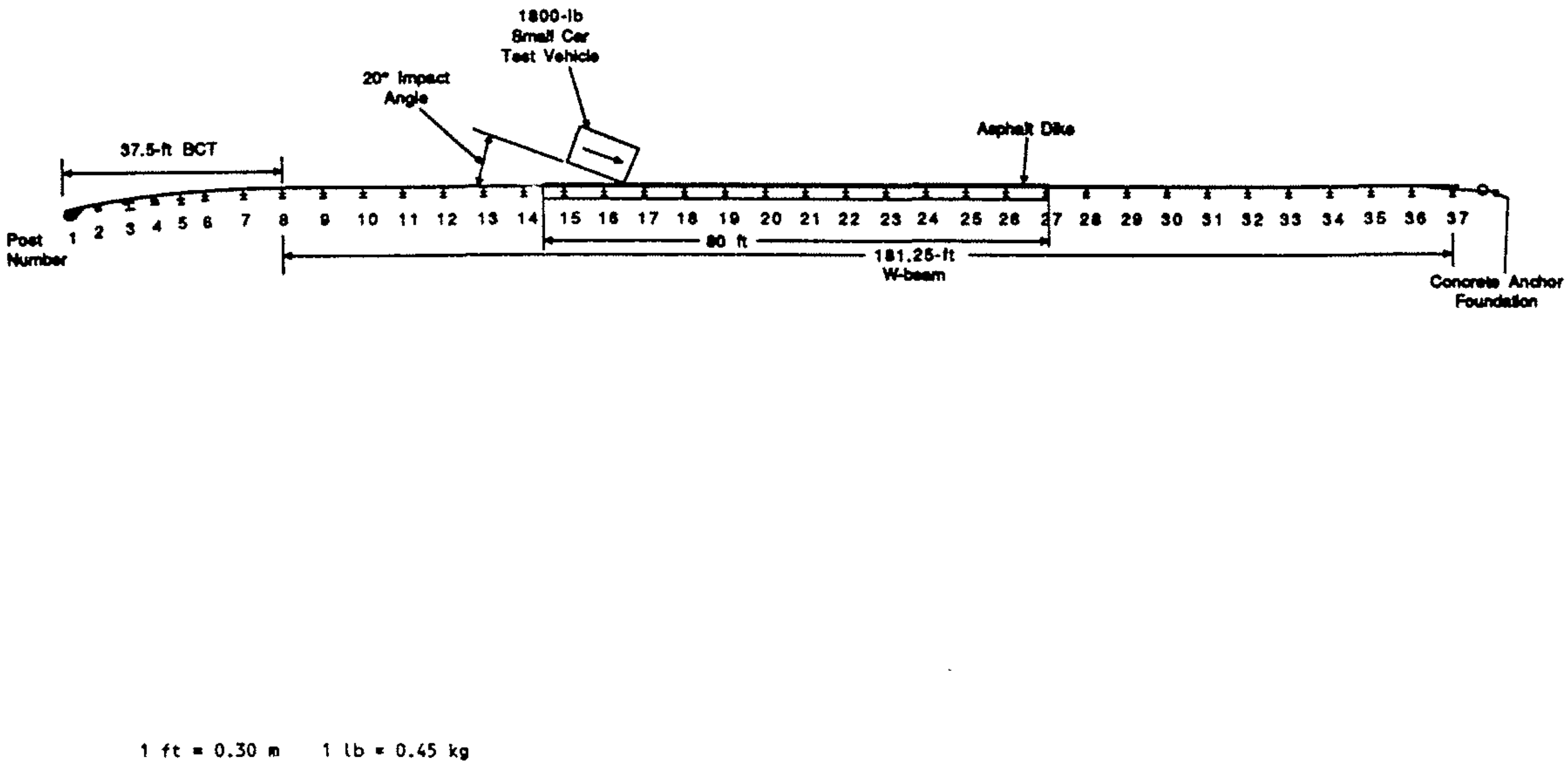


Figure 26. Test site layout, test 1862-4-89.

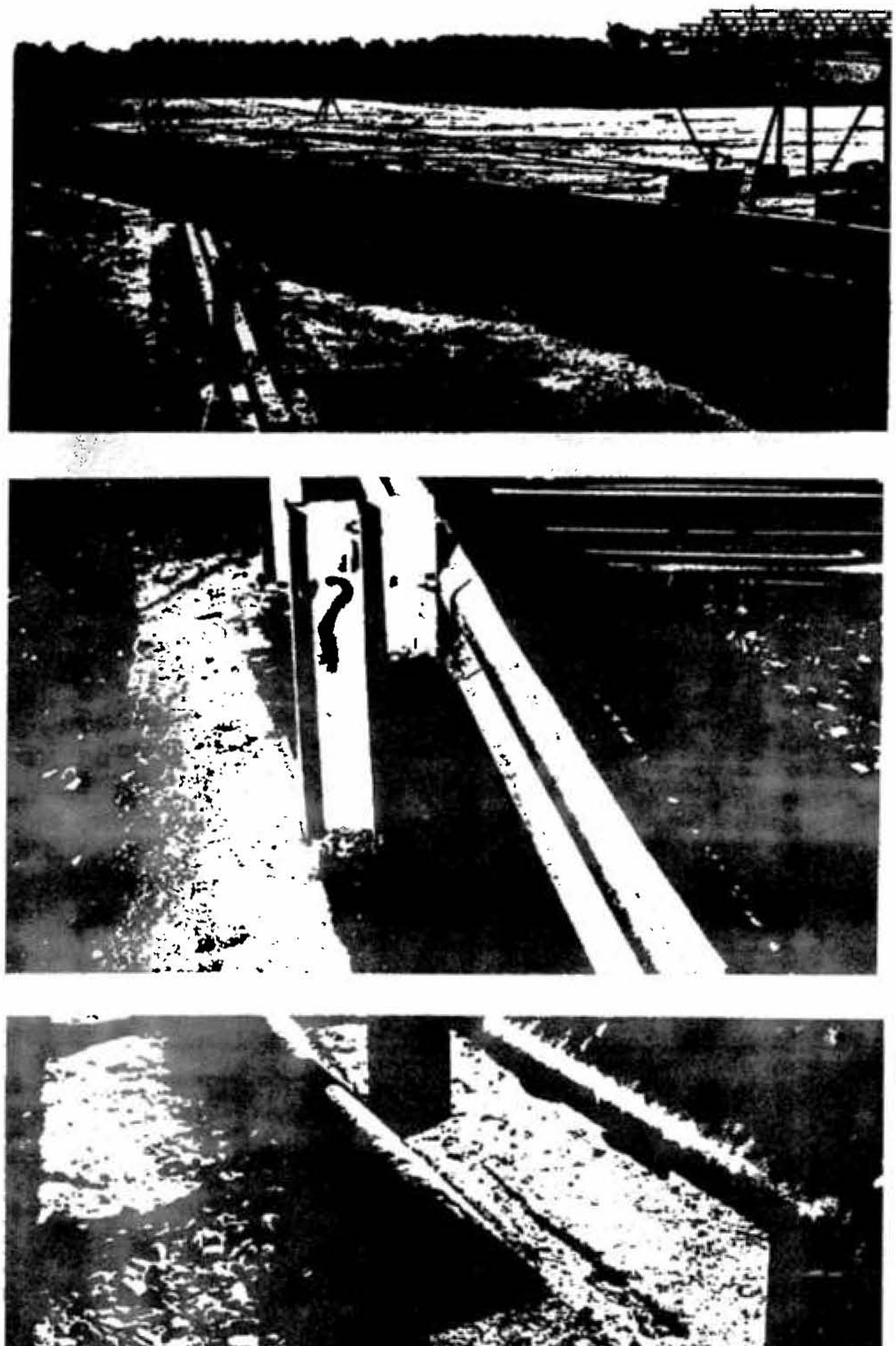


Figure 27. Pretest photographs of guardrail system, test 1862-4-89.

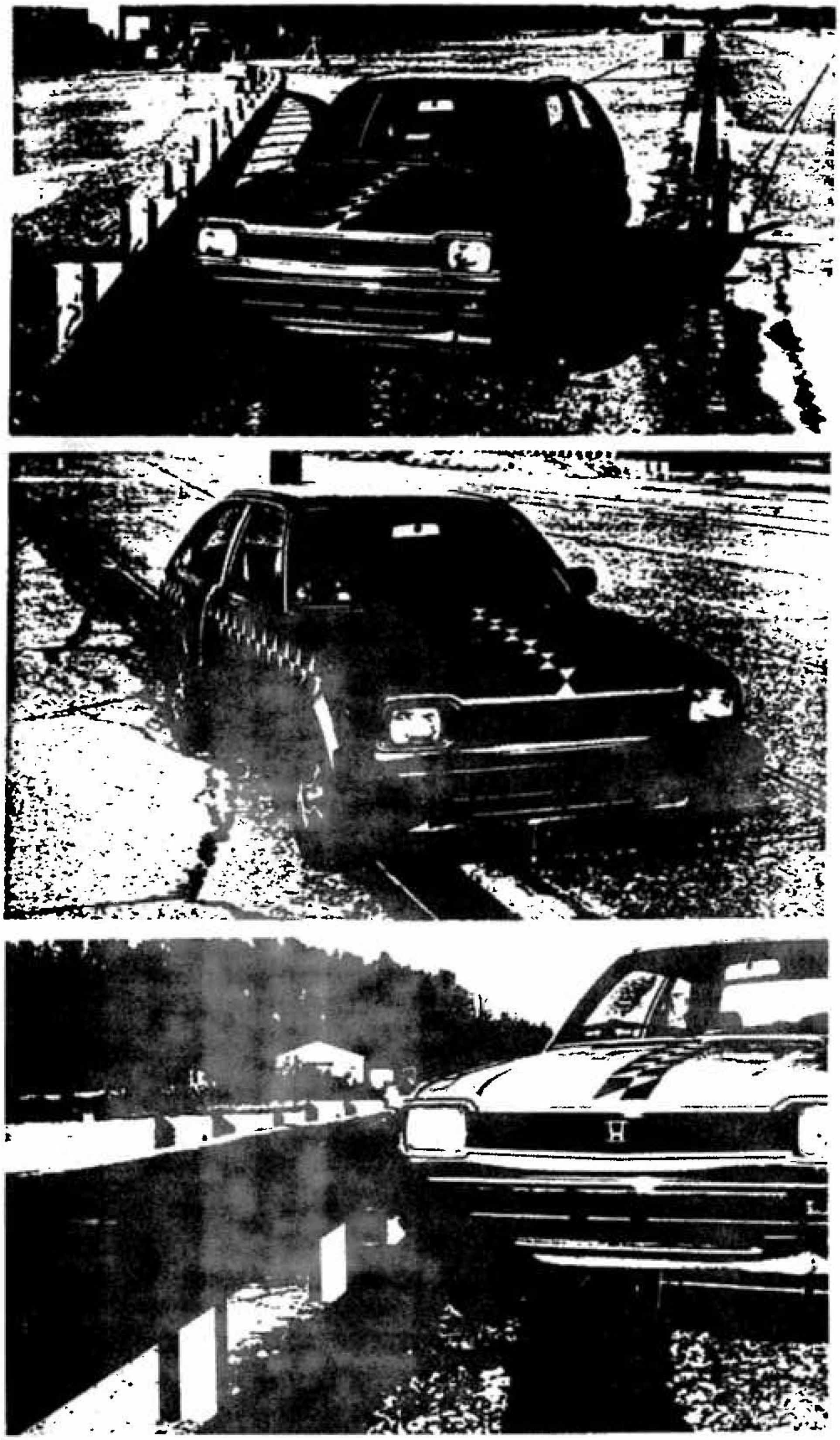
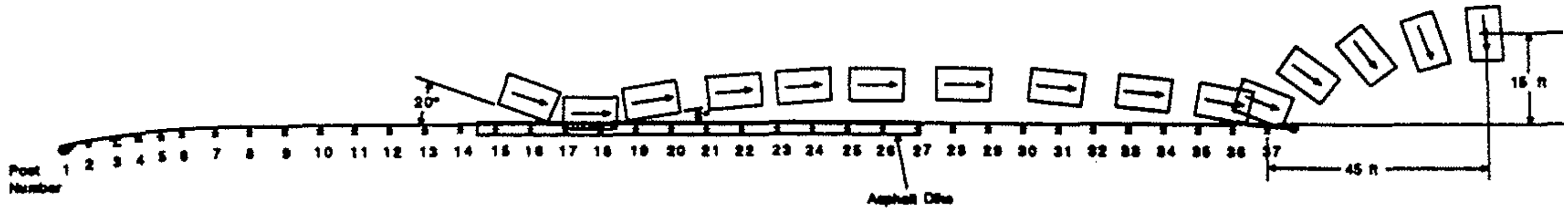


Figure 28. Pretest photographs of test vehicle, test 1862-4-89.



Date:	17 March 1989
Weather:	Clear 60° F
Test Vehicle:	1982 Honda Civic
Device Configuration:	G4(1S) W-Beam with AASHTO 6-in, Type G asphalt dike in front of barrier, 219 ft total length, 37.5-ft BCT

1. Vehicle Weight:
   - Planned, Inertial: 1800
   - Actual, Inertial: 1799
   - Planned, Gross: 1950
   - Actual, Gross: 1946
2. Number of Occupants: One
3. Occupant Model: Part 572, 50th percentile male, fully instrumented
4. Occupant Location: Driver Seat, Restrained
5. Impact:

	Speed	Angle (a)	Location
Planned:	60.0 mi/h	20°	Midspan posts 16 and 17
Actual:	62.2 mi/h	20°	Midspan posts 16 and 17

   Tolerances: Speed: -1.0, +2.5 mi/h; Angle: -1.0, +2.5 degrees
6. Redirection Angle: 6°
7. Redirection Speed: 45.5 mi/h (66.8 ft/s)
8. Total Speed Change: 16.7 mi/h (24.4 ft/s)
9. Total Momentum Change: 1475 lb-s
10. Vehicle Damage Index: 01RFEW2 (SAE J224a)
11. NCHRP 230 Test Number: S13; AASHTO Test Type: PL2
12. NCHRP 230 Impact Severity:

$$\frac{m(V \sin a)^2}{2}$$ 27.2 kip-ft (Spec: 23 to 29 kip-ft)

13. Vehicle Analysis:

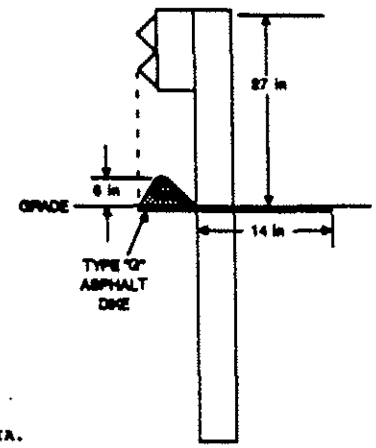
	Observed	Design/ Limit Value
Longitudinal:		
Delta-V at 2 ft:	-22.8 ft/s	30/40 ft/s
Ridedown Acceleration:	-2.4 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	23.7 ft/s	20/30 ft/s
Ridedown Acceleration:	12.5 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-5.8 g's	
Lateral:	10.0 g's	

14. Vehicle-Railing Interaction Coefficient of Friction:

$$mu = \frac{\text{Cos theta} - V_p/V}{\text{Sin theta}}$$ mu 0.43, assessment Marginal

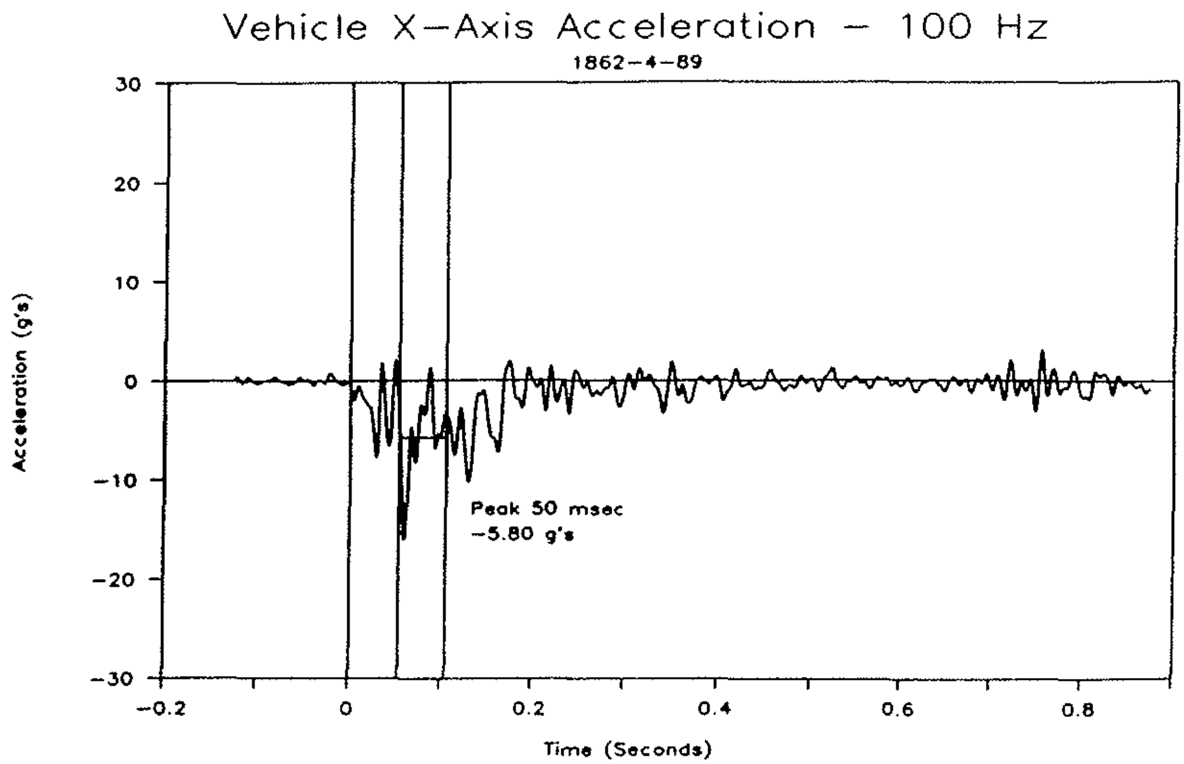
V_p = 49.4 mi/h (72.4 ft/s)

15. Test Results Conclusion:
   - AASHTO Bridge Rail Specification: MEETS ALL REQUIRED CRITERIA.
   - NCHRP 230: MEETS ALL CRITERIA.



32°F = 0°C   1 ft = 0.30 m   1 lb = 0.45 kg   1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s   1 kip-ft = 1360 N-m   1 g = 9.8 m/s^2

Figure 29. Test summary, test 1862-4-89.



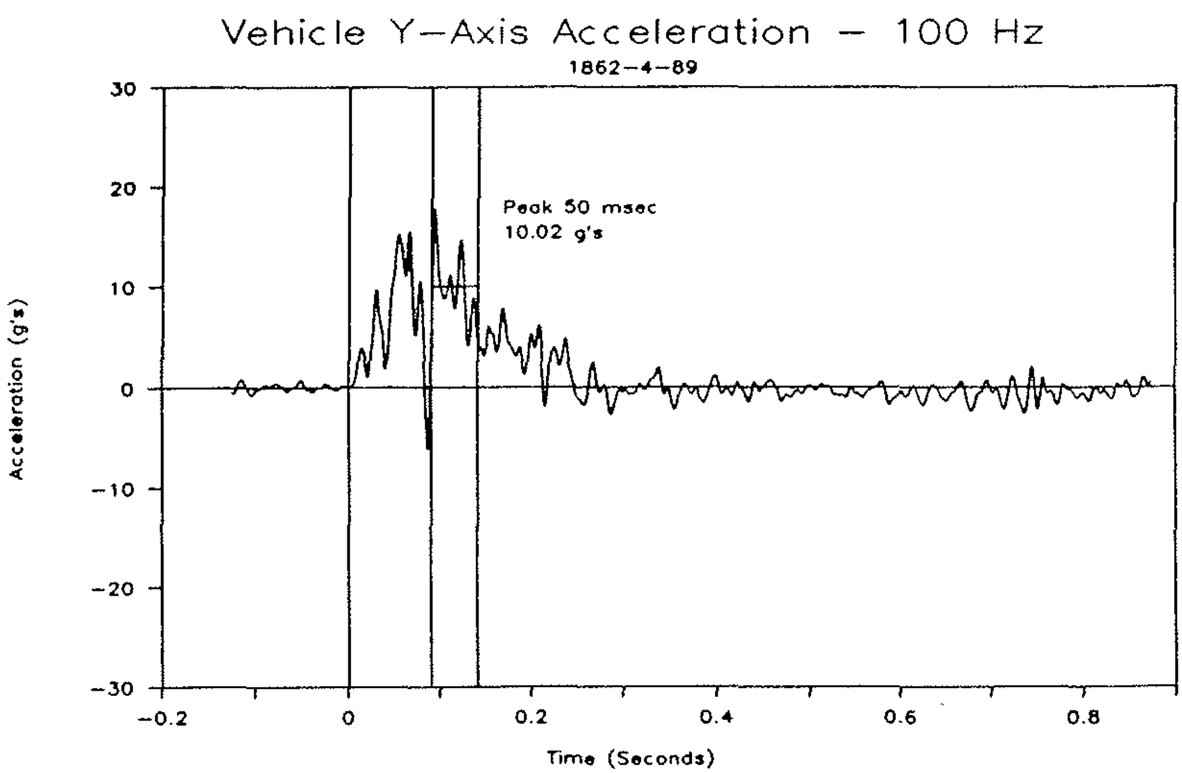


Figure 30. Vehicle accelerations, test 1862-4-89.

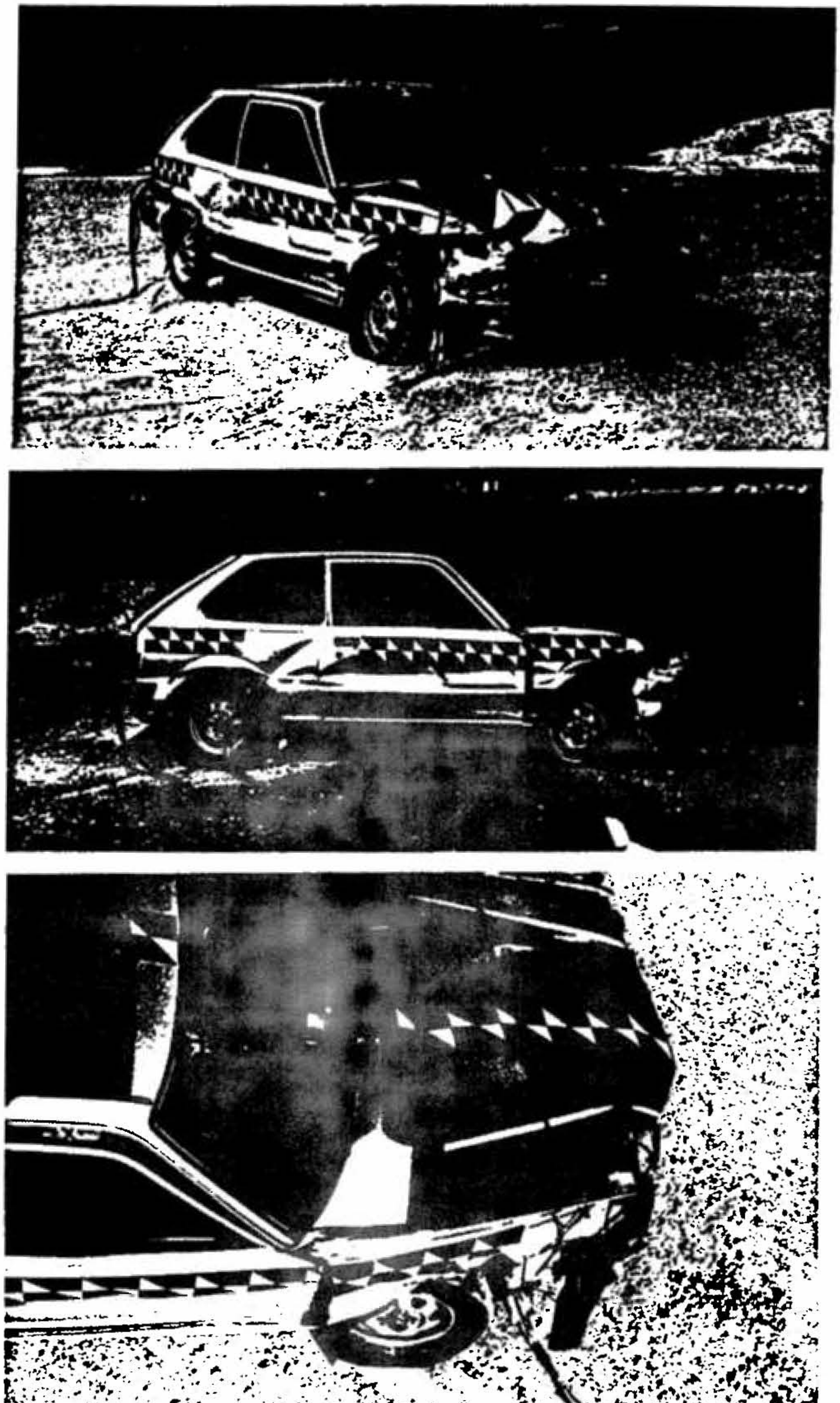


Figure 31. Post-test photographs of test vehicle, test 1862-4-89.

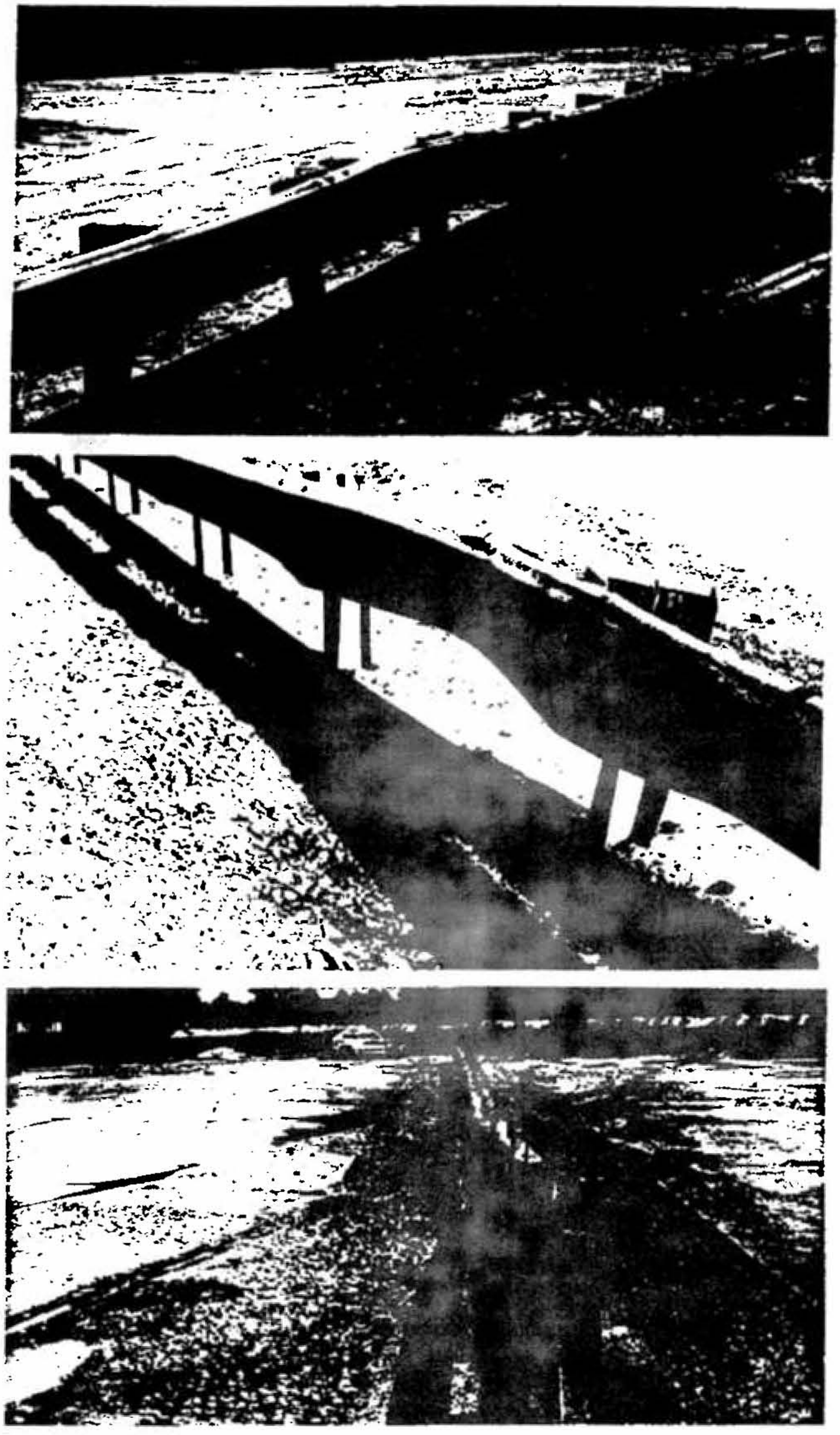


Figure 32. Post-test photographs of guardrail system, test 1862-4-89.

5. TEST 1862-5-89

a. Test Device

The test device was a standard G4(1S) W-beam rail with an AASHTO 6-in (152.4-mm) type G asphalt dike placed in front of the posts. The front of the dike was aligned with the face of the W-beam. The dike was formed on the top of a 2-in (50.8-mm) thick, 16-in (406.4-mm) wide asphalt layer. Approximately 80 ft (24.4 m) of curb was installed along the rail system. The curb began between posts 14 and 15 or approximately 12 ft (3.70 m) upstream of the impact point. The posts that were located in the area of the curb were driven through the 2-in (50.8-mm) asphalt layer.

The entire system was 218.75 ft (66.7 m) long. The system consisted of 181.25 ft (55.3 m) of W-beam and a 37.5-ft (11.4-m) standard BCT. A cable anchor assembly was used on the downstream end. This assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 33 shows the test site and test device. Figure 34 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1980 Plymouth Gran Fury. The target inertial vehicle weight was 4500 ± 200 lb (2043 ± 91 kg). The vehicle weighed approximately 3900 lb (1771 kg) empty. Ballast weighing 380 lb (173 kg) was added to the vehicle. The inertial weight of the vehicle was 4310 lb (1957 kg). The target gross vehicle weight was 4500 ± 300 lb (2043 ± 136 kg). The gross vehicle weight was 4625 lb (2100 kg).

X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the vehicle. Two uninstrumented dummies were placed in the vehicle. The driver was restrained and the passenger was unrestrained. Pretest photographs of the test vehicle are shown in figure 35. Table 16 lists important parameters of the test vehicle.

c. Impact Description

Review of the high speed films and fifth-wheel data indicated that the test vehicle impacted at 60.3 mi/h (97.0 km/h) and 25°. This review also indicated that the right corner of the vehicle

Table 16. Test vehicle parameters, test 1862-5-89.

Item	Actual	Specification
Empty Weight	3907 lb	n/a
Ballast	380 lb	n/a
Total Weight, Inertial	4310 lb	4500 ± 200 lb
Total Weight, Gross	4625 lb	4500 ± 300 lb
Vehicle Length	216 in	
Vehicle Wheelbase	118.5 in	

1 lb = 0.45 kg   1 in = 25.4 mm

impacted the rail 6 in (152.4 mm) downstream of the desired point.

Upon impact, the vehicle penetrated into the rail approximately 3.5 ft (1.1 m) before starting to redirect. As the vehicle was redirecting, the vehicle penetration caused the posts to push back, lowering the rail and allowing the vehicle to ride up on the rail and vault the system. The rail was broken by the rear of the vehicle approximately 0.350 s after impact. The rail broke just past post 18. While the vehicle was airborne, it continued yawing and began to roll toward the driver side. The vehicle nosed in while still yawing. The driver side of the vehicle impacted the ground first and the midsection of the car came down on the rail past post 25 [56 ft (17.1 m) past impact]. The vehicle was at a 30° angle to the rail when it reimpacted. With the vehicle moving forward (in relation to the vehicle), the rear wheel rolled up over the rail and the trunk flexed when the trunk was supporting the vehicle weight. Significant damage was done to the undercarriage and lower passenger side of the vehicle from scraping over the top of the rail. The vehicle continued moving, coming to rest 6 ft (1.8 m) past the end foundation, 20 ft (6.1 m) in front of the rail.

Upon impact, the driver dummy fell into the passenger seat, held by the seat belt. The passenger dummy punched out the passenger-side window and bent the passenger-side door. When the vehicle impacted the ground, the driver impacted the steering wheel, fell into the passenger seat, and came to rest there. The passenger had its head and shoulders out the side window for the entire impact event.

A summary of test conditions and results are shown in figure 36. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 37.

d. Vehicle Damage

Damage occurred to the grill, front and rear bumpers, and entire right side of the vehicle. Significant damage was done to the undercarriage and lower passenger side of the vehicle from scraping over the top of the rail after reimpact. The passenger-side door was pushed out due to the impact of the passenger dummy. Post-test photographs of the vehicle are shown in figure 38.

e. Barrier Damage

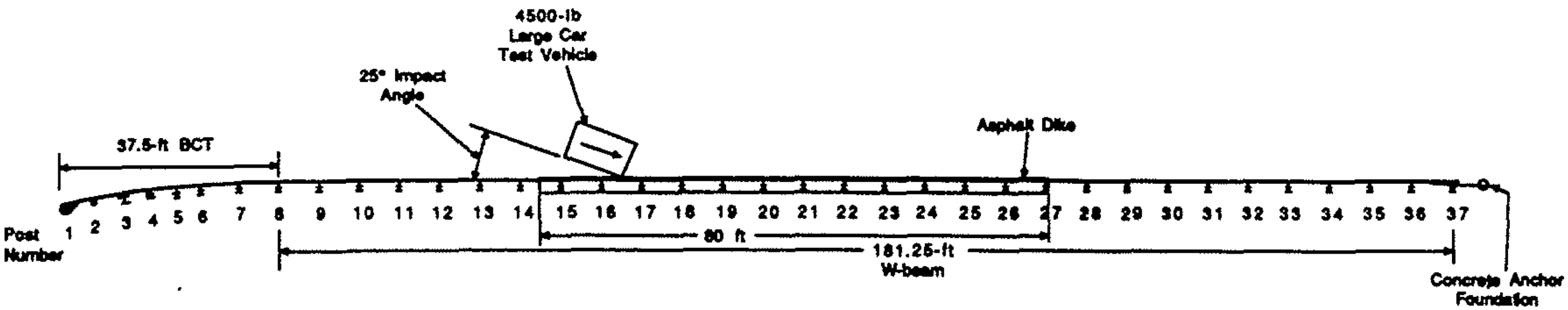
The barrier was damaged one rail length [12.5 ft (3.8 m)] upstream and 1.5 rail lengths [19 ft (5.8 m)] downstream of the impact point and from post 25 to post 34 [4.5 rail lengths, 56 ft (17.1 m)] where the vehicle reimpacted the rail. The posts and rail were severely bent and twisted for two rail lengths downstream of the impact point. The rail was severed just past post 18. The rail was not damaged from post 20 to post 25, where the vehicle was airborne. In the area where the vehicle reimpacted, the rail and posts were bent and twisted to varying degrees. The BCT was pulled 1 in (25.4 mm) at the ground line. The downstream end anchor showed no movement. The maximum permanent deflection of the rail occurred at post 17 and was 34 in (863.6 mm). There was only slight damage to the curb from this test. Post-test photographs of the rail are shown in figure 39.

f. Test Evaluation

This test was evaluated using NCHRP 230. The following is an item-by-item evaluation using this guideline.

- a. The test article redirected the vehicle.
- d. There were no detached elements.
- e. The vehicle remained upright during and after the collision. Integrity of the passenger compartment was maintained.
- h. Vehicle trajectory and stopping position did not intrude into adjacent traffic lanes.
- i. Because the vehicle trajectory and stopping position did not intrude into adjacent traffic lanes, vehicle speed change and exit angle criteria do not apply.

MEETS ALL CRITERIA. Although the test barrier met the evaluation criteria, its performance was very marginal because the vehicle was launched much higher into the air than it would have been if the curb was not present. It is clear the barrier is at its performance limit when used with a 6-in (152.4-mm) curb. .



1 ft = 0.30 m   1 lb = 0.45 kg

Figure 33. Test site layout, test 1862-5-89.

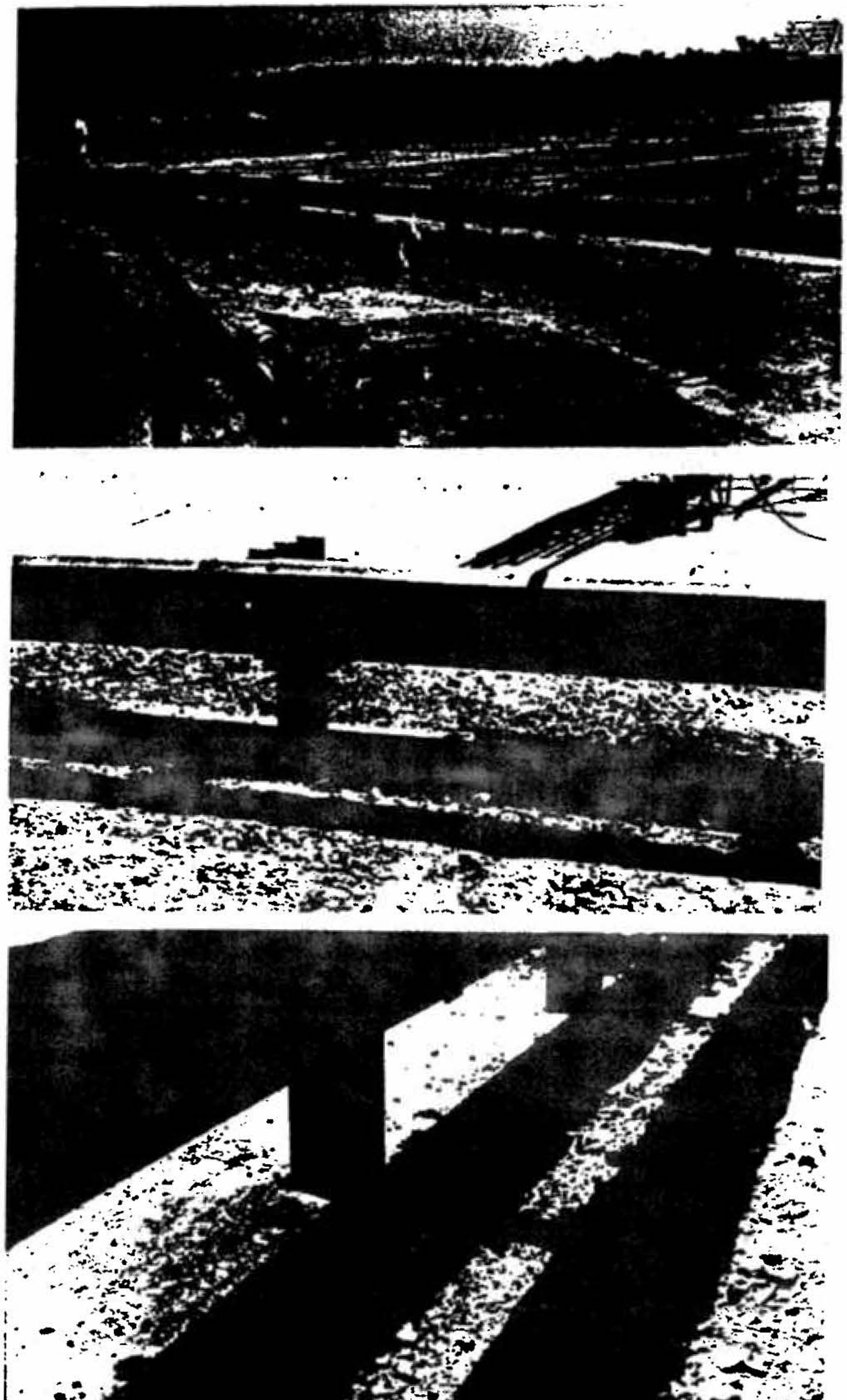


Figure 34. Pretest photographs of guardrail system, test 1862-5-89.

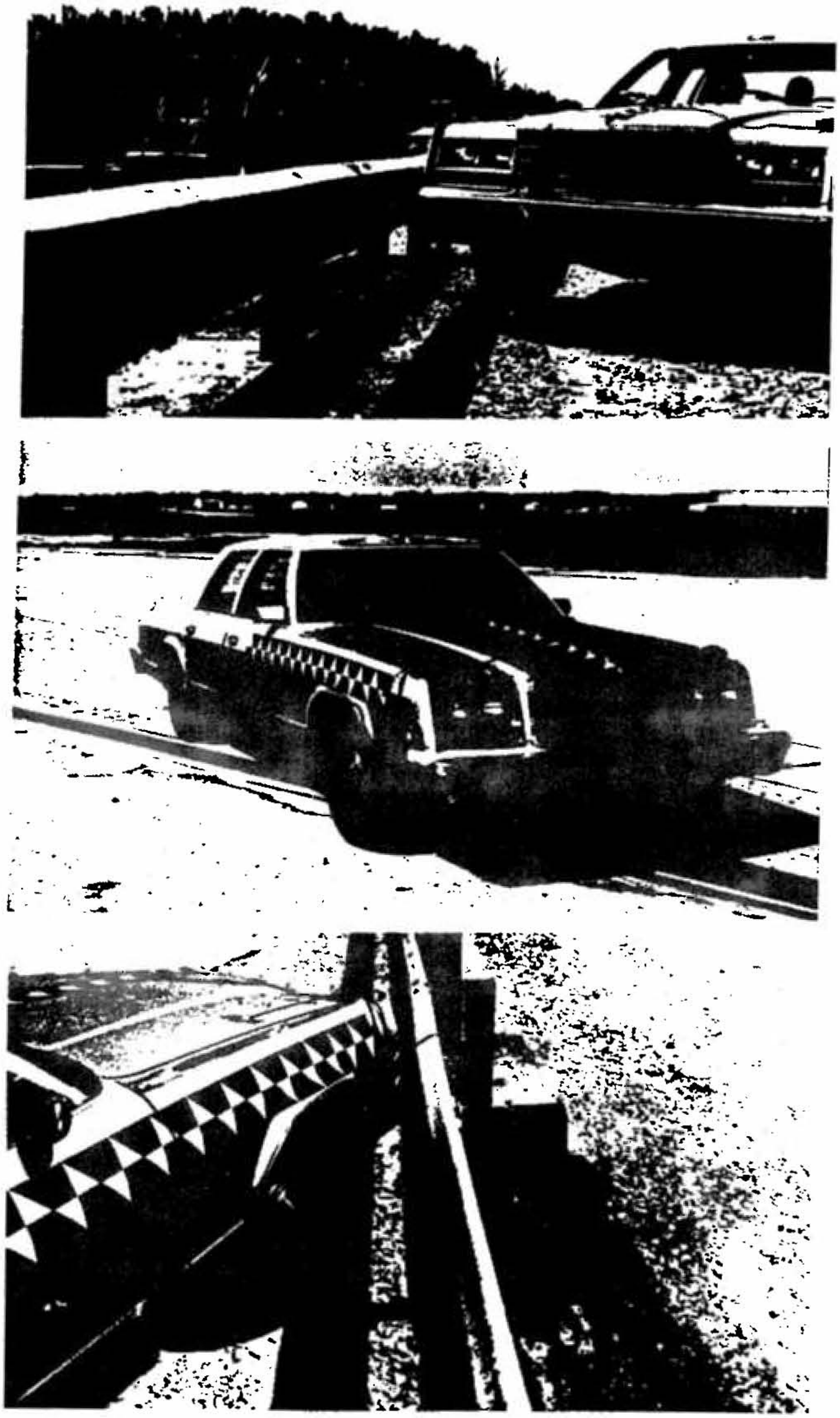
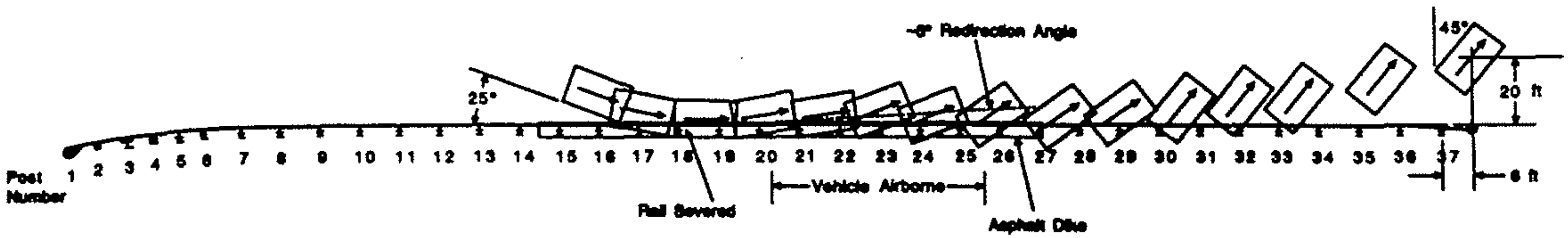


Figure 35. Pretest photographs of test vehicle, test 1862-5-89.



Date:	28 March 1989
Weather:	Clear 80° F
Test Vehicle:	1980 Plymouth Gran Fury
Device Configuration:	G4(1S) W-Beam with AASHTO 6-in, Type G asphalt dike in front of barrier, 219 ft total length, 37.5-ft BCT

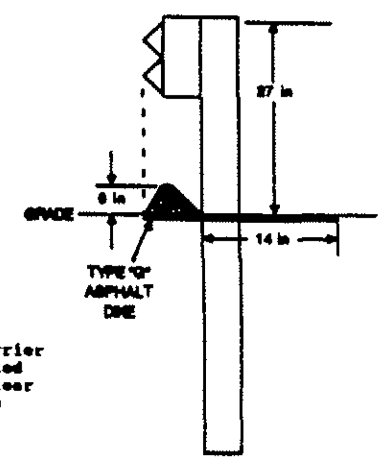
1. Vehicle Weight:
   - Planned, Inertial: 4500 ± 200
   - Actual, Inertial: 4310
   - Planned, Gross: 4500 ± 300
   - Actual, Gross: 4625
2. Number of Occupants: Two
3. Occupant Model: Part 572, 50th percentile male, uninstrumented
4. Occupant Location: Driver Seat, Restrained; Passenger Seat, Unrestrained
5. Impact:

	Speed	Angle (a)	Location
Planned:	60.0 mi/h	25°	Midspan posts 16 and 17
Actual:	60.3 mi/h	25°	6 in downstream of desired point

6. Redirection Angle: ~5°*
7. Redirection Speed: ~39.8 mi/h (~58.4 ft/s)*
8. Total Speed Change: ~20.5 mi/h (~30 ft/s)*
9. Total Momentum Change: ~4309 lb-s*
10. Vehicle Damage Index: (SAE J224a) 01RDEW2
11. NCHRP 230 Test Number: S13
    AASHTO Test Type: n/a
12. NCHRP 230 Impact Severity:
    $\frac{m(V \sin a)^2}{2}$ 93.4 kip-ft (Spec: 89 to 114 kip-ft)
13. Vehicle Analysis:

	Observed	Design/ Limit Value
Longitudinal:		
Delta-V at 2 ft:	-21.7 ft/s	30/40 ft/s
Ridedown Acceleration:	-4.7 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	17.2 ft/s	20/30 ft/s
Ridedown Acceleration:	9.8 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-4.3 g's	
Lateral:	5.6 g's	

14. Test Results Conclusion:
    NCHRP 230: MEETS ALL CRITERIA. Although the test barrier successfully redirected the vehicle, it is clear the barrier is at its performance limit.



* Due to the yawing and pitching of the vehicle, exact measures of the redirection angle and speed are not possible.

32°F = 0°C 1 ft = 0.30 m 1 lb = 0.45 kg 1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s 1 kip-ft = 1360 N-m 1 g = 9.8 m/s²

Figure 36. Test summary, test 1862-5-89.

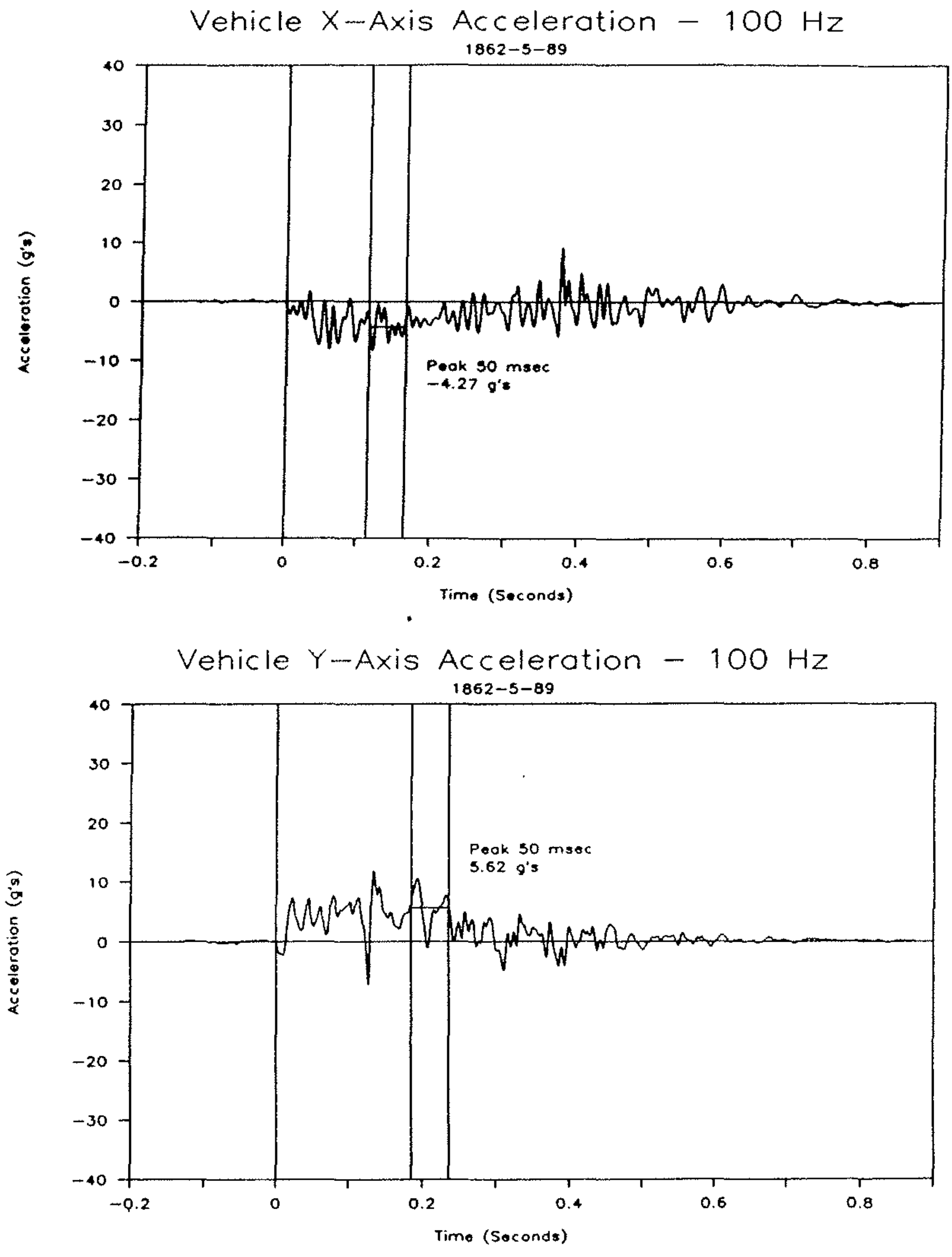


Figure 37. Vehicle accelerations, test 1862-5-89.

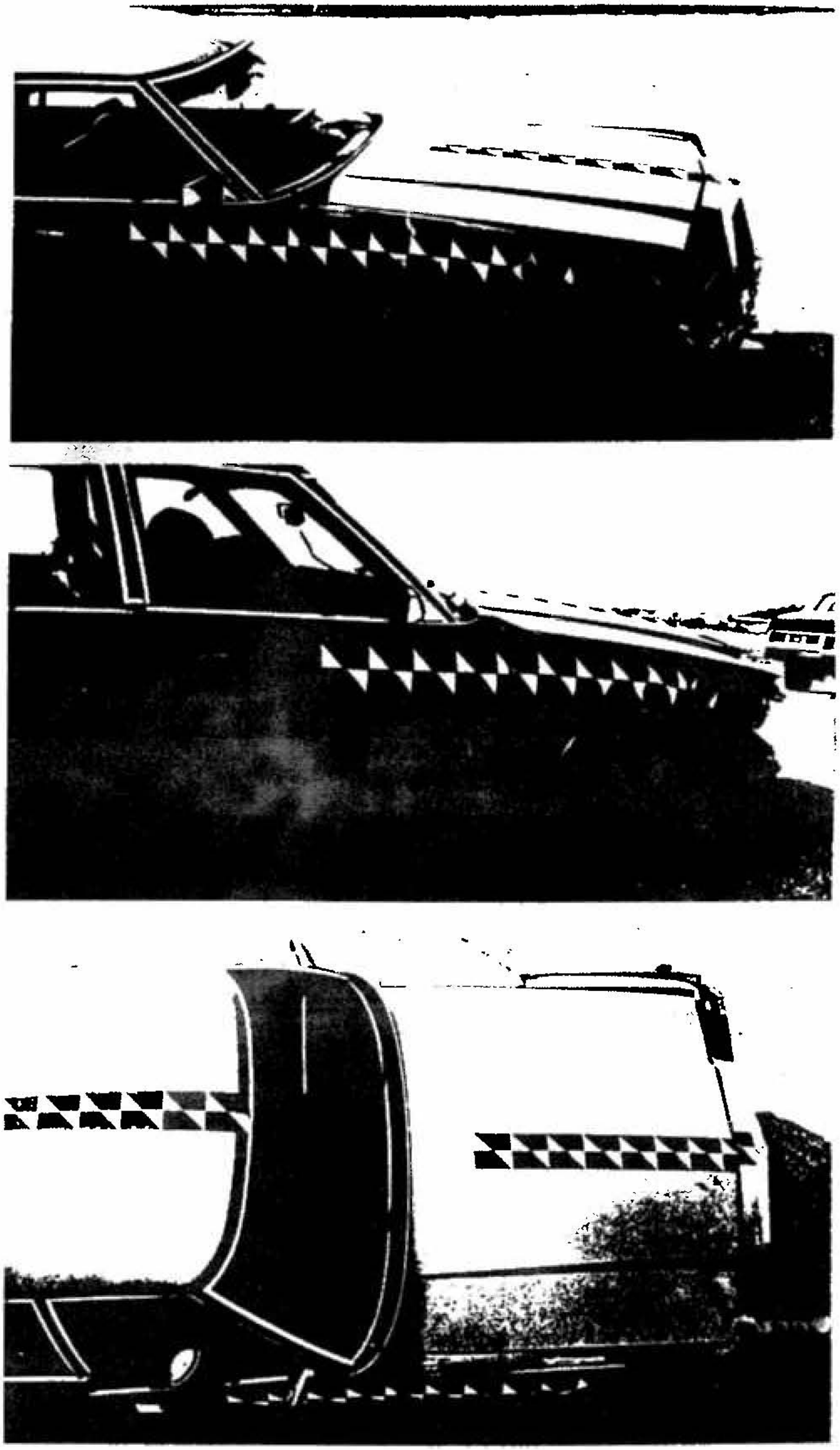


Figure 38. Post-test photographs of test vehicle, test 1862-5-89.

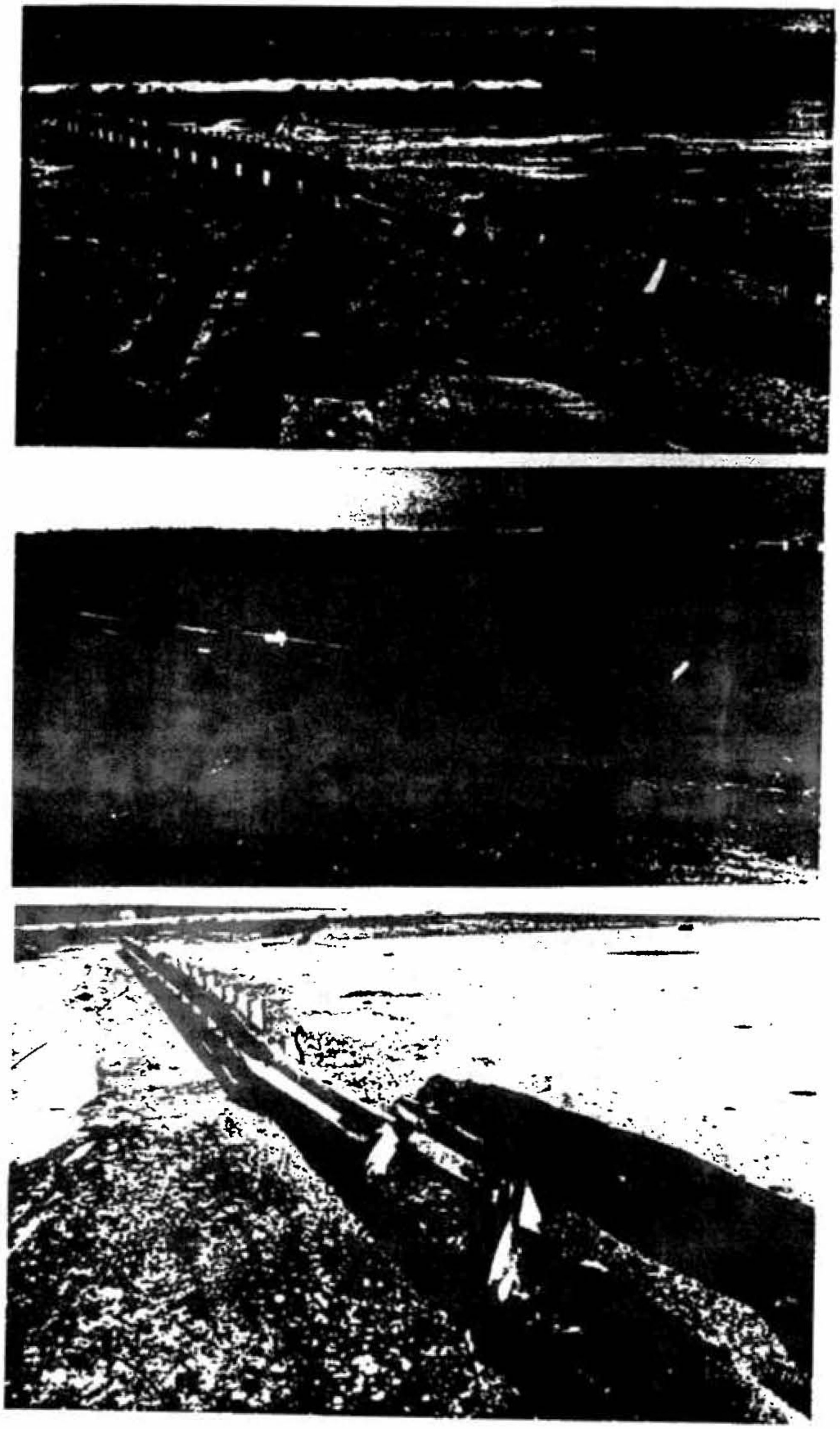


Figure 39. Post-test photographs of guardrail system, test 1862-5-89.

6. TEST 1862-6-89

a. Test Device

The test device was a standard G4(1S) W-beam rail installed on a superelevation with a 1192-ft (363.6-m) radius curve. The entire system was 262.5 ft (80.1 m) long. The system consisted of 150 ft (45.8 m) of W-beam in the curved section, 75 ft (22.9 m) of straight rail prior to the curve and a 37.5-ft (11.4-m) standard BCT on the upstream end. The superelevation consisted of 20 ft (6.1 m) of a 10-percent upslope and 10 ft (3.1 m) of a 2-percent rising shoulder. The front face of the rail was 9 in (228.6 mm) past the edge of the shoulder. The terrain fell away in a 2:1 downslope 4 ft (1.2 m) past the edge of the shoulder. For 4 ft (1.2 m) on both sides of the 2-percent/2:1 slope breakpoint, the slopes were rounded. With the rounding, a smooth merge existed between these two slopes rather than a sharp breakpoint. The upstream-end BCT used steel slipbase posts that incorporate large soil plates in lieu of the concrete anchor. A cable anchor assembly was used on the downstream end. This assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 40 shows the test site and test device. Figure 41 shows a rail profile drawing. Figure 42 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1982 Ford F100 pickup. The target inertial vehicle weight was 5400 lb (2452 kg). The vehicle weighed approximately 4000 lb (1816 kg) empty. Approximately 1400 lb (636 kg) of ballast were added. The ballasted inertial weight of the truck was 5399 lb (2451 kg). The gross vehicle weight was 5727 lb (2600 kg).

Two dummies were placed in the vehicle. The driver was restrained while the passenger was unrestrained. X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the cab of the truck. Pretest photographs of the test vehicle are shown in figure 43. Table 17 lists important parameters of the test vehicle.

c. Impact Description

Review of the high-speed films and fifth-wheel data indicated that the test vehicle impacted at 60.9 mi/h (98.0 km/h) and 20°

Table 17. Test vehicle parameters, test 1862-6-89.

Item	Actual	Specification
Empty Weight	~4000 lb	n/a
Ballast	~1400 lb	n/a
Total Weight, Inertial	5399 lb	5400 lb
Total Weight, Gross	5727 lb	n/a
H_{cg}	27 in	27 ± 1 in
A (front to cg), Inertial	8.60 ft	8.5 ± 0.1 ft
B (width)	6.42 ft	6.5 ft
Truck Length	214 in	
Truck Wheelbase	134 in	
Wheel/Tire Size	235 85R15	
Truck Box Size	8 ft long by 1.5 ft high by 5.5 ft wide	
Ground to Box Floor	27 in	

1 lb = 0.45 kg   1 ft = 0.31 m   1 in = 25.4 mm

measured relative to the straight rail section. This review also indicated that the right corner of the vehicle impacted the rail approximately 1 ft (0.3 m) upstream of the desired point.

Approximately 20 ft (6.1 m) prior to impact, as the vehicle was traversing the superelevation, all four wheels of the vehicle left the ground, although not simultaneously.

Upon impact, the vehicle penetrated into the rail 25 to 30 in (635.0 to 762.0 mm) before beginning to redirect. As the vehicle was redirecting, it maintained the rail penetration and started to roll toward the driver side. By this time, the truck was past the breakpoint of the foreslope, falling down the slope. This caused the vehicle to continue to roll. The truck came off the rail at post 31 and was slightly airborne after rolling approximately 75°. The vehicle rolled to 90° and pitched slightly (in the vehicle frame of reference). The vehicle tires gouged the ground in front of post 33. The truck skidded on the driver side and then rolled onto its top. The roll bar impacted the ground in front of post 36. The vehicle came to rest 125 ft (38.1 m) downstream of impact, approximately 9 ft (2.7 m) in front of the rail, on its roof, yawed approximately 26° in relation to the straight rail.

The driver dummy impacted the driver-side door and window. The passenger dummy violently impacted the driver dummy. The passenger came to rest with its upper body between the dash and the crushed roof. The driver came to rest in its seat (although upside down).

A summary of test conditions and results are shown in figure 44. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 45.

d. Vehicle Damage

The entire front of the vehicle including the cab, fenders, doors, hood, tires/wheels and suspension was damaged. The entire left side of the vehicle was also damaged. Post-test photographs of the test vehicle are shown in figure 46.

e. Barrier Damage

The barrier was damaged for 63 ft (19.2 m), beginning 15 ft (4.6 m) upstream of impact. Most posts in this area were pushed away (did not reach yield strength prior to the soil giving away). The rail was detached from the block at post 23. The downstream foundation was pulled toward the rail approximately 1.5 in (38.1 mm) by the lateral rail deflection. The maximum permanent rail deflection occurred at post 25 and was 43 in (1092.2 mm). Posttest photographs of the rail are shown in figure 47.

f. Test Evaluation

This test was evaluated using the AASHTO Guide Specifications for Bridge Railings. The following is an item-by-item evaluation using this guideline.

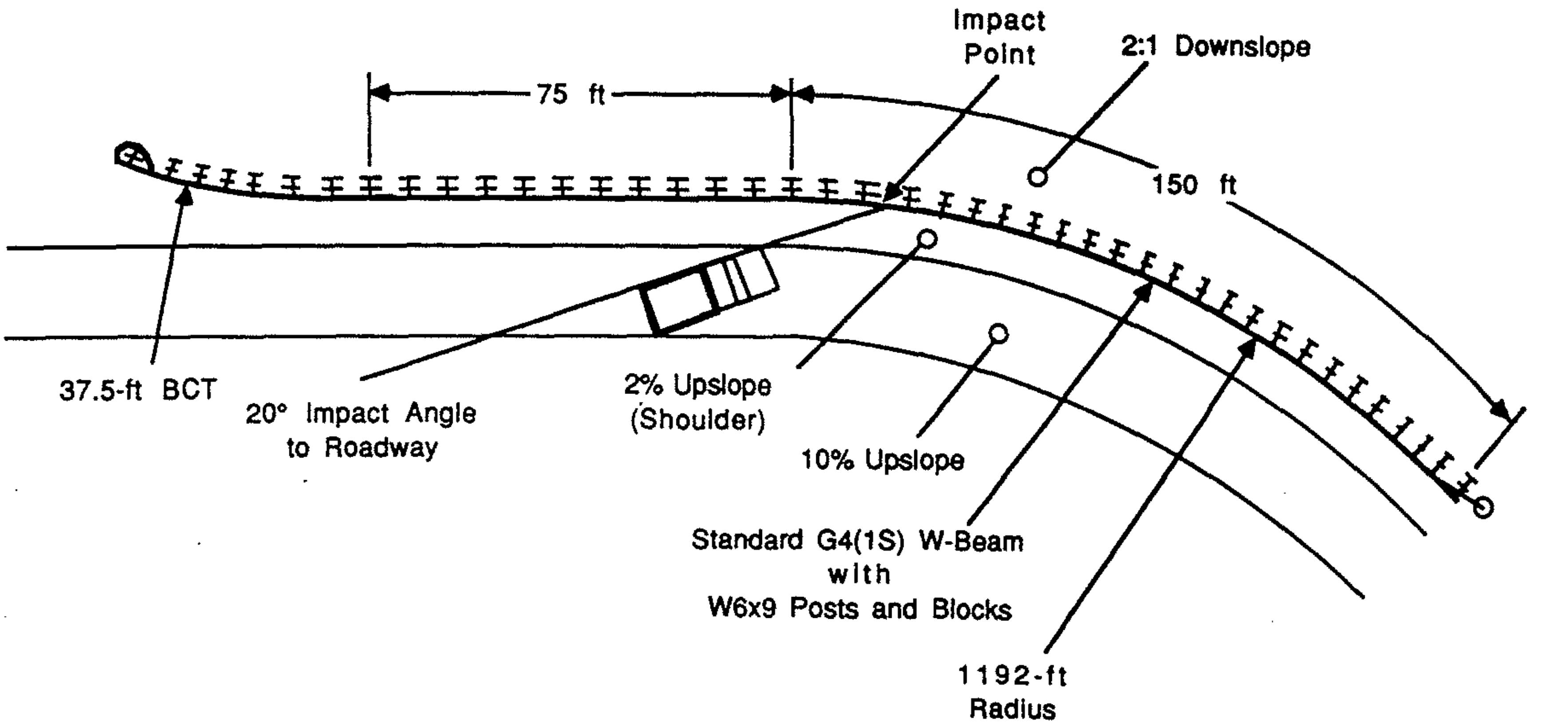
Required Criteria:

a. The vehicle was contained by the test article.
b. There were no detached elements.
c. Integrity of the passenger compartment was NOT maintained, the vehicle rolled over.
d. The vehicle did NOT remain upright, the vehicle rolled over.

Desirable Criteria:

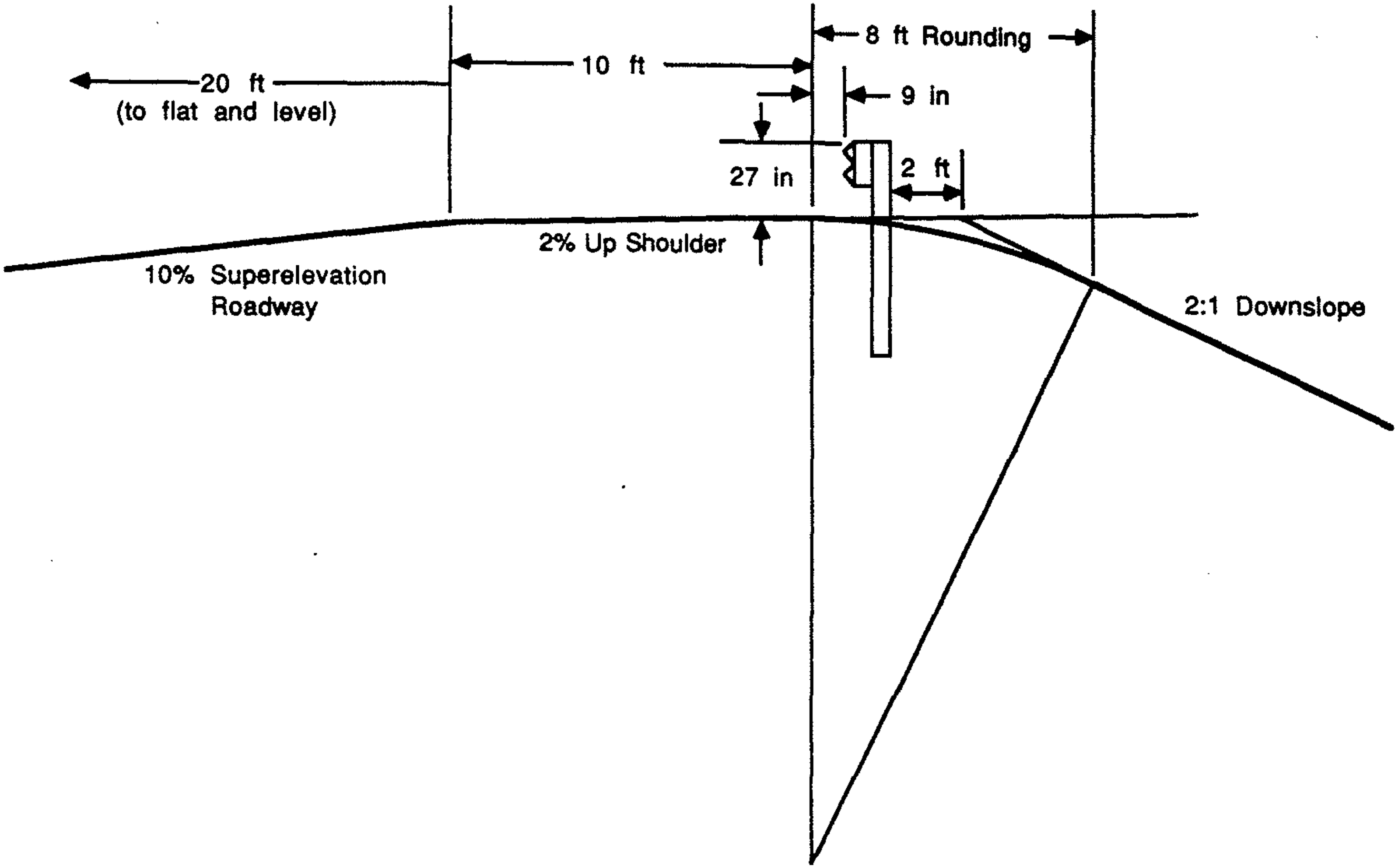
e. The vehicle was NOT smoothly redirected (redirection angle not measured due to rollover)
f. Vehicle railing interaction: mu = 0.42, assessment: Marginal.
g. Delta-V and Ridedown values were within limits.
h. The exit angle was less than 12° (however, redirection angle was not measured due to rollover). Vehicle was within 20 ft (6.1 m) of the rail, 100 ft (30.5 m) downstream of the impact point.

TEST ARTICLE FAILS DUE TO VEHICLE ROLLOVER.



1 ft = 0.30 m

Figure 40. Test site layout, test 1862-6-89.



1 ft = 0.30 m   1 in = 25.4 mm

Figure 41. Rail profile, test 1862-6-89.

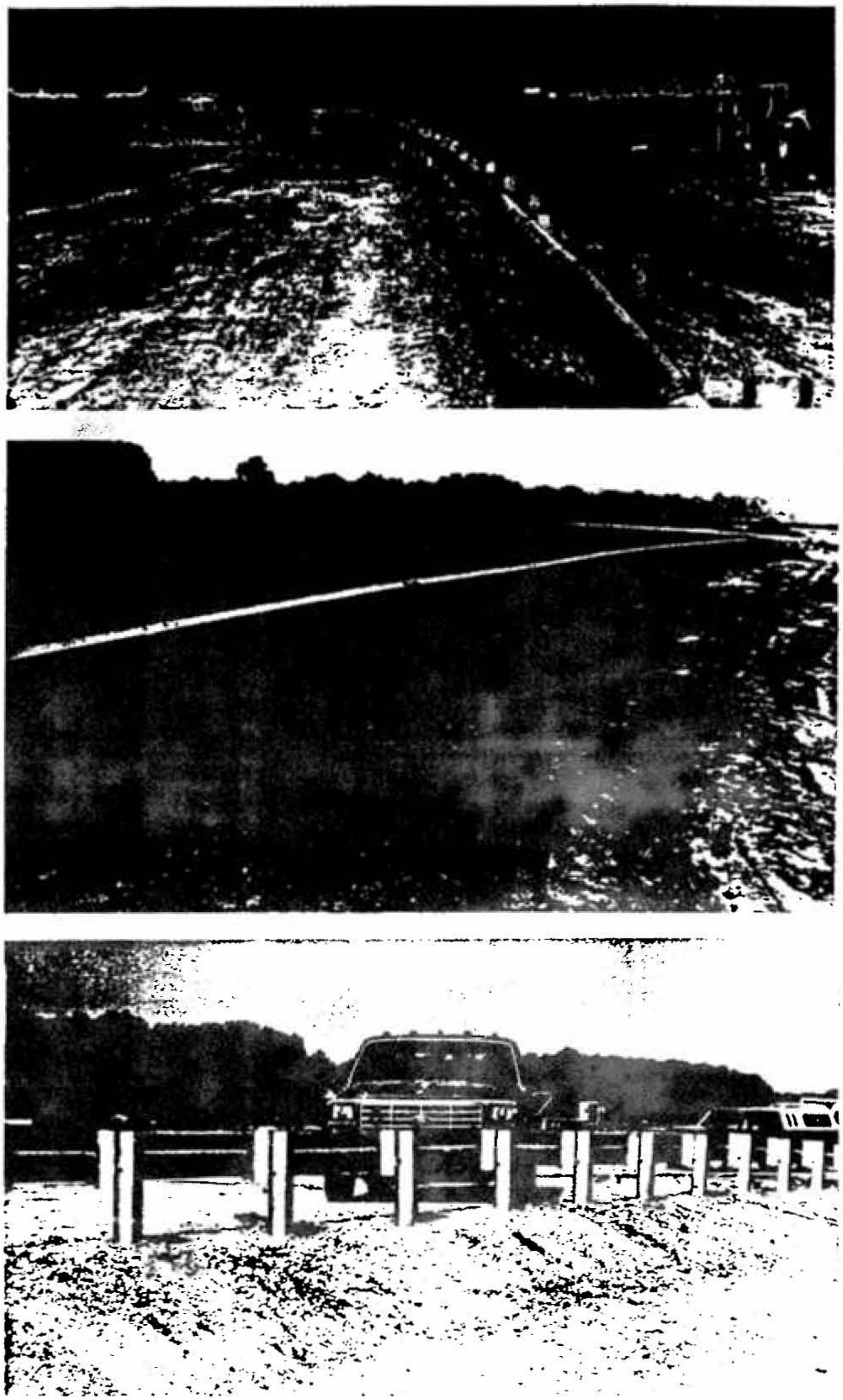
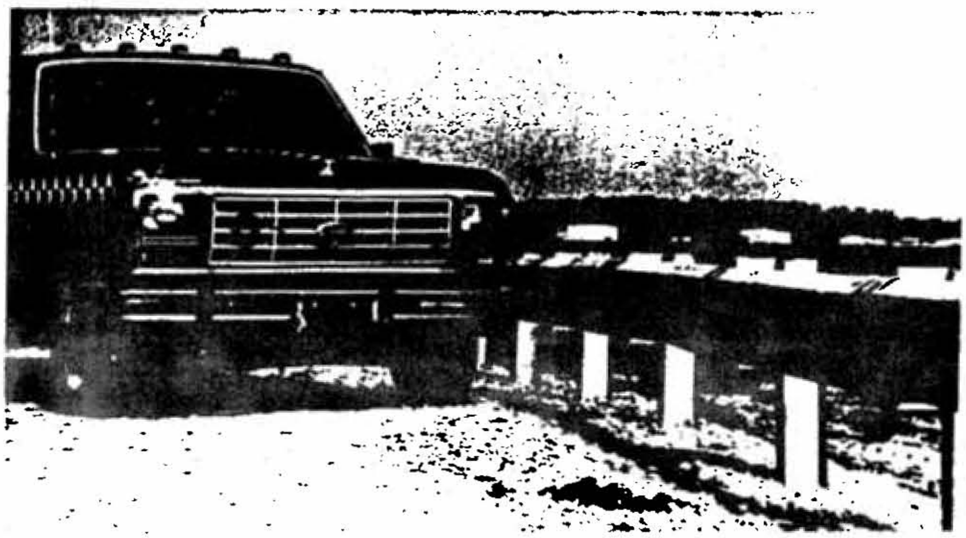


Figure 42. Pretest photographs of guardrail system, test 1862-6-89.



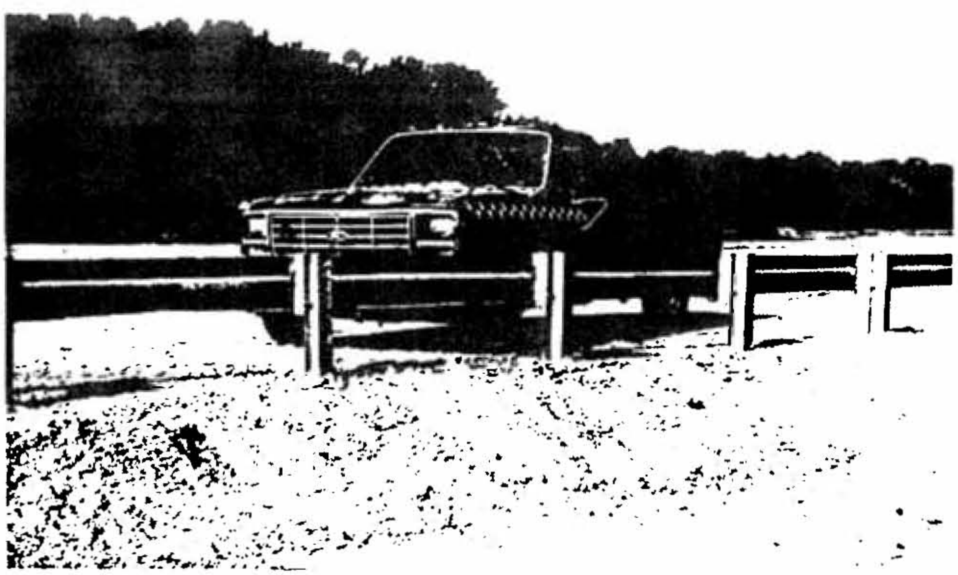
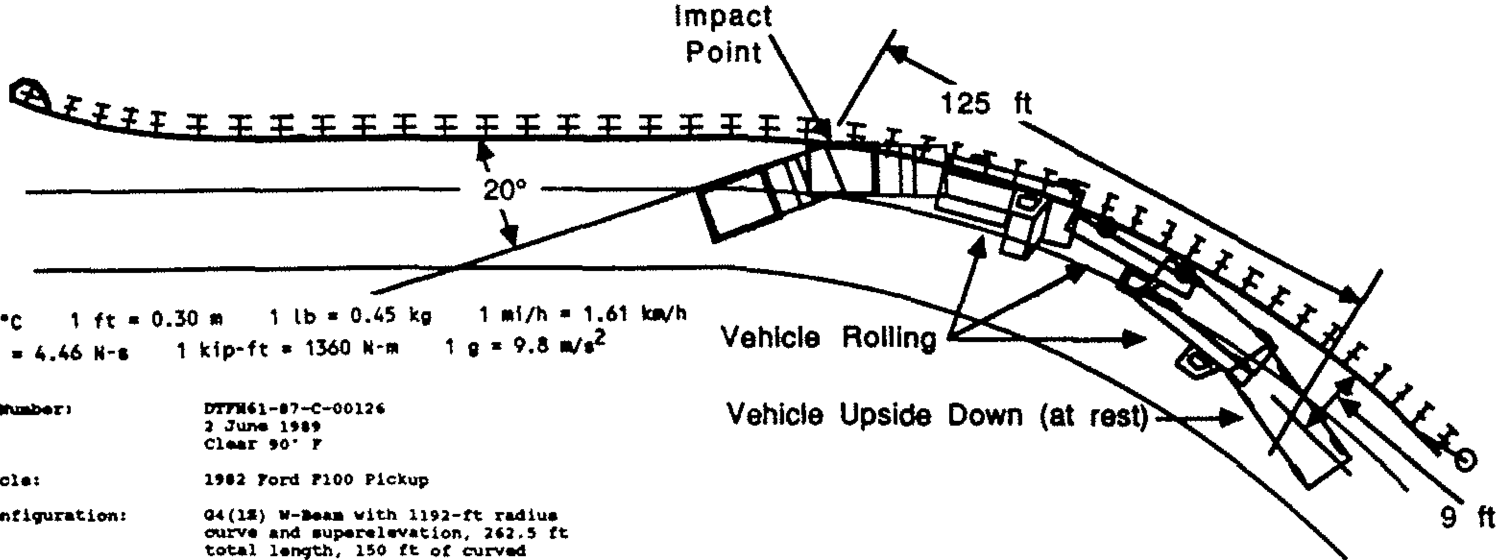


Figure 43. Pretest photographs of test vehicle, test 1862-6-89.



32°F = 0°C 1 ft = 0.30 m 1 lb = 0.45 kg 1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s 1 kip-ft = 1360 N-m 1 g = 9.8 m/s²

Contract Number:	DTFH61-87-C-00126
Date:	2 June 1989
Weather:	Clear 90° F
Test Vehicle:	1982 Ford F100 Pickup
Device Configuration:	G4(1S) W-Beam with 1192-ft radius curve and superelevation, 262.5 ft total length, 150 ft of curved rail, 75 ft of straight rail, 37.5-ft BCT.

1. Vehicle Weight:
   - Planned, Inertial: 5400
   - Actual, Inertial: 5399
   - Actual, Gross 5727
2. Number of Occupants: Two
3. Occupant Model: Part 572, 50 percentile male
4. Occupant Locations: Driver Seat, Restrained; Passenger Seat, Unrestrained
5. Impact:

	Speed	Angle	Location
Planned:	60.0 mi/h	20°	Midspan posts 21 and 22
Actual:	60.9 mi/h	20°	Midspan posts 21 and 22

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

6. Redirection Angle: Not measured due to vehicle rollover
7. Redirection Speed: n/a
8. Total Speed Change: n/a
9. Total Momentum Change: n/a
10. Vehicle Damage Index: (SAE J224a) 11LYEO2
11. NCHRP 230 Test Number: Special; AASHTO Test Type: PL2
12. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-17.0 ft/s	30/40 ft/s
Ridedown Acceleration:	-6.1 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-13.6 ft/s	20/30 ft/s
Ridedown Acceleration:	-7.2 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-3.4 g's	
Lateral:	-4.9 g's	

13. Vehicle-Railing Interaction Coefficient of Friction:

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

mu	Assessment
0.42	Marginal

V_p = 48.5 mi/h (71.2 ft/s)

14. Test Results Conclusion:

AASHTO Bridge Rail Specification: TEST ARTICLE FAILS DUE TO VEHICLE ROLLOVER.

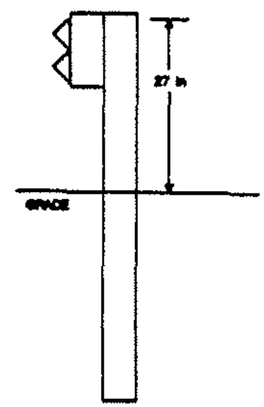
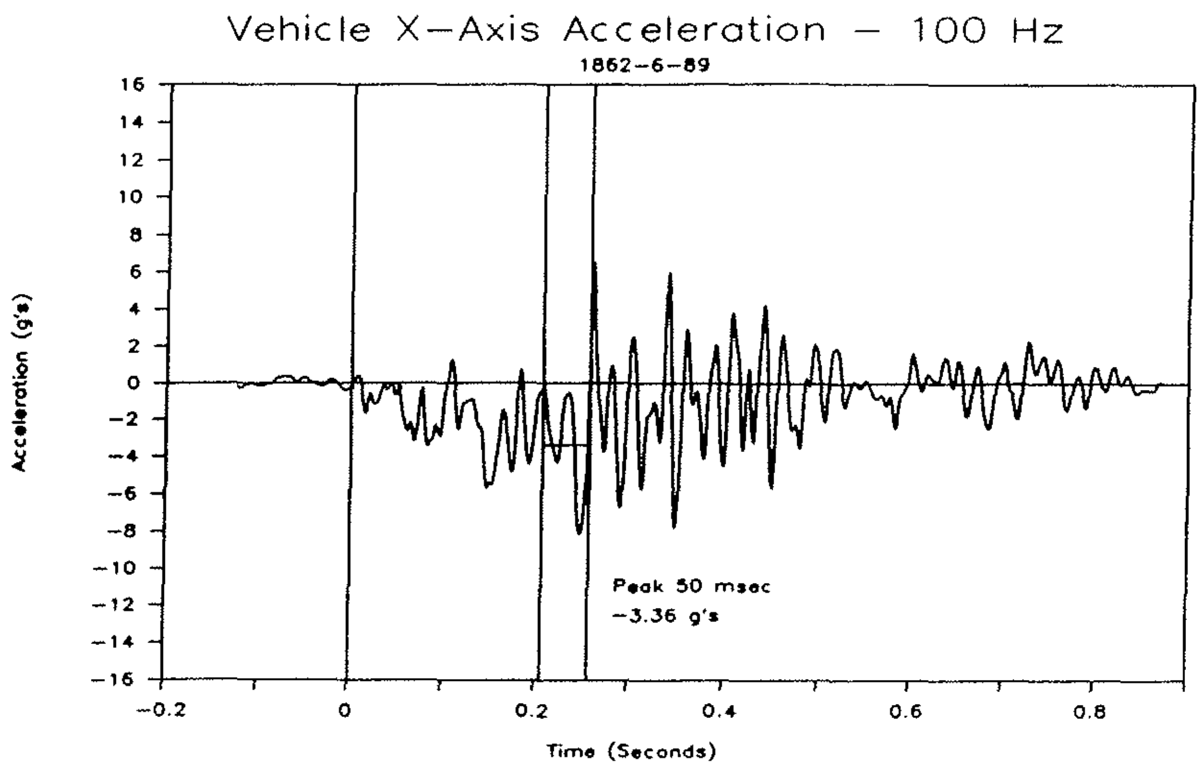


Figure 44. Test summary, test 1862-6-89.



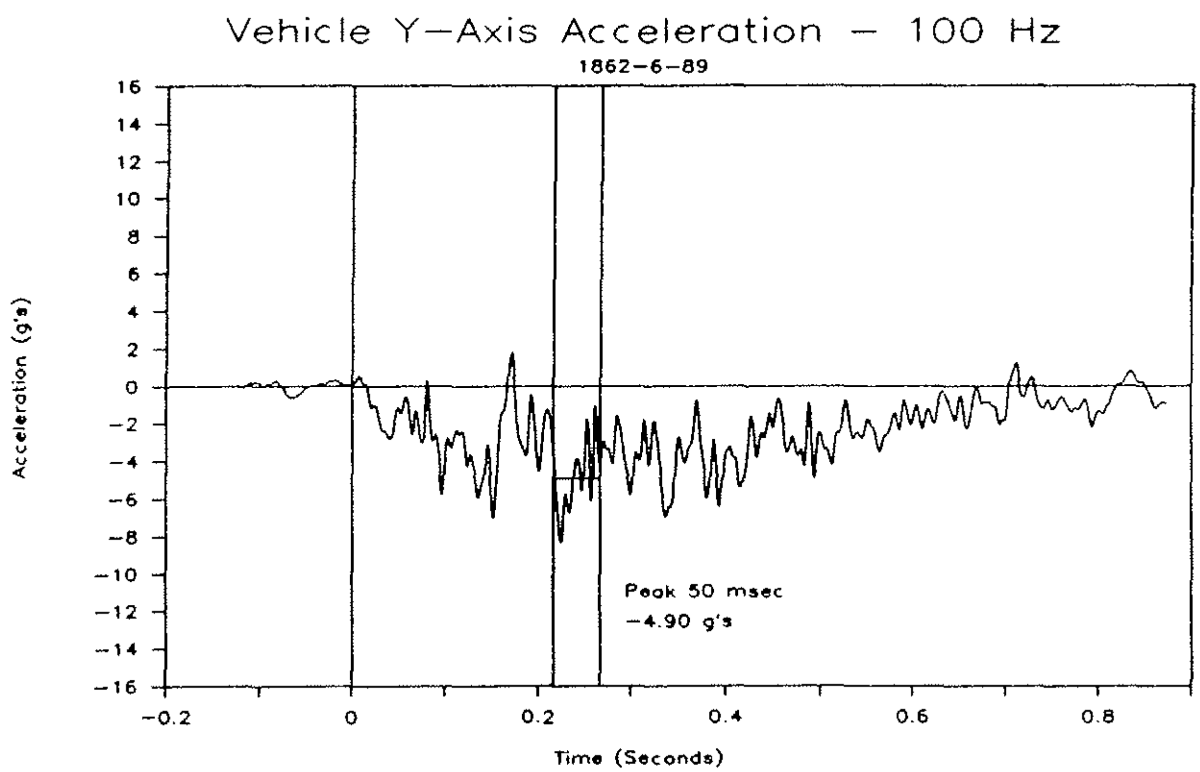


Figure 45. Vehicle accelerations, test 1862-6-89.

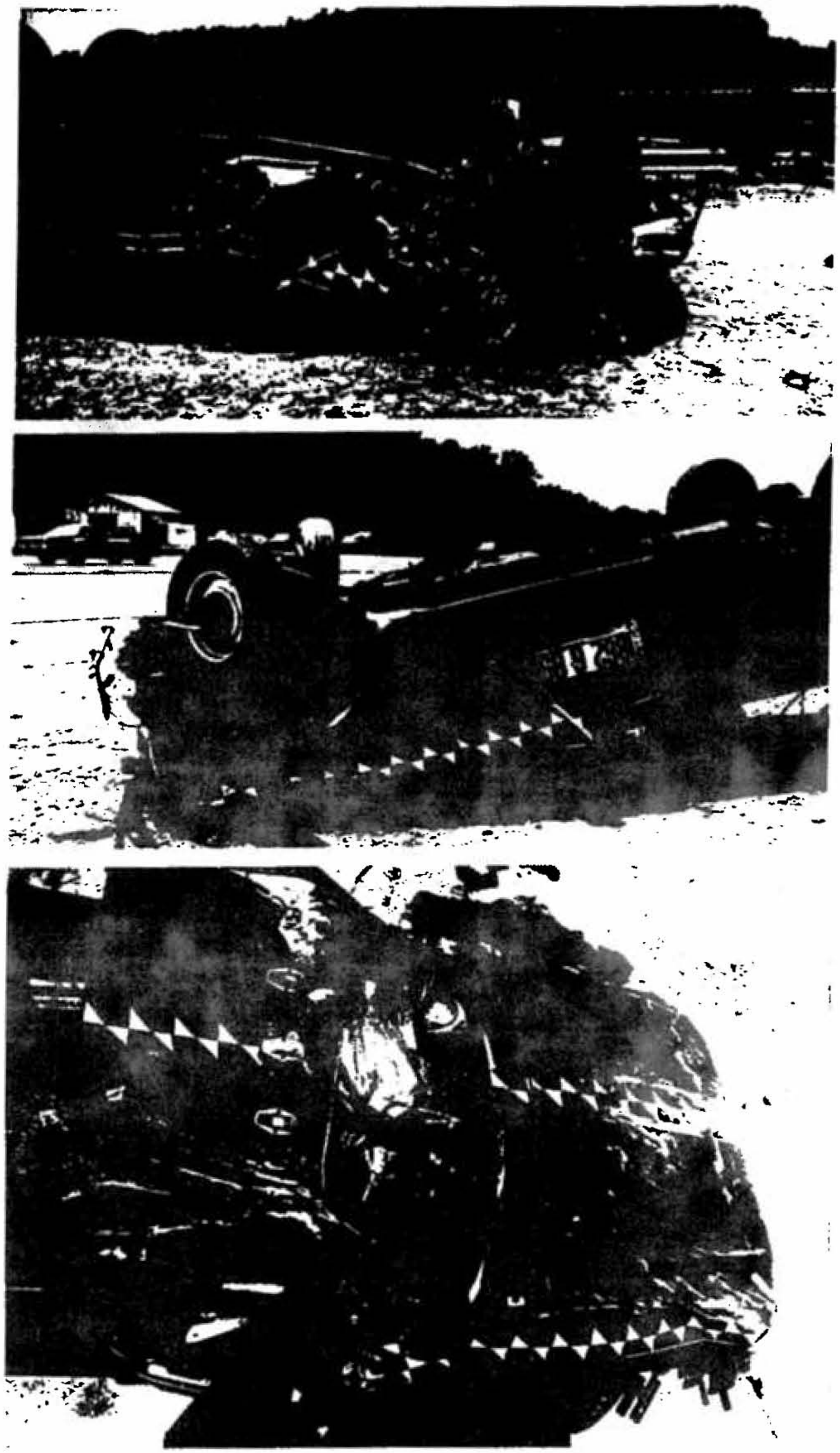


Figure 46. Post-test photographs of test vehicle, test 1862-6-89.

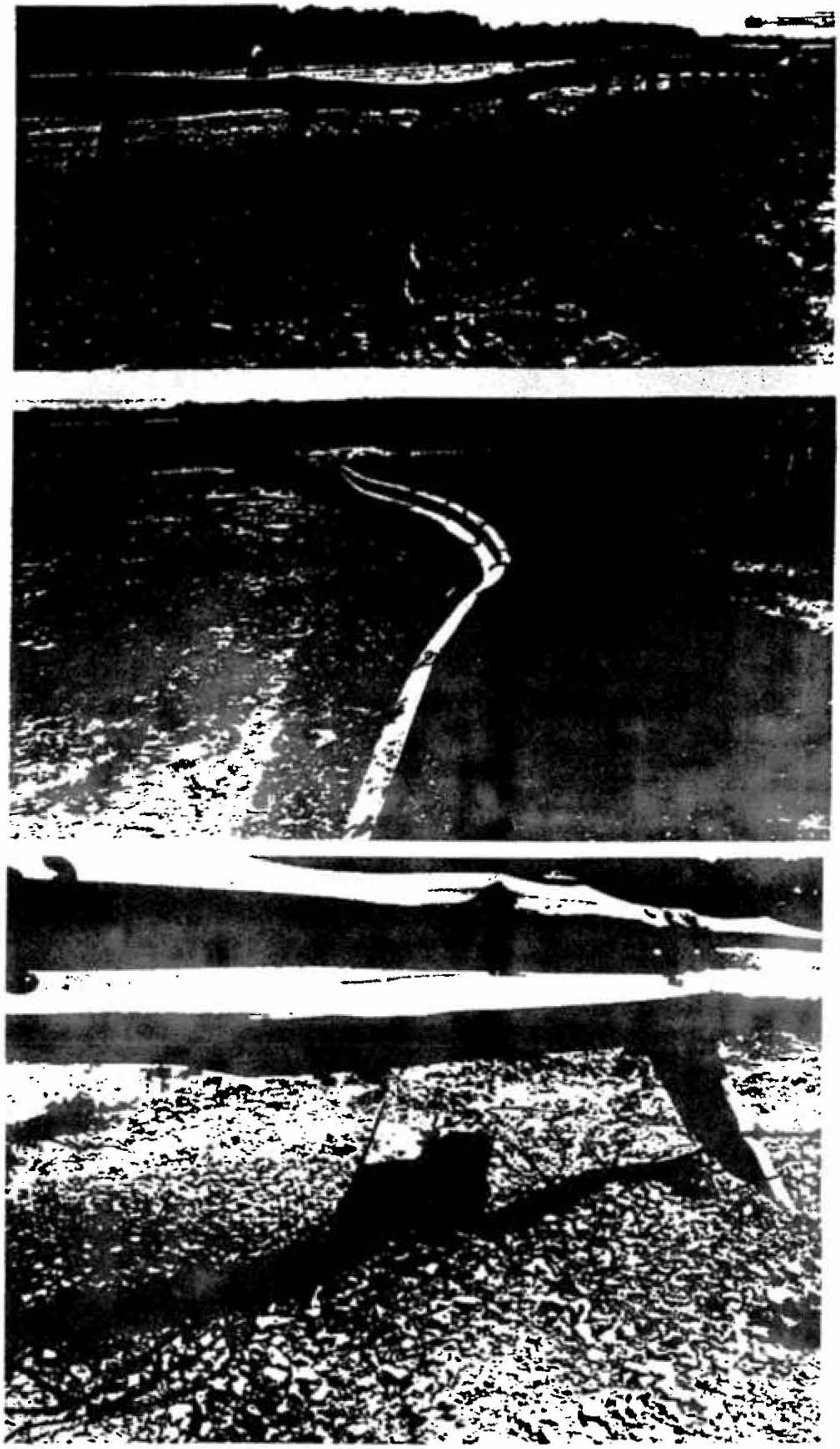


Figure 47. Post-test photographs of guardrail system, test 1862-6-89.

7. TEST 1862-7-89

a. Test Device

The test device was a concrete wall with a concrete curb. The wall was 27 in (685.8 mm) high and 9 in (228.6 mm) thick. The wall was 75 ft (22.9 m) long and was located at the edge of a cantilevered concrete deck attached to a rigid, simulated support structure. The curb was 8 in by 8 in (203.2 mm by 203.2 mm) with a 1-in (25.4-mm) rake on the front face and ran the entire length of the wall. Epoxy-coated rebar was used throughout. Lateral deck bars were set on 6-in (152.4-mm) centers. FHWA 4000-lbf/in^2 (27560-kPa) class D(AE) concrete was used for the deck and wall. Standard 4000-lbf/in^2 (27560-kPa) concrete was used for the curb. Rebar was not used in the curb.

Figure 48 shows the test site and test device. Figure 49 shows pretest photographs of the concrete wall and curb system.

b. Test Vehicle

The test vehicle was a 1982 Honda Civic. The target inertial vehicle weight was 1800 lb (817 kg). The vehicle weighed approximately 1750 lb (795 kg) empty. With the instrumentation (no ballast was required), the inertial weight of the vehicle was 1805 lb (819 kg). The target gross vehicle weight was 1950 lb (885 kg). The gross vehicle weight was 1980 lb (899 kg).

X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the vehicle. One fully-instrumented dummy was placed in the vehicle in the driver's seat and was restrained. The dummy instrumentation consisted of x-, y-, and z-axis accelerometers in the head and chest, and load cells in the legs. Pretest photographs of the test vehicle are shown in figure 50. Table 18 lists important parameters of the test vehicle.

c. Impact Description

Review of the high-speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 61.8 mi/h (99.5 km/h) and 15°. This review also indicated that the right corner of the vehicle impacted the wall at the desired point.

Upon impact, the vehicle front end deformed until the vehicle A-pillar struck the wall. The vehicle yawed around and climbed the wall when the vehicle rode up on the curb. The vehicle's right side climbed onto the wall producing approximately 12° of roll angle. The front wheel became locked and scraped along the top portion of the face of the wall. The vehicle remained in contact with the wall for 13 ft (4.0 m). The tire and wheel rode up onto the curb for 5 ft (1.5 m) starting at impact. As the vehicle was returning to an upright position, the wheel recontacted the curb 25 ft (7.6 m) past impact and remained in contact with the curb for 20 ft (6.1 m). The vehicle was redirected at a 5° angle to

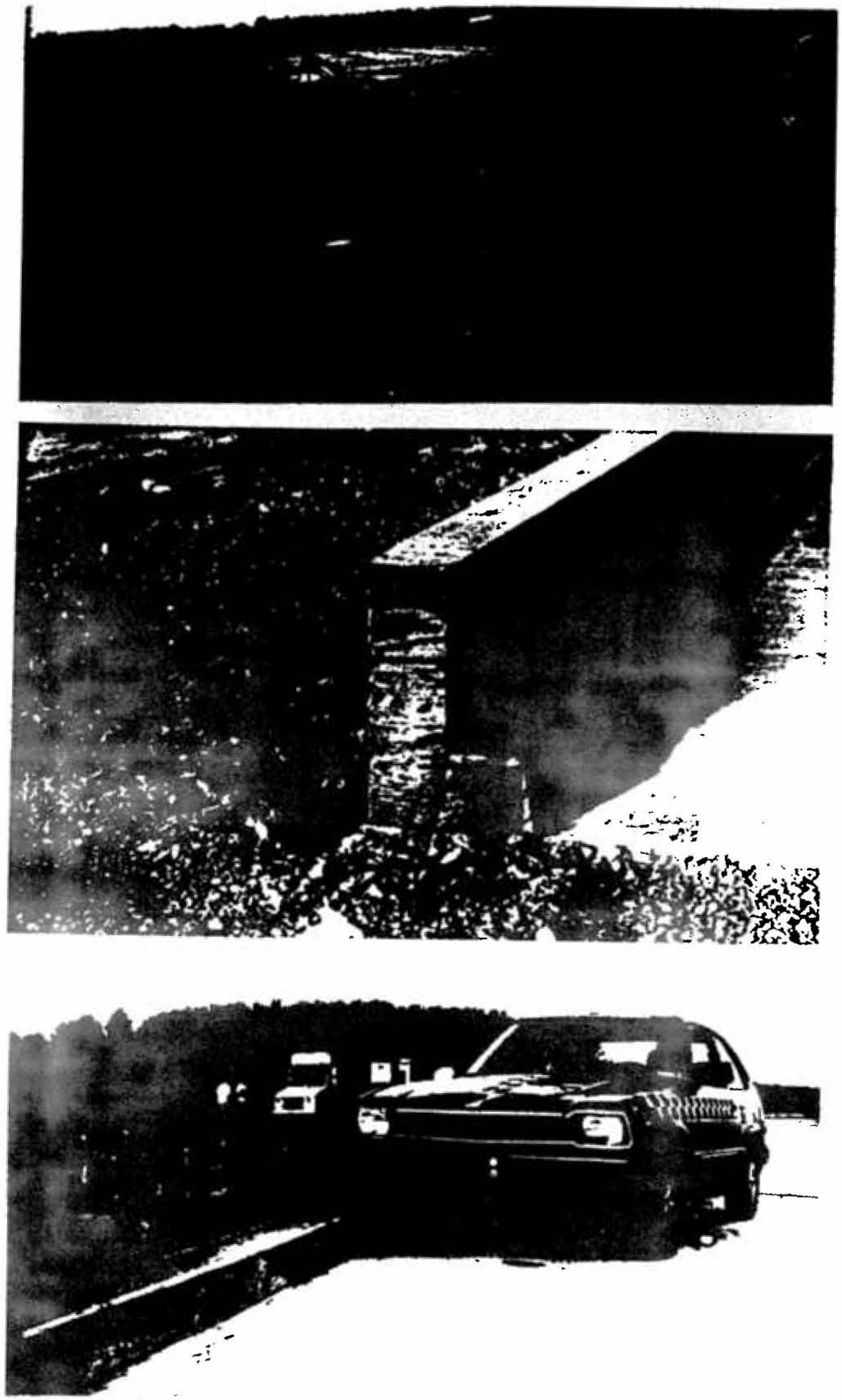


Figure 49. Pretest photographs of concrete wall system, test 1862-7-89.

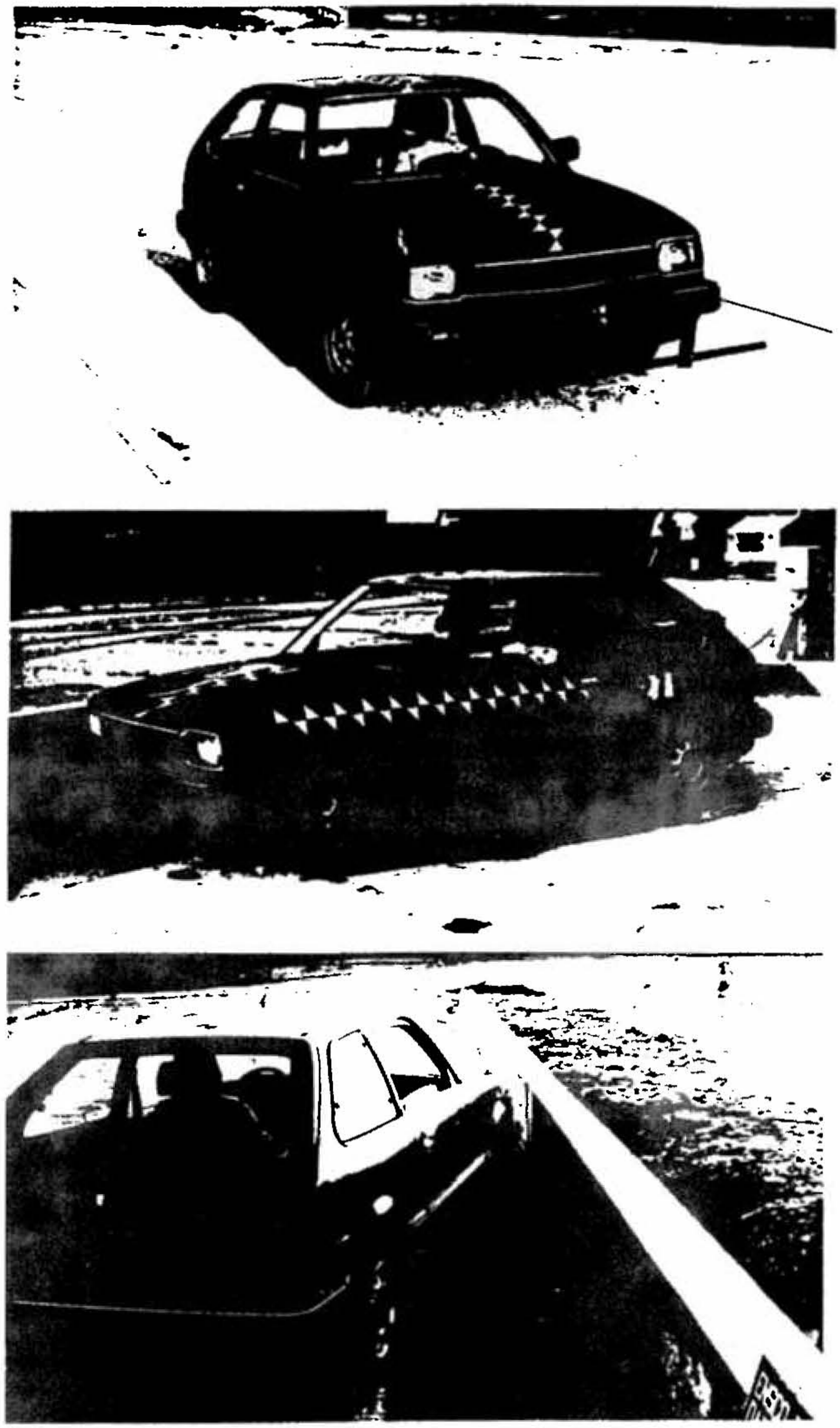
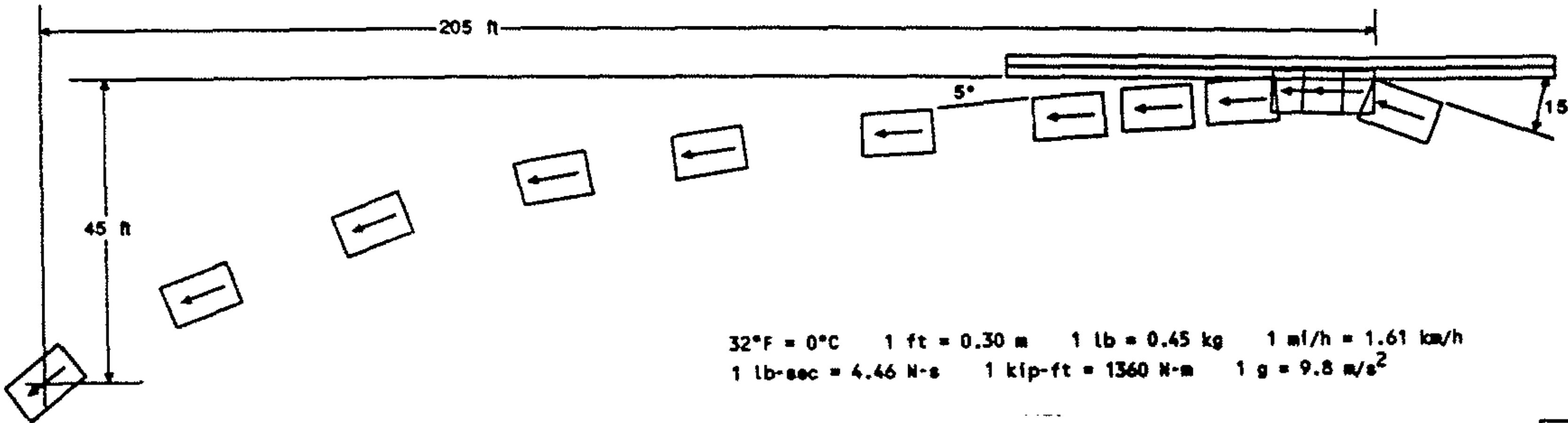
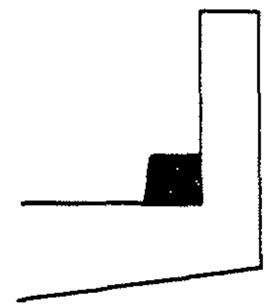


Figure 50. Pretest photographs of test vehicle, test 1862-7-89.





Date: 7 September 1989
Weather: Partially cloudy, 70° F

Test Vehicle: 1982 Honda Civic

Device Configuration: Concrete wall with concrete curb, 75 ft total length, 27 in by 9 in wall, 8 in by 8 in curb with 1 in rake on front face

1. Vehicle Weight:
   - Planned, Inertial: 1800
   - Actual, Inertial: 1805
   - Planned, Gross: 1950
   - Actual, Gross: 1980

2. Number of Occupants: One

3. Occupant Model: Part 572, 50th percentile male, fully instrumented

4. Occupant Location: Driver Seat, Restrained

5. Impact:

	Speed	Angle (a)	Location
Planned:	60.0 mi/h	15°	25 ft from end
Actual:	61.8 mi/h	15°	25 ft from end

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

6. Redirection Angle: 5°

7. Redirection Speed: 51.1 mi/h (74.9 ft/s)

8. Total Speed Change: 10.7 mi/h (15.7 ft/s)

9. Total Momentum Change: 965 lb-s

10. Vehicle Damage Index: 01RFEW2
    (SAE J224a)

11. NCHRP 230 Test Number: 12
    AASHTO Test Type: n/a

12. NCHRP 230 Impact Severity:

    $\frac{m(V \sin a)^2}{2}$ 15.4 kip-ft (Spec: 12 to 16 kip-ft)

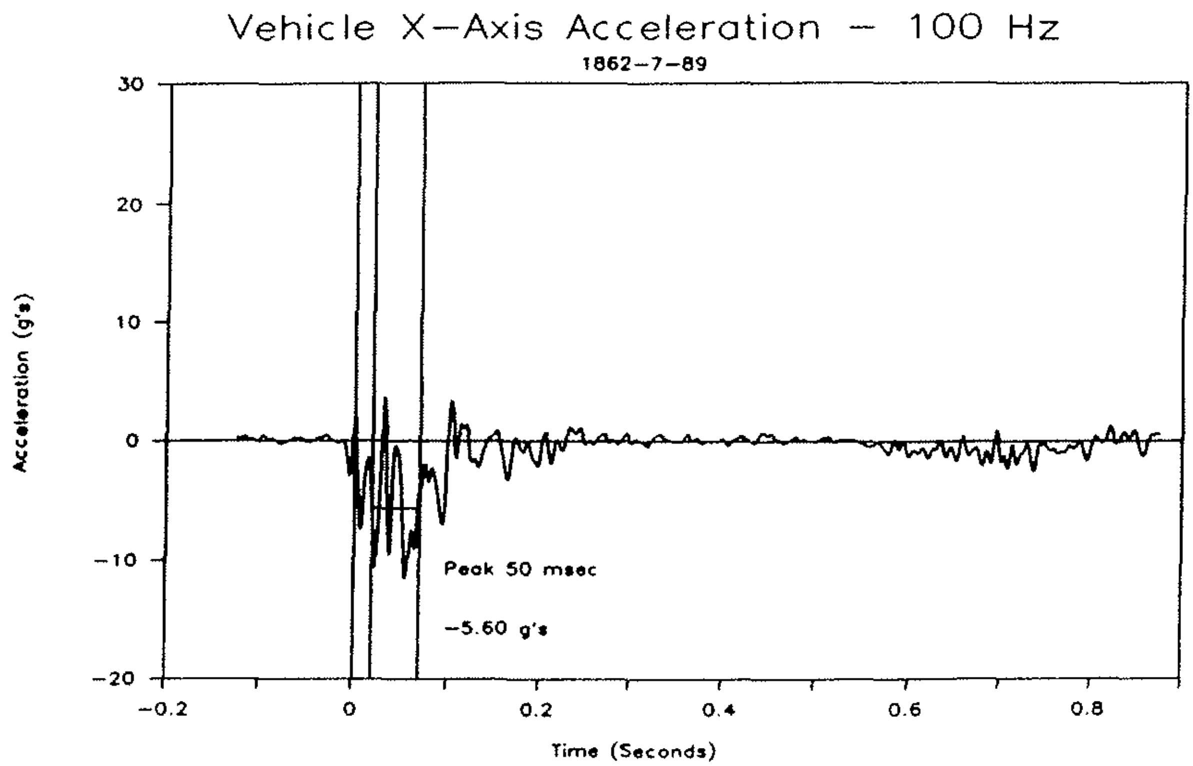
13. Vehicle Analysis:

	Observed	Design/ Limit Value
Longitudinal:		
Delta-V at 2 ft:	-15.5 ft/s	30/40 ft/s
Ridedown Acceleration:	-2.0 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	20.9 ft/s	30/30 ft/s
Ridedown Acceleration:	3.7 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-5.6 g's	
Lateral:	10.0 g's	

14. Test Results Conclusion:

    NCHRP 230: WITH THE EXCEPTION OF THE TRAJECTORY AND STOPPING POSITION, THE TEST MEETS ALL CRITERIA.

Figure 51. Test summary, test 1862-7-89.



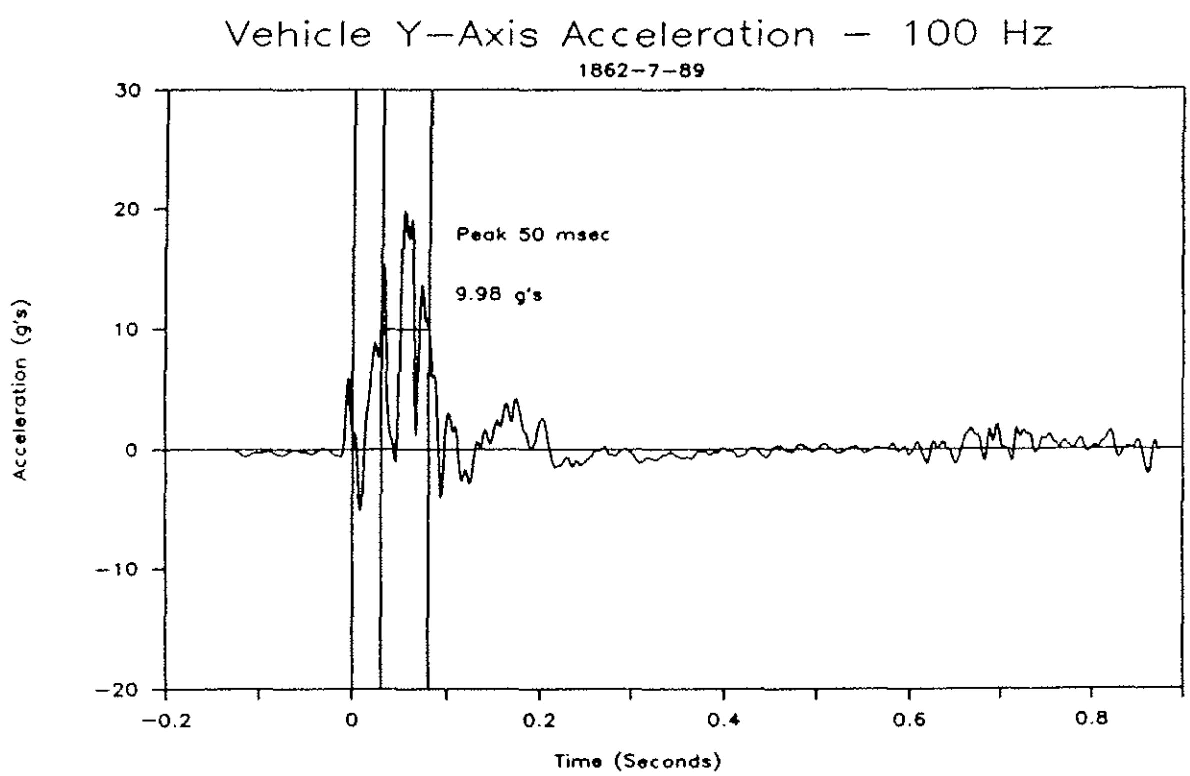


Figure 52. Vehicle accelerations, test 1862-7-89.

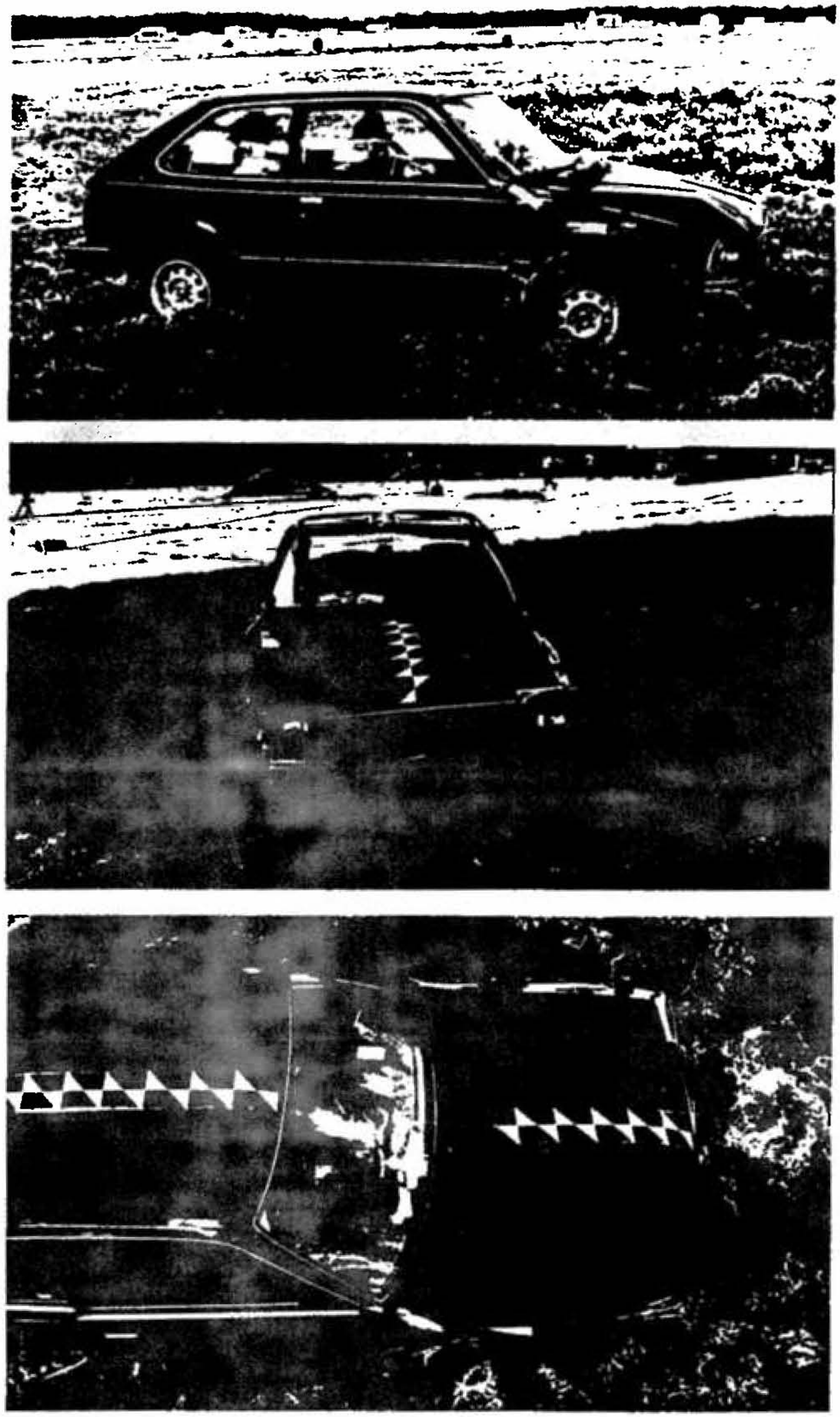


Figure 53. Post-test photographs of test vehicle, test 1862-7-89.

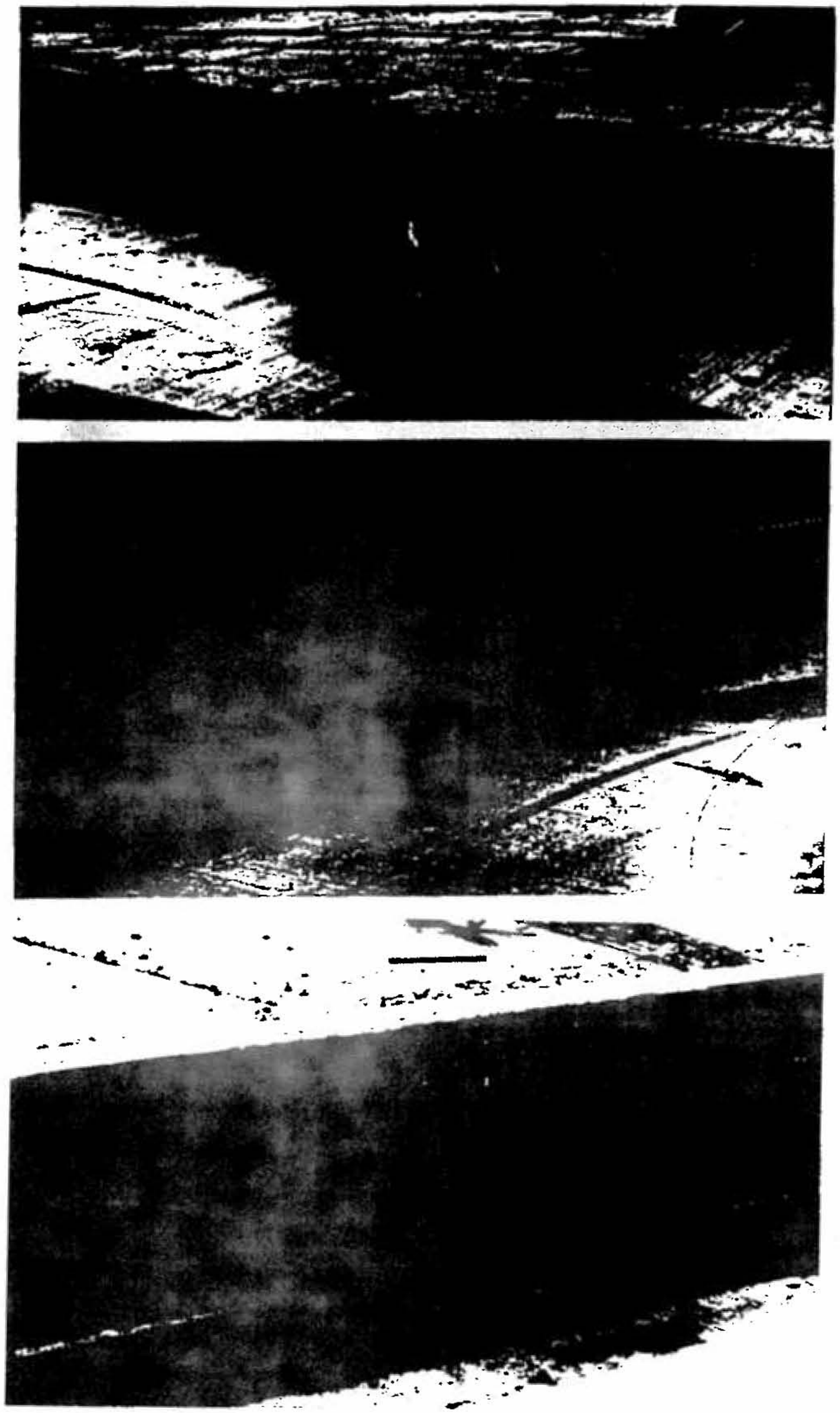


Figure 54. Post-test photographs of concrete wall system, test 1862-7-89.

8. TEST 1862-8-89

a. Test Device

The test device was a concrete wall with a concrete curb. The wall was 27 in (685.89 mm) high and 9 in (228.6 mm) thick. The wall was 75 ft (22.9 m) long and was located at the edge of a cantilevered concrete deck attached to a rigid, simulated support structure. The curb was 8 in by 8 in (203.2 mm by 203.2 mm) with a 1-in (25.4-mm) rake on the front face and ran the entire length of the wall. Epoxy-coated rebar was used throughout. Lateral deck bars were set on 6-in (152.4-mm) centers. FHWA 4000-lbf/in^2 (27560-kPa) class D(AE) concrete was used for the deck and wall. Standard 4000-lbf/in^2 (27560-kPa) concrete was used for the curb. Rebar was not used in the curb.

Figure 55 shows the test site and test device. Figure 56 shows pretest photographs of the concrete wall and curb system.

b. Test Vehicle

The test vehicle was a 1982 Chevrolet C20 pickup. The target inertial vehicle weight was 5400 lb (2452 kg). The vehicle weighed approximately 4400 lb (1998 kg) empty. Approximately 1000 lb (454 kg) of ballast were added. The ballasted inertial weight of the truck was 5402 lb (2453 kg). The gross vehicle weight was 5742 lb (2607 kg).

Two dummies were placed in the vehicle. The driver was restrained while the passenger was unrestrained. X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the cab of the truck. Pretest photographs of the test vehicle are shown in figure 57. Table 19 lists important parameters of the test vehicle.

c. Impact Description

Review of the high-speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 62.1 mi/h (99.9 km/h) and 10°. This review also indicated that the right corner of the vehicle impacted the wall at the desired point.

Upon impact, the vehicle front end was deformed by the concrete wall. The vehicle yawed around and climbed the wall when the vehicle rode up on the curb. The vehicle remained in contact with the wall for 20 ft (6.1 m). The tire and wheel rode up onto the curb for 15 ft (4.6 m) starting at impact. The vehicle front end rode off the curb and was pitched forward, totally airborne. The vehicle was redirected at a 2° angle to the wall. The vehicle came to rest 430 ft (131.2 m) past impact, 20 ft (6.1 m) in front of the wall, at a 0° angle to the wall.

Upon impact, the two dummies fell towards the passenger side. When the vehicle was redirected, the passenger fell back onto the

Table 19. Test vehicle parameters, test 1862-8-89.

Item	Actual	Specification
Empty Weight	~4400 lb	n/a
Ballast	~1000 lb	n/a
Total Weight, Inertial	5402 lb	5400 lb
Total Weight, Gross	5742 lb	n/a
H_{cg}	27 in	27 ± 1 in
A (front to cg), Inertial	8.51 ft	8.5 ± 0.1 ft
B (width)	6.5 ft	6.5 ft
Truck Length	216 in	
Truck Wheelbase	132 in	
Wheel/Tire Size	235 85R16	
Truck Box Size	8 ft long by 1.5 ft high by 5.5 ft wide	
Ground to Box Floor	27 in	

1 lb = 0.45 kg   1 ft = 0.31 m   1 in = 25.4 mm

driver. The passenger dummy fell forward when the vehicle brakes were applied. The driver dummy came to rest upright, leaning toward the passenger side. The passenger dummy came to rest with its body over the hump and its head at the driver's feet.

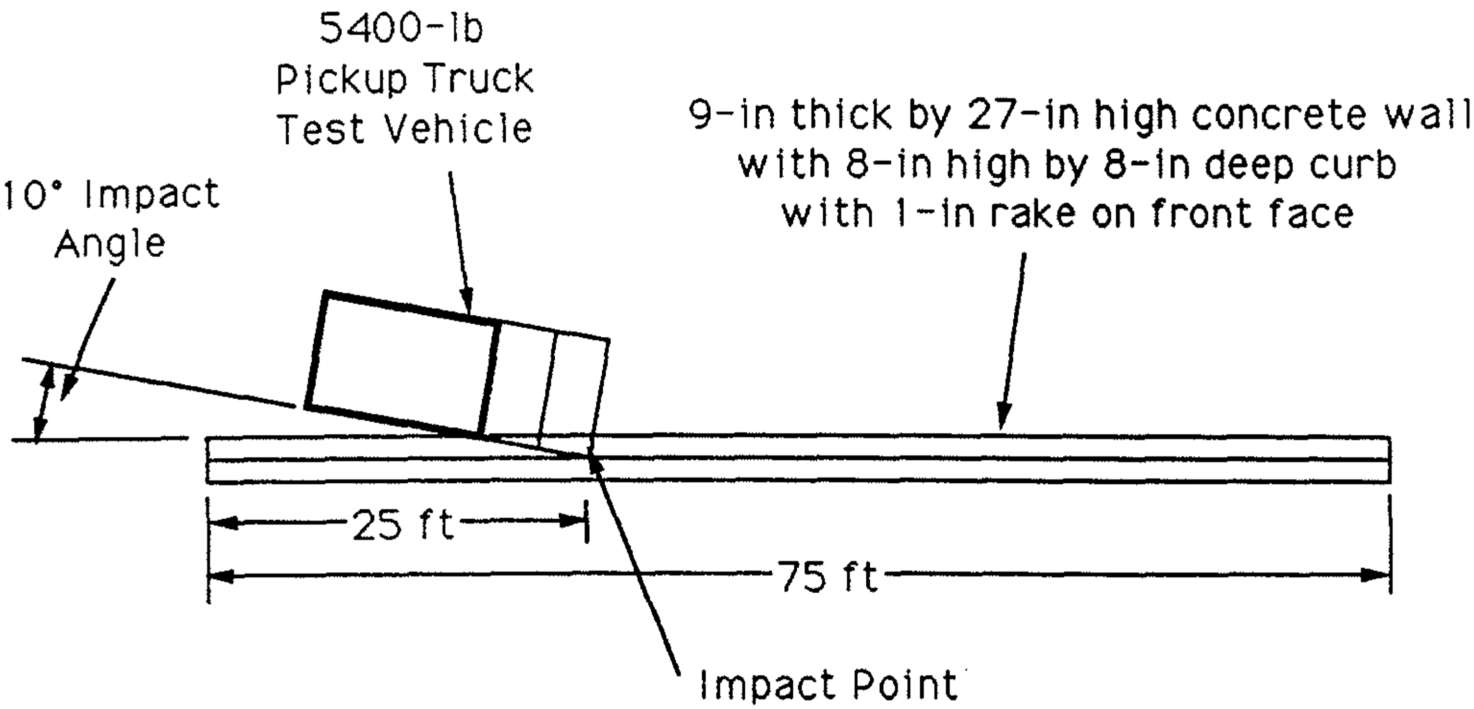
A summary of test conditions and results are shown in figure 58. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 59.

d. Vehicle Damage

Damage occurred to the bumper and entire right side of the vehicle. However, this damage was very minor, consisting of scrub from the concrete wall. Post-test photographs of the vehicle are shown in figure 60.

e. Barrier Damage

The wall and curb suffered very little damage. The curb was spalled for 3 ft (0.9 m) prior to impact and the wall was spalled for 2 ft (0.6 m) prior to impact. Downstream of the impact point, the wall suffered only scuffing and minor scraping. Post-test photographs of the rail are shown in figure 61.



1 ft = 0.30 m   1 in = 25.4 mm

Figure 55. Test site layout, test 1862-8-89.

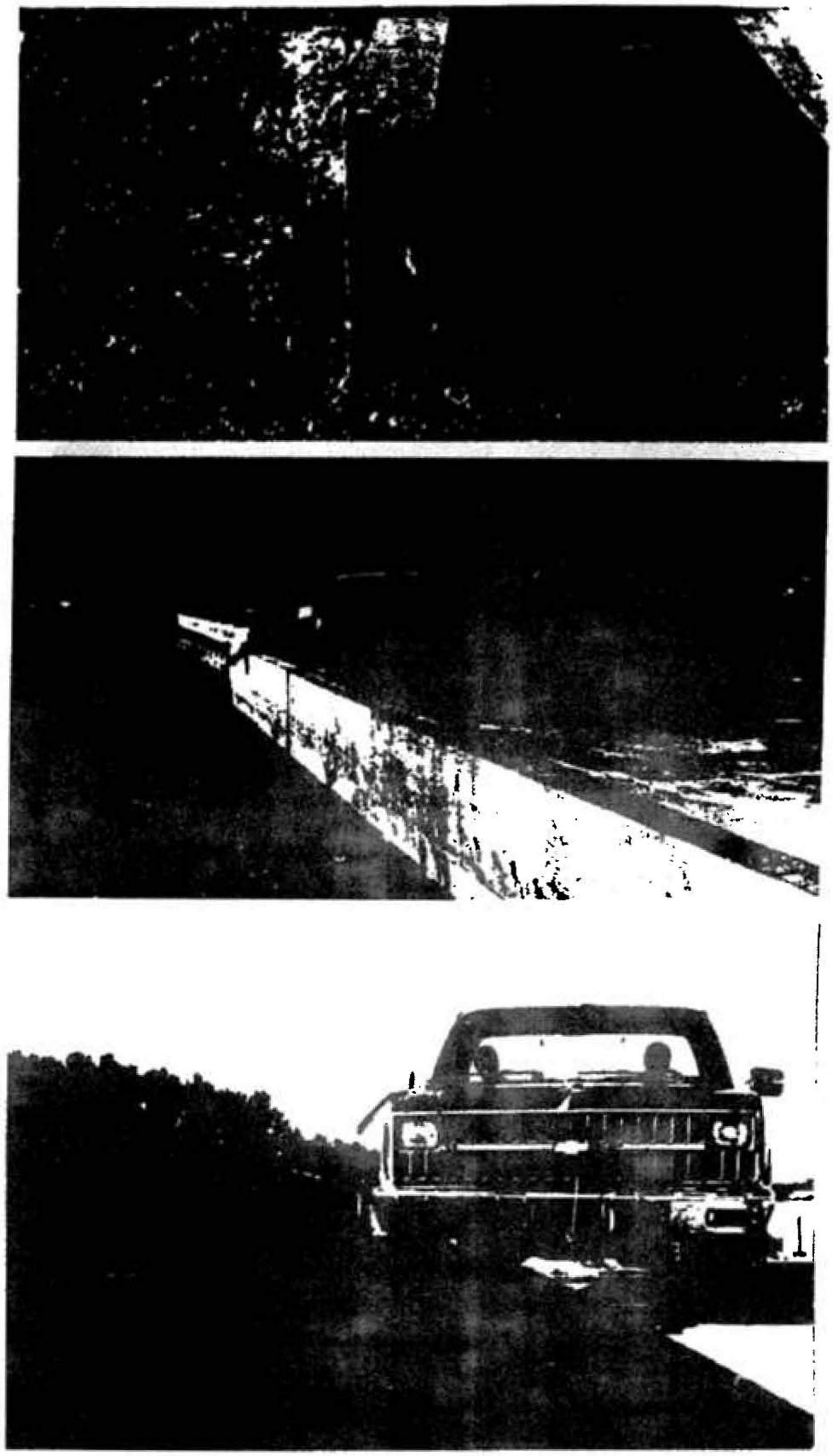


Figure 56. Pretest photographs of concrete wall system, test 1862-8-89.

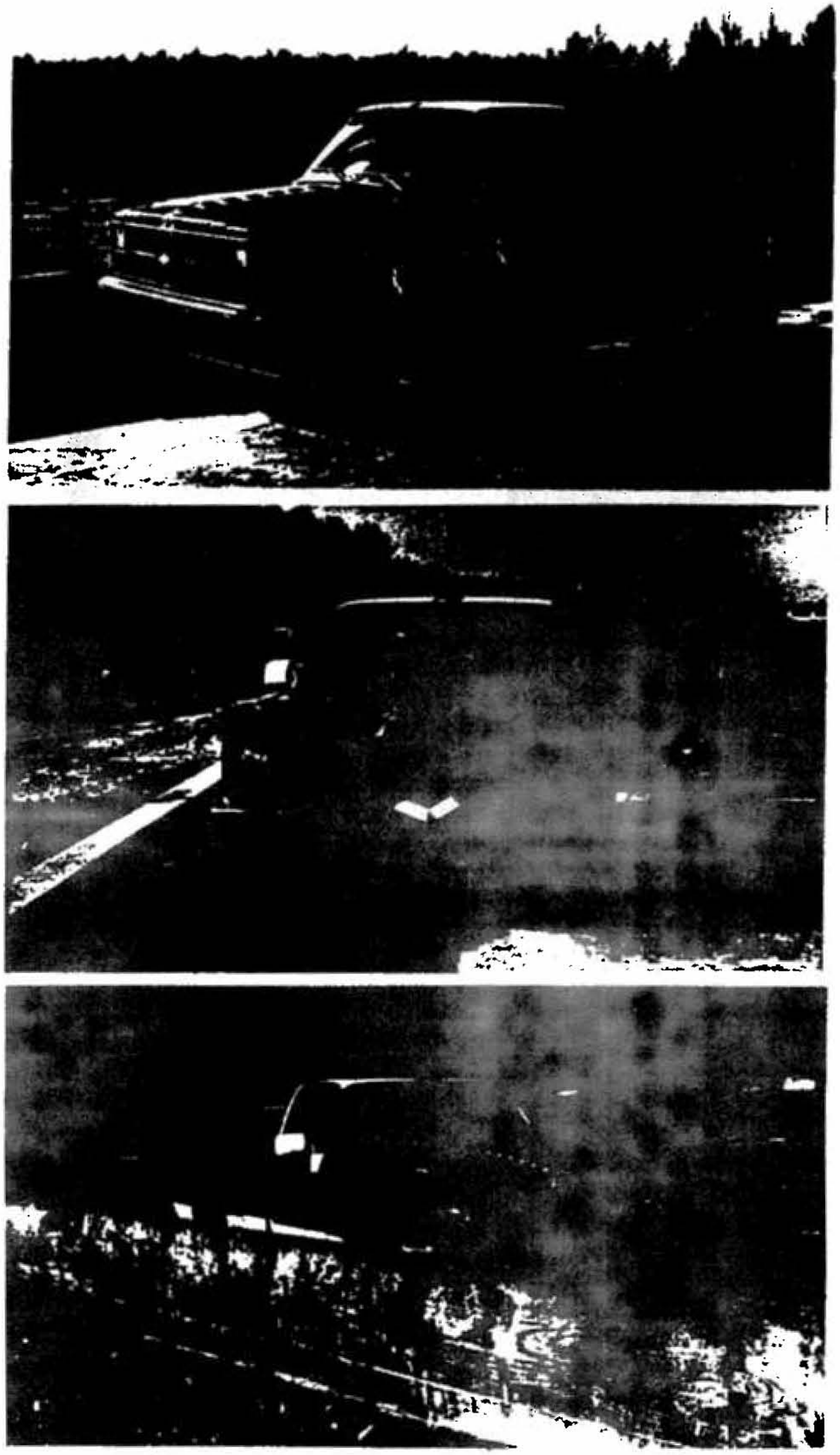
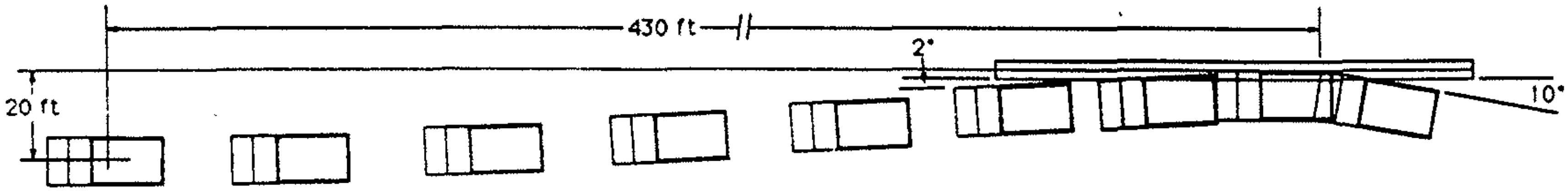
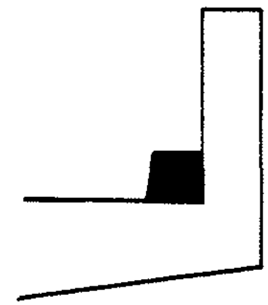


Figure 57. Pretest photographs of test vehicle, test 1862-8-89.



32°F = 0°C   1 ft = 0.30 m   1 lb = 0.45 kg   1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s   1 kip-ft = 1360 N-m   1 g = 9.8 m/s²



Date:	4 December 1989
Weather:	Clear, Windy, 30° F
Test Vehicle:	1982 Chevrolet C20 Pickup
Device Configuration:	Concrete wall with concrete curb, 75 ft total length, 27 in by 9 in wall, 8 in by 8 in curb with 1 in rake on front face

1. Vehicle Weight:
   - Inertial, planned: 5400
   - Inertial, actual: 5402
   - Gross, actual: 5742
2. Number of Occupants: Two
3. Occupant Model: Part 572, 50th percentile male, fully instrumented
4. Occupant Location: Driver Seat, Restrained; Passenger Seat, Unrestrained
5. Impact:

Impact:	Speed	Angle (a)	Location
Planned:	60.0 mi/h	10°	25 ft from end
Actual:	62.1 mi/h	10°	25 ft from end

   Tolerances: Speed: −1.0, +2.5 mi/h; Angle: −1.0, +2.5 degrees
6. Redirection Angle: 2°
7. Redirection Speed: 56.5 mi/h (82.9 ft/s)
8. Total Speed Change: 5.6 mi/h (8.2 ft/s)
9. Total Momentum Change: 1462 lb-s
10. Vehicle Damage Index: (SAE J224a) 01RDEW1
11. NCHRP 230 Test Number: Special; AASHTO Test Type: PL2
12. Vehicle Analysis:

	Observed	Design/ Limit Value
Longitudinal:		
Delta-V at 2 ft:	-8.0 ft/s	30/40 ft/s
Ridedown Acceleration:	1.2 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	15.6 ft/s	20/30 ft/s
Ridedown Acceleration:	5.9 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-2.3 g's	
Lateral:	7.9 g's	

13. Vehicle-Railing Interaction Coefficient of Friction:

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

mu	assessment
0.30	Fair

V_p = 57.9 mi/h (84.9 ft/s)

14. Test Results Conclusion:

AASHTO Bridge Rail Specification: MEETS ALL CRITERIA.

Figure 58. Test summary, test 1862-8-89.

Table 18. Test vehicle parameters, test 1862-7-89.

Item	Actual	Specification
Empty Weight	~1750 lb	n/a
Ballast	0 lb	n/a
Total Weight, Inertial	1805 lb	1800 lb
Total Weight, Gross	1980 lb	1950 lb
H_{cg}	20 in	20 ± 1 in
A (front to cg), Inertial	5.3 ft	5.4 ± 0.1 ft
B (width)	5.2 ft	5.5 ft
Vehicle Length	147.5 in	
Vehicle Wheelbase	89 in	
Wheel/Tire Size	155 SR13	

1 lb = 0.45 kg   1 ft = 0.31 m   1 in = 25.4 mm

the wall. The vehicle came to rest 205 ft (62.5 m) past impact, 40 ft (12.2 m) in front of the wall, at a 45° angle to the wall.

Upon impact, the driver dummy fell into the passenger seat, held by the seat belt. The dummy came back upright when the vehicle rolled up the wall and then fell again into the passenger seat when the vehicle rolled back to upright. The driver dummy came to rest in this position.

A summary of test conditions and results are shown in figure 51. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 52.

d. Vehicle Damage

Damage occurred to the hood, grill, bumper, and entire right side of the vehicle. The passenger side door was pushed out, the roof on the passenger side was deformed, and the windshield was popped out on three edges. Prior to impact, the rear hatch came open. Post-test photographs of the vehicle are shown in figure 53.

e. Barrier Damage

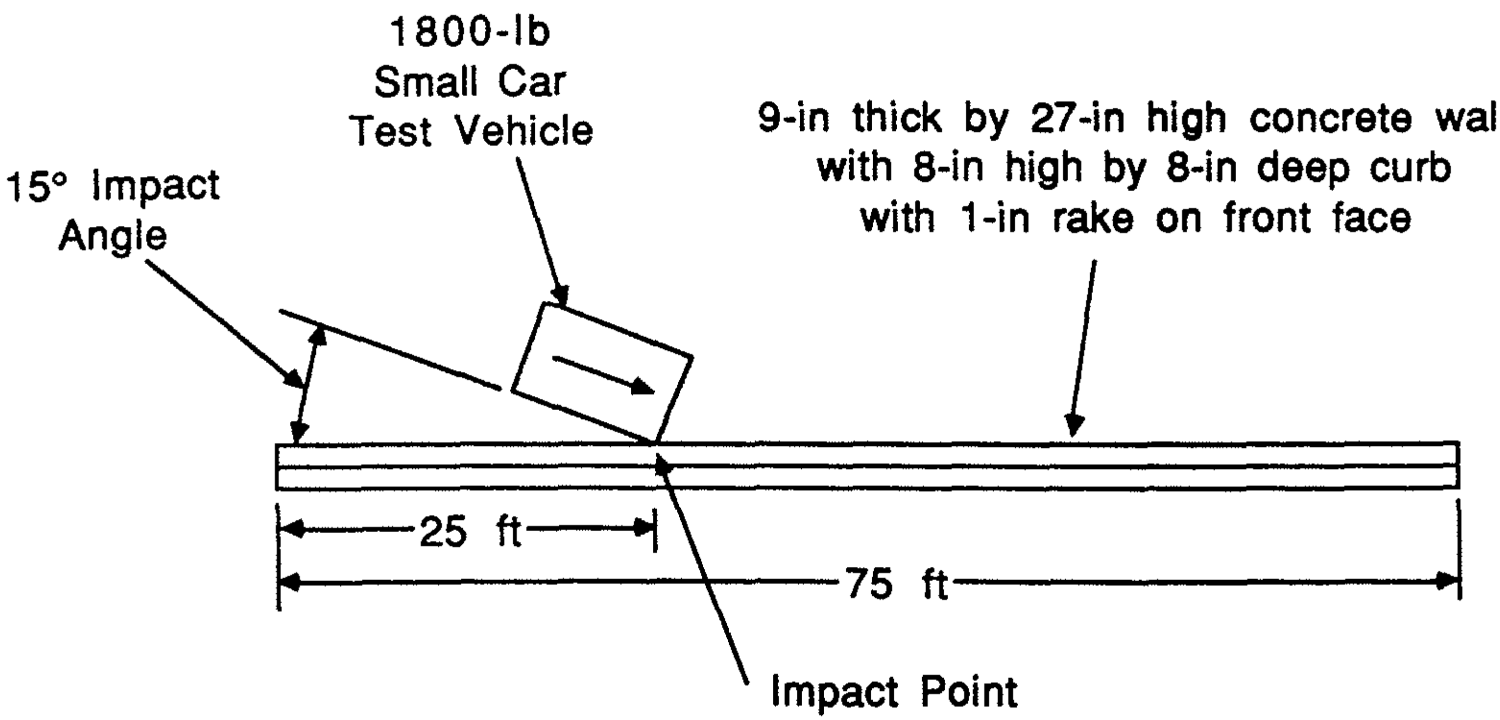
The wall and curb suffered very little damage. The curb was spalled slightly for 2.5 ft (0.8 m) prior to impact and the wall suffered only scuffing and minor scraping. Post-test photographs of the rail are shown in figure 54.

f. Test Evaluation

This test was evaluated using NCHRP 230. The following is an item-by-item evaluation using this guideline.

a. The test article smoothly redirected the vehicle.
d. There were no detached elements.
e. The vehicle remained upright during and after the collision. Integrity of the passenger compartment was maintained.
h. Vehicle trajectory and stopping position did intrude into adjacent traffic lanes.
i. The test met the vehicle speed change and exit angle criteria. The vehicle redirection angle was 5° (less than 60 percent of impact) and the redirection speed was 51.1 mi/h (82.2 km/h) [speed change less than 15 mi/h (24.1 km/h)].

WITH THE EXCEPTION OF THE TRAJECTORY AND STOPPING POSITION, THE TEST MEETS ALL CRITERIA.



1 ft = 0.30 m   1 in = 25.4 mm

Figure 48. Test site layout, test 1862-7-89.

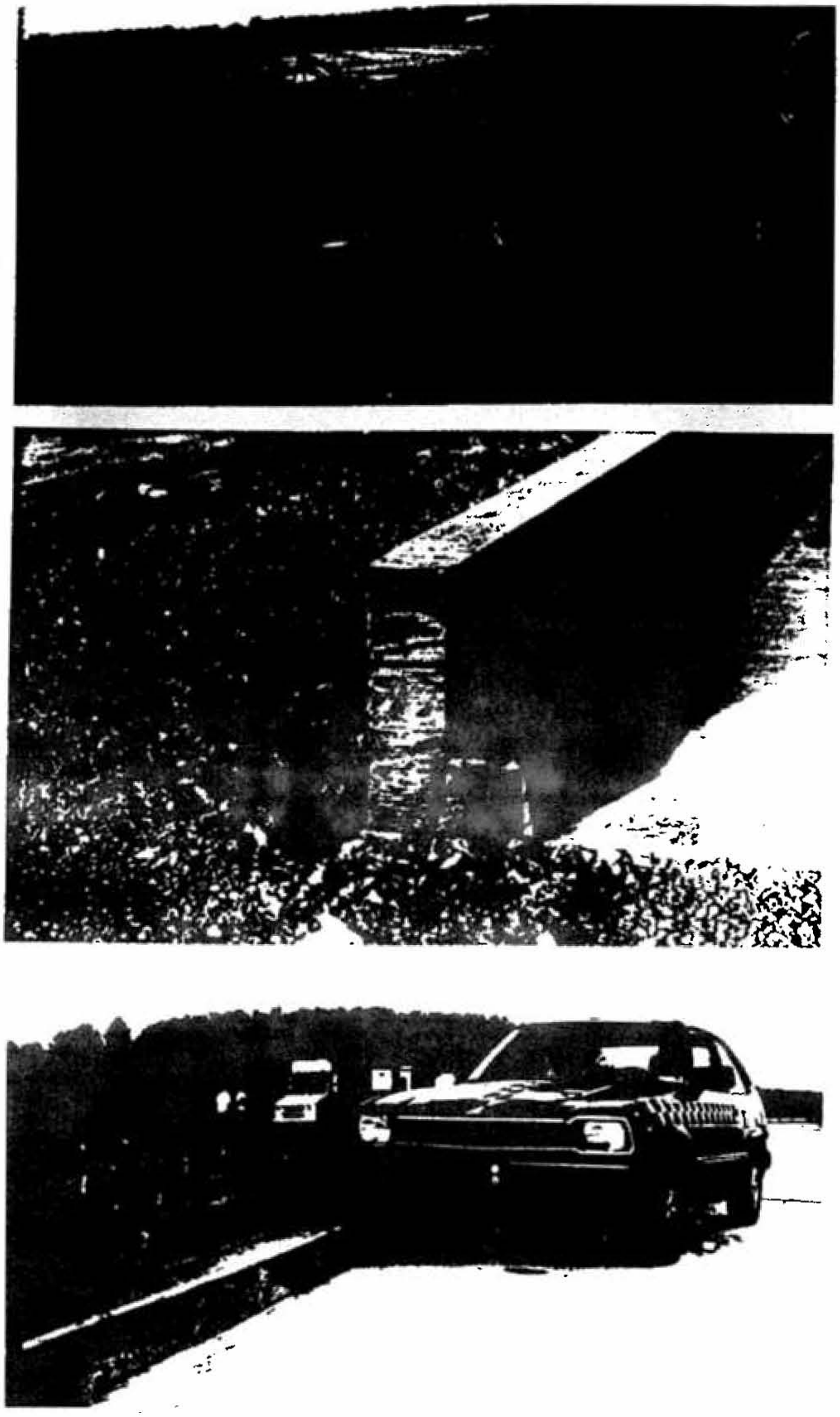


Figure 49. Pretest photographs of concrete wall system, test 1862-7-89.

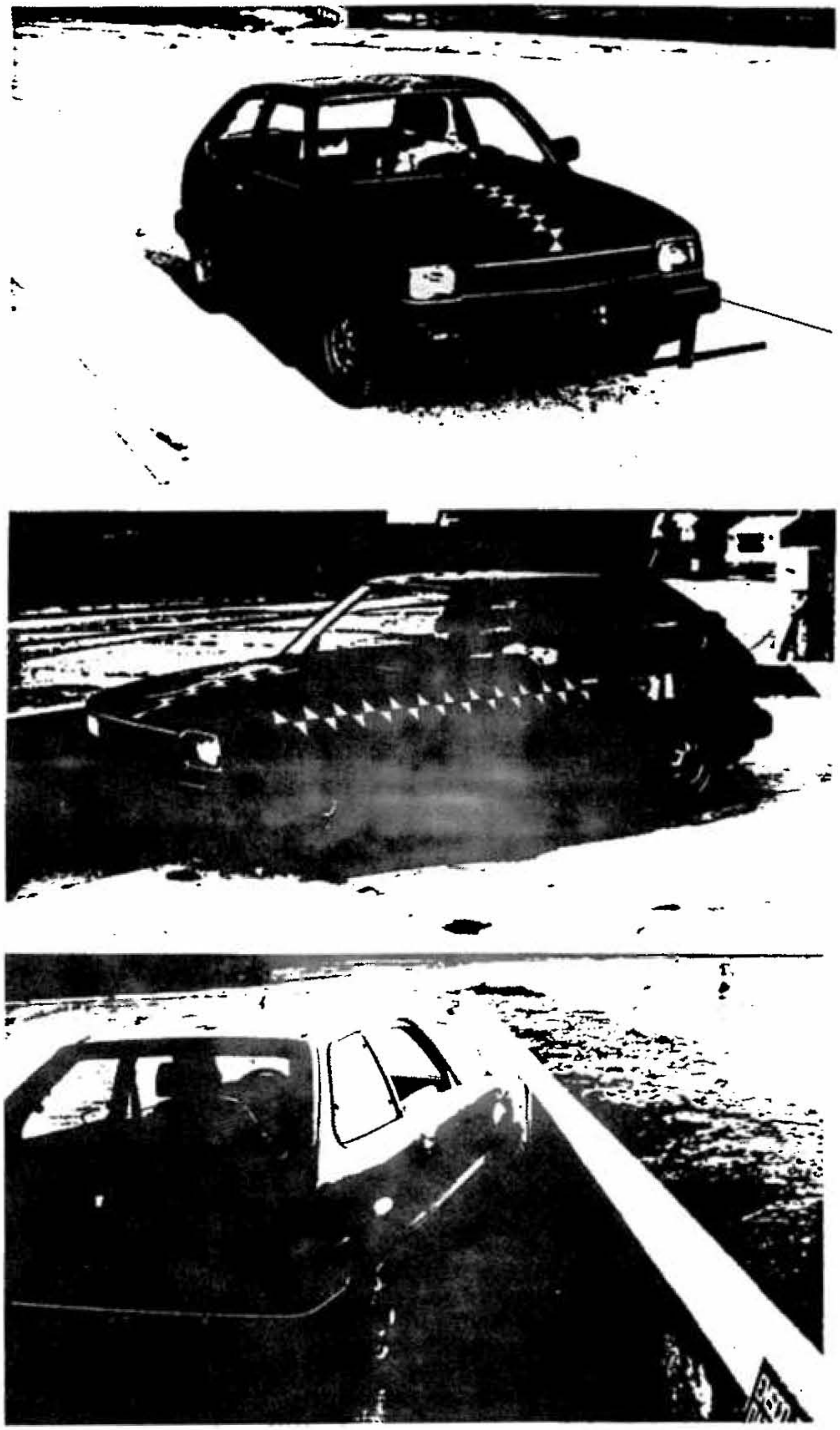
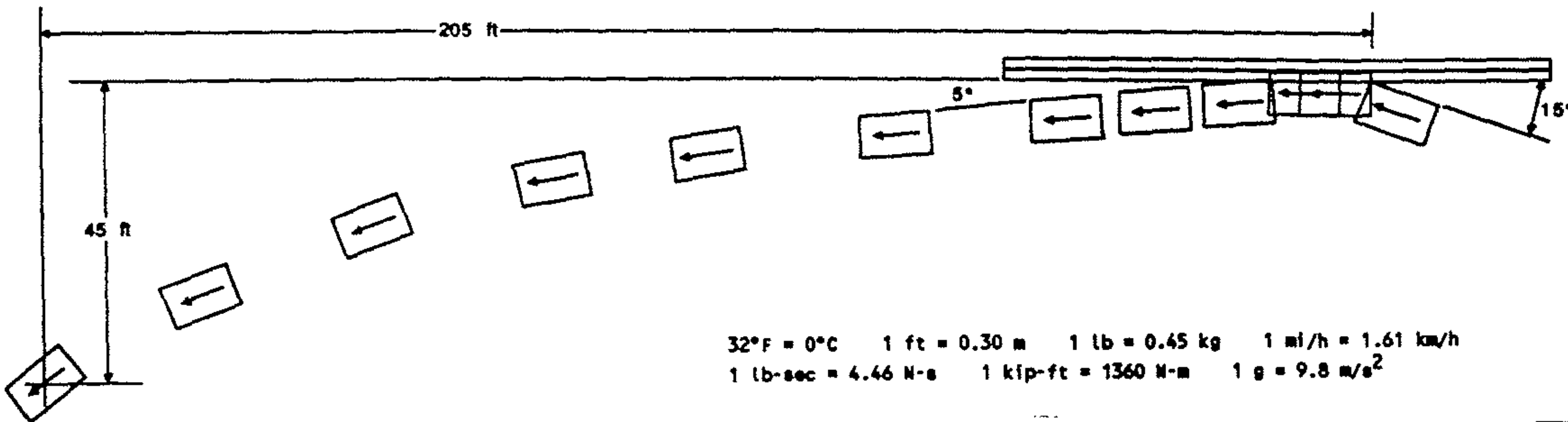
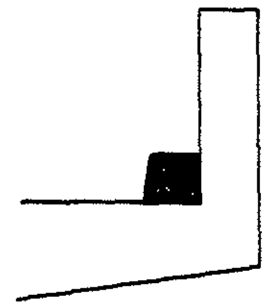


Figure 50. Pretest photographs of test vehicle, test 1862-7-89.



32°F = 0°C   1 ft = 0.30 m   1 lb = 0.45 kg   1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s   1 kip-ft = 1360 N-m   1 g = 9.8 m/s²



Date: 7 September 1989
Weather: Partially cloudy, 70° F

Test Vehicle: 1982 Honda Civic

Device Configuration: Concrete wall with concrete curb, 75 ft total length, 27 in by 9 in wall, 8 in by 8 in curb with 1 in rake on front face

1. Vehicle Weight:
   - Planned, Inertial: 1800
   - Actual, Inertial: 1805
   - Planned, Gross: 1950
   - Actual, Gross: 1980

2. Number of Occupants: One

3. Occupant Model: Part 572, 50th percentile male, fully instrumented

4. Occupant Location: Driver Seat, Restrained

5. Impact:

Impact:	Speed	Angle (a)	Location
Planned:	60.0 mi/h	15°	25 ft from end
Actual:	61.8 mi/h	15°	25 ft from end

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

6. Redirection Angle: 5°

7. Redirection Speed: 51.1 mi/h (74.9 ft/s)

8. Total Speed Change: 10.7 mi/h (15.7 ft/s)

9. Total Momentum Change: 965 lb-s

10. Vehicle Damage Index: 01RFEW2
    (SAE J224a)

11. NCHRP 230 Test Number: 12
    AASHTO Test Type: n/a

12. NCHRP 230 Impact Severity:
    $\frac{m(V \sin a)^2}{2}$ 15.4 kip-ft
    (Spec: 12 to 16 kip-ft)

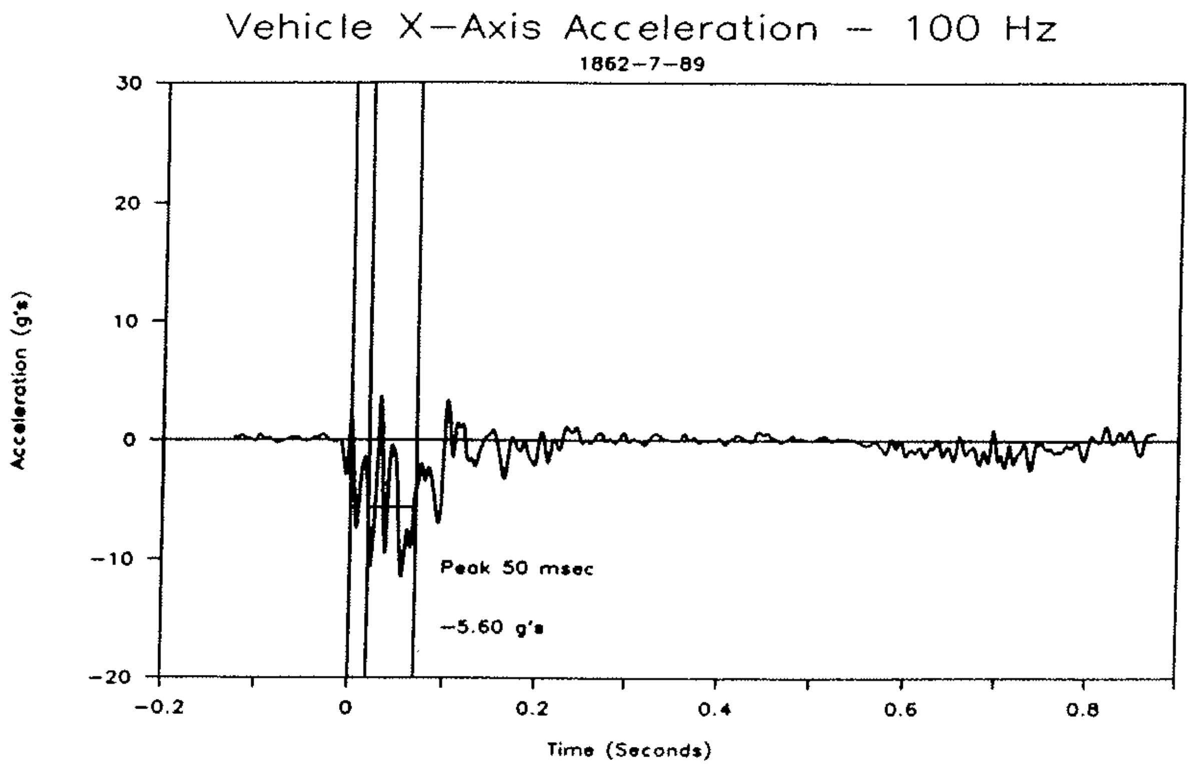
13. Vehicle Analysis:

Vehicle Analysis:	Observed	Design/ Limit Value
Longitudinal:		
Delta-V at 2 ft:	-15.5 ft/s	30/40 ft/s
Ridedown Acceleration:	-2.0 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	20.9 ft/s	20/30 ft/s
Ridedown Acceleration:	3.7 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-5.6 g's	
Lateral:	10.0 g's	

14. Test Results Conclusion:

    NCHRP 230: WITH THE EXCEPTION OF THE TRAJECTORY AND STOPPING POSITION, THE TEST MEETS ALL CRITERIA.

Figure 51. Test summary, test 1862-7-89.



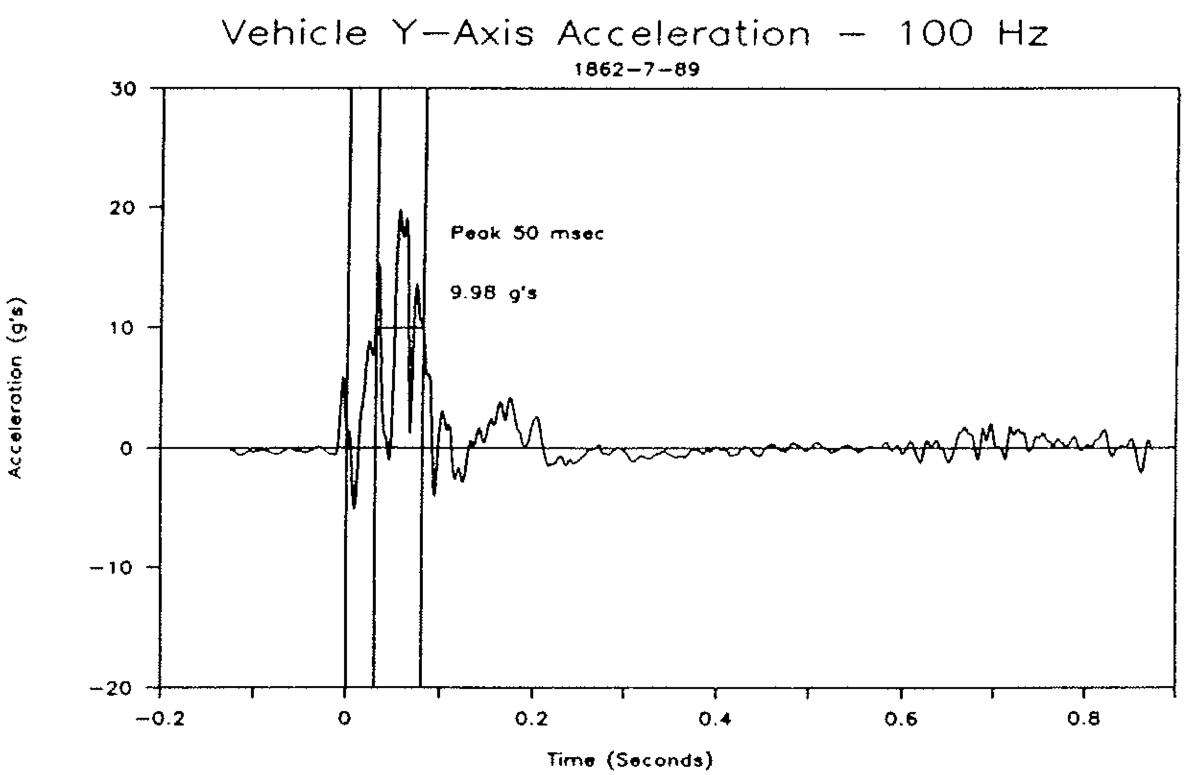


Figure 52. Vehicle accelerations, test 1862-7-89.

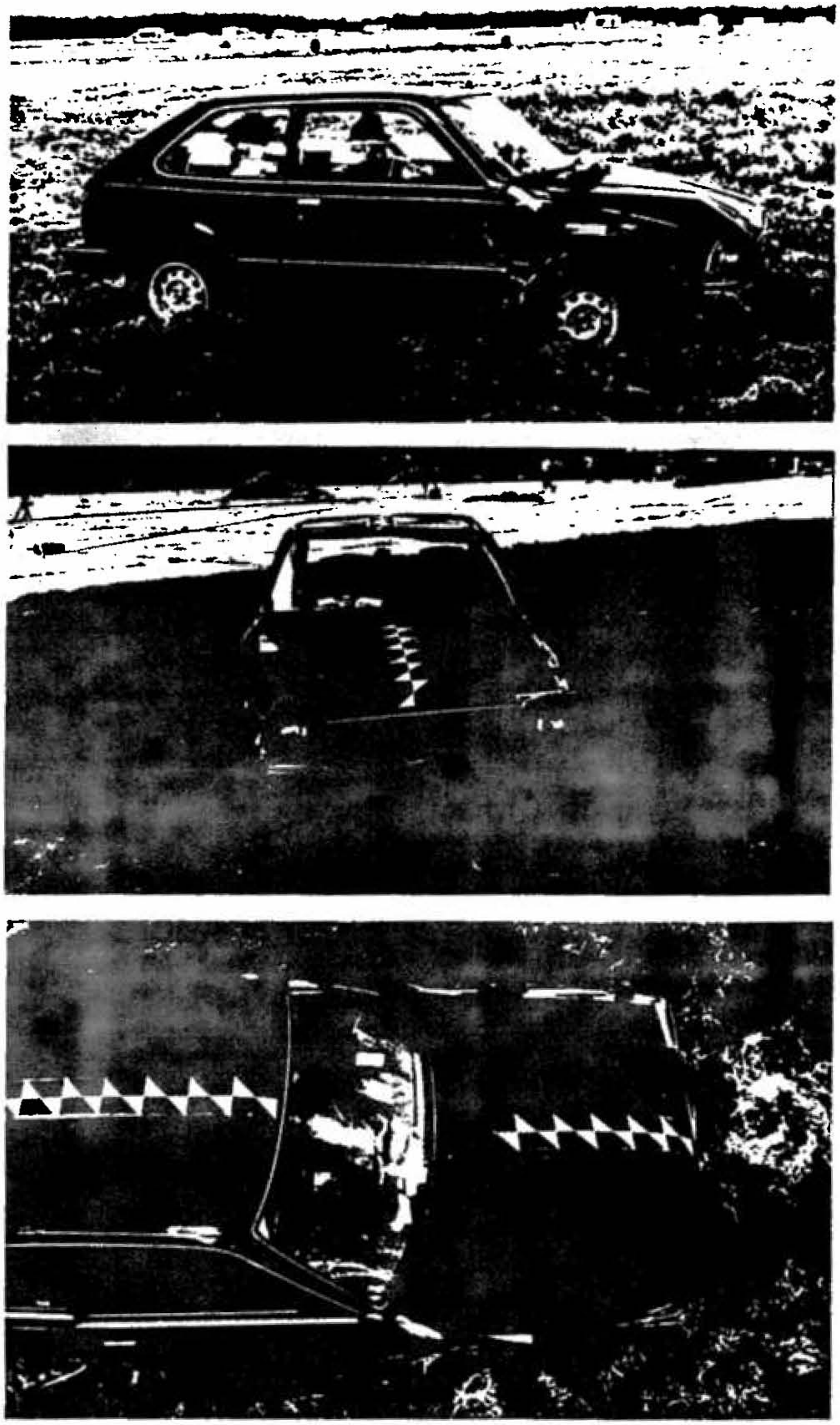


Figure 53. Post-test photographs of test vehicle, test 1862-7-89.

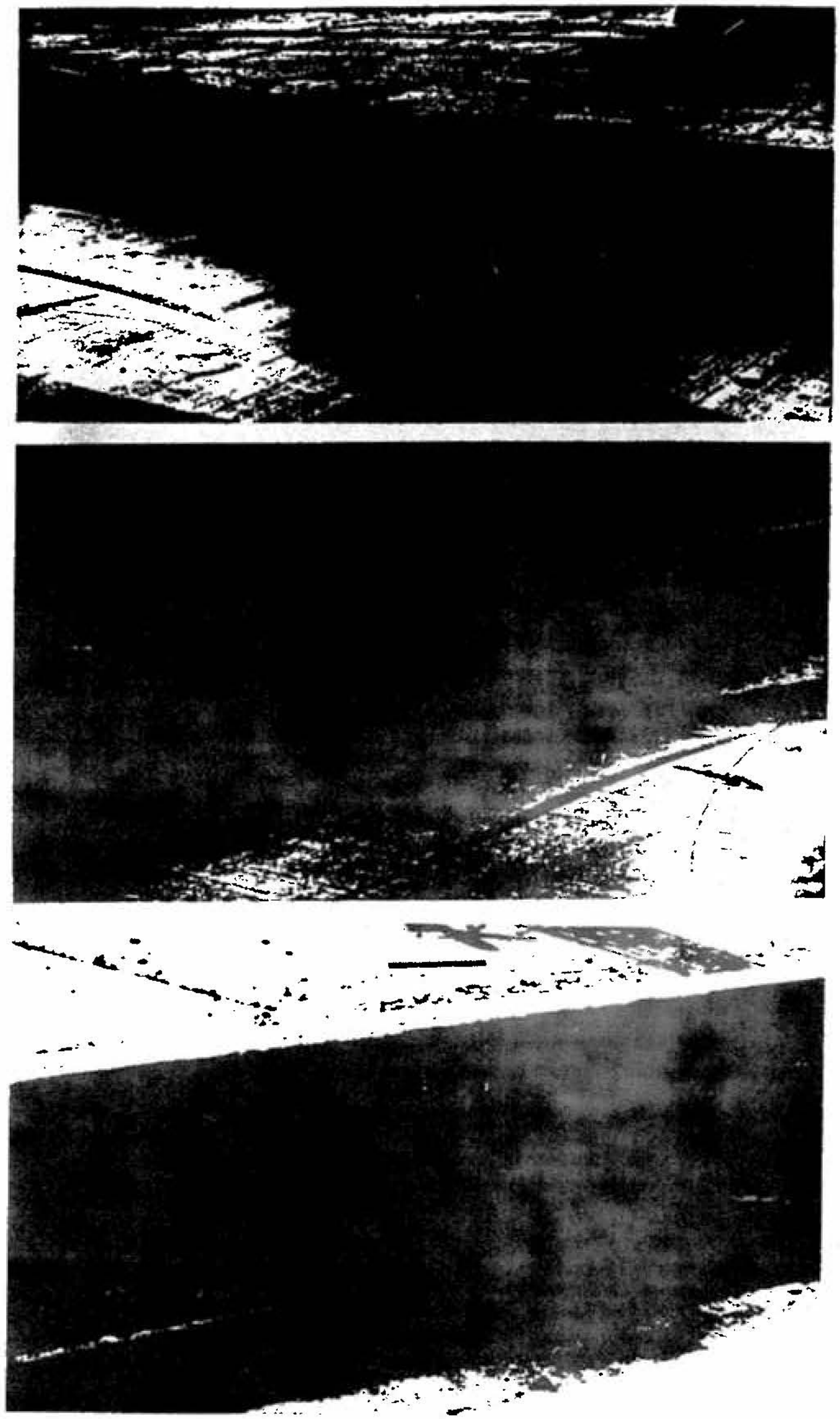


Figure 54. Post-test photographs of concrete wall system, test 1862-7-89.

8. TEST 1862-8-89

a. Test Device

The test device was a concrete wall with a concrete curb. The wall was 27 in (685.89 mm) high and 9 in (228.6 mm) thick. The wall was 75 ft (22.9 m) long and was located at the edge of a cantilevered concrete deck attached to a rigid, simulated support structure. The curb was 8 in by 8 in (203.2 mm by 203.2 mm) with a 1-in (25.4-mm) rake on the front face and ran the entire length of the wall. Epoxy-coated rebar was used throughout. Lateral deck bars were set on 6-in (152.4-mm) centers. FHWA 4000-lbf/in^2 (27560-kPa) class D(AE) concrete was used for the deck and wall. Standard 4000-lbf/in^2 (27560-kPa) concrete was used for the curb. Rebar was not used in the curb.

Figure 55 shows the test site and test device. Figure 56 shows pretest photographs of the concrete wall and curb system.

b. Test Vehicle

The test vehicle was a 1982 Chevrolet C20 pickup. The target inertial vehicle weight was 5400 lb (2452 kg). The vehicle weighed approximately 4400 lb (1998 kg) empty. Approximately 1000 lb (454 kg) of ballast were added. The ballasted inertial weight of the truck was 5402 lb (2453 kg). The gross vehicle weight was 5742 lb (2607 kg).

Two dummies were placed in the vehicle. The driver was restrained while the passenger was unrestrained. X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the cab of the truck. Pretest photographs of the test vehicle are shown in figure 57. Table 19 lists important parameters of the test vehicle.

c. Impact Description

Review of the high-speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 62.1 mi/h (99.9 km/h) and 10°. This review also indicated that the right corner of the vehicle impacted the wall at the desired point.

Upon impact, the vehicle front end was deformed by the concrete wall. The vehicle yawed around and climbed the wall when the vehicle rode up on the curb. The vehicle remained in contact with the wall for 20 ft (6.1 m). The tire and wheel rode up onto the curb for 15 ft (4.6 m) starting at impact. The vehicle front end rode off the curb and was pitched forward, totally airborne. The vehicle was redirected at a 2° angle to the wall. The vehicle came to rest 430 ft (131.2 m) past impact, 20 ft (6.1 m) in front of the wall, at a 0° angle to the wall.

Upon impact, the two dummies fell towards the passenger side. When the vehicle was redirected, the passenger fell back onto the

Table 19. Test vehicle parameters, test 1862-8-89.

Item	Actual	Specification
Empty Weight	~4400 lb	n/a
Ballast	~1000 lb	n/a
Total Weight, Inertial	5402 lb	5400 lb
Total Weight, Gross	5742 lb	n/a
H_{cg}	27 in	27 ± 1 in
A (front to cg), Inertial	8.51 ft	8.5 ± 0.1 ft
B (width)	6.5 ft	6.5 ft
Truck Length	216 in	
Truck Wheelbase	132 in	
Wheel/Tire Size	235 85R16	
Truck Box Size	8 ft long by 1.5 ft high by 5.5 ft wide	
Ground to Box Floor	27 in	

1 lb = 0.45 kg   1 ft = 0.31 m   1 in = 25.4 mm

driver. The passenger dummy fell forward when the vehicle brakes were applied. The driver dummy came to rest upright, leaning toward the passenger side. The passenger dummy came to rest with its body over the hump and its head at the driver's feet.

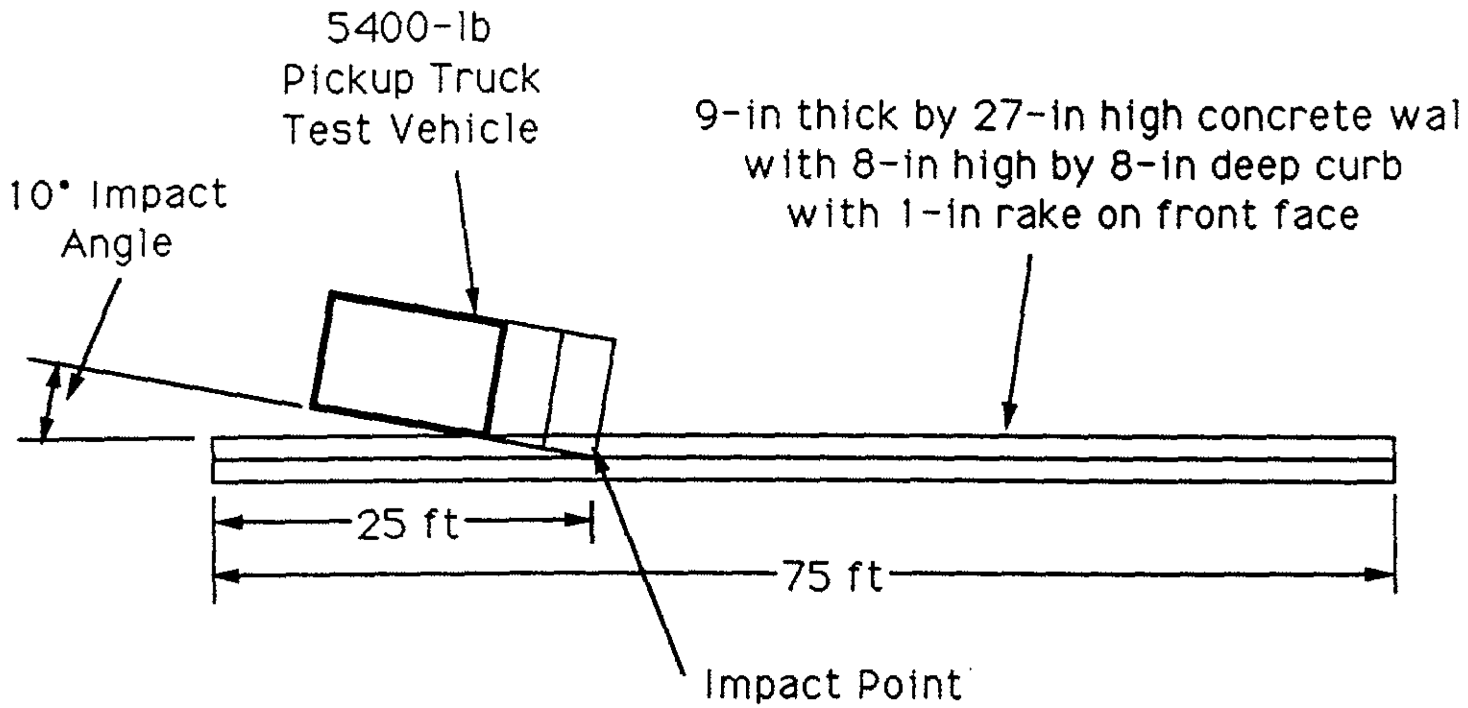
A summary of test conditions and results are shown in figure 58. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 59.

d. Vehicle Damage

Damage occurred to the bumper and entire right side of the vehicle. However, this damage was very minor, consisting of scrub from the concrete wall. Post-test photographs of the vehicle are shown in figure 60.

e. Barrier Damage

The wall and curb suffered very little damage. The curb was spalled for 3 ft (0.9 m) prior to impact and the wall was spalled for 2 ft (0.6 m) prior to impact. Downstream of the impact point, the wall suffered only scuffing and minor scraping. Post-test photographs of the rail are shown in figure 61.



1 ft = 0.30 m   1 in = 25.4 mm

Figure 55. Test site layout, test 1862-8-89.

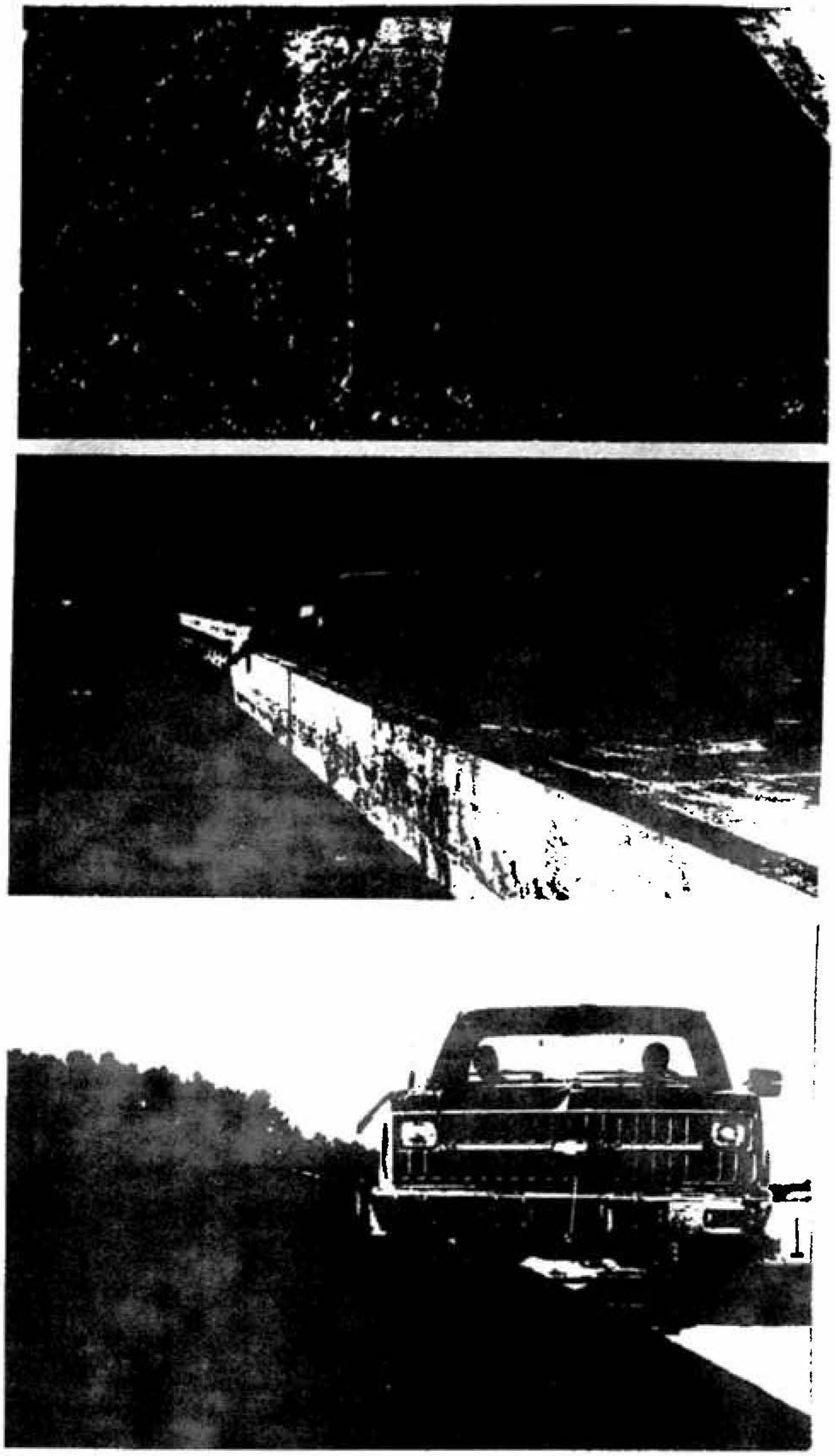


Figure 56. Pretest photographs of concrete wall system, test 1862-8-89.

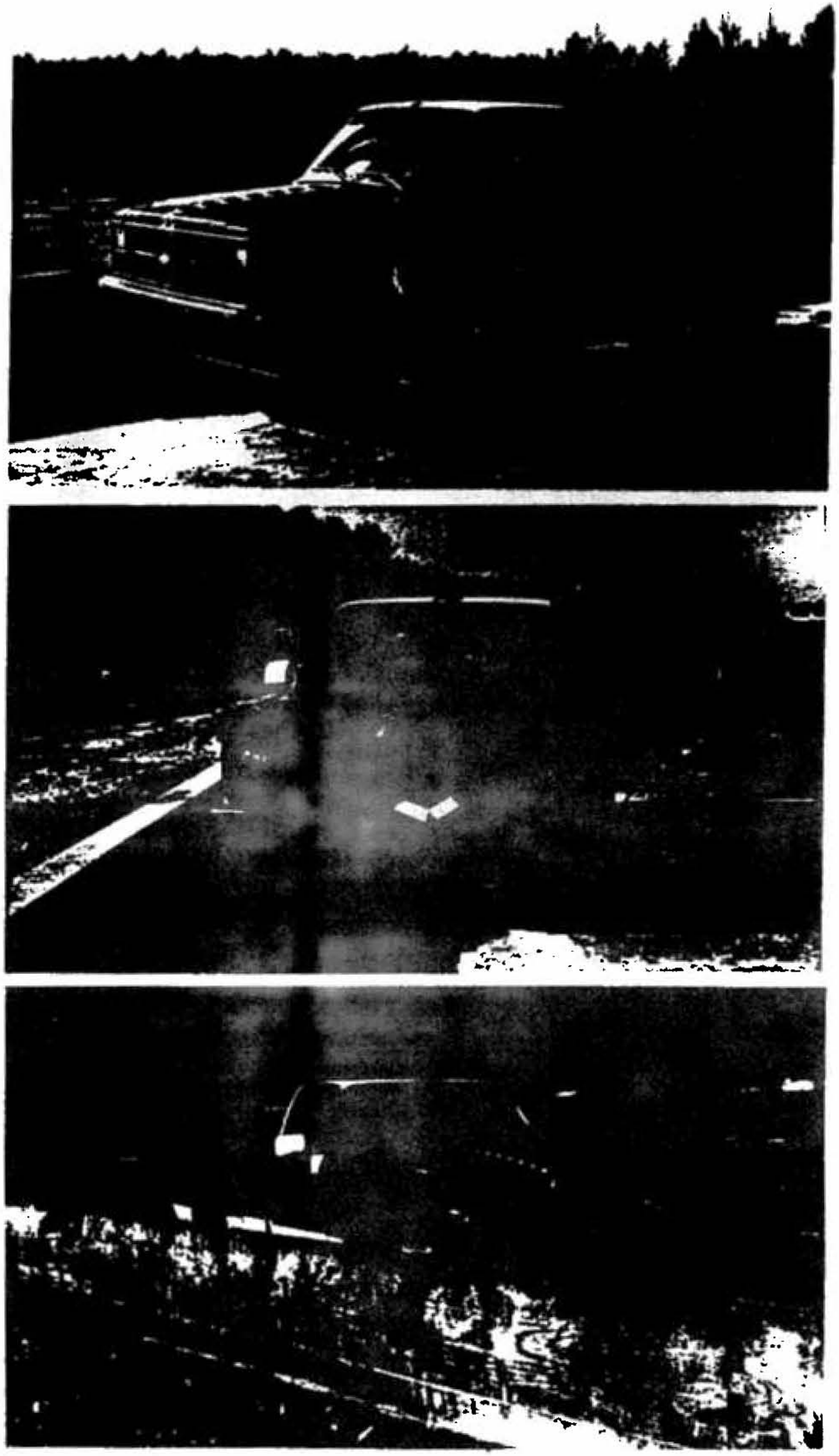
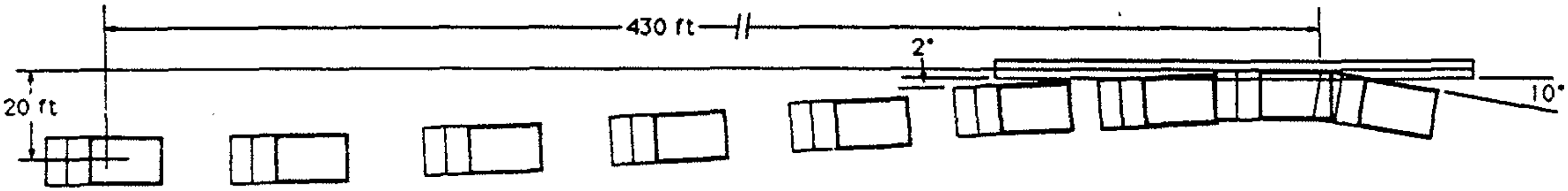
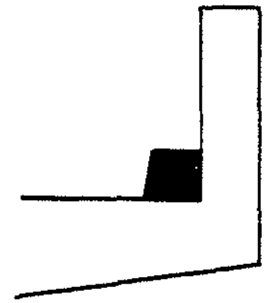


Figure 57. Pretest photographs of test vehicle, test 1862-8-89.



32°F = 0°C   1 ft = 0.30 m   1 lb = 0.45 kg   1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s   1 kip-ft = 1360 N-m   1 g = 9.8 m/s²



Date: 4 December 1989
Weather: Clear, Windy, 30° F

Test Vehicle: 1982 Chevrolet C20 Pickup

Device Configuration: Concrete wall with concrete curb, 75 ft total length, 27 in by 9 in wall, 8 in by 8 in curb with 1 in rake on front face

1. Vehicle Weight:
   - Inertial, planned: 5400
   - Inertial, actual: 5402
   - Gross, actual: 5742
2. Number of Occupants: Two
3. Occupant Model: Part 572, 50th percentile male, fully instrumented
4. Occupant Location: Driver Seat, Restrained; Passenger Seat, Unrestrained
5. Impact:

Impact:	Speed	Angle (a)	Location
Planned:	60.0 mi/h	10°	25 ft from end
Actual:	62.1 mi/h	10°	25 ft from end

   Tolerances: Speed: -1.0, +2.5 mi/h; Angle: -1.0, +2.5 degrees
6. Redirection Angle: 2°
7. Redirection Speed: 56.5 mi/h (82.9 ft/s)
8. Total Speed Change: 5.6 mi/h (8.2 ft/s)
9. Total Momentum Change: 1462 lb-s
10. Vehicle Damage Index: (SAE J224a) 01RDEW1
11. NCHRP 230 Test Number: Special; AASHTO Test Type: PL2
12. Vehicle Analysis:

	Observed	Design/ Limit Value
Longitudinal:		
Delta-V at 2 ft:	-8.0 ft/s	30/40 ft/s
Ridedown Acceleration:	1.2 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	15.4 ft/s	20/30 ft/s
Ridedown Acceleration:	5.9 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-2.3 g's	
Lateral:	7.9 g's	

13. Vehicle-Railing Interaction Coefficient of Friction:

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

mu	assessment
0.30	Fair

V_p = 57.9 mi/h (84.9 ft/s)

14. Test Results Conclusion:

AASHTO Bridge Rail Specification: MEETS ALL CRITERIA.

Figure 58. Test summary, test 1862-8-89.

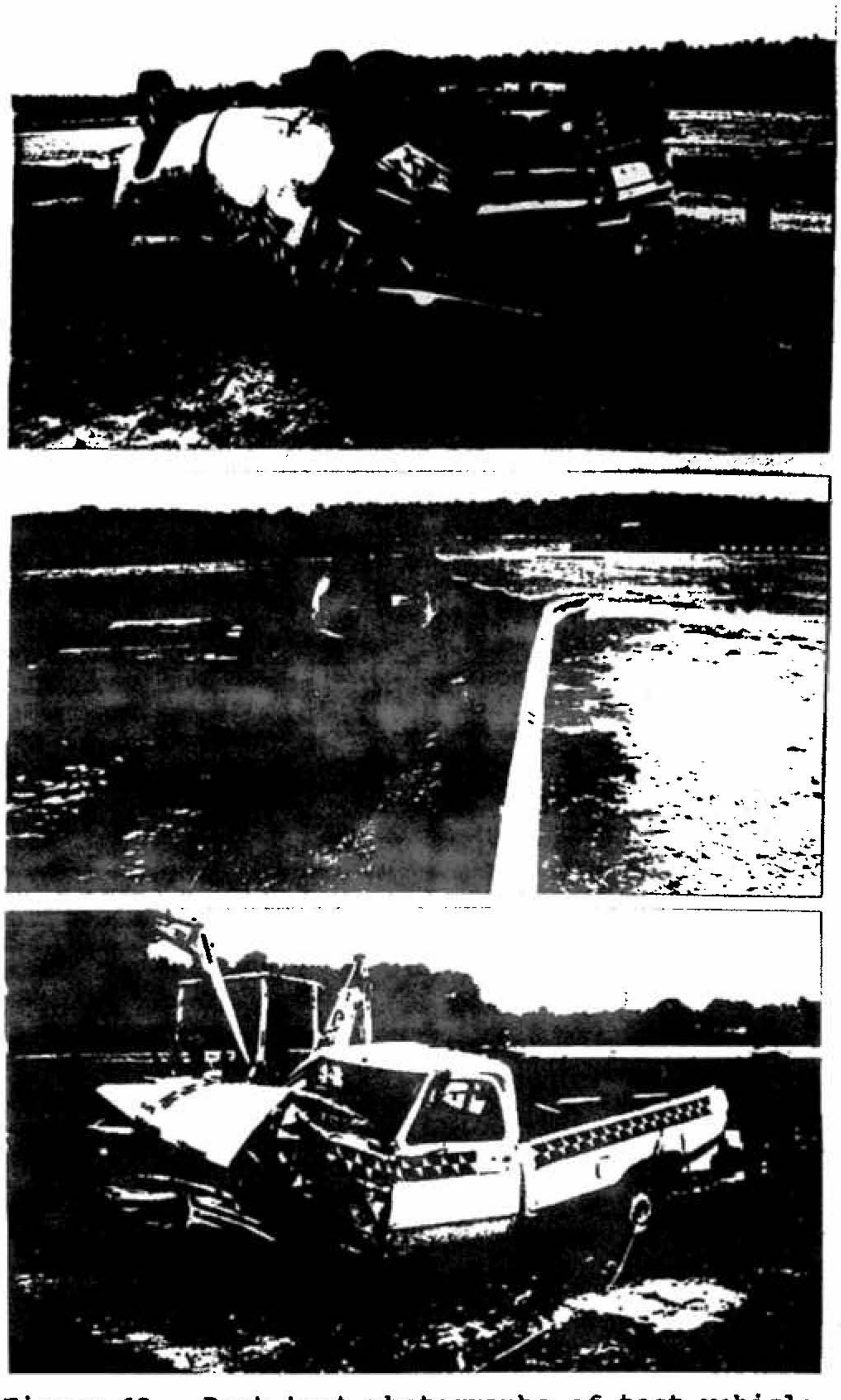


Figure 68. Post-test photographs of test vehicle, test 1862-9-90.

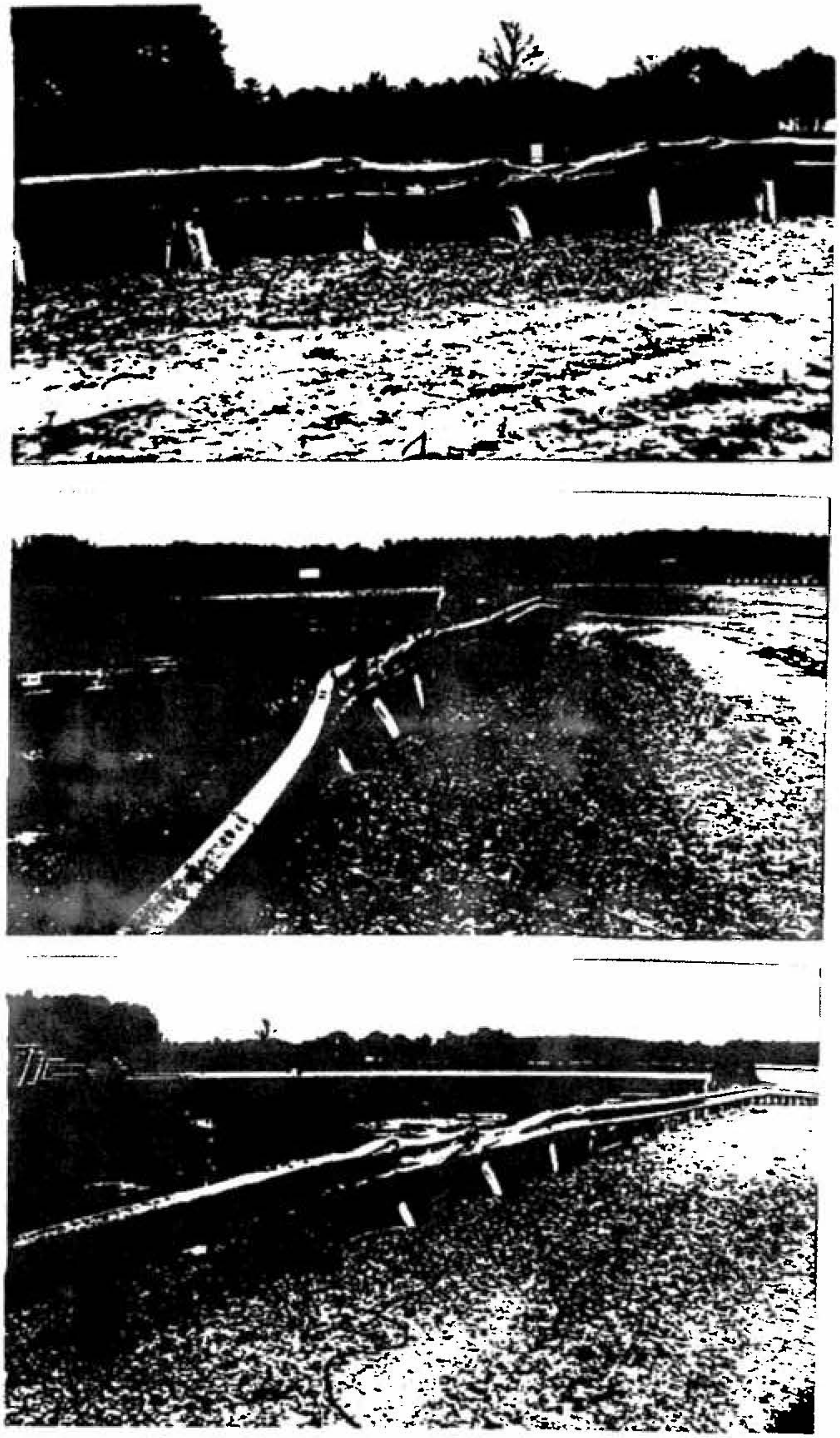


Figure 69. Post-test photographs of guardrail system, test 1862-9-90.

10. TEST 1862-10-90

a. Test Device

The test device was the Modified Thrie Beam guardrail installed on a superelevation with a 1192-ft (363.6-m) radius curve. The entire system was 262.5 ft (80.1 m) long. The system consisted of 181.25 ft (55.3 m) of thrie beam in the curved section, a 6.25-ft (1.9-m) W-beam to thrie beam transition, 37.5 ft (11.4 m) of straight W-beam rail prior to the curve and a 37.5-ft (11.4-m) standard BCT on the upstream end. The thrie beam was mounted at the standard height of 34 in (863.6 mm). The superelevation consisted of 20 ft (6.1 m) of a 10-percent upslope and 10 ft (3.1 m) of a 2-percent rising shoulder. For this test, the posts were in the same location as compared to previous tests of the superelevated system (tests 1862-6-89 and 1862-9-90). In effect, this moved the front face of the rail closer to the edge of the shoulder. The front face of the rail was 1 in (25.4 mm) past the edge of the shoulder. The terrain fell away in a 2:1 downslope 4 ft (1.2 m) past the edge of the shoulder. For 4 ft (1.2 m) on both sides of the 2-percent/2:1 slope breakpoint, the slopes were rounded. With the rounding, a smooth merge existed between these two slopes rather than a sharp breakpoint. The upstream end BCT used steel slipbase posts that incorporate large soil plates in lieu of the concrete anchor. A cable anchor assembly was used on the downstream end. This assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 70 shows the test site and test device. Figure 71 shows a rail profile drawing. Figure 72 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1982 Ford F100 pickup. The target inertial vehicle weight was 5400 lb (2452 kg). The vehicle weighed approximately 3700 lb (1680 kg) empty. Approximately 1600 lb (726 kg) of ballast were added. The ballasted inertial weight of the truck was 5408 lb (2455 kg). The gross vehicle weight was 5743 lb (2607 kg).

Two dummies were placed in the vehicle. The driver was restrained while the passenger was unrestrained. X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the cab of the truck. Pretest photographs of the test vehicle are shown in figure 73. Table 21 lists important parameters of the test vehicle.

c. Impact Description

Review of the high-speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 61.0 mi/h (98.2 km/h) and 20° measured relative to the straight rail section. This review also indicated that the left corner of the vehicle impacted the rail at the desired point. It should be noted that the impact point mark on the rail system was located in error. The mark was 6.25 ft (1.9 m) downstream of the actual desired impact point.

Approximately 20 ft (6.1 m) prior to impact, as the vehicle was traversing the superelevation, all four wheels of the vehicle left the ground, although not simultaneously.

Upon impact, the vehicle penetrated into the rail approximately 3 ft (0.9 m). As the vehicle was redirected by the rail, the vehicle rolled into the rail approximately 45°. The vehicle became slightly airborne and pitched and rolled such that the driver-side front corner was contained by the rail while the passenger-side rear end was in the air (the vehicle skewing into the rail). As the vehicle continued downstream, it returned to an upright position. The vehicle came to rest approximately 22 ft (6.7 m) in front of the face of the rail, 134 ft (40.9 m) past the impact point. The vehicle remained in contact with the rail for approximately 55 ft (16.8 m).

This thrie beam rail had sufficient strength to redirect the vehicle. The rail remained vertical due to the notched blockout design, aiding in the redirection of the vehicle.

The driver dummy impacted the driver side door, pushing open the door. The passenger dummy impacted the driver dummy. The driver dummy came to rest in the driver's seat. The passenger came to rest leaning toward the driver dummy.

A summary of test conditions and results are shown in figure 74. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 75.

d. Vehicle Damage

The entire left side of the vehicle, including the cab, fenders, door, tires/wheels, and suspension were damaged. The driver side door was pushed open by the impact of the dummy. Post-test photographs of the test vehicle are shown in figure 76.

e. Barrier Damage

The barrier was damaged for 62.5 ft (19.1 m), beginning 9 ft (2.7 m) upstream of impact. The rail had permanent deflection from

Table 21. Test vehicle parameters, test 1862-10-90.

Item	Actual	Specification
Empty Weight	~3700 lb	n/a
Ballast	~1600 lb	n/a
Total Weight, Inertial	5408 lb	5400 lb
Total Weight, Gross	5743 lb	n/a
H_{cg}	27 in	27 ± 1 in
A (front to cg), Inertial	8.57 ft	8.5 ± 0.1 ft
B (width)	6.33 ft	6.5 ft
Truck Length	212 in	
Truck Wheelbase	134 in	
Wheel/Tire Size	215-75/15 (front), 235-75/15 (rear)	
Truck Box Size	8 ft long by 1.5 ft high by 5.5 ft wide	
Ground to Box Floor	27 in	

1 lb = 0.45 kg   1 ft = 0.31 m   1 in = 25.4 mm

posts 18 through 28. Posts 22 through 25 were bent and twisted. The rail was detached from the block at post 23. Blockouts were bent and twisted from post 21 to 25. Posts 4 through 17 and 29 through 41 were twisted by the deformation of the rail. The downstream end foundation was pulled 1 in (25.4 mm) toward the impact point. The maximum permanent rail deflection [35 in (889.0 mm)] occurred midspan post 22 and 23. Posttest photographs of the rail are shown in figure 77.

f. Test Evaluation

This test was evaluated using the AASHTO Guide Specifications for Bridge Railings. The following is an item-by-item evaluation using this guideline.

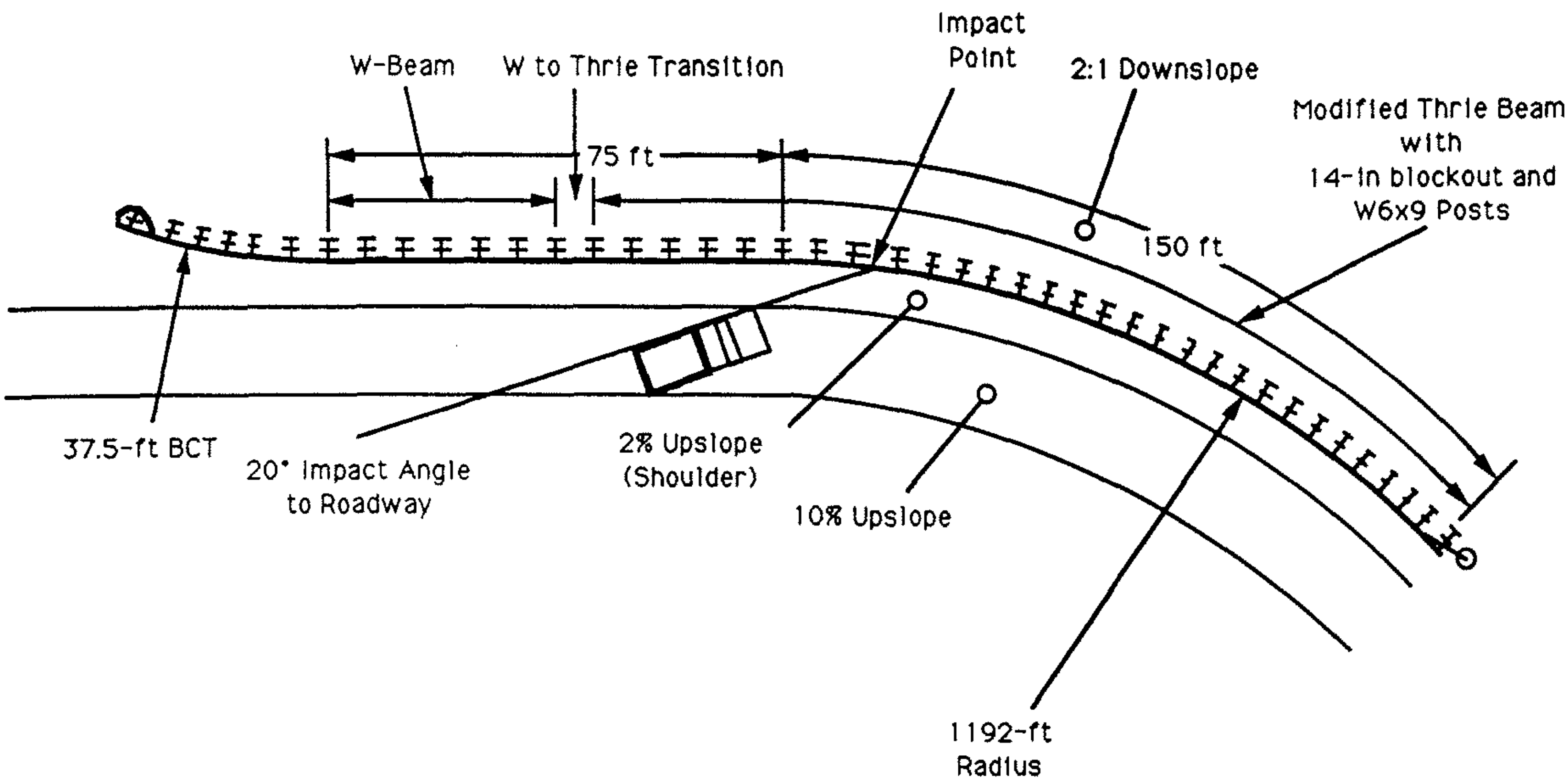
Required Criteria:

a. The vehicle was contained by the test article.
b. There were no detached elements.
c. Integrity of the passenger compartment was maintained.
d. The vehicle remained upright.

Desirable Criteria:

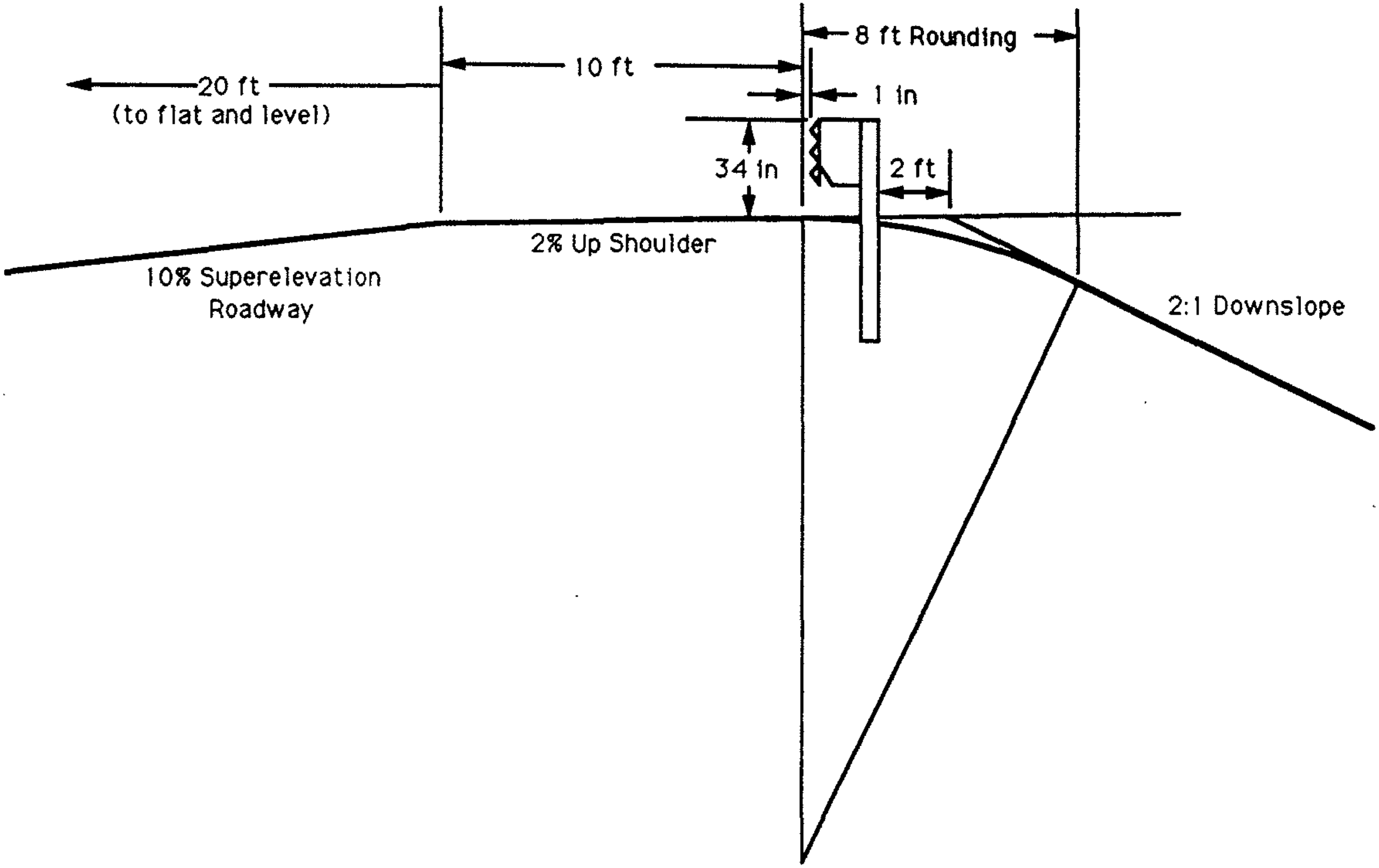
e. The vehicle was smoothly redirected.
f. Vehicle railing interaction:
   mu = 0.49, assessment: Marginal.
g. Delta-V and Ridedown values were within limits.
h. The exit angle was less than 12°. Vehicle was within 20 ft (6.1 m) of the rail, 100 ft (30.5 m) downstream of the impact point.

MEETS ALL CRITERIA.



1 ft = 0.30 m   1 in = 25.4 mm

Figure 70. Test site layout, test 1862-10-90.



1 ft = 0.30 m   1 in = 25.4 mm

Figure 71. Rail profile, test 1862-10-90.

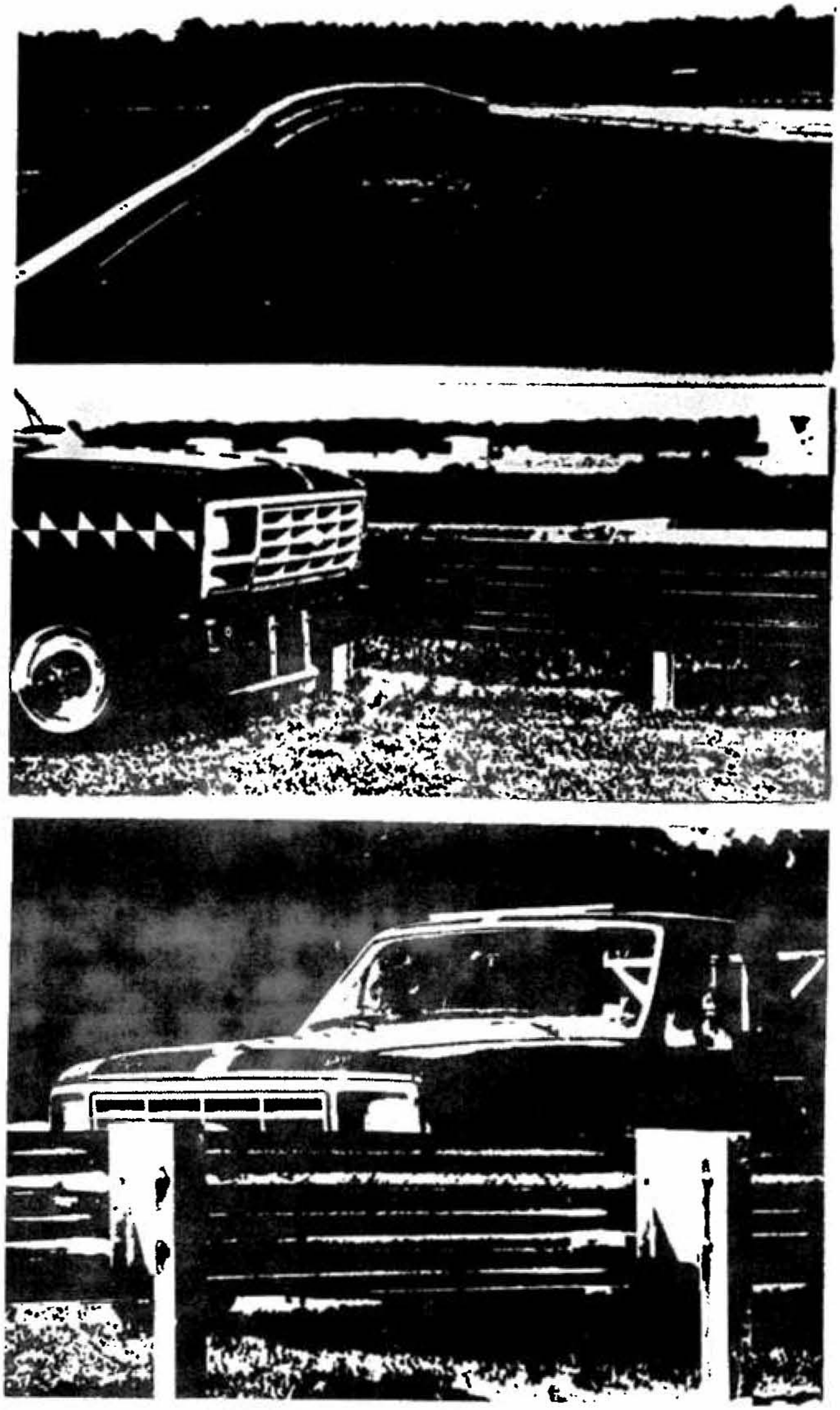
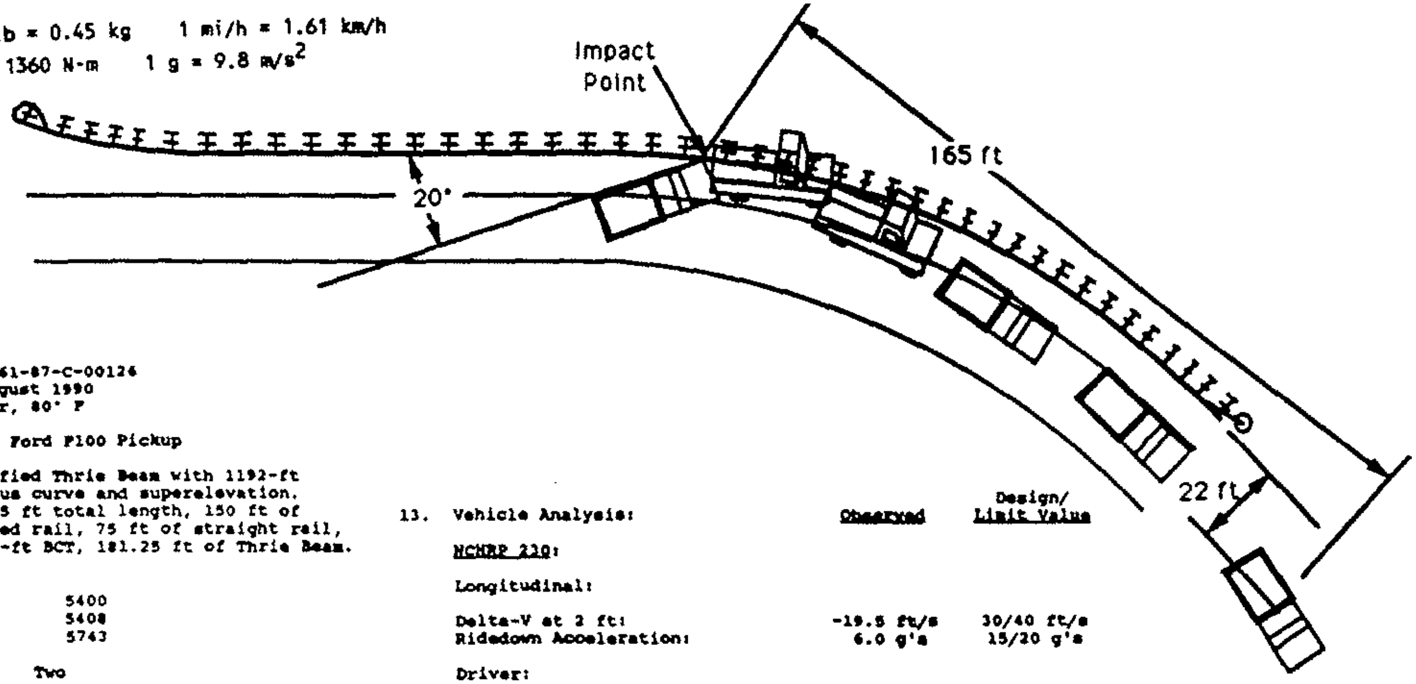


Figure 72. Pretest photographs of guardrail system, test 1862-10-90.

Figure 73. Pretest photographs of test vehicle, test 1862-10-90.

32°F = 0°C 1 ft = 0.30 m 1 lb = 0.45 kg 1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s 1 kip-ft = 1360 N-m 1 g = 9.8 m/s²



Contract Number:	DTFH61-87-C-00126
Date:	1 August 1990
Weather:	Clear, 80° F
Test Vehicle:	1982 Ford F100 Pickup
Device Configuration:	Modified Thrie Beam with 1192-ft radius curve and superelevation. 262.5 ft total length, 150 ft of curved rail, 75 ft of straight rail, 37.5-ft BCT, 181.25 ft of Thrie Beam.

1. Vehicle Weight:
   - Planned, Inertial: 5400
   - Actual, Inertial: 5408
   - Actual, Gross: 5743
2. Number of Occupants: Two
3. Occupant Model: Part 572, 50 percentile male
4. Occupant Locations: Driver Seat, Restrained; Passenger Seat, Unrestrained
5. Impact:

	Speed	Angle	Location
Planned:	60.0 mi/h	20°	Midspan posts 21 and 22
Actual:	61.0 mi/h	20°	Midspan posts 21 and 22

   Tolerances: Speed: -1.0, +2.5 mi/h; Angle: -1.0, +2.5 degrees
6. Redirection Angle: ~5 degrees
7. Redirection Speed: 46.6 mi/h (68.3 ft/s)
8. Total Speed Change: 14.4 mi/h (21.1 ft/s)
9. Total Momentum Change: 3763 lb-sec
10. Vehicle Damage Index: (SAE J224a) 11LDEW3
11. NCHRP 230 Test Number: Special; AASHTO Test Type: PL2
12. Vehicle-Railing Interaction Coefficient of Friction:

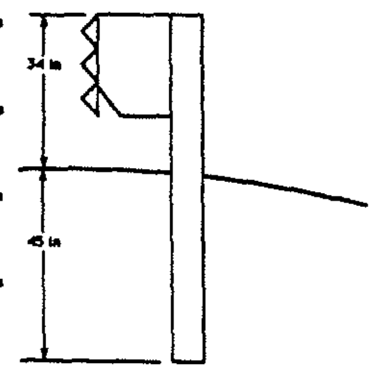
$$mu = \frac{\text{Cos theta} - V_p/V}{\text{Sin theta}}$$

mu	assessment
0.49	Marginal

V_p = 47.0 mi/h (69.0 ft/s)

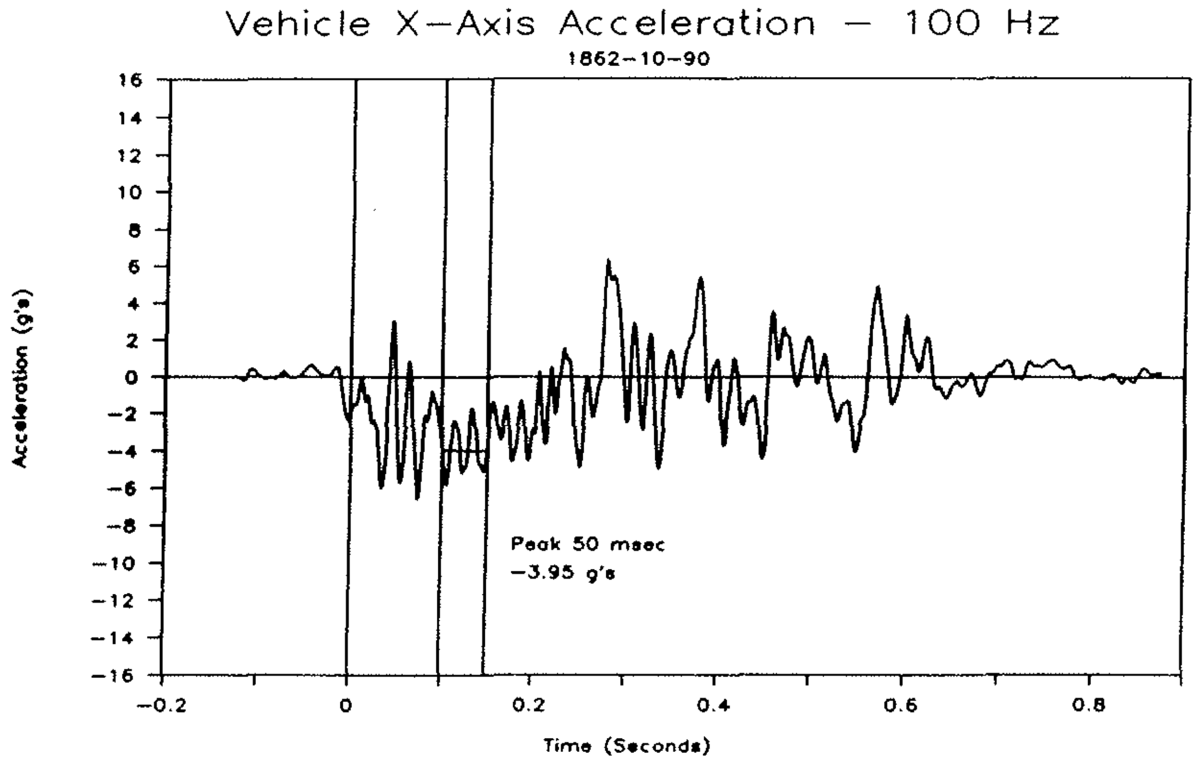
13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-19.5 ft/s	30/40 ft/s
Ridedown Acceleration:	6.0 g's	15/20 g's
Driver:		
Delta-V at 2.50 ft (actual):	-19.3 ft/s	30/40 ft/s
Ridedown Acceleration:	6.0 g's	15/20 g's
Passenger:		
Delta-V at 2.33 ft (actual):	-19.4 ft/s	30/40 ft/s
Ridedown Acceleration:	6.0 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-18.0 ft/s	20/30 ft/s
Ridedown Acceleration:	-6.9 g's	15/20 g's
Driver:		
Delta-V at 1.08 ft (actual):	-18.6 ft/s	20/30 ft/s
Ridedown Acceleration:	-6.9 g's	15/20 g's
Passenger:		
Delta-V at 0.83 ft (actual):	-16.5 ft/s	30/40 ft/s
Ridedown Acceleration:	-6.9 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-4.0 g's	
Lateral:	-5.7 g's	



14. Test Results Conclusion:
    AASHTO Bridge Rail Specification: MEETS ALL CRITERIA.

Figure 74. Test summary, test 1862-10-90.



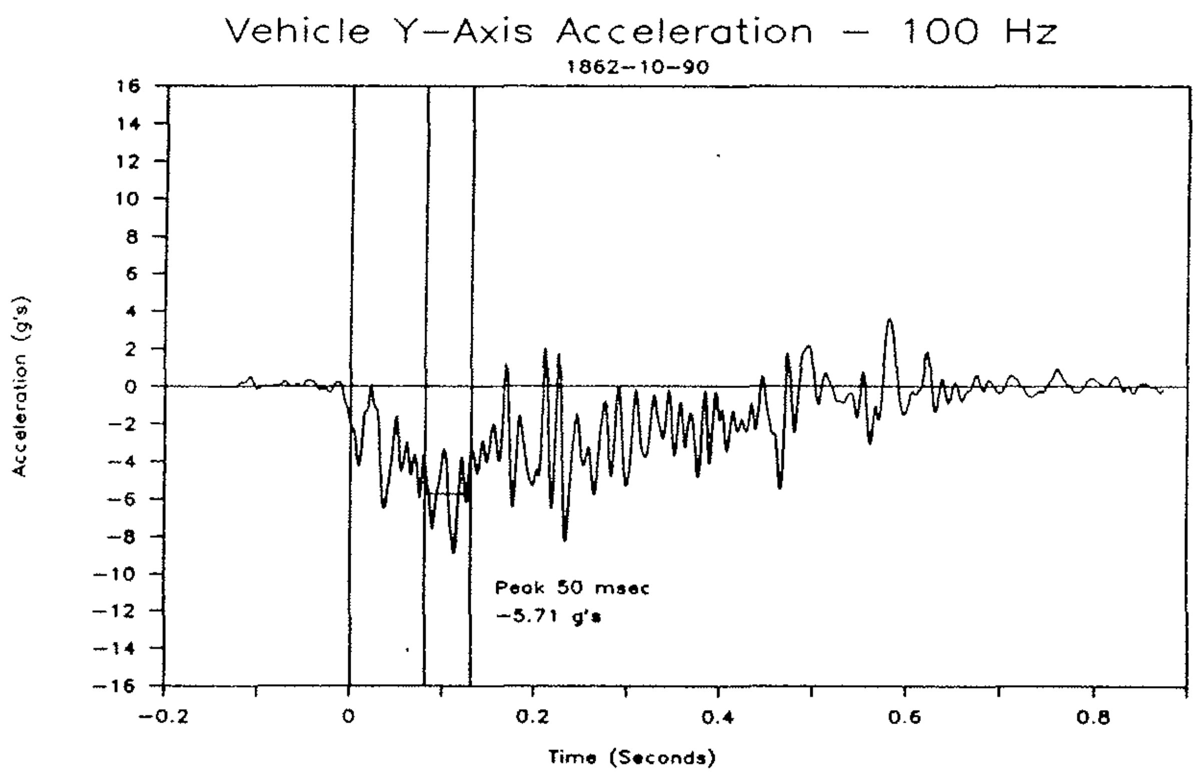


Figure 75. Vehicle accelerations, test 1862-10-90.

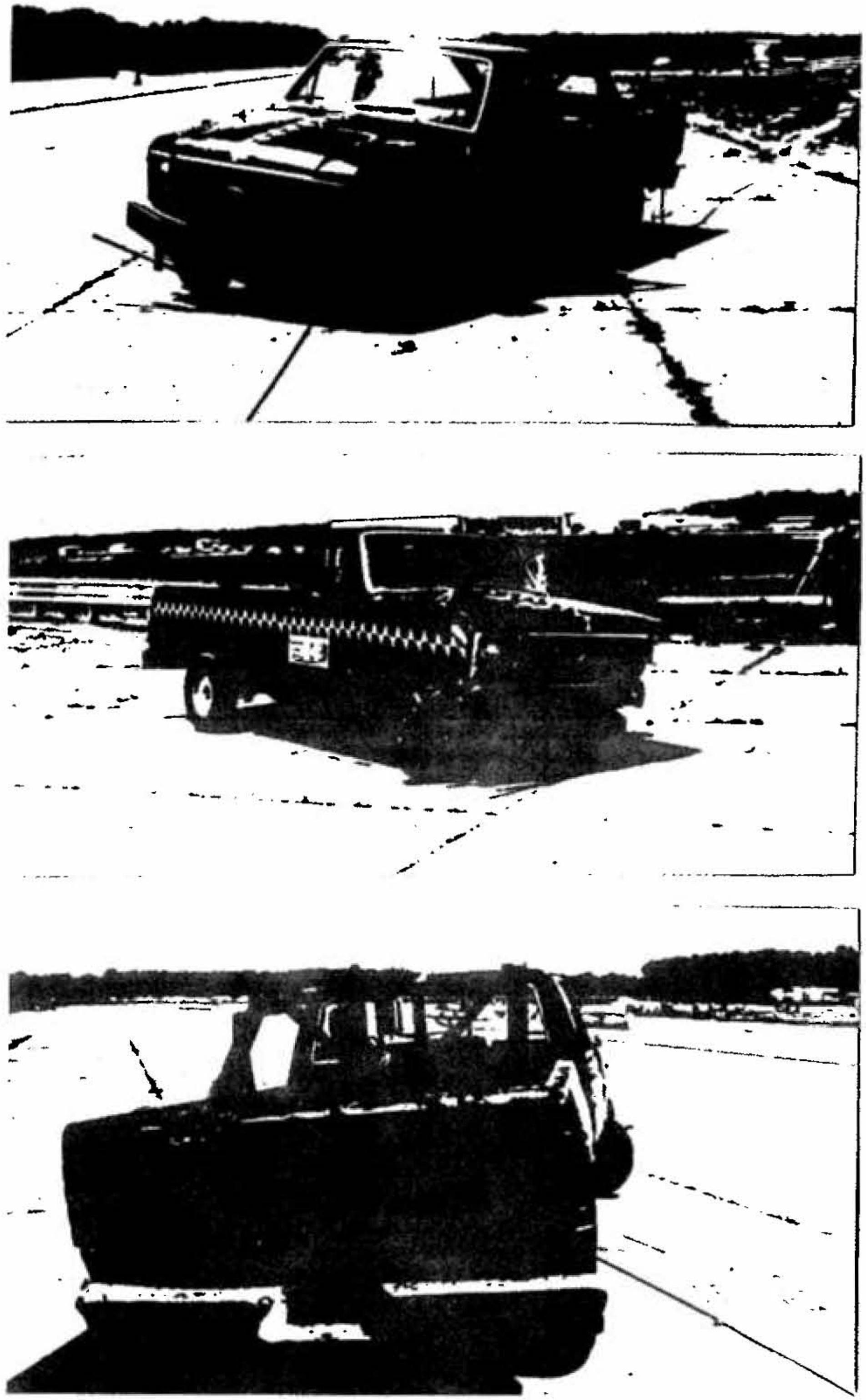


Figure 76. Post-test photographs of test vehicle, test 1862-10-90.

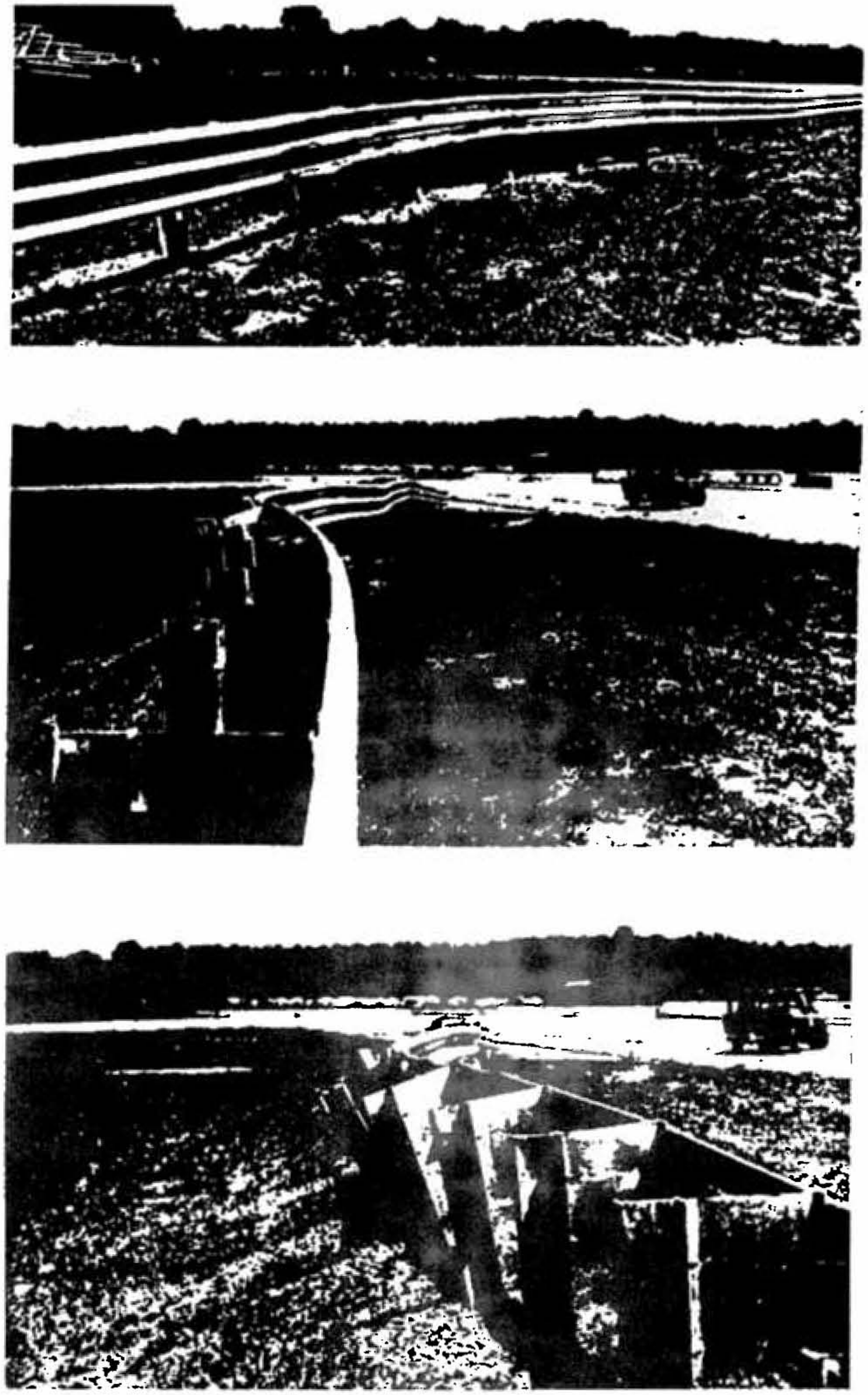


Figure 77. Post-test photographs of guardrail system, test 1862-10-90.

11. TEST 1862-11-90

a. Test Device

The test device was the Federal Highway Administration-designed Modified Eccentric Loader Terminal (MELT). It was included in the test program to gain insight into the behavior of guardrails with a convex curvature. The entire system was 131.25 ft (40.0 m) long. The system consisted of the 37.5-ft (11.4-m) MELT and 93.75 ft (28.6 m) of W-beam in the LON section. The baffles were steel plates bolted into the wrap-around section of the terminal. These baffles also bolt to the rail where the wrap-around section bolts to the rail and to the end-shoe where the wrap-around bolts to the end-shoe. The wrap-around was bolted to the rail and to the end-shoe with two rail-splice bolts and two rail-post bolts. The rail-post bolts were used where all three pieces join (wrap-around, baffle, and rail or end-shoe). The end-shoe was bolted to the backside of the rail with a rail-post bolt and two rail washers. Posts 1 and 2 were the standard 42.5-in (1079.5-mm) wood BCT posts in the buried box-beam sleeves with soil plates. Post 1 was modified to include a 2-in by 0.75-in (50.8-mm by 19.1-mm) slot where the rail attached. Tube sleeves were installed in the grade-line hole of posts 1 and 2. A 0.75-in (19.1-mm) cable, anchored to the rail with a BCT anchor plate, tensioned the rail through the grade-line hole of post 1. The rail was attached to post 1 with a 0.625-in by 9-in (15.9-mm by 228.6-mm) bolt with a rail washer on the rail side and a round washer on the post side. The rail was not attached to posts 2 through 6. A shelf angle was bolted to post 2. The spreader bar (as used on the Eccentric Loader BCT) was attached to posts 1 and 2 with 0.75-in by 10-in (19.1-mm by 254.0-mm) bolts through the wood post and the steel box beam. Posts 3 through 6 were 6-ft (1.8-m) wood posts with blockouts. The remaining posts were W6x9 steel with blockouts. A cable anchor assembly was used on the downstream end. This assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 78 shows the test site and test device. Figure 79 shows pretest photographs of the terminal and guardrail system.

b. Test Vehicle

The test vehicle was a 1979 Chrysler Newport. The target inertial vehicle weight was 4500 ± 200 lb (2043 ± 91 kg). The vehicle weighed approximately 3750 lb (1703 kg) empty. Ballast weighing 560 lb (254 kg) was added to the vehicle. The inertial weight of the vehicle was 4307 lb (1955 kg). The target gross vehicle weight was 4500 ± 300 lb (2043 ± 136 kg). The gross vehicle weight was 4645 lb (2109 kg).

X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the vehicle. Two uninstrumented dummies were placed in the vehicle. The driver and the passenger were restrained. Pretest photographs of the test vehicle are shown in figure 80. Table 22 lists important parameters of the test vehicle.

c. Impact Description

Review of the high-speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 61.0 mi/h (98.2 km/h) and 25° measured relative to the straight rail section (approximately 29° to the rail at impact). This review also indicated that the left corner of the vehicle impacted the rail at the desired point.

Upon impact, the vehicle penetrated into the rail, causing deflection of the rail, pulling of the BCT toward impact, the breaking off of wood posts, the bending of steel posts, and the flattening of the rail. The BCT retained sufficient strength to redirect the errant vehicle. The vehicle redirected at an angle of approximately 15°, staying flat and level throughout the impact event, pitching up only approximately 6 to 9 in (152.4 to 228.6 mm). The vehicle came to rest 150 ft (45.8 m) downstream of the impact point, 47 ft (14.3 m) in front of the face of the rail. The vehicle remained in contact with the rail for approximately 37 ft (11.3 m).

Due to a camera failure, no onboard vehicle film was available. The driver dummy came to rest in the driver's seat. The passenger dummy came to rest leaning on the driver dummy.

A summary of test conditions and results are shown in figure 81. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 82.

d. Vehicle Damage

The entire left side of the vehicle, including the fenders, doors, tires/wheels, and suspension; the front grill and bumper; and the rear bumper were damaged. Post-test photographs of the test vehicle are shown in figure 83.

e. Barrier Damage

The barrier was damaged for approximately 50 ft (15.3 m), beginning at the beginning of the terminal. The rail had permanent deflection from posts 1 through 12. Post 1 was pulled toward impact, toward the road side of the installation, and up out of the ground. Post 2 was pulled toward impact and back

Table 22. Test vehicle parameters, test 1862-11-90.

Item	Actual	Specification
Empty Weight	~3750 lb	n/a
Ballast	560 lb	n/a
Total Weight, Inertial	4307 lb	4500 ± 200 lb
Total Weight, Gross	4645 lb	4500 ± 300 lb
Vehicle Length	216 in	
Vehicle Wheelbase	118.5 in	

1 lb = 0.45 kg   1 in = 25.4 mm

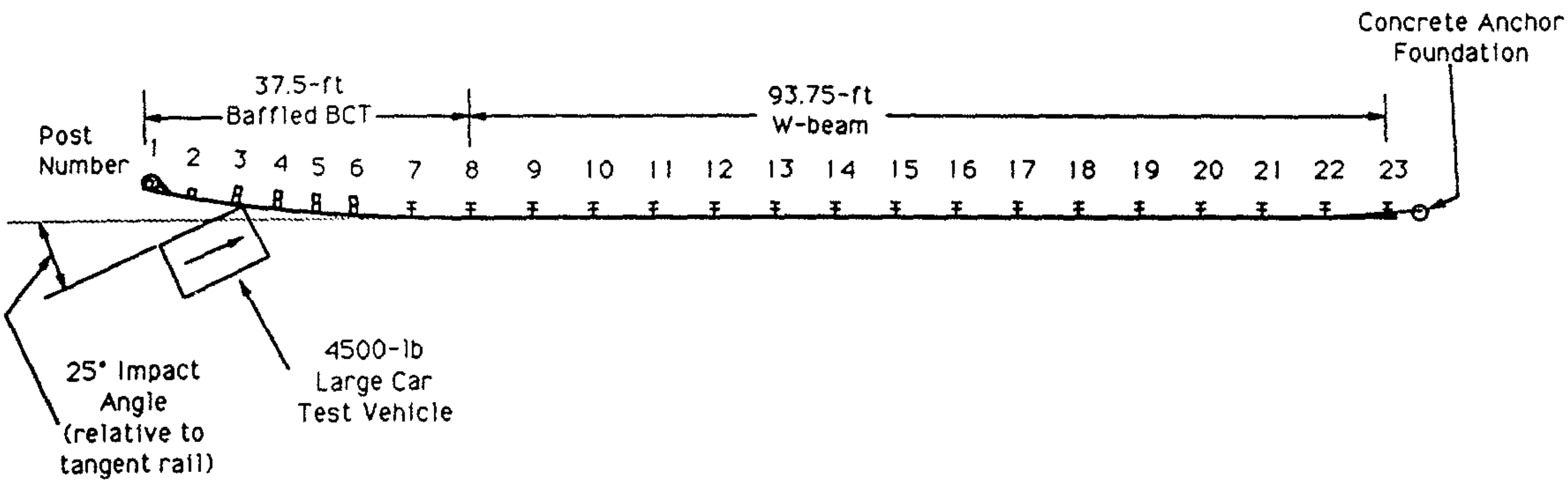
toward the filed side. Posts 3 and 4 were pushed back. The block was detached from post 4. Posts 5 and 6 were broken off through the grade-line hole and thrown behind the rail 18 and 13 ft (5.5 and 4.0 m), respectively, and in the direction of vehicle travel 15 and 17 ft (4.6 and 5.2 m), respectively. Post 7 was bent over, post 8 was pulled out of the ground, and moved 9 ft (2.7 m) downstream, and posts 9 and 10 were twisted and bent. The rail was detached from posts or blocks from post 2 through post 9. The maximum permanent rail deflection occurred at post 8 and was 54 in (1371.6 mm). Post-test photographs of the rail are shown in figure 84.

f. Test Evaluation

This test was evaluated using NCHRP 230. The following is an item-by-item evaluation using this guideline.

a. The test article redirected the vehicle.
d. There were no detached elements.
e. The vehicle remained upright during and after the collision. Integrity of the passenger compartment was maintained.
h. Vehicle trajectory and stopping position did intrude into adjacent traffic lanes.
i. Because the vehicle trajectory and stopping position did intrude into adjacent traffic lanes, vehicle speed change and exit angle criteria are applied. The vehicle was redirected at approximately 31.2 mi/h (45.7 ft/s) [50.2 km/h)] and 15°. The redirection angle is equal to the 60-percent maximum criteria. However, the vehicle speed change is greater than the 15-mi/h (24.1-km/h) maximum criteria.

DOES NOT MEET ALL CRITERIA. The vehicle speed change at redirection is greater than the 15-mi/h (24.1-km/h) maximum. The test meets all other evaluation criteria.



1 ft = 0.30 m   1 lb = 0.45 kg

Figure 78. Test site layout, test 1862-11-90.

Figure 79. Pretest photographs of terminal and guardrail system, test 1862-11-90.

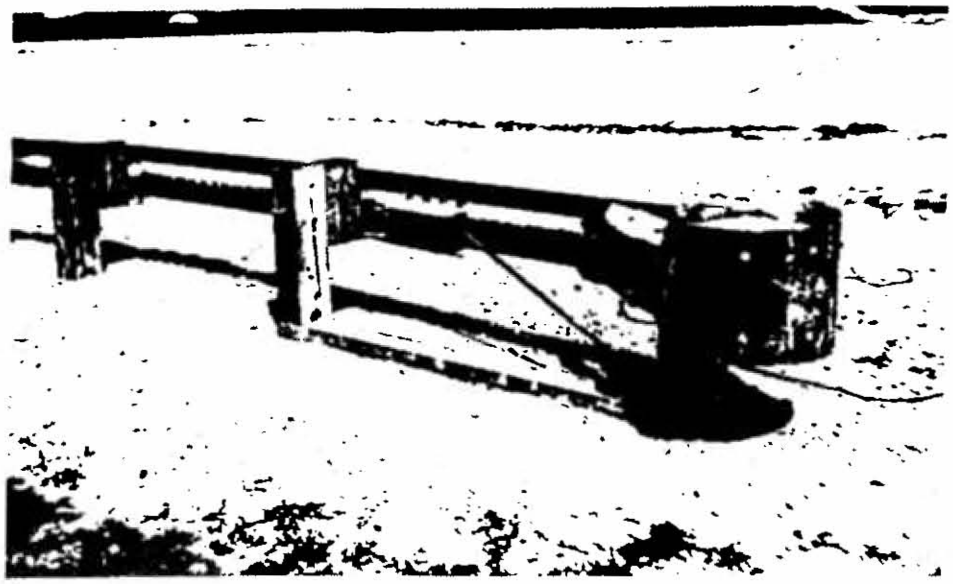


Figure 79. Pretest photographs of terminal and guardrail system, test 1862-11-90 (continued).

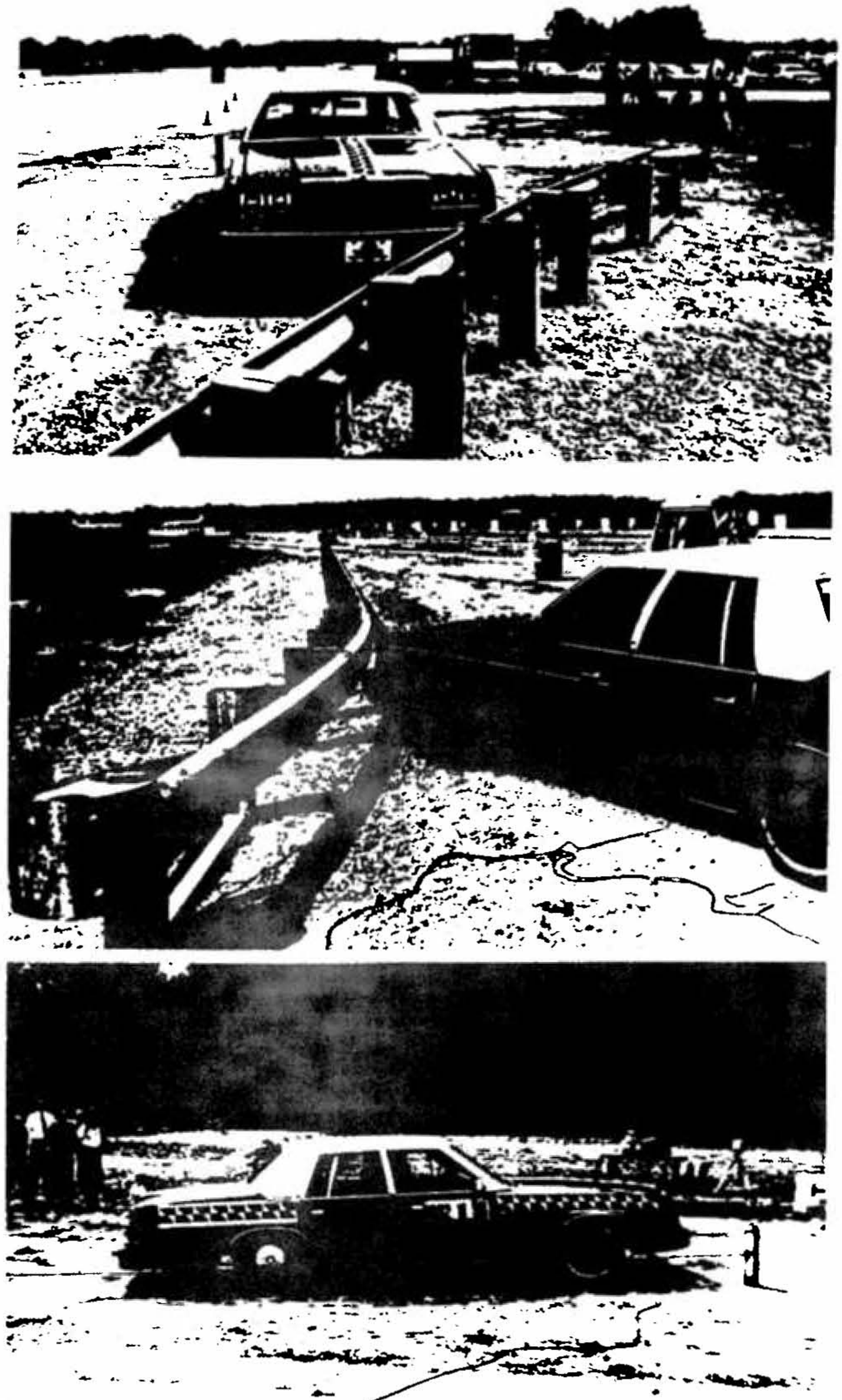
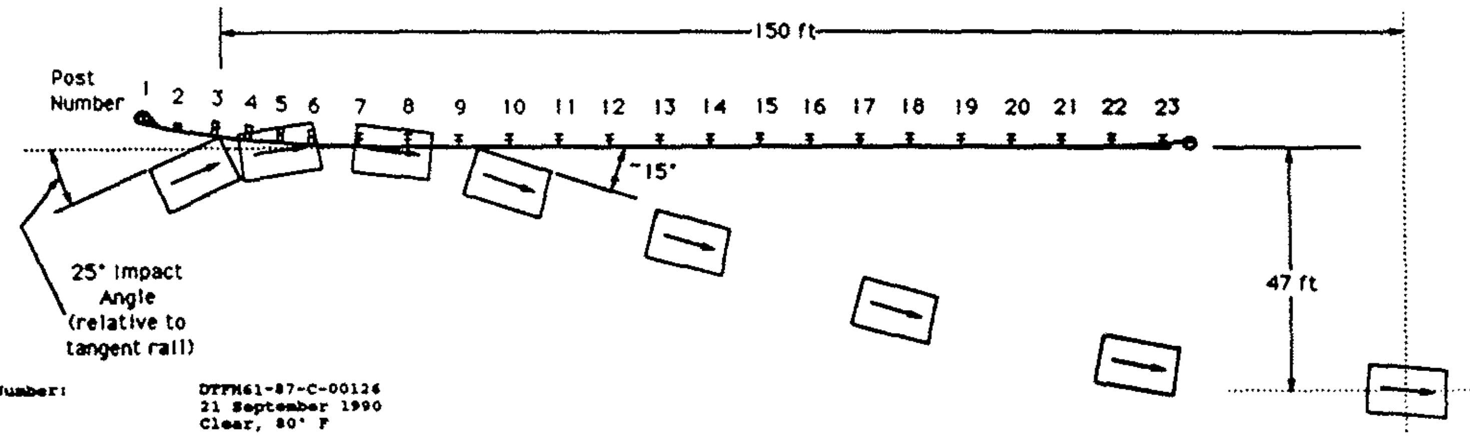


Figure 80. Pretest photographs of test vehicle, test 1862-11-90.



Contract Number:	DTFH61-87-C-00126
Date:	21 September 1990
Weather:	Clear, 80° F
Test Vehicle:	1979 Chrysler Newport
Device Configuration:	Federal Highway Administration Baffled BCT, G4(1S) Terminal. 37.5-ft Terminal, 93.75-ft LON, total length 131.25 ft. Baffles bolted to the inside of the wrap-around section of the terminal.

32°F = 0°C 1 ft = 0.30 m 1 lb = 0.45 kg 1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s 1 kip-ft = 1360 N-m 1 g = 9.8 m/s^2

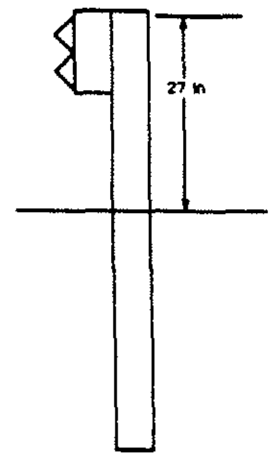
1. Vehicle Weight:
   - Planned, Inertial: 4500 ± 200
   - Actual, Inertial: 4307
   - Planned, Gross: 4500 ± 300
   - Actual, Gross: 4645
2. Number of Occupants: Two
3. Occupant Model: Part 572, 50 percentile male
4. Occupant Locations: Driver Seat, Restrained; Passenger Seat, Restrained
5. Impact:

	Speed	Angle	Location
Planned:	60.0 mi/h	25°	1 ft past post 3
Actual:	61.0 mi/h	25°	1 ft past post 3

6. Redirection Angle: ~15 degrees
7. Redirection Speed: 31.2 mi/h (45.7 ft/s)
8. Total Speed Change: 29.8 mi/h (43.7 ft/s)
9. Total Momentum Change: 6304 lb-sec
10. Vehicle Damage Index: (SAE J224a) 11LDEW2
11. NCHRP 230 Test Number: 10
12. NCHRP 230 Impact Severity:
    $\frac{m(V \sin a)^2}{2}$ 95.5 kip-ft (Spec: 89 to 114 kip-ft)

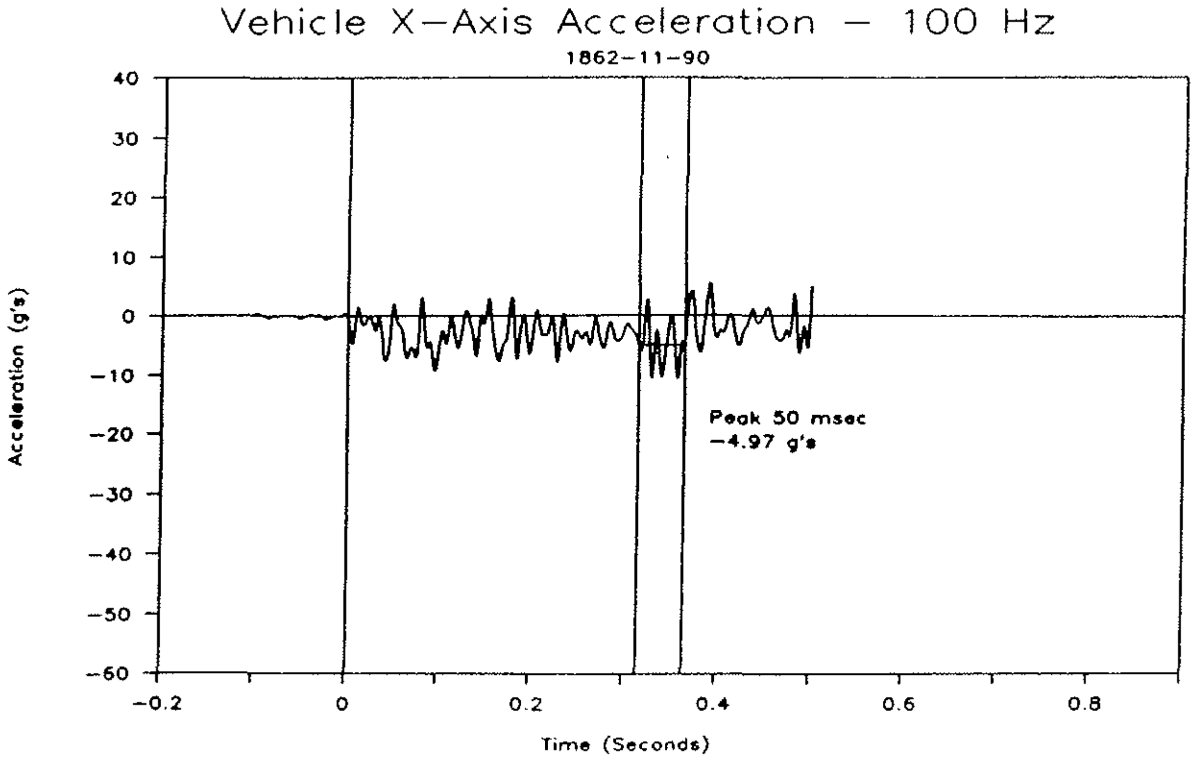
13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-19.3 ft/s	30/40 ft/s
Ridedown Acceleration:	-8.6 g's	15/20 g's
Driver and passenger actual flail was also 2.00 ft		
Lateral:		
Delta-V at 1 ft:	-13.1 ft/s	20/30 ft/s
Ridedown Acceleration:	-8.1 g's	15/20 g's
Driver actual flail was also 1.00 ft		
Passenger:		
Delta-V at 1.08 ft (actual):	-13.4 ft/s	20/30 ft/s
Ridedown Acceleration:	-8.1 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-5.0 g's	
Lateral:	-5.3 g's	



14. Test Results Conclusion:
    NCHRP 230: DOES NOT MEET ALL CRITERIA. The vehicle speed change at redirection is greater than the 15 mi/h maximum. The test meets all other evaluation criteria.

Figure 81. Test summary, test 1862-11-90.



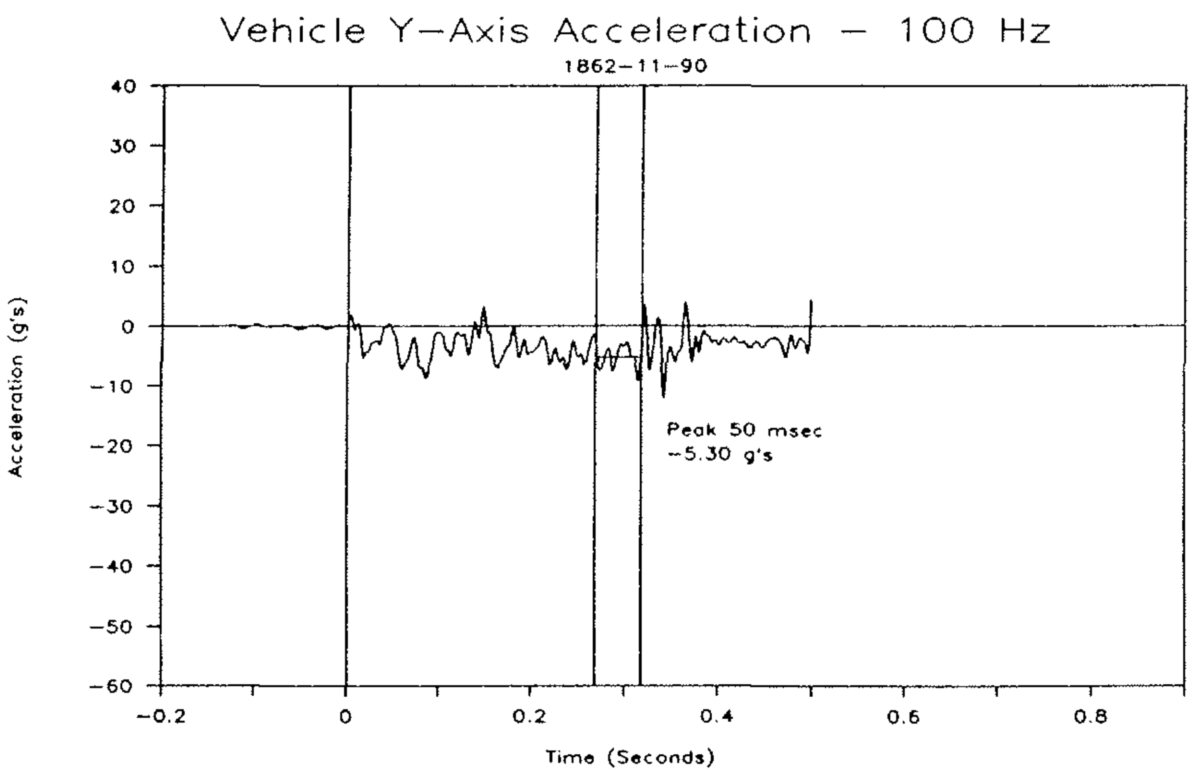


Figure 82. Vehicle accelerations, test 1862-11-90.

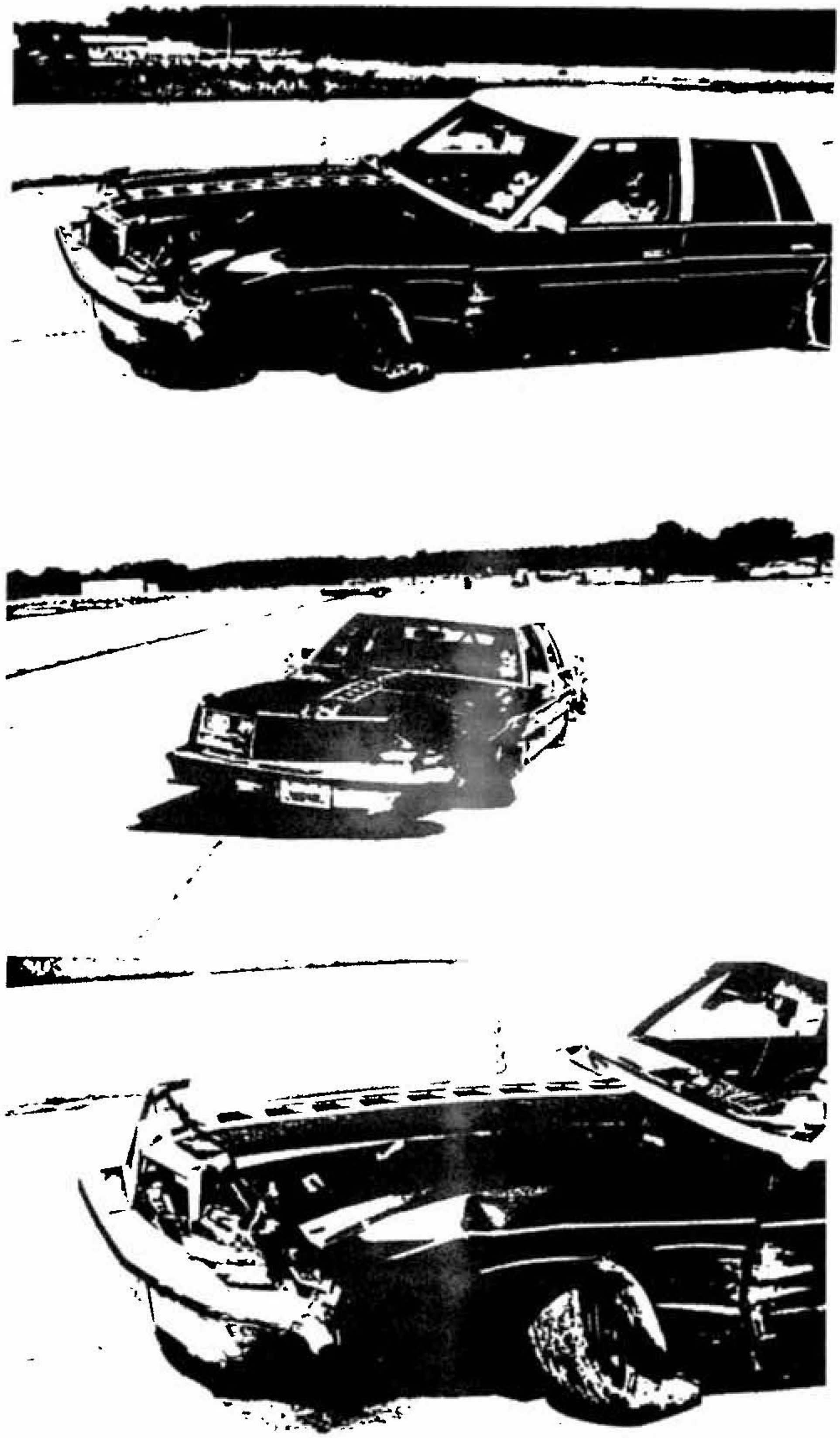


Figure 83. Post-test photographs of test vehicle, test 1862-11-90.

Figure 84. Post-test photographs of terminal and guardrail system, test 1862-11-90.

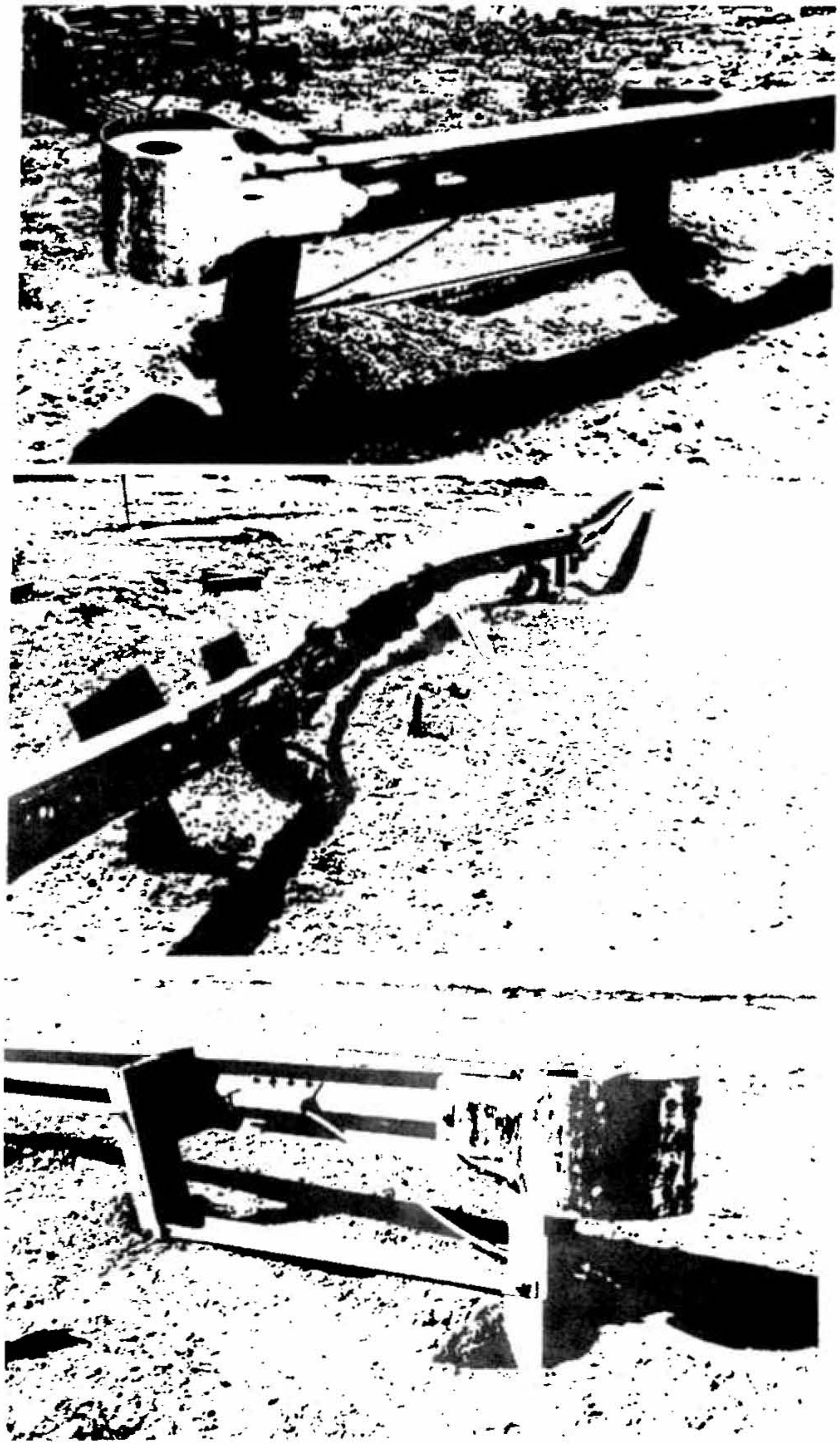


Figure 84. Post-test photographs of terminal and guardrail system, test 1862-11-90 (continued).

12. TEST 1862-12-90

a. Test Device

The test device was a G4(1S) W-beam rail with an AASHTO 4-in (101.6-mm) type H concrete curb placed in front of the posts.

The back of the curb was positioned 2 in (50.8 mm) in front of the posts. The top of the curb was 4 in (101.6 mm) deep. The curb sloped up for 8 in (203.2 mm). Thus, the total width of the curb was 12 in (304.8 mm) and the front of the curb was 14 in (355.6 mm) in front of the post and 5 in (127.0 mm) in front of the face of the rail [6-in (152.4-mm) blockout, 3-in (76.2-mm) wide W-beam rail]. Approximately 80 ft (24.4 m) of curb was installed along the rail system. The curb began between posts 9 and 10, or approximately 12.5 ft (3.8 m) upstream of the impact point.

The entire system was 131.25 ft (40.0 m) long. The system consisted of 93.75 ft (28.6 m) of W-beam and a 37.5-ft (11.4-m) standard BCT. A cable anchor assembly was used on the downstream end. This assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 85 shows the test site and test device. Figure 86 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1980 Chrysler Newport. The target inertial vehicle weight was 4500 ± 200 lb (2043 ± 91 kg). The vehicle weighed approximately 3700 lb (1680 kg) empty. Approximately 600 lb (272 kg) of ballast were added to the vehicle. The inertial weight of the vehicle was 4316 lb (1959 kg). The target gross vehicle weight was 4500 ± 300 lb (2043 ± 136 kg). The gross vehicle weight was 4645 lb (2109 kg).

X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the vehicle. Two uninstrumented dummies were placed in the vehicle. The driver was restrained and the passenger was unrestrained. Pretest photographs of the test vehicle are shown in figure 87. Table 23 lists important parameters of the test vehicle.

Table 23. Test vehicle parameters, test 1862-12-90.

Item	Actual	Specification
Empty Weight	~3700 lb	n/a
Ballast	~600 lb	n/a
Total Weight, Inertial	4316 lb	4500 ± 200 lb
Total Weight, Gross	4645 lb	4500 ± 300 lb
Vehicle Length	216 in	
Vehicle Wheelbase	119 in	

1 lb = 0.45 kg   1 in = 25.4 mm

c. Impact Description

Review of the high-speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 61.6 mi/h (99.1 km/h) and 25°. This review also indicated that the left corner of the vehicle impacted the rail at the desired point.

Upon impact, the vehicle penetrated into the rail approximately 45 in (1143.0 mm) before starting to redirect. As the vehicle redirected and became parallel with the rail, it vaulted up on top of the LON rail, pitching up and rolling to approximately 45°. The vehicle continued to yaw while airborne. The entire vehicle was airborne before it impacted the ground and it stayed airborne to almost the end of the rail [approximately 55 ft (16.8 m)]. The rear bumper of the vehicle impacted the top of the last post. The vehicle velocity redirection angle was approximately 3°. The vehicle came to rest 145 ft (44.2 m) downstream of the impact point, 28 ft (8.5 m) in front of the face of the rail. The vehicle remained in contact with the rail for approximately 35 ft (10.7 m).

Inside the vehicle, the driver dummy pushed out on the driver-side door and the passenger dummy impacted the driver. Both dummies fell into the passenger side when the vehicle impacted the ground. When the vehicle rolled upright, the driver dummy broke the driver-side window. The driver dummy came to rest in the driver's seat. The passenger dummy came to rest leaning on the driver dummy.

A summary of test conditions and results are shown in figure 88. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 89.

d. Vehicle Damage

The entire left side of the vehicle, including the fenders, doors, tires/wheels, and suspension; and the front grill and bumpers were damaged. The front tire was deflated and the front wheel was damaged. The rear bumper was torn where it impacted the last post when the vehicle impacted the ground. Post-test photographs of the test vehicle are shown in figure 90.

e. Barrier Damage

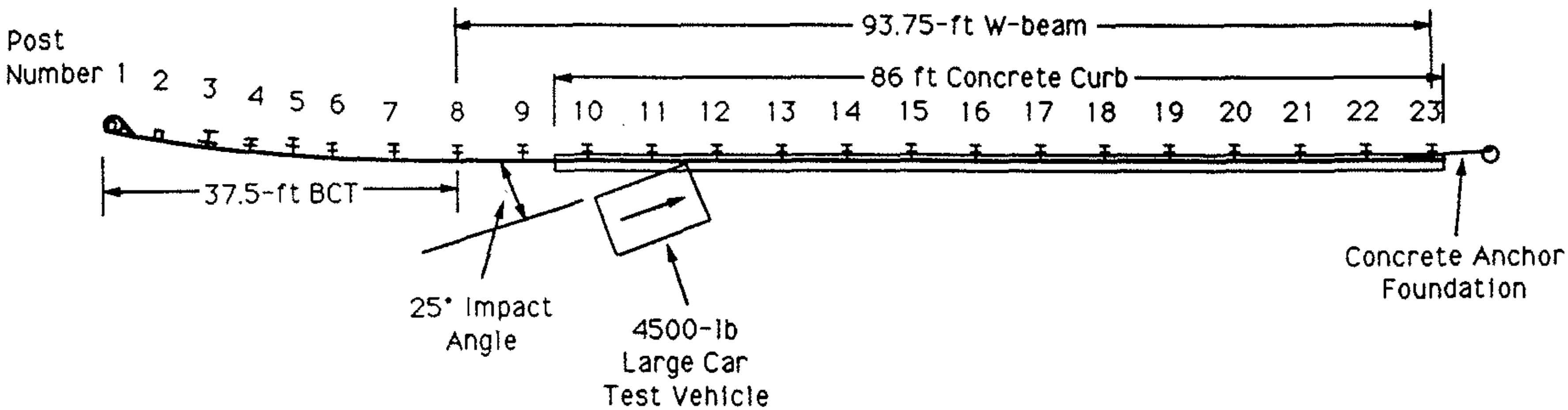
The barrier was damaged for approximately 44 ft (13.4 m), beginning before impact. The rail had permanent deflection from posts 10 through 20. The end post of the BCT was pulled approximately 1 in (25.4 mm) toward impact. Undamaged posts upstream and downstream of impact were twisted toward impact. The rail was detached from post 13 through 16. The rail section was flattened from post 12 through 16. Posts 11 through 15 were bent and twisted. The maximum permanent rail deflection [31 in (787.4 mm)] occurred at post 14. Post-test photographs of the rail are shown in figure 91.

f. Test Evaluation

This test was evaluated using NCHRP 230. The following is an item-by-item evaluation using this guideline.

a. The test article redirected the vehicle.
d. There were no detached elements.
e. The vehicle remained upright during and after the collision. Integrity of the passenger compartment was maintained.
h. Vehicle trajectory and stopping position did not intrude into adjacent traffic lanes.
i. Because the vehicle trajectory and stopping position did not intrude into adjacent traffic lanes, vehicle speed change and exit angle criteria are not applied.

MEETS ALL CRITERIA.



1 ft = 0.30 m 1 lb = 0.45 kg

Figure 85. Test site layout, test 1862-12-90.

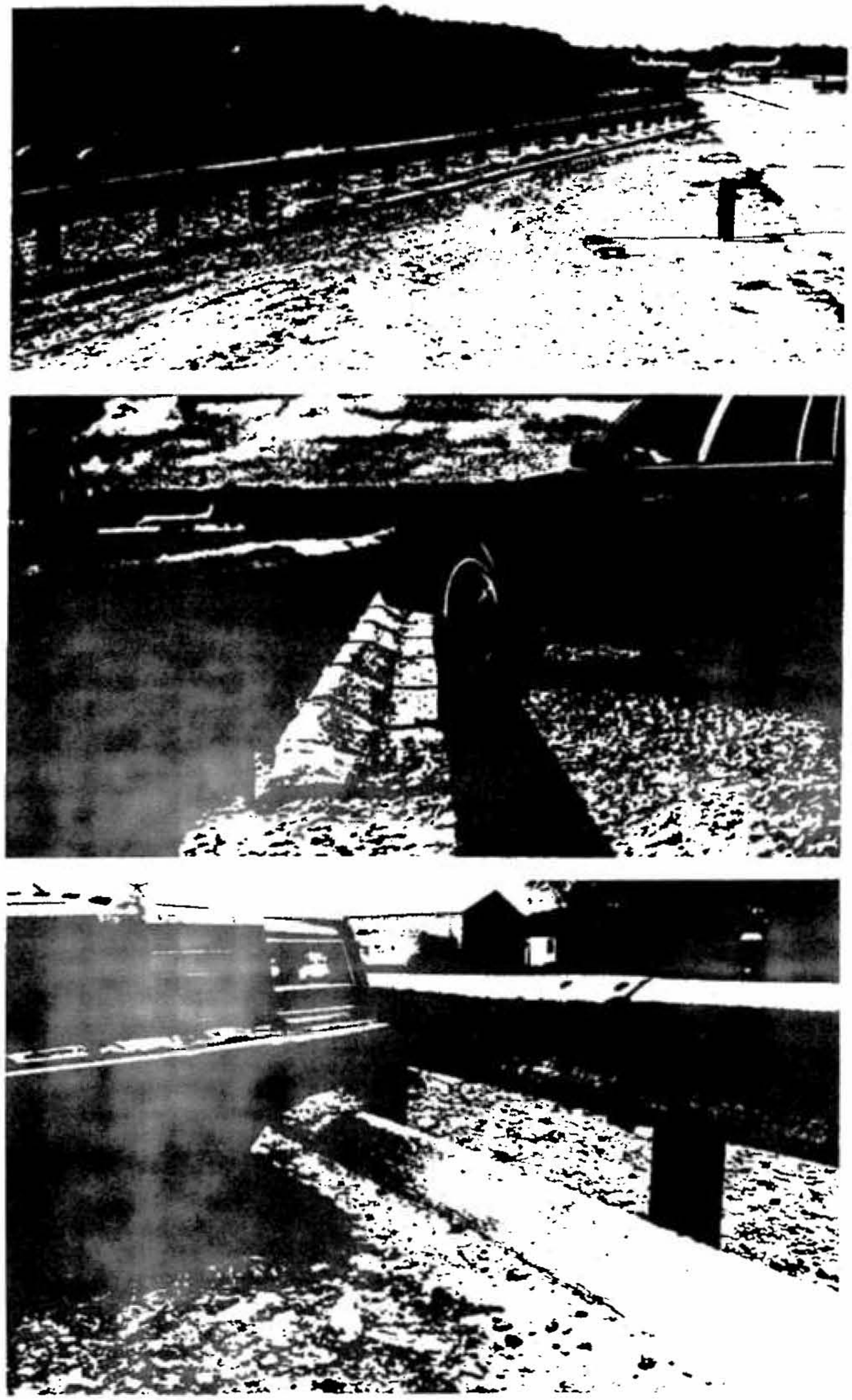
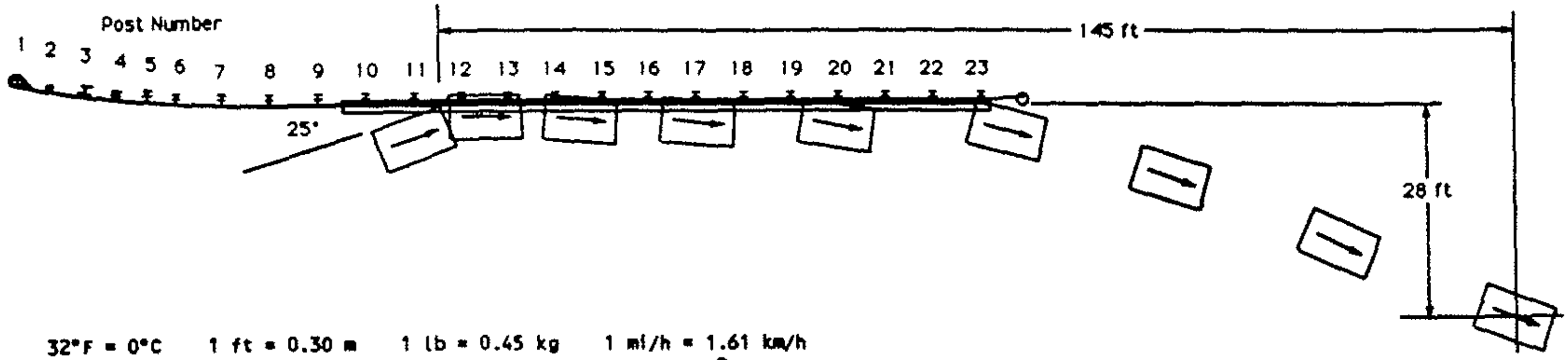


Figure 86. Pretest photographs of guardrail system, test 1862-12-90.

Figure 87. Pretest photographs of test vehicle, test 1862-12-90.



32°F = 0°C   1 ft = 0.30 m   1 lb = 0.45 kg   1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s   1 kip-ft = 1360 N-m   1 g = 9.8 m/s²

Contract Number:	DTFH61-87-C-00126
Date:	10 October 1990
Weather:	Clear, 80° F
Test Vehicle:	1980 Chrysler Newport
Device Configuration:	G4(1S) W-Beam with AASHTO 4-in, Type H concrete curb in front of barrier, 131.25 ft total length, 37.5-ft BCT Terminal, 93.75-ft LON.

1. Vehicle Weight:

Planned, Inertial:	4500 ± 200
Actual, Inertial:	4316
Planned, Gross:	4500 ± 300
Actual, Gross	4645

2. Number of Occupants: Two
3. Occupant Model: Part 572, 50 percentile male
4. Occupant Locations: Driver Seat, Restrained; Passenger Seat, Unrestrained
5. Impact:

	Speed	Angle	Location
Planned:	60.0 mi/h	25°	Midspan, posts 11 and 12
Actual:	61.6 mi/h	25°	Midspan, posts 11 and 12

6. Redirection Angle: -3 degrees
7. Redirection Speed: 38.3 mi/h (56.2 ft/s)
8. Total Speed Change: 23.3 mi/h (34.2 ft/s)
9. Total Momentum Change: 4934 lb-sec
10. Vehicle Damage Index: (SAE J224a) 11LDEW2
11. NCHRP 230 Test Number: 10
12. NCHRP 230 Impact Severity:

$\frac{m(V \sin a)^2}{2}$ 97.8 kip-ft (Spec: 89 to 114 kip-ft)

13. Vehicle Analysis:

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-21.1 ft/s	30/40 ft/s
Ridedown Acceleration:	-5.4 g's	15/20 g's
Driver:		
Delta-V at 2.25 ft (actual):	-22.3 ft/s	30/40 ft/s
Ridedown Acceleration:	-5.4 g's	15/20 g's
Passenger actual was also 2.25 ft		
Lateral:		
Delta-V at 1 ft:	-14.8 ft/s	20/30 ft/s
Ridedown Acceleration:	-10.0 g's	15/20 g's
Driver and passenger actuals were also 1.00 ft		
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-4.5 g's	
Lateral:	-5.5 g's	

14. Test Results Conclusion:

NCHRP 230: MEETS ALL CRITERIA.

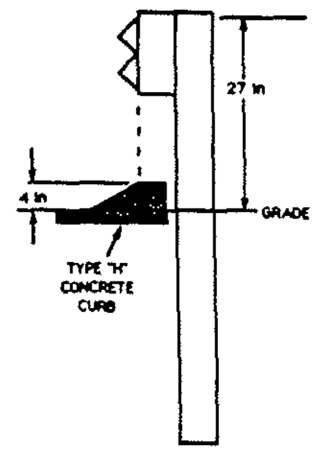
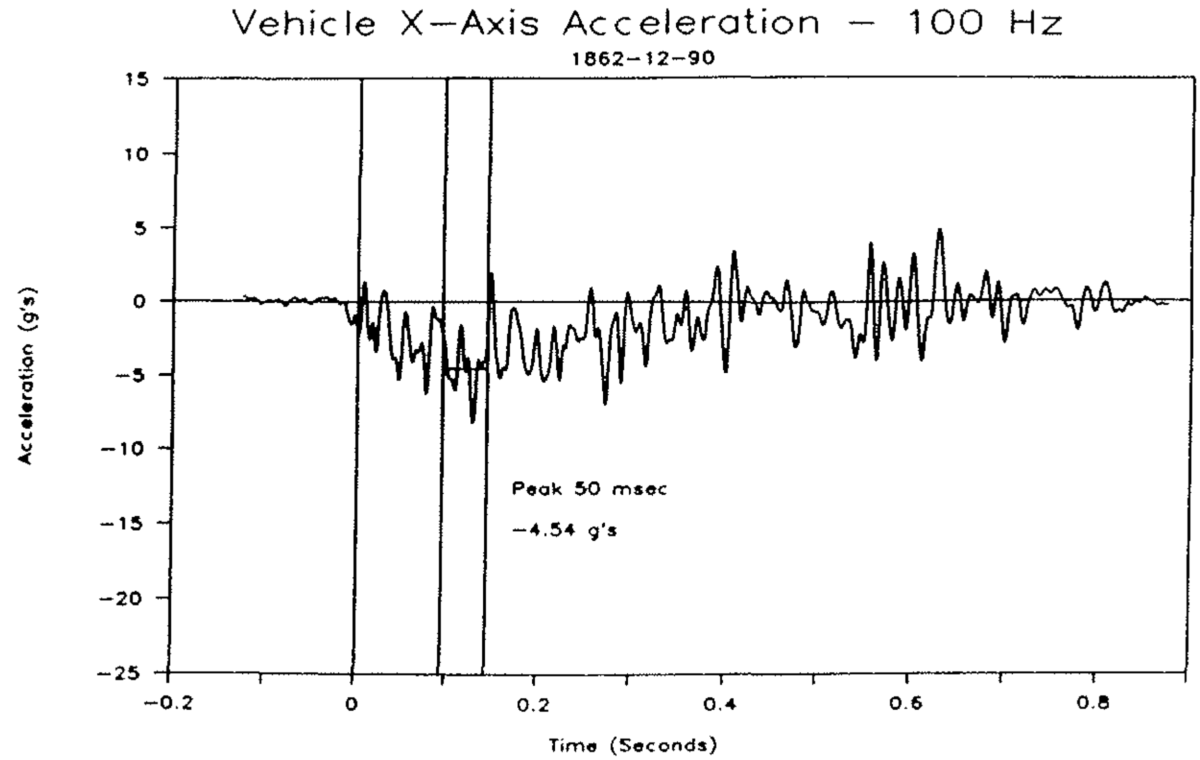


Figure 88. Test summary, test 1862-12-90.



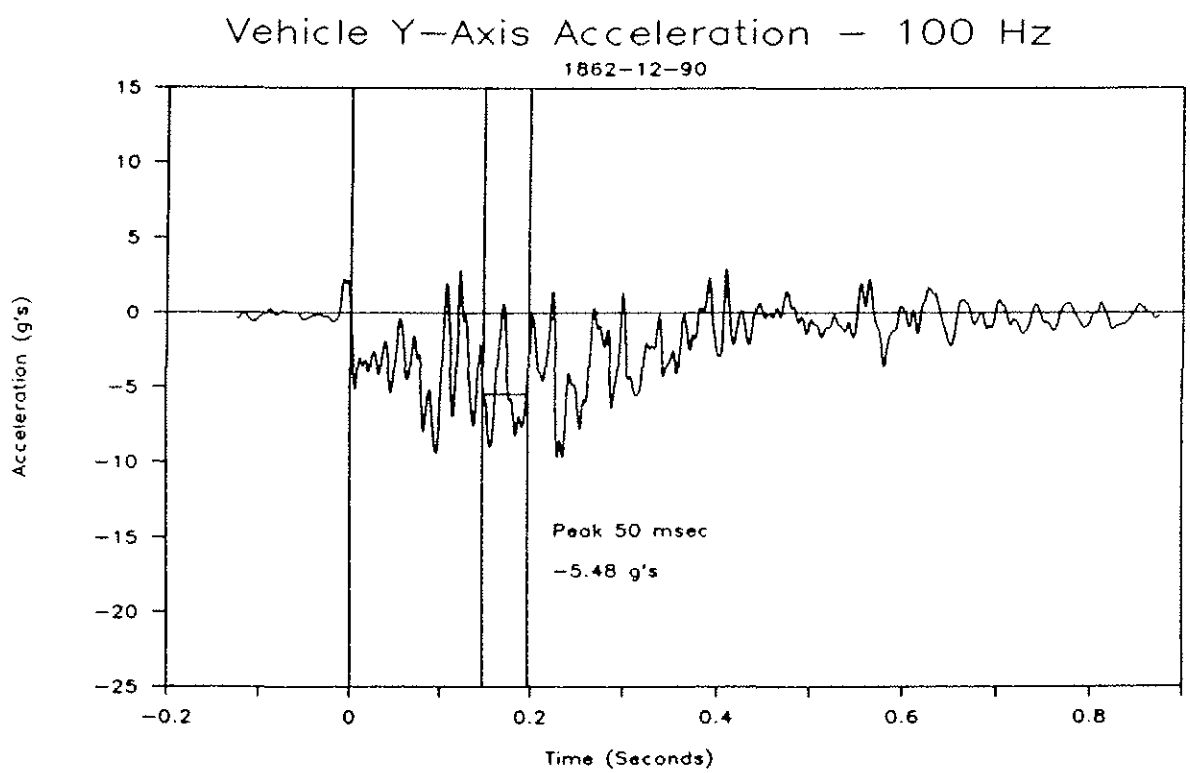
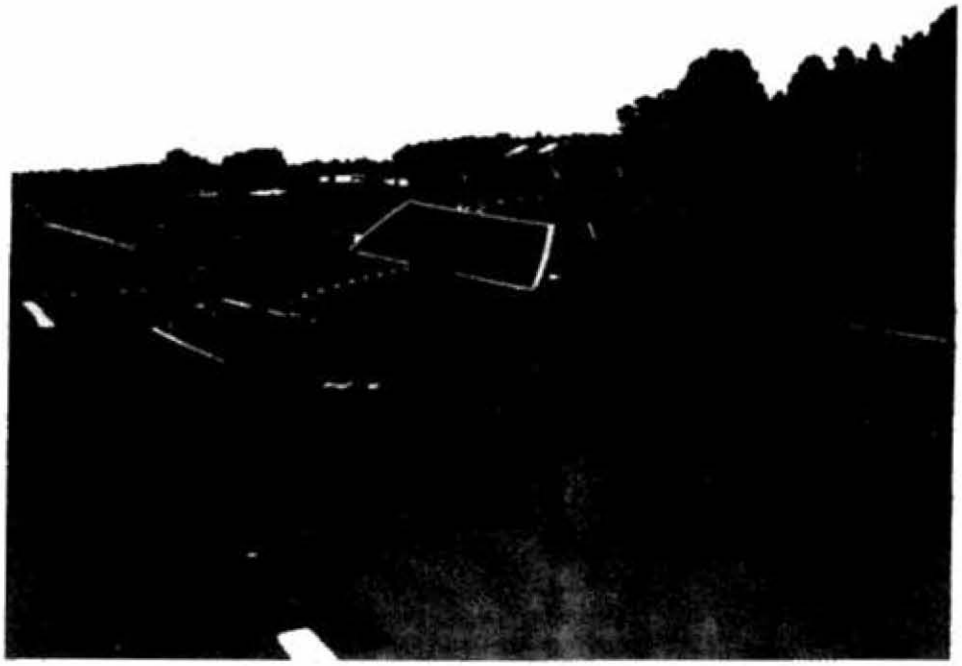


Figure 89. Vehicle accelerations, test 1862-12-90.



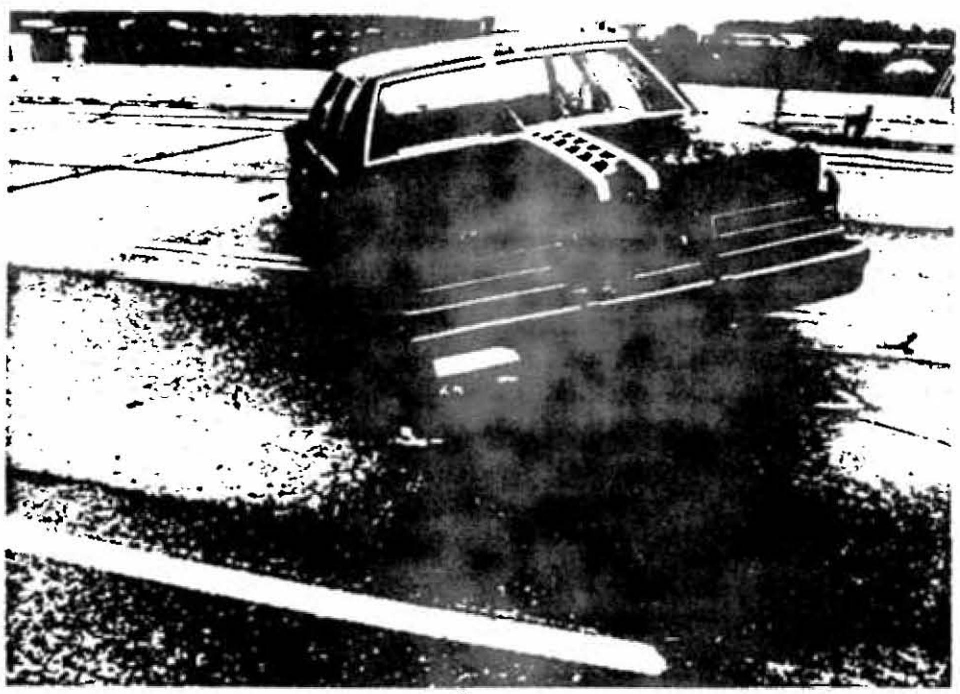


Figure 90. Post-test photographs of test vehicle, test 1862-12-90.

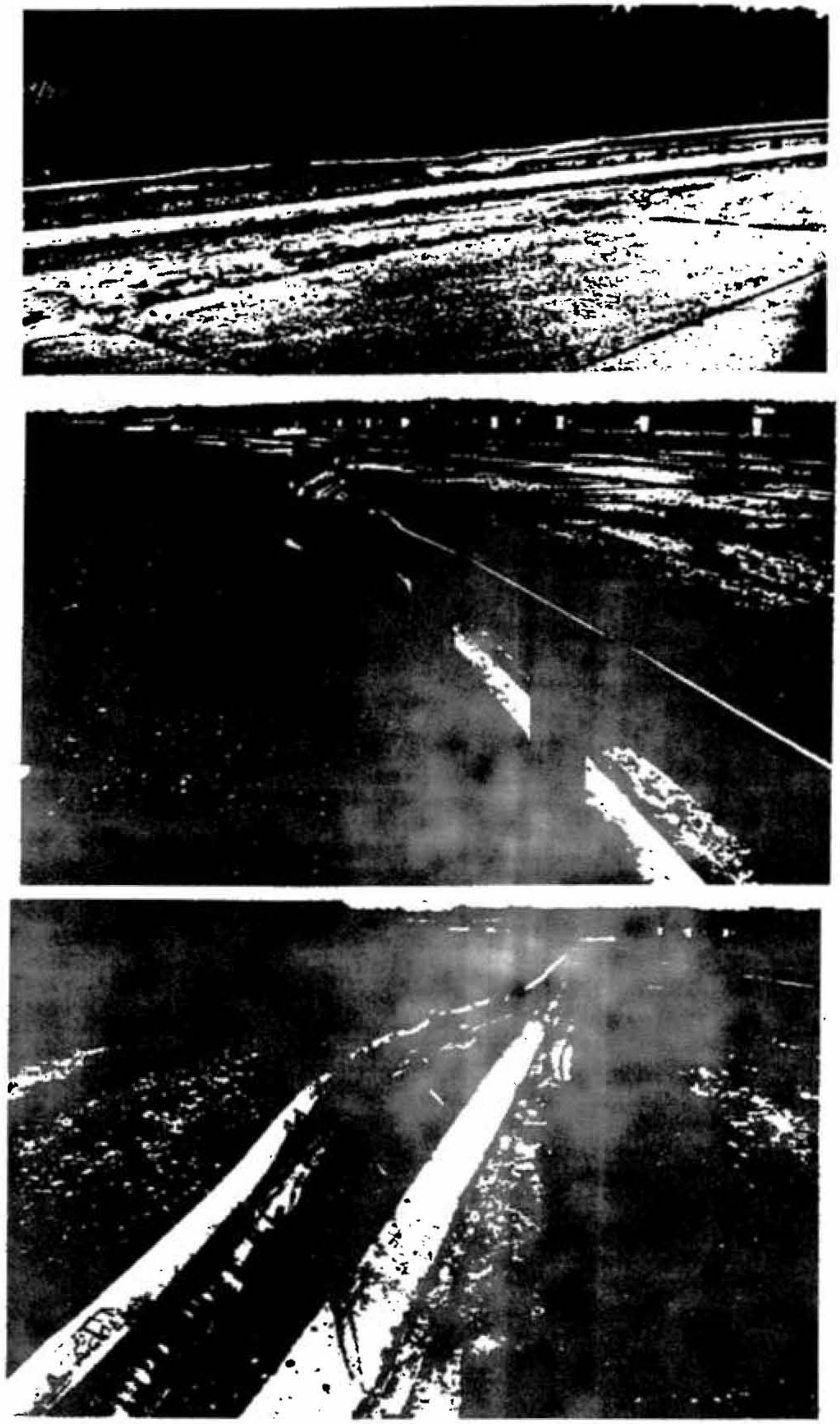


Figure 91. Post-test photographs of guardrail system, test 1862-12-90.

13. TEST 1862-13-91

a. Test Device

The test device was a modified G4(1S) W-beam rail with an AASHTO 6-in (152.4-mm) type G asphalt dike placed in front of the posts. The modification consisted of a second W-beam rail bolted to the back of the posts, at the same height as the front rail, and with no blockout. Approximately 94 ft (28.7 m) of W-beam was installed on the backside of the posts. The backside rail began at post 7, or approximately 22 ft (6.7 m) upstream of the impact point.

The front of the dike was aligned with the face of the W-beam. The dike was formed on the top of a 2-in (50.8-mm) thick, 16-in (406.4-mm) wide asphalt layer. Approximately 80 ft (24.4 m) of curb was installed along the rail system. The curb began at post 10, or approximately 9 ft (2.7 m) upstream of the impact point. The posts that were located in the area of the curb were driven through the 2-in (50.8-mm) asphalt layer.

The entire system was 131.25 ft (40.0 m) long. The system consisted of 93.75 ft (28.6 m) of W-beam and a 37.5-ft (11.4-m) standard BCT. A cable anchor assembly was used on the downstream end. This assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 92 shows the test site and test device. Figure 93 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1979 Chrysler Newport. The target inertial vehicle weight was 4500 ± 200 lb (2043 ± 91 kg). The vehicle weighed approximately 3800 lb (1725 kg) empty. Ballast weighing 550 lb (250 kg) was added to the vehicle. The inertial weight of the vehicle was 4341 lb (1971 kg). The target gross vehicle weight was 4500 ± 300 lb (2043 ± 136 kg). The gross vehicle weight was 4679 lb (2124 kg).

X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the vehicle. Two uninstrumented dummies were placed in the vehicle. The driver was unrestrained and the passenger was restrained. Pretest photographs of the test vehicle are shown in figure 94. Table 24 lists important parameters of the test vehicle.

Table 24. Test vehicle parameters, test 1862-13-91.

Item	Actual	Specification
Empty Weight	~3800 lb	n/a
Ballast	550 lb	n/a
Total Weight, Inertial	4341 lb	4500 ± 200 lb
Total Weight, Gross	4679 lb	4500 ± 300 lb
Vehicle Length	216 in	
Vehicle Wheelbase	119 in	

1 lb = 0.45 kg   1 in = 25.4 mm

c. Impact Description

Review of the high-speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 61.4 mi/h (98.8 km/h) and 26°. This review also indicated that the left corner of the vehicle impacted the rail at the desired point.

Upon impact, the vehicle penetrated into the rail approximately 28 in (711.2 mm) before starting to redirect. The vehicle rolled slightly while redirecting. As the vehicle was redirecting, the vehicle penetration caused the posts to push back, lowering the rail, allowing the vehicle to ride up on the rail. This override of the rail caused the vehicle to roll to approximately 45° while exiting the system. The vehicle rolled back to level and continued downstream of the rail. The vehicle redirected at an angle of approximately 10°. The vehicle came to rest 270 ft (82.4 m) downstream of the impact point, 60 ft (18.3 m) behind the face of the rail. The vehicle remained in contact with the rail for approximately 25 ft (7.6 m). The hood came open after the impact event.

Inside the vehicle, the driver dummy pushed out on the driver-side door and broke the driver-side window while the vehicle was redirecting. When the vehicle rolled to approximately 40°, the driver dummy had its upper body out of the window. The driver dummy came to rest leaning on the driver-side door. The passenger dummy came to rest leaning toward the driver dummy.

A summary of test conditions and results are shown in figure 95. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 96.

d. Vehicle Damage

The entire left side of the vehicle, including the fenders, doors, tires/wheels, and suspension; the front grill; and bumper were damaged. The front of the car was skewed toward the non-impact side. The front tire was off the wheel on the impact side. The driver-side door was pushed outward approximately 4 in (101.6 mm) by the impact of the dummy. Post-test photographs of the test vehicle are shown in figure 97.

e. Barrier Damage

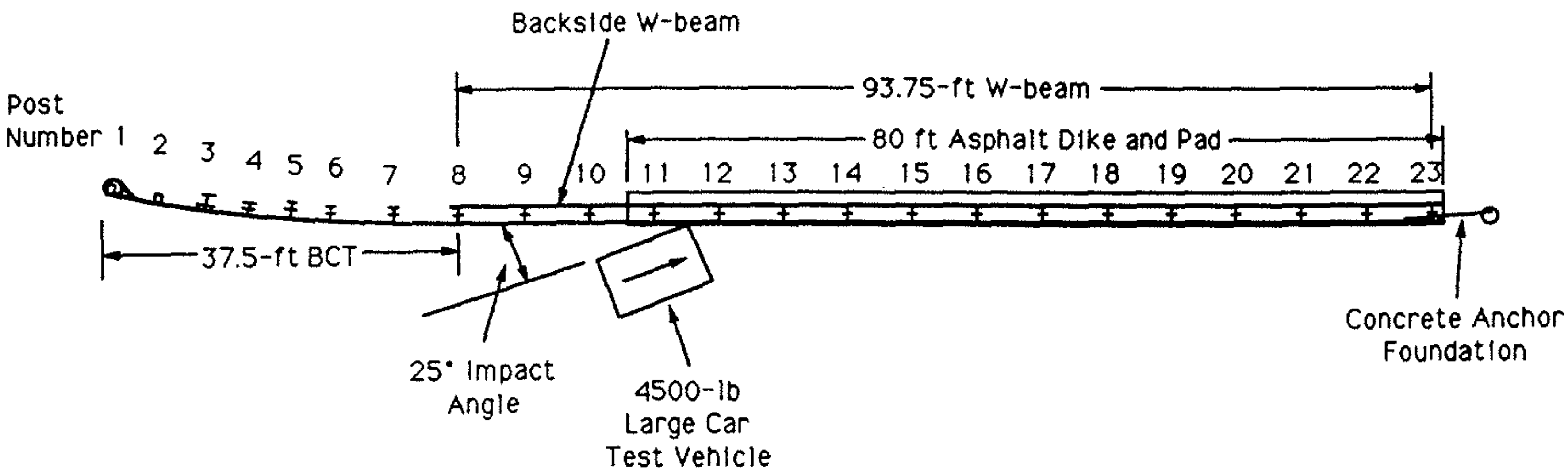
The barrier was damaged for approximately 38 ft (11.6 m), beginning before impact. The rail had permanent deflection from posts 10 through 15. The end post of the BCT was pulled approximately 2 in (50.8 mm) toward impact. Posts upstream of impact were twisted. The rail was detached at posts 13 and 15. The backside rail was detached at post 13. In the impact zone, the curb was pushed back approximately 5 in (127.0 mm). The maximum permanent rail deflection [21 in (533.4 mm)] occurred at post 13. Post-test photographs of the rail are shown in figure 98.

f. Test Evaluation

This test was evaluated using NCHRP 230. The following is an item-by-item evaluation using this guideline.

a. The test article redirected the vehicle.
d. There were no detached elements.
e. The vehicle remained upright during and after the collision. Integrity of the passenger compartment was maintained.
h. Vehicle trajectory and stopping position did not intrude into adjacent traffic lanes.
i. Because the vehicle trajectory and stopping position did not intrude into adjacent traffic lanes, vehicle speed change and exit angle criteria are not applied. The vehicle was redirected at approximately 33.1 mi/h [48.5 ft/s (53.3 km/h)] and 10°.

MEETS ALL CRITERIA.



1 ft = 0.30 m   1 lb = 0.45 kg

Figure 92. Test site layout, test 1862-13-91.

Figure 93. Pretest photographs of guardrail system, test 1862-13-91.

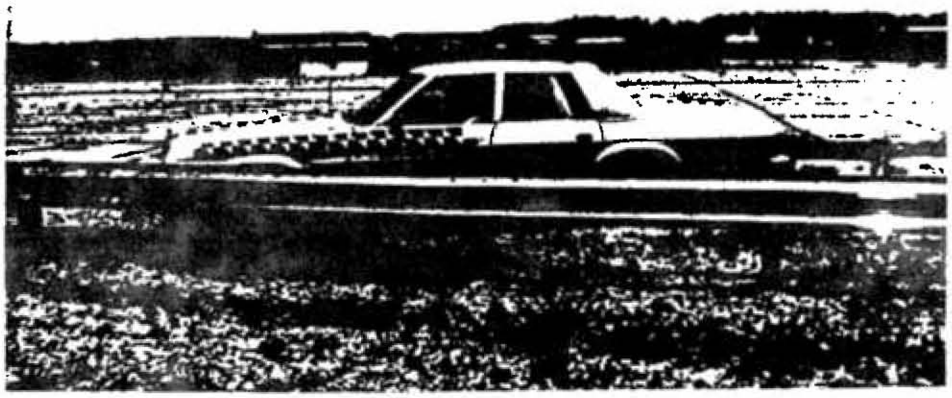
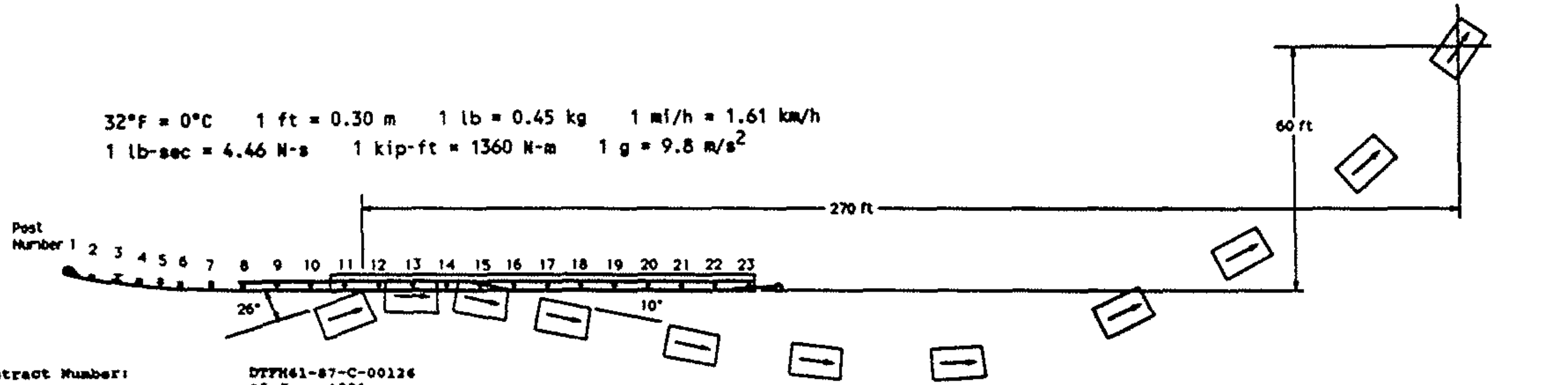


Figure 94. Pretest photographs of test vehicle, test 1862-13-91.

32°F = 0°C   1 ft = 0.30 m   1 lb = 0.45 kg   1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s   1 kip-ft = 1360 N-m   1 g = 9.8 m/s²



Contract Number:	DTFH61-87-C-00126
Date:	25 June 1991
Weather:	Clear, 70° F
Test Vehicle:	1979 Chrysler Newport
Device Configuration:	Modified G4(1S) W-Beam with AASHTO 6-in, Type G asphalt dike in front of barrier, 131.25 ft total length, 37.5-ft BCT Terminal, 93.75-ft LON. Second span of W-beam bolted to back of posts with no blockout, at 27 in height.

1. Vehicle Weight:
   - Planned, Inertial: 4500 ± 200
   - Actual, Inertial: 4341
   - Planned, Gross: 4500 ± 300
   - Actual, Gross 4679
2. Number of Occupants: Two
3. Occupant Model: Part 572, 50 percentile male
4. Occupant Locations: Driver Seat, Unrestrained; Passenger Seat, Restrained
5. Impact:

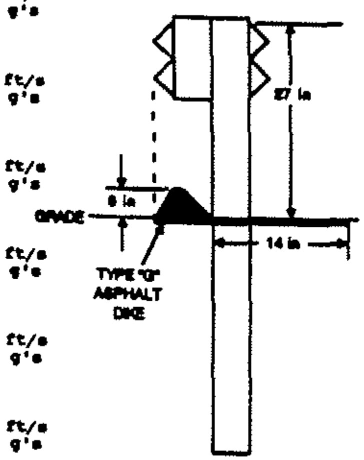
	Speed	Angle	Location
Planned:	60.0 mi/h	25°	Midspan, posts 11 and 12
Actual:	61.4 mi/h	26°	Midspan, posts 11 and 12

6. Redirection Angle: -10 degrees
7. Redirection Speed: 33.1 mi/h (48.5 ft/s)
8. Total Speed Change: 28.3 mi/h (41.6 ft/s)
9. Total Momentum Change: 6045 lb-sec
10. Vehicle Damage Index: (SAE J224a) 11LDEW2
11. NCHRP 230 Test Number: 10
12. NCHRP 230 Impact Severity:

$\frac{m(V \sin a)^2}{2}$ 105.2 kip-ft (Spec: 89 to 114 kip-ft)

13. Vehicle Analysis:

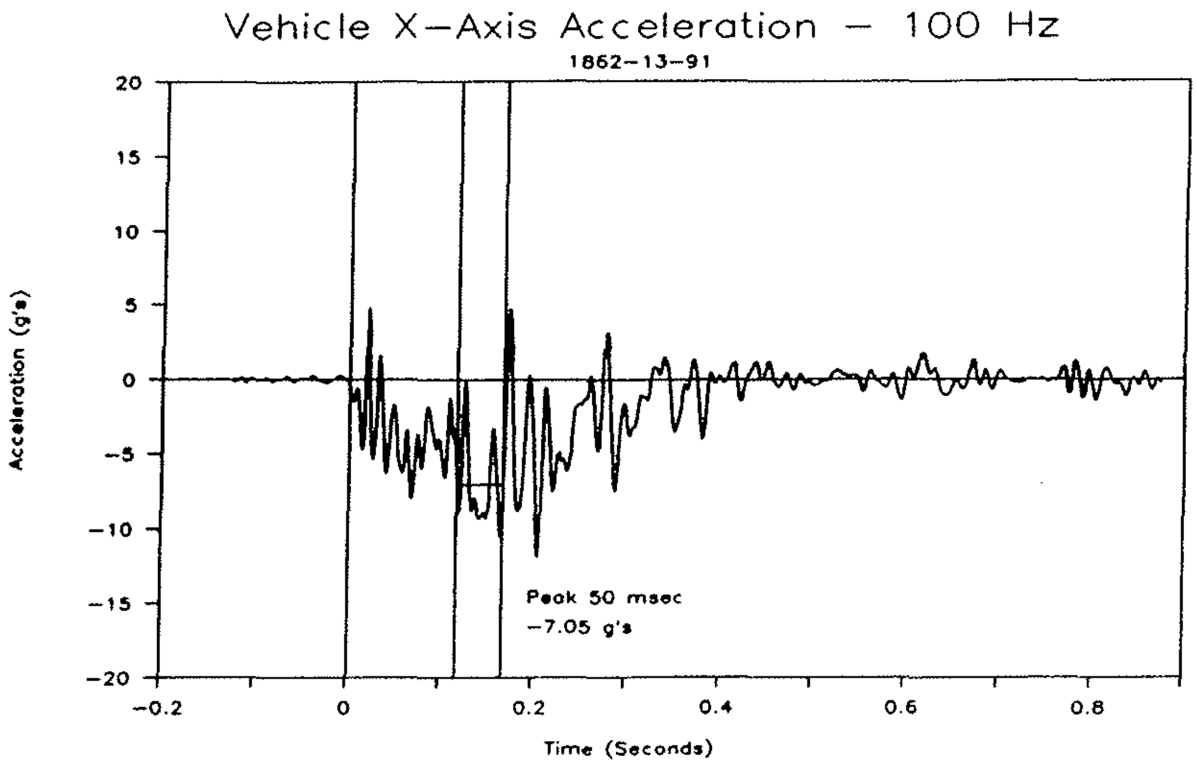
	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-26.4 ft/s	30/40 ft/s
Ridedown Acceleration:	-9.2 g's	15/20 g's
Driver:		
Delta-V at 2.17 ft (actual):	-27.2 ft/s	30/40 ft/s
Ridedown Acceleration:	-9.2 g's	15/20 g's
Passenger:		
Delta-V at 1.83 ft (actual):	-24.8 ft/s	30/40 ft/s
Ridedown Acceleration:	-9.2 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-18.3 ft/s	20/30 ft/s
Ridedown Acceleration:	-8.8 g's	15/20 g's
Driver:		
Delta-V at 1.25 ft (actual):	-20.2 ft/s	20/30 ft/s
Ridedown Acceleration:	-8.8 g's	15/20 g's
Passenger:		
Delta-V at 1.17 ft (actual):	-19.6 ft/s	20/30 ft/s
Ridedown Acceleration:	-8.8 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-7.1 g's	
Lateral:	-6.2 g's	



14. Test Results Conclusion:

NCHRP 230: MEETS ALL CRITERIA.

Figure 95. Test summary, test 1862-13-91.



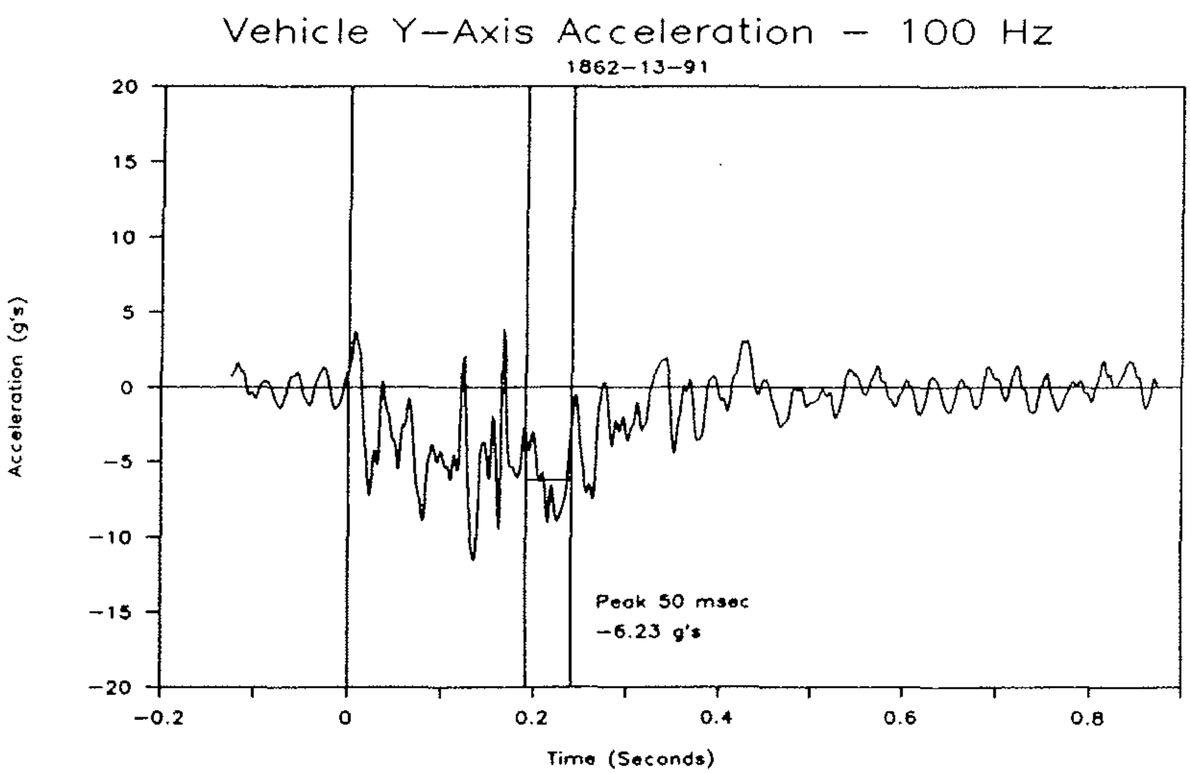


Figure 96. Vehicle accelerations, test 1862-13-91.

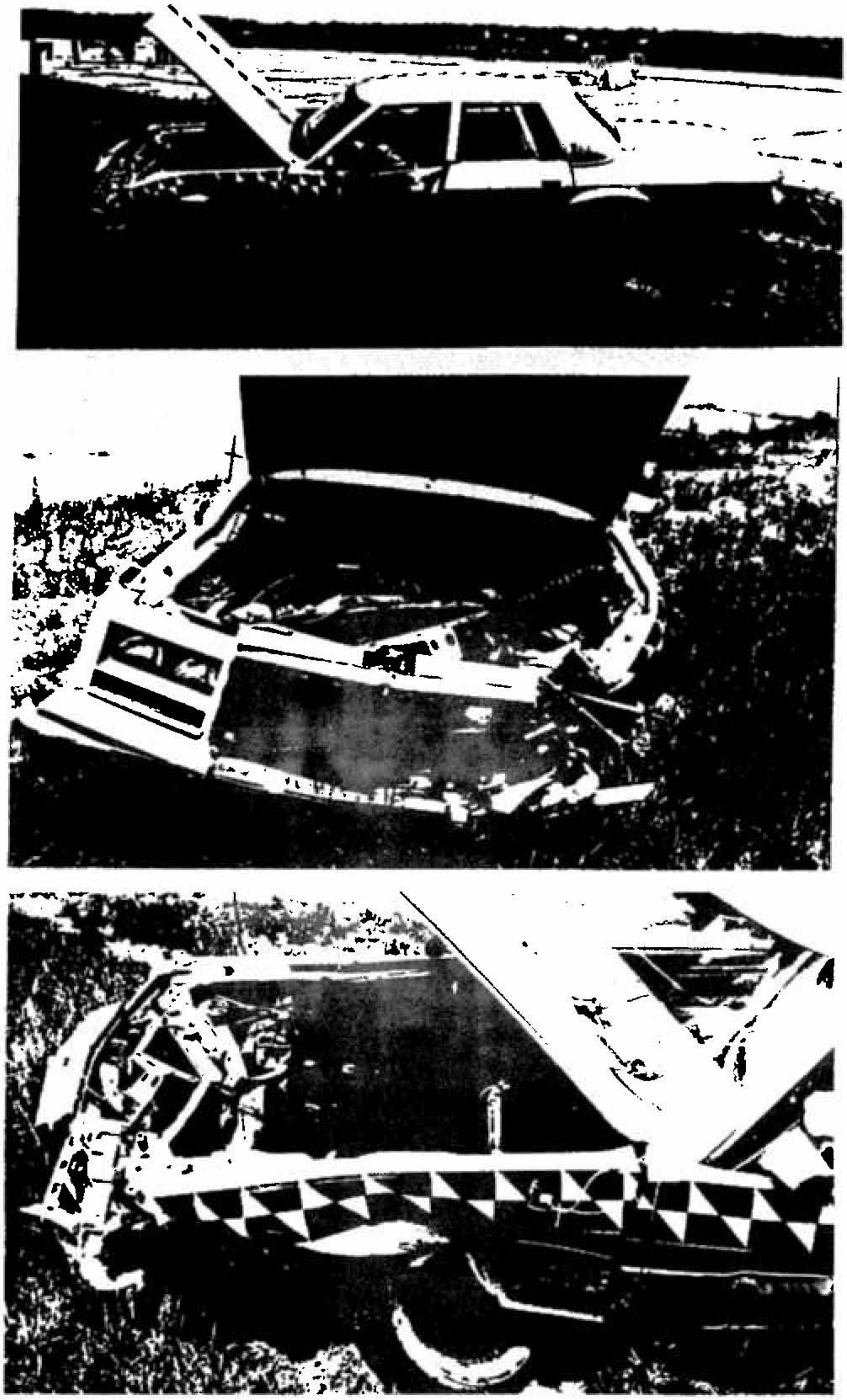


Figure 97. Post-test photographs of test vehicle, test 1862-13-91.

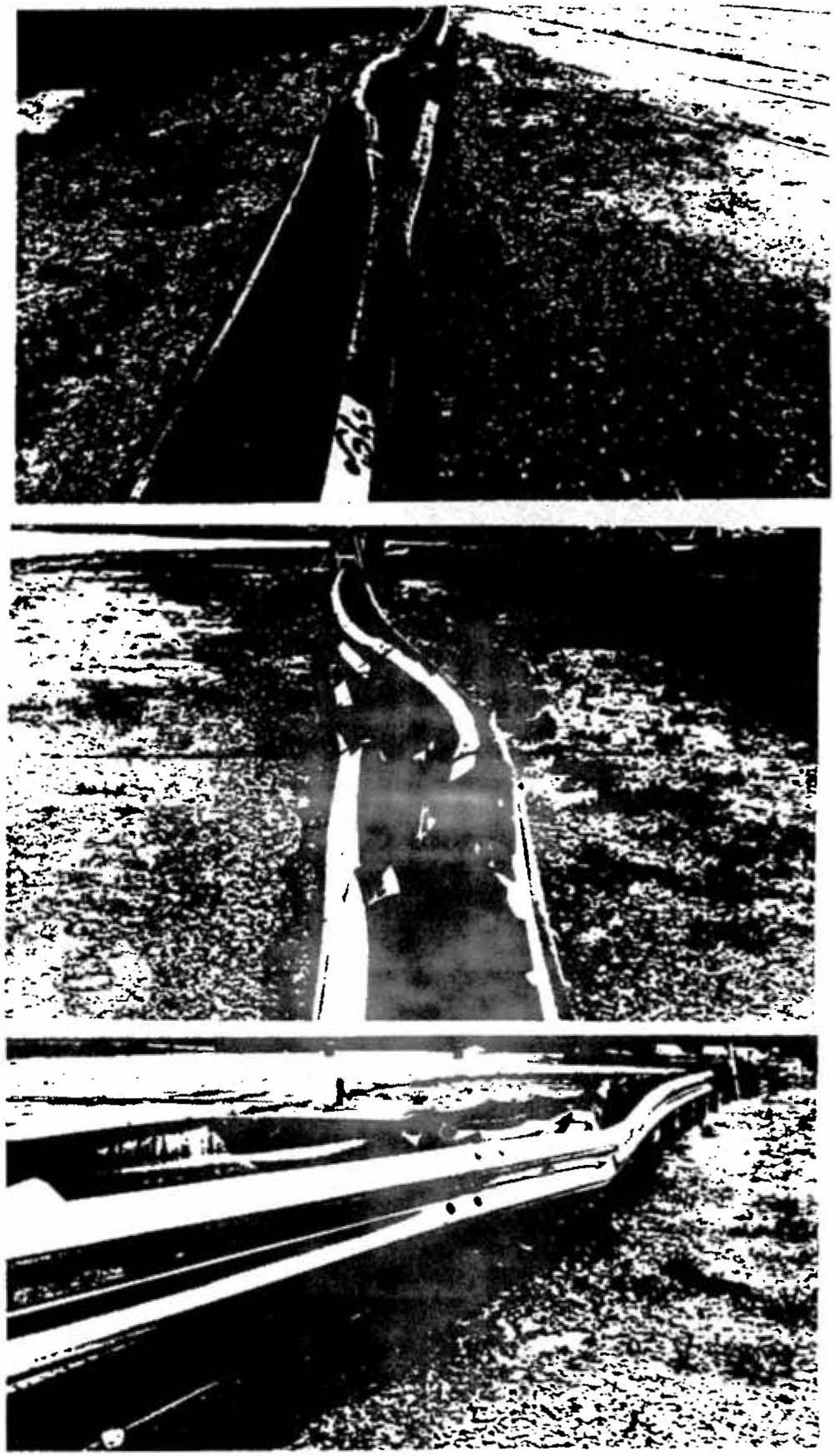


Figure 98. Post-test photographs of guardrail system, test 1862-13-91.

14. TEST 1862-14-91

a. Test Device

The test device was a modified G4(1S) W-beam rail with an AASHTO 6-in (152.4-mm) type G asphalt dike placed in front of the posts. The modification consisted of a C6x8.2 channel rubrail installed 0.5 in (12.7 mm) below the bottom of the blockout. Approximately 81 ft (24.7 m) of rubrail was installed, beginning at post 10, or approximately 16 ft (4.9 m) upstream of the impact point.

The front of the dike was aligned with the face of the W-beam. The dike was formed on the top of a 2-in (50.8-mm) thick, 16-in (406.4-mm) wide asphalt layer. Approximately 80 ft (24.4 m) of curb was installed along the rail system. The curb began at post 10, or approximately 9 ft (2.7 m) upstream of the impact point. The posts that were located in the area of the curb were driven through the 2-in (50.8-mm) asphalt layer.

The entire system was 131.25 ft (40.0 m) long. The system consisted of 93.75 ft (28.6 m) of W-beam and a 37.5-ft (11.4-m) standard BCT. A cable anchor assembly was used on the downstream end. This assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 99 shows the test site and test device. Figure 100 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1981 Plymouth Gran Fury. The target inertial vehicle weight was 4500 ± 200 lb (2043 ± 91 kg). The vehicle weighed approximately 3800 lb (1725 kg) empty. Ballast weighing 550 lb (250 kg) was added to the vehicle. The inertial weight of the vehicle was 4380 lb (1989 kg). The target gross vehicle weight was 4500 ± 300 lb (2043 ± 136 kg). The gross vehicle weight was 4708 lb (2137 kg).

X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the vehicle. Two uninstrumented dummies were placed in the vehicle. The driver was unrestrained and the passenger was restrained. Pretest photographs of the test vehicle are shown in figure 101. Table 25 lists important parameters of the test vehicle.

Table 25. Test vehicle parameters, test 1862-14-91.

Item	Actual	Specification
Empty Weight	~3800 lb	n/a
Ballast	550 lb	n/a
Total Weight, Inertial	4380 lb	4500 ± 200 lb
Total Weight, Gross	4708 lb	4500 ± 300 lb
Vehicle Length	216 in	
Vehicle Wheelbase	119 in	

1 lb = 0.45 kg   1 in = 25.4 mm

c. Impact Description

Review of the high-speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 62.1 mi/h (99.9 km/h) and 25°. This review also indicated that the left corner of the vehicle impacted the rail 3 ft (0.9 m) downstream (past) the desired point.

Upon impact, the vehicle penetrated into the rail approximately 25 in (635.0 mm) before starting to redirect. The vehicle remained nearly upright throughout the entire impact event. The vehicle yawed around and exited the rail. The vehicle redirected at an angle of approximately 9°. The vehicle came to rest 260 ft (79.3 m) downstream of the impact point, 45 ft (13.7 m) in front of the face of the rail. The vehicle remained in contact with the rail for approximately 25 ft (7.6 m).

Inside the vehicle, the driver dummy pushed out on the driver side door and broke the driver-side window while the vehicle was redirecting. During redirection, the driver dummy had its upper body out of the window. The driver dummy came to rest leaning on the driver-side door. The passenger dummy came to rest leaning toward the driver dummy.

A summary of test conditions and results are shown in figure 102. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 103.

d. Vehicle Damage

The entire left side of the vehicle, including the fenders, doors, tires/wheels, and suspension; the front grill; and bumper were damaged. The front of the car was skewed toward the non-impact side. The front tire was deflated and the front wheel was damaged. The driver-side door was pushed outward by the impact of the dummy. Post-test photographs of the test vehicle are shown in figure 104.

e. Barrier Damage

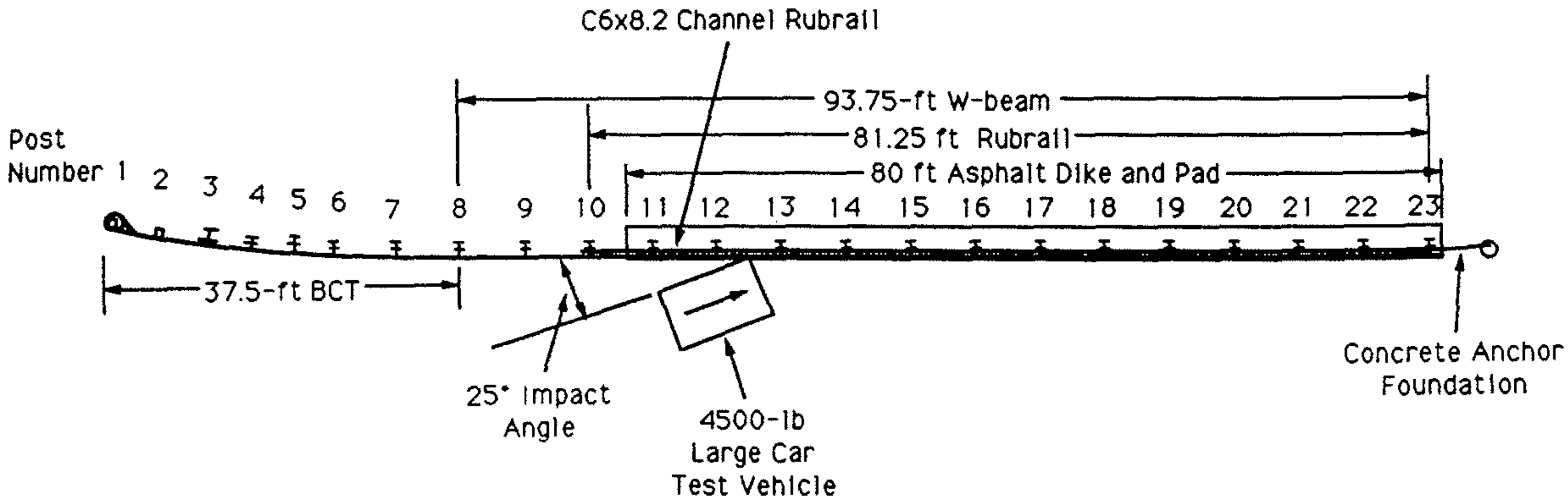
The barrier was damaged for approximately 38 ft (11.6 m), beginning before impact. The rail had permanent deflection from posts 10 through 17. The end post of the BCT was pulled approximately 1 in (25.4 mm) toward impact. Posts upstream of impact were twisted. The rail was not detached from any posts. Where there was rail and post deflection, the posts had pushed back through the asphalt pad in triangular cone shapes. The maximum permanent rail deflection occurred between posts 14 and 15 and was 18.5 in (469.9 mm). Post-test photographs of the rail are shown in figure 105.

f. Test Evaluation

This test was evaluated using NCHRP 230. The following is an item-by-item evaluation using this guideline.

a. The test article redirected the vehicle.
d. There were no detached elements.
e. The vehicle remained upright during and after the collision. Integrity of the passenger compartment was maintained.
h. Vehicle trajectory and stopping position did intrude into adjacent traffic lanes. The vehicle came to rest 260 ft (79.3 m) downstream of the impact point, 45 ft (13.7 m) in front of the face of the rail.
i. Because the vehicle trajectory and stopping position did intrude into adjacent traffic lanes, vehicle speed change and exit angle criteria are applied. The vehicle was redirected at approximately 45.7 mi/h [67.1 ft/s (73.5 km/h)] and 9°. The vehicle speed change was 16.4 mi/h (26.4 km/h), greater than the maximum 15.0-mi/h (24.1-km/h) criteria. The 9° exit angle is within the 60 percent of impact angle criteria.

DOES NOT MEET ALL CRITERIA. The vehicle speed change at redirection is greater than the 15-mi/h (24.1-km/h) maximum. The test meets all other evaluation criteria.



1 ft = 0.30 m   1 lb = 0.45 kg

Figure 99. Test site layout, test 1862-14-91.

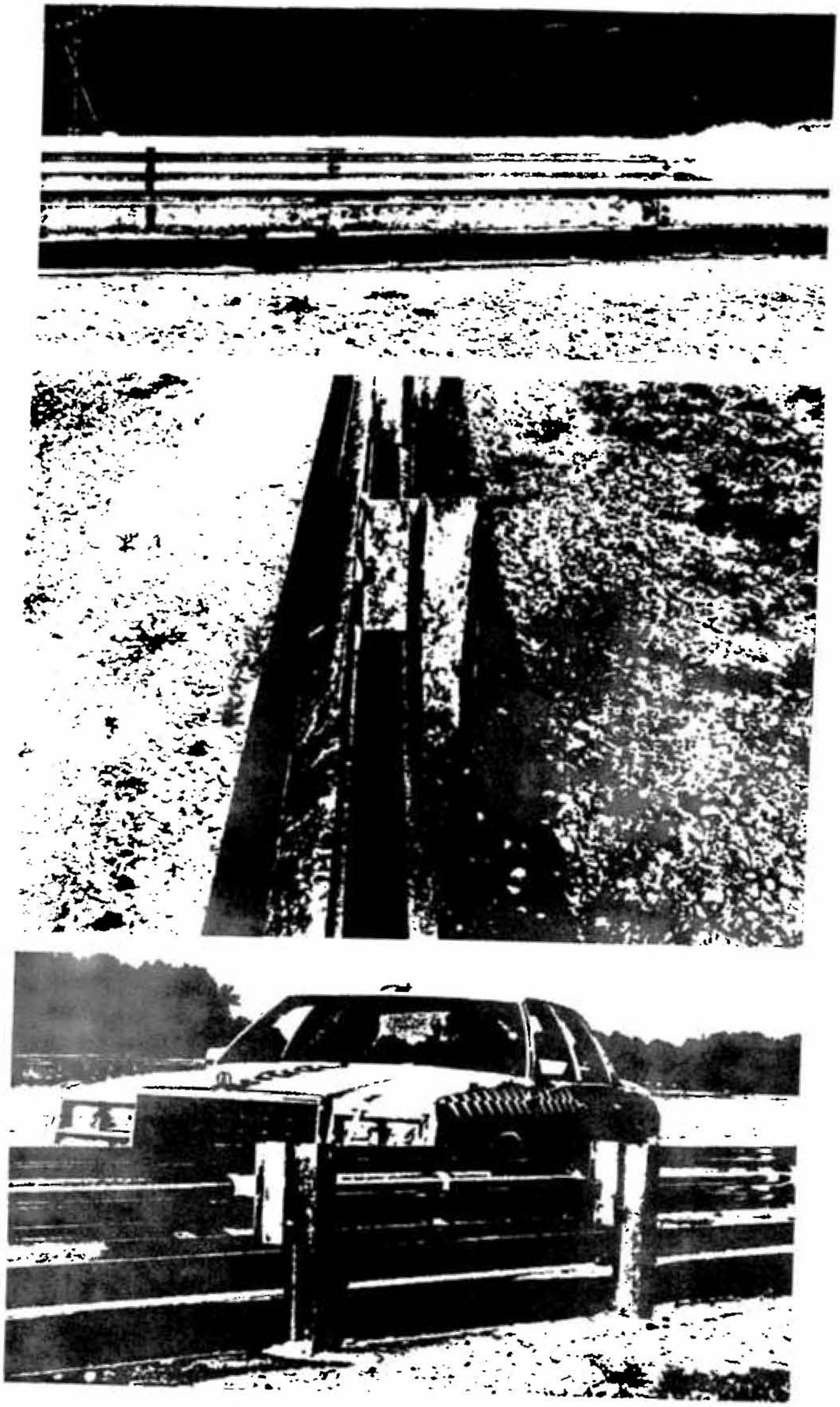


Figure 100. Pretest photographs of guardrail system, test 1862-14-91.

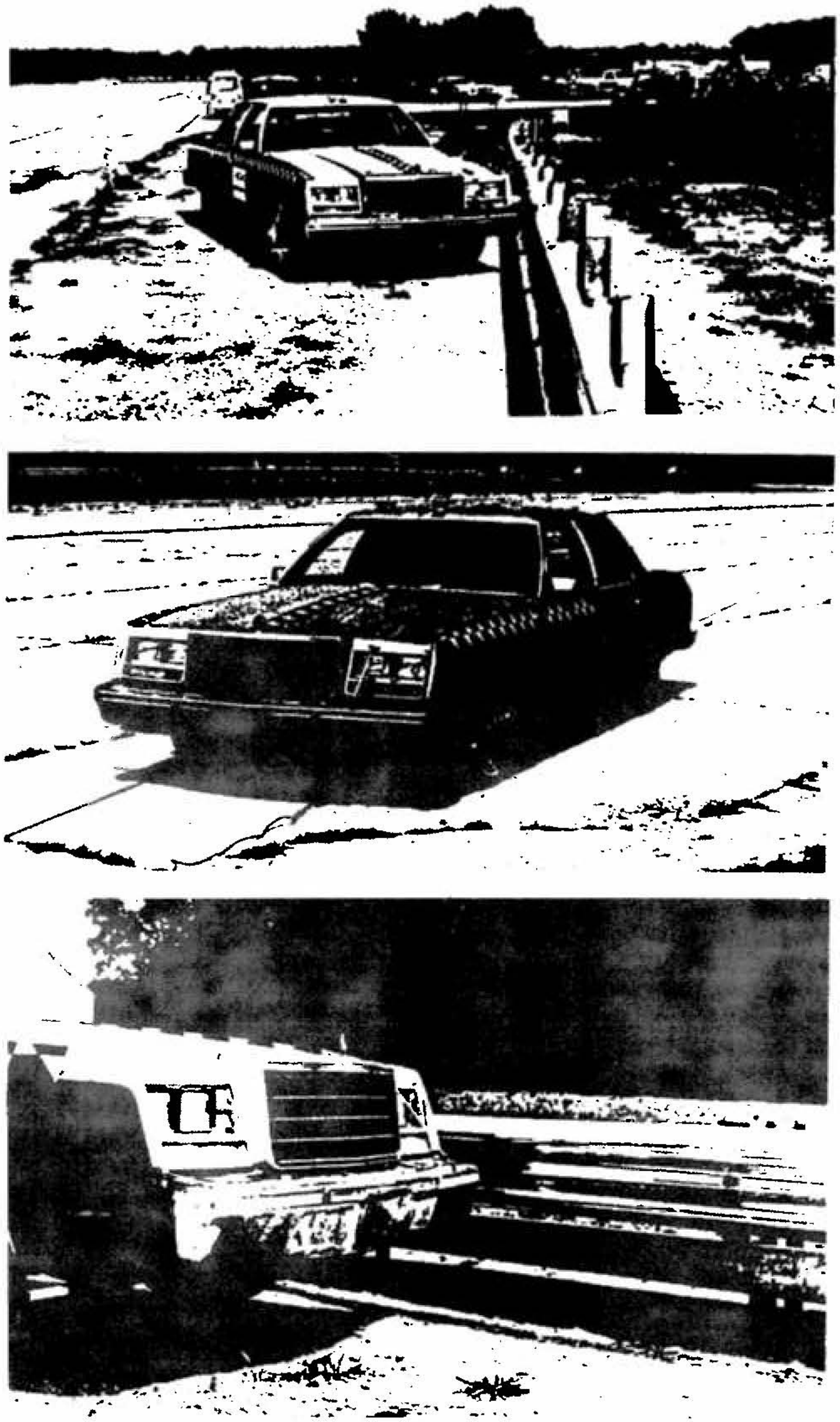
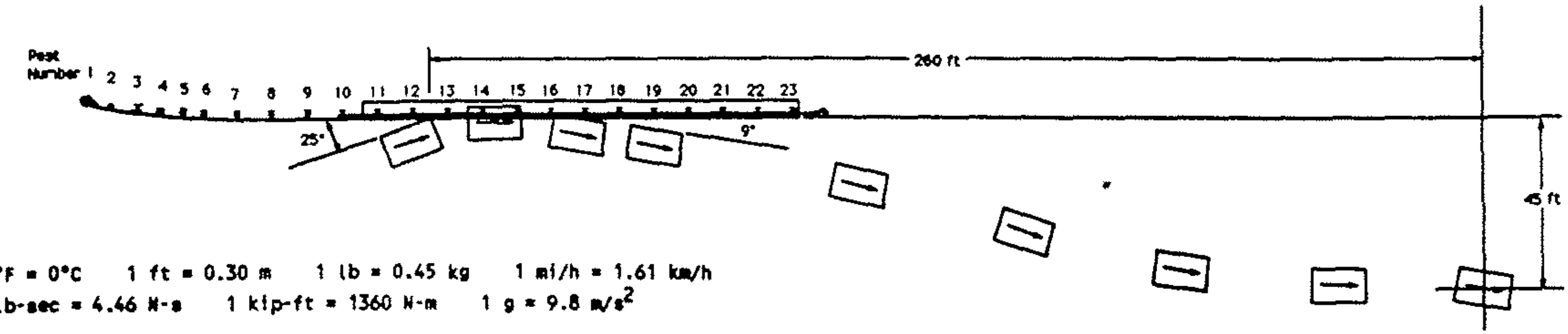


Figure 101. Pretest photographs of test vehicle, test 1862-14-91.



32°F = 0°C   1 ft = 0.30 m   1 lb = 0.45 kg   1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s   1 kip-ft = 1360 N-m   1 g = 9.8 m/s^2

Contract Number:	DTFH61-87-C-00126
Date:	18 July 1991
Weather:	Clear, 90° F
Test Vehicle:	1981 Plymouth Gran Fury
Device Configuration:	Modified G4(1S) W-Beam with AASHTO 6-in, Type G asphalt dike in front of barrier, 131.25 ft total length, 37.5-ft BCT Terminal, 93.75-ft LON. C6x8.2 channel rubrail mounted 0.5 in below bottom of blockout.

1. **Vehicle Weight:**
   - Planned, Inertial: 4500 ± 200
   - Actual, Inertial: 4380
   - Planned, Gross: 4500 ± 300
   - Actual, Gross: 4708
2. **Number of Occupants:** Two
3. **Occupant Model:** Part 572, 50 percentile male
4. **Occupant Locations:** Driver Seat, Unrestrained; Passenger Seat, Restrained
5. **Impact:**

	Speed	Angle	Location
Planned:	60.0 mi/h	25°	Midspan, posts 12 and 13
Actual:	62.1 mi/h	25°	3 ft downstream of desired

6. **Redirection Angle:** -9 degrees
7. **Redirection Speed:** 45.7 mi/h (67.1 ft/s)
8. **Total Speed Change:** 16.4 mi/h (24.0 ft/s)
9. **Total Momentum Change:** 3509 lb-sec
10. **Vehicle Damage Index:** (SAE J224a) 11LDEW2
11. **NCHRP 230 Test Number:** 10
12. **NCHRP 230 Impact Severity:**

$\frac{m(V \sin a)^2}{2}$ — 100.8 kip-ft (Spec: 89 to 114 kip-ft)

13. **Vehicle Analysis:**

	Observed	Design/ Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-18.8 ft/s	30/40 ft/s
Ridedown Acceleration:	-4.0 g's	15/20 g's
Driver:		
Delta-V at 2.42 ft (actual):	-20.6 ft/s	30/40 ft/s
Ridedown Acceleration:	-2.5 g's	15/20 g's
Passenger:		
Delta-V at 2.08 ft (actual):	-18.7 ft/s	30/40 ft/s
Ridedown Acceleration:	-4.0 g's	15/20 g's
Lateral:		
Delta-V at 1 ft:	-16.9 ft/s	20/30 ft/s
Ridedown Acceleration:	-9.4 g's	15/20 g's
Driver:		
Delta-V at 1.04 ft (actual):	-17.2 ft/s	20/30 ft/s
Ridedown Acceleration:	-9.4 g's	15/20 g's
Passenger:		
Delta-V at 0.92 ft (actual):	-16.5 ft/s	20/30 ft/s
Ridedown Acceleration:	-9.4 g's	15/20 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-4.0 g's	
Lateral:	-7.0 g's	

14. **Test Results Conclusion:**

NCHRP 230: DOES NOT MEET ALL CRITERIA. The vehicle speed change at redirection is greater than the 15 mi/h maximum. The test meets all other evaluation criteria.

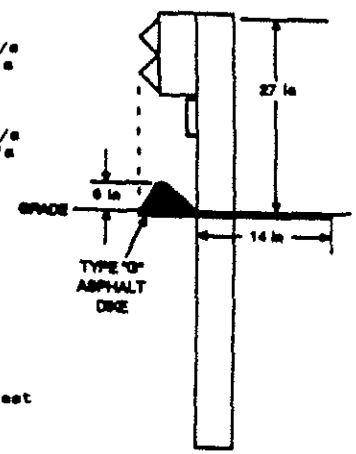
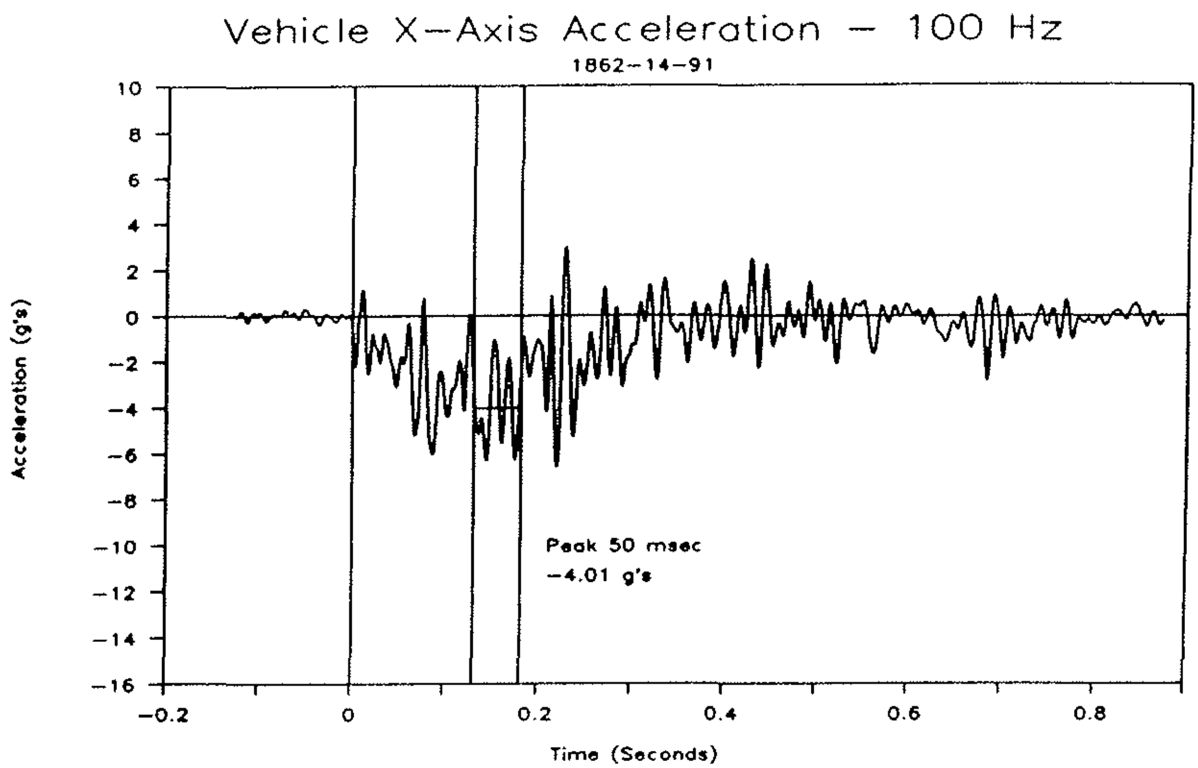


Figure 102. Test summary, test 1862-14-91.



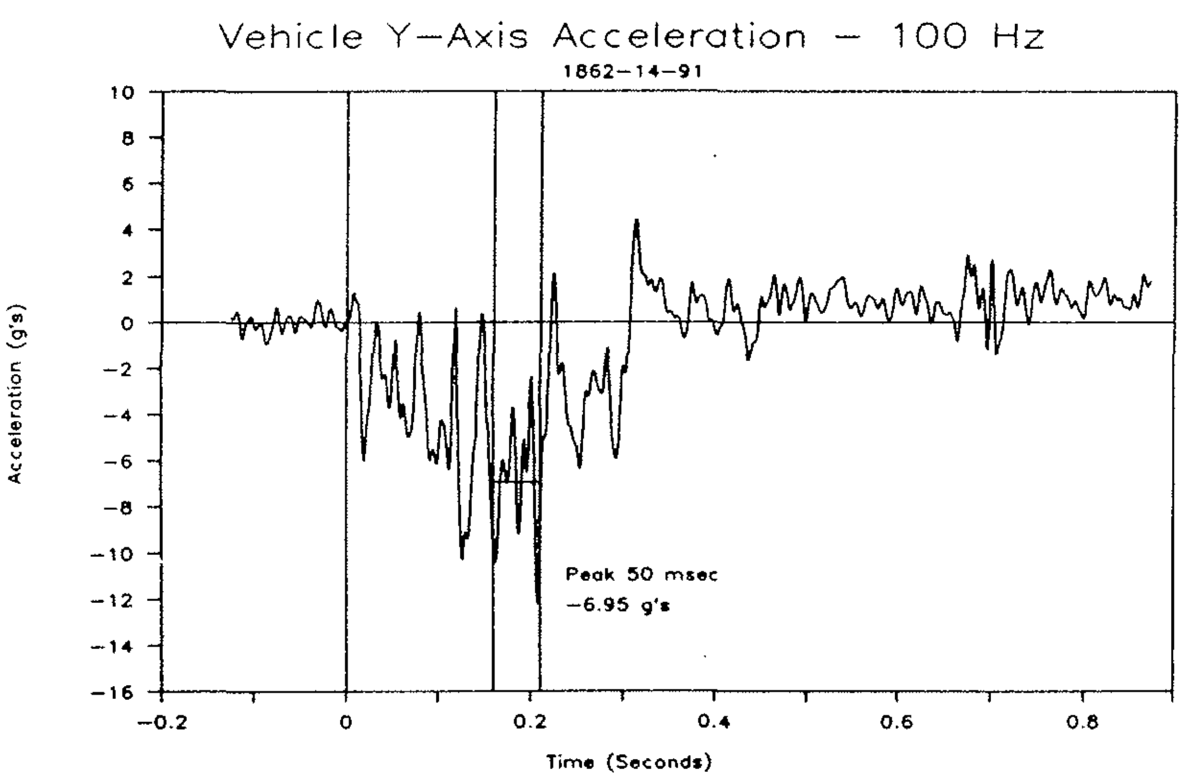


Figure 103. Vehicle accelerations, test 1862-14-91.

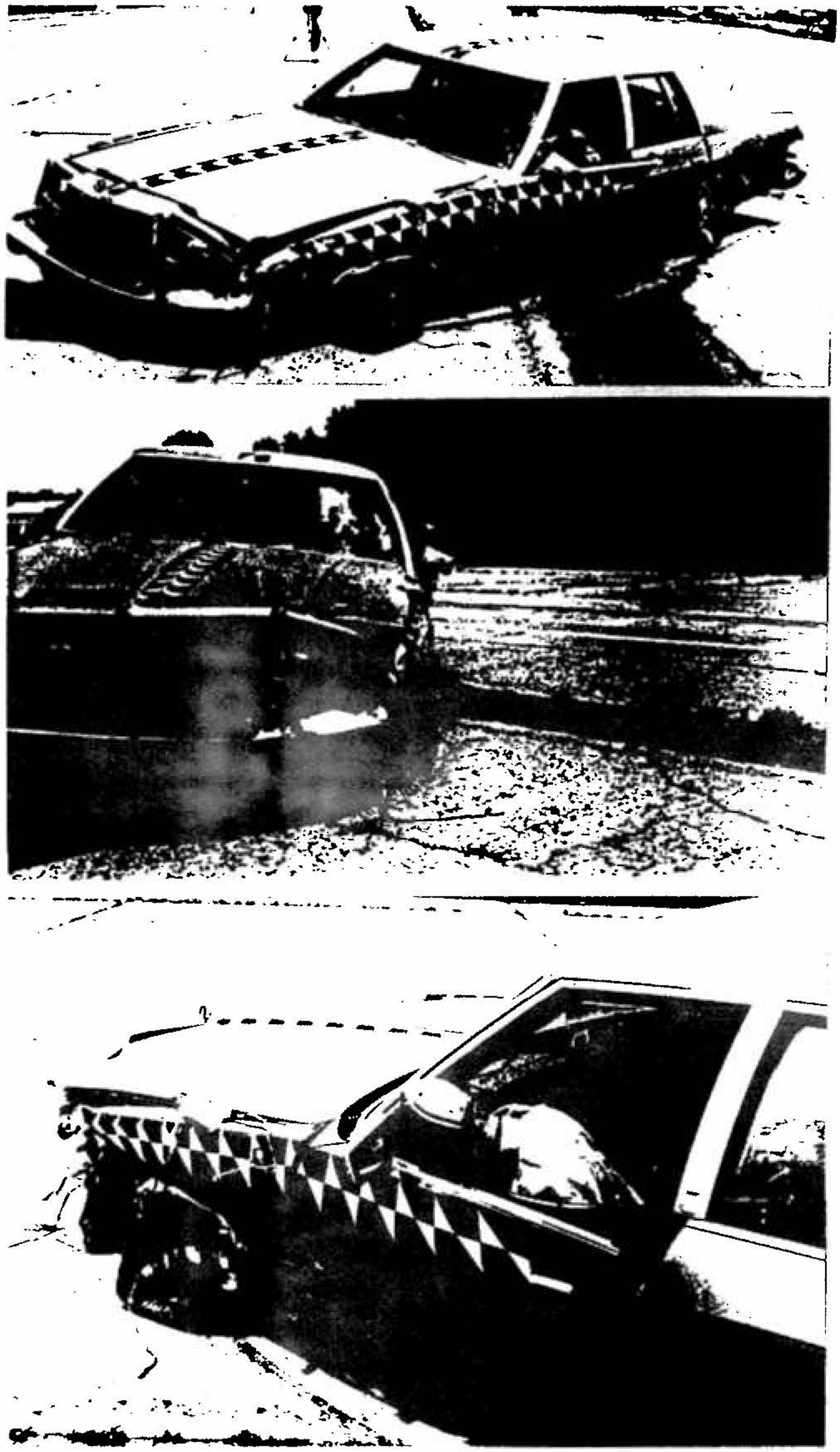


Figure 104. Post-test photographs of test vehicle, test 1862-14-91.

Figure 105. Post-test photographs of guardrail system, test 1862-14-91.

15. TEST 1862-15-92

a. Test Device

The test device was a G4(1S) guardrail installed on downsloped terrain. The entire system was 125 ft (38.1 m) long. The downslope consisted of 12 ft (3.7 m) of a 2 percent downsloped shoulder, 18 ft (5.5 m) of a 6:1 downslope, followed by 12 ft (3.7 m) of a 2:1 downslope. The front face of the rail was 39 in (990.6 mm) in front of the breakpoint between the 6:1 and the 2:1 downslopes [26 ft 9 in (8.2 m) from the edge of the roadway]. The system was installed so that the height of the rail was 27 in (685.8 mm) at its local grade. For 2 ft (0.6 m) on both sides of the 2-percent/6:1 downslope breakpoint, the slopes were rounded. With the rounding, a smooth merge existed between these two slopes rather than a sharp breakpoint. Cable anchor assemblies were used to anchor the rail at both the upstream and downstream ends. Each assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation, a 4-ft 7.25-in (1.43-m) diameter hook eye rod, and a single-swaged 0.75-in (19.1-mm) 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 cable anchor assembly was used on the downstream end.

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

Figure 106 shows the test site and test device. Figure 107 shows a rail profile drawing. Figure 108 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1982 Chevrolet C20 pickup. The target inertial vehicle weight was 5400 lb (2452 kg). The vehicle weighted approximately 4400 lb (1998 kg) empty. Approximately 1000 lb (454 kg) of ballast were added. The ballasted inertial weight of the truck was 5393 lb (2448 kg). The gross vehicle weight was 5710 lb (2592 kg).

Two dummies were placed in the vehicle. The driver was unrestrained while the passenger was restrained. X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the cab of the truck. Pretest photographs of the test vehicle are shown in figure 109. Table 26 lists important parameters of the test vehicle.

c. Impact Description

Review of the high-speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 59.7 mi/h (96.1 km/h) and 20°. This review also indicated that the front right corner

Table 26. Test vehicle parameters, test 1862-15-92.

Item	Actual	Specification
Empty Weight	~4400 lb	n/a
Ballast	~1000 lb	n/a
Total Weight, Inertial	5393 lb	5400 lb
Total Weight, Gross	5710 lb	n/a
H_{cg}	27 in	27 ± 1 in
A (front to cg), Inertial	8.60 ft	8.5 ± 0.1 ft
B (width)	6.46 ft	6.5 ft
Truck Length	215 in	
Truck Wheelbase	131 in	
Wheel/Tire Size	235 85R16	
Truck Box Size	8 ft long by 1.5 ft high by 5.5 ft wide	
Ground to Box Floor	27 in	

1 lb = 0.45 kg 1 ft = 0.31 m 1 in = 25.4 mm

of the vehicle impacted the rail at the desired impact point, between posts 5 and 6.

Upon impact, the bumper of the vehicle impacted the rail at the center of the 12-in (304.8-mm) W-beam. The rail pushed back, but due to the vehicle's downward momentum, there was no tendency to vault or climb the guardrail. As the vehicle redirected, becoming parallel with the rail, the rail was flattened and pushed back. The maximum roll angle of the vehicle was approximately 15°. The vehicle remained in contact with the rail for approximately 45 ft (13.7 m). The vehicle redirected at an exit angle of approximately 16°. Due to front suspension damage and the downslope, the vehicle slowly curved back into the rail. The vehicle reimpacted the rail approximately 80 ft (24.4 m) downstream from the impact point. The vehicle came to rest along the rail approximately 100 ft (30.5 m) from the impact point.

Upon impact, the unrestrained driver dummy was thrown to the passenger side of the cab. The head of the driver dummy impacted the windshield directly in front of the passenger dummy. The head impacted 5 in (127.0 mm) up from the bottom of the windshield, causing the windshield to break and spider web. The driver dummy came to rest on the passenger dummy's lap with its head resting on the dashboard, its knees under the dash, and its feet resting on the seat. The restrained passenger-dummy did not break either the passenger door glass or the front windshield. The passenger dummy remained seated in the normal riding position.

A summary of test conditions and results are shown in figure 110. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 111.

d. Vehicle Damage

The right side of the vehicle was damaged. The most severe damage occurred to the right front corner of the vehicle. The front bumper was fractured and pushed into the engine compartment. The right fender was buckled. The vehicle front suspension sustained severe damage. The right front wheel was mangled and both right side tires were deflated. The top of the passenger door was bent away from the truck 1 in (25.4 mm). There was minor damage to the right rear of the truck due to tail slap and redirection contact. There was no intrusion into the occupant compartment. Post-test photographs of the test vehicle are shown in figure 112.

e. Barrier Damage

The barrier was damaged for 45 ft (13.7 m), beginning at impact. The concrete foundation for the upstream cable anchor assembly was pulled upwards 3 in (76.2 mm) and downstream 3 in (76.2 mm). The rail had permanent deflection from posts 2 through 14. Posts 2 and 3 were twisted toward impact. Posts 4 and 5 were twisted and bent. Post 6 was bend back and the splice bolt pulled through the rail. Post 7 was pulled from the soil and thrown 27 ft (8.2 m). Posts 8 and 9 were also pulled from the soil and detached from the rail. Posts 7 through 9 were slightly bent and twisted. Posts 10 through 14 were bent, but were not twisted. Posts 15 through 21 were not damaged. The maximum permanent rail deflection occurred at post 8 and was 46 in (1168.4 mm). Post-test photographs of the rail are shown in figure 113.

f. Test Evaluation

This test was evaluated using the AASHTO Guide Specifications for Bridge Railings. The following is an item-by-item evaluation using this guideline.

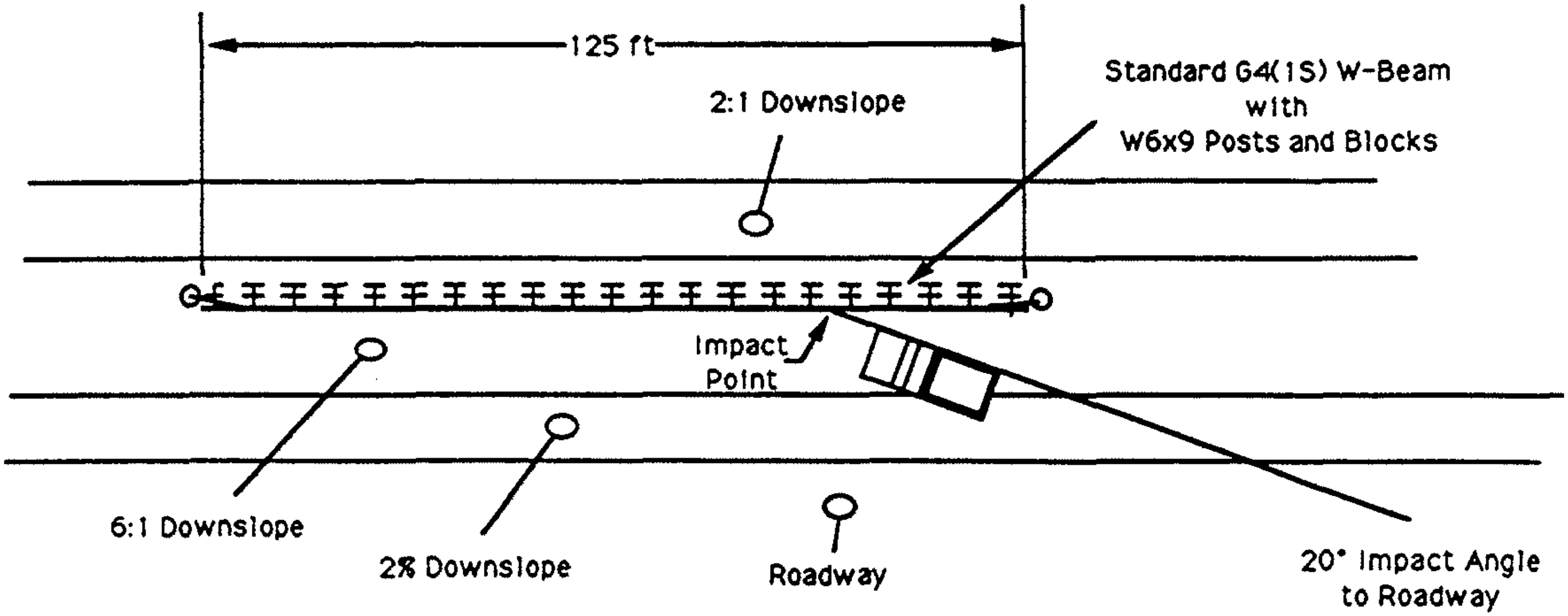
Required Criteria:

a. The post vehicle was contained by the test article.
b. Post 7 was detached from the rail and thrown from it pretest location, but presented no hazard to the test vehicle or other traffic.
c. Integrity of the passenger compartment was maintained.
d. The vehicle remained upright.

Desirable Criteria:

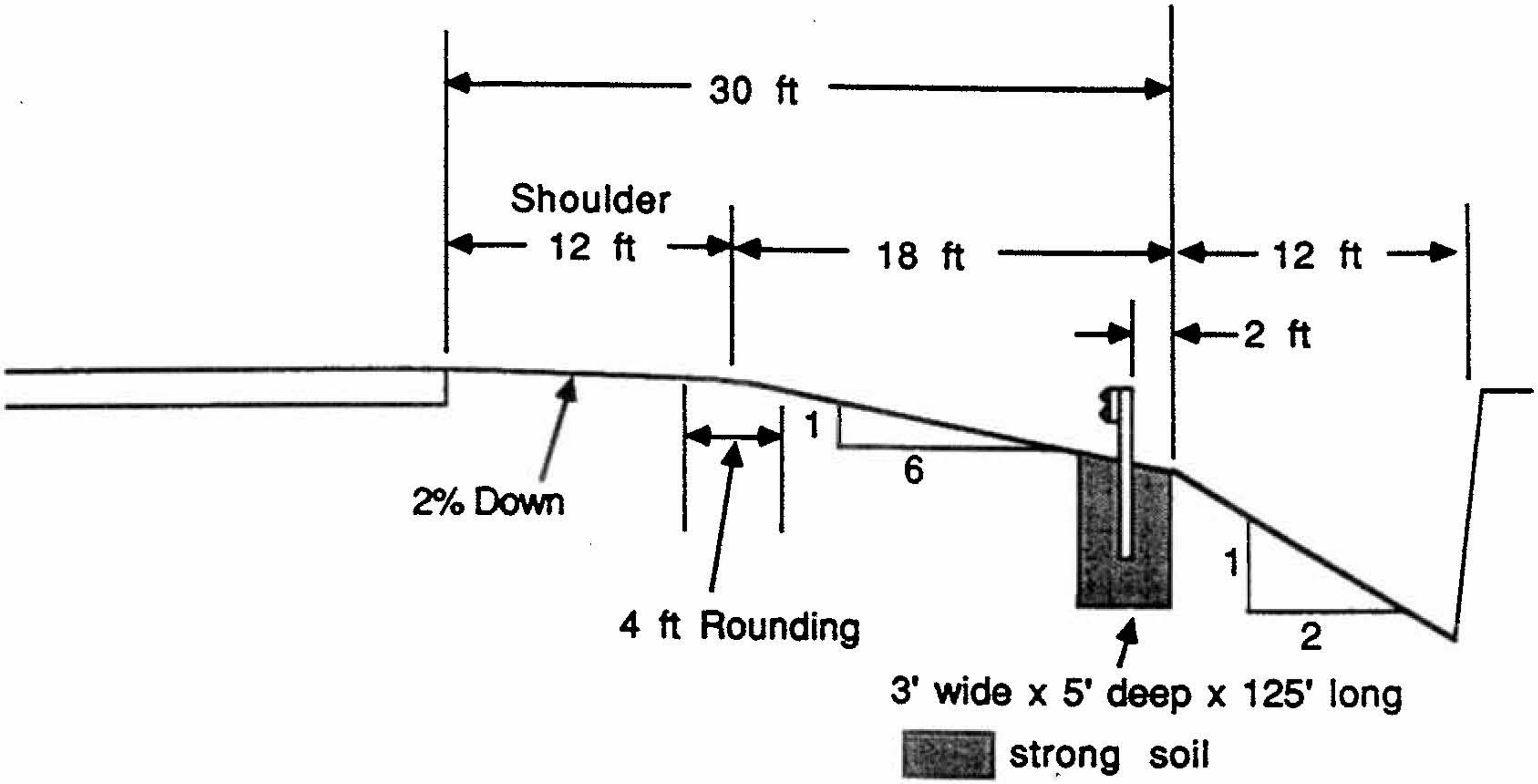
e. The vehicle was smoothly redirected.
f. Vehicle railing interaction:
   mu = 0.54, assessment: Marginal.
g. Delta-V and Ridedown values were within limits.
h. The exit angle was **NOT** less than 12°. The vehicle redirected at approximately 16°.

TEST ARTICLE MEETS ALL REQUIRED CRITERIA.



1 ft = 0.30 m

Figure 106. Test site layout, test 1862-15-92.



1 ft = 0.30 m

Figure 107. Rail profile, test 1862-15-92.

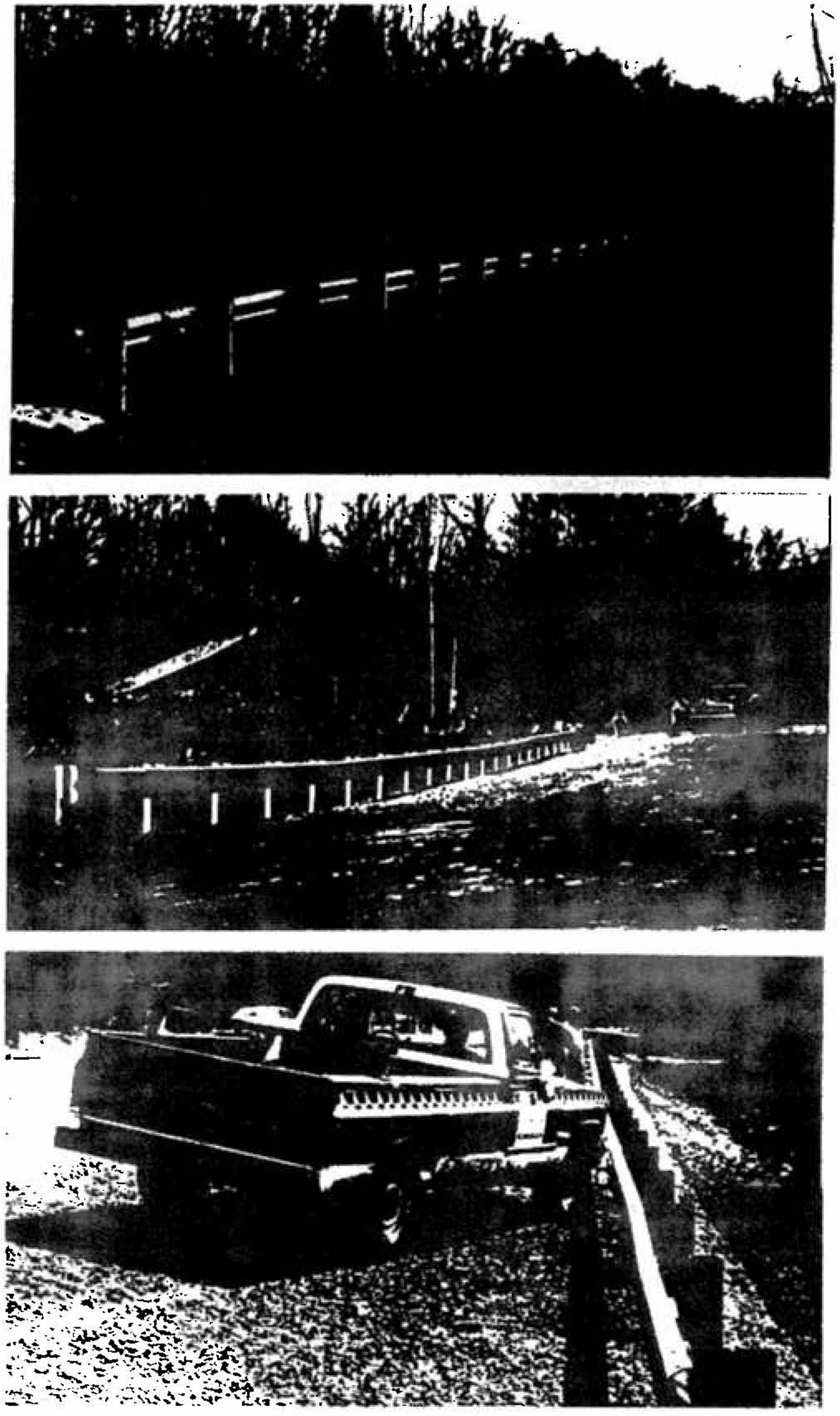


Figure 108. Pretest photographs of guardrail system, test 1862-15-92.

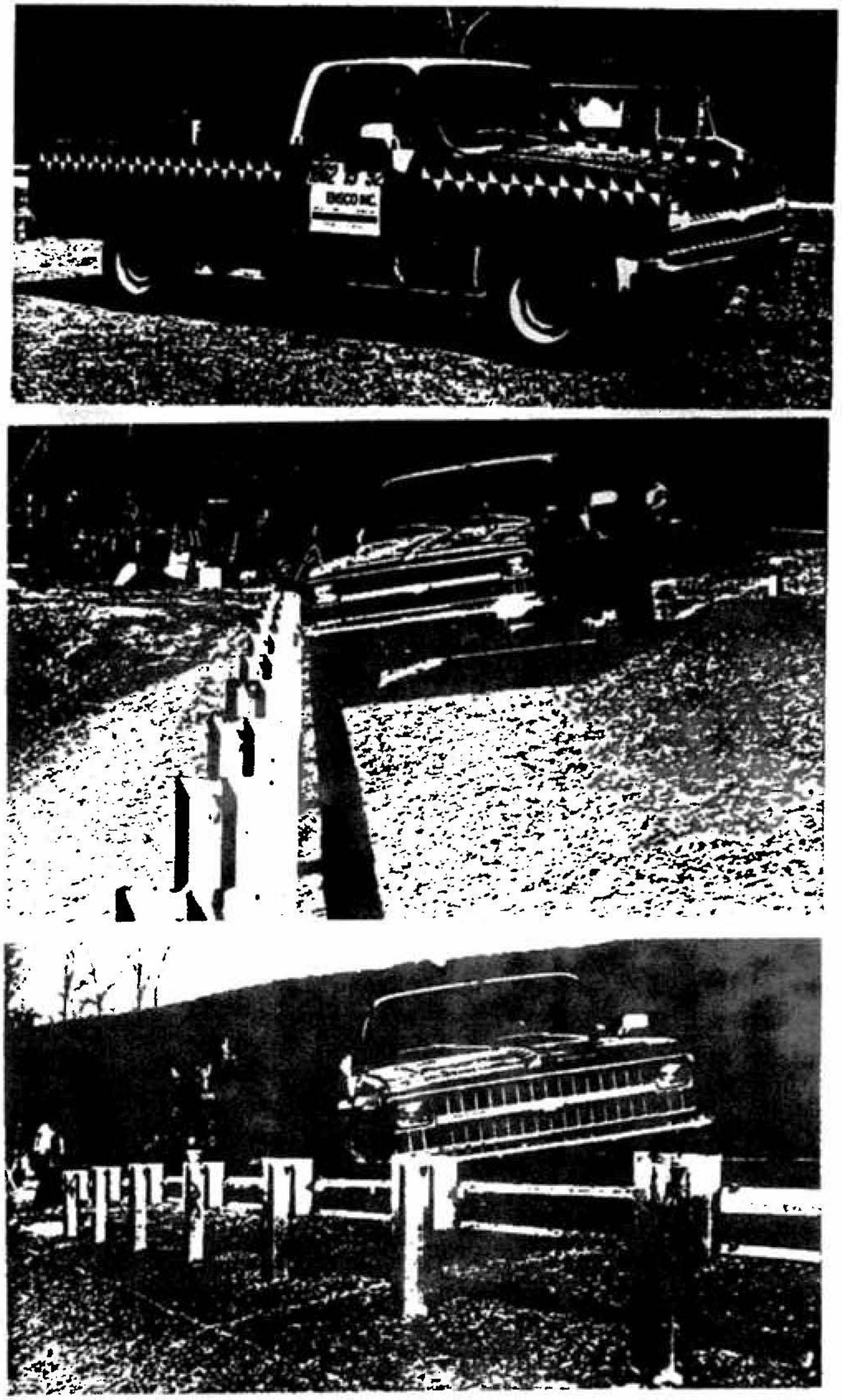
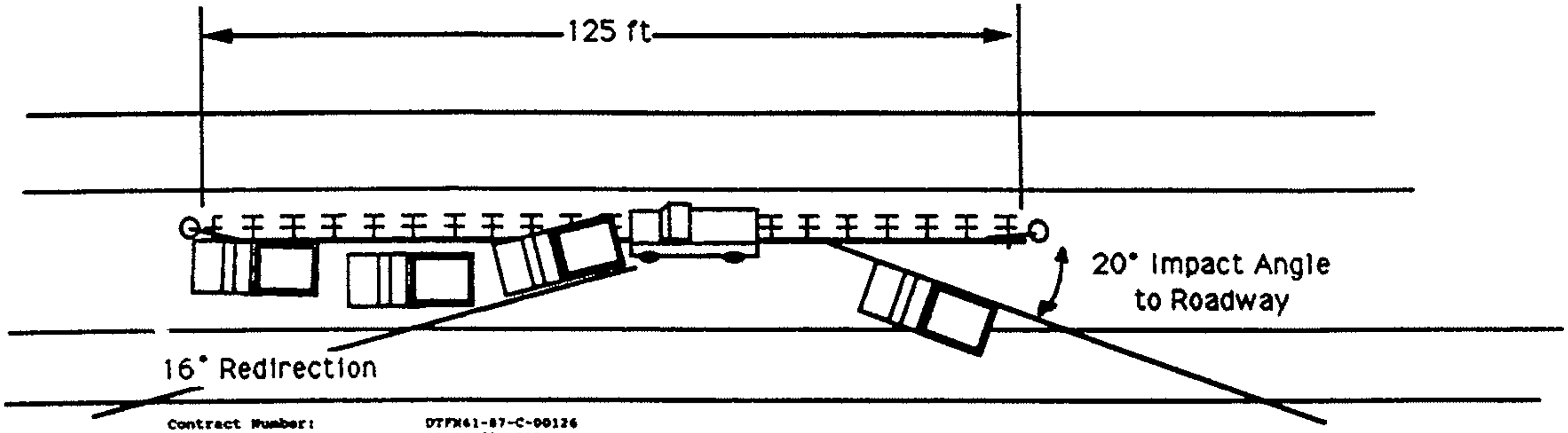


Figure 109. Pretest photographs of test vehicle, test 1862-15-92.



Contract Number: DTFH61-87-C-00126
Date: 08 April 1992
Weather: Clear, 65° F

Test Vehicle: 1982 Chevrolet C20 Pickup

Device Configuration: G4(1S) installed on downsloped terrain (12 ft of 2% downslope, 18 ft of 6:1 downslope, 12 ft of 2:1 downslope). 125 ft total length.

1. Vehicle Weight:
   - Planned, Inertial: 5400
   - Actual, Inertial: 5393
   - Actual, Gross: 5710
2. Number of Occupants: Two
3. Occupant Model: Part 572, 50 percentile male
4. Occupant Locations: Driver Seat, Unrestrained; Passenger Seat, Restrained
5. Impact:

Impact:	Speed	Angle	Location
Planned:	60.0 mi/h	20°	Midspan posts 5 and 6
Actual:	59.7 mi/h	20°	Midspan posts 5 and 6

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

6. Redirection Angle: Approximately 16°.
7. Redirection Speed: 24 mi/hr (35 ft/s)
8. Total Speed Change: 36 mi/hr (53 ft/s)
9. Total Momentum Change: 8900 lb-s
10. Vehicle Damage Index: (SAE J224a) 01RFEW3
11. AASHTO Test Type: PL2
12. Vehicle-Railing Interaction Coefficient of Friction:

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

mu	Assessment
0.54	Marginal

V_p = 45 mi/h (66 ft/s)

32°F = 0°C 1 ft = 0.30 m 1 lb = 0.45 kg 1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s 1 kip-ft = 1360 N-m 1 g = 9.8 m/s^2

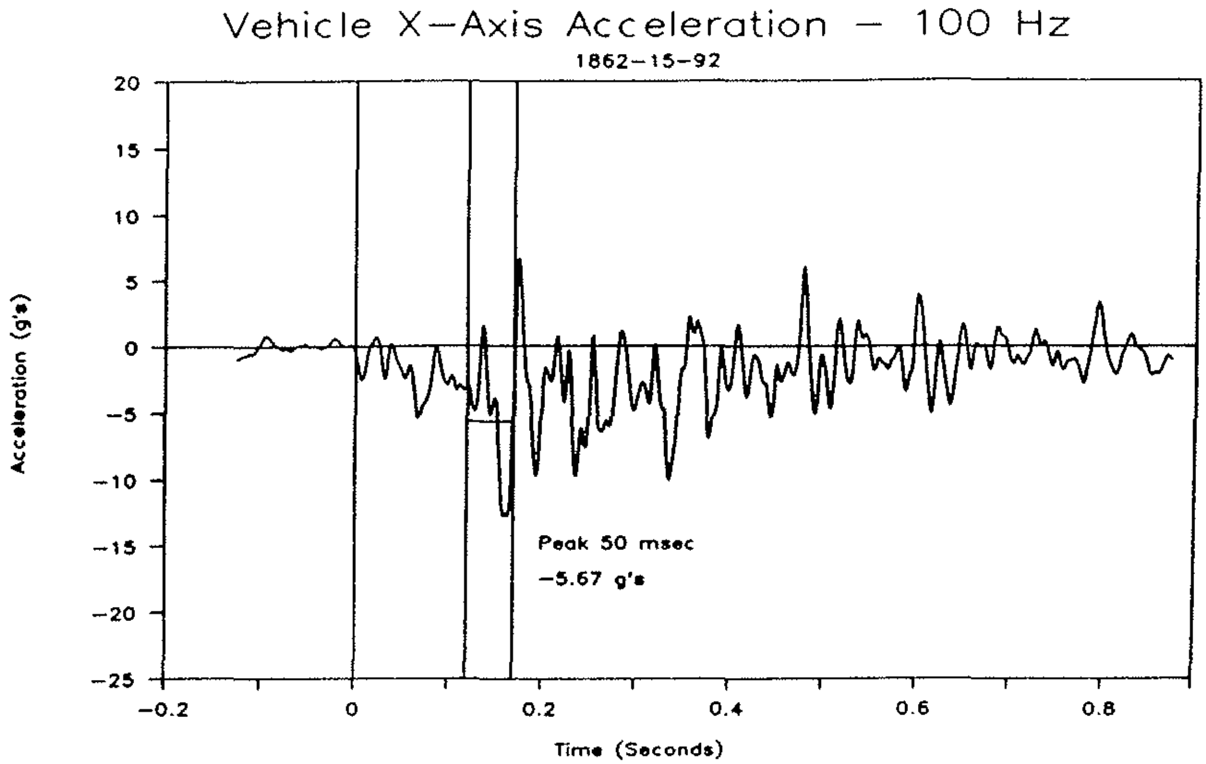
13. Vehicle Analysis:

	Observed	Limit Value
NCHRP 230:		
LONGITUDINAL:		
Delta-V at 2 ft:	-20.6 ft/s	30 ft/s
Ridedown Acceleration:	-9.0 g's	15 g's
Driver:		
Delta-V at 2.25 ft (actual):	-23.6 ft/s	30 ft/s
Ridedown Acceleration:	-9.0 g's	15 g's
Passenger:		
Delta-V at 2.25 ft (actual):	-23.6 ft/s	30 ft/s
Ridedown Acceleration:	-9.0 g's	15 g's
LATERAL:		
Delta-V at 1 ft:	-13.9 ft/s	25 ft/s
Ridedown Acceleration:	-8.7 g's	15 g's
Passenger:		
Delta-V at 1.13 ft (actual):	-15.1 ft/s	25 ft/s
Ridedown Acceleration:	-8.7 g's	15 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-5.7 g's	
Lateral:	-5.2 g's	

14. Test Results Conclusion:

AASHTO Bridge Rail Specification: TEST ARTICLE MEETS ALL CRITERIA.

Figure 110. Test summary, test 1862-15-92.



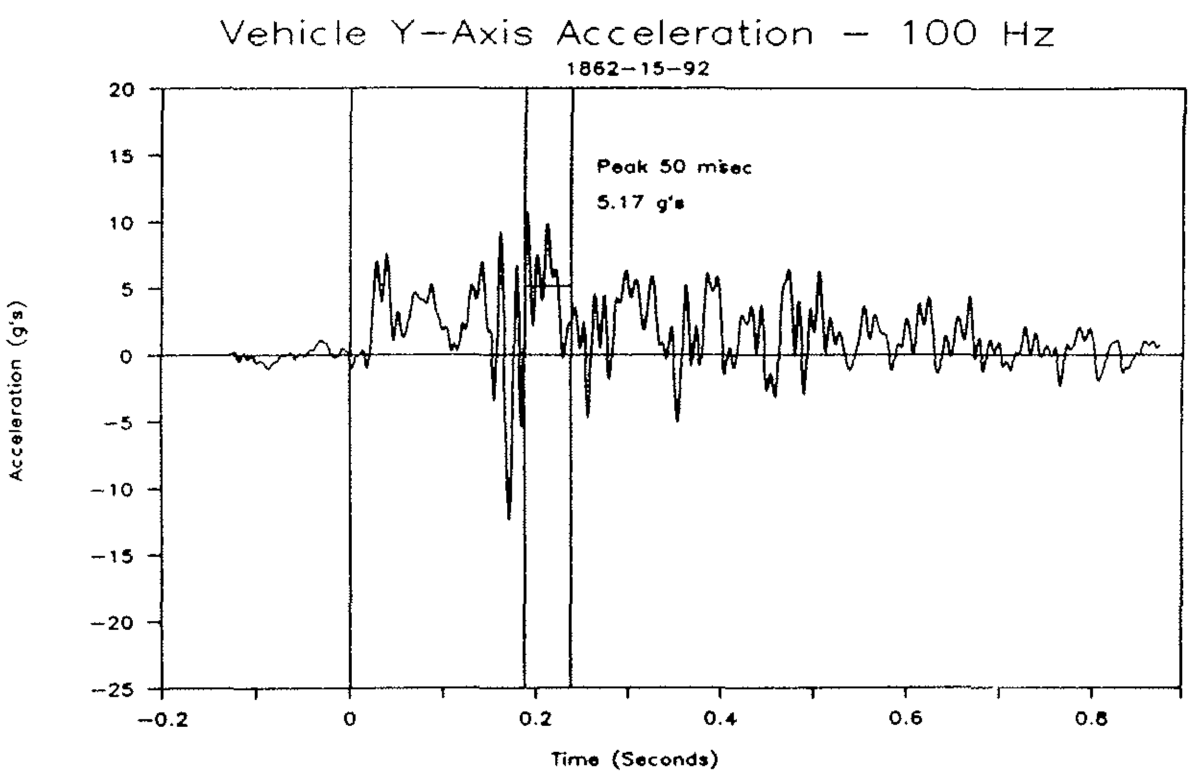


Figure 111. Vehicle accelerations, test 1862-15-92.

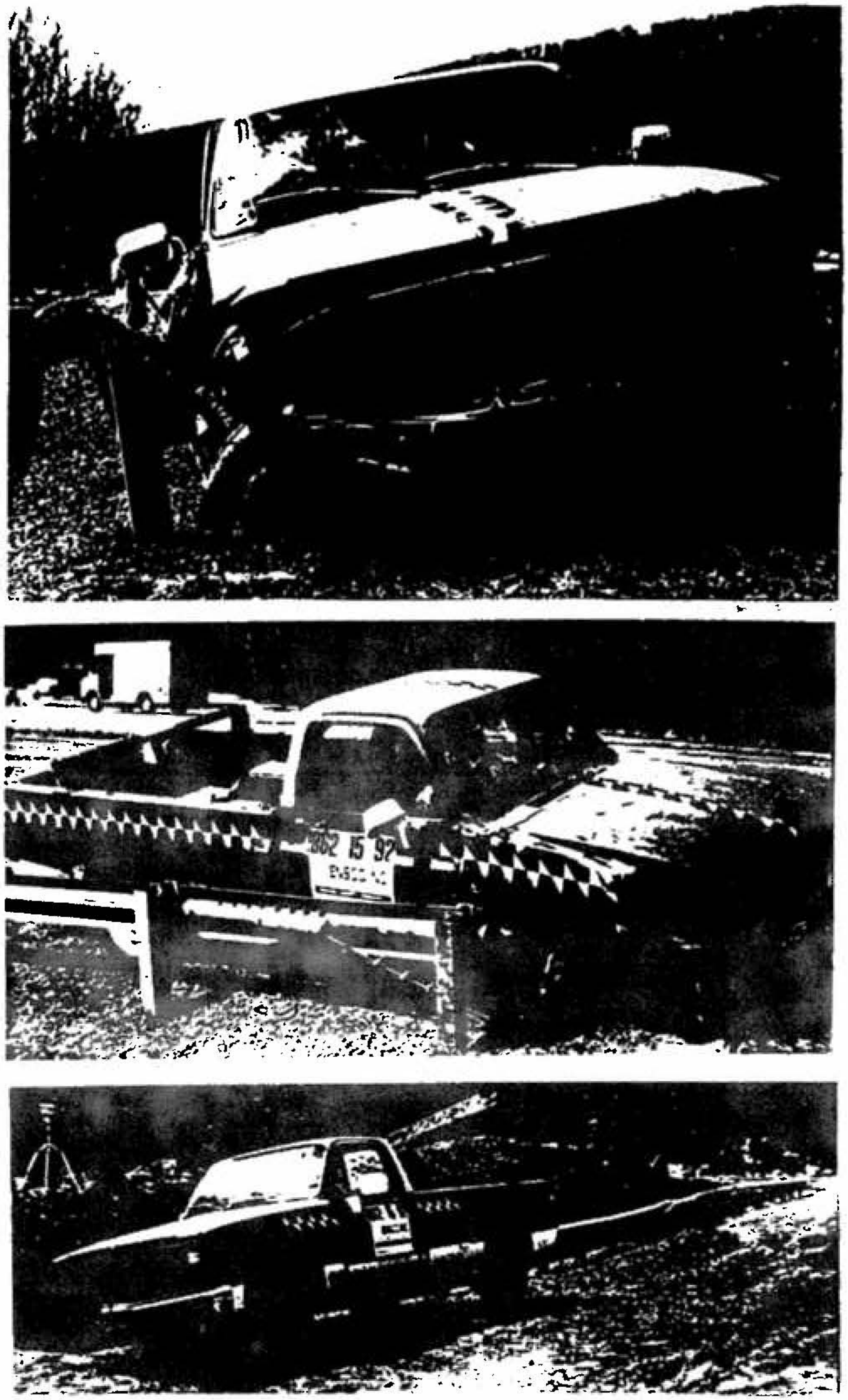


Figure 112. Post-test photographs of test vehicle, test 1862-15-92.

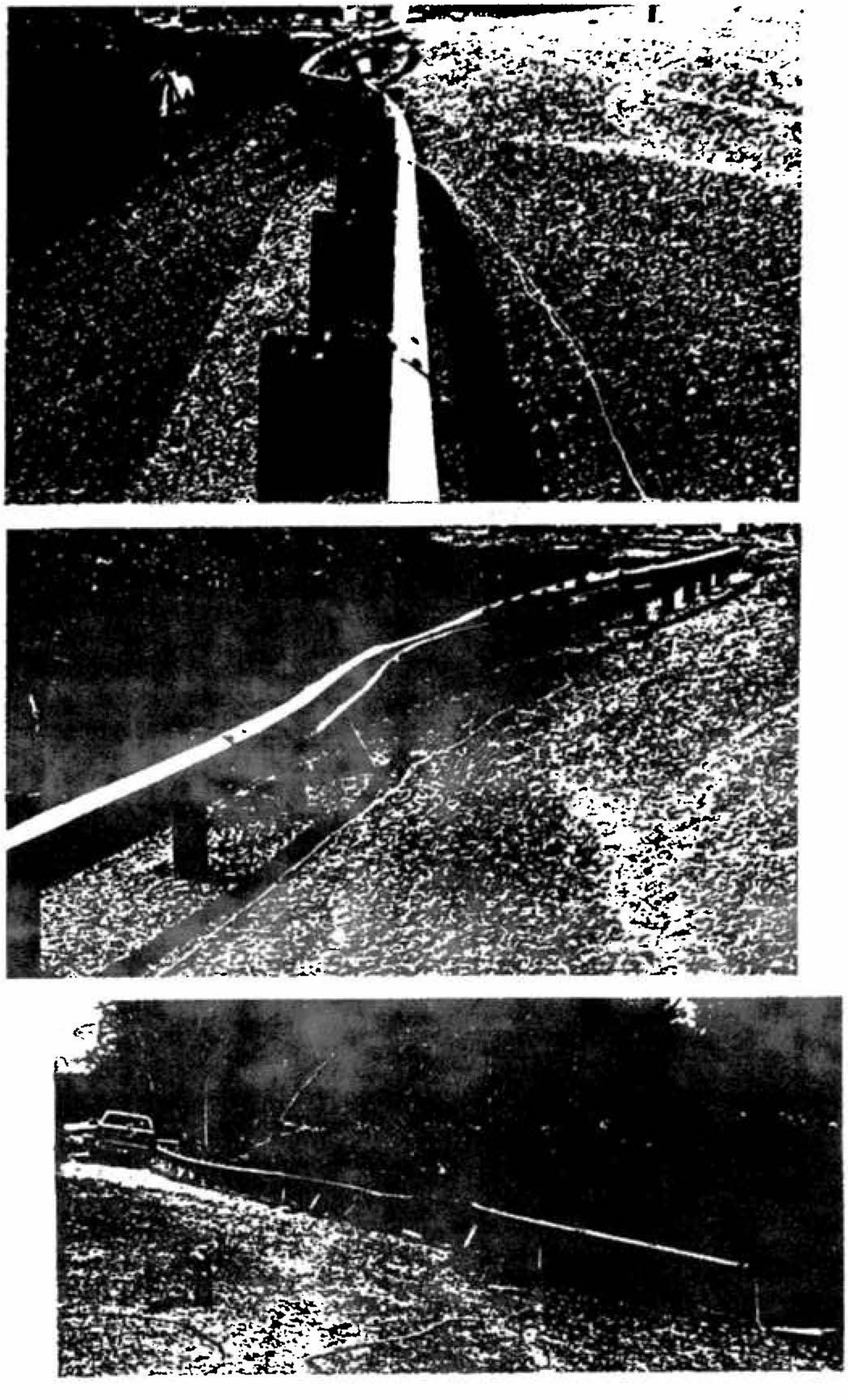


Figure 113. Post-test photographs of guardrail system, test 1862-15-92.

16. TEST 1862-16-91

a. Test Device

The test device was the G4(1S) guardrail installed at the edge of the roadway on a superelevation with a 1192-ft (363.6-m) radius curve. The entire system was 218.75 ft (66.7 m) long. The system consisted of 125 ft (38.1 m) of curved G4(1S) with 93.75 ft (28.6 m) of straight G4(1S) prior to the curve.

The superelevation consisted of 20 ft (6.1 m) of a 10-percent upsloped roadway and 10 ft (3.1 m) of a 2-percent rising shoulder. The front face of the rail was 6 in (152.4 mm) past the edge of the roadway. This is a modification to the test configuration of test 1862-6-89. The placement of the rail at the edge of the roadway effectively moved the rail 10 ft 3 in (3.1 m) down the slope of the superelevation. The terrain fell away in a 2:1 downslope 4 ft (1.2 m) past the edge of the shoulder [14 ft (4.3 m) behind the rail installation]. For 4 ft (1.2 m) on both sides of the 2-percent/2:1 slope breakpoint, the slopes were rounded. With the rounding, a smooth merge existed between these two slopes rather than a sharp breakpoint. Cable anchor assemblies were used to anchor the rail at both the upstream and downstream ends. Each assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 114 shows the test site and test device. Figure 115 shows a rail profile drawing. Figure 116 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1984 Ford F150 pickup. The target inertial vehicle weight was 5400 lb (2452 kg). The vehicle weighed approximately 3700 lb (1680 kg) empty. Approximately 1700 lb (772 kg) of ballast were added. The ballasted inertial weight of the truck was 5422 lb (2462 kg). The gross vehicle weight was 5748 lb (2610 kg).

Two dummies were placed in the vehicle. The driver was unrestrained while the passenger was restrained. X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the cab of the truck. Pretest photographs of the test vehicle are shown in figure 117. Table 27 lists important parameters of the test vehicle.

Table 27. Test vehicle parameters, test 1862-16-91.

Item	Actual	Specification
Empty Weight	~3700 lb	n/a
Ballast	~1700 lb	n/a
Total Weight, Inertial	5422 lb	5400 lb
Total Weight, Gross	5748 lb	n/a
H_{cg}	27 in	27 ± 1 in
A (front to cg), Inertial	8.54 ft	8.5 ± 0.1 ft
B (width)	6.10 ft	6.5 ft
Truck Length	212.5 in	
Truck Wheelbase	133.5 in	
Wheel/Tire Size	225-75/15 (front), 235-75/15 (rear)	
Truck Box Size	8 ft long by 1.5 ft high by 5.5 ft wide	
Ground to Box Floor	27 in	

1 lb = 0.45 kg 1 ft = 0.31 m 1 in = 25.4 mm

c. **Impact Description**

Review of the high-speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 61.6 mi/h (99.1 km/h) and 20° measured relative to the straight rail section. This review also indicated that the front left corner of the vehicle impacted the rail approximately 1 ft (0.3 m) downstream of the desired impact point.

Upon impact, the bumper of the vehicle impacted the rail at the center of the 12-in (304.8-mm) W-beam. The front wheels turned sharply into the rail. The driver side tire and wheel snagged and ripped apart from the vehicle as the vehicle penetrated into the rail. As the vehicle redirected, becoming parallel with the rail, the rail was flattened and pushed back. The vehicle remained in contact with the rail for approximately 26 ft (7.9 m). At this point, the rail/vehicle interaction caused the vehicle to launch into the air and begin severe rolling and yawing. After rolling 180° and yawing 180°, the vehicle landed upside down on top of the rail, approximately 60 ft (18.3 m) downstream of the impact point. Upon re-impacting the system, the vehicle continued to roll down the length of the system. After completing 3-3/4 rollovers (1350° of roll), the vehicle came to rest 165 ft (50.3 m) from the impact point.

The driver dummy was thrown from the vehicle during the second rollover. The driver dummy exited the vehicle between the top of the driver's door and the vehicle roof. The top of the door bent away from the roof of the vehicle to allow this ejection (the door never opened). The driver dummy came to rest 45 ft (13.7 m) downstream of the vehicle resting point. The passenger dummy broke the passenger-side window during the second rollover. The right leg broke from the passenger dummy and exited the vehicle through the passenger-side window. The rest of the dummy remained inside the vehicle. The passenger dummy came to rest on the passenger door, with its right arm sticking through the rear window of the cab.

A summary of test conditions and results are shown in figure 118. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 119.

d. Vehicle Damage

The entire vehicle was damaged, including the cab, fenders, doors, hood, tires/wheels, and suspension; the entire left and right side; and the rear of the vehicle. The severe damage to the front suspension and frame was caused by the impact with the rail. The side and rear-end damage was due primarily to the impacts sustained while rolling and vaulting. Post-test photographs of the test vehicle are shown in figure 120.

e. Barrier Damage

The barrier was damaged for 26 ft (7.9 m), beginning at impact. The rail had permanent deflection from posts 19 through 25. Posts 16 through 19 were twisted toward the impact point. Posts 20 through 24 were twisted and bent (posts reached yield strength prior to the soil giving way). The rail was detached from the block at post 22. The maximum permanent rail deflection [24 in (609.6 mm)] occurred at post 22. Post-test photographs of the rail are shown in figure 121.

f. Test Evaluation

This test was evaluated using the AASHTO Guide Specifications for Bridge Railings. The following is an item-by-item evaluation using this guideline.

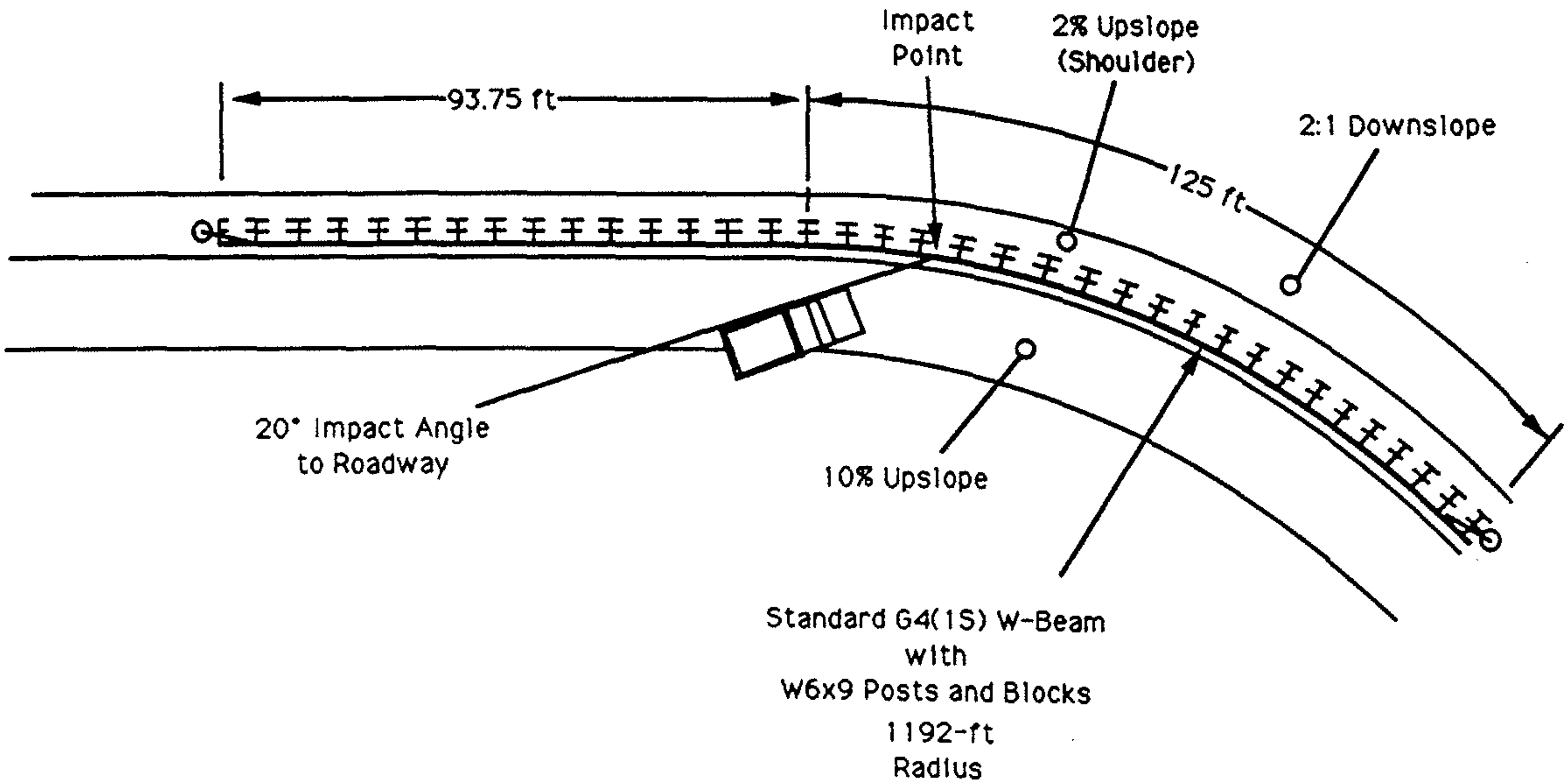
Required Criteria:

a. The vehicle was <u>NOT</u> contained by the test article.
b. There were no detached elements.
c. Integrity of the passenger compartment was <u>NOT</u> maintained, the vehicle rolled over.
d. The vehicle did <u>NOT</u> remain upright, the vehicle rolled over.

Desirable Criteria:

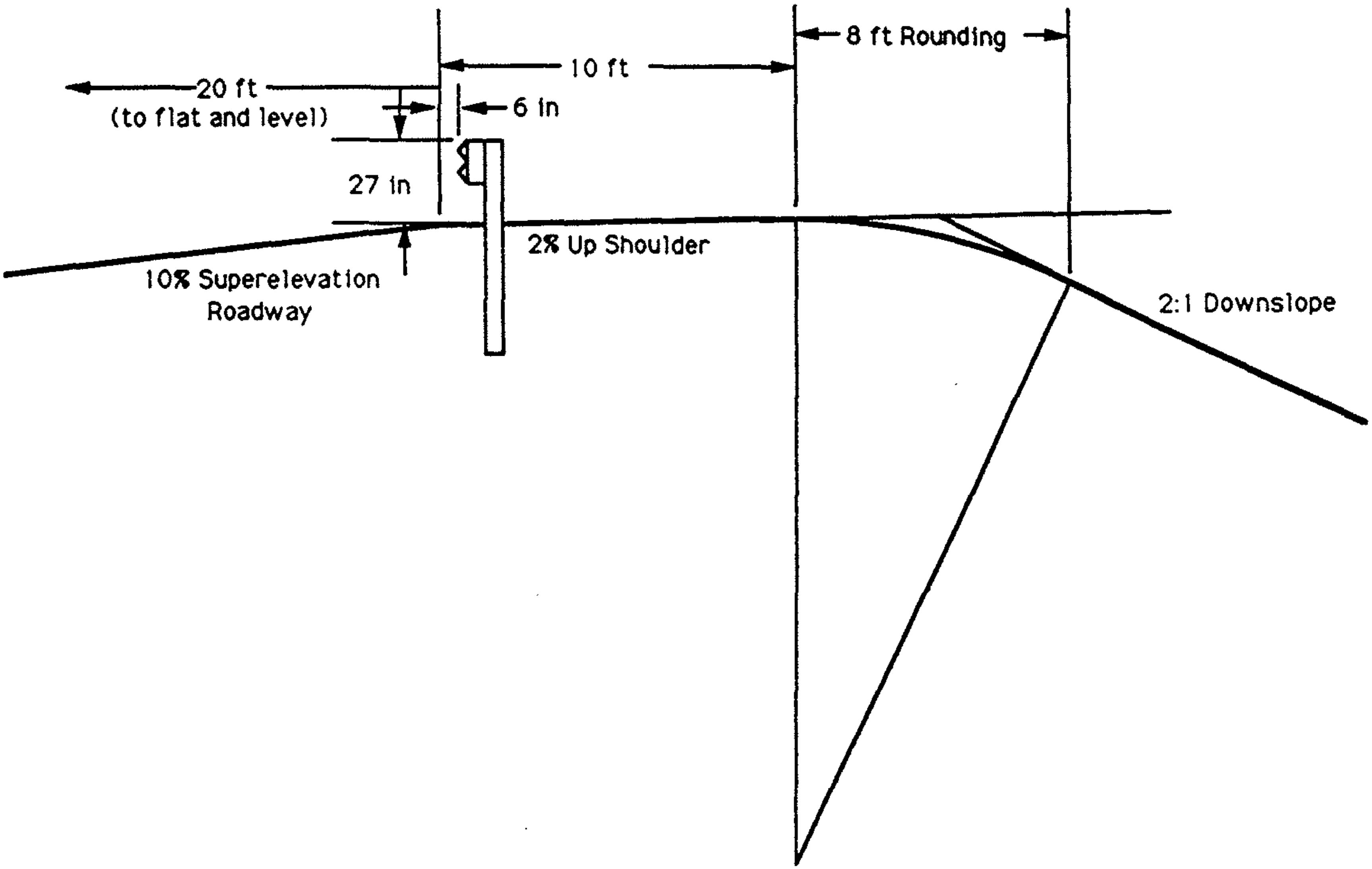
e. The vehicle was **NOT** smoothly redirected (redirection angle not measured due to rollover).
f. Vehicle railing interaction: mu = 0.64, assessment: Marginal.
g. Delta-V and Ridedown values were within limits.
h. The exit angle was less than 12° (however, redirection angle was not measured due to rollover).

TEST ARTICLE FAILS DUE TO VEHICLE ROLLOVER.



1 ft = 0.30 m

Figure 114. Test site layout, test 1862-16-91.



1 ft = 0.30 m   1 in = 25.4 mm

Figure 115. Rail profile, test 1862-16-91.

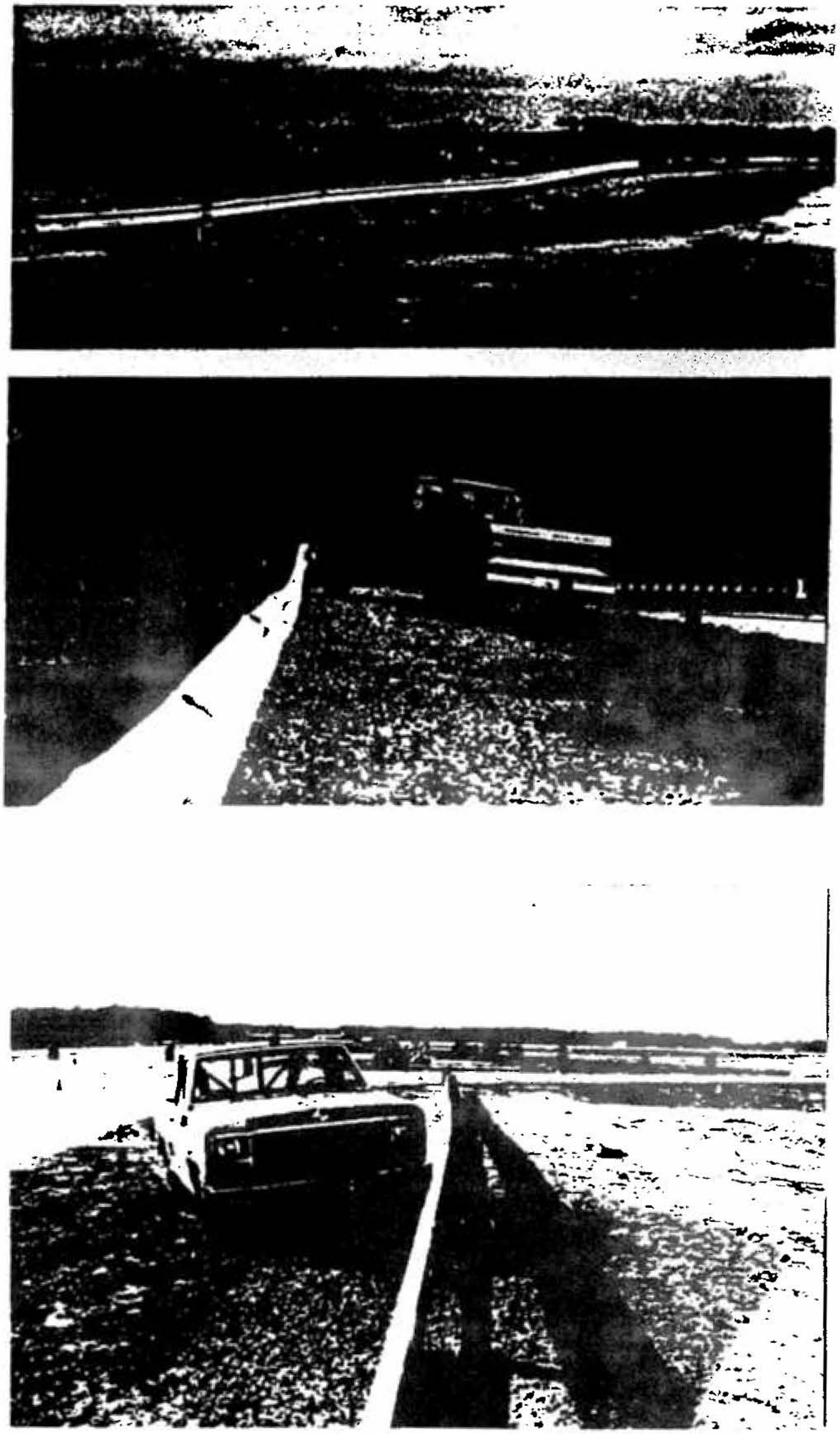


Figure 116. Pretest photographs of guardrail system, test 1862-16-91.

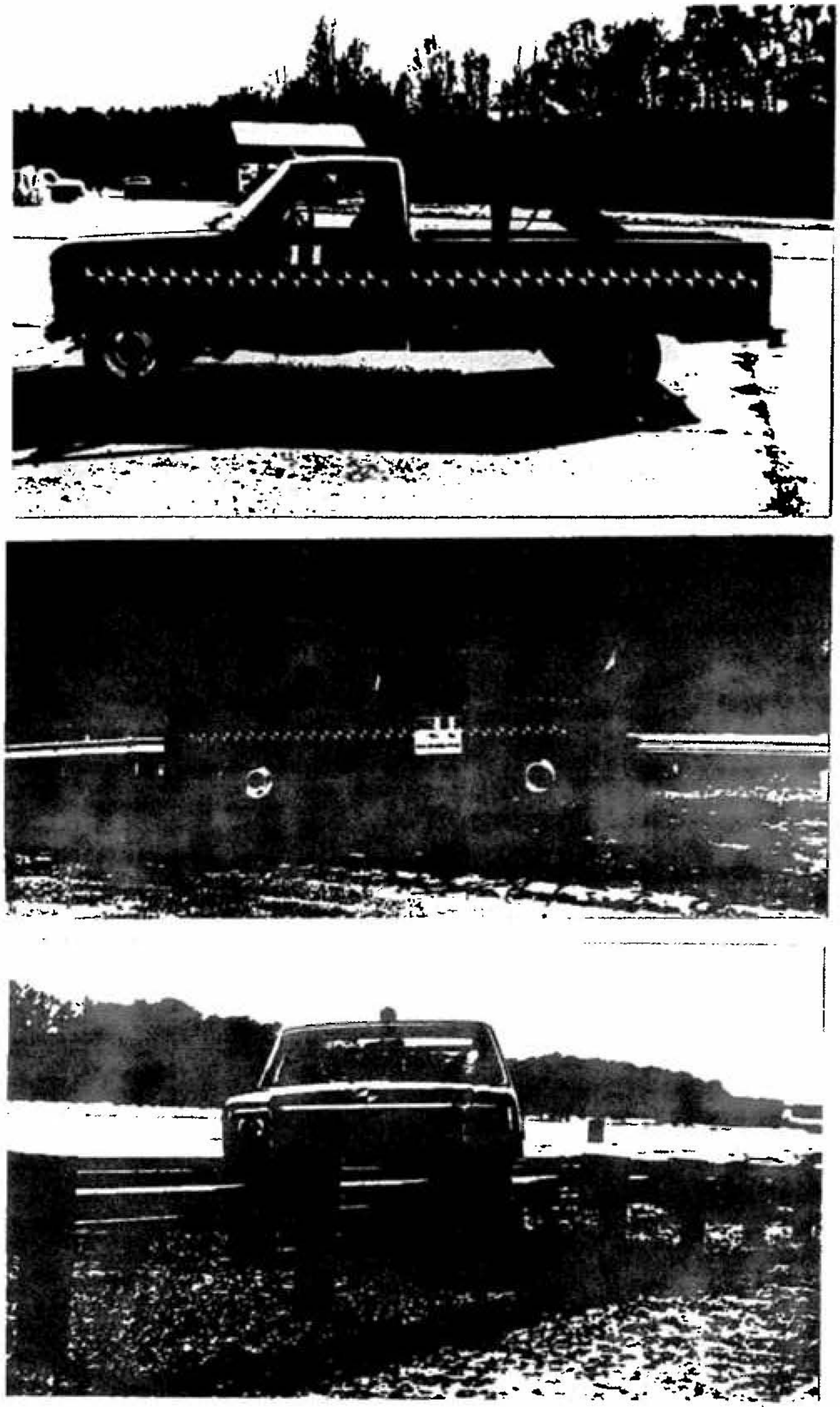
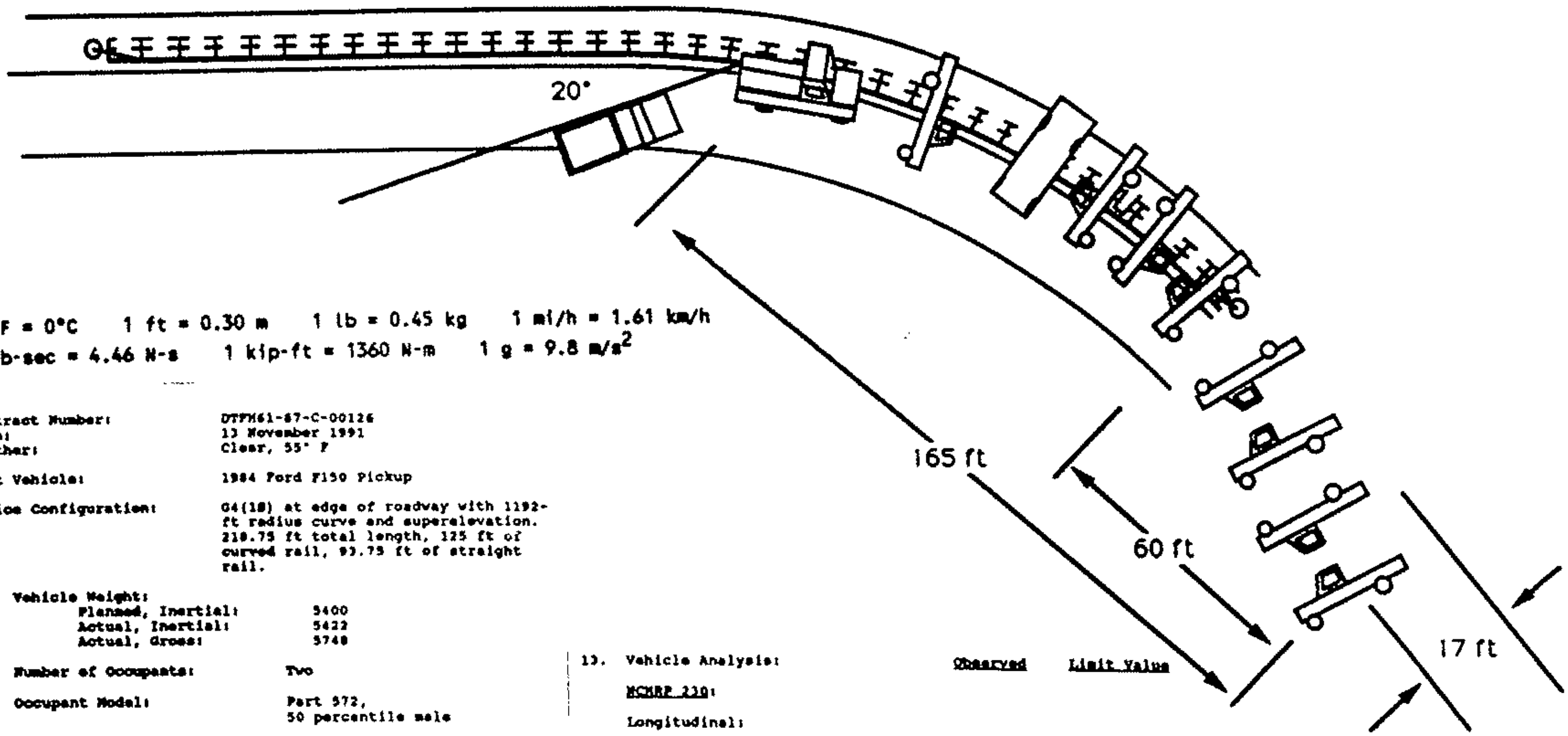


Figure 117. Pretest photographs of test vehicle, test 1862-16-91.



32°F = 0°C 1 ft = 0.30 m 1 lb = 0.45 kg 1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s 1 kip-ft = 1360 N-m 1 g = 9.8 m/s²

Contract Number:	DTFH61-87-C-00126
Date:	13 November 1991
Weather:	Clear, 55° F
Test Vehicle:	1984 Ford F150 Pickup
Device Configuration:	G4(1S) at edge of roadway with 1192-ft radius curve and superelevation. 218.75 ft total length, 125 ft of curved rail, 93.75 ft of straight rail.

1. Vehicle Weight:
   - Planned, Inertial: 5400
   - Actual, Inertial: 5422
   - Actual, Gross: 5748
2. Number of Occupants: Two
3. Occupant Model: Part 572, 50 percentile male
4. Occupant Locations: Driver Seat, Unrestrained; Passenger Seat, Restrained
5. Impact:

	Speed	Angle	Location
Planned:	60.0 mi/h	20°	Midspan posts 19 and 20
Actual:	61.6 mi/h	20°	Midspan posts 19 and 20

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

6. Redirection Angle: Not measured due to roll-over.
7. Redirection Speed: n/a
8. Total Speed Change: n/a
9. Total Momentum Change: n/a
10. Vehicle Damage Index (SAE J224a): 11LDA02
11. AASHTO Test Type: PL2
12. Vehicle-Railing Interaction Coefficient of Friction:

$$\mu = \frac{\cos\theta - V_p/V}{\sin\theta}$$

RU	Assessment
0.64	Marginal

V_p = 44.3 mi/h (64.9 ft/s)

13. Vehicle Analysis:

	Observed	Limit Value
NCHRP 230:		
Longitudinal:		
Delta-V at 2 ft:	-20.5 ft/s	30 ft/s
Ridedown Acceleration:	-6.0 g's	15 g's
Driver:		
Delta-V at 2.29 ft (actual):	-22.2 ft/s	30 ft/s
Ridedown Acceleration:	-4.0 g's	15 g's
Passenger:		
Delta-V at 2.33 ft (actual):	-22.4 ft/s	30 ft/s
Ridedown Acceleration:	-4.0 g's	15 g's
Lateral:		
Delta-V at 1 ft:	-17.0 ft/s	25 ft/s
Ridedown Acceleration:	-10.8 g's	15 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-5.4 g's	
Lateral:	-5.7 g's	

14. Test Results Conclusion:

AASHTO Bridge Rail Specification: TEST ARTICLE FAILS DUE TO VEHICLE ROLL-OVER.

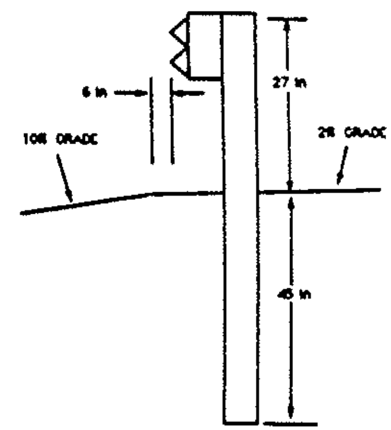
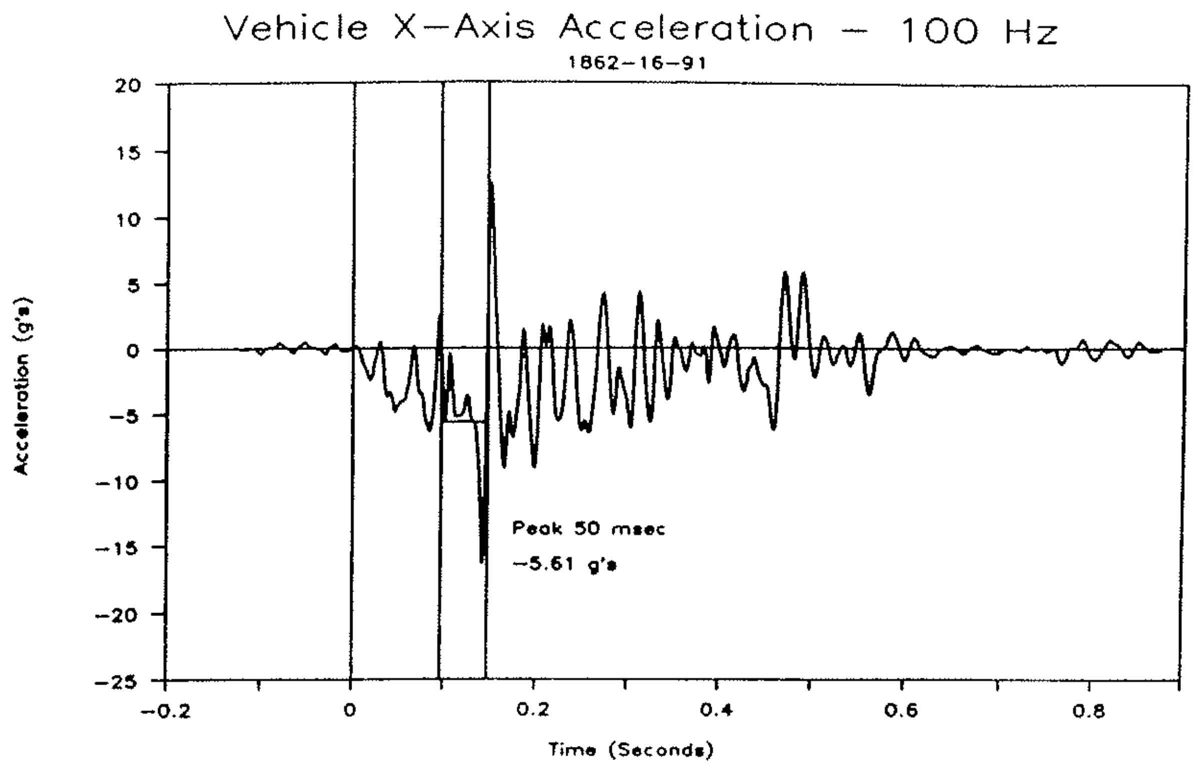


Figure 118. Test summary, test 1862-16-91.



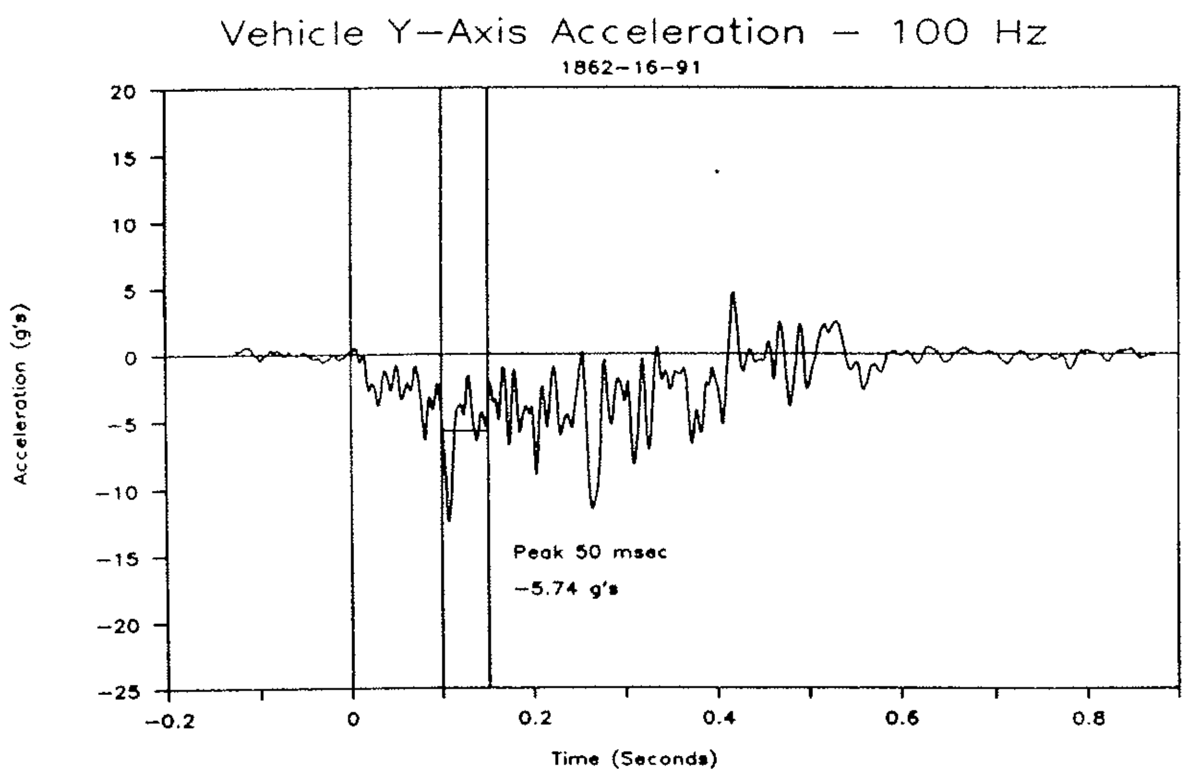


Figure 119. Vehicle accelerations, test 1862-16-91.

Figure 120. Post-test photographs of test vehicle, test 1862-16-91.

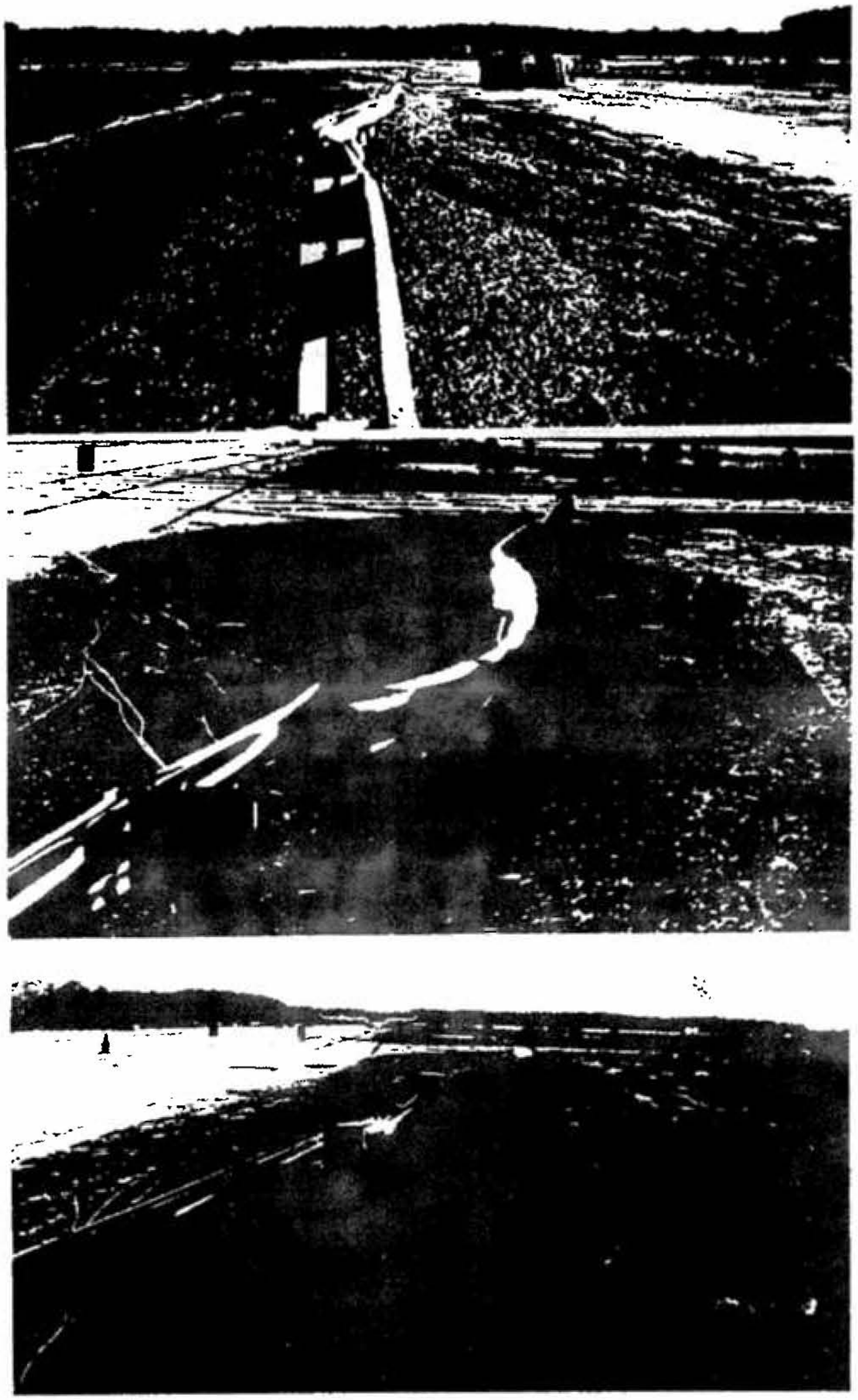


Figure 121. Post-test photographs of guardrail system, test 1862-16-91.

17. TEST 1862-17-92

a. Test Device

The test device was a G4(1S) guardrail with a 6-in (152.4-mm) Type A concrete curb. The entire system was 112.5 ft (34.3 m) long. The concrete curb consisted of a 6-in (152.4-mm) Type A curb with a 12-in (304.8-mm) wide gutter. The front of the gutter was located 12 ft (3.7 m) from the edge of the roadway on a 2-percent downslope. The front face of the curb was located 13 ft (4.0 m) from the edge of roadway. The front face of the rail was 9 in (228.6 mm) behind the curb face. The system was installed so that the height of the rail was 27 in (685.8 mm) from the front of the gutter. For 3 ft (0.9 m) behind the curb, fill dirt was added to make the local grade the same height as the curb. Cable anchor assemblies were used to anchor the rail at both the upstream and downstream ends. Each assembly featured a 1.5-ft (0.5-m) diameter, 5-ft (1.5-m) deep cast-in-place concrete foundation; a 4.5-ft (1.4-m) long, 1.25-in (31.8-mm) diameter hook eye rod; and a single-swaged 0.75-in (19.1-mm) 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 percent) NCHRP 230 S1 strong soil.

Figure 122 shows the test site and test device. Figure 123 shows a rail profile drawing. Figure 124 shows pretest photographs of the guardrail system.

b. Test Vehicle

The test vehicle was a 1984 Ford F150 pickup. The target inertial vehicle weight was 4400 ± 100 lb (2000 ± 45 kg). The vehicle weighed approximately 3900 lb (1770 kg) empty. Approximately 500 lb (227 kg) of ballast and instrumentation were added. The ballasted inertial weight of the truck was 4399 lb (1995 kg). The gross vehicle weight was 4562 lb (2069 kg).

One dummy was placed in the vehicle. This dummy was placed in the driver's seat and was restrained. X-, y-, and z-axis accelerometers and roll and yaw rate gyros were mounted in the cab of the truck. Pretest photographs of the test vehicle are shown in figure 125. Table 28 lists important parameters of the test vehicle. This table is in the format of NCHRP 350.

c. Impact Description

Review of the high-speed films, fifth-wheel, and speed-trap data indicated that the test vehicle impacted at 46.1 mi/h (74.2 km/h) and 25°. This review also indicated that the front left corner of the vehicle impacted the rail at the desired impact point, between posts 5 and 6.

Table 28. Test vehicle parameters, test 1862-17-92.

Item	Actual	Specification
Empty Weight	˜3900 lb (˜1770 kg)	n/a
Ballast	˜500 lb (˜227 kg)	n/a
Total Weight, Inertial	4399 lb (1995 kg)	4400 ± 100 lb (2000 ± 45 kg)
Total Weight, Gross	4562 lb (2069 kg)	n/a
H_{cg}	27 in (69 cm)	27 ± 1 in (70 ± 5 cm)
A (front to cg), Inertial	8.60 ft (2.62 m)	8.5 ± 0.1 ft (2.59 ± .03 m)
B (width)	6.46 ft (1.97 m)	6.5 ft (2.0 m)
Truck Length	215 in (546 cm)	211 ± 10 in (535 ± 25 cm)
Truck Wheelbase	131 in (333 cm)	132 ± 10 in (335 ± 25 cm)
Wheel/Tire Size	235 85R16	
Truck Box Size	8 ft long by 1.5 ft high by 5.5 ft wide (2.4 m long by .46 m high by 1.68 m wide)	
Ground to Box Floor	27 in (69 cm)	27.6 ± 2 in (70 ± 5 cm)

The vehicle impacted the curb first and then the rail. The vehicle's front left wheel impacted the curb face causing the suspension to steer up the curb and into the rail. Upon impact with the rail, the bumper of the vehicle impacted the rail at the vertical center of the W-beam. The rail pushed back as the vehicle penetrated into the rail. The vehicle penetrated approximately 3 ft (0.9 m) into the rail as it redirected. The vehicle sustained heavy damage to the front suspension as a result of snagging on one of the rail posts. As a result of the severe suspension damage, the vehicle's front end buried itself into the ground. At the same time, the rear suspension of the vehicle climbed the curb and unsprung itself. As a result, the rear of the vehicle pitched upward approximately 50° while it rolled approximately 50° towards the left side. The vehicle initially remained in contact with the rail for approximately 20 ft (6.1 m). The vehicle nosed in and continued to yaw to a position over the rail. The vehicle returned to flat and level, impacting the rail from the top, approximately 30 ft (9.2 m) downstream from the impact point. The vehicle did not redirect.

Upon impact, the restrained driver dummy was thrown towards the driver side of the cab. The dummy impacted the driver's side door and window causing the top of the door to bend away from the cab. Although the dummy impacted the driver side-door window and the rear cab window, no windows were broken. The dummy came to rest in the normal riding position.

A summary of test conditions and results are shown in figure 126. Data analysis was performed. The vehicle x- and y-axis 100-Hz data plots are shown in figure 127.

d. Vehicle Damage

The front-half of the vehicle was damaged. The most severe damage occurred to the front left corner of the vehicle. In the front left corner of the vehicle, there were 30 in (762.0 mm) of crush from the front and 30 in (762.0 mm) of crush from the side. The vehicle front suspension sustained severe damage due to its interaction with the curb and the snagging of a post. The front bumper, the grill, and the left fender sustained heavy damage as they were pushed into the engine compartment. The top of the driver door was bent away from the truck 2 in (50.8 mm). The bottom of the door was buckled due to reimpact with the rail. The vehicle frame was bent. There was intrusion into the occupant compartment as the floorboard was crushed up to the clutch and brake pedals. Post-test photographs of the test vehicle are shown in figure 128.

e. Barrier Damage

The concrete curb was not damaged. The guardrail was damaged for 25 ft (7.6 m), beginning at impact. The upstream cable anchor assembly was pulled upwards 2 in (50.8 mm) and downstream 2 in (50.8 mm). The rail had permanent deflection from posts 4 through 9. Post 4 through 9 were pushed back. Post 5 through 7 were also bent. The rail was detached at post 6. The maximum permanent rail deflection occurred at post 7 and was 21 in (533.4 mm). Posts 1 through 3 and 10 through 19 were not damaged. Post-test photographs of the rail are shown in figure 129.

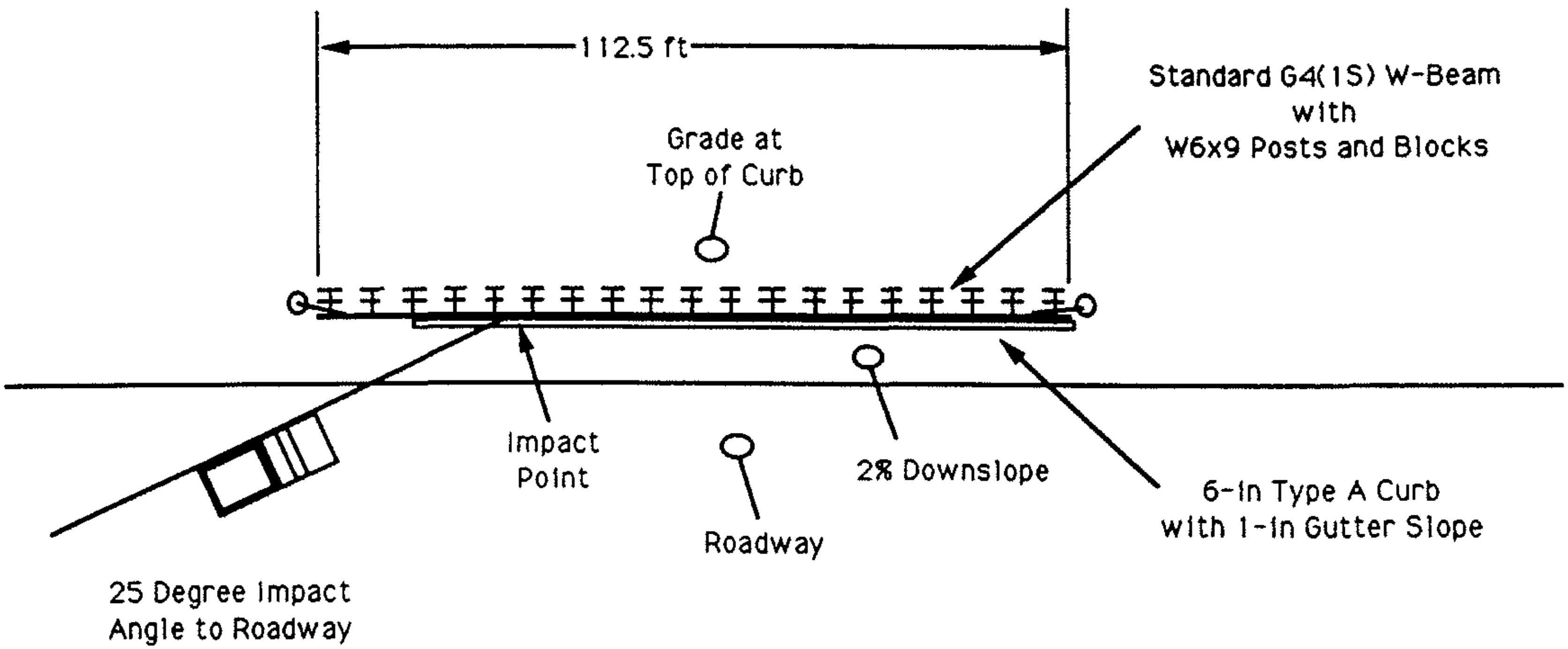
f. Test Evaluation

This test (test designation 2-11) was evaluated using the Recommended Procedures for the Safety Performance Evaluation of Highway Features, NCHRP Report 350. The following is an item-by-item evaluation using this guideline:

Required Criteria:

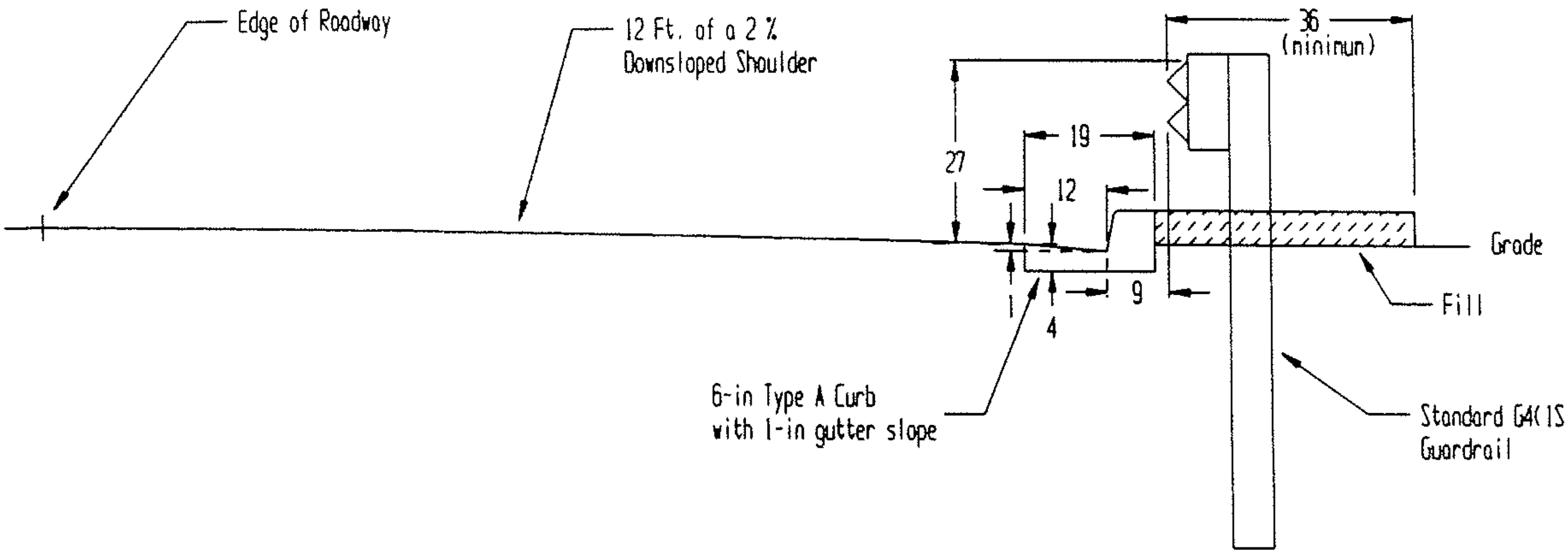
a. The vehicle was contained by the test article.
d. Integrity of the passenger compartment was **NOT** maintained.
f. The vehicle pitched 50° and rolled 50°.
k. The vehicle did not intrude into adjacent traffic lanes.
l. Delta-V and Ridedown values were within limits.
m There was no measurable exit angle as the vehicle did not redirect.

TEST ARTICLE FAILS TO MEET ALL REQUIRED CRITERIA.



1 ft = 0.30 m   1 in = 25.4 mm

Figure 122. Test site layout, test 1862-17-92.



1 ft = 0.30 m   1 in = 25.4 mm

Figure 123. Rail profile, test 1862-17-92.

Figure 124. Pretest photographs of guardrail system, test 1862-17-92.

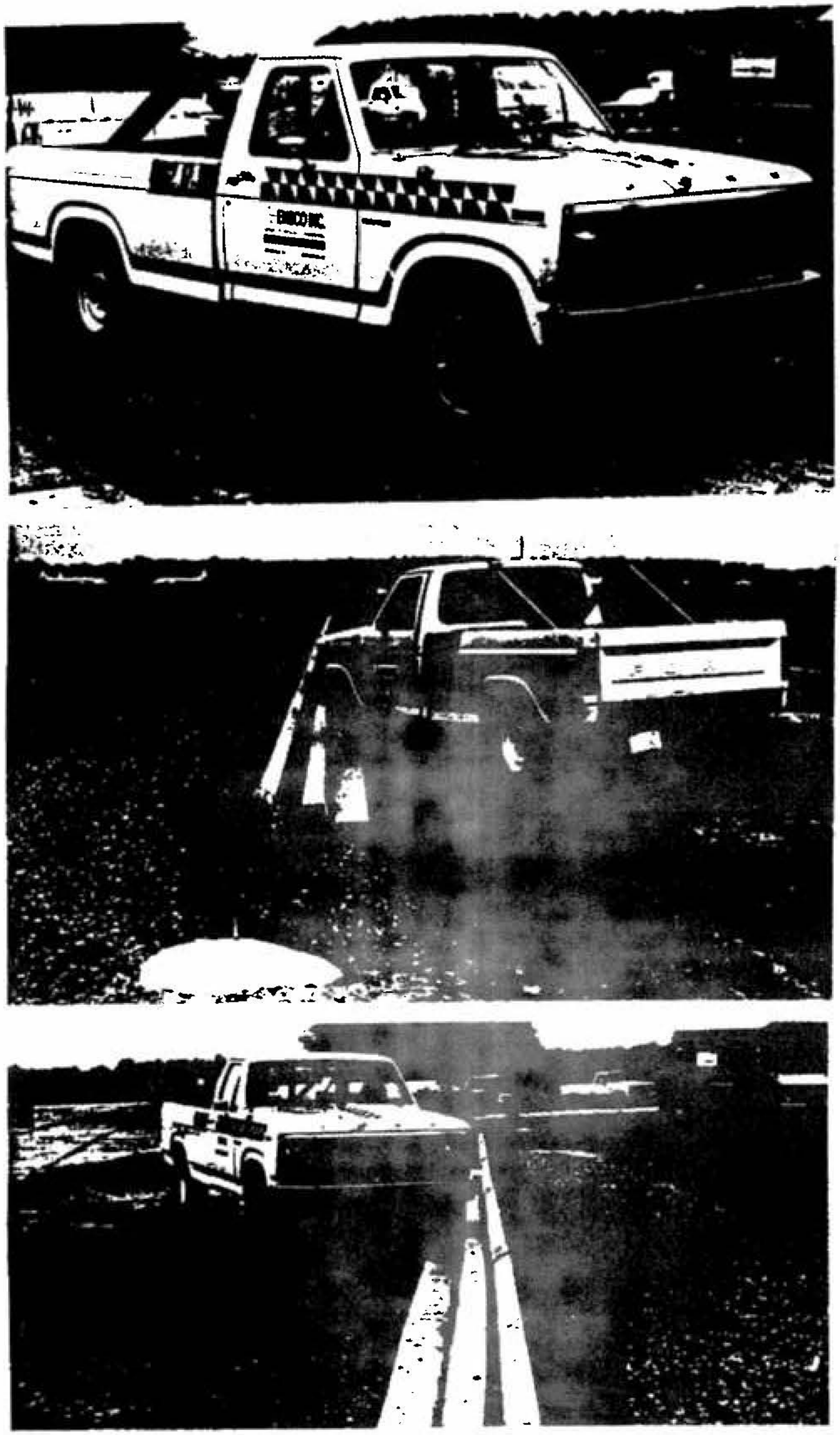
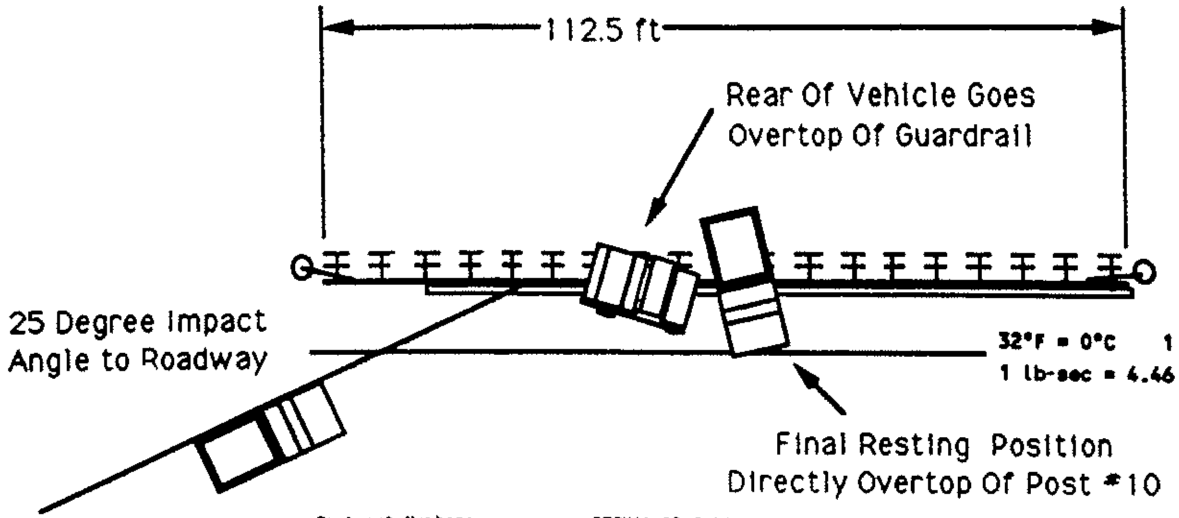


Figure 125. Pretest photographs of test vehicle, test 1862-17-92.



32°F = 0°C   1 ft = 0.30 m   1 lb = 0.45 kg   1 mi/h = 1.61 km/h
1 lb-sec = 4.46 N-s   1 kip-ft = 1360 N-m   1 g = 9.8 m/s^2

Contract Number:	DTFH61-87-C-00126
Date:	27 July 1992
Weather:	Overcast, 75° F
Test Vehicle:	1984 Ford F150 Pickup
Device Configuration:	G4(1S) with a 6-in Type A concrete curb and gutter section. 12 ft of a 2% downsloped shoulder. 1-ft gutter section with 1:12 downslope. 7-in deep curb. Rail face 9-in behind curb face. 27-in rail height in relation to front of gutter section. 112.5 ft total length.

1. Vehicle Weight (lb):
   - Planned, Inertial: 4400 ± 100 (2000 ± 45 kg)
   - Actual, Inertial: 4399 (1995 kg)
   - Actual, Gross: 4562 (2069 kg)
2. Number of Occupants: One
3. Occupant Model: Part 572, 50 percentile male
4. Occupant Location: Driver Seat, Restrained
5. Impact:

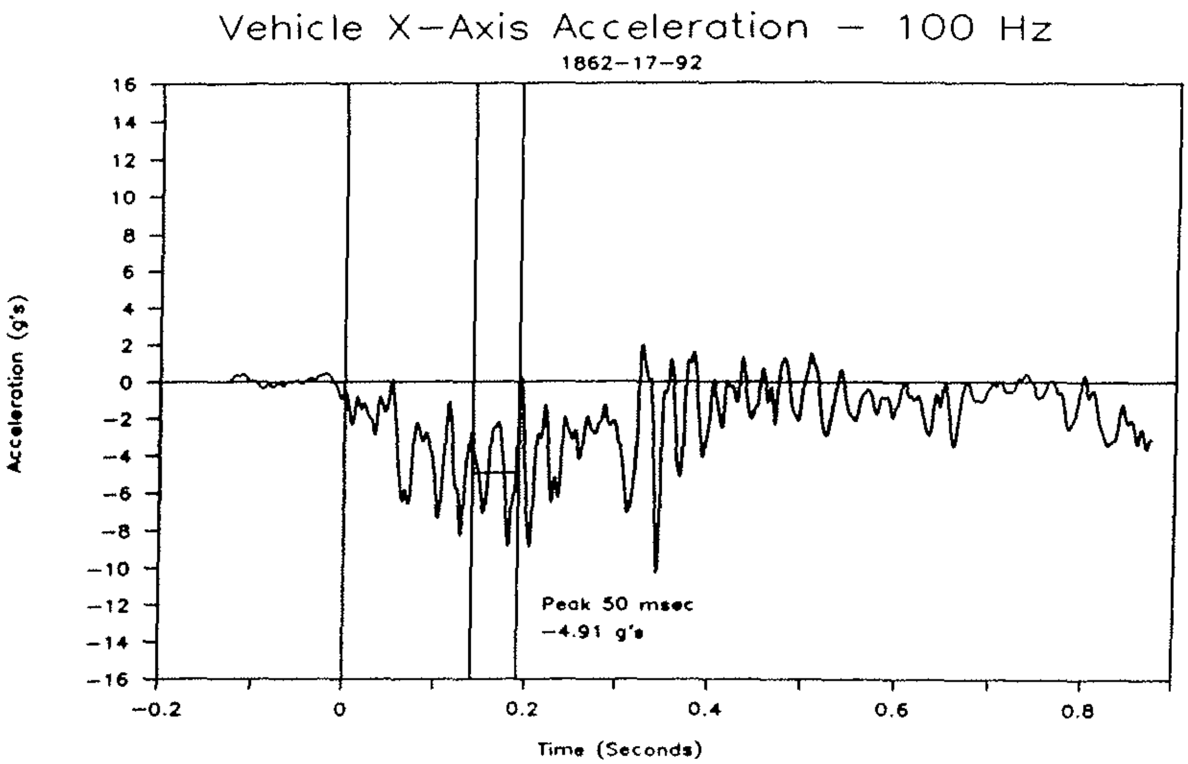
	Speed	Angle	Location
Planned:	45.0 mi/h	25°	Midspan posts 5 and 6
Actual:	46.1 mi/h	25°	Midspan posts 5 and 6

   Tolerances: Speed: ± 1.8 mi/h (± 4 km/h); Angle: ± 1.5 degrees
6. Redirection Angle: No redirection
7. Redirection Speed: No redirection
8. Total Speed Change: 46.1 mi/hr (67.6 ft/s)
9. Total Momentum Change: 9200 lb-s
10. Vehicle Damage Index: (SAE J224a) 11FLEW3
11. Test Type: 2-11
   "Recommended Procedures For The Safety Performance Evaluation Of Highway Features", NCHRP Project 22-7, Third Draft, March 1992, Table 3.1
12. Vehicle Analysis:

	Observed	Limit Value
NCHRP 230:		
LONGITUDINAL:		
Delta-V at 2 ft:	-23.8 ft/s	30 ft/s
Ridedown Acceleration:	-8.0 g's	15 g's
Driver:		
Delta-V at 2.42 ft (actual):	-26.3 ft/s	30 ft/s
Ridedown Acceleration:	-8.1 g's	15 g's
LATERAL:		
Delta-V at 1 ft:	-13.5 ft/s	20 ft/s
Ridedown Acceleration:	-5.8 g's	15 g's
Driver:		
Delta-V at 0.83 ft (actual):	-11.6 ft/s	20 ft/s
Ridedown Acceleration:	-5.8 g's	15 g's
TRC 191:		
Peak 50 ms acceleration:		
Longitudinal:	-4.9 g's	
Lateral:	-3.5 g's	

13. Test Results Conclusion: TEST ARTICLE **FAILS** TO MEET REQUIRED CRITERIA.
   "Recommended Procedures For The Safety Performance Evaluation Of Highway Features", NCHRP Project 22-7, Third Draft, March 1992, Table 5.1

Figure 126. Test summary, test 1862-17-92.



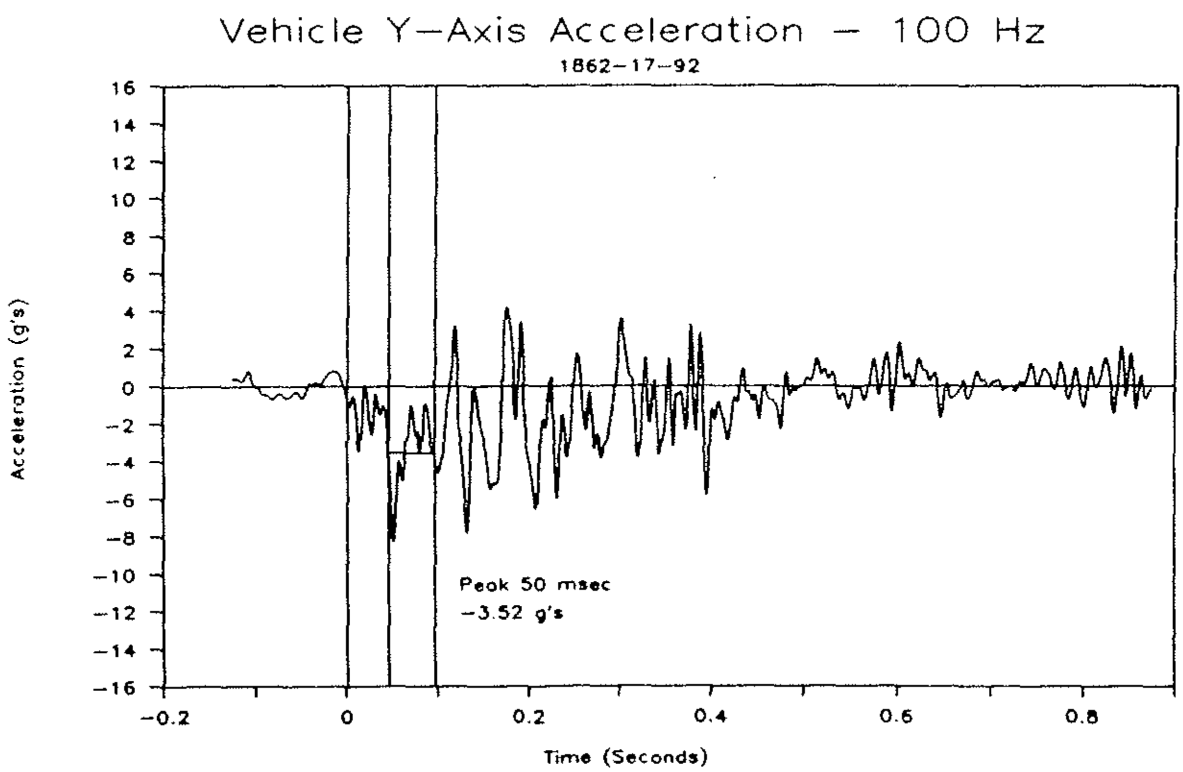


Figure 127. Vehicle accelerations, test 1862-17-92.

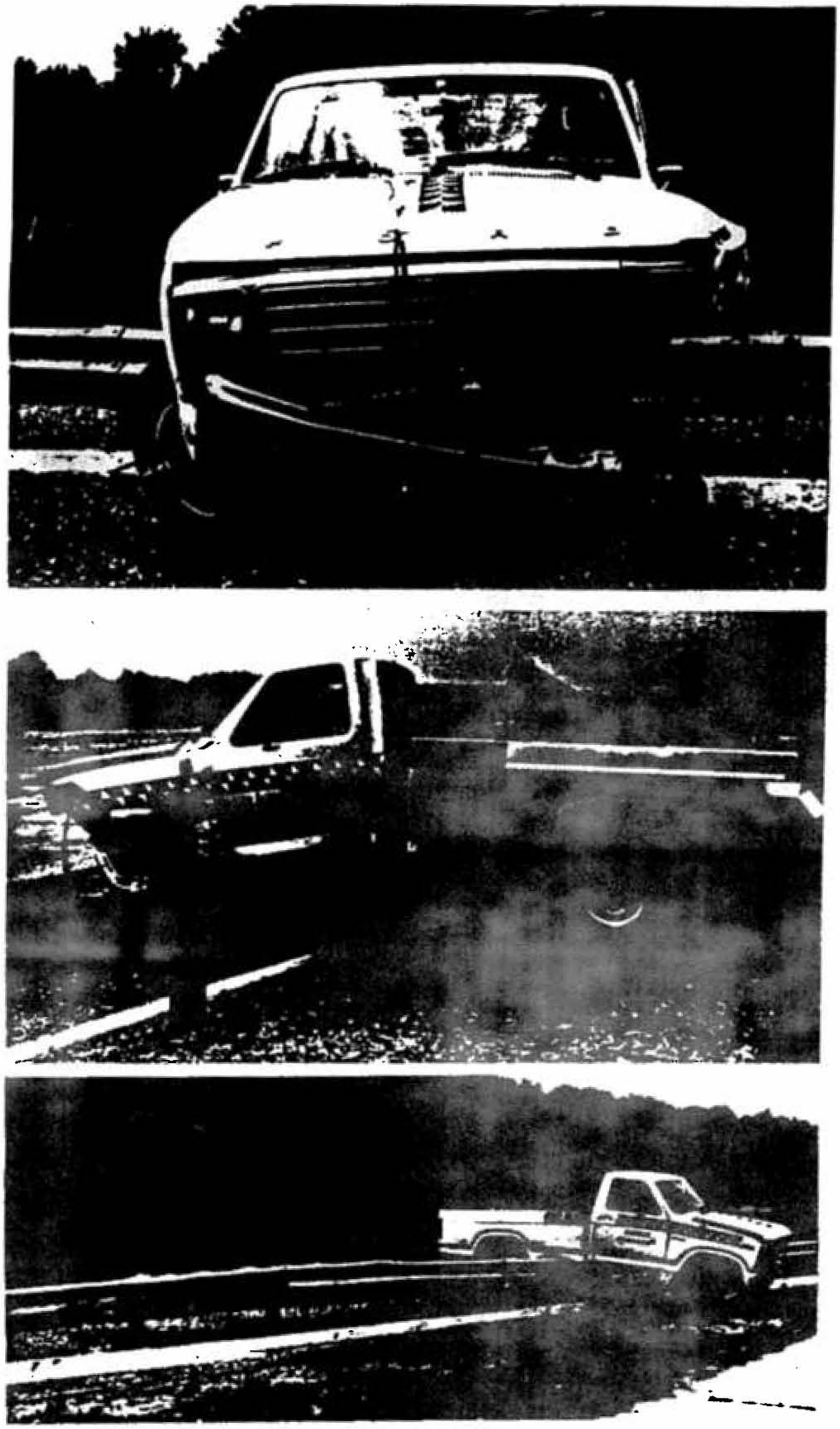


Figure 128. Post-test photographs of test vehicle, test 1862-17-92.

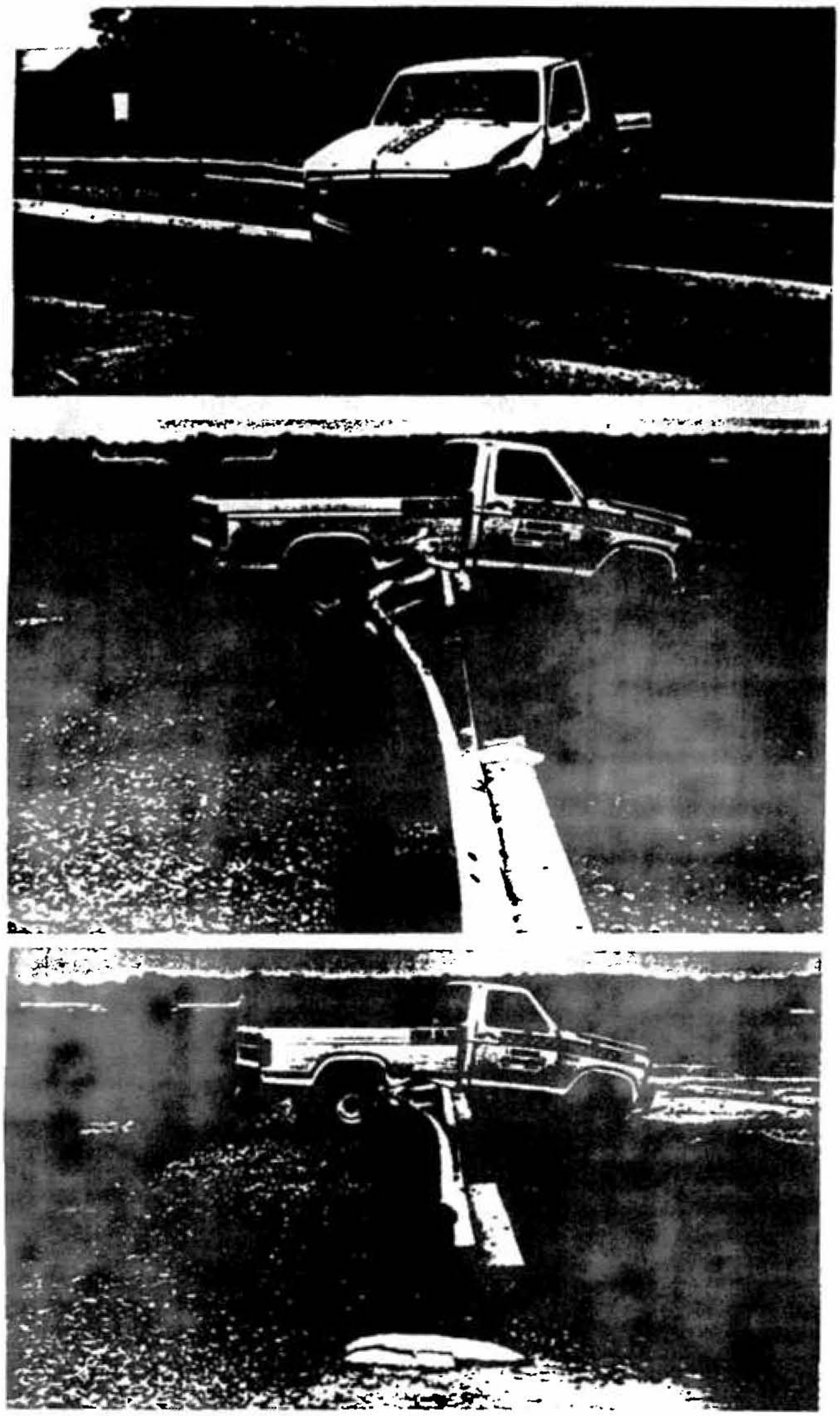


Figure 129. Post-test photographs of guardrail system, test 1862-17-92.

TASK D - PROGRAM VALIDATION

The goal of task D was the validation of a computer program that would correctly model vehicle/barrier impacts. The planned, eight initial tests conducted in task C were to be modeled and validated.

Simulation data files were developed for the first tests conducted in task C. A goal was the modeling of an impact with the 27-in (685.8-mm) high concrete wall in order to conduct the most severe test possible based upon the simulation results.

Work had been conducted using a mainframe version of NARD using the Johns Hopkins University Applied Physics Laboratory computer. When a PC version of NARD became available, it was decided to use only the PC version.

The data sets for the simulation runs were downloaded to the PC and simulations were conducted.

The simulation of the 27-in (685.8-mm) high concrete wall and curb revealed that the critical impact angle was 15° with the 5400-lb (2452-kg) pickup truck. However, the vehicle modeled included only the 5400-lb (2452-kg) pickup truck and the 4500-lb (2043-kg) large car. Once the 1800-lb (817-kg) vehicle was included in the simulations, the critical impact conditions for rollover were: 1800-lb car (817-kg), 60 mi/h (96.6 km/h), and 15°. This test was conducted as test 1862-7-89. No rollover occurred. This error in the simulation was later identified and corrected. The problems encountered are detailed in the following text.

Simulations were conducted for the eight initial tests conducted in task C. These simulations were then validated against the actual test results from task C.

The validation showed generally good results with the exception of the lack of prediction of vaulting when impacting deformable barriers. The simulation for test 1862-1-88 predicted that the pickup truck test vehicle would be redirected by the barrier. This did not agree with the actual results from the test. In the test, the vehicle penetrated into the barrier, rode up on the curb and the rail and vaulted to the rear of the system without any redirection.

The lack of an accurate tire model for the prediction of vertical forces on the test vehicle is one of the problems discovered during the course of this task of the contract.

Other problems with the code for NARD were also discovered during the course of the simulation. One involved an integration error in one of the barrier modules. This error caused the vehicle displacement to be less than the actual displacement. It was later discovered that the error was by a factor of two. This was due to an incorrect timestep used during the integration routine.

Another problem was discovered during review of the validation report. By externally integrating the simulated vehicle velocity trace, it was found that the simulated displacement did not agree with the direct integration of the simulated velocity.

Both of these problems were due to discrepancies in the overlaid version of PCNARD2.0. After comparison with the output from the previous mainframe simulation runs, inconsistencies were discovered.

After fixing the errors in the code, the simulations were rerun. the new simulations made it necessary for the regeneration of the validation report.

Prior to the regeneration of the validation report, however, a detailed examination of the output from the new simulations was conducted. This was done to make sure the results made physical sense prior to the revalidation effort and to ensure that the revalidation would not be a waste of effort, if other inconsistencies were discovered. The examination found that the errors had been corrected, but that NARD continued to contain limitations to accurately simulate complex vehicle/barrier interactions.

It was proposed to revalidate with the new simulation output. The development of ranges of use and limits of applicability for using NARD based upon the validation results was also proposed. It was hoped that the simulation results would be useful up to the time when the vehicle tire loses contact with the barrier. However, as demonstrated in the simulation results for test 1862-1-88, it was not feasible to do this because of the lack of ability to appropriately decide at what point in time that the simulation began to produce incorrect results.

Due to these major difficulties in the simulation effort, it was decided to redirect the remaining contract effort at solving geometric and hardware problems with barriers rather than attempting to create simulation results with unknown reliability.

A tentative simulation matrix for the 80 simulations to be conducted in task E was created prior to the abandonment of the simulation program. No work was conducted on these simulation due to the redirection of effort.

To further investigate the problems in NARD and to solve these problems, a separate task was initiated in a different existing contract.

CONCLUSIONS

The following conclusions are based on the findings of this research project.

1. TRAFFIC BARRIERS ON CURVES, CURBS, AND SLOPES

The first and most important conclusion is a confirmation of the engineering insight that traffic barriers on curves, curbs, and slopes can perform differently than they do when tested as tangent sections installed on flat and level terrain.

From reading this report, this conclusion seems to be extremely obvious, but prior to this contract, very little effort had been devoted to the testing of barriers in non-level conditions with curved rail sections.

Other observations that can be made include a description of the interaction between vehicle and curb. When a vehicle impacts a curb/rail combination, the vehicle suspension is compressed. This produces a force that lifts the vehicle. Another lifting force occurs when a vehicle rides onto a rail after rotation of the rail, due to deflection. This leads to an unbalanced force on the vehicle, which can cause the vehicle to vault a rail or roll over a rail. The compression of the suspension is a function of curb height in curb/rail combinations. The shape of the curb plays a role in the rate of compression and/or the time at which compression begins. For example, the 4-in (101.6-mm) Type H curb is a worst case 4-in curb because it causes the suspension to compress earlier.

The rail deflection can be reduced by stiffening the rail system, thus reducing the potential for vehicle override . This was done with a channel rub rail or with an additional W-beam bolted to the backside of the guardrail posts during the testing effort.

In the case of the concrete wall/concrete brush curb tests, the suspension of the vehicle was compressed by the curb, but no deflection of the wall occurred, eliminating the potential for override. This vertical-shape wall could be a more effective barrier, relative to a standard safety shape.

Conclusions by test article type and/or curve, curb, or slope conditions are contained in the following text.

2. TRAFFIC BARRIERS ON CURVES

a. CURVED GUARDRAIL

Tests 1862-2-89 and 1862-3-89 investigated the performance of a 1192-ft (364-m) radius curved guardrail installation on flat and level terrain. The tests were conducted using the 1800-lb (817-kg) small car at 60 mi/h (96.6 km/h) and 20° and the 5400-lb

(2452-kg) pickup truck at 60 mi/h (96.6 km/h) and 20°. Both tests met all required evaluation criteria. The 1192-ft (363.3-m) curvature of the rail made no appreciable difference in the performance of the tested guardrails.

b. CURVED GUARDRAIL ON SUPERELEVATED SECTION

Tests 1862-6-89, 1862-9-90, 1862-10-90, and 1862-16-91 investigated the performance of a 1192-ft (364-m) radius curved guardrail installed on a superelevated terrain.

The results of these tests are discussed in the section dealing with guardrails on slopes.

3. TRAFFIC BARRIERS WITH CURBS

a. GUARDRAIL WITH 8-IN (203.2-mm) TYPE A CONCRETE CURB

Test 1862-1-88 investigated the performance of a guardrail in combination with an 8-in (203.2-mm) concrete curb using the 5400-lb (2452-kg) pickup truck at 60 mi/h (96.6 km/h) and 20°. This test was not successful. The pickup truck vaulted over the rail.

b. GUARDRAIL WITH 6-IN (152.4-mm) ASPHALT DIKE

Tests 1862-4-89, 1862-5-89, 1862-13-91, and 1862-14-91 investigated the performance of a guardrail in combination with a 6-in (152.4-mm) asphalt dike.

Test 4, with an 1800-lb (817-kg) vehicle at 60 mi/h (96.6 km/h) and 20°, met all required evaluation criteria.

Test 5, with a 4500-lb (2043-kg) vehicle at 60 mi/h (96.6 km/h) and 25° met all required criteria and redirected the vehicle. However, since the car climbed on top of the guardrail, it was clear that this was the barrier's performance limit.

For test 13, with the 4500-lb (2043-kg) test vehicle at 60 mi/h (96.6 km/h) and 25°, the guardrail was stiffened by bolting a W-beam rail mounted on the backside of the posts. This test met all evaluation criteria.

A second modification was utilized for test 14. For this test, a C6x8.2 channel rub rail was mounted below the W-beam rail. The test vehicle was the 4500-lb (2043-kg) large car at 60 mi/h (96.6 km/h) and 25°. This test met all evaluation criteria. This guardrail with the additional rub rail will improve the performance of the guardrail for the wedge-shaped cars that are coming into the vehicle fleet.

c. GUARDRAIL WITH 4-IN (101.6-mm) TYPE H CURB

Test 1862-12-90 investigated the performance of a standard G4(1S) barrier in combination with a 4-in (101.6-mm) type H curb using a

4500-lb (2043-kg) test vehicle at 60 mi/h (96.6 km/h) and 25°. This test met all evaluation criteria. However, this system did not perform as well as the stiffened guardrails used in tests 13 and 14. Stiffening the guardrail produces a better performing system than lowering the height of the curb.

d. GUARDRAIL WITH 6-IN (152.4-mm) TYPE A CURB AND GUTTER

Test 1862-17-92 investigated the performance of a G4(1S) guardrail in combination with a 6-in (152.4-mm) curb and gutter section and a shoulder downslope. This test was conducted with the 4500-lb (2043-kg) pickup truck test vehicle from NCHRP Report 350 at 45 mi/h (72.4 km/h) and 25°. This low-speed test did not meet the evaluation criteria. Integrity of the passenger compartment was not maintained and vehicle pitching and rolling was greater than the specified "moderate." This is the strength test required for NCHRP report 350 test level 2.

e. 27-IN (685.8-mm) VERTICAL CONCRETE WALL WITH 8-IN (203.2-mm) CONCRETE BRUSH CURB

Tests 1862-7-89 and 1862-8-89 investigated the performance of an 8-in (203.2-mm) concrete brush curb in combination with a 27-in (685.8-mm) high concrete wall. The test conditions were chosen based upon the simulation results from the early stages of task D. These two tests were designed to be the critical impact conditions for the test vehicles and test article. The impact conditions were: 1800-lb (817-kg) car, 60 mi/h (96.6 km/h), 15° and 5400-lb (2452-kg) pickup truck, 60 mi/h (96.6 km/h), 10°. Both tests met all evaluation criteria.

4. TRAFFIC BARRIERS ON SLOPES

a. CURVED GUARDRAIL ON SUPERELEVATED SECTION

Tests 1862-6-89, 1862-9-90, 1862-10-90, and 1862-16-91 investigated the performance of a 1192-ft (364-m) radius curved guardrail installed on a superelevated terrain.

Test 6 was conducted with a 5400-lb (2452-kg) pickup truck at 60 mi/h (96.6 km/h) and 20°. This test was not successful. The vehicle stayed on the traffic side of the barrier but rolled over.

Test 9 was an attempt to design a hardware fix for this system configuration. The 5400-lb (2452-kg) pickup truck was used as the test vehicle at 60 mi/h (96.6 km/h) and 20°. The barrier was stiffened by using 7-ft (2.1-m) long posts versus the standard 6-ft (1.8-m) long posts. This test was not successful because of the lateral torsional buckling of the steel posts. The vehicle vaulted the rail and rolled over.

Test 10 investigated the possibility of solving the rollover and vaulting problems by using a high performance guardrail system.

The barrier was the Modified Thrie Beam guardrail. This test also used the 5400-lb (2452-kg) pickup truck at 60 mi/h (96.6 km/h) and 20°. The results of this test met all evaluation criteria.

Test 16 was an attempt to develop a geometric fix for the standard system. For this test, the barrier was moved to the edge of the roadway, in effect moving the barrier approximately 10 ft (3.0 m) down to the edge of the superelevated slope. This geometric fix was intended to eliminate the possibility of the vehicle becoming airborne as it crossed the slope breakpoint between the shoulder and the superelevated section. This test also used a 5400-lb (2452-kg) pickup truck at 60 mi/h (96.6 km/h) and 20°. However, this test was not successful because the vehicle vaulted and rolled.

b. GUARDRAIL ON DOWNSLOPE

Test 1862-15-92 investigated the performance of a standard G4(1S) guardrail installed on an 18-ft (5.5-m) long 6:1 downslope. This test used a 5400-lb (2452-kg) pickup truck at 60 mi/h (96.6 km/h) and 20°. This test met all required evaluation criteria.

5. ACCIDENT DATA ANALYSIS

The accident data seemed to support the crash test results that vehicles can vault over guardrail/curb combinations under certain impact conditions.

The data also supported the fact that barrier performance on curves is not worse than barrier performance on tangents.

As expected, barrier performance and accident severity were found to be worse for cable guardrails with curbs. Cable barriers allow larger deflections, allowing the wheel to contact the curb.

6. COMPUTER SIMULATION

As demonstrated in task D of this research project, computer simulation of vehicle impacts is not a reliable way to evaluate barrier performance. The version of NARD utilized was found to contain limitations so that it could not be used to accurately simulate the complex vehicle/barrier interactions. The development of ranges of use and limits of applicability for using NARD based upon the validation results was attempted. It was hoped that the simulation results would be useful up to the time when the vehicle tire loses contact with the barrier. However, as demonstrated in the simulation results for test 1862-1-88, even this was not feasible because it could not be determined at what point in time the simulation began to produce incorrect results.

At present, computer simulation of vehicle/barrier impacts is not reliable enough to define performance ranges for barriers.

RECOMMENDATIONS

1. TRAFFIC BARRIERS ON CURVES

a. CURVED GUARDRAIL

This 1192-ft (363.3-m) radius curved guardrail showed acceptable performance. If not currently in design standards, this curve radius design should be implemented for new service locations.

b. CURVED GUARDRAIL ON SUPERELEVATED SECTION

The Modified Thrie Beam guardrail was found to be a hardware solution which provides acceptable performance in comparison to the unacceptable performance encountered in the previous tests of this configuration. This should be implemented for retrofit and new service locations.

2. TRAFFIC BARRIERS WITH CURBS

a. GUARDRAIL WITH 8-IN (203.2-mm) TYPE A CONCRETE CURB

A test of a hardware modification such as the addition of a backside W-beam or a channel rubrail should be conducted for this guardrail/curb combination.

b. GUARDRAIL WITH 6-IN (152.4-mm) ASPHALT DIKE

The tests of the guardrails that had been stiffened with a rub rail or an extra W-beam were successful. These hardware modifications should be implemented for retrofit and new service locations.

c. GUARDRAIL WITH 4-IN (101.6-mm) TYPE H CURB

This guardrail/curb combination showed acceptable performance. However, it did not perform as well as the stiffened guardrails. Stiffening the guardrail produces a better performing system than lowering the height of the curb.

d. GUARDRAIL WITH 6-IN (152.4-mm) TYPE A CURB AND GUTTER

This guardrail/curb combination (without hardware modifications) is often found in urban areas. The 4500-lb (2043-kg) pickup truck vaulted over the test barrier even at the lower speed of 45 mi/h (72.4 km/h). Therefore, this curb is not recommended for use.

However, the tests of the hardware modifications such as the addition of a backside W-beam or a channel rubrail were successful for the 6-in (152.4-mm) asphalt dike.

The vaulting problems are caused primarily by compression of the wheel suspension. The amount of compression is a function of the curb height.

This curb should be tested in combination with the stiffening hardware modifications.

e. 27-IN (685.8-mm) VERTICAL CONCRETE WALL WITH 8-IN (203.2-mm) CONCRETE BRUSH CURB

This rigid bridge rail system showed acceptable performance.

Additional crash tests should be conducted in accordance with NCHRP report 350 to verify the performance of the bridge rail at larger impact angles.

3. TRAFFIC BARRIERS ON SLOPES

a. CURVED GUARDRAIL ON SUPERELEVATED SECTION

The Modified Thrie Beam guardrail was found to be a hardware solution which provides acceptable performance in comparison to the unacceptable performance encountered in the previous tests of this configuration. This high-performance guardrail should be implemented for retrofit and new service locations.

b. GUARDRAIL ON DOWNSLOPE

The particular guardrail/downslope combination that was crash tested showed acceptable performance. This configuration is currently in use on some highways. It is recommended for inclusion in design standards for new service locations.

4. ACCIDENT DATA ANALYSIS

As discussed in the task B section, the sample sizes for most of the analyses conducted were small. Larger sample sizes are necessary to verify the conclusions drawn.

5. COMPUTER SIMULATION

The problems identified in NARD should be corrected. At present, computer simulation with NARD is not a reliable way to evaluate barrier performance.

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August 31, 1993

Mr. Charles McDevitt, HSR-20
Federal Highway Administration
Turner-Fairbanks Highway Research Center
6300 Georgetown Pike
McLean, VA 22101

Reference: Contract DTFH61-87-C-00126, Traffic Barriers on Curves, Curbs and Slopes, Revised, Camera-ready Final Report

Dear Mr. McDevitt:

Enclosed is the revised, camera-ready Final Report for Contract DTFH61-87-C-00126, titled "Traffic Barriers on Curves, Curbs, and Slopes."

This is the ORIGINAL of the report and includes all ORIGINAL photographs and figures.

One copy of the revised Final Report will be sent to Mr. Helman, Contracting Officer.

Also enclosed are the FHWA editor's copy and the package of comments.

The Technical Summary will follow soon.

If you have any questions regarding this report, please feel free to contact me at (703) 321-9000.

Sincerely,

ENSCO, Inc.

Dale Stout

Dale Stout
Co-PI

DRS:

cc: E. Embry, ENSCO
T. Helman, FHWA, HCP-32
T-L. Yang, ENSCO