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VOLUME V: APPENDIX D - CRASH TESTING AND EVALUATION OF A WASHINGTON, DC, PL-1 BRIDGE RAIL

by

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FOREWORD

Because of specific needs or constraints of individual states, new or modified roadside safety hardware are being designed and developed on a continuing basis. To ensure that these new or modified designs perform according to established guidelines, full-scale crash testing and evaluation were deemed necessary. The objective of this study is to crash test and evaluate these roadside safety hardware and, where necessary, redesign the devices to improve their impact performance. The three major areas addressed in this study are the impact performance of bridge railings, transitions from guardrails to bridge railings, and end treatments for guardrails and median barriers.

Detailed drawings are presented for documentation, as well as a summary of findings and conclusions for each of the devices tested, and where necessary, recommendations for improvement.

A. George Ostensen, Director
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NOTICE

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16. Abstract

The purpose of this study is to crash test and evaluate new or modified roadside safety hardware and, where necessary, redesign the devices to improve their impact performance. The three major areas addressed in this study are the impact performance of bridge railings, transitions from guardrails to bridge railings, and end treatments for guardrails and median barriers.

This report presents the results of three crash tests conducted on a new Washington, DC historic bridge railing design in accordance with guidelines set forth in the 1989 American Association of State Highway and Transportation Officials (AASHTO) *Guide Specifications on Bridge Railings* for a performance level 1 (PL-1) and National Cooperative Highway Research Program (NCHRP) Report 230. The original bridge rail design was crash tested in the first test (test no. 471470-6) with an 817-kg (1800-lb) passenger car impacting the bridge rail at a nominal impact speed and angle of 80.5 km/h (50 mi/h) and 20 degrees. The original bridge rail design failed to perform satisfactorily. The bridge rail design was then modified and crash tested. The second crash test (test no. 471470-8) was a repeat of the first test on the modified bridge rail design, involving an 817-kg (1800-lb) passenger car impacting the bridge rail at a nominal impact speed and angle of 80.5 km/h (50 mi/h) and 20 degrees. The third test (test no. 471470-9) involved a 2452-kg (5400-lb) pickup truck impacting the bridge rail at a nominal impact speed and angle of 72.5 km/h (45 mi/h) and 20 degrees. The modified bridge rail design was judged to have performed satisfactorily in both tests.

This volume is the fifth in a series of 14 volumes for the final report. The other volumes in the series are: Volume I - Technical Report; Volume II, Appendix A - Crash Testing and Evaluation of a Michigan Thrie-Beam Transition Design; Volume III, Appendix B - Crash Testing and Evaluation of a Guardrail System for Low-Fill Culvert; Volume IV, Appendix C - Crash Testing and Evaluation of a Pennsylvania Transition Design; Volume VI, Appendix E - Crash Testing and Evaluation of a Modified Breakaway Cable Terminal (BCT) Design; Volume VII, Appendix F - Crash Testing and Evaluation of the Minnesota Swing-Away Mailbox Support; Volume VIII, Appendix G - Crash Testing and Evaluation of the Single Slope Bridge Rail; Volume IX, Appendix H - Crash Testing and Evaluation of the NETC PL-2 Bridge Rail Design; Volume X, Appendix I - Crash Testing and Evaluation of a Mini-MELT for a W-Beam, Weak-Post (G2) Guardrail System; Volume XI, Appendix J - Crash Testing and Evaluation of Existing Guardrail Systems; Volume XII, Appendix K - Crash Testing and Evaluation of the MELT; Volume XIII, Appendix L - Crash Testing and Evaluation of the Modified MELT; and Volume XIV, Appendix M - Laboratory and Pendulum Testing of Modified Breakaway Wooden Posts.

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PREFACE

Because of specific needs or constraints of individual states, new or modified roadside safety hardware are being designed and developed on a continuing basis. To ensure that these new or modified designs perform according to established guidelines, full-scale crash testing and evaluation were deemed necessary. The objective of this study is to crash test and evaluate these roadside safety hardware and, where necessary, redesign the devices to improve their impact performance. The three major areas addressed in this study are the impact performance of bridge railings, transitions from guardrails to bridge railings, and end treatments for guardrails and median barriers.

This is Volume V of a 14-volume series of final reports for this study. The 14 volumes are listed as follows:

Volume	Appendix	Title
I		Technical Report.
II	A	Crash Testing and Evaluation of a Michigan Thrie-Beam Transition Design.
III	B	Crash Testing and Evaluation of a Guardrail System for Low-Fill Culvert.
IV	C	Crash Testing and Evaluation of a Pennsylvania Transition Design.
V	D	Crash Testing and Evaluation of a Washington, DC, PL-1 Bridge Rail.
VI	E	Crash Testing and Evaluation of a Modified Breakaway Cable Terminal (BCT) Design.
VII	F	Crash Testing and Evaluation of the Minnesota Swing-Away Mailbox Support.
VIII	G	Crash Testing and Evaluation of the Single Slope Bridge Rail.
IX	H	Crash Testing and Evaluation of the NETC PL-2 Bridge Rail Design.
X	I	Crash Testing and Evaluation of a Mini-MELT for a W-Beam, Weak-Post (G2) Guardrail System.
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XII	K	Crash Testing and Evaluation of the MELT.
XIII	L	Crash Testing and Evaluation of the Modified MELT.
XIV	M	Laboratory and Pendulum Testing of Modified Breakaway Wooden Posts.

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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I. INTRODUCTION

Because of specific needs or constraints of individual states, new or modified roadside safety hardware have been designed and developed recently. To ensure that these new or modified designs perform according to established performance guidelines, full-scale crash testing and evaluation were deemed necessary. The objective of this study is to crash test and evaluate these roadside safety hardware and, where necessary, redesign the tested devices to improve their performance. The three major areas addressed in this study are the impact performance of bridge railings, transitions from guardrails to bridge railings, and end treatments for guardrails and median barriers.

The Washington, DC, Department of Public Works, in cooperation with the Federal Highway Administration (FHWA), has designed a bridge railing that is aesthetically pleasing for use with bridges on highways through historic districts. The bridge railing is to be evaluated with two full-scale crash tests in accordance with requirements for a performance level 1 (PL-1) bridge railing of the 1989 Americam Association of State Highway and Transportation Officials (AASHTO) *Guide Specifications for Bridge Railings*:[1]

1. An 817-kg (1800-lb) passenger car impacting the bridge railing at a nominal speed of 80.5 km/h (50 mi/h) and at an angle of 20 degrees.
2. A 2452-kg (5400-lb) pickup truck impacting the bridge railing at a nominal speed of 72.5 km/h (45 mi/h) and at an angle of 20 degrees.

The first crash test (test no. 7147-6) was conducted on the original design of the Washington, DC, bridge rail, and its performance was judged unsatisfactory. The bumper of the vehicle underrode the beam element of the bridge railing, allowing the front tire to impact and snag severely on the posts. It was then recommended that the bottom TS 102 mm × 76.2 mm × 6.4 mm (4 × 3 × 1/4) box beams be replaced with wider TS 152 mm × 50.8 mm × 6.4 mm (6 × 2 × 1/4) box beams and the box beams be moved forward to be flush with the face of the posts on the traffic side. This modification would reduce the potential of the bumper and the front wheel of the vehicle to underride the beam element and snag on the posts.

Two crash tests were performed on this modified design. The first test was with an 817-kg (1800-lb) passenger car impacting the bridge railing at a nominal speed of 80.5 km/h (50 mi/h) and at an angle of 20 degrees. The modified bridge railing performed satisfactorily in this test with the small vehicle (test no. 7147-8). The second test was with a 2452-kg (5400-lb) pickup traveling at a nominal speed and angle of 72.5 km/h (45 mi/h) and 20 degrees.

This report details the full-scale crash tests and performance evaluation of the Washington, DC, historic bridge railing. Testing and evaluation were performed according to guidelines outlined in National Cooperative Highway Research Program (NCHRP) Report 230[2] and the 1989 AASHTO *Guide Specifications for Bridge Railings*.

II. STUDY APPROACH

2.1 TEST ARTICLE

The overall test installation consisted of a 23.5-m- (77-ft-) long simulated bridge deck and a 22.9-m- (75-ft-) long bridge railing, as shown in figure 1. The simulated bridge deck was attached to an existing simulated bridge deck foundation and cantilevered out for a length of 1.02 m (40 in). It should be noted that the bridge railing is typically used with a sidewalk behind the railing for pedestrian traffic. However, for the purpose of evaluating the impact performance of the bridge railing, the pedestrian sidewalk was not deemed necessary and thus was not included in the test installation. Details of the steel reinforcement are shown in figure 2. The bridge railing sat on top of a 15.2-cm- (6-in-) high curb with cutouts for anchoring the base plates of the metal bridge railing posts.

The original bridge railing design, details of which are shown in figure 3, consisted of a TS 203-mm × 152-mm × 6.4-mm (8-in × 6-in × 1/4-in) box beam welded onto the tops of 152-mm × 102-mm × 12.7-mm (6-in × 4-in × 1/2-in) posts spaced 1.9 m (6 ft, 3 in) center to center. TS 102-mm × 76-mm × 6.4-mm (4-in × 3-in × 1/4-in) box beams were placed between the posts, which were welded to the bottom of the TS 203-mm × 152-mm × 6.4-mm (8-in × 6-in × 1/4-in) box beam and to the sides of the posts. The purpose of these TS 102-mm × 76-mm × 6.4-mm (4-in × 3-in × 1/4-in) box-beam sections was to reduce the height of the opening beneath the TS 203-mm × 152-mm × 6.4-mm (8-in × 6-in × 1/4-in) box beam.

The bridge railing was fabricated in four sections, each 5.7 m (18 ft, 8 in) in length. The sections were connected with joint sleeves and welded in place after installation. The bridge railing would typically have an expansion joint and anchorage at both ends. However, these details were deemed unnecessary for the purpose of evaluating the impact performance of the bridge railing and thus were not included for the test installation.

Each railing post was welded to a 305-mm × 305-mm × 25.4-mm (12-in × 12-in × 1-in) base plate and attached to the simulated bridge deck using four 32-mm- (1-1/4-in-) diameter high-strength bolts that were built into the bridge deck with an anchor plate. Grout pads, approximately 25.4-mm (1-in) thick, were used under the base plates to level the bridge railing and to adjust the height of the bridge railing to 686 mm (27 in). The cutouts were then backfilled with concrete after installation of the metal bridge railing. Photographs of the completed test installation are shown in figure 4.

The first crash test (test no. 7147-6) with an 820-kg passenger car was conducted on the original design of the Washington, DC, bridge rail, and its performance was judged to be unsatisfactory. The bumper of the vehicle underrode the beam element of the bridge railing, allowing the front tire to impact and snag severely on the posts. It was then recommended that the bottom TS 102-mm × 76.2-mm × 6.4-mm (4-in × 3-in × 1/4-in) box beams be replaced with wider TS-152 mm × 50.8-mm × 6.4-mm (6-in × 2-in × 1/4-in) box beams and that the box beams be moved forward to be flush with the face of the posts on the traffic side.

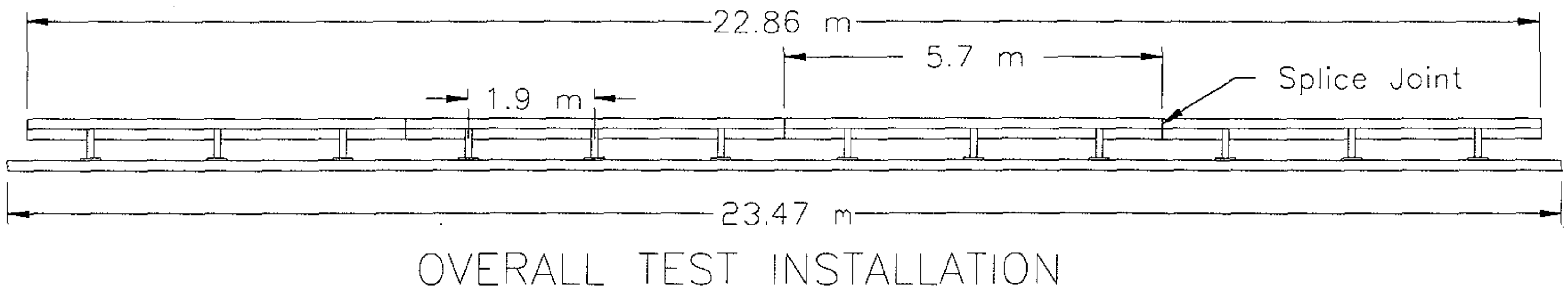
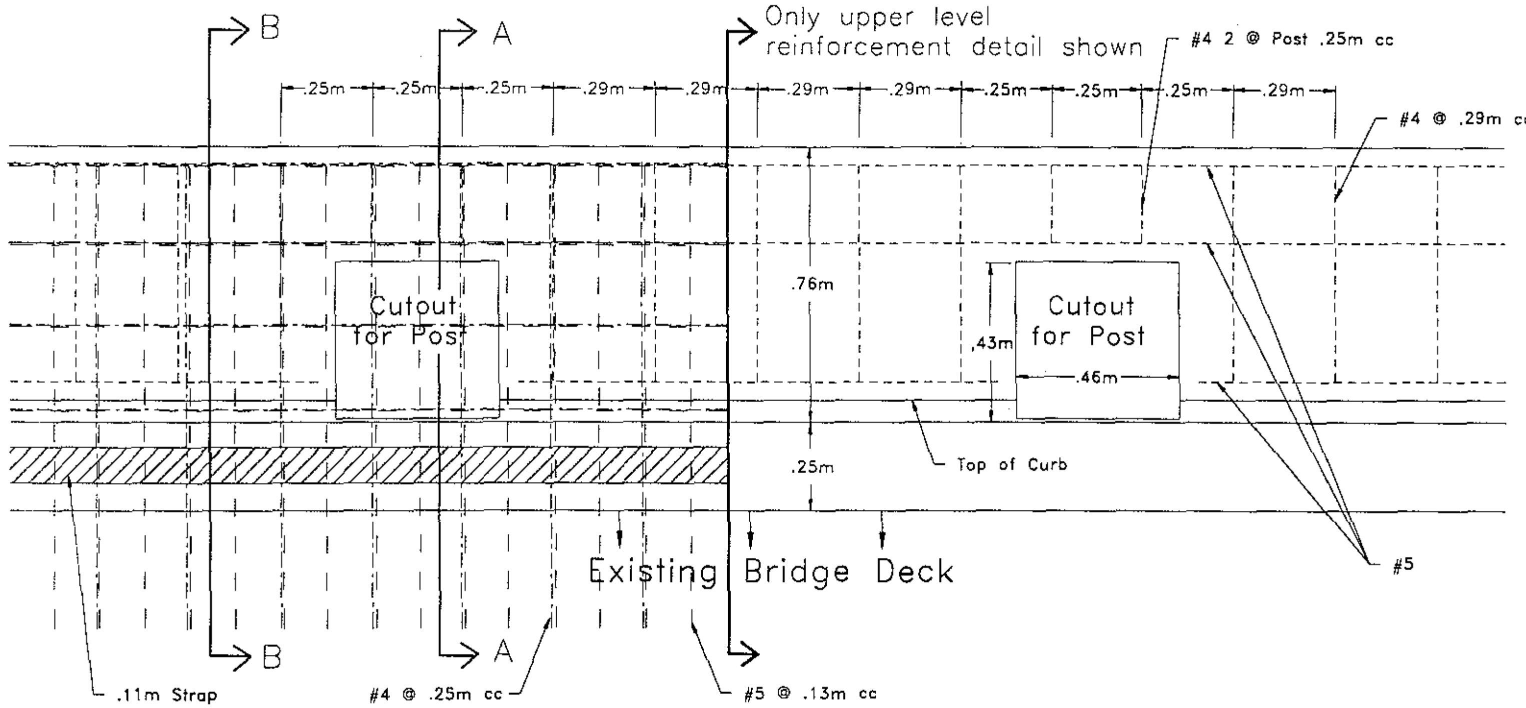
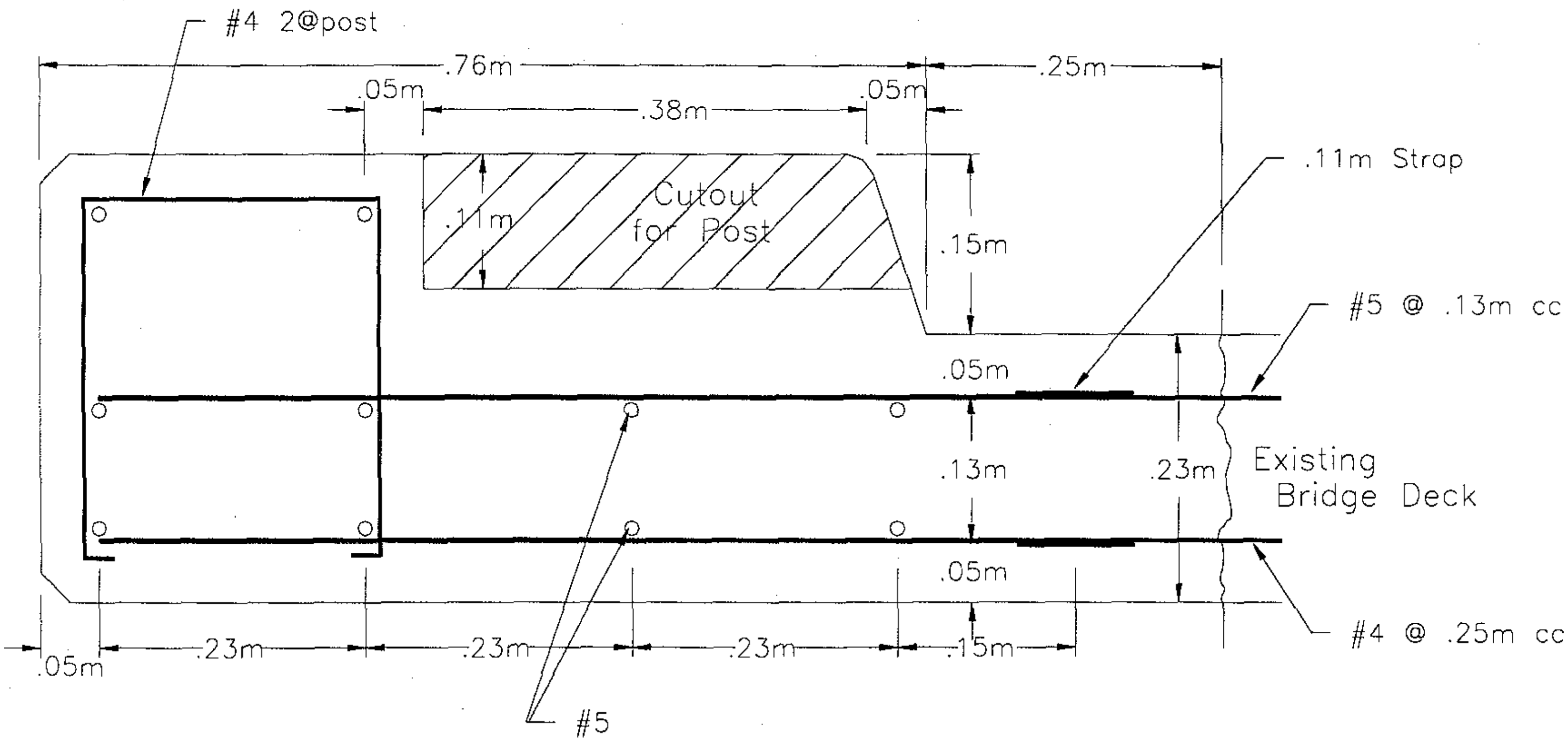


Figure 1. Washington, DC, historic bridge rail overall test installation.



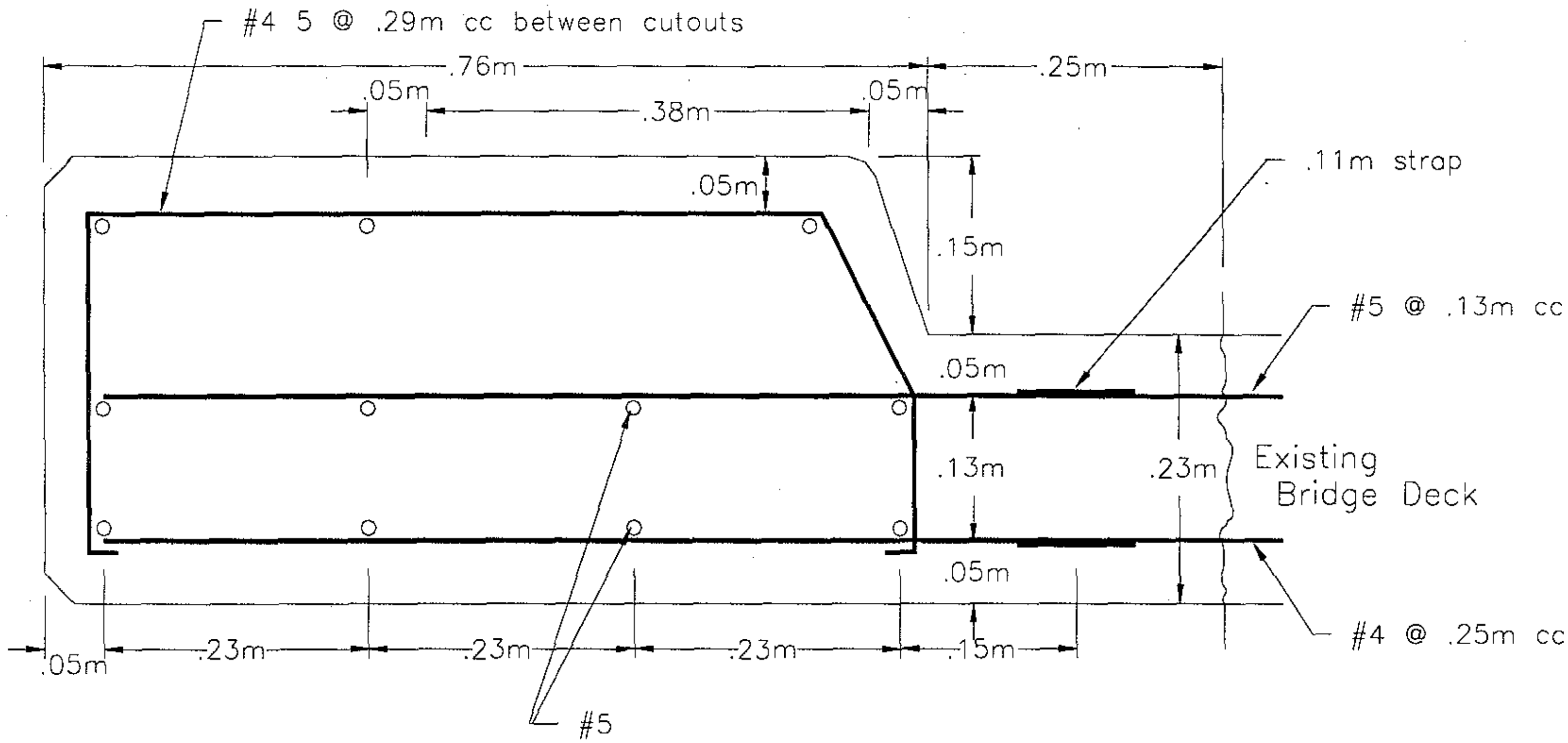
PLAN VIEW OF REINFORCEMENT DETAILS

Figure 2. Steel reinforcement details for Washington, DC, historic bridge rail.



SECTION A–A

Figure 2. Steel reinforcement details for Washington, DC, historic bridge rail (continued).



SECTION B-B

Figure 2. Steel reinforcement details for Washington, DC, historic bridge rail (continued).

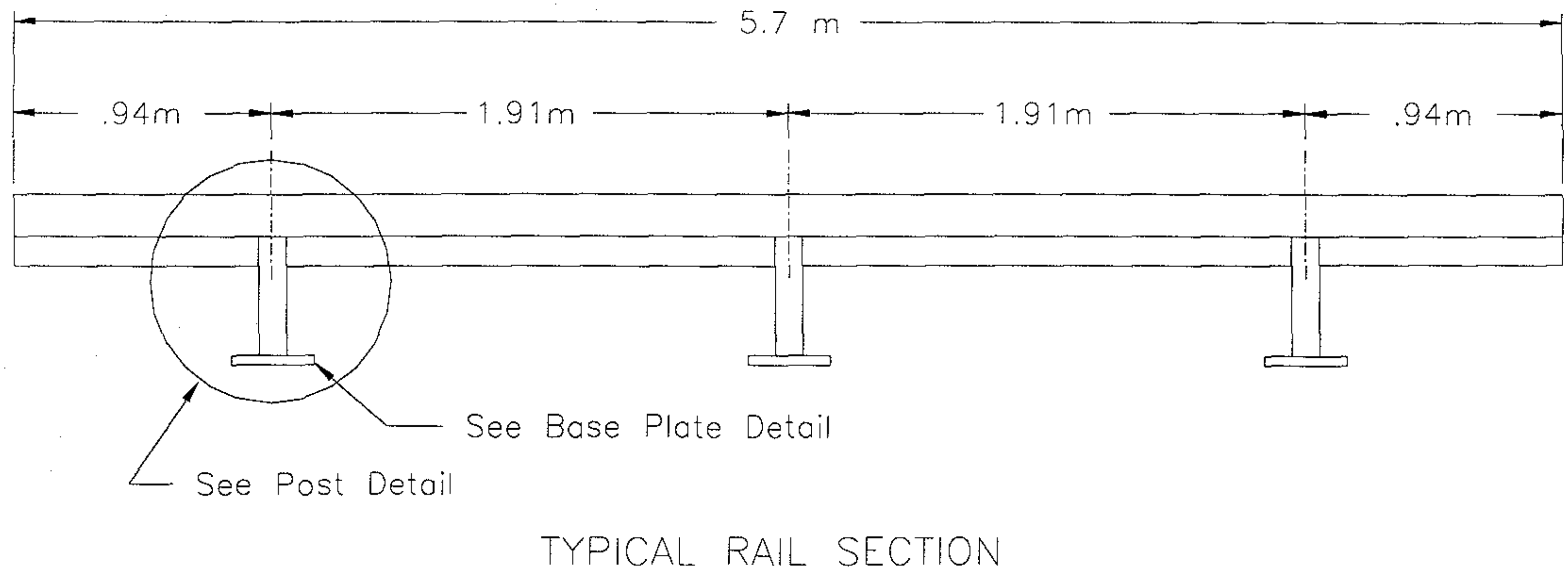


Figure 3. Details of metal bridge railing for Washington, DC, historic bridge rail.

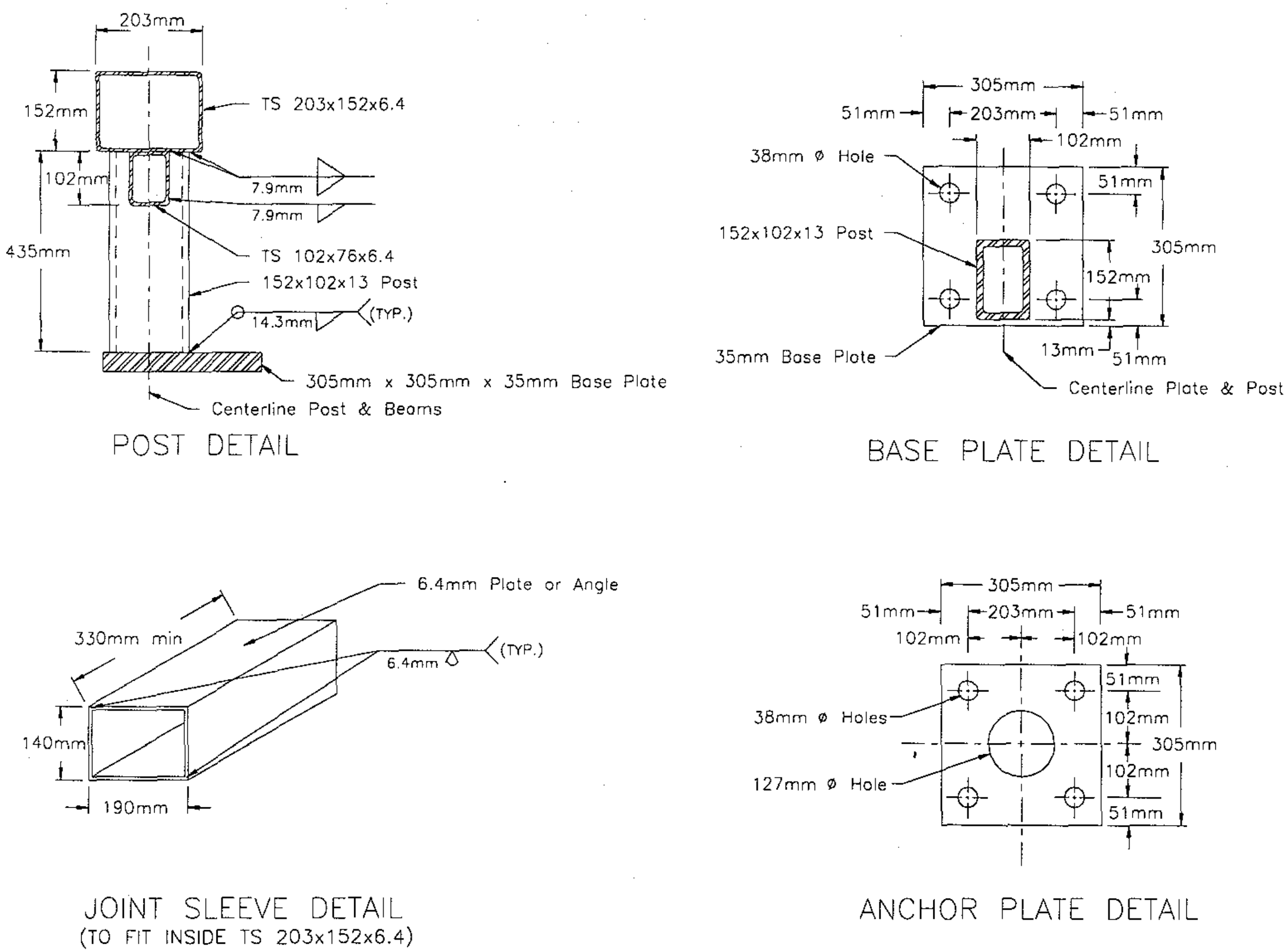


Figure 3. Details of metal bridge railing for Washington, DC, historic bridge rail (continued).

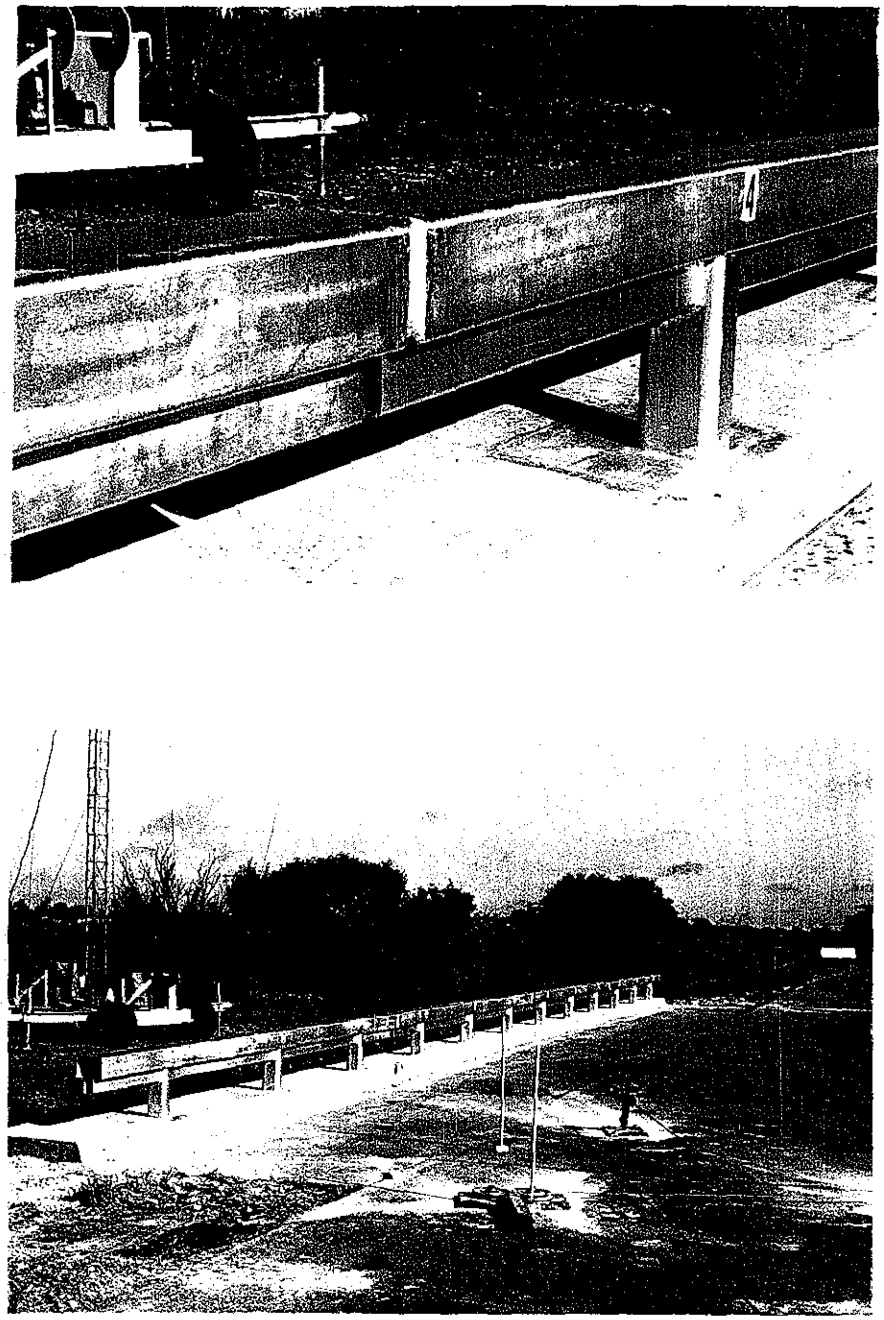


Figure 4. Washington, DC, historic bridge rail (before test 7147-6).

These box beams were welded to the bottom of the TS 203-mm × 152-mm × 6.4-mm (8-in × 6-in × 1/4-in) box beam and to the sides of the posts. This modification would reduce the height of the opening beneath the beam element and thus reduce the potential of the bumper and the front wheel of the vehicle to underride the beam element and snag on the posts. The modified bridge rail design was then crash tested in the next two crash tests (test nos. 471470-8 and 471470-9). Photographs of the modified test installation are shown in figures 5 and 6.

2.2 CRASH TEST CONDITIONS

The Washington, DC historic bridge railing was evaluated with two full-scale crash tests in accordance with requirements for a performance level 1 (PL-1) bridge railing of the 1989 AASHTO *Guide Specifications for Bridge Railings*: [1]

1. An 817-kg (1800-lb) passenger car impacting the bridge railing at a nominal speed of 80.5 km/h (50 mi/h) and at an angle of 20 degrees.

2. A 2452-kg (5400-lb) pickup truck impacting the bridge railing at a nominal speed of 72.5 km/h (45 mi/h) and at an angle of 20 degrees.

As mentioned previously, a total of three crash tests were conducted, including a small car test on the original bridge rail design, which failed to perform satisfactorily, and then the two tests on the modified bridge rail design.

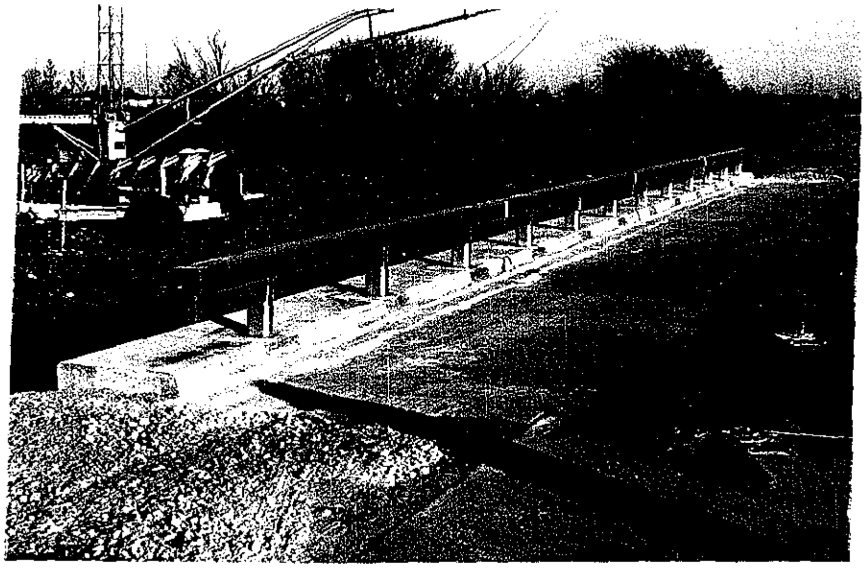
2.3 CRASH TEST AND DATA ANALYSIS PROCEDURES

The crash test and data analysis procedures were in accordance with guidelines presented in NCHRP Report 230.[2] Brief descriptions of these procedures are presented as follows.

2.3.1 Electronic Instrumentation and Data Processing

The test vehicle was instrumented with three solid-state angular rate transducers to measure roll, pitch and yaw rates; a triaxial accelerometer near the vehicle center of gravity to measure longitudinal, lateral, and vertical acceleration levels; and a backup biaxial accelerometer in the rear of the vehicle to measure longitudinal and lateral acceleration levels. The accelerometers were strain-gauge type with a linear millivolt output proportional to acceleration.

The electronic signals from the accelerometers and transducers were transmitted to a base station by means of constant bandwidth FM/FM telemetry link for recording on magnetic tape and for display on a real-time strip chart. Provision was made for the transmission of calibration signals before and after the test, and an accurate time reference signal was



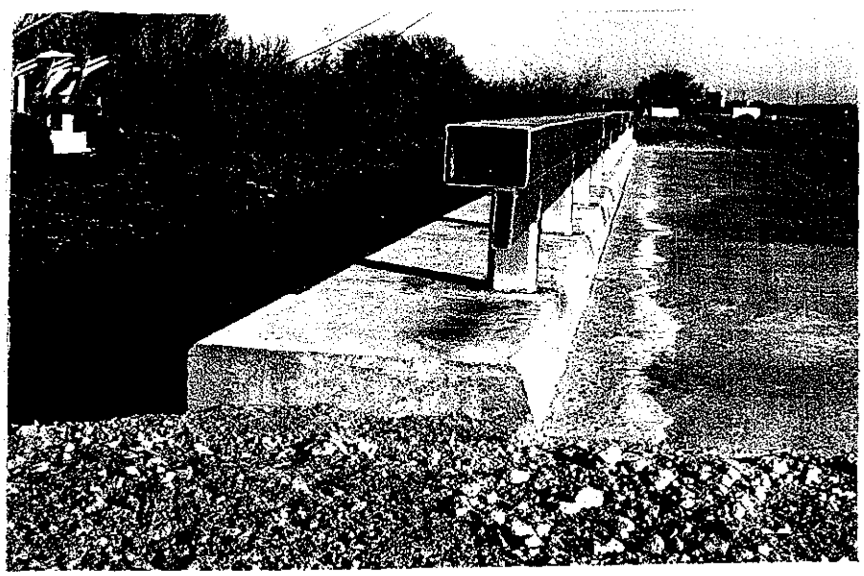
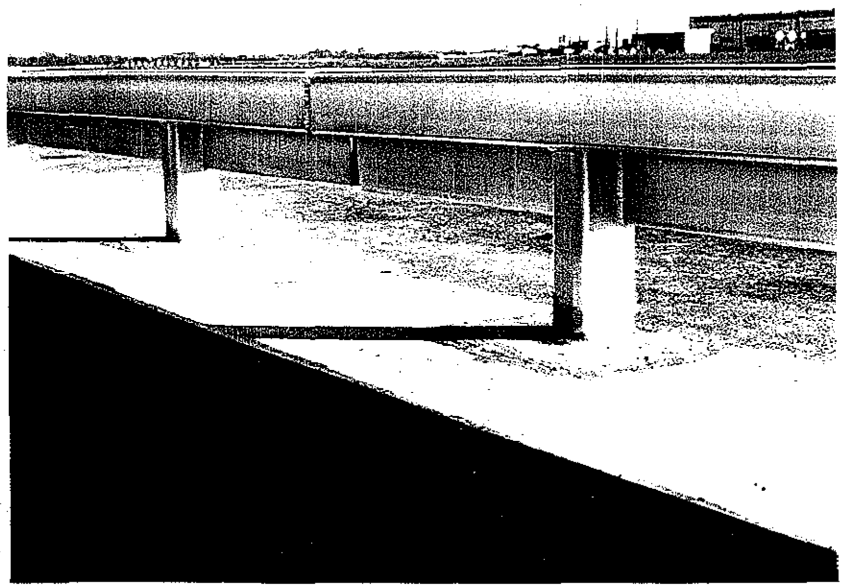


Figure 5. Washington, DC, historic bridge rail before testing (overall view).



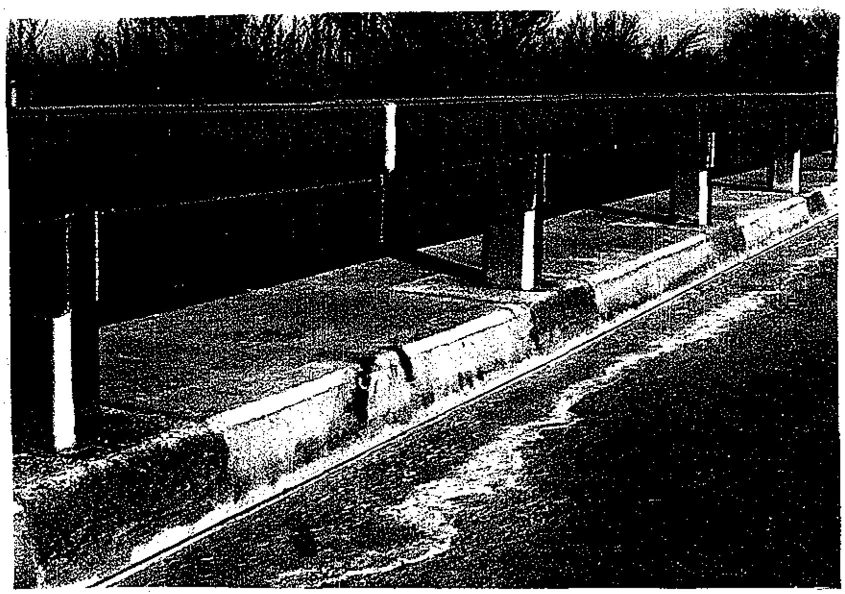


Figure 6. Washington, DC, historic bridge rail before testing (front and rear view).

simultaneously recorded with the data. Pressure-sensitive contact switches on the bumper were actuated just prior to impact by wooden dowels to indicate the elapsed time over a known distance to provide a measurement of impact velocity. The initial contact also produced an "event" mark on the data record to establish the exact instant of contact with the bridge railing.

The multiplex of data channels, transmitted on one radio frequency, was received at the data acquisition station, and demultiplexed into separate tracks of Intermediate Range Instrumentation Group (I.R.I.G.) tape recorders. After the test, the data were played back from the tape machines, filtered with a Class 180 filter, and digitized using a microcomputer, for analysis and evaluation of performance. The digitized data were then processed using two computer programs: DIGITIZE and PLOTANGLE. Brief descriptions of the functions of these two computer programs are provided as follows.

The DIGITIZE program uses digitized data from vehicle-mounted linear accelerometers to compute occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and the highest 0.010-s average ridedown acceleration. The DIGITIZE program also calculates a vehicle impact velocity and the change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 0.050-s intervals in each of the three directions are computed. Acceleration versus time curves for the longitudinal, lateral, and vertical directions are then plotted from the digitized data of the vehicle-mounted linear accelerometers using a commercially available software package (QUATTRO PRO).

The PLOTANGLE program uses the digitized data from the yaw, pitch, and roll rate transducers to compute angular displacement in degrees at 0.001-s intervals and then instructs a plotter to draw a reproducible plot: yaw, pitch, and roll versus time. These displacements are in reference to the vehicle-fixed coordinate system, with the initial position and orientation of the vehicle-fixed coordinate system being that which existed at initial impact.

2.3.2 Anthropomorphic Dummy Instrumentation

An Alderson Research Laboratories Hybrid II, 50th-percentile male anthropomorphic dummy, restrained with lap and shoulder belts, was placed in the driver's position of the vehicle. The dummy was uninstrumented; however, a high-speed onboard camera recorded the motions of the dummy during the test.

2.3.3 Photographic Instrumentation and Data Processing

Photographic coverage of the test included four high-speed cameras: one from the back of the bridge railing; one overhead with a field of view perpendicular to the ground and directly over the impact point; and a third placed to have a field of view parallel to and aligned with the bridge railing at the downstream end. A high-speed camera was also placed onboard the vehicle to record the motions of the dummy placed in the driver seat during the test sequence. A flashbulb activated by pressure-sensitive tape switches was positioned on the impacting vehicle to indicate the instant of contact with the bridge railing and was visible from each camera. The films from these high-speed cameras were analyzed on a computer-linked Motion Analyzer to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A 16-mm movie cine, a 3/4-in videotape camcorder and still cameras were used for documentary purposes and to record conditions of the test vehicle and bridge railing before and after the test.

2.3.4 Test Vehicle Propulsion and Guidance

The test vehicle was towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding the test vehicle was stretched along the path, anchored at each end, and threaded through an attachment to the front wheel of the test vehicle. Another steel cable was connected to the test vehicle, passed around a pulley near the impact point, through a pulley on the tow vehicle, and then anchored to the ground such that the tow vehicle moved away from the test site. A 2 to 1 speed ratio between the test and tow vehicle existed with this system.

III. CRASH TEST RESULTS

A total of three crash tests were conducted on the Washington, DC, historic bridge rail design, including:

1. Test no. 471470-6. An 817-kg (1800-lb) passenger car impacting the original bridge railing design at a nominal speed of 80.5 km/h (50 mi/h) and at an angle of 20 degrees.

2. Test no. 471470-8. An 817-kg (1800-lb) passenger car impacting the modified bridge railing design at a nominal speed of 80.5 km/h (50 mi/h) and at an angle of 20 degrees.

3. Test no. 471470-9. A 2452-kg (5400-lb) pickup truck impacting the modified bridge railing design at a nominal speed of 72.5 km/h (45 mi/h) and at an angle of 20 degrees.

Detailed descriptions of the three crash tests are presented in the following sections.

3.1 TEST NO. 471470-6

A 1987 Yugo GV, shown in figures 7 and 8, was used for this crash test on the original bridge railing design. Test inertia weight of the vehicle was 817 kg (1800 lb) and its gross static weight was 894 kg (1970 lb). The height to the lower edge of the vehicle bumper was 343 mm (13.5 in) and it was 470 mm (18.5 in) to the upper edge of the bumper. Additional dimensions and information on the vehicle are given in figure 9. The vehicle was directed into the bridge railing using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact.

3.1.1 Test Description

The vehicle impacted the bridge railing midspan between posts 3 and 4, or approximately 5.72 m (18 ft 9 in) downstream from the upstream end of the bridge railing, at a speed of 82.4 km/h (51.2 mi/h) and at an angle of 20.1 degrees. As the vehicle bumper contacted the bridge rail, the left front tire contacted the curb at the same time. At 0.028 s after initial impact, the left front tire appeared to partially air out. At 0.030 s after initial impact, the vehicle bumper hit post 4 and the vehicle began to redirect. The left front tire of the vehicle mounted the curb at 0.033 s and contacted post 4 at 0.053 s, at which time the roof of the vehicle began to buckle. Tire marks indicated that the left front tire folded and went underneath the box beam and overlapped post 4 by a distance of 254 mm (10 in). At 0.059 s, the tires began to pull to the left. The front bumper began to come apart at approximately 0.072 s and was extending out behind the rail at 0.080 s. There was sudden left steer input again at 0.087 s. The front bumper of the vehicle contacted post 5 at 0.134 s. At

Figure 7. Vehicle prior to test 7147-6.

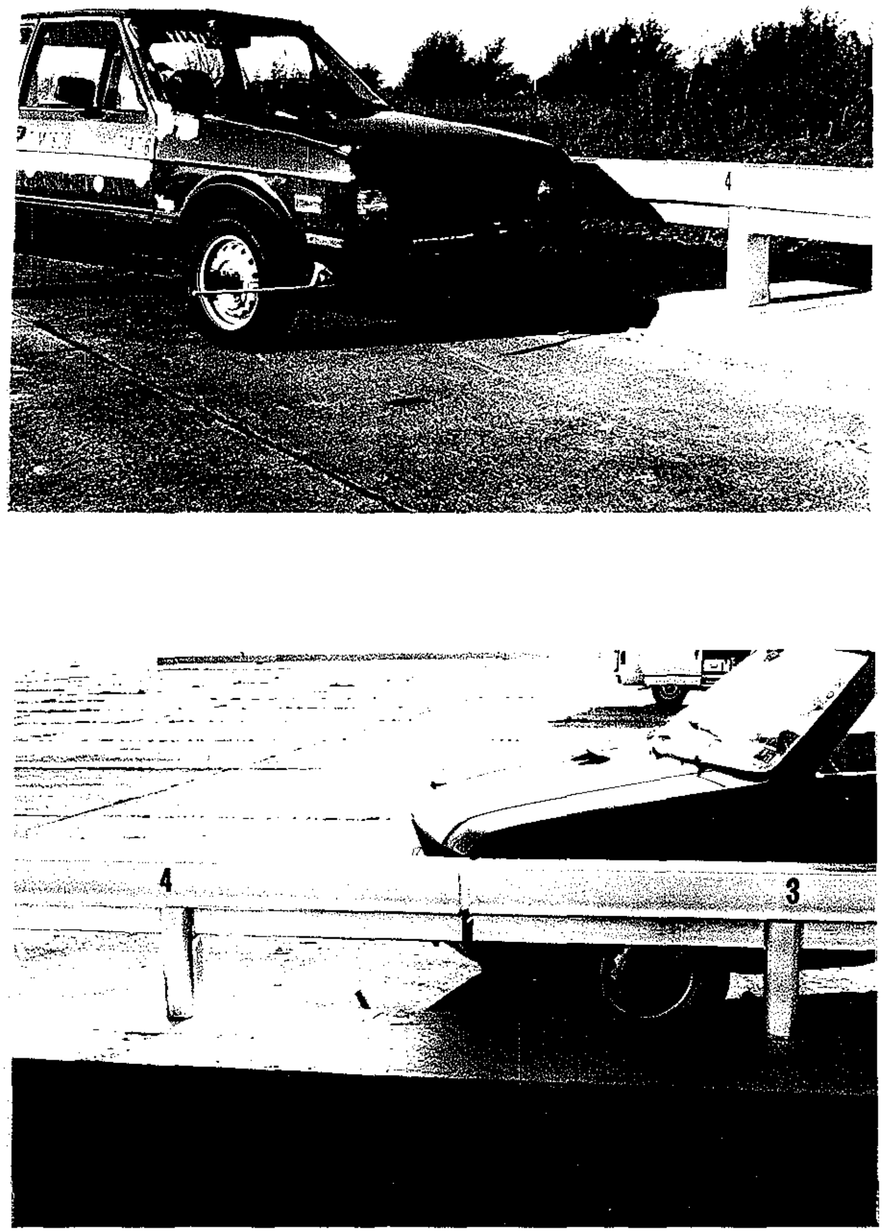


Figure 8. Vehicle/bridge rail geometric for test 7147-6.

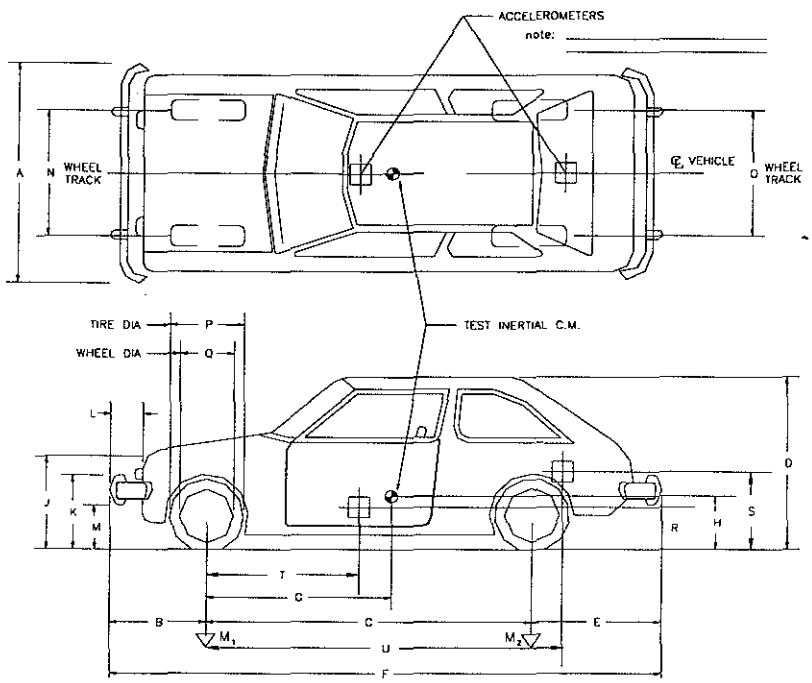
DATE: 09-17-91 TEST NO.: 471470-6 VIN NO.: VX1BA1215HK345835

YEAR: 1987 MAKE: Yugo MODEL: GV

TIRE INFLATION PRESSURE: ______ ODOMETER: 32404 TIRE SIZE: 145 R13

MASS DISTRIBUTION (kg) LF 256 RF 254 LR 150.6 RR 156

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:



ENGINE TYPE: 4 cyl

ENGINE CID: 1.1L

TRANSMISSION TYPE:

__ AUTO

X MANUAL

OPTIONAL EQUIPMENT:

DUMMY DATA:

TYPE: 50th male

MASS: 77 kg

SEAT POSITION: Driver's

GEOMETRY – (mm)

A 1543	E 635	J 781	N 1327	R 393.7
B 673	F 3442	K 470	O	S
C 2133.6	G 805.9	L 38	P 546	T 800
D 1435.1	H	M 343	Q 362	U 2451

MASS – (kg)	CURB	TEST INERTIAL	GROSS STATIC
M_1	527	510	548
M_2	276	306	345.6
M_T	802	816	893.6

Figure 9. Vehicle properties for test 7147-6.

0.149 s, the vehicle was traveling parallel to the bridge rail system at a speed of 62.9 km/h (39.1 mi/h). The left front tire impacted post 5 at 0.171 s, again pulling the front tires to the left. The vehicle exited the bridge rail at 0.262 s, traveling at a speed of 55.5 km/h (34.5 mi/h), with an exit angle of 1.5 degrees.

After the vehicle exited from the bridge rail, the bumper struck post 6 at 0.282 s and cleared the rail at 0.292 s. The left front tire dropped off the curb at 0.377 s. Because of the damage sustained by the left front tire and the orientation of the front tires, the vehicle turned back toward the bridge rail after exiting the bridge rail from the initial impact and impacted the bridge rail again near post 8 and rode along the bridge rail until the end of the bridge rail. The brakes were applied after the vehicle cleared the test installation, and the vehicle came to rest 32.0 m (105 ft) downstream from and 7.6 m (25 ft) behind the point of initial impact. Sequential photographs of the test sequence are presented in figures 10 and 11.

3.1.2 Damage to Test Installation

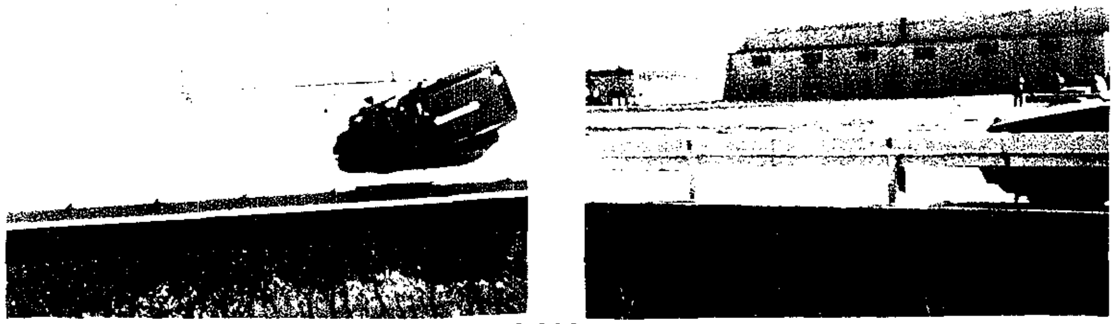
The bridge rail system received minimal damage, as shown in figure 12. There was no permanent deformation of the bridge railing. The total length of-contact for the initial impact was 4.0 m (13.0 ft). Tire marks extended 254 mm (10.0 in) under the rail element at post 4.

3.1.3 Vehicle Damage

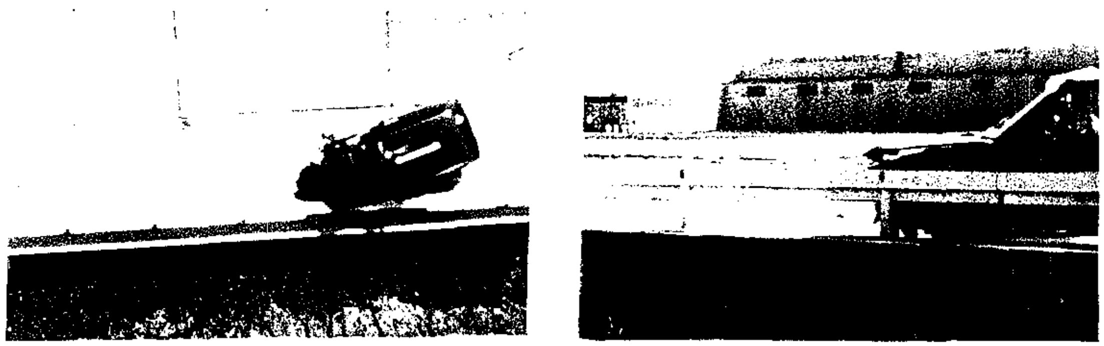
The vehicle (shown in figure 13) sustained extensive damage. The sway bar, left strut, and inner C.V. joint was damaged. The windshield was broken, and the roof, floor pan and instrument panel were bent. There was damage to the front bumper, hood, grill, radiator, left front quarter panel, left rear door and glass, left rear quarter panel, and the rear bumper. The firewall and floor pan were pushed into the steering column and clutch pedal for a maximum intrusion into the occupant compartment of 356 mm (14.0 in). The wheelbase on the right side was shortened from 2.1 m (84.0 in) to 1.7 m (66.5 in). The left front tire and rim were damaged from contact with the posts and the rear tire and rim were damaged in later contact with the curb. Maximum crush to the vehicle was 254 mm (10.0 in) at the left front corner at bumper height.

3.1.4 Occupant Risk Values

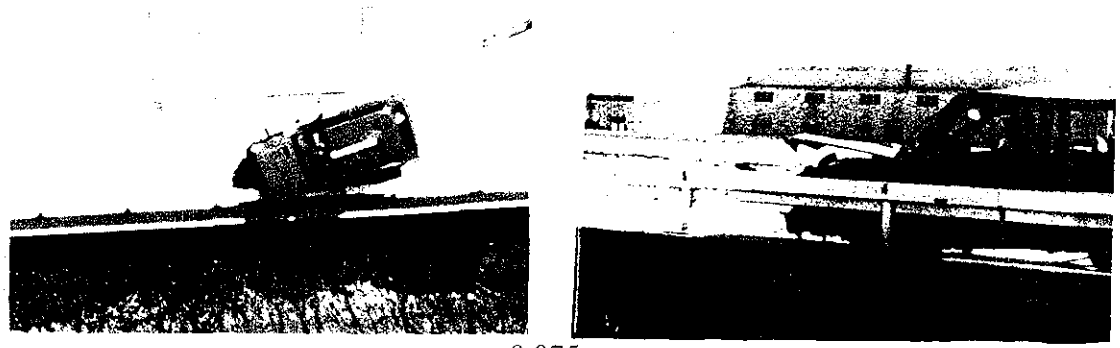
Data from the electronic instrumentation were digitized for evaluation and occupant risk factors were computed as follows. In the longitudinal direction, occupant impact velocity was 7.5 m/s (24.7 ft/s) at 0.155 s; the highest 0.010-s average ridedown acceleration was -6.5 g's from 0.185 to 0.195 s; and the 0.050-s average acceleration was -8.5 g's between 0.044 and 0.094 s. Lateral occupant impact velocity was 5.1 m/s (16.6 ft/s) at 0.096 s; the highest 0.010-s average ridedown acceleration was -9.9 g's from 0.178 to 0.188 s; and the maximum 0.050-s average acceleration was -9.4 g's between 0.026 and 0.076 s. The change in vehicle velocity at loss of contact was 26.9 km/h (16.7 mi/h) and the change in momentum was 6090 N-s (1369 lb-s).



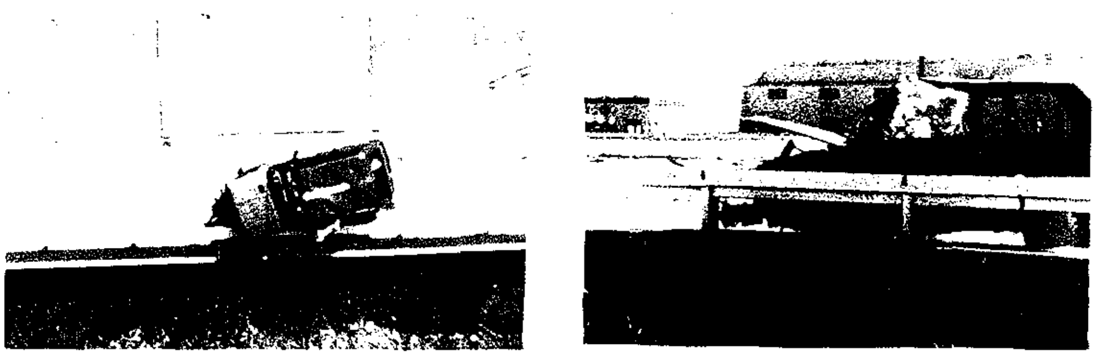
0.000 s



0.037 s

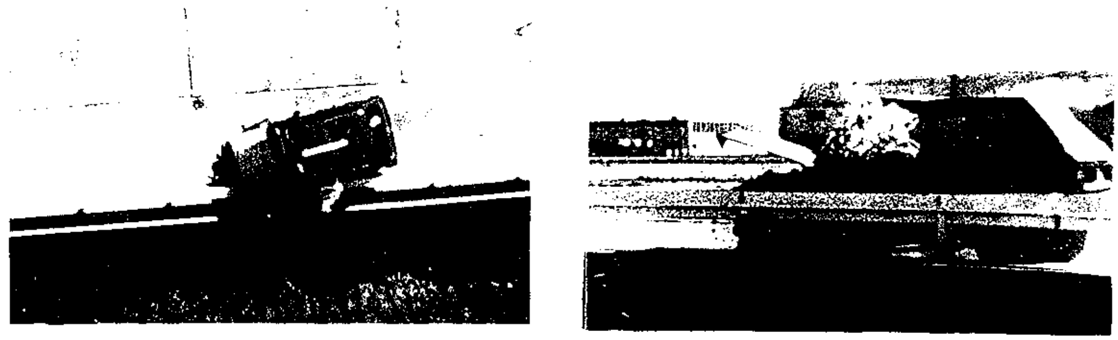


0.075 s

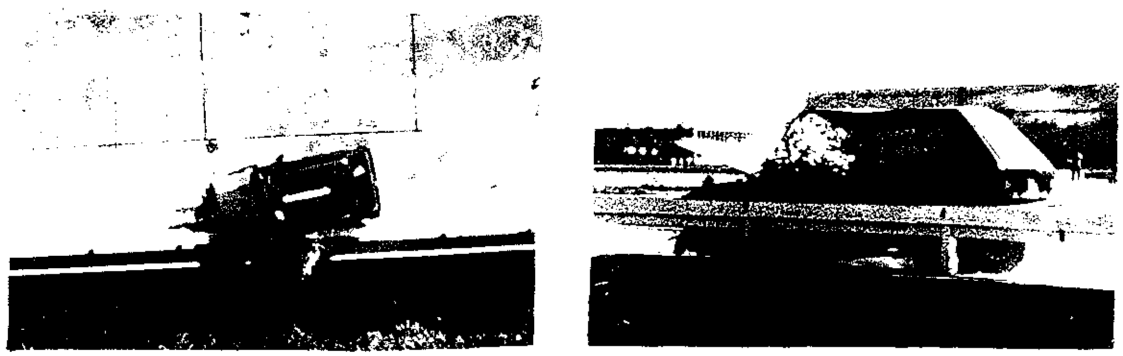


0.112 s

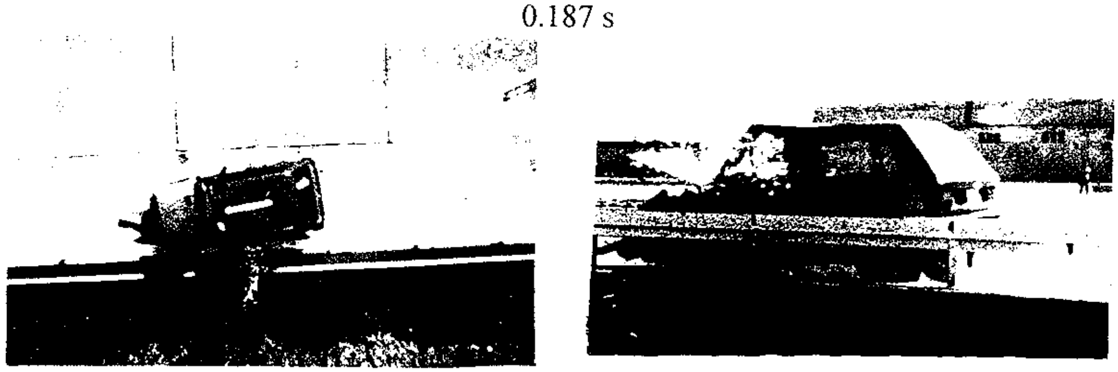
Figure 10. Sequential photographs for test 7147-6
(overhead and behind the rail views).



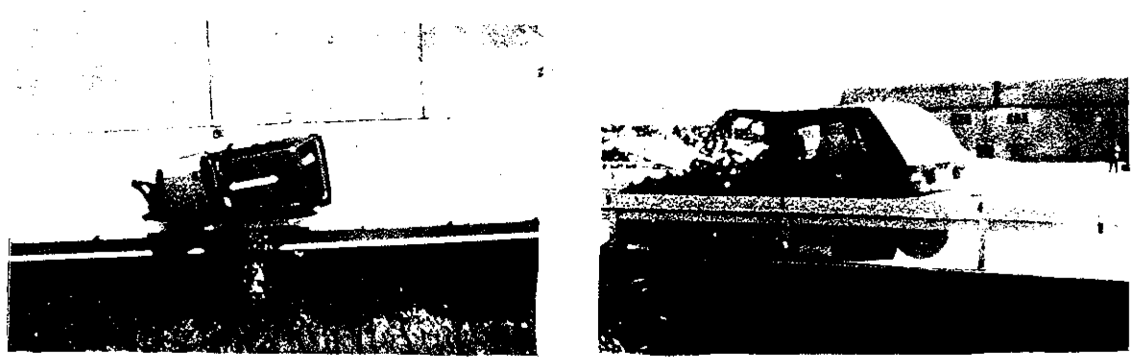
0.149 s



0.187 s



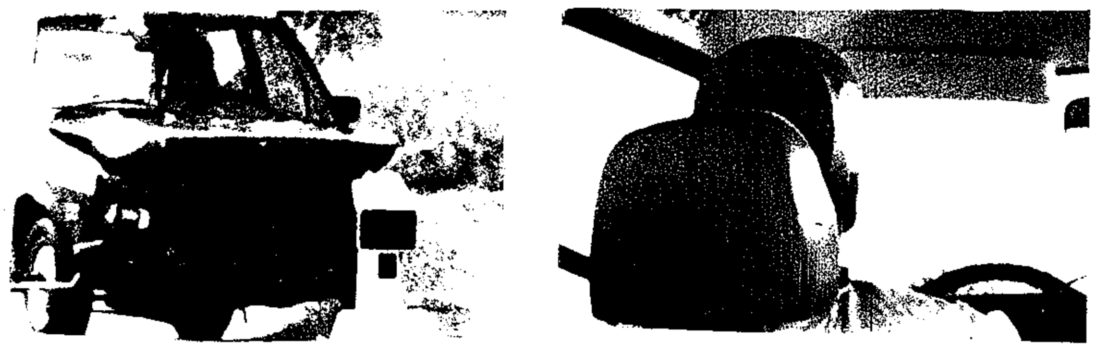
0.224 s



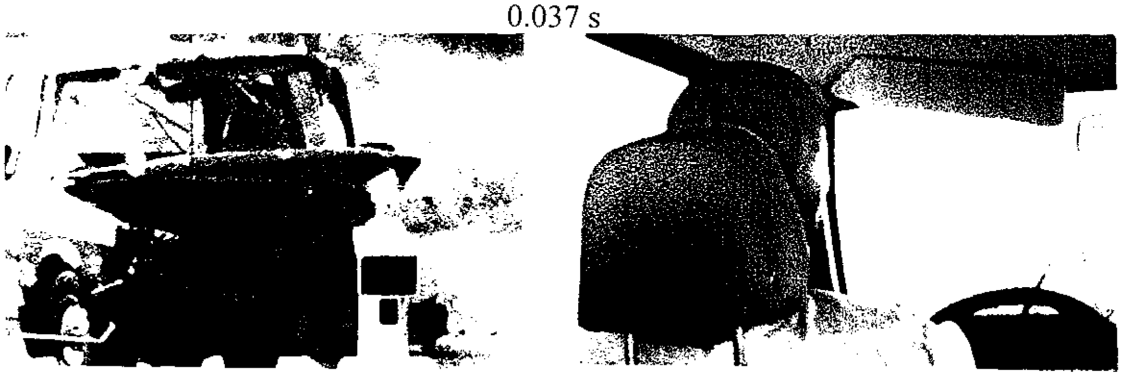
0.262 s

Figure 11. Sequential photographs for test 7147-6
(overhead and behind the rail views) (continued).

0.000 s



0.037 s

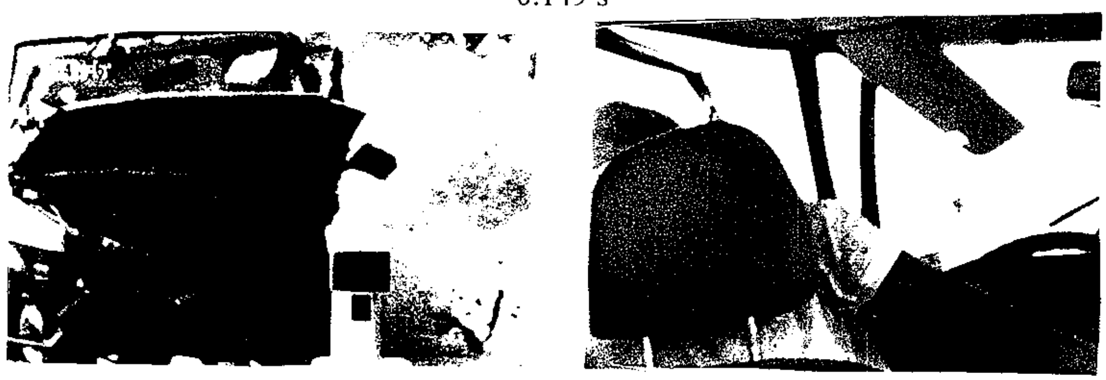


0.075 s

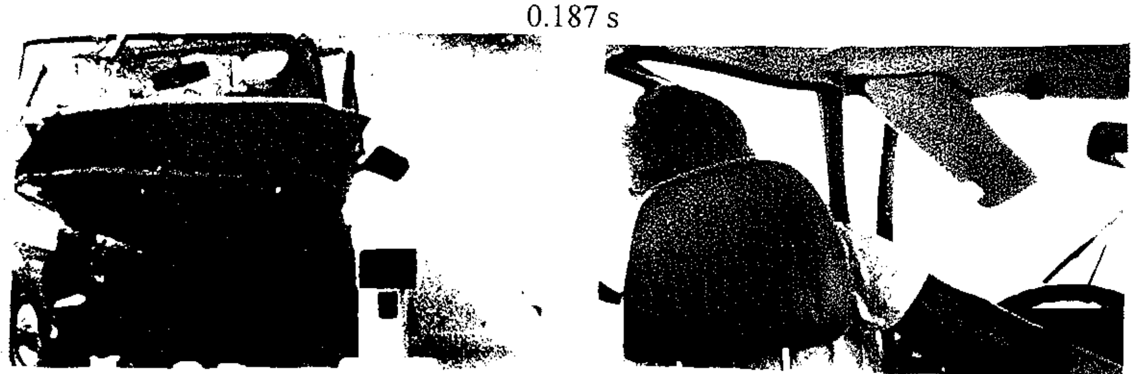
0.112 s

Figure 11. Sequential photographs for test 7147-6
(frontal and interior views).

0.149 s



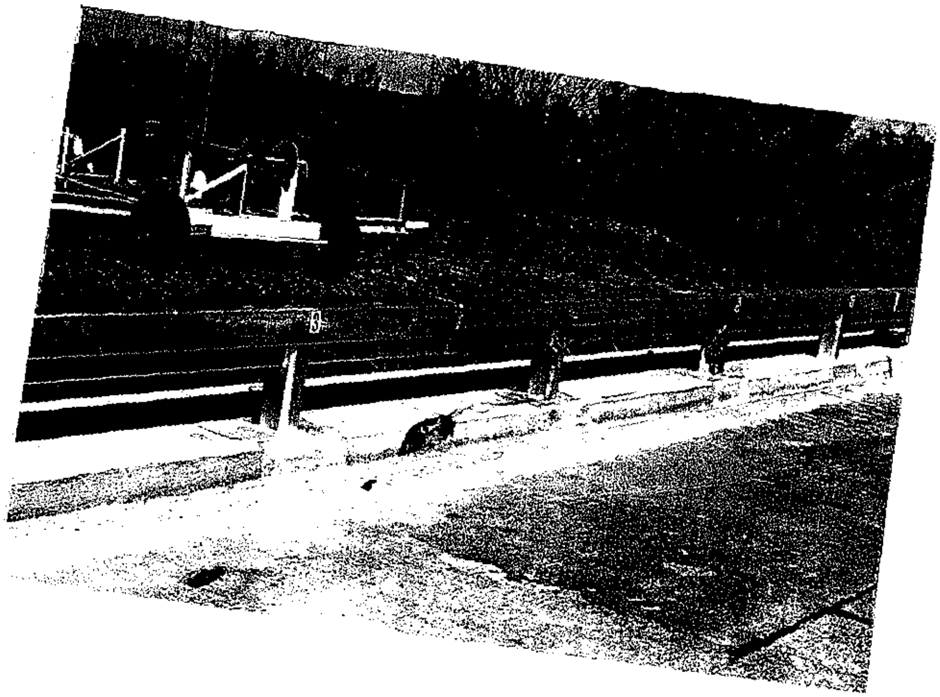
0.187 s



0.224 s

0.262 s

Figure 11. Sequential photographs for test 7147-6
(frontal and interior views) (continued).



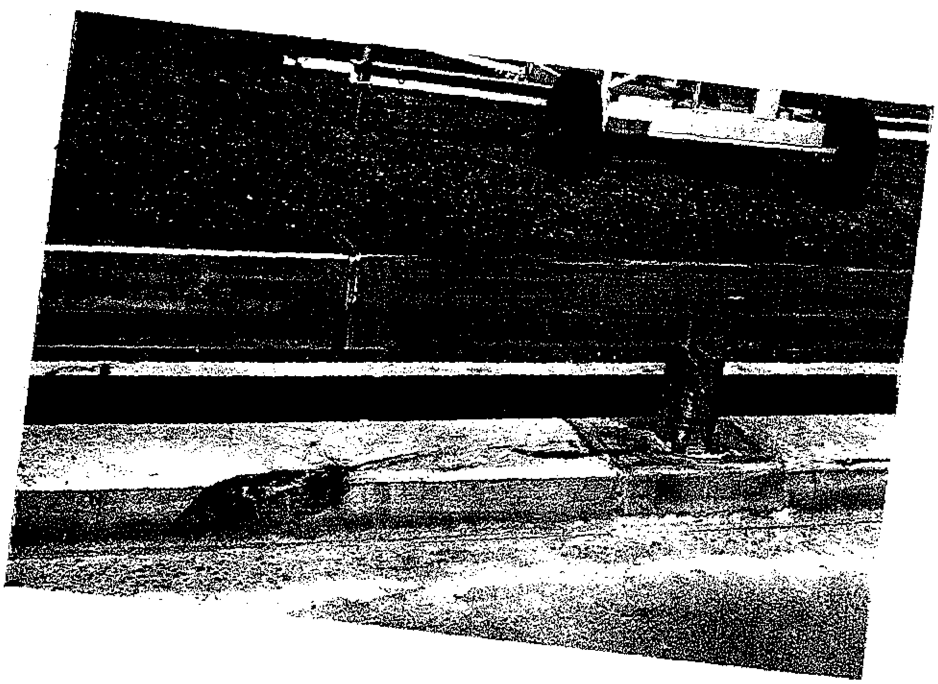


Figure 12. Washington, DC, historic bridge rail after test 7147-6.

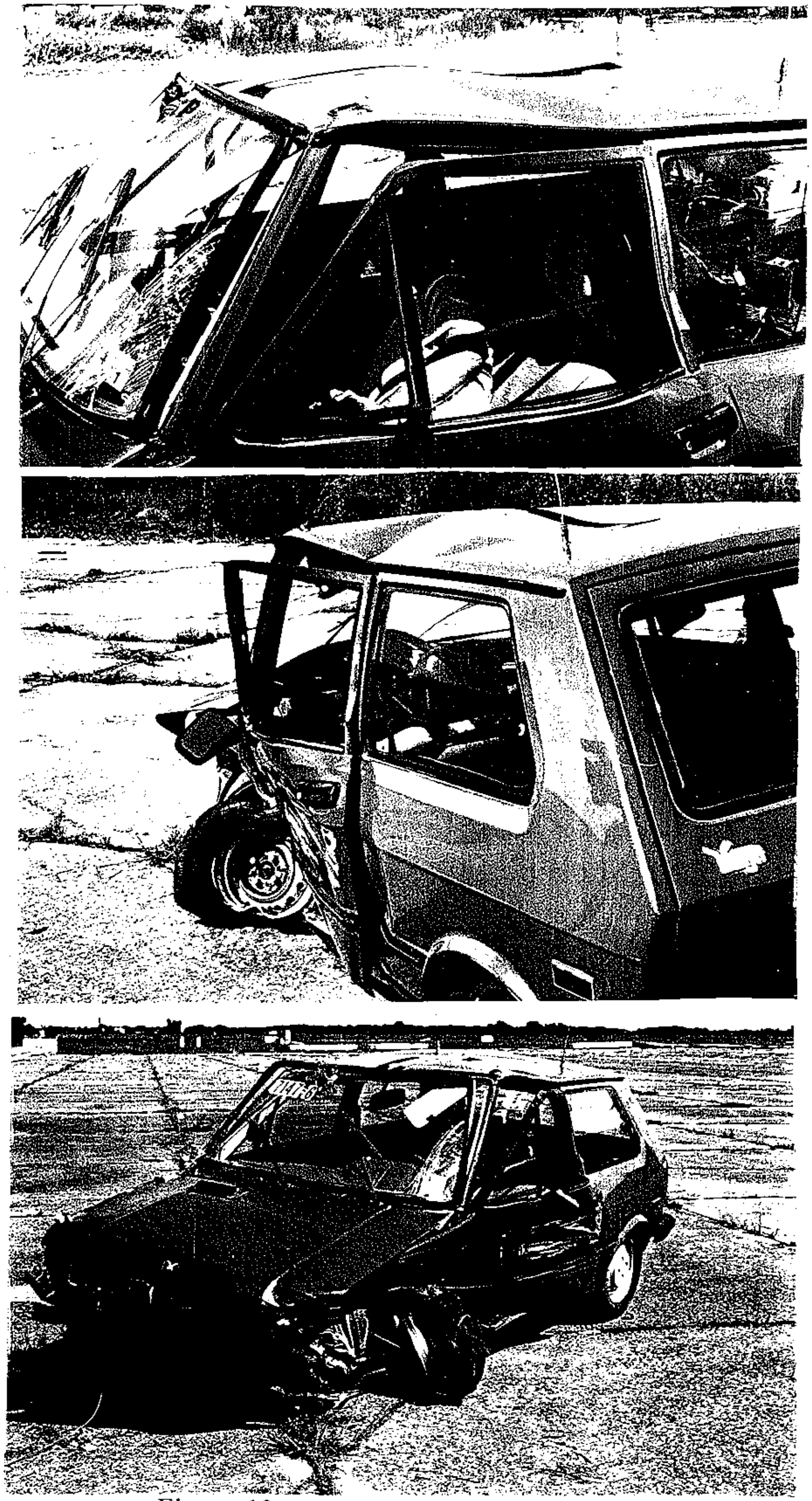


Figure 13. Vehicle after test 7147-6.

A summary of pertinent data from the electronic instrumentation, high-speed film, and field measurements is given in figure 14. Vehicle angular displacements are displayed in figure 15, and vehicular accelerations versus time traces filtered at 300 Hz are presented in figures 16 through 18.

3.2 TEST NO. 471470-8

A 1988 Ford Festiva, shown in figures 19 and 20, was used for this crash test with the modified bridge railing design. Test inertia weight of the vehicle was 817 kg (1800 lb) and its gross static weight was 892 kg (1965 lb). The height to the lower edge of the vehicle bumper was 349 mm (13.75 in) and it was 502 mm (19.75 in) to the upper edge of the bumper. Additional dimensions and information on the vehicle are given in figure 21. The vehicle was directed into the bridge railing using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact.

3.2.1 Test Description

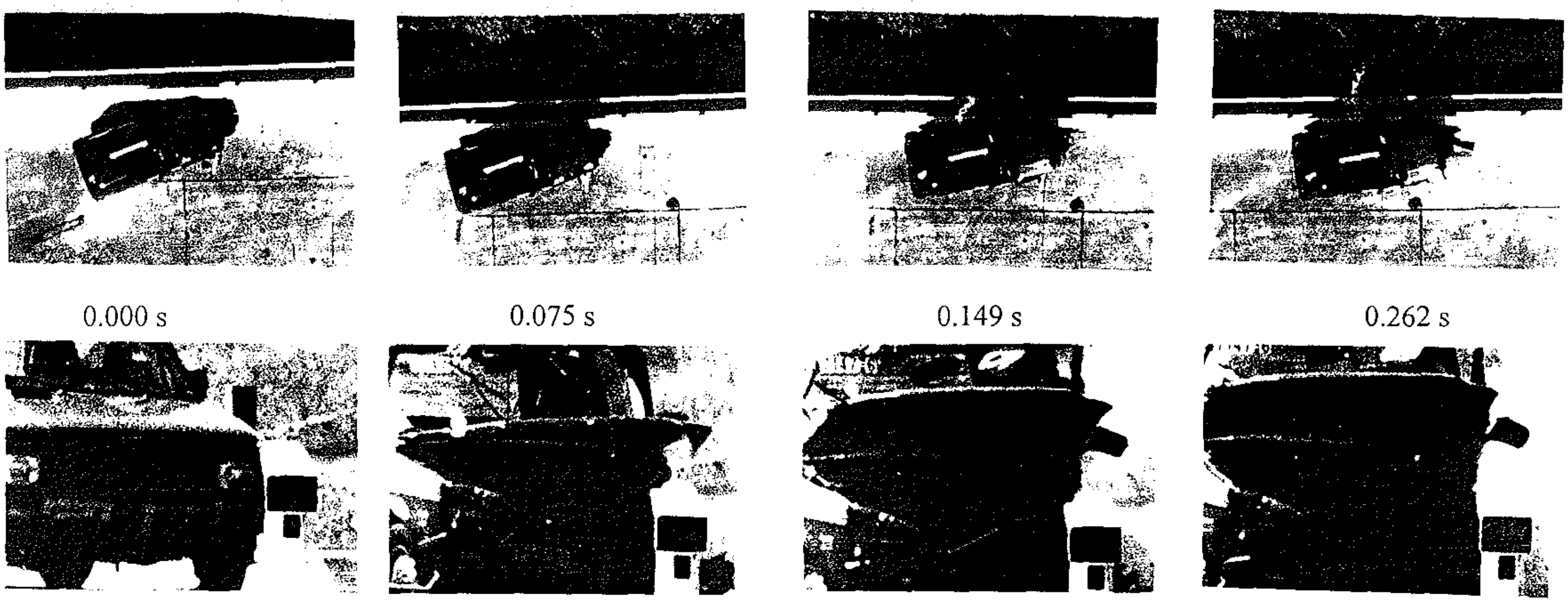
The vehicle impacted the bridge railing midspan between posts 3 and 4, or approximately 5.72 m (18 ft 9 in) downstream from the upstream end of the bridge railing, at a speed of 80.0 km/h (49.7 mi/h) and at an angle of 21.5 degrees. As the vehicle bumper contacted the bridge rail, the left front tire contacted the curb at the same time. The front of the vehicle began to shift to the right at 0.017 s after initial impact, and at 0.019 s the left front tire aired out. At 0.028 s after initial impact, the vehicle began to redirect. The left front tire of the vehicle mounted the curb at 0.043 s and contacted post 4 at 0.077 s. Tire marks indicated that the left front tire went underneath the box beam a distance of 64 mm (2.5 in) just before impacting post 4. At 0.152 s, the vehicle was traveling parallel to the bridge rail system at a speed of 65.3 km/h (40.6 mi/h) and the rear of the vehicle contacted the rail at 0.160 s. The vehicle exited the bridge rail at 0.239 s, traveling at a speed of 64.5 km/h (40.1 mi/h), with an exit angle of 3.5 degrees. The brakes were applied after the vehicle cleared the test installation, and the vehicle came to rest 59 m (195 ft) downstream from and 29 m (95 ft) forward of the point of initial impact. Sequential photographs of the test sequence are presented in figures 22 and 23.

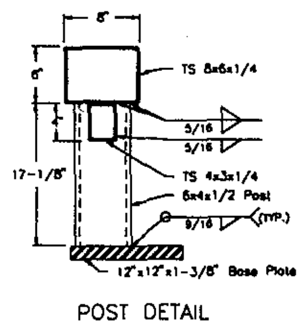
3.2.2 Damage to Test Installation

The bridge railing received minimal damage, as shown in figure 24. There was no permanent deformation of the bridge railing. The total length of contact with the rail was 2.5 m (8.3 ft). Tire marks extended 64 mm (2.5 in) under the rail element just before post 4.

3.2.3 Vehicle Damage

The vehicle (shown in figure 25) received moderate damage. The left strut and C.V. joint were damaged. The driver's window was broken and there was damage to the front bumper, hood, grill, radiator, left front quarter panel, left door, left rear quarter panel, and the





Test No.	7147-6	Impact Speed	82.4 km/h (51.2 mi/h)
Date	09/17/91	Impact Angle	20.1 deg
Test Installation	Washington, DC, Historic Bridge Rail	Speed at Parallel	62.9 km/h (39.1 mi/h)
		Exit Speed	55.5 km/h (34.5 mi/h)
Installation Length	23 m (75 ft)	Exit Trajectory	1.5 deg
Max. Dynamic Deflection	Nil	Vehicle Accelerations	
Max. Perm. Deformation	None	(Max. 0.050-s avg)	
Test Vehicle	1987 Yugo GV	Longitudinal	-8.5 g's
Vehicle Weight		Lateral	- 9.4 g's
Test Inertia	817 kg (1800 lb)	Occupant Impact Velocity at true c.g.	
Gross Static	894 kg (1970 lb)	Longitudinal	7.5 m/s (24.7 ft/s)
Vehicle Damage Classification		Lateral	5.1 m/s (16.6 ft/s)
TAD	11FL6 & 11LD7	Occupant Ridedown Accelerations	
CDC	11FLEK4 & 11LDEW4	Longitudinal	-6.5 g's
Maximum Vehicle Crush	254 mm (10.0 in)	Lateral	-9.9 g's

Figure 14. Summary of results for test 7147-6.

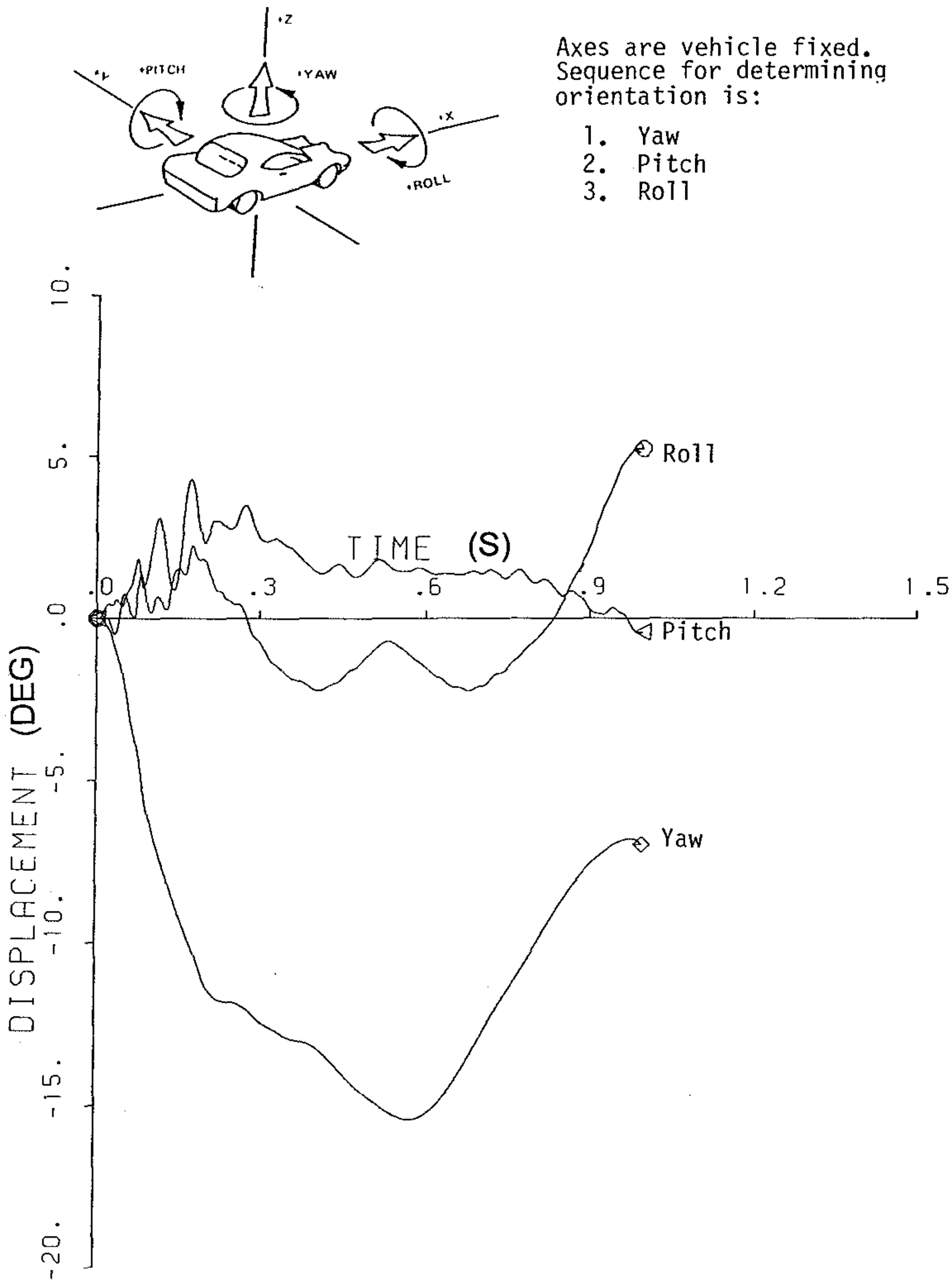


Figure 15. Vehicle angular displacement for test 7147-6.

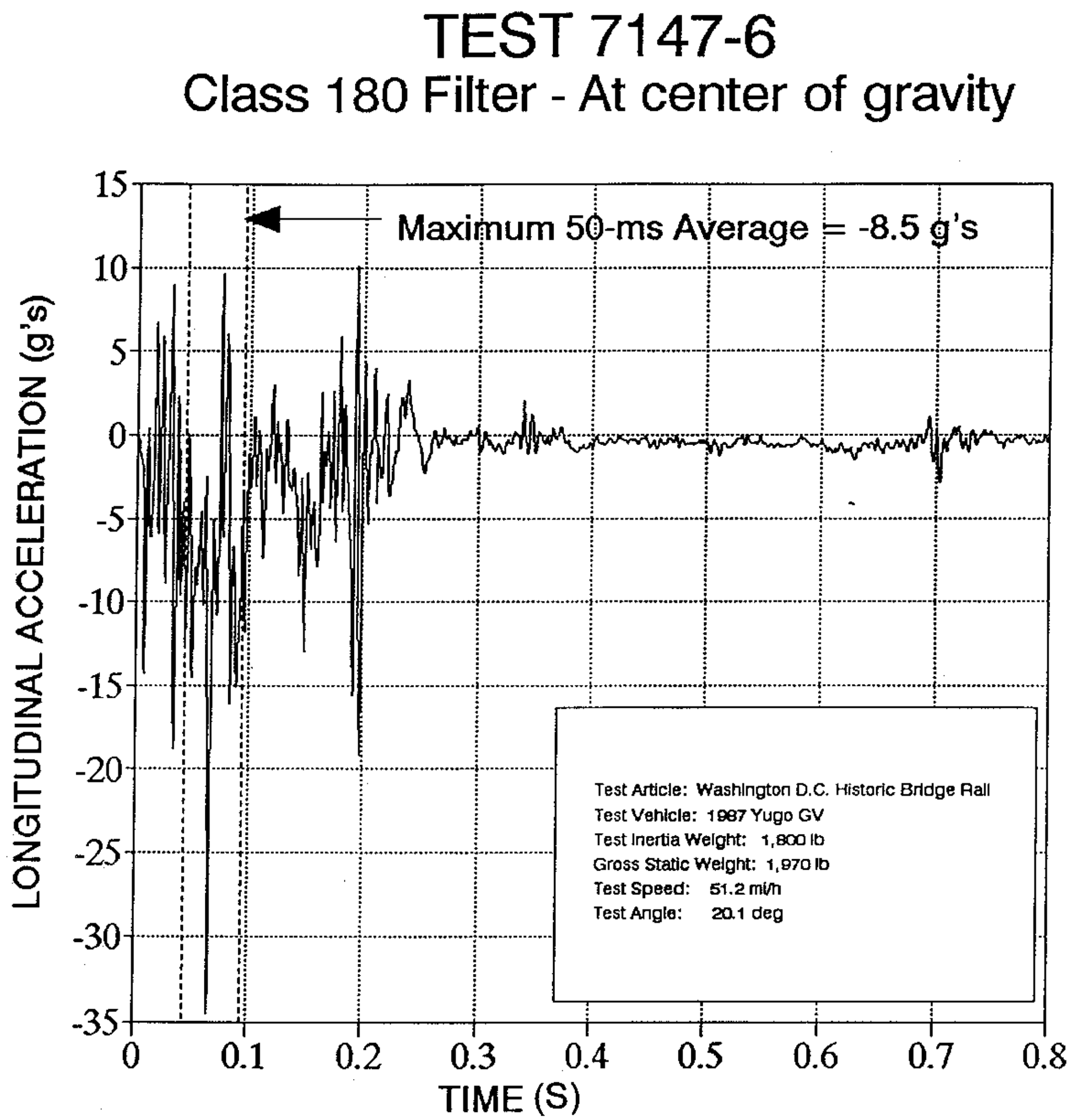


Figure 16. Vehicle longitudinal accelerometer trace for test 7147-6.

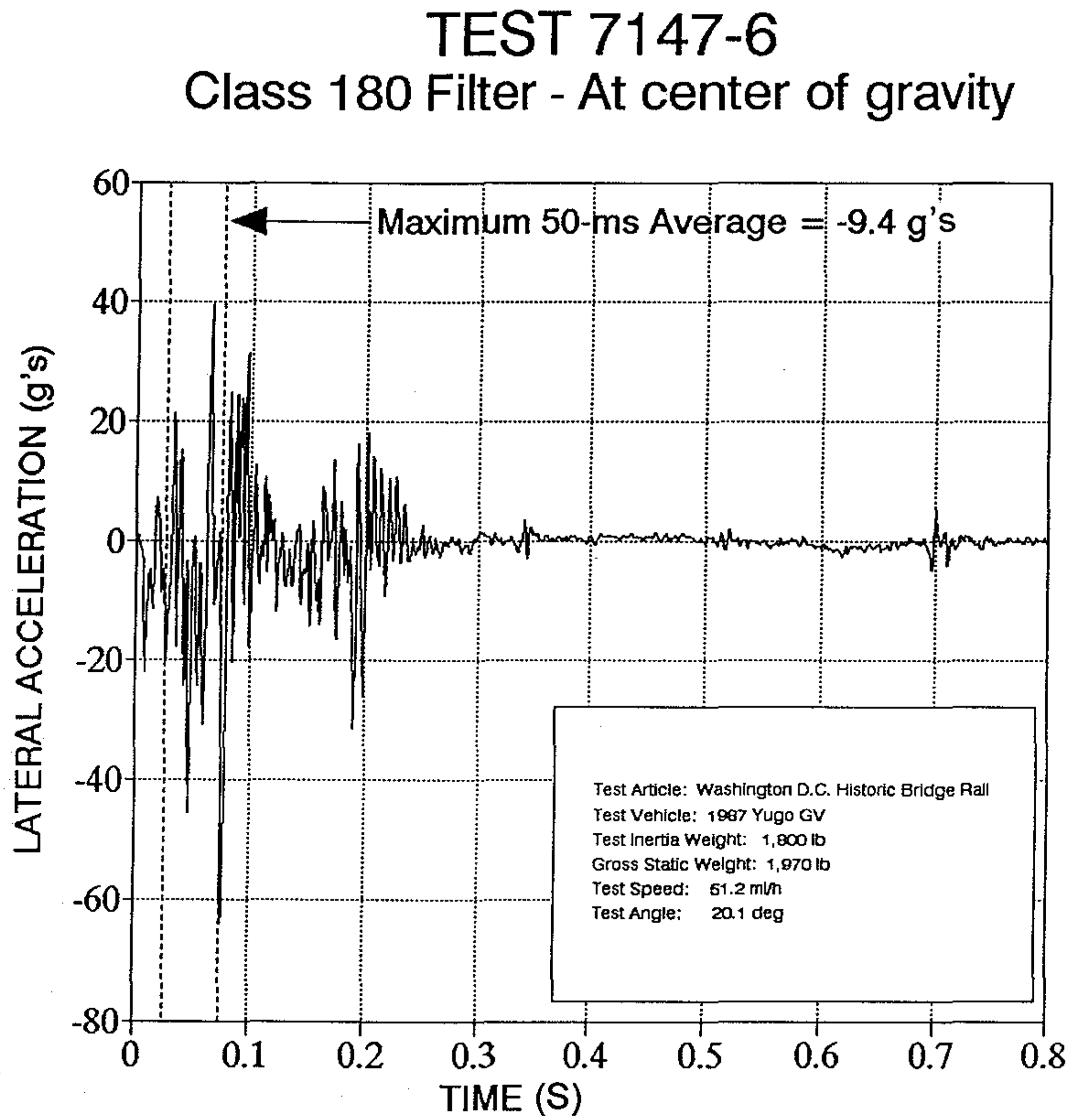


Figure 17. Vehicle lateral accelerometer trace for test 7147-6.

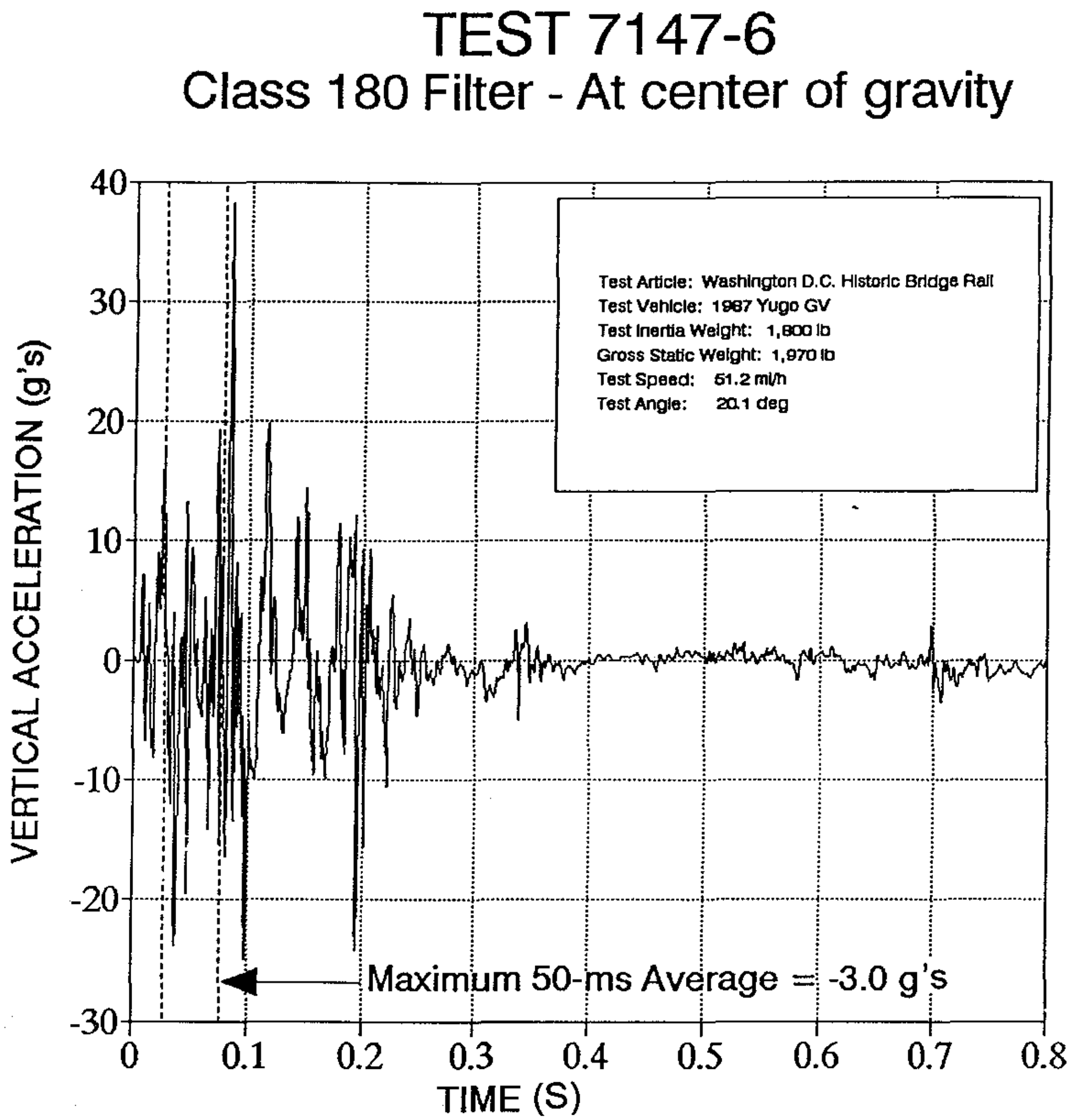


Figure 18. Vehicle vertical accelerometer trace for test 7147-6.

Figure 19. Vehicle before test 7147-8.

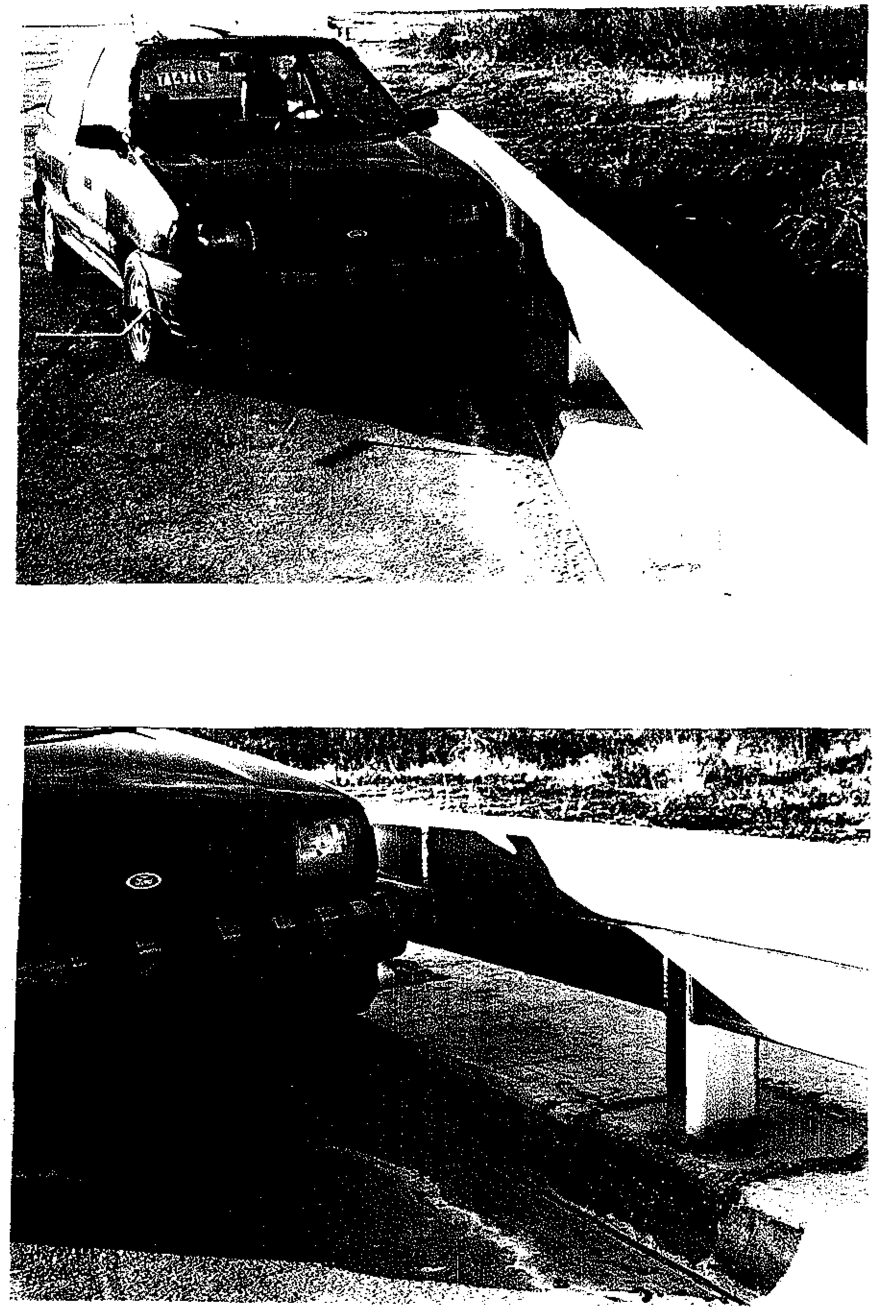


Figure 20. Vehicle/bridge rail geometrics for test 7147-8.

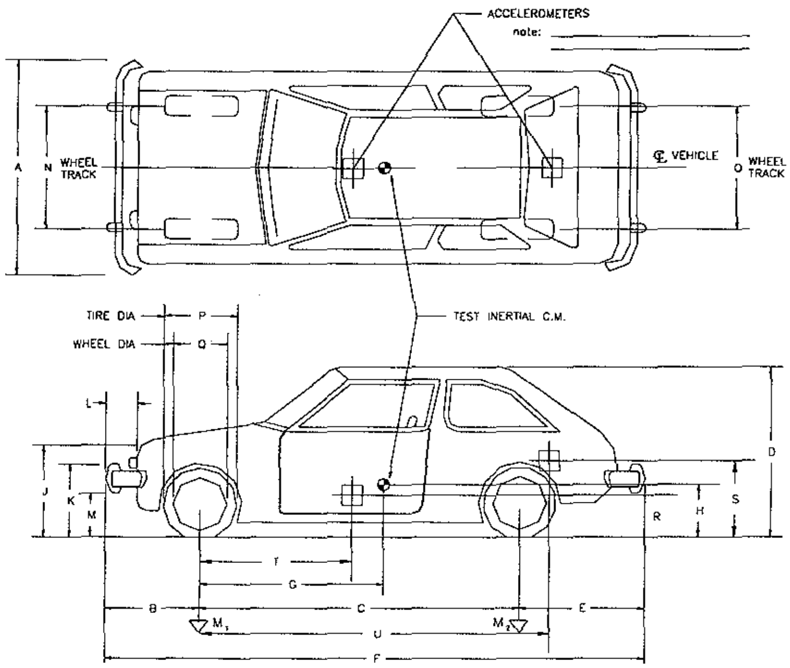
DATE: 12-10-91 TEST NO.: 471470-8 VIN NO.: KNJBT07K6J6147832

YEAR: 1988 MAKE: Ford MODEL: Festiva

TIRE INFLATION PRESSURE: ________ ODOMETER: 113304 TIRE SIZE: 165/70SR12

MASS DISTRIBUTION (kg) LF 257 RF 253 LR 153 RR 154

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:



ENGINE TYPE: 4 cyl

ENGINE CID: 1.3

TRANSMISSION TYPE:

_ AUTO

X MANUAL

OPTIONAL EQUIPMENT:

DUMMY DATA:

TYPE: 50th male

MASS: 75 kg

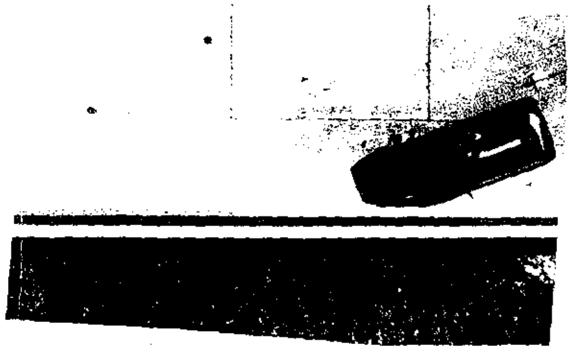
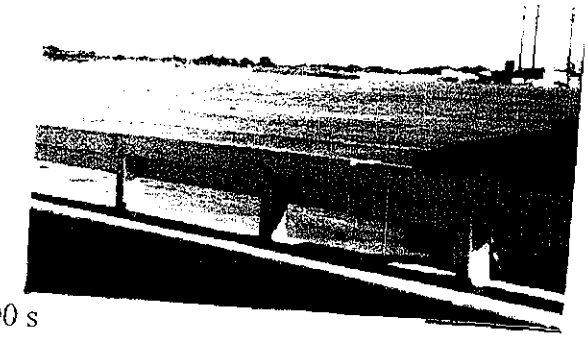
SEAT POSITION: Driver's

GEOMETRY - (mm)

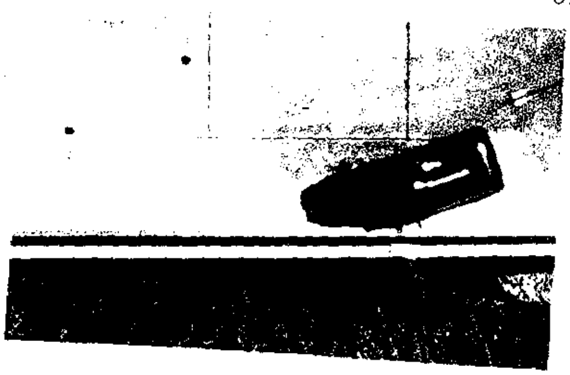
A 1613	E 559	J 686	N 1410	R 362
B 686	F 3537	K 501.7	O	S
C 2292	G 863.6	L 119	P 546	T 940
D 1429	H	M 349.3	Q 340	U 2445

MASS - (kg)	CURB	TEST INERTIAL	GROSS STATIC
M_1	526	509	544
M_2	307	308	348
M_T	833	817.2	892

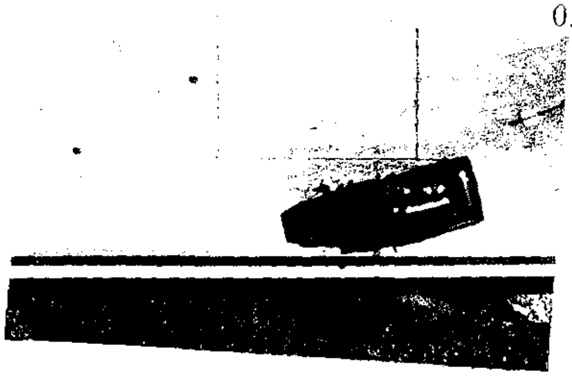
Figure 21. Vehicle properties for test 7147-8.

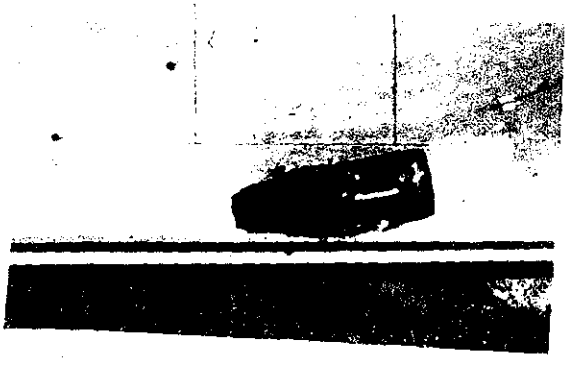
0.000 s

0.034 s

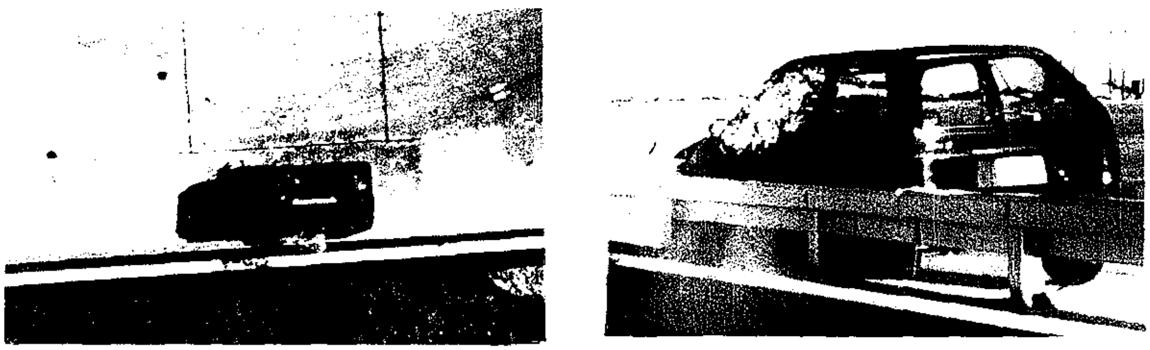
0.068 s

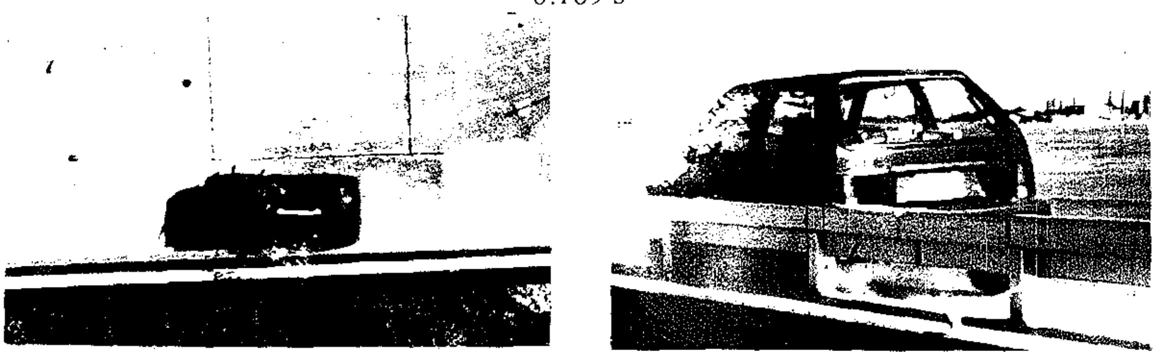
0.101 s

Figure 22. Sequential photographs for test 7147-8 (overhead and behind the rail views).

0.135 s



0.169 s



0.211 s

0.253 s

Figure 22. Sequential photographs for test 7147-8
(overhead and behind the rail views) (continued).

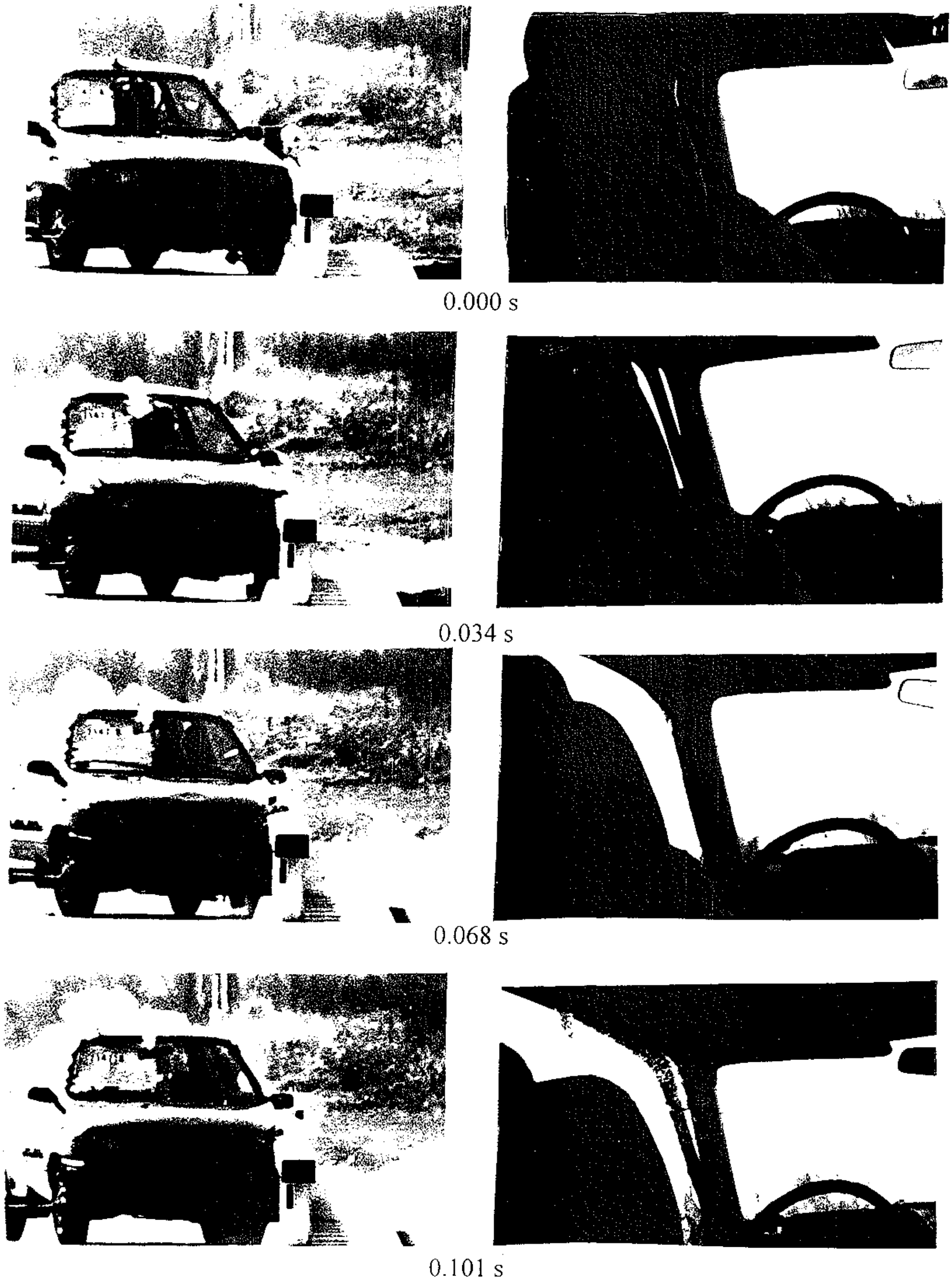
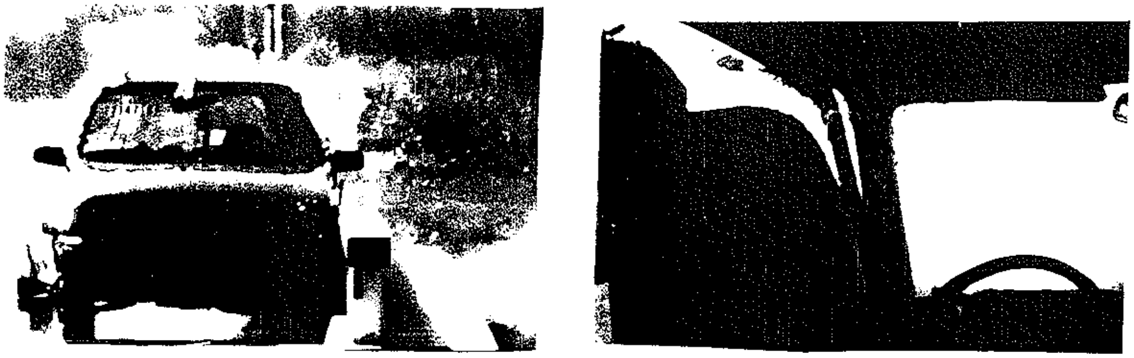
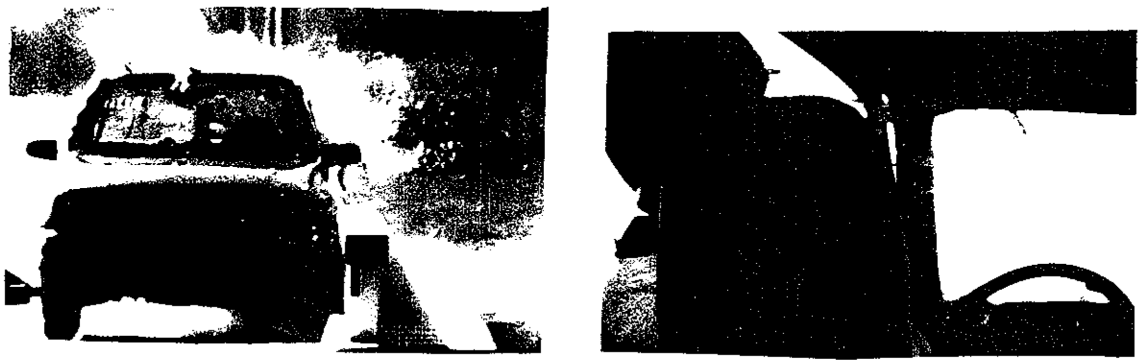


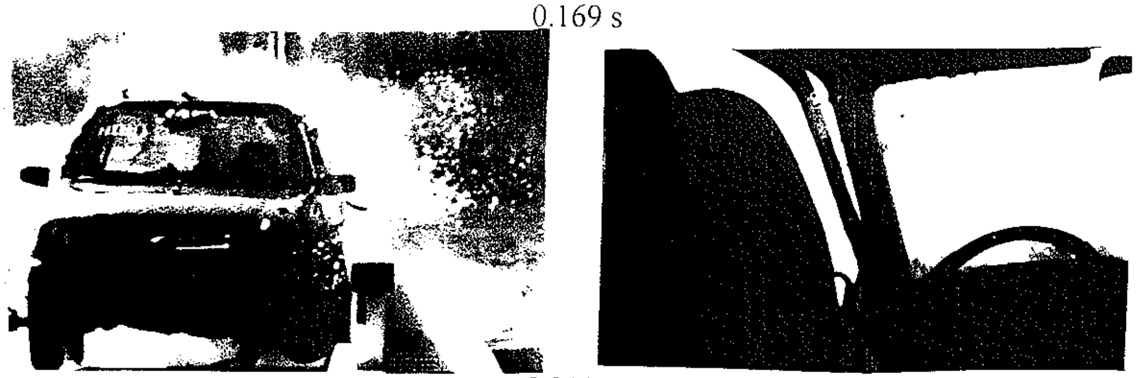
Figure 23. Sequential photographs for test 7147-8
(frontal and interior views).



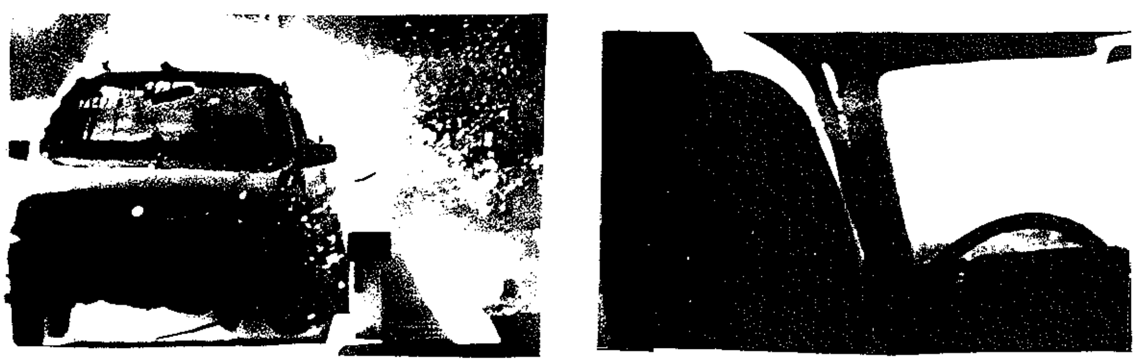
0.135 s



0.169 s

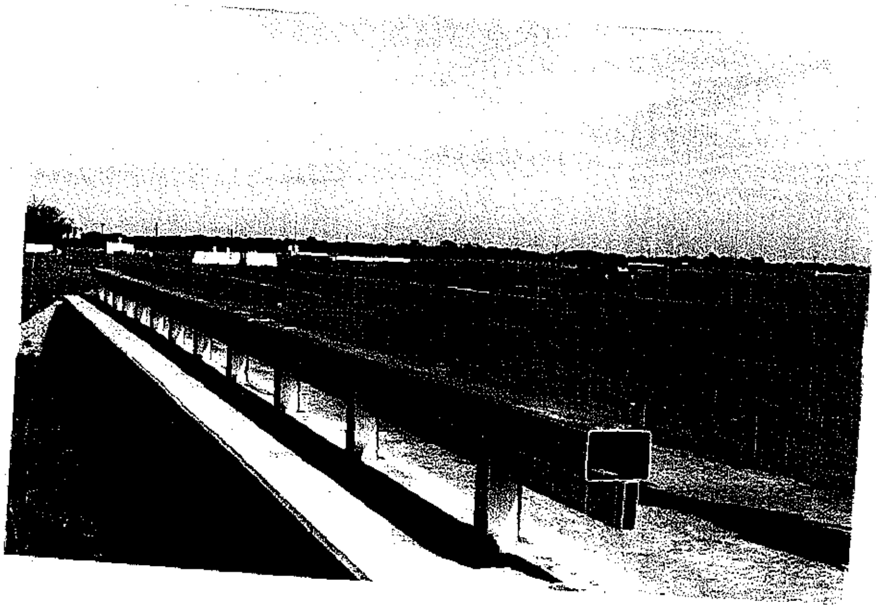


0.211 s



0.253 s

Figure 23. Sequential photographs for test 7147-8
(frontal and interior views) (continued).



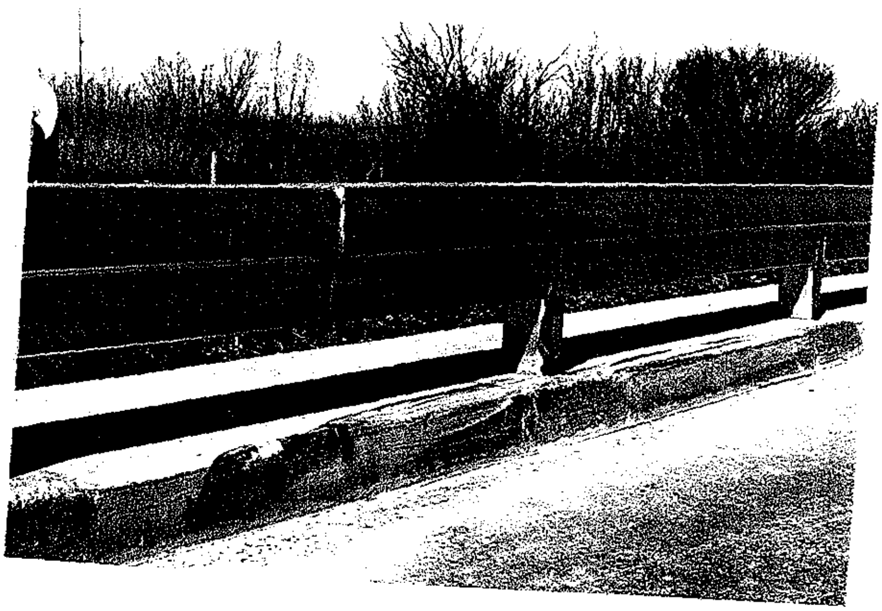
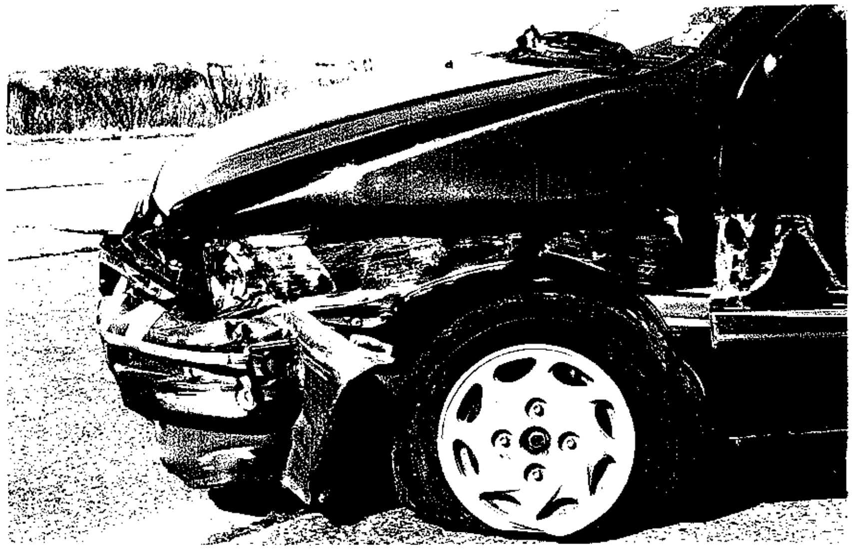


Figure 24. Test site and bridge rail after 7147-8.



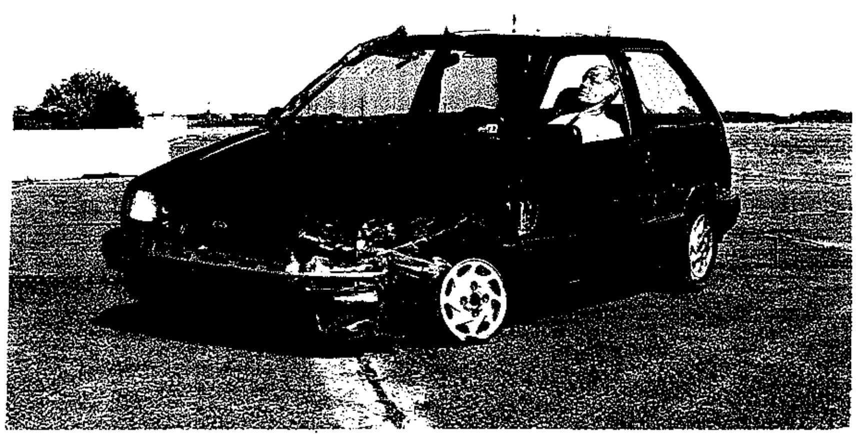


Figure 25. Vehicle after test 7147-8.

rear bumper. The wheelbase on the left side was shortened from 2.3 m (90.25 in) to 2.2 m (87.0 in). The left front tire and rim were damaged from contact with the curb and post 4. Maximum crush to the vehicle was 216 mm (8.5 in) at the left front corner at bumper height.

3.2.4 Occupant Risk Values

Data from the electronic instrumentation were digitized for evaluation, and occupant risk factors were computed as follows. In the longitudinal direction, occupant impact velocity was 4.3 m/s (14.2 ft/s) at 0.198 s; the highest 0.010-s average ridedown acceleration was -1.4 g's from 0.201 to 0.211 s; and the 0.050-s average acceleration was -6.0 g's between 0.029 and 0.079 s. Lateral occupant impact velocity was 5.7 m/s (18.7 ft/s) at 0.097 s, the highest 0.010-s average ridedown acceleration was -6.9 g's from 0.183 to 0.193 s; and the maximum 0.050-s average acceleration was -10.2 g's between 0.025 and 0.075 s. The change in vehicle velocity at loss of contact was 15.4 km/h (9.6 mi/h) and the change in momentum was 3501 N-s (787 lb-s).

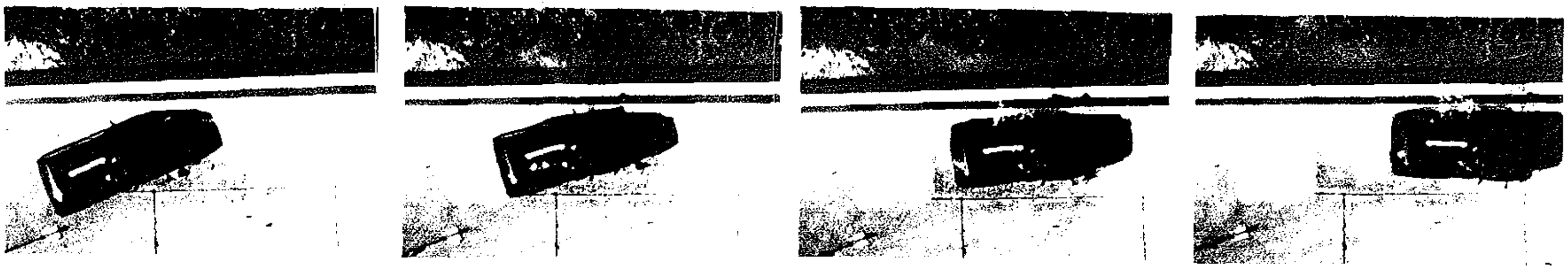
A summary of pertinent data from the electronic instrumentation, high-speed film, and field measurements is given in figure 26. Vehicle angular displacements are displayed in figure 27, and vehicular accelerations versus time traces filtered at 300 Hz are presented in figures 28 through 30.

3.3 TEST 7147-9

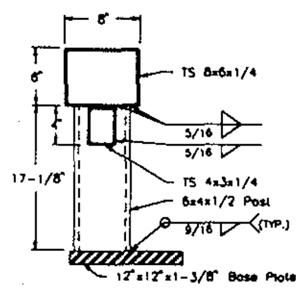
A 1986 Chevrolet pickup, shown in figures 31 and 32, was used for the second crash test on the modified bridge rail design. Test inertia weight of the vehicle was 2452 kg (5400 lb) and its gross static weight was 2527 kg (5565 lb). The height to the lower edge of the vehicle bumper was 451 mm (17.75 in) and it was 679 mm (26.75 in) to the upper edge of the bumper. Additional dimensions and information on the vehicle are given in figure 33. The vehicle was directed into the bridge railing using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact.

3.3.1 Test Description

The vehicle impacted the bridge railing midspan between posts 3 and 4, or approximately 5.72 m (18 ft 9 in) downstream from the upstream end of the bridge railing, at a speed of 76.7 km/h (47.7 mi/h) and at an angle of 20.6 degrees. The left front tire contacted the curb 0.019 s after the bumper of the vehicle contacted the rail. At 0.038 s after initial impact, the vehicle began to redirect. The left front tire of the vehicle mounted the curb at 0.062 s and contacted post 4 at 0.069 s. Tire marks indicated that the left front tire did not go underneath the box-beam rail element. At 0.194 s, the vehicle was traveling parallel to the bridge rail system at a speed of 71.4 km/h (44.4 mi/h) and the rear of the vehicle contacted the rail at 0.213 s. The vehicle exited the bridge rail at 0.297 s, traveling at a speed of 70.3 km/h (43.7 mi/h), with an exit angle of 5.4 degrees. The brakes were applied after the vehicle cleared the test installation and the vehicle came to rest 82 m (270 ft)



0.000 s | 0.068 s | 0.135 s | 0.211 s

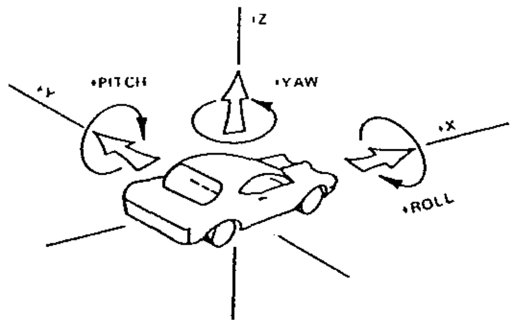


POST DETAIL

Test No.	7147-8
Date	12/10/91
Test Installation	Washington, DC, Historic Bridge Rail
Installation Length	23 m (75 ft)
Max. Dynamic Deflection	Nil
Max. Perm. Deformation	None
Test Vehicle	1988 Ford Festiva
Vehicle Weight	
Test Inertia	817 kg (1800 lb)
Gross Static	892 kg (1965 lb)
Vehicle Damage Classification	
TAD	11FL2 & 11LD3
CDC	11FLEK1 & 11LDEW3
Maximum Vehicle Crush	216 mm (8.5 in)

Impact Speed	80.0 km/h (49.7 mi/h)
Impact Angle	21.5 deg
Speed at Parallel	65.3 km/h (40.6 mi/h)
Exit Speed	64.5 km/h (40.1 mi/h)
Exit Trajectory	3.5 deg
Vehicle Accelerations (Max, 0.050-s avg)	
Longitudinal	-6.0 g's
Lateral	-10.2 g's
Occupant Impact Velocity at true c.g.	
Longitudinal	4.3 m/s (14.2 ft/s)
Lateral	5.7 m/s (18.7 ft/s)
Occupant Ridedown Accelerations	
Longitudinal	-1.4 g's
Lateral	-6.9 g's

Figure 26. Summary of results for test 7147-8.



Axes are vehicle fixed.
Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

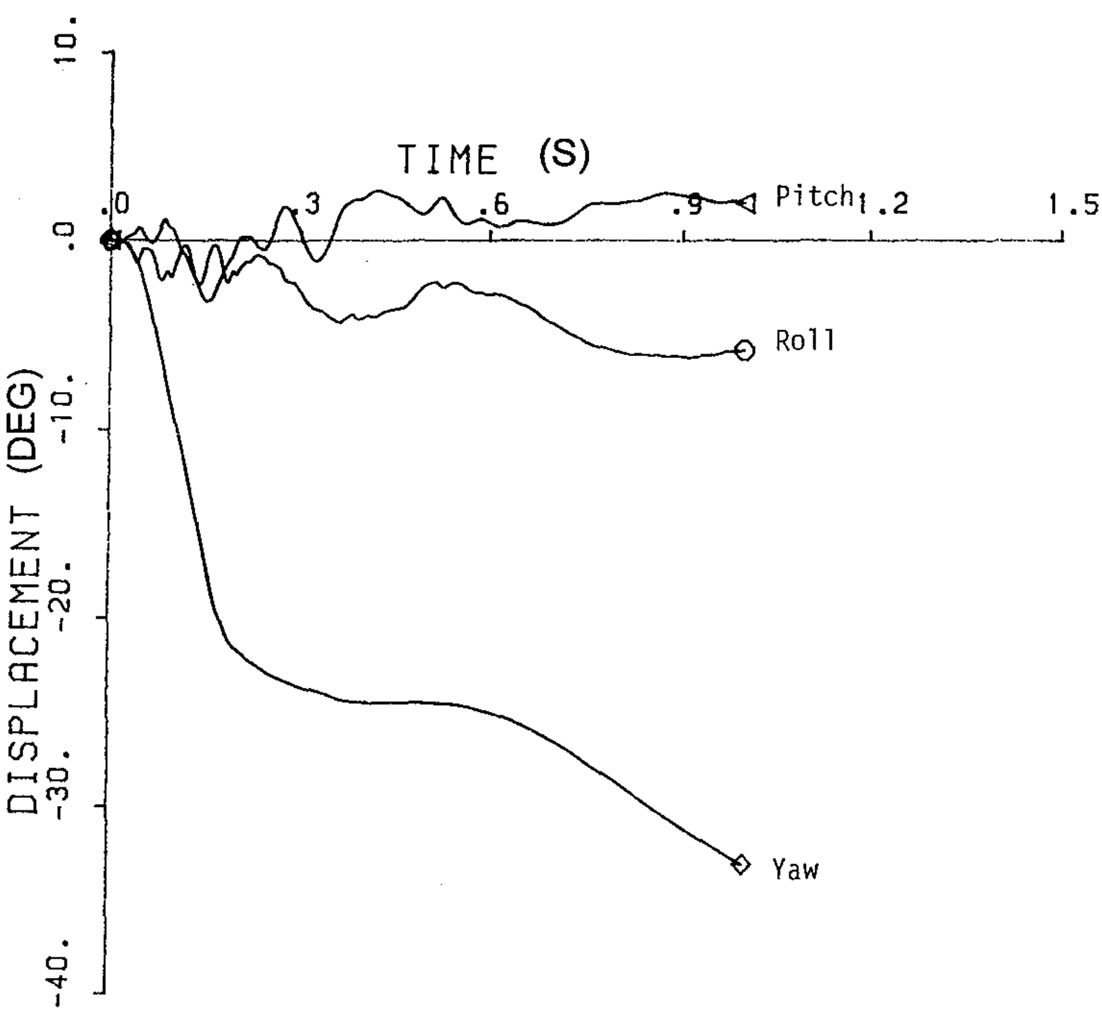


Figure 27 . Vehicle angular displacements for test 7147-8.

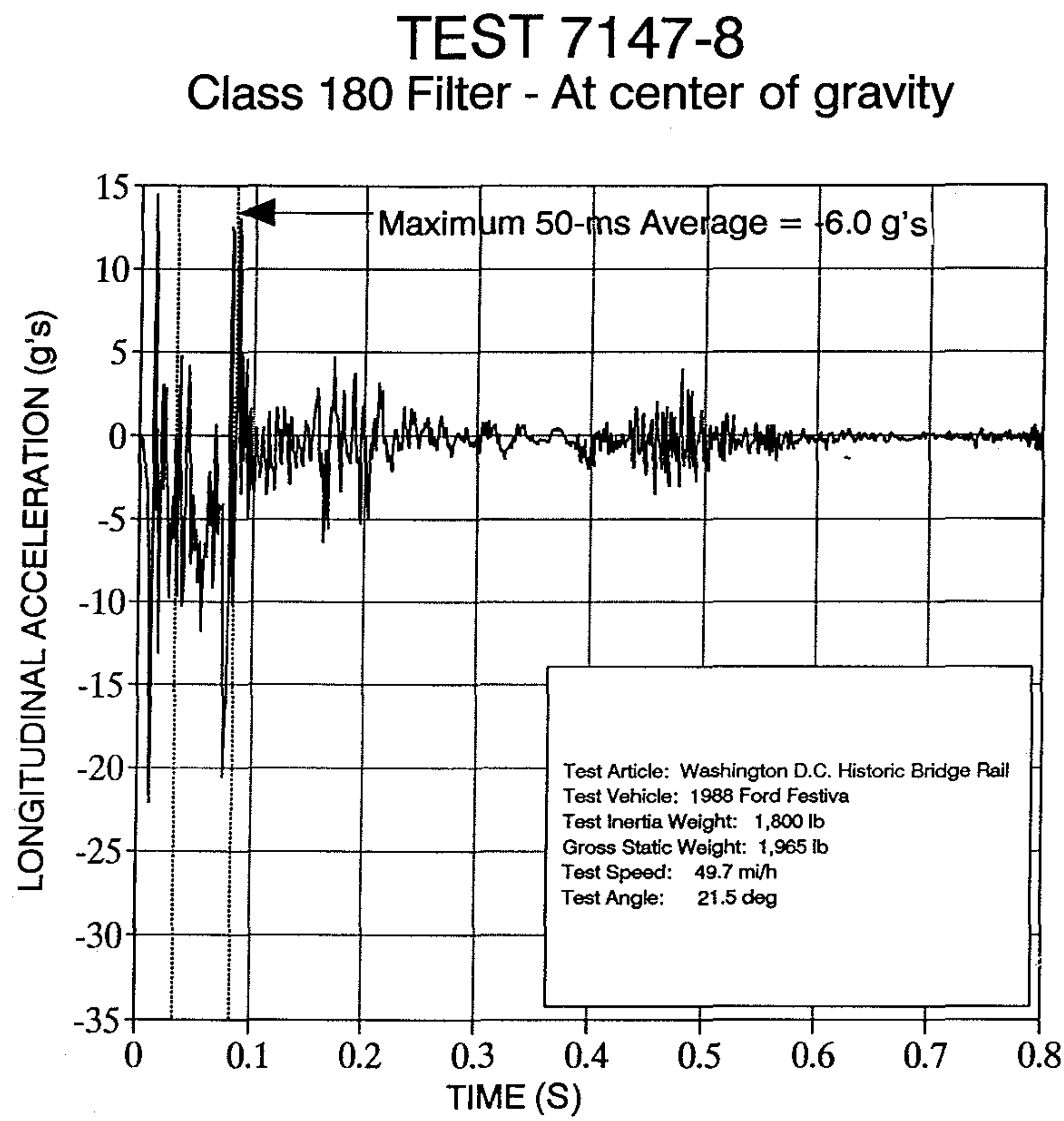


Figure 28. Vehicle longitudinal accelerometer trace for test 7147-8.

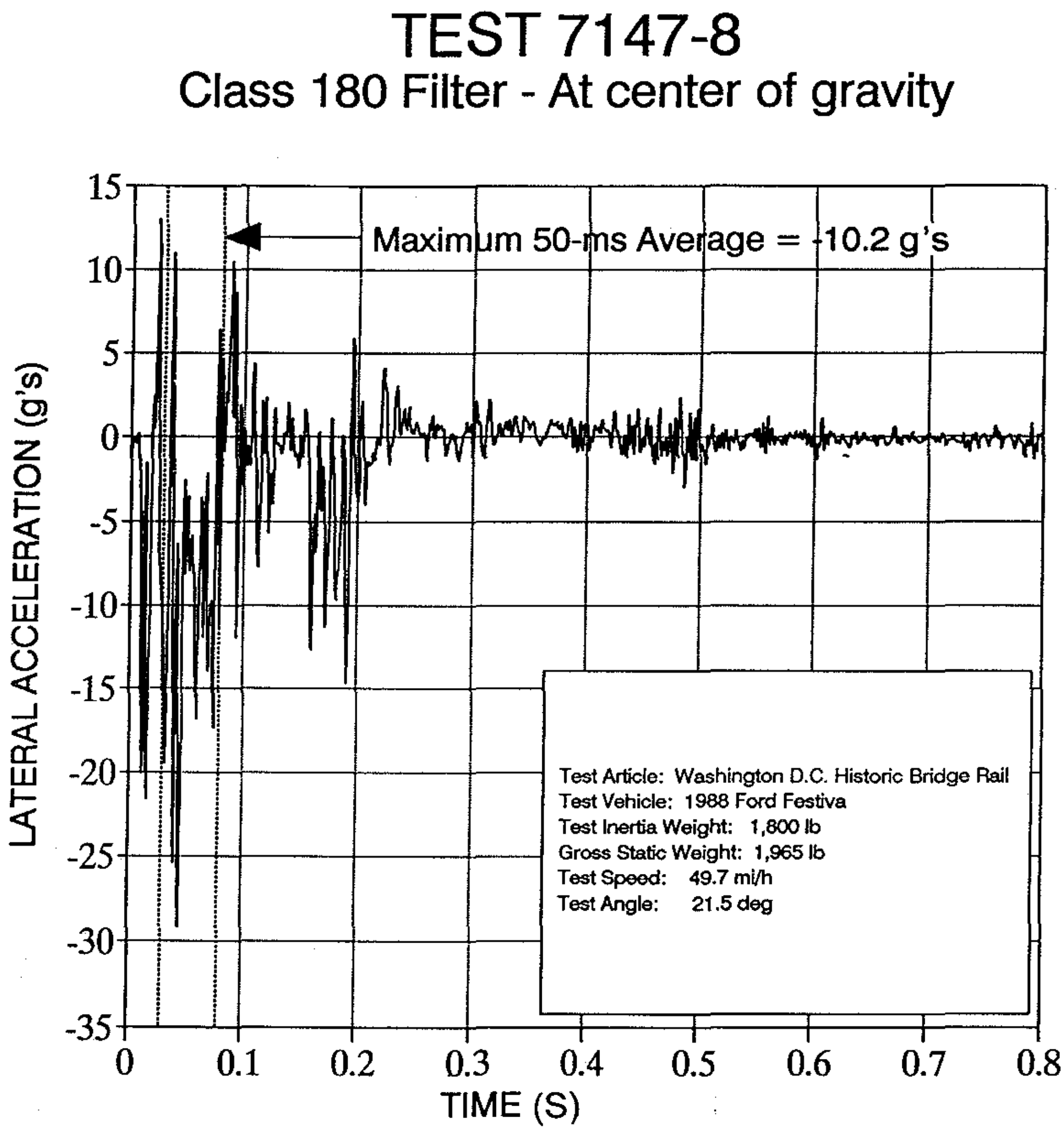


Figure 29. Vehicle lateral accelerometer trace for test 7147-8.

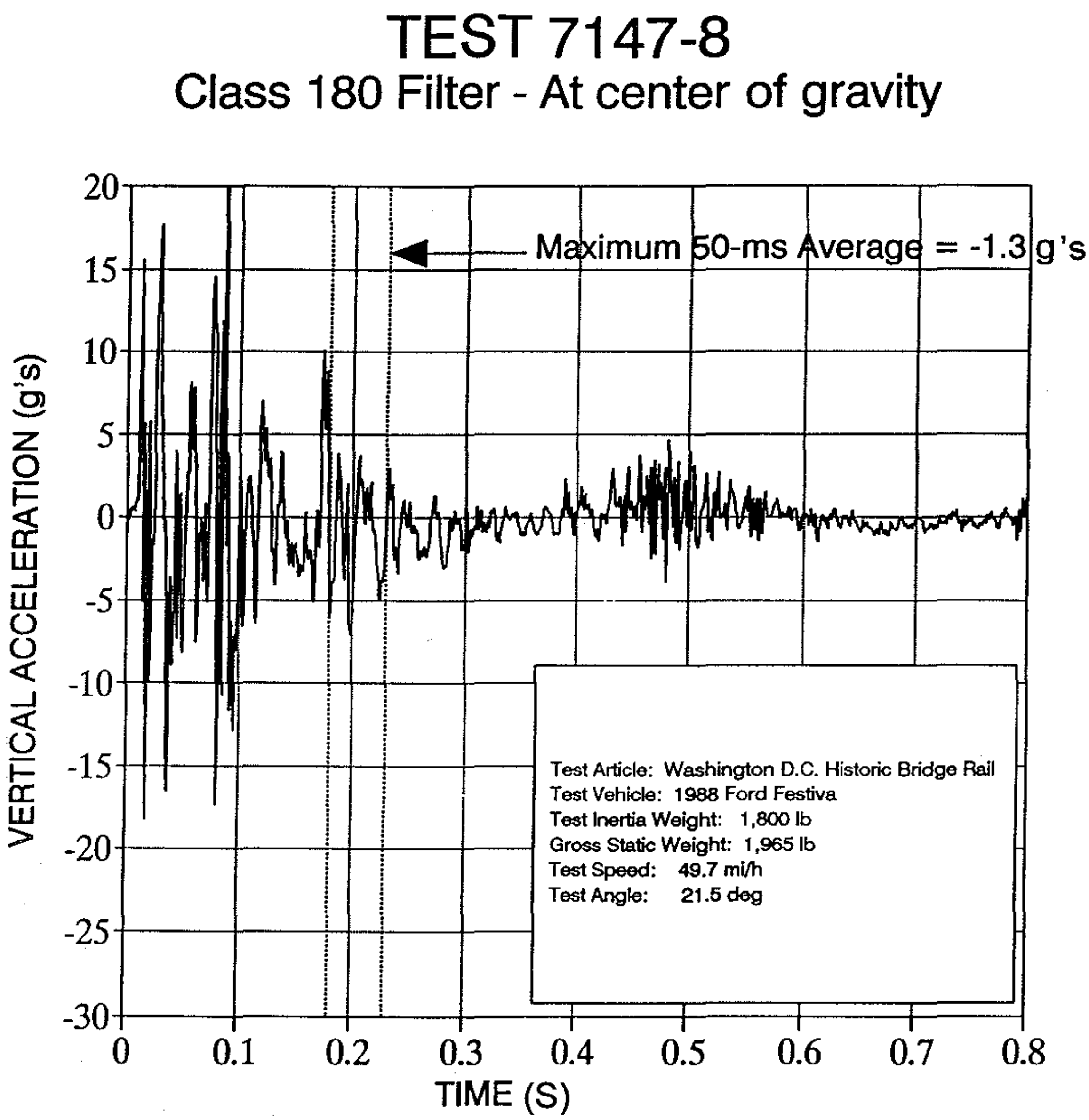


Figure 30. Vehicle vertical accelerometer trace for test 7147-8.

Figure 31. Vehicle before test 7147-9.

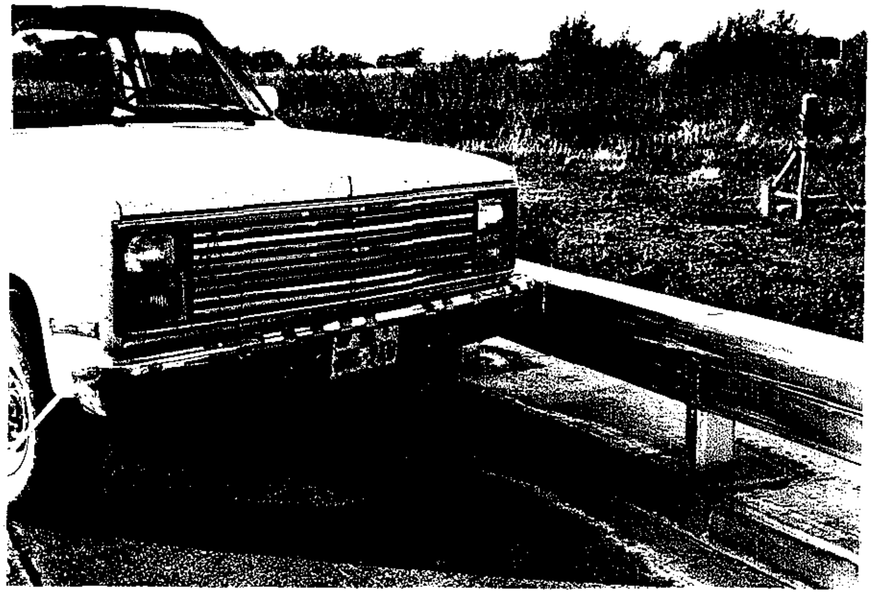


Figure 32. Vehicle/bridge rail geometrics for test 7147-9.

DATE: 12/16/91 TEST NO.: 471470-9 VIN NO.: IGCGC24M3GS123191

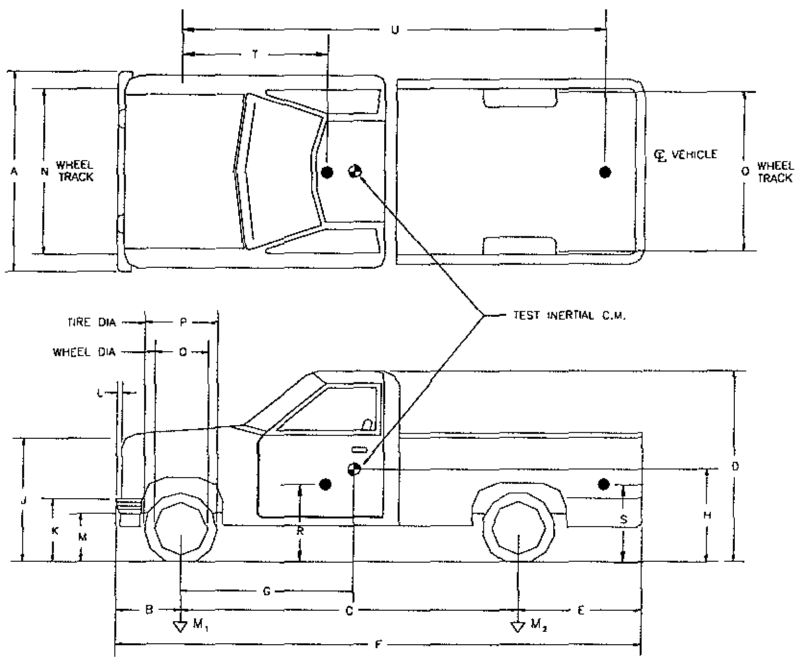
YEAR: 1986 MAKE: Chevrolet MODEL: Custom Deluxe

TIRE INFLATION PRESSURE: ______ ODOMETER: 103577 TIRE SIZE: LT235/85R16

MASS DISTRIBUTION (kg) LF 578 RF 582 LR 653 RR 638

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:

Crack in windshield marked



ENGINE TYPE: V-8

ENGINE CID: 350

TRANSMISSION TYPE:

__ AUTO

X MANUAL

OPTIONAL EQUIPMENT:

DUMMY DATA:

TYPE: 50th male

MASS: 75 kg

SEAT POSITION: Driver's

GEOMETRY - (mm)

A 2013	E 1321	J 1156	N 1664	R 787
B 800	F 5461	K 679.5	O	S 946
C 3340	G 1760	L 76	P 775	T 1854
D 1816	H	M 451	Q 445	U 4229

MASS - (kg)	CURB	TEST INERTIAL	GROSS STATIC
M_1	1210	1160	1203
M_2	984	1292	1323
M_T	2194	2452	2527

Figure 33. Vehicle properties for test 7147-9.

downstream from and 9 m (30 ft) forward of the point of initial impact. Sequential photographs of the test sequence are presented in figures 34 and 35.

3.3.2 Damage to Test Installation

The bridge railing received minimal damage, as shown in figure 36. There was no permanent deformation of the bridge railing. The total length of contact with the rail was 3.9 m (12.9 ft). Tire marks indicated that the tire did not go under the rail element.

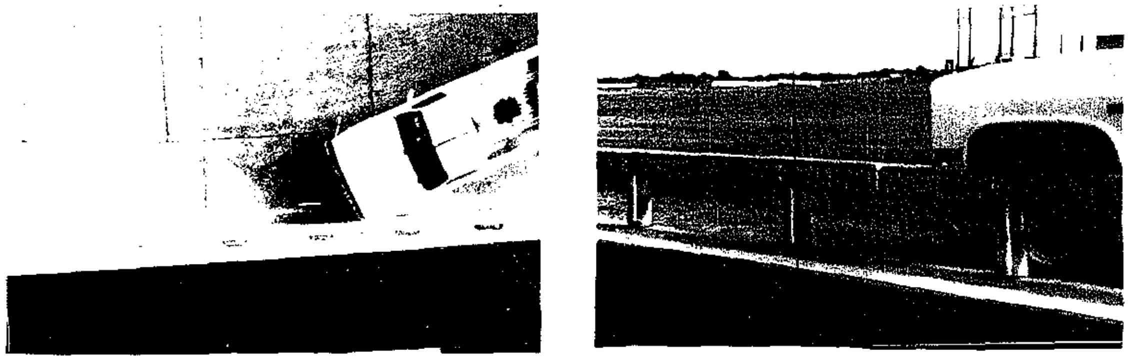
3.3.3 Vehicle Damage

The vehicle (shown in figure 37) received moderate damage. The driver's window was broken and there was damage to the front bumper, hood, grill, left front quarter panel, left door, left rear quarter panel, and the rear bumper. The left front and rear rims were damaged from contact with the curb and rail element. Maximum crush to the vehicle was 254 mm (10.0 in) at the left front corner at bumper height.

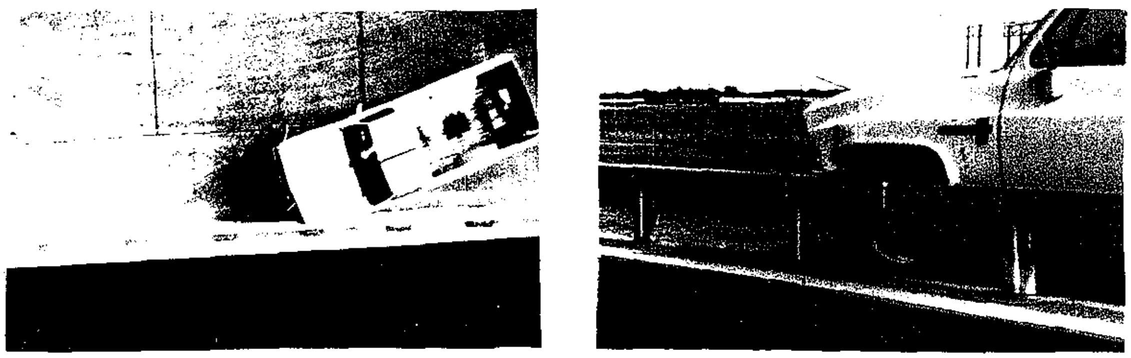
3.3.4 Occupant Risk Values

Data from the electronic instrumentation were digitized for evaluation, and occupant risk factors were computed as follows. In the longitudinal direction, occupant impact velocity was 2.7 m/s (8.9 ft/s) at 0.315 s; the highest 0.010-s average ridedown acceleration was -2.2 g's from 0.356 to 0.366 s; and the 0.050-s average acceleration was -3.6 g's between 0.069 and 0.119 s. Lateral occupant impact velocity was 4.8 m/s (15.6 ft/s) at 0.146 s; the highest 0.010-s average ridedown acceleration was -14.1 g's from 0.238 to 0.248 s; and the maximum 0.050-s average acceleration was -8.7 g's between 0.068 and 0.118 s. The change in vehicle velocity at loss of contact was 6.4 km/h (4.0 mi/h) and the change in momentum was 4376 N-s (984 lb-s).

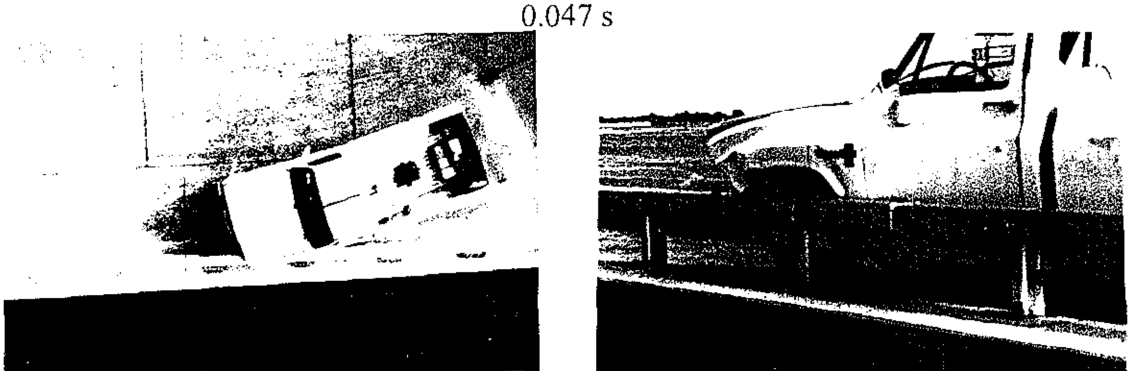
A summary of pertinent data from the electronic instrumentation, high-speed film, and field measurements is given in figure 38. Vehicle angular displacements are displayed in figure 39, and vehicular accelerations versus time traces filtered at 300 Hz are presented in figures 40 through 42.



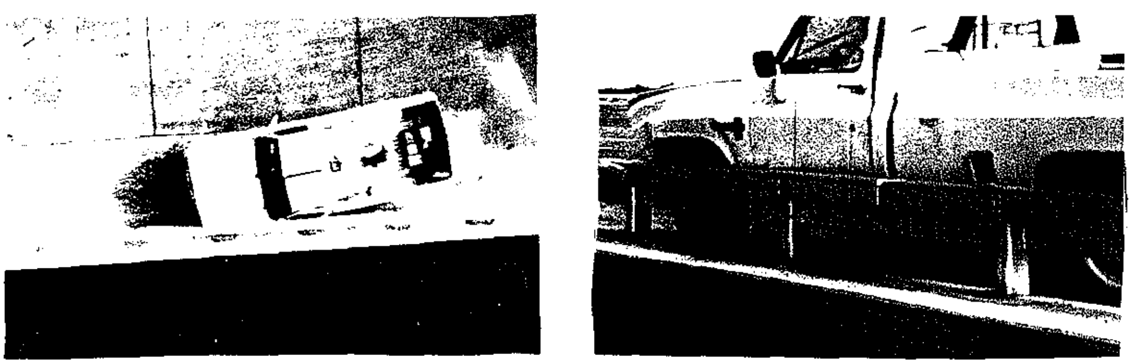
0.000 s



0.047 s



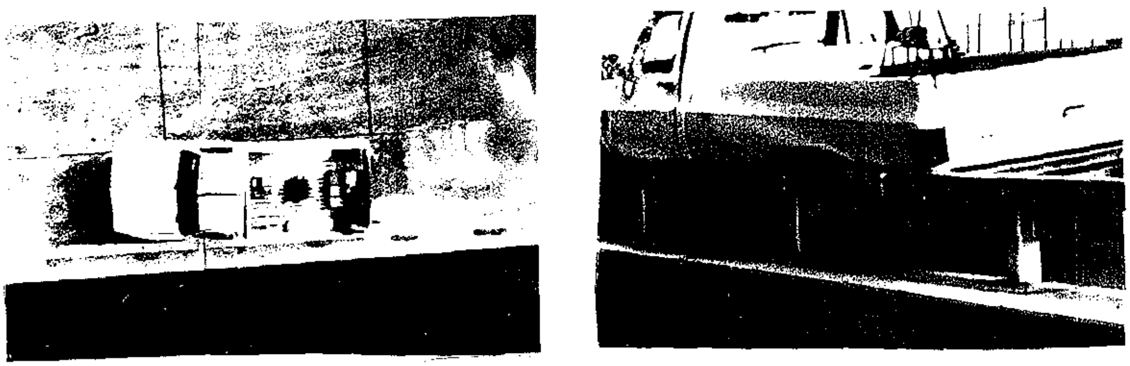
0.094 s



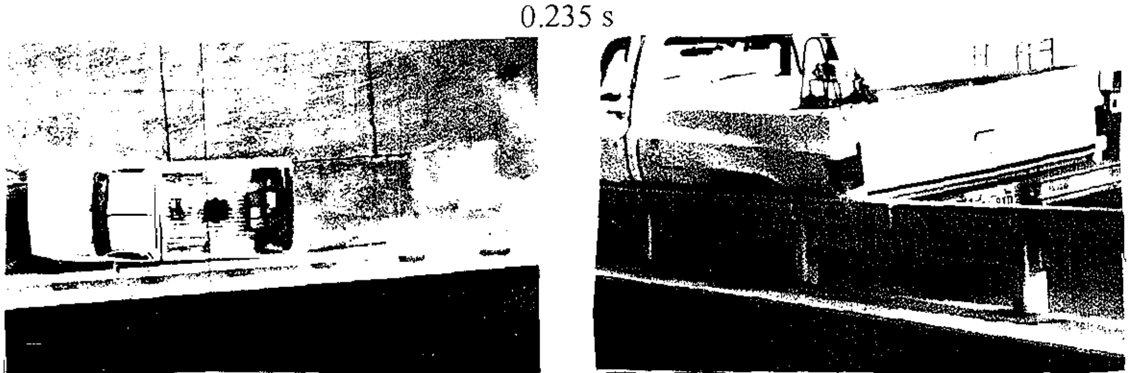
0.141 s

Figure 34. Sequential photographs for test 7147-9
(overhead and behind the rail views).

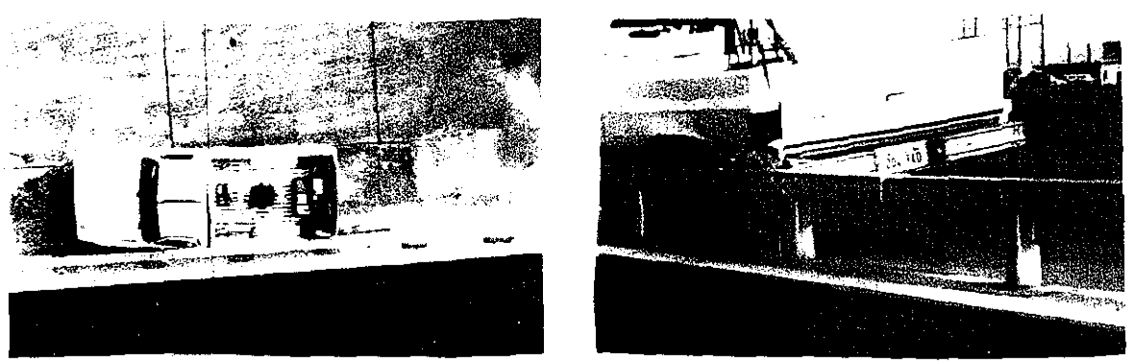
0.188 s



0.235 s



0.281 s



0.328 s

Figure 34. Sequential photographs for test 7147-9
(overhead and behind the rail views) (continued).

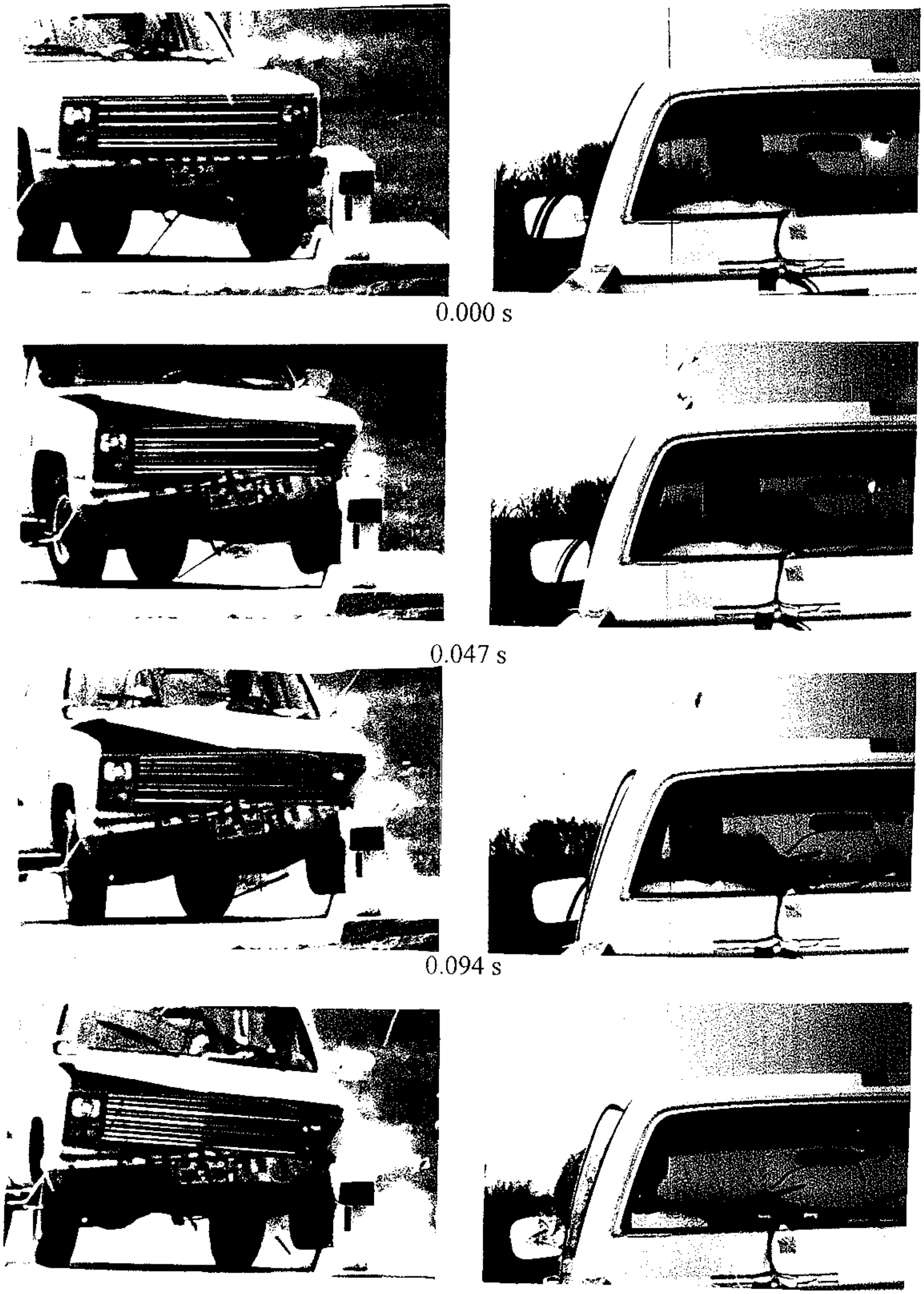
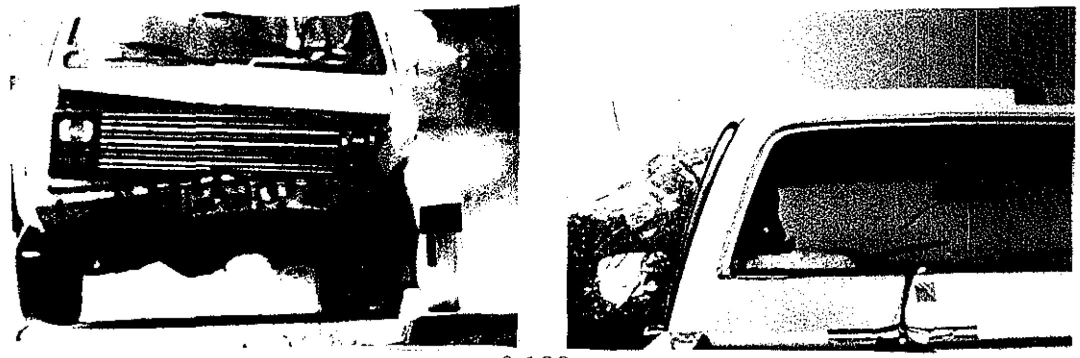
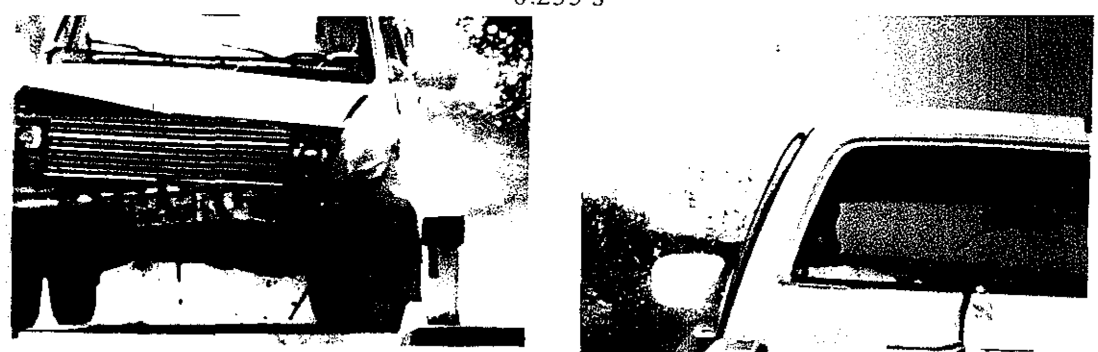


Figure 35. Sequential photographs for test 7147-9
(frontal and interior views).



0.188 s

0.235 s



0.281 s

0.328 s

Figure 35. Sequential photographs for test 7147-9 (frontal and interior views) (continued).

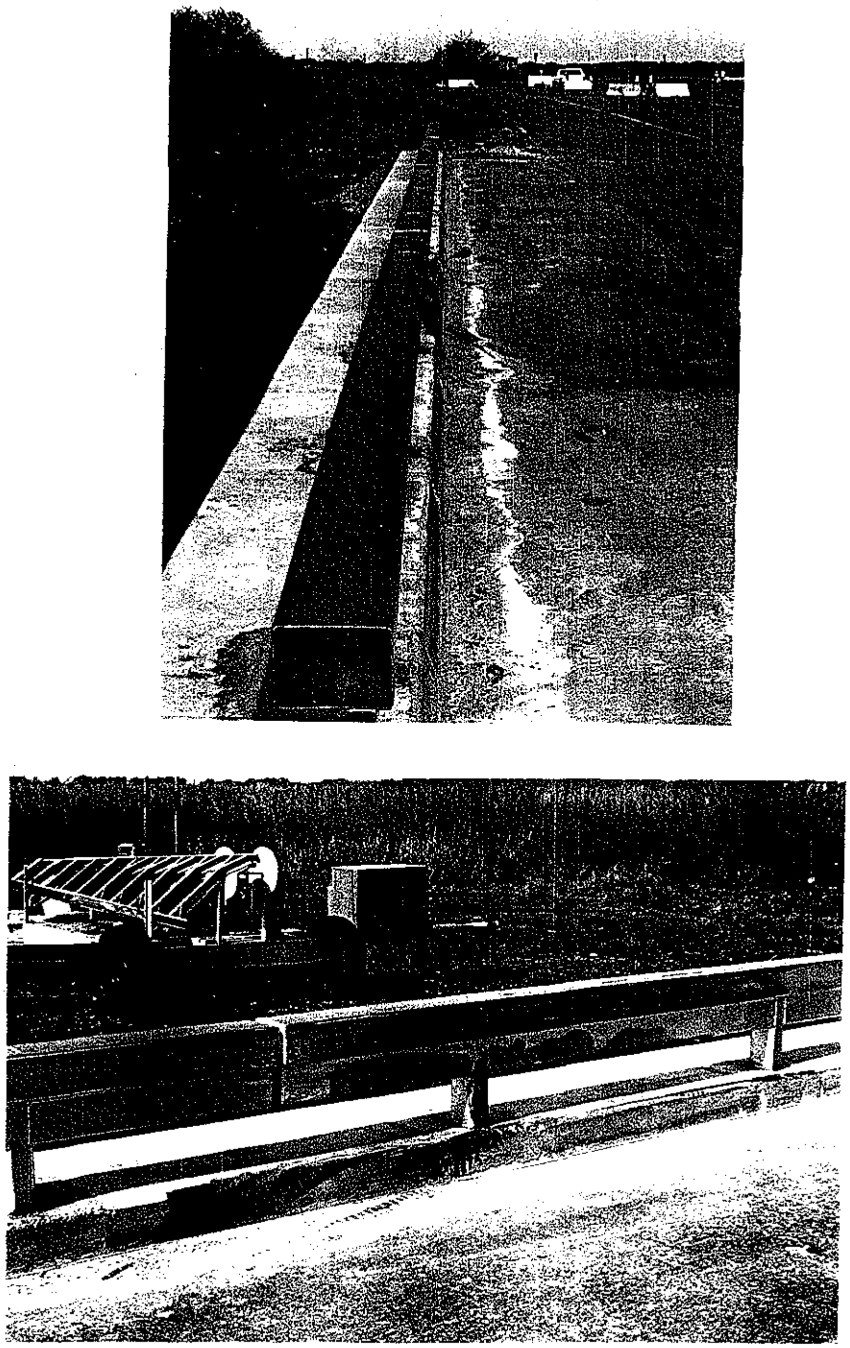


Figure 36. Washington, DC, bridge rail after test 7147-9.

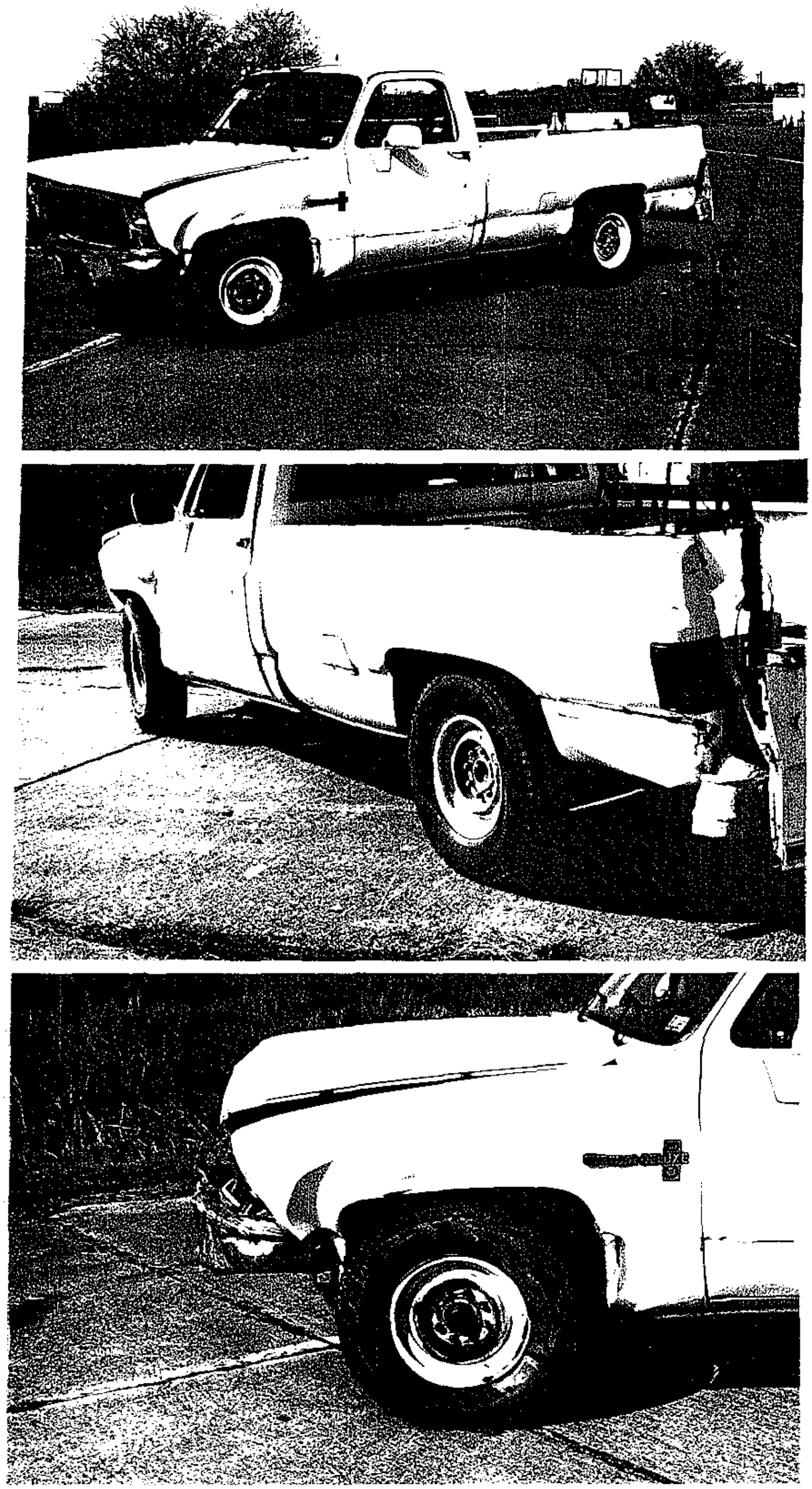
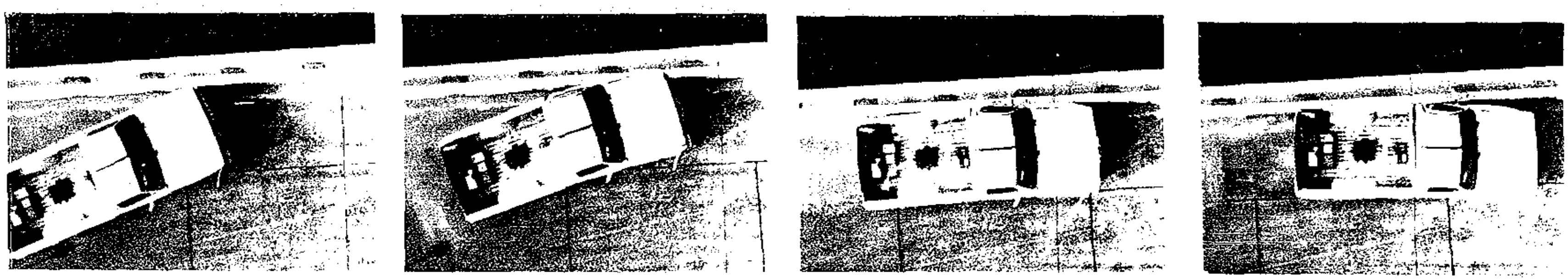
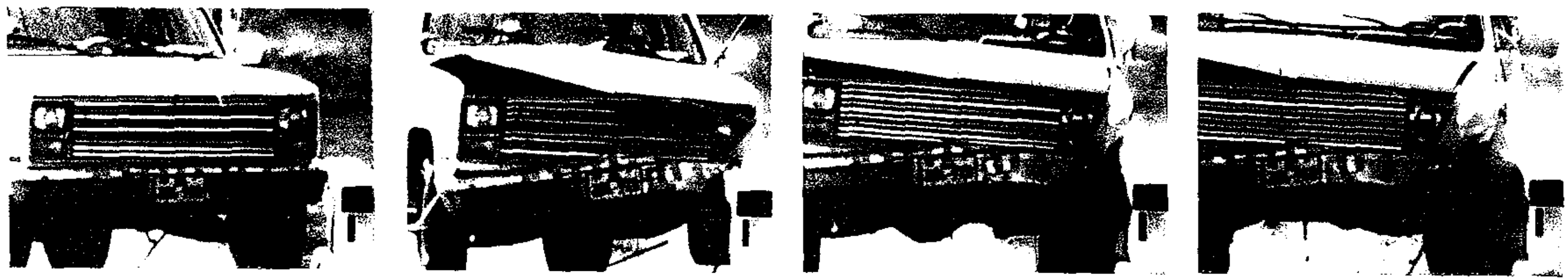
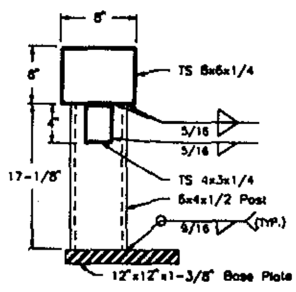


Figure 37. Vehicle after test 7147-9.



0.000 s 0.094 s 0.188 s 0.281 s





POST DETAIL

Test No.	7147-9
Date	12/16/91
Test Installation	Washington, DC, Historic Bridge Rail
Installation Length	23 m (75 ft)
Max. Dynamic Deflection	Nil
Max. Perm. Deformation	None
Test Vehicle	1986 Chevrolet Pickup
Vehicle Weight	
Test Inertia	2352 kg (5400 lb)
Gross Static	2527 kg (5565 lb)
Vehicle Damage Classification	
TAD	11FL2 & 11LD3
CDC	11FLEK2 & 11LDEW2
Maximum Vehicle Crush	254 mm (10.0 in)

Impact Speed	76.7 km/h (47.7mi/h)
Impact Angle	20.6 deg
Speed at Parallel	71.4 km/h (44.4 mi/h)
Exit Speed	70.3 km/h (43.7 mi/h)
Exit Trajectory	5.4 deg
Vehicle Accelerations (Max. 0.050-s avg)	
Longitudinal	-3.6 g's
Lateral	-8.7 g's
Occupant Impact Velocity at true c.g.	
Longitudinal	2.7 m/s (8.9 ft/s)
Lateral	4.8 m/s (15.6 ft/s)
Occupant Ridedown Accelerations	
Longitudinal	-2.2 g's
Lateral	-14.1 g's

Figure 38. Summary of results for test 7147-9.

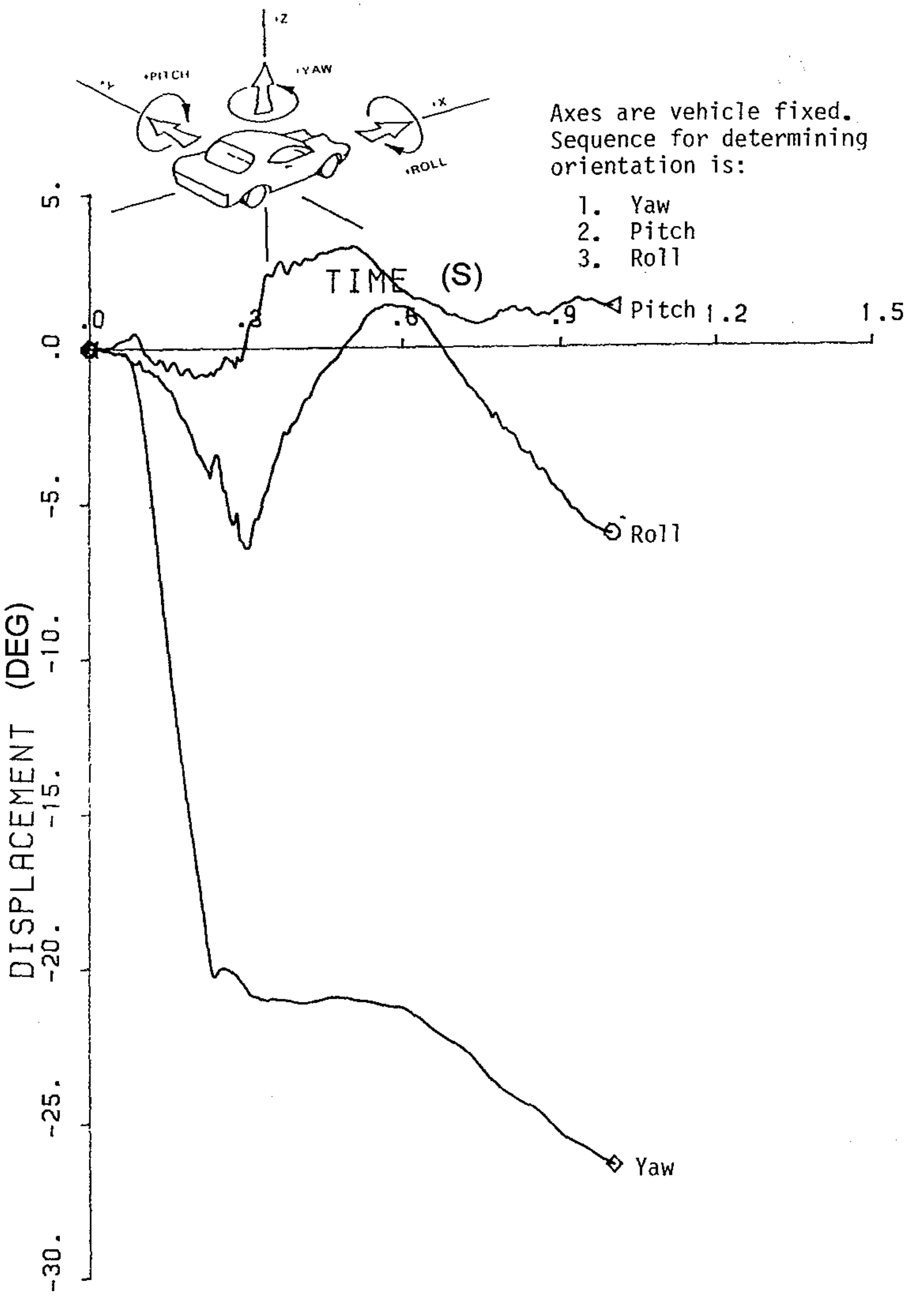


Figure 39. Vehicle angular displacements for test 7147-9.

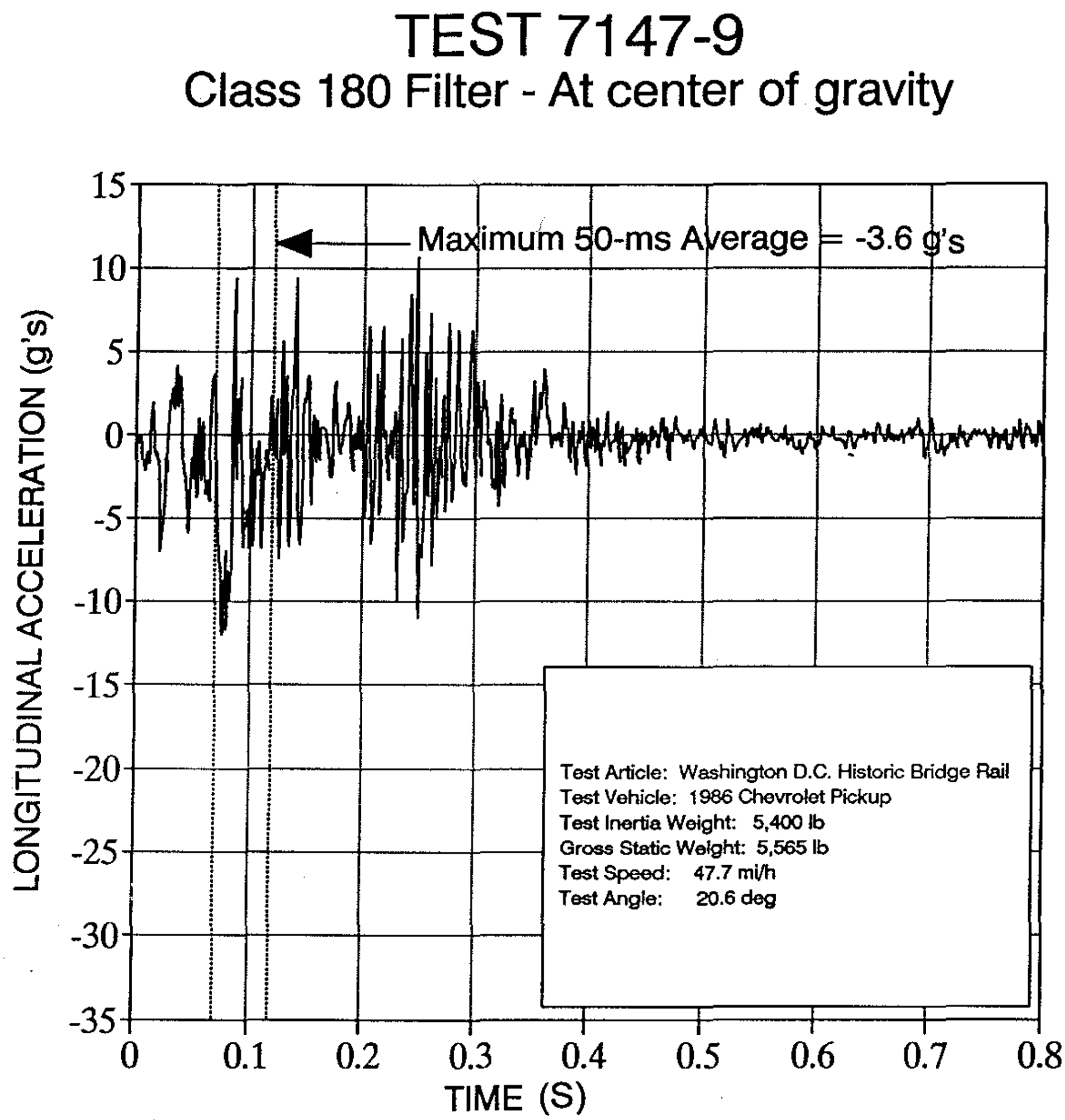


Figure 40. Vehicle longitudinal accelerometer trace for test 7147-9.

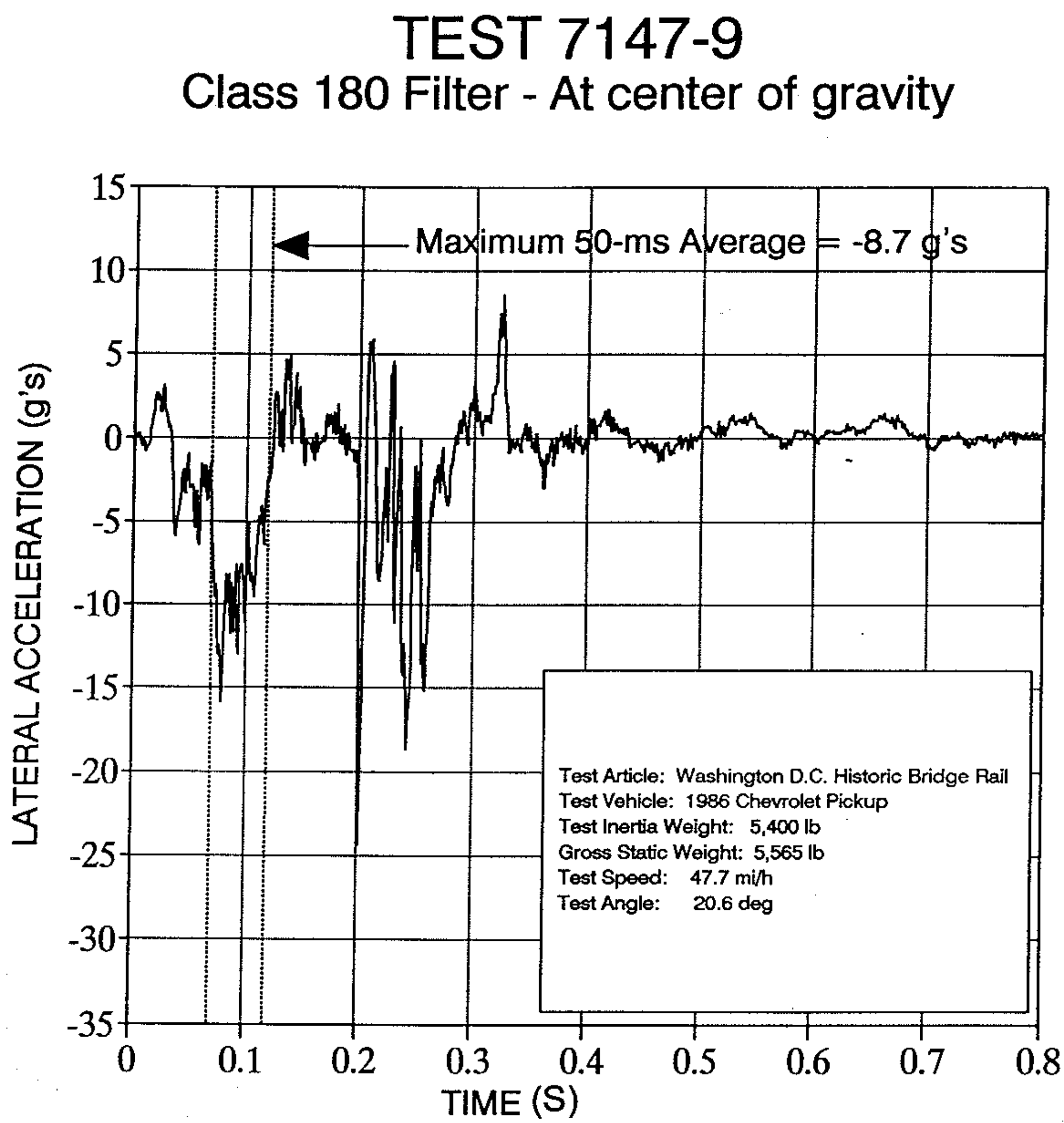


Figure 41. Vehicle lateral accelerometer trace for test 7147-9.

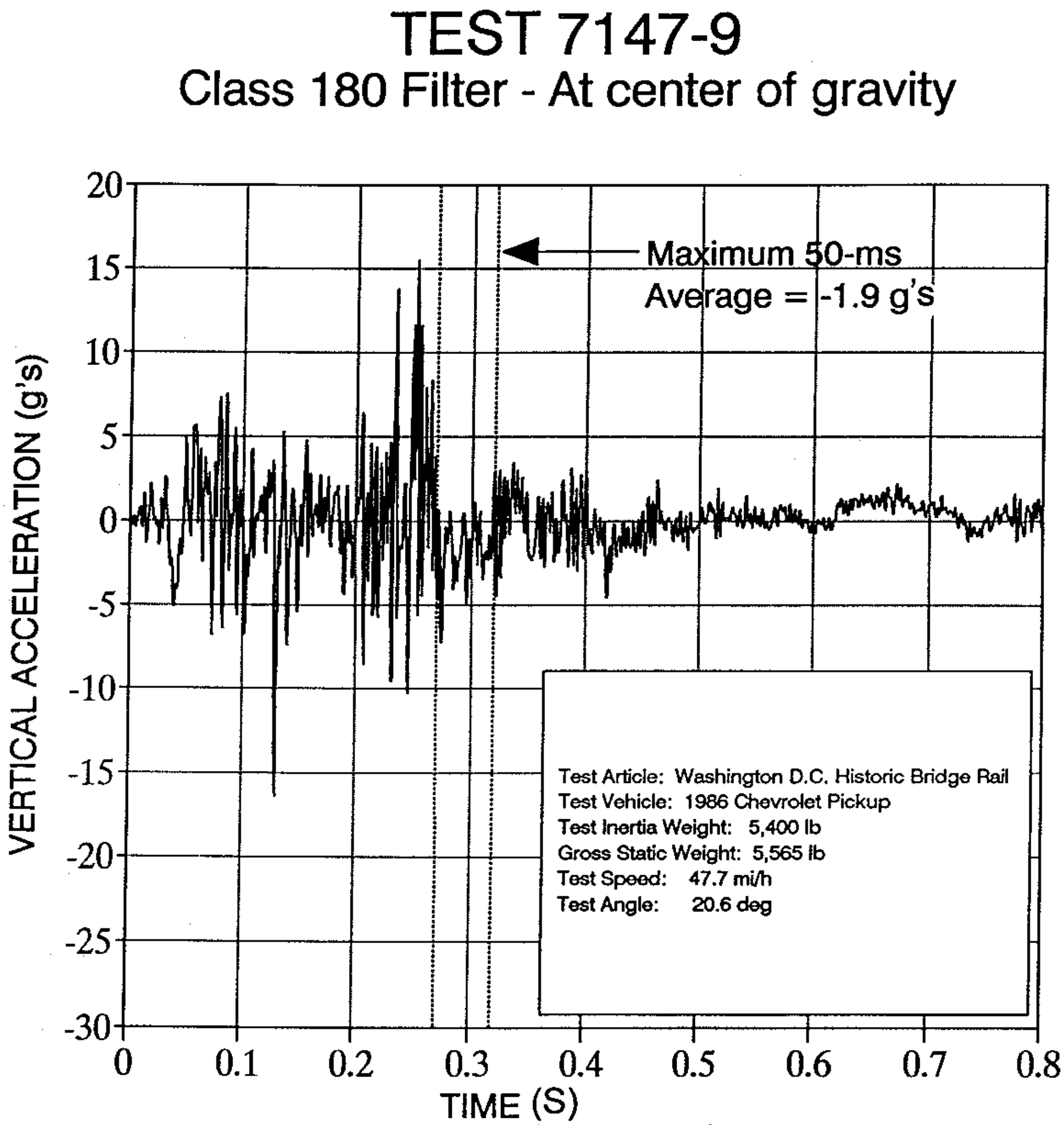


Figure 42. Vehicle vertical accelerometer trace for test 7147-9.

IV. SUMMARY OF FINDINGS AND CONCLUSIONS

4.1 SUMMARY OF FINDINGS

In the first test (test no. 471470-6) with the original bridge rail design, the vehicle was redirected and did not penetrate or go over the bridge railing. The bridge railing received only minimal damage and there were no detached elements or debris to show potential for penetration of the occupant compartment or to present undue hazard to other traffic. The vehicle remained upright and stable during the impact with the bridge railing and after exiting the test installation. However, the vehicle sustained extensive damage and there was considerable deformation and intrusion into the passenger compartment. The velocity change of 26.9 km/h (16.7 mi/h) was higher than the recommended limit of 24.1 km/h (15 mi/h) according to NCHRP Report 230 guidelines, but the exit angle of 1.5 degrees was substantially less than 60 percent of the impact angle. Moreover, the exit trajectory of the vehicle was judged not to pose any potential hazard to adjacent traffic, and this evaluation criterion was thus considered not to be applicable. The occupant impact velocities and ridedown accelerations were within the acceptable limits.

The impact performance of the original Washington, DC, historic bridge rail design was judged to be unsatisfactory according to evaluation criteria set forth in the 1989 AASHTO *Guide Specifications for Bridge Railings* and NCHRP Report 230, as summarized in tables 1 and 2, respectively. The bumper of the vehicle underrode the beam element of the bridge rail and impacted the posts, resulting in the bumper being torn off the vehicle. The left front tire of the vehicle snagged extensively on the posts, pushing the tire back into the wheel well, resulting in considerable deformation and intrusion into the passenger compartment in the firewall and floor pan area.

Review of the results of the first test suggested that the unsatisfactory performance of the original bridge rail design was caused by the bumper underriding the beam element of the bridge rail, resulting in the bumper impacting the posts head-on and the left front tire of the vehicle snagging severely on the posts. It was therefore recommended that the bottom TS 102-mm × 76.2-mm × 6.4-mm (4-in × 3-in × 1/4-in) box beams be replaced with wider TS 152-mm × 50.8-mm × 6.4-mm (6-in × 2-in × 1/4-in) box beams and the box beams be moved forward to be flush with the face of the posts on the traffic side. This would reduce the potential for the bumper and the front wheel of the vehicle to underride the beam element of the bridge rail and impact the posts directly.

The modified Washington, DC, historic bridge rail was then crash tested with successful results. The second test (test no. 471470-8) was a repeat of the first test with a small passenger car on the modified bridge rail design. Summaries of the performance evaluation according to evaluation criteria set forth in the 1989 AASHTO *Guide Specifications for Bridge Railings* and NCHRP Report 230 are presented in tables 3 and 4, respectively. The vehicle was redirected smoothly and did not penetrate or go over the bridge railing. The bridge railing received only minimal damage and there were no detached elements or debris to show potential for penetration of the occupant compartment or to present undue hazard to other traffic. The vehicle remained upright and stable during the impact with the bridge railing and after exiting the test installation. The vehicle sustained moderate damage with essentially no deformation or intrusion into the passenger compartment. The occupant impact velocities and ridedown accelerations were well within the acceptable limits.

The modified bridge rail design was then crash tested with a 2451-kg (5400-lb) pickup truck in the third test (test no. 471470-9). Summaries of the performance evaluation for this test according to evaluation criteria set forth in the 1989 AASHTO *Guide Specifications for Bridge Railings* and NCHRP Report 230 are presented in tables 5 and 6, respectively. The vehicle was smoothly redirected and did not penetrate or go over the bridge railing. The bridge railing received only minimal damage and there were no detached elements or debris to show potential for penetration of the occupant compartment or to present undue hazard to other traffic. The vehicle remained upright and stable during the impact with the bridge railing and after exiting the test installation. The vehicle sustained moderate damage with essentially no deformation or intrusion into the passenger compartment.

4.2 CONCLUSIONS

The modified Washington, DC, historic bridge rail design performed satisfactorily in both crash tests and met all requirements as outlined under NCHRP Report 230 and the 1989 AASHTO *Guide Specifications for Bridge Railings*. It is, therefore, recommended that the modified Washington, DC, historic bridge railing design be approved for field implementation.

4.3 RECOMMENDATIONS

Two observations unrelated to the impact performance of the bridge railing are presented herein for consideration. One observation is that repair of the bridge rail may be a potential problem. The base plates of the posts and the bolts and nuts attaching the posts to the bridge deck are recessed into cutouts in the curb on the bridge deck. The cutouts are then backfilled with concrete after installation of the bridge rail. If the bridge rail was damaged to such an extent as to require replacement of a section of the rail, the concrete in the cutouts will have to be manually chipped out before workers can get to the bolts and nuts to remove the posts. Also, this increases the likelihood of the threads in the anchor bolts being damaged, which would further complicate the removal of the posts.

The second observation is that the continuous welding used to attach the TS 152-mm × 50.8-mm × 6.4-mm (6-in × 2-in × 1/4-in) box beams to the top TS 203-mm × 152-mm × 6.4-mm (8-in × 6-in × 1/4-in) box beam caused the bridge rail system to warp significantly during fabrication. Heat treatment to the top beam elements was required to straighten out the bridge rail sections. It is believed that a zippered weld would be adequate from a structural standpoint, which would minimize this problem of warping due to overheating.

Table 1. Assessment of results of test on 471470-6 (according to 1989 AASHTO Guide).

AASHTO EVALUATION CRITERIA*	TEST RESULTS	ASSESSMENT
a. The test shall contain the vehicle; neither the vehicle nor its cargo shall penetrate or go over the installation. Controlled lateral deflection of the test article is acceptable.	The bridge rail contained the vehicle, i.e., the vehicle did not penetrate or go over the bridge rail.	Pass
b. Detached elements, fragments, or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	No debris showed potential for penetrating the passenger compartment or presenting undue hazard to other traffic.	Pass
c. Integrity of the passenger compartment must be maintained with no intrusion and essentially no deformation.	There was intrusion and deformation into the passenger compartment.	Fail
d. The vehicle shall remain upright during and after collision.	The vehicle remained upright and stable during and after the collision.	Pass
e. The test article must smoothly redirect the vehicle.	The vehicle was smoothly redirected.	N/A
f. The smoothness of the vehicle-railing interaction is further assessed by the effective coefficient of friction, μ: μ — Assessment 0 - .25 — Good .26 - .35 — Fair >.35 — Marginal where $\mu = (\cos\theta - V_p/V)/\sin\theta$	μ — Assessment 0.53 — Marginal	N/A
g. The impact velocity shall be less than: Occupant Impact Velocity - m/s (ft/s) Longitudinal: 9.2 (30) — Lateral: 7.6 (25) Occupant Ridedown Accelerations - g's Longitudinal: 15 — Lateral: 15	Occupant Impact Velocity - m/s (ft/s) Longitudinal: 7.5 (24.7) — Lateral: 5.1 (16.6) Occupant Ridedown Accelerations - g's Longitudinal: -6.5 — Lateral: -9.9	Pass
h. Vehicle exit angle from the barrier shall not be more than 12 degrees. Within 30 m (100 ft) plus the length of the test vehicle from the point of initial impact with the railing, the railing side of the vehicle shall move no more than 6 m (20 ft) from the line of the traffic face of the railing.	Exit angle at loss of contact was 1.5 degrees. Vehicle came to rest 32 m (105 ft) down and 8 m (25 ft) behind the point of impact.	N/A

*a, b, c, d, and g are required. e, f, and h are desired.

Table 2. Assessment of results of test 471470-6 (according to NCHRP 230).

Test Agency: Texas Transportation Institute | Test No.: 7147-6 | Test Date: 09/17/91

Evaluation Criteria	Test Results	Assessment
Structural Adequacy		
A. Test article shall contain and redirect the vehicle; the vehicle should not penetrate or go over the installation although controlled lateral deflection of the test article is acceptable.	The vehicle did not penetrate or go over the barrier and was smoothly redirected.	Pass
D. Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	No debris showed potential for penetrating the passenger compartment or presenting undue hazard to other traffic.	Pass
Occupant Risk		
E. The vehicle shall remain upright during and after collision although moderate roll, pitching and yawing are acceptable. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.	The vehicle remained upright and stable during collision. There was deformation and intrusion into the passenger compartment.	Fail
F. Impact velocity of hypothetical front seat passenger against the vehicle interior shall be less than Occupant Impact Velocity Limits (m/s): Longitudinal 12.2 (40 ft/s); Lateral 9.1 (30 ft/s)	Longitudinal Impact Velocity = 7.5 m/s (24.7 ft/s) Lateral Impact Velocity = 5.1 m/s (16.6 ft/s)	Pass
and vehicle highest 10 ms average accelerations subsequent to instant of hypothetical passenger contact should be less than: Occupant Ridedown Acceleration Limits (g's): Longitudinal 20; Lateral 20	Longitudinal Ridedown Acceleration = -6.5 g's Lateral Ridedown Acceleration = -9.9 g's	Pass
Vehicle Trajectory		
H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.	The vehicle came to rest 32 m (105 ft) downstream and 8 m (25 ft) behind the point of impact	Pass
I. In test where the vehicle is judged to be redirected into or stopped while in adjacent traffic lanes, vehicle speed change during test article collision should be less than 15 mi/h and the exit angle from the test article should be less than 60 percent of test impact angle, both measured at time of vehicle loss of contact with test device.	Velocity change was 26.9 km/h (16.7 mi/h), which was greater than 24.1 km/h (15 mi/h); exit angle was 1.5 degrees, which was less than 12.1 degrees (or 60 percent of 20.1 degrees)	Pass

Table 3. Assessment of results of test on 471470-8 (according to 1989 AASHTO Guide).

AASHTO EVALUATION CRITERIA*	TEST RESULTS	ASSESSMENT
a. The test shall contain the vehicle; neither the vehicle nor its cargo shall penetrate or go over the installation. Controlled lateral deflection of the test article is acceptable.	The bridge rail contained the vehicle, i.e., the vehicle did not penetrate or go over the bridge rail.	Pass
b. Detached elements, fragments, or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	No debris showed potential for penetrating the passenger compartment or presenting undue hazard to other traffic.	Pass
c. Integrity of the passenger compartment must be maintained with no intrusion and essentially no deformation.	There was no intrusion or deformation into the passenger compartment.	Pass
d. The vehicle shall remain upright during and after collision.	The vehicle remained upright and stable during and after the collision.	Pass
e. The test article must smoothly redirect the vehicle.	The vehicle was smoothly redirected.	N/A
f. The smoothness of the vehicle-railing interaction is further assessed by the effective coefficient of friction, μ: μ — Assessment 0 - .25 — Good .26 - .35 — Fair >.35 — Marginal where $\mu = (\cos\theta - V_p/V)/\sin\theta$	μ — Assessment 0.31 — Fair	N/A
g. The impact velocity shall be less than: Occupant Impact Velocity - m/s (ft/s) Longitudinal 9.2 (30); Lateral 7.6 (25) Occupant Ridedown Accelerations - g's Longitudinal 15; Lateral 15	Occupant Impact Velocity - m/s (ft/s) Longitudinal 4.3 (14.2); Lateral 5.7 (18.7) Occupant Ridedown Accelerations - g's Longitudinal -1.4; Lateral -6.9	Pass
h. Vehicle exit angle from the barrier shall not be more than 12 degrees. Within 30 m (100 ft) plus the length of the test vehicle from the point of initial impact with the railing, the railing side of the vehicle shall move no more than 6 m (20 ft) from the line of the traffic face of the railing.	Exit angle at loss of contact was 3.5 degrees. Vehicle came to rest 59 m (195 ft) down and 29 m (95 ft) forward of point of impact.	N/A

*a, b, c, d and g are required. e, f, and h are desired.

Table 4. Assessment of results of test 471470-8 (according to NCHRP 230).

Test Agency: Texas Transportation Institute — Test No.: 7147-8 — Test Date: 12/10/91

Evaluation Criteria	Test Results	Assessment
<u>Structural Adequacy</u>		
A. Test article shall contain and redirect the vehicle; the vehicle should not penetrate or go over the installation although controlled lateral deflection of the test article is acceptable.	The vehicle did not penetrate or go over the barrier and was smoothly redirected.	Pass
D. Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	No debris showed potential for penetrating the passenger compartment or presenting undue hazard to other traffic.	Pass
<u>Occupant Risk</u>		
E. The vehicle shall remain upright during and after collision although moderate roll, pitching and yawing are acceptable. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.	The vehicle remained upright and stable during collision. There was no deformation or intrusion into the passenger compartment.	Pass
F. Impact velocity of hypothetical front seat passenger against the vehicle interior shall be less than Occupant Impact Velocity Limits (m/s) Longitudinal: 12.2 (40 ft/s); Lateral: 9.1 (30 ft/s)	Longitudinal Impact Velocity = 4.3 m/s (14.2 ft/s) Lateral Impact Velocity = 5.7 m/s (18.7 ft/s)	Pass
and vehicle highest 10 ms average accelerations subsequent to instant of hypothetical passenger contact should be less than: Occupant Ridedown Acceleration Limits (g's) Longitudinal: 20; Lateral: 20	Longitudinal Ridedown Acceleration = -1.4 g's Lateral Ridedown Acceleration = -6.9 g's	Pass
<u>Vehicle Trajectory</u>		
H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.	The vehicle came to rest 59 m (195 ft) downstream and 29 m (95 ft) forward of the point of impact	Pass
I. In test where the vehicle is judged to be redirected into or stopped while in adjacent traffic lanes, vehicle speed change during test article collision should be less than 15 mi/h and the exit angle from the test article should be less than 60 percent of test impact angle, both measured at time of vehicle loss of contact with test device.	Velocity change was 15.4 km/h (9.6 mi/h), which was less than 24.1 km/h (15 mi/h); exit angle was 3.5 degrees, which was less than 12.9 degrees (or 60 percent of 21.5 degrees)	Pass

Table 5. Assessment of results of test on 471470-9 (according to 1989 AASHTO Guide).

AASHTO EVALUATION CRITERIA*	TEST RESULTS	ASSESSMENT
a. The test shall contain the vehicle; neither the vehicle nor its cargo shall penetrate or go over the installation. Controlled lateral deflection of the test article is acceptable.	The bridge rail contained the vehicle, i.e., the vehicle did not penetrate or go over the bridge rail.	Pass
b. Detached elements, fragments, or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	No debris showed potential for penetrating the passenger compartment or presenting undue hazard to other traffic.	Pass
c. Integrity of the passenger compartment must be maintained with no intrusion and essentially no deformation.	There was no intrusion or deformation into the passenger compartment.	Pass
d. The vehicle shall remain upright during and after collision.	The vehicle remained upright and stable during and after the collision.	Pass
e. The test article must smoothly redirect the vehicle.	The vehicle was smoothly redirected.	N/A
f. The smoothness of the vehicle-railing interaction is further assessed by the effective coefficient of friction, μ: μ — Assessment 0 - .25 — Good .26 - .35 — Fair >.35 — Marginal where $\mu = (\cos\theta - V_p/V)/\sin\theta$	μ — Assessment 0.03 — Good	N/A
g. The impact velocity shall be less than: Occupant Impact Velocity - m/s (ft/s) Longitudinal — Lateral 9.2 (30) — 7.6 (25) Occupant Ridedown Accelerations - g's Longitudinal — Lateral 15 — 15	Occupant Impact Velocity - m/s (ft/s) Longitudinal — ' Lateral 2.7 (8.9) — 4.8 (15.6) Occupant Ridedown Accelerations - g's Longitudinal — Lateral -2.2 — -14.1	N/A
h. Vehicle exit angle from the barrier shall not be more than 12 degrees. Within 30 m (100 ft) plus the length of the test vehicle from the point of initial impact with the railing, the railing side of the vehicle shall move no more than 6 m (20 ft) from the line of the traffic face of the railing.	Exit angle at loss of contact was 5.4 degrees. Vehicle came to rest 82 m (270 ft) and 9 m (30 ft) forward of the point of impact.	N/A

*a, b, c, and d are required. e, f, and h are desired.

Table 6. Assessment of results of test 471470-9 (according to NCHRP 230).

Test Agency: Texas Transportation Institute | Test No.: 7147-9 | Test Date: 09/17/91

<table>
<tr><th colspan="2">Evaluation Criteria</th><th>Test Results</th><th>Assessment</th></tr>
<tr><td colspan="4"><u>Structural Adequacy</u></td></tr>
<tr><td colspan="2">A. Test article shall contain and redirect the vehicle; the vehicle should not penetrate or go over the installation although controlled lateral deflection of the test article is acceptable.</td><td>The vehicle did not penetrate or go over the barrier and was smoothly redirected.</td><td>Pass</td></tr>
<tr><td colspan="2">D. Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.</td><td>No debris showed potential for penetrating the passenger compartment or presenting undue hazard to other traffic.</td><td>Pass</td></tr>
<tr><td colspan="4"><u>Occupant Risk</u></td></tr>
<tr><td colspan="2">E. The vehicle shall remain upright during and after collision although moderate roll, pitching and yawing are acceptable. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.</td><td>The vehicle remained upright and stable during collision. There was no deformation and intrusion into the passenger compartment.</td><td>Pass</td></tr>
<tr><td colspan="2">F. Impact velocity of hypothetical front seat passenger against the vehicle interior shall be less than</td><td rowspan="4">Longitudinal Impact Velocity = 2.7 m/s (8.9 ft/s)
Lateral Impact Velocity = 4.8 m/s (15.6 ft/s)</td><td rowspan="4">Pass</td></tr>
<tr><td colspan="2">Occupant Impact Velocity Limits (m/s)</td></tr>
<tr><td>Longitudinal</td><td>Lateral</td></tr>
<tr><td>12.2 (40 ft/s)</td><td>9.1 (30 ft/s)</td></tr>
<tr><td colspan="2">and vehicle highest 10 ms average accelerations subsequent to instant of hypothetical passenger contact should be less than:</td><td></td><td></td></tr>
<tr><td colspan="2">Occupant Ridedown Acceleration Limits (g's)</td><td rowspan="3">Longitudinal Ridedown Acceleration = -2.2 g's
Lateral Ridedown Acceleration = -14.1 g's</td><td rowspan="3">Pass</td></tr>
<tr><td>Longitudinal</td><td>Lateral</td></tr>
<tr><td>20</td><td>20</td></tr>
<tr><td colspan="4"><u>Vehicle Trajectory</u></td></tr>
<tr><td colspan="2">H. After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.</td><td>The vehicle came to rest 82 m (270 ft) downstream and 9 m (30 ft) forward of the point of impact</td><td>Pass</td></tr>
<tr><td colspan="2">I. In test where the vehicle is judged to be redirected into or stopped while in adjacent traffic lanes, vehicle speed change during test article collision should be less than 15 mi/h and the exit angle from the test article should be less than 60 percent of test impact angle, both measured at time of vehicle loss of contact with test device.</td><td>Velocity change was 6.4 km/h (4.0 mi/h), which was less than 24.1 km/h (15 mi/h); exit angle was 5.4 degrees, which was less than 12.4 degrees (or 60 percent of 20.6 degrees)</td><td>Pass</td></tr>
</table>

REFERENCES

1. *Guide Specifications for Bridge Railings*, 1989, American Association of State Highway and Transportation Officials, Washington, DC, 1989.

2. Michie, J. D., *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, NCHRP Report 230, National Cooperative Highway Research Program, Transportation Research Board, Washington, DC, March 1981.