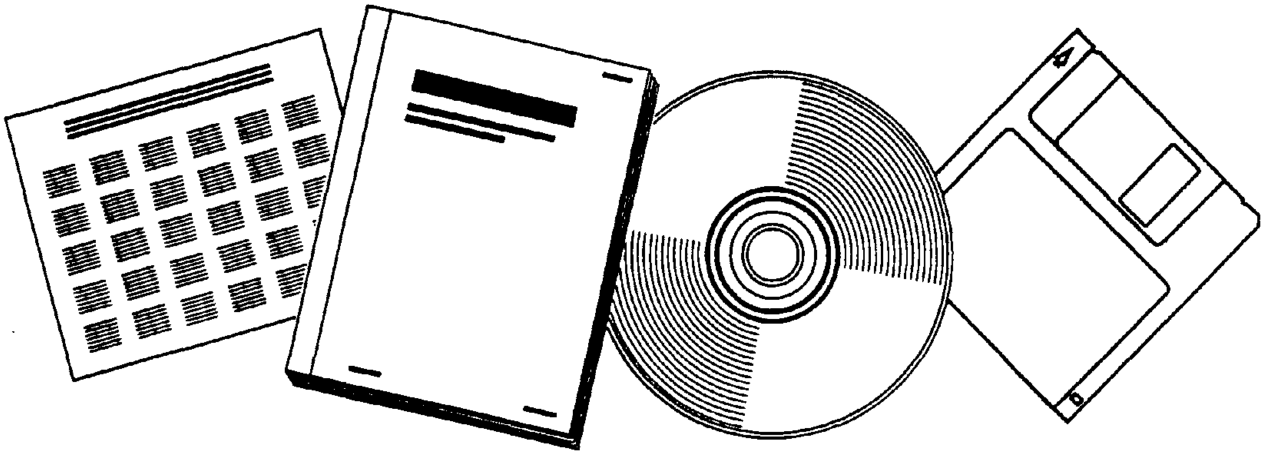
PB97-170484

TESTING OF NEW BRIDGE RAIL AND TRANSITION DESIGNS. VOLUME 3. APPENDIX B. BR27D BRIDGE RAILING

TEXAS TRANSPORTATION INST., COLLEGE STATION

JUN 97



U.S. DEPARTMENT OF COMMERCE
National Technical Information Service

PB97-170484

Testing of New Bridge Rail and Transition Designs

Volume III: Appendix B

BR27D Bridge Railing

PUBLICATION NO. FHWA-RD-93-060

JUNE 1997

U.S. Department of Transportation
Federal Highway Administration

Research and Development
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, VA 22101-2296

FOREWORD

This report presents the results of a State Planning and Research (SP&R) pooled-fund study to develop safer bridge rail and transition designs.This pooled-fund study was sponsored by the Federal Highway Administration, 23 States, and the District of Columbia. A panel of representatives from those agencies selected the designs to be studied.Ten bridge rails and two transitions were designed and crash tested in accordance with the recommendations for the various Performance Levels in the *1989 AASHTO Guide Specifications for Bridge Railings.* Acceptable performance was demonstrated for all of the crash tested designs.

Detailed drawings are presented for documentation and to facilitate implementation.

A. George Ostensen

A. George Ostensen, Director
Office of Safety and Traffic
Operations, Research and
Development

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-RD-93-060		

4. Title and Subtitle

TESTING OF NEW BRIDGE RAIL AND TRANSITION DESIGNS
Volume III: Appendix B
BR27D Bridge Railing

5. Report Date
June 1997

6. Performing Organization Code

7. Author(s)

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8. Performing Organization Report No.
Research Foundation 7069-Vol. III

9. Performing Organization Name and Address

Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843-3135

10. Work Unit No.
NCP #3A5C0042

11. Contract or Grant No.
DTFH61-86-C-00071

12. Sponsoring Agency Name and Address

Office of Safety and Traffic Operations R&D
Federal Highway Administration
6300 Georgetown Pike
McLean, Virginia 22101-2296

13. Type of Report and Period Covered
Final Report
August 1986 - September 1993

14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with DOT, FHWA
Research Study Title: Pooled Funds Bridge Rail Study
Contracting Officer's Technical Representative (COTR) - Charles F. McDevitt

16. Abstract

A combination concrete parapet and metal railing for performance level one of the 1989 *Guide Specifications for Bridge Railings* was designed and tested while mounted both on a sidewalk and flush on the deck. The upper portion of the railing permits some visibility through the railing while the 42-in (1.07-m) height is provided for pedestrians. Acceptable performance was demonstrated in the tests.

This volume is the third in a series. The other volumes in the series are: Volume I: Technical Report; Volume II: Appendix A, "Oregon Side Mounted Bridge Railing;" Volume IV: Appendix C, "Illinois 2399-1 Bridge Railing;" Volume V: Appendix D, "32-in (813-mm) Concrete Parapet Bridge Railing;" Volume VI: Appendix E, "32-in (813-mm) New Jersey Safety Shape;" Volume VII: Appendix F, "32-in (813-mm) F-Shape Bridge Railing;" Volume VIII: Appendix G, "BR27C Bridge Railing;" Volume IX: Appendix H, "Illinois Side Mount Bridge Rail;" Volume X: Appendix I, "42-in (1.07-m) Concrete Parapet Bridge Railing;" Volume XI: Appendix J, "42-in (1.07-m) F-Shape Bridge Railing;" Volume XII: Appendix K, "Oregon Transition;" Volume XIII: Appendix L, "32-in (813-mm) Thrie-Beam Transition;" and Volume XIV: Appendix M, "Axial Tensile Strength of Thrie and W-Beam Terminal Connectors."

17. Key Words

Bridge Rail, Longitudinal Barriers,
Barrier Collision Forces, Ultimate Strength,
Yieldline Analysis, Full-Scale Crash Tests,
Highway Safety

18. Distribution Statement

No restrictions. This document
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National Technical Information Service
5285 Port Royal Road
Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	107	

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
		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

NOTE: Volumes greater than 1000 l shall be shown in m^3.

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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CHAPTER 1. DESIGN OF RAILING

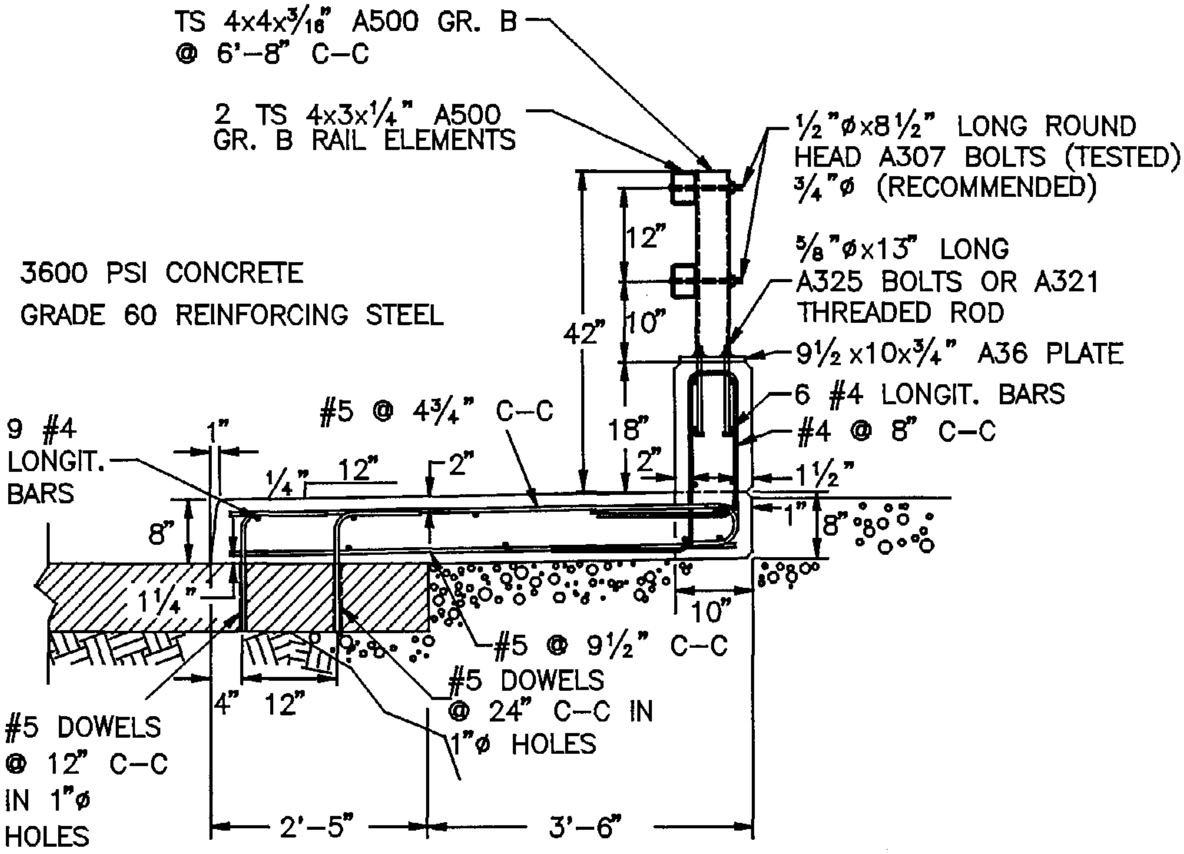
The BR27D bridge railing was designed to meet performance level one of the 1989 *Guide Specifications for Bridge Railings.*(1) It was designed to be mounted on a 5-ft (1.5 m) wide sidewalk with an 8-in (203-mm) curb at the face of the sidewalk. The design force used was 30 kips (133 kN) of uniformly distributed line force 42 in (1.07 m) long and located 35 in (90 cm) above the surface of the sidewalk.

The railing (mounted on sidewalk) was tested to performance level one (1989 guide specifications).(1) The prototype installation was then modified by lowering it 8 in (203 mm) making the top of the sidewalk become the top of the deck with no curb. It was again tested to performance level one of the 1989 guide specifications.(1) Design force for the railing mounted on the deck is 30 kips (133 kN) of uniformly distributed line force 42 in (1.07 m) long located at least 24 in (610 mm) above the surface of the deck.

A detailed analysis of strength of the railing is presented in Chapter 4.

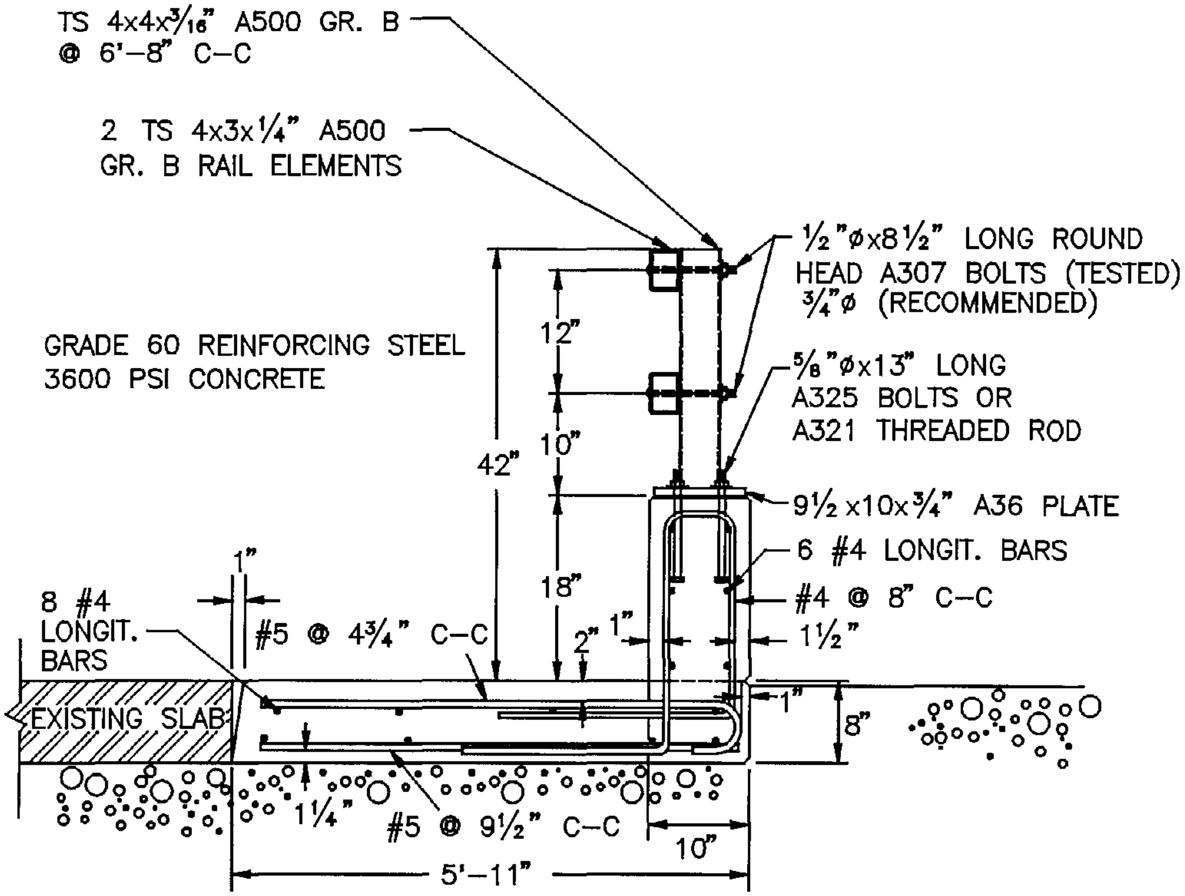
A cross section of the railing design on sidewalk is shown in figure 1. Total height of the railing is 42 in (1.07 m). The lower portion of the railing consists of an 18-in (457-mm) high concrete parapet that is 10 in (254 mm) thick. Specified concrete strength was 3,600 psi ($24.8x10^3$ kPa) at 28 days, and specified steel yield for the reinforcement was 60,000 psi ($413x10^3$ kPa).

The two-tube metal railing installed on top of the parapet consists of two TS 4 by 4 by 1/4-in (102 by 102 by 6-mm) A500 grade B rail elements mounted on posts made of TS 4 by 3 by 3/16-in (102 by 76 by 5-mm) A500 grade B with A36 baseplates. The installation was originally constructed along the edge of an existing concrete pavement with the sidewalk mounted on the top surface of the existing pavement and cantilevered from that pavement to simulate the cantilever condition that would exist in an actual bridge structure. Heavy rainfall and runoff eroded the soil beneath the concrete pavement and caused structural failure of the pavement. The railing and sidewalk structure was then lifted from the site and the space was filled with crushed limestone pavement base material. The sidewalk and railing structure was then replaced with the sidewalk being supported throughout its length and width instead of being cantilevered as originally designed. A cross section of this railing design is shown in figure 2. This test installation was considered suitable because strength of the cantilevered sidewalk was not being investigated in the performance level one tests performed on this railing installation. Adequacy of the cantilevered sidewalk was being investigated in a series of tests on another similar prototype railing installation.



1 in = 25.4 mm
1 psi = 6.89 kPa

Figure 1. BR27D bridge railing on sidewalk.



1 in = 25.4 mm
1 psi = 6.89 kPa

Figure 2. BR27D bridge railing on deck.

CHAPTER 2. CRASH TEST PROCEDURES

The BR27D bridge railing on sidewalk was tested to performance level one requirements.(1) The nominal test conditions for these tests were as follows:

1,800-lb (817-kg) passenger car | 50 mi/h (80.5 km/h) | 20 degrees (test 7069-22)
5,400-lb (2 452-kg) pickup | 45 mi/h (72.4 km/h) | 20 degrees (test 7069-23)

The BR27D bridge railing on deck was also tested to performance level one requirements.(1) The nominal test conditions for these tests were as follows:

1,800-lb (817-kg) passenger car | 50 mi/h (80.5 km/h) | 20 degrees (test 7069-30)
5,400-lb (2 452-kg) pickup | 45 mi/h (72.4 km/h) | 20 degrees (test 7069-31)

Each of the test vehicles was instrumented with three solid-state angular rate transducers to measure roll, pitch, and yaw rates and a triaxial accelerometer at the vehicle center-of-gravity to measure longitudinal, lateral, and vertical acceleration levels. In addition, each pickup was equipped with two biaxial accelerometers, one forward of the center-of-gravity and one in the rear of the pickup, 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 band width 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 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 installation.

The multiplex of data channels transmitted on one radio frequency was received at a data acquisition station and demultiplexed into separate tracks of Intermediate Range Instrumentation Group (I.R.I.G.) tape recorders. After the test, the data was played back from the tape machines, filtered with an SAE J211 filter, and digitized using a microcomputer for analysis and evaluation of impact performance. The digitized data were then processed using two computer programs: DIGITIZE and PLOTANGLE. Brief descriptions on the functions of these two computer programs are 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 50-ms 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). For each graph, a 0.050-s average window was calculated at the center of the 0.050-s interval and plotted with the first 0.050-s average plotted at 0.026 s.

The PLOTANGLE program uses the digitized data from the yaw, pitch, and roll rate charts 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. It should be noted that these angular displacements are sequence dependent with the sequence being yaw-pitch-roll for the data presented herein. 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.

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

Photographic coverage of the test included four high-speed cameras: one overhead with a field of view perpendicular to the ground and directly over the impact point, one placed to have a field of view parallel to and aligned with the bridge rail system at the downstream end, and a third placed perpendicular to the front of the bridge rail. 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 flash bulb activated by pressure sensitive tape switches was positioned on the impacting vehicle to indicate the instant of contact with the bridge rail curb 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 professional video camera, and a 3/4-in (19-mm) video recorder along with 35-mm still cameras were used for documentary purposes and to record conditions of the test vehicle and bridge rail system before and after the test.

Each 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. Immediately prior to impact, the test vehicle was released to be free-wheeling and unrestrained. The vehicle remained free-wheeling, i.e., no steering or braking inputs, until the vehicle cleared the immediate area of the test site, at which time brakes on the vehicle were activated to bring the vehicle to a safe and controlled stop.

CHAPTER 3. FULL-SCALE CRASH TESTS

BR27D BRIDGE RAILING ON SIDEWALK

Test 7069-22

Test Description

A 1983 Honda Civic (figures 3 and 4) was used for the crash test. Test inertia mass of the vehicle was 1,800 lb (817 kg) and its gross static mass was 1,967 lb (893 kg). The height to the lower edge of the vehicle bumper was 15.0 in (381 mm) and it was 20.25 in (514 mm) to the top of the bumper. Additional dimensions and information on the test vehicle are given in figure 5. The vehicle was directed into the BR27D bridge railing on sidewalk (figure 6) using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact. The vehicle impacted the curb of the sidewalk approximately 20 ft (6 m) upstream of post 5 at a speed of 51.7 mi/h (83.2 km/h) and the angle of impact was 20.8 degrees.

Upon impact with the curb, the left front tire folded under the vehicle, and at 0.109 s after impact the left rear wheel impacted the curb. As the left rear wheel climbed the curb, the right front wheel lost contact with the roadway. At 0.217 s the right front wheel contacted the curb and the left side of the vehicle was airborne. When the right front wheel reached the top the curb, the vehicle was totally airborne and remained as such as it impacted the concrete parapet at 0.261 s. The vehicle impacted the parapet at post 5 traveling at a speed of 46.6 mi/h (75.0 km/h) and at an angle of 13.4 degrees. As the vehicle continued forward, the bumper protruded between the upper and lower metal railing elements, and at 0.332 s the vehicle began to redirect. The right rear wheel struck the curb at 0.414 s as the vehicle was still airborne. By 0.510 s the vehicle was traveling parallel to the bridge railing at a speed of 41.0 mi/h (66.0 km/h), and at the same time the rear of the vehicle impacted the parapet. The vehicle lost contact with the parapet at 0.610 s traveling at 40.8 mi/h (65.6 km/h) and 6.1 degrees. The vehicle contacted the roadway again as it reached posts 7 and 8 and the brakes were applied. The vehicle left the installation and subsequently came to rest 165 ft (50.3 m) from the point of impact.

As can be seen in figure 7, the bridge railing system received minimal damage. There was no measurable permanent deformation to the railing elements and only cosmetic damage to the concrete parapet. There were tire marks on the concrete parapet, on the face of the lower metal railing element in the area of impact, and also on the lower part of post 6. The vehicle was in contact with the bridge railing for 11.5 ft (3.5 m). Length of contact with the concrete parapet was 7.0 ft (2.1 m).

The vehicle sustained damage to the left side as shown in figure 8. Maximum crush at the left front corner at bumper height was 6.0 in (152 mm). The left front strut was damaged, and the left front wheel was canted inward at the bottom and pushed back reducing the wheelbase on the driver side by 2 in (51 mm). Also, damage was done to the front bumper, hood, left headlight, left front quarter panel, left rear quarter panel, left front and rear tires and rims, and right front tire.

Test Results

The vehicle impacted the curb of the sidewalk at 51.7 mi/h (83.2 km/h) and the angle of impact was 20.8 degrees. As the vehicle impacted the concrete parapet, it was traveling at a speed of 46.6 mi/h (75.0 km/h) and an angle of 13.4 degrees. The speed of the vehicle at time of parallel was 41.0 mi/h (66.0 km/h). In determining the effective coefficient of friction which is an assessment of the smoothness of the "vehicle-railing" interaction, it should be noted that vehicle impact speed and angle is used in the calculation. If "vehicle-railing" interaction is interpreted literally, impact at the time of contact with the concrete parapet would be used; however, the curb could be considered to be part of this "vehicle-railing" interaction. Therefore, two assessments could be made: (1) interpreting "vehicle-railing" interaction literally disregarding the impact at the curb and using the speed and angle at which the vehicle impacted the concrete parapet or (2) considering the curb as an element of the "railing" system and using the speed and angle at which the vehicle impacted the curb. The coefficient of friction was calculated both ways for this test. Considering the curb as part of the vehicle-railing interaction the coefficient of friction was 0.40, while using impact with the concrete parapet in the calculation it was also 0.40. The vehicle lost contact with the bridge railing traveling at 40.8 mi/h (65.6 km/h), and the exit angle between the vehicle path and the bridge railing was 6.1 degrees. Data from the accelerometer located at the center-of-gravity were digitized for evaluation and occupant risk factors were computed as follows. In the longitudinal direction, occupant impact velocity was 12.2 ft/s (3.7 m/s) at 0.331 s, the highest 0.010-s average ridedown acceleration was -4.7 g between 0.347 and 0.357 s, and the maximum 0.050-s average acceleration was -4.4 g between 0.305 and 0.355 s. Lateral occupant impact velocity was 6.3 ft/s (1.9 m/s) at 0.214 s, the highest 0.010-s occupant ridedown acceleration was -13.3 g between 0.320 and 0.330 s, and the maximum 0.050-s average acceleration was -6.8 g between 0.302 and 0.352 s. The change in vehicle velocity at loss of contact using impact with the curb was 10.9 mi/h (17.5 km/h) and the change in momentum was 894 lb-s (3,971 N-s). These data and other pertinent information from the test are summarized in figure 9 and tables 1 and 2. Sequential photographs are shown in figures 10 and 11. Vehicular angular displacements are displayed in figure 12. Vehicular accelerations versus time traces filtered with SAE J211 filters are presented in figures 13 through 15.

Conclusions

The BR27D bridge railing on sidewalk contained the test vehicle with no lateral movement of the bridge railing. There was no intrusion of railing components into the occupant compartment and no debris to present undue hazard to other traffic. The integrity of the occupant compartment was maintained with no intrusion and no deformation. The vehicle remained upright and relatively stable during the collision. The bridge railing smoothly redirected the vehicle. The effective coefficient of friction was considered marginal.

The 1989 American Association of State Highway and Transportation Officials (AASHTO) guide specifications sets forth desired limits for occupant risk factors for tests with the 1,800-lb (817-kg) vehicle.(1) The AASHTO specifications recommend a limit of 30 ft/s (9.1 m/s) for longitudinal occupant impact velocity and 25 ft/s (7.6 m/s) for the lateral occupant impact velocity. The occupant impact velocities and the occupant ridedown accelerations were within the limits. The vehicle trajectory at loss of contact indicates minimum intrusion into adjacent traffic lanes. See figure 9 and table 1 for more details.

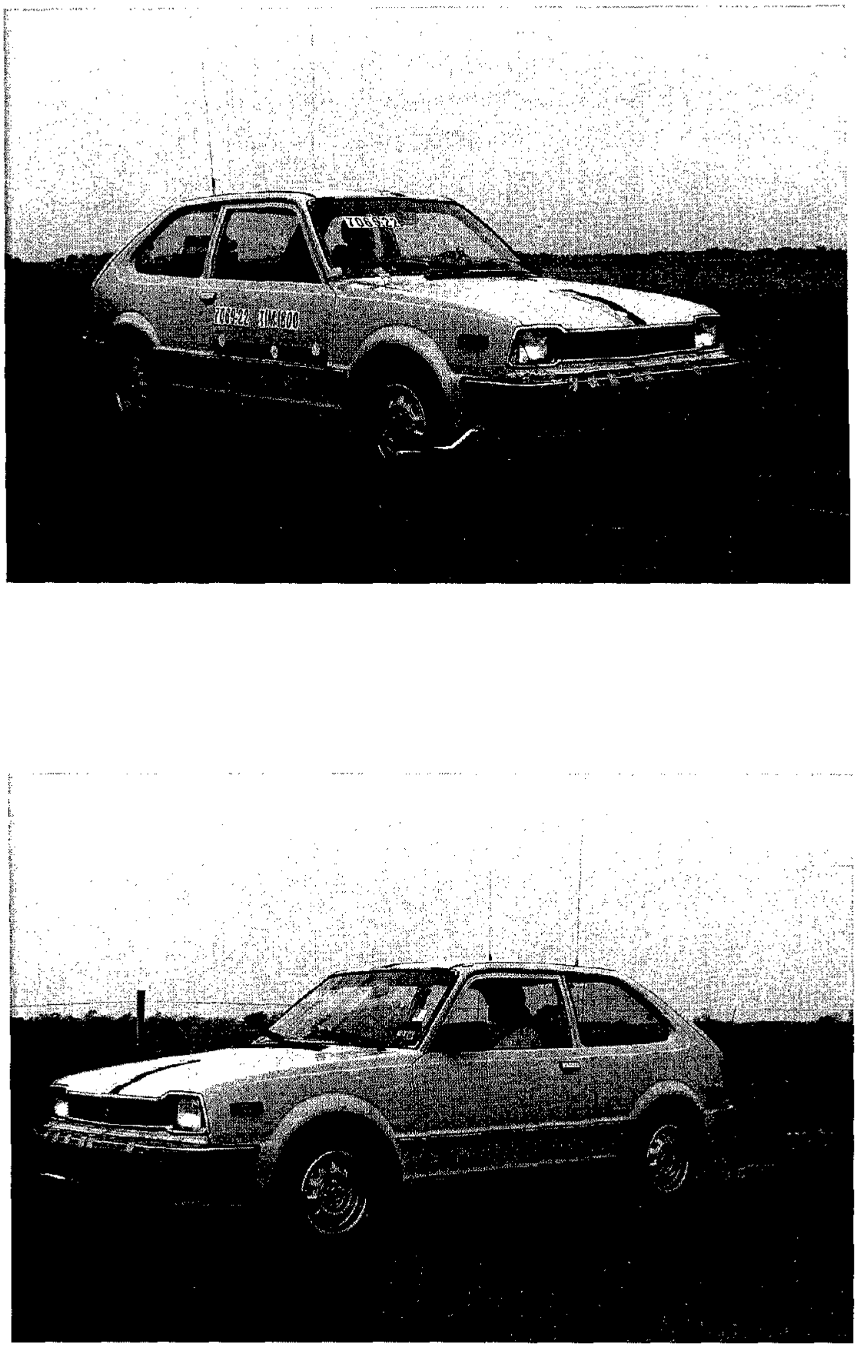


Figure 3. Vehicle before test 7069-22.

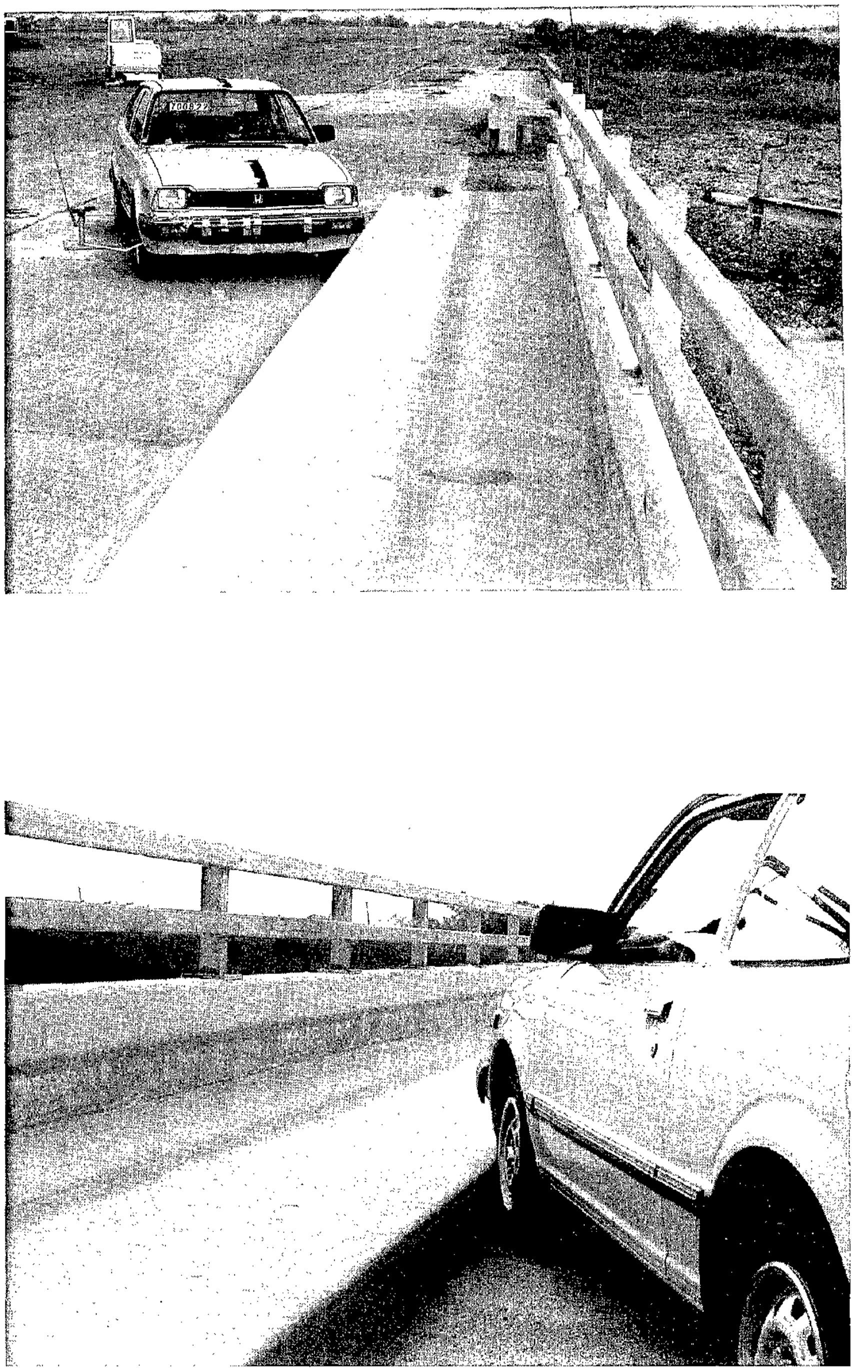
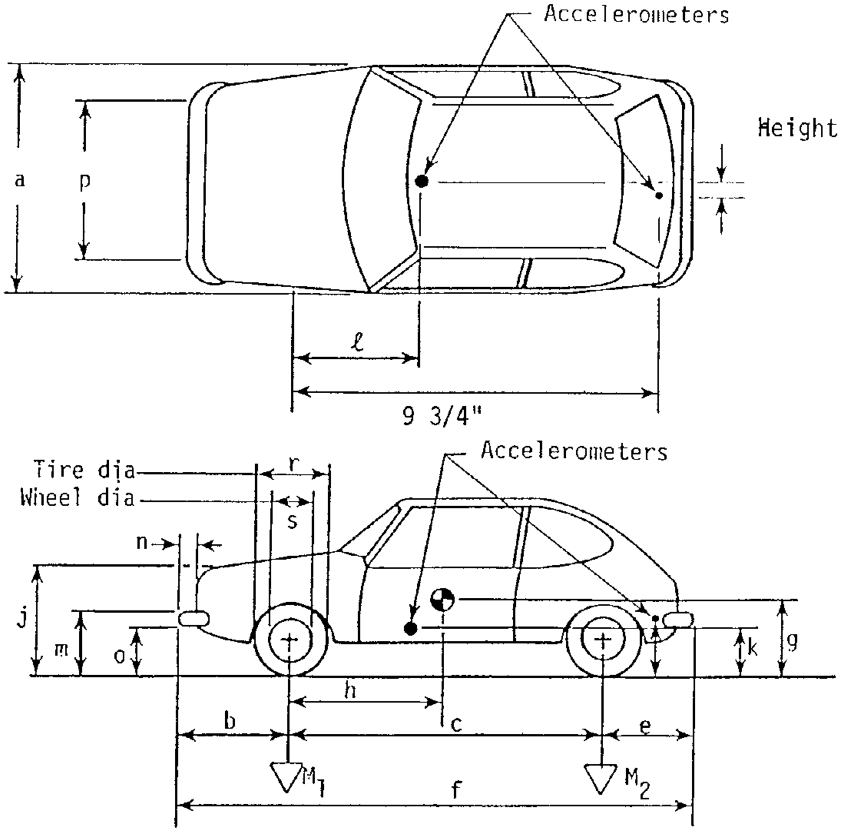


Figure 4. Vehicle/bridge railing geometrics for test 7069-22.

Date: 3-24-92 Test No.: 7069-22 VIN: JHMSR532XDS031645

Make: Honda Model: Civic Year: 1983 Odometer: 119264

Tire Size: 155R13 Ply Rating: ____ Bias Ply: ___ Belted: ___ Radial: X



4-wheel weight for c.g. det. ℓf 595 rf 538 ℓr 330 rr 337

Mass - pounds	Curb	Test Inertial	Gross Static
M_1	1188	1133	1213
M_2	659	667	754
M_T	1847	1800	1967

Note any damage to vehicle prior to test:

Crack in windshield (marked)

*d = overall height of vehicle

1 in = 25.4 mm
1 lb = .454 kg

Tire Condition: good ___
fair X
badly worn ___

Height = 30"

Vehicle Geometry - inches

a	62 3/4	b	29"
c	88 1/4"	d*	52 1/2"
e	29"	f	146.25
g		h	32.7
i	----	j	28"
k	17 1/4"	ℓ	35"
m	20 1/4"	n	3 1/4"
o	15"	p	52 1/2"
r	22	s	14 1/4

Engine Type: 4 cyl

Engine CID: 91

Transmission Type:

Automatic or Manual

FWD or ~~RWD~~ or ~~4WD~~

Body Type: 3 door

Steering Column Collapse Mechanism:

- __Behind wheel units
- __Convoluted tube
- __Cylindrical mesh units
- __Embedded ball
- __NOT collapsible
- __Other energy absorption
- __Unknown

Brakes:

Front: disc X drum ___

Rear: disc ___ drum X

Figure 5. Vehicle properties for test 7069-22.

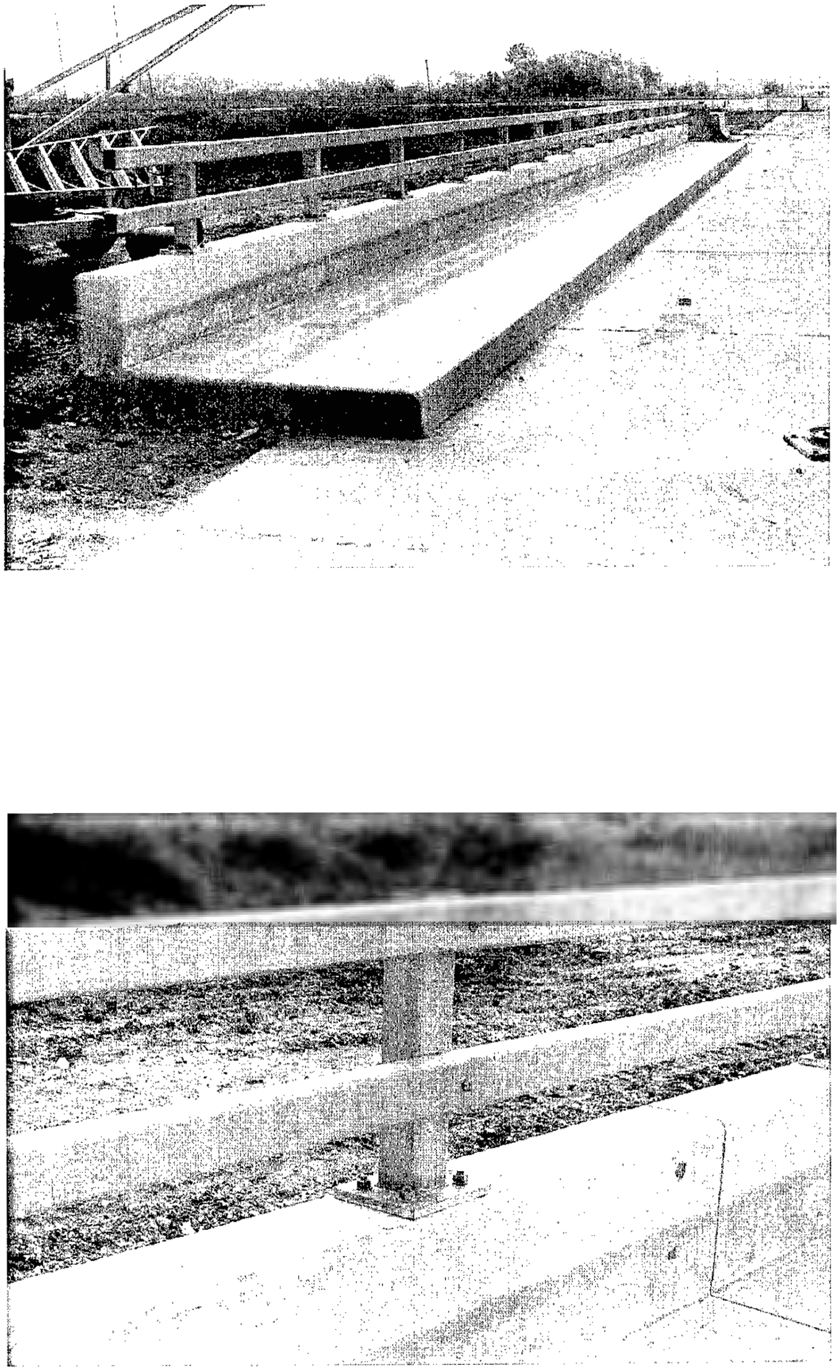


Figure 6. BR27D bridge railing on sidewalk before test 7069-22.

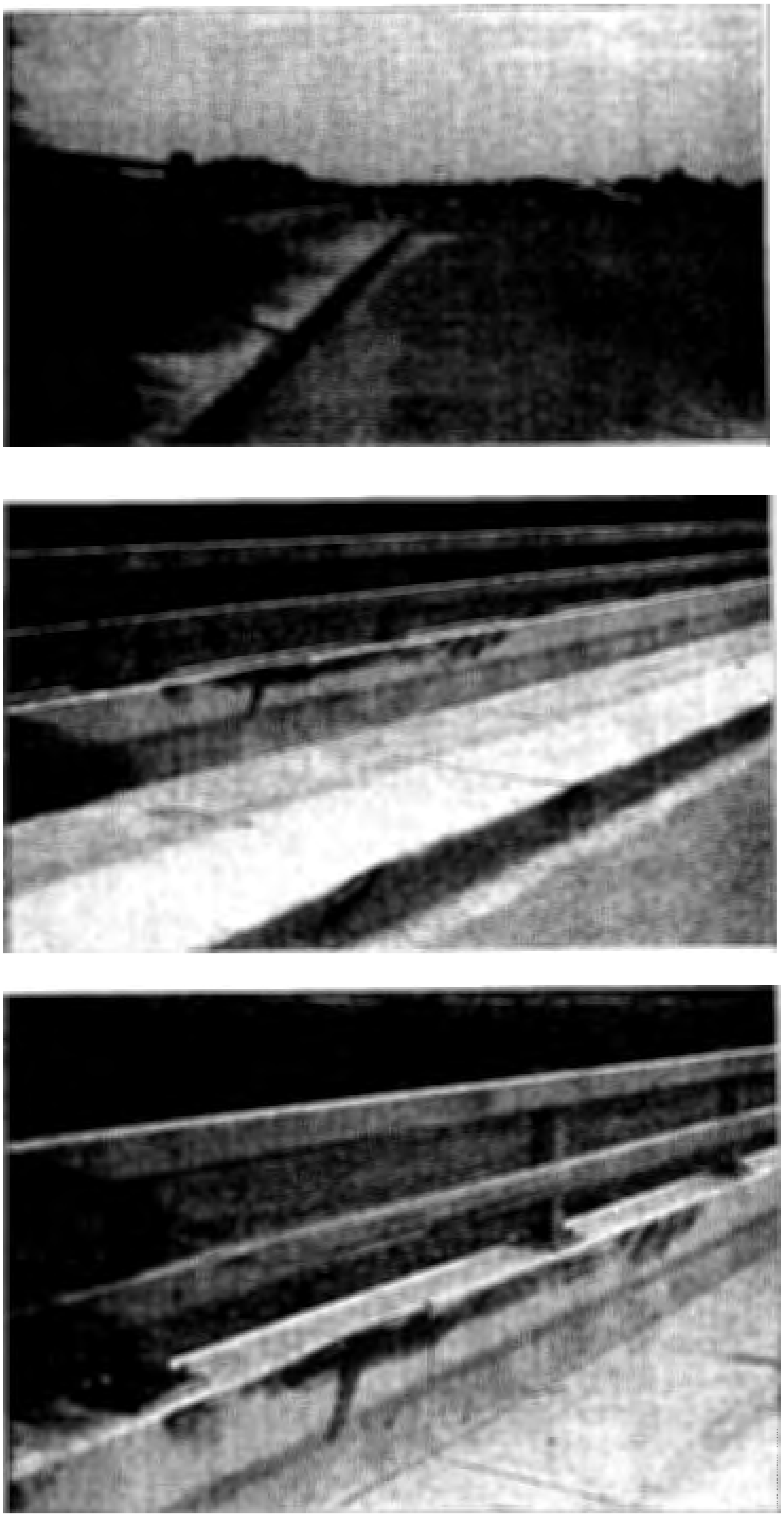


Figure 7. BR27D bridge railing on sidewalk after test 7069-22.

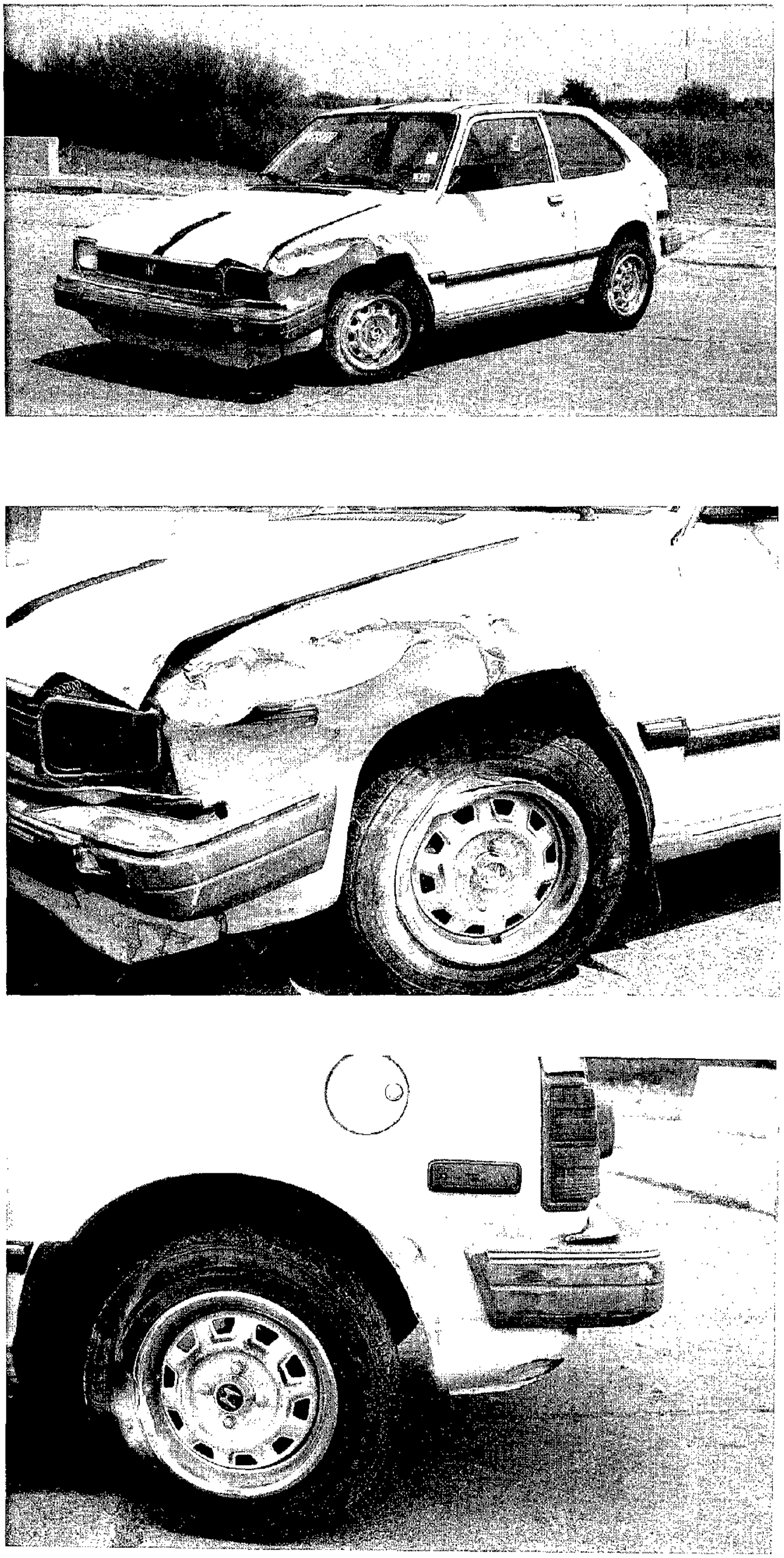
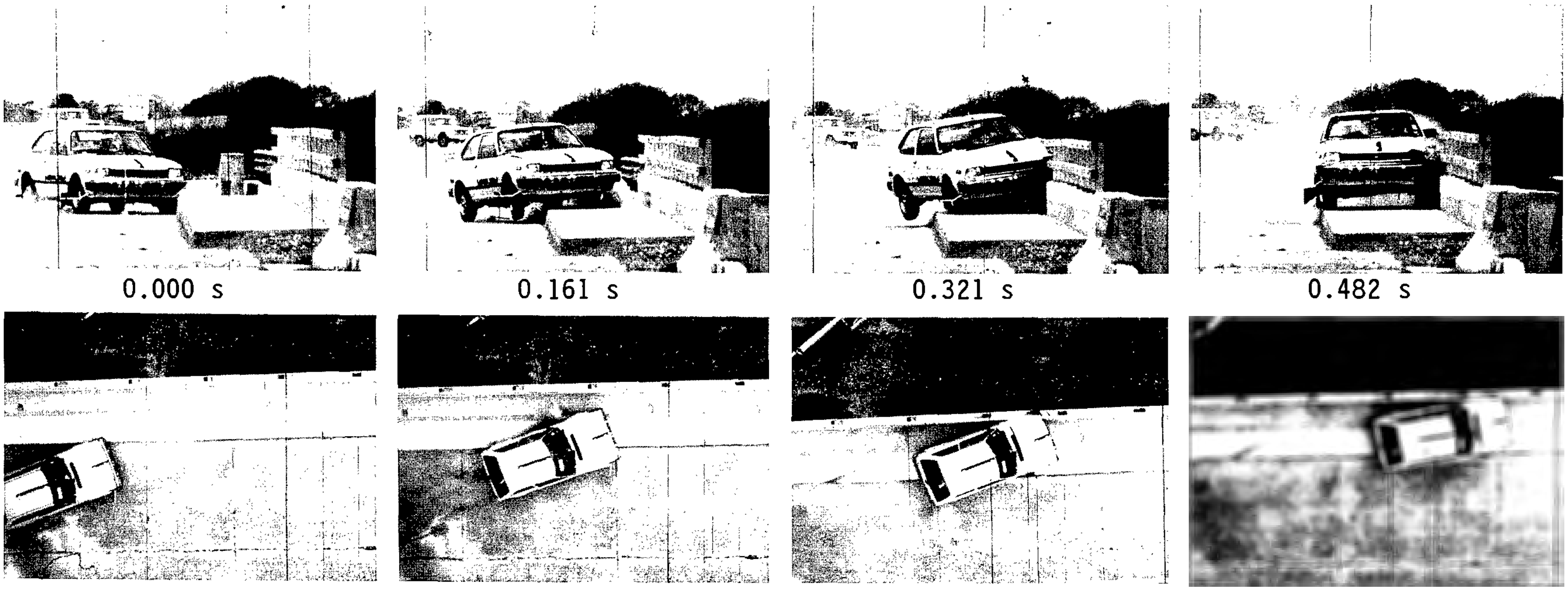


Figure 8. Vehicle after test 7069-22.

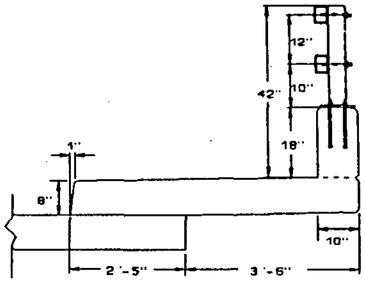


0.000 s

0.161 s

0.321 s

0.482 s



(1 in = 25.4 mm)

Test No.	7069-22
Date	03/24/92
Test Installation . . .	BR27D Bridge Railing on sidewalk
Installation Length . .	100 ft (30 m)
Test Vehicle	1983 Honda Civic
Vehicle Weight	
Test Inertia	1,800 lb (817 kg)
Gross Static	1,967 lb (893 kg)
Vehicle Damage Classification	
TAD	11LFQ3
CDC	11FLEK2 & 11LFES2
Maximum Vehicle Crush .	6.0 in (152 mm)

Impact Speed. . . .	51.7 mi/h (83.2 km/h)
Impact Angle. . . .	20.8 deg
Speed at Parallel .	41.0 mi/h (66.0 km/h)
Exit Speed	40.8 mi/h (65.6 km/h)
Exit Trajectory . .	6.1 deg
Vehicle Accelerations (Max. 0.050-sec Avg) at true c.g.	
Longitudinal. . .	-4.4 g
Lateral	-6.8 g
Occupant Impact Velocity at true c.g.	
Longitudinal. . .	12.2 ft/s (3.7 m/s)
Lateral	6.3 ft/s (1.9 m/s)
Occupant Ridedown Accelerations	
Longitudinal. . .	-4.7 g
Lateral	-13.3 g

Figure 9. Summary of results for test 7069-22.

Table 1. Evaluation of crash test no. 7069-22.
{BR27D bridge railing on sidewalk [1,800 lb (817 kg)|51.7 mi/h (83.2 km/h)|20.8 degrees]}

	CRITERIA		TEST RESULTS		PASS/FAIL*
A.	Must contain vehicle		Vehicle was contained		Pass
B.	Debris shall not penetrate passenger compartment		No debris penetrated passenger compartment		Pass
C.	Passenger compartment must have essentially no deformation		No deformation		Pass
D.	Vehicle must remain upright		Vehicle did remain upright		Pass
E.	Must smoothly redirect the vehicle		Vehicle was smoothly redirected		Pass
F.	Effective coefficient of friction				
	μ	Assessment	μ	Assessment	
	0 - .25	Good	.40 (Impact @ curb)	Marginal	Pass
	.26 - .35	Fair	.40 (Impact @ rail)	Marginal	
	> .35	Marginal			
G.	Shall be less than				
	Occupant Impact Velocity - ft/s (m/s)		Occupant Impact Velocity - ft/s (m/s)		Pass
	Longitudinal	Lateral	Longitudinal	Lateral	
	30 (9.2)	25 (7.6)	12.2 (3.7)	6.3 (1.9)	
	Occupant Ridedown Accelerations - g's		Occupant Ridedown Accelerations - g's		Pass
	Longitudinal	Lateral	Longitudinal	Lateral	
	15	15	-4.7	-13.3	
H.	Exit angle shall be less than 12 degrees		Exit angle was 6.1 degrees		Pass

* A, B, C, D and G are required. E, F, and H are desired. (See table 2)

Table 2. Bridge railing performance levels and crash test criteria.
(Excerpt from 1989 AASHTO *Guide Specifications for Bridge Railings*)(1)

		TEST SPEEDS—mph[1,2]			
		TEST VEHICLE DESCRIPTIONS AND IMPACT ANGLES			
		Small Automobile	Pickup Truck	Medium Single-Unit Truck	Van-Type Tractor-Trailer[4]
PERFORMANCE LEVELS		$W = 1.8$ Kips $A = 5.4' \pm 0.1'$ $B = 5.5'$ $H_{cg} = 20'' \pm 1''$ $\theta = 20$ deg.	$W = 5.4$ Kips $A = 8.5' \pm 0.1'$ $B = 6.5'$ $H_{cg} = 27'' \pm 1''$ $\theta = 20$ deg.	$W = 18.0$ Kips $A = 12.8' \pm 0.2'$ $B = 7.5'$ $H_{cg} = 49'' \pm 1''$ $\theta = 15$ deg.	$W = 50.0$ Kips $A = 12.5' \pm 0.5'$ $B = 8.0'$ H_{cg} = See Note 4 $R = 0.61 \pm 0.01$ $\theta = 15$ deg.
PL-1		50	45		
PL-2		60	60	50	
PL-3		60	60		50
CRASH TEST EVALUATION · CRITERIA[3]	Required	a, b, c, d, g	a, b, c, d	a, b, c	a, b, c
	Desirable[5]	e, f, h	e, f, g, h	d, e, f, h	d, e, f, h

Notes:

1. Except as noted, all full-scale tests shall be conducted and reported in accordance with the requirements in NCHRP Report No. 230. In addition, the maximum loads that can be transmitted from the bridge railing to the bridge deck are to be determined from static force measurements or ultimate strength analysis and reported.
2. Permissible tolerances on the test speeds and angles are as follows:

Speed	−1.0 mph	+2.5 mph
Angle	−1.0 deg.	+2.5 deg.

Tests that indicate acceptable railing performance but that exceed the allowable upper tolerances will be accepted.

3. Criteria for evaluating bridge railing crash test results are as follows:
   a. The test article 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.
   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.
   c. Integrity of the passenger compartment must be maintained with no intrusion and essentially no deformation.
   d. The vehicle shall remain upright during and after collision.
   e. The test article shall smoothly redirect the vehicle. A redirection is deemed smooth if the rear of the vehicle or, in the case of a combination vehicle, the rear of the tractor or trailer does not yaw more than 5 degrees away from the railing from time of impact until the vehicle separates from the railing.
   f. The smoothness of the vehicle-railing interaction is further assessed by the effective coefficient of friction, μ:

μ	Assessment
0–0.25	Good
0.26–0.35	Fair
>0.35	Marginal

where $\mu = (\cos\theta - V_p/V)/\sin\theta$

Table 2. Bridge railing performance levels and crash test criteria. (Excerpt from 1989 AASHTO *Guide Specifications for Bridge Railings*)(1) (continued)

g. The impact velocity of a hypothetical front-seat passenger against the vehicle interior, calculated from vehicle accelerations and 2.0-ft. longitudinal and 1.0-ft. lateral diplacements, shall be less than:

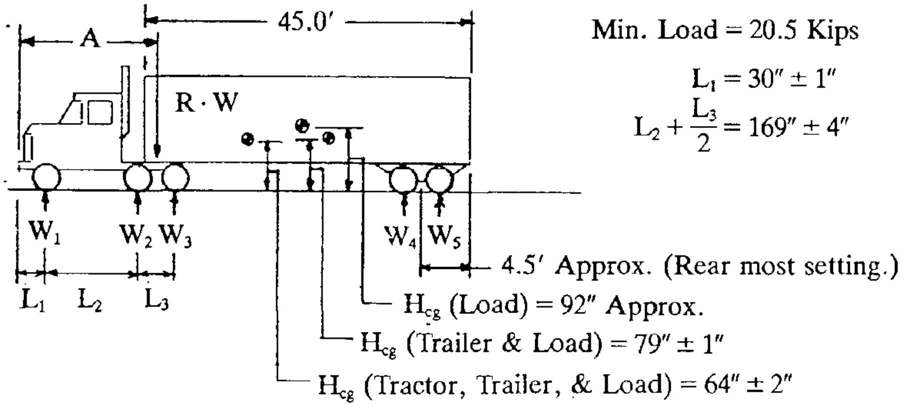
Occupant Impact Velocity–fps	
Longitudinal	Lateral
30	25

and the vehicle highest 10-ms average accelerations subsequent to the instant of hypothetical passenger impact should be less than:

Occupant Ridedown Acceleration—g's	
Longitudinal	Lateral
15	15

h. Vehicle exit angle from the barrier shall not be more than 12 degrees. Within 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 20-ft. from the line of the traffic face of the railing. The brakes shall not be applied until the vehicle has traveled at least 100-ft. plus the length of the test vehicle from the point of initial impact.

4. Values A and R are estimated values describing the test vehicle and its loading. Values of A and R are described in the figure below and calculated as follows:



Min. Load = 20.5 Kips

$L_1 = 30'' \pm 1''$

$L_2 + \frac{L_3}{2} = 169'' \pm 4''$

4.5′ Approx. (Rear most setting.)

H_{cg} (Load) = 92″ Approx.

H_{cg} (Trailer & Load) = 79″ ± 1″

H_{cg} (Tractor, Trailer, & Load) = 64″ ± 2″

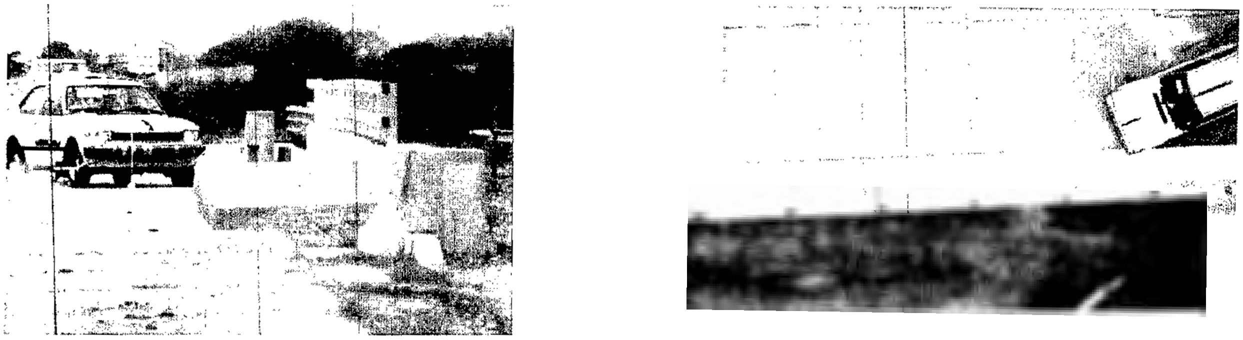
$$A = L_1 + \frac{W_2L_2 + W_3(L_2 + L_3)}{W_1 + W_2 + W_3}$$

$$R = \frac{W_1 + W_2 + W_3}{W}$$

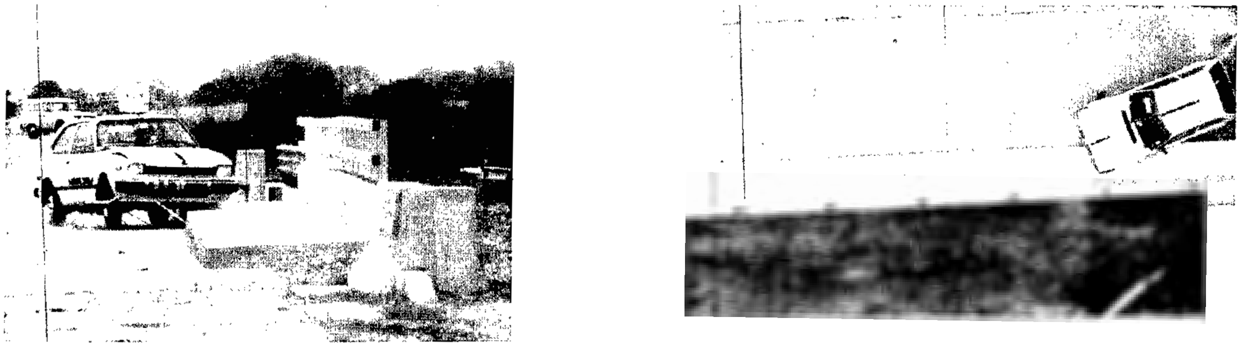
$W = W_1 + W_2 + W_3 + W_4 + W_5$
= total vehicle weight.

5. Test articles that do not meet the desirable evaluation criteria shall have their performance evaluated by a designated authority that will decide whether the test article is likely to meet its intended use requirements.

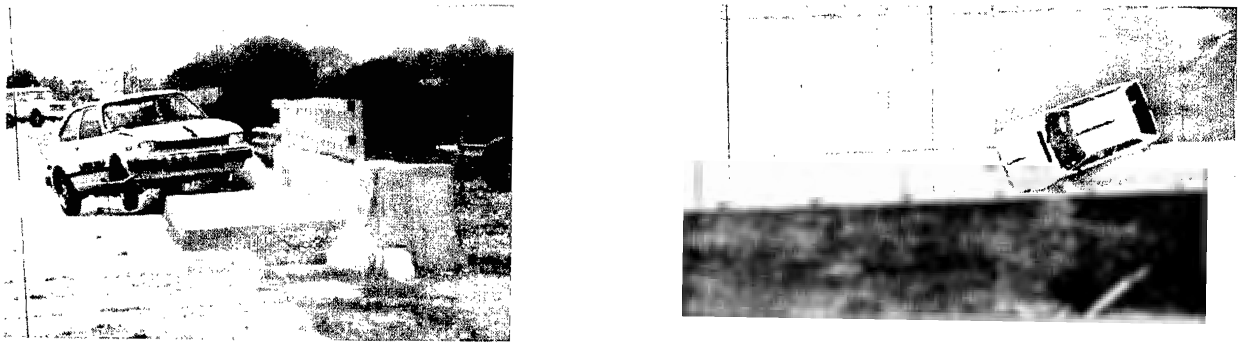
1 mi = 1.61 km
1 kip = 4.45 kN
1 in = 25.4 mm



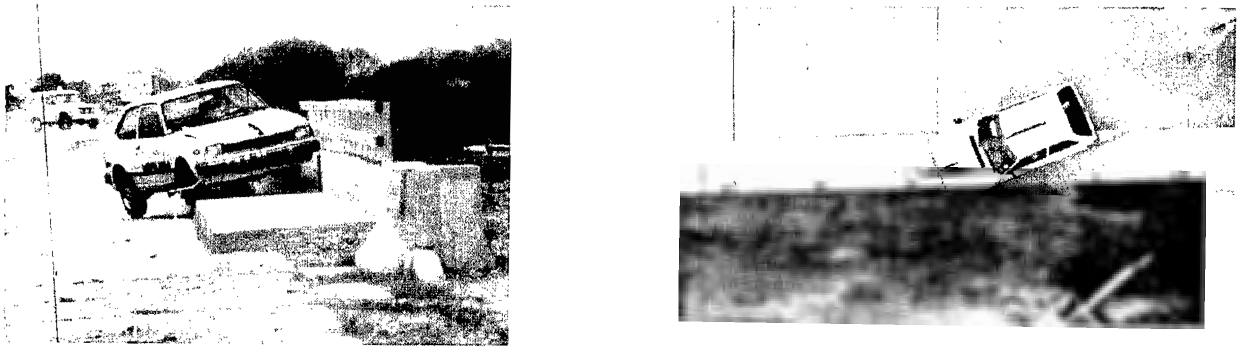
0.000 s



0.080 s



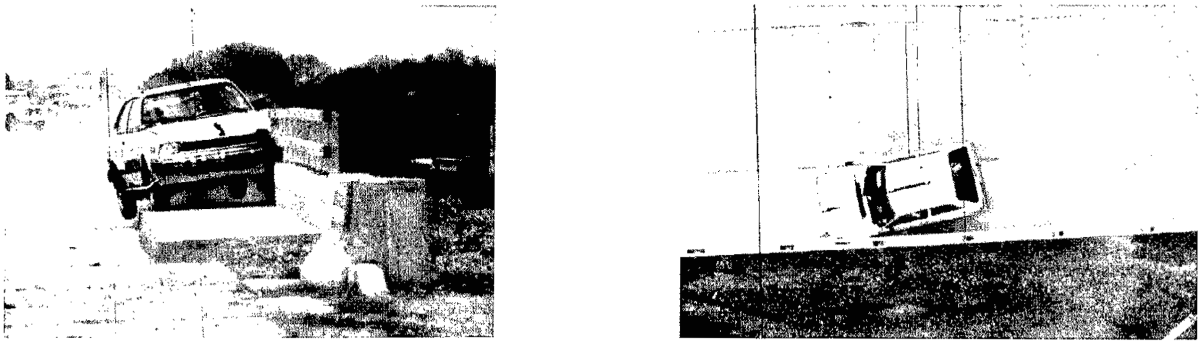
0.161 s



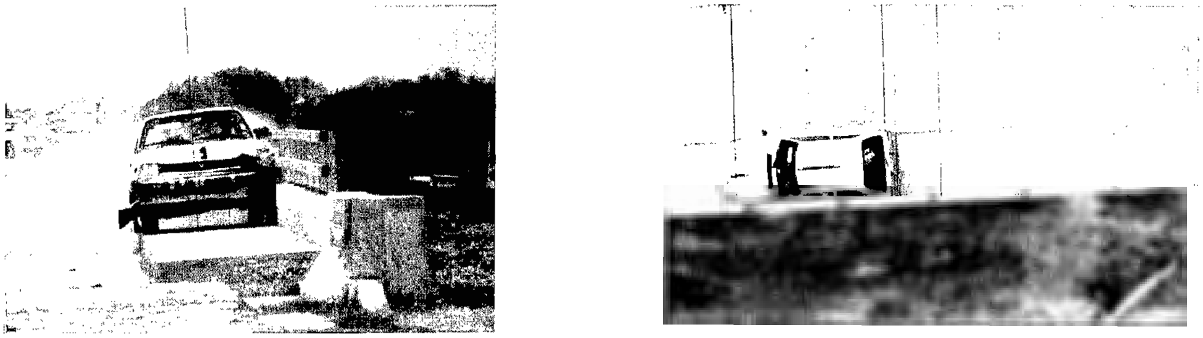
0.241 s

Figure 10. Sequential photographs for test 7069-22 (front and overhead views).

0.321 s



0.402 s



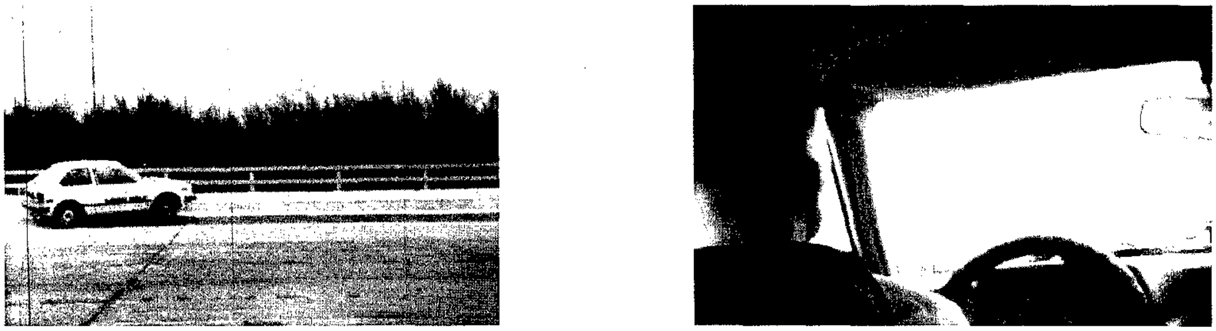
0.482 s

0.562 s

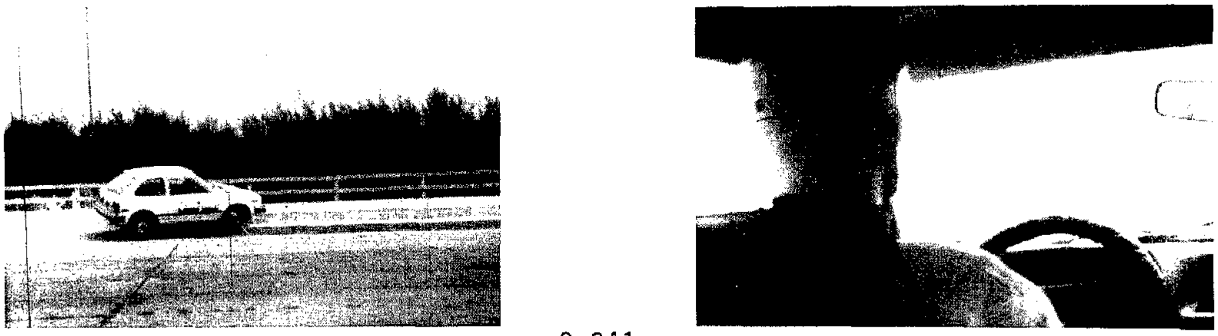
Figure 10. Sequential photogrpahs for test 7069-22
(front and overhead views continued).

0.000 s

0.080 s

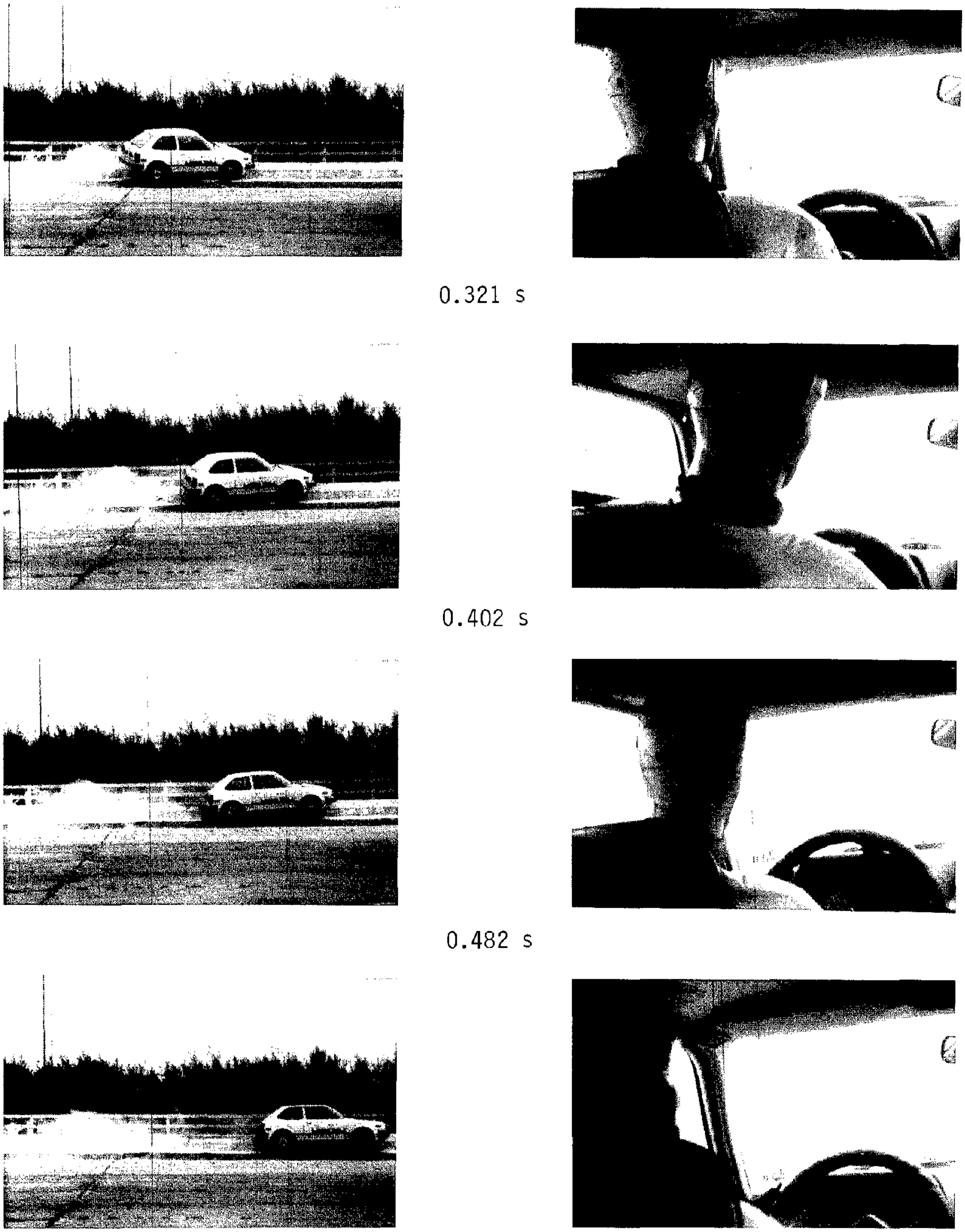


0.161 s



0.241 s

Figure 11. Sequential photographs for test 7069-22 (perpendicular and interior views).



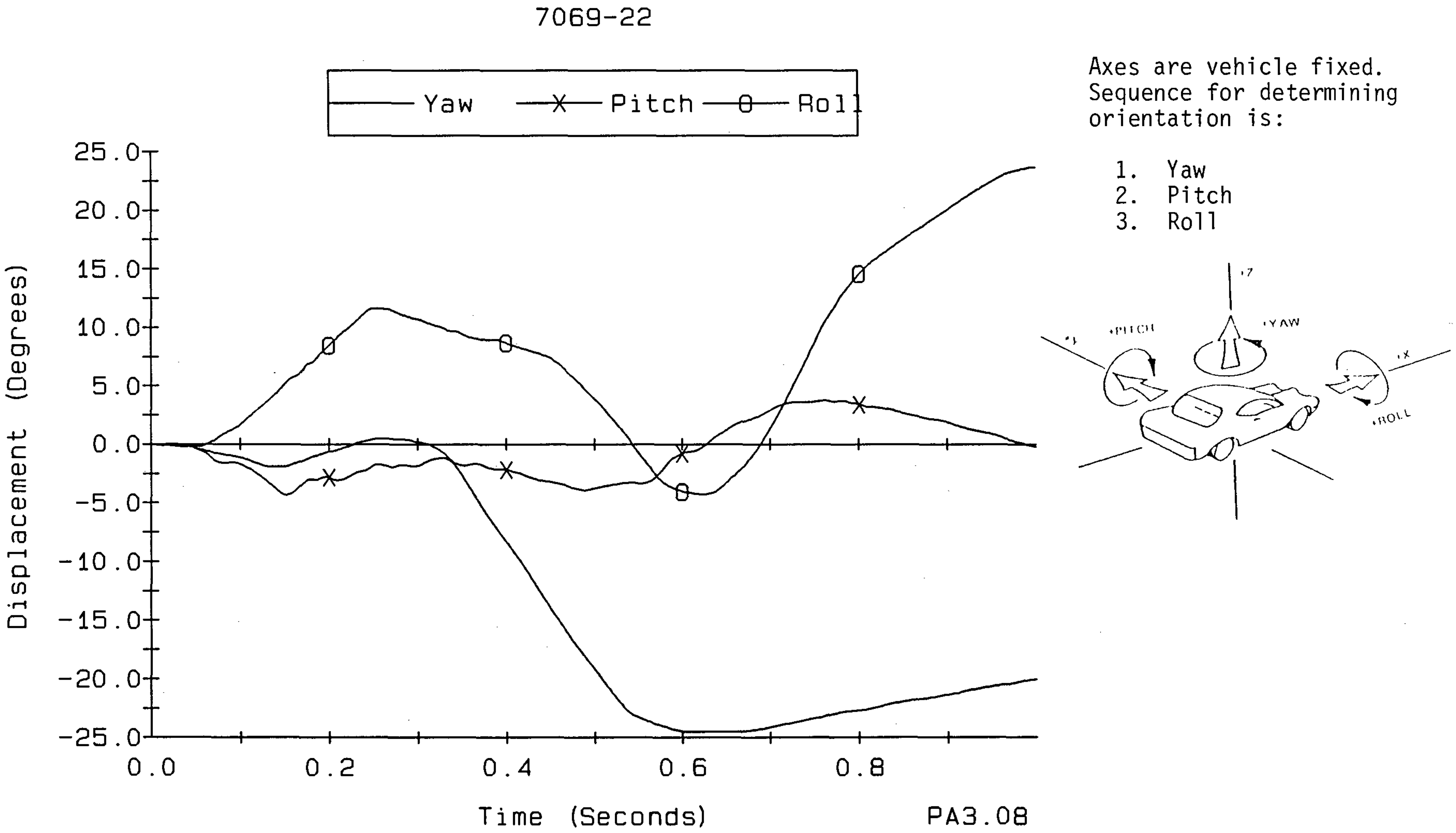
0.321 s

0.402 s

0.482 s

0.562 s

Figure 11. Sequential photogrpahs for test 7069-22
(perpendicular and interior views continued).



Axes are vehicle fixed.
Sequence for determining
orientation is:

1. Yaw
2. Pitch
3. Roll

Figure 12. Vehicle angular displacements for test 7069-22.

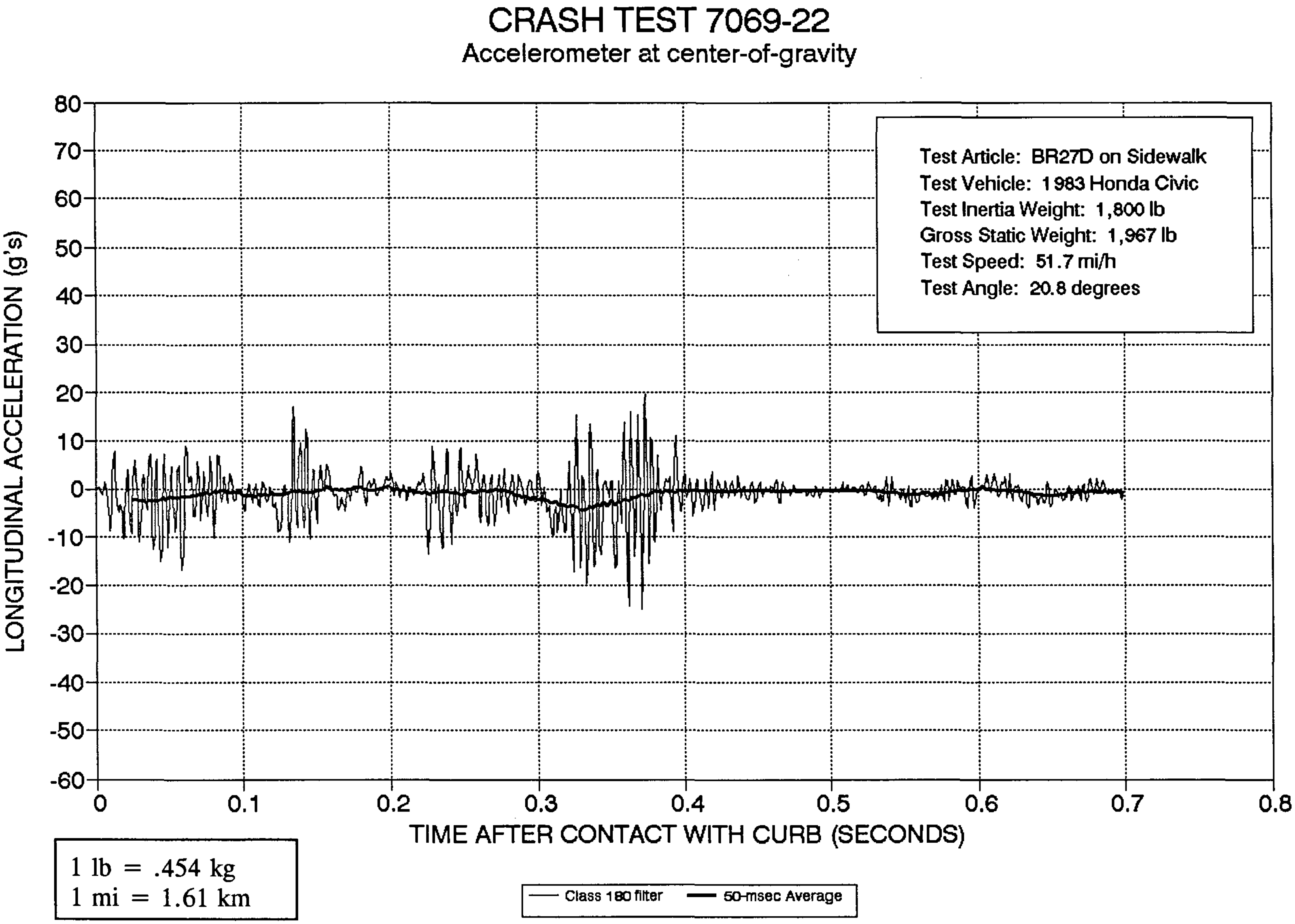
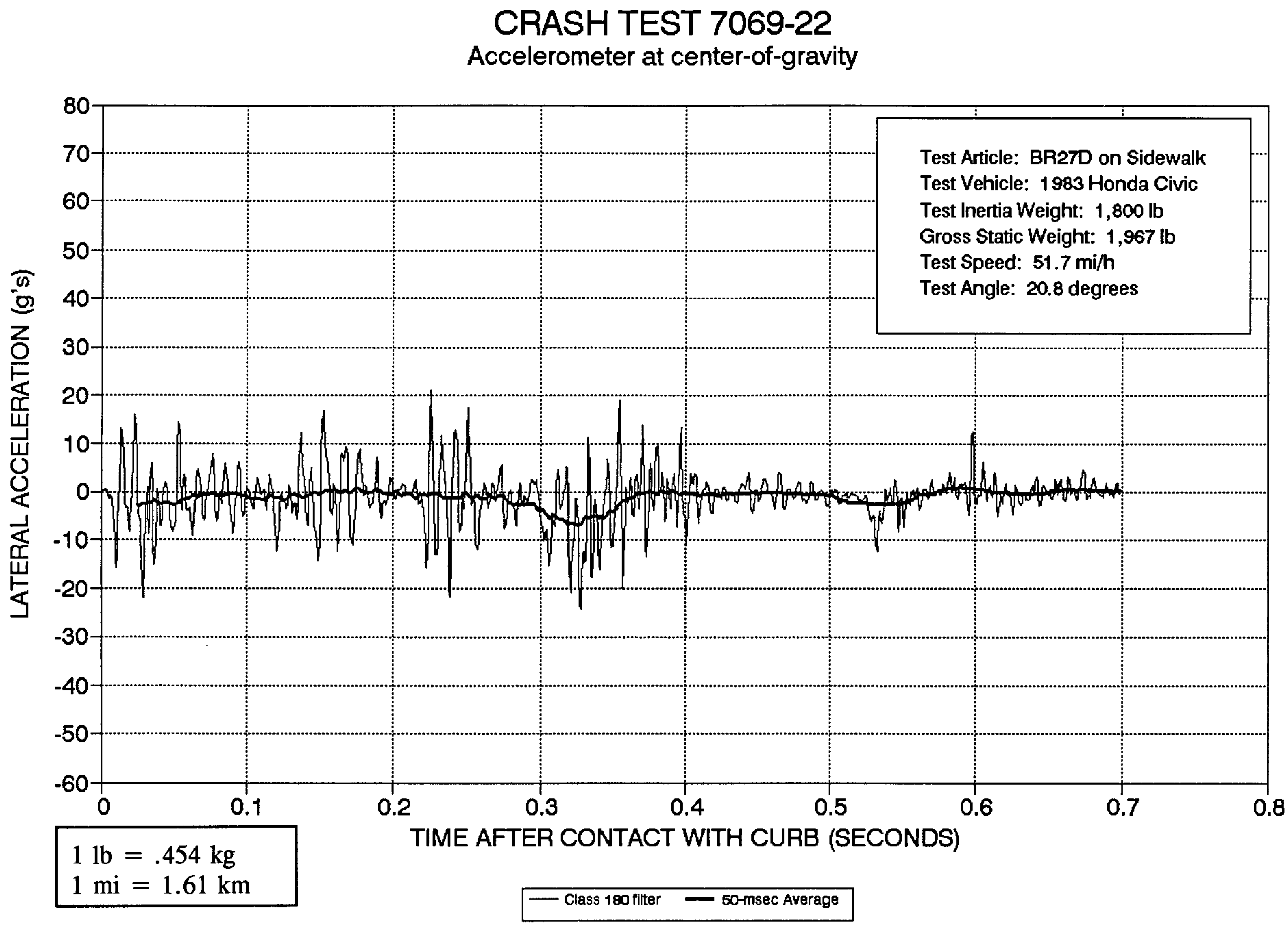


Figure 13. Vehicle longitudinal accelerometer trace for test 7069-22 (accelerometer located at center-of-gravity).



Test Article: BR27D on Sidewalk
Test Vehicle: 1983 Honda Civic
Test Inertia Weight: 1,800 lb
Gross Static Weight: 1,967 lb
Test Speed: 51.7 mi/h
Test Angle: 20.8 degrees

1 lb = .454 kg
1 mi = 1.61 km

Figure 14. Vehicle lateral accelerometer trace for test 7069-22 (accelerometer located at center-of-gravity).

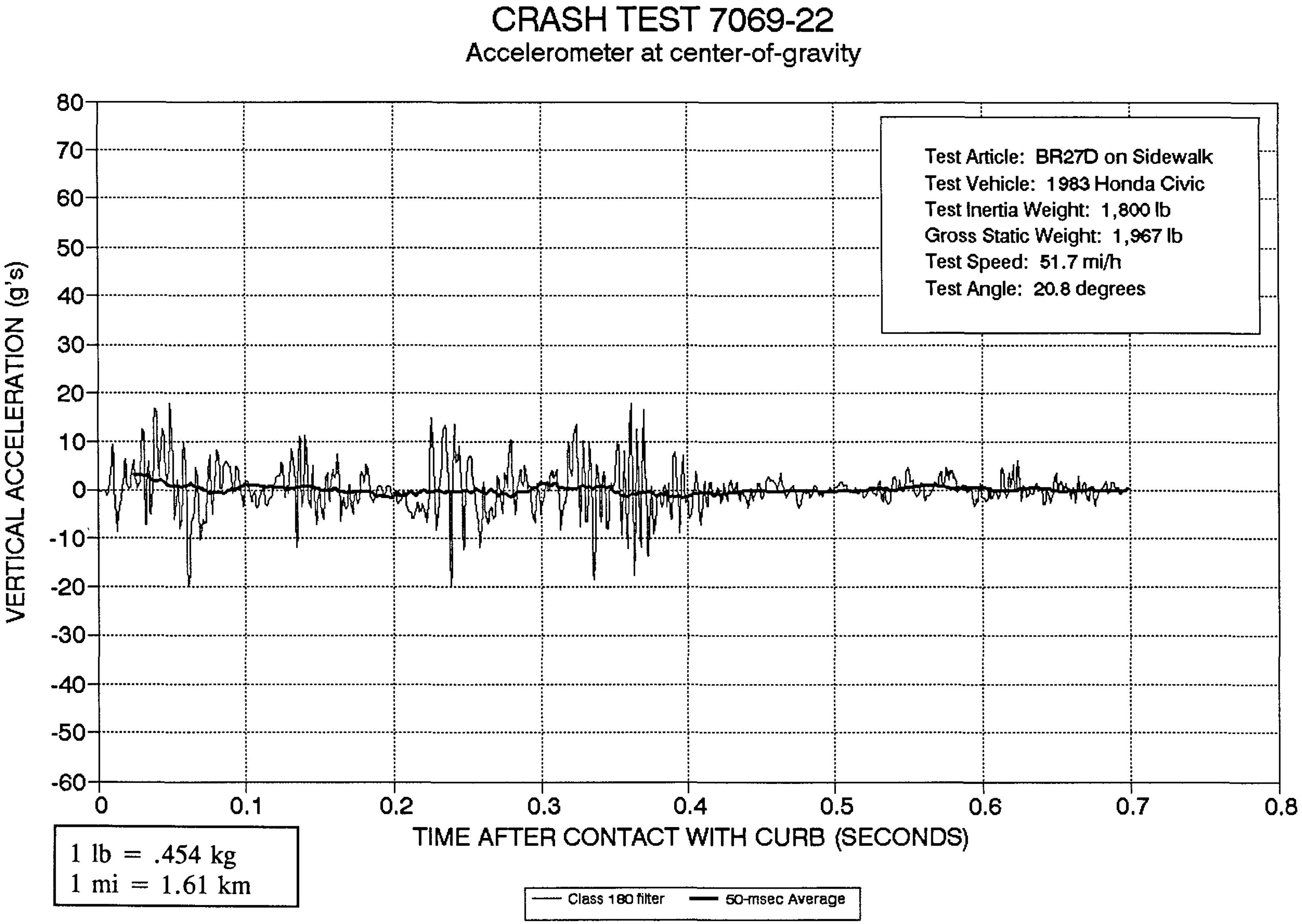


Figure 15. Vehicle vertical accelerometer trace for test 7069-22
(accelerometer located at center-of-gravity)

Test 7069-23

Test Description

A 1984 Chevrolet Custom pickup (figures 16 and 17) was used for the crash test. Test inertia mass of the vehicle was 5,400 lb (2 452 kg) and its gross static mass was 5,565 lb (2 527 kg). The height to the lower edge of the vehicle bumper was 18.0 in (457 mm) and it was 27.0 in (686 mm) to the top of the bumper. Additional dimensions and information on the test vehicle are given in figure 18. The vehicle was directed into the BR27D bridge railing on sidewalk (figure 19) using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact. The vehicle impacted the curb of the sidewalk approximately 20 ft (6 m) upstream of post 5 at a speed of 45.3 mi/h (72.9 km/h) and the angle of impact was 20.2 degrees.

At 0.171 s the right front wheel contacted the curb and the left side of the vehicle was airborne. The vehicle impacted the concrete parapet at 0.218 s. The vehicle impacted the parapet 3 ft from post 5 (between posts 4 and 5) traveling at a speed of 43.8 mi/h (70.5 km/h) and at an angle of 19.7 degrees. As the vehicle continued forward, the bumper protruded between the lower metal railing element and the concrete parapet. The right front wheel struck the curb at 0.235 s, and at 0.295 s the vehicle began to redirect. By 0.487 s the vehicle was traveling parallel to the bridge railing at a speed of 40.3 mi/h (64.8 km/h), and at 0.501 s the rear of the vehicle impacted the parapet. The vehicle lost contact with the concrete parapet at 0.587 s traveling at 37.2 mi/h (59.9 km/h) and 5.3 degrees. The brakes were applied as the vehicle left the installation. The vehicle yawed counterclockwise and subsequently came to rest 113 ft (34 m) from the point of impact resting against another barrier downstream of the bridge railing installation.

As can be seen in figures 20 and 21, the bridge railing received minimal damage. The maximum permanent deformation to the railing element was 0.5 in (13 mm) between posts 5 and 6. Posts 5 and 6 were also pushed rearward approximately 3/16 in (4.8 mm) as shown in figure 22. There was only cosmetic damage to the concrete parapet. There were tire marks on the concrete parapet, on the face of the lower metal railing element in the area of impact, and also on the lower part of post 5 and 6. The vehicle was in contact with the bridge railing system for 12.8 ft (3.9 m).

The vehicle sustained damage to the left side as shown in figures 23 and 24. Maximum crush at the left front corner at bumper height was 12.5 in (318 mm) and the right side was deformed outward 5.0 in (127 mm). Also, damage was done to the front bumper, hood, grill, radiator and fan, left front quarter panel, left door, left rear quarter panel, left front and rear tires and rims, rear bumper, and right front quarter panel and right door.

Test Results

The vehicle impacted the curb of the sidewalk at 45.3 mi/h (72.9 km/h) and the angle of impact was 20.2 degrees. As the vehicle impacted the concrete parapet, it was traveling at a speed of 43.8 mi/h (70.5 km/h) and an angle of 19.7 degrees. The speed of the vehicle at time of parallel was 40.3 mi/h (64.8 km/h). In determining the effective coefficient of friction which is an assessment of the smoothness of the "vehicle-railing" interaction, it should be noted that vehicle impact speed and angle is used in the calculation. If "vehicle-railing" interaction is interpreted literally, impact at the time of contact with the concrete parapet would be used; however, the curb could be considered to be part of this "vehicle-railing" interaction. Therefore, two assessments could be made: (1) interpreting "vehicle-railing" interaction literally disregarding the impact at the curb and using the speed and angle at which the vehicle impacted the concrete parapet or (2) considering the curb as an element of the "railing" system and using the speed and angle at which the vehicle impacted the curb. The coefficient of friction was calculated both ways for this test. Considering the curb as part of the vehicle-railing interaction, the coefficient of friction was 0.07 while using impact with the concrete parapet in the calculation it was 0.06. The vehicle lost contact with the bridge railing traveling at 37.2 mi/h (59.9 km/h), and the exit angle between the vehicle path and the bridge railing was 5.3 degrees. Data from the accelerometer located at the center-of-gravity were digitized for evaluation, and occupant risk factors were computed as follows. In the longitudinal direction, occupant impact velocity was 13.2 ft/s (4.0 m/s) at 0.405 s, the highest 0.010-s average ridedown acceleration was -2.3 g between 0.510 and 0.520 s, and the maximum 0.050-s average acceleration was -3.7 g between 0.282 and 0.332 s. Lateral occupant impact velocity was 14.0 ft/s (4.3 m/s) at 0.360 s, the highest 0.010-s occupant ridedown acceleration was -10.6 g between 0.484 and 0.494 s, and the maximum 0.050-s average acceleration was -7.8 g between 0.224 and 0.274 s. The change in vehicle velocity at loss of contact using impact with the curb was 8.1 mi/h (13.0 km/h) and the change in momentum was 1,992 lb-s (8 860 N-s). These data and other pertinent information from the test are summarized in figure 25 and table 3. Sequential photographs are shown in figures 26 and 27. Vehicular angular displacements are displayed in figure 28. Vehicular accelerations versus time traces filtered with SAE J211 filters are presented in figures 29 through 35.

Conclusions

The BR27D bridge railing on sidewalk contained the test vehicle with minimal lateral movement of the metal railing element of the bridge railing. There was no intrusion of railing components into the occupant compartment and no debris to present undue hazard to other traffic. The integrity of the occupant compartment was maintained with no intrusion and no deformation. The vehicle remained upright and relatively stable during the collision. The bridge railing smoothly redirected the vehicle. The effective coefficient of friction was considered good.

The 1989 AASHTO guide specifications sets forth desired (but not required) limits for occupant risk factors for tests with the 5,400-lb (2 452-kg) vehicle.(1) The AASHTO specifications recommend a limit of 30 ft/s (9.1 m/s) for longitudinal occupant impact velocity and 25 ft/s (7.6 m/s) for the lateral occupant impact velocity. The occupant impact velocities and the occupant ridedown accelerations were within the limits. The vehicle trajectory at loss of contact indicated minimum intrusion into adjacent traffic lanes. For more details see figure 25 and table 3.

Figure 16. Vehicle before test 7069-23.

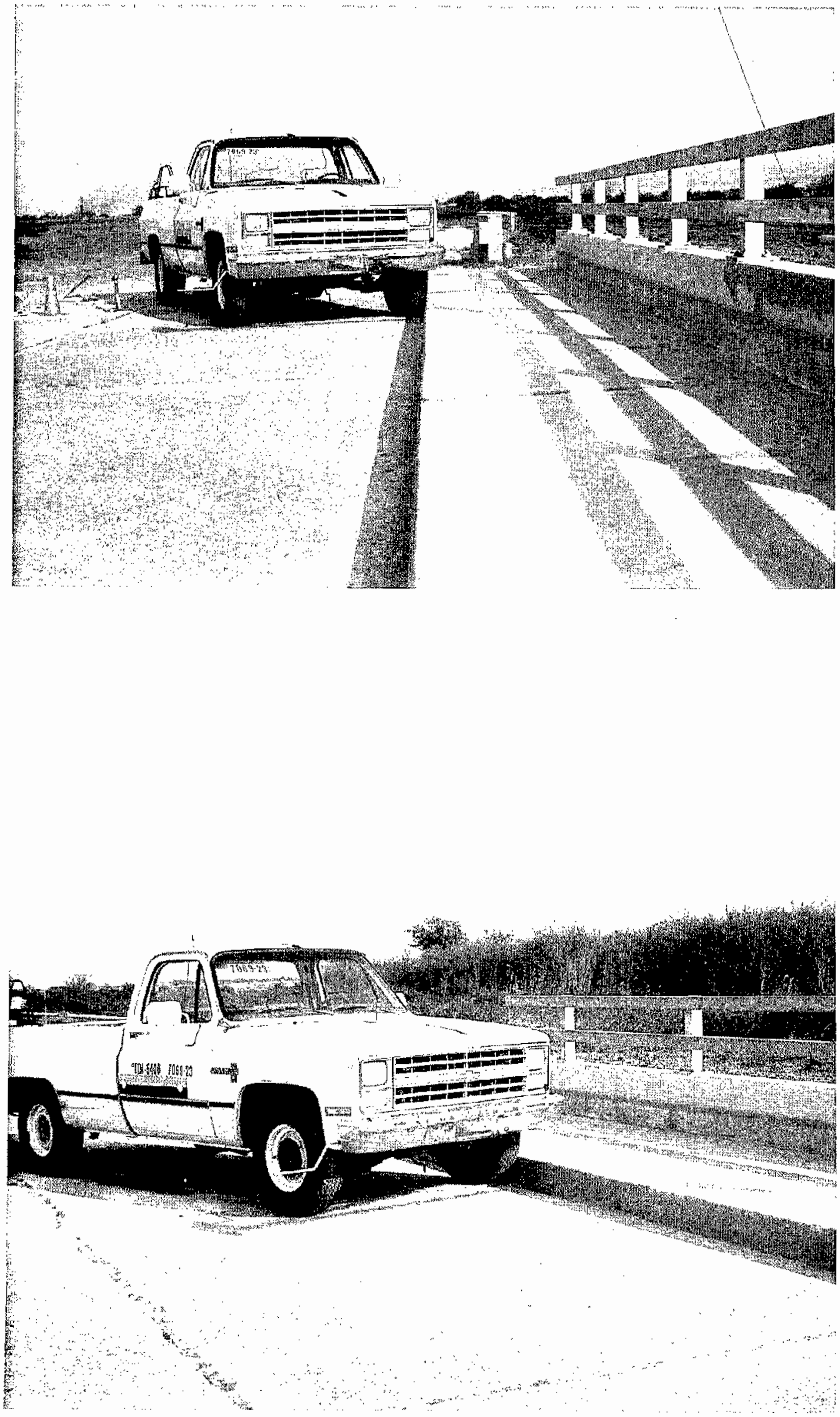


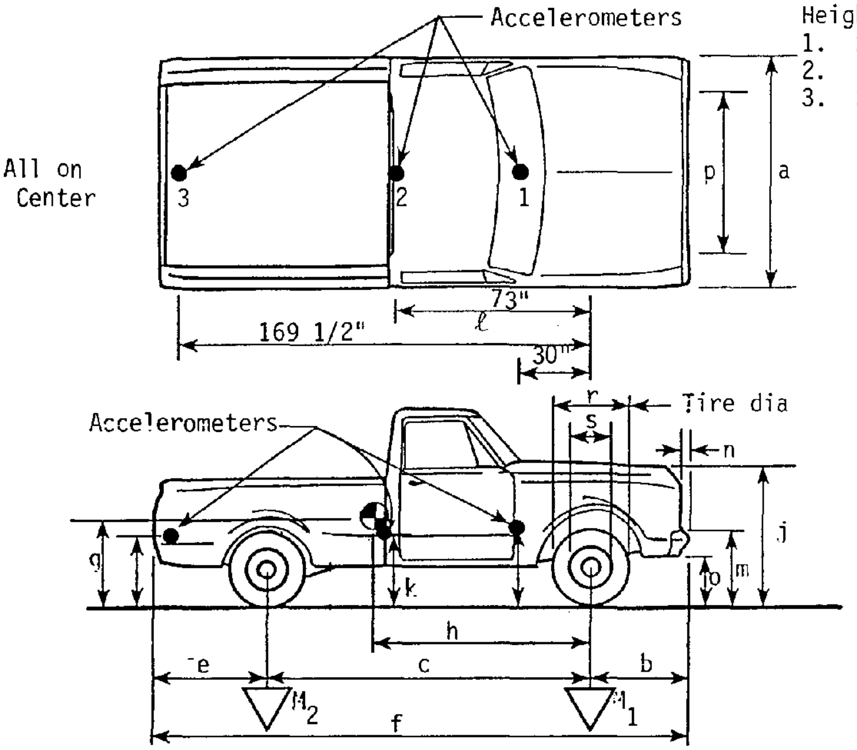
Figure 17. Vehicle/bridge railing geometrics for test 7069-23.

Date: 3-26-92 Test No.: 7069-23 VIN: 2GCEC24H5E1155177

Make: Chevrolet Model: Custom Deluxe Year: 1984 Odometer: 110142

Tire Size: LT 235 85 R16 Ply Rating: ______ Bias Ply: ___ Belted: ___ Radial: X

Tire Condition: good ___ fair X badly worn ___



Height of Accelerometer
1. 28 1/4"
2. 30 1/2"
3. 36 1/2"

Vehicle Geometry - inches

a	79"	b	32"
c	131.5"	d*	71"
e	53"	f	
g		h	70.9"
i	----	j	45 1/4"
k	30 1/2"	ℓ	169 1/2"
m	27"	n	2 7/8"
o	18"	p	65 1/4"
r	30 1/2"	s	17 1/2"

4-wheel weight for c.g. det. ℓf 1293 rf 1194 ℓr 1480 rr 1433

Mass - pounds	Curb	Test Inertial	Gross Static
M_1	2445	2487	2580
M_2	1820	2913	2985
M_T	4265	5400	5565

Note any damage to vehicle prior to test:

Crack in windshield (marked)

*d = overall height of vehicle

1 in = 25.4 mm
1 lb = .454 kg

Engine Type: V-8

Engine CID: 5.0 liter

Transmission Type:

Automatic or ~~Manual~~

~~FWD~~ or RWD or ~~4WD~~

Body Type: PU

Steering Column Collapse Mechanism:

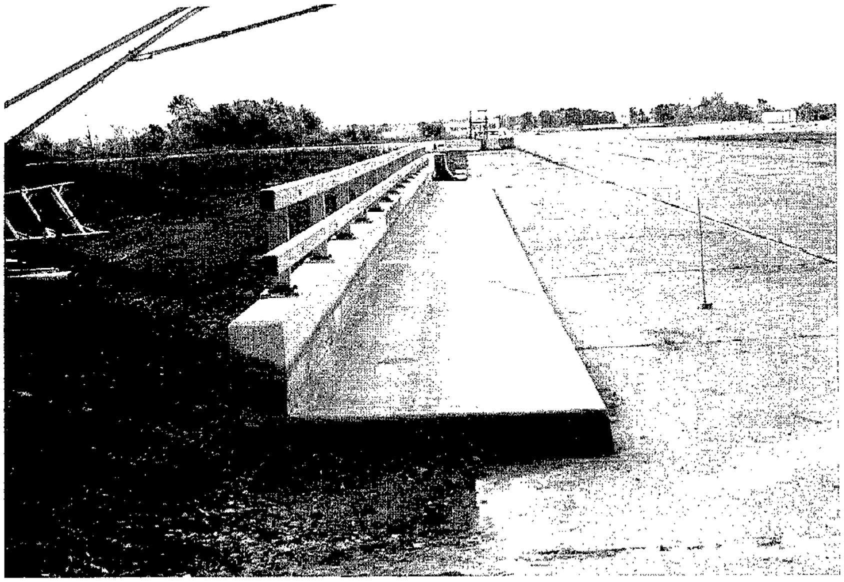
___Behind wheel units
___Convoluted tube
___Cylindrical mesh units
___Embedded ball
___NOT collapsible
___Other energy absorption
___Unknown

Brakes:

Front: disc X drum ___

Rear: disc ___ drum X

Figure 18. Vehicle properties for test 7069-23.



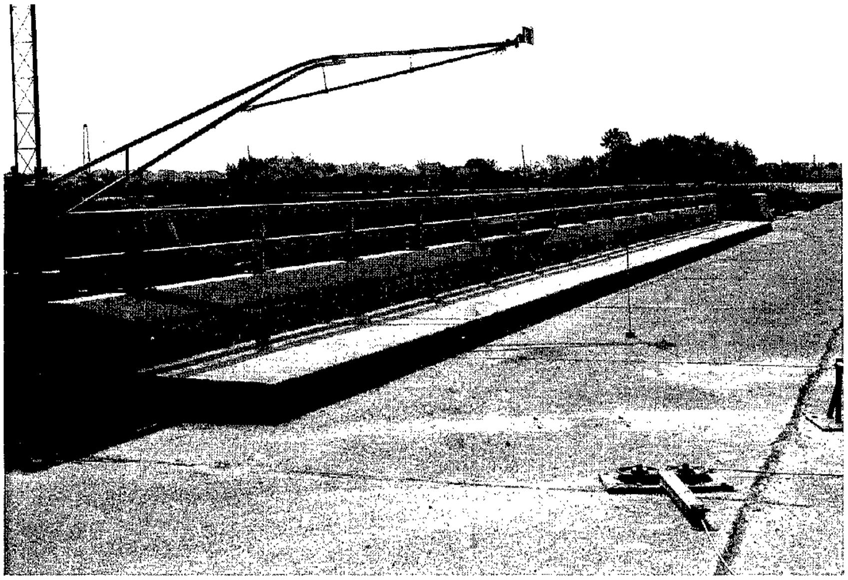


Figure 19. BR27D bridge railing on sidewalk before test 7069-23.

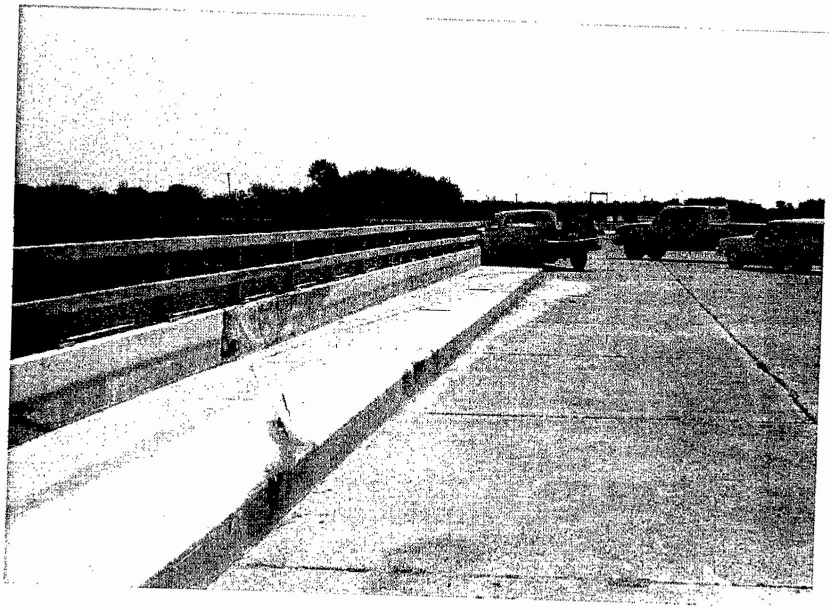
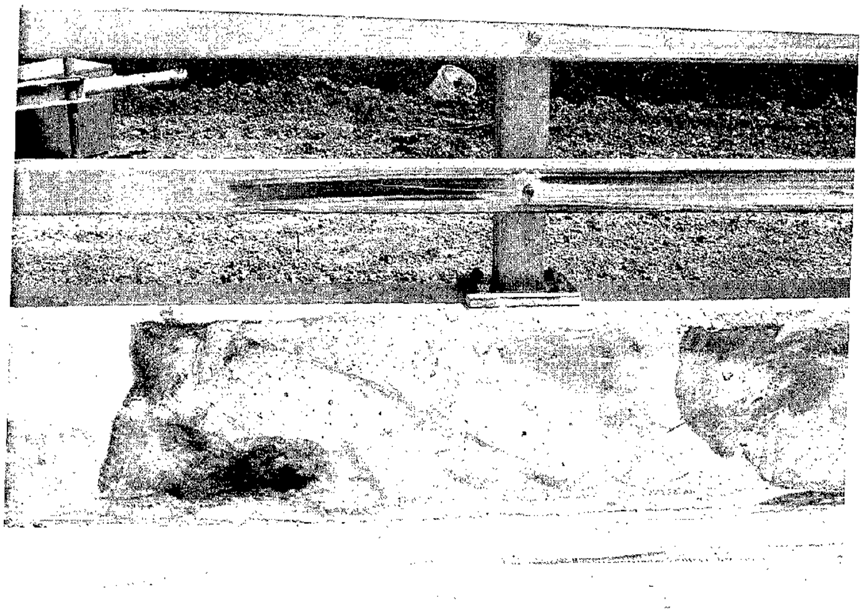


Figure 20. BR27D bridge railing on sidewalk after test 7069-23.



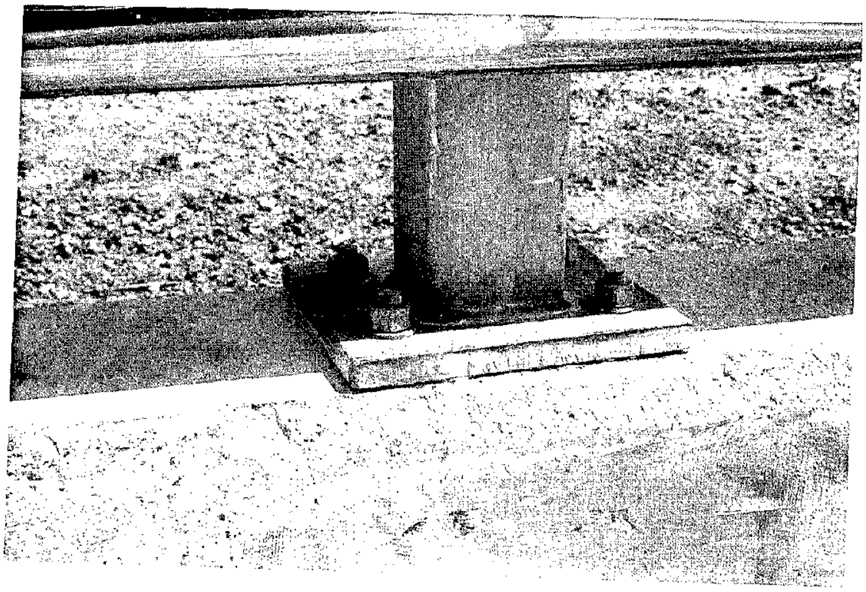
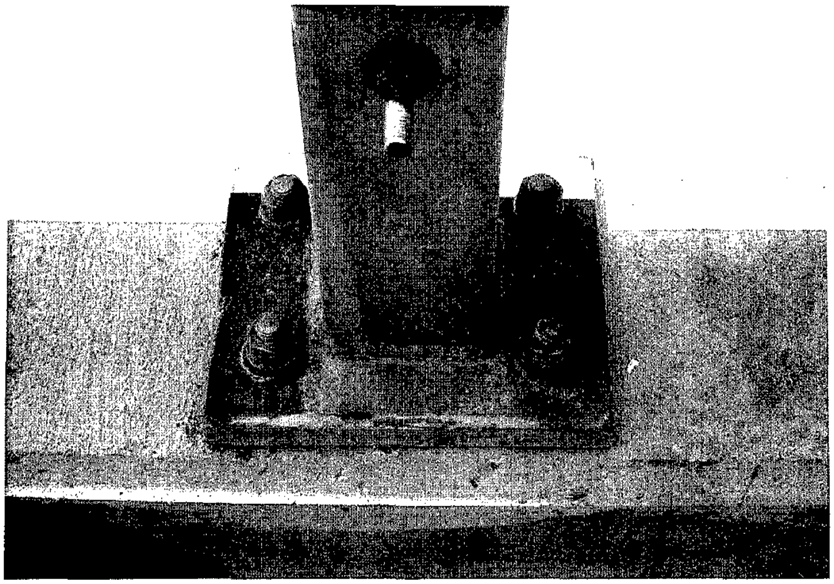


Figure 21. Damage at post 5, test 7069-23.



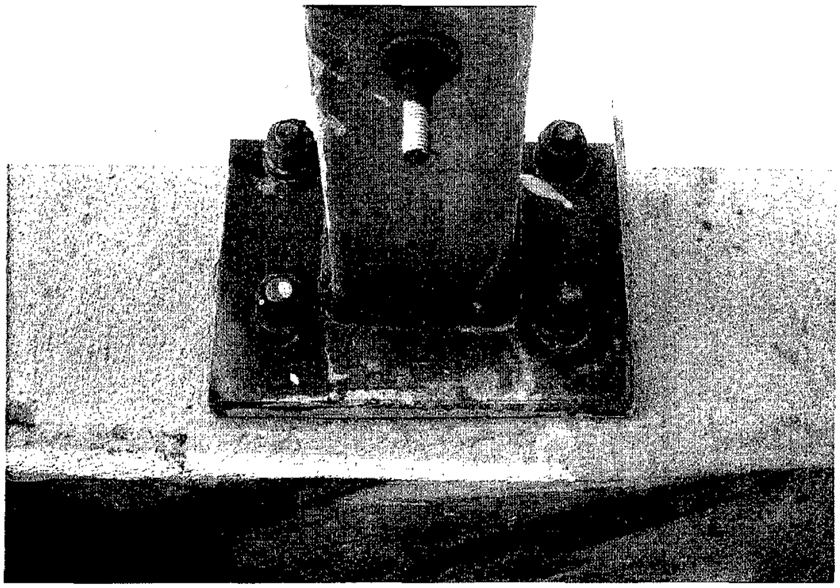


Figure 22. Movement of posts at 5 and 6, test 7069-23.

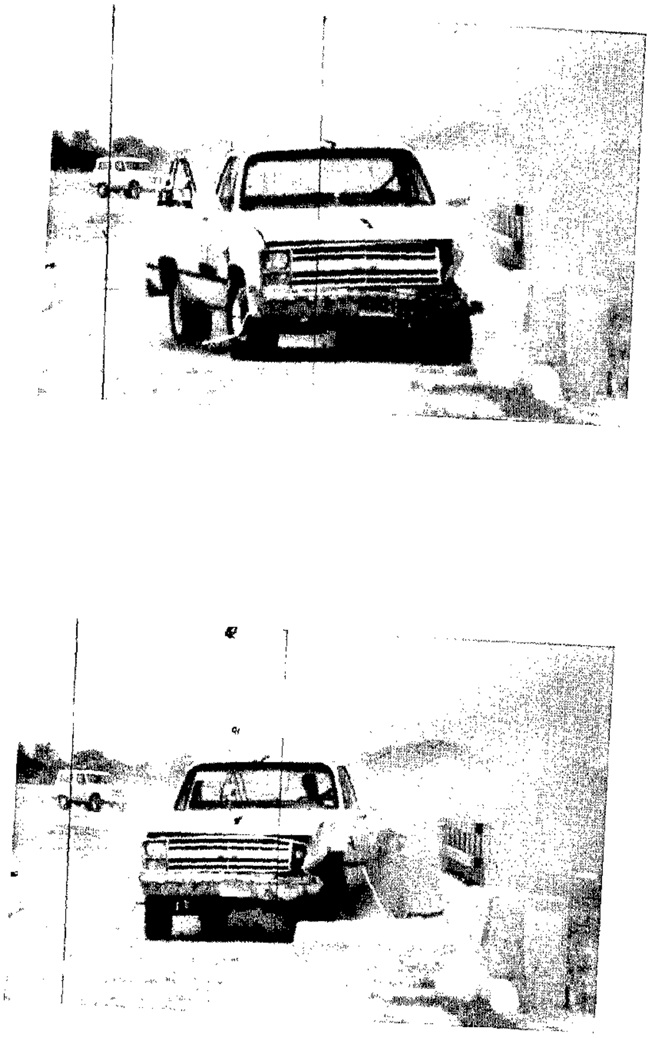
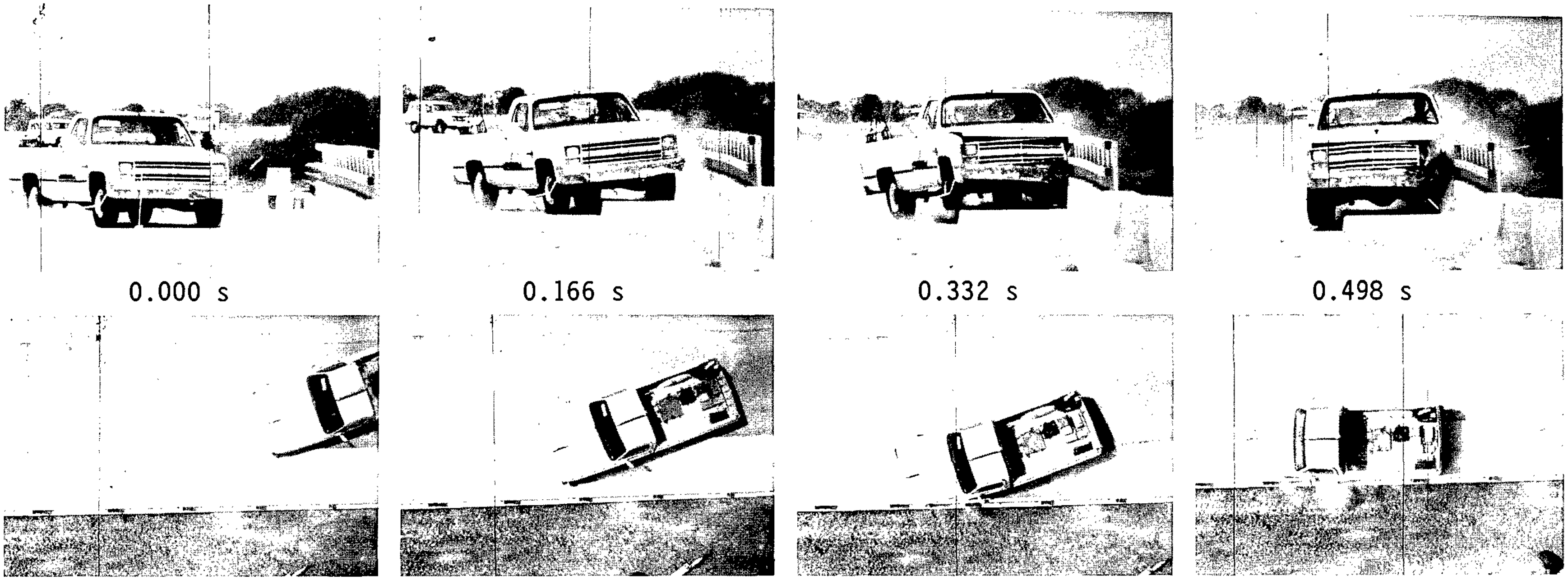
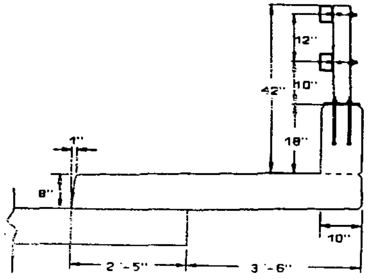


Figure 23. Vehicle after test 7069-23.

Figure 24. Damage to left side of vehicle after test 7069-23.



0.000 s
0.166 s
0.332 s
0.498 s



(1 in = 25.4 mm)

Test No.	7069-23
Date	03/26/92
Test Installation . . .	BR27D Bridge Railing on sidewalk
Installation Length . .	100 ft (30 m)
Test Vehicle	1984 Chevrolet Custom Pickup
Vehicle Weight	
Test Inertia	5,400 lb (2,452 kg)
Gross Static	5,565 lb (2,527 kg)
Vehicle Damage Classification	
TAD	11FL4 & 11LD4
CDC	11FLEK2 & 11LDEW3
Maximum Vehicle Crush .	12.5 in (318 mm)

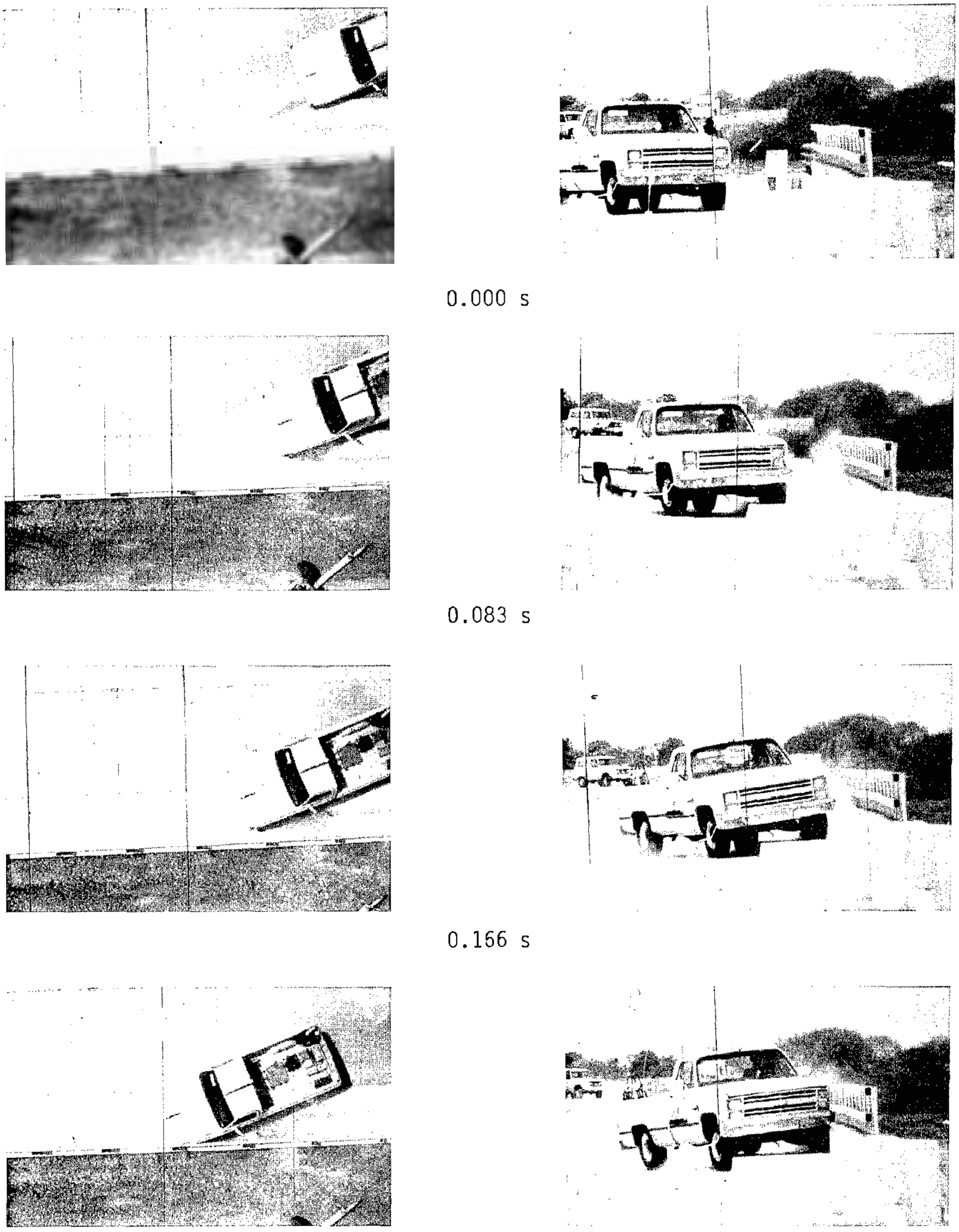
Impact Speed. . . .	45.3 mi/h (72.9 km/h)
Impact Angle. . . .	20.2 deg
Speed at Parallel .	40.3 mi/h (64.8 km/h)
Exit Speed	37.2 mi/h (59.9 km/h)
Exit Trajectory . .	5.3 deg
Vehicle Accelerations (Max. 0.050-sec Avg) at true c.g.	
Longitudinal. . .	-3.7 g
Lateral	-7.8 g
Occupant Impact Velocity at true c.g.	
Longitudinal. . .	13.2 ft/s (4.0 m/s)
Lateral	14.0 ft/s (4.3 m/s)
Occupant Ridedown Accelerations	
Longitudinal. . .	-2.3 g
Lateral	-10.6 g

Figure 25. Summary of results for test 7069-23.

Table 3. Evaluation of crash test no. 7069-23.
{BR27D bridge railing on sidewalk [5,400 lb (2 452 kg)|45.3 mi/h (72.9 km/h)20.2 degrees]}

	CRITERIA	TEST RESULTS	PASS/FAIL*
A.	Must contain vehicle	Vehicle was contained	Pass
B.	Debris shall not penetrate passenger compartment	No debris penetrated passenger compartment	Pass
C.	Passenger compartment must have essentially no deformation	No deformation	Pass
D.	Vehicle must remain upright	Vehicle did remain upright	Pass
E.	Must smoothly redirect the vehicle	Vehicle was smoothly redirected	Pass
F.	Effective coefficient of friction μ — Assessment 0 - .25 — Good .26 - .35 — Fair > .35 — Marginal	μ — Assessment .07 (Impact @ curb) — Good .06 (Impact @ rail) — Good	Pass
G.	Shall be less than Occupant Impact Velocity - ft/s (m/s) Longitudinal 30 (9.2) Lateral 25 (7.6)	Occupant Impact Velocity - ft/s (m/s) Longitudinal 13.2 (4.0) Lateral 14.0 (4.3)	Pass
	Occupant Ridedown Accelerations - g's Longitudinal 15 Lateral 15	Occupant Ridedown Accelerations - g's Longitudinal -2.3 Lateral -10.6	Pass
H.	Exit angle shall be less than 12 degrees	Exit angle was 5.3 degrees	Pass

* A, B, C, and D are required. E, F, G, and H are desired. (See table 2)



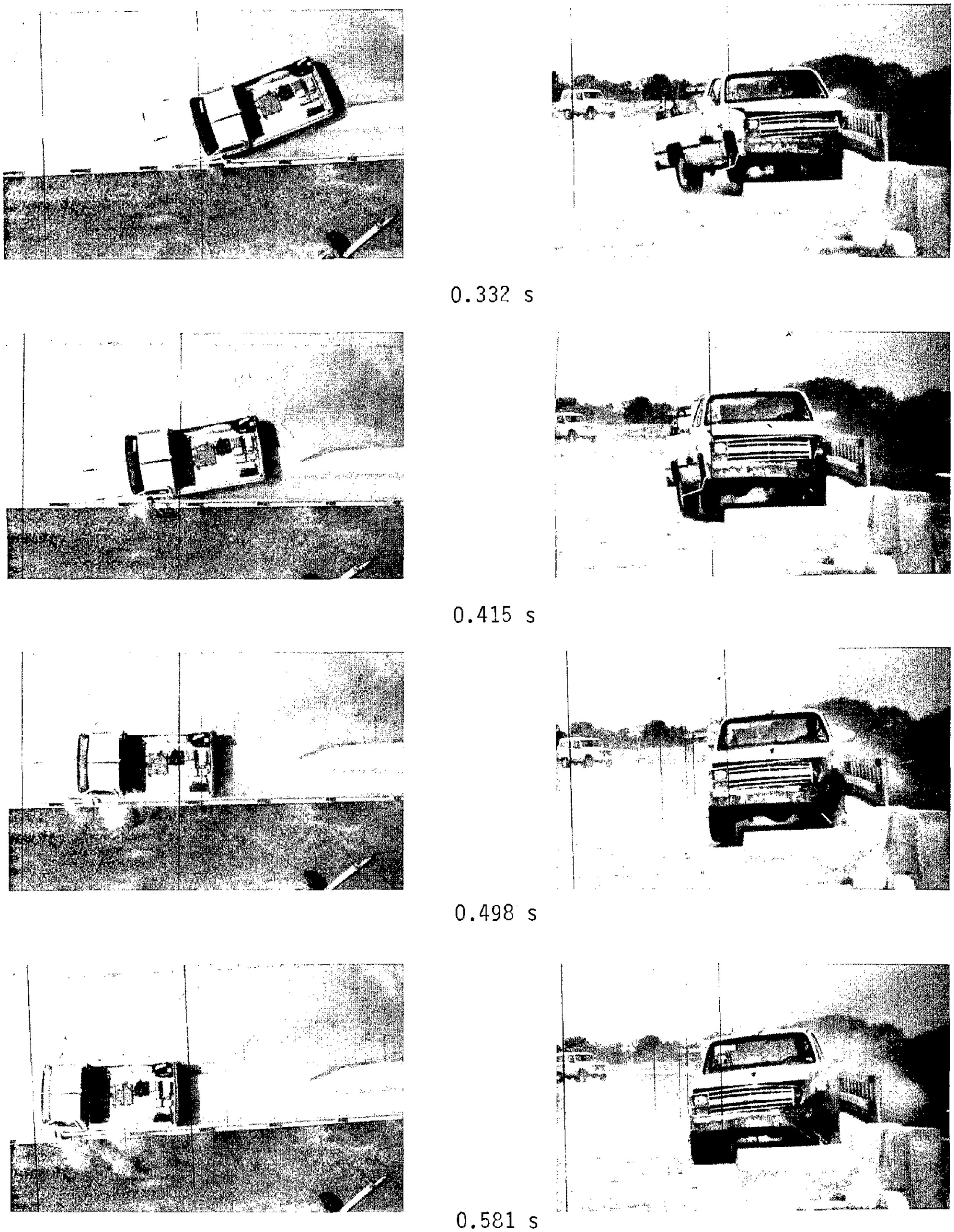
0.000 s

0.083 s

0.166 s

0.249 s

Figure 26. Sequential photographs for test 7069-23 (overhead and frontal views).



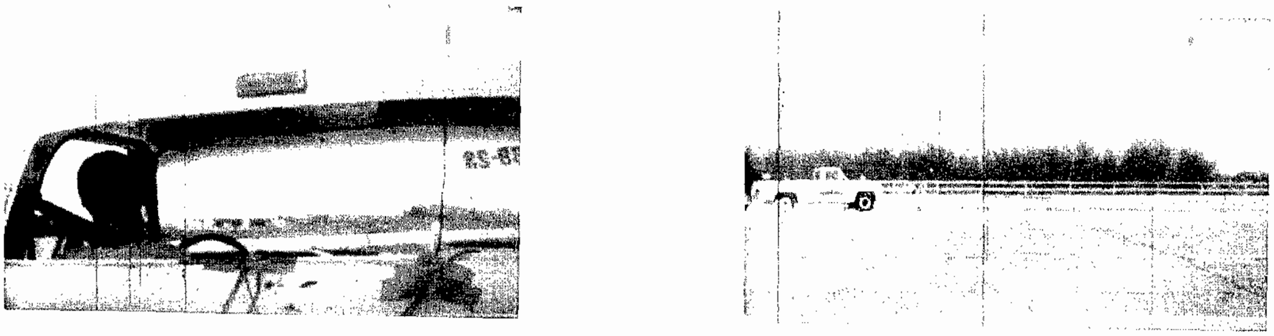
0.332 s

0.415 s

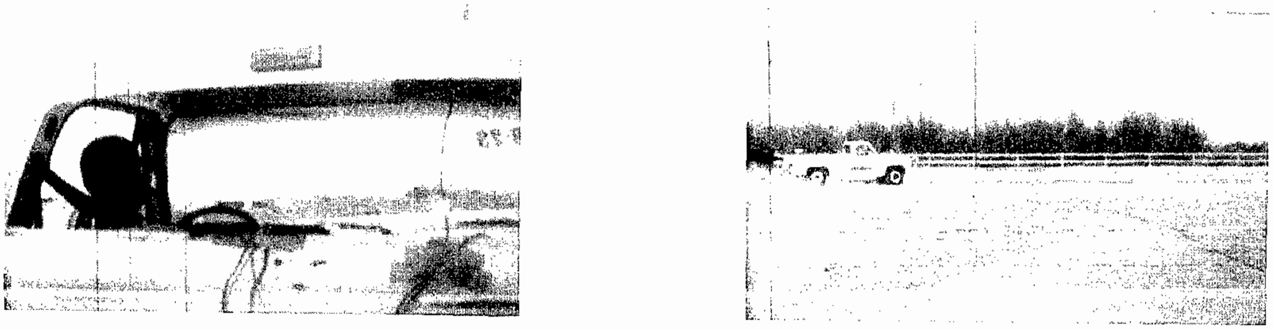
0.498 s

0.581 s

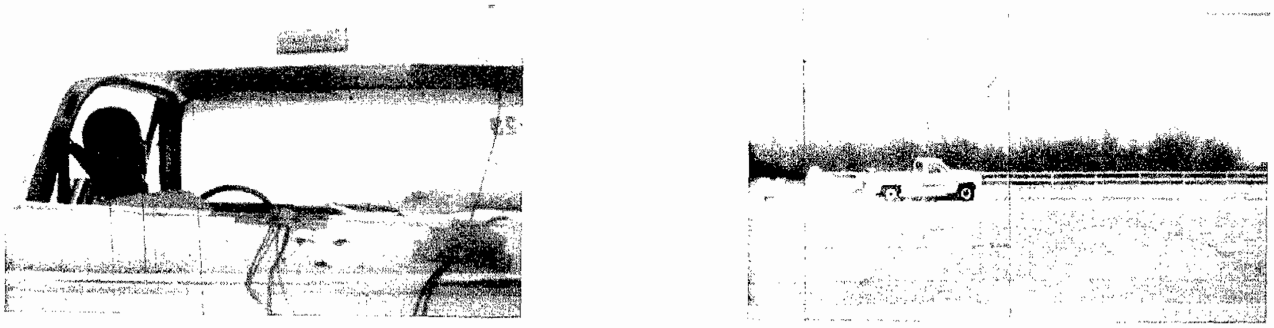
Figure 26 Sequential photogrpahs for test 7069-23
(overhead and frontal views continued).



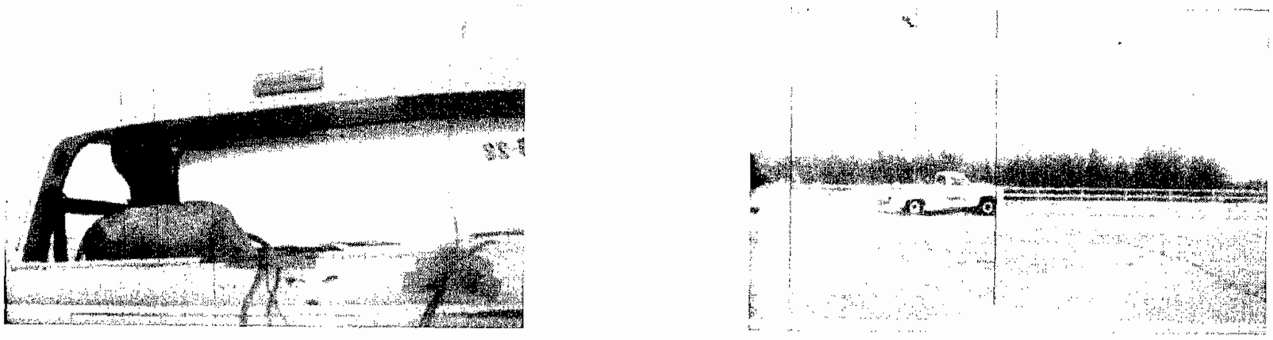
0.000 s



0.083 s

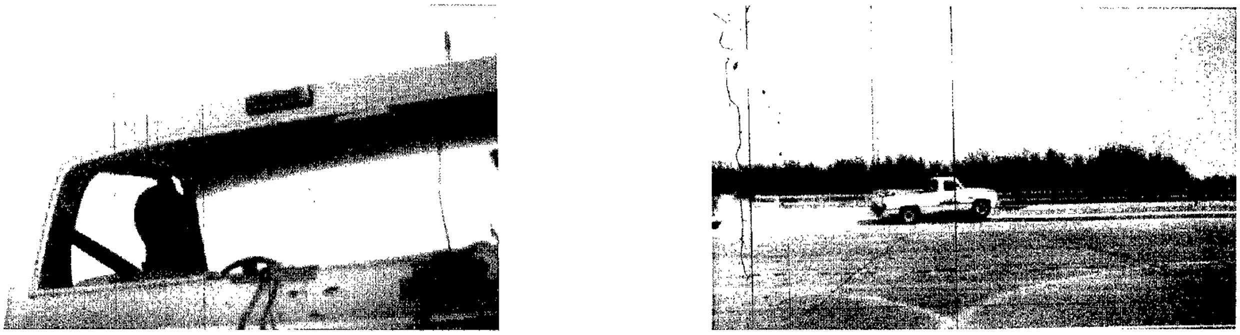


0.166 s

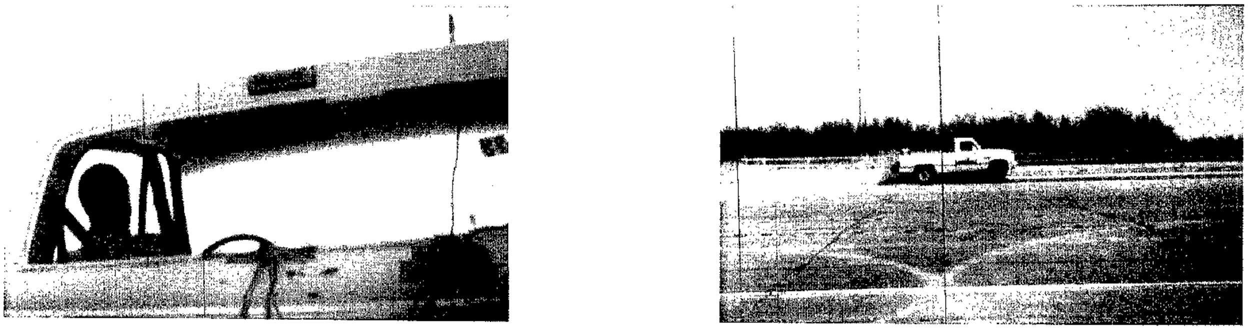


0.249 s

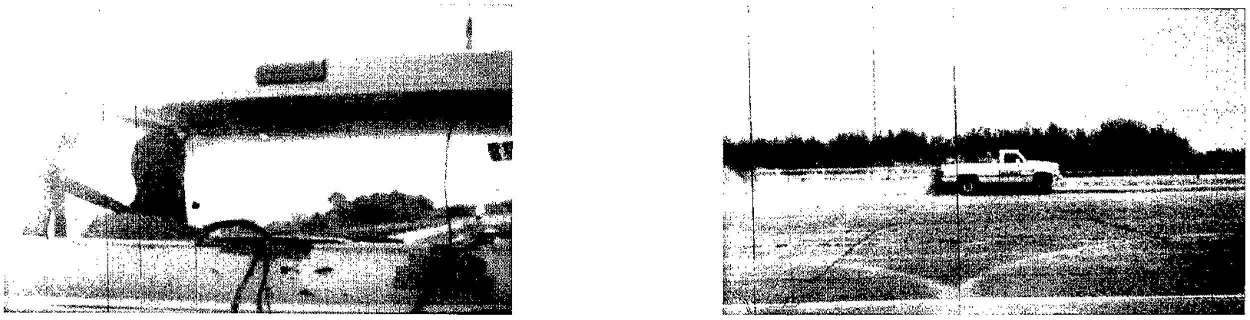
Figure 27. Sequential photographs for test 7069-23 (interior and perpendicular views).



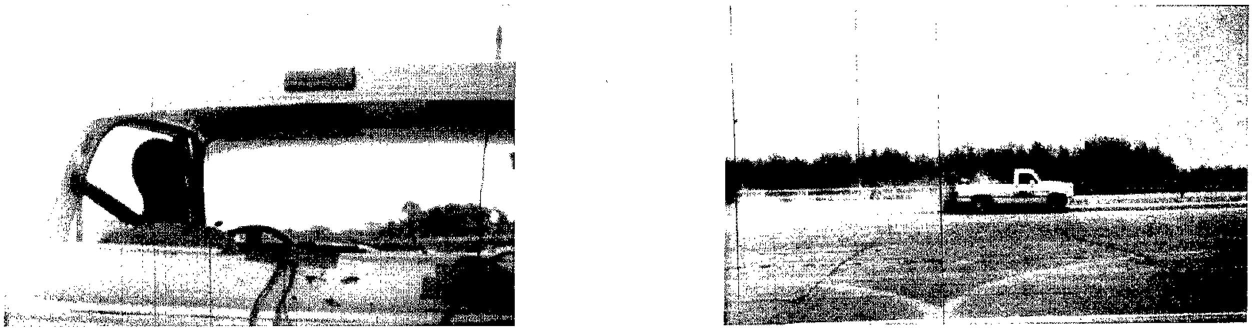
0.332 s



0.415 s

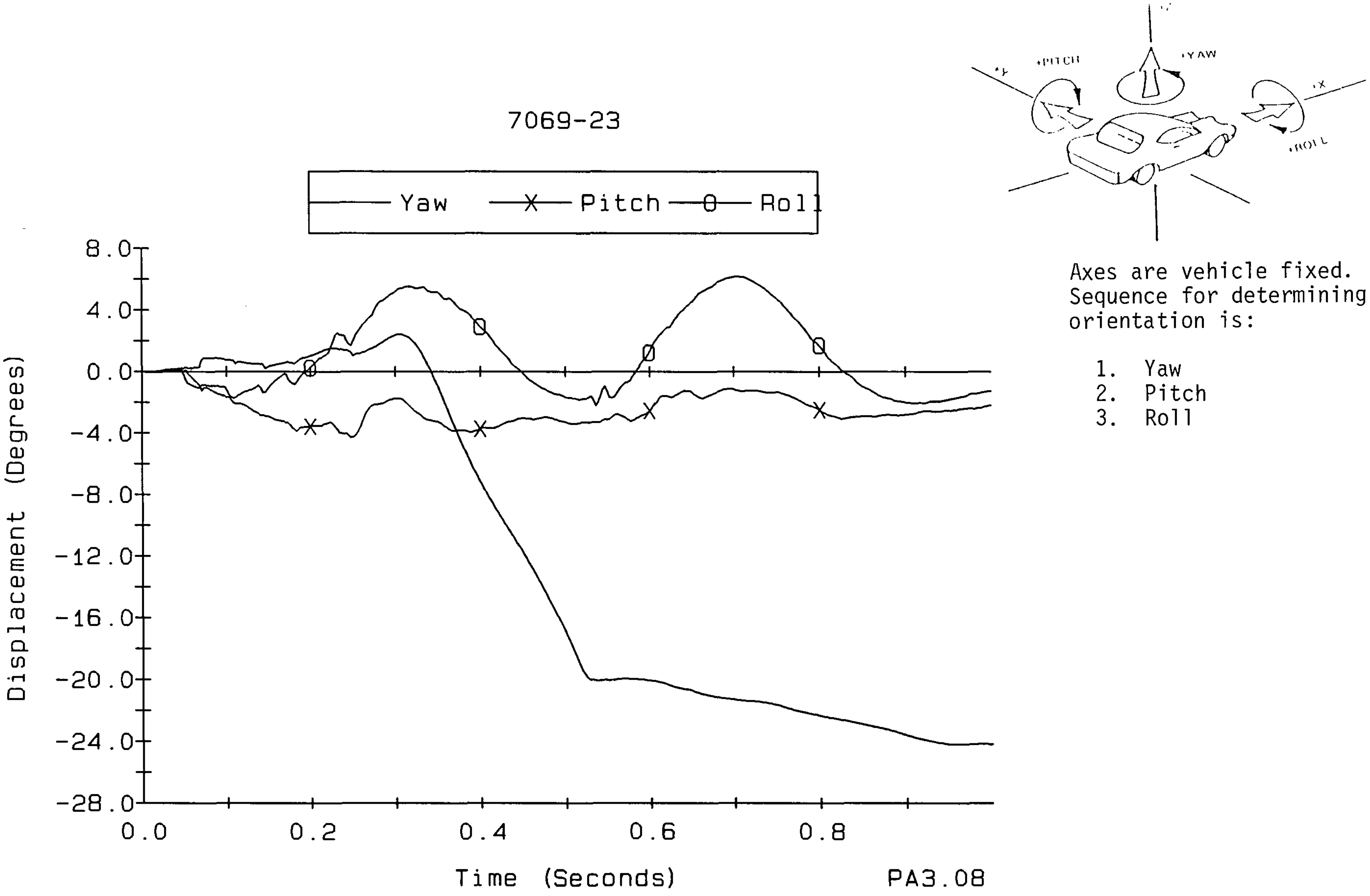


0.498 s



0.581 s

Figure 27. Sequential photogrpahs for test 7069-23
(interior and perpendicular views continued).



Axes are vehicle fixed.
Sequence for determining
orientation is:

1. Yaw
2. Pitch
3. Roll

Figure 28. Vehicle angular displacements for test 7069-23.

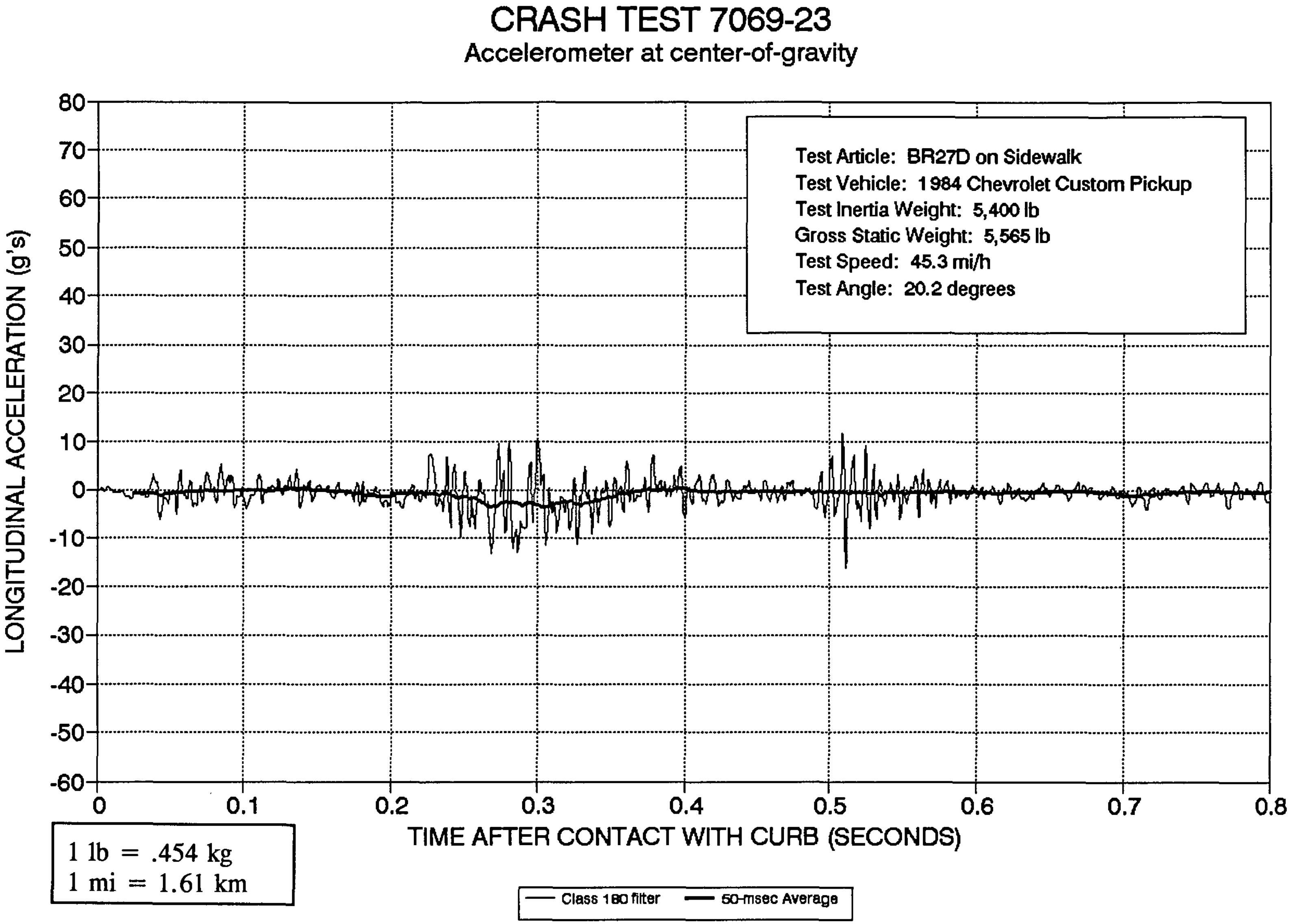
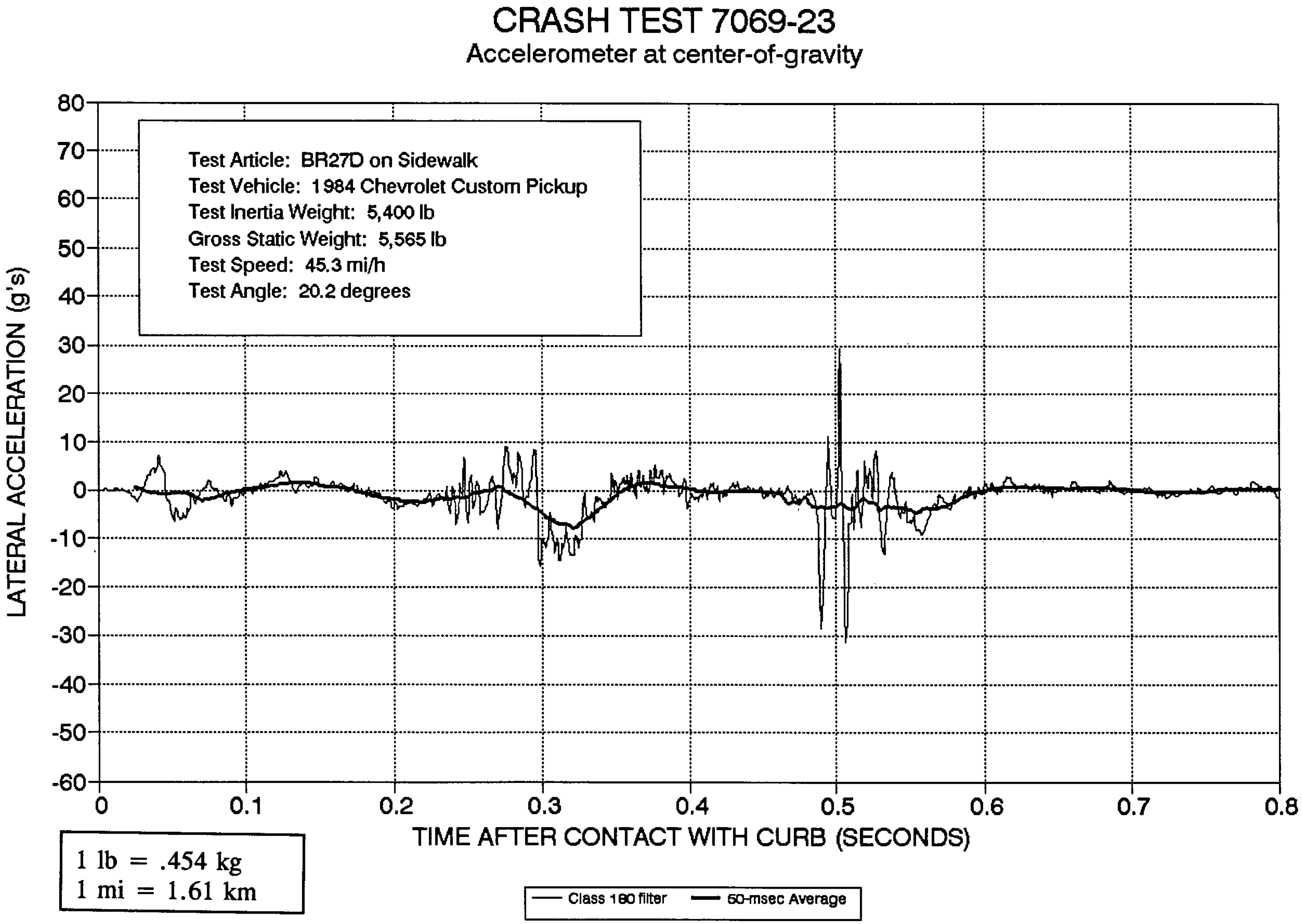
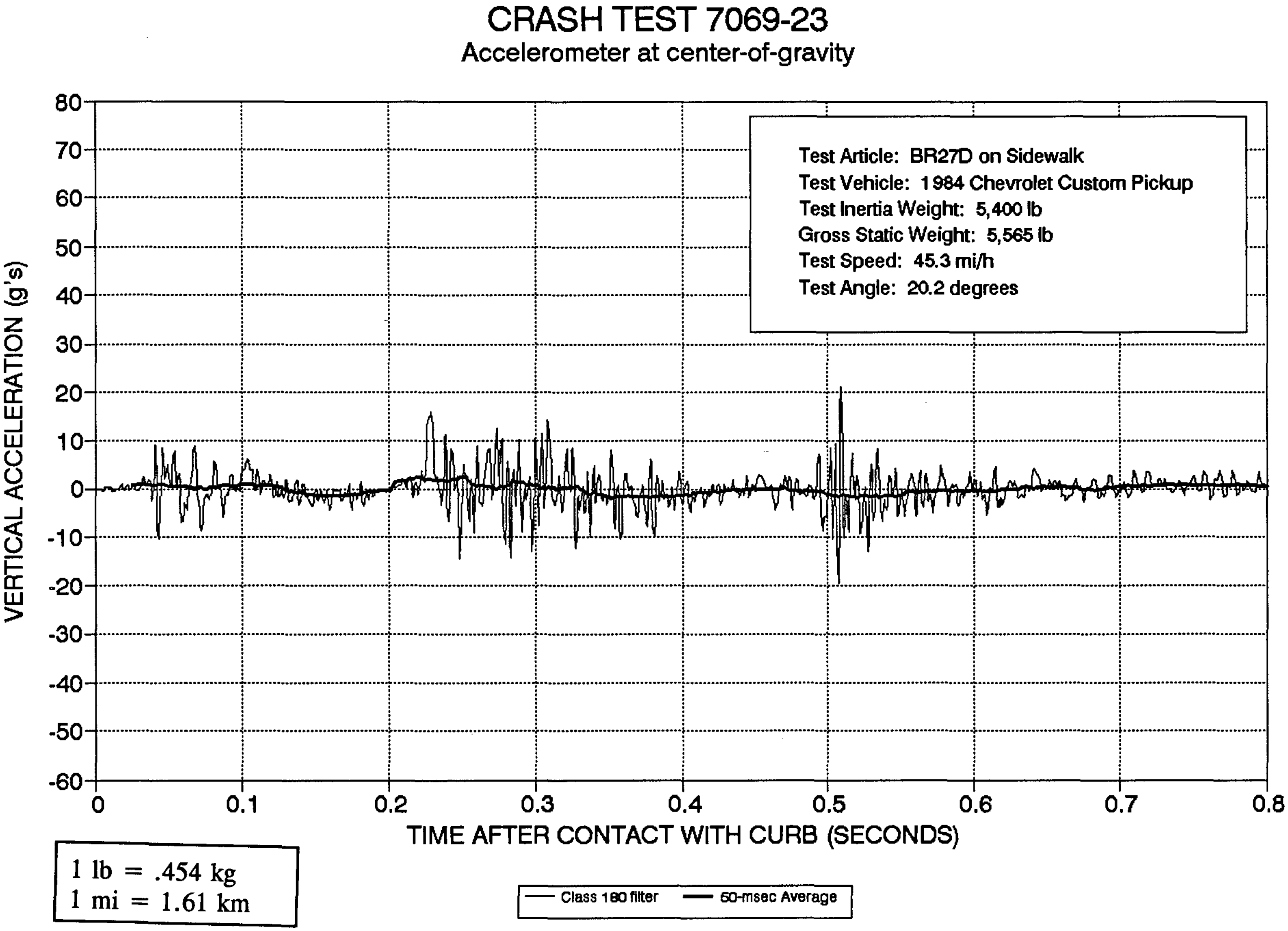


Figure 29. Vehicle longitudinal accelerometer trace for test 7069-23
(accelerometer located at center-of-gravity).



1 lb = .454 kg
1 mi = 1.61 km

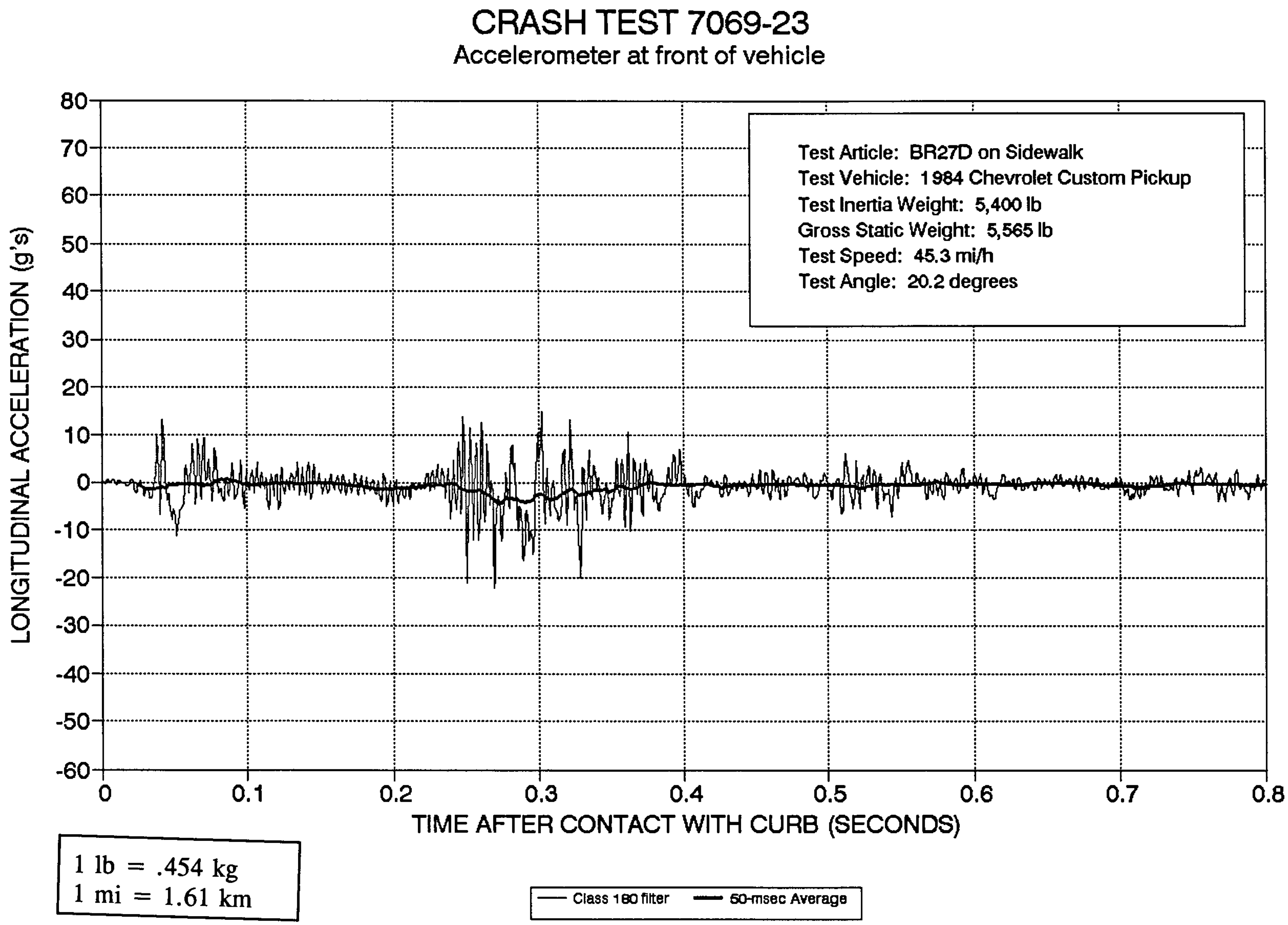
Figure 30. Vehicle lateral accelerometer trace for test 7069-23 (accelerometer located at center-of-gravity).



Test Article: BR27D on Sidewalk
Test Vehicle: 1984 Chevrolet Custom Pickup
Test Inertia Weight: 5,400 lb
Gross Static Weight: 5,565 lb
Test Speed: 45.3 mi/h
Test Angle: 20.2 degrees

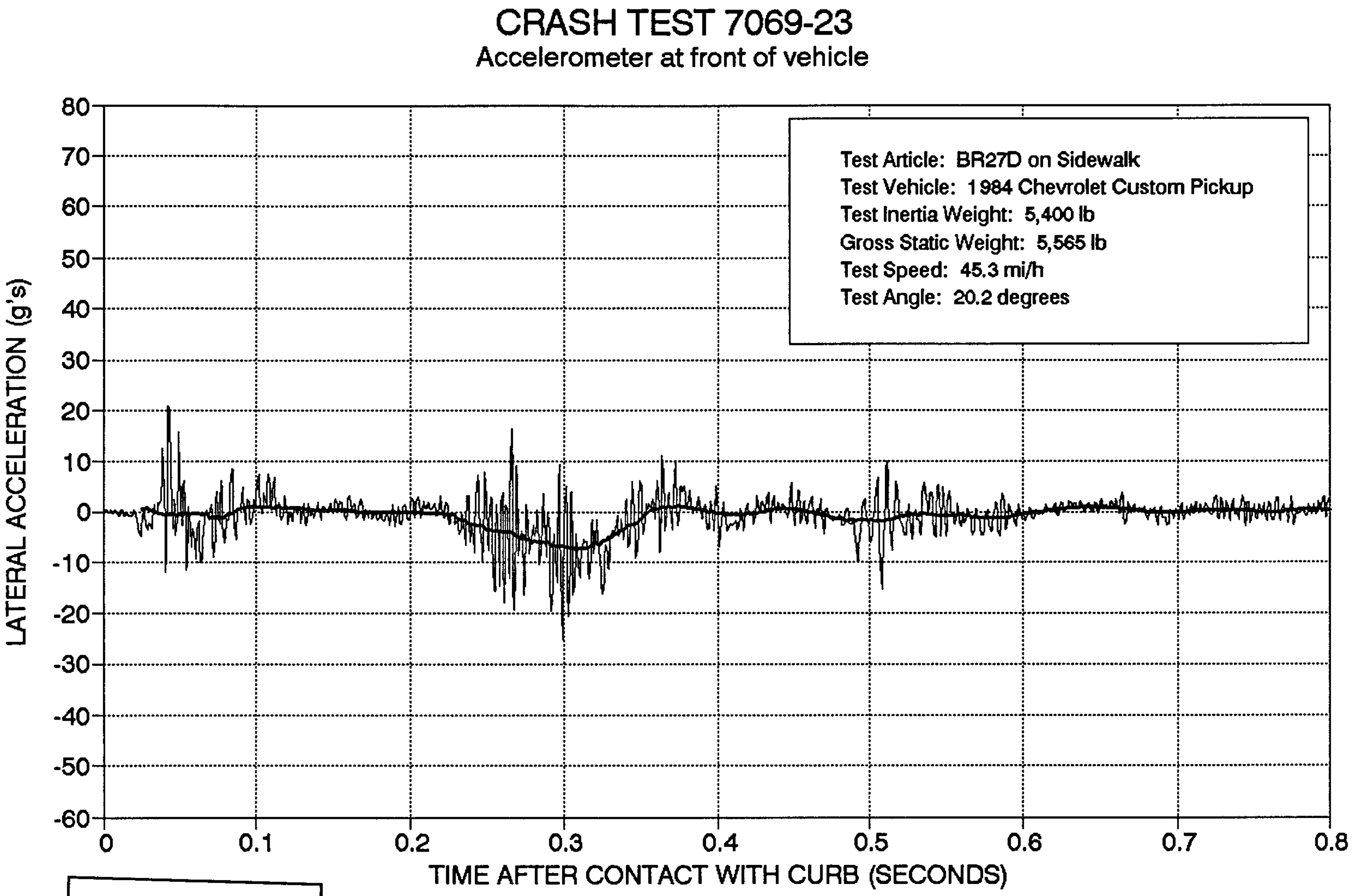
1 lb = .454 kg
1 mi = 1.61 km

Figure 31. Vehicle vertical accelerometer trace for test 7069-23 (accelerometer located at center-of-gravity)



1 lb = .454 kg
1 mi = 1.61 km

Figure 32. Vehicle longitudinal accelerometer trace for test 7069-23 (accelerometer located at front of vehicle).



1 lb = .454 kg
1 mi = 1.61 km

Figure 33. Vehicle lateral accelerometer trace for test 7069-23 (accelerometer located at front of vehicle).

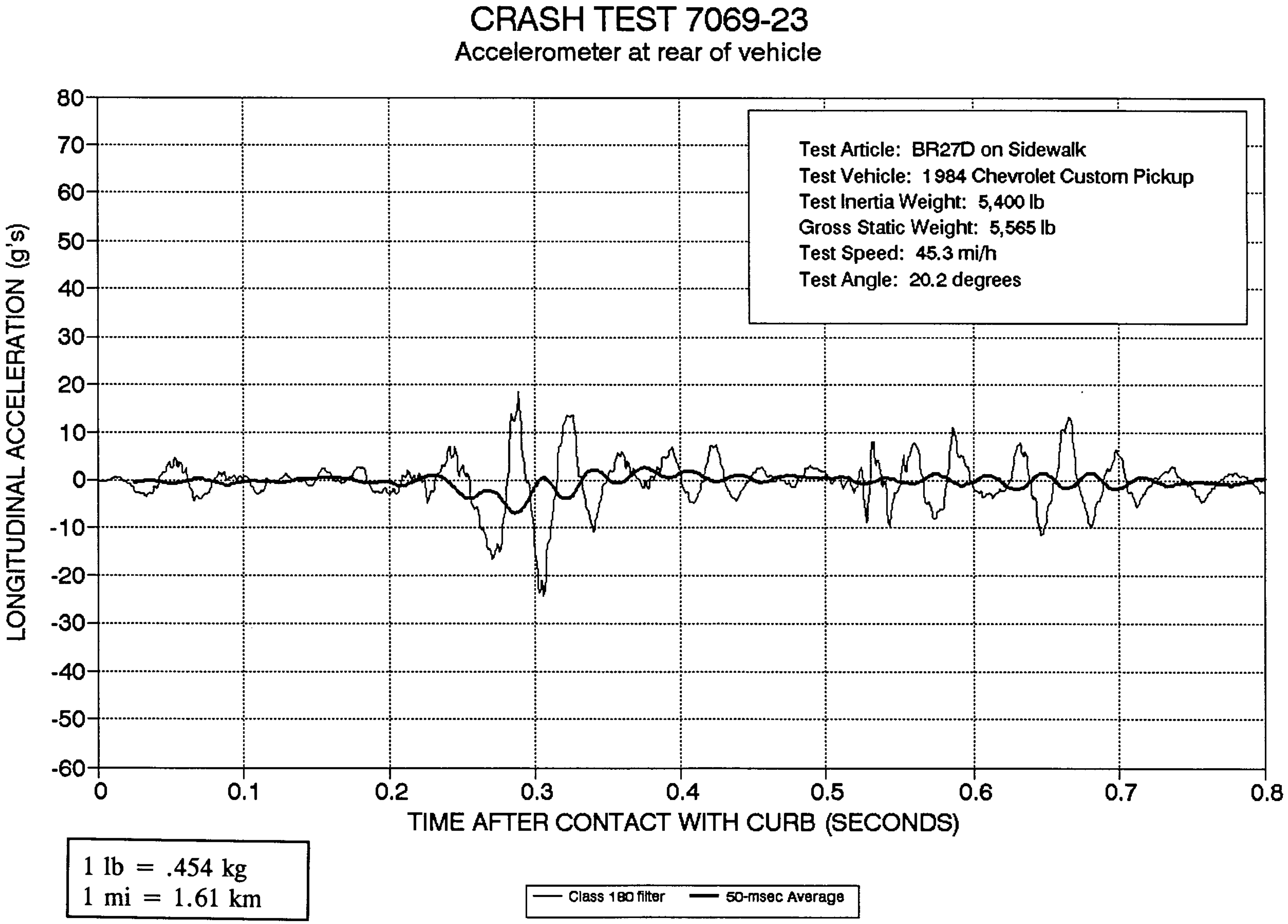
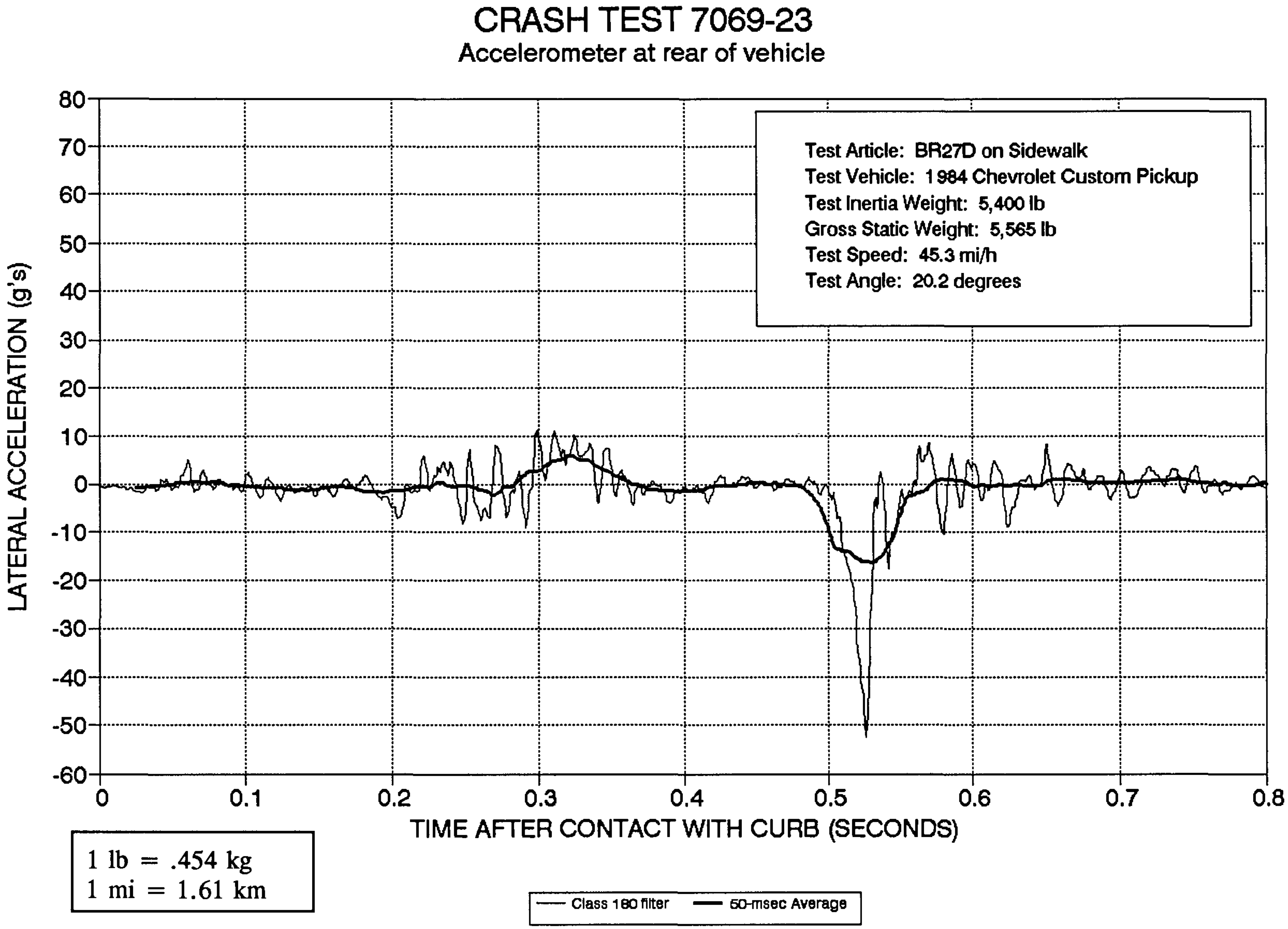


Figure 34. Vehicle longitudinal accelerometer trace for test 7069-23 (accelerometer located at rear of vehicle).



1 lb = .454 kg
1 mi = 1.61 km

Figure 35. Vehicle lateral accelerometer trace for test 7069-23 (accelerometer located at rear of vehicle).

BR27D BRIDGE RAILING ON DECK

Test 7069-30

Test Description

A 1983 Honda Civic (figures 36 and 37) was used for the crash test. Test inertia mass of the vehicle was 1,800 lb (817 kg) and its gross static mass was 1,970 lb (894 kg). The height to the lower edge of the vehicle bumper was 14.5 in (368 mm) and it was 19.5 in (495 mm) to the top of the bumper. Additional dimensions and information on the test vehicle are given in figure 38. The vehicle was directed into the BR27D bridge railing on deck (figure 39) using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just prior to impact. The vehicle impacted the concrete parapet approximately 25.5 ft (7.8 m) from the end of the bridge railing at a speed of 51.2 mi/h (82.4 km/h) and the angle of impact was 20.5 degrees.

Shortly after impact (0.036 s) the vehicle began to redirect, and at 0.093 s the right front corner of the vehicle began to shift outward. At approximately 0.095 s after impact the dummy impacted the driver side door and shattered the door glass. The right front tire lost contact with the roadway at 0.108 s. By 0.164 s the vehicle was traveling parallel to the bridge railing at a speed of 43.6 mi/h (70.2 km/h), and at 0.178 s the rear of the vehicle impacted the parapet. The right rear tire lost contact with the roadway at 0.196 s. The vehicle lost contact with the bridge railing at 0.319 s traveling at 43.0 mi/h (69.2 km/h) and 6.8 degrees. The right front tire of the vehicle contacted the roadway again at 0.476 s and the right rear at 0.0557 s. The brakes were applied as the vehicle exited the test site. The vehicle subsequently came to rest 150 ft (46 m) down from and 70 ft (21 m) in front of the point of impact.

As can be seen in figure 40, the bridge railing received minimal damage. There was no measurable permanent deformation to the railing elements and only cosmetic damage to the concrete parapet. There were tire marks on the concrete parapet and on the face of the lower metal railing element in the area of impact. The vehicle was in contact with the bridge railing for 8.0 ft (2.4 m).

The vehicle sustained damage to the left side as shown in figure 41. Maximum crush at the left front corner at bumper height was 7.0 in (178 mm). The left front strut was damaged and the left front wheel was canted inward at the bottom and pushed back reducing the wheelbase on the driver side by 2.25 in (57 mm). Also, damage was done to the right front quarter panel, front bumper, hood, left headlight, left front quarter panel, left door and glass, left rear quarter panel, rear bumper, and left front and rear tires and rims.

Test Results

The vehicle impacted the bridge railing at 51.2 mi/h (82.4 km/h) and the angle of impact was 20.5 degrees. The speed of the vehicle at time of parallel was 43.6 mi/h (70.2 km/h). The effective coefficient of friction was calculated at 0.24. The vehicle lost contact with the bridge railing traveling at 43.0 mi/h (69.2 km/h), and the exit angle between the vehicle path and the bridge railing was 6.8 degrees. Data from the accelerometer located at the center-of-gravity were digitized for evaluation, and occupant risk factors were computed as follows. In the longitudinal direction, occupant impact velocity was 16.0 ft/s (4.9 m/s) at 0.179 s, the highest 0.010-s average ridedown acceleration was -3.6 g between 0.248 and 0.258 s, and the maximum 0.050-s average acceleration was -7.5 g between 0.032 and 0.082 s. Lateral occupant impact velocity was 21.5 ft/s (6.6 m/s) at 0.098 s, the highest 0.010-s occupant ridedown acceleration was -6.1 g between 0.175 and 0.185 s, and the maximum 0.050-s average acceleration was -12.8 g between 0.031 and 0.081 s. The change in vehicle velocity at loss of contact was 8.2 mi/h (13.2 km/h) and the change in momentum was 672 lb-s (2,990 N-s). These data and other pertinent information from the test are summarized in figure 42 and table 4. Sequential photographs are shown in figures 43 and 44. Vehicular angular displacements are displayed in figure 45. Vehicular accelerations versus time traces filtered with SAE J211 filters are presented in figures 46 through 48.

Conclusions

The BR27D bridge railing on deck contained the test vehicle with no lateral movement of the bridge railing. There was no intrusion of railing components into the occupant compartment and no debris to present undue hazard to other traffic. The integrity of the occupant compartment was maintained with no intrusion and no deformation. The vehicle remained upright and relatively stable during the collision. The bridge railing smoothly redirected the vehicle. The effective coefficient of friction was considered good.

The 1989 AASHTO guide specifications sets forth desired limits for occupant risk factors for tests with the 1,800-lb (817-kg) vehicle.(1) The AASHTO specifications recommend a limit of 30 ft/s (9.1 m/s) for longitudinal occupant impact velocity and 25 ft/s (7.6 m/s) for the lateral occupant impact velocity. The occupant impact velocities and the occupant ridedown accelerations were within the limits. The vehicle trajectory at loss of contact indicated minimum intrusion into adjacent traffic lanes. For more details see figure 42 and table 4.

Figure 36. Vehicle before test 7069-30.

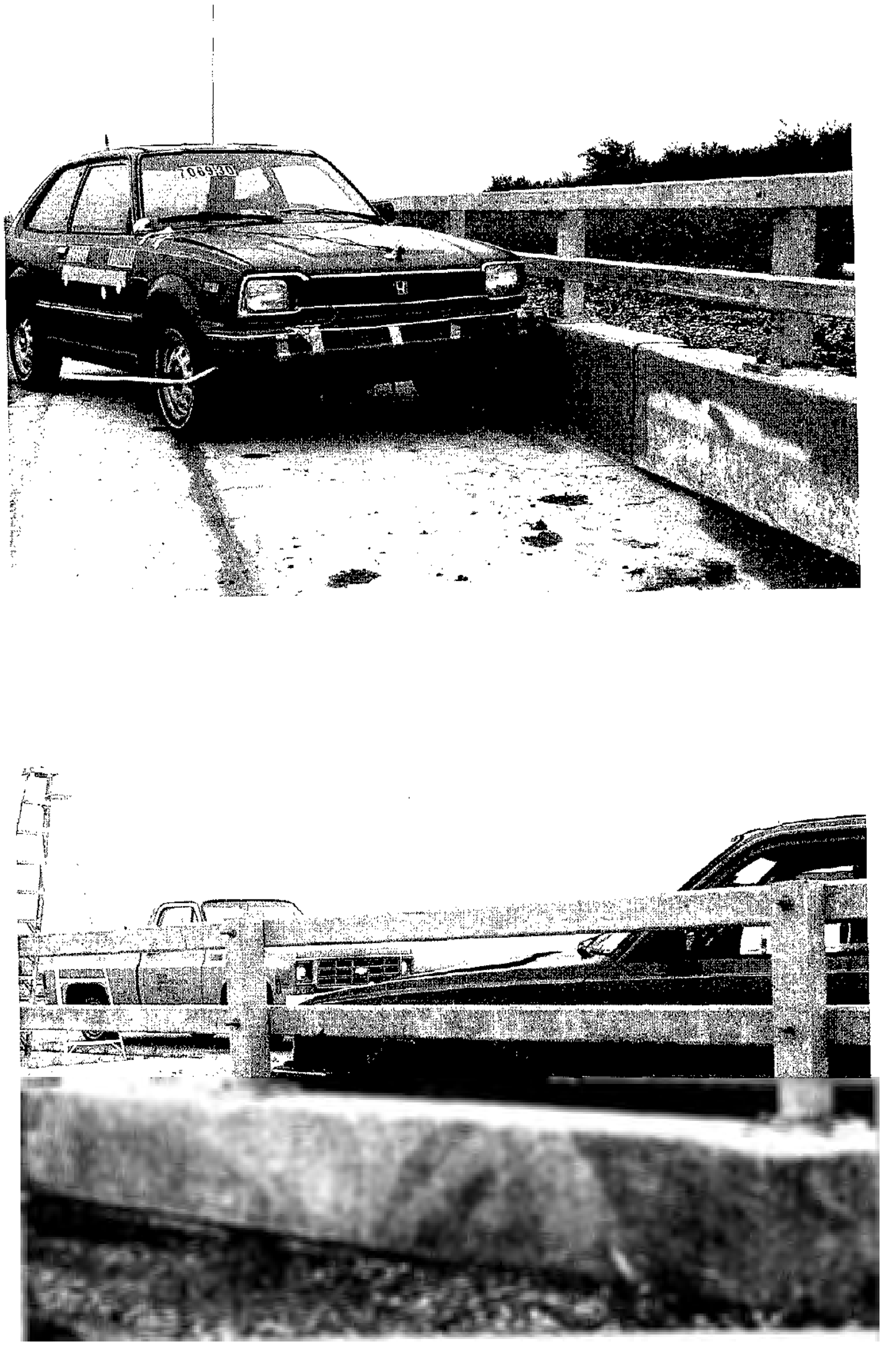
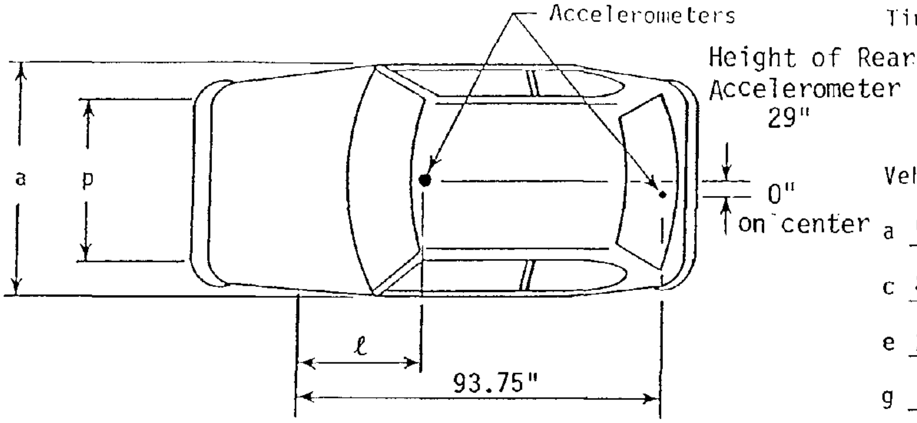


Figure 37. Vehicle/bridge railing geometrics for test 7069-30.

Date: 5-19-92 Test No.: 7069-30 VIN: JHMSR5324CS021403

Make: HONDA Model: CIVIC Year: 1983 Odometer: 086248

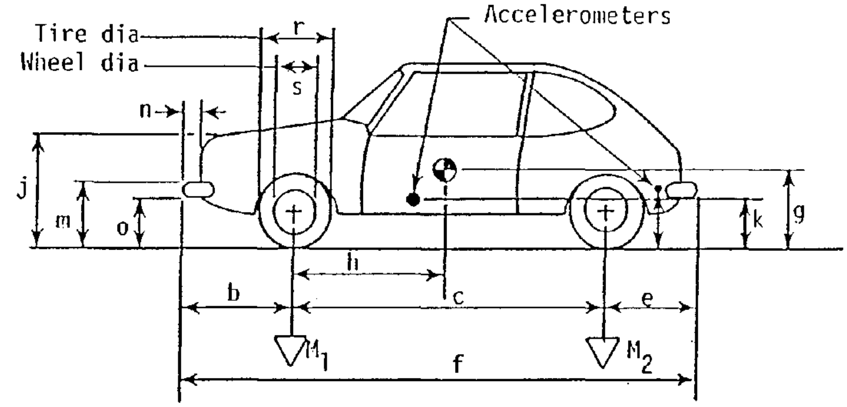
Tire Size: P155/80R13 Ply Rating: ___ Bias Ply: ___ Belted: ___ Radial: X



Tire Condition: good ___ fair X badly worn ___

Vehicle Geometry - inches

a	62.5"	b	30.5"
c	88.25"	d*	52.5"
e	28.5"	f	147.25"
g		h	33.1"
i	----	j	28.5"
k	16"	ℓ	30"
m	19.5"	n	3.75"
o	14.5"	p	53.25"
r	22.75"	s	14.5"



4-wheel weight for c.g. det. ℓf 586 rf 538 ℓr 327 rr 349

Mass - pounds	Curb	Test Inertial	Gross Static
M_1	1140	1124	1212
M_2	706	676	758
M_T	1846	1800	1970

Note any damage to vehicle prior to test:

*d = overall height of vehicle

1 in = 25.4 mm
1 lb = .454 kg

Engine Type: 4 cyl

Engine CID: 91 CID

Transmission Type:

Automatic or [✓ Manual]

[✓ FWD] or RWD or 4WD

Body Type: HATCH

Steering Column Collapse Mechanism:

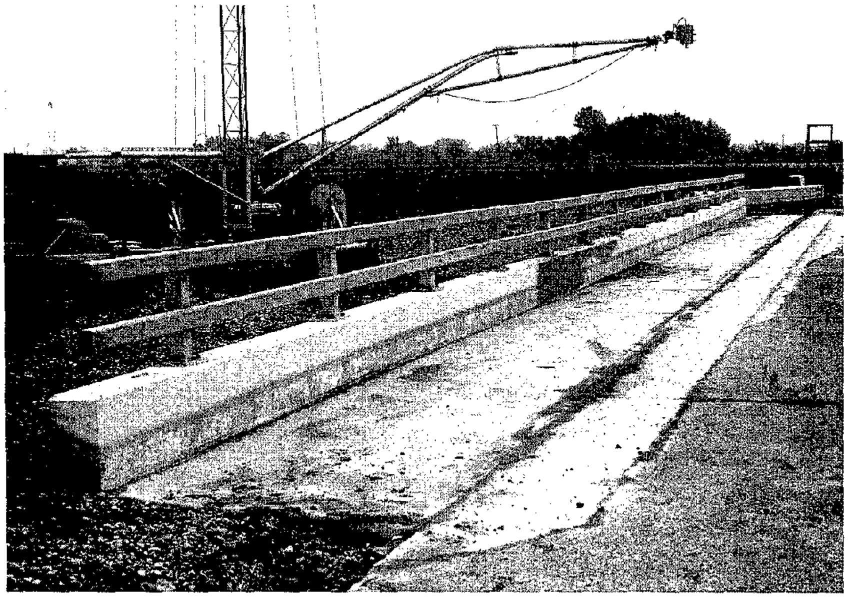
___ Behind wheel units
___ Convoluted tube
___ Cylindrical mesh units
___ Embedded ball
___ NOT collapsible
___ Other energy absorption
___ Unknown

Brakes:

Front: disc X drum ___

Rear: disc ___ drum X

Figure 38. Vehicle properties for test 7069-30.



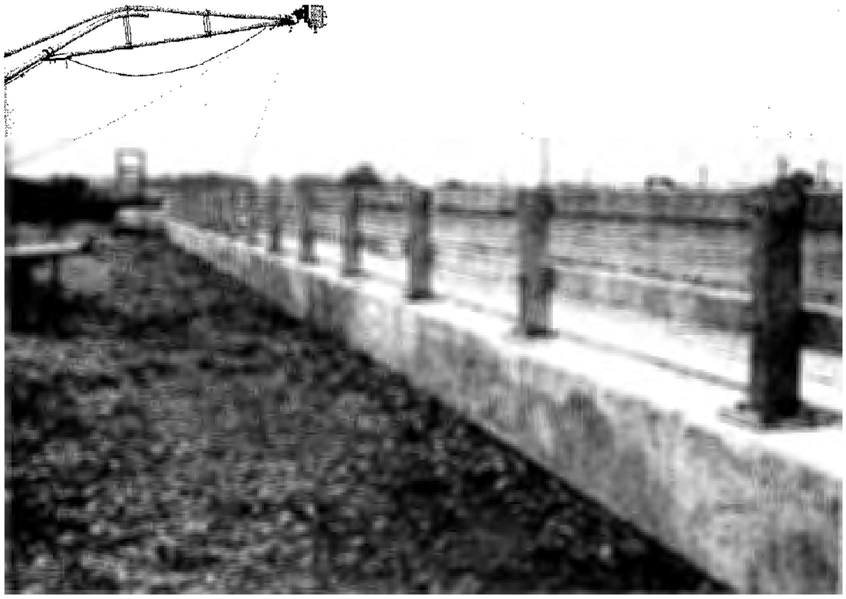


Figure 39. BR27D bridge railing on deck before test 7069-30.

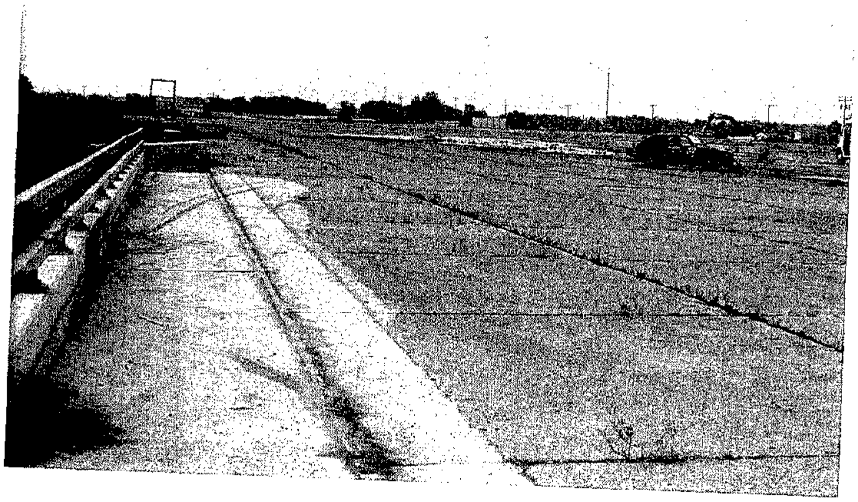
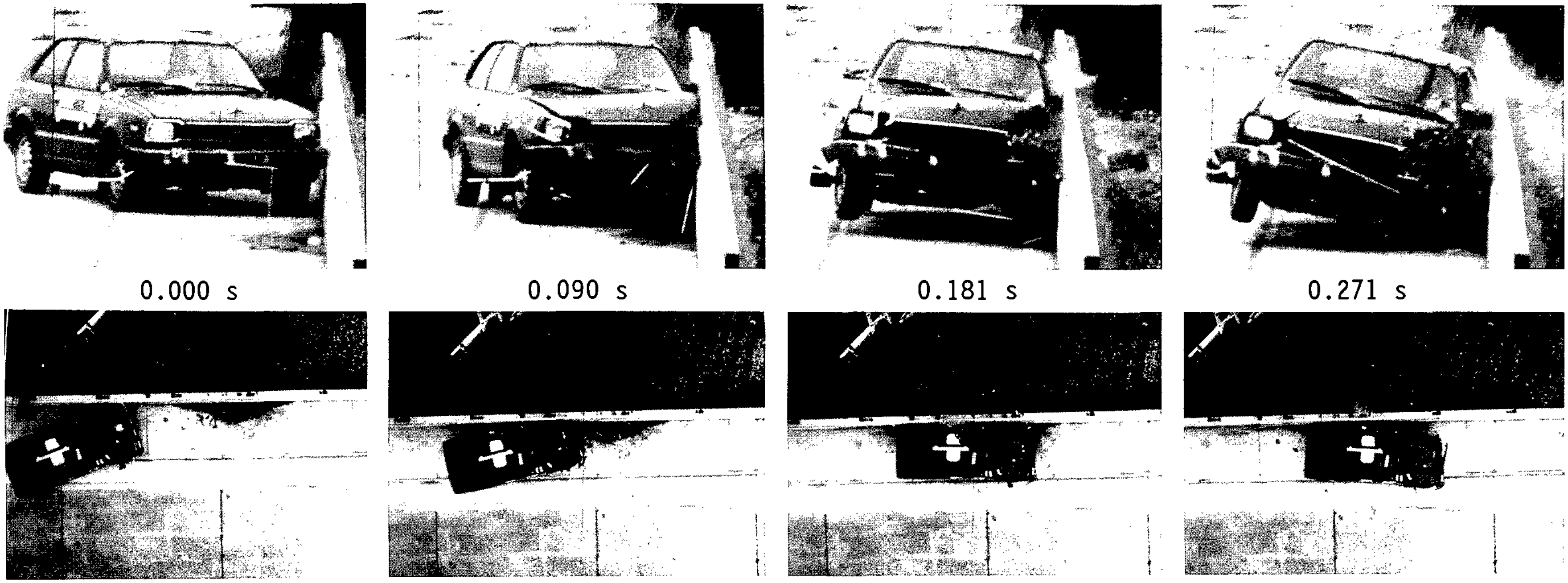
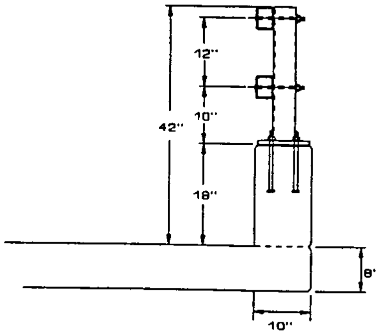


Figure 40. BR27D bridge railing on deck after test 7069-30.

Figure 41. Vehicle after test 7069-30.





(1 in = 25.4 mm)

Test No.	7069-30
Date	05/19/92
Test Installation	BR27D Bridge Railing on deck
Installation Length	100 ft (30 m)
Test Vehicle	1983 Honda Civic
Vehicle Weight	
Test Inertia	1,800 lb (817 kg)
Gross Static	1,970 lb (894 kg)
Vehicle Damage Classification	
TAD	11LFQ3
CDC	11FLEK2 & 11LFES2
Maximum Vehicle Crush	7.0 in (178 mm)

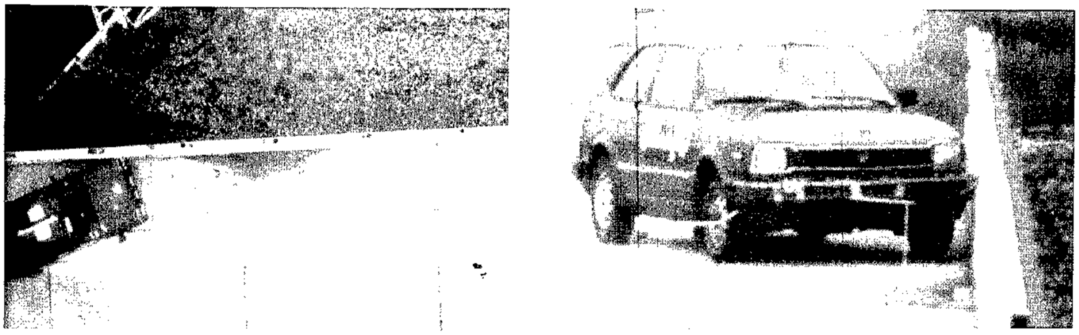
Impact Speed	51.2 mi/h (82.4 km/h)
Impact Angle	20.5 deg
Speed at Parallel	43.6 mi/h (70.2 km/h)
Exit Speed	43.0 mi/h (69.2 km/h)
Exit Trajectory	6.8 deg
Vehicle Accelerations (Max. 0.050-sec Avg) at true c.g.	
Longitudinal	-7.5 g
Lateral	-12.8 g
Occupant Impact Velocity at true c.g.	
Longitudinal	16.0 ft/s (4.9 m/s)
Lateral	21.5 ft/s (6.6 m/s)
Occupant Ridedown Accelerations	
Longitudinal	-3.6 g
Lateral	-6.1 g

Figure 42. Summary of results for test 7069-30.

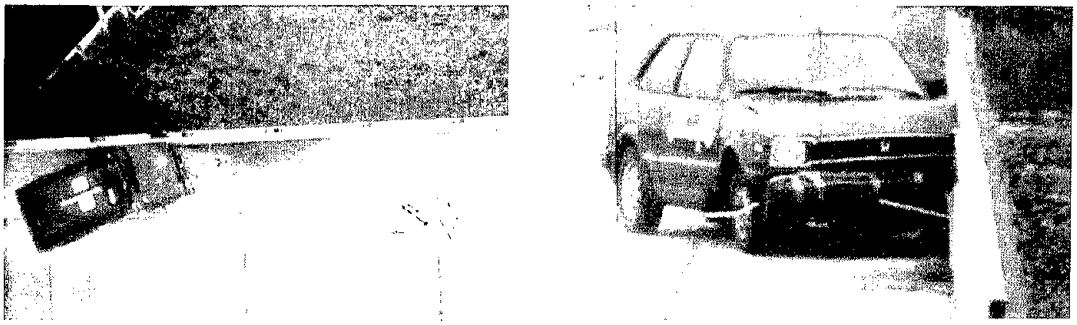
Table 4. Evaluation of crash test no. 7069-30.
{BR27D bridge railing on deck [1,800 lb (817 kg)|51.2 mi/h (82.4 km/h)|20.5 degrees]}

	CRITERIA	TEST RESULTS	PASS/FAIL*
A.	Must contain vehicle	Vehicle was contained	Pass
B.	Debris shall not penetrate passenger compartment	No debris penetrated passenger compartment	Pass
C.	Passenger compartment must have essentially no deformation	No deformation	Pass
D.	Vehicle must remain upright	Vehicle did remain upright	Pass
E.	Must smoothly redirect the vehicle	Vehicle was smoothly redirected	Pass
F.	Effective coefficient of friction		
	μ — Assessment 0 - .25 — Good .26 - .35 — Fair > .35 — Marginal	μ — Assessment .24 — Good	Pass
G.	Shall be less than		
	Occupant Impact Velocity - ft/s (m/s) Longitudinal — Lateral 30 (9.2) — 25 (7.6)	Occupant Impact Velocity - ft/s (m/s) Longitudinal — Lateral 16.0 (4.9) — 21.5 (6.6)	Pass
	Occupant Ridedown Accelerations - g's Longitudinal — Lateral 15 — 15	Occupant Ridedown Accelerations - g's Longitudinal — Lateral -3.6 — -6.1	Pass
H.	Exit angle shall be less than 12 degrees	Exit angle was 6.8 degrees	Pass

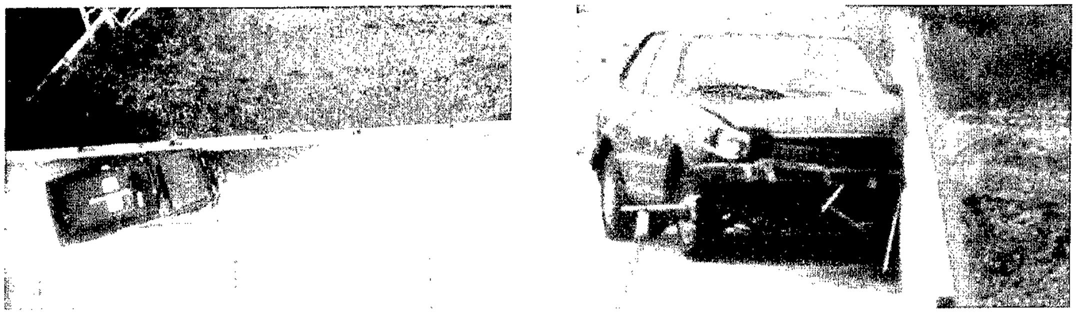
* A, B, C, D and G are required. E, F, and H are desired. (See table 2)



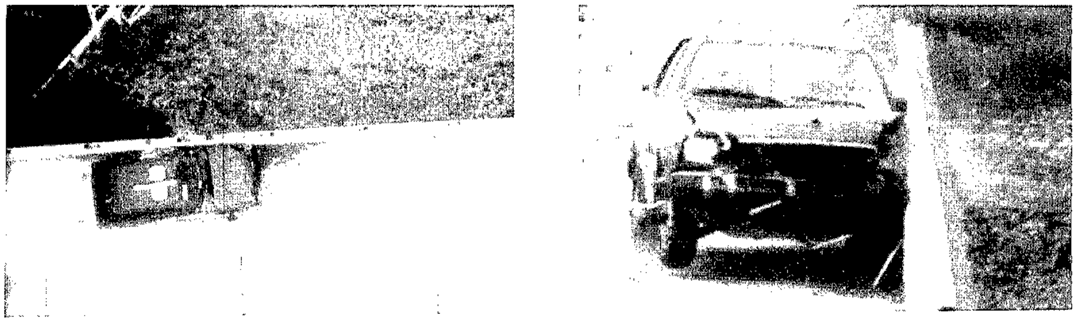
0.000 s



0.045 s

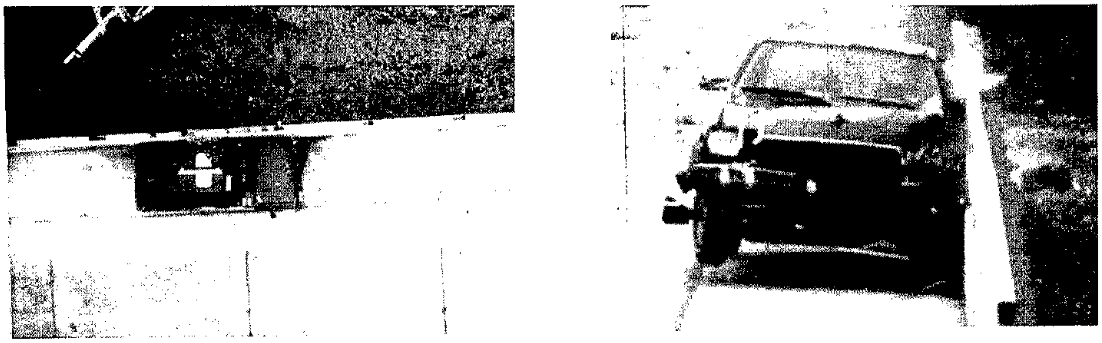


0.090 s

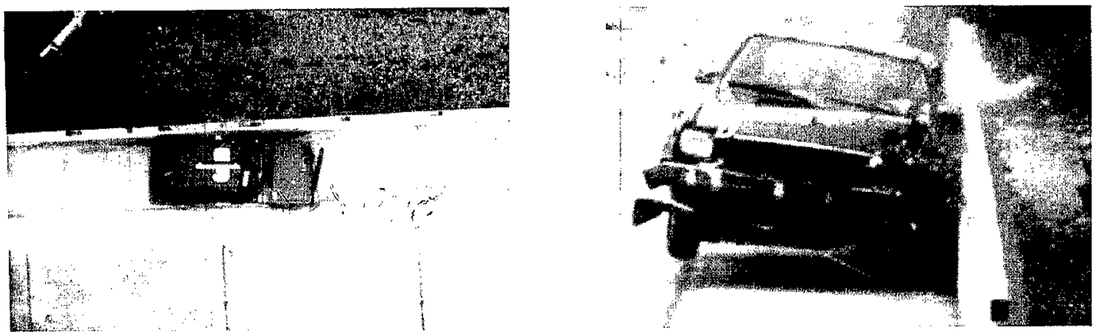


0.136 s

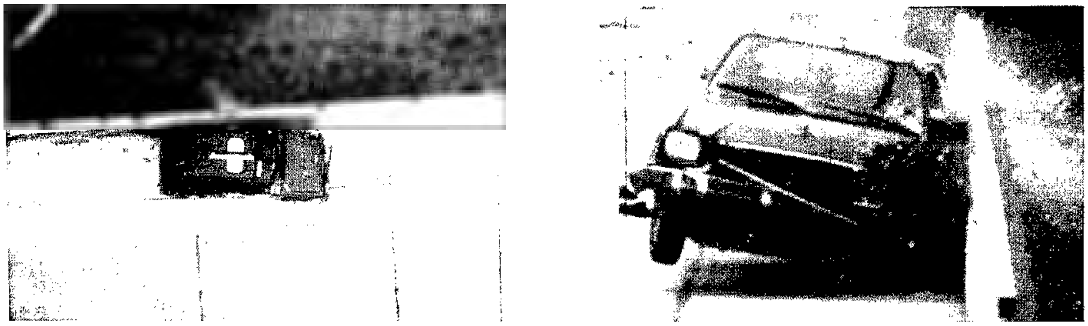
Figure 43. Sequential photographs for test 7069-30 (overhead and frontal views).



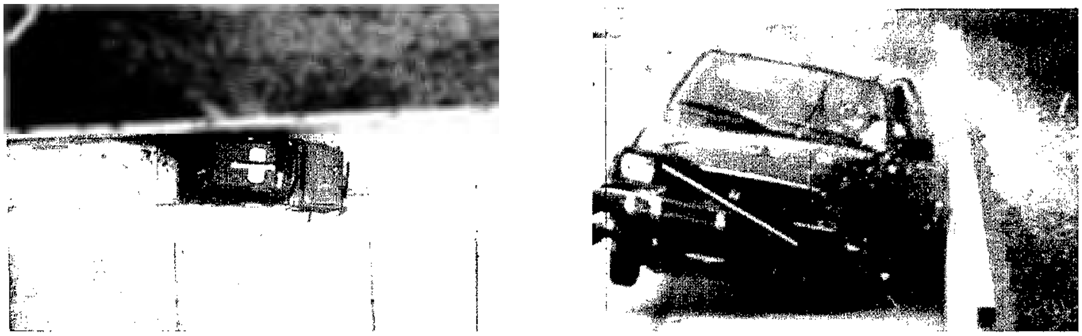
0.181 s



0.226 s



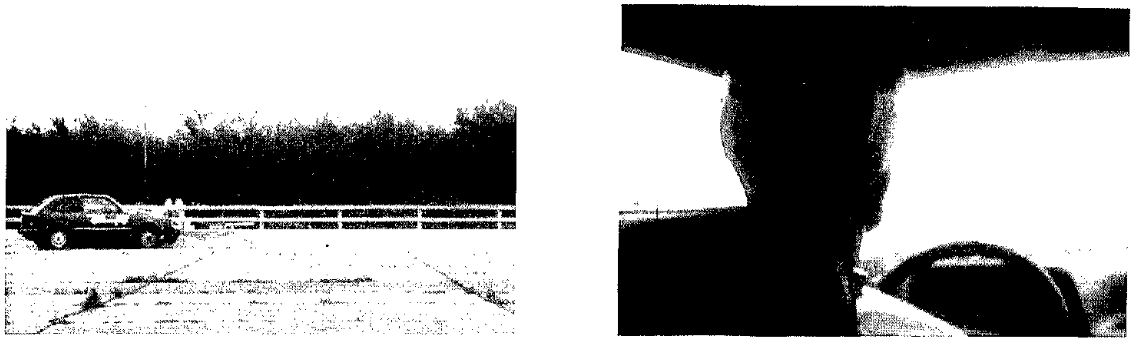
0.271 s



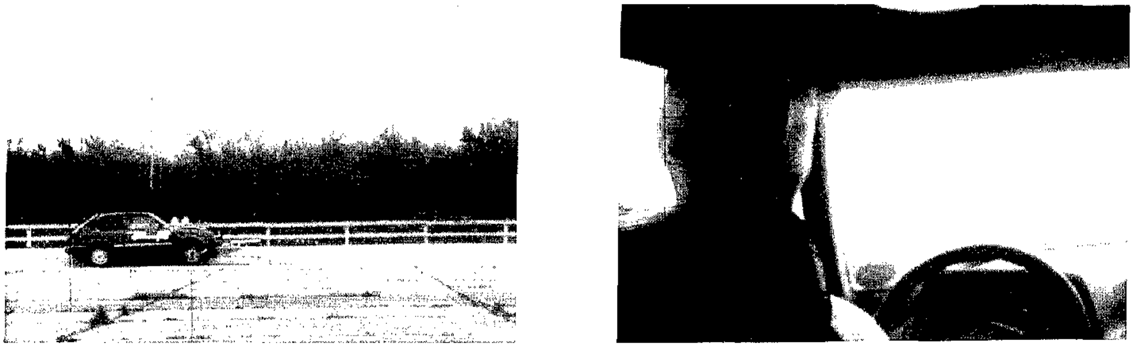
0.319 s

Figure 43. Sequential photogrpahs for test 7069-30 (overhead and frontal views continued).

0.000 s



0.045 s

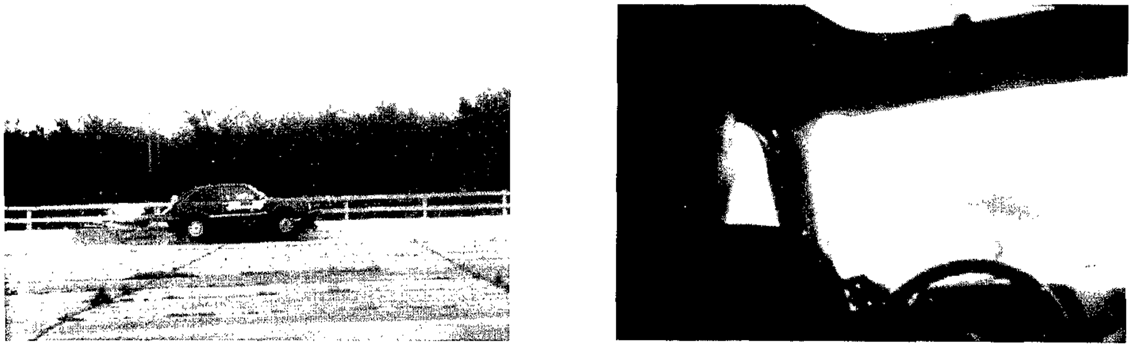


0.090 s

0.136 s

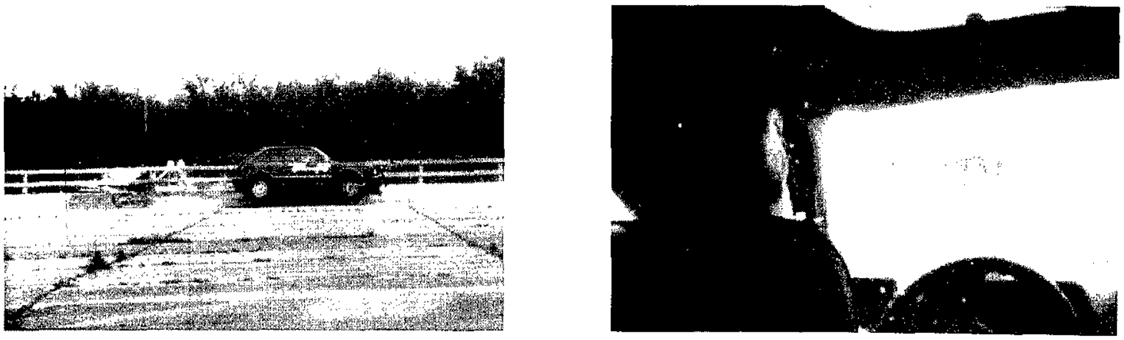
Figure 44. Sequential photographs for test 7069-30 (perpendicular and interior views).

0.181 s



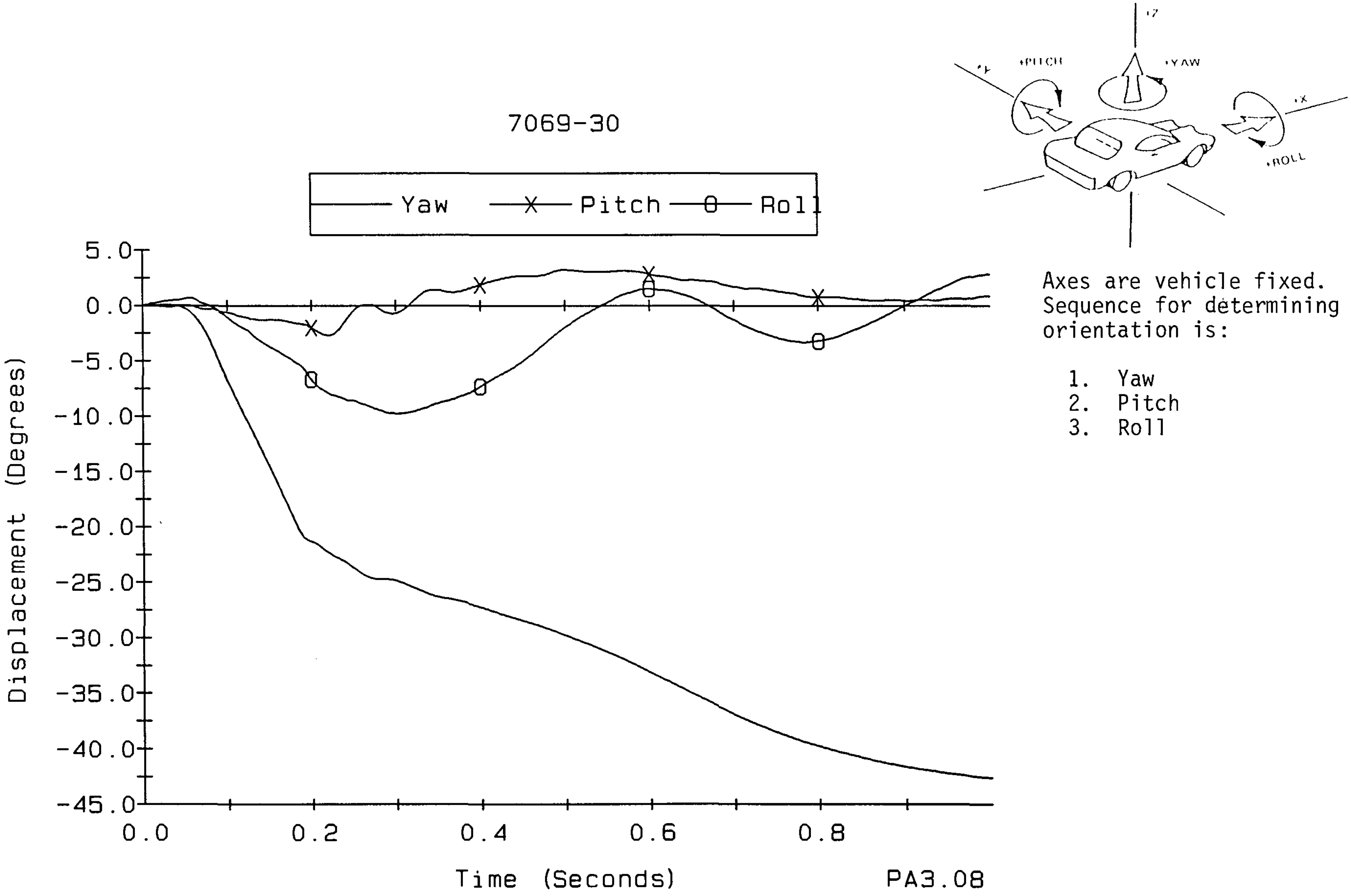
0.226 s

0.271 s



0.319 s

Figure 44. Sequential photogrpahs for test 7069-30 (perpendicular and interior views continued).



Axes are vehicle fixed.
Sequence for determining
orientation is:

1. Yaw
2. Pitch
3. Roll

Figure 45. Vehicle angular displacements for test 7069-30.

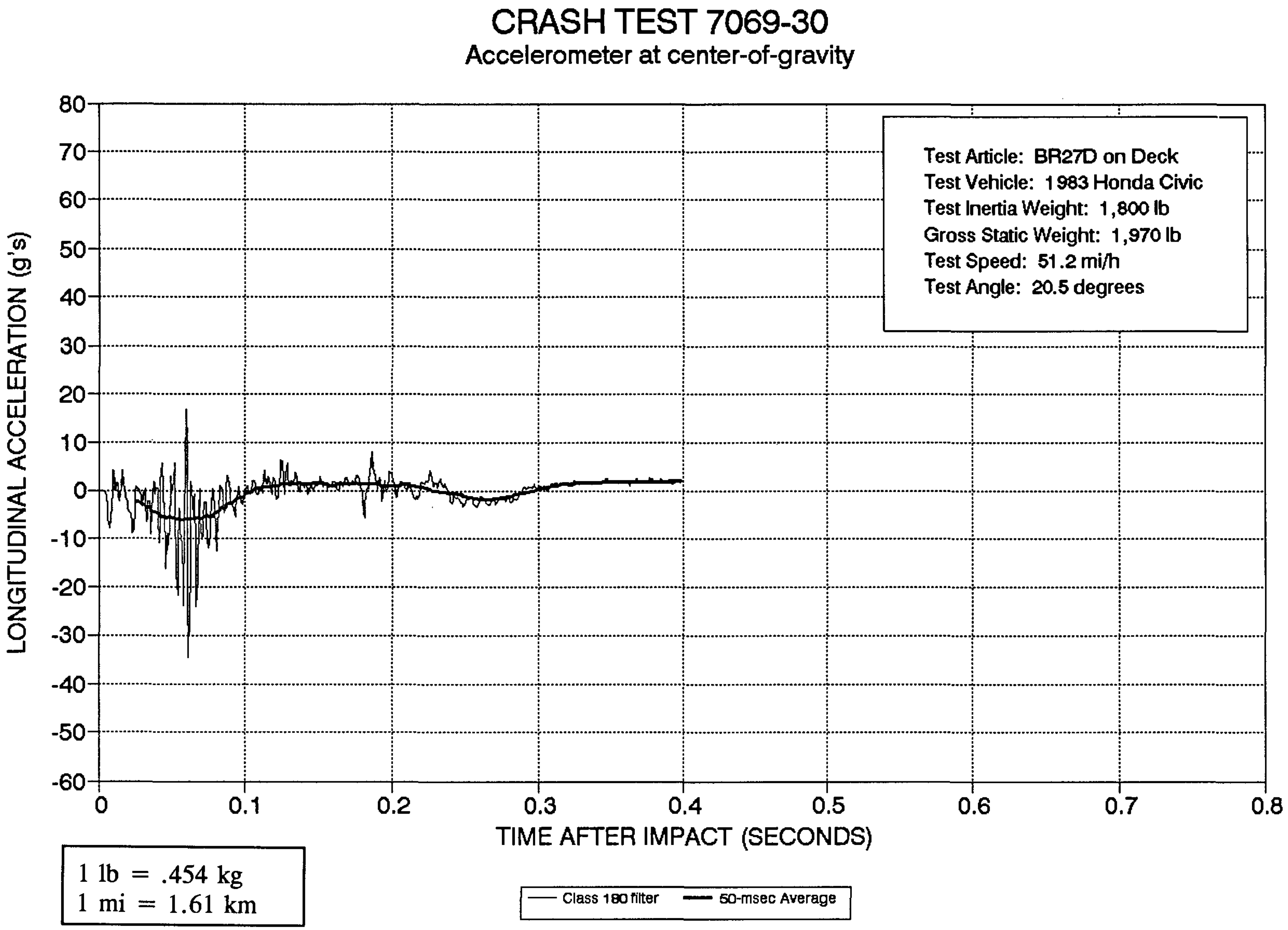
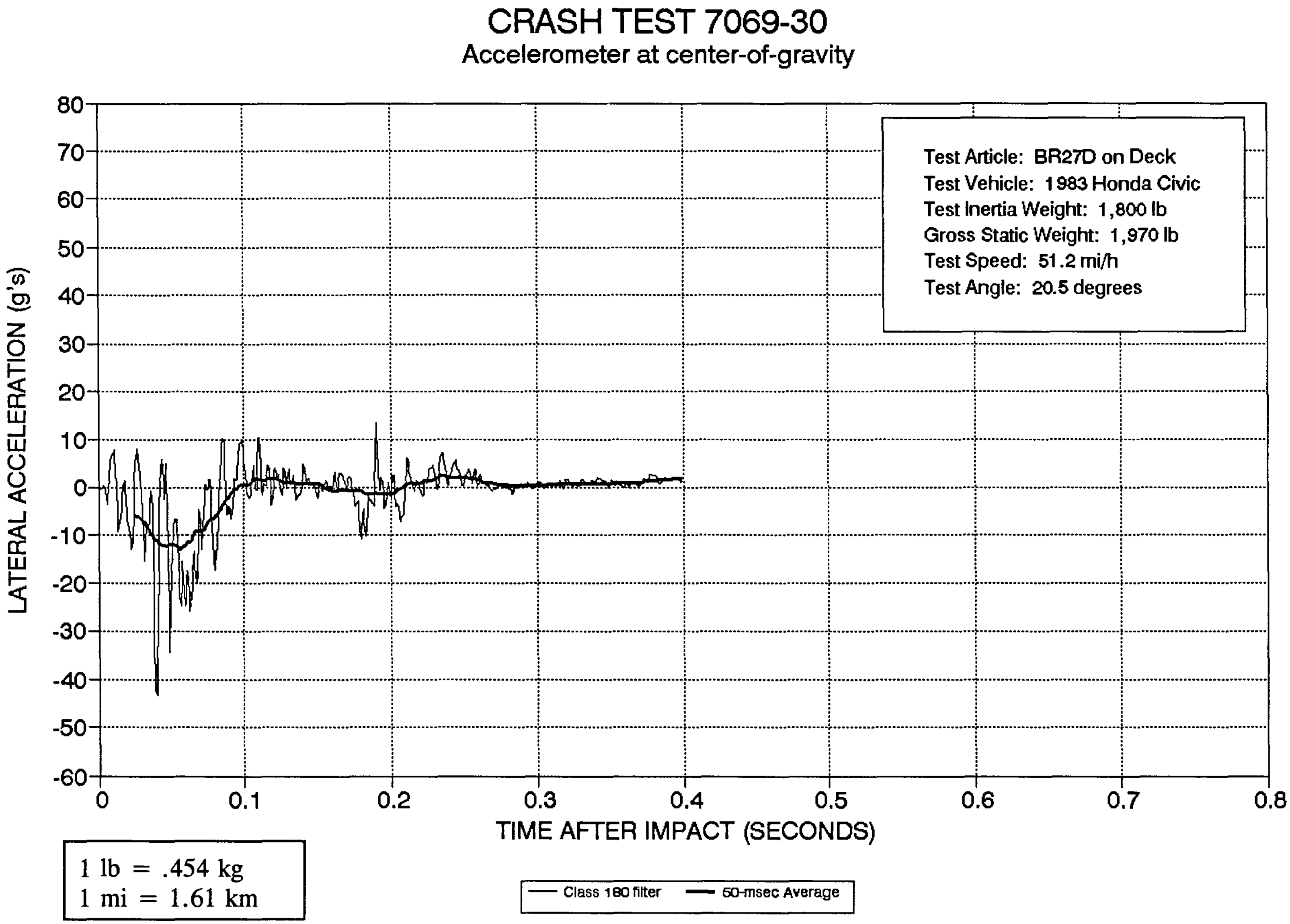
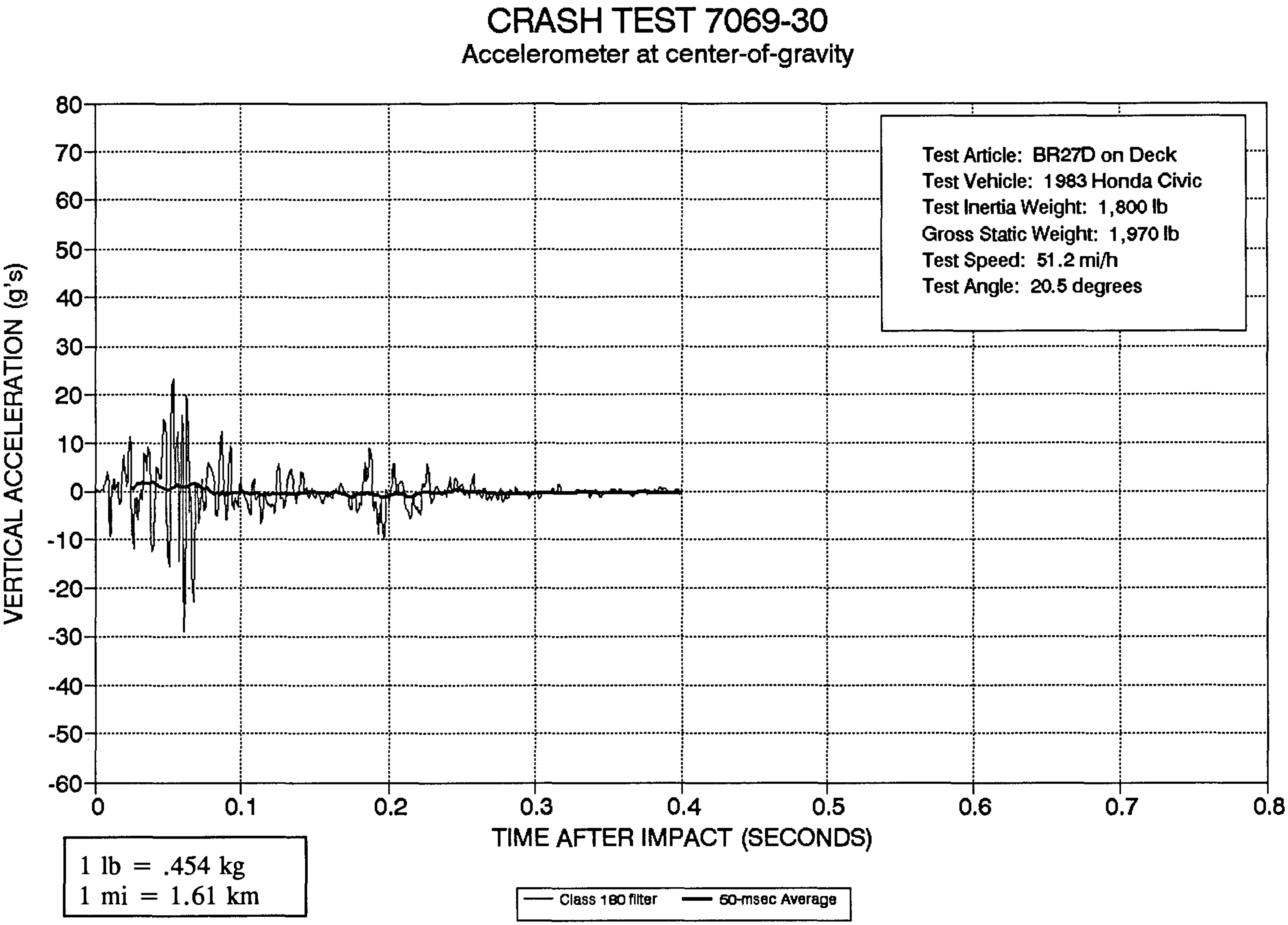


Figure 46. Vehicle longitudinal accelerometer trace for test 7069-30 (accelerometer located at center-of-gravity).



1 lb = .454 kg
1 mi = 1.61 km

Figure 47. Vehicle lateral accelerometer trace for test 7069-30 (accelerometer located at center-of-gravity).



1 lb = .454 kg
1 mi = 1.61 km

Figure 48. Vehicle vertical accelerometer trace for test 7069-30 accelerometer located at center-of-gravity).

Test 7069-31

Test Description

A 1985 Chevrolet Custom pickup (figures 49 and 50) was used for the crash test. Test inertia mass of the vehicle was 5,400 lb (2 452 kg) and its gross static mass was 5,566 lb (2 527 kg). The height to the lower edge of the vehicle bumper was 18.0 in (457 mm) and it was 27.0 in (686 mm) to the top of the bumper. Additional dimensions and information on the test vehicle are given in figure 51. The vehicle was directed into the bridge railing (figure 52) using the cable reverse tow and guidance system and was released to be free-wheeling and unrestrained just prior to impact. The vehicle impacted the concrete parapet approximately 1 ft (305 mm) downstream of post 5 at a speed of 45.6 mi/h (73.4 km/h) and the angle of impact was 18.8 degrees.

At 0.020 s the left front wheel contacted the concrete parapet, and at 0.029 s the right front corner of the vehicle began to deform outward. The vehicle began to redirect at 0.048 s after impact, and at 0.148 s the dummy impacted the driver side door and shattered the glass. By 0.231 s the vehicle was traveling parallel to the bridge railing at a speed of 40.8 mi/h (65.6 km/h), and shortly thereafter the rear of the vehicle impacted the parapet. The vehicle lost contact with the bridge railing at 0.333 s traveling at 38.0 mi/h (61.1 km/h) and 6.2 degrees. The brakes were applied 2.3 s after impact. The vehicle yawed counterclockwise due to the deflated left front tire and subsequently came to rest 225 ft (69 m) down from and 40 ft (12 m) behind the point of impact.

As can be seen in figure 53, the bridge railing received minimal damage. The maximum permanent deformation to the railing element was 0.5 in (13 mm) between posts 5 and 6. There was only cosmetic damage to the concrete parapet. There were tire marks on the concrete parapet, on the face of the lower metal railing element in the area of impact, and also on the lower part of post 6. The vehicle was in contact with the bridge railing for 11.7 ft (3.6 m).

The vehicle sustained damage to the left side as shown in figure 54. Maximum crush at the left front corner at bumper height was 6.5 in (165 mm) and the right side was deformed outward 4.0 in (102 mm). Also, damage was done to the front bumper, hood, grill, left front quarter panel, left door, left rear quarter panel, left front and rear tires and rims, rear bumper, and right front quarter panel and right door.

Test Results

The vehicle impacted the bridge railing at 45.6 mi/h (73.4 km/h) and the angle of impact was 18.8 degrees. The speed of the vehicle at time of parallel was 40.8 mi/h (65.6 km/h). The effective coefficient of friction was calculated at 0.16 for this test. The vehicle lost contact with the bridge railing traveling at 38.0 mi/h (61.1 km/h), and the exit angle between the vehicle path and the bridge railing was 6.2 degrees. Data from the accelerometer located at the center-of-gravity were digitized for evaluation and occupant risk factors were computed as follows. In the longitudinal direction, occupant impact velocity was 11.7 ft/s

(3.6 m/s) at 0.277 s, the highest 0.010-s average ridedown acceleration was 2.2 g between 0.282 and 0.292 s, and the maximum 0.050-s average acceleration was -4.1 g between 0.058 and 0.108 s. Lateral occupant impact velocity was 12.3 ft/s (3.7 m/s) at 0.158 s, the highest 0.010-s occupant ridedown acceleration was -8.2 g between 0.209 and 0.219 s, and the maximum 0.050-s average acceleration was -7.5 g between 0.054 and 0.104 s. The change in vehicle velocity at loss of contact was 7.6 mi/h (12.2 km/h) and the change in momentum was 1,869 lb-s (8,315 N-s). These data and other pertinent information from the test are summarized in figure 55 and table 5. Sequential photographs are shown in figures 56 and 57. Vehicular angular displacements are displayed in figure 58. Vehicular accelerations versus time traces filtered with SAE J211 filters are presented in figures 59 through 65.

Conclusions

The BR27D bridge railing on deck contained the test vehicle with minimal lateral movement of the metal railing element of the bridge railing system. There was no intrusion of railing components into the occupant compartment and no debris to present undue hazard to other traffic. The integrity of the occupant compartment was maintained with no intrusion and no deformation. The vehicle remained upright and relatively stable during the collision. The bridge railing smoothly redirected the vehicle. The effective coefficient of friction was considered good.

The 1989 AASHTO guide specifications sets forth desired (but not required) limits for occupant risk factors for tests with the 5,400-lb (2 452-kg) vehicle.(1) The AASHTO specifications recommend a limit of 30 ft/s (9.1 m/s) for longitudinal occupant impact velocity and 25 ft/s (7.6 m/s) for the lateral occupant impact velocity. The occupant impact velocities and the occupant ridedown accelerations were within the limits. The vehicle trajectory at loss of contact indicated minimum intrusion into adjacent traffic lanes. See figure 55 and table 5 for more details.

Figure 49. Vehicle before test 7069-31.

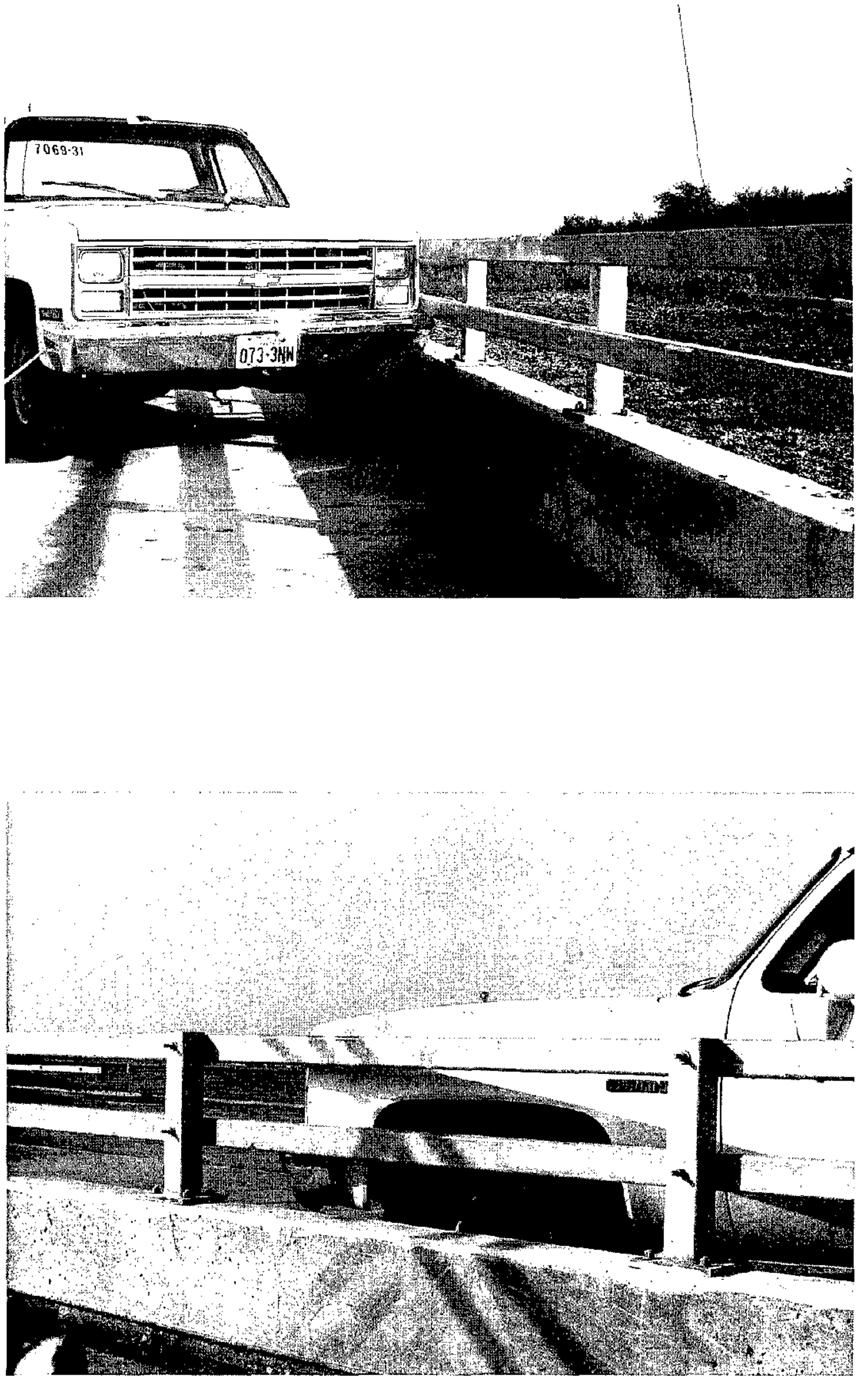


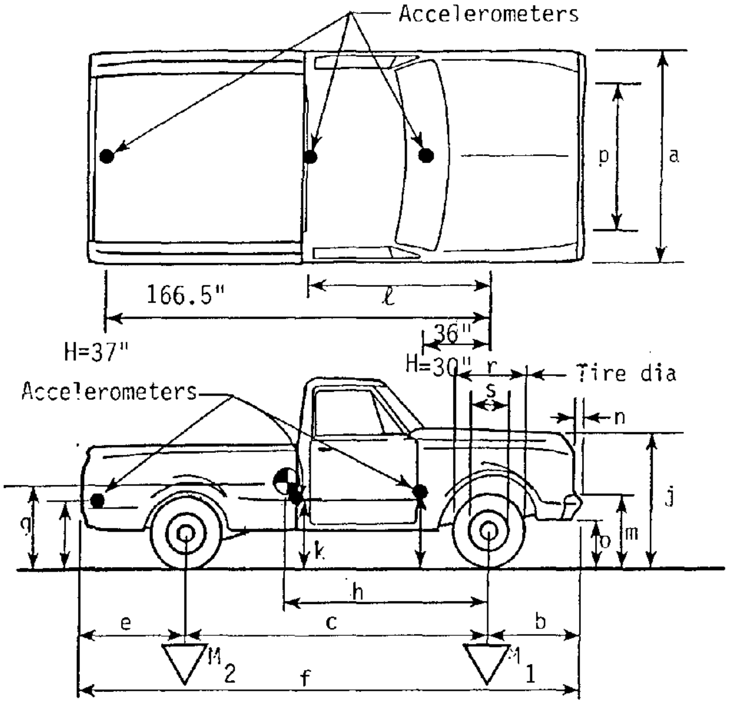
Figure 50. Vehicle/bridge railing geometrics for test 7069-31.

Date: 5-21-92 Test No.: 7069-31 VIN: 1GCGC24M8FS110063

Make: Chevy Model: Custom 20 Year: 1985 Odometer: 25421

Tire Size: 7.5016LT Ply Rating: ______ Bias Ply: x Belted: ___ Radial: ___

Tire Condition: good ___
fair x
badly worn ___



Vehicle Geometry - inches

a	79"	b	32"
c	131.5"	d*	71.25"
e	51"	f	
g		h	70.2"
i	----	j	44.5"
k	30.75"	ℓ	73"
m	27"	n	3.75"
o	18"	p	66.5"
r	31.75"	s	17.5"

Engine Type: 8 cyl

Engine CID: 5.7 Liter

Transmission Type:
Automatic or [✓ Manual]
FWD or [✓ RWD] or 4WD

Body Type: Pick-Up

Steering Column Collapse Mechanism:
- ___Behind wheel units
- ___Convoluted tube
- ___Cylindrical mesh units
- ___Embedded ball
- ___NOT collapsible
- ___Other energy absorption
- ___Unknown

Brakes:
Front: disc x drum ___
Rear: disc ___ drum x

4-wheel weight for c.g. det. ℓf 1285 rf 1231 ℓr 1427 rr 1457

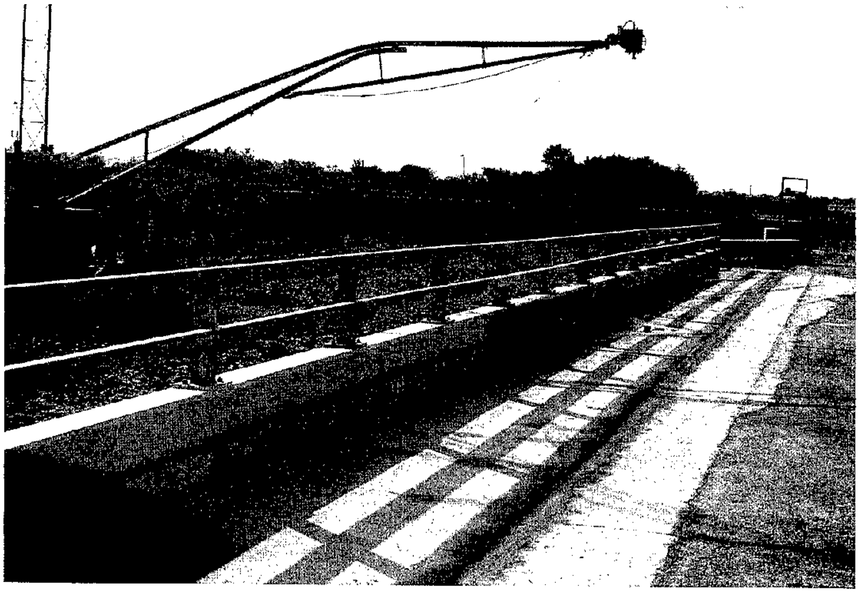
Mass - pounds	Curb	Test Inertial	Gross Static
M_1	2567	2516	2611
M_2	1926	2884	2955
M_T	4493	5400	5566

Note any damage to vehicle prior to test:

*d = overall height of vehicle

1 in = 25.4 mm
1 lb = .454 kg

Figure 51. Vehicle properties for test 7069-31.



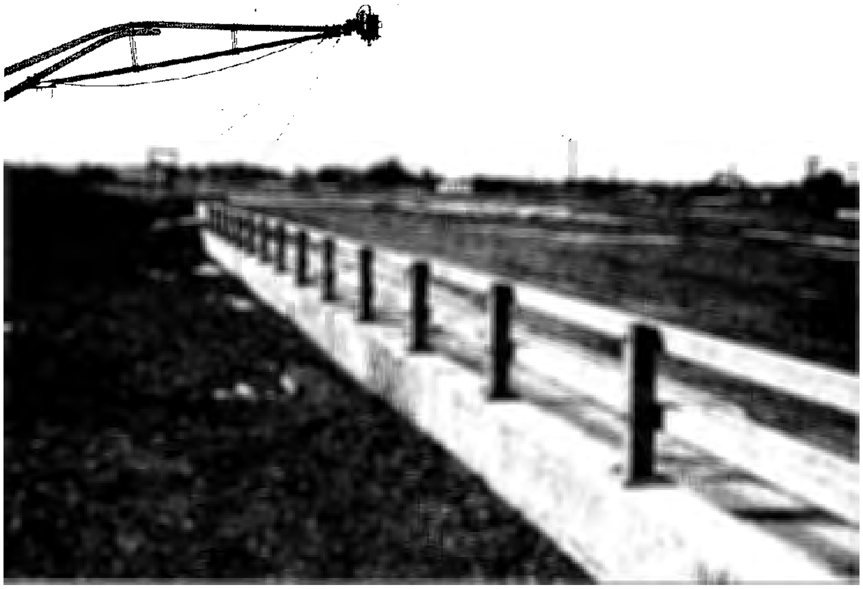


Figure 52. BR27D bridge railing on deck before test 7069-31.

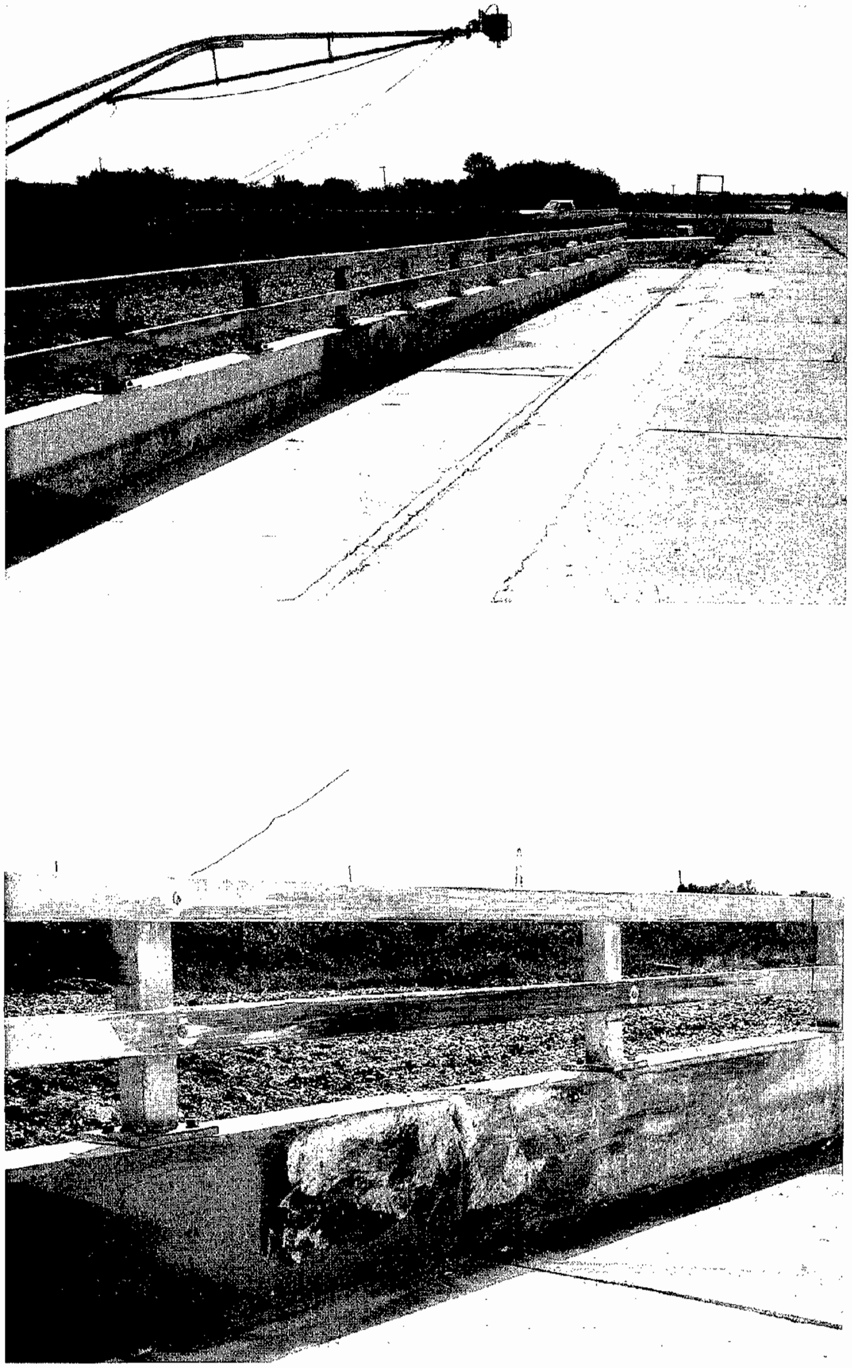


Figure 53. BR27D bridge railing on deck after test 7069-31.

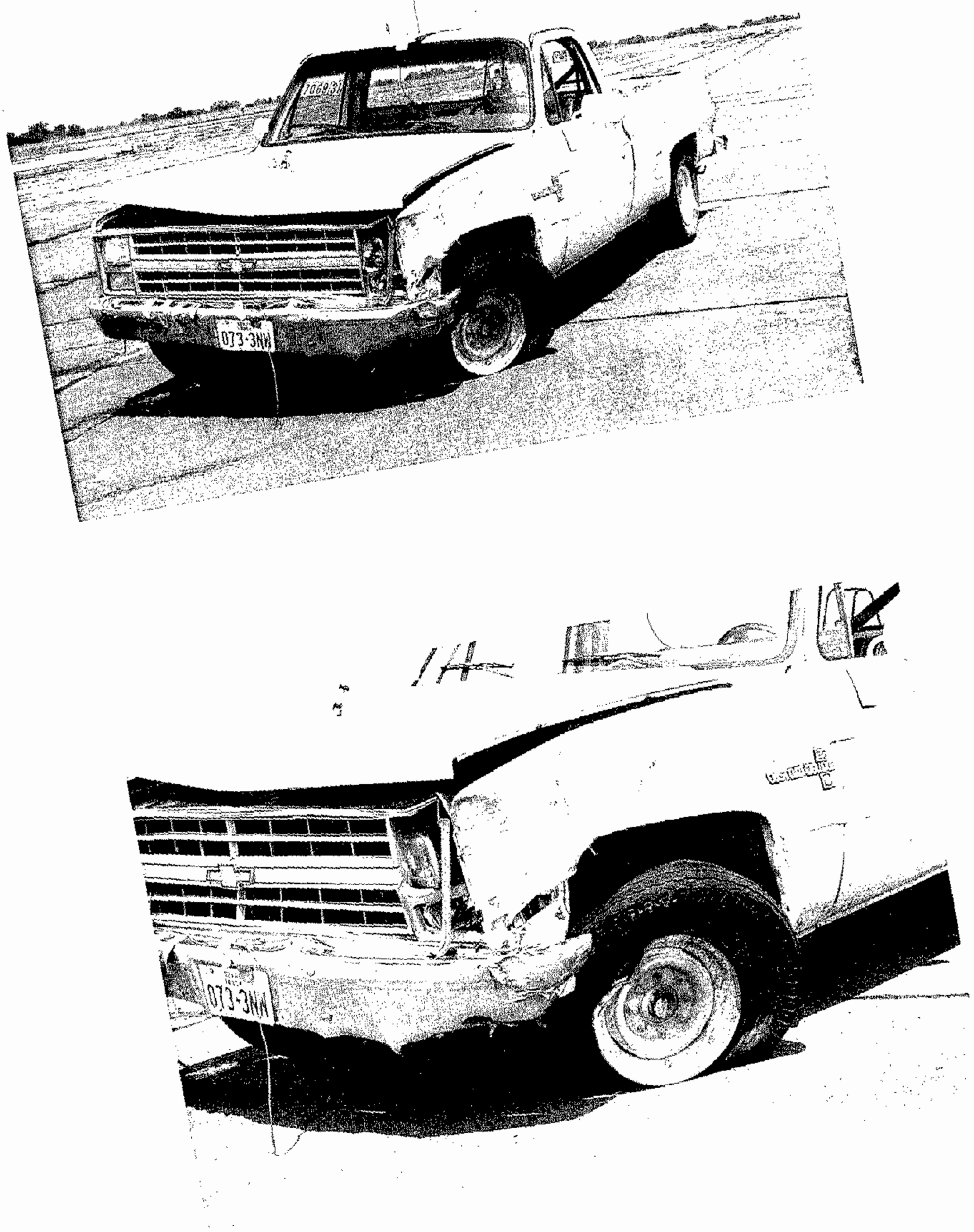
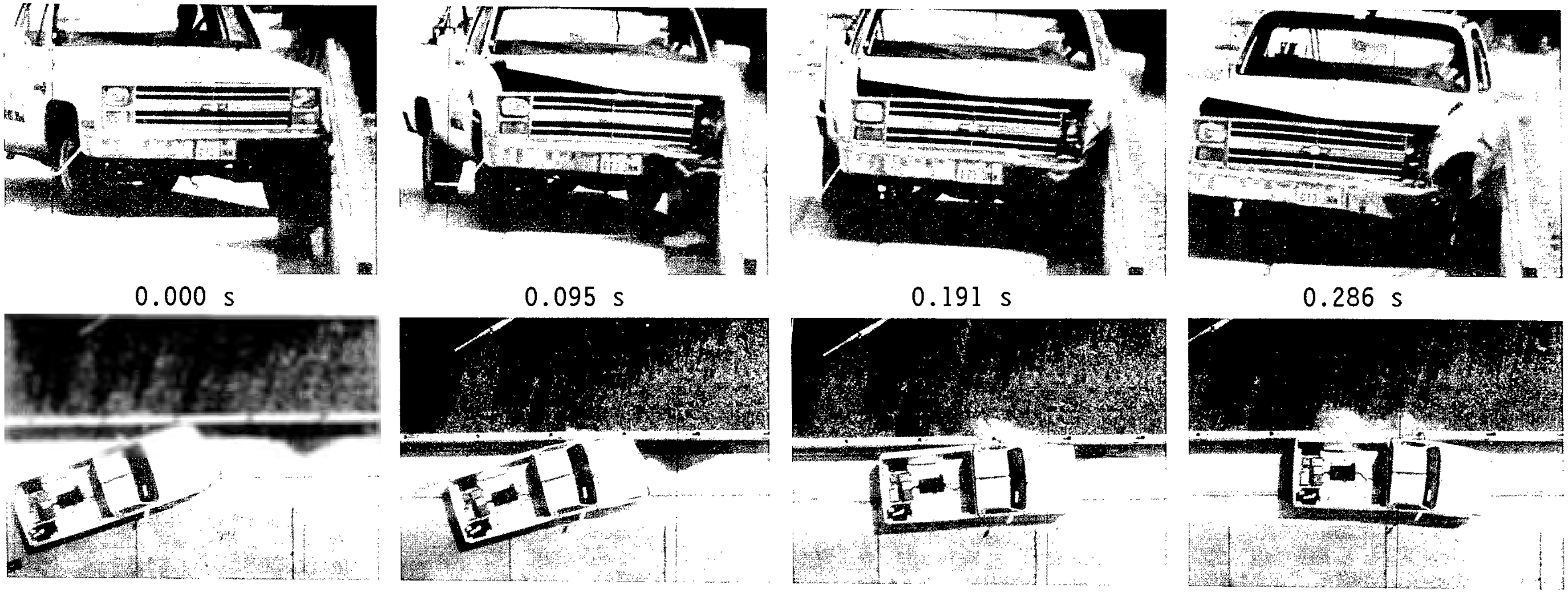
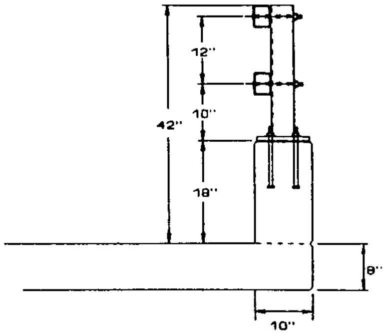


Figure 54. Vehicle after test 7069-31.





(1 in = 25.4 mm)

Test No.	7069-31
Date	05/21/92
Test Installation . . .	BR27D Bridge Railing on deck
Installation Length . .	100 ft (30 m)
Test Vehicle	1985 Chevrolet Custom Pickup
Vehicle Weight	
Test Inertia	5,400 lb (2,452 kg)
Gross Static	5,566 lb (2,527 kg)
Vehicle Damage Classification	
TAD	11LFQ3 & 11LD2
CDC	11FLEK2 & 11LDEW2
Maximum Vehicle Crush .	6.5 in (165 mm)

Impact Speed. . . .	45.6 mi/h (73.4 km/h)
Impact Angle. . . .	18.8 deg
Speed at Parallel .	40.8 mi/h (65.6 km/h)
Exit Speed	38.0 mi/h (61.1 km/h)
Exit Trajectory . .	6.2 deg
Vehicle Accelerations (Max. 0.050-sec Avg) at true c.g.	
Longitudinal. . .	-4.1 g
Lateral	-7.5 g
Occupant Impact Velocity at true c.g.	
Longitudinal. . .	11.7 ft/s (3.6 m/s)
Lateral	12.3 ft/s (3.7 m/s)
Occupant Ridedown Accelerations	
Longitudinal. . .	2.2 g
Lateral	-8.2 g

Figure 55. Summary of results for test 7069-31.

Table 5. Evaluation of crash test no. 7069-31.
{BR27D bridge railing on deck [5,400 lb (2 452 kg)|45.6 mi/h (73.4 km/h)|18.8 degrees]}

	CRITERIA	TEST RESULTS	PASS/FAIL*
A.	Must contain vehicle	Vehicle was contained	Pass
B.	Debris shall not penetrate passenger compartment	No debris penetrated passenger compartment	Pass
C.	Passenger compartment must have essentially no deformation	No deformation	Pass
D.	Vehicle must remain upright	Vehicle did remain upright	Pass
E.	Must smoothly redirect the vehicle	Vehicle was smoothly redirected	Pass
F.	Effective coefficient of friction		
	μ — Assessment 0 - .25 — Good .26 - .35 — Fair > .35 — Marginal	μ — Assessment .16 — Good	Pass
G.	Shall be less than		
	Occupant Impact Velocity - ft/s (m/s) Longitudinal — Lateral 30 (9.2) — 25 (7.6)	Occupant Impact Velocity - ft/s (m/s) Longitudinal — Lateral 11.7 (3.6) — 12.3 (3.7)	Pass
	Occupant Ridedown Accelerations - g's Longitudinal — Lateral 15 — 15	Occupant Ridedown Accelerations - g's Longitudinal — Lateral 2.2 — -8.2	Pass
H.	Exit angle shall be less than 12 degrees	Exit angle was 6.2 degrees	Pass

* A, B, C, and D are required. E, F, G, and H are desired. (See table 2)

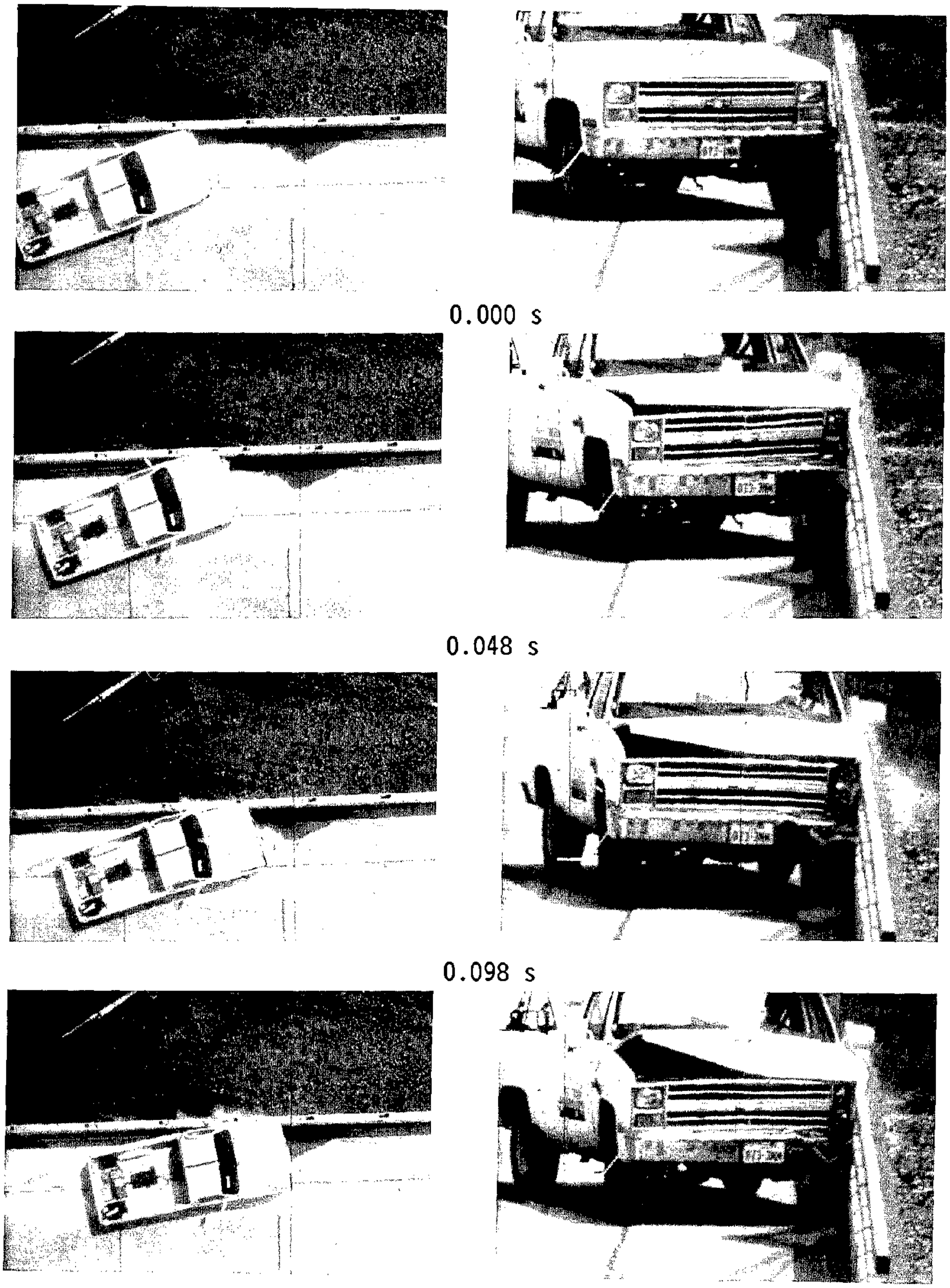
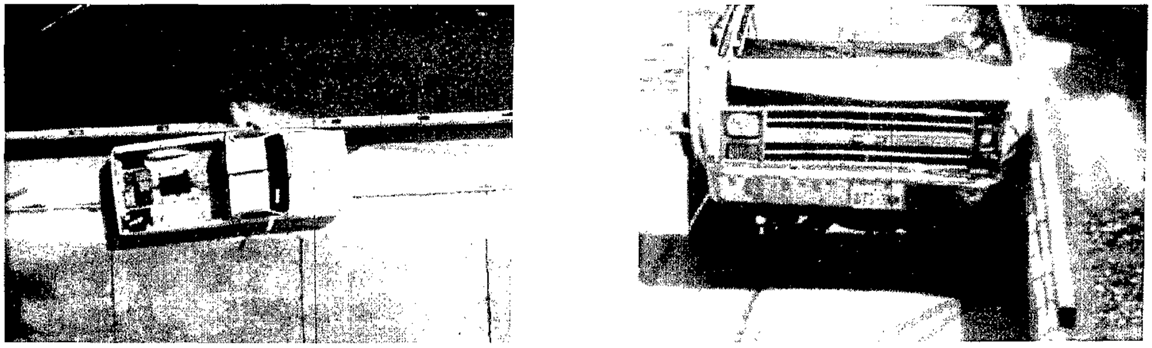
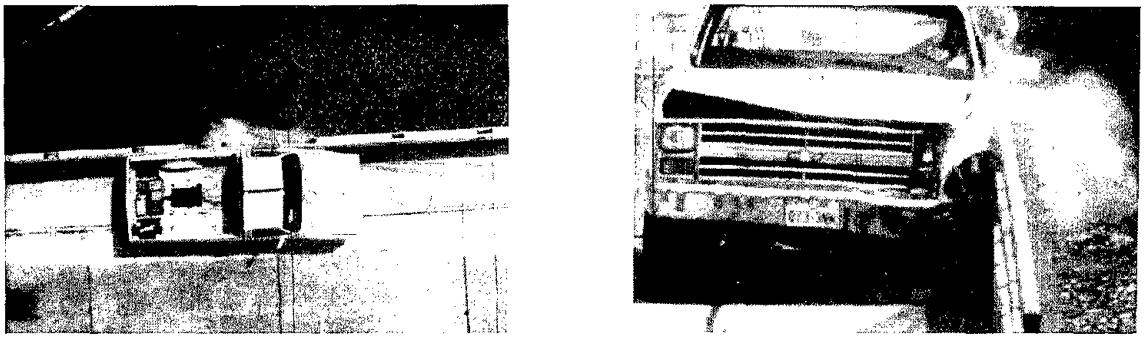


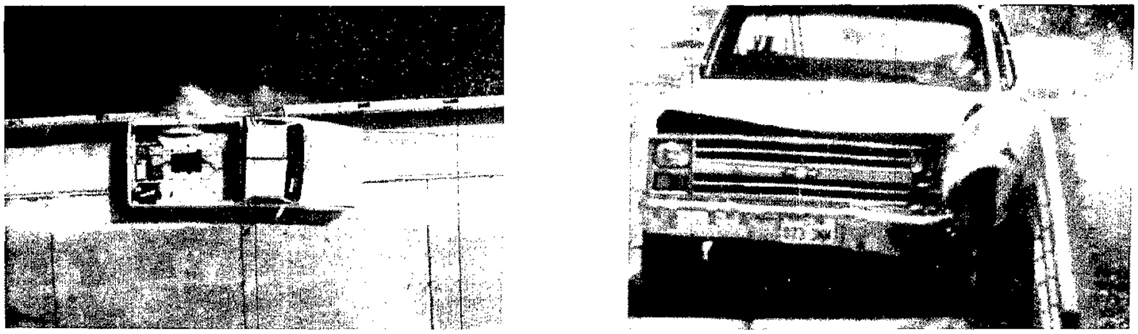
Figure 56. Sequential photographs for test 7069-31 (overhead and frontal views).



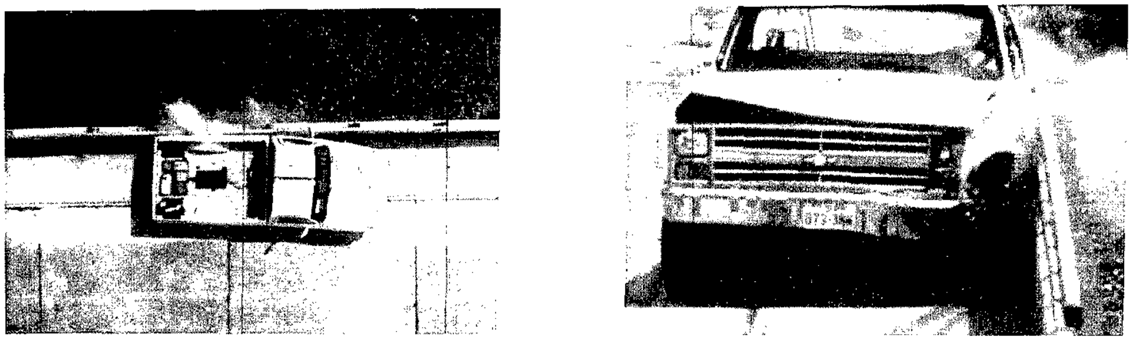
0.191 s



0.238 s



0.286 s



0.333 s

Figure 56. Sequcntial photogrpahs for test 7069-31 (overhead and frontal views continued).

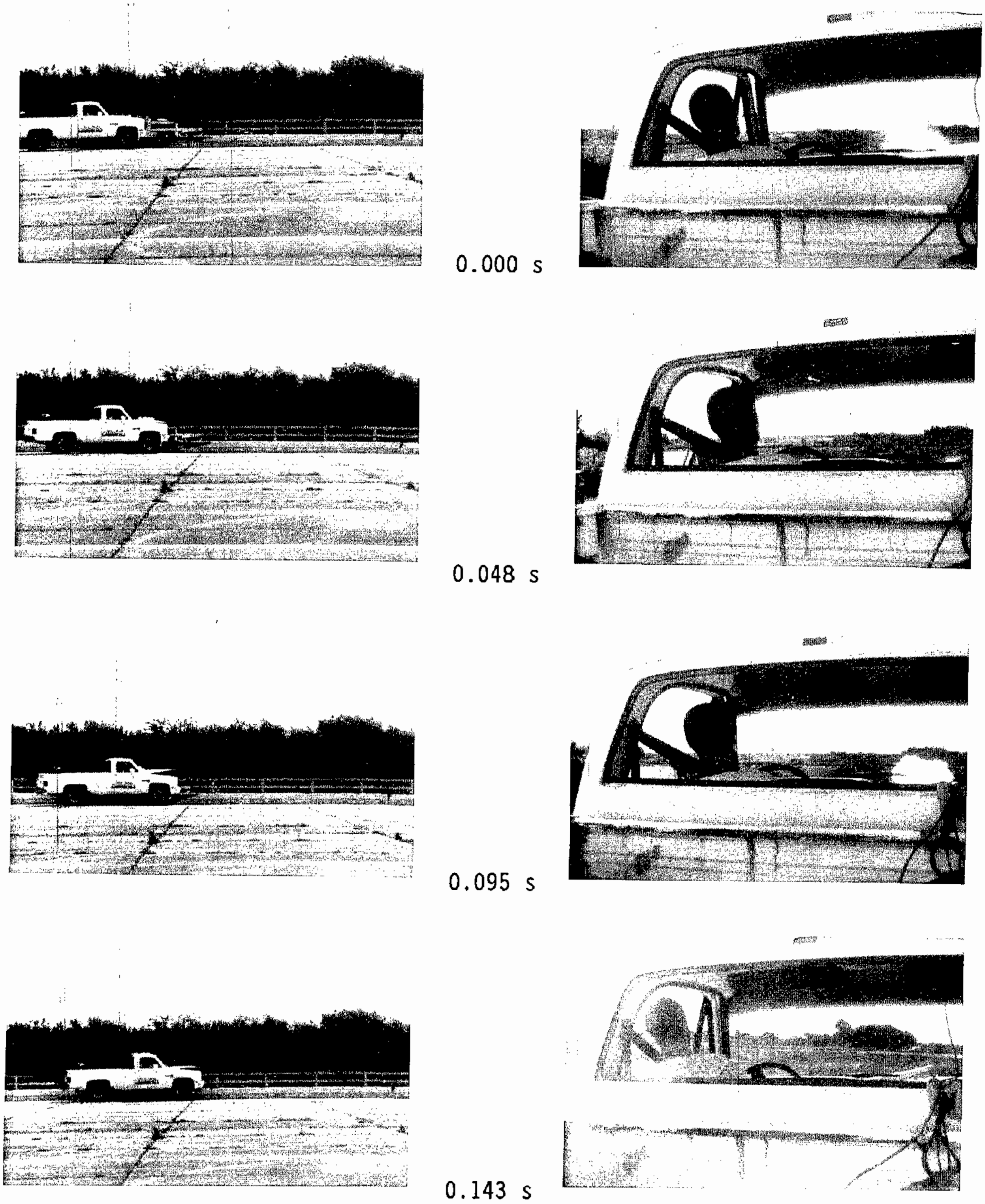
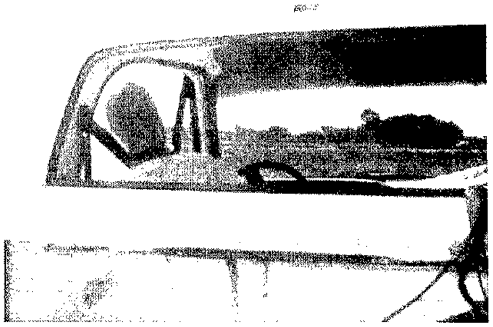
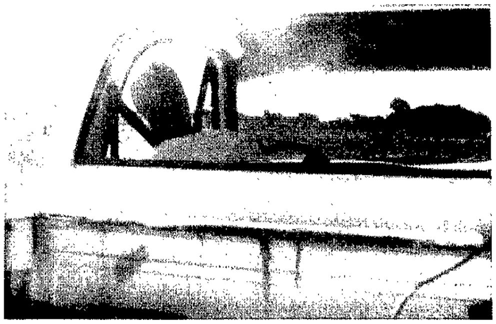


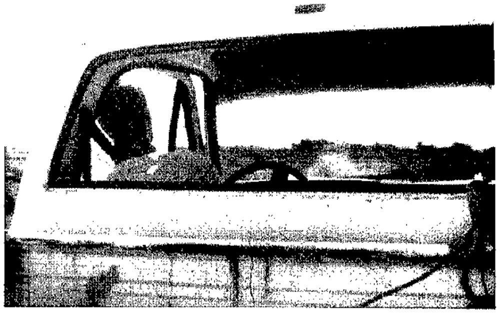
Figure 57. Sequential photographs for test 7069-31 (perpendicular and interior views).



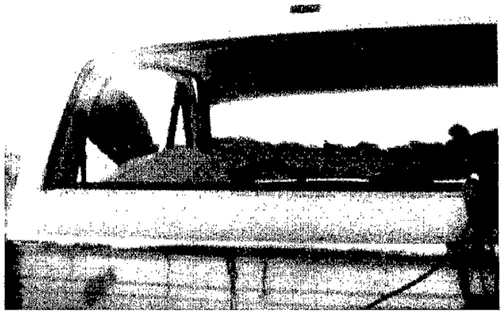
0.191 s



0.238 s

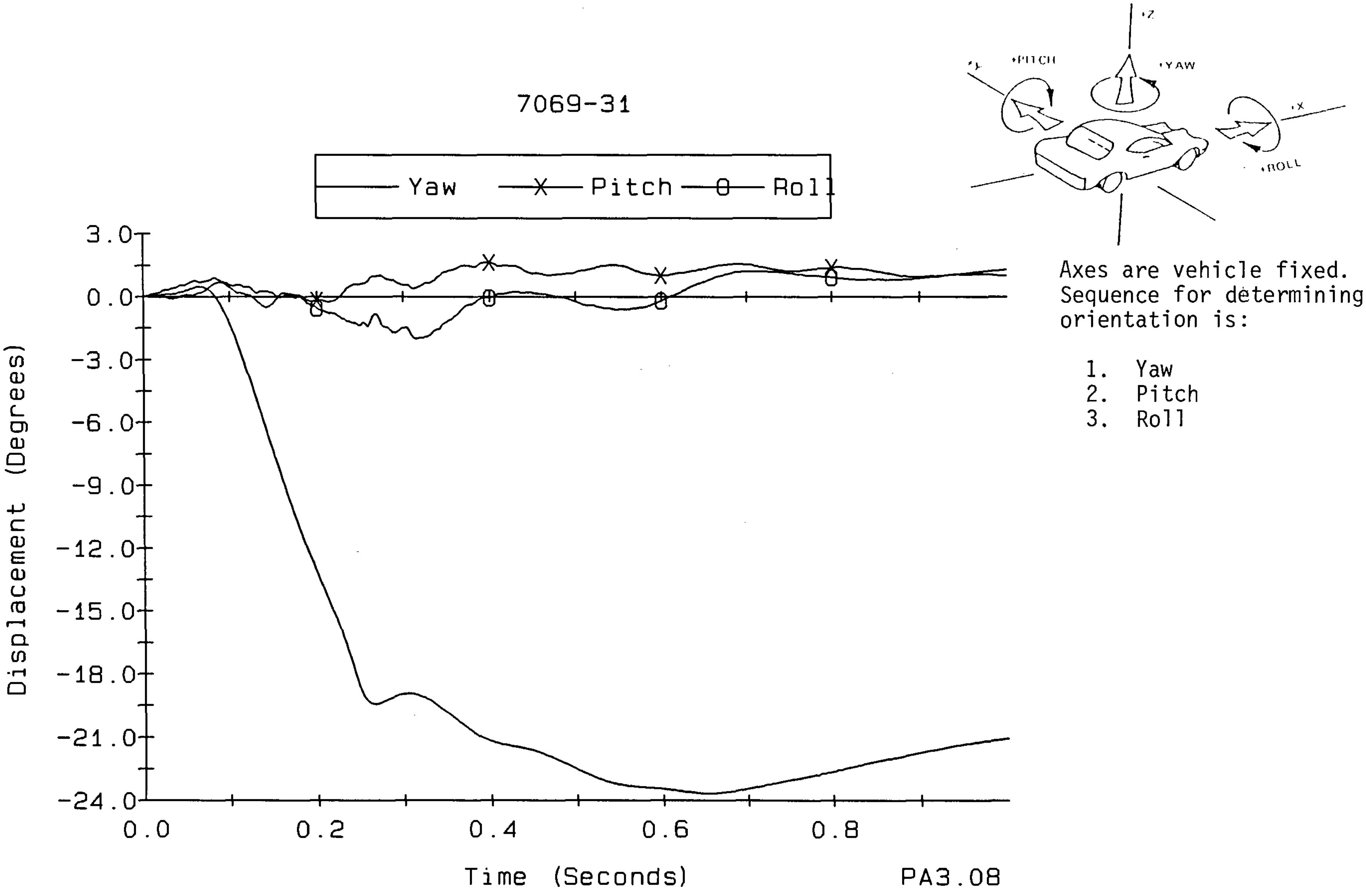


0.286 s



0.333 s

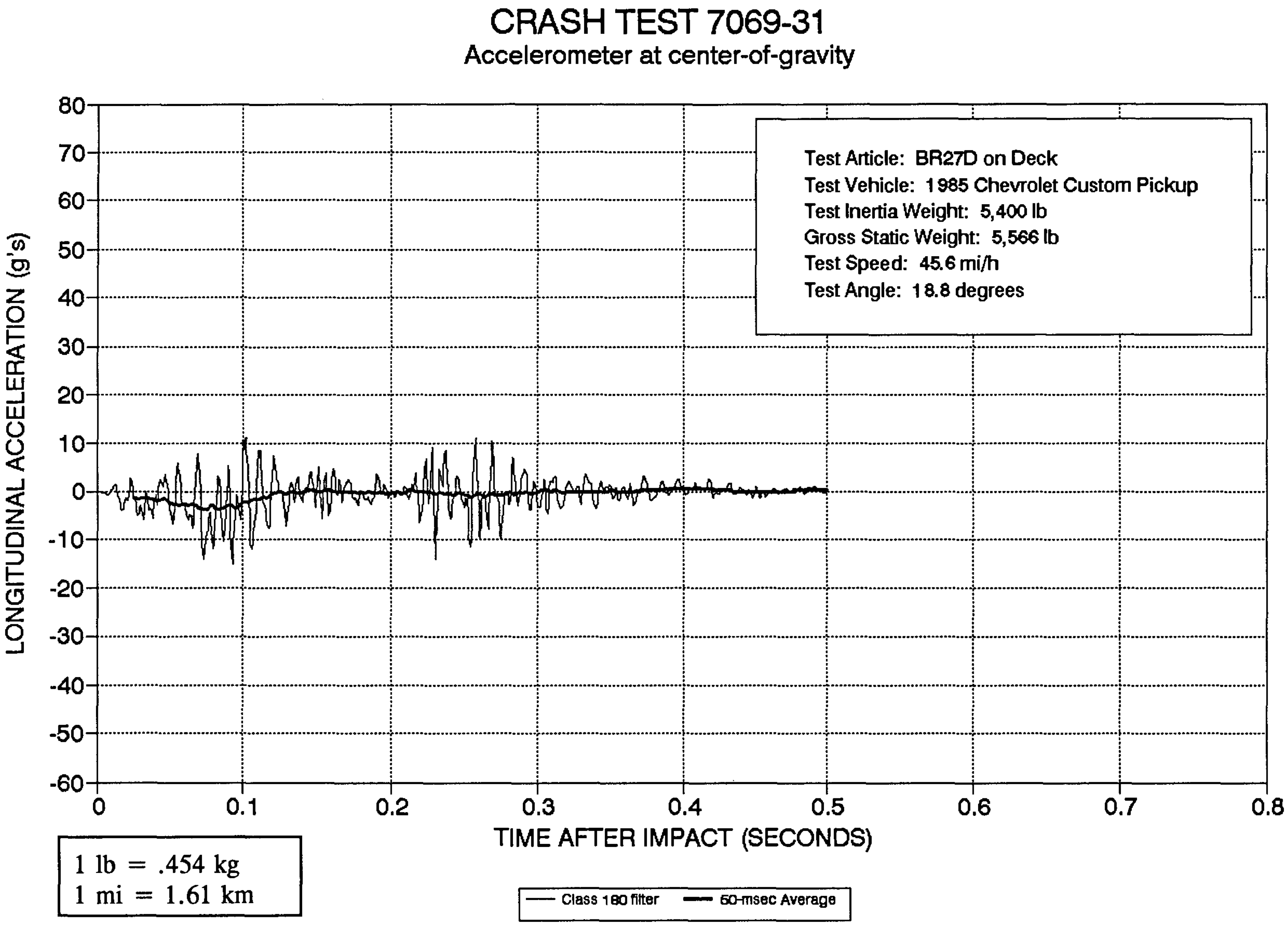
Figure 57. Sequential photogrpahs for test 7069-31
(perpendicular and interior views continued).



Axes are vehicle fixed.
Sequence for determining
orientation is:

1. Yaw
2. Pitch
3. Roll

Figure 58. Vehicle angular displacements for test 7069-31.



1 lb = .454 kg
1 mi = 1.61 km

Figure 59. Vehicle longitudinal accelerometer trace for test 7069-31 (accelerometer located at center-of-gravity).

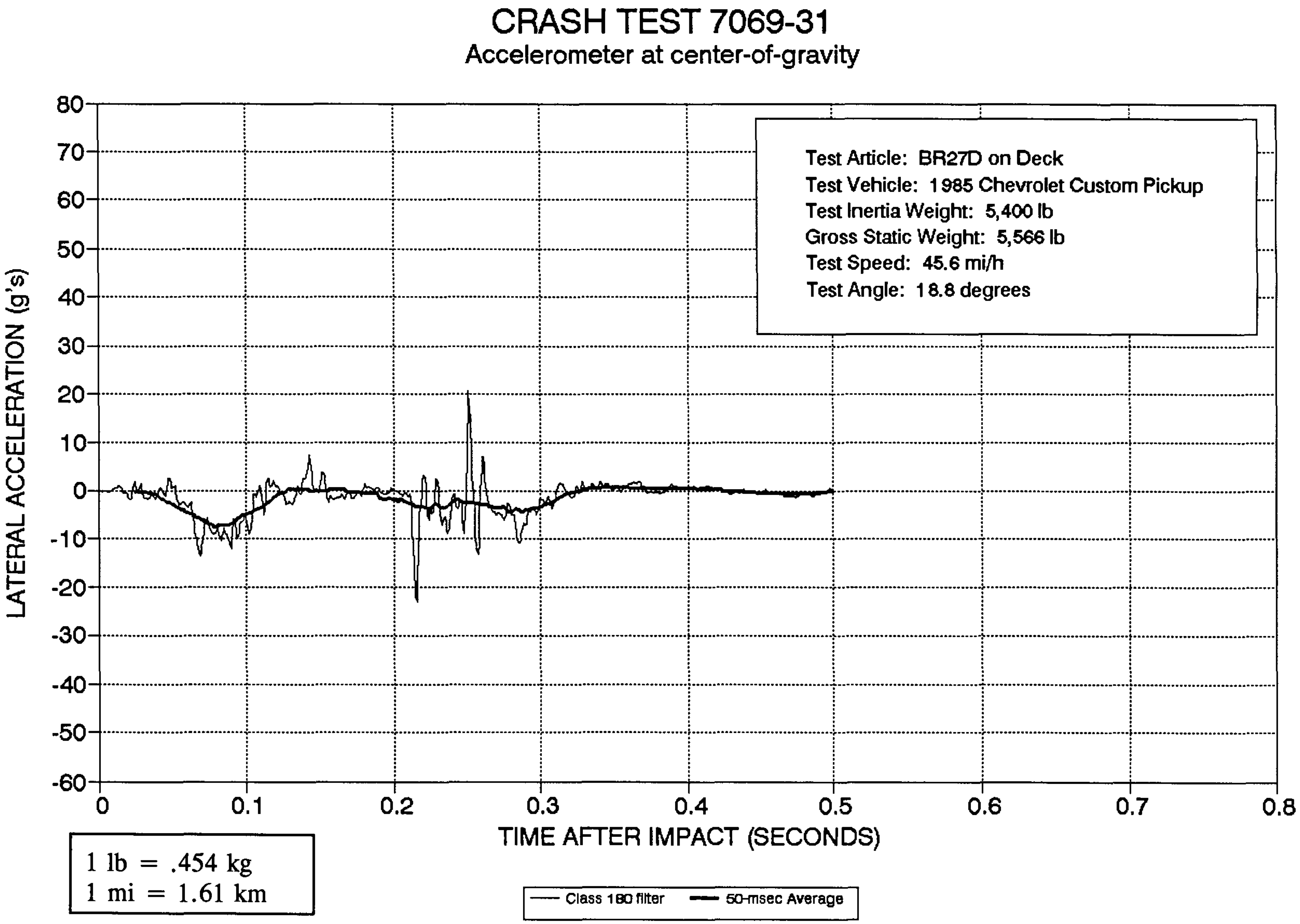


Figure 60. Vehicle lateral accelerometer trace for test 7069-31
(accelerometer located at center-of-gravity).

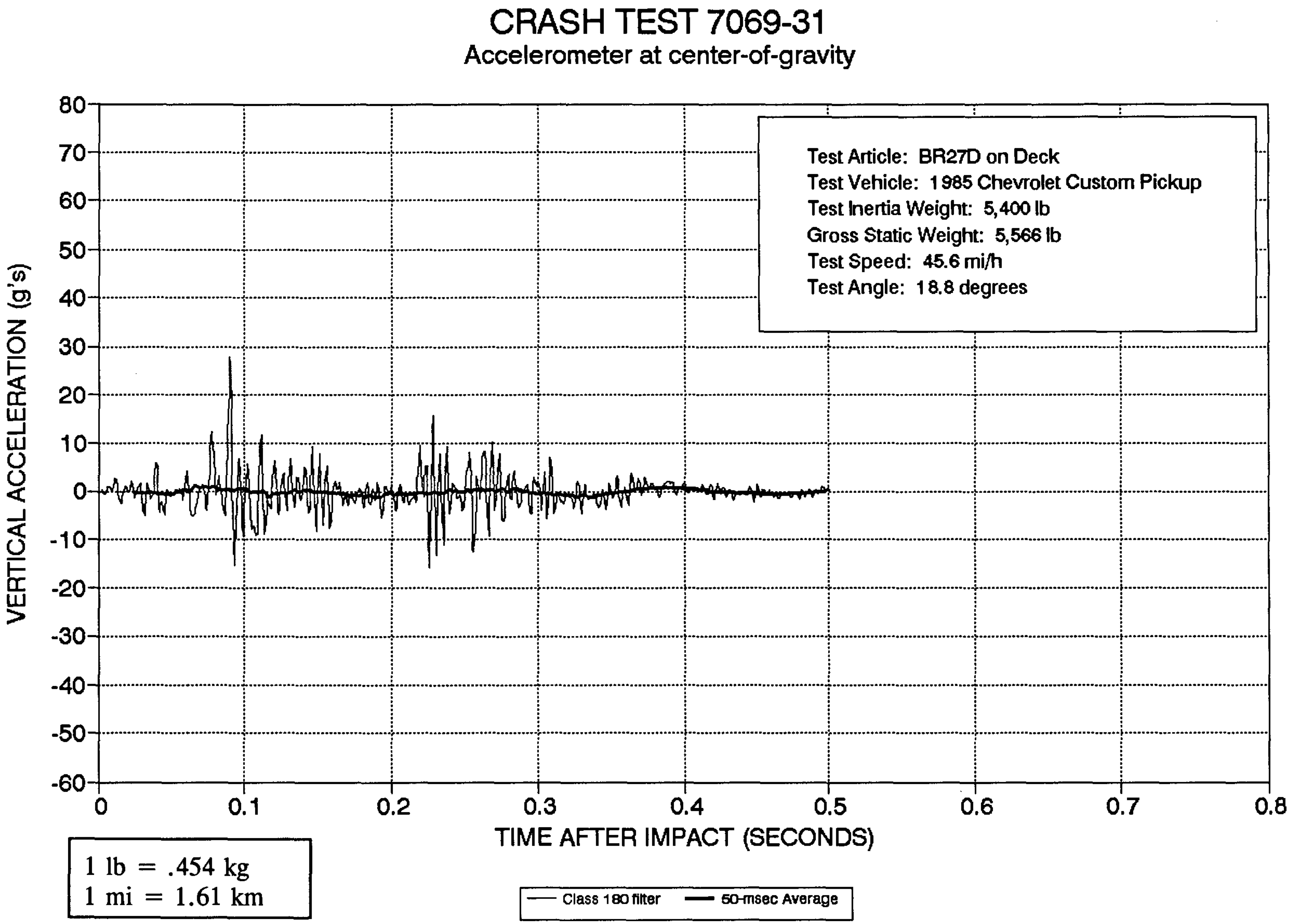


Figure 61. Vehicle vertical accelerometer trace for test 7069-31 (accelerometer located at center-of-gravity).

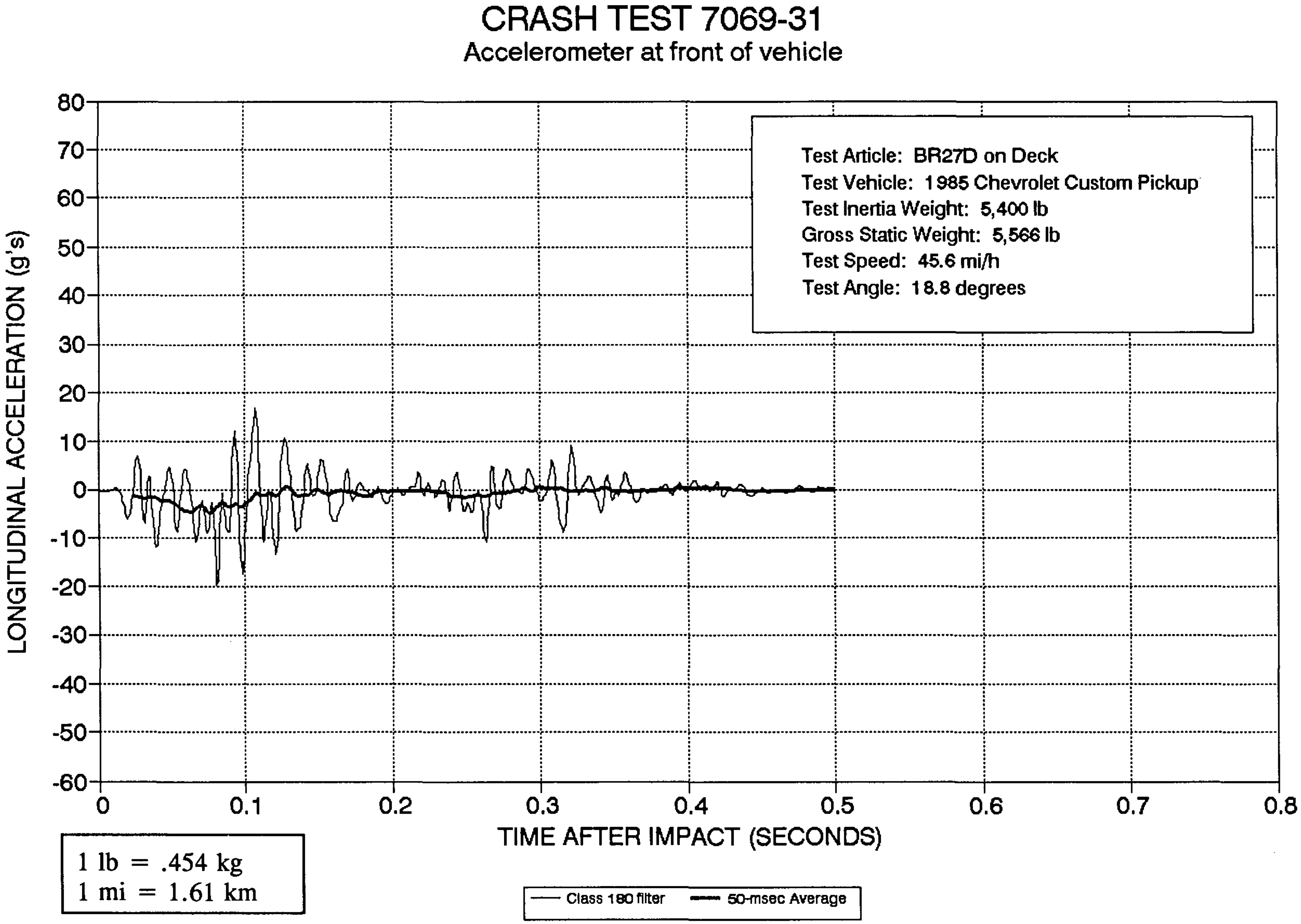
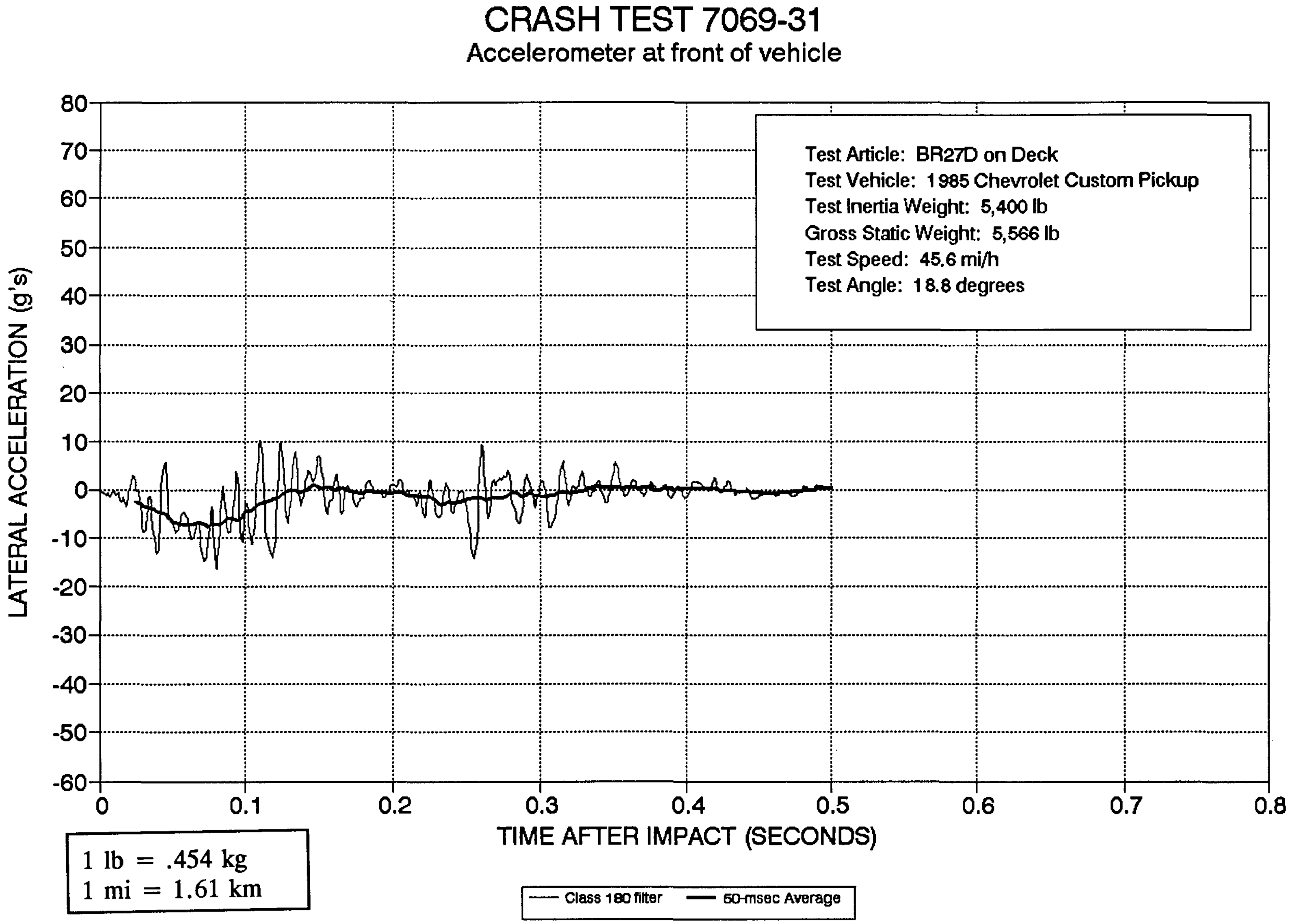


Figure 62. Vehicle longitudinal accelerometer trace for test 7069-31 (accelerometer located at front of vehicle).



1 lb = .454 kg
1 mi = 1.61 km

Figure 63. Vehicle lateral accelerometer trace for test 7069-31 (accelerometer located at front of vehicle).

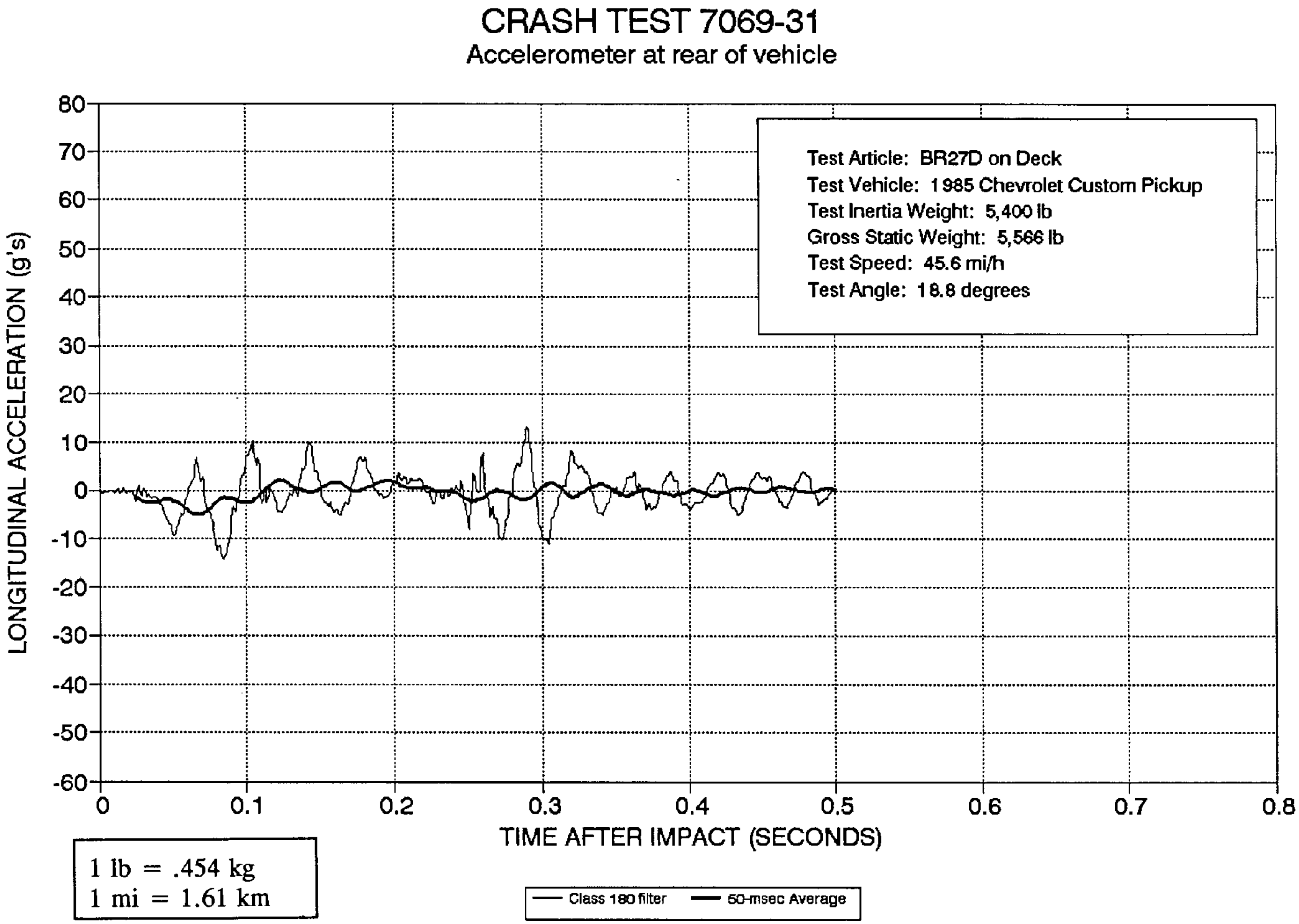


Figure 64. Vehicle longitudinal accelerometer trace for test 7069-31
(accelerometer located at rear of vehicle)

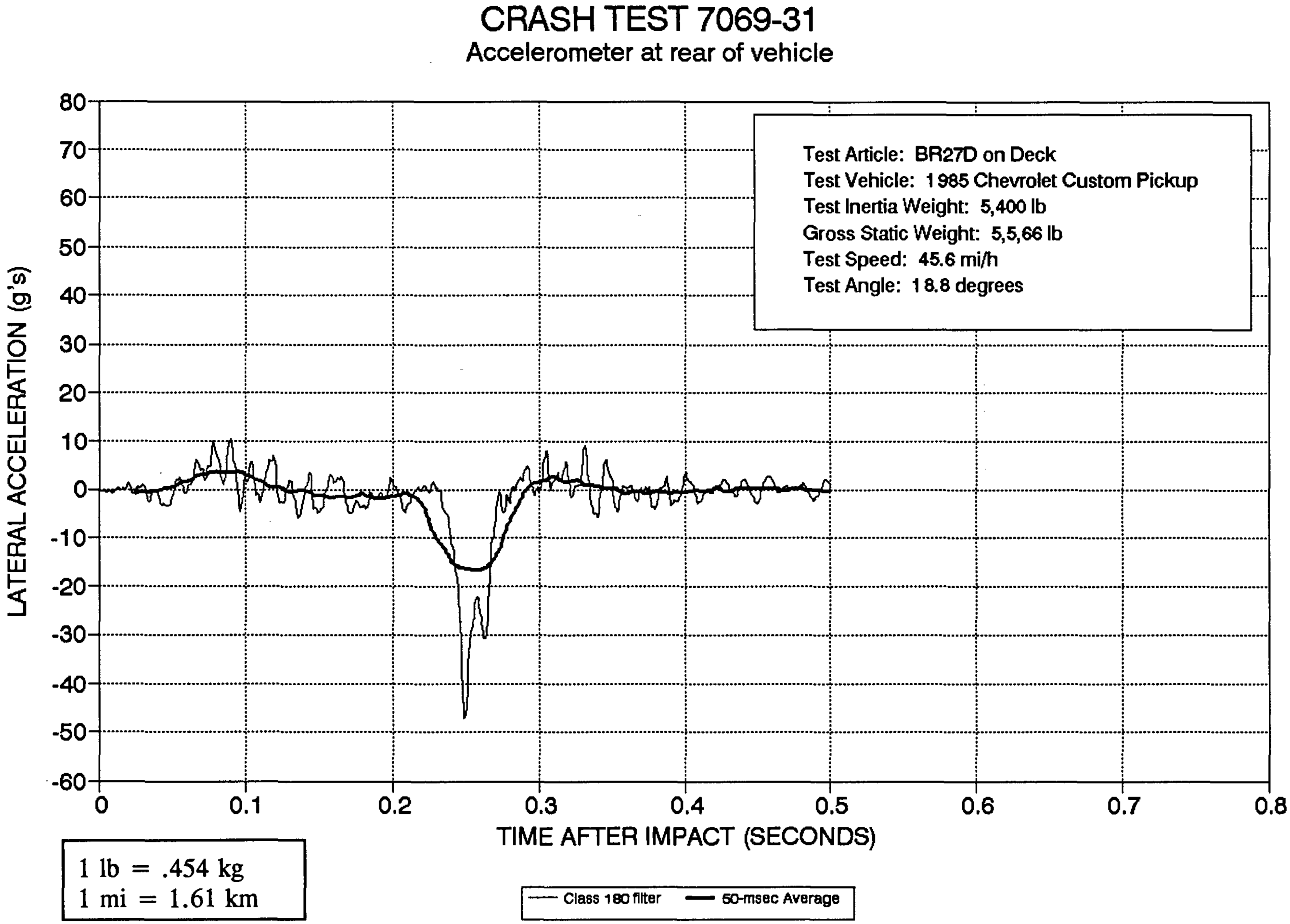


Figure 65. Vehicle lateral accelerometer trace for test 7069-31 (accelerometer located at rear of vehicle).

CHAPTER 4. STRENGTH CALCULATIONS

The railing consists of a metal beam-and-post portion mounted on top of a concrete parapet. Strength of the metal portion is first analyzed assuming that the concrete parapet has adequate strength to support the metal railing. Equations given in figure 66 are used to compute strength of the metal railing. The two metal rail elements are TS 4 by 3 by 1/4 (102 by 76 by 6-mm) ASTM A500 grade B with a plastic section modulus of 3.3 in^3 ($54x10^3$ mm^3) and a plastic moment capacity of 12.7 ft-kips (17.2 m-Kn). Total plastic moment capacity for the two rail elements is 25.3 ft-kips (34.3 m-Kn).

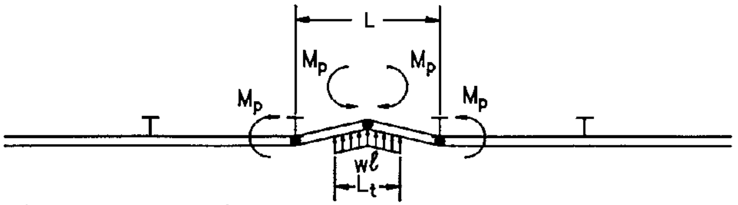
The plastic moment capacity of the post section [TS 4 by 4 by 3/16-in (102 by 102 by 5-mm) ASTM A500 grade B] is 15.0 ft-kips (20.4 m-Kn). The anchor bolts provide a computed moment capacity at the base of the post of 23.1 ft-kips (31.4 m-Kn). The post-to-baseplate weld provides a moment capacity of 11.3 ft-kips (15.3 m-Kn) which is the controlling failure mode. It is noted that strength of the weld should be increased so that the moment capacity of the post section would control and the plastic hinge would be forced into the post section rather than in the welded connection.

The resistance of the post to lateral load depends on the location of the applied force. If the force were located midway between the two rail elements, it would be 15.25 in (387 mm) above the base of the post and strength of the post would be 8.9 kips (39.6 kN). Under this loading situation, strength of the metal portion of the railing, computed in accordance with figure 66, would be 41.1 kips (182.8 kN) for a one-span mechanism, 27.7 kips (123.2 kN) for a two-span mechanism, 24.1 kips (107.2 kN) for a three-span mechanism, and 27.2 kips (121.0 kN) for a four-span mechanism. The three-span mechanism controls and computed capacity of the metal railing is 24.1 kips (107.2 kN) located at 34 in (864 mm) above the top of the sidewalk.

If the force were located at the top rail element, it would be 22 in (559 mm) above the base of the post and strength of the post would be 6.2 kips (27.6 kN). Under this loading situation, strength of the metal portion of the railing, computed in accordance with figure 66, would be 41.1 kips (182.8 kN) for a one-span mechanism, 24.6 kips (109.4 kN) for a two-span mechanism, 20.1 kips (89.4 kN) for a three-span mechanism, and 21.4 kips (95.2 kN) for a four-span mechanism. The three-span mechanism controls and computed capacity of the railing is 20.1 kips (89.4 kN). The force would be located at 40 in (1.02 m) above the top of the sidewalk.

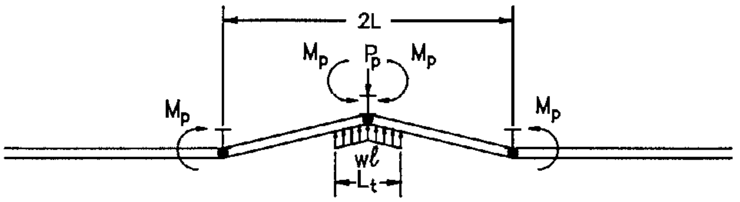
Strength of the concrete parapet may be analyzed using the equations for the yieldline mechanism shown in figure 68. Computed cantilever moment capacity of the parapet, M_c, is 10.8 ft-k/ft (48.1 m-kN/m). Moment capacity of the parapet about a vertical axis, M_w, is 25.5 ft-k/ft (113.5 m-kN/m). No additional beam stiffening exists along the top of the parapet; therefore, M_b is zero. These values result in a length of failure mechanism, L, of 8.5 ft (2.6 m) and computed strength of the parapet of 122.4 kips (544.4 kN).

If it is assumed that load is applied to both metal rail elements and to the parapet such that maximum resistance of the railing system is obtained, a three-span failure mechanism would be involved in the metal portion of the railing and a yieldline failure pattern in the parapet would be located at midlength of the failure mechanism in the metal railing. Total strength of the railing system would be approximately 24.1 kips (107.2 kN) plus 122.4 kips (544.4 kN) equals 146.5 kips (651.6 kN) located 20.6 in (523 mm) above the sidewalk.



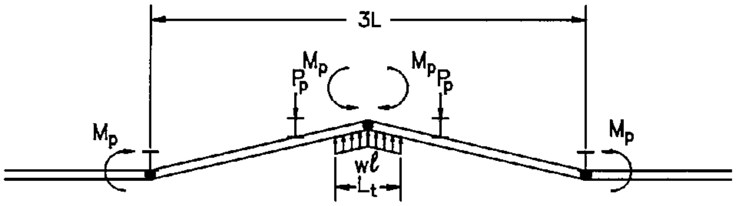
Single–Span Failure Mode

$$w\ell = \frac{16M_p}{2L-L_t}$$



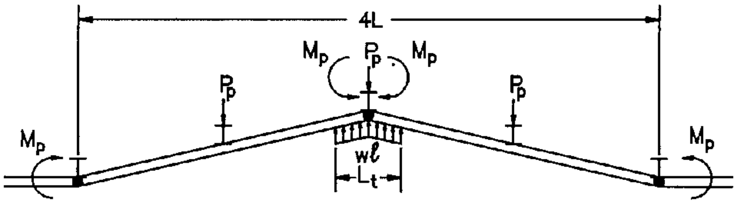
Two–Span Failure Mode

$$w\ell = \frac{16M_p\ +4P_p\,L}{4L-L_t}$$



Three–Span Failure Mode

$$w\ell = \frac{16M_p\ +8P_p\,L}{6L-L_t}$$



Four–Span Failure mode

$$w\ell = \frac{16M_p+16P_p\,L}{8L-L_t}$$

Longer mechanisms may also be possible.

Figure 66. Plan view illustrating some possible failure mechanisms.

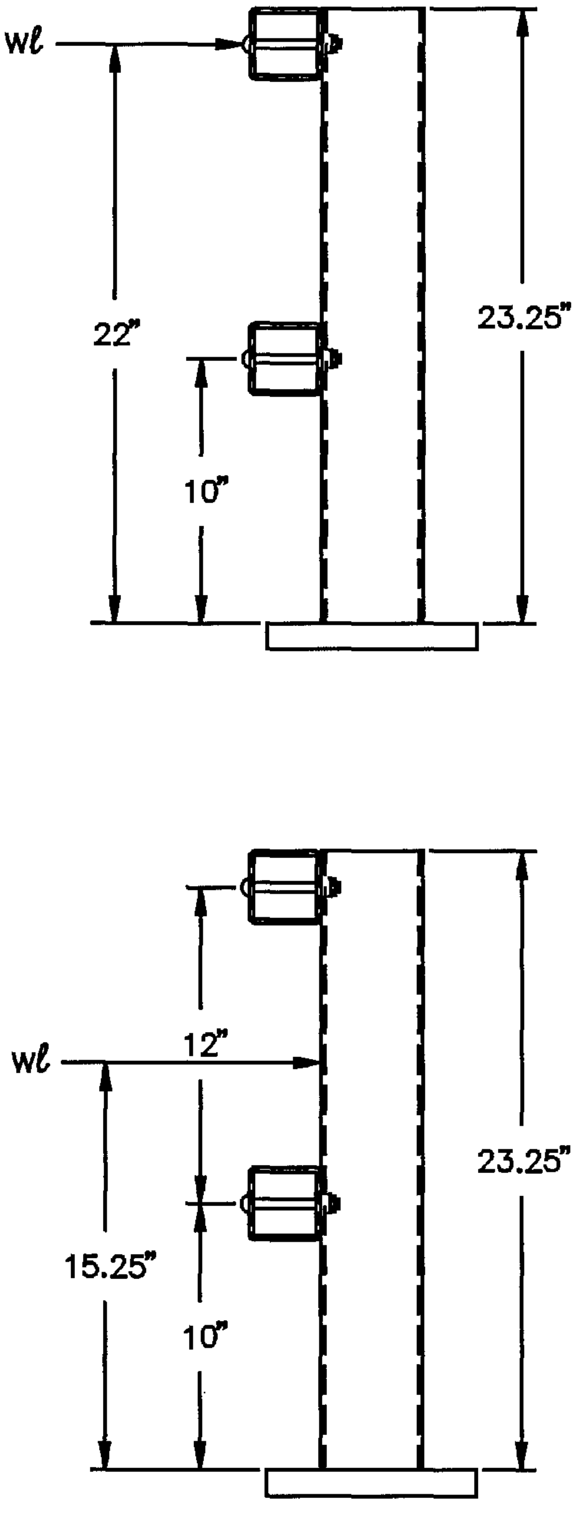
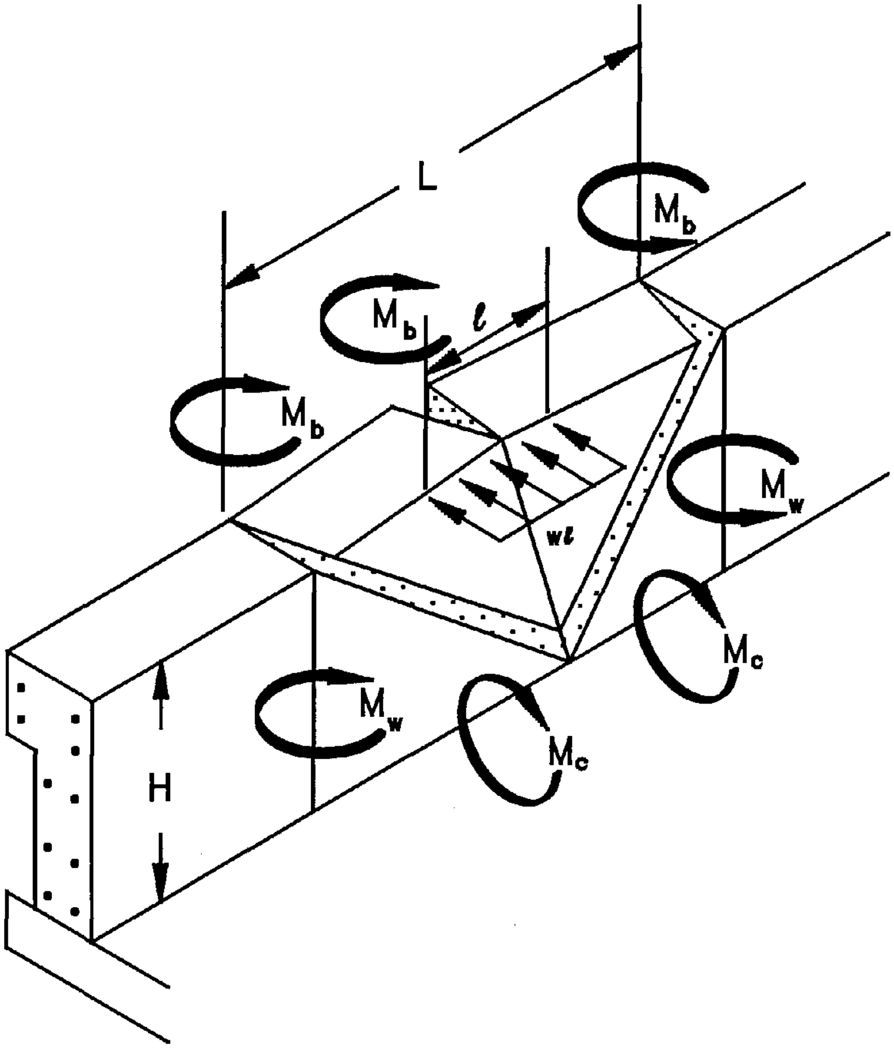


Figure 67. Location of resultant force on metal portion of railing.



$$L = \frac{\ell}{2} + \sqrt{\left(\frac{\ell}{2}\right)^2 + \frac{8H(M_b + M_w H)}{M_c}}$$

$$(w\ell)_{ult} = \frac{8M_b}{L - \frac{\ell}{2}} + \frac{8M_w H}{L - \frac{\ell}{2}} + \frac{M_c L^2}{H\left(L - \frac{\ell}{2}\right)}$$

Figure 68. Yieldline failure pattern for concrete parapet.

REFERENCES

1. *Guide Specifications For Bridge Railings*, American Association of State Highway and Transportation Officials (AASHTO), Washington, DC, 1989.

2. Hirsch. T. J., "Analytical Evaluation of Texas Bridge Rails to Contain Buses and Trucks," Research Report 230-2, Texas Transportation Institute, Texas A&M University, College Station, TX, August 1978.

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