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16. Abstract

The original Illinois 2399 bridge railing design has been used as a retrofit railing on selected structures. A structural analysis indicated that strength of the railing could be increased by changing positions of the lower and upper rail elements to obtain more beam strength along the top. The modified design (Illinois 2399-1) was tested to performance level two of the 1989 *Guide Specifications for Bridge Railings*. Accepteble performance was demonstrated.

This volume is the fourth in a series. The other volumes in the series are: Volume I: Technical Report; Volume II: Appendix A, "Oregon Side Mounted Bridge Railing;" Volume III: Appendix B, "BR27D 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."

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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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CHAPTER 1. DESIGN OF RAILING

A cross section of the prototype test installation is shown in figure 1. The original Illinois 2399 railing design consisted of W6x25 posts spaced at 6 ft-3 in (1.9 m) with a TS 4 by 3 by 5/16-in (102 by 76 by 8-mm) top rail element and a TS 8 by 3 by 1/4-in (203 by 76 by 6-mm) bottom rail element. Height of the metal railing above the top of the curb was 23 in (584 mm) [total height of 30 in (762 mm)].

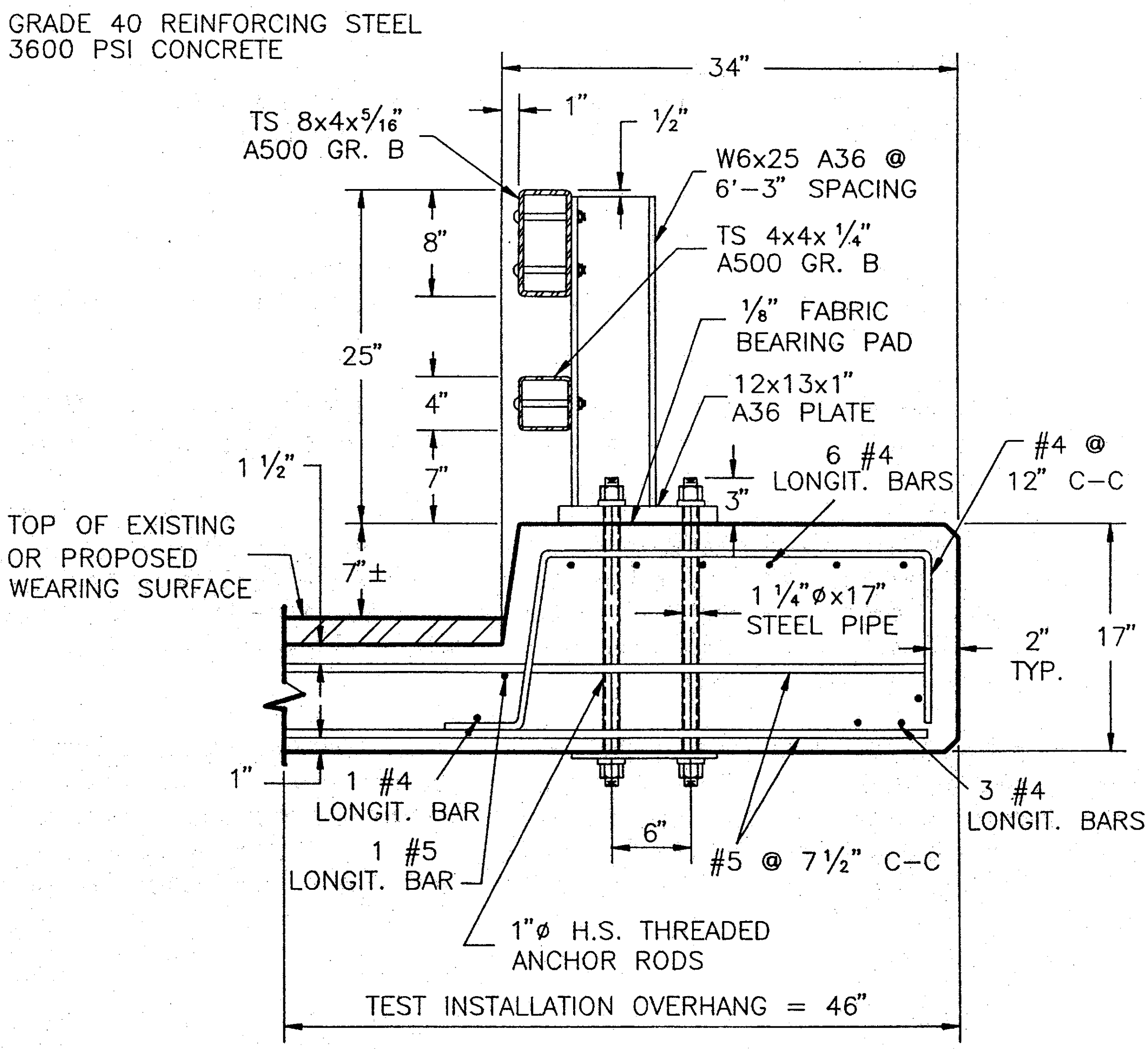
An analysis of the original design indicated that it would be inadequate for the expected forces for performance level two and it was modified to that shown in figure 1. Computations indicate that a smaller post (W6x15) would be adequate but the original W6x25 was retained.

The original Illinois 2399 design was used as a retrofit railing. The modified prototype (Illinois 2399-1) was tested on a cantilevered slab that simulated situations where it would be used as a retrofit, but it is deemed suitable for new construction if adequate bridge deck strength is provided.

Computations of strength of the railing indicate that it will resist approximately 93.5 kips (415.9 kN) at 23 in (584 mm) above the surface of the deck or 83.6 kips (371.9 kN) at 28 in (711 mm).

At the time the railing was designed, the proposed strength test conditions for performance level two was 5,400 lb (2 452 kg)|65 mi/h (104.6 km/h)|20 degrees. For performance level three it was 40,000 lb (18 160 kg)|60 mi/h (96.5 km/h)|15 degrees. Available data indicated that the design force for performance level two was 50 kips (222.5 kN) at 23 in (584 mm) above the deck.

The strength test for performance level two given in the 1989 *Guide Specifications for Bridge Railings* is 18,000 lb (8 172 kg)|50 mi/h (80.5 km/h)|15 degrees.[(1)] The design force for this test condition is a line force of 56 kips (249 kN) uniformly distributed over a longitudinal distance of 42 in (1.07 m) at 29 (or 28) in (731 or 711 mm) above the deck surface. The Illinois 2399-1 design meets this requirement as shown in the strength analysis presented in chapter 4.



1 in = 25.4 mm

Figure 1. Cross section of Illinois 2399-1 bridge railing.

CHAPTER 2. CRASH TEST PROCEDURES

This railing was tested to performance level two requirements.[1] The following nominal test conditions were used:

1,800-lb (817-kg) passenger car | 60 mi/h (96.5 km/h) | 20 degrees (test 7069-1)
5,400-lb (2 452-kg) pickup | 65 mi/h (104.6 km/h) | 20 degrees (test 7069-2)
18,000-lb (8 172-kg) single-unit truck | 50 mi/h (80.5 km/h) | 15 degrees (test 7069-15)

Each vehicle was instrumented with three solid-state angular rate transducers to measure yaw, pitch, and roll rates and a triaxial accelerometer mounted near the center-of-gravity. In addition, on the 18,000-lb (8 172-kg) truck a biaxial accelerometer was mounted forward of the center-of-gravity and another biaxial accelerometer in the rear of the truck. The accelerometers were strain gauge type with a linear millivolt output proportional to acceleration. The electronic signals for 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 displaying on a real-time strip chart. Provision was made for transmission of calibration signals before and after each test, and an accurate time reference signal was simultaneously recorded with the data.

Pressure sensitive contact switches on the bumper of each vehicle 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. Each initial contact also produced an "event" mark on the data record to establish the instant of impact. Data from the electronic transducers were digitized with a microcomputer for analysis and evaluation of performance.

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 were played back from the tape machines, filtered with an SAE J211 filter, and digitized using a microcomputer for analysis and evaluation of performance.

Alderson Research Laboratories Hybrid II, 50th percentile anthropomorphic dummies were used in the passenger car and the pickup. One uninstrumented dummy was placed in the driver's seat of the passenger car and was restrained with standard restraint equipment. The pickup truck was equipped with two uninstrumented dummies restrained with standard restraint equipment. The single-unit truck carried no dummies.

The digitized data obtained from the electronic transducers 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, the highest 0.010-s average of vehicle acceleration after occupant/compartment impact, and time of highest 0.010-s average. 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). For each of these graphs, a 0.050-s average window was calculated at the center of the 0.050-s interval and then 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, instructing the plotter to draw a reproducible plot: yaw, pitch, and roll versus time. It should be noted that these angular displacements are sequence dependent with sequence being yaw, pitch, and 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.

Photographic coverage of the test included three high-speed cameras: one over head 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 railing system at the downstream end, and a third placed perpendicular to the front of the railing system. In the passenger car and pickup tests a high-speed camera was placed onboard the vehicle to record the actions of the dummy(ies) during the test. A flash bulb activated by pressure sensitive tape switches was positioned on the impacting vehicle to indicate the instant of contact with the railing system 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 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 railing 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 with the railing system, 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 this time brakes on the vehicle were activated to bring it to a safe and controlled stop.

CHAPTER 3. FULL-SCALE CRASH TESTS

TEST 7069-1

Test Description

The 1980 Honda shown in figure 2 was directed into the Illinois 2399-1 bridge railing (figures 3 and 4) using a cable reverse tow and guidance system. Test inertia mass of the vehicle was 1,795 lb (815 kg) and its gross static mass was 1,961 lb (890 kg). The height to the lower edge of the vehicle bumper was 14.0 in (356 mm) and it was 19.5 in (495 mm) to the top of the bumper. Other dimensions and information on the test vehicle are given in figure 5. The vehicle was free-wheeling and unrestrained just prior to impact.

The speed of the vehicle at impact was 58.7 mi/h (94.4 km/h) and the angle of impact was 20.0 degrees. The vehicle impacted the barrier midway between posts 6 and 7. At approximately 0.020 s after impact the right front tire contacted the curb, and by 0.030 s the vehicle began to redirect. As the tire and rim rode against the curb, the tire aired-out. The frame around the windshield began to deform and at about 0.070 s the windshield broke. At 0.151 s the vehicle was traveling parallel with the railing and at 0.168 s the rear of the vehicle impacted the railing. The vehicle lost contact with the railing at 0.226 s after impact. As the vehicle exited the railing, the brakes were applied and the vehicle yawed slightly in clockwise rotation. The vehicle subsequently came to rest 225 ft (68.6 m) downstream and 21 ft (6.4 m) behind the point of impact.

As can be seen in figure 6, the railing received very little damage. There were tire marks on the face of the railings and the curb and minor chips on the edge of the curb. There was no measurable movement or deformation in the railing. The vehicle was in contact with the lower railing element for 9.7 ft (2.9 m).

The vehicle sustained extensive damage to the right front as shown in figure 7. Maximum crush at the right front corner at bumper height was 8.0 in (203 mm). The right front tire was aired-out, the wheel rim was bent, and the wheel assembly and suspension damaged. The front bumper was disconnected on the left side but still attached to the right side. The passenger door was bent and jammed and the right rear quarter panel was bent and scraped. The hood was bent and shifted to the left. The windshield frame was bent and the windshield was broken and partially out. The roof of the vehicle was twisted.

Test Results

Impact speed was 58.7 mi/h (94.4 km/h), and the angle of impact was 20.0 degrees. The exit speed at time of contact (0.226 s) was 48.5 mi/h (78.0 km/h), and the exit angle was 5.2 degrees. The effective coefficient of friction was calculated to be 0.28. Occupant impact velocity was 16.9 ft/s (5.2 m/s) in the longitudinal direction and 25.1 ft/s (7.7 m/s) in the lateral direction. The highest 0.010-s occupant ridedown accelerations were -1.4 g (longitudinal) and 8.5 g (lateral). The maximum 0.050-s averages were -6.4 g (longitudinal) and 14.2 g (lateral). These data and other pertinent information from the test are summarized in figure 8 and table 1. Sequential photographs of the test are shown in figures 9 and 10. Vehicular angular displacements are displayed in figure 11, and all other traces from the vehicle are shown in figures 12 through 14.

Conclusions

The Illinois 2399-1 bridge railing contained and smoothly redirected the vehicle with no lateral movement of the bridge railing. There were no debris or detached elements. There was minimal intrusion into the occupant compartment. The vehicle trajectory at loss of contact indicates minimum intrusion into adjacent traffic lanes. The vehicle remained upright and stable during the entire test period.

According to the criteria recommended by FHWA and NCHRP Report 230 test S13, this test meets the requirements for structural adequacy, vehicle trajectory, and occupant risk factors. FHWA sets a limit of 25 ft/s (7.6 m/s) for lateral occupant impact velocity in vehicles impacting at a 20-degree angle. Therefore, due to the slightly high lateral occupant impact velocity of 25.1 ft/s (7.7 m/s), performance of the railing is considered marginally acceptable.

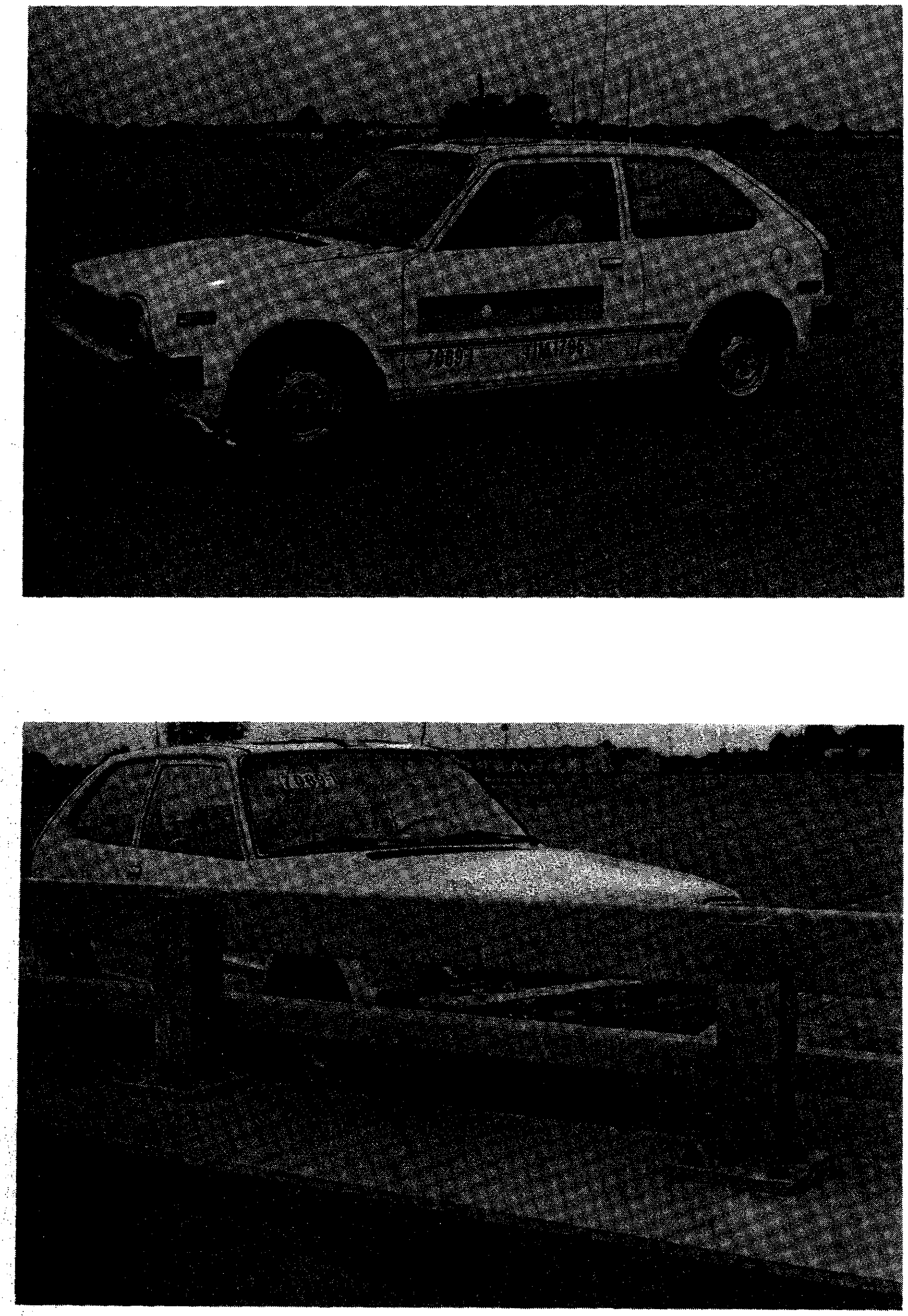


Figure 2. Vehicle before test 7069-1.

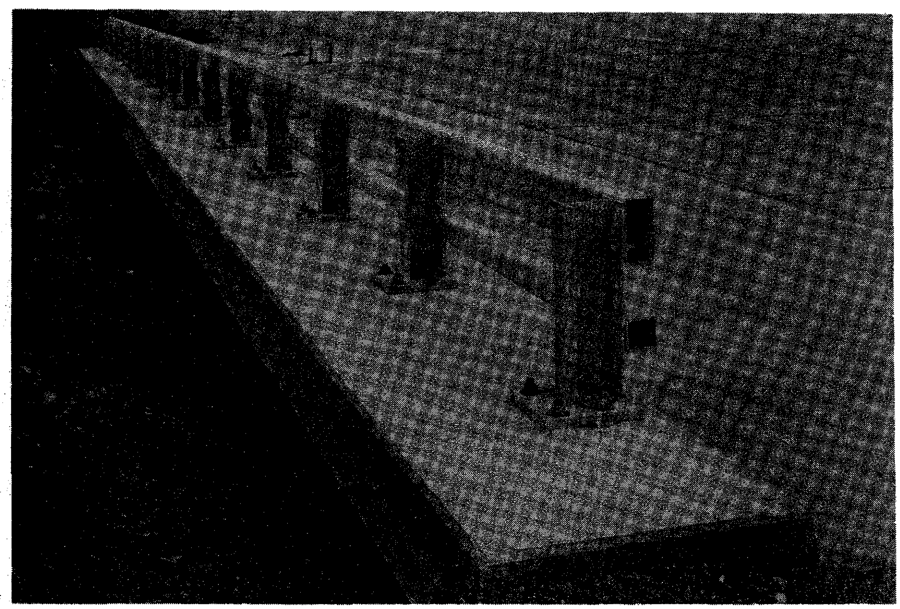


Figure 3. Illinois 2399-1 bridge railing before test 7069-1.

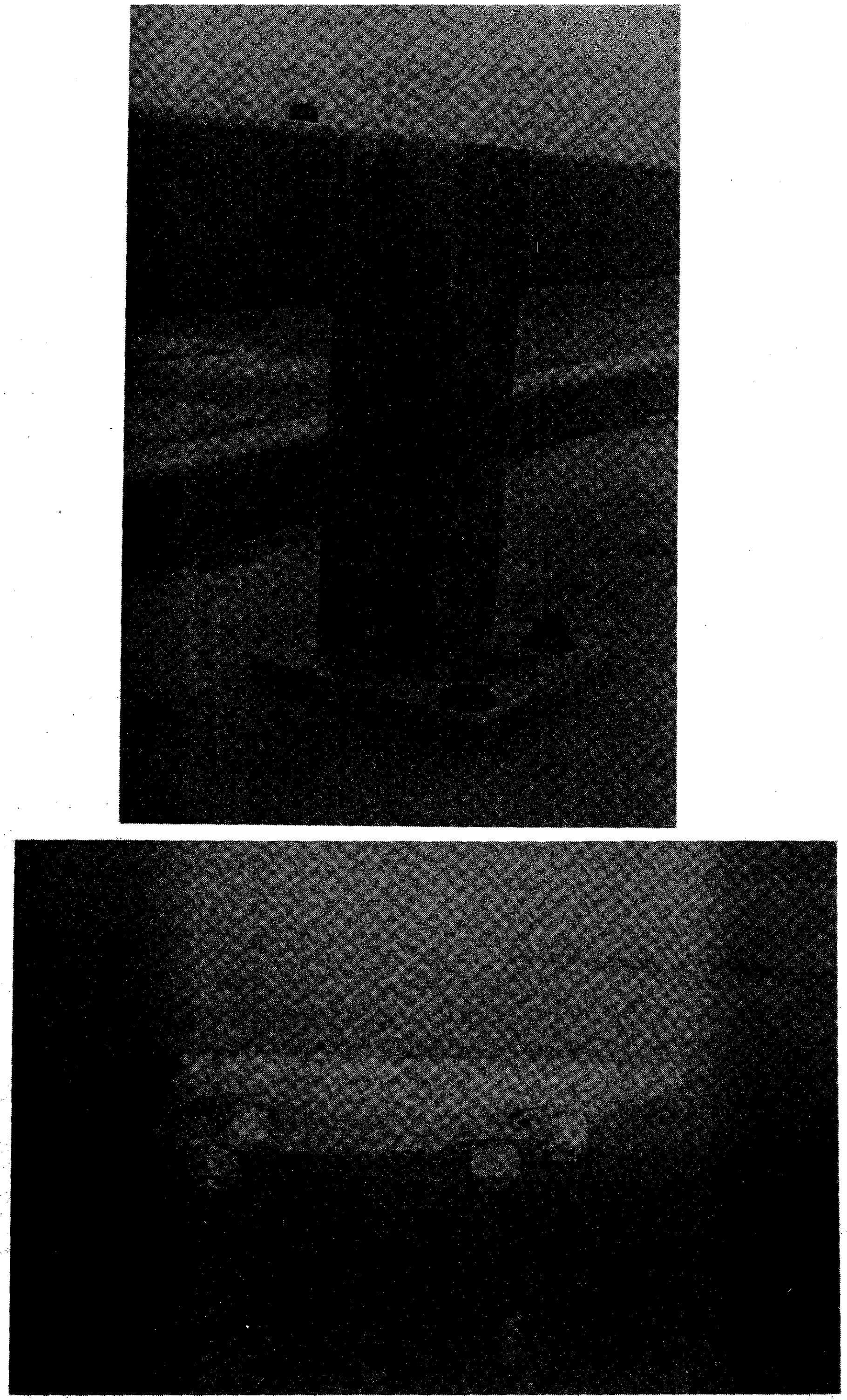
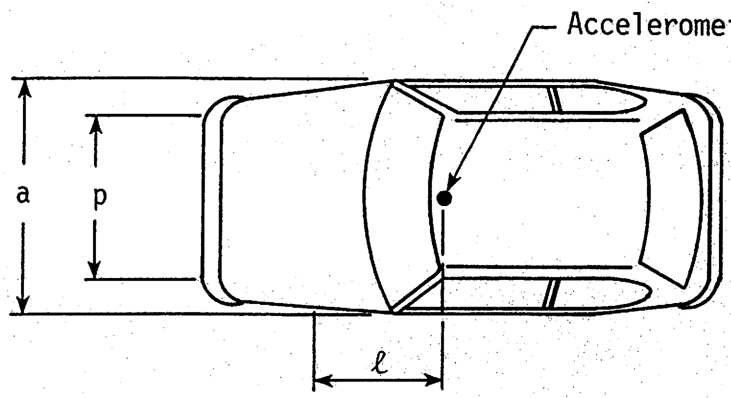


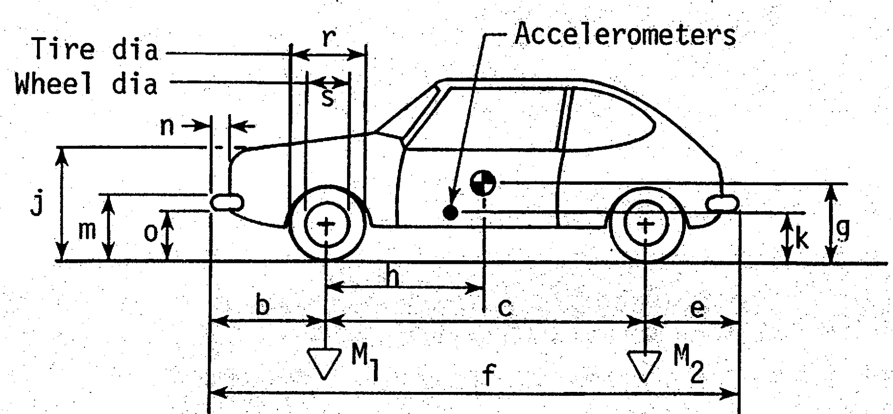
Figure 4. Post and plate washer below deck for Illinois 2399-1 bridge railing.

Date: 7-14-87 Test No.: 7069-1 VIN: SL-C1019237

Make: Honda Model: 1300 DX Year: 1980 Odometer: 90954

Tire Size: 155 R 12 Ply Rating: 1 Bias Ply: ___ Belted: x Radial: ___





Tire Condition: good ___ fair ___ badly worn ___

Vehicle Geometry - inches

a	60.50	b	29.50
c	88.00	d*	52.50
e	28.25	f	146.00
g		h	31.82
i	----	j	29.50
k	15.00	ℓ	27.00
m	19.50	n	3.00
o	14.00	p	53.75
r	22.25	s	13.25

4-wheel weight for c.g. det. ℓf 581 rf 568 ℓr 338 rr 308

Mass - pounds	Curb	Test Inertial	Gross Static
M_1		1149	1234
M_2		646	727
M_T		1795	1961

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 cylinder

Engine CID: ___

Transmission Type:

Automatic or (Manual)

(FWD) or RWD or 4WD

Body Type: Hatch

Steering Column Collapse Mechanism:

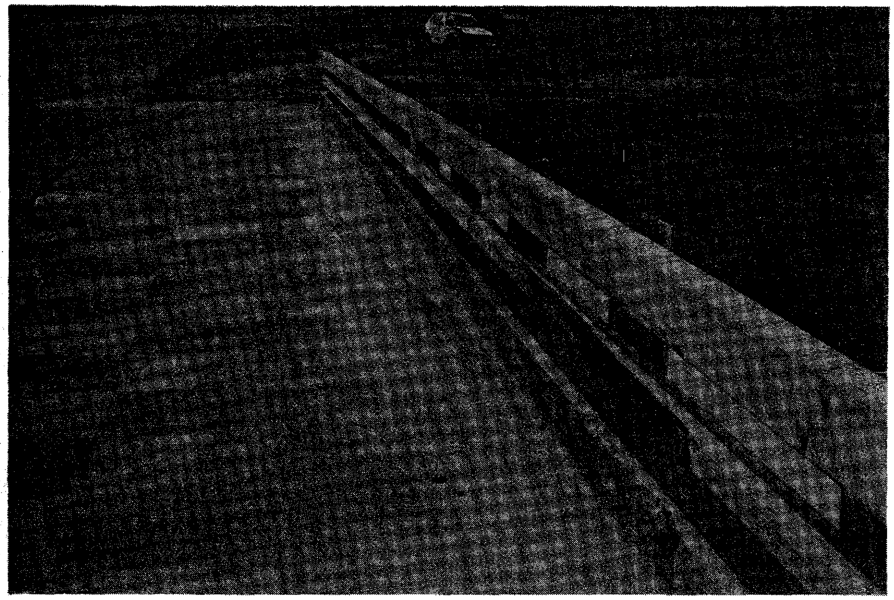
- ___ Behind wheel units
- ___ Convoluted tube
- ___ Cylindrical mesh units
- ___ Embedded ball
- ___ NOT collapsible
- ___ Other energy absorption
- ___ Unknown

Brakes:

Front: disc x drum ___

Rear: disc ___ drum x

Figure 5. Vehicle properties for test 7069-1.



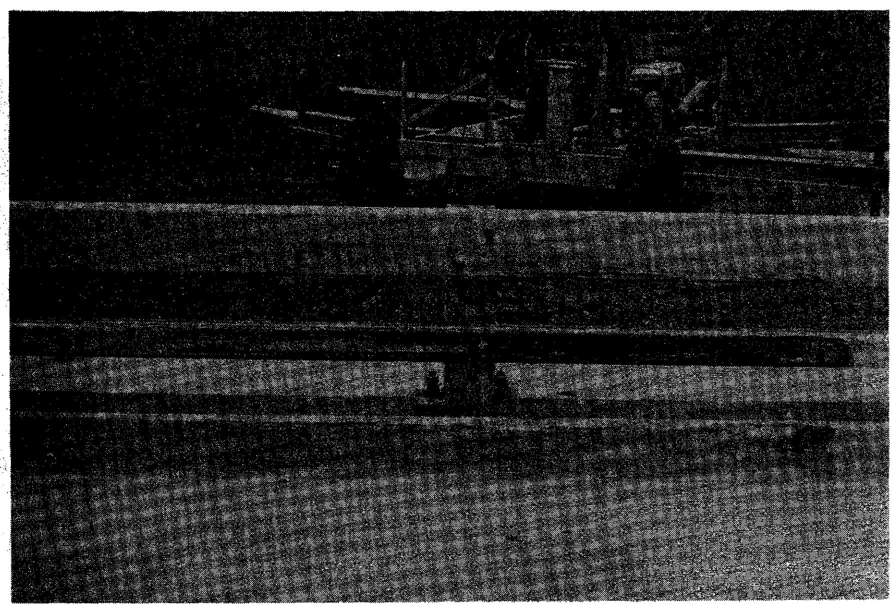


Figure 6. Illinois 2399-1 bridge railing after 7069-1.

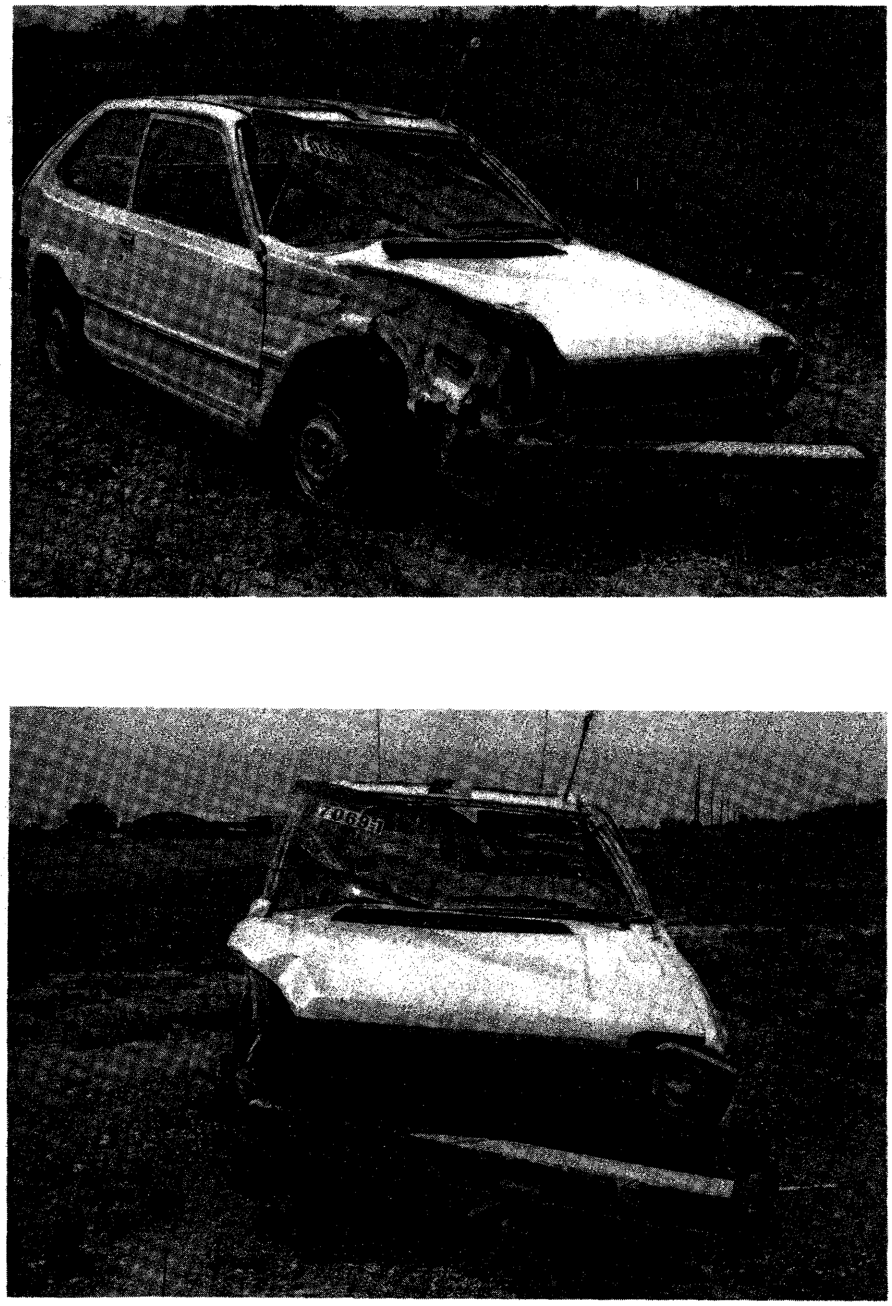
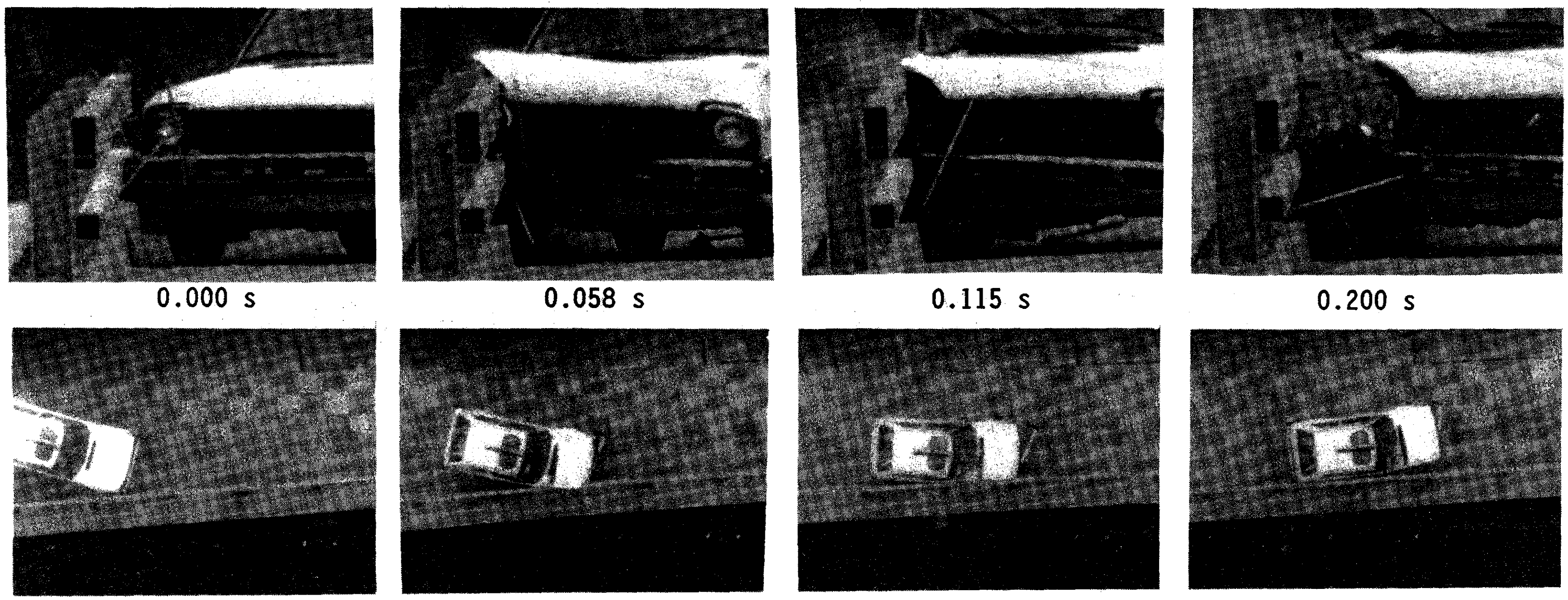
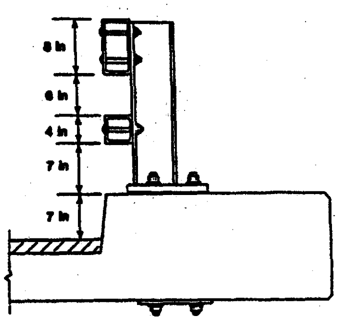


Figure 7. Vehicle after test 7069-1.





(1 in = 25.4 mm)

Test No.	7069-1
Date	7/14/87
Test Installation	Illinois 2399-1 Bridge Railing
Installation Length	100 ft (30 m)
Vehicle	1980 Honda
Vehicle Weight	
Test Inertia	1,795 lb (815 kg)
Gross Static	1,961 lb (890 kg)
Vehicle Damage Classification	
TAD	01RFQ5
CDC	01FREK2 & 01RFEW3
Maximum Vehicle Crush	8.0 in (203 mm)
Max. Dyn. Rail Deflct.	Nil
Max. Perm. Rail Deform	None

Impact Speed	58.7 mi/h (94.4 km/h)
Impact Angle	20.0 deg
Exit Speed	48.5 mi/h (78.0 km/h)
Exit Angle	5.2 deg
Vehicle Accelerations (Max. 0.050-sec Avg)	
Longitudinal	-6.4 g
Lateral	14.2 g
Occupant Impact Velocity	
Longitudinal	16.9 ft/s (5.2 m/s)
Lateral	25.1 ft/s (7.7 m/s)
Occupant Ridedown Accelerations	
Longitudinal	-1.4 g
Lateral	8.5 g

Figure 8. Summary of results for test 7069-1.

Table 1. Evaluation of crash test no. 7069-1.
{Illinois 2399-1 Railing [1,795 lb (815 kg)|58.7 mi/h (94.4 km/h)|20.0 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	Acceptable 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 .28 Fair	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 16.9 (5.2); Lateral 25.1 (7.7)	Pass
	Occupant Ridedown Accelerations - g's Longitudinal 15; Lateral 15	Occupant Ridedown Accelerations - g's Longitudinal -1.4; Lateral 8.5	Pass
H.	Exit angle shall be less than 12 degrees	Exit angle was 5.2 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]

PERFORMANCE LEVELS		TEST SPEEDS—mph[1,2] — TEST VEHICLE DESCRIPTIONS AND IMPACT ANGLES: Small Automobile W = 1.8 Kips A = 5.4′ ± 0.1′ B = 5.5′ H_{cg} = 20″ ± 1″ θ = 20 deg.	Pickup Truck W = 5.4 Kips A = 8.5′ ± 0.1′ B = 6.5′ H_{cg} = 27″ ± 1″ θ = 20 deg.	Medium Single-Unit Truck W = 18.0 Kips A = 12.8′ ± 0.2′ B = 7.5′ H_{cg} = 49″ ± 1″ θ = 15 deg.	Van-Type Tractor-Trailer[4] W = 50.0 Kips A = 12.5′ ± 0.5′ B = 8.0′ H_{cg} = See Note 4 R = 0.61 ± 0.01 θ = 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:

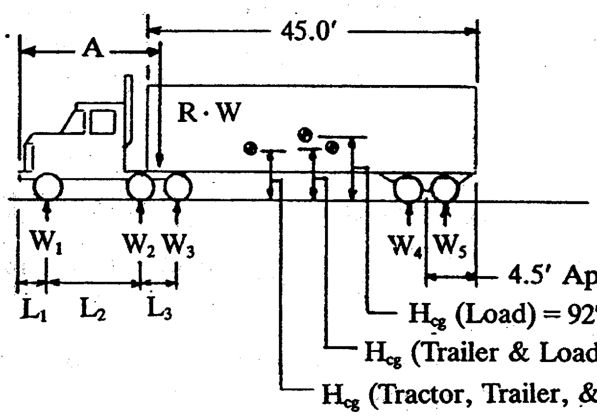
Occupant Impact Velocity–fps	
Longitudinal	Lateral
30	25

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

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

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

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

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

$W = W_1 + W_2 + W_3 + W_4 + W_5$
= 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

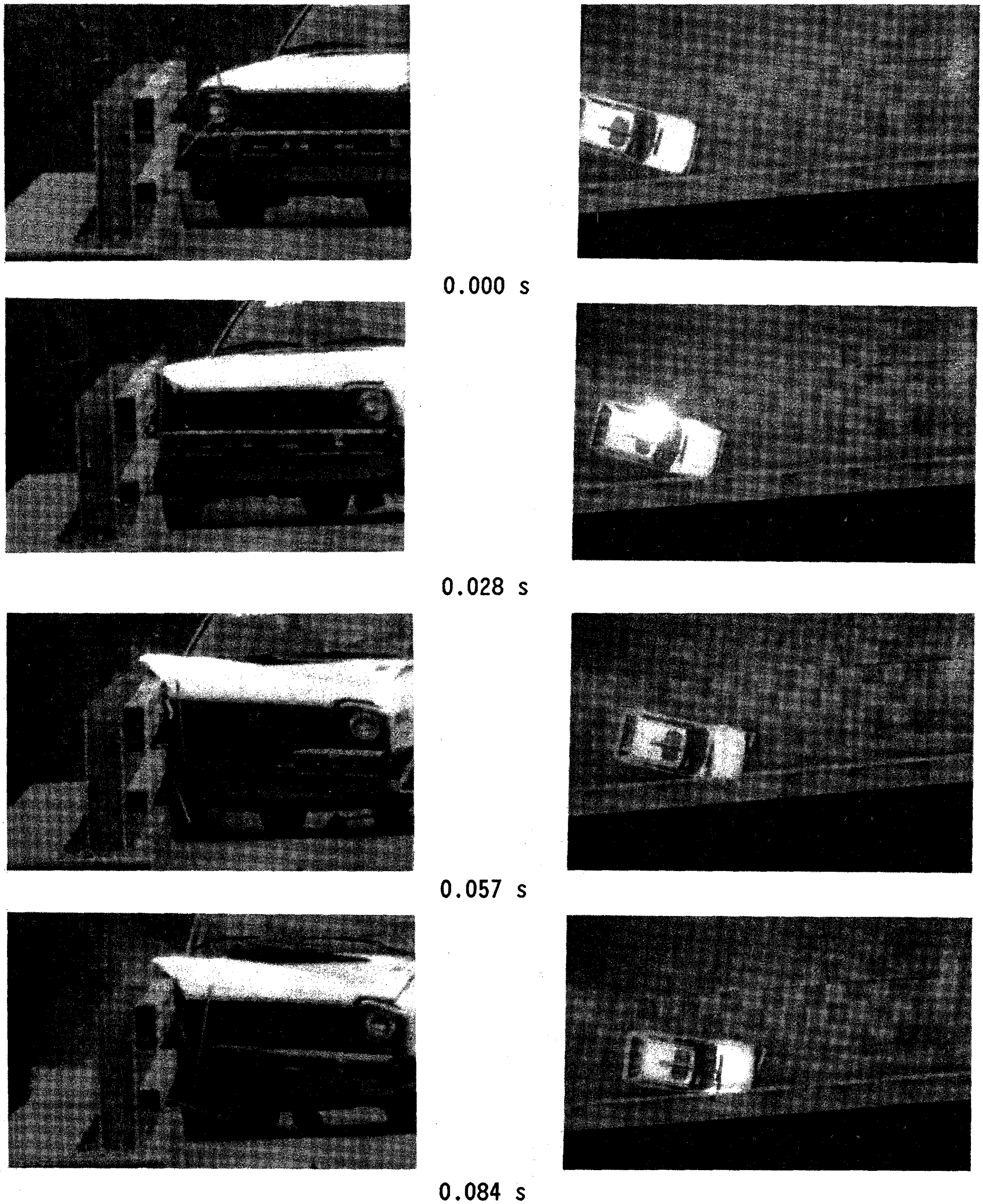


Figure 9. Sequential photographs for test 7069-1.

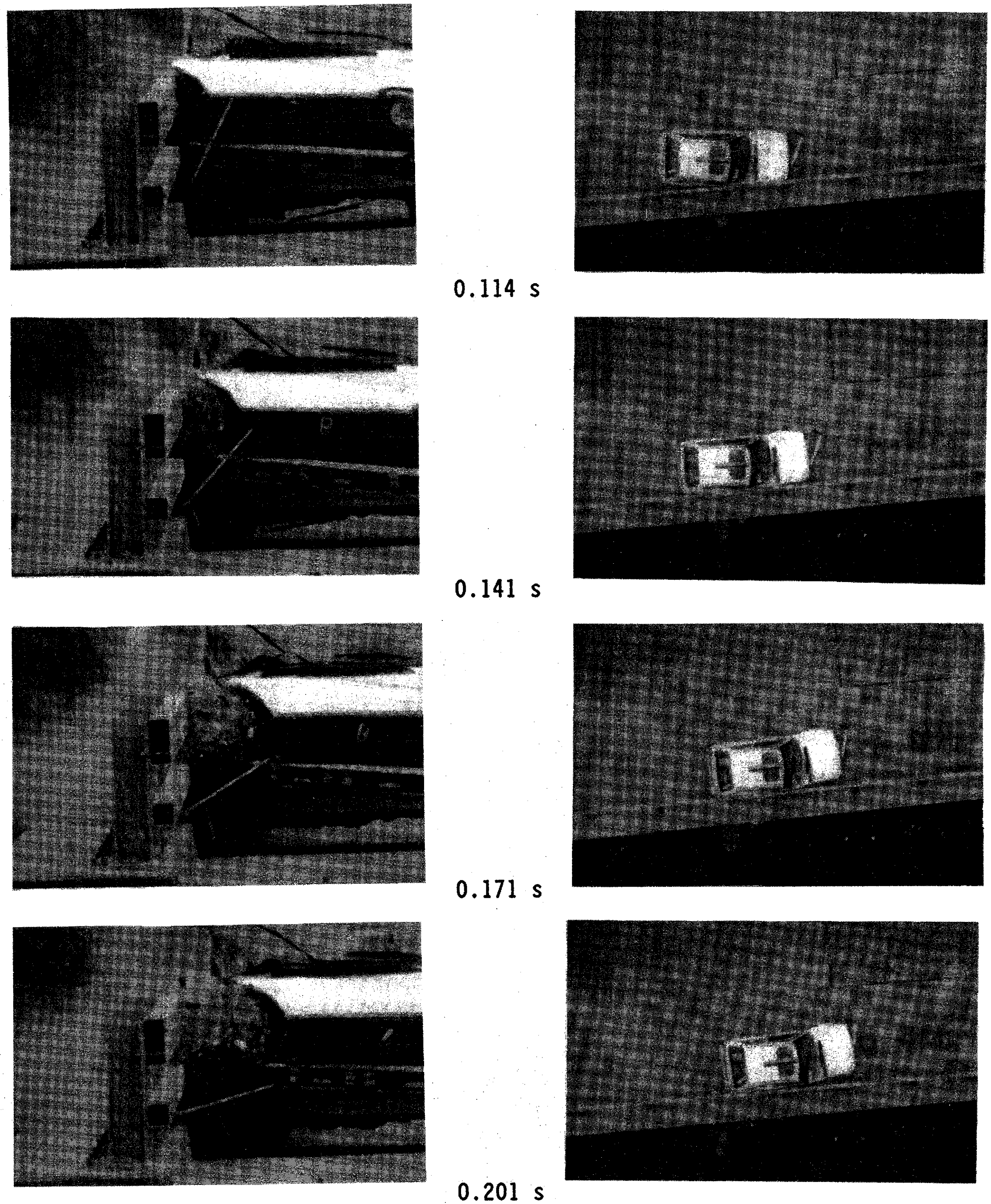


Figure 9. Sequential photographs for test 7069-1
(frontal and overhead views continued).

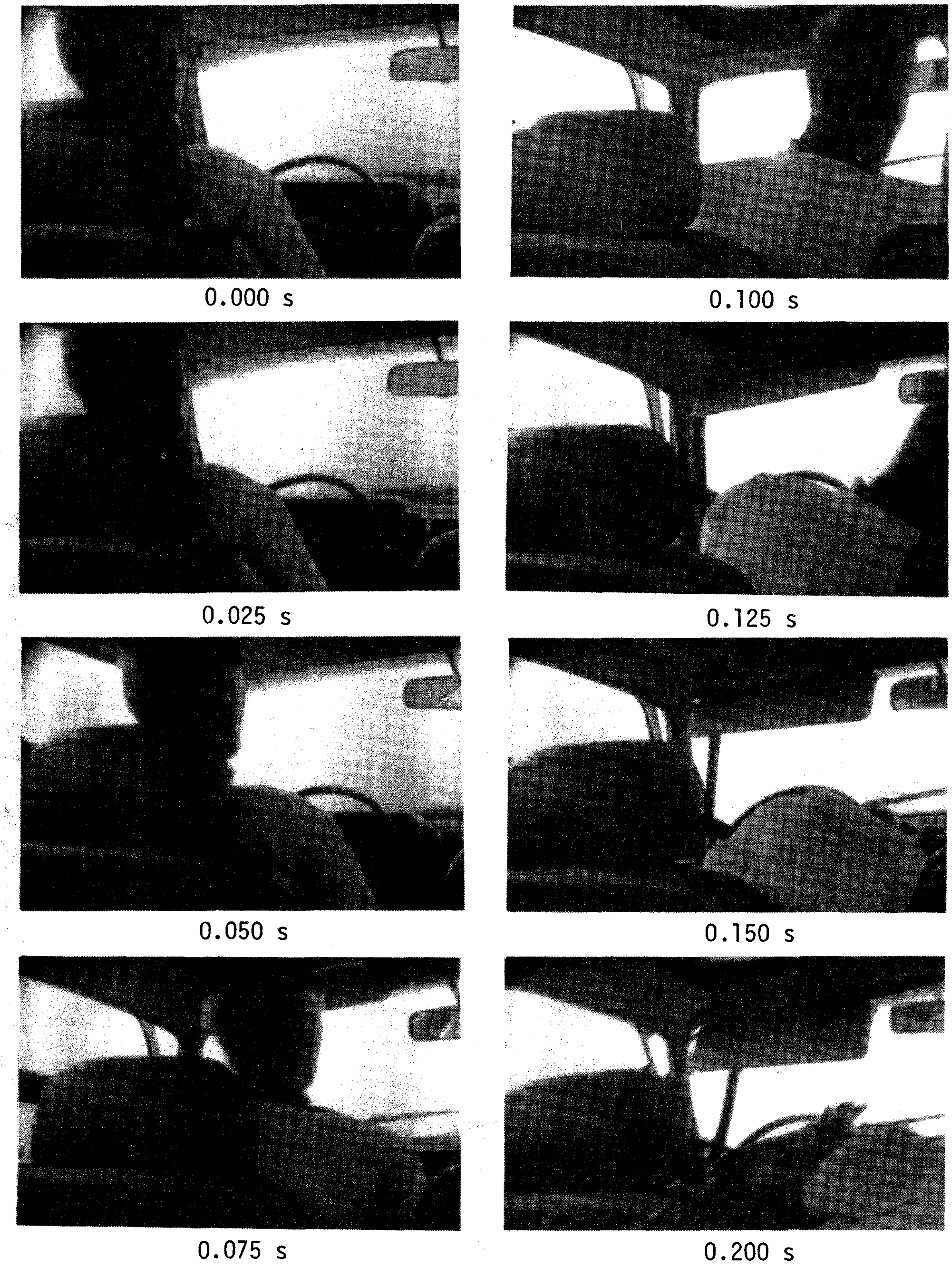


Figure 10. Interior sequential photographs for test 7069-1.

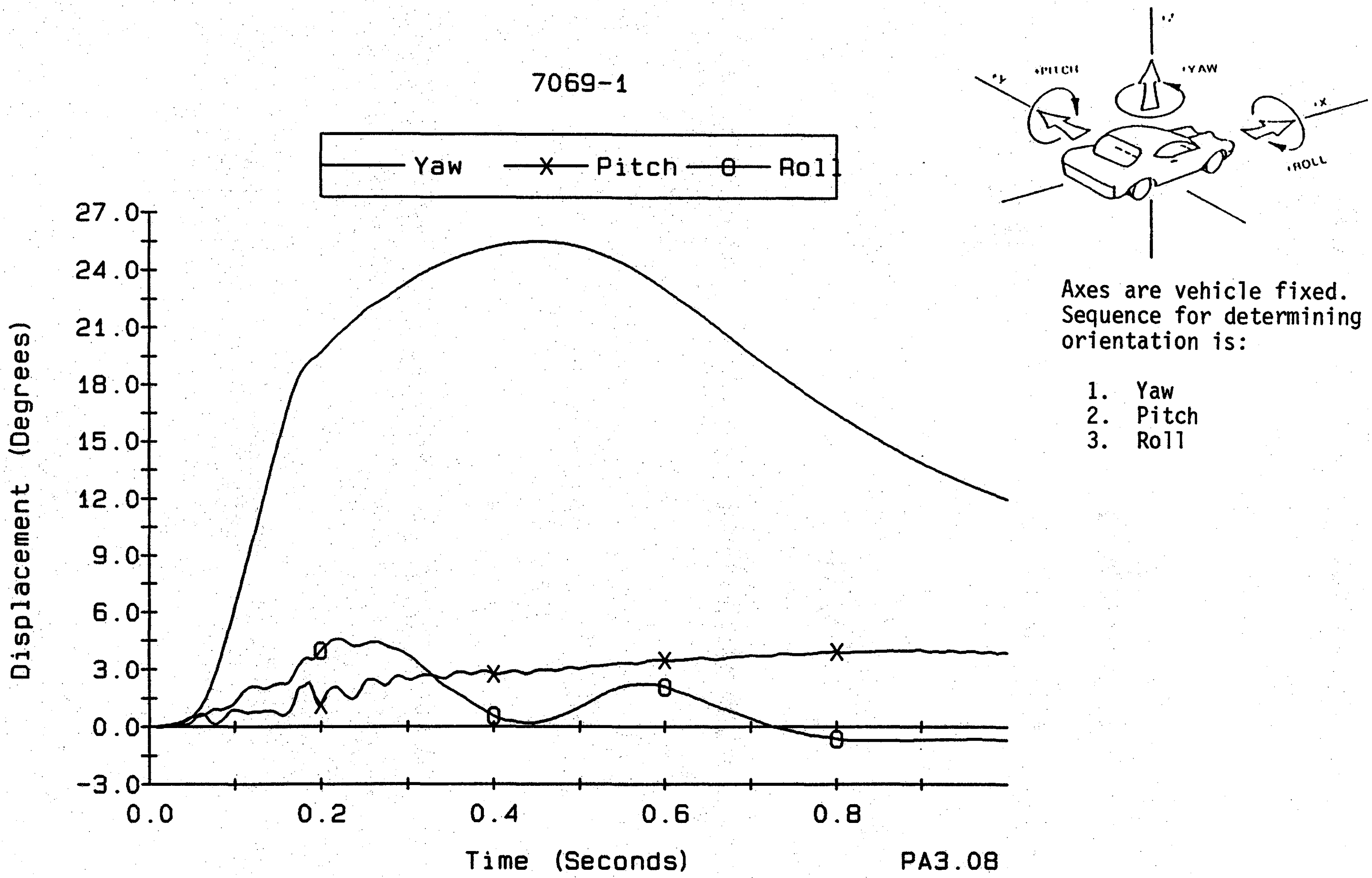


Figure 11. Vehicle angular displacement for test 7069-1.

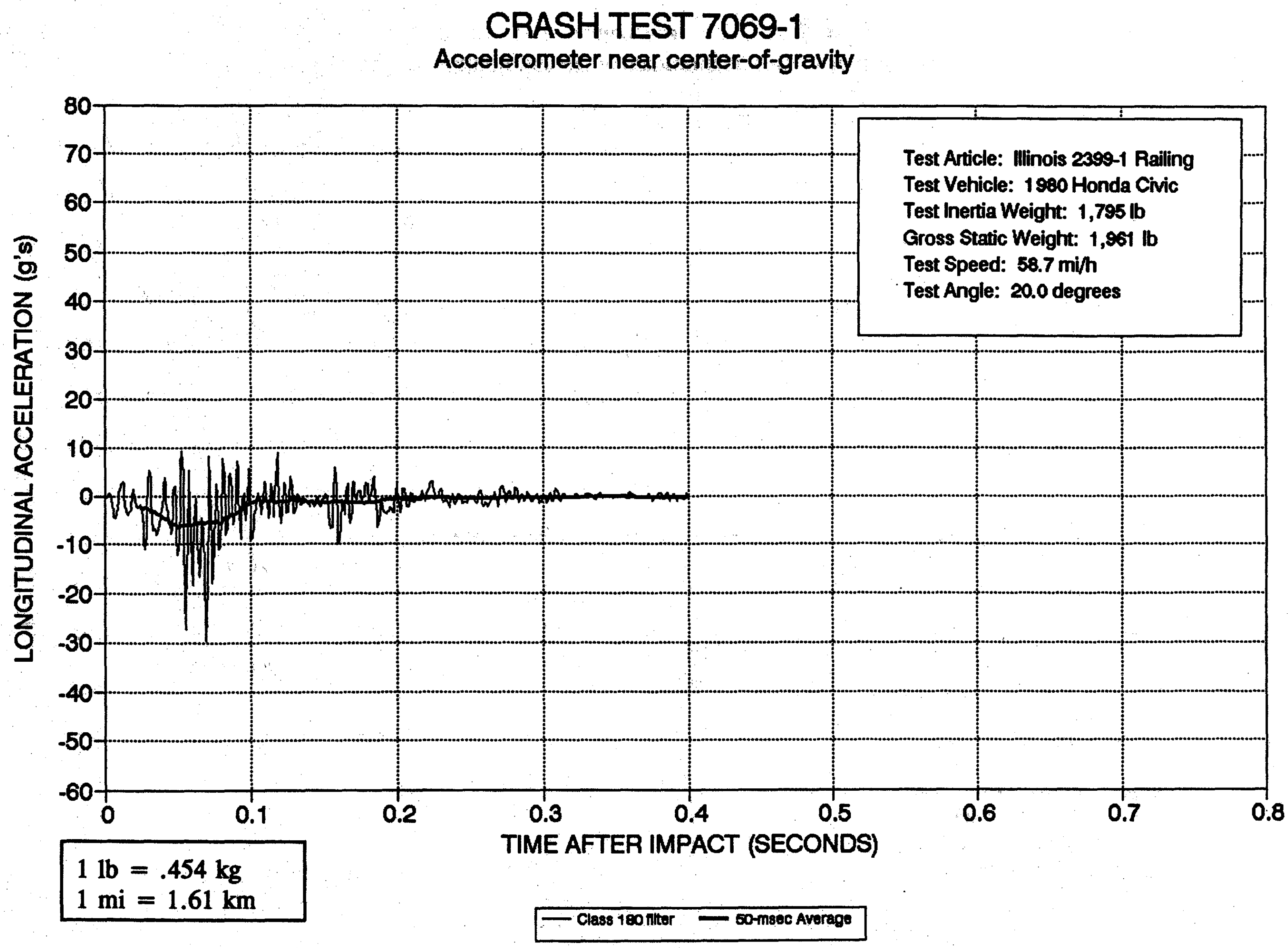


Figure 12. Vehicle longitudinal accelerometer trace for test 7069-1
(accelerometer located near center-of-gravity).

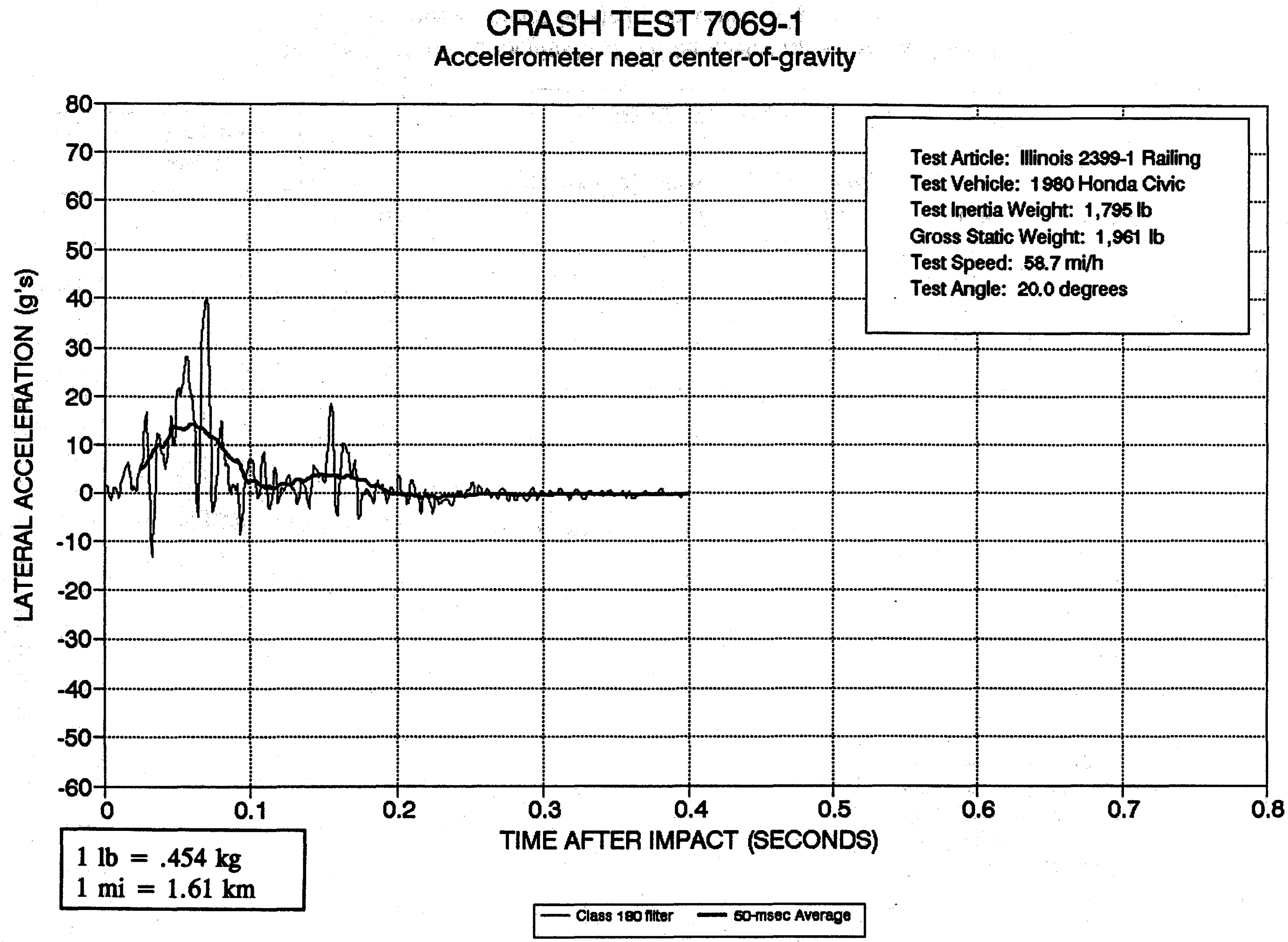


Figure 13. Vehicle lateral accelerometer trace for test 7069-1 (accelerometer located near center-of-gravity).

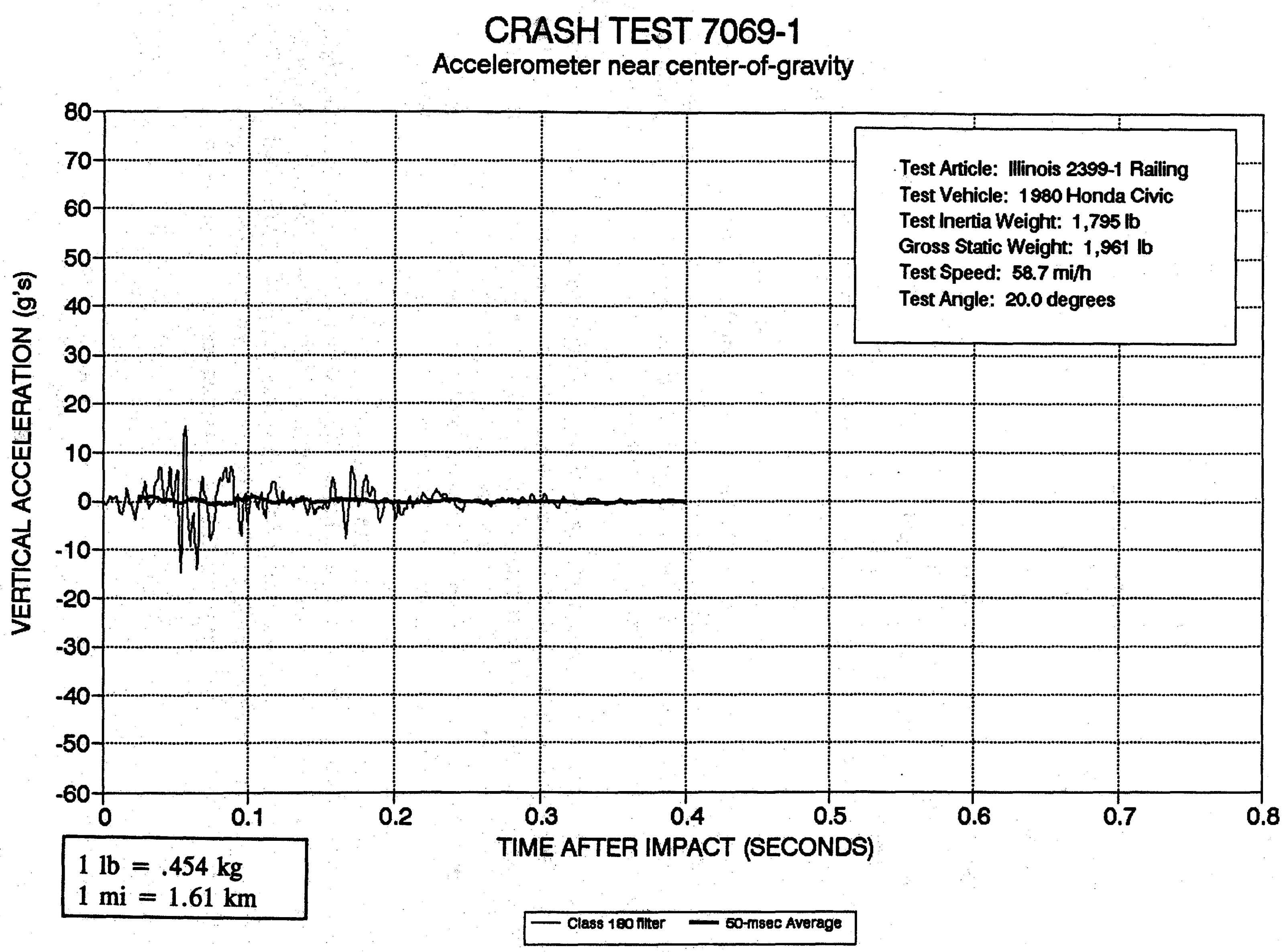


Figure 14. Vehicle vertical accelerometer trace for test 7069-1 (accelerometer located near center-of-gravity).

TEST 7069-2

Test Description

The 1981 Chevrolet pickup (shown in figures 15 and 16) was directed into the Illinois 2399-1 bridge railing (figures 17 and 18) using a cable reverse tow and guidance system. Test inertia mass of the vehicle was 5,450 lb (2 474 kg) and its gross static mass was 5,797 lb (2 632 kg). The height to the lower edge of the vehicle bumper was 17.0 in (432 mm) and it was 26.25 in (667 mm) to the top of the bumper. Other dimensions and information on the test vehicle are given in figure 19. The vehicle was free-wheeling and unrestrained just prior to impact.

The speed of the vehicle at impact was 63.6 mi/h (102.3 km/h) and the angle of impact was 19.2 degrees. The vehicle impacted the barrier midway between posts 6 and 7. At approximately 0.017 s after impact the right front tire contacted the curb, and by 0.032 s the vehicle began to redirect. As the vehicle continued forward, the wheel rim rubbed the edge of the curb chipping off pieces of concrete. The dummies began to move abruptly to the right at 0.057 s, and at 0.063 s the passenger dummy impacted the right door so hard it knocked the top portion ajar. By 0.069 s the left front tire of the vehicle went airborne. The rear of the vehicle hit the railing at 0.154 s and at 0.169 s the path of the vehicle c.g. was parallel with the railing. The vehicle lost contact with the railing at 0.234 s after impact. As the vehicle exited the railing, it had a yaw angle of 1.0 degree and a trajectory path of 5.8 degrees. The vehicle brakes were applied and the vehicle subsequently came to rest 270 ft (82 m) downstream from the point of impact.

As can be seen in figure 20, the railing received moderate damage. There were tire marks on the face of the railings and the curb and minor chips on the edge of the curb. The maximum dynamic deflection of the railing was 2.4 in (61 mm) and maximum permanent deformation was 0.5 in (13 mm). The front of the base plate on post 6 was pulled up slightly and the concrete was chipped around the bolts to the rear of the base plate as shown in figure 21. The vehicle was in contact with the upper railing element for 14.5 ft (4.4 m).

The vehicle sustained extensive damage to the right front as shown in figure 22. Maximum crush at the right front corner at bumper height was 5.0 in (127 mm). The right front and right rear wheel rims were bent and the wheel assembly and suspension damaged. The passenger door was bent and jammed and the right rear panel was dented and scraped. The hood was bent and shifted to the left. The windshield frame was bent and the windshield was cracked. The cab of the vehicle was twisted and the frame was bent.

Test Results

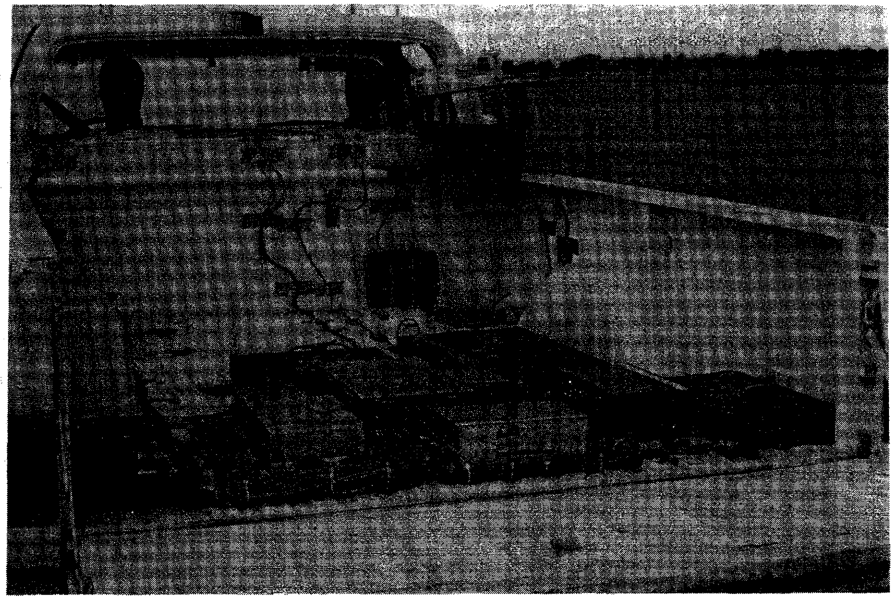
Impact speed was 63.6 mi/h (102.3 km/h), and the angle of impact was 19.2 degrees. The exit speed at time of contact (0.234 s) was 57.6 mi/h (92.7 km/h), and the vehicle trajectory path was 5.8 degrees with a vehicle yaw angle of 1.0 degree. The effective coefficient of friction was calculated to be 0.12. Occupant impact velocity was 8.5 ft/s (2.6 m/s) in the longitudinal direction and 24.6 ft/s (7.5 m/s) in the lateral direction. The highest

0.010-s occupant ridedown accelerations were -1.1 g (longitudinal) and 14.3 g (lateral). These data and other pertinent information from the test are summarized in figure 23 and table 3. Sequential photographs of the test are shown in figures 24 and 25. Vehicular angular displacements are displayed in figure 26, and accelerometer traces from the vehicle are shown in figures 27 through 29.

Conclusions

The Illinois 2399-1 bridge railing contained and smoothly redirected the vehicle with minimal lateral movement of the railing. There were no debris or detached elements. There was no intrusion into the occupant compartment. The vehicle trajectory at loss of contact indicates minimum intrusion into adjacent traffic lanes. The vehicle remained upright and stable during the entire test period.

According to the criteria set forth by FHWA in the recommended test matrix of February 1987, this test meets the requirements for structural adequacy, vehicle trajectory, and occupant risk factors. Therefore, this test should be considered acceptable.



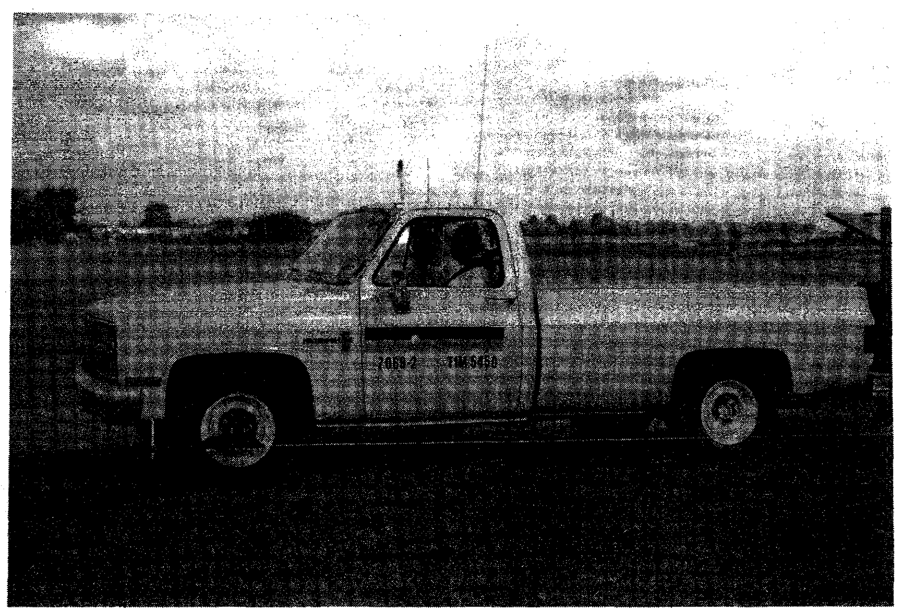


Figure 15. Vehicle before test 7069-2.

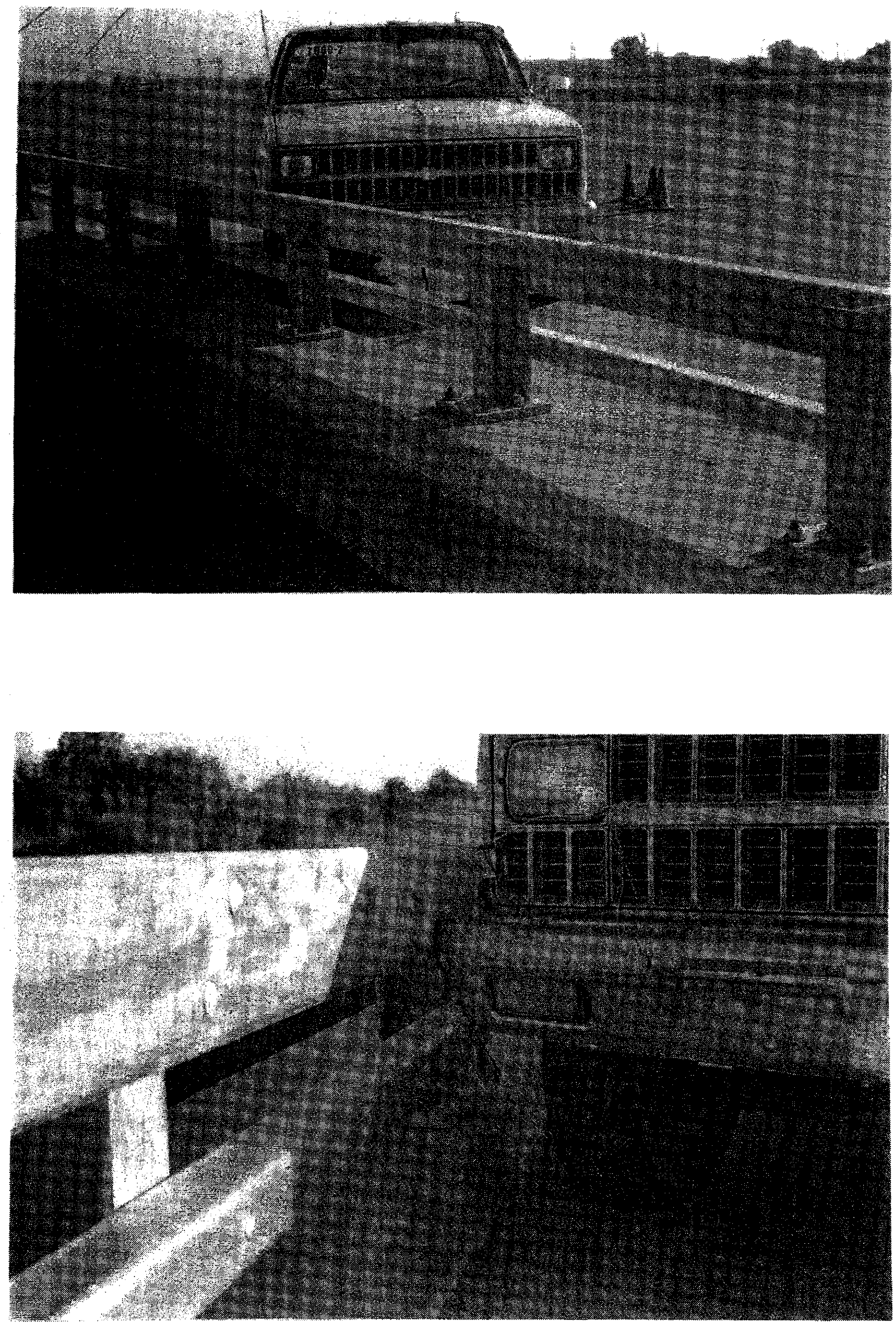
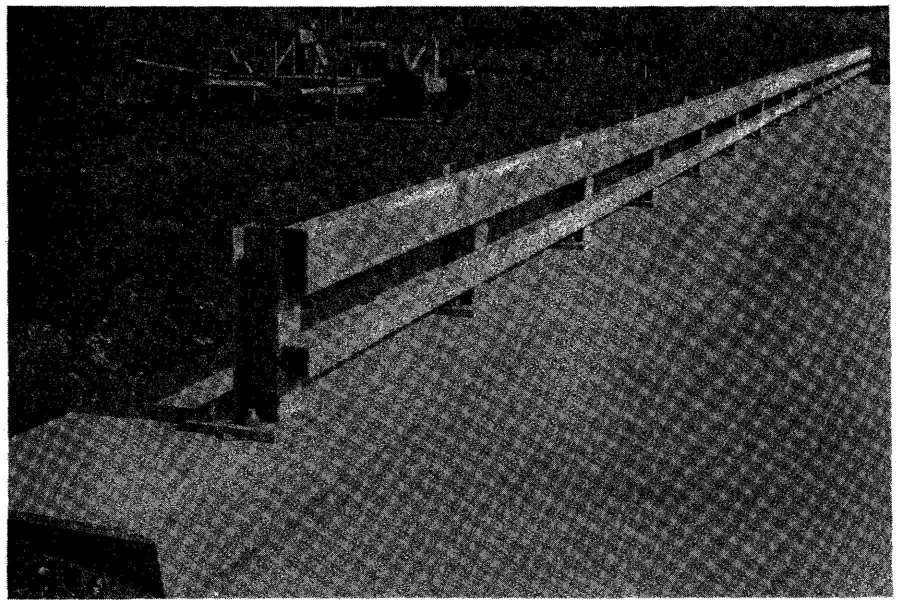


Figure 16. Vehicle/bridge railing geometrics for test 7069-2.



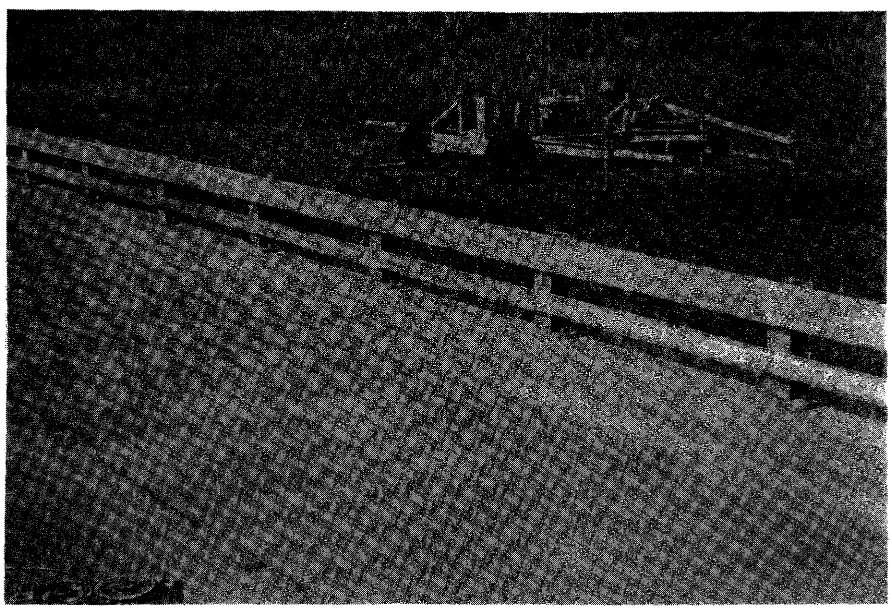


Figure 17. Illinois 2399-1 bridge railing before test 7069-2.

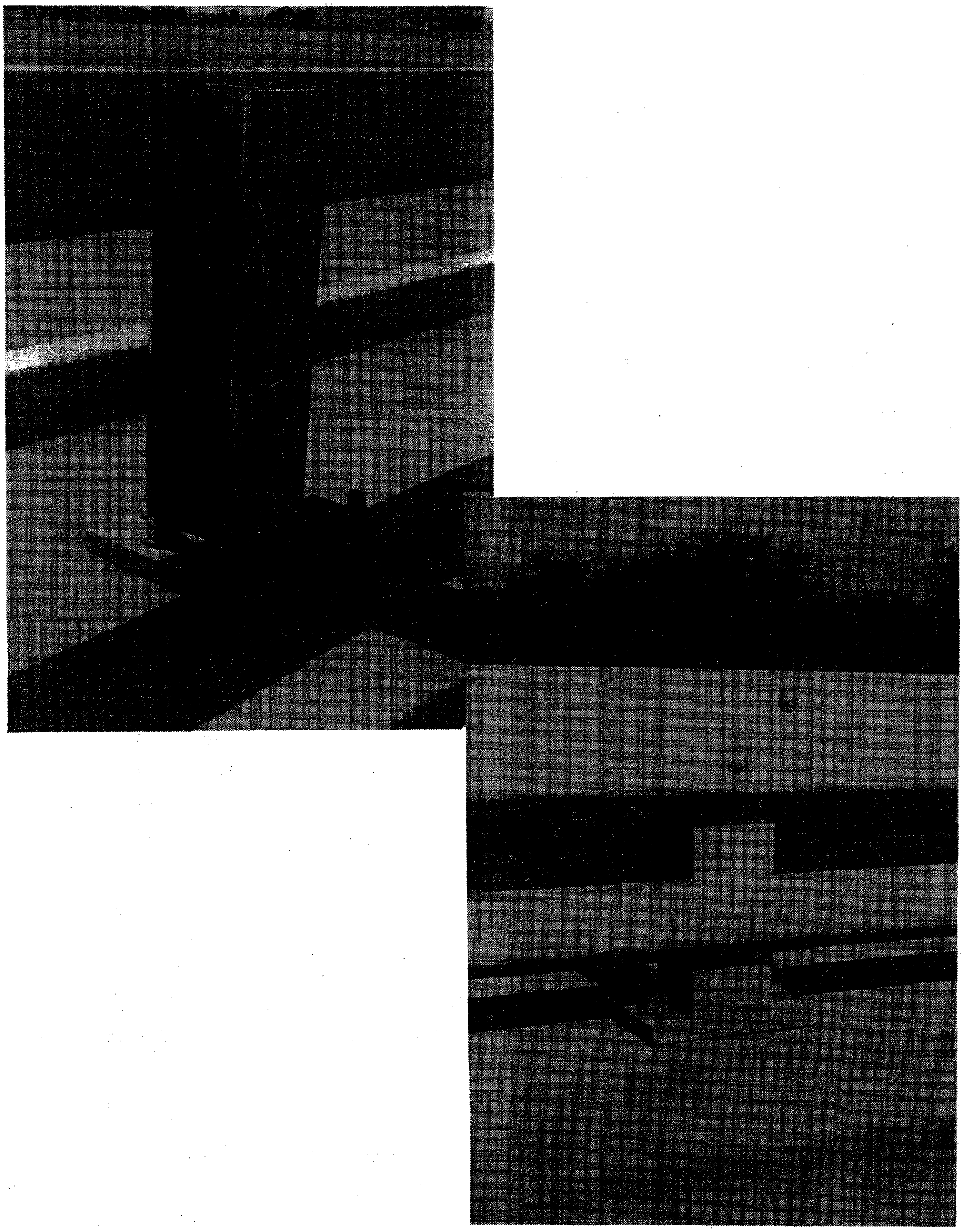


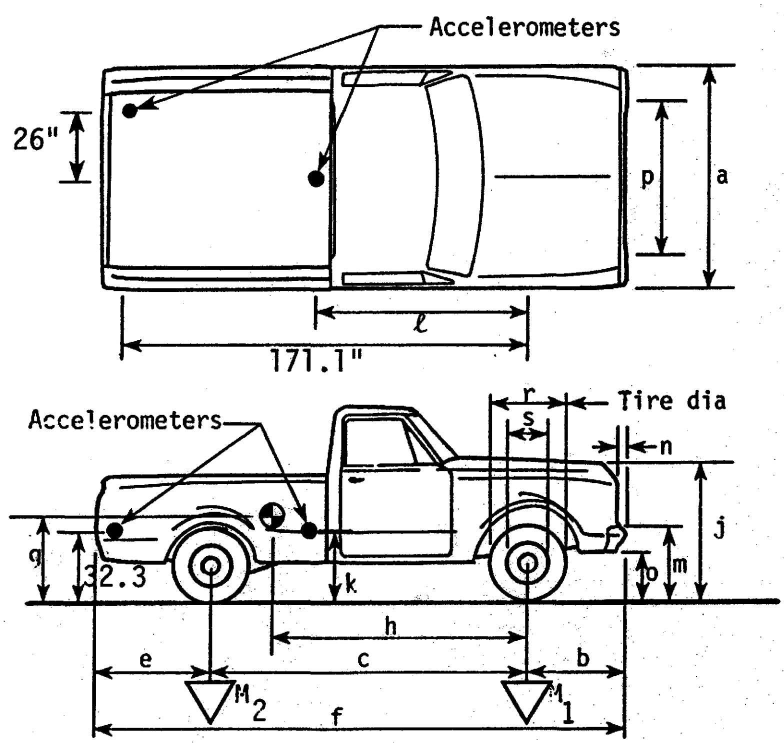
Figure 18. Post detail for Illinois 2399-1 bridge railing.

Date: 7-24-87 Test No.: 7069-2 VIN: 16CFC24D8BS169670

Make: Chevrolet Model: Custom Deluxe Year: 1981 Odometer: 138612

Tire Size: 7.50 16 LT Ply Rating: 4 Bias Ply: x Belted: ___ Radial: ___

Tire Condition: good ___
fair X
badly worn ___



Vehicle Geometry - inches

a	79.25	b	33.50
c	132.00	d*	71.00
e	50.25	f	216.00
g	27.25	h	72.70
i	----	j	44.25
k	30.00	ℓ	73.00
m	26.25	n	4.00
o	17.00	p	65.50
r	29.00	s	17.00

4-wheel weight for c.g. det. ℓf 1257 rf 1192 ℓr 1483 rr 1518

Mass - pounds	Curb	Test Inertial	Gross Static
M_1		2449	2649
M_2		3001	3148
M_T		5450	5797

Note any damage to vehicle prior to test:

___

___

*d = overall height of vehicle

1 in = 25.4 mm
1 lb = .454 kg

Engine Type: 6 cylinder

Engine CID: 250

Transmission Type:

Automatic or Manual

FWD or RWD or 4WD

Body Type: Pickup

Steering Column Collapse Mechanism:

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

Brakes:

Front: disc___ drum___

Rear: disc___ drum___

Figure 19. Vehicle properties for test 7069-2.

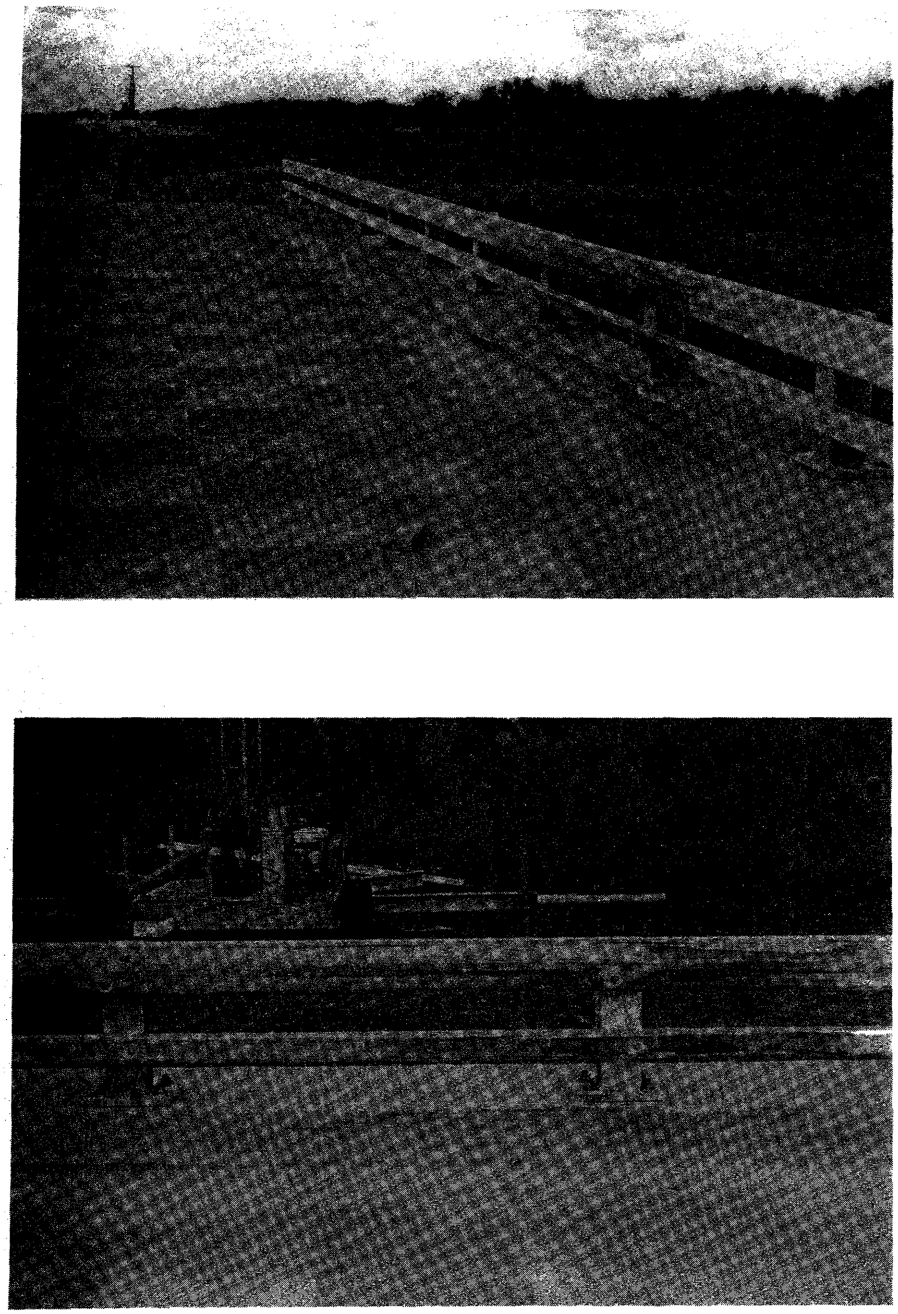
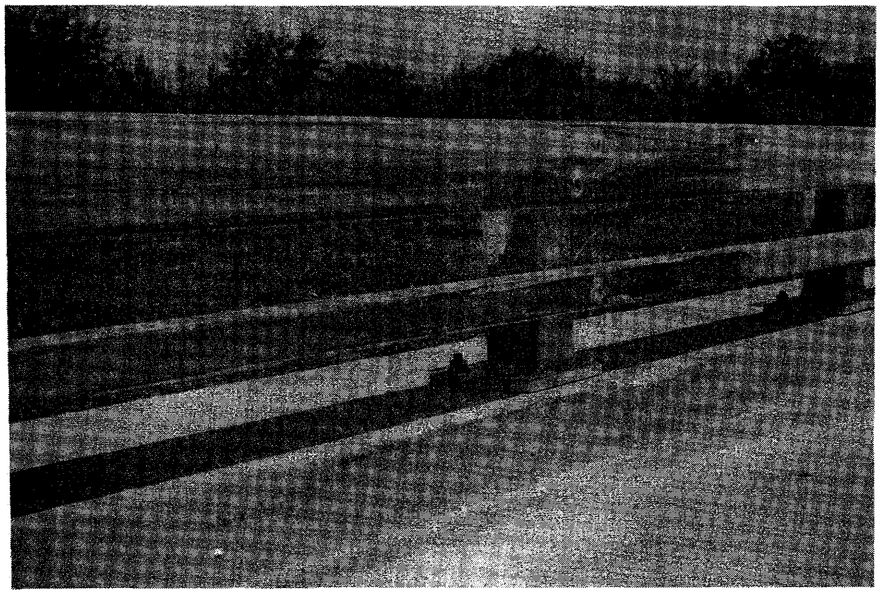
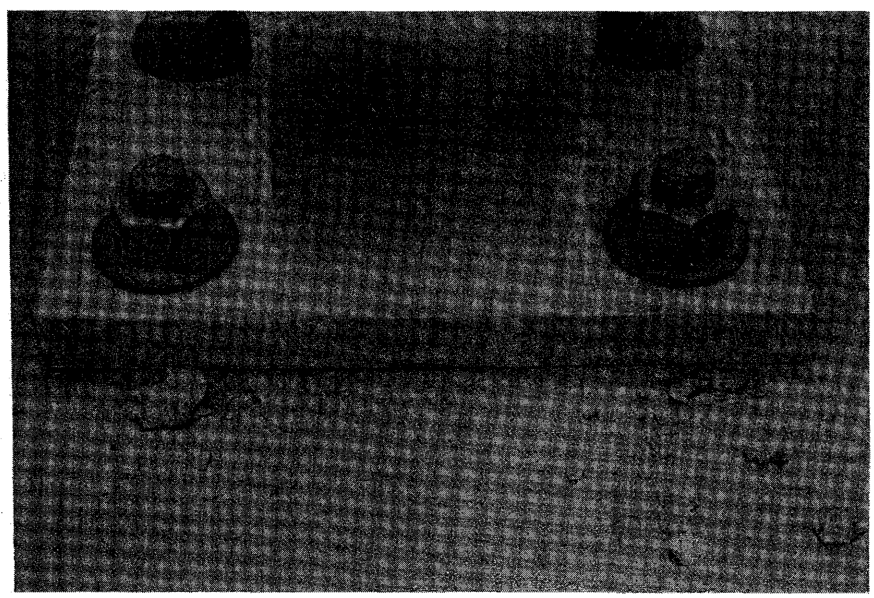


Figure 20. Illinois 2399-1 bridge railing after test 7069-2.





rear of post 6

Figure 21. Detail of damage to railing and post 6.

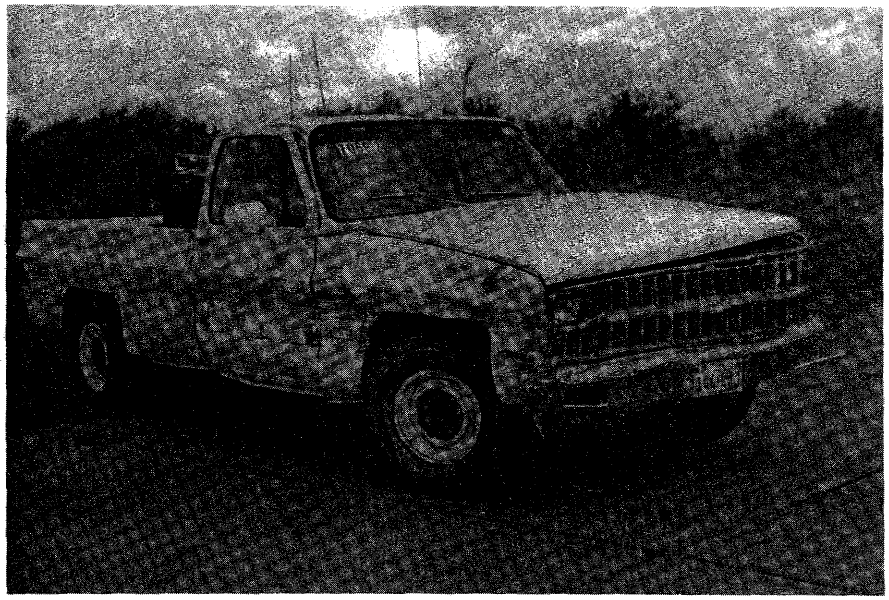
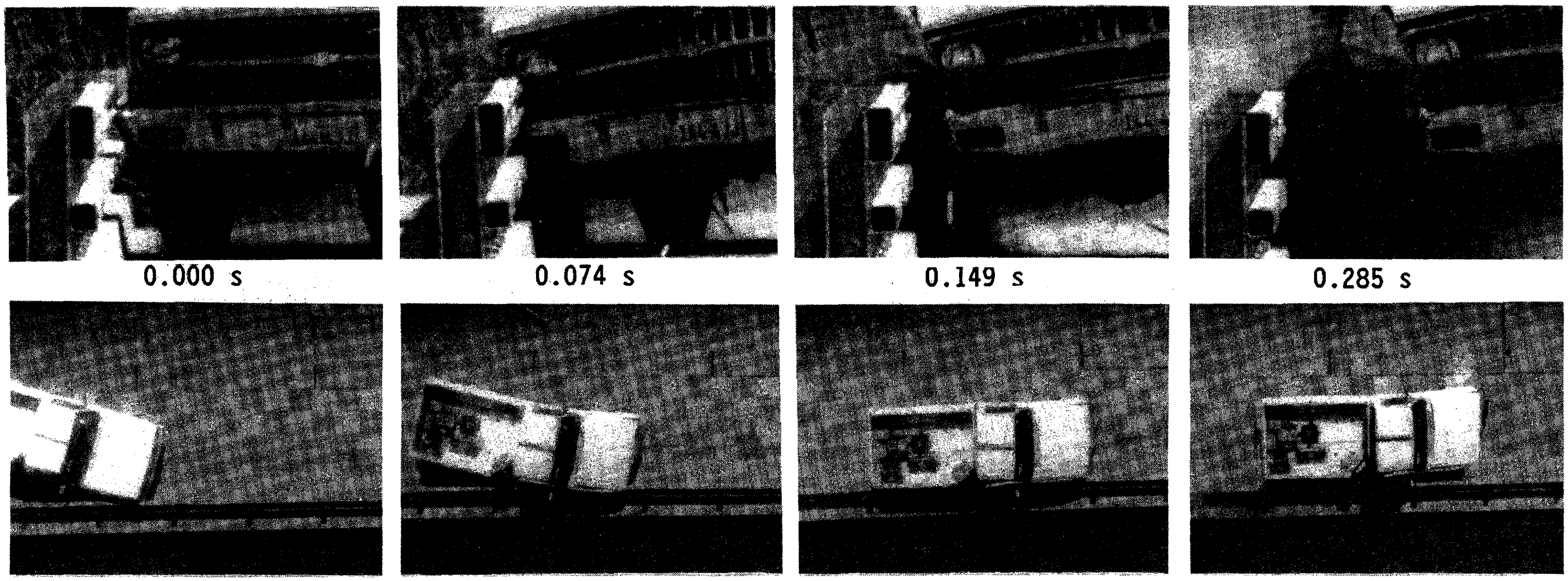
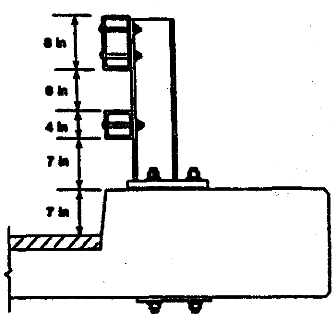


Figure 22. Vehicle after test 7069-2.





(1 in = 25.4 mm)

Test No. 7069-2
Date 7/24/87
Test Installation . . . Illinois 2399-1 Bridge Railing
Installation Length . . 100 ft (30 m)
Vehicle . . . . 1981 Chevrolet Pickup
Vehicle Weight
  Test Inertia . . . . . 5,450 lb (2,474 kg)
  Gross Static . . . . . 5,797 lb (2,632 kg)
Vehicle Damage Classification
  TAD 01RD4
  CDC . . . . 01FREK1 & 01RYEW2
Maximum Vehicle Crush . 5.0 in (127 mm)
Max. Dyn. Rail Deflct. . 2.4 in (610 mm)
Max. Perm. Rail Deform . 0.5 in (13 mm)

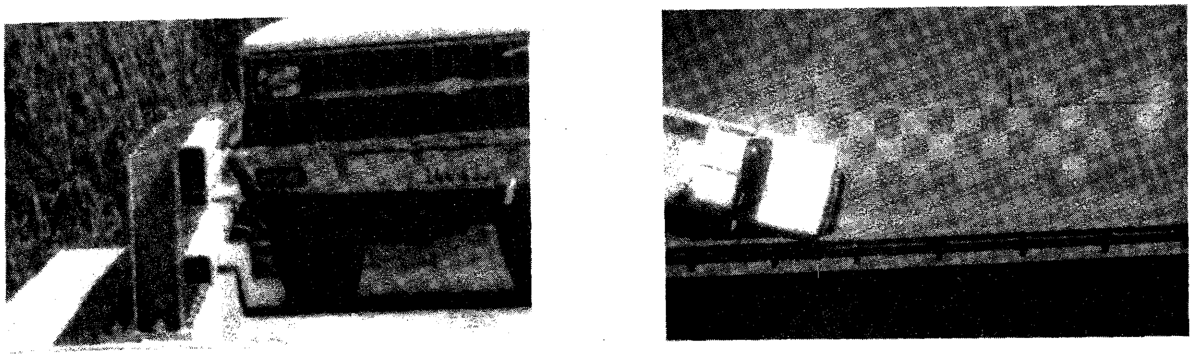
Impact Speed. . . 63.6 mi/h (102.3 km/h)
Impact Angle. . . 19.2 deg
Exit Speed. . . . 57.6 mi/h (92.7 km/h)
Exit Trajectory . 5.8 deg
Vehicle Accelerations
  (Max. 0.050-sec Avg)
  Longitudinal. . -3.8 g
  Lateral . . . . 14.3 g
Occupant Impact Velocity
  Longitudinal. . 8.5 ft/s (2.6 m/s)
  Lateral . . . . 24.6 ft/s (7.5 m/s)
Occupant Ridedown Accelerations
  Longitudinal. . -1.1 g
  Lateral . . . . 12.8 g

Figure 23. Summary of results for test 7069-2.

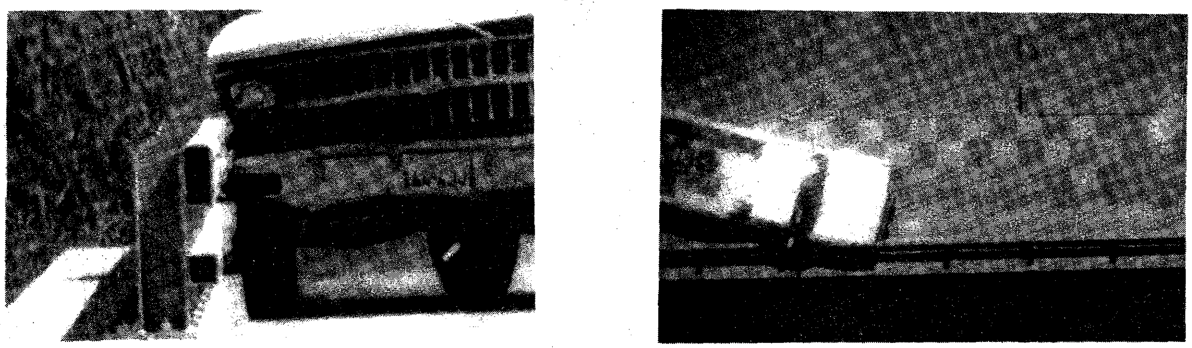
Table 3. Evaluation of crash test no. 7069-2.
{Illinois 2399-1 Railing [5,450 lb (2 474 kg)|63.6 mi/h (102.3 km/h)|19.2 degrees]}

	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	Minimal 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 .12 — 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: 8.5 (2.6) — Lateral: 24.6 (7.5)	Pass
	Occupant Ridedown Accelerations - g's Longitudinal: 15 — Lateral: 15	Occupant Ridedown Accelerations - g's Longitudinal: -1.1 — Lateral: 12.8	Pass
H.	Exit angle shall be less than 12 degrees	Exit angle was 5.8 degrees	Pass

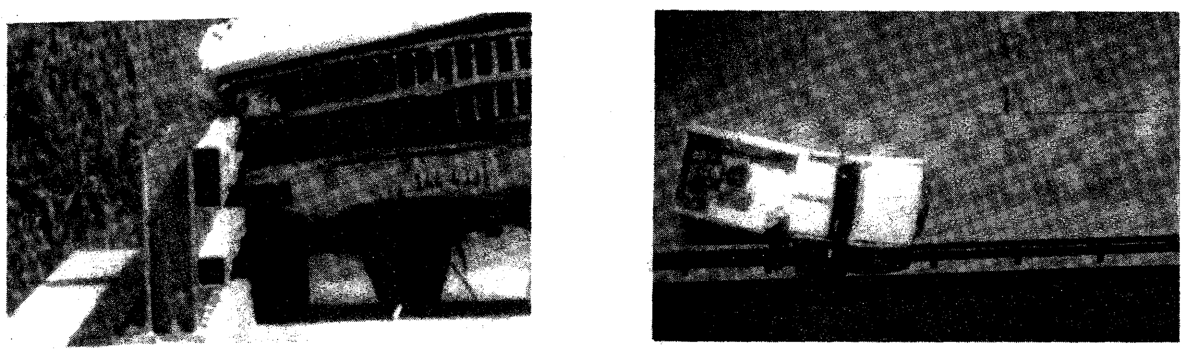
* A, B, C, and D are required. E, F, G, and H are desired. (See table 2)



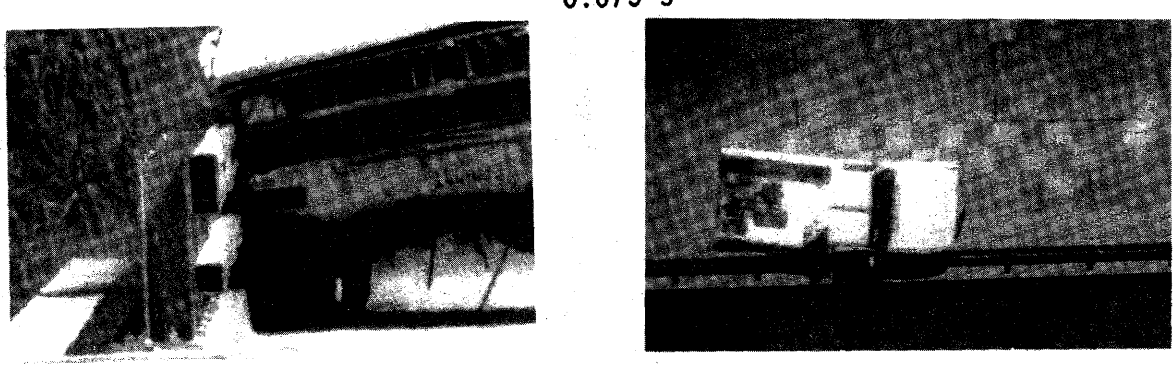
0.000 s



0.037 s

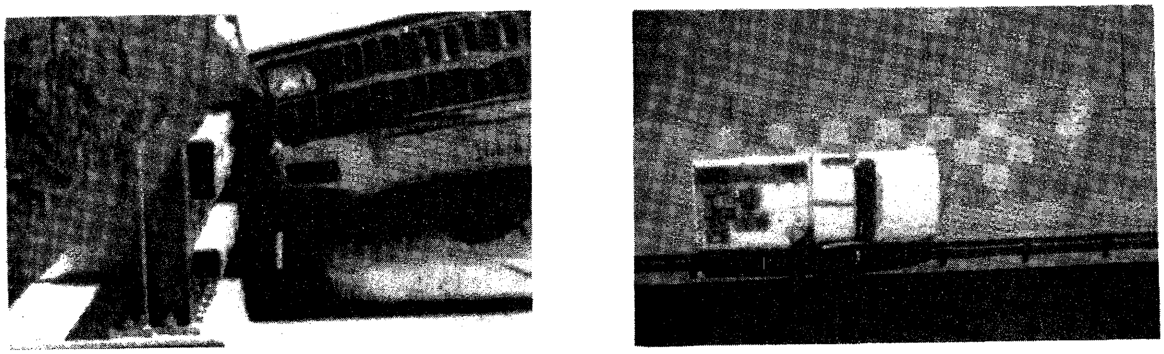


0.075 s

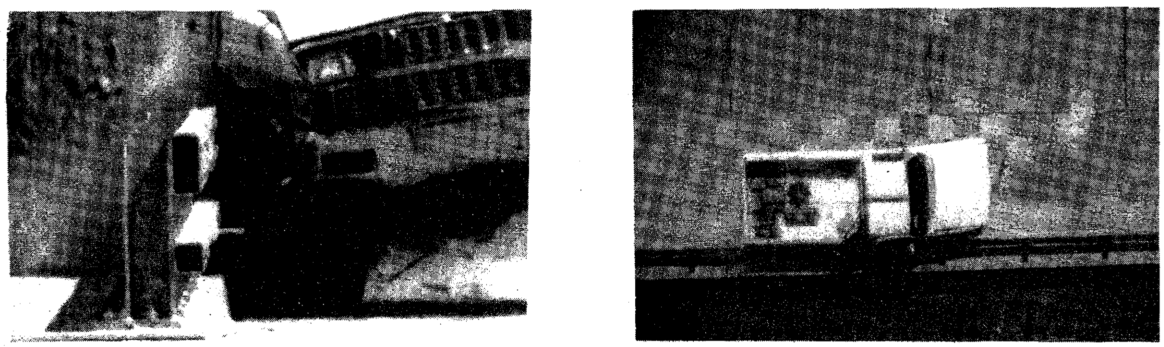


0.112 s

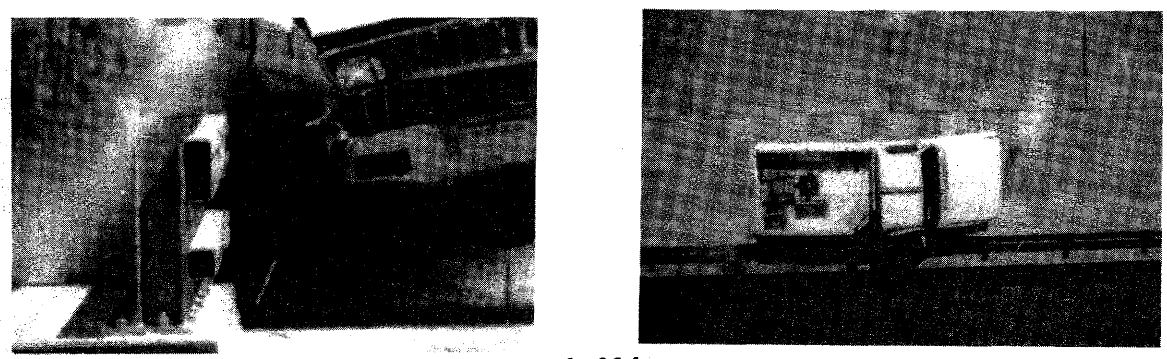
Figure 24. Sequential photographs for test 7069-2 (frontal and overhead views).



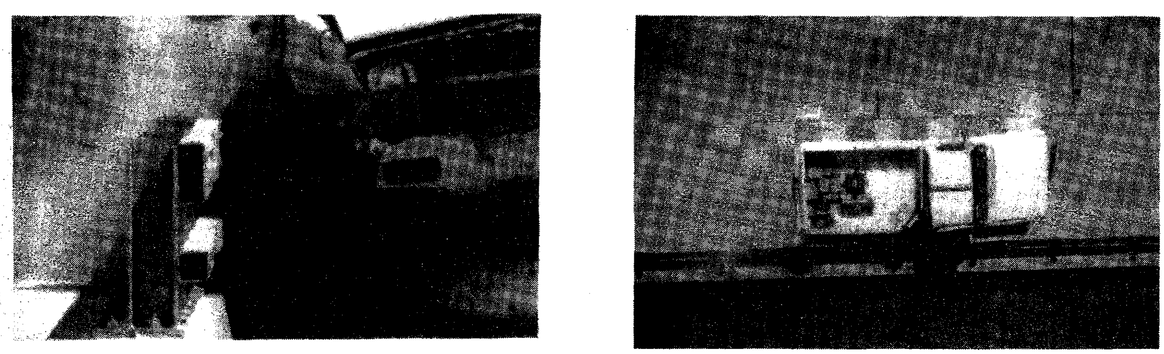
0.149 s



0.192 s



0.234 s



0.284 s

Figure 24. Sequential photographs for test 7069-2 (frontal and overhead views continued).

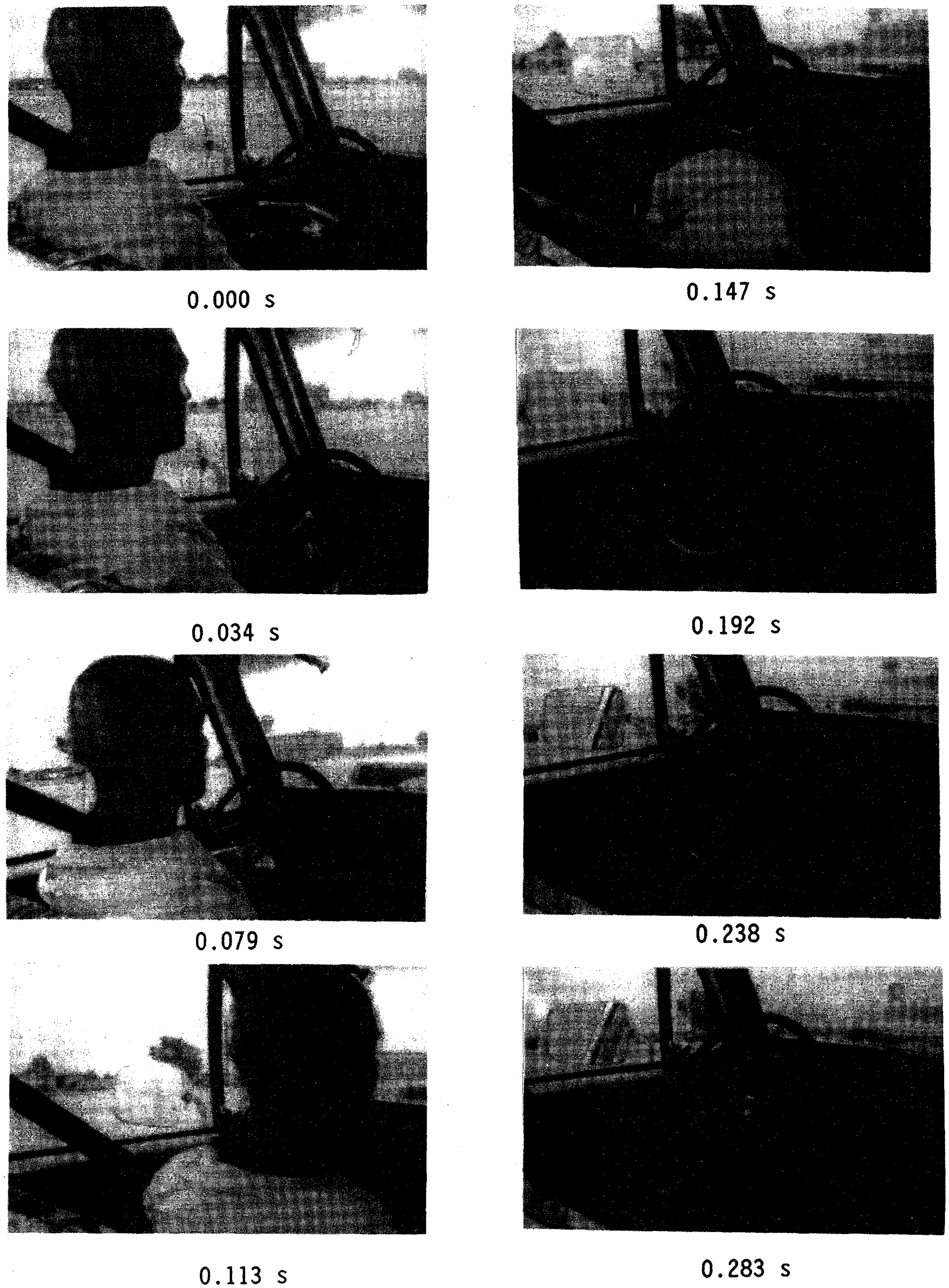


Figure 25. Interior sequential photographs for test 7069-2.

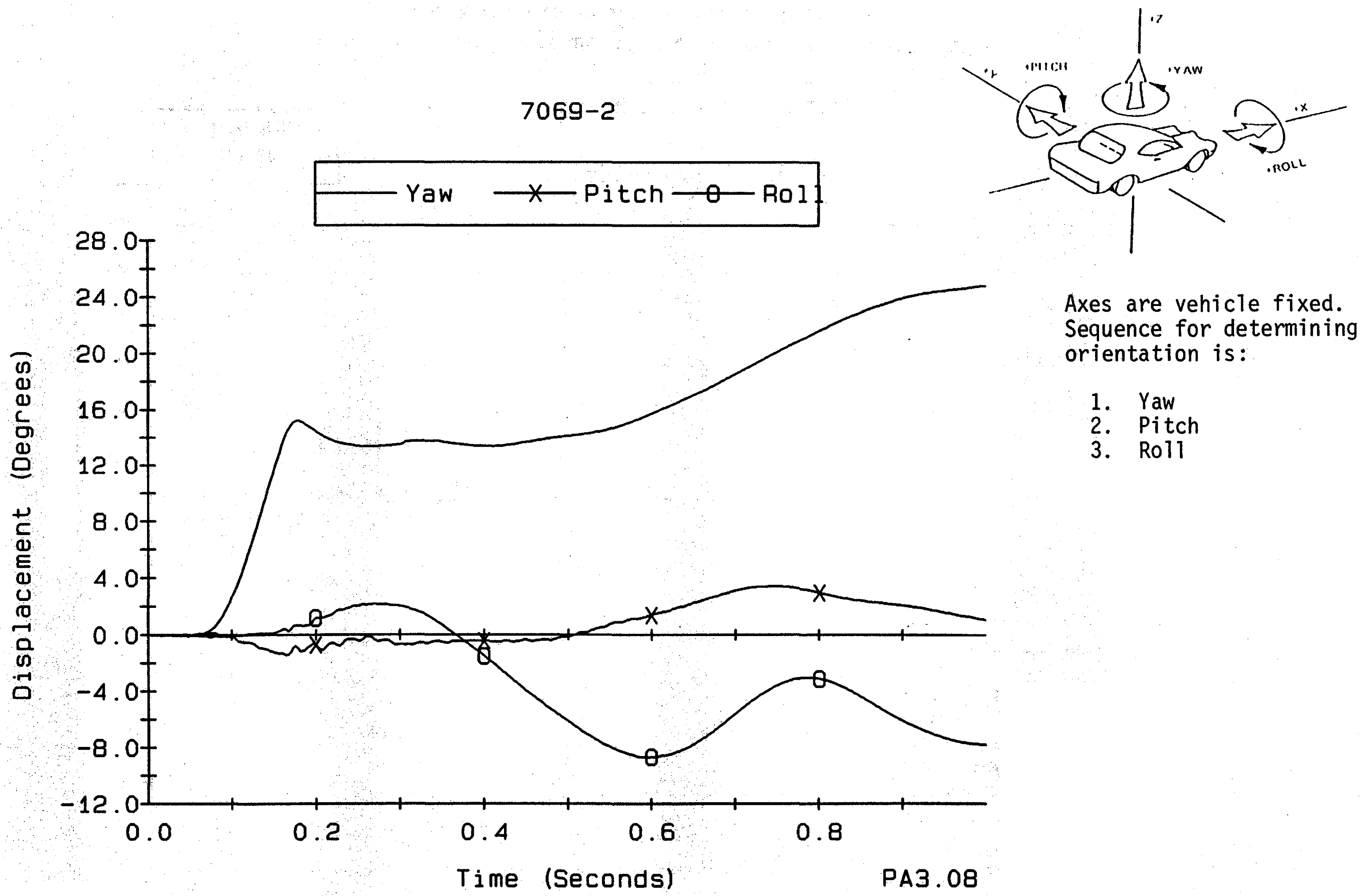


Figure 26. Vehicle angular displacements for test 7069-2.

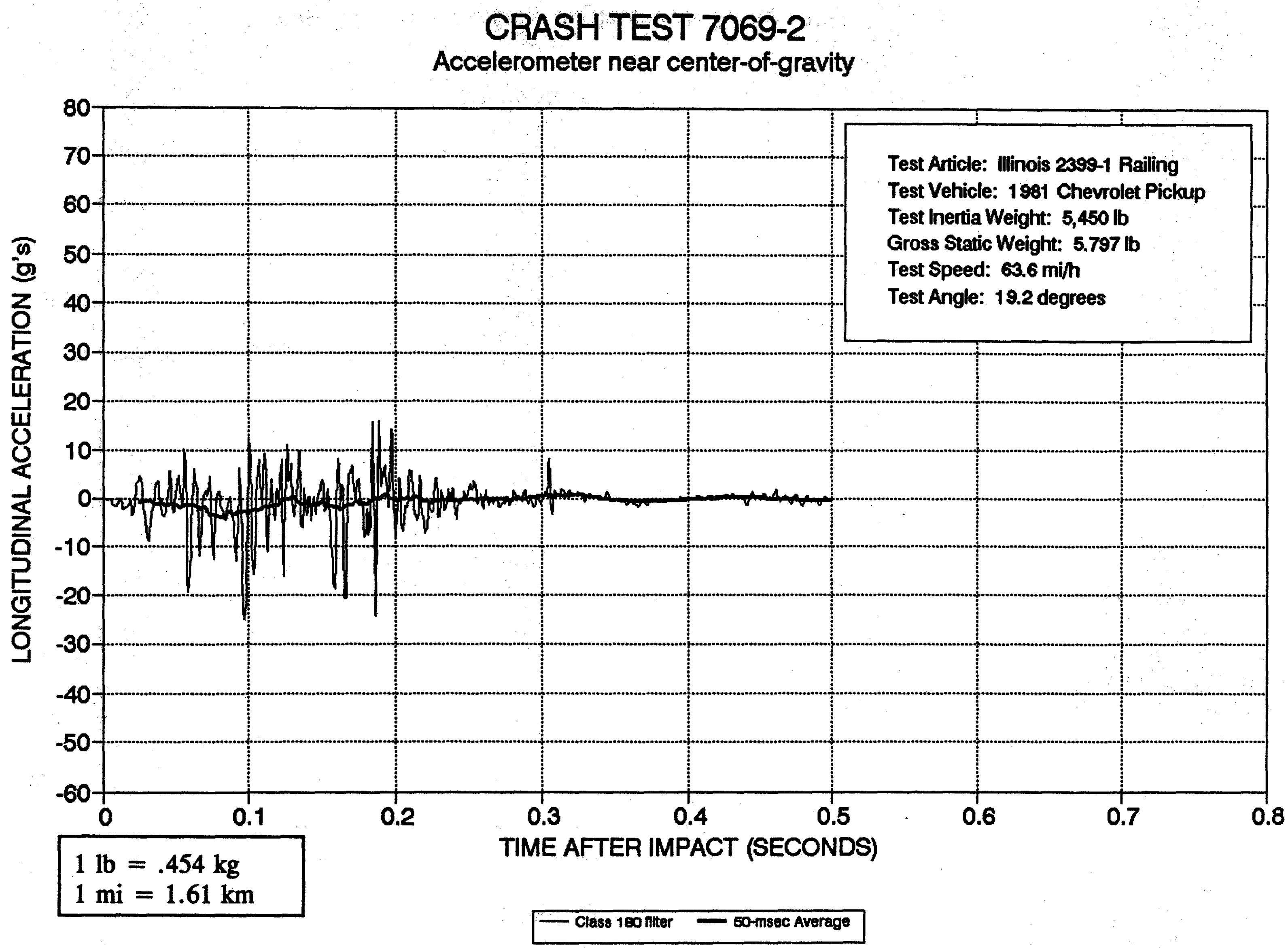


Figure 27. Vehicle longitudinal accelerometer trace for test 7069-2 (accelerometer located near center-of-gravity).

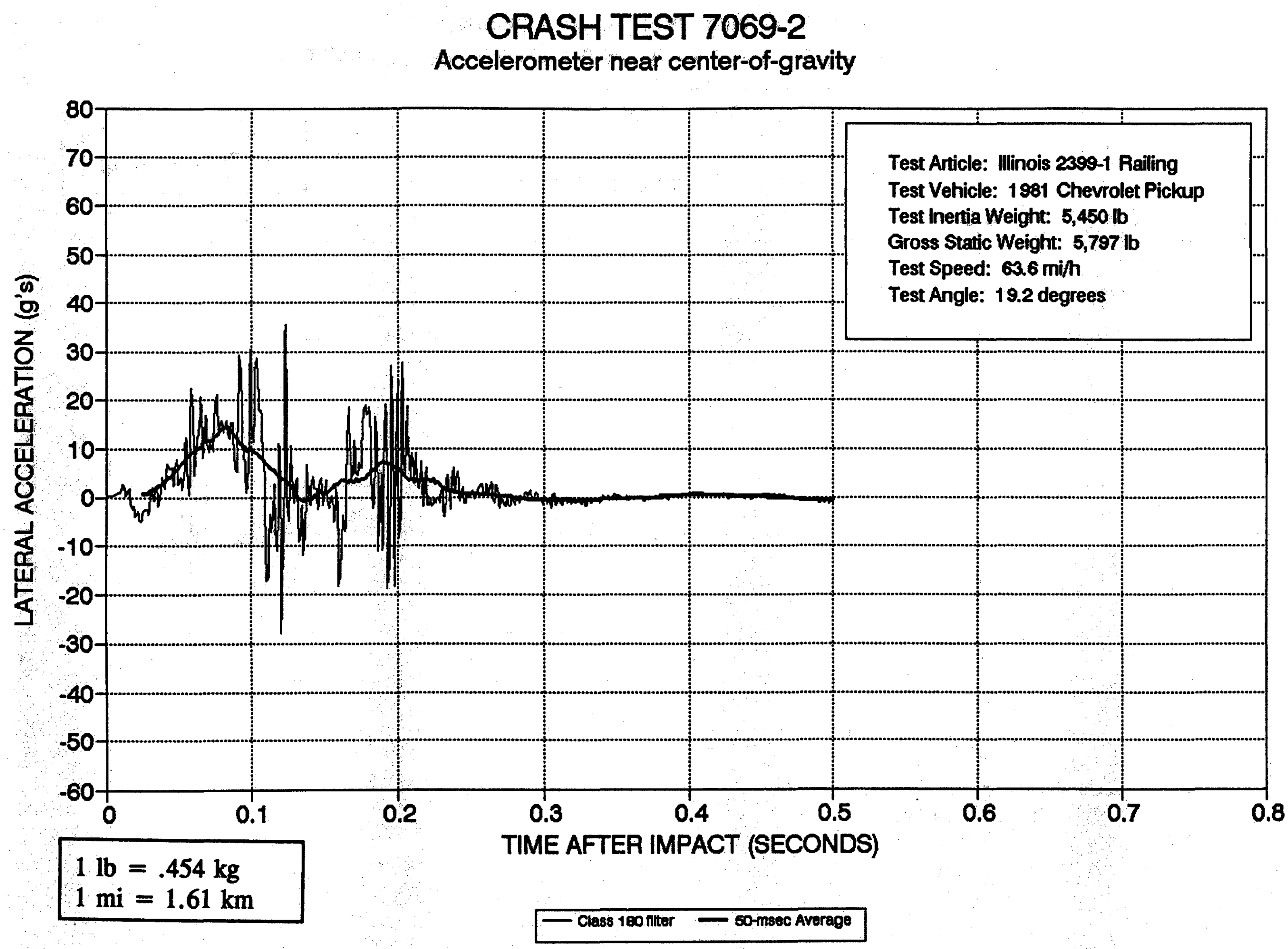


Figure 28. Vehicle lateral accelerometer trace for test 7069-2
(accelerometer located near center-of-gravity).

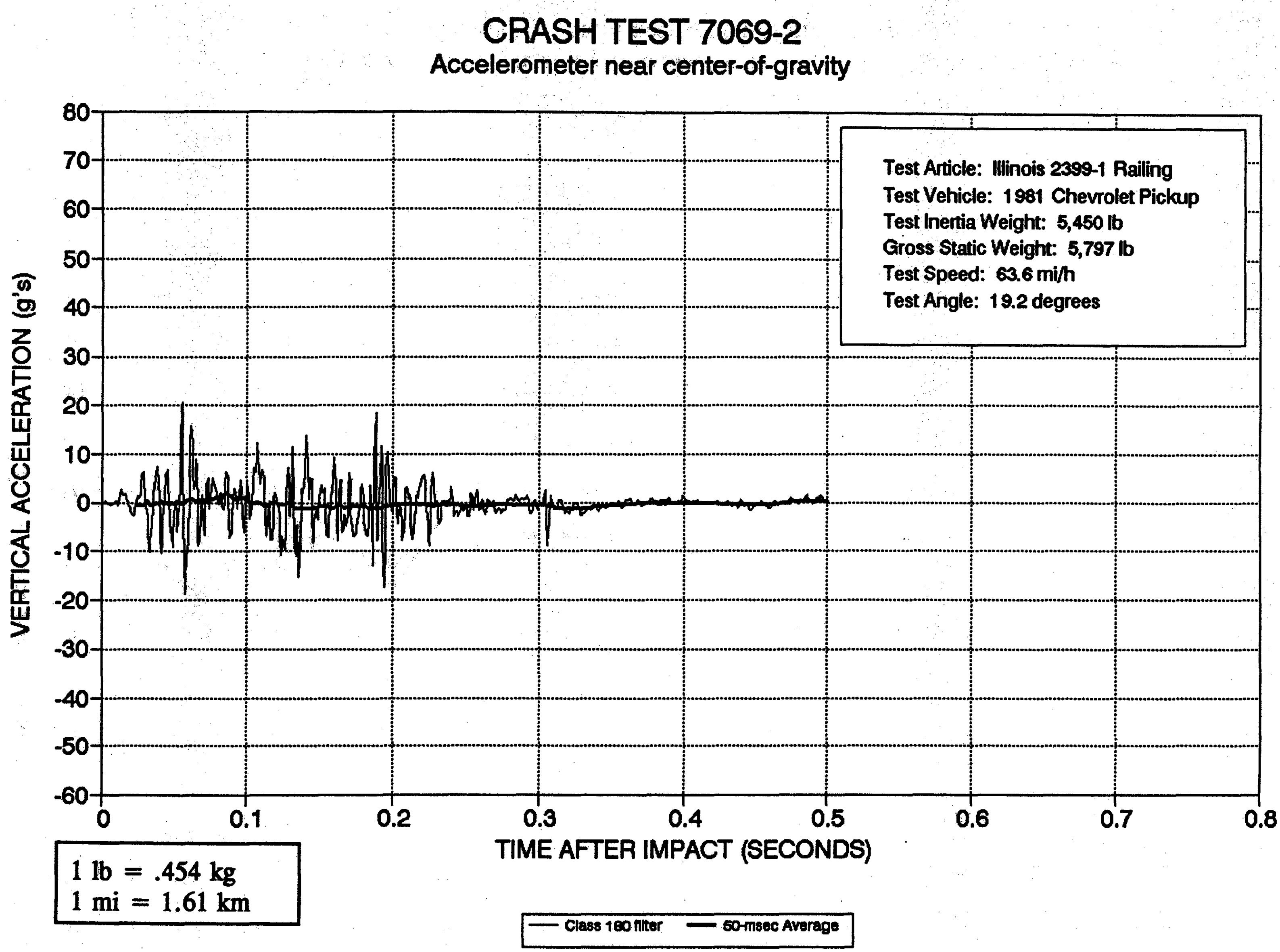


Figure 29. Vehicle vertical accelerometer trace for test 7069-2 (accelerometer located near center-of-gravity).

TEST 7069-15

Test Description

The 1980 Ford 7000 Single-Unit Truck (figures 30 and 31) was directed into the Illinois 2399-1 bridge railing (figures 31 and 32) using a remote control system. Empty weight of the vehicle was 12,320 lb (5 593 kg) and its test inertia weight was 18,000 lb (8 172 kg). The height to the bottom of the bumper was 29.5 in (394 mm) and it was 23.5 in (597 mm) to the top of the bumper. Other dimensions and information on the test vehicle are given in figures 33 and 34. The vehicle was free-wheeling and unrestrained just prior to impact.

The speed of the vehicle just prior to impact was 50.8 mi/h (81.7 km/h) and the impact angle was 15.1 degrees. The vehicle impacted the railing approximately 26 ft (7.9 m) from the end between post 4 and 5. Shortly after impact the right front tire made contact with the lower railing element and began to ride up the curb. As the vehicle continued its forward motion into the railing the right front tire pushed the lower railing element down. By 0.071 s after impact the cab began to shift to the left and at approximately 0.109 s the vehicle began to redirect. At 0.149 s the right front tire made contact with post 6 and by 0.276 s the vehicle was airborne. The rear of the vehicle slapped the railing at approximately 0.310 s and began to move parallel to the bridge railing at 0.320 s traveling at 47.5 mi/h (76.4 km/h). The vehicle continued along the top of the railing, and at 0.447 s the lower edge of the box made contact with the top edge of post 8 and began to tear the box as the vehicle continued down the railing while still airborne. The vehicle made contact with the ground at about 1.129 s and lost contact with the railing at 1.392 s. Total length of contact with the bridge railing was 74 ft (22.6 m). After the vehicle left the railing, the brakes were applied but the left side of the vehicle made contact with another barrier. The vehicle came to rest 132 ft (40 m) from the point of impact.

Damage to the railing is shown in figures 35 through 39. The bolts connecting the lower railing element to the post were sheared on posts 3 through 7. At post 5 the bolt on the upper railing element was sheared and the face of the element itself was gouged. The flange on post 6 was bent and the concrete curb was cracked at posts 6 through 9. The top of post 8 was bent where it made contact with the box. During the test, the lower railing element was pushed down. After the test, the maximum vertical movement was 3 in (76 mm) at post 5.

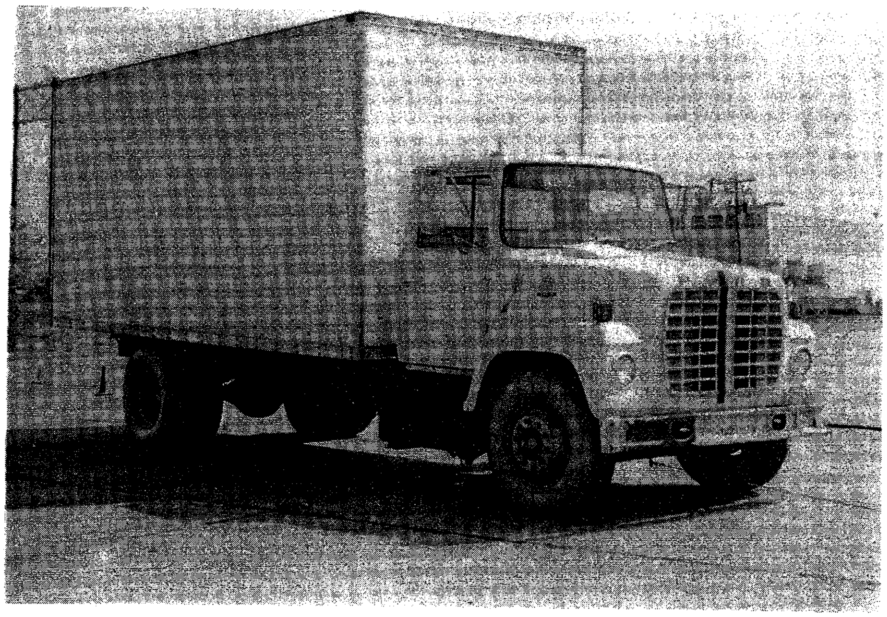
Damage to the vehicle was extensive and is shown in figures 40 and 41. The steering arm rod, u-bolts, spring pins, and front and rear spring mounts were damaged. The frame was bent as well as the rear part of the drive shaft, the rear u-joint, the battery box, and the gas tank. The cargo box was torn during the test and as the vehicle left the railing and rolled to the right, the load shifted and tore open the right side of the box.

Test Results

Impact speed was 50.8 mi/h (81.7 km/h), and the angle of impact was 15.1 degrees. The exit speed was not attainable, but exit angle was 0 degrees. The effective coefficient of friction was calculated to be 0.115. Occupant impact velocity was 9.8 ft/s (3.0 m/s) in the longitudinal direction and 12.4 ft/s (3.8 m/s) in the lateral direction. The highest 0.010-s occupant ridedown accelerations were -2.5 g (longitudinal) and 7.4 g (lateral). 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. Vehicle angular displacements are displayed in figure 45. Vehicular accelerations versus time traces are presented in figures 46 through 52. These data were further analyzed to obtain 0.050-s averages measured at the center-of-gravity were -1.9 g (longitudinal) and 4.9 g (lateral).

Conclusions

The Illinois 2399-1 bridge railing contained and smoothly redirected the test vehicle with minimal lateral movement of the bridge railing. There was no intrusion into the occupant compartment and very little deformation of the compartment. The vehicle trajectory at loss of contact indicates minimum intrusion into adjacent traffic lanes, and the vehicle remained relatively stable during the collision.



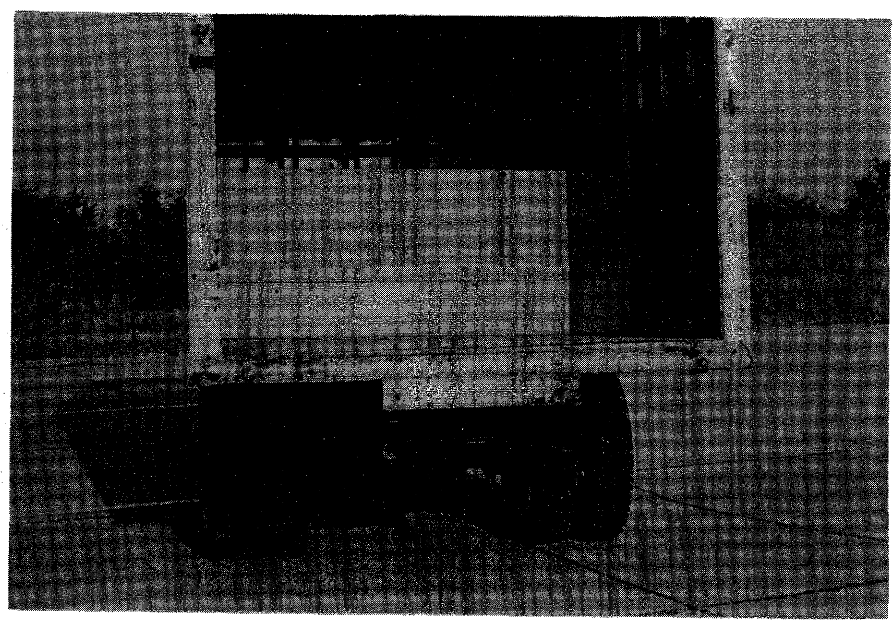


Figure 30. Vehicle before test 7069-15.

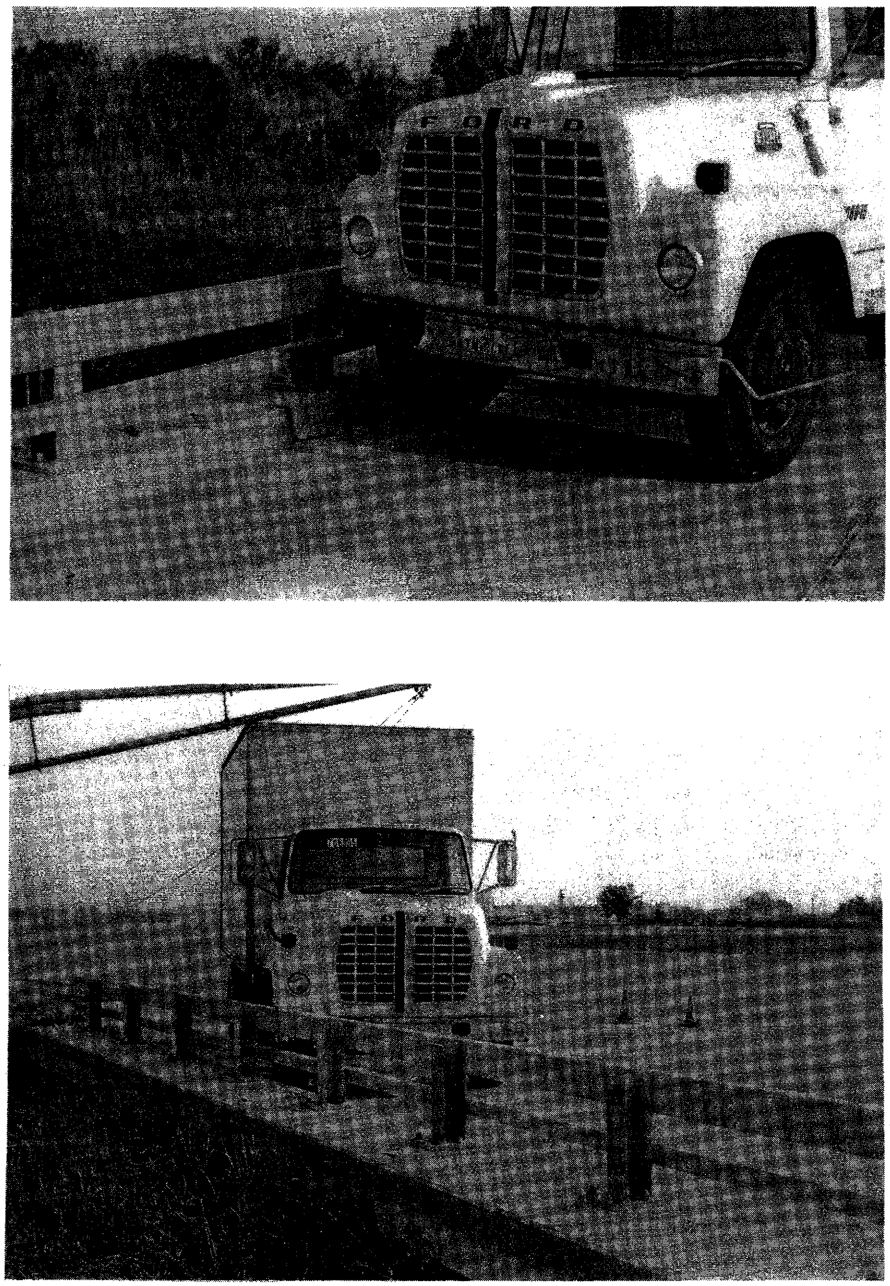


Figure 31. Vehicle/bridge railing geometrics for test 7069-15.

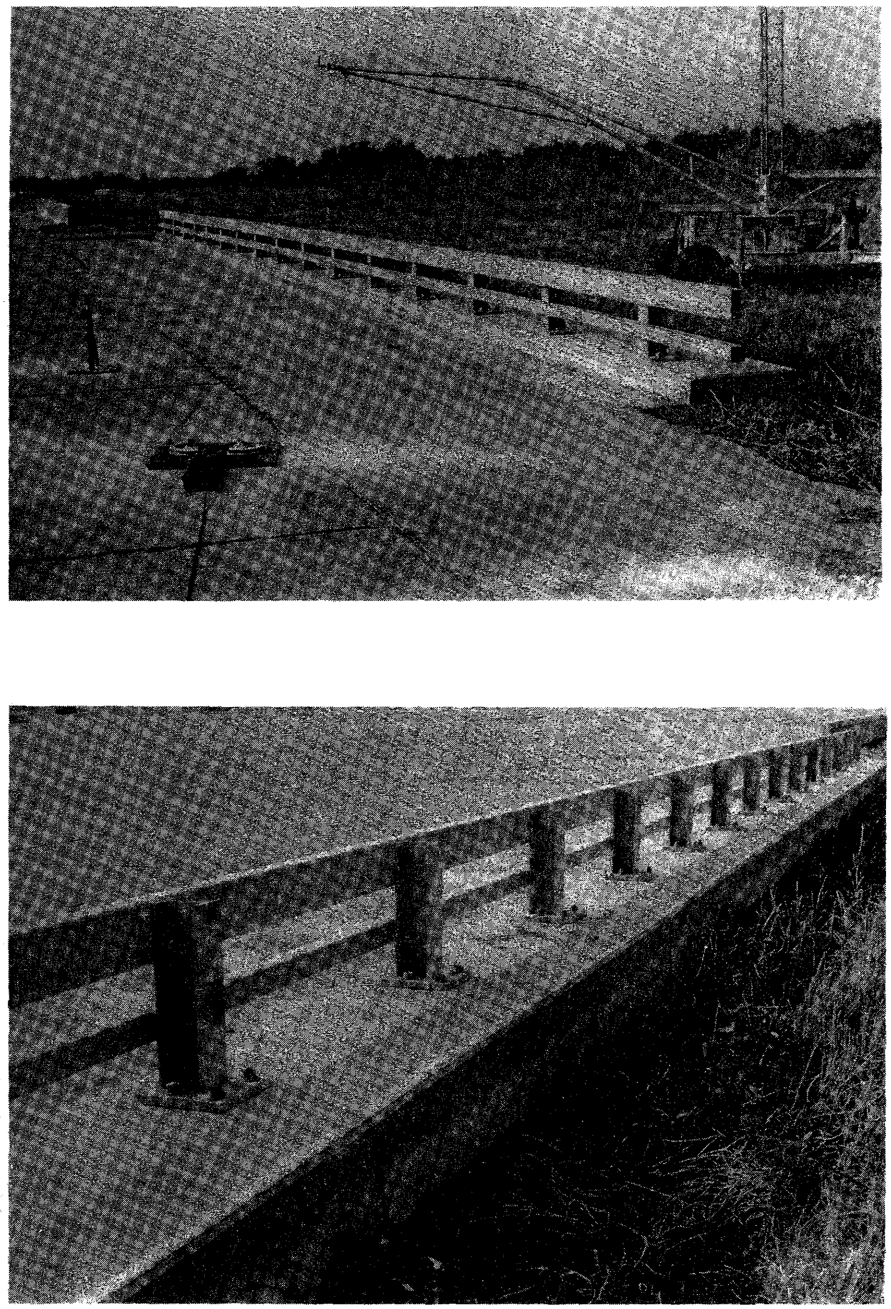
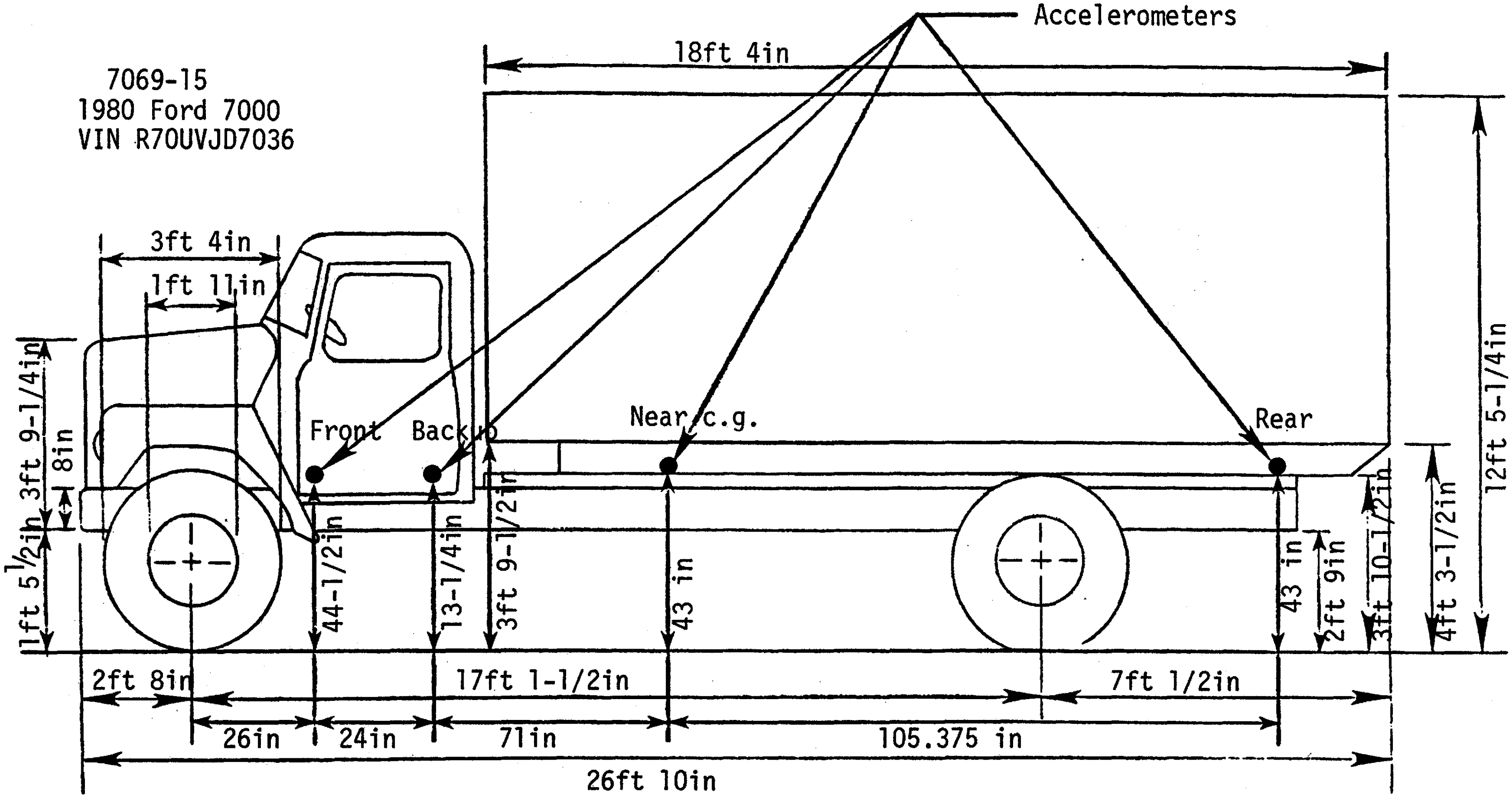


Figure 32. Illinois 2399-1 bridge railing before test 7069-15.



EMPTY WEIGHTS

Weight on Front Axle : LF 3,200 RF 2,960

Weight on Rear Axle : LR 2,970 RR 3,190

TOTAL EMPTY WEIGHT : 12,320

LOADED WEIGHTS

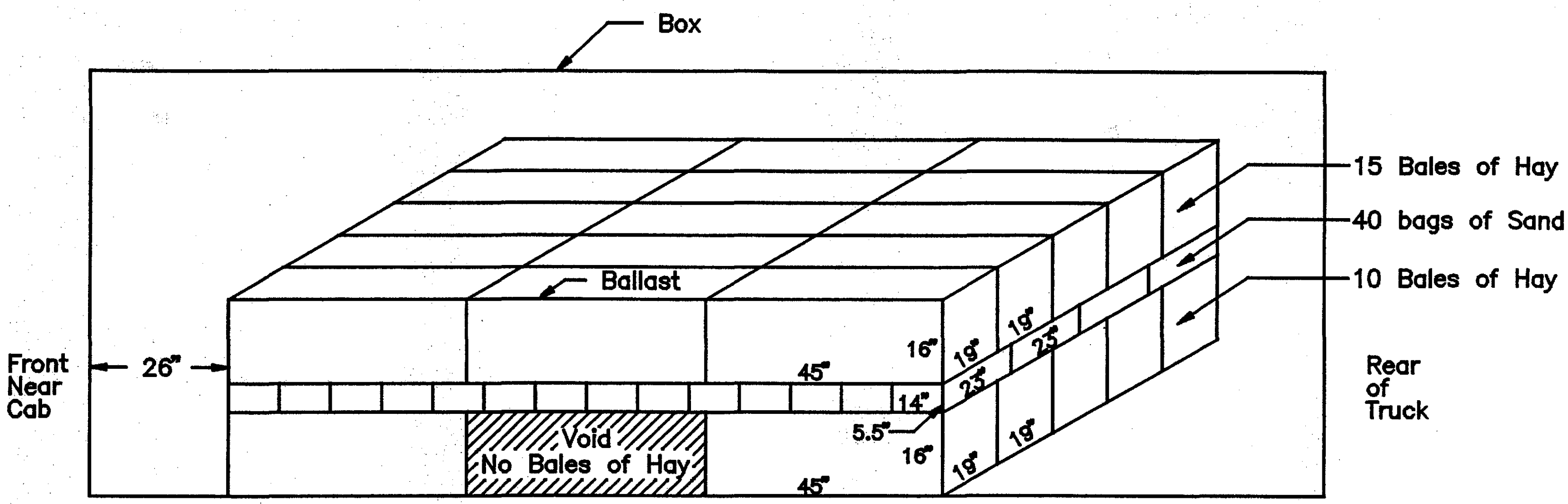
Weight on Front Axle : LF 3,750 RF 3,610

Weight on Rear Axle : RF 5,160 RR 5,480

TOTAL LOADED WEIGHT : 18,000

1 in = 25.4 mm
1 ft = .305 m

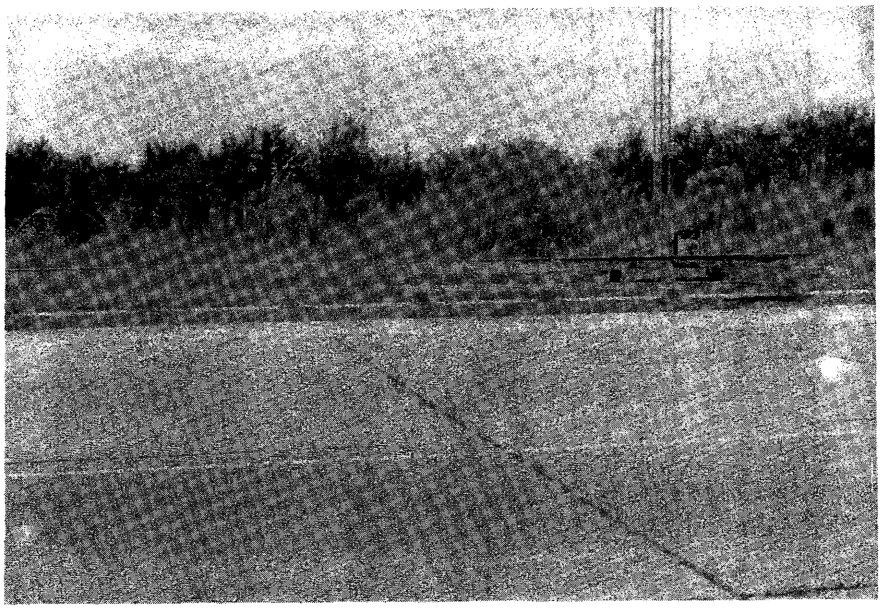
Figure 33. Vehicle properties for test 7069-15.



25 Bales of Hay @ 66 lb = 1650 lb
40 Bags of Sand @ 100 lb = 4000 lb
Total Ballast = 5650 lb

1 lb = .454 kg
1 in = 25.4 mm

Figure 34. Load distribution for test 7069-15.



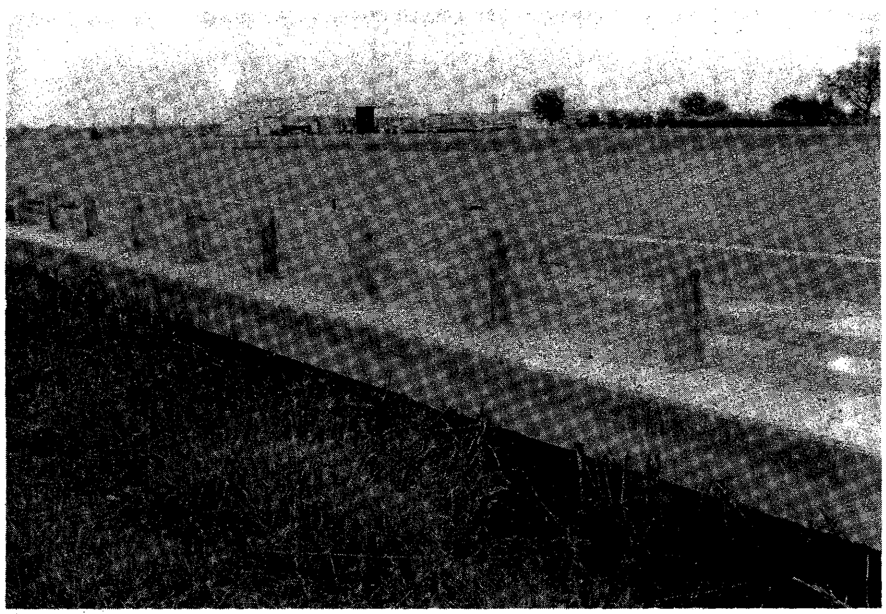
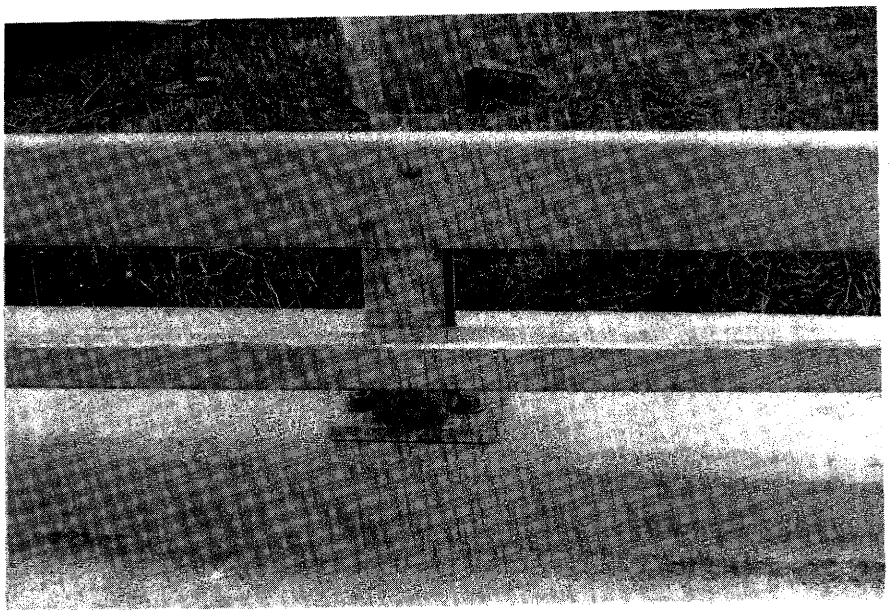


Figure 35. Illinois 2399-1 bridge railing after test 7069-15.



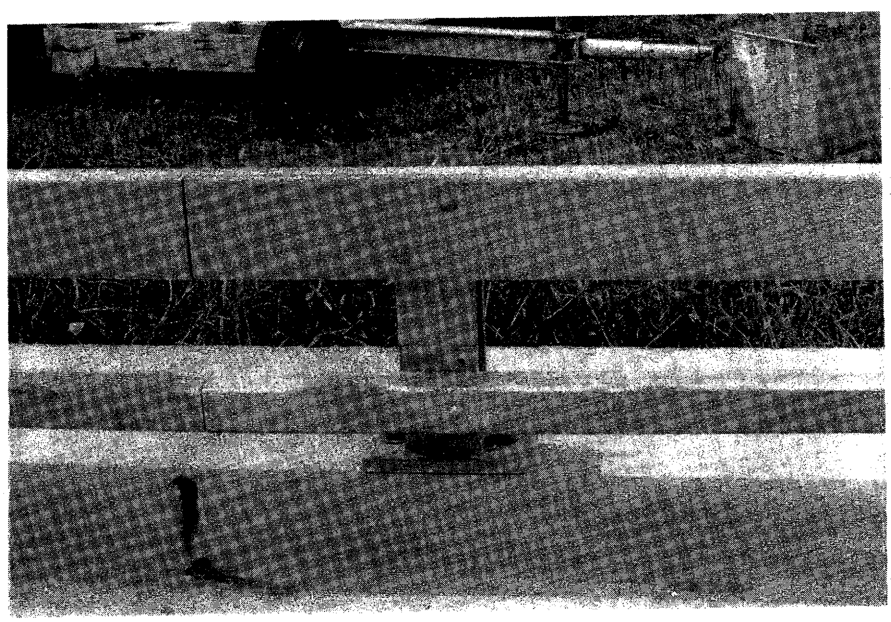


Figure 36. Damage at posts 3 and 4.

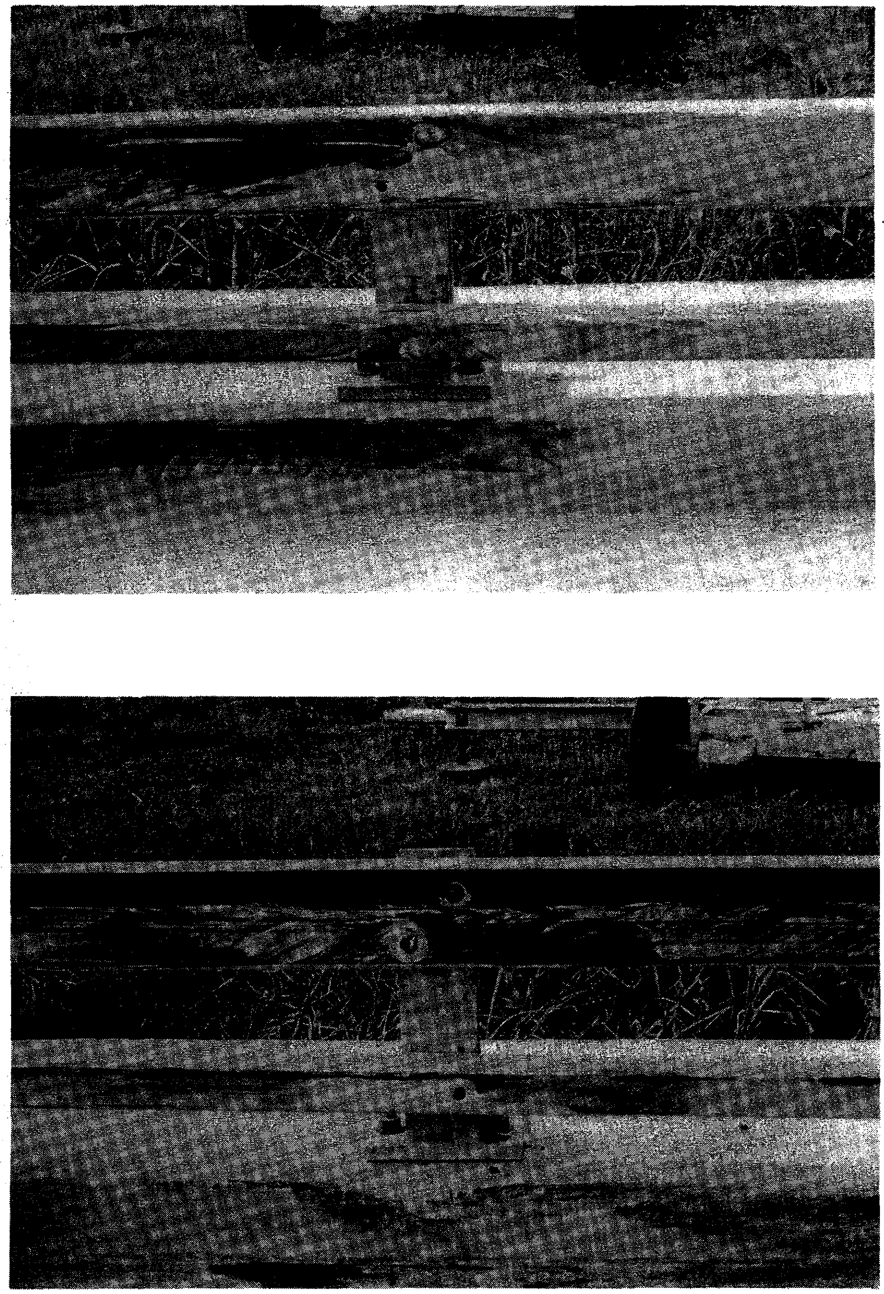


Figure 37. Damage at posts 5 and 6.

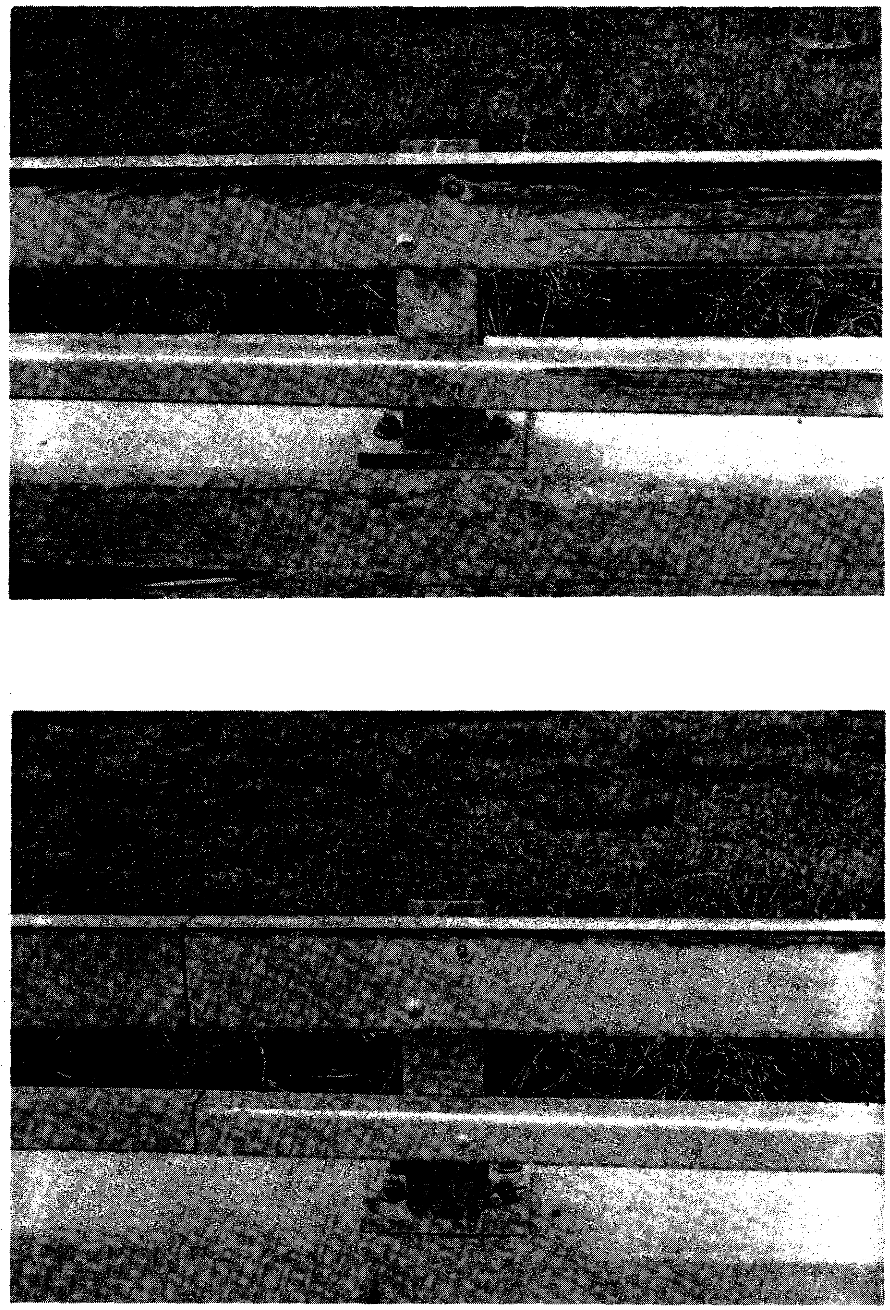
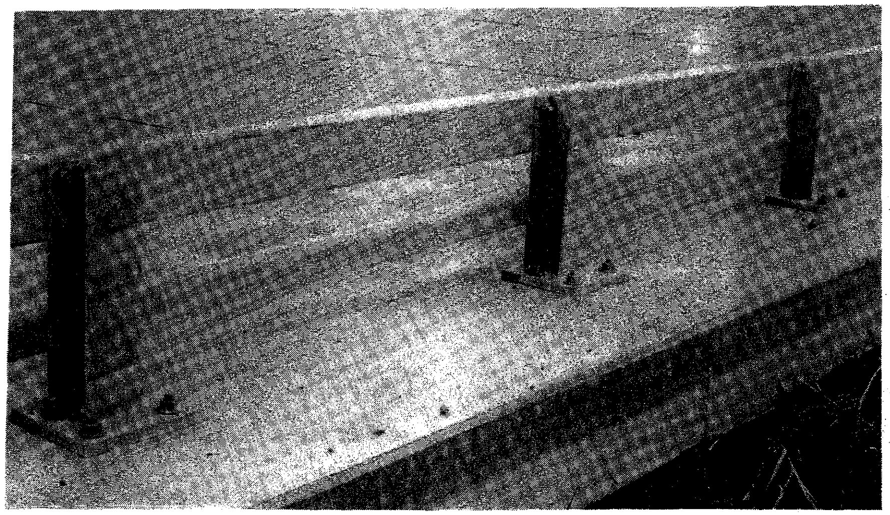


Figure 38. Damage at posts 7 and 8.



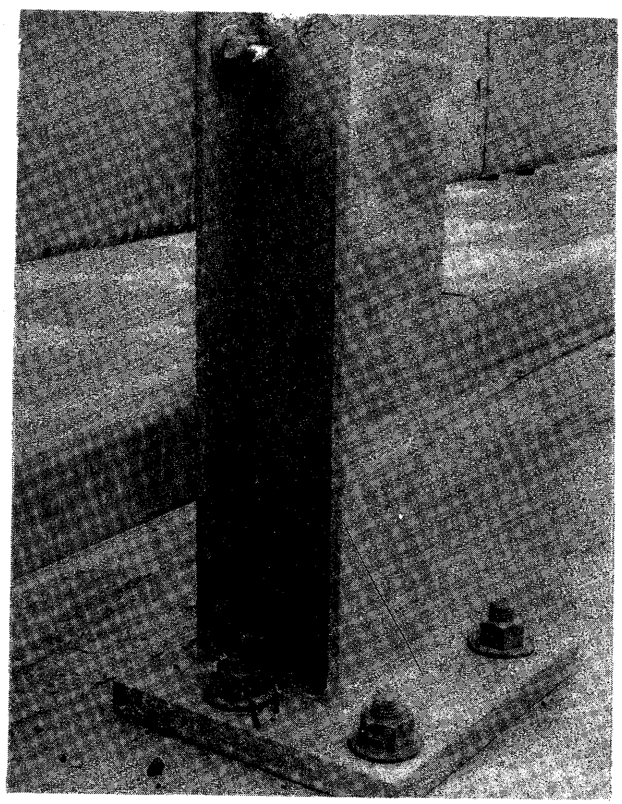


Figure 39. Damage to post 8.

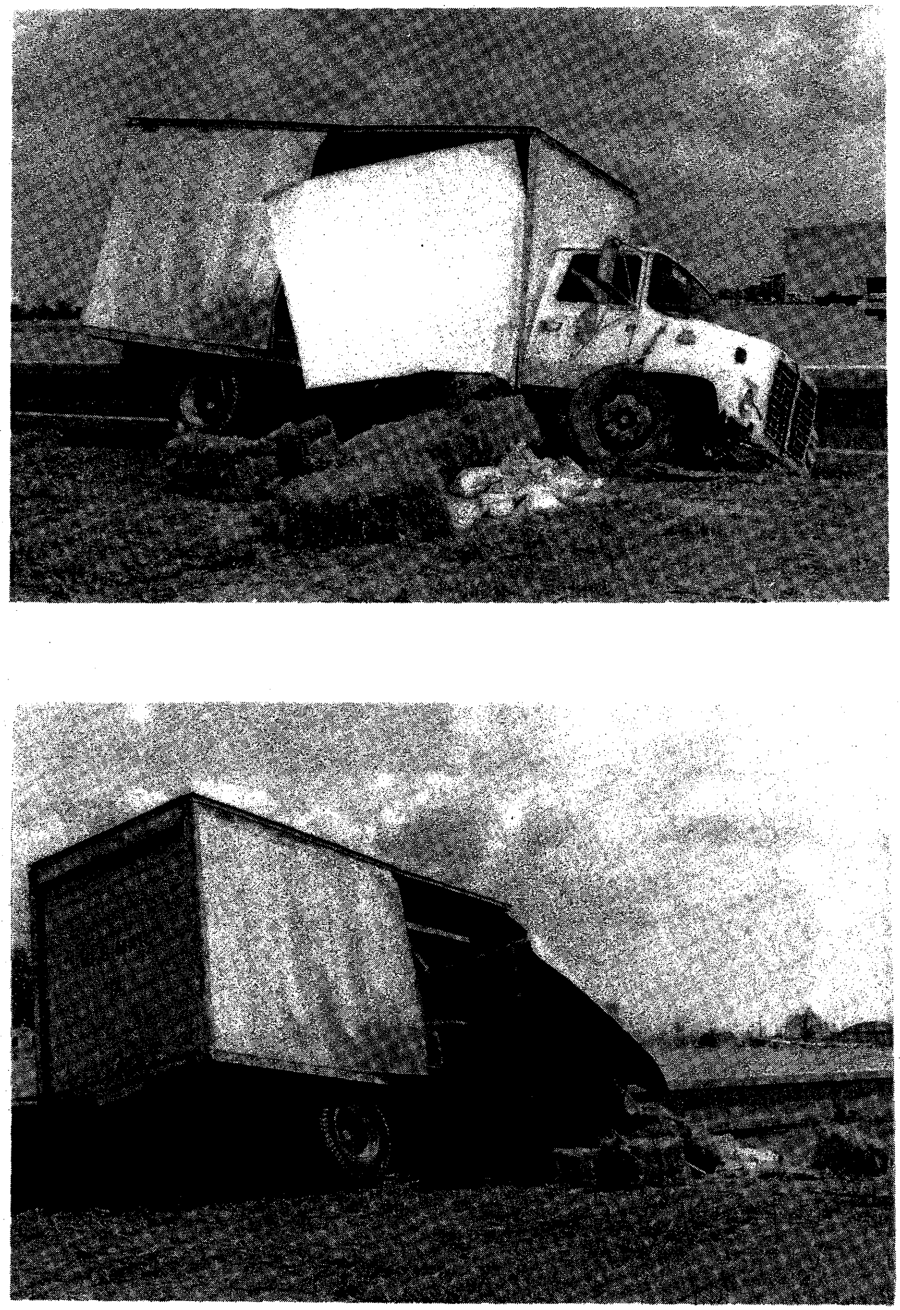


Figure 40. Vehicle after test 7069-15.

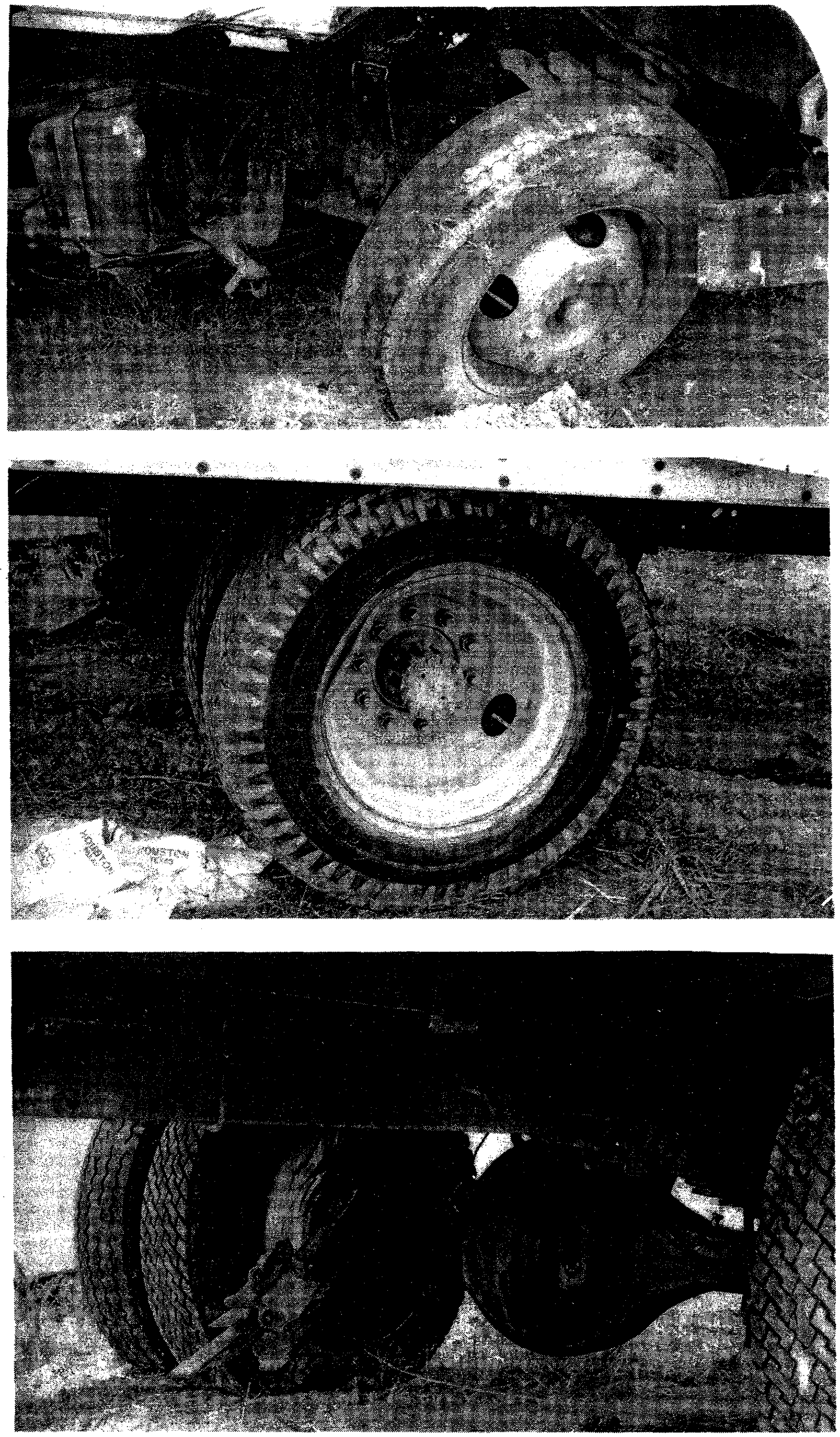
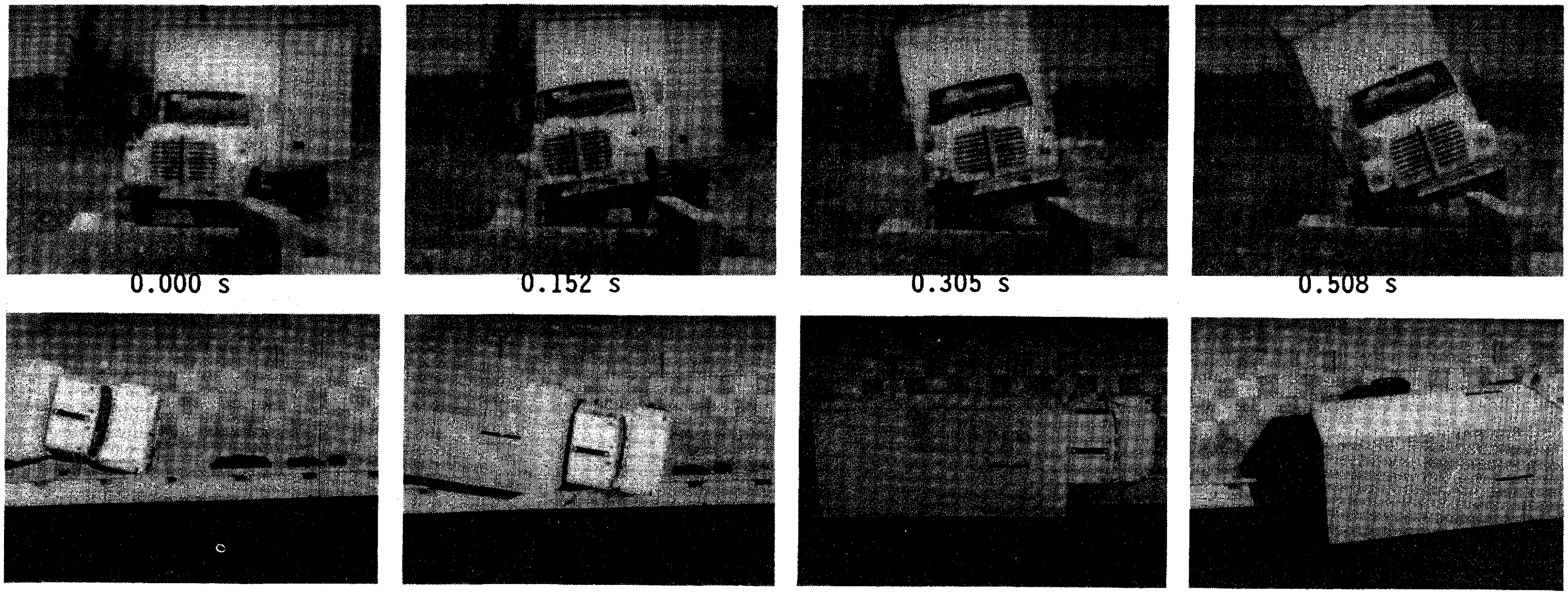
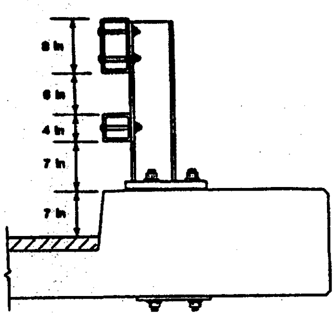


Figure 41. Damage to suspension and undercarriage (7069-15).





(1 in = 25.4 mm)

Test No. 7069-15
Date 9/13/88
Test Installation . . . Illinois 2399-1 Bridge Railing
Installation Length . . 100 ft (30 m)
Vehicle . . . . 1980 Ford 7000 Single-Unit Truck
Vehicle Weight
  Empty Weight . . . . . 12,320 lb (5,593 kg)
  Test Inertia . . . . . 18,000 lb (8,172 kg)
Maximum Vehicle Crush . 10.0 in (254mm)

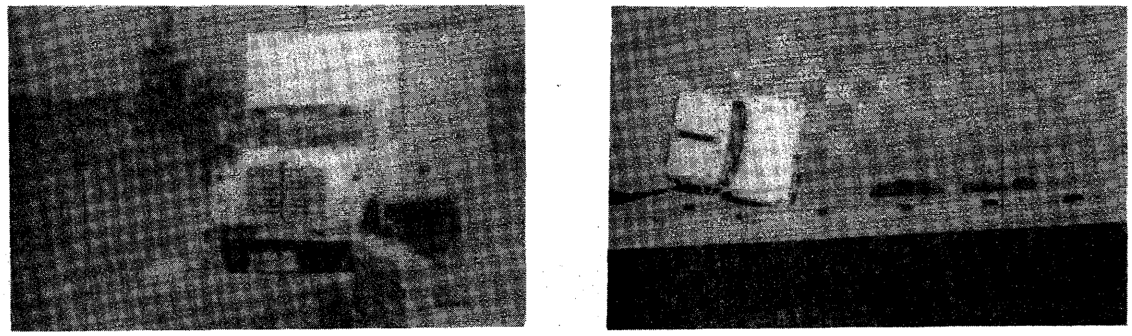
Impact Speed. . . . 50.8 mi/h (81.7 km/h)
Impact Angle. . . . 15.1 deg
Exit Speed . . . . N/A
Exit Trajectory . . 0 deg
Vehicle Accelerations
  (Max. 0.050-sec Avg)
  Longitudinal. . . -1.9 g
  Lateral . . . . . 4.9 g
Occupant Impact Velocity
  Longitudinal. . . 9.8 ft/s (3.0 m/s)
  Lateral . . . . . 12.4 ft/s (3.8 m/s)
Occupant Ridedown Accelerations
  Longitudinal. . . -2.5 g
  Lateral . . . . . 7.4 g

Figure 42. Summary of results for test 7069-15.

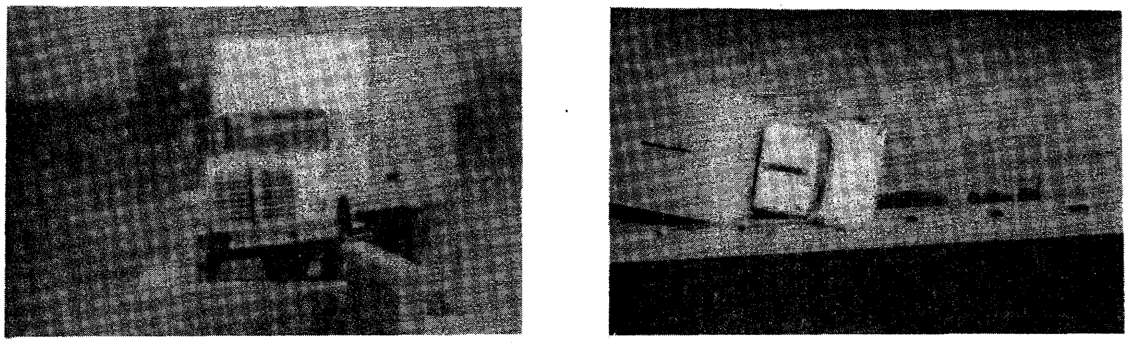
Table 4. Evaluation of crash test no. 7069-15.
{Illinois 2399 Bridge Railing [18,000 lb (8 172 kg)|50.8 mi/h (81.7 km/h)|15.1 degrees]}

	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	Acceptable deformation	Pass
D.	Vehicle must remain upright	Vehicle remained 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 0.12 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 9.8 (3.0) Lateral 12.4 (3.8)	N/A
	Occupant Ridedown Accelerations - g's Longitudinal 15 Lateral 15	Occupant Ridedown Accelerations - g's Longitudinal -2.5 Lateral 7.4	N/A
H.	Exit angle shall be less than 12 degrees	Exit angle was about 0 degrees	Pass

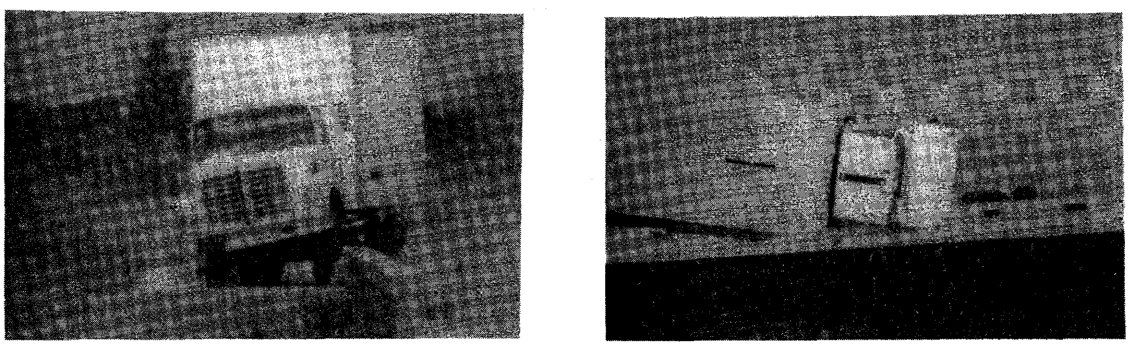
* A, B, C, are required. D, E, F, and H are desired. G is not applicable for this test. (See table 2)



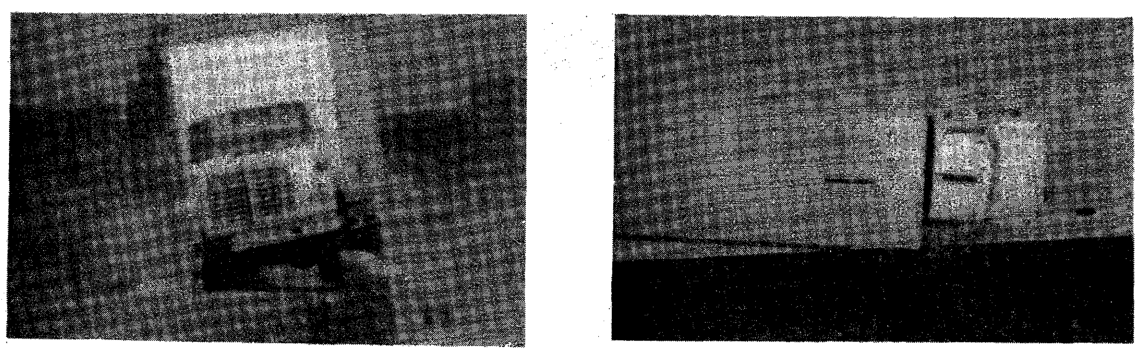
0.000 s



0.076 s

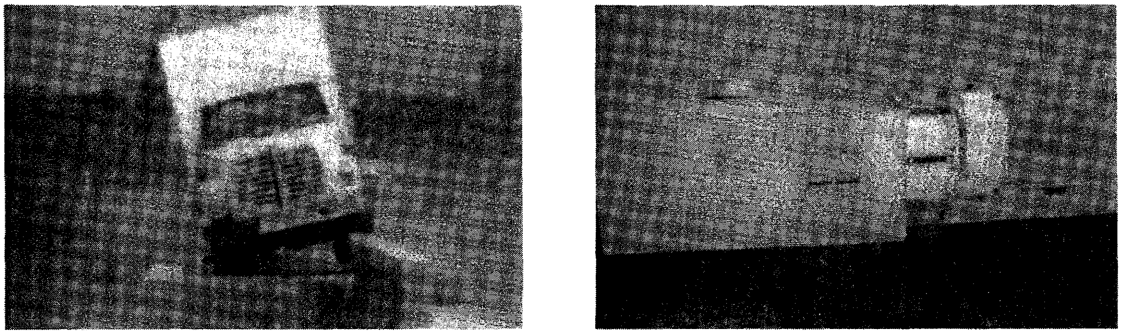


0.152 s

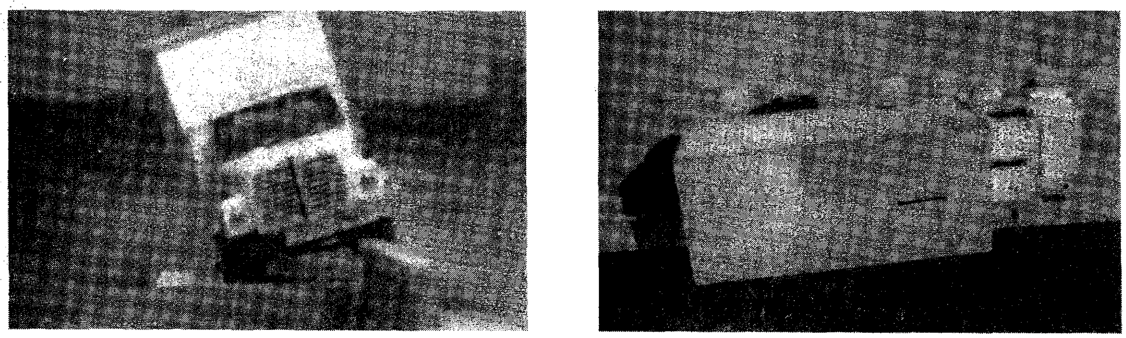


0.229 s

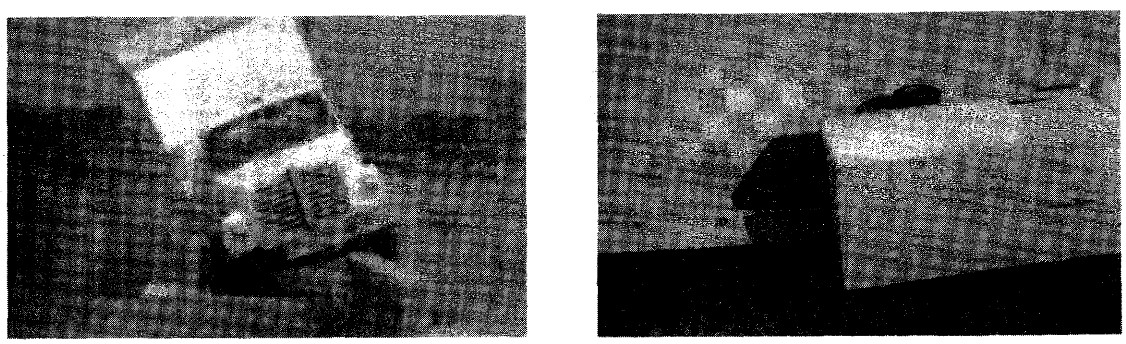
Figure 43. Sequential photographs for test 7069-15.
(frontal and overhead views).



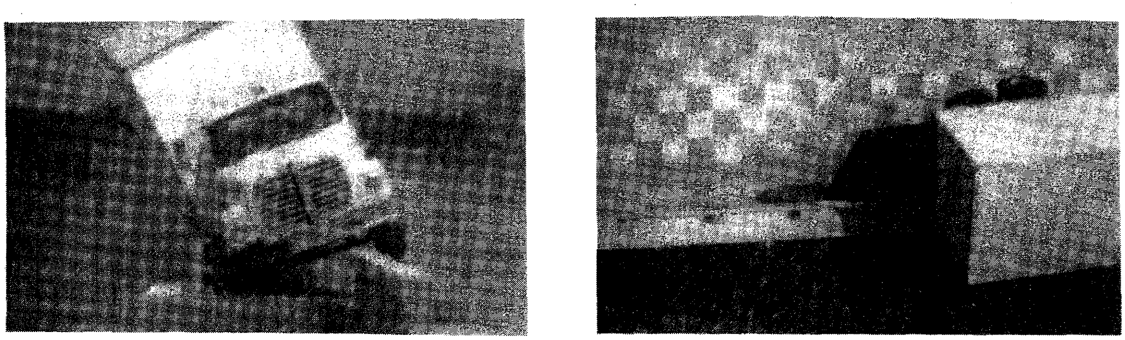
0.305 s



0.381 s



0.508 s



0.635 s

Figure 43. Sequential photographs for test 7069-15 (continued).

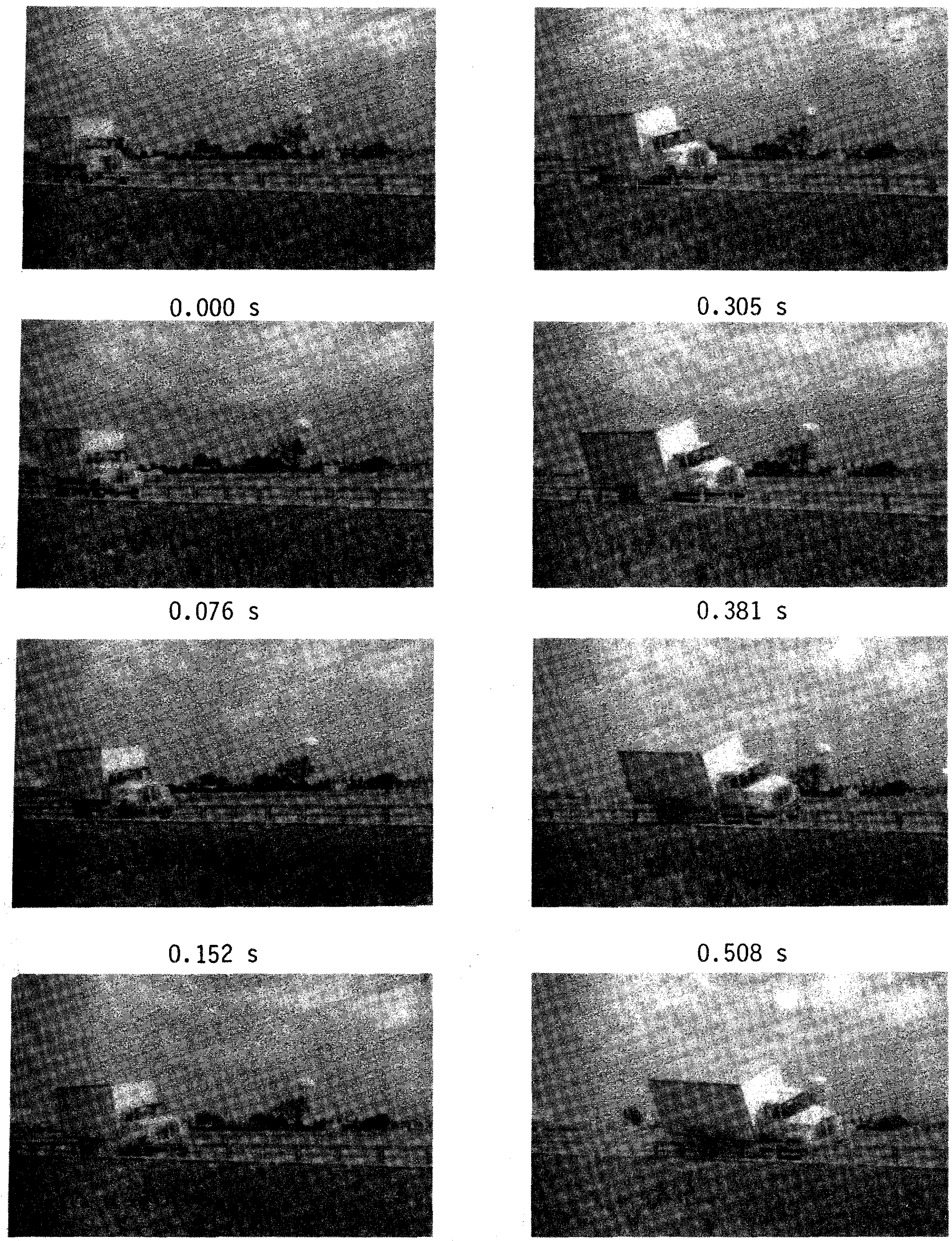


Figure 44. Perpendicular sequential photographs for test 7069-15.

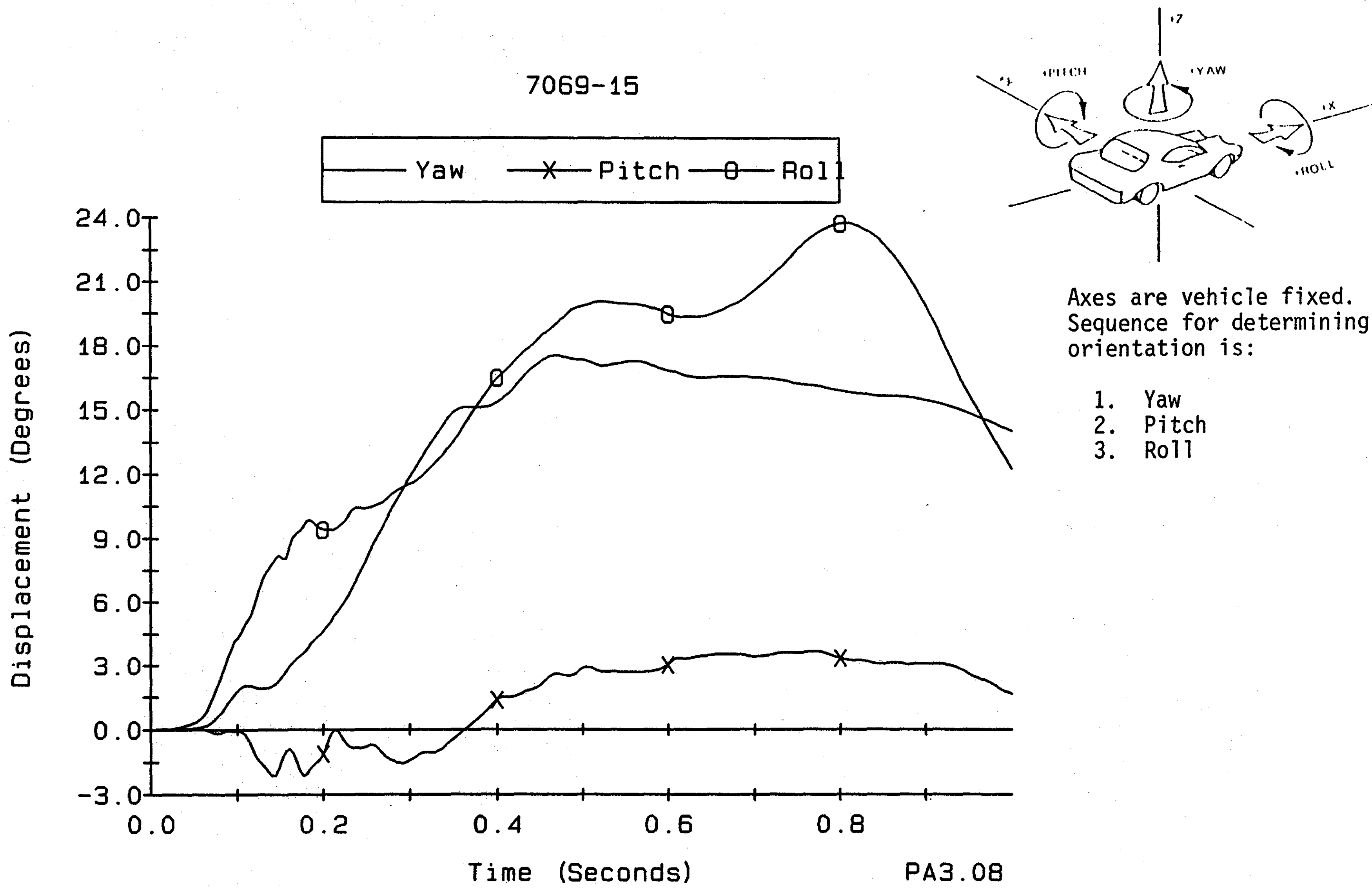


Figure 45. Vehicle angular displacements for test 7069-15.

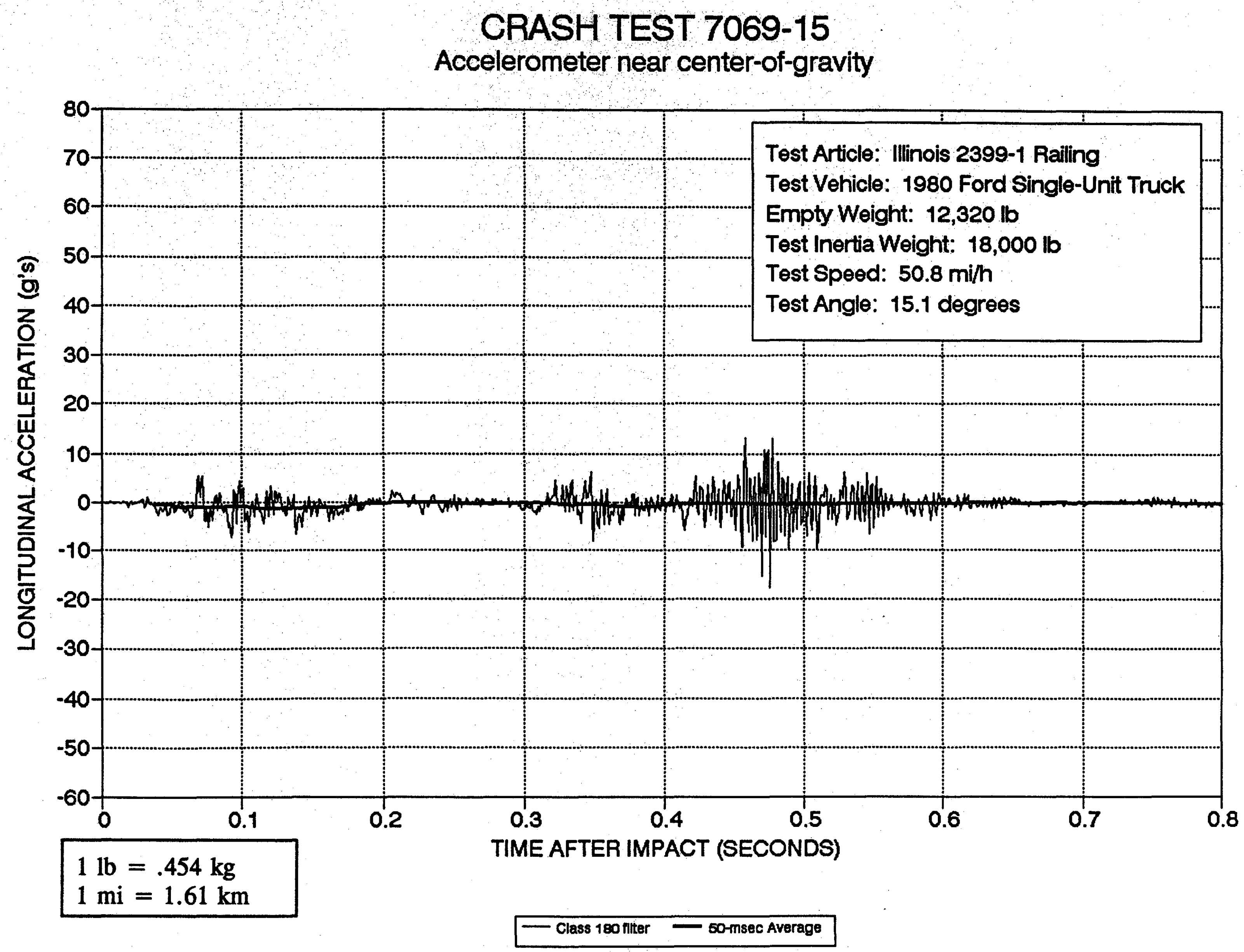


Figure 46. Vehicle longitudinal accelerometer trace for test 7069-15 (accelerometer located near center-of-gravity).

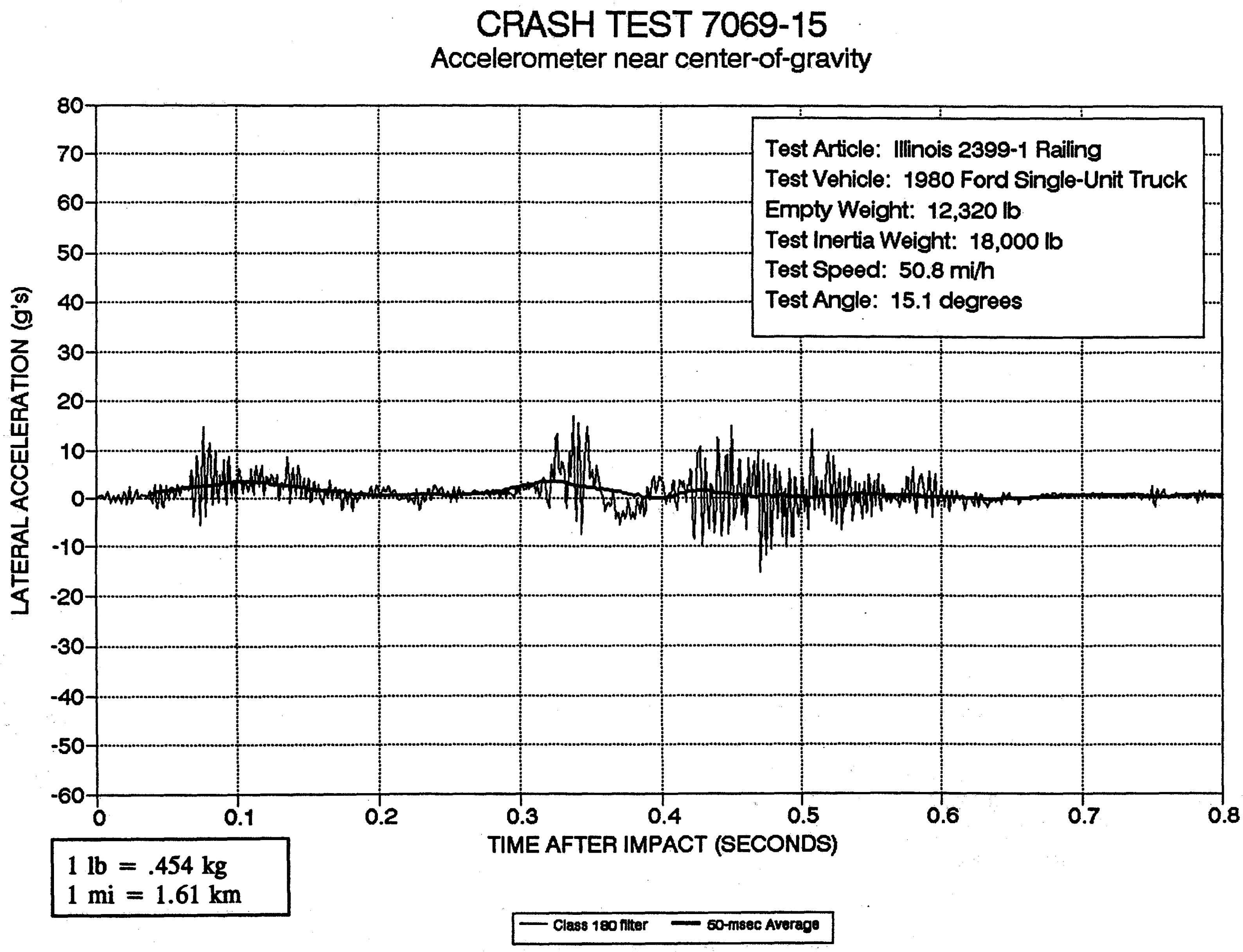


Figure 47. Vehicle lateral accelerometer trace for test 7069-15 (accelerometer located near center-of-gravity).

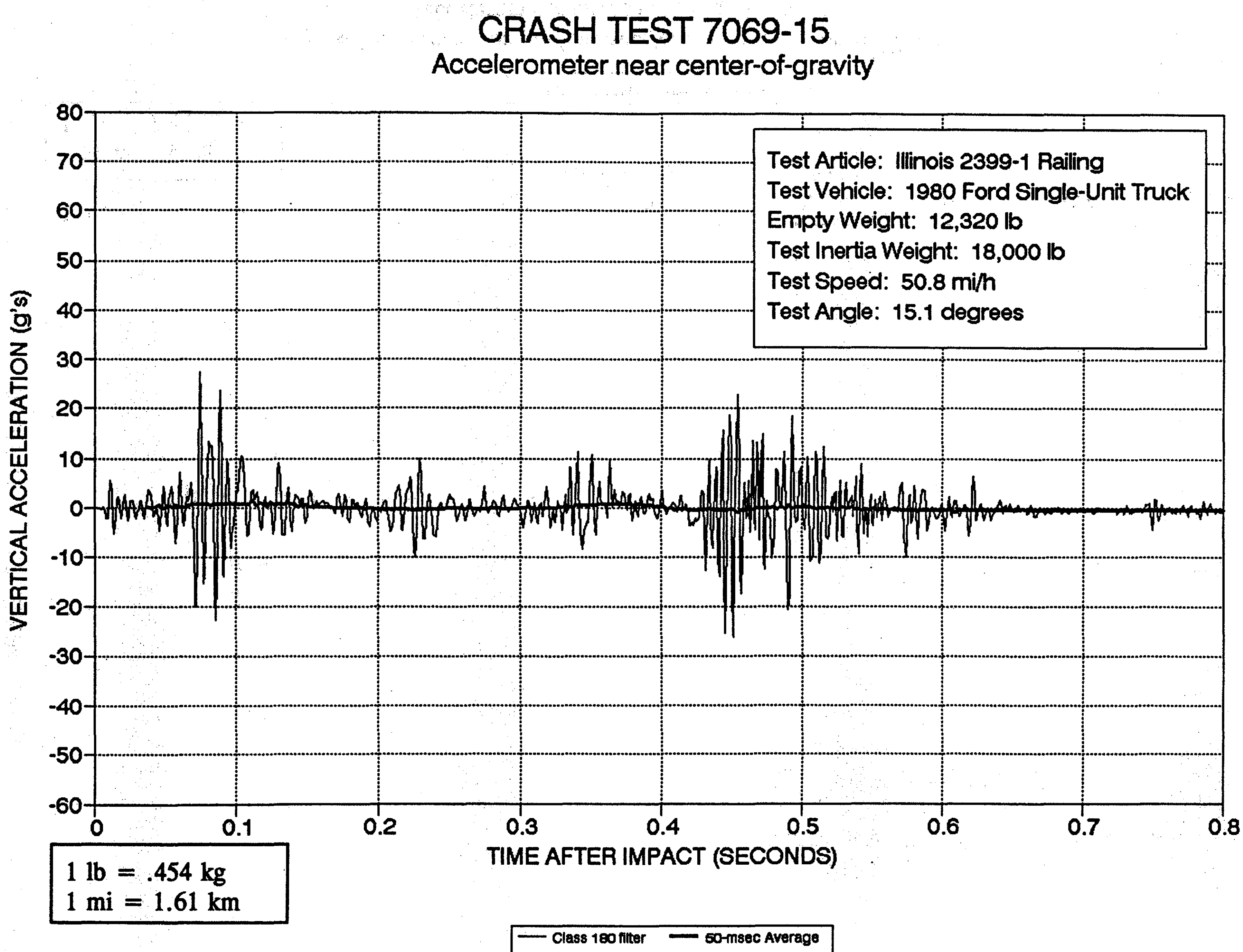


Figure 48. Vehicle vertical accelerometer trace for test 7069-15 (accelerometer located near center-of-gravity).

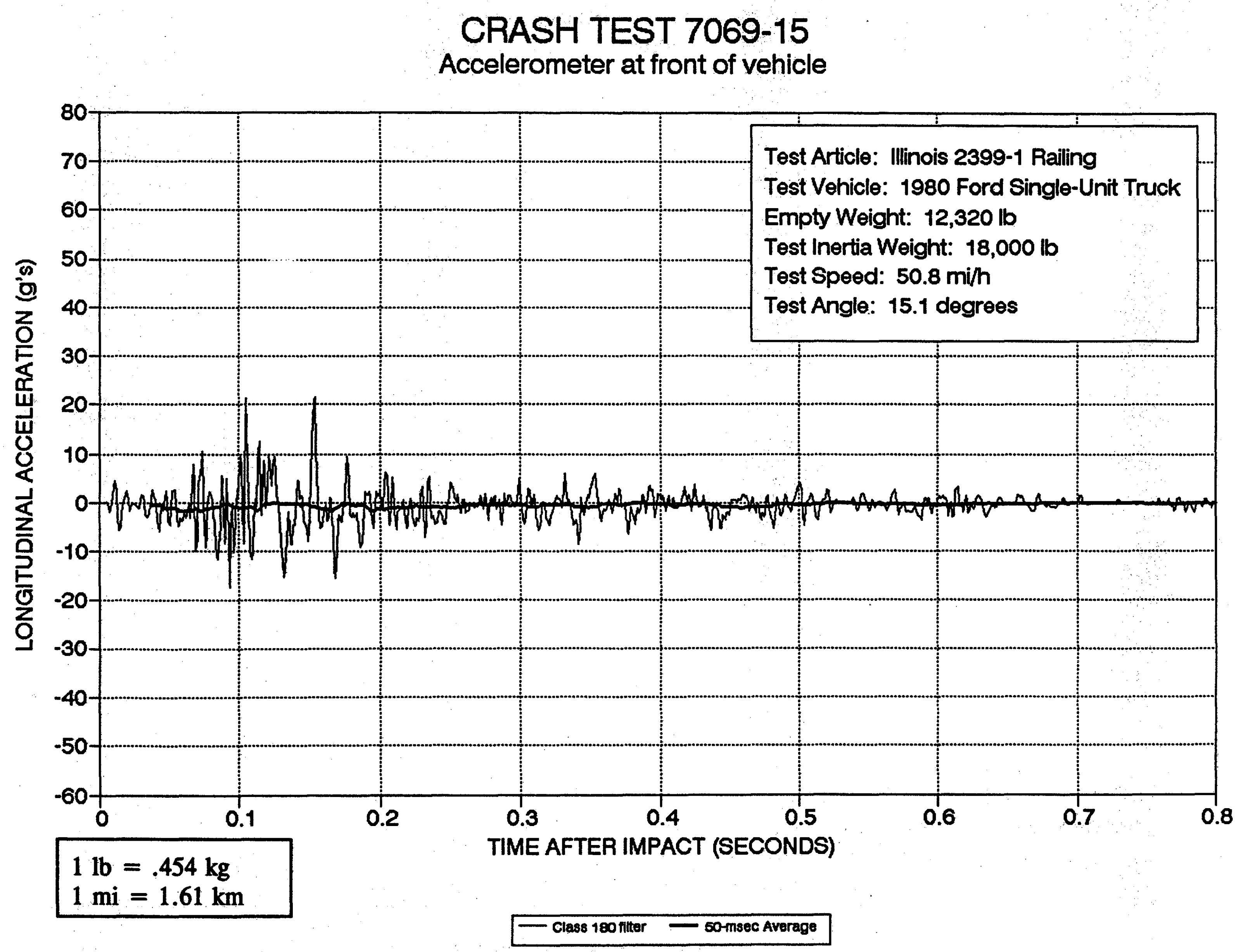


Figure 49. Vehicle longitudinal accelerometer trace for test 7069-15 (accelerometer located at front of vehicle).

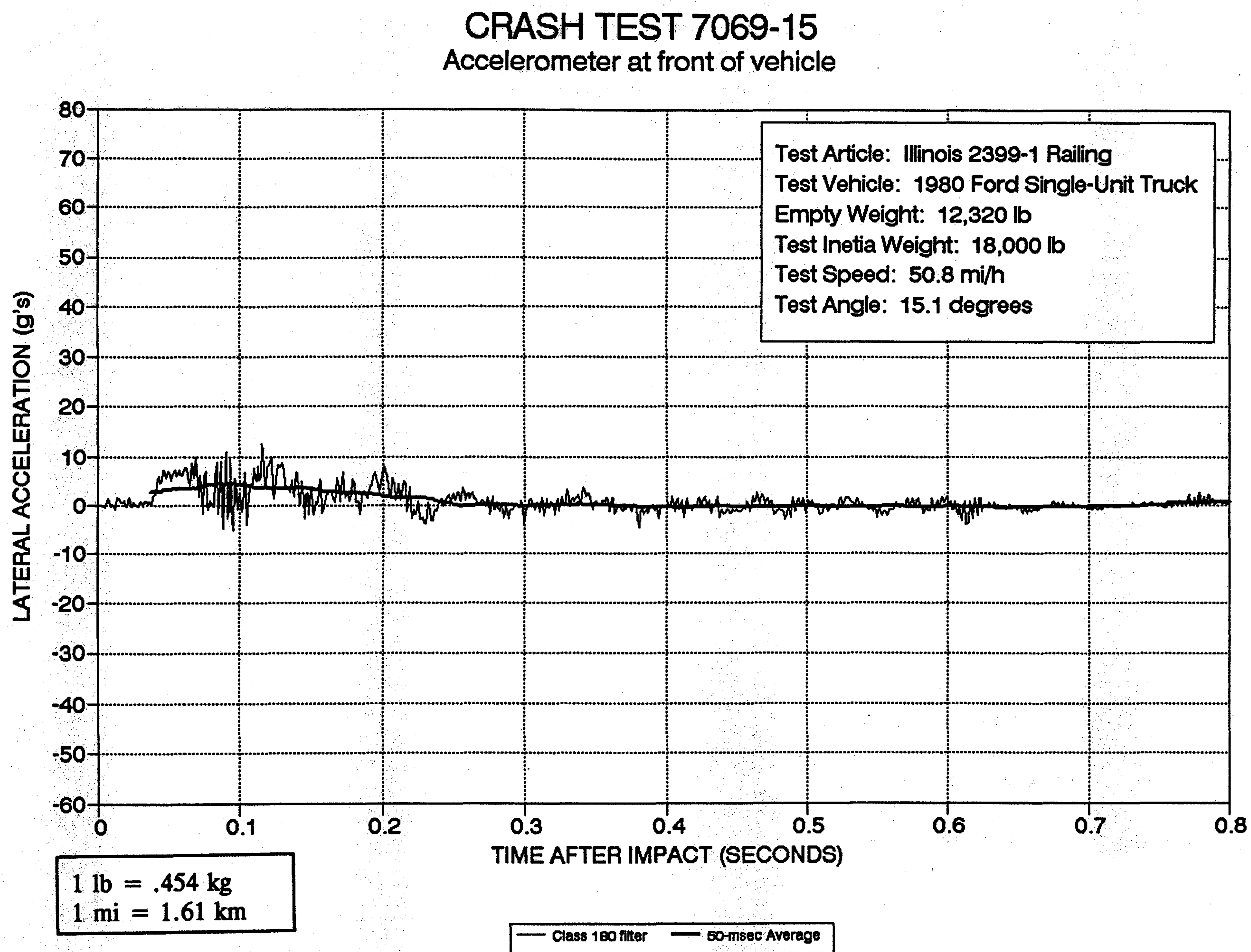


Figure 50. Vehicle lateral accelerometer trace for test 7069-15 (accelerometer located at front of vehicle).

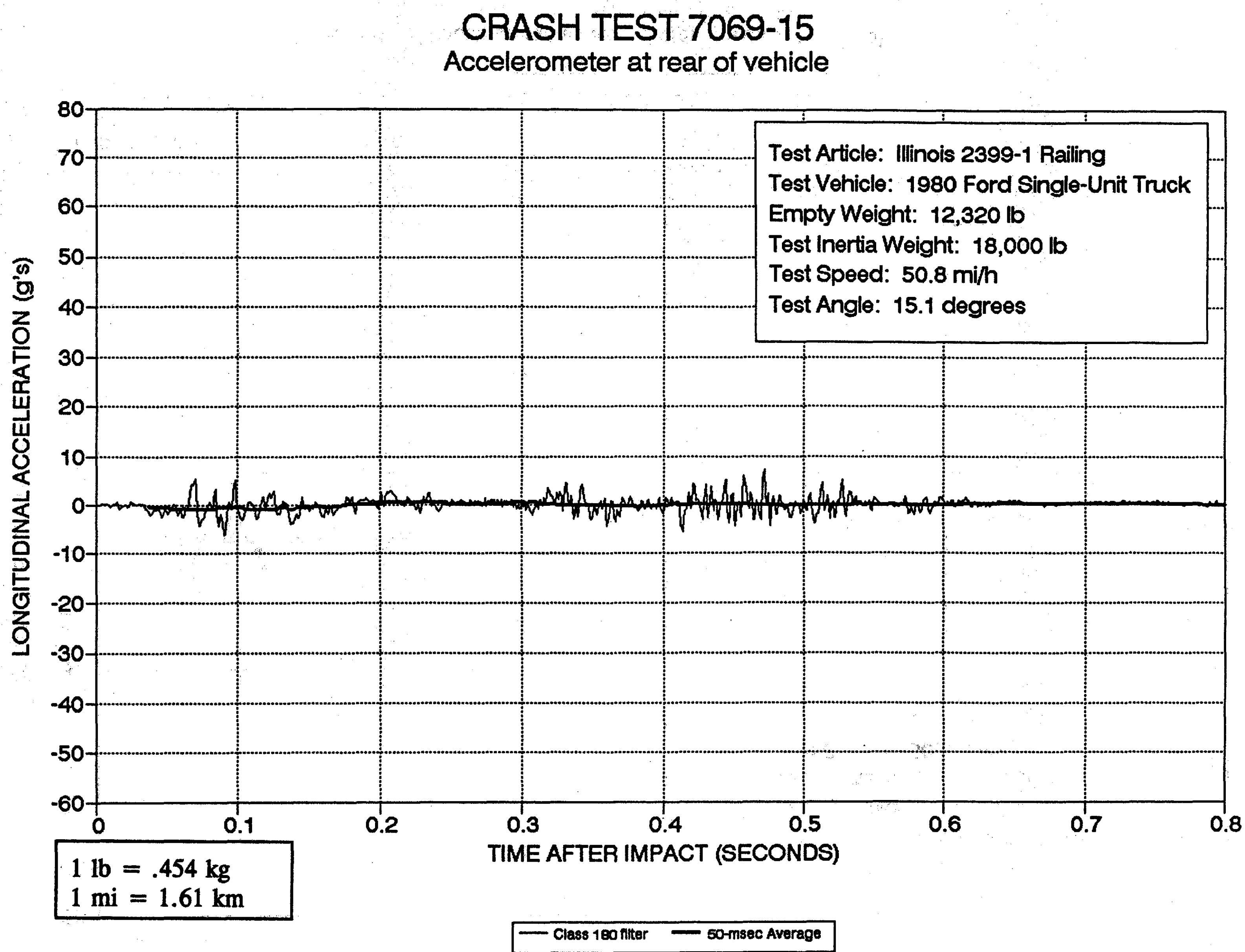


Figure 51. Vehicle longitudinal accelerometer trace for test 7069-15 (accelerometer located at rear of vehicle).

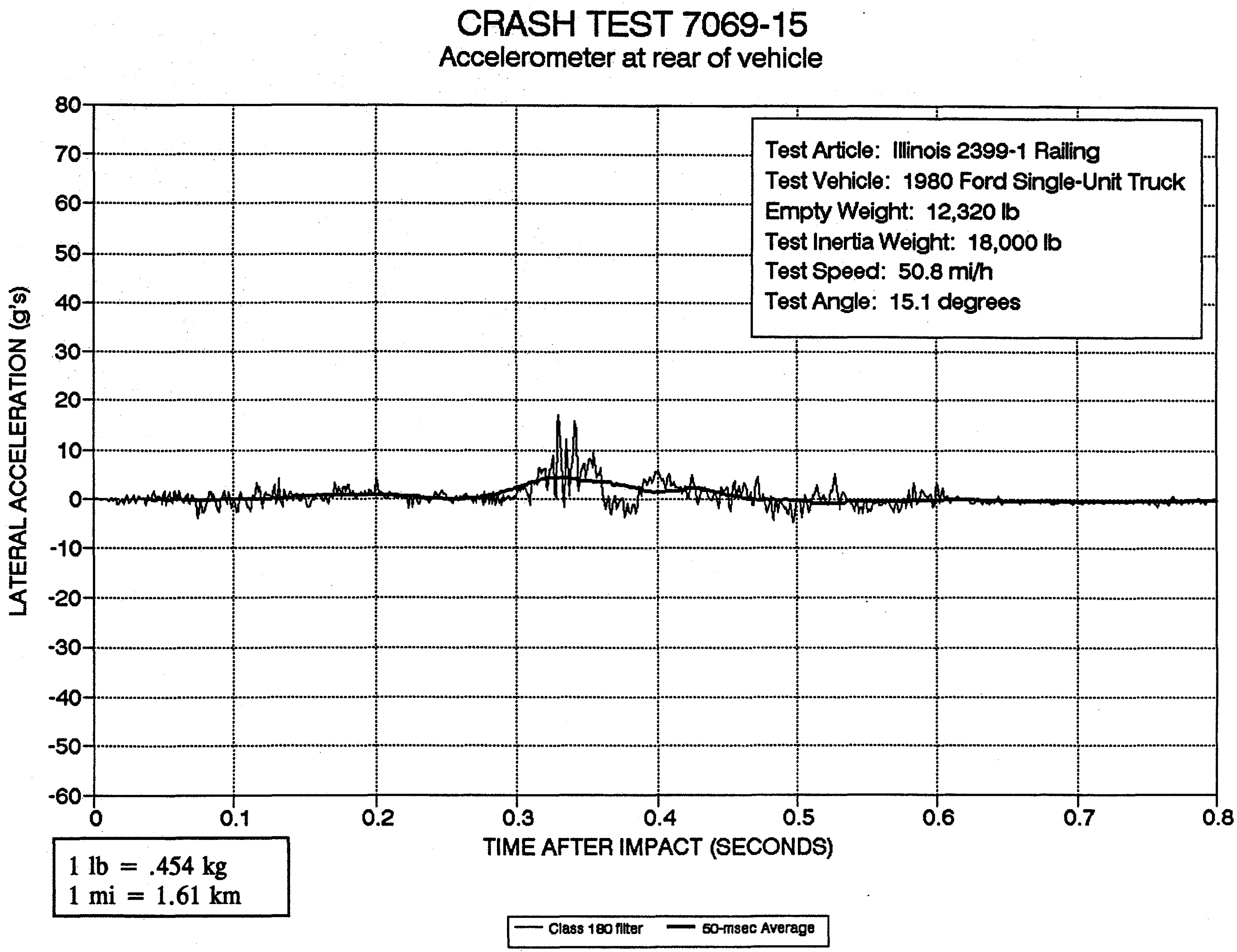


Figure 52. Vehicle lateral accelerometer trace for test 7069-15 (accelerometer located at rear of vehicle).

CHAPTER 4. STRENGTH CALCULATIONS

Analysis of the strength of the railing is based on a plastic hinge, ultimate strength failure mechanism.[(2)] Force from a colliding vehicle is idealized as being a uniformly distributed line load extending over 3.5 ft (1.1 m). The load may be applied at any location along the railing. Possible failure mechanisms are illustrated in figure 53. Relative strengths of the rail elements and the posts will determine the controlling mechanism.

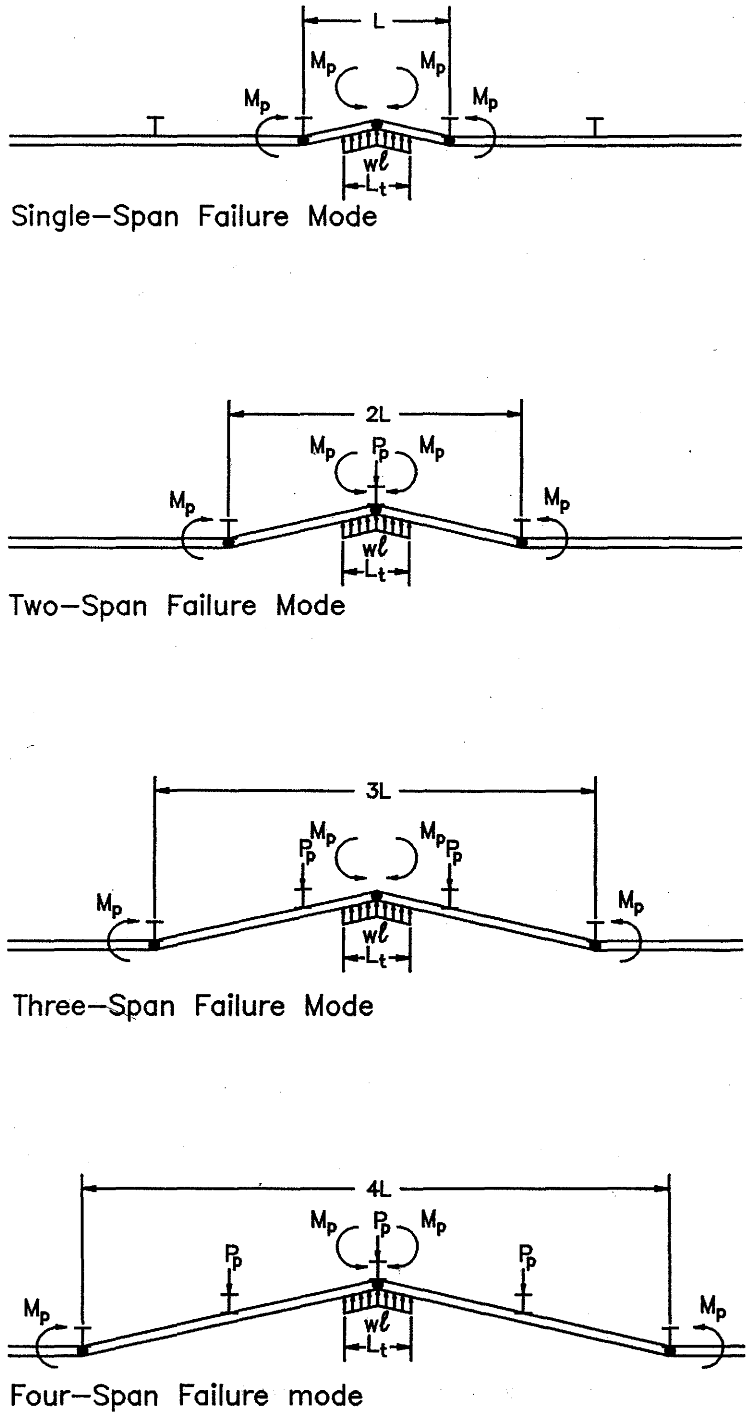
The gross plastic section modulus for the TS 8 by 4 by 5/16-in (203 by 102 by 8-mm) upper tubular rail element is 10.5 in^3 ($173x10^3$ mm^3) for bending about its weak axis. The moment capacity of the upper rail element is 483 in-kips (54.6 kN-m). The gross plastic section modulus for the TS 4 by 4 by 1/4-in (102 by 102 by 6-mm) lower tubular rail element is 4.97 in^3 ($81.4x10^3$ mm^3) for bending about either axis. The moment capacity of the lower rail element is 229 in-kips (25.9 k/n-m).

If it is assumed that the applied load is positioned such that each rail element is loaded to capacity, it would be positioned at 16.1 in (409 mm) above the baseplate. If the load were positioned at the centroid of the top rail element, it would be 20 in (508 mm) above the baseplate and 28 in (711 mm) above the top of the bridge deck.

The plastic section modulus for the W6x25 post is 18.9 in^3 ($310x10^3$ mm^3) and its moment capacity, M_p, is 945 in-kips (106.8 kN-m). Analysis of the strength of the anchor bolts indicates they will develop a moment at the base of the post of 804 in-kips (90.9 kN-m) which is less than the strength of the post itself. The welds are adequate to develop the capacity of the post section. If the load were placed at 16.1 in (409 mm), the capacity of the post would be 49.9 kips (222.0 kN); and it if were placed at 20 in (508 mm), the capacity of the post would be 40.2 kips (178.8 kN).

Strength of the railing may be computed using equations given in figure 53. If the load were positioned at 16.1 in (409 mm) above the post baseplate, the capacity for a one-span mechanism would be 105 kips (467.0 kN); for a two-span mechanism, it would be 102 kips (453.7 kN), for a three-span mechanism, it would be 101 kips (449.3 kN); and for a four-span mechanism, it would be 128 kips (569.3 kN). The three-span mechanism is the controlling mechanism and the railing strength is 101 kips (449.3 kN).

If the load were positioned at 20 in (508 mm) above the post baseplate, the capacity for a one-span mechanism would be 105 kips (467.0 kN); for a two-span mechanism, it would be 91 kips (404.8 kN); for a three-span mechanism, it would be 87 kips (387.0 kN); and for a four-span mechanism, it would be 146 kips (649.4 kN). The three-span mechanism is the controlling mechanism and the railing strength is 87 kips (387.0 kN).



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

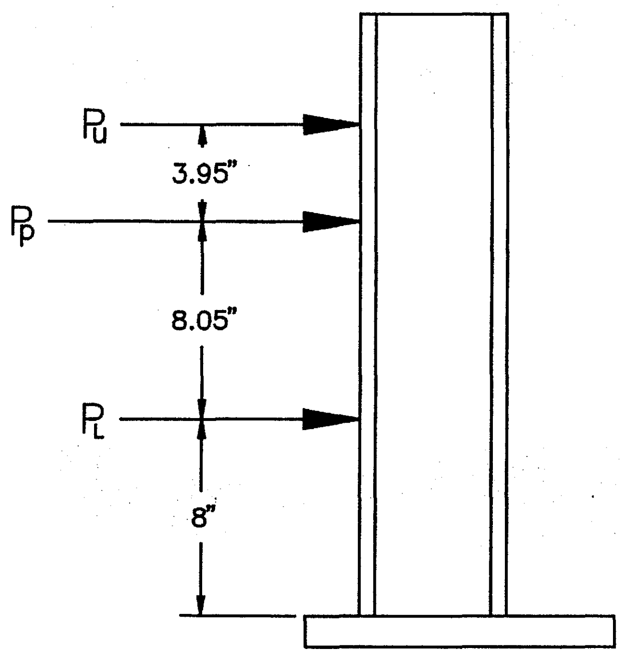
$$w\ell = \frac{16M_p + 4P_p L}{4L-L_t}$$

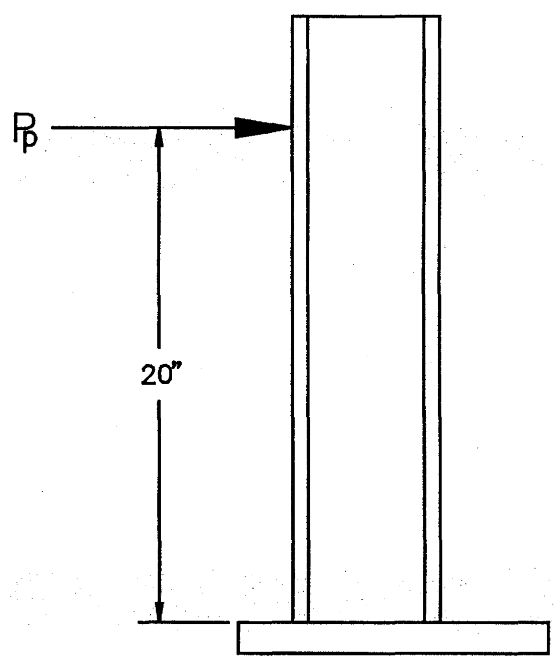
$$w\ell = \frac{16M_p + 8P_p L}{6L-L_t}$$

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

Longer mechanisms may also be possible.

Figure 53. Failure mechanisms for beam-and-post railing.





1 in = 25.4 mm

Figure 54. Location of resultant force on posts.

REFERENCES

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