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Research Study Title: Aesthetically Pleasing Bridge Rails

16. Abstract

Research has developed railing to withstand impact loads from vehicles of ever-increasing size; however aesthetic considerations have been overshadowed by safety and structural requirements. The objective of this research study was to develop aesthetically pleasing, structurally sound railings that can serve as alternative railings in city or urban areas.

This report presents a new open type concrete bridge rail--Texas Type T411. This bridge rail is constructed of reinforced concrete 32 in. high by 12 in. thick and contains 8 in. wide by 18 in. high openings at 18 in. center-to-center longitudinal spacing.

The bridge rail was crash tested and evaluated in accordance with NCHRP Report 230 for Service Level 2. Two crash tests were required--a 4,500 lb passenger car at 60 mph and 25° impact angle and an 1,800 lb passenger car at 60 mph and 20° impact angle.

In both tests the bridge rail contained and redirected the test vehicle. There were no detached elements or debris to present undue hazard to other traffic. The vehicle remained upright and relatively stable during the collision. The occupant/compartment impact velocities and 10-ms occupant ridedown accelerations were within the limits specified in NCHRP Report 230. The vehicle trajectory at loss of contact indicates no intrusion into adjacent traffic lanes (exit angles of 0° and 5.9°). This test also met the safety evaluation guidelines proposed in the new <u>AASHTO Guide Specification for Bridge Railings</u>.

17. Key Words	18. Distribution Statement
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AESTHETICALLY PLEASING CONCRETE BEAM AND POSTS BRIDGE RAIL - TEXAS TYPE T411

by

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Research Report 1185-1

on

Research Study No. 2-5-88/89-1185
Aesthetically Pleasing Bridge Rails

Sponsored by

Texas State Department of Highways and Public Transportation

in cooperation with

The U.S. Department of Transportation
Federal Highway Administration

March 1989

Texas Transportation Institute
Texas A&M University
College Station, Texas

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

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

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac

MASS (weight)

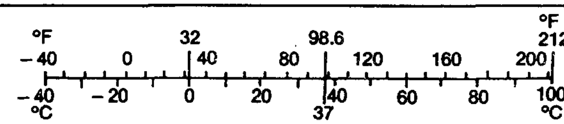
Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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

* SI is the symbol for the International System of Measurements

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

KEY WORDS

Bridge Rails, Traffic Barriers, Highway Safety, Cars

ACKNOWLEDGMENTS

This research study was conducted under a cooperative program between the Texas Transportation Institute (TTI), the State Department of Highways and Public Transportation (SDHPT), and the Federal Highway Administration (FHWA). Dean Van Landuyt (Designing Engineer, SDHPT), John J. Panak (Bridge Designing Engineer, SDHPT), and Van M. McElroy (Supervising Bridge Engineer, SDHPT, Dallas) were closely involved in all phases of this study.

IMPLEMENTATION STATEMENT

As of the writing of this report, none of the findings or conclusions presented have been implemented.

ABSTRACT

Research has developed railing to withstand impact loads from vehicles of ever-increasing size; however aesthetic considerations have been overshadowed by safety and structural requirements. The objective of this research study was to develop aesthetically pleasing, structurally sound railings that can serve as alternative railings in city or urban areas.

This report presents a new open type concrete bridge rail--Texas Type T411. This bridge rail is constructed of reinforced concrete 32 in. high by 12 in. thick and contains 8 in. wide by 18 in. high openings at 18 in. center-to-center longitudinal spacing.

The bridge rail was crash tested and evaluated in accordance with NCHRP Report 230 for Service Level 2. Two crash tests were required--a 4,500 lb passenger car at 60 mph and 25° impact angle and an 1,800 lb passenger car at 60 mph and 20° impact angle.

In both tests the bridge rail contained and redirected the test vehicle. There were no detached elements or debris to present undue hazard to other traffic. The vehicle remained upright and relatively stable during the collision. The occupant/compartment impact velocities and 10-ms occupant ridedown accelerations were within the limits specified in NCHRP Report 230. The vehicle trajectory at loss of contact indicates no intrusion into adjacent traffic lanes (exit angles of 0° and 5.9°). This test also met the safety evaluation guidelines proposed in the new AASHTO Guide Specification for Bridge Railings.

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INTRODUCTION

Research has developed railing to withstand impact loads from vehicles of ever-increasing size; however aesthetic considerations have been overshadowed by safety and structural requirements. Engineers often fail to recognize the impact of our structures on the landscape, particularly in city or urban areas. Architects and developers often propose aesthetically pleasing railings that engineers cannot accept because of structural inadequacies. The objective of this research study was to develop aesthetically pleasing, structurally sound railings that can serve as alternative railings.

This study is attempting to develop one or more new concrete, steel, and aluminum railings or combination railings, some with curb and sidewalk.

This report presents a new open type concrete bridge rail--Texas Type T411. The research study advisory committee composed of

Luis Ybanez, Bridge Engineer, Bridge Division, Austin,
John J. Panak, Bridge Designing Engineer, Bridge Division, Austin,
Dean Van Landuyt, Designing Engineer, Bridge Division, Austin,
Van M. McElroy, Supervising Bridge Engineer, District 18, Dallas,
John V. Blain, Jr., District Design Engineer, District 18, Dallas,
John P. Kelley, Supervising Design Engineer, District 18, Dallas,
Don Simpson, Architect, Hellmuth, Obata, Kassabaum, Inc.,
Dave Retzsch, Architect, Hellmuth, Obata, Kassabaum, Inc.,
T. J. Hirsch, Research Engineer, TTI, and
W. Lynn Beason, Associate Research Engineer, TTI,

reviewed design sketches of twenty-two different bridge rail designs before selecting the new Texas Type T411 as its top priority.

DESCRIPTION OF BRIDGE RAIL
TEXAS TYPE T411

This bridge rail is constructed of reinforced concrete 32 in. high by 12 in. thick and contains 8 in. wide by 18 in. high openings at 18 in. center-to-center longitudinal spacing. Figures 1 and 2 present a plan view, elevation, and cross section of the T411 rail. The bridge deck is an 8 in. thick typical Texas bridge slab design in accordance with AASHTO specifications (4)*.

Figure 3 shows a photograph of the bridge rail installation prior to crash testing. The installation is 75 ft 10 in. long. The three pilasters are not super strong posts as they appear to be. They contain styrofoam blocks 10.5 in. by 13 in. by 21 in., (void) which means the pilasters are similar to the 8 in. by 18 in. openings. The use of the pilasters is thus optional since they did not contribute to the bridge rail strength as built and crash tested.

This bridge rail was designed using a failure mechanism (or yield line) method of analysis (1). The design strength of the concrete was f_c = 3,600 psi and the yield strength of reinforcing steel was f_y = 60,000 psi. The top beam was nominally 7 in. wide and 11 in. thick (b = 7 in. and d = 8.25 in.), yielding an ultimate moment capacity of 20.0 kip-ft. The posts were 10 in. wide and 10 in. thick (b = 10 in. and d = 8 in.), yielding an ultimate moment capacity of 20.6 kip-ft. With a moment arm of 2.2 ft, each post could resist a lateral load of about 9.5 kips. Figure 4 presents a summary of the failure mechanism analysis of the strength of the T411 bridge rail. The failure load would be about 65.9 kips or more. Five posts would crack and a 9 ft length of bridge rail would be involved.

Concrete specimens taken from the simulated bridge deck yielded a compressive strength of 4,880 psi at 28 days of age. The compressive strength of the concrete rail was 5,110 psi at 28 days of age.

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* Numbers in parentheses, thus (4), refer to corresponding item in References.

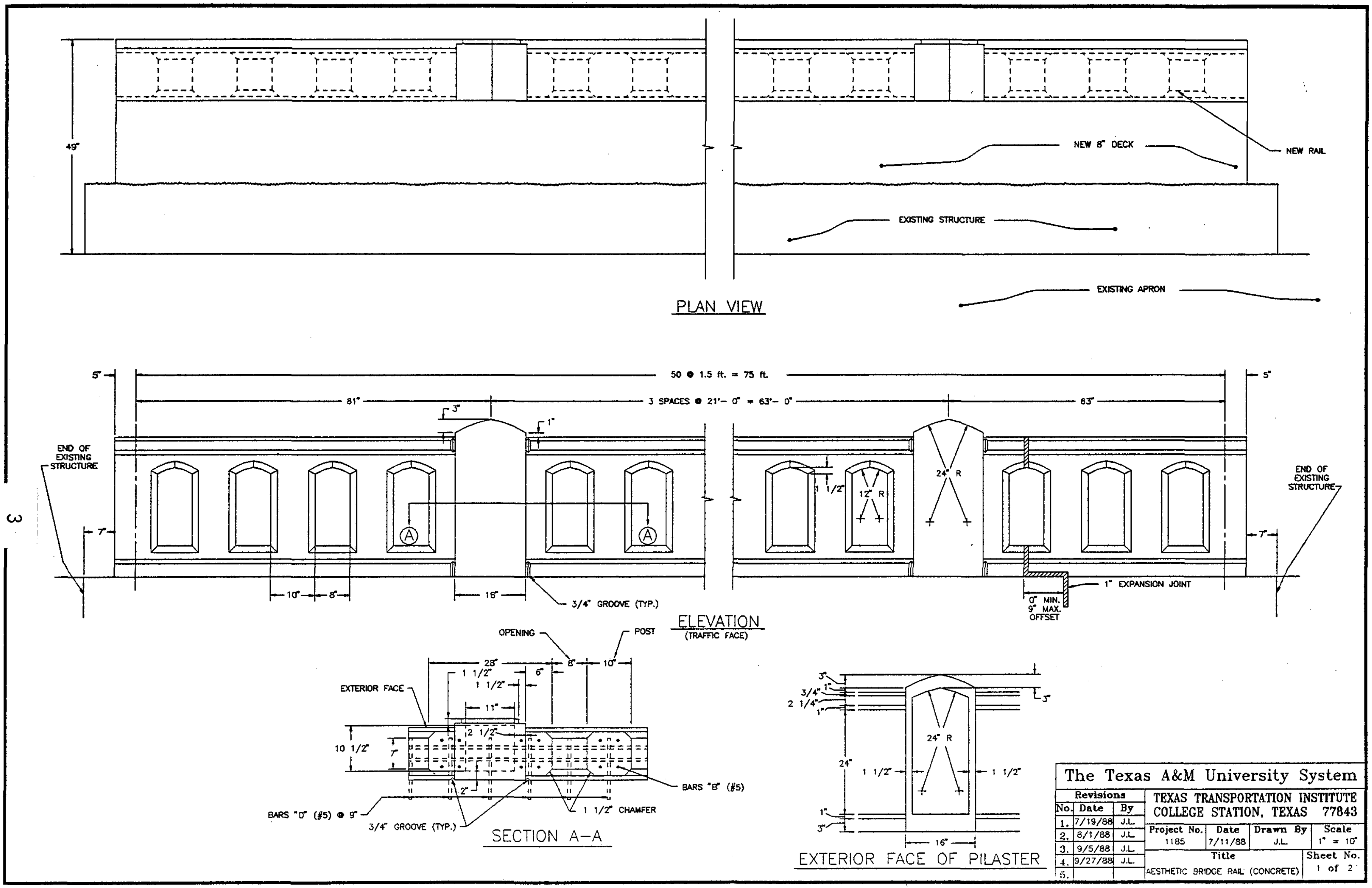
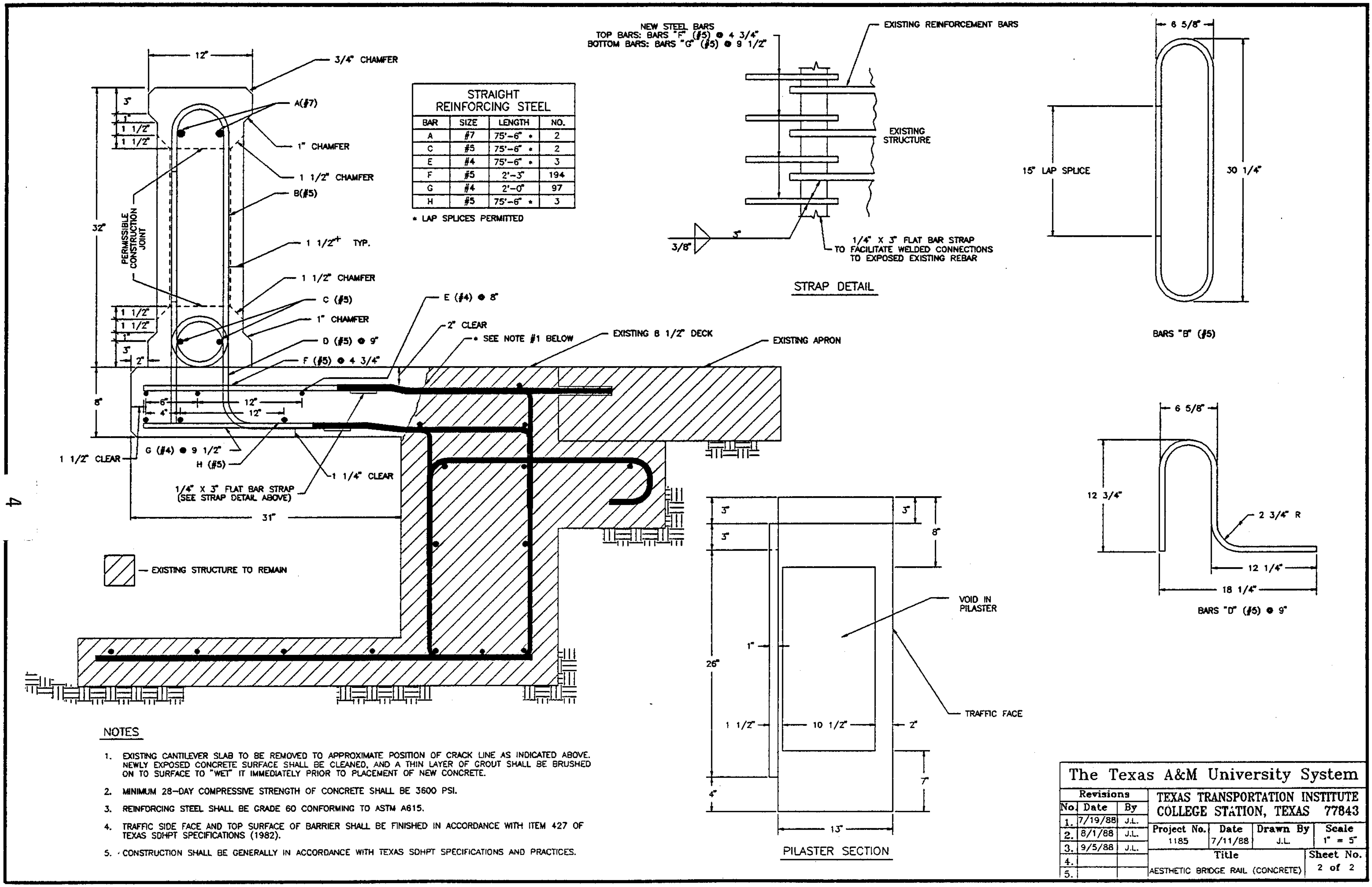


Figure 1. Texas type T411 bridge rail - plan and elevation.



STRAIGHT REINFORCING STEEL

BAR	SIZE	LENGTH	NO.
A	#7	75'-6" *	2
C	#5	75'-6" *	2
E	#4	75'-6" *	3
F	#5	2'-3"	194
G	#4	2'-0"	97
H	#5	75'-6" *	3

* LAP SPLICES PERMITTED

NOTES

1. EXISTING CANTILEVER SLAB TO BE REMOVED TO APPROXIMATE POSITION OF CRACK LINE AS INDICATED ABOVE. NEWLY EXPOSED CONCRETE SURFACE SHALL BE CLEANED, AND A THIN LAYER OF GROUT SHALL BE BRUSHED ON TO SURFACE TO "WET" IT IMMEDIATELY PRIOR TO PLACEMENT OF NEW CONCRETE.
2. MINIMUM 28-DAY COMPRESSIVE STRENGTH OF CONCRETE SHALL BE 3600 PSI.
3. REINFORCING STEEL SHALL BE GRADE 60 CONFORMING TO ASTM A615.
4. TRAFFIC SIDE FACE AND TOP SURFACE OF BARRIER SHALL BE FINISHED IN ACCORDANCE WITH ITEM 427 OF TEXAS SDHPT SPECIFICATIONS (1982).
5. CONSTRUCTION SHALL BE GENERALLY IN ACCORDANCE WITH TEXAS SDHPT SPECIFICATIONS AND PRACTICES.

The Texas A&M University System
TEXAS TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS 77843

Revisions No.	Date	By
1.	7/19/88	J.L.
2.	8/1/88	J.L.
3.	9/5/88	J.L.
4.		
5.		

Project No.	Date	Drawn By	Scale
1185	7/11/88	J.L.	1" = 5"

Title: AESTHETIC BRIDGE RAIL (CONCRETE) — Sheet No. 2 of 2

Figure 2. Texas type T411 bridge rail - cross section.

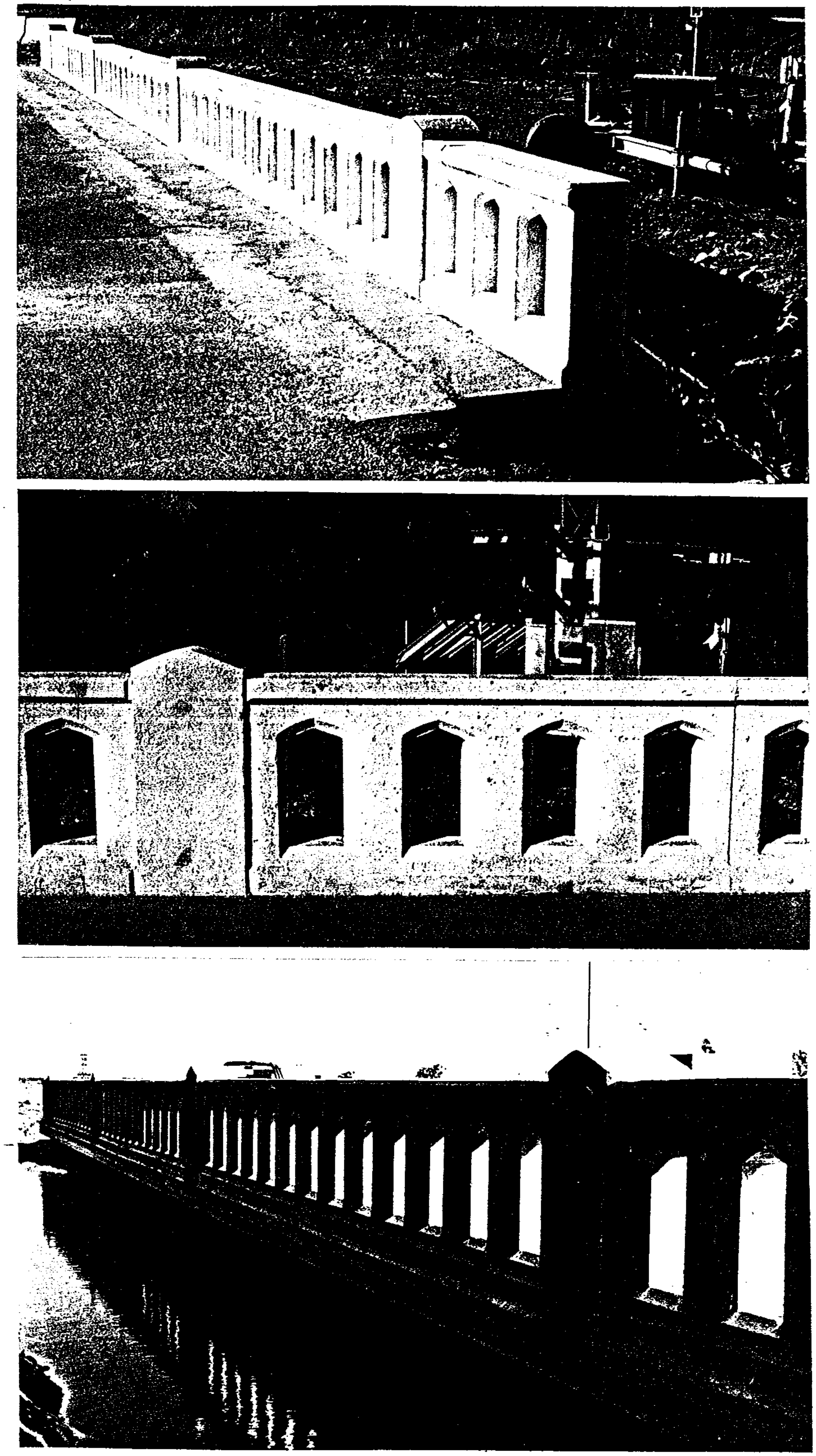


Figure 3 . Installation before test 1185-1.

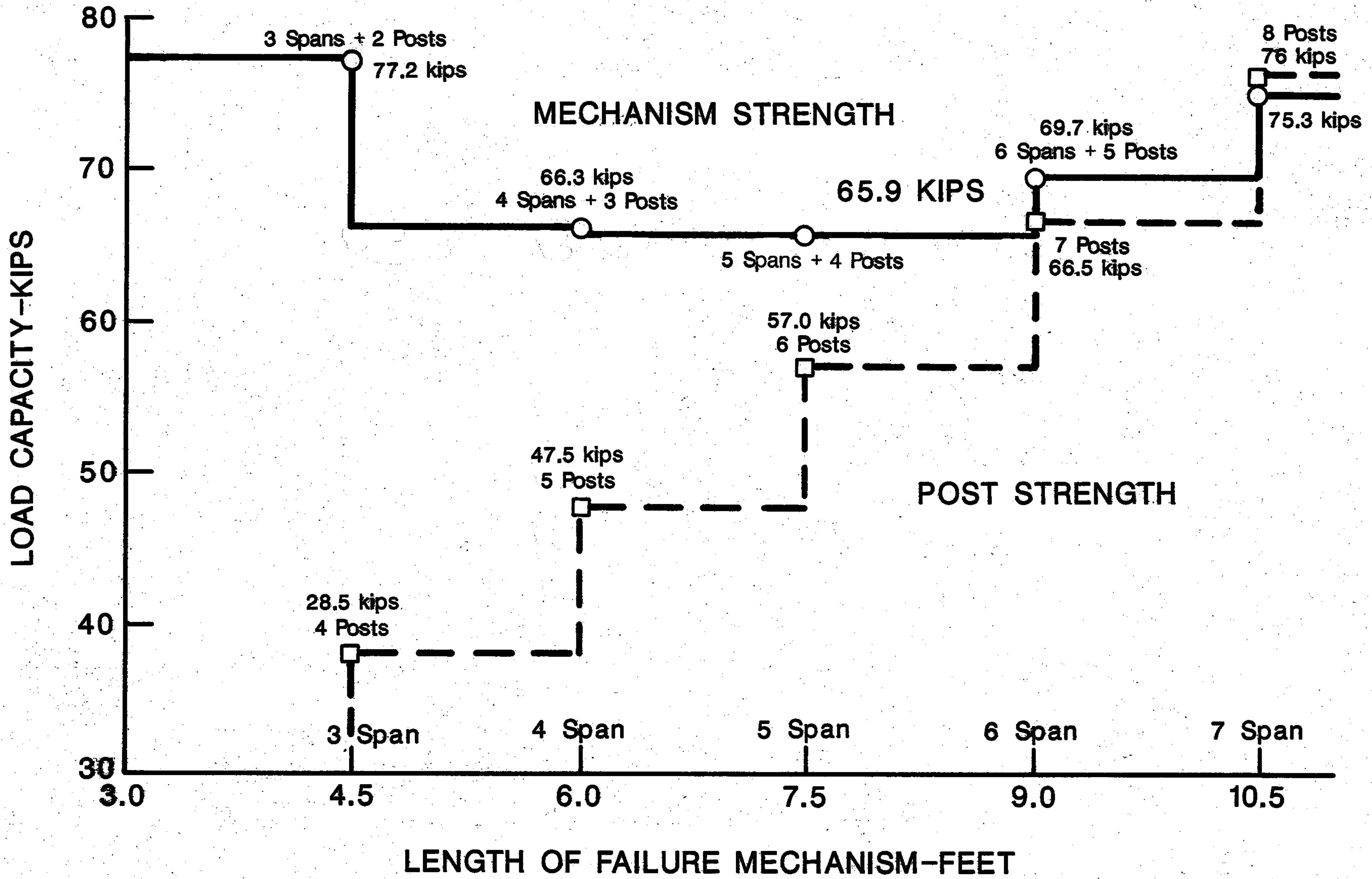
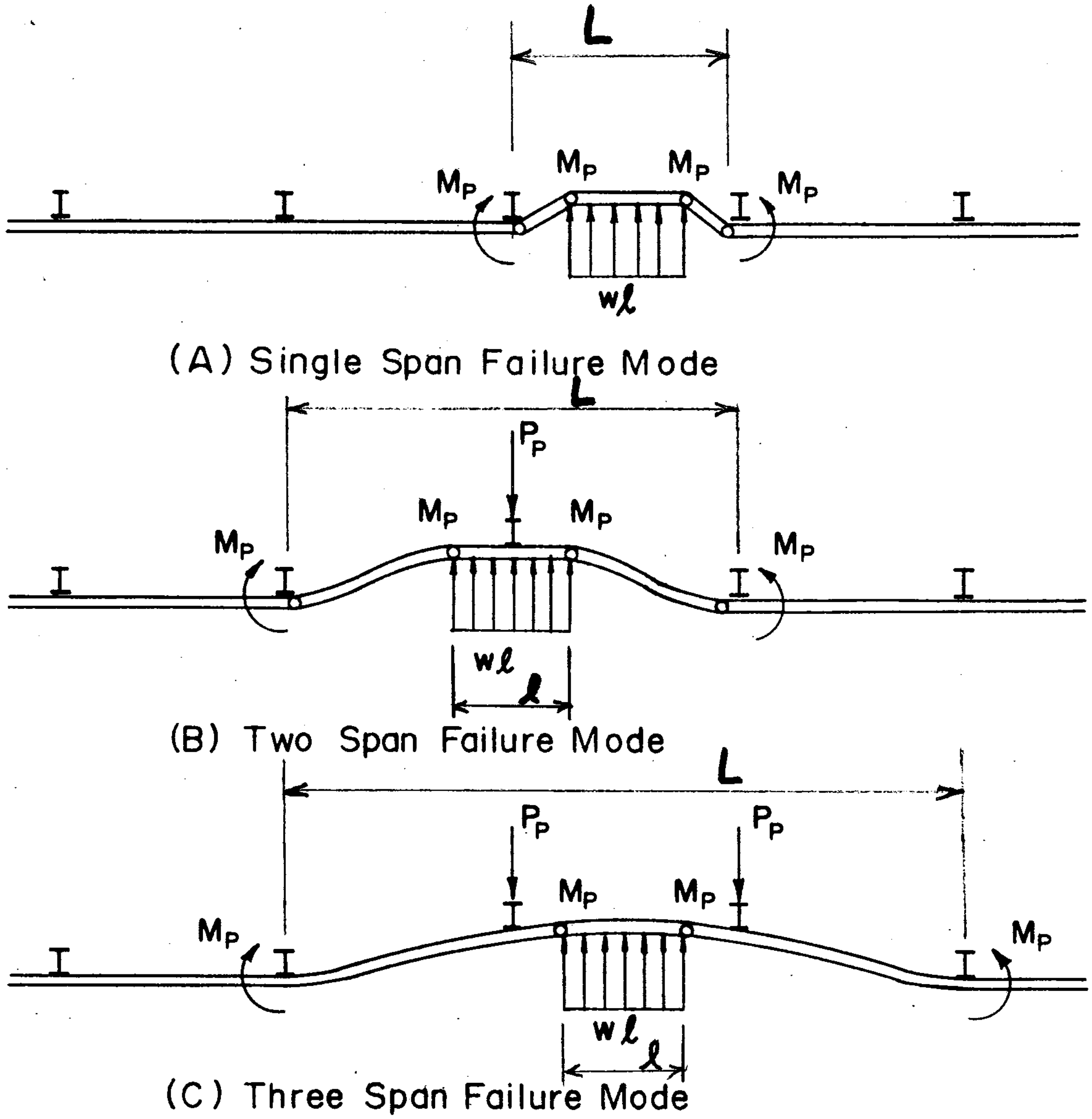


Figure 4. Failure Mechanism Analysis Texas Type T411 Bridge Rail



M_P = plastic moment capacity of rail $= M_{ult}$

P_P = ultimate load capacity of a single post

$w\ell$ = total ultimate vehicle impact load $= \dfrac{8 M_P}{L - \ell/2} + \sum P_P$

$\ell = 3.5$ ft

PLAN VIEW

FIGURE 5. POSSIBLE FAILURE MODES FOR RAILS.

CRASH TESTS

In order to qualify this bridge rail for use on federal aid highways, it was crash tested and evaluated in accordance with NCHRP Report 230 (3) for Service Level 2. Two crash tests were required--Test Designation 10 with a 4,500 lb passenger car at 60 mph and 25° impact angle and Test Designation S13 with an 1,800 lb passenger car at 60 mph and 20° impact angle.

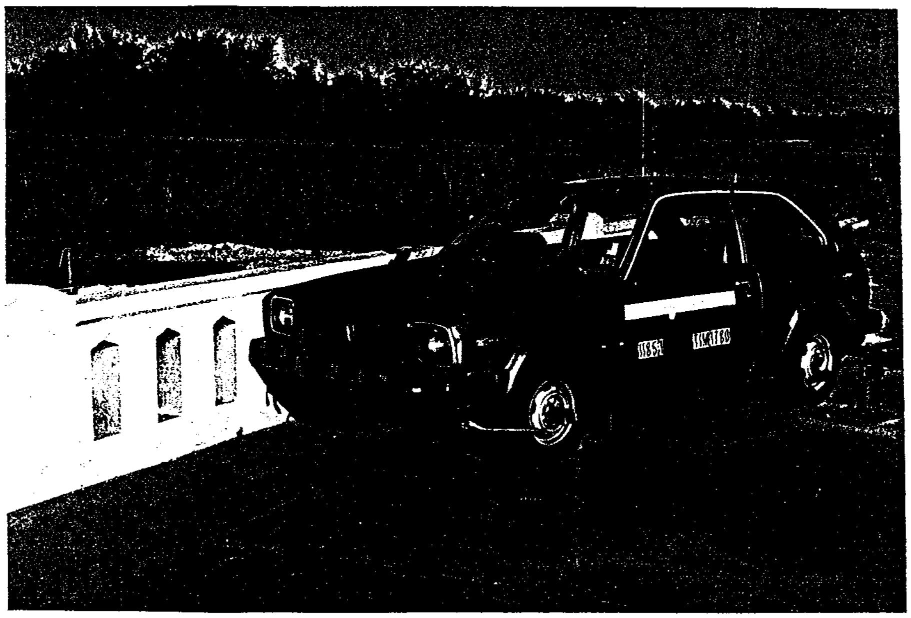
A description of the instrumentation and data analysis is presented in Appendix A.

HONDA CRASH TEST

The 1980 Honda Civic (figure 6) was directed into the bridge rail using a reverse tow and guidance system. Test inertia mass of the vehicle was 1,800 lb (808 kg). The height to the lower edge of the vehicle bumper was 14.25 in. (36.2 cm) and to the top of the bumper it was 19.25 in. (48.9 cm). Other dimensions and information on the test vehicle are given in Appendix C. The vehicle was free-wheeling and unrestrained just prior to impact.

The speed of the vehicle at impact was 60.2 mph (96.9 km/h) and the angle of impact was 21.2°. The vehicle impacted the bridge rail approximately 22 ft (6.7 m) from the end. The right front wheel made contact with the bridge rail shortly after impact. The vehicle began to redirect at 0.039 seconds. By 0.052 seconds, the vehicle had deformed to the A-pillar which allowed the windshield to begin to pop out, and at 0.075 seconds, the windshield broke. At 0.378 seconds, the vehicle was traveling almost parallel with the bridge rail and its speed was about 39.3 mph. The front of the vehicle remained in contact with the bridge rail until it rode off the end at 0.974 seconds at a speed of 30.2 mph. When brakes were applied, the vehicle yawed clockwise and subsequently came to rest 100 ft (30.5 m) from the point of impact. Sequential photographs are shown in Appendix B.

As can be seen in figures 7 and 8, the rail received only minimal cosmetic damage. No structural cracking occured in the rail or deck. There were tire marks on the face of the bridge rail from the point of impact to the end of the rail. There was some scraping and gouging along the edges of the portholes and of the first pilaster beyond impact. The vehicle was in contact with the bridge rail for 53 ft (16 m). The vehicle sustained severe damage to the right side as shown in figure 9. Maximum crush at the right front corner at bumper height was 11.0 in. (27.9 cm). The drive axle universal joint and right strut were



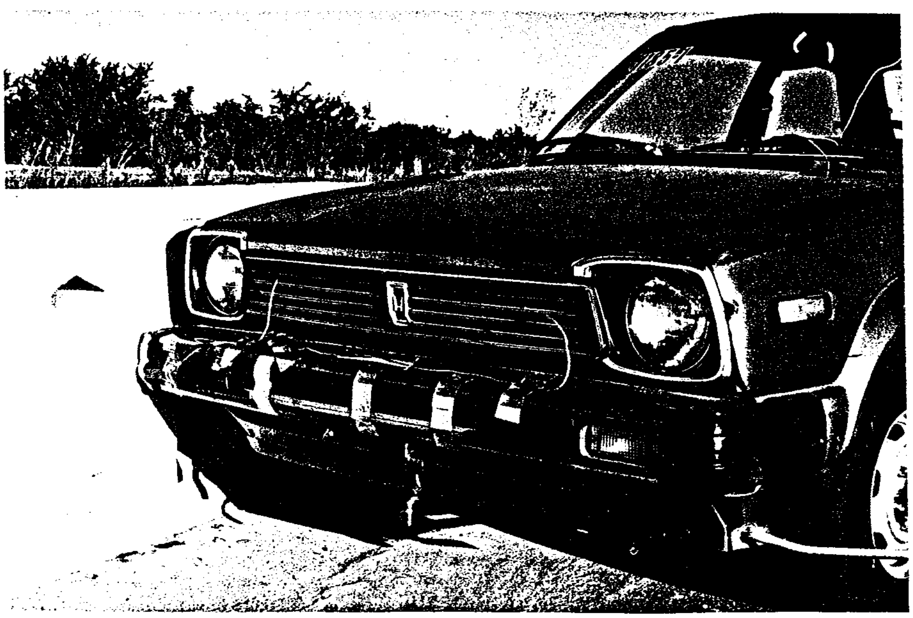


Figure 6 . Vehicle/bridge rail geometrics for test 1185-1.

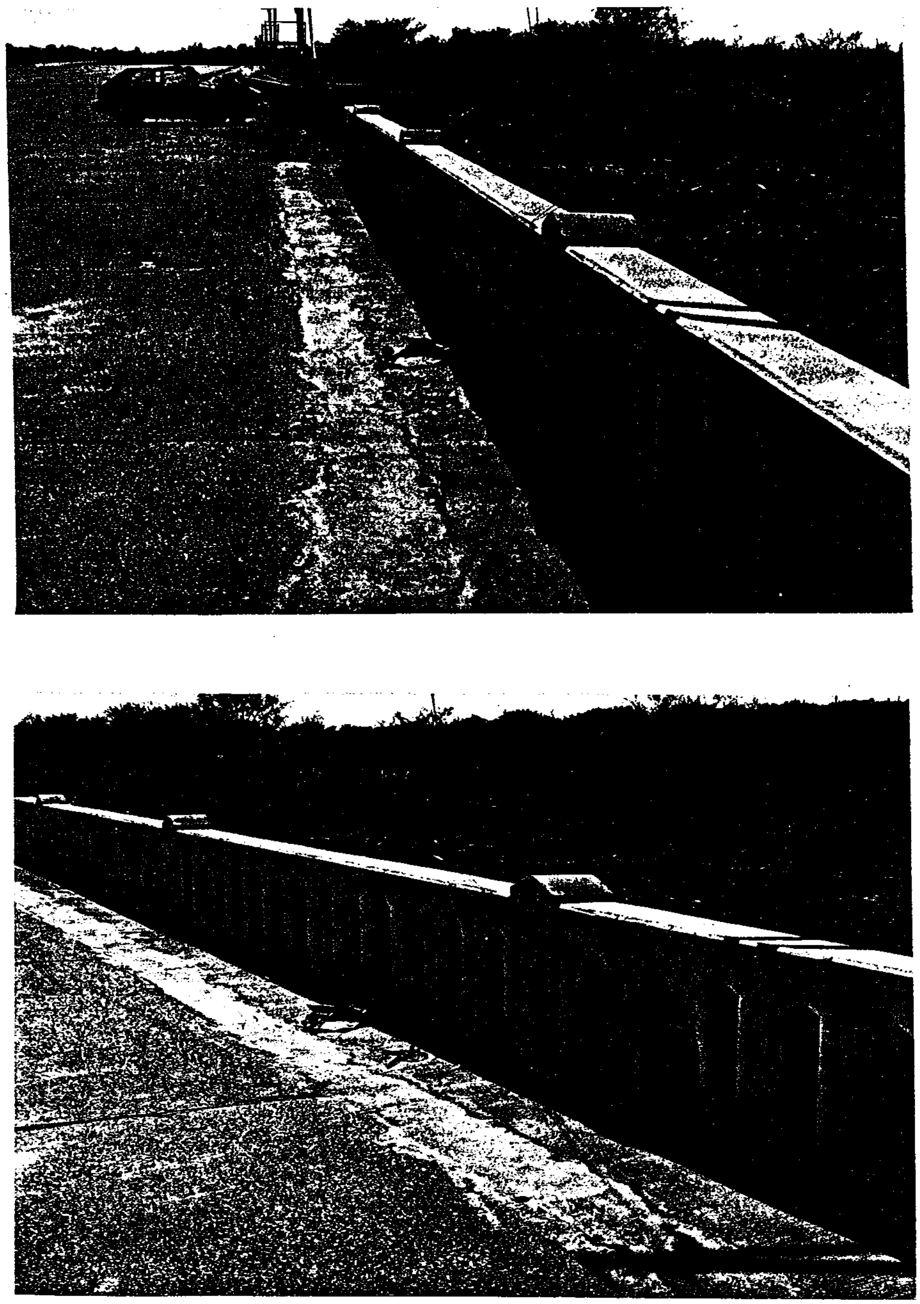


Figure 7. Test installation after test 1185-1.

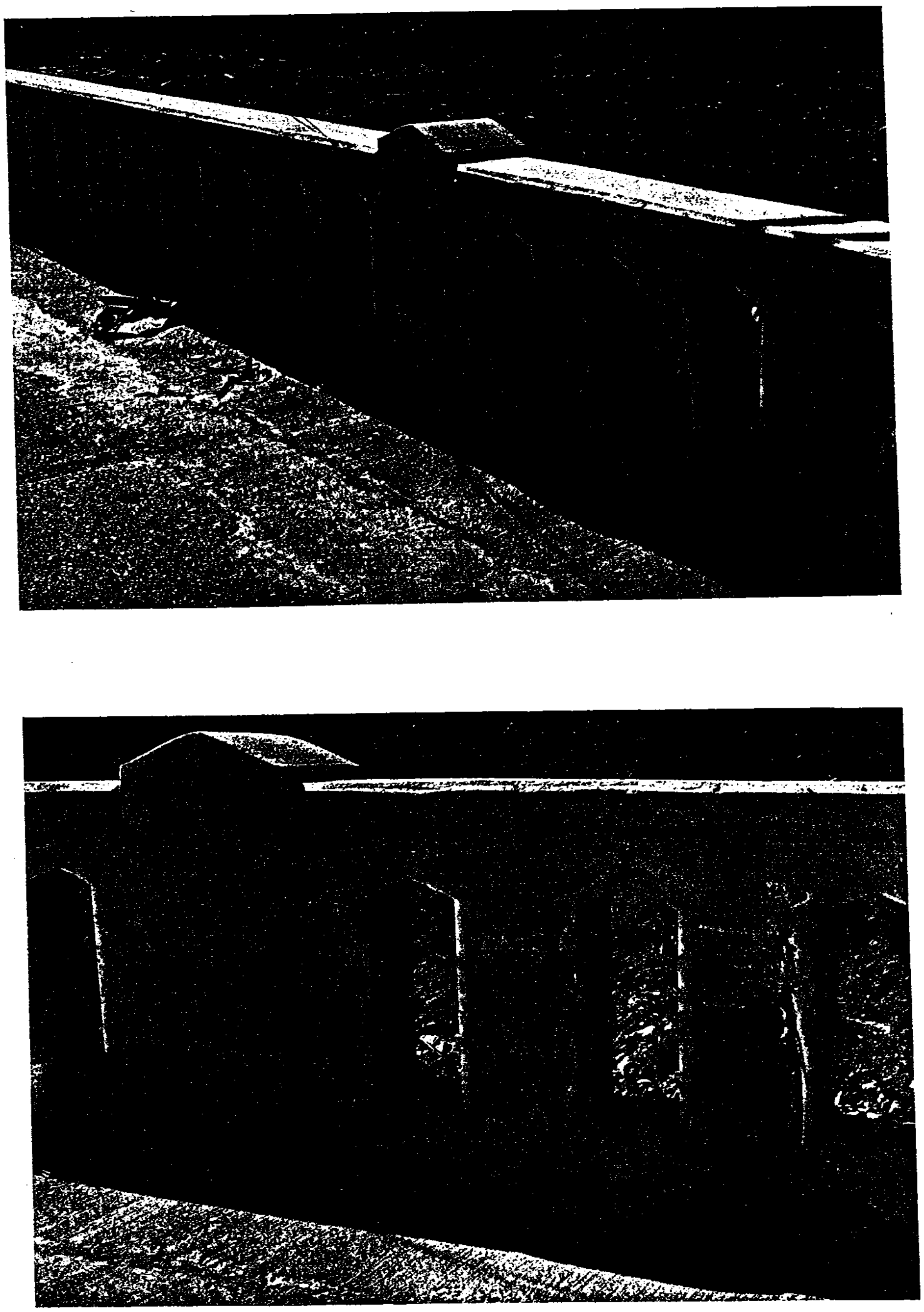


Figure 8. Damage to rail at point of impact.

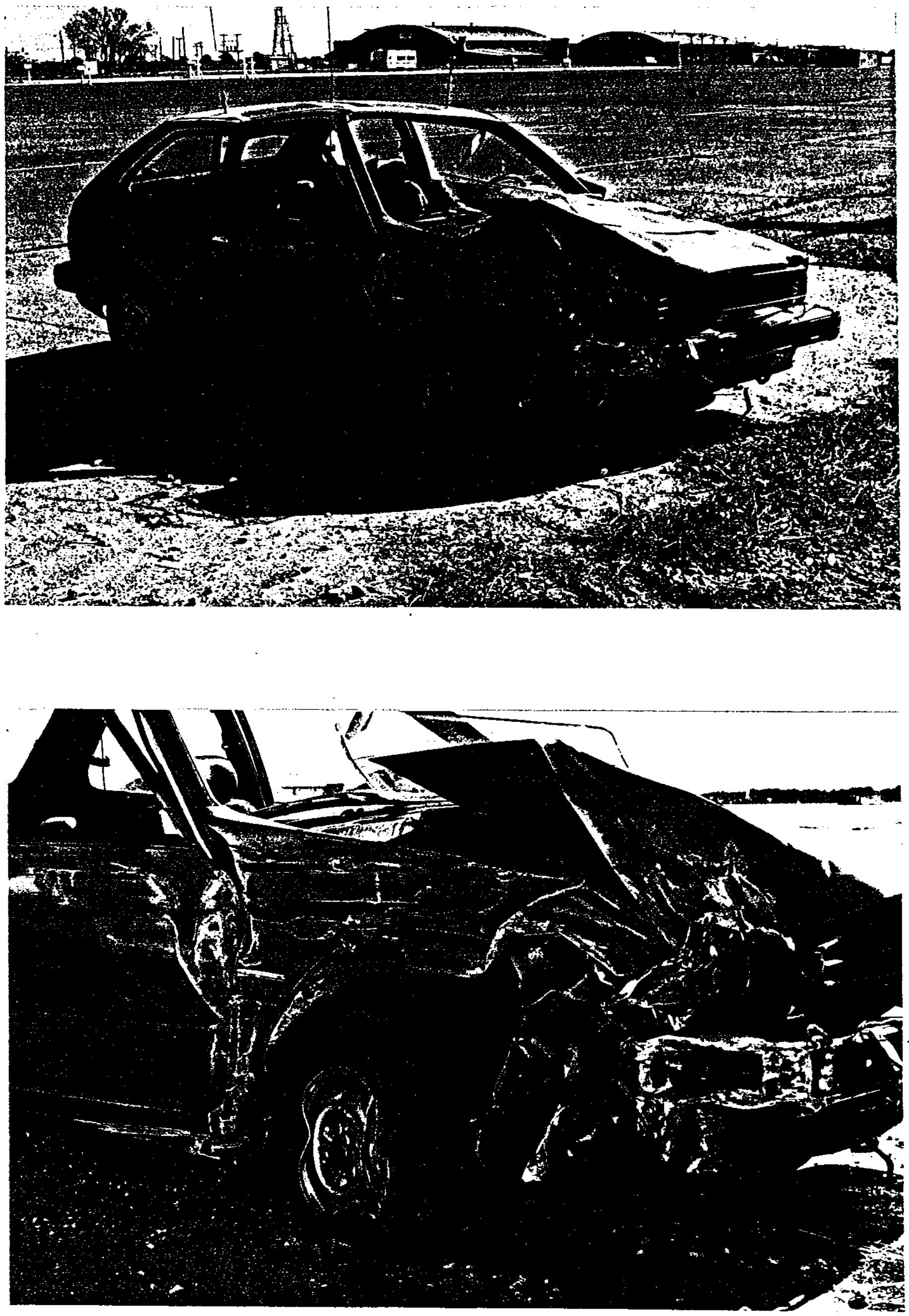


Figure 9. Vehicle after test 1185-1.

damaged. The instrument panel in the passenger compartment was bent as well as the floor pan and roof, and the windshield was broken. The right front rim was bent and the tire damaged. There was damage to the hood, grill, bumper, right front quarter panel, the right door and glass, the right rear quarter panel and the rear bumper.

TEST RESULTS

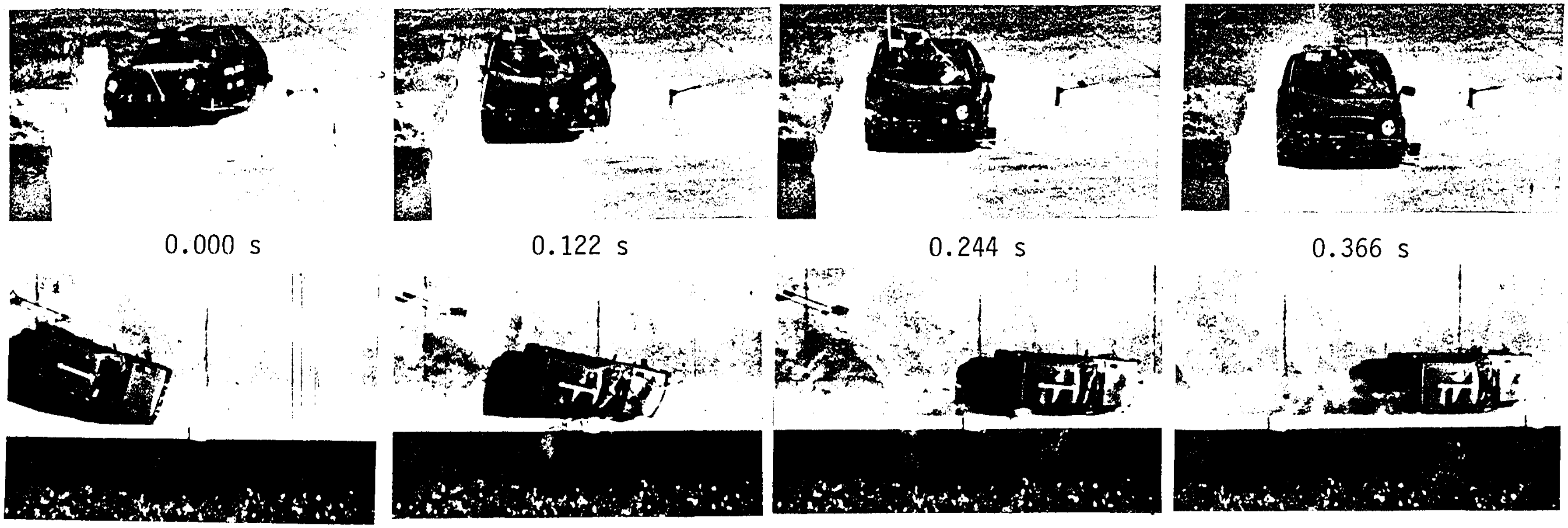
Impact speed was 60.2 mph (96.9 km/h) and the angle of impact was 21.2 degrees. Occupant impact velocity was 28.6 ft/s (8.7 m/s) in the longitudinal direction and 16.5 ft/s (5.0 m/s) in the lateral direction. The highest 0.010-second occupant ridedown accelerations were -2.0 g (longitudinal) and 3.6 g (lateral). These data and other pertinent information from the test are summarized in figure 10. Vehicular angular displacements are displayed in Appendix C.

Vehicular accelerations versus time traces filtered at 300 Hz are also presented in Appendix C. These data were further analyzed to obtain 0.050-second average accelerations versus time. The maximum 0.050-second averages measured at the center of gravity were -13.5 g (longitudinal) and 11.3 g (lateral).

CONCLUSIONS

The bridge rail contained and smoothly redirected the test vehicle with no lateral movement of the bridge rail. There were no detached elements or debris to present undue hazard to other traffic. The vehicle remained upright and relatively stable during the collision. The occupant/compartment impact velocities and 10-ms occupant ridedown accelerations were within the limits specified in NCHRP Report 230 (see Appendix F). The vehicle trajectory at loss of contact indicates no intrusion into adjacent traffic lanes (exit angle 0°).

This test also met the safety evaluation guidelines proposed in the new AASHTO Guide Specification for Bridge Railings (see Appendix F). The effective coefficient of friction u was found to be 0.54 or marginal for this test.



Test No. 1185-1
Date 11/29/88

Test Installation . . . T411 Bridge Rail
Installation length . . 75 ft (23 m)

Vehicle . . . . 1980 Honda Civic
Vehicle Weight
  Test Inertia . . . . . . 1,780 lb (808 kg)
Vehicle Damage Classification
  TAD . . . . 01FR5 & 01RFQ5
  CDC . . . . 01FREK2 & 01RYAW3
Maximum Vehicle Crush . 11.0 in (27.9 cm)

Impact Speed . . . 60.2 mi/h (96.0 km/h)
Impact Angle . . . 21.2 degrees
Speed at Parallel . 39.3 mi/h (63.3 km/h)
Exit Speed . . . . 30.2 mi/h (48.6 km/h)
Exit Trajectory . . 0 degrees
Vehicle Accelerations
  (Max. 0.050-sec Avg)
  Longitudinal . . -13.5 g
  Lateral . . . . . 11.3 g
Occupant Impact Velocity
  Longitudinal . . 28.6 ft/s (8.7 m/s)
  Lateral . . . . . 16.6 ft/s (5.0 m/s)
Occupant Ridedown Accelerations
  Longitudinal . . -2.0 g
  Lateral . . . . . 3.6 g

Figure 10. Summary of results for test 1185-1.

CADILLAC CRASH TEST

The 1980 Cadillac Sedan DeVille (figure 11) was directed into the bridge rail using a reverse tow and guidance system. Test inertia mass of the vehicle was 4,500 lb (2,043 km). The height to the lower edge of the vehicle bumper was 12.5 in. (31.8 cm) and to the top of the bumper it was 21.0 in. (53.3 cm). Other dimensions and information on the test vehicle are given in Appendix E. The vehicle was free-wheeling and unrestrained just prior to impact.

The speed of the vehicle at impact was 62.2 mph (100.1 km/h) and the angle of impact was 26.0°. The vehicle impacted the bridge rail approximately 38 ft (12 m) from the end. The right front wheel made contact with the bridge rail shortly after impact. The vehicle began to redirect at 0.064 seconds. By 0.085 seconds, the vehicle had deformed to the A-pillar and the windshield broke. At 0.240 seconds, the vehicle began to move parallel with the bridge rail traveling at a speed of 41.7 mph (66.9 km/h). The rear of the vehicle impacted the bridge rail at 0.264 seconds. The vehicle lost contact with the bridge rail at 0.379 seconds, traveling at 38.9 mph (62.6 km/h) and 5.9°. The brakes were then applied; the vehicle yawed clockwise and subsequently came to rest against a safety barrier 125 ft (30.5 m) from the point of impact. Sequential photographs are shown in Appendix D.

As can be seen in figure 12, the rail received only minimal cosmetic damage. No structural cracking occured in the rail or deck. There were tire marks on the face of the bridge rail from the point of impact to the end of the rail. There was some scraping and gouging along the edges of the portholes and of the first pilaster beyond impact. The vehicle was in contact with the bridge rail for 12 ft (3.7 m).

The vehicle sustained moderate damage to the right side, as shown in figure 13. Maximum crush at the right front corner at bumper height was 16.0 in. (49.6 cm). The right A-arm, the tie rod, and the upper and lower ball joints were damaged and the subframe was bent. The instrument panel in the passenger compartment was bent as well as the floor pan and roof, and the windshield was broken. The right front and rear rims were bent and the tires damaged. There was damage to the hood, grill, bumper, right front quarter panel, the right front and rear doors, the right rear quarter panel and the rear bumper.

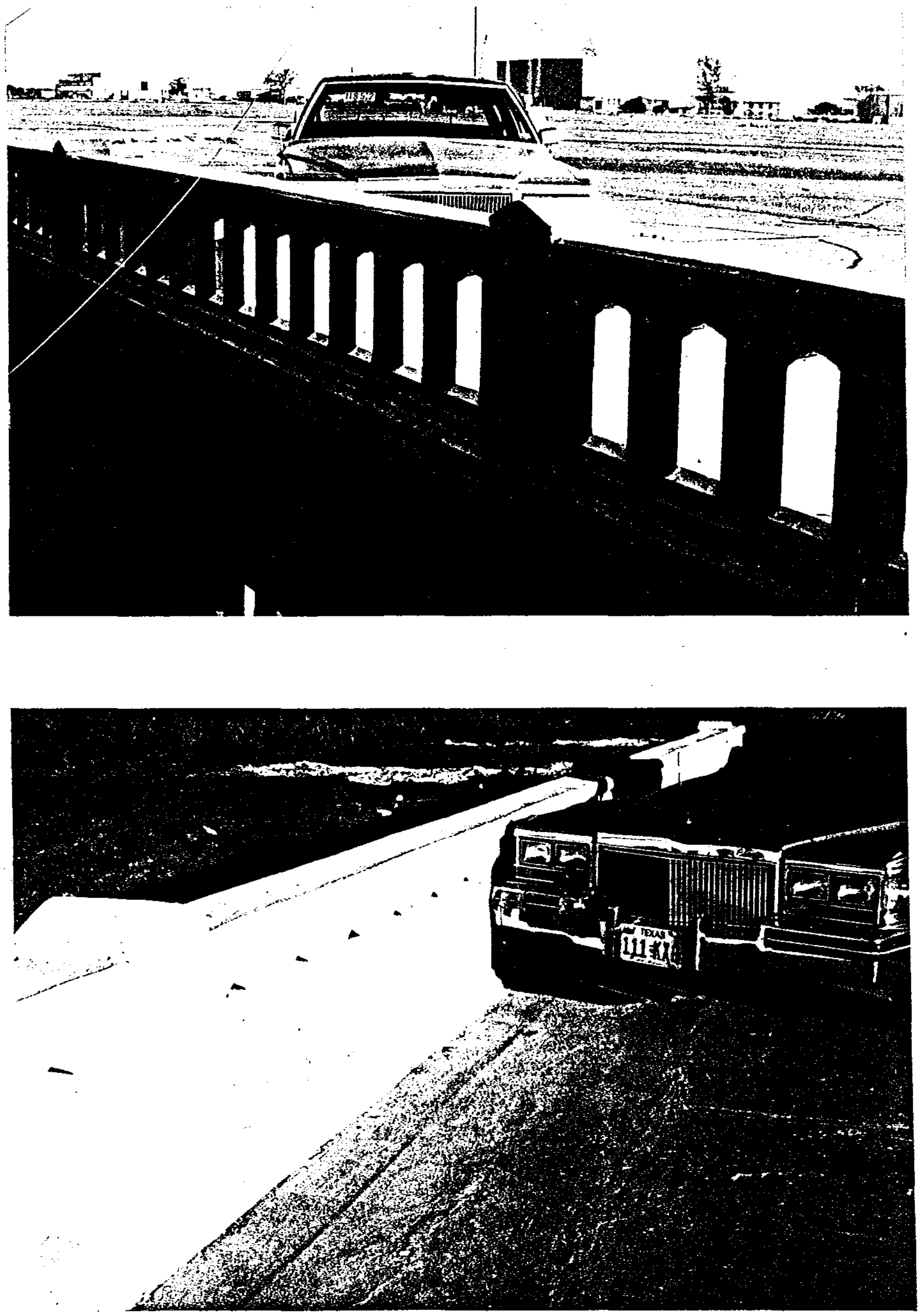


Figure 11. Vehicle/bridge rail geometrics for test 1185-2.

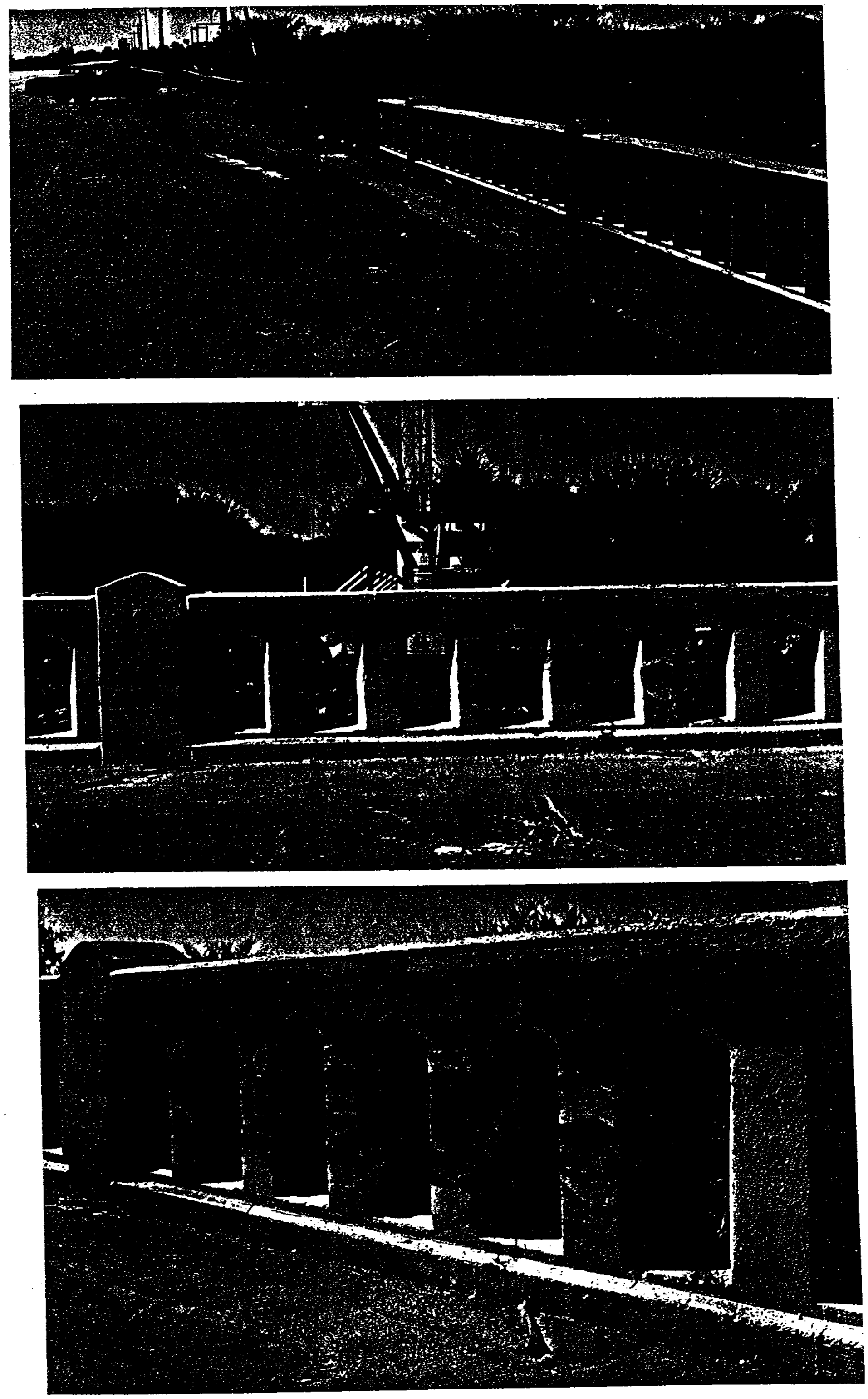


Figure 12. Test installation after test 1185-2.

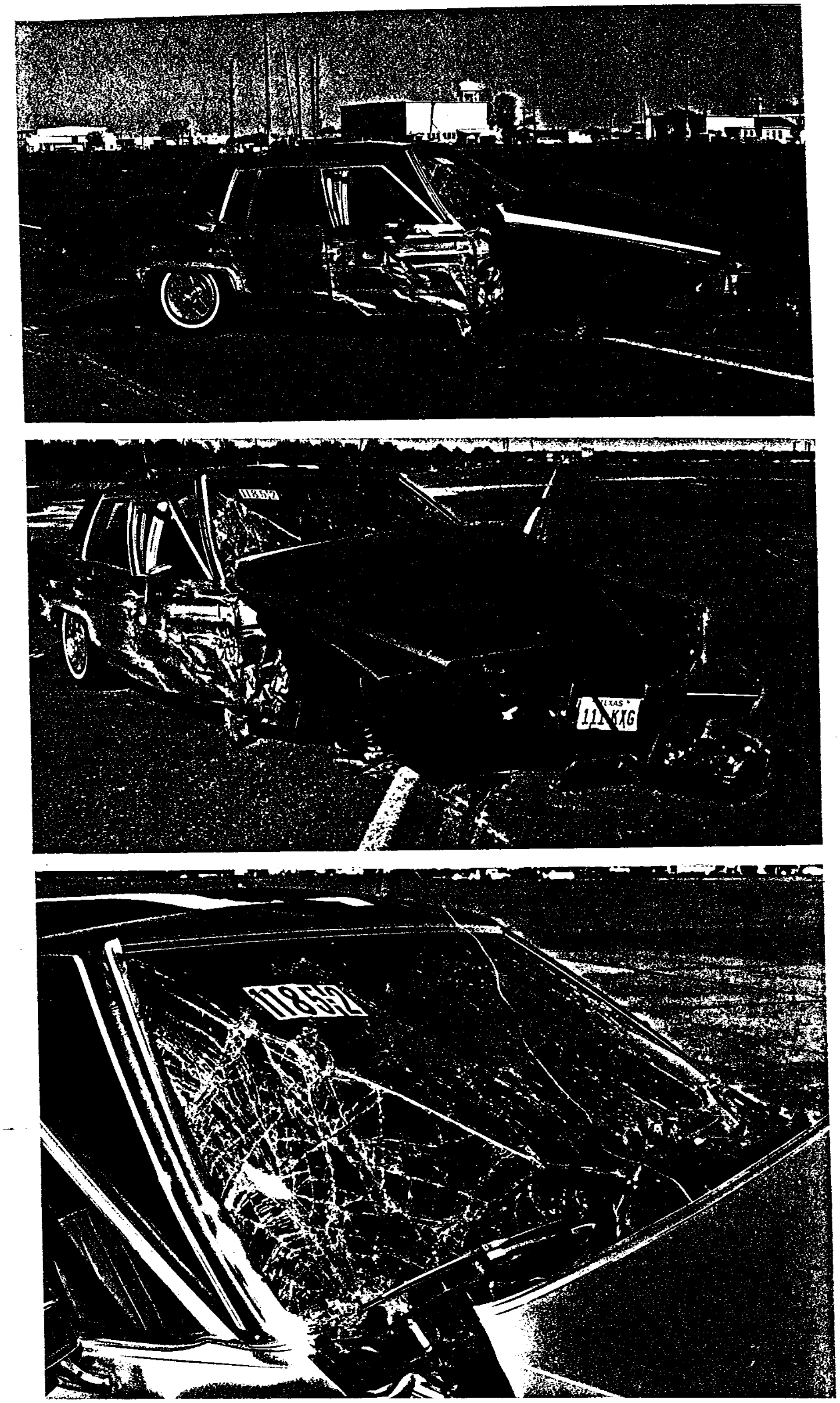


Figure 13. Vehicle after test 1185-2.

TEST RESULTS

Impact speed was 62.2 mph (100.1 km/h) and the angle of impact was 26.0°. The vehicle exited the rail at 38.9 mph (62.6 km/h) and 5.9°. NCHRP Report 230 describes occupant risk evaluation criteria and places limits on these for acceptable performance for tests conducted at 15° impact angles. These limits do not apply to tests conducted at 25° impact angles but were computed and reported for information only. Occupant impact velocity was 28.7 ft/s (8.7 m/s) in the longitudinal direction and 23.0 ft/s (7.0 m/s) in the lateral direction. The highest 0.010-second occupant ridedown accelerations were -12.4 g (longitudinal) and 10.5 g (lateral). These data and other pertinent information from the test are summarized in figure 14. Vehicular angular displacements are displayed in Appendix E.

Vehicular accelerations versus time traces filtered at 300 Hz are presented in Appendix E. These data were further analyzed to obtain 0.050-second average accelerations versus time. The maximum 0.050-second averages measured at the center of gravity were -12.8 g (longitudinal) and 16.5 g (lateral).

CONCLUSIONS

The bridge rail contained and smoothly redirected the test vehicle with no lateral movement of the bridge rail. The vehicle remained upright and relatively stable during the collision. The vehicle trajectory at loss of contact indicates minimum intrusion into adjacent traffic lanes (exit angle 5.9°). This test met all the safety evaluation criteria of NCHRP 230 and of the new, proposed AASHTO Guide Specifications for Bridge Railings (see Appendix F). The effective coefficient of friction u for this test was 0.77 or marginal.

0.000 s 0.133 s 0.267 s 0.400 s

Test No. 1185-2
Date 12/01/88

Test Installation . . . T411 Bridge Rail
Installation Length . . 75 ft (23 m)

Vehicle . . . . 1980 Cadillac
Vehicle Weight
  Test Inertia . . . . . 4,500 lb (2,043 kg)
Vehicle Damage Classification
  TAD . . . . 01FR6 & 01RFQ7
  CDC . . . . 01FZEK2 & 01RYAW4
Maximum Vehicle Crush . 16.0 in (40.6 cm)

Impact Speed . . . 62.2 mi/h (100.1 km/h)
Impact Angle . . . 26.0 degrees
Speed at Parallel . 41.7 mi/h (67.1 km/h)
Exit Speed . . . . 38.9 mi/h (62.6 km/h)
Exit Trajectory . . 5.9 degrees
Vehicle Accelerations
  (Max. 0.050-sec Avg)
  Longitudinal . . -12.8 g
  Lateral . . . . . 16.5 g
Occupant Impact Velocity
  Longitudinal . . 28.7 ft/s (8.7 m/s)
  Lateral . . . . . 23.0 ft/s (7.0 m/s)
Occupant Ridedown Accelerations
  Longitudinal . . -12.4 g
  Lateral . . . . . 10.5 g

Figure 14. Summary of results for test 1185-2.

SUMMARY and CONCLUSIONS

Table 1 compares the vehicle impact behavior of the aesthetic bridge rail T411 with vehicle impact behavior obtained from several other rigid longitudinal traffic barriers. It can be seen that the change in speeds of the vehicles during impact (23.3 mph and 30.0 mph) is larger than those obtained from the other barriers, but the exit angles (0° and 5.9°) are smaller than those obtained from the others. Since the vehicles did not return to the traffic lanes but stayed against the rail, the larger change in speed is also not important. NCHRP 230 safety evaluation guidelines recommend, "In tests where the vehicle is judged to be redirected into or stopped while in adjacent traffic lanes, vehicle speed change during test article collision should be less than 15 mph and the exit angle from the test article should be less than 60 percent of test impact angle, both measured at time of vehicle loss of contact with test device."

The longitudinal accelerations (12.8 g's and 13.5 g's) are larger than those obtained from the other rails but are acceptable. These larger longitudinal accelerations were expected because the vehicle grinds into the verticle openings. The larger effective coefficients of friction u of 0.54 and 0.77 were also expected and attributed to the verticle openings in the T411 rail. The transverse accelerations of 11.3 g's and 16.5 g's are about the same as those obtained from the other barriers.

The longitudinal occupant impact velocities of 28.6 fps and 28.7 fps are larger than those obtained from the other rails but are less than the proposed limit of 30.0 fps. The transverse occupant impact velocities of 16.6 fps and 23.0 fps are less than those obtained from the other rails but smaller than the proposed limit of 25.0 fps.

The longitudinal ridedown accelerations of -2.0 g's and -12.4 g's are larger than those obtained from the other rails but less than the proposed limit of -15.0 g's. The transverse ridedown accelerations of 3.6 g's and 10.5 g's are smaller than those obtained from the other rails and smaller than the proposed limit of 15.0 g's.

It is therefore concluded that the new Texas T411 bridge has successfully met the crash test requirements.

TABLE 1. COMPARISON OF VEHICLE IMPACTS INTO THE AESTHETIC BRIDGE RAIL T411 WITH VEHICLE IMPACTS INTO OTHER RIGID LONGITUDINAL TRAFFIC BARRIERS.

NCHRP 230 Test 10 - 4,500 lb, 60 mph, 25°

(1) Test No.	(2) Change in Speed mph	(3) Exit Angle degrees	(4) Long. Accel. g's	(5) Trans. Accel. g's	(6) Long. Occupant Impact Vel. fps	(7) Trans. Occupant Impact Vel. g's	(8) Long. Ridedown Accel. g's	(9) Trans. Ridedown Accel. g's	(10) Type Rail
1179-2	14.5	2.0	- 9.7	14.3	23.9	27.3	- 4.9	16.7	Conc. C202
7046-1	15.9	17.5	- 4.8	14.0	19.4	28.2	- 5.4	14.4	Conc. Wall
3451-7	18.5	13.5	- 5.2	6.9	11.9	15.4	-	-	T101
7091-10	12.9	6.3	- 6.3	12.5	18.6	27.0	- 5.9	10.8	IBC
3451-36	17.4	6.3	- 9.1	15.4	10.9	23.0	-	-	Conc. Wall
7091-11	13.4	7.3	- 6.4	11.6	23.2	26.6	- 3.8	10.6	IBC
Avg.	15.4	8.8	- 6.9	12.5	18.0	24.6	- 5.0	13.1	
1185-1	23.3	5.9	-12.8	16.5	28.7	23.0	-12.4	10.5	T411

NCHRP 230 Test 13 - 1,800 lb, 60 mph, 20°

(1) Test No.	(2) Change in Speed mph	(3) Exit Angle degrees	(4) Long. Accel. g's	(5) Trans. Accel. g's	(6) Long. Occupant Impact Vel. fps	(7) Trans. Occupant Impact Vel. g's	(8) Long. Ridedown Accel. g's	(9) Trans. Ridedown Accel. g's	(10) Type Rail
1179-1	16.8	0.6	-11.2	14.0	23.3	25.7	- 2.0	9.3	Conc. C202
3451-27	13.2	1.0	- 9.2	10.3	18.6	19.5	-	-	Indiana Alum.
3451-28	19.9	3.5	-13.6	10.2	20.1	20.3	-	-	Indiana Alum.
7069-3	7.1	6.2	- 8.0	12.8	19.0	23.7	- 2.1	4.9	Conc. F Shape
7069-5	11.9	6.2	- 8.0	14.0	20.1	26.0	- 1.6	9.4	Conc. Wall
7069-10	10.2	5.2	- 6.4	14.2	16.9	25.1	- 1.4	8.5	Ill. Steel
Avg.	13.2	3.8	- 9.4	12.6	19.7	23.4	- 1.7	8.0	
1185-2	30.0	0	-13.5	11.3	28.6	16.6	- 2.0	3.6	

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5. Noel, J.S., T.J. Hirsch, C.E. Buth, and A. Arnold, "Loads on Bridge Railings," Transportation Research Record 796, Transportation Research Board, Jan. 1981.

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7. Buth, C.E., "Safer Bridge Railings," Vol. 1, 2, 3, and 4, Report No. FHWA/RD-82-072, Texas Transportation Institute, Texas A&M University, June 1984.

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9. Guide Specifications for Bridge Railings--An Alternative Bridge Railing Specification in the AASHTO Standard Specifications for Highway Bridges, American Association of State Highway Officials, 1988.

10. Arnold, A.G., and T.J. Hirsch, "Bridge Deck Designs for Railing Impacts," Research Report 295-1F, Texas Transportation Institute, Texas A&M University, Aug. 1985.

11. Hirsch, T.J., "Longitudinal Barriers for Buses and Trucks," Transportation Research Record 1052, Transportation Research Board, 1986.

APPENDIX A

Instrumentation and Data Analysis

APPENDIX A

INSTRUMENTATION AND DATA ANALYSIS

The vehicle was equipped with triaxial accelerometers mounted near the center of gravity to measure x, y, and z components of acceleration. In addition, yaw, pitch, and roll rates were measured by on-board instruments. The electronic signals were telemetered to a base station for recording on magnetic tape and for display on a real-time strip chart. Provision was made for transmission of calibration signals before and after the test, and an accurate time reference signal was simultaneously recorded with the data.

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 instant of impact. Data from the electronic transducers were digitized, using a microcomputer, for analysis and evaluation of performance.

Analog data obtained from the electronic transducers were digitized and then analyzed on a microcomputer using three computer programs: DIGITIZE, VEHICLE, and PLOTANGLE.

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, final occupant displacement, highest 0.010-second average of vehicle acceleration after occupant/compartment impact, and time of highest 0.010-second average. The DIGITIZE program also calculates a vehicle impact velocity and the change in vehicle velocity at the end of a given impulse period.

The VEHICLE program also uses digitized data from vehicle-mounted linear accelerometers to compute vehicle accelerations, areas enclosed by acceleration-time curves, changes in velocity, changes in momentum, instantaneous forces, average forces, and maximum average accelerations over 0.050-second intervals in each of three directions. The VEHICLE program plots acceleration versus time curves for the longitudinal, lateral, and vertical directions.

The PLOTANGLE program uses the digitized data from the yaw, pitch, and roll rate charts to compute angular displacement in degrees at 0.001-second 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.

Still photography, real-time cine, and video were used to record conditions of the test vehicle and bridge rail before and after the test. Video and real-time and high-speed cine were used to document the test. One high-speed camera was placed to have a field of view parallel to and aligned with the bridge rail at the downstream end, one was placed over the bridge rail to have a field of view perpendicular to the ground, another was placed perpendicular to the front of the bridge rail, and one was placed behind the bridge rail. The films from these cameras were used to observe phenomena occurring during collision and obtain time-event, displacement, and angular data.

APPENDIX B

Sequential Photographs of Test 1185-1

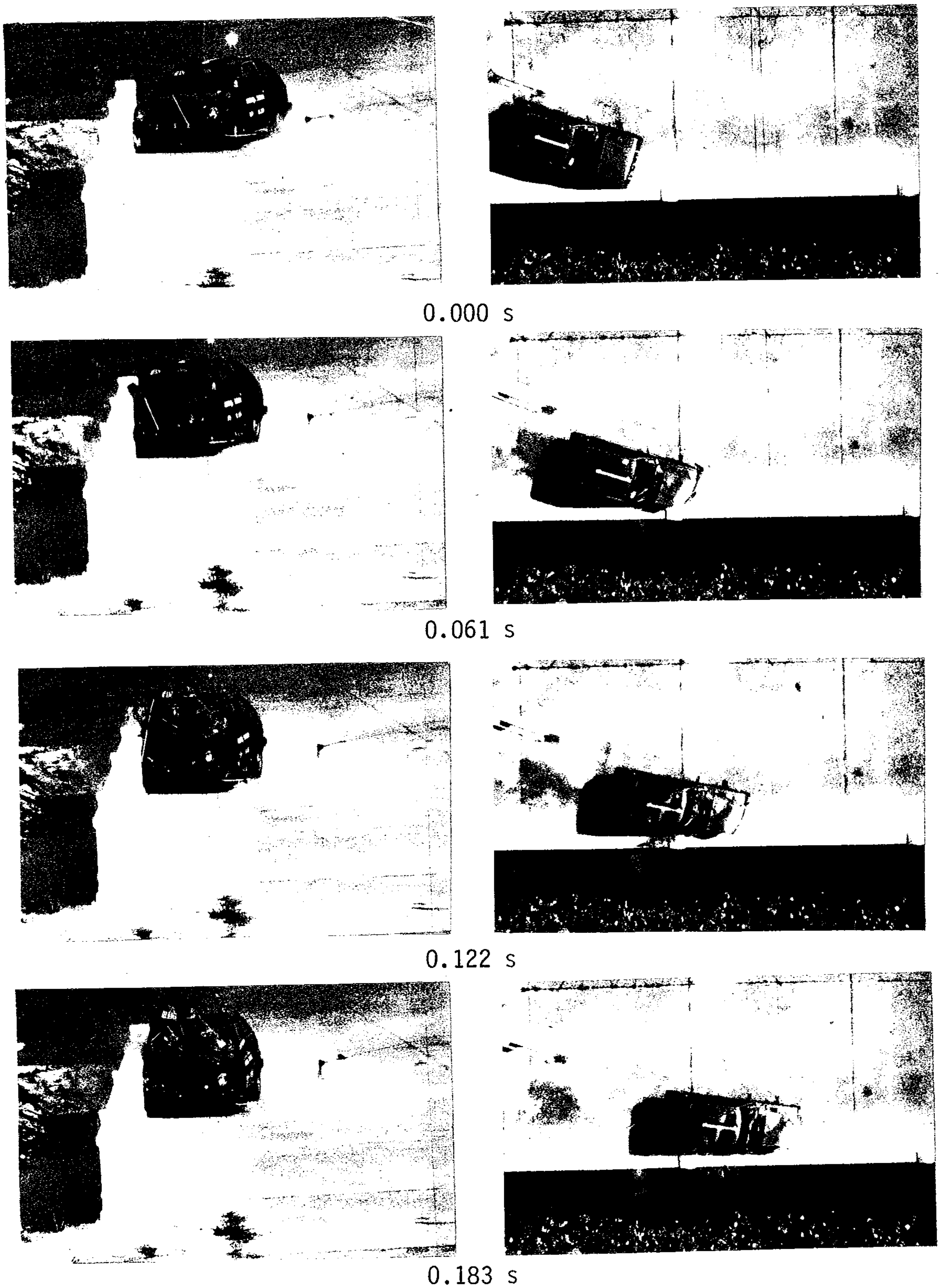
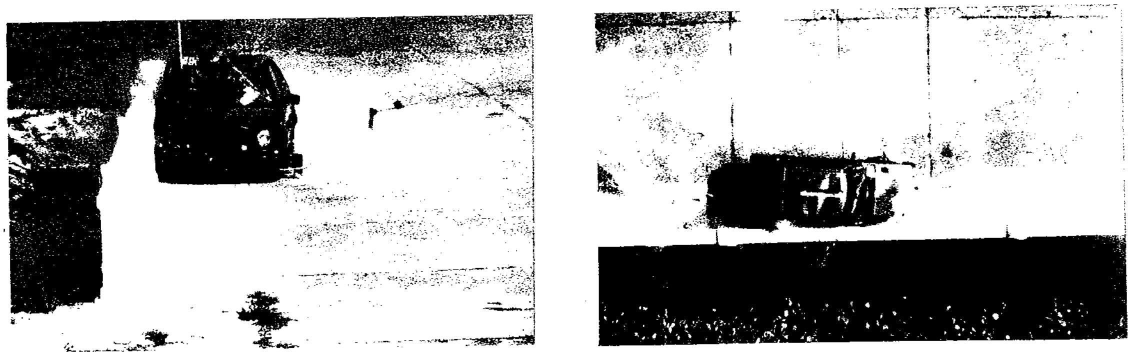


Figure B1. Sequential photographs for test 1185-1.



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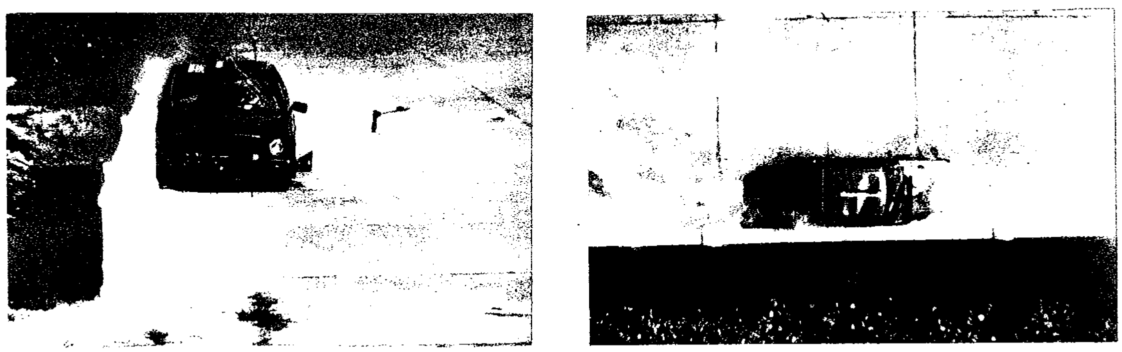

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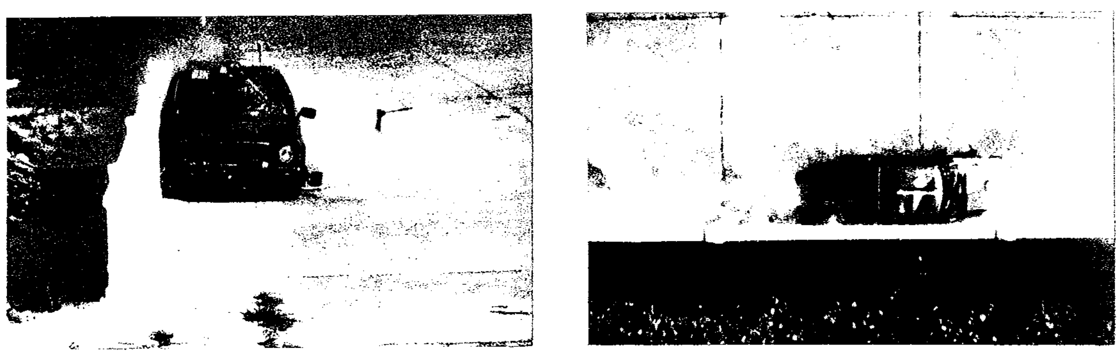

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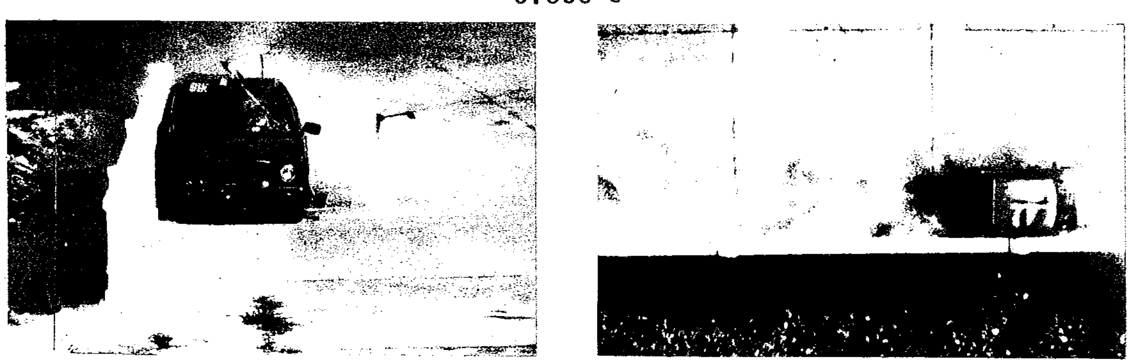

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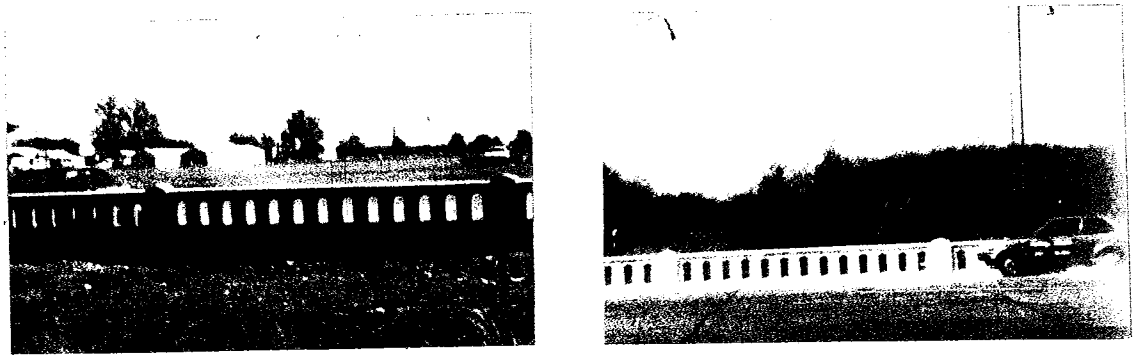
Figure B1. Sequential photographs for test 1185-1. (Continued)



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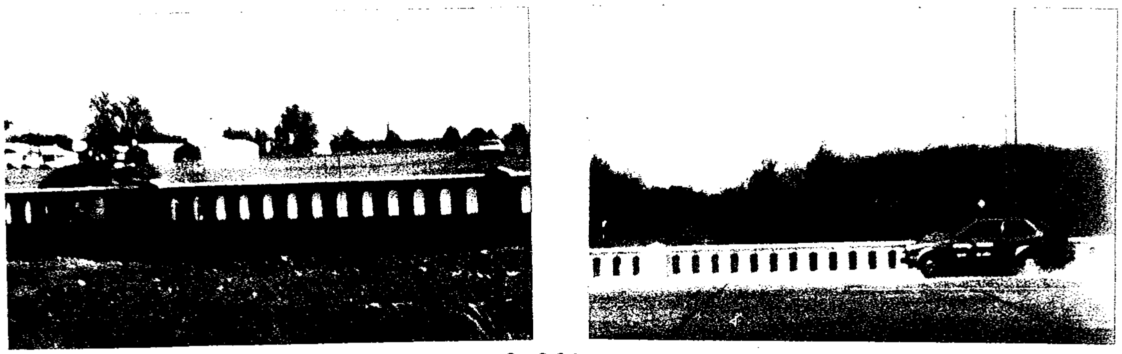

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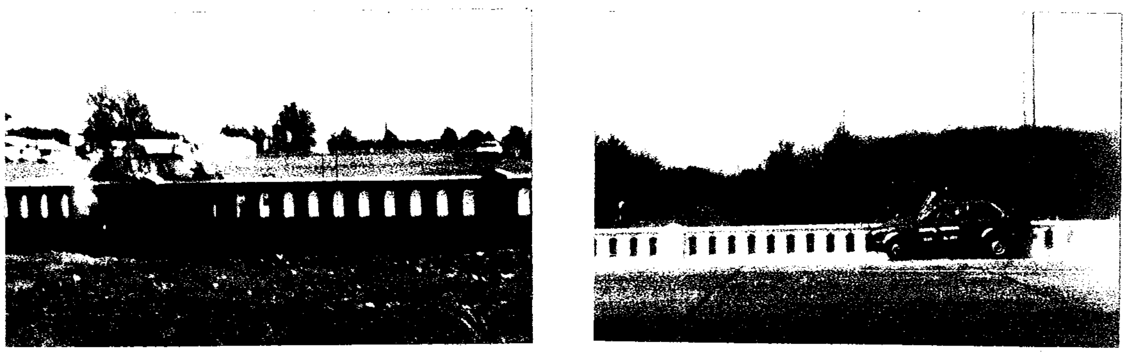

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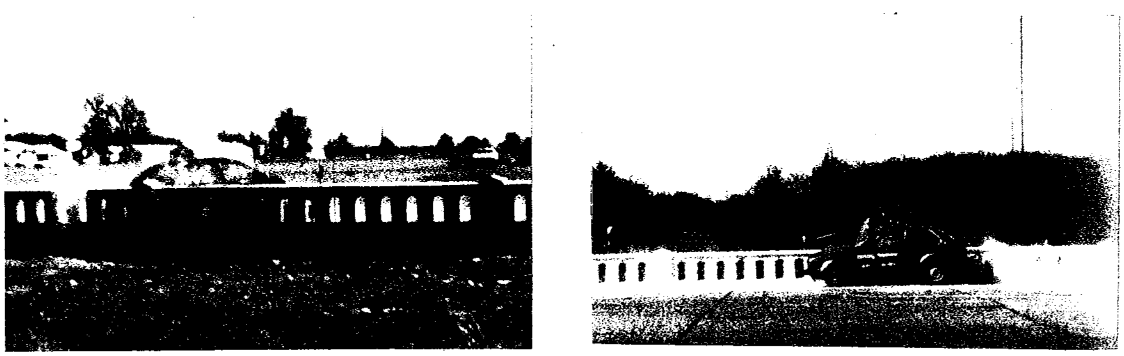

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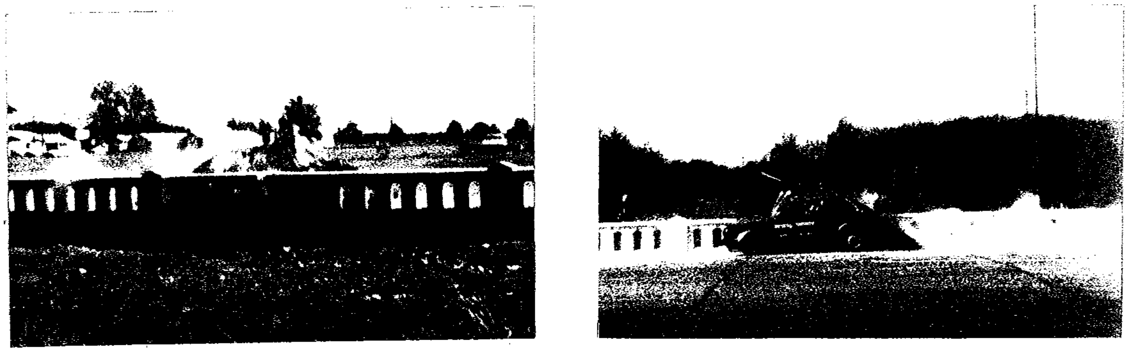
Figure B2. Sequential photographs for test 1185-1.



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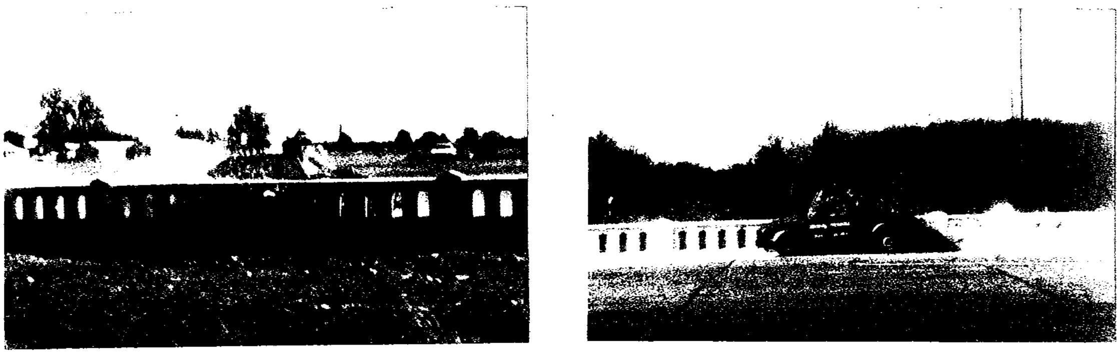

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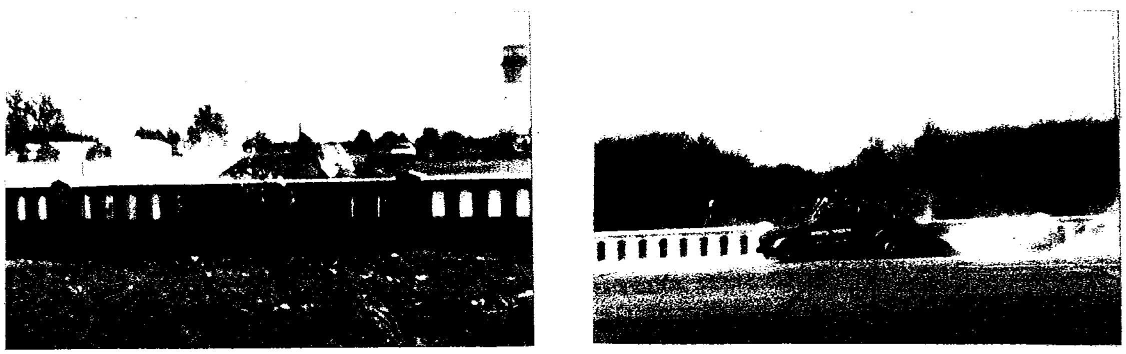


0.366 s

0.488 s

Figure B2. Sequential photographs for test 1185-1.
(Continued)

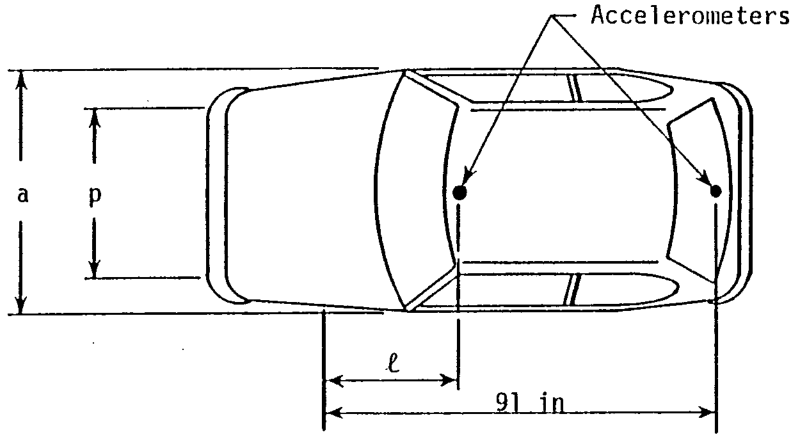
APPENDIX C

Electronic Accelerometer, Roll, Pitch, and Yaw Data Test 1185-1

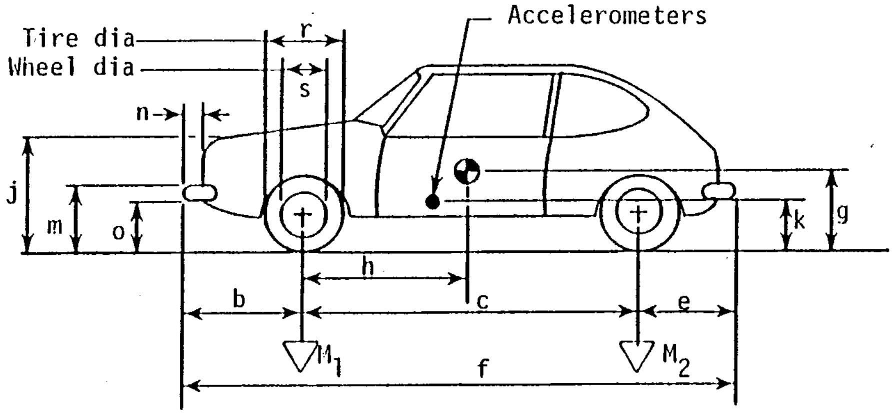
Date: 11-28-88 Test No.: 1185-1 VIN: SLC117354

Make: Honda Model: Civic Year: 1980 Odometer: 121585

Tire Size: 155 R 12 Ply Rating: 2 Bias Ply: ___ Belted: ___ Radial: x



Tire Condition: good ___ fair x badly worn ___



4-wheel weight for c.g. det. ℓf 563 rf 543 ℓr 348 rr 326

Mass - pounds	Curb	Test Inertial	Gross Static
M_1	1120	1106	
M_2	610	674	
M_T	1730	1780	

Note any damage to vehicle prior to test:

*d = overall height of vehicle

Vehicle Geometry - inches

a	62.25	b	29.50
c	88.00	d*	52.50
e	29.00	f	146.50
g	---	h	33.3
i	----	j	29.50
k	16.25	ℓ	28.50
m	19.25	n	5.00
o	14.25	p	54.00
r	21.75	s	13.25

Engine Type: 4 cylinder

Engine CID: ___

Transmission Type:

Automatic or (Manual)

(FWD) or RWD or 4WD

Body Type: Hatch

Steering Column Collapse Mechanism:

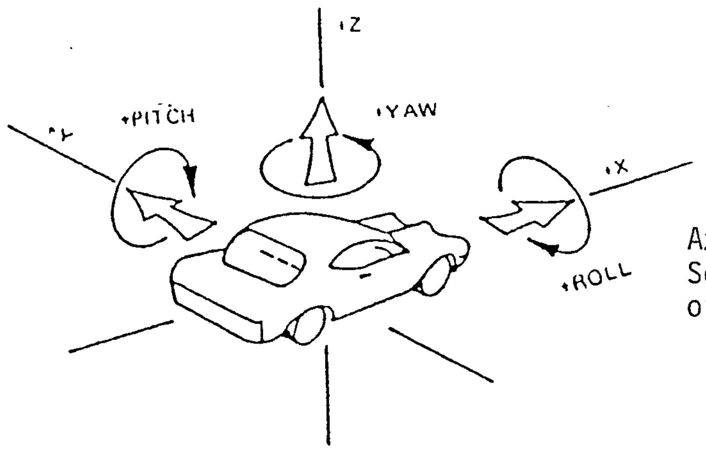
- ___Behind wheel units
- ___Convoluted tube
- ___Cylindrical mesh units
- ___Embedded ball
- ___NOT collapsible
- ___Other energy absorption
- ___Unknown

Brakes:

Front: disc x drum ___

Rear: disc ___ drum x

Figure C1. Test vehicle properties (test 1185-1).



Axes are vehicle fixed.
Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

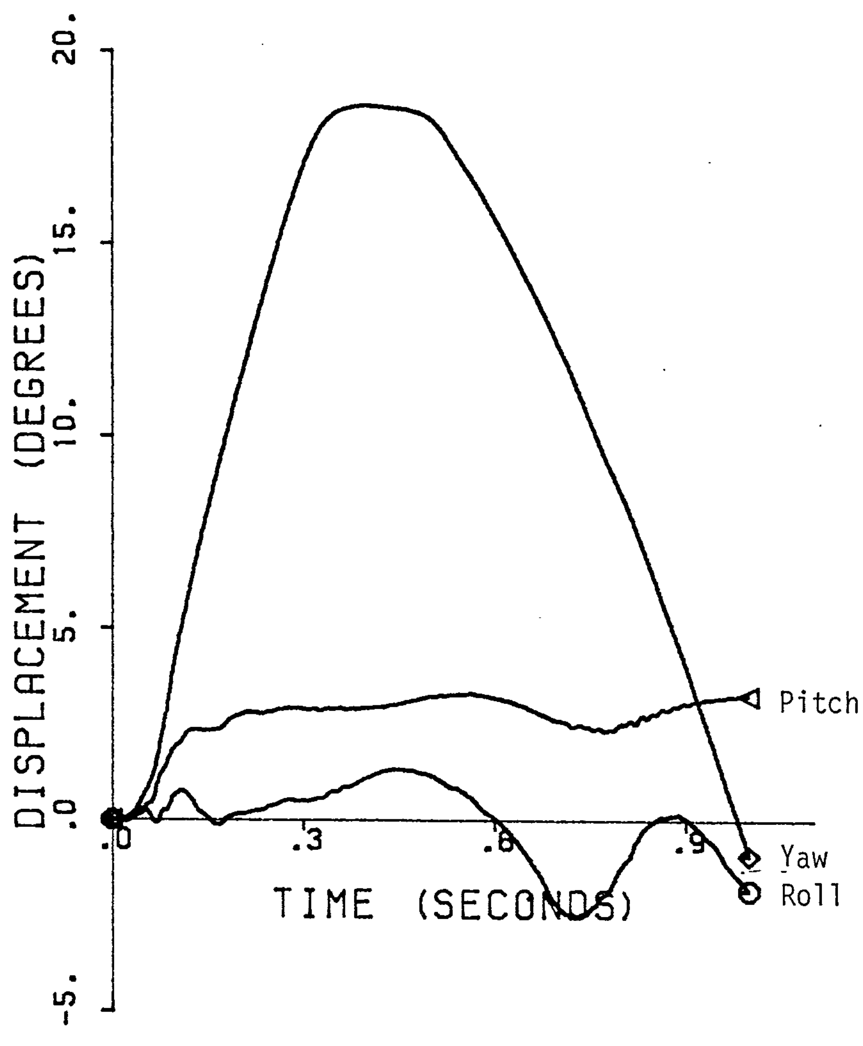


Figure C2. Vehicle angular displacements for test 1185-1.

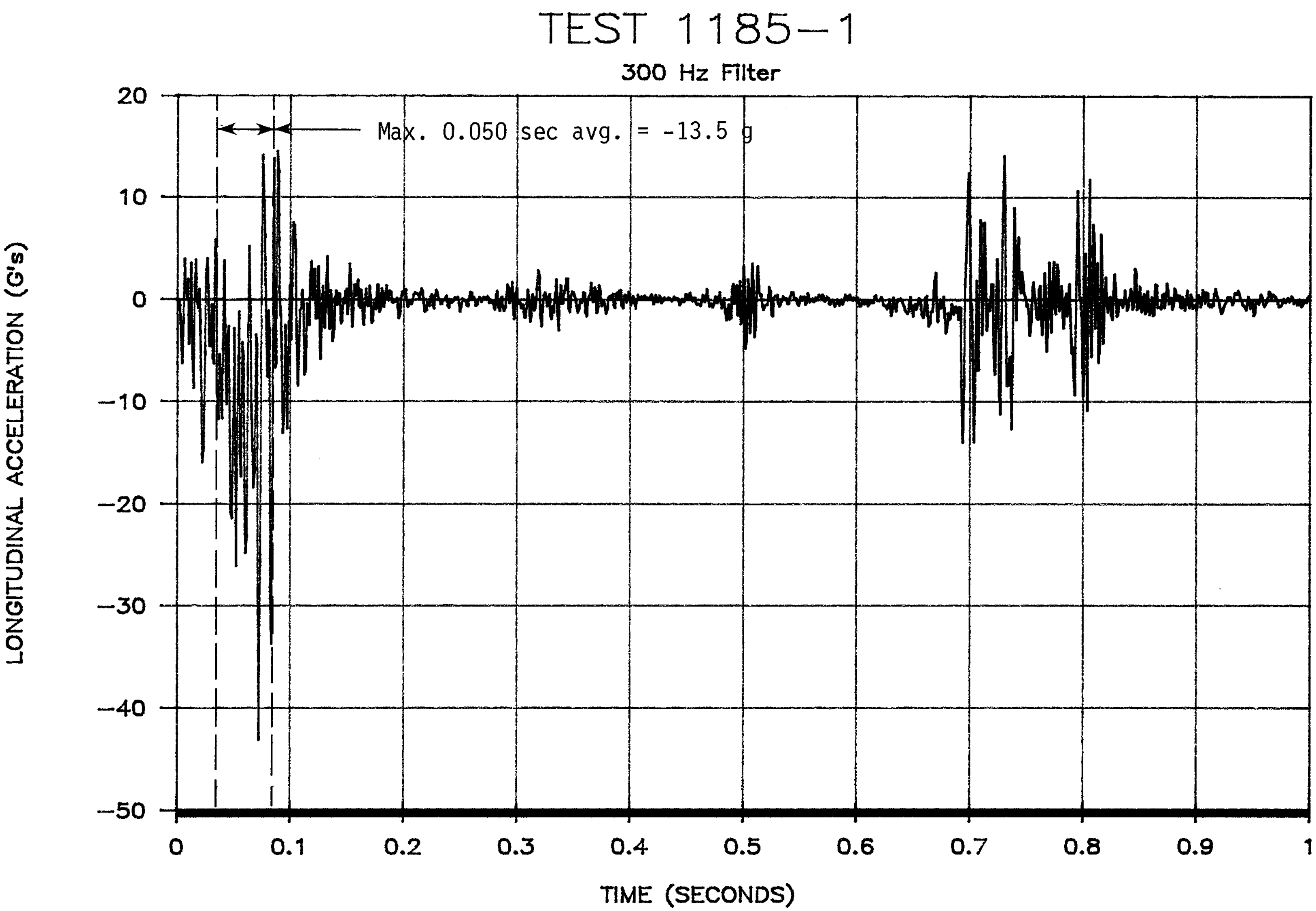


Figure C3. Vehicle longitudinal accelerometer trace for test 1185-1.

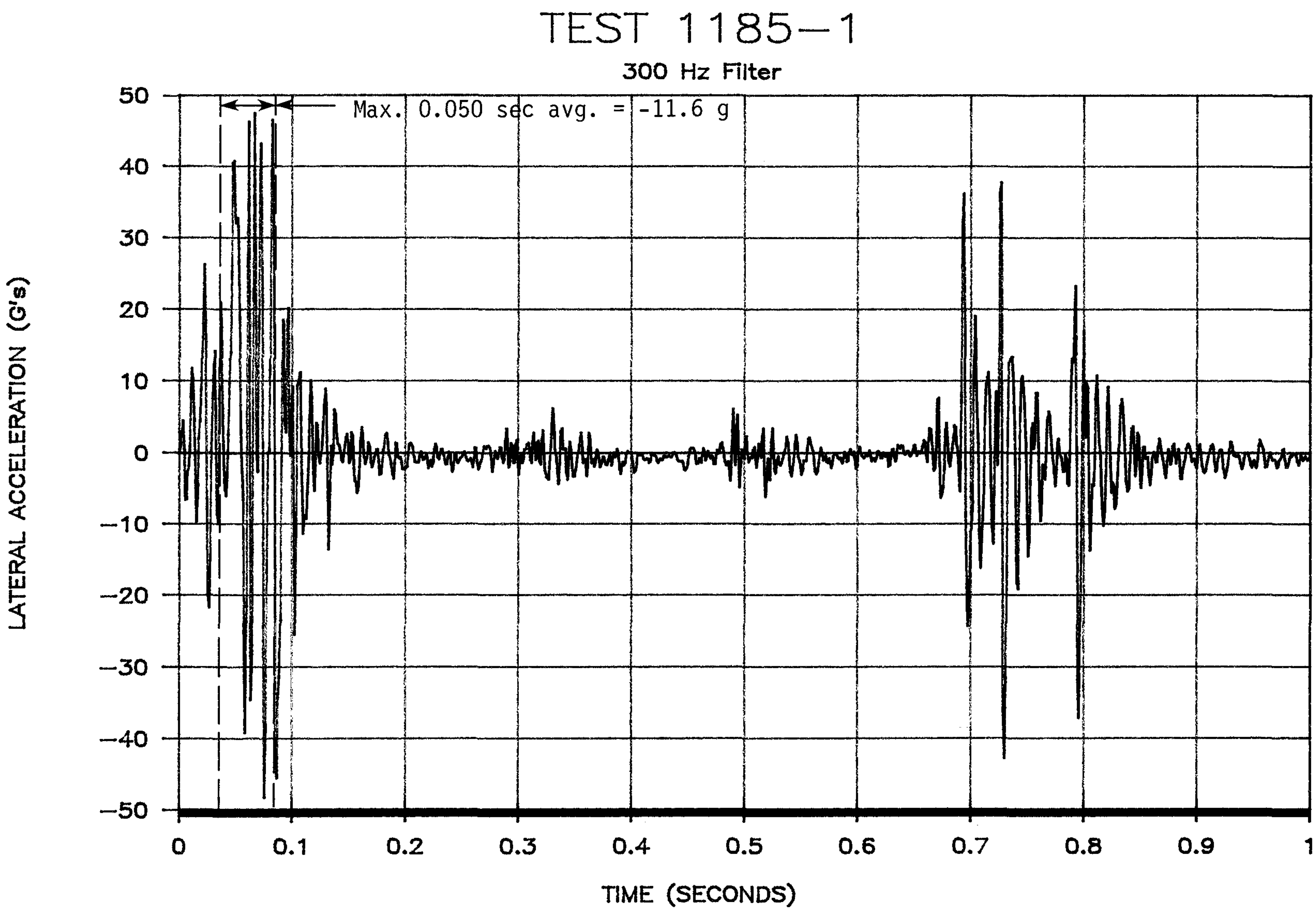


Figure C4. Vehicle lateral accelerometer trace for test 1185-1.

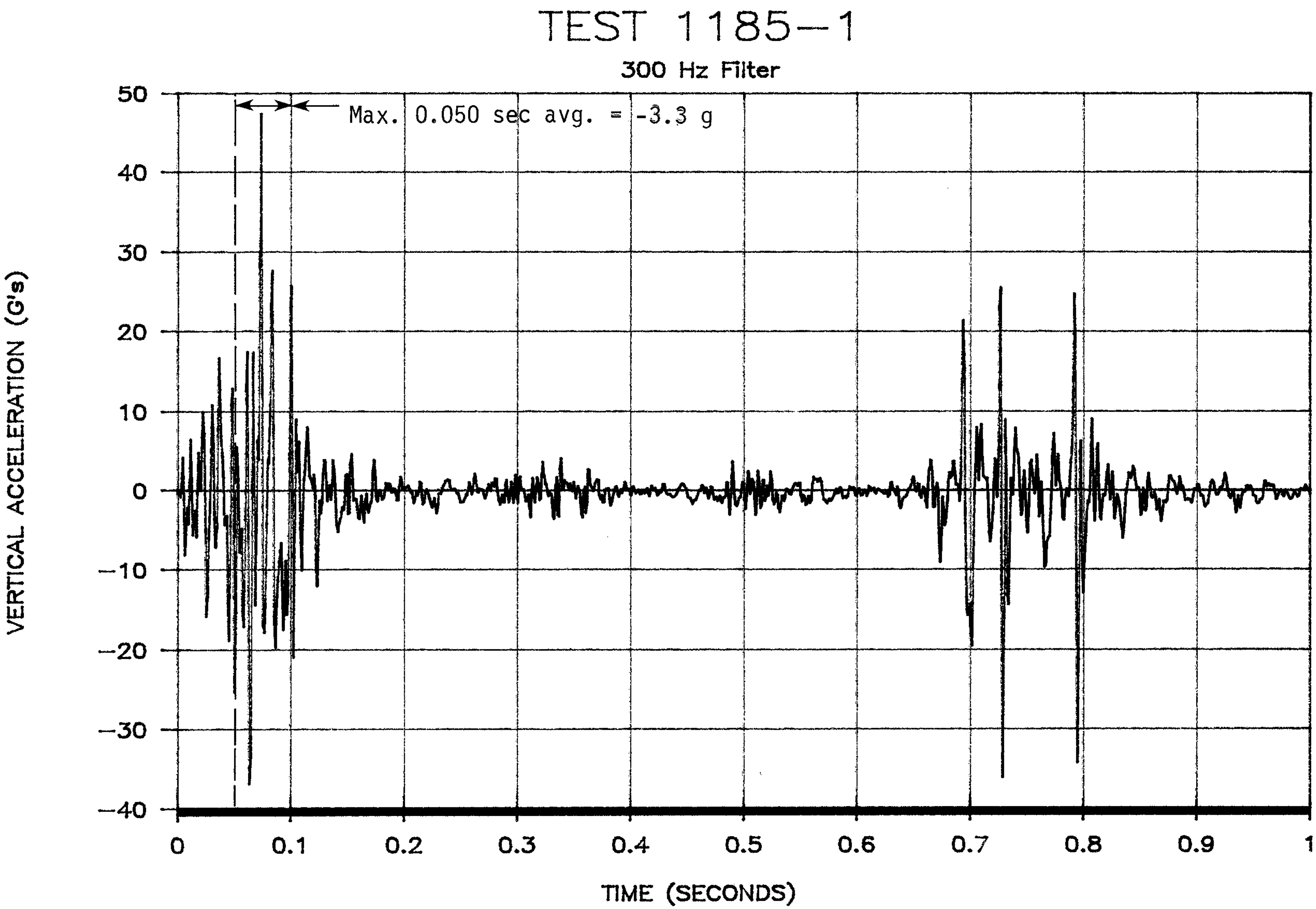


Figure C5. Vehicle vertical accelerometer trace for test 1185-1.

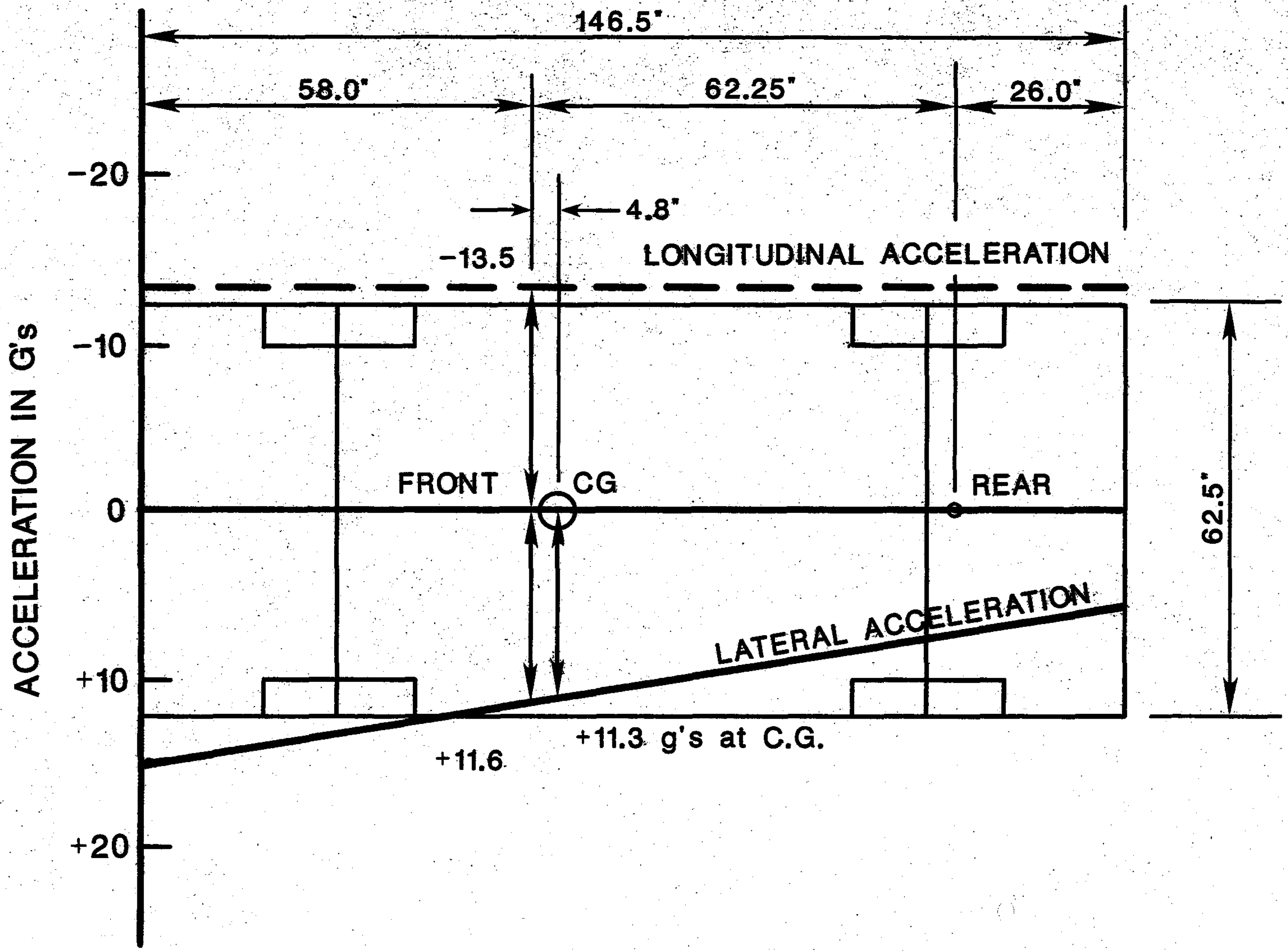


Figure C6. Test 1185-1 graph of max. 0.050 sec average acceleration along vehicle length at 0.058 sec after impact.

APPENDIX D

Sequential Photographs of Test 1185-2

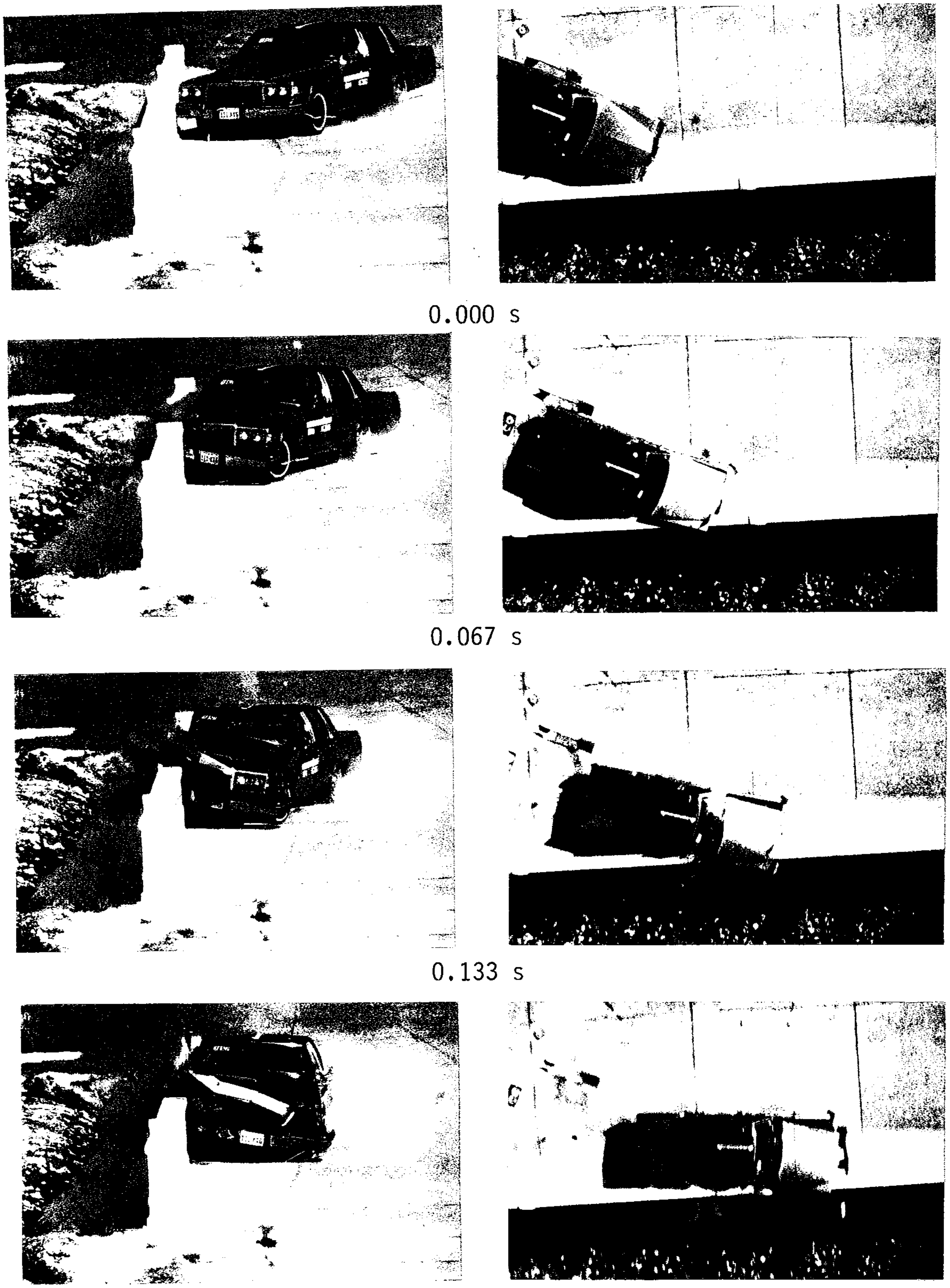
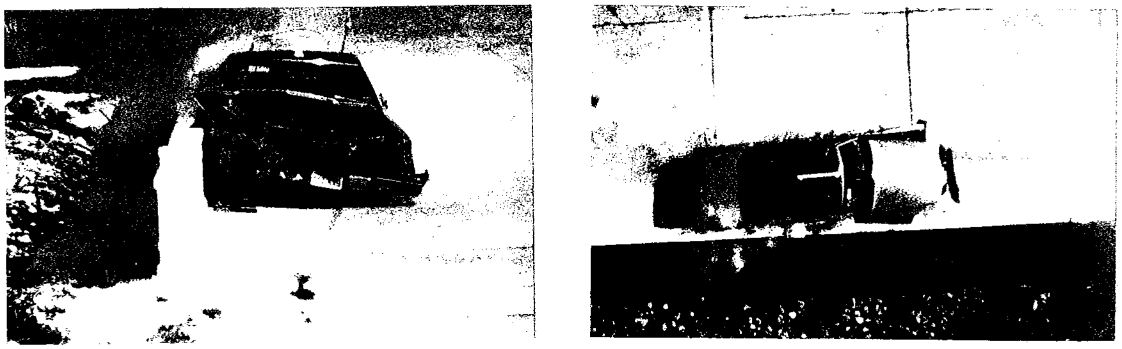


Figure D1. Sequential photographs for test 1185-2.



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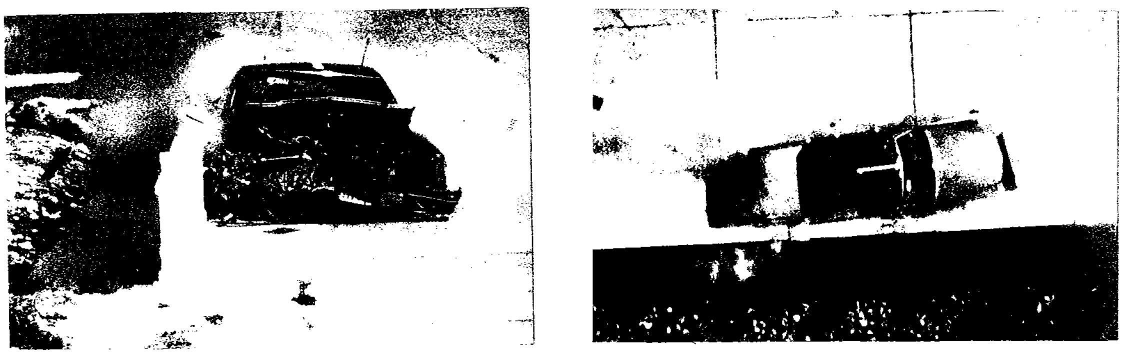
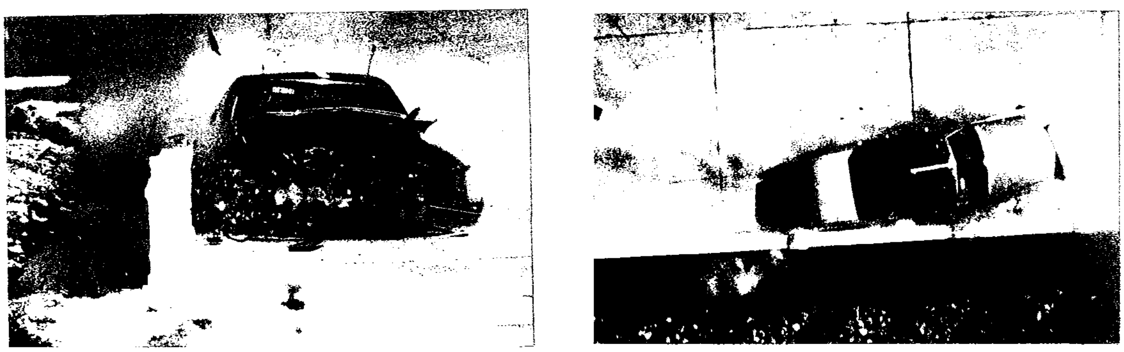


0.334 s



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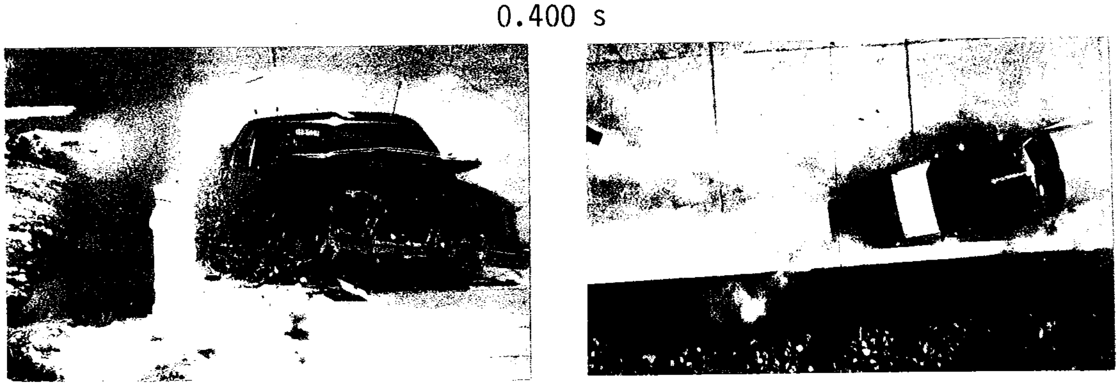
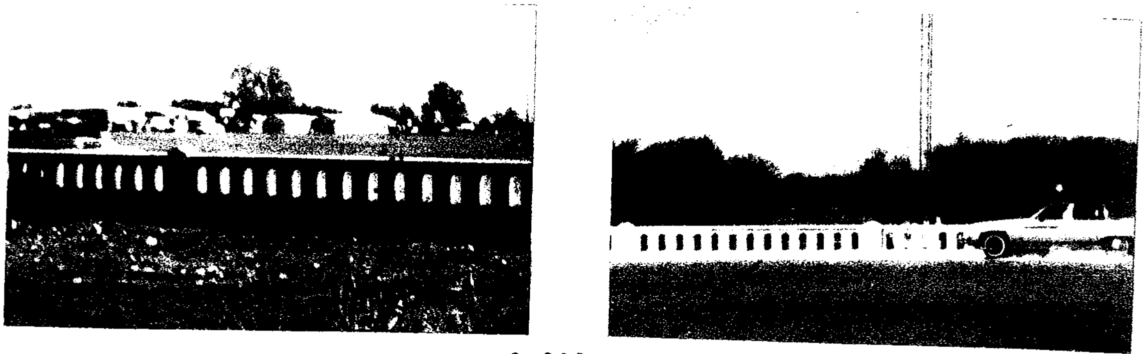


0.500 s

Figure D1. Sequential photographs for test 1185-2. (Continued)



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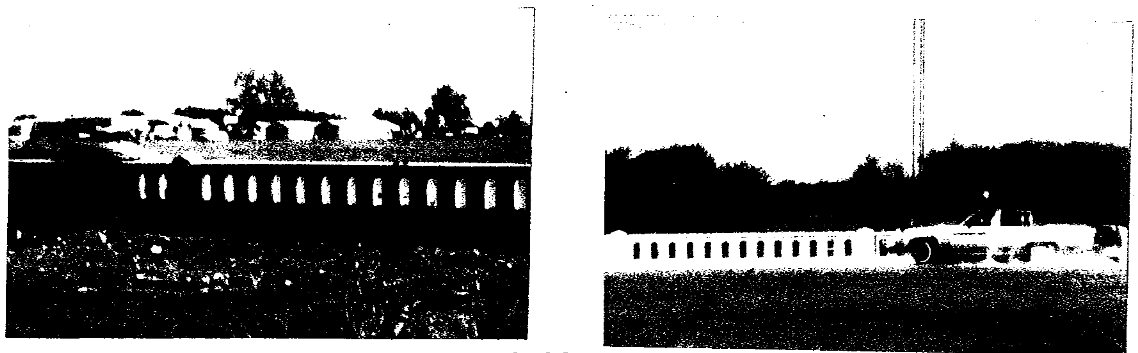

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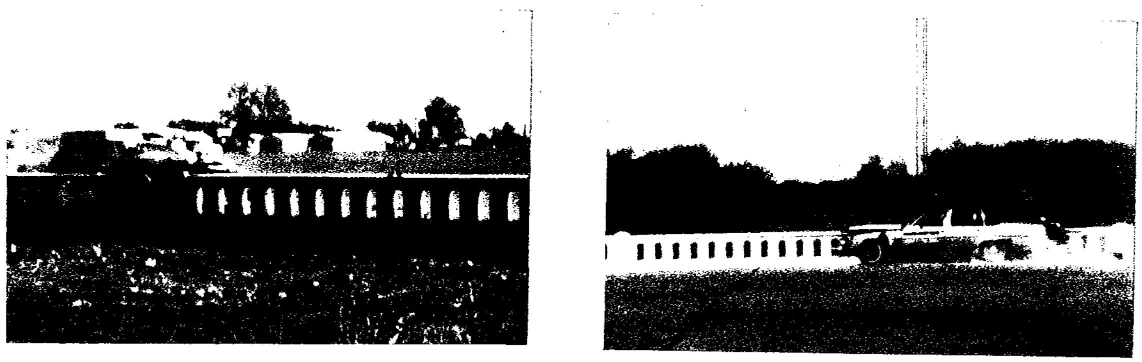

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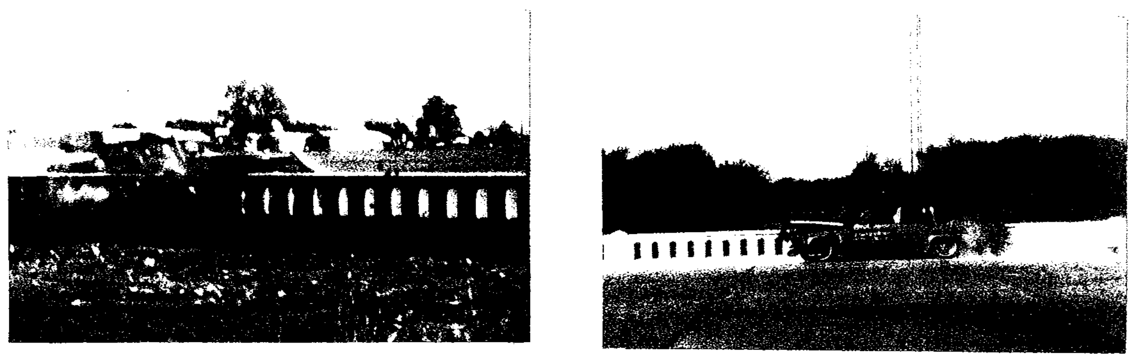
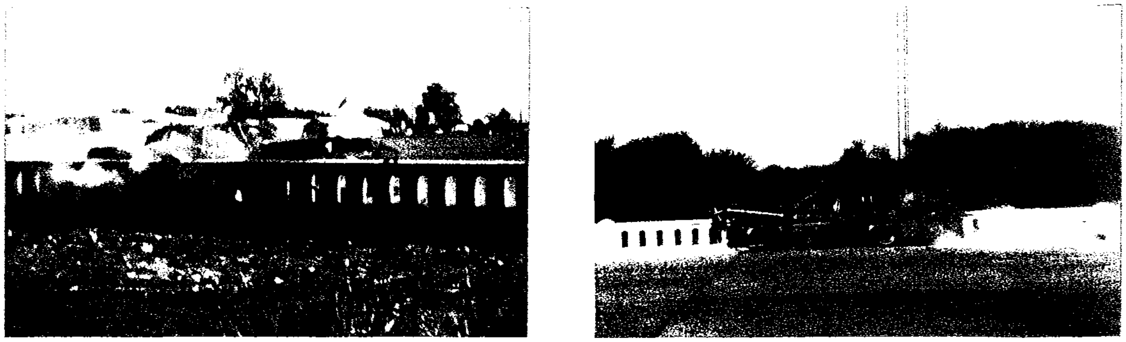
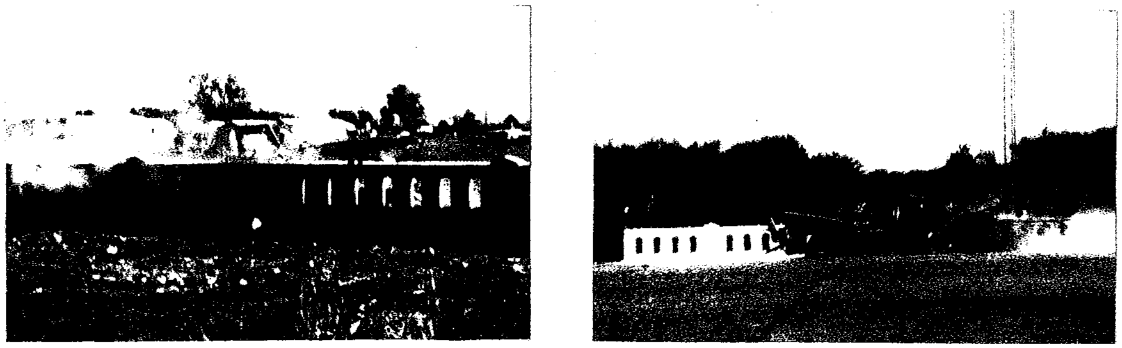


0.200 s

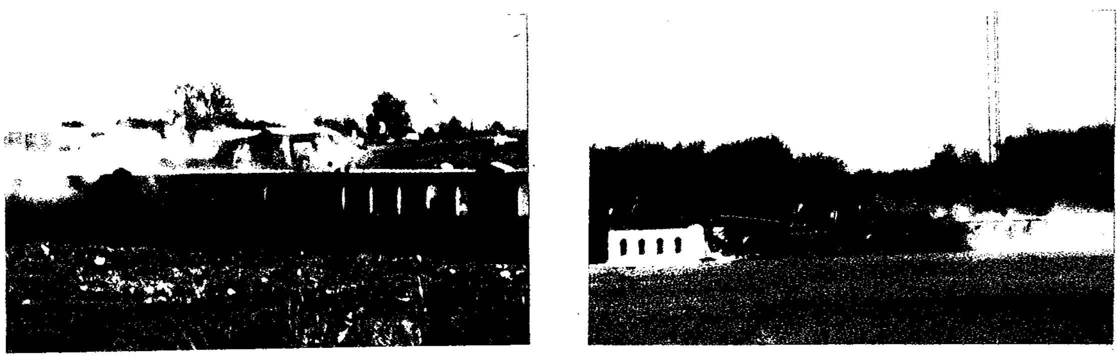
Figure D2. Sequential photographs for test 1185-2.



0.267 s



0.334 s



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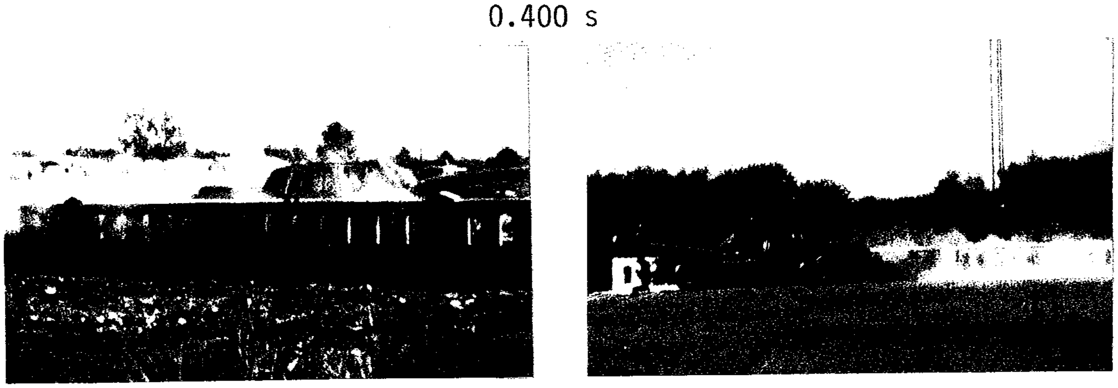


0.500 s

Figure D2. Sequential photographs for test 1185-2.
(Continued)

APPENDIX E

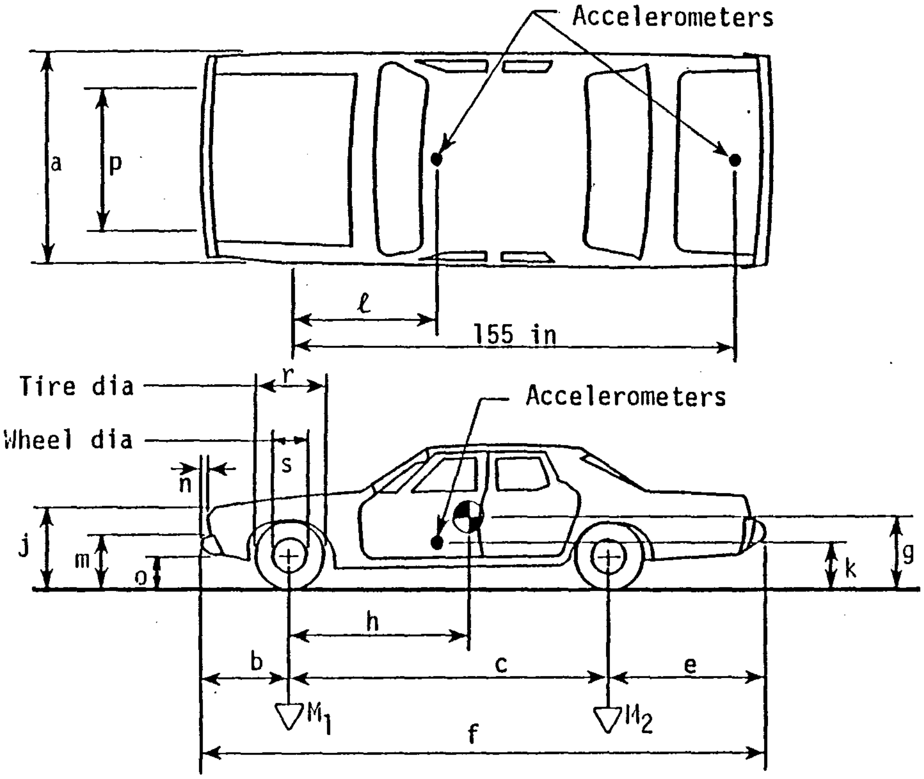
Electronic Accelerometer, Roll, Pitch, and Yaw Data Test 1185-2

Date: 11-30-88 Test No.: 1185-2 VIN: 6069NA9140137

Make: Cadillac Model: Sedan DeVille Year: 1980 Odometer: 109514

Tire Size: P225/75R15 Ply Rating: 4 Bias Ply: ___ Belted: ___ Radial: x

Tire Condition: good x
fair ___
badly worn ___



Vehicle Geometry - inches

a	77.25	b	43.00
c	121.25	d*	58.25
e	57.00	f	221.25
g	---	h	55.6
i	----	j	34.00
k	21.00	ℓ	39.00
m	21.00	n	5.00
o	12.50	p	61.00
r	27.50	s	16.25

Engine Type: V-8

Engine CID: 5.7 Liter

Transmission Type:

(Automatic) or Manual

FWD or (RWD) or 4WD

Body Type: 4-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

4-wheel weight for c.g. det. ℓf 1204 rf 1231 ℓr 1030 rr 1035

Mass - pounds	Curb	Test Inertial	Gross Static
M_1	2490	2435	
M_2	1787	2065	
M_T	4277	4500	

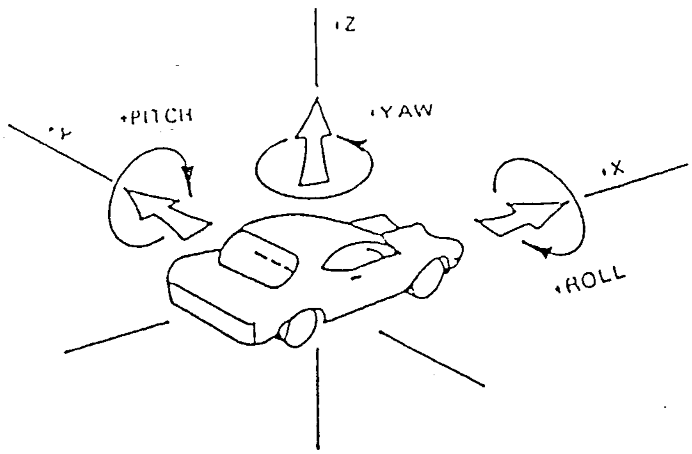
Note any damage to vehicle prior to test:

____

____

*d = overall height of vehicle

Figure E1. Test vehicle properties (test 1185-2).



Axes are vehicle fixed. Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

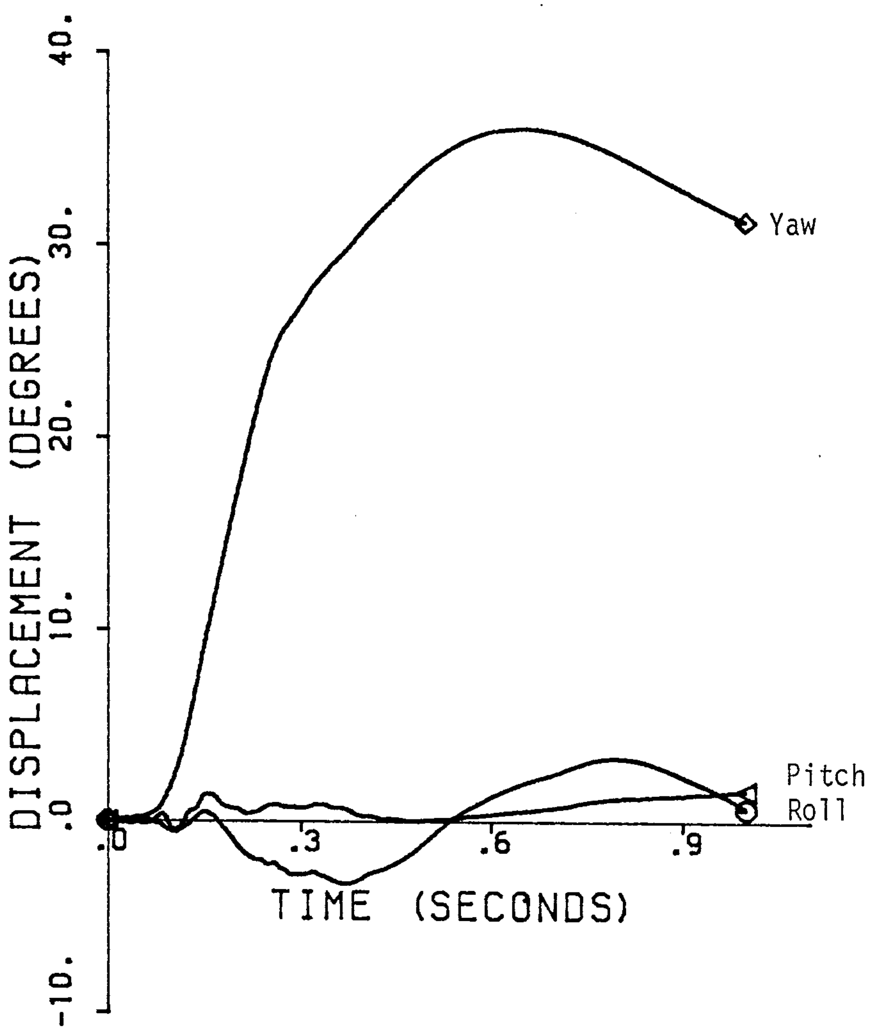


Figure E2. Vehicle angular displacements for test 1185-2.

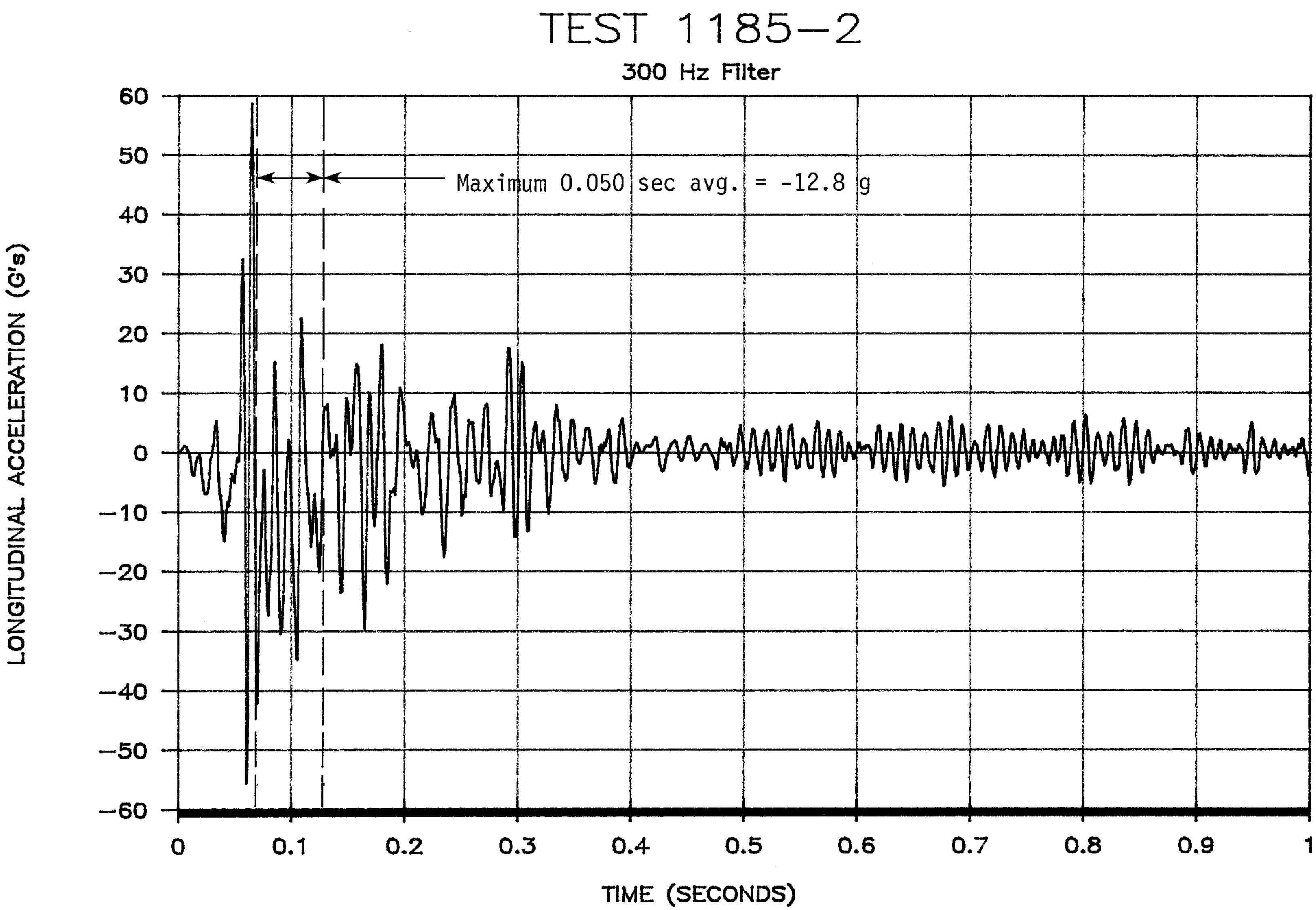


Figure E3. Vehicle longitudinal accelerometer trace for test 1185-2.

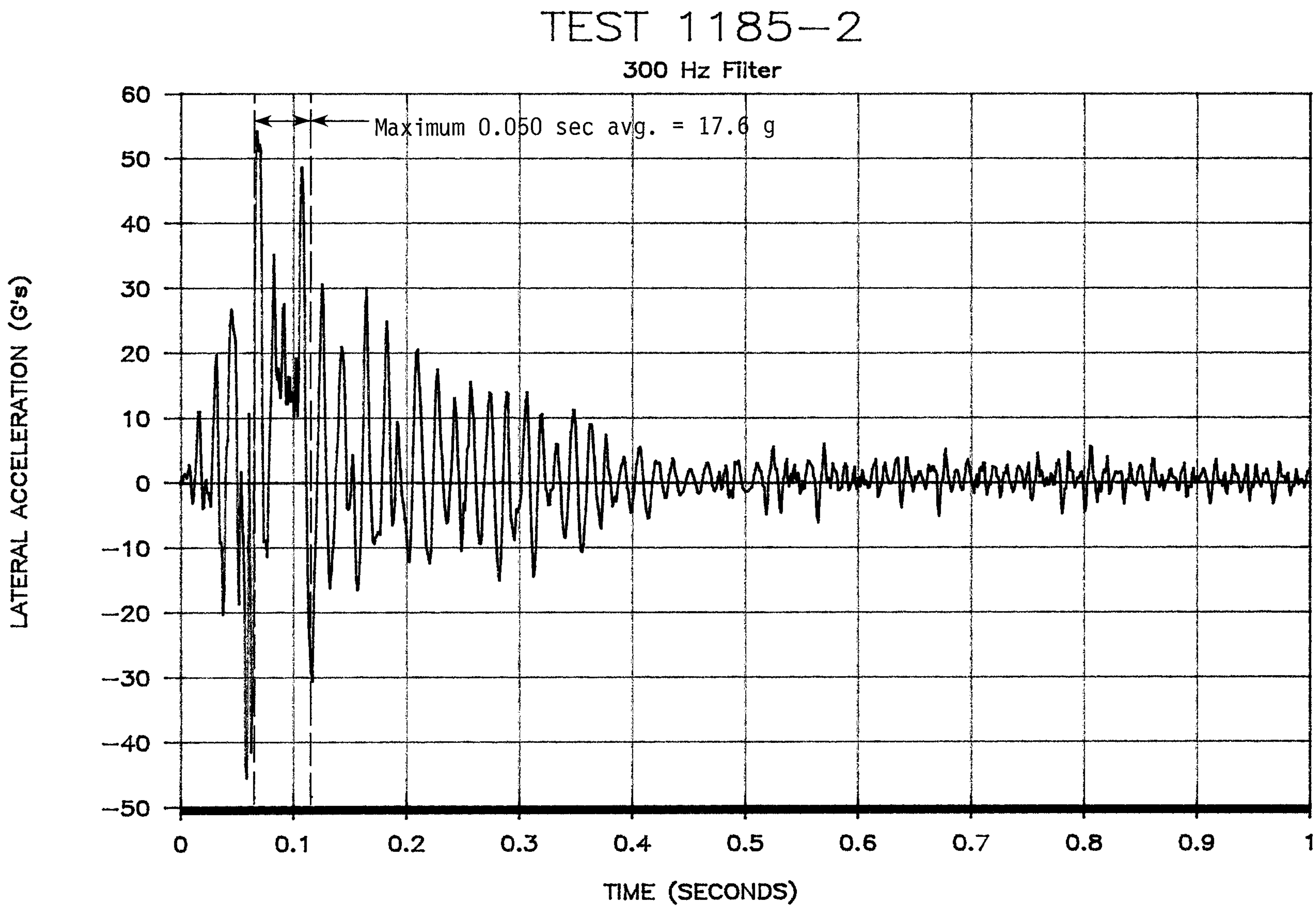


Figure E4. Vehicle lateral accelerometer trace for test 1185-2.

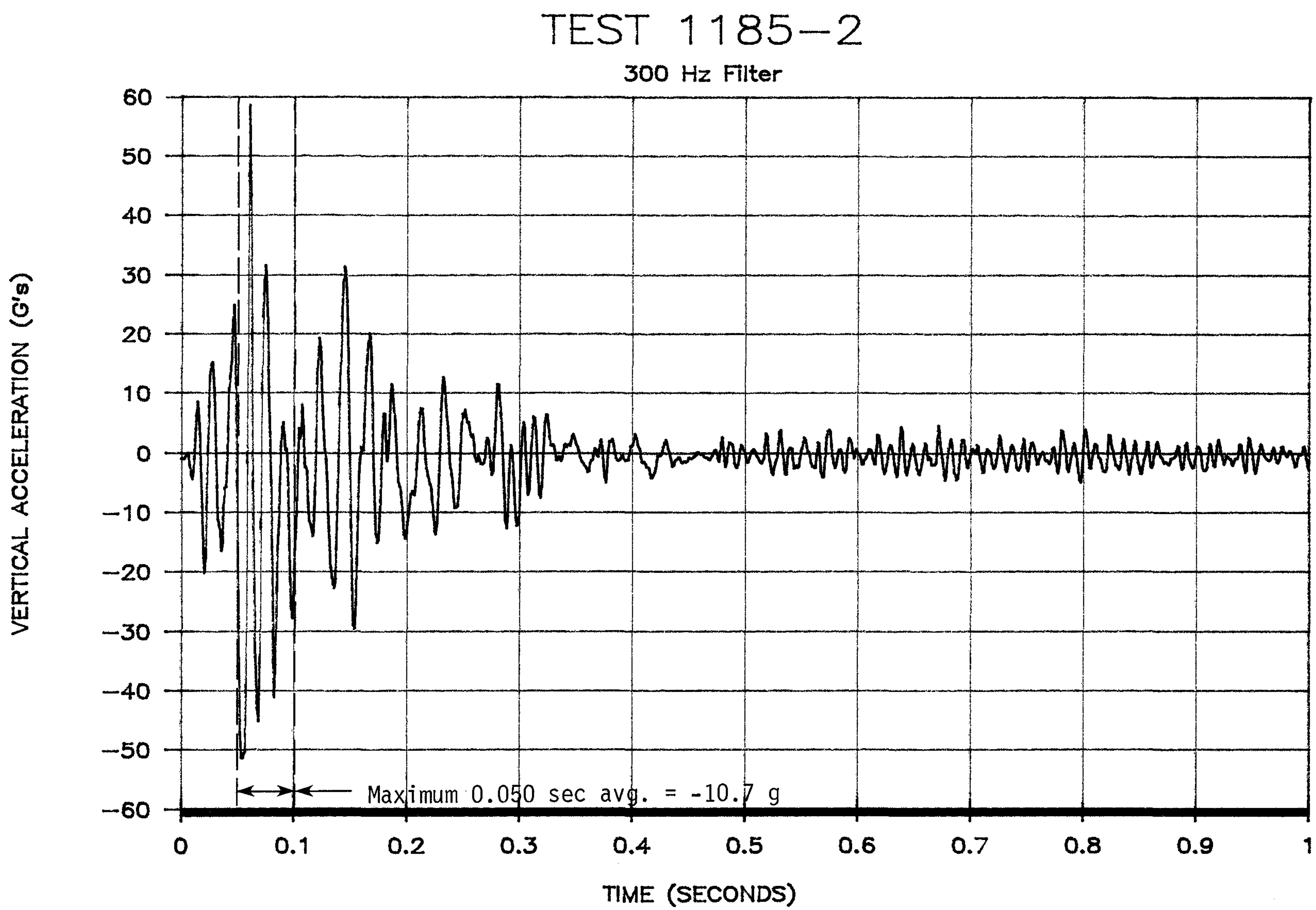


Figure E5. Vehicle vertical accelerometer trace for test 1185-2.

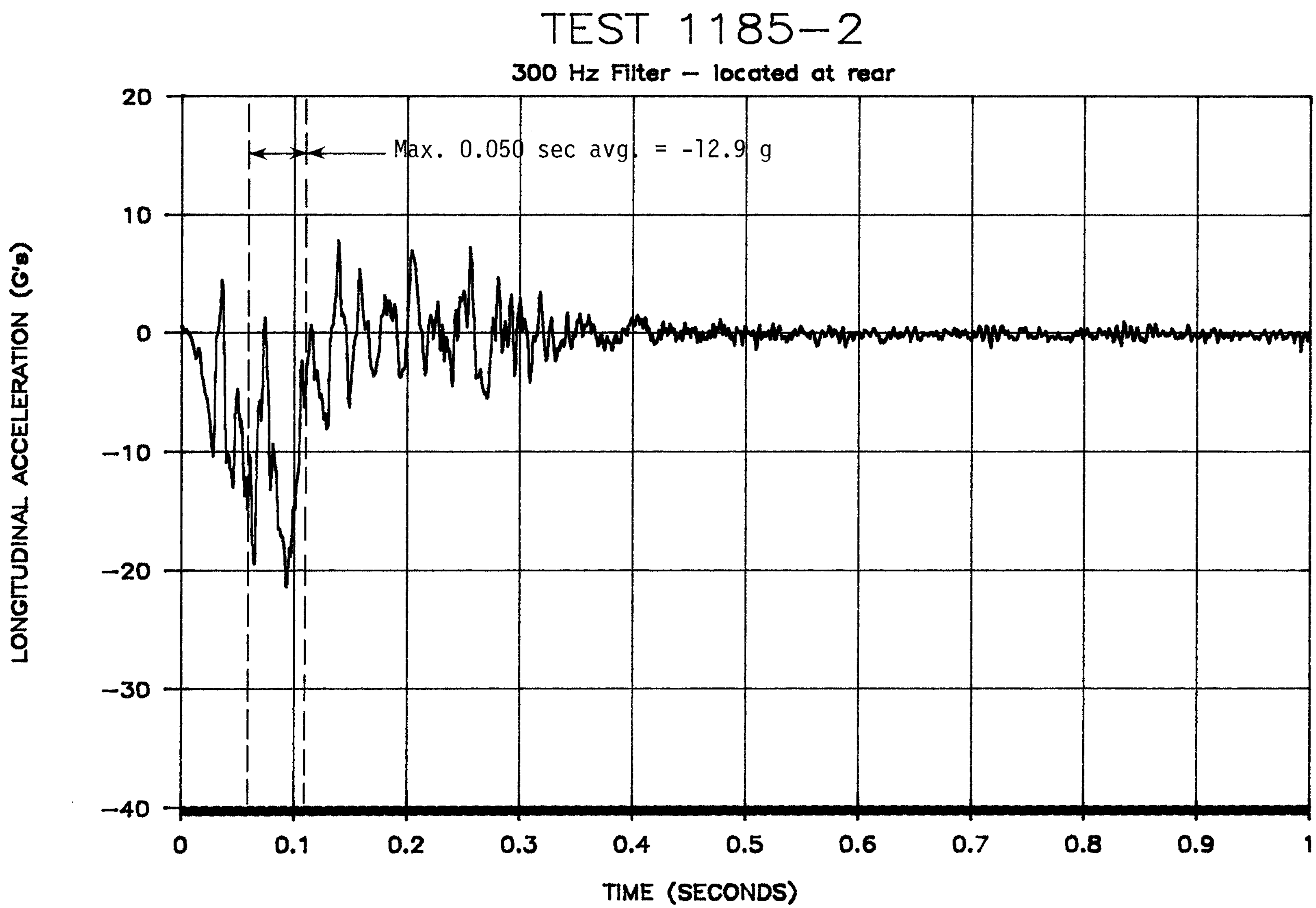


Figure E6 . Vehicle longitudinal accelerometer trace for test 1185-2. (At rear of vehicle)

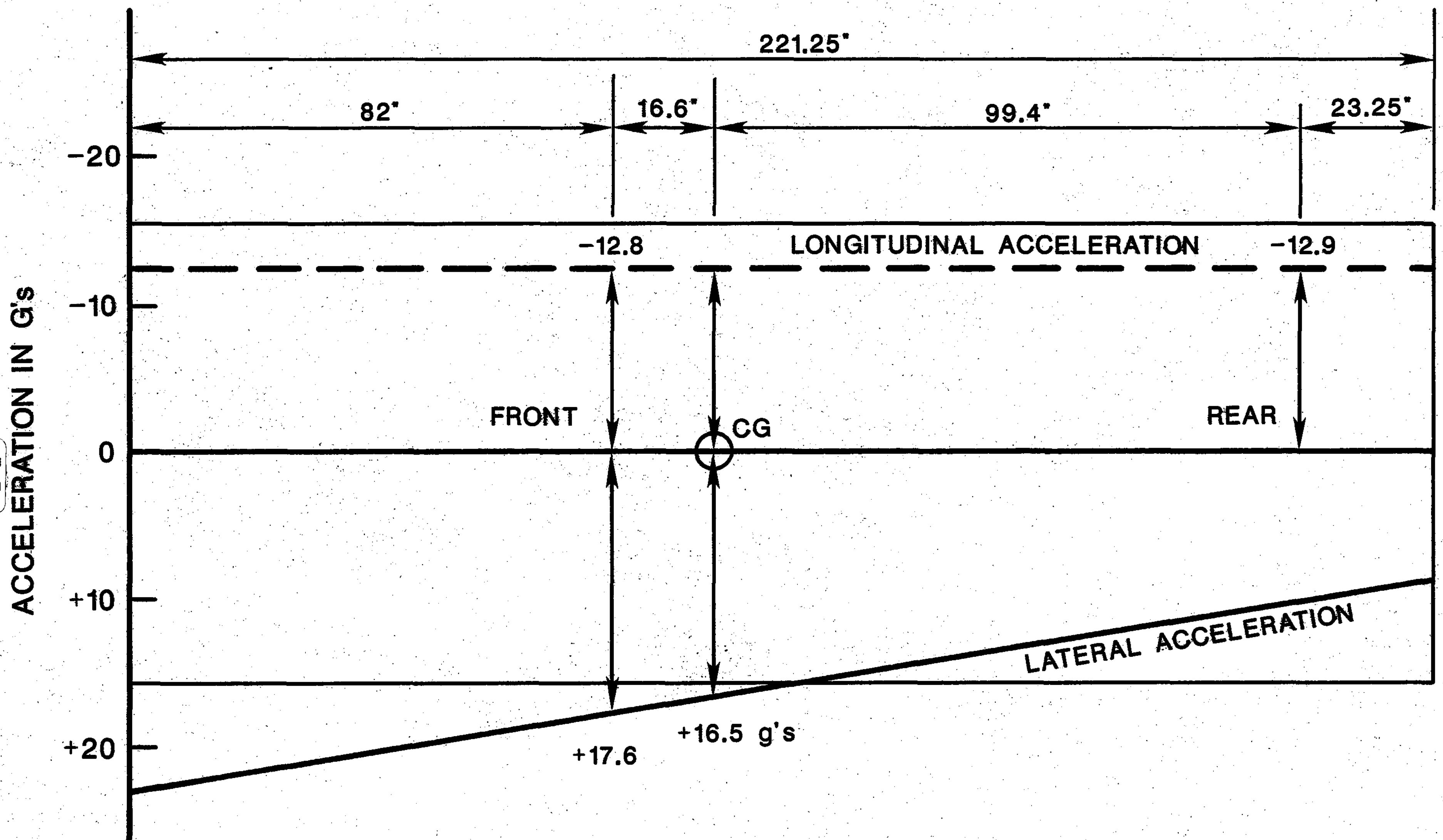


Figure E7. Test 1185-2 graph of max. 0.050 sec average acceleration along vehicle length at 0.092 sec after impact.

APPENDIX F

Bridge Rail Safety Evaluation Guidelines

NCHRP 230

TABLE 6. SAFETY EVALUATION GUIDELINES

Evaluation Factors		Evaluation Criteria	Applicable to Minimum Matrix Test Conditions (see Table 3)
Structural Adequacy	A.	Test article shall smoothly redirect the vehicle; the vehicle shall not penetrate or go over the installation although controlled lateral deflection of the test article is acceptable.	10, 11, 12, 30, 40
	B.	The test article shall readily activate in a predictable manner by breaking away or yielding.	60, 61, 62, 63
	C.	Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle	41, 42, 43, 44, 45, 50, 51, 52, 53, 54
	D.	Detached elements, fragments or other debris from the test article shall not penetrate or show potential for penetrating the passenger compartment or present undue hazard to other traffic.	All
Occupant Risk	E.	The vehicle shall remain upright during and after collision although moderate roll, pitching and yawing are acceptable. Integrity of the passenger compartment must be maintained with essentially no deformation or intrusion.	All
	F.	Impact velocity of hypothetical front seat passenger against vehicle interior, calculated from vehicle accelerations and 24 in. (0.61m) forward and 12 in. (0.30m) lateral displacements, shall be less than: Occupant Impact Velocity-fps Longitudinal: $40/F_1$ — Lateral: $30/F_2$ and vehicle highest 10 ms average accelerations subsequent to instant of hypothetical passenger impact should be less than: Occupant Ridedown Accelerations—g's Longitudinal: $20/F_3$ — Lateral: $20/F_4$ where F_1, F_2, F_3, and F_4 are appropriate acceptance factors (see Table 8, Chapter 4 for suggested values).	11, 12, 41, 42, 43, 44, 45, 50, 51, 52, 54, 60, 61, 62, 63
	G.	(Supplementary) Anthropometric dummy responses should be less than those specified by FMVSS 208, i.e., resultant chest acceleration of 60g, Head Injury Criteria of 1000, and femur force of 2250 lb (10 kN) and by FMVSS 214, i.e., resultant chest acceleration of 60 g, Head Injury Criteria of 1000 and occupant lateral impact velocity of 30 fps (9.1 m/s).	11, 12, 41, 42, 43, 44, 45, 50, 51, 52, 54, 60, 61, 62, 63
Vehicle Trajectory	H.	After collision, the vehicle trajectory and final stopping position shall intrude a minimum distance, if at all, into adjacent traffic lanes.	All
	I.	In test where the vehicle is judged to be redirected into or stopped while in adjacent traffic lanes, vehicle speed change during test article collision should be less than 15 mph and the exit angle from the test article should be less than 60 percent of test impact angle, both measured at time of vehicle loss of contact with test device.	10, 11, 12, 30, 40, 42, 44, 53
	J.	Vehicle trajectory behind the test article is acceptable.	41, 42, 43, 44, 45, 50, 51, 53, 54, 60, 61, 62, 63

PERFORMANCE LEVELS		TEST SPEEDS -- mph[1,2]			
		TEST VEHICLE DESCRIPTIONS AND IMPACT ANGLES			
		Small Automobile W = 1.8 Kips A = 5.4' B = 5.5' H_{cg} = 19" θ = 20 deg.	Pickup Truck W = 5.4 Kips A = 8.9' B = 6.5' H_{cg} = 33" θ = 20 deg.	Intercity Bus (loose ballast) W = 40.0 Kips A = 23.2' B = 8.0' H_{cg} = 56" θ = 15 deg.	Van-Type Tractor-Trailer[4] No. 2 W = 80.0 Kips A = 13.1' B = 8.0' H_{cg} = 72" R = 0.58 θ = 15 deg.
PL-1		50	45		
PL-2		60	65		
PL-3		60	65	60	
PL-4		60	65		55
CRASH TEST EVALUATION CRITERIA[3]	Required	a,b,c,d,g	a,b,c,d	a,b,c,d	a,b,c
	Desirable[5]	e,f,h	e,f,g,h	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.

Table G2.7.1.3A Bridge Railing Performance Levels and Crash Test Criteria

Proposed to AASHTO April 2, 1987

Notes (cont.):

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

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 displacements, shall be less than:

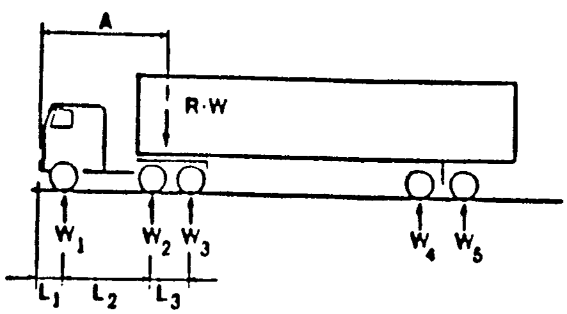
Occupant Impact Velocity - fps	
Longitudinal	Lateral
30	25

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

Occupant Ridedown Accelerations - 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:



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

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

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

= 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.

Table G2.7.1.3A (cont.) Bridge Railing Performance Levels and Crash Test Criteria