Testing and Evaluation of the W-Beam Transition (On Steel Posts With Timber Blockouts) to the Vertical Flared Back Concrete Bridge Parapet

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Research and Development
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FOREWORD

This report contains information on full-scale crash testing of a modified W-beam transition with timber blockouts that may be of interest to those who select, locate, and design traffic barriers. This crash test was performed to evaluate a modified W-beam transition design (on steel posts with timber blockouts) to the vertical flared back concrete bridge parapet according to NCHRP Report 350 guidelines.

The W-beam transition was modified by using 150-mm by 200-mm by 360-mm timber blockouts on W150×12.6 steel posts. A full-scale crash test with the 2000-kg pickup truck traveling at a nominal speed and angle of 100 km/h and 25 degrees, respectively, was performed on the modified G4(IS) guardrail with timber blockouts. The modified system contained and redirected the 2000-kg pickup. However, the pickup rolled over after exiting the test installation.

The modified W-beam transition (on steel posts with timber blockouts) to the vertical flared back concrete bridge parapet did not meet the evaluation criteria set forth in NCHRP Report 350.

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Director
Office of Safety and Traffic
Operations Research and Development

NOTICE

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16. Abstract

The W-beam transition is one of the most commonly used transition designs on the Nation's highways. The transition design has successfully met all evaluation criteria set forth in National Cooperative Highway Research Program (NCHRP) Report 230. However, with the adoption of NCHRP Report 350 by the Federal Highway Administration (FHWA) as the official guidelines for crash testing of roadside safety features, it became necessary to reevaluate the transition design to the new guidelines. Of particular importance is the replacement of one of the design test vehicles specified in NCHRP Report 230, the 2044-kg passenger car, by a 2000-kg pickup truck (2000P) under NCHRP Report 350 guidelines. The crash test reported herein was performed in an effort to evaluate a modified W-beam transition design (on steel posts with timber blockouts) to the vertical flared back concrete bridge parapet according to NCHRP Report 350 guidelines.

The crash test performed corresponded to NCHRP Report 350 test designation 3-11 involving a 2000P test vehicle impacting the transition at a nominal speed and angle of 100 km/h and 25 degrees. The transition contained and redirected the vehicle. However, the vehicle rolled over after exiting from the test installation. The modified W-beam transition (on steel posts with timber blockouts) to the vertical flared back concrete bridge parapet was therefore judged as not meeting the evaluation criteria set forth in NCHRP Report 350.

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Form DOT F 1700.7 (8-69)

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.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

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

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

(Revised September 1993)

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I. INTRODUCTION

The Federal Highway Administration (FHWA) has recently adopted the new performance evaluation guidelines for roadside safety features set forth in National Cooperative Highway Research Program (NCHRP) Report 350.[1] In addition, FHWA has required that all new roadside safety features to be installed on the National Highway System (NHS) after September 1996 meet the NCHRP Report 350 performance evaluation guidelines. Most of the existing roadside safety features were tested according to the previous guidelines contained in NCHRP Report 230.[2] It is, therefore, necessary to test existing roadside safety features to evaluate how they would perform under the new guidelines.

Under a previous FHWA study, a series of crash tests was conducted with the 2000P test vehicle on the more commonly used guardrail systems, one of which was the W-beam, strong-steel-post, G4(1S) guardrail system. The G4(1S) guardrail system was crash tested in accordance with NCHRP Report 350 test designation 3-11, i.e., impact by a 2000P test vehicle at a nominal speed and angle of 100 km/h and 25 degrees. The guardrail successfully contained and redirected the test vehicle, but the vehicle rolled over on its side after exiting the test installation and the performance of the guardrail system was judged to be unsatisfactory.[3] The vehicle rollover was the result of the front wheel assembly snagging on a post. The snagging problem was attributed to a number of factors, including the collapse of the steel blockout due to low torsional strength, the shallower blockout depth, the geometrical shape and lack of torsional stiffness of the posts, the resulting larger dynamic deflections, and the short front overhang on the pickup truck.

The G4(1S) W-beam guardrail system was subsequently modified and retested under another FHWA study. The modification consisted of replacing the W150×12.6 steel blockouts with 150 mm by 200 mm timber blockouts. The modified G4(1S) W-beam guardrail system with timber blockouts successfully contained and redirected the 2000P vehicle which remained stable during and after the impact sequence. The modified G4(1S) guardrail system was judged to have performed satisfactorily in accordance with evaluation criteria for NCHRP Report 350 under test level 3 (TL-3) conditions.[4]

With the satisfactory performance of the modified G4(1S) W-beam guardrail system with timber blockouts, FHWA decided to evaluate a transition design from a W-beam, steel-post guardrail system with similar modification (i.e., timber blockouts) to a vertical flared back concrete parapet. This report contains the results of the crash test conducted on this modified transition design with a 2000-kg pickup truck under NCHRP Report 350 test level 3 conditions.

II. STUDY APPROACH

2.1 TEST ARTICLE

The standard W-beam transition (on steel posts) to the vertical flared back concrete parapet is detailed in FHWA Technical Advisory No. T 5040.26 dated January 28, 1988, which is included in its entirety in appendix A. The details of the standard W-beam transition on steel posts are shown in figure 3B of the Technical Advisory.

A flared back vertical parapet wall and a short section of concrete safety shaped barrier was constructed according to details shown in figure 3C of the Technical Advisory in appendix A. The modified W-beam transition (on steel posts with timber blockouts) shown in figure 1 was then attached to the parapet. As mentioned previously, the difference between the modified and the standard W-beam transition design is the use of 150 mm by 200 mm timber blockouts in place of the W150×12.6 steel blockouts. A cross-section of the modified post detail is shown in figure 2. The transition design consists of: 1830 mm long W150×12.6 steel posts spaced as shown in figure 1, 150 mm by 200 mm by 360 mm long timber blockouts, and nested 3.8 m long 12-gauge W-beam rail elements. The offset depth of the timber blockout is 190 mm. A 100-mm wide channel is routed out and centered on the post side of the blockout to fit over the face of the post. The W-beam rail elements and timber blockouts are attached to the posts with 16-mm diameter carriage bolts without washers. The bolt hole on the blockout is offset to match one of the two bolt holes on the post. The height of the transition to the center of the W-beam rail element is 550 mm.

The completed test installation consisted of: a short section of concrete safety shaped barrier with the flared back parapet wall, a 7.6-m long transition section, a 34-m long modified G4(1S) guardrail length-of-need section, and a ET-2000 terminal. Photographs of the test installation are shown in figure 3.

2.2 CRASH TEST CONDITIONS

2.2.1 NCHRP Report 350 Test Designation

According to NCHRP Report 350, two tests are required to evaluate the performance of the transition section of a longitudinal barrier under the TL-3 test conditions:

1. **Test designation 3-20:** An 820C vehicle impacting the transition section at a nominal speed and angle of 100 km/h and 20 degrees at the critical impact point (CIP) of the transition. The purpose of the small car test is to evaluate the overall performance of the transition in general, and occupant risks in particular.

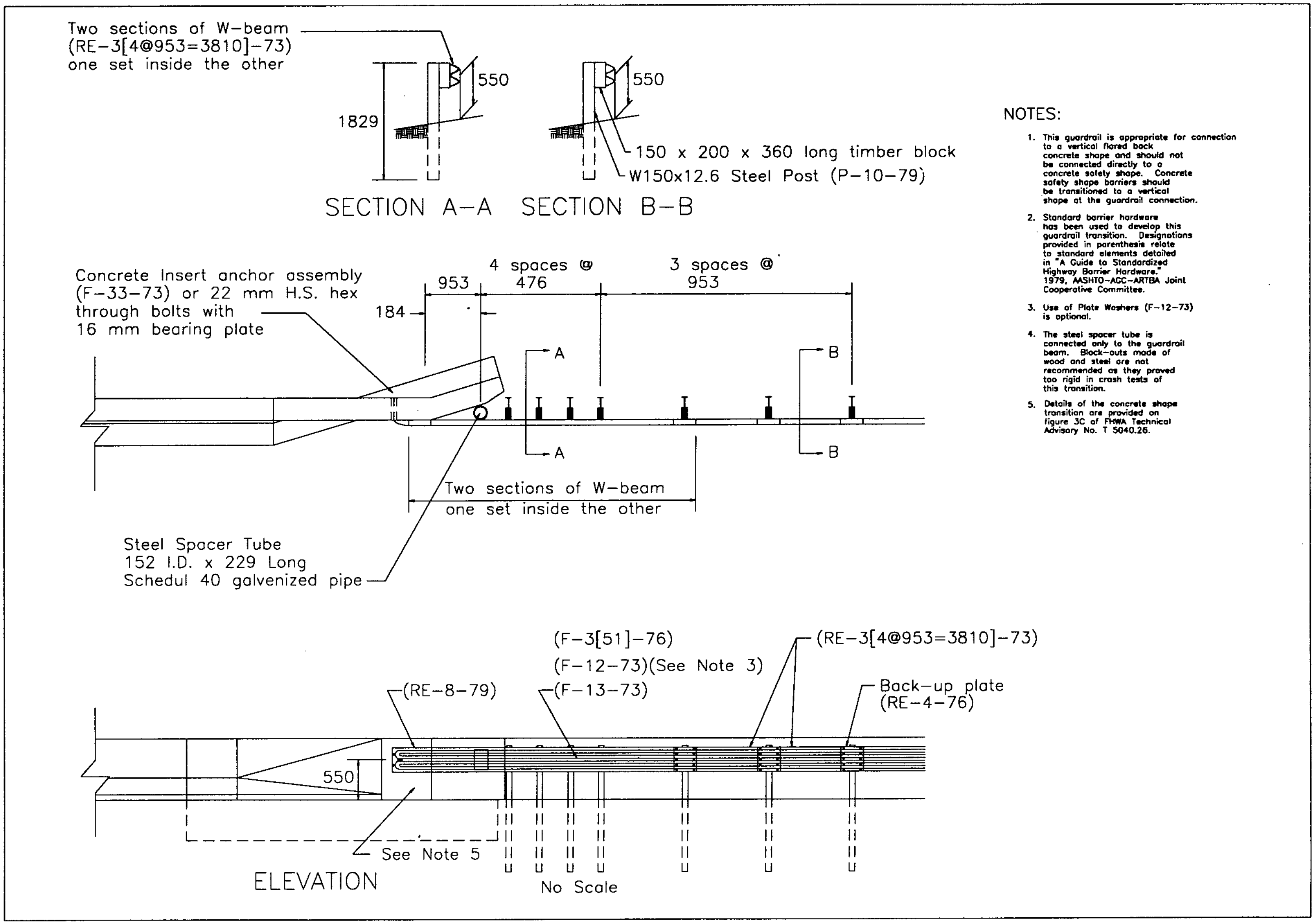


Figure 1. Details of the W-beam transition (on steel posts with timber blockouts).

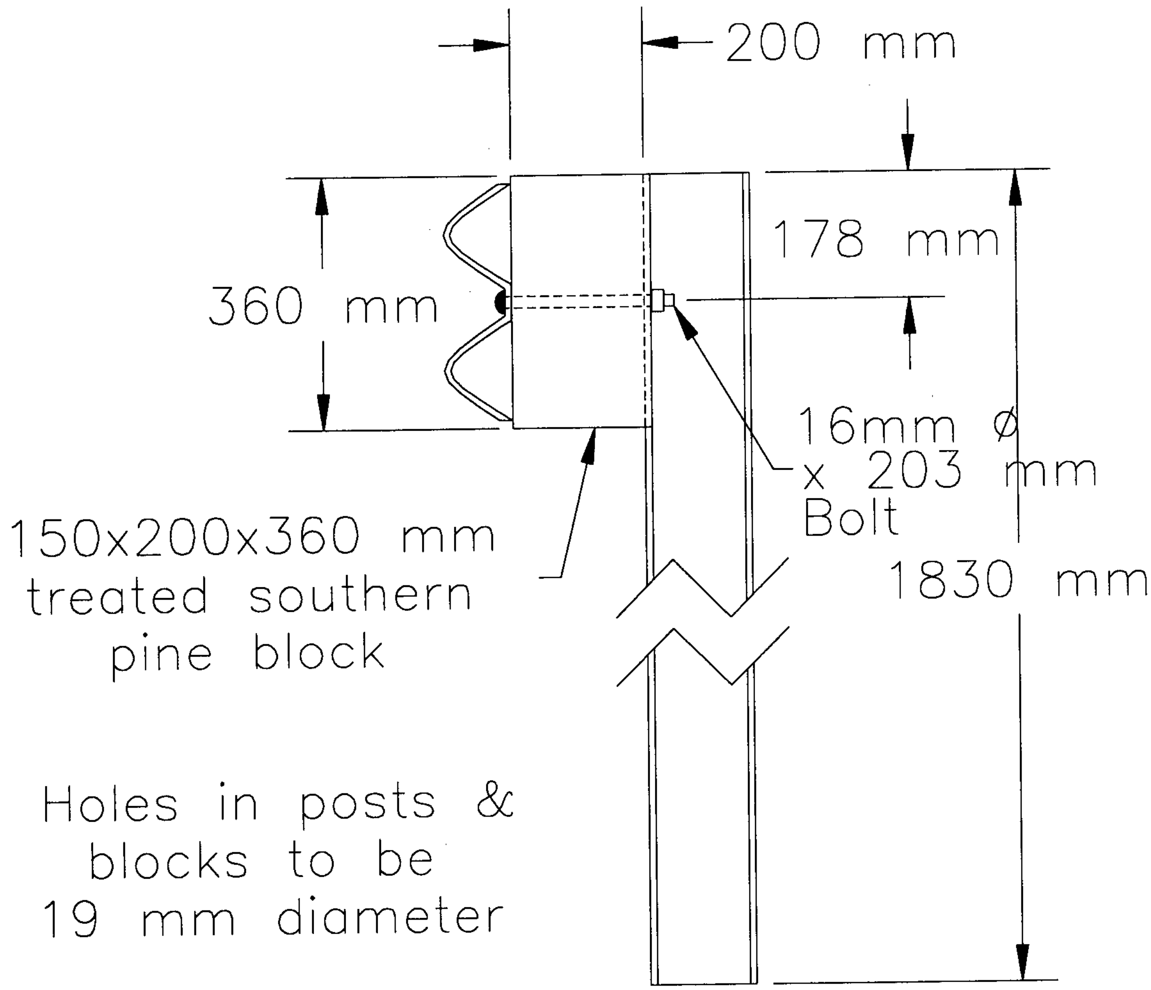


Figure 2. Cross-section of W-beam transition (on steel posts with timber blockouts).

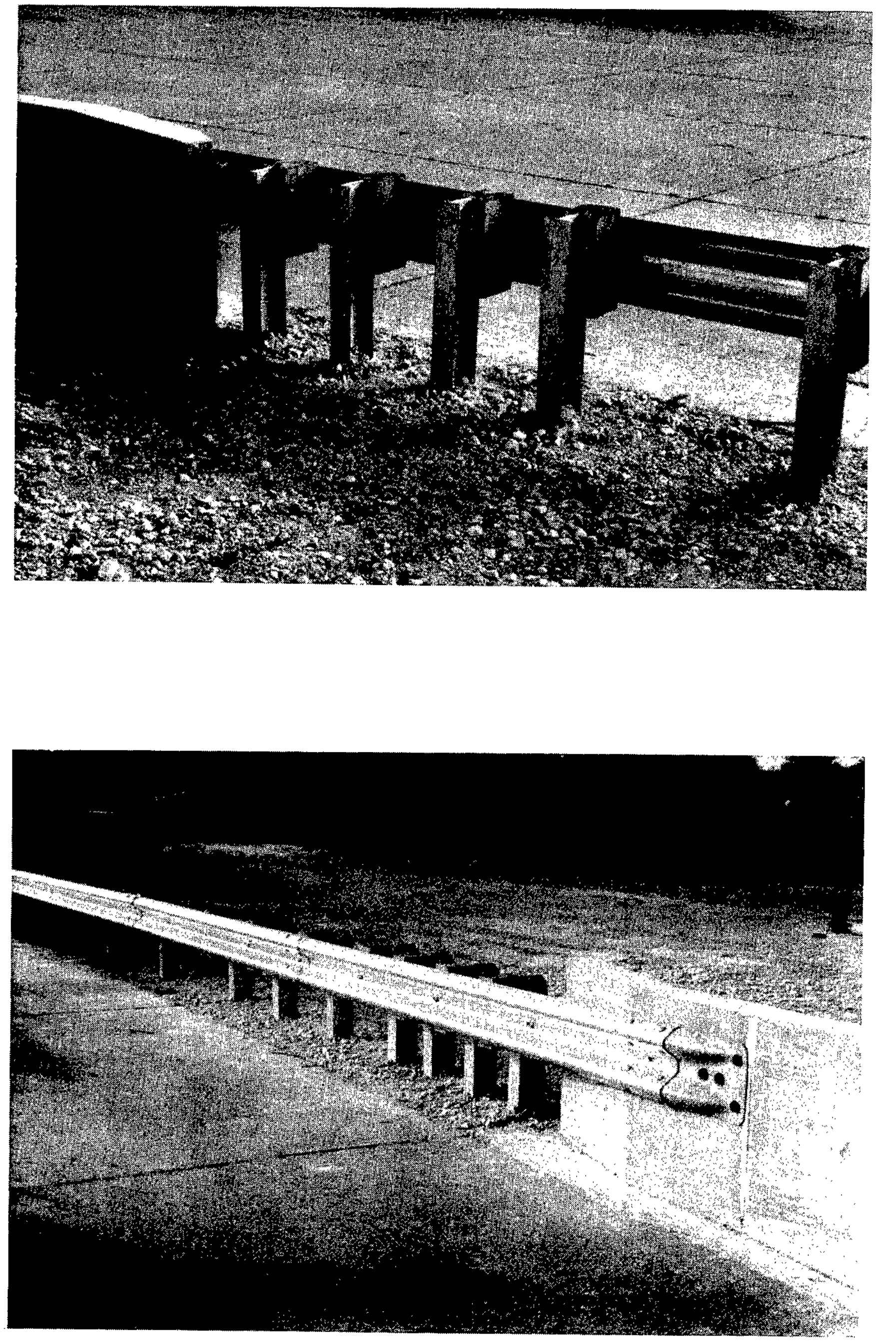


Figure 3. W-beam transition (on steel posts with timber blockouts) before test 405491-2.

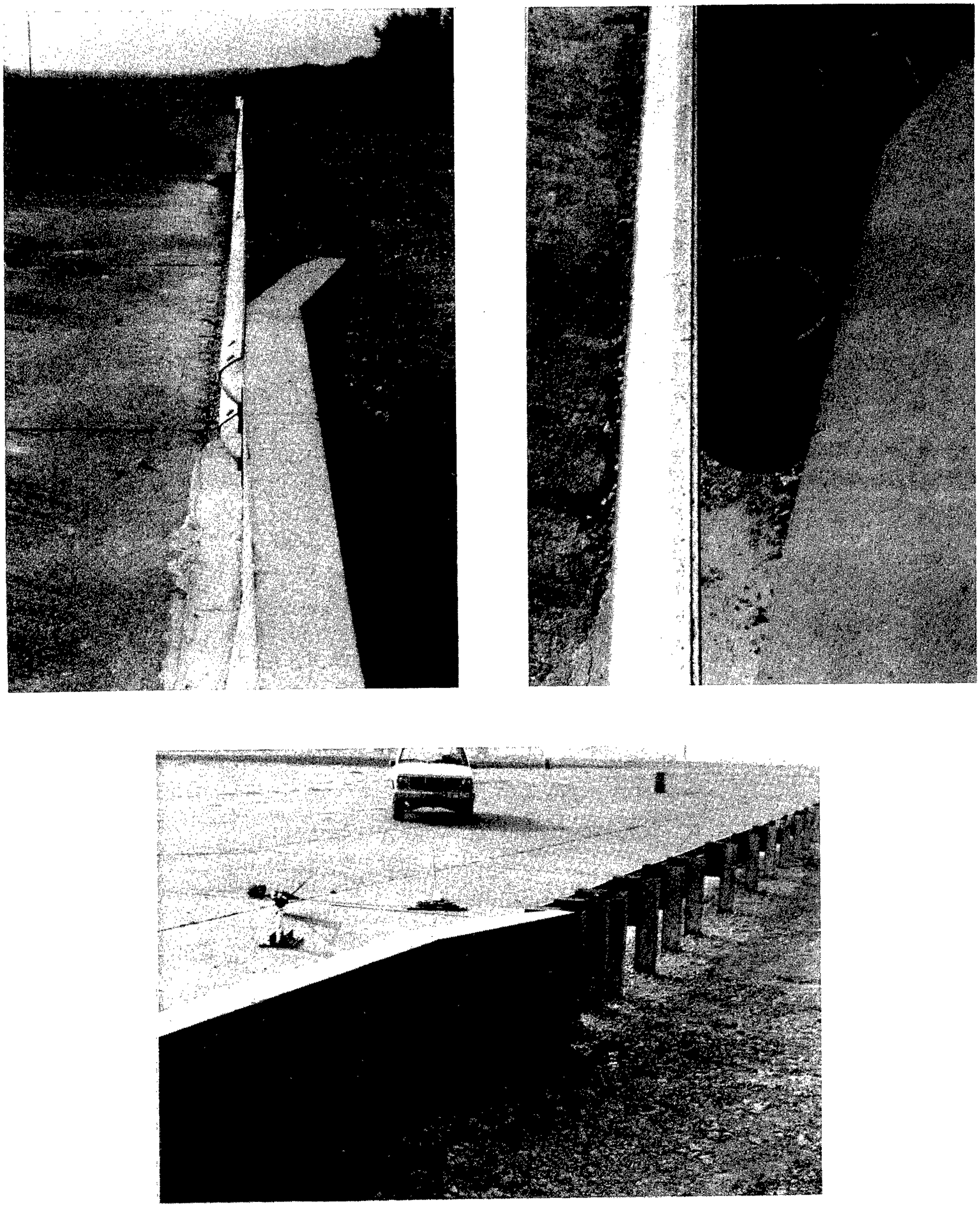


Figure 4. Transition attachment to flared back concrete bridge parapet.

2. **Test designation 3-21:** A 2000P vehicle impacting the transition section at a nominal speed and angle of 100 km/h and 25 degrees at the CIP of the transition section. The purpose of this test is to evaluate the strength of the transition section in containing and redirecting the 2000P vehicle.

Since test designation 3-20 is similar to the small-car test required under NCHRP Report 230 guidelines, only test designation 3-21 was performed under this study.

2.2.2 NCHRP Report 350 Evaluation Criteria

The crash test performed was evaluated in accordance with the criteria presented in NCHRP Report 350. As stated in NCHRP Report 350, "Safety performance of a highway appurtenance cannot be measured directly but can be judged on the basis of three factors: structural adequacy, occupant risk, and vehicle trajectory after collision." Accordingly, the following safety evaluation criteria from table 5.1 of NCHRP Report 350 were used to evaluate the crash test reported herein:

- **Structural Adequacy**

  A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.

- **Occupant Risk**

  D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformation of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.

  F. The vehicle should remain upright during and after collision although moderate roll, pitching and yawing are acceptable.

- **Vehicle Trajectory**

  K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.

L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/s and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 G's.

M. The exit angle from the test article preferably should be less than 60 percent of the test impact angle, measured at time of vehicle loss of contact with the test device.

2.3 CRASH TEST AND DATA ANALYSIS PROCEDURES

The crash test and data analysis procedures were in accordance with guidelines presented in NCHRP Report 350. Brief descriptions of these procedures are presented as follows.

2.3.1 Electronic Instrumentation and Data Processing

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

The electronic signals from the accelerometers and transducers were transmitted to a base station by means of constant bandwidth FM/FM telemetry link for recording on magnetic tape and for display on a real-time strip chart. Calibration signals were recorded before and after the test, and an accurate time reference signal was simultaneously recorded with the data. Pressure sensitive switches on the bumper of the impacting 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. The initial contact also produced an "event" mark on the data record to establish the exact instant of contact with the installation.

The multiplex of data channels, transmitted on one radio frequency, was received at the data acquisition station, and demultiplexed into separate tracks of Inter-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 impact performance.

The test vehicle was instrumented with five uniaxial accelerometers mounted in the following locations; (1) center top surface of the instrument panel; (2) inside end of right front wheel spindle; (3) inside end of left front wheel spindle; (4) top of engine block; and (5) bottom of engine block. The exact location of each accelerometer was measured and is reported in table 1. These accelerometers were ENDEVCO Model 7264A low mass piezoresistive accelerometers with a ±2000 g range.

Table 1. Locations of vehicle accelerometers for test 405491-2.

Location	X (mm) (distance from front axle)	Y (mm) (distance from centerline)	Z (mm) (distance from ground)	Data Axis
Instrument panel	-660	-120	-1300	X
Right front wheel spindle	0	+690	-385	X
Left front wheel spindle	0	-690	-370	Y
Top of engine block	+75	0	-965	X
Bottom of engine block	-270	0	-400	X
Vehicle c.g.	-1500	0	-750	X,Y,Z
Vehicle rear axle	-3300	0	-890	X,Y,Z

The data from these uniaxial accelerometers were captured using a Prosig P4000 data acquisition system. The P4000 is a modular, distributed data acquisition system based on independent data collection elements called POD's. Each POD has four high-speed analog, three digital and time-zero inputs. The POD's sample synchronously at up to 10,000 samples per second, per channel, with 12-bit resolution. Non-volatile memory holds up to 13 s at the maximum data rate. Analog inputs have integral, strain gauge accelerometer signal conditioning and anti-aliasing filters. Each channel has a fully programmable amplifier and input offset adjustment. After extracting the data from the POD units to the host computer, fourth order, Bessel, digital filtering is used to produce SAE J211 data for processing. Data capture is started by a trigger pulse from a bumper switch or a predefined g level. Twenty-five percent of the captured data is prior to the trigger signal.

The digitized data were then processed using two computer programs: DIGITIZE and PLOTANGLE. Brief descriptions on the functions of these two computer programs are provided as follows.

The DIGITIZE program uses digitized data from vehicle-mounted linear accelerometers to compute occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and the highest 10-ms average ridedown acceleration. The DIGITIZE program also calculates a vehicle impact velocity and the change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms intervals in each of the three directions are computed. For reporting purposes, the data from the vehicle-mounted accelerometers were then filtered with a 60 Hz digital filter and acceleration versus time curves for the longitudinal, lateral, and vertical directions were plotted using a commercially available software package (QUATTRO PRO).

The PLOTANGLE program used the digitized data from the yaw, pitch, and roll rate transducers to compute angular displacement in degrees at 0.00067-s intervals and then instructs a plotter to draw a reproducible plot: yaw, pitch, and roll versus time. These displacements are in reference to the vehicle-fixed coordinate system with the initial position and orientation of the vehicle-fixed coordinate system being that which existed at initial impact.

2.3.2 Anthropomorphic Dummy Instrumentation

An Alderson Research Laboratories Hybrid II, 50th percentile male anthropomorphic dummy, restrained with lap and shoulder belts, was placed in the driver's position of the 820C vehicle. The dummy was un-instrumented. Use of a dummy in the 2000P vehicle is optional according to NCHRP Report 350, and there was no dummy used in this test with the 2000P vehicle.

2.3.3 Photographic Instrumentation and Data Processing

Photographic coverage of the test included three high-speed cameras: one overhead with a field of view perpendicular to the ground and directly over the impact point; and one placed behind the installation at an angle; a third placed to have a field of view parallel to and aligned with the installation at the downstream end. A fourth high-speed camera was placed onboard the vehicle to record the motions of the dummy placed in the driver seat during the test sequence. A flash bulb activated by pressure sensitive tapeswitches was positioned on the impacting vehicle to indicate the instant of contact with the installation 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 Betacam, a VHS-format video camera and recorder, and still cameras were used to record and document conditions of the test vehicle and installation before and after the test.

2.3.4 Test Vehicle Propulsion and Guidance

The test vehicle was towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding the test vehicle was tensioned along the path, anchored at each end, and threaded through an attachment to the front wheel of the test vehicle. An additional 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. Just prior to impact with the installation, the test vehicle was released to be free-wheeling and unrestrained. The vehicle remained free-wheeling, i.e., no steering or braking inputs, until the vehicle cleared the immediate area of the test site, at which time brakes on the vehicle were activated to bring the vehicle to a safe and controlled stop.

III. CRASH TEST RESULTS

3.1 PICKUP TRUCK REDIRECTION TEST (TEST NO. 405491-2)

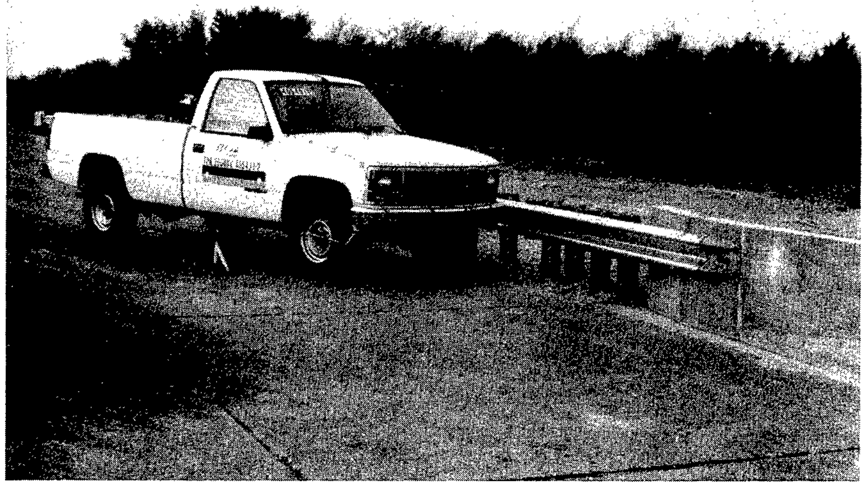
A 1989 GMC 2500 pickup truck, shown in figures 5 and 6, was used for the crash test. Test inertia weight of the vehicle was 2000 kg, and its gross static weight was 2075 kg. The height to the lower edge of the vehicle bumper was 455 mm and it was 685 mm to the upper edge of the bumper. Additional dimensions and information on the vehicle are given in figure 7. The vehicle was directed into the installation using the cable reverse tow and guidance system, and was released to be free-wheeling and unrestrained just prior to impact.

3.1.1 Test Description

The test vehicle, traveling at a speed and angle of 99.8 km/h and 25.3 degrees, impacted the transition section 150 mm upstream of post 4, which was determined to be the Critical Impact Point (CIP). Shortly after impact, movement was noted at posts 4, 3, and 2, respectively. At 0.022 s, the front of the vehicle made contact with post 3 and, at 0.024 s, post 1 began to move. The front of the vehicle made contact with post 2 at 0.039 s and with post 1 at 0.053 s. At 0.066 s, the front of the vehicle impacted the end of the flared back concrete bridge parapet. The vehicle began to redirect at 0.068 s and the bridge parapet began to move at 0.077 s. At 0.194 s, the vehicle became parallel with the transition, traveling at a speed of 72.4 km/h. The rear of the vehicle impacted the W-beam rail element at 0.245 s and the concrete parapet at 0.272 s. At 0.289 s, the rear bumper caught on the bridge parapet. The vehicle lost contact with the bridge parapet at 0.573 s, traveling at an exit speed and angle of 66.2 km/h and 18.5 degrees. As the vehicle exited the test installation, it yawed clockwise and rolled counterclockwise. The vehicle rolled 360 degrees and subsequently came to rest facing the impact point 47.5 m down and 11.9 m forward. Sequential photographs of the test period are shown in figures 8 and 9.

3.1.2 Damage to Test Installation

Damage to the installation is shown in figures 10 through 13. Posts 6 through 1 were pushed back 10 mm, 35 mm, 85 mm, 125 mm, 160 mm, and 140 mm, respectively. The timber blockouts were damaged as shown in figure 12. There were tire marks on the face of the W-beam rail element and on the concrete parapet (see figure 13). There were shear cracks in the parapet and the parapet was pushed away from the bridge deck 35 mm, as can be seen in figure 13. Total length of contact of the vehicle with the installation was 4.1 m.



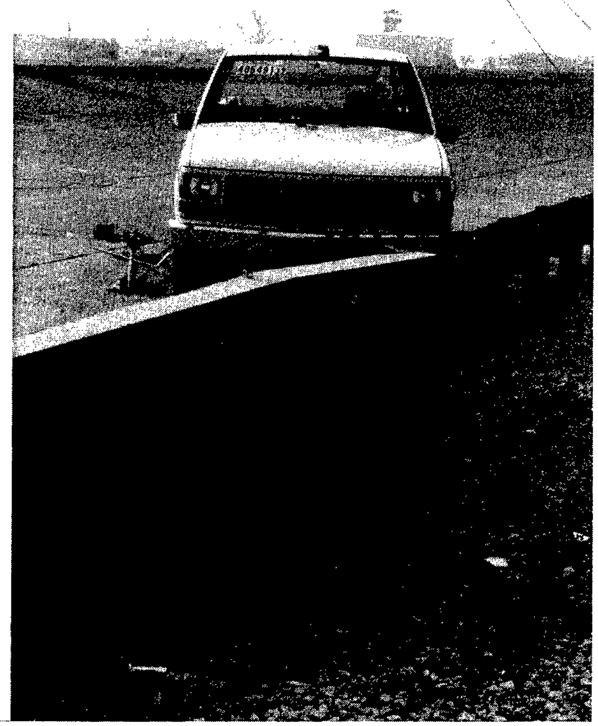


Figure 5. Vehicle/installation geometrics for test 405491-2.

Figure 6. Vehicle before test 405491-2.

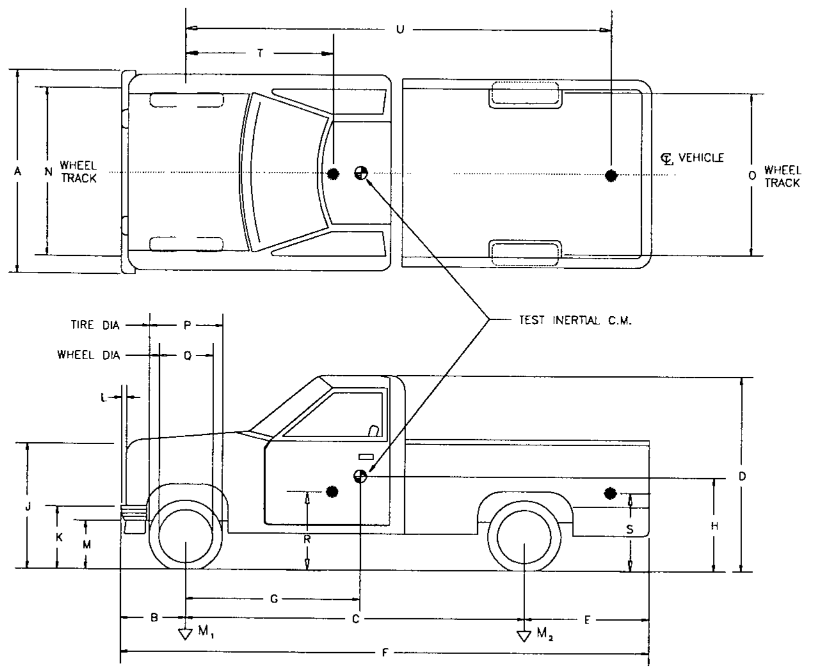
DATE: 02/22/96 TEST NO.: 405491-2 VIN NO.: 1GTGC24K3KE540879

YEAR: 1989 MAKE: GMC MODEL: 2500 pickup

TIRE INFLATION PRESSURE: ______ ODOMETER: 192753 TIRE SIZE: 245 75R16

MASS DISTRIBUTION (kg) LF 550 RF 525 LR 479 RR 446

DESCRIBE ANY DAMAGE TO VEHICLE PRIOR TO TEST:



● Denotes accelerometer location.

NOTES: ______

ENGINE TYPE: 8 cylinder

ENGINE SIZE: 5.7 L

TRANSMISSION TYPE:

X AUTO

_ MANUAL

OPTIONAL EQUIPMENT:

DUMMY DATA:

TYPE: 50th perc male

MASS: 76 kg

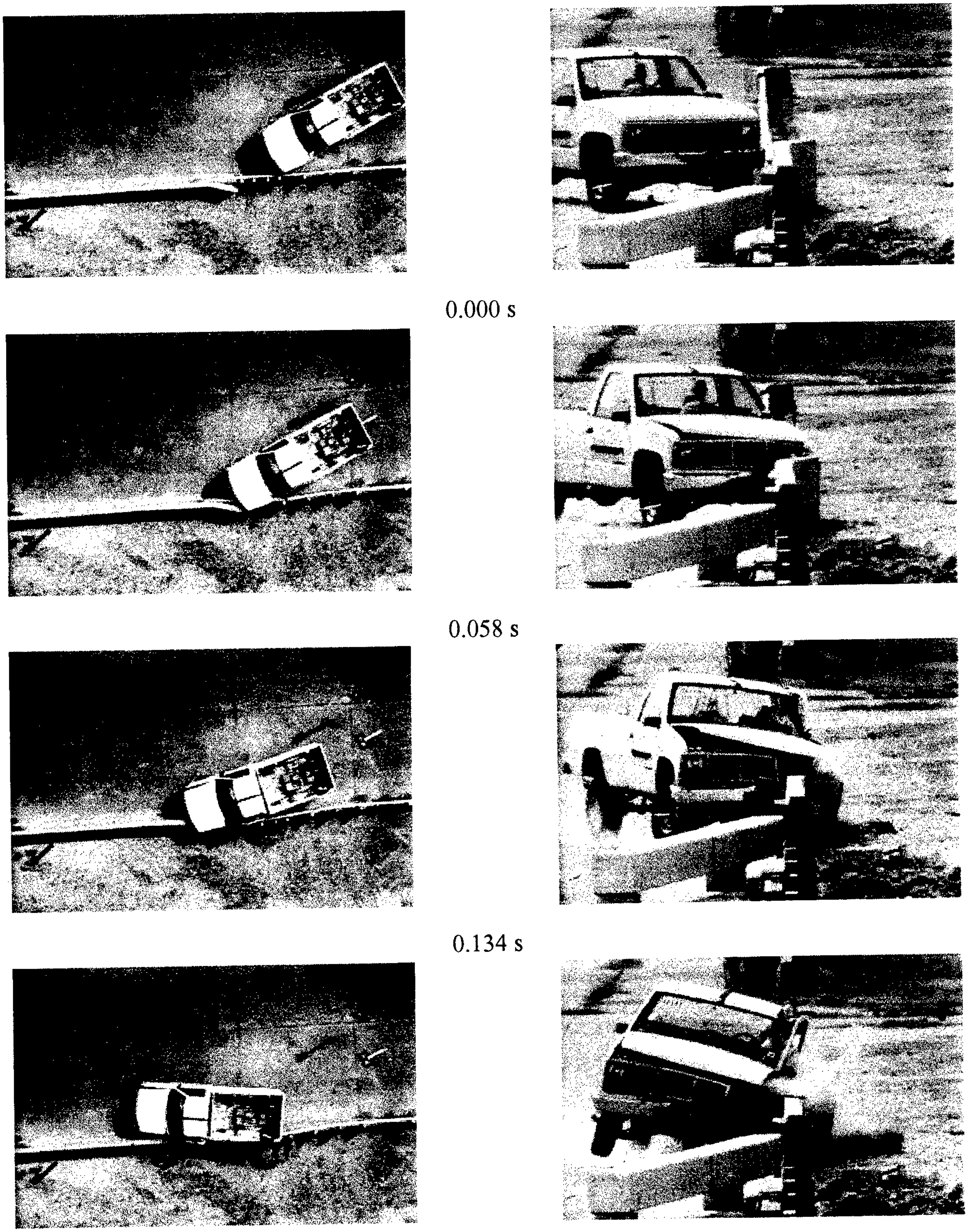
SEAT POSITION: Driver

GEOMETRY - (mm)

A	890	E	1250	J	1090	N	1590	R	750
B	760	F	5360	K	695	O	1630	S	940
C	3350	G	1549.4	L	80	P	770	T	1500
D	1850	H		M	455	Q	440	U	3300

MASS - (kg)	CURB	TEST INERTIAL	GROSS STATIC
M_1	1097	1075	1123
M_2	834	925	953
M_T	1931	2000	2076

Figure 7. Vehicle properties for test 405491-2.



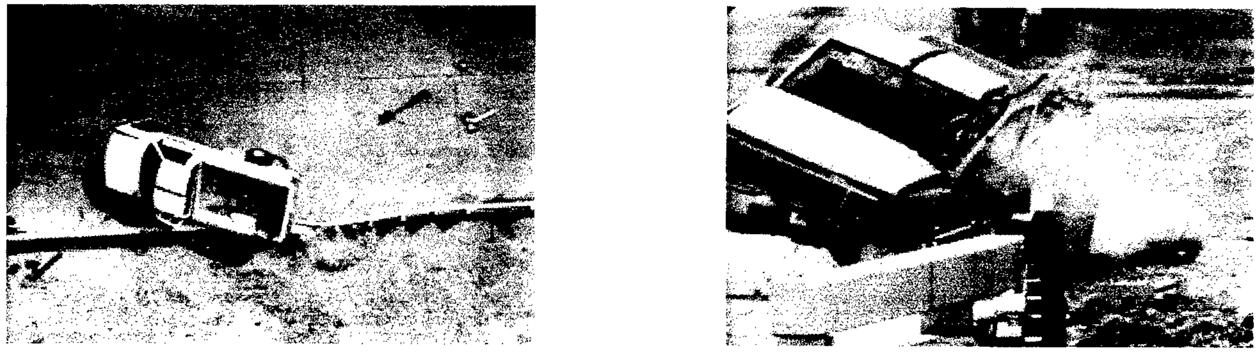
0.000 s

0.058 s

0.134 s

0.232 s

Figure 8. Sequential photographs for test 405491-2
(overhead and frontal views).



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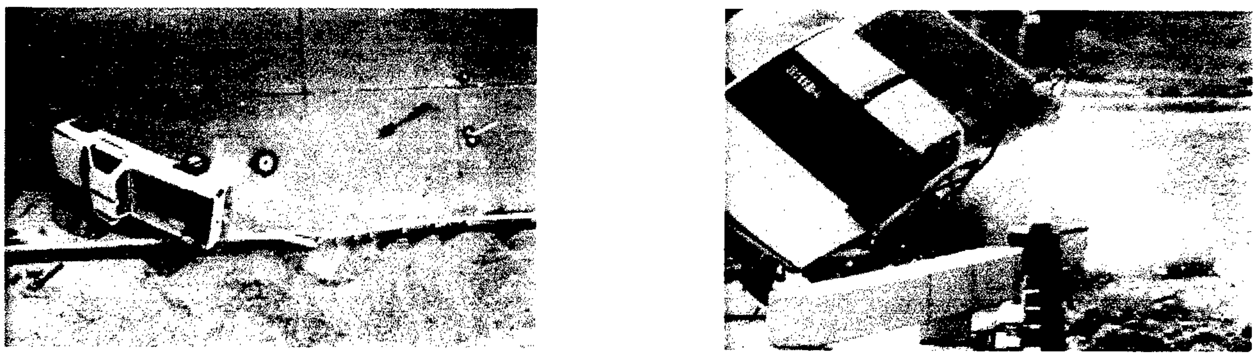

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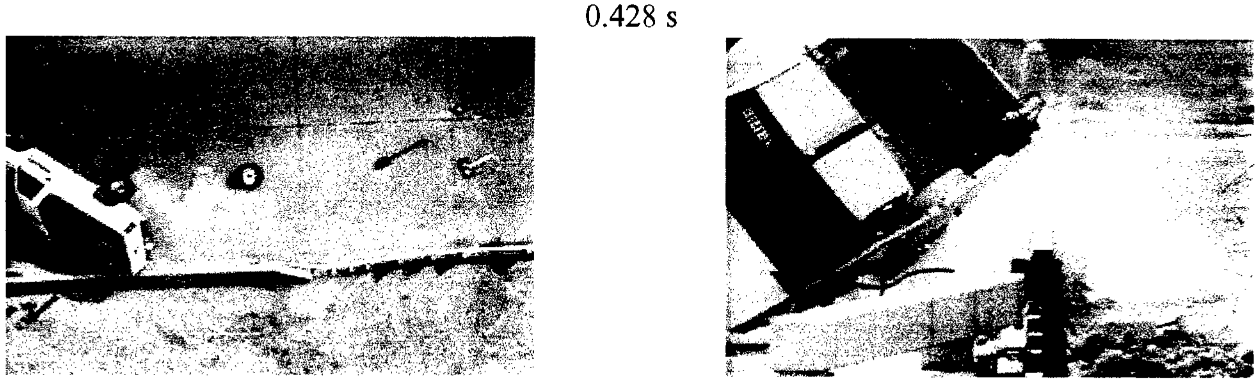

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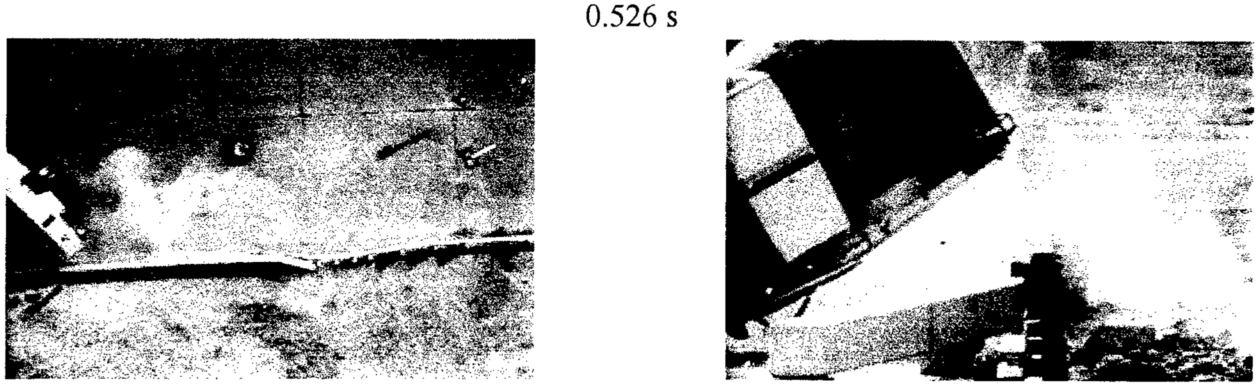

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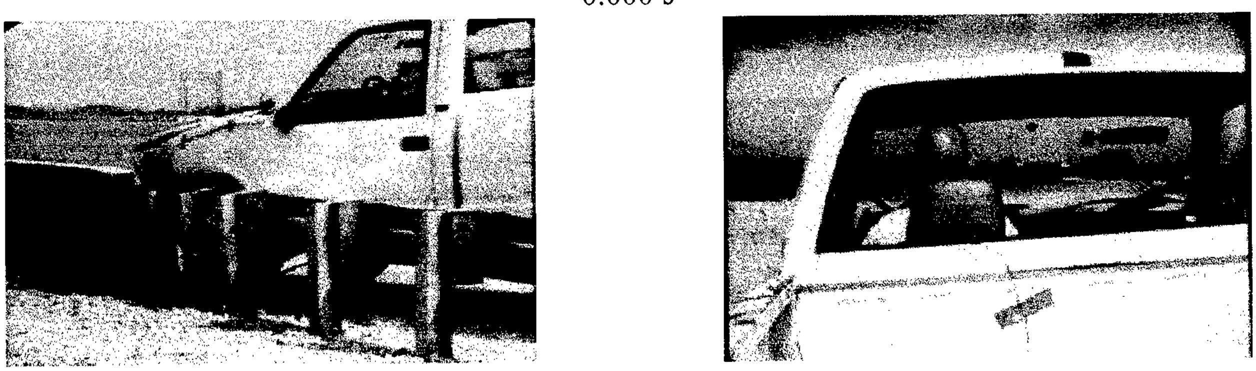
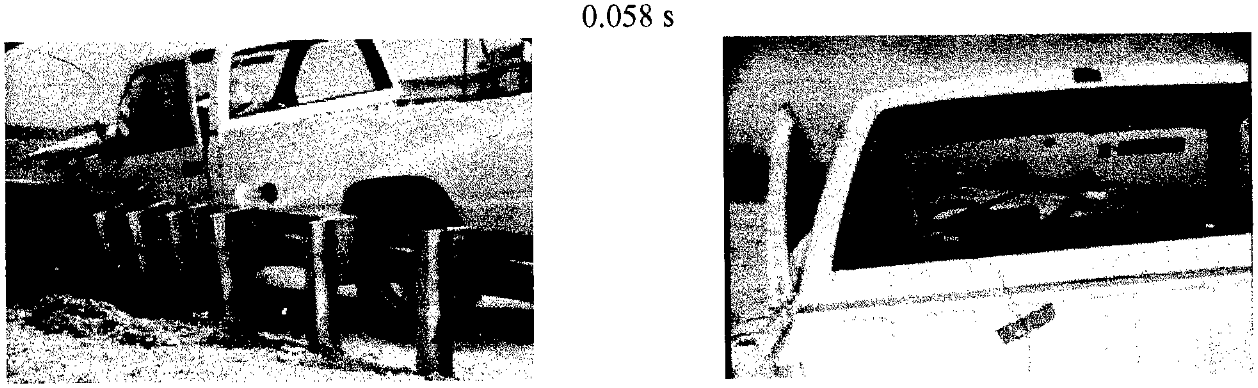
Figure 8. Sequential photographs for test 405491-2
(overhead and frontal views) (continued).

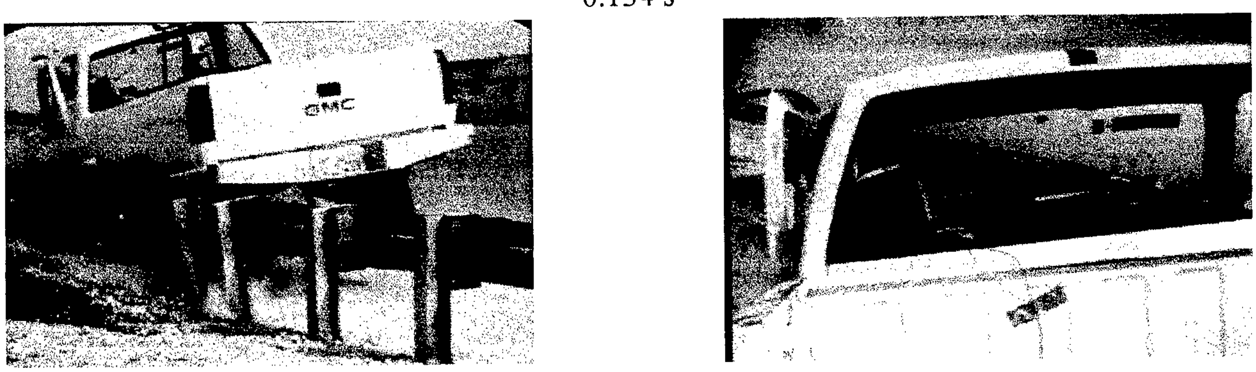
0.000 s



0.058 s



0.134 s

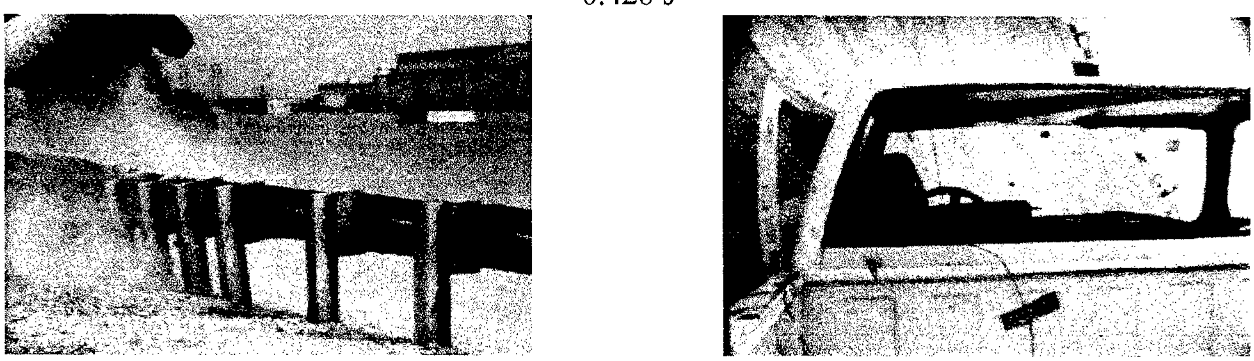


0.232 s

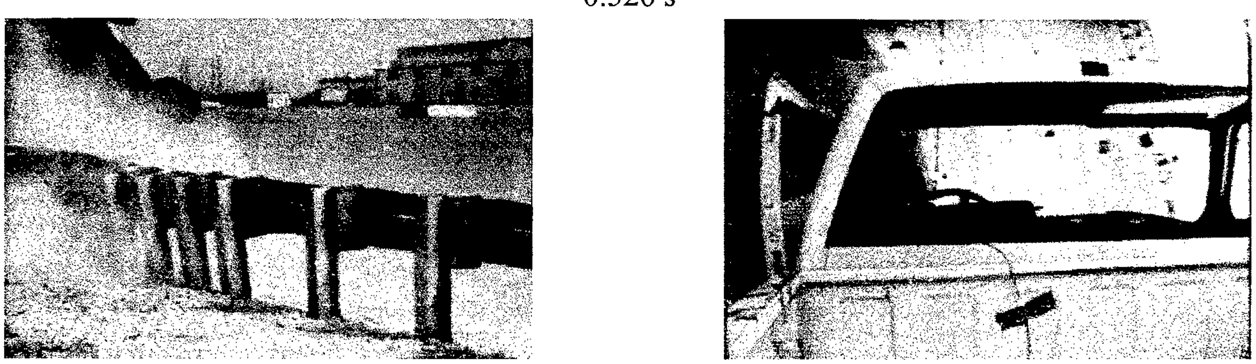
Figure 9. Sequential photographs for test 405491-2 (rear and onboard views).

0.330 s

0.428 s



0.526 s



0.624 s

Figure 9. Sequential photographs for test 405491-2
(rear and onboard views) (continued).

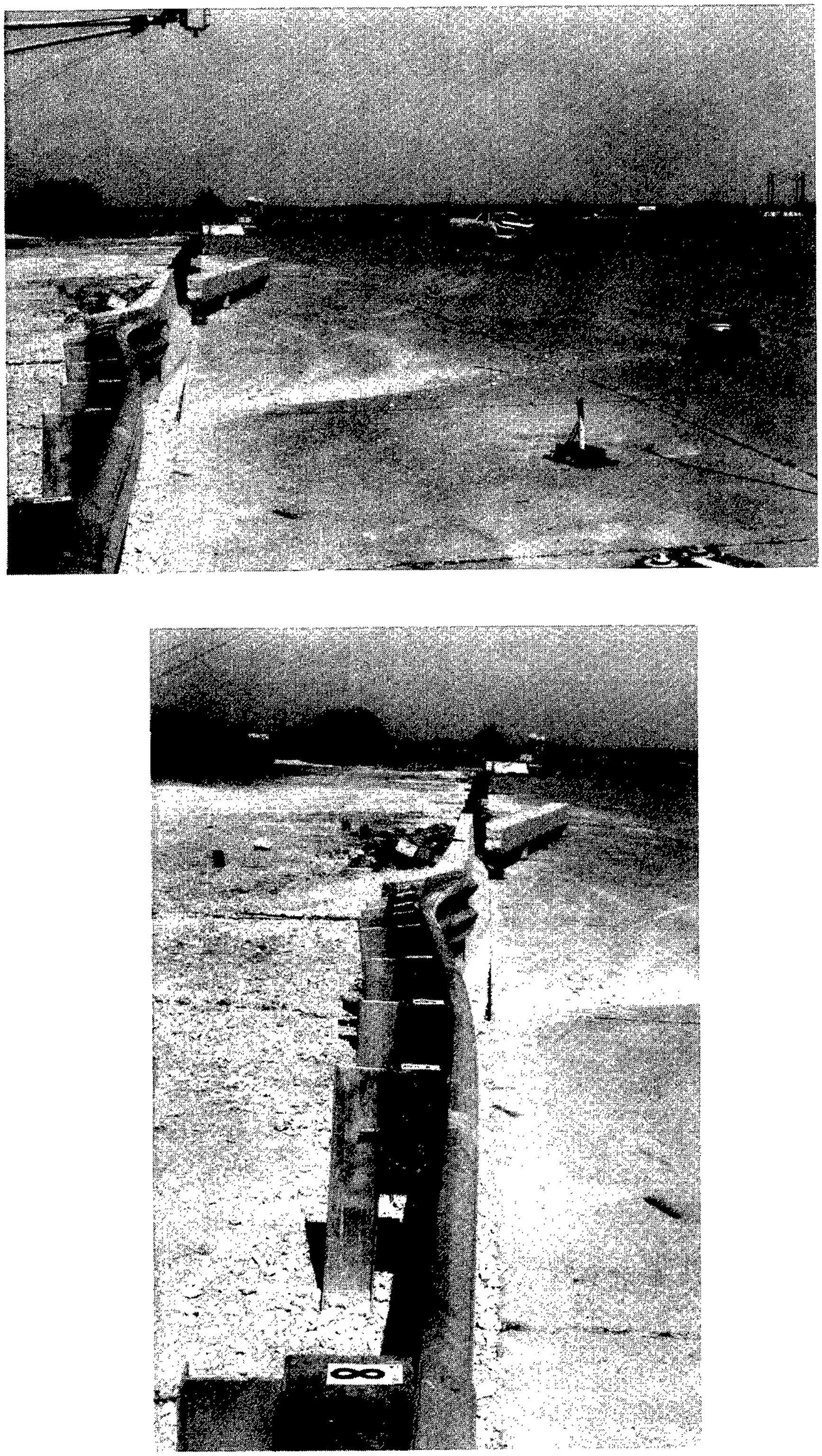


Figure 10. After impact trajectory for test 405491-2.

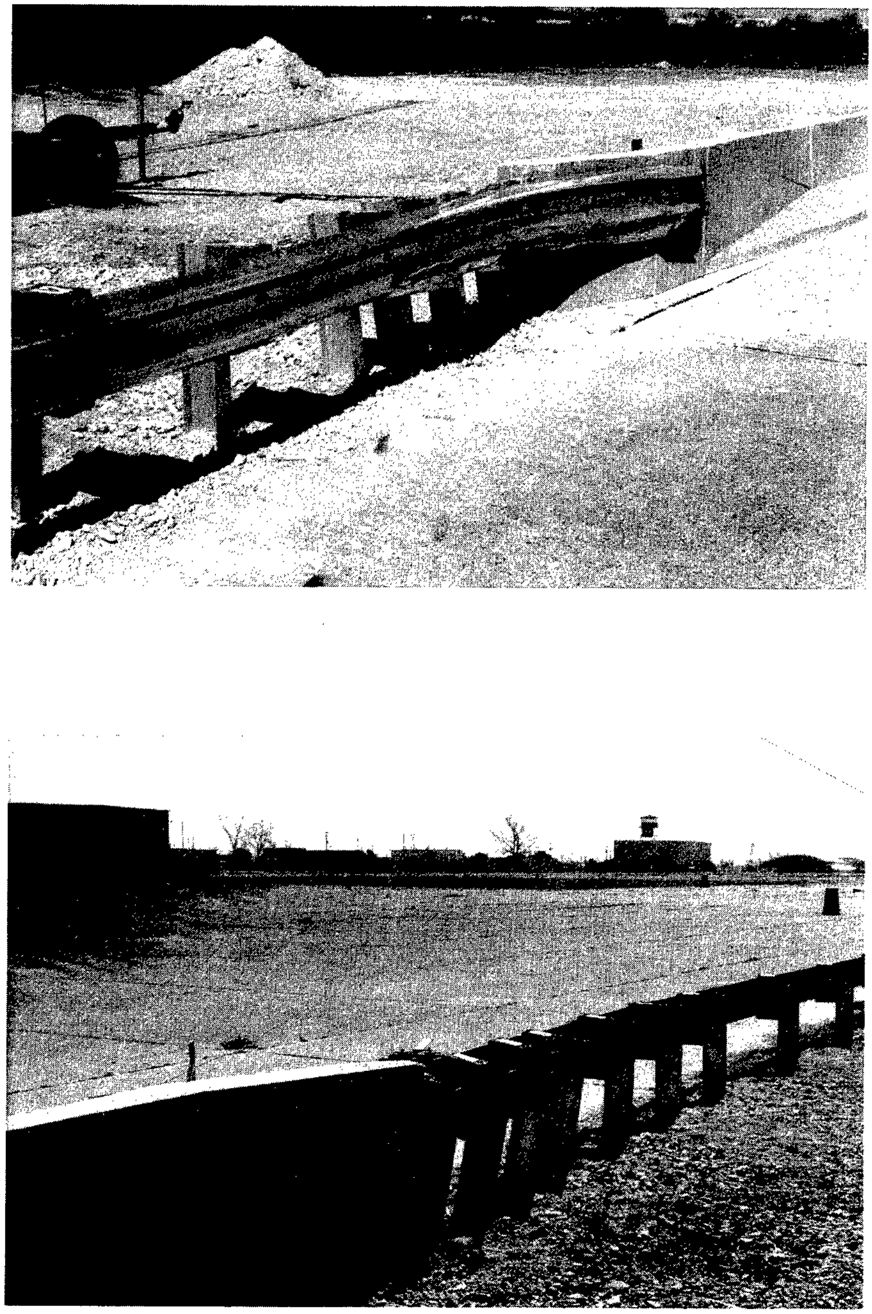


Figure 11. Transition after test 405491-2.

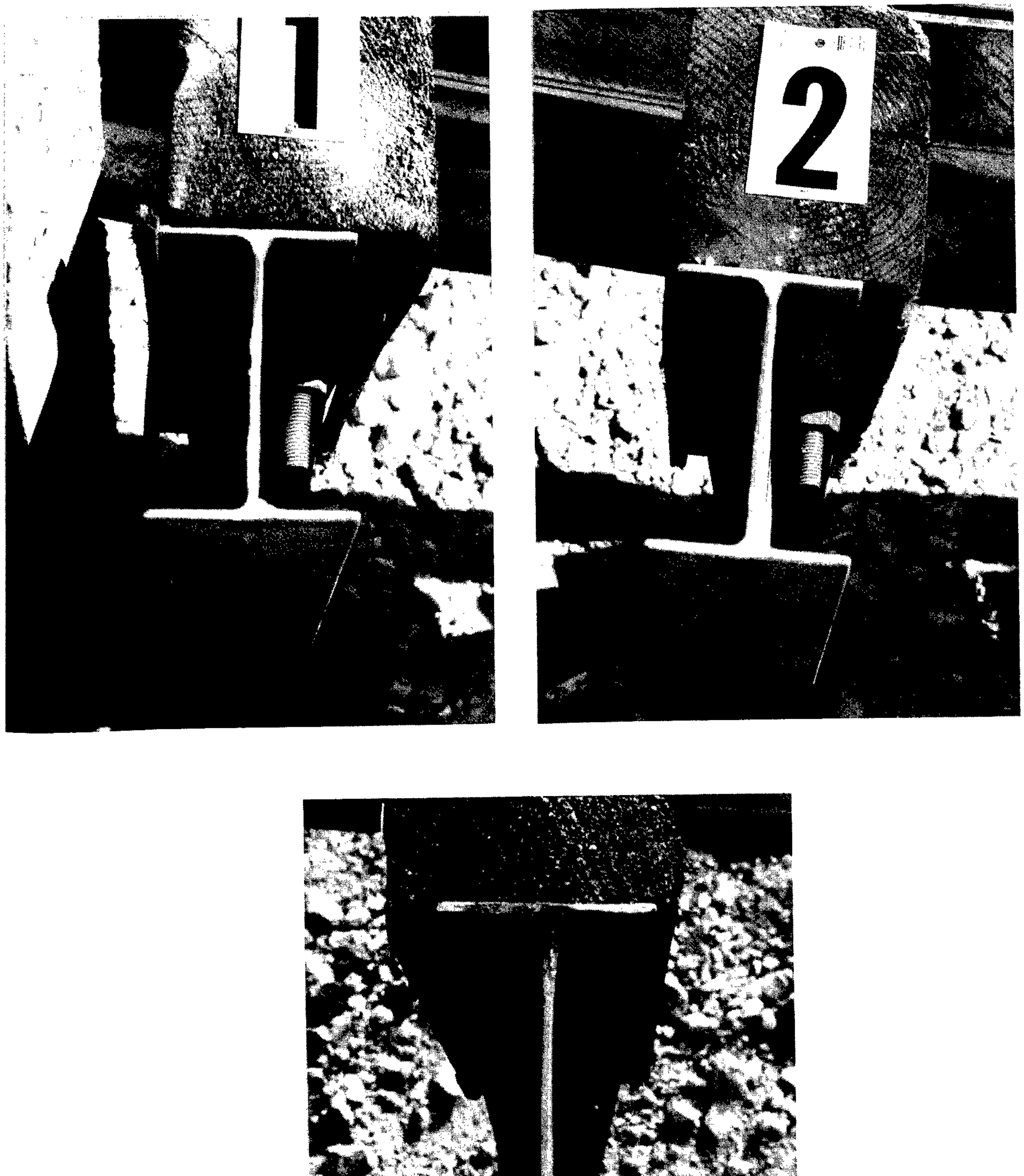


Figure 12. Damage to blockouts at posts 1 through 3 after test 405491-2.

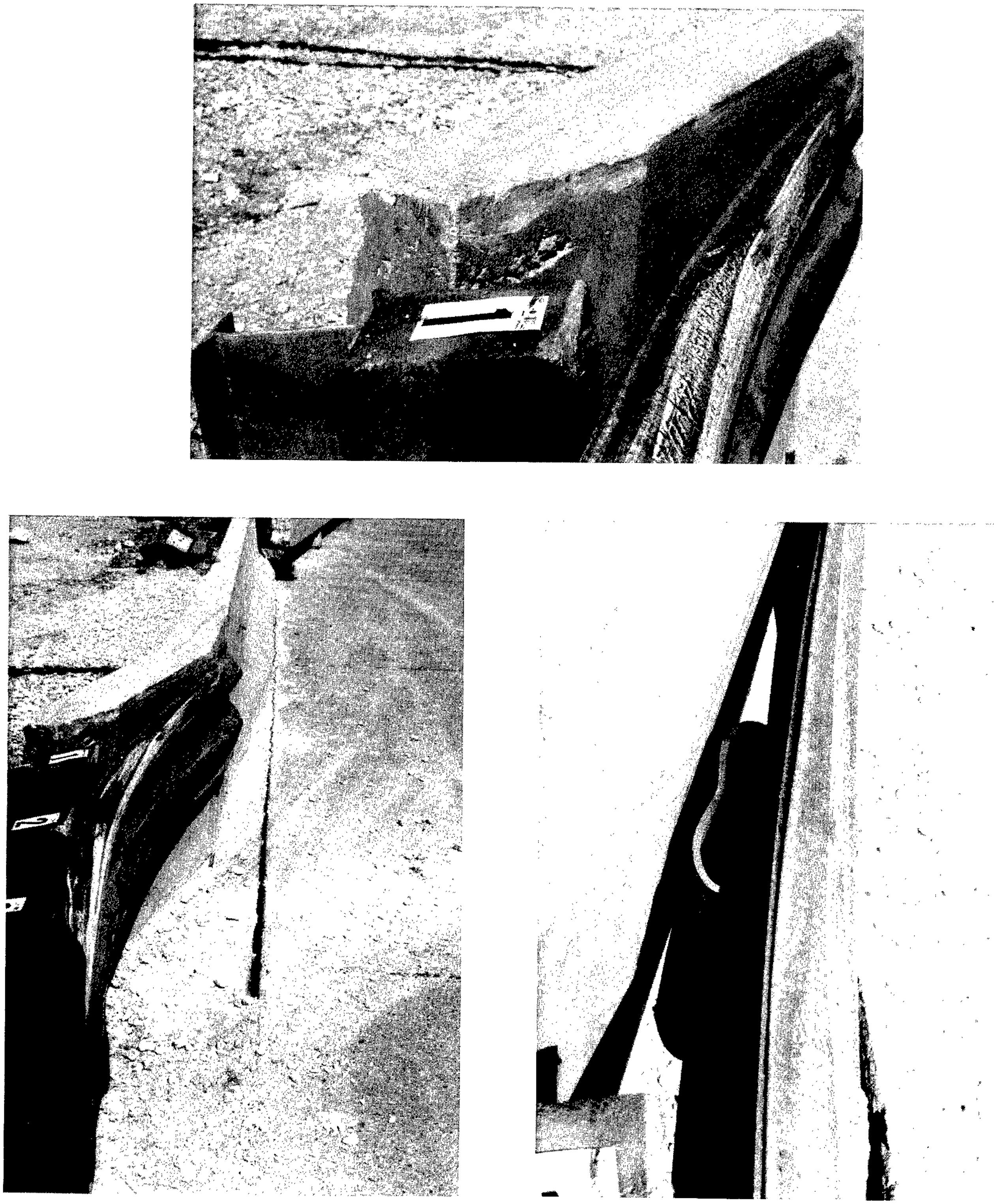


Figure 13. Damage to concrete parapet after test 405491-2.

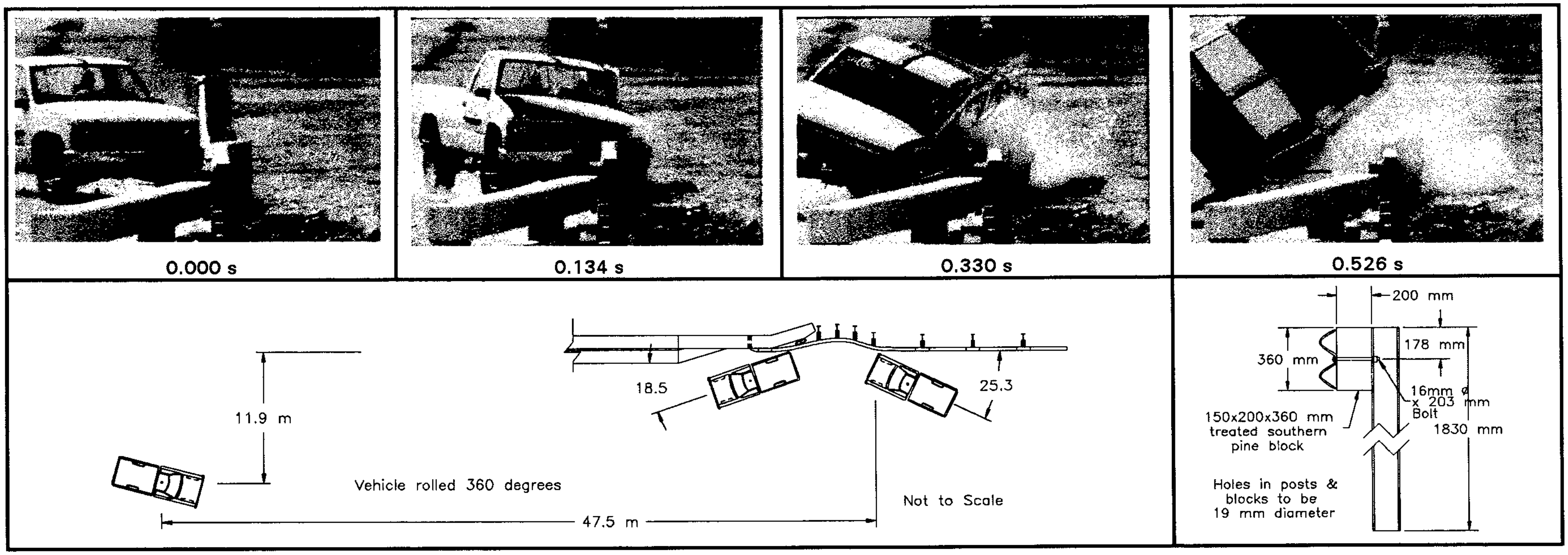
3.1.3 Vehicle Damage

The vehicle received extensive damage as shown in figure 14. Damage to the left front wheel assembly included the upper and lower A-arms, tie rods, stabilizer bar, pitman arm, and steering box, and the tire, wheel and spindle were torn from the vehicle. The frame was bent and the floorpan was buckled. The front bumper, hood, grill, fan, radiator, left front quarter panel, left door, left side of the bed, and left tire and rim were also damaged. The roof, windshield, both door windows, and the right side of the vehicle were damaged during the rollover.

3.1.4 Occupant Risk Values

Data from the accelerometer located at the vehicle center-of-gravity were digitized for evaluation of occupant risk and were computed as follows. In the longitudinal direction, the occupant impact velocity was 9.3 m/s at 0.157 s, the highest 0.010-s occupant ridedown acceleration was -10.4 g from 0.147 to 0.157 s, and the maximum 0.050-s average acceleration was -11.6 g between 0.066 and 0.116 s. In the lateral direction, the occupant impact velocity was 6.9 m/s at 0.116 s, the highest 0.010-s occupant ridedown acceleration was 17.6 g from 0.148 to 0.158 s, and the maximum 0.050-s average was 10.8 g between 0.058 and 0.108 s. These data and other pertinent information from the test are summarized in figure 15. Vehicle angular displacements are displayed in figure 16. Vehicular accelerations versus time traces are presented in figures 17 through 27.

Figure 14. Vehicle after test 405491-2.

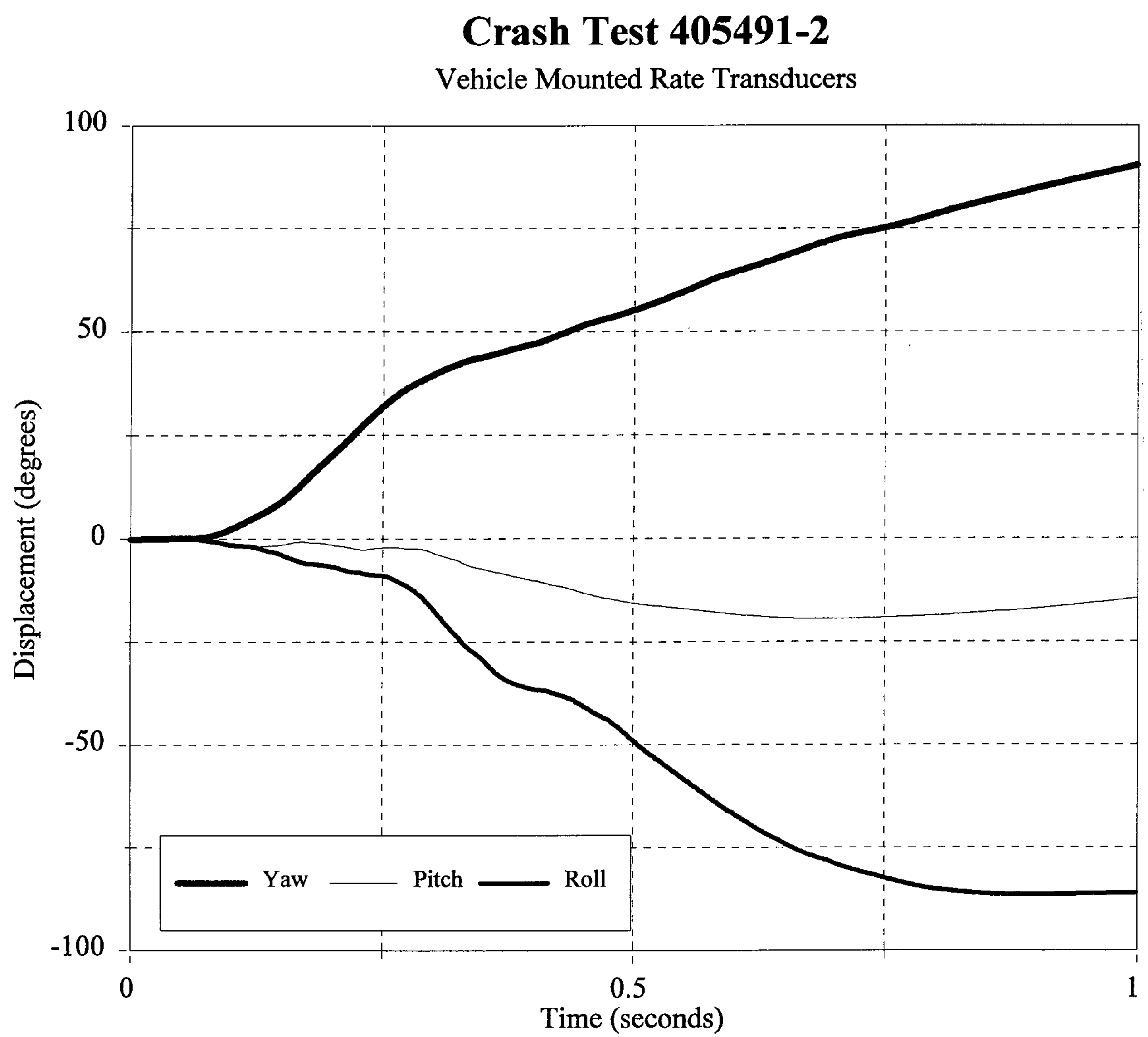


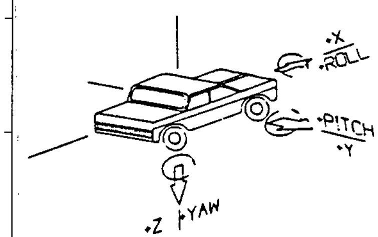
General Information	
Test Agency	Texas Transportation Institute
Test No.	405491-2
Date	02/22/96
Test Article	
Type	Transition
Name	W-beam transition
Installation Length (m)	42
Size and/or dimension and material of key elements	Nested W-beam on steel posts with wood blockouts to vertical flared back concrete parapet
Soil Type and Condition	Standard soil, dry
Test Vehicle	
Type	Production
Designation	2000P
Model	1989 GMC 2500 pickup
Mass (kg) Curb	1931
Test Inertial	2000
Dummy	76
Gross Static	2076

Impact Conditions	
Speed (km/h)	99.8
Angle (deg)	25.3
Exit Conditions	
Speed (km/h)	66.2
Angle (deg)	18.5
Occupant Risk Values	
Impact Velocity (m/s)	
x-direction	9.3
y-direction	6.9
THIV (optional)	
Ridedown Accelerations (g's)	
x-direction	-10.4
y-direction	17.6
PHD (optional)	
ASI (optional)	
Max. 0.050-s Average (g's)	
x-direction	-11.6
y-direction	10.8
z-direction	6.2

Test Article Deflections (mm)	
Dynamic	N/A
Permanent	160
Vehicle Damage	
Exterior	
VDS	11LFQ5 &11L&T4
CDC	11FYEK4 & 00TDHO3
Interior	
OCDI	FS0202001
Maximum Exterior Vehicle Crush (mm)	600
Max. Occ. Compart. Deformation (mm)	133
Post-Impact Behavior	
Max. Roll Angle (deg)	-360
Max. Pitch Angle (deg)	-19
Max. Yaw Angle (deg)	90

Figure 15. Summary of results for test 405491-2.





Axes are vehicle fixed.
Sequence for determining orientation is:

1. Yaw
2. Pitch
3. Roll

Figure 16. Vehicle angular displacements for test 405491-2.

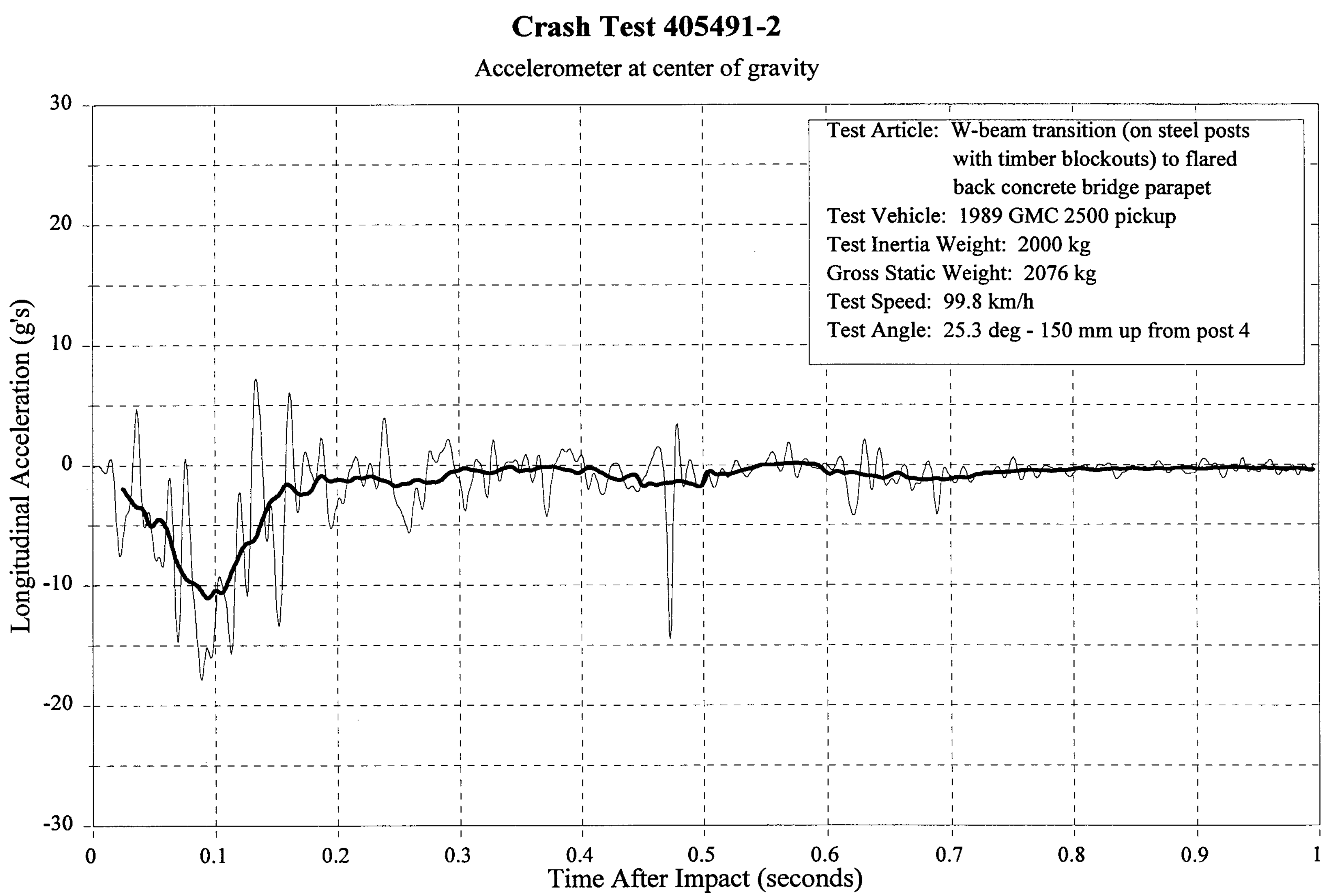


Figure 17. Vehicle longitudinal accelerometer trace for test 405491-2 (accelerometer located at center of gravity).

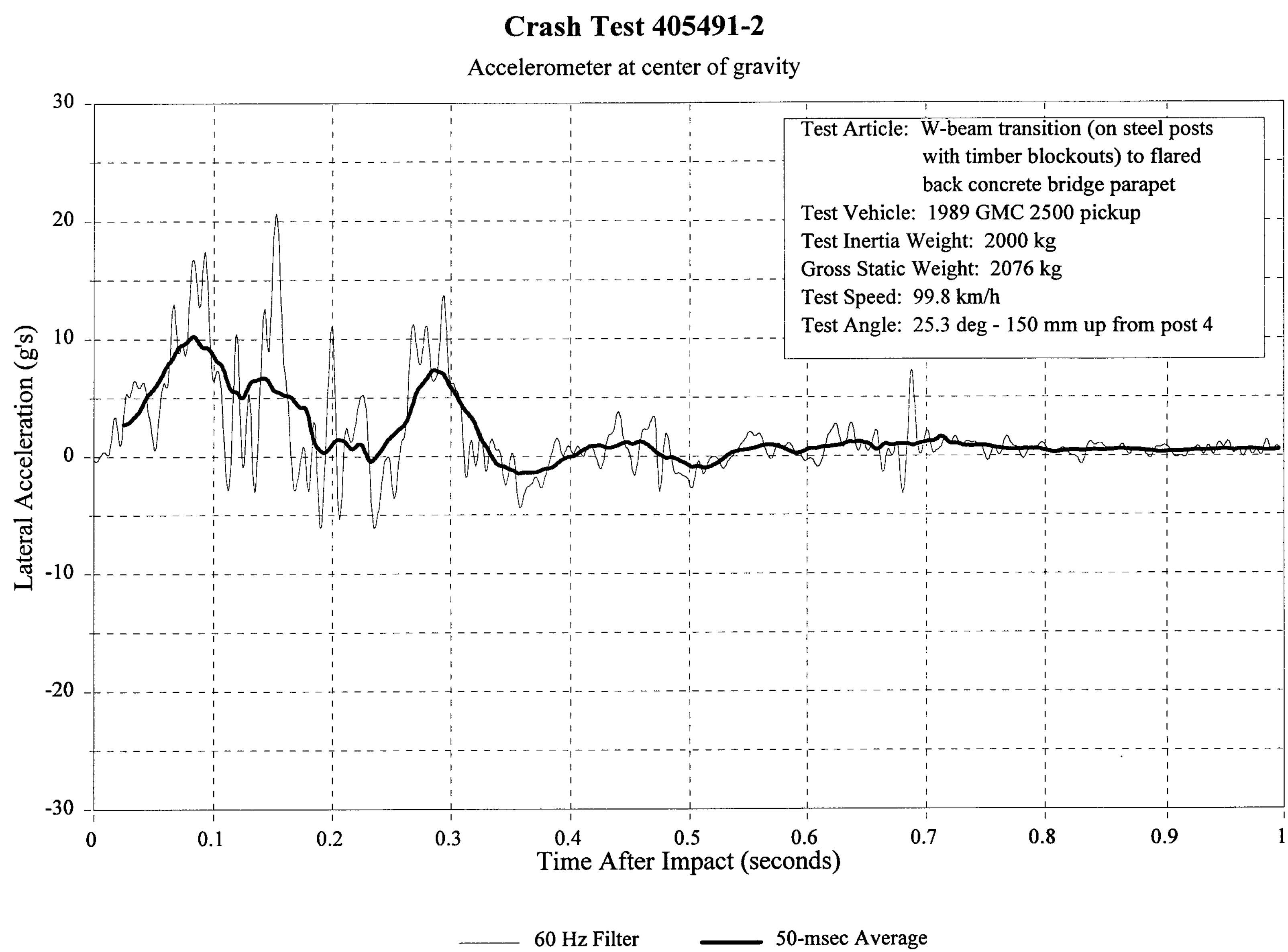


Figure 18. Vehicle lateral accelerometer trace for test 405491-2 (accelerometer located at center of gravity).

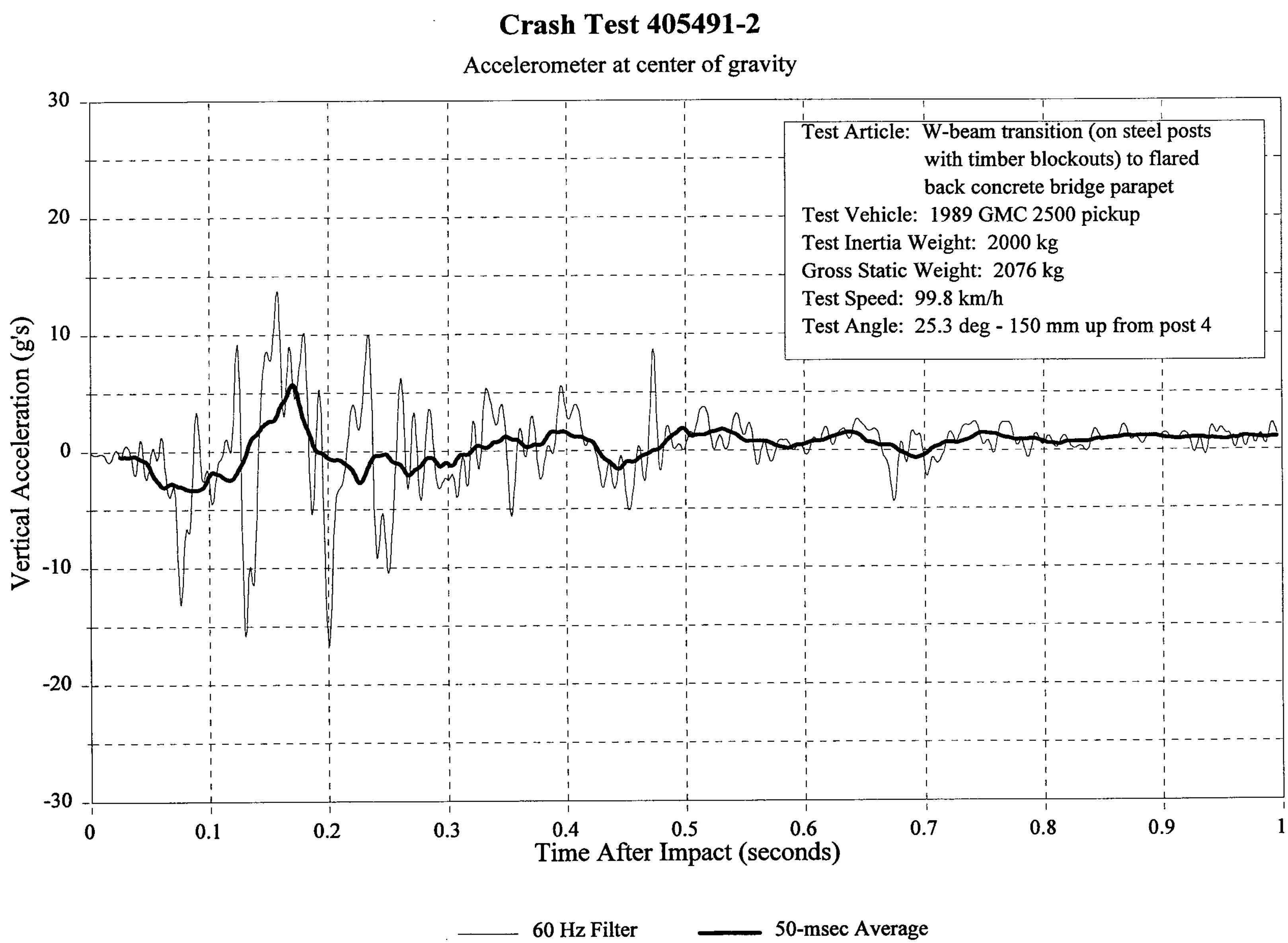


Figure 19. Vehicle vertical accelerometer trace for test 405491-2 (accelerometer located at center of gravity).

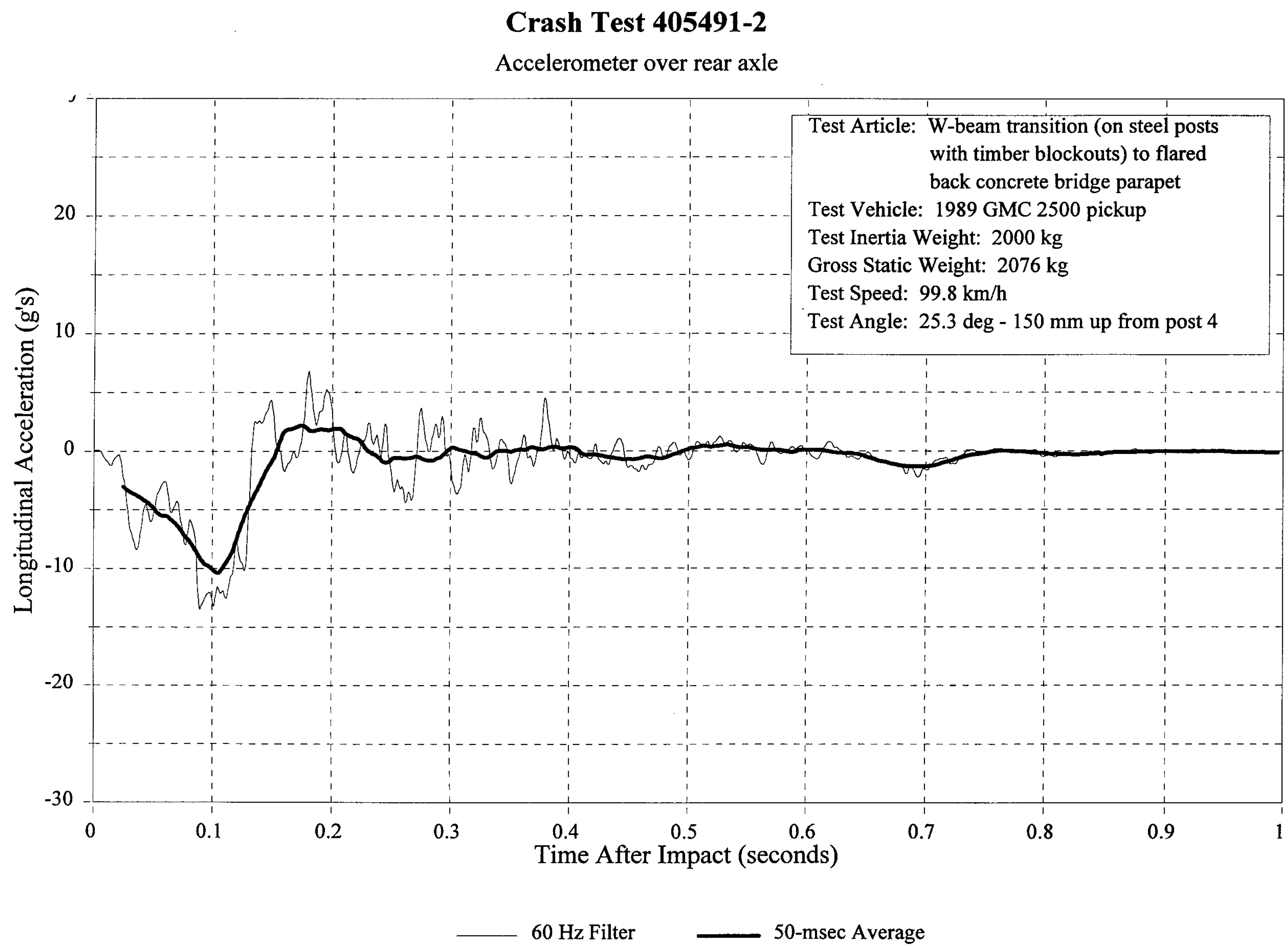


Figure 20. Vehicle longitudinal accelerometer trace for test 405491-2 (accelerometer located over rear axle).

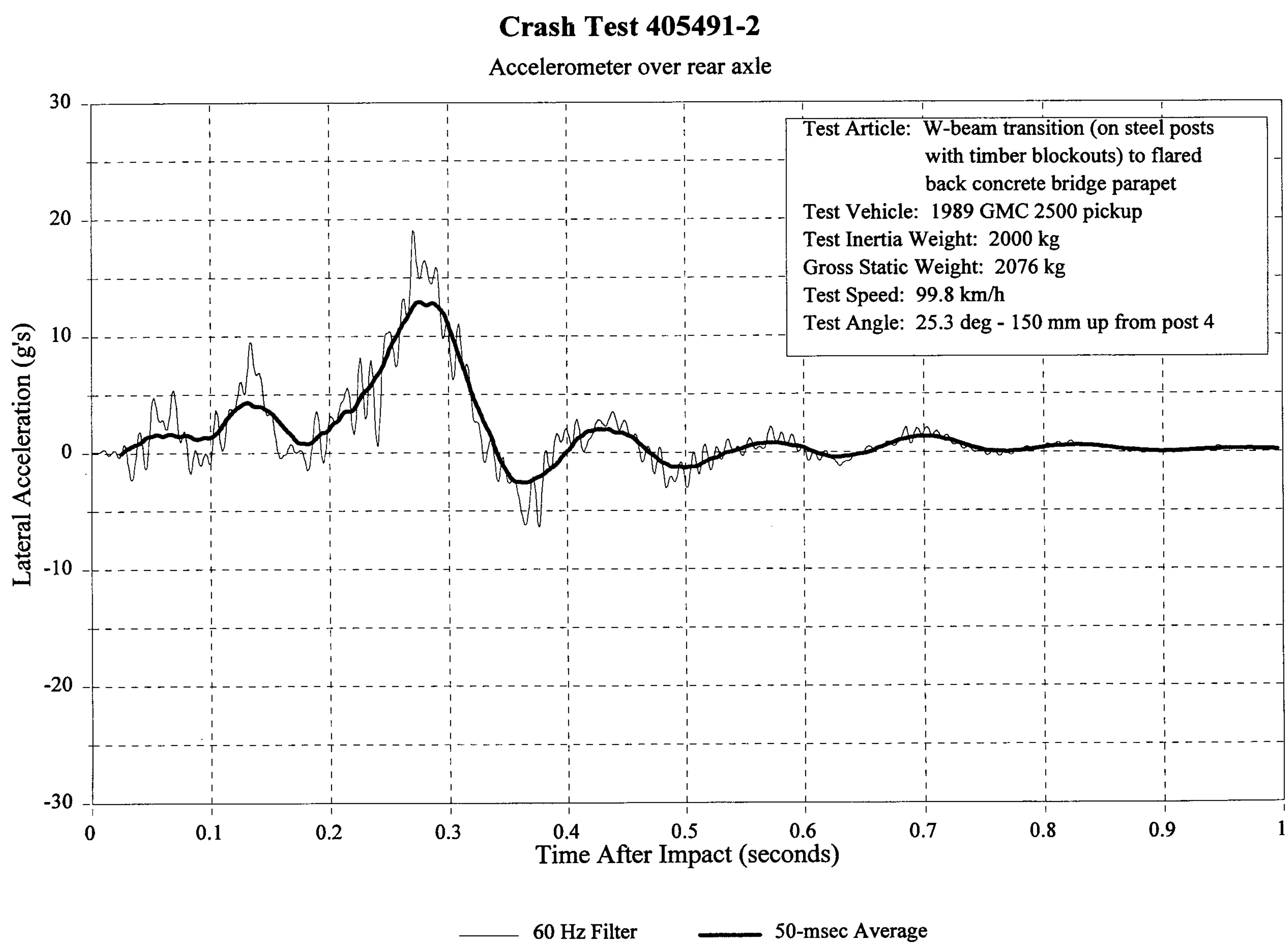


Figure 21. Vehicle lateral accelerometer traces for test 405491-2 (accelerometer located over rear axle).

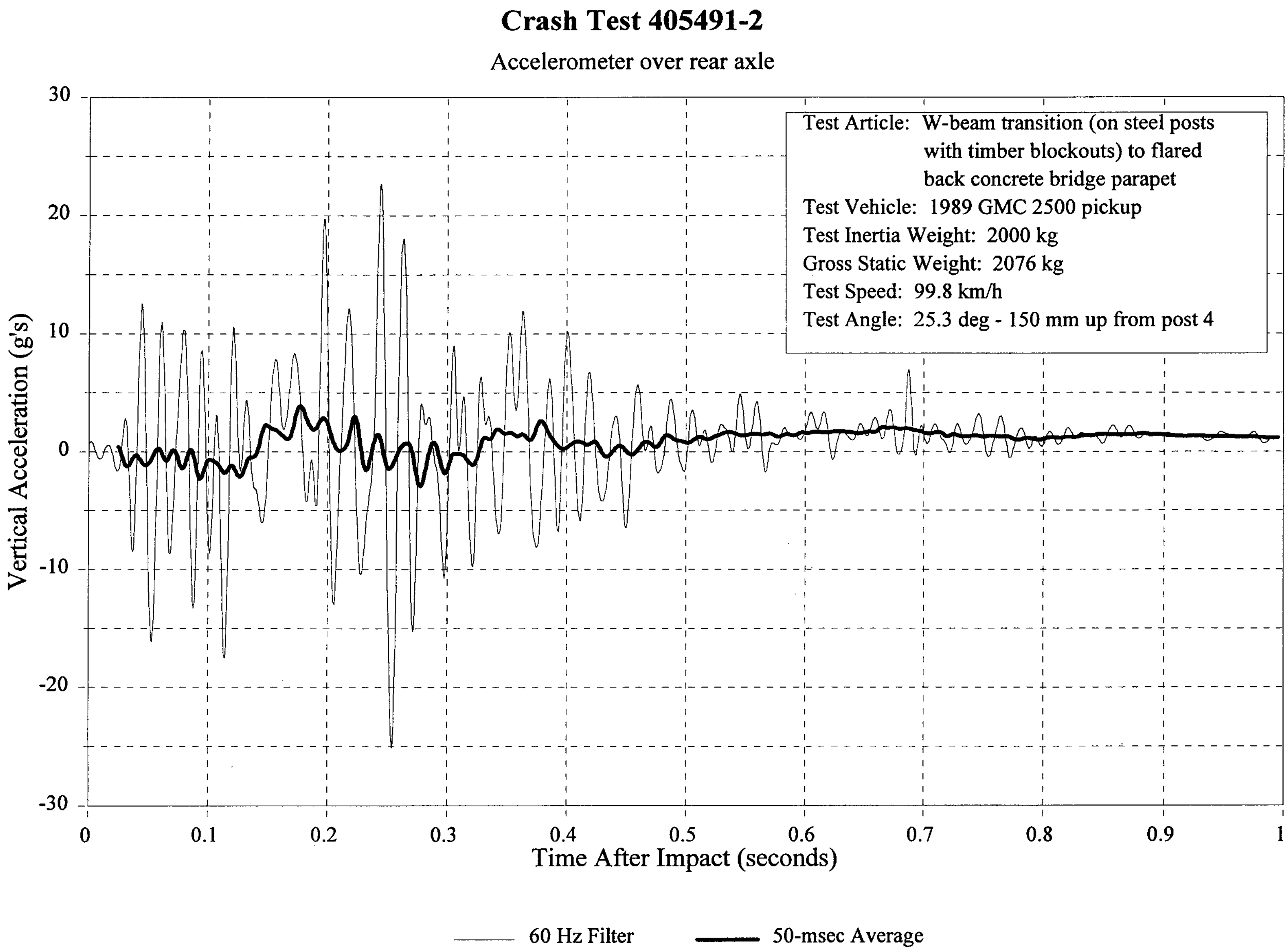


Figure 22. Vehicle vertical accelerometer trace for test 405491-2 (accelerometer located over rear axle).

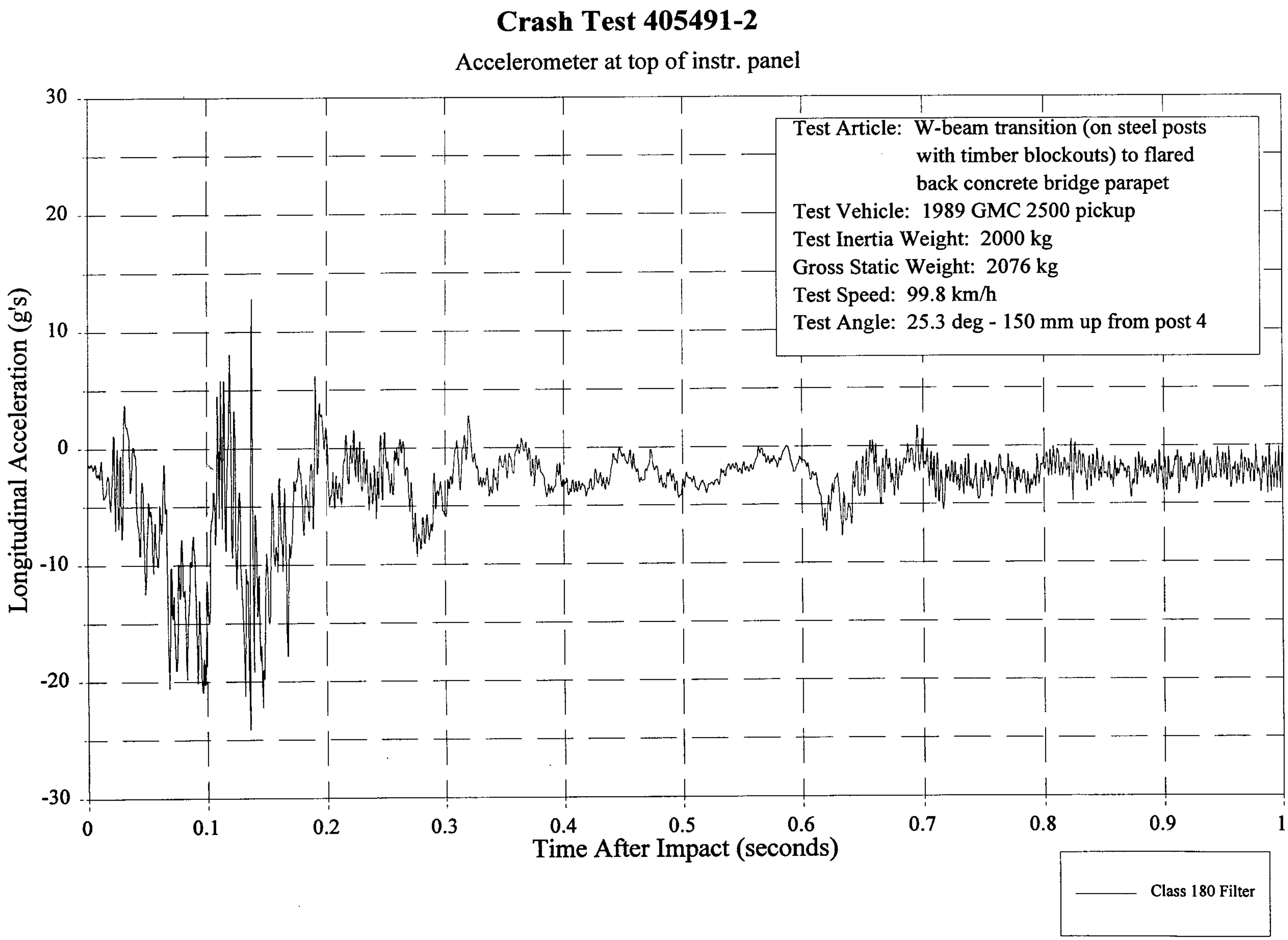


Figure 23. Vehicle longitudinal accelerometer trace for test 405491-2 (accelerometer located on instrument panel).

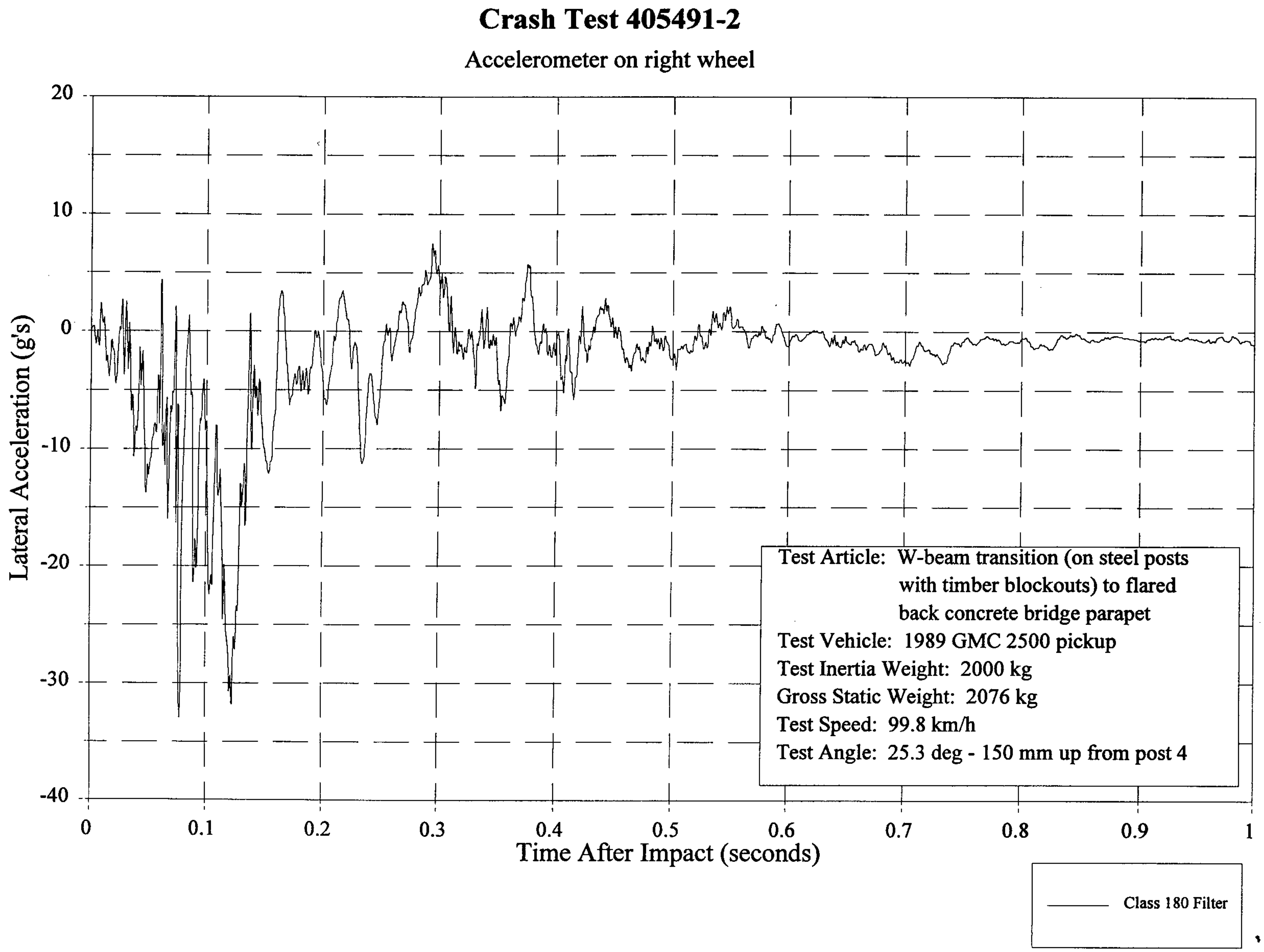


Figure 24. Vehicle lateral accelerometer trace for test 405491-2 (accelerometer located on right wheel).

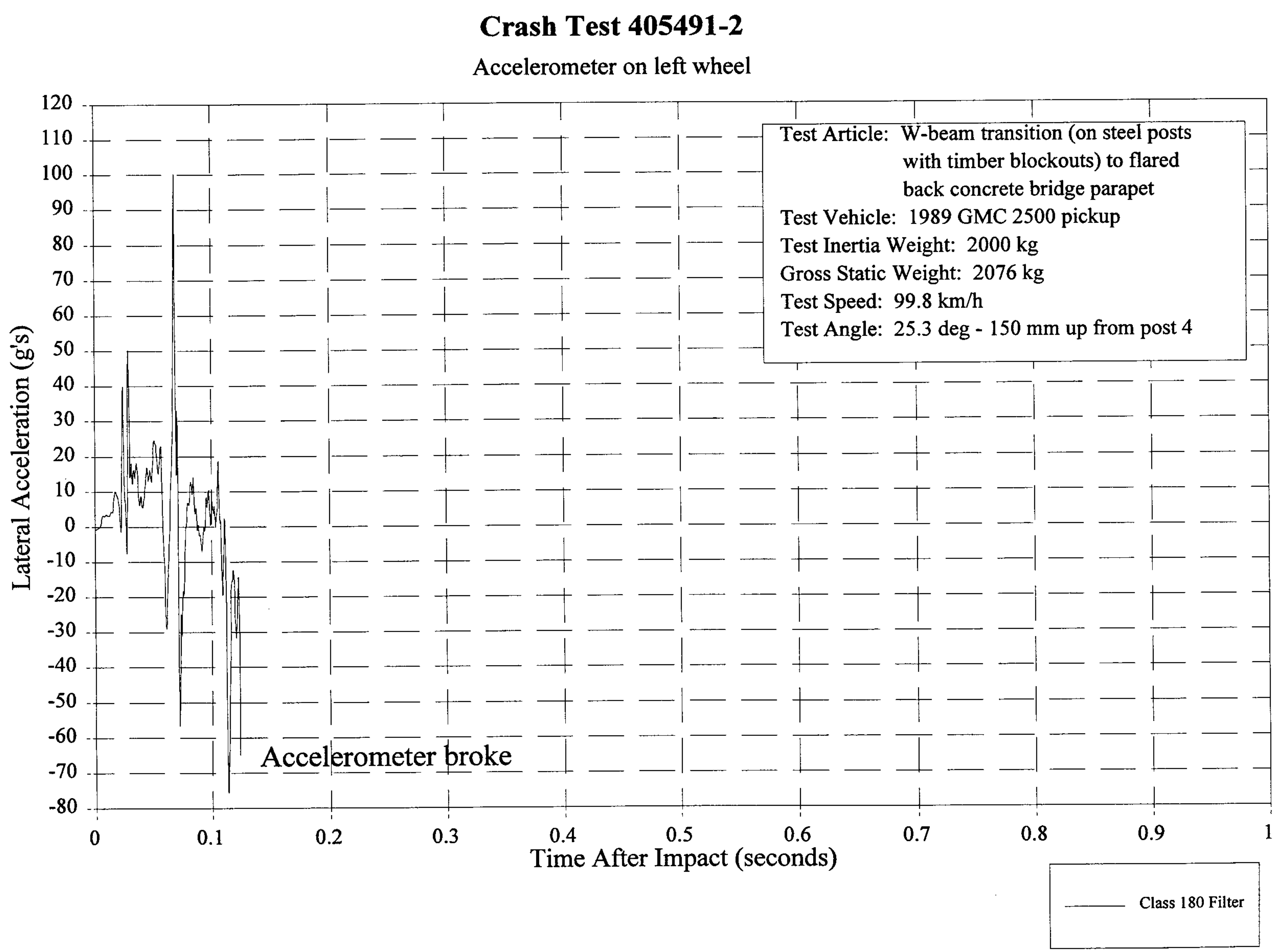


Figure 25. Vehicle lateral accelerometer trace for test 405491-2 (accelerometer on left wheel).

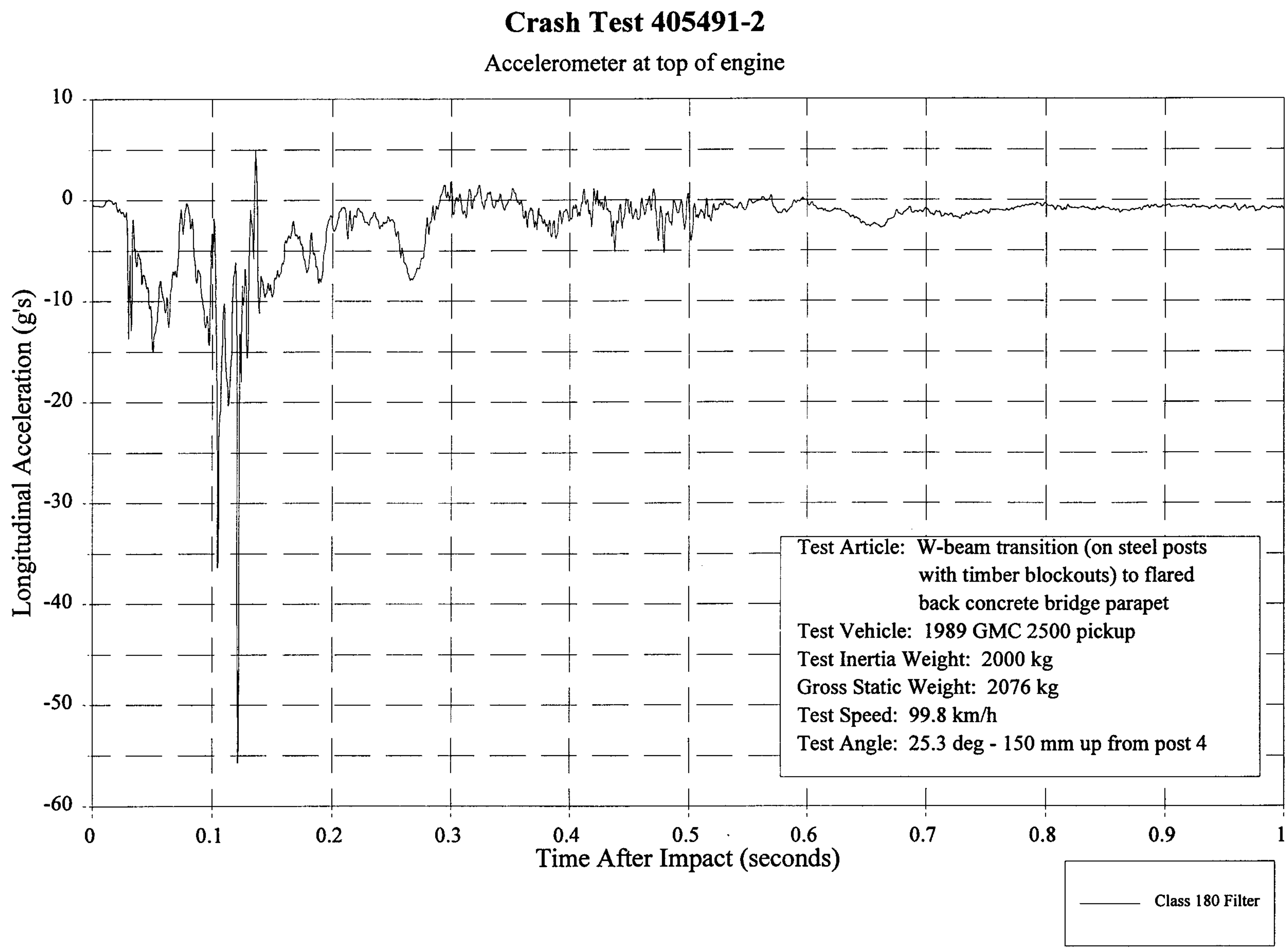


Figure 26. Vehicle longitudinal accelerometer trace for test 405491-2 (accelerometer located on top of engine block).

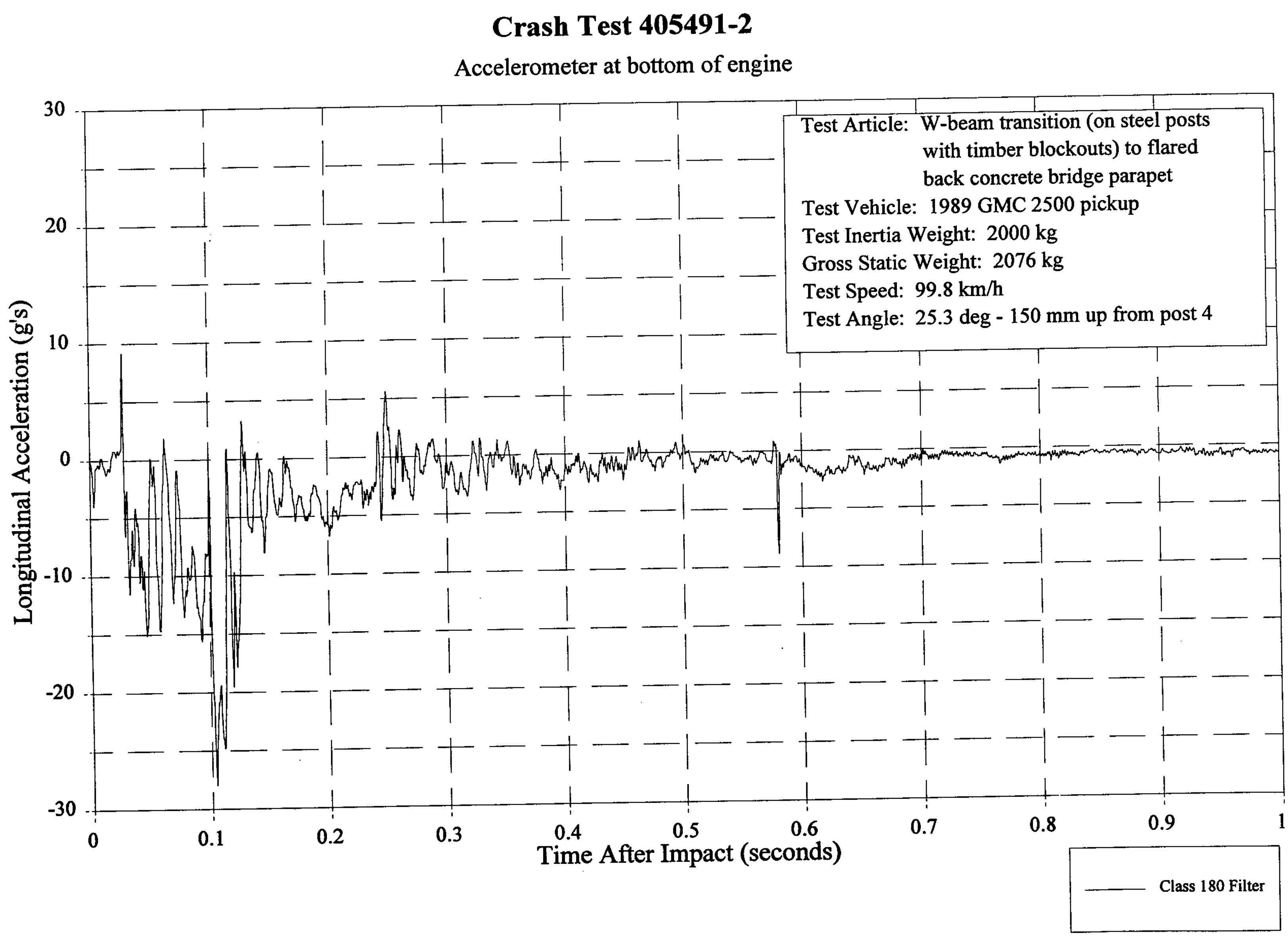


Figure 27. Vehicle longitudinal accelerometer trace for test 405491-2 (accelerometer located on bottom of engine block).

IV. SUMMARY OF FINDINGS AND CONCLUSIONS

4.1 SUMMARY OF FINDINGS

The W-beam transition (on steel posts with timber blockouts) to the vertical flared back concrete bridge parapet contained and redirected the vehicle through controlled lateral deflection. The vehicle did not penetrate or go over nor under the transition. However, there was some snagging of the vehicle as it impacted the end of the concrete parapet wall. There were no detached elements or debris to show potential for penetrating the occupant compartment or to present undue hazard to others in the area. Occupant deformations from the initial impact were moderate and may not have caused serious injury. However, deformations which occurred from the rollover after the vehicle exited the installation may have caused serious injury. The vehicle remained upright during the collision and then rolled 360 degrees upon exiting the test installation. The vehicle yawed and then rolled into the adjacent traffic lanes. The occupant risk factors were within the limits specified in NCHRP 350. The exit angle at loss of contact was 18.5 degrees, which was greater than 60 percent of the test impact angle.

4.2 CONCLUSIONS

In summary, the modified W-beam transition (on steel posts with timber blockouts) to the vertical flared back concrete bridge parapet did not meet the evaluation criteria set forth in NCHRP Report 350 for test designation 3-21, as shown in table 2.

Table 2. Performance evaluation summary for test 405491-2, NCHRP Report 350 test 3-21.

Test Agency: Texas Transportation Institute | Test No.: 405491-2 | Test Date: 02/22/96

NCHRP Report 350 Evaluation Criteria	Test Results	Assessment
Structural Adequacy		
A. Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	The W-beam transition contained and redirected the vehicle through controlled lateral deflection. There was some snagging of the vehicle as it impacted the end of the concrete parapet wall.	Pass
Occupant Risk		
D. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment that could cause serious injuries should not be permitted.	There were no detached elements or debris to show potential for penetrating the occupant compartment or to present undue hazard to others in the area. Occupant deformations from the initial impact were minimal; however, deformations from the rollover may have caused serious injury.	Fail
F. The vehicle should remain upright during and after collision although moderate roll, pitching and yawing are acceptable.	The vehicle remained upright during the collision; however, the vehicle rolled upon exiting the test installation.	Fail
Vehicle Trajectory		
K. After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	The vehicle yawed and then rolled into the adjacent traffic lanes.	Fail
L. The occupant impact velocity in the longitudinal direction should not exceed 12 m/s and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 G's.	Longitudinal occupant impact velocity was 9.3 m/s. Longitudinal occupant ridedown acceleration was 17.6 g.	Pass
M The exit angle from the test article preferably should be less than 60 percent of test impact angle, measured at time of vehicle loss of contact with test device.	The exit angle at loss of contact was 18.5 degrees which was greater than 60 percent of the test impact angle.	Fail'

U.S. DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

SUBJECT	FHWA TECHNICAL ADVISORY
GUARDRAIL TRANSITIONS	T 5040.26 January 28, 1988

1. **PURPOSE.** To transmit information pertaining to the design and installation of the transition from an approach W-beam or thrie beam guardrail system to concrete bridge rail, wingwall or parapet, or other concrete barrier or rigid wall.

2. **BACKGROUND**

   a. Nationwide, most bridge guardrail transitions consist of a semi-rigid W-beam connecting to a rigid bridge rail. (Field reviews show that the concrete safety shape bridge rail is the most common bridge rail being constructed.) These transitions vary in detail with the most common generally conforming to the design principles contained in the 1977 American Association of State Highway and Transportation Officials' "Guide for Selecting, Locating and Designing Traffic Barriers" (Barrier Guide).

   b. Some of these guardrail transitions have been recently crash tested in accordance with the guidelines in "National Cooperative Highway Research Program (NCHRP) Report 230." The initial test results were unsatisfactory, marginal or inconclusive. Further tests of improved designs were satisfactory. Common elements of the failed systems included the following:

      (1) A vertical concrete face or the toe of a concrete safety shape barrier which came in contact with the vehicle wheel resulted in snagging.

      (2) Inadequate guardrail stiffening (such as standard guardrail posts at 3 foot, 1½-inch spacing) resulted in substantial deflection of guardrail and subsequent snagging or poor redirection of the vehicle.

3. **OBJECTIVE.** To provide information which will help identify existing substandard guardrail transition designs and to describe new and updated transition systems which have been successfully crash tested and are acceptable for both retrofit and new construction.

DISTRIBUTION: Headquarters
Special: Regions
Divisions

OPI: HHS-10
HNG-10

4. SUMMARY

a. Almost all existing W-beam guardrail systems that connect directly to a bridge rail without adequate blockouts or a rubrail near the bridge connection should be considered unsatisfactory because they can result in vehicle snagging, which in turn can contribute to a catastrophic accident. Not only are these hazardous transitions between the guardrail and bridge rail common, but many State standards still detail the transition without adequate blockouts, rubrail, or other features.

b. Crash tests have demonstrated that a stiffer guardrail transition to the bridge rail is necessary. Stiffer transitions can be accomplished through reduced post spacing, larger posts, doubled (nested) rail elements and other special features. Both new and retrofitted transitions have been tested and several have proven satisfactory. Examples of crashworthy designs are shown in Figures 1A, 1B, 2, 3A, 3B, 4 and 5.

c. Crash testing of additional guardrail transitions is planned over the next several years. It is anticipated that additional transition designs will become available throughout this period.

5. RECOMMENDATIONS

a. Standard drawings and plan sheets should be reviewed for adequacy and upgraded or replaced, as needed, to prevent future construction of known transition deficiencies.

b. All the transitions presented in this Technical Advisory are guardrail attachments to vertical or nearly vertical concrete barrier ends. Successful crash tests of guardrail transitions connected directly to the concrete safety shape barrier have not been conducted. Consequently, the transitions included in this Technical Advisory should not be connected directly to a concrete safety shape barrier. To use the transitions tested to date, the concrete safety shape barrier must be transitioned to a vertical or flared back vertical wall. Transitioning from the concrete safety shape barrier to a vertical wall should not be abrupt. A 10-foot transition (as shown in Figure 3C) is recommended.

c. Most of the crashworthy transitions discussed in this Technical Advisory require that special attention be given to designing drainage features consistent with the transition selected. Coordination will be required among those responsible for bridge rail, guardrail and drainage design. For example, the use of more closely spaced posts, as recommended, may require that special attention be given to drainage inlet and pipe locations.

d. Many of the existing transitions previously reviewed are substandard as compared to the treatments recommended in this Technical Advisory. Consideration should be given to replacing or upgrading these existing transitions as the opportunity becomes available.

e. New transition designs, modifications to existing designs or untested existing designs should be verified as crashworthy by testing in accordance with NCHRP Report 230 before implementation in the field.

6. RELATED TECHNICAL INFORMATION

a. The following bridge guardrail transitions have been successfully crash tested under the required conditions for a passenger car (4,500-pound car at 60 mph and 25 degrees).

(1) **W-Beam Guardrail Transitions.** Three W-beam transitions were crash tested with satisfactory results.

(a) **Vertical Concrete Bridge Rail End (Figures 1A and 1B).** An older design similar to that shown in Figure 1A, except lacking the rubrail, the double section of W-beam on the top rail, and extra posts, was crash tested with catastrophic results. The retrofit designs shown in Figures 1A and 1B were tested and produced satisfactory results. The critical features of these transitions include:

1 Use of a rubrail.

2 Use of a double section of W-beam (one W-beam nested inside the other) on the top rail near the guardrail to bridge rail connection.

3 Additional posts.

4 Construction of a vertical face bridge rail end at the guardrail connection.

(b) **Vertical Curved Back Concrete Bridge Rail End (Figure 2)** Bridge rails or bridge parapets that terminate by curving or flaring back are also relatively common. The bridge guardrail transition shown in Figure 2 was tested and proven satisfactory.

1 The critical features of this transition include:

a Use of a rubrail.

b Additional posts.

c Construction of a vertical face bridge rail end flared or curved back at the guardrail connection.

2 These additional features reduce possible snag points and gradually increase the strength and stiffness of the guardrail as it approaches the bridge rail end, thus reducing vehicle snagging and improving redirection characteristics.

(c) **Vertical Flared Back Concrete Bridge Parapet (Figures 3A and 3B)**. The bridge guardrail transitions shown in Figures 3A and 3B provide another method of connecting guardrail to a vertical bridge parapet. The blocked out W-beam guardrail transitions shown in Figure 3A and 3B include the following critical features:

1 Additional posts.

2 Use of a double section of W-beam (one W-beam nested inside the other) on the top rail near the guardrail to bridge rail connection.

3 Flared back parapet wall as detailed in Figure 3C.

4 Use of a steel pipe section as a crushable block to absorb energy and facilitate redirection of the vehicle. (A wood block was found to be undesirable in this transition because it was too rigid.)

(2) <u>Thrie Beam Guardrail Transitions</u>. Two thrie beam transitions were crash tested with excellent results. Each system smoothly redirected the vehicle.

(a) <u>Vertical Tapered Concrete Bridge Rail End (Figure 4)</u>. This transition provides a large open space between the bridge rail end and the first post which is suitable for a drainage structure. The following features are critical:

1 Larger posts are used to compensate for the loss of strength from not using closer spaced standard wood posts.

2 Use of a double section of thrie beam (one thrie beam nested inside the other) near the guardrail to bridge rail connection.

3 Tapered parapet wall.

(b) <u>Vertical Flared Back Concrete Bridge Rail End (Figure 5)</u> This transition includes the following critical features:

1 Additional posts.

2 Use of a double section of thrie beam (one thrie beam nested inside the other) near the guardrail to bridge rail connection.

3 Use of a steel pipe section as a crushable block to absorb energy and facilitate redirection.

4 Flared back parapet wall as detailed in Figure 3C.

b. The following general features are also important in the performance of the guardrail transition to the bridge rail or parapet end.

(1) Adequate grading is essential to good safety performance. It is recommended the area in front of all guardrail sections and especially the area at guardrail transition to the bridge rail end be relatively flat and clear.

(a) The roadway cross section slope in front of the guardrail transition should be 10:1 or flatter.

(b) Curbs, raised drop inlets, depressed inlets or any other features that can trip a vehicle or initiate instability should be avoided in this area. Flush drop inlets are recommended. Inlets should be constructed to minimize conflicts with the post spacing and the subsurface drainage system.

(2) Adequate strength of the concrete bridge rail or parapet terminal to which the guardrail is connected is essential. This will ensure that upon impact the concrete section does not dislocate or rotate.

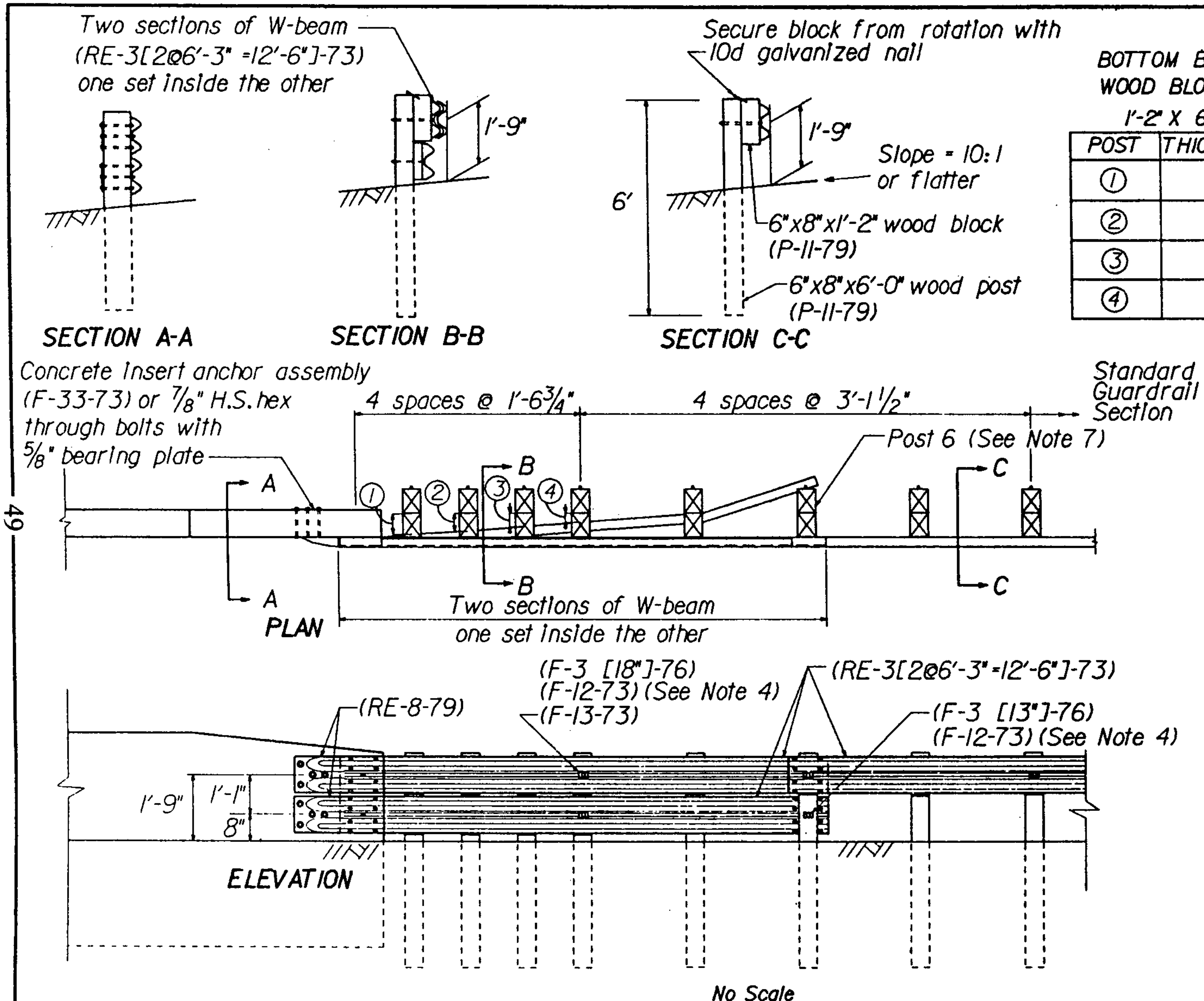
(3) Proper anchorage of the guardrail to the concrete bridge rail or parapet terminal is essential. Use of a cast-in-place anchor insert or a through bolt connection is recommended.

c. The attached drawings, in a format suitable for use on the Intergraph CAD System, are available from the Federal Highway Administration, Office of Engineering, Geometric and Roadside Design Branch, HNG-14, 400 Seventh Street, SW., Washington, D.C. 20590.

Thomas O. Willett
Thomas O. Willett
Director, Office of Engineering

R. Clarke Bennett
R. Clarke Bennett
Director, Office of Highway Safety

Attachments



BOTTOM BEAM WOOD BLOCKS

1'-2" X 6"

POST	THICKNESS
1	7"
2	6"
3	4.5"
4	3"

NOTES :

1. This guardrail transition is appropriate for connection to a vertical concrete shape and should not be connected directly to a concrete safety shape. Concrete safety shape barriers should be transitioned to a vertical shape at the guardrail connection.

2. Bridge rail ends and bridge parapets must be of adequate strength to accept full impact loading.

3. Standard barrier hardware has been used to develop this guardrail transition. Designations provided in parenthesis relate to standard elements detailed in "A Guide to Standardized Highway Barrier Rail Hardware," 1979, AASHTO-AGC-ARTBA Joint Cooperative Committee.

4. Use of plate washers (F-12-73) is optional.

5. The rubrail may be shop bent in the last 3 feet to facilitate installation.

6. Bottom wood blocks, located on posts 1, 2, 3, and 4 are center drilled and secured with 5/8" carriage bolts (F-3[as required]-76).

7. Posts 1, 2, 3, 4, and 6 require an additional hole to attach lower blocks and/or lower beam.

REG	STATE	PROJECT	SHEET NO.	TOTAL SHEETS

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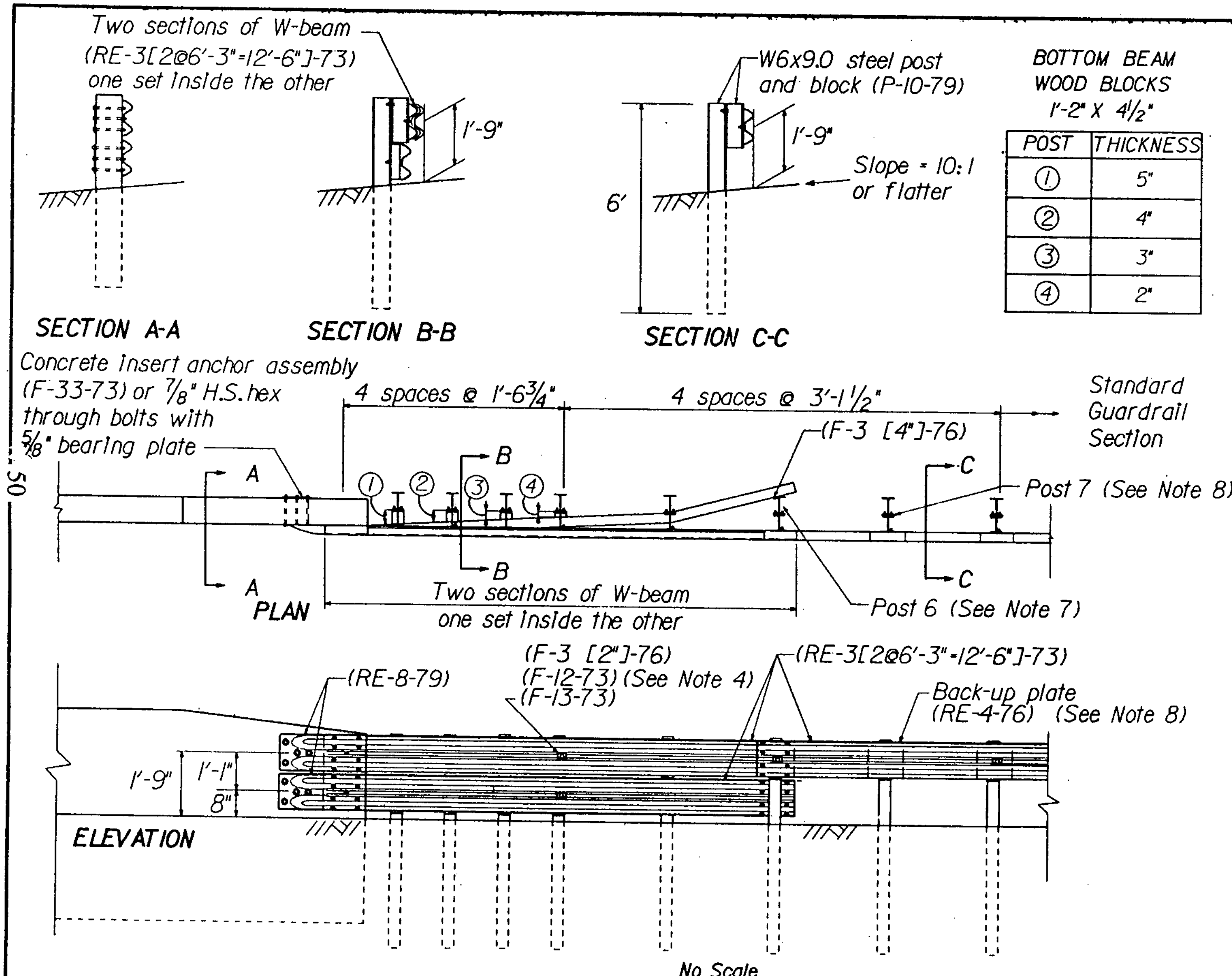
Figure 1A
VERTICAL CONCRETE BRIDGE RAIL END
W-BEAM WITH RUBRAIL WOOD POSTS
December 1987

REG	STATE	PROJECT	SHEET NO.	TOTAL SHEETS



BOTTOM BEAM WOOD BLOCKS
1'-2" X 4 1/2"

POST	THICKNESS
1	5"
2	4"
3	3"
4	2"

NOTES :

1. This guardrail transition is appropriate for connection to a vertical concrete shape and should not be connected directly to a concrete safety shape. Concrete safety shape barriers should be transitioned to a vertical shape at the guardrail connection.
2. Bridge rail ends and bridge parapets must be of adequate strength to accept full impact loading.
3. Standard barrier hardware has been used to develop this guardrail transition. Designations provided in parenthesis relate to standard elements detailed in "A Guide to Standardized Highway Barrier Rail Hardware, 1979, AASHTO-AGC-ARTBA Joint Cooperative Committee.
4. Use of plate washers (F-12-73) is optional.
5. Bottom beam blocks are offset drilled to sit squarely on the post flange. Blocks are attached with 5/8" carriage bolts (F-3[as required]-76).
6. The rubrail may be shop bent in the last 3 feet to facilitate installation.
7. Posts 1, 2, 3, 4, and 6 require an additional hole to attach lower blocks and/or lower beam.
8. At Post 7 back-up plate bolted to block only.

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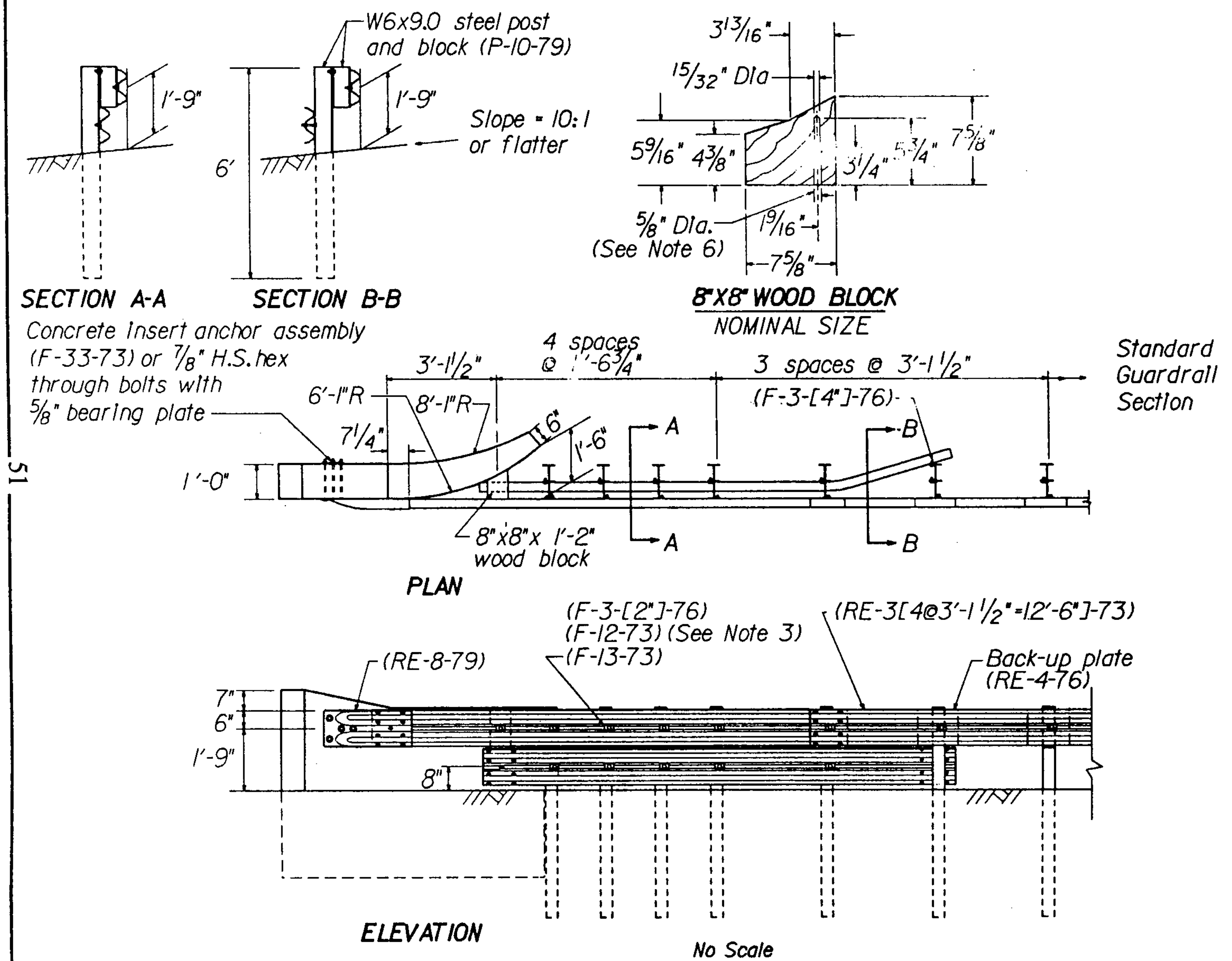
Figure 1B
VERTICAL CONCRETE BRIDGE RAIL END
W-BEAM WITH RUBRAIL STEEL POSTS
December 1987

REG	STATE	PROJECT	SHEET NO.	TOTAL SHEETS



NOTES :

1. This guardrail transition is appropriate for connection to a vertical curved back concrete wall and should not be connected directly to a concrete safety shape or vertical concrete wall. The appropriate vertical curved back concrete wall is detailed in North Carolina highway standard drawings.

2. Standard barrier hardware has been used to develop this guardrail transition. Designations provided in parenthesis relate to standard elements detailed in " A Guide to Standardized Highway Barrier Rail Hardware," 1979, AASHTO-AGC-ARTBA Joint Cooperative Committee.

3. Use of plate washers (F-12-73) is optional.

4. The rubrail is not connected to the vertical curved back concrete wall. The rubrail and the first top rail require special punching of holes for bolting to posts. Additionally, the rubrail may be shop bent in the last 3 feet to facilitate installation.

5. Posts 1 through 6 require an additional hole to mount the rubrail.

6. Wood Block shall be connected to the beam with a 5/8" x 6" long galvanized lag bolt.

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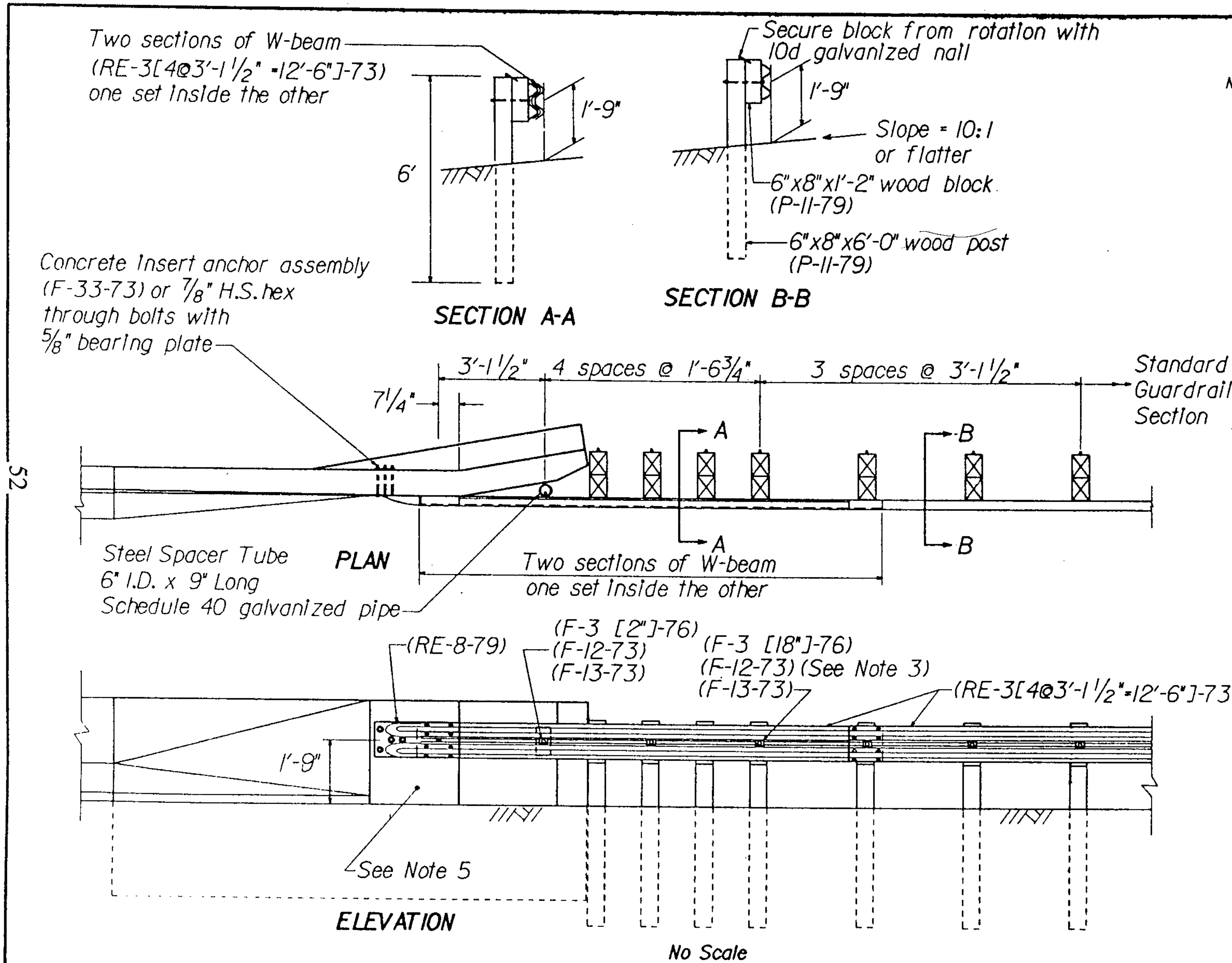
Figure 2
VERTICAL CURVED BACK CONCRETE BRIDGE RAIL END
W-BEAM WITH RUBRAIL
STEEL POSTS
December 1987



REG	STATE	PROJECT	SHEET NO.	TOTAL SHEETS

NOTES :

1. This guardrail transition is appropriate for connection to a vertical flared back concrete shape and should not be connected directly to a concrete safety shape. Concrete safety shape barriers should be transitioned to a vertical shape at the guardrail connection.
2. Standard barrier hardware has been used to develop this guardrail transition. Designations provided in parenthesis relate to standard elements detailed in "A Guide to Standardized Highway Barrier Rail Hardware," 1979, AASHTO-AGC-ARTBA Joint Cooperative Committee.
3. Use of plate washers (F-12-73) is optional.
4. The steel spacer tube is connected only to the guardrail beam. Block-outs made of wood and steel are not recommended as they proved too rigid in crash tests of this transition.
5. Details of the concrete shape transition are provided on figure 3C .

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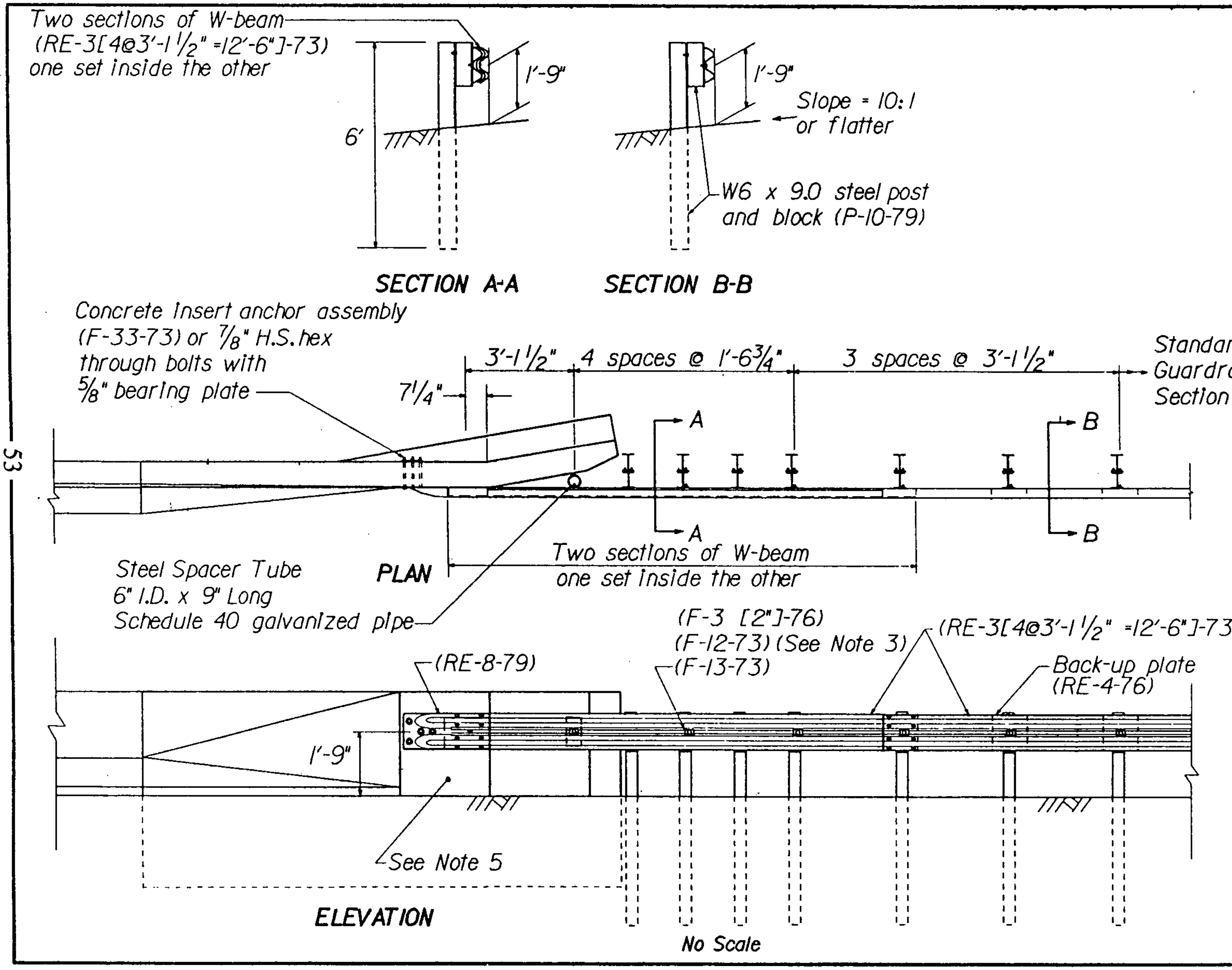
Figure 3A
VERTICAL FLARED BACK CONCRETE BRIDGE PARAPET
W-BEAM
WOOD POSTS
December 1987

REC	STATE	PROJECT	SHEET NO.	TOTAL SHEETS



NOTES :

1. This guardrail transition is appropriate for connection to a vertical flared back concrete shape and should not be connected directly to a concrete safety shape. Concrete safety shape barriers should be transitioned to a vertical shape at the guardrail connection.

2. Standard barrier hardware has been used to develop this guardrail transition. Designations provided in parenthesis relate to standard elements detailed in "A Guide to Standardized Highway Barrier Rail Hardware," 1979, AASHTO-AGC-ARTBA Joint Cooperative Committee.

3. Use of plate washers (F-12-73) is optional.

4. The steel spacer tube is connected only to the guardrail beam. Block-outs made of wood and steel are not recommended as they proved too rigid in crash tests of this transition.

5. Details of the concrete shape transition are provided on figure 3C .

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Figure 3B
VERTICAL FLARED BACK
CONCRETE BRIDGE PARAPET
W-BEAM
STEEL POSTS
December 1987

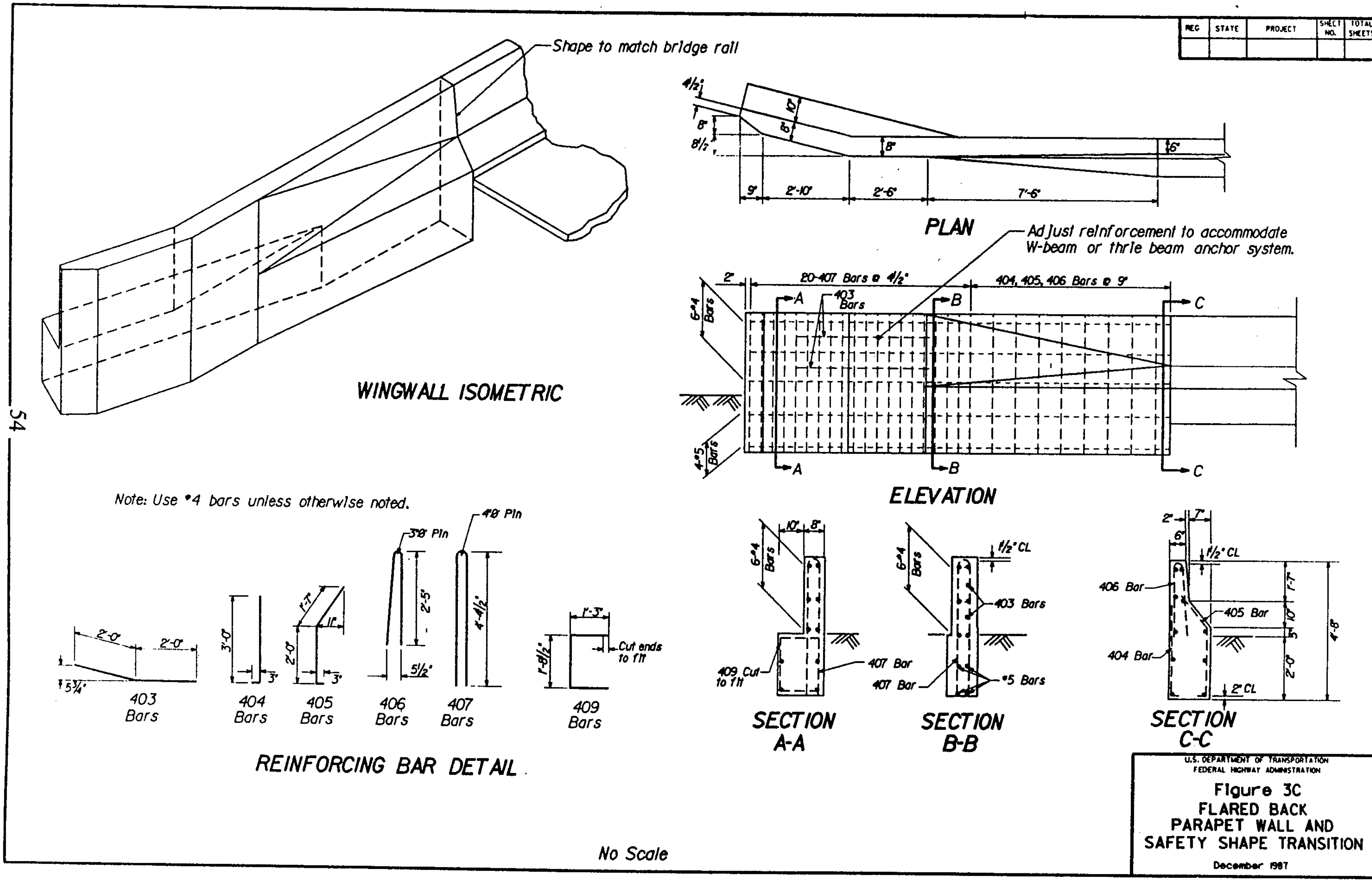
REG | STATE | PROJECT | SHEET NO. | TOTAL SHEETS
Shape to match bridge rail
WINGWALL ISOMETRIC
PLAN
4½"
8"
8½"
10"
6"
8"
6"
9"
2'-10"
2'-6"
7'-6"
Adjust reinforcement to accommodate W-beam or thrie beam anchor system.
2"
20-407 Bars @ 4½"
404, 405, 406 Bars @ 9"
403 Bars
6-#4 Bars
4-#5 Bars
A
B
C
ELEVATION
Note: Use #4 bars unless otherwise noted.
2'-0"
2'-0"
5¾"
403 Bars
3'-0"
3"
404 Bars
1'-7"
11"
2'-0"
3"
405 Bars
3⁄8" Pin
2'-5"
5½"
406 Bars
4⁄8" Pin
4'-4½"
407 Bars
1'-3"
1'-8½"
Cut ends to fit
409 Bars
REINFORCING BAR DETAIL
10"
8"
6-#4 Bars
409 Cut to fit
407 Bar
SECTION A-A
1½" CL
6-#4 Bars
403 Bars
407 Bar
#5 Bars
SECTION B-B
2"
7"
6"
1½" CL
406 Bar
405 Bar
404 Bar
1'-7"
10"
5"
2'-0"
4'-8"
2" CL
SECTION C-C
No Scale
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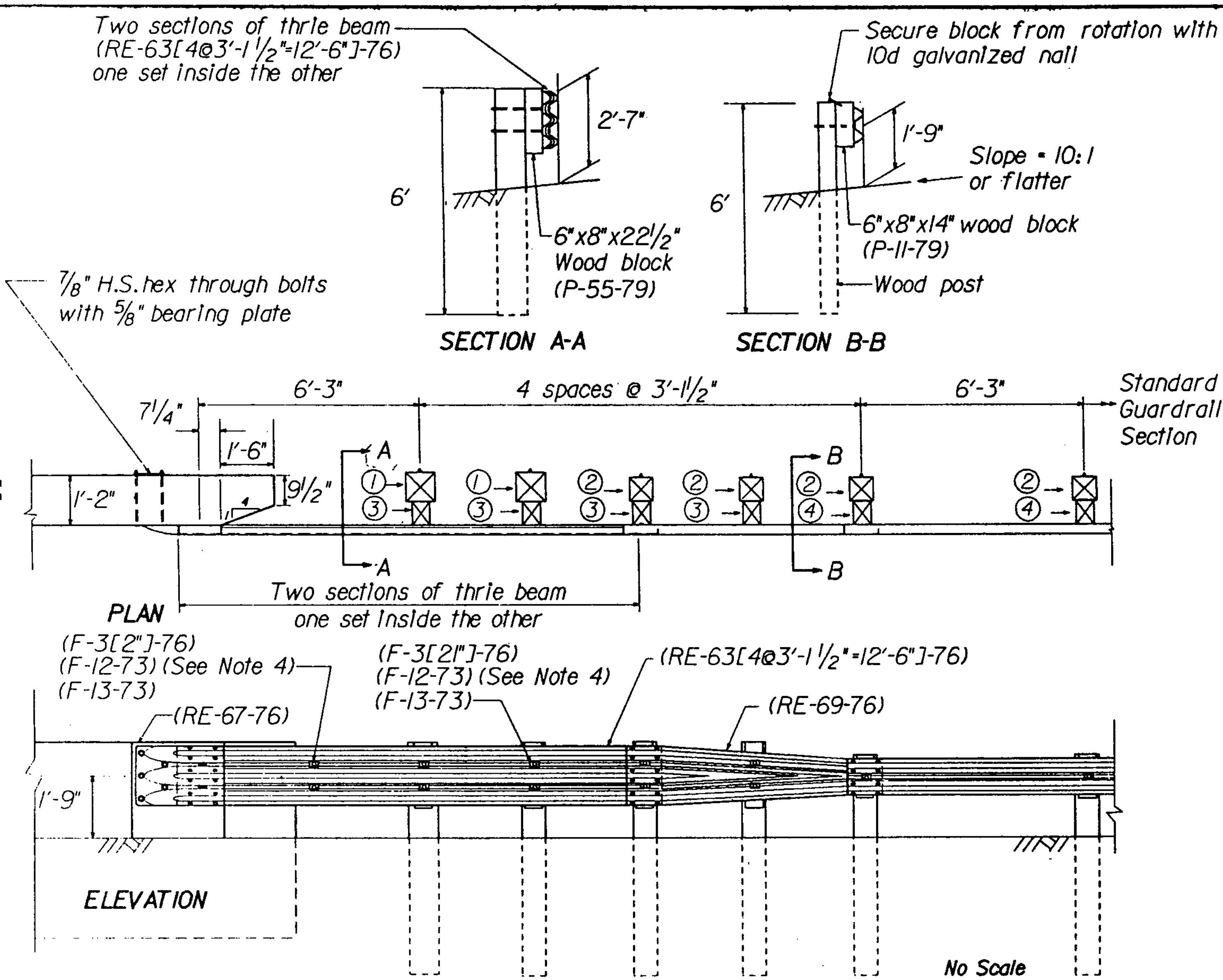
Figure 3C
FLARED BACK PARAPET WALL AND SAFETY SHAPE TRANSITION
December 1987

REG	STATE	PROJECT	SHEET NO.	TOTAL SHEETS



NOTES :

1. This guardrail transition is appropriate for connection to a flared back vertical concrete shape as shown.
2. Bridge rail ends and bridge parapets must be of adequate strength to accept full impact loading.
3. Standard barrier hardware has been used to develop this guardrail transition. Designations provided in parenthesis relate to standard elements detailed in "A Guide to Standardized Highway Barrier Rail Hardware," 1979, AASHTO-AGC-ARTBA Joint Cooperative Committee.
4. Use of plate washers (F-12-73) is optional.
5. Post and block are drilled in similar pattern as (P-11-79) and (P-55-79).

Post and block dimensions

1	10" X 10" X 6'
2	8" X 8" X 6'
3	6" X 8" X 22 1/2"
4	6" X 8" X 14"

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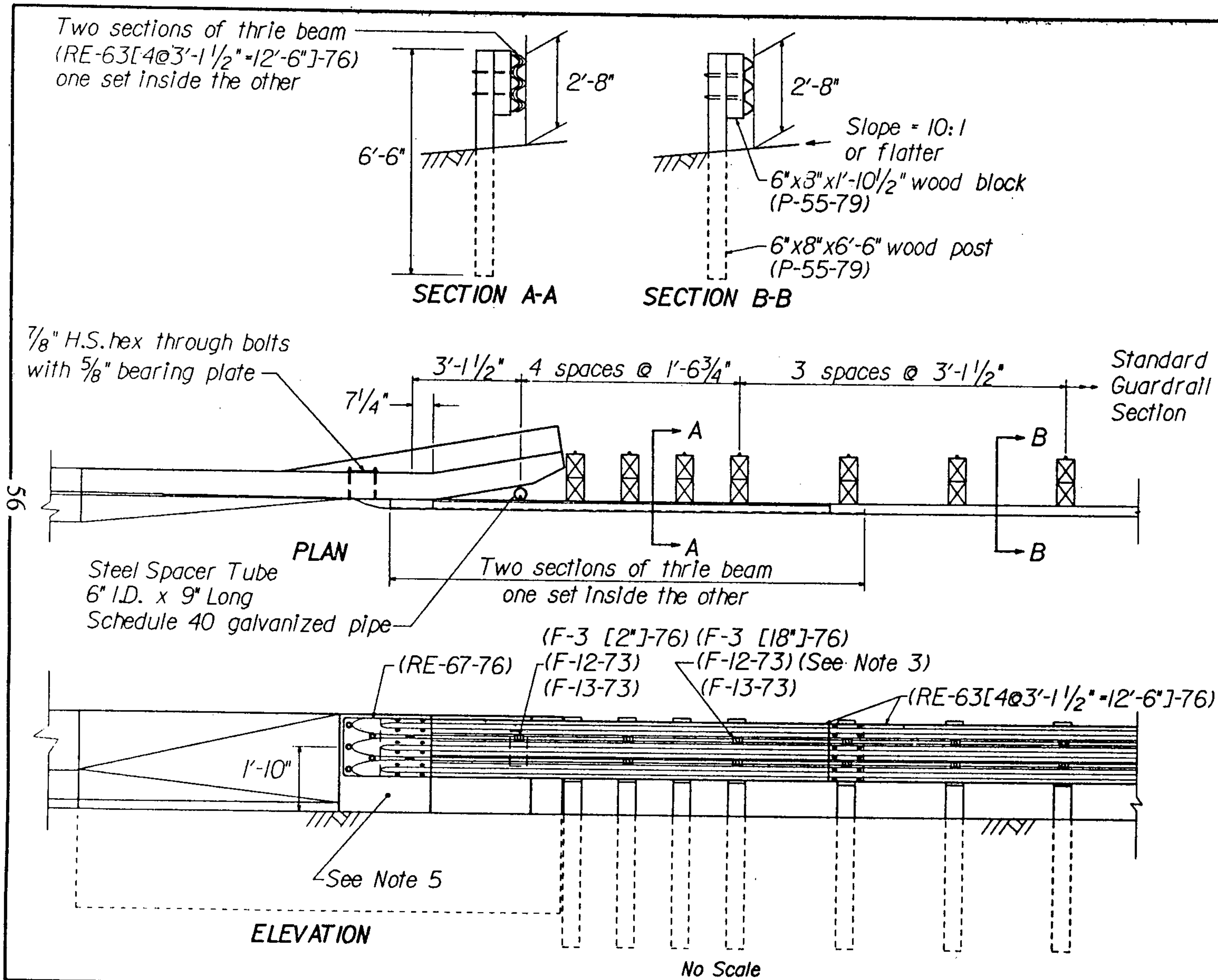
Figure 4
VERTICAL TAPERED CONCRETE BRIDGE RAIL END
THRIE BEAM WOOD POSTS
December 1987



REG	STATE	PROJECT	SHEET NO.	TOTAL SHEETS

NOTES :

1. This guardrail transition is appropriate for connection to a vertical flared back concrete shape and should not be connected directly to a concrete safety shape. Concrete safety shape barriers should be transitioned to a vertical shape at the guardrail connection.

2. Standard barrier hardware has been used to develop this guardrail transition. Designations provided in parenthesis relate to standard elements detailed in " A Guide to Standardized Highway Barrier Rail Hardware," 1979, AASHTO-AGC-ARTBA Joint Cooperative Committee.

3. Use of plate washers (F-12-73) is optional.

4. The steel spacer tube is connected only to the guardrail beam. Block-outs made of wood and steel are not recommended as they proved too rigid in crash tests of this transition.

5. Details of the concrete shape transition are provided on figure 3C .

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Figure 5
VERTICAL FLARED BACK CONCRETE BRIDGE RAIL END
THRIE BEAM
WOOD POSTS
December 1987

REFERENCES

1. H. E. Ross, Jr., D. L. Sicking, R. A. Zimmer, and J. D. Michie, "Recommended Procedures for the Safety Performance Evaluation of Highway Features," NCHRP Report 350, Transportation Research Board, Washington, DC, 1993.

2. J. D. Michie, "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances," NCHRP Report 230, Transportation Research Board, Washington, DC, 1980.

3. King K. Mak, Roger P. Bligh, and Wanda L. Menges, "Testing of State Roadside Safety Systems," (final report in progress), FHWA Contract DTFH61-89-C-00089, Research Study RF471470, Texas Transportation Institute and Federal Highway Administration, McLean, Virginia 1996.

4. D. Lance Bullard, Jr., Wanda L. Menges, and Dean C. Alberson, "NCHRP Report 350 Compliance Test 3-11 of the Modified G4(1S) Guardrail With Timber Blockouts," FHWA Contract DTFH61-95-C-00090, Research Study 405421-1, Texas Transportation Institute and Federal Highway Administration, McLean, Virginia January 1996.