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GUARDRAIL AND GUARDRAIL TERMINALS INSTALLED OVER CURBS - PHASE II

Submitted by

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16. Abstract (Limit: 200 words)

A barrier system was developed for installation where W-beam is placed over curbs. The guardrail design was constructed with two 2.66-mm (12-gauge) thick nested W-beam rails totaling 26.67 m in length. The nested W-beam rail was supported by fifteen W152x13.4 steel posts, each measuring 1,830-mm long. Post spacings were 1,905-mm on center. The concrete curb was a type "G" curb that measured 203 mm wide x 102 mm high x 19.05 m long.

The research study included full-scale vehicle crash testing, using a ¾-ton pickup truck. The full-scale test, impacting at a speed of 100.3 km/hr and an angle of 28.6 degrees, was conducted and reported in accordance with the requirements specified in NCHRP Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features*. The safety performance of the guardrail/curb combination barrier system was determined to be acceptable according to the Test Level 3 (TL-3) evaluation criteria specified in NCHRP Report No. 350.

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1 INTRODUCTION

1.1 Problem Statement

Guardrail and guardrail terminals are frequently installed over curbs. However, in recent years, the safety performance of these systems has been a concern for researchers and designers. Previous crash testing efforts with passenger-size sedans and pickup trucks on guardrails installed over curbs and dikes have been met with mixed results (1-4). While some guardrail/curb combinations have been successfully crash tested, other combinations have resulted in vehicles vaulting over the guardrail. These crash testing efforts were largely evaluated using passenger-size sedans according to the guidelines set forth in the National Cooperative Highway Research Program (NCHRP) Report No. 230, *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances* (5). However to date, only two pickup truck crash tests have been performed on guardrail/curb combinations and resulted in unsuccessful performances. One crash test was evaluated according to the criteria provided in the American Association of State Highway and Transportation Official's (AASHTO's) *Guide Specifications for Bridge Railings* (6) and the other according to the guidelines presented in NCHRP Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* (7). In addition, no crash testing efforts have been performed on guardrail terminals installed over curbs. Therefore, all guardrails and guardrail terminals installed over curbs must be crash tested and shown to meet current impact safety standards in order for its use to be continued on federal-aid highways.

1.2 Objective

The evaluation of the myriad of potential effects of curbs adjacent to longitudinal barriers is a significant undertaking. Therefore, the objective of this research study was to study the effects of curb placement adjacent to a W-beam longitudinal barrier when impacted by a ¾-ton pickup truck. A guardrail/curb combination was evaluated according to the Test Level 3 (TL-3) safety performance criteria provided in NCHRP Report No. 350. In an effort to reduce the scope of the research study, one standard-size curb geometry was selected for testing. For the research study, the member states of the pooled fund program chose an 102-mm high by 203-mm wide triangular-shape, mountable curb. An 102 mm rather than a 152-mm high curb was selected; since, it offered an increased potential for meeting the safety standards while also providing an acceptable level of hydraulic capacity.

1.3 Scope

The research objective was to be achieved by performing several tasks. First, a literature review was performed on existing guardrail/curb combinations. Second, the member states of the pooled fund program were polled to determine one standard-size curb geometry for use in the crash test program. Third, a full-scale vehicle crash test was performed using a ¾-ton pickup truck, weighing approximately 2,000 kg, with a target impact speed and angle of 100.0 km/hr and 25 degrees, respectively. Finally, the test results were analyzed, evaluated, and documented. Conclusions and recommendations were then made that pertain to the safety performance of the guardrail/curb combination.

2 LITERATURE REVIEW

In the past, it has been assumed that the performances of guardrail/curb combinations were acceptable as long as the front vertical face of the curb and the front face of the W-beam were in the same vertical plane. However, full-scale crash tests have shown that the combination of curb and guardrail may reduce the effectiveness of the guardrail system to contain and redirect the impacting vehicle (1-2). The effectiveness of containing and redirecting an impacting vehicle is affected by the interaction between the impacting side-wheel assembly and the guardrail element. In some cases, the impacting vehicle is partially restrained as the wheel's rim protrudes under the barrier. Previous testing has shown that curbs at the base of the posts have a significant effect on the ability of the guardrail to engage the vehicle. Further, curbs have been shown to lift the tires on the impact side of the barrier and cause higher vehicles, such as the pickup truck to ride over or vault over the barrier (1-2).

Previous testing under NCHRP Report No. 230 criteria as well as the AASHTO *Guide Specifications for Bridge Railings* conducted at ENSCO, Inc. has shown that curbs, with the front face placed in the same vertical plane as the front face of the W-beam, can still reduce the guardrail's performance. Under severe impact conditions, the semi-rigid guardrail can deflect enough to allow wheel contact with the curb and potential vaulting over or onto the guardrail (1-2). Previous testing under NCHRP Report No. 230 criteria as well as the AASHTO *Guide Specifications for Bridge Railings* conducted at the Midwest Roadside Safety Facility (MwRSF) has shown that curbs, with the front face placed in the same vertical plane as the front face of the W-beam, does not affect the guardrail's performance (3). These previous test results are summarized in Table 1.

Table 1. Previous Guardrail/Curb Combination Test Results

TEST PARAMETER	1862-1-88 [1]	1862-4-89 [1]	1862-5-89 [1]	1862-12-90 [1]	1862-13-91 [1]	1862-14-91 [1]	MO6C-1 [2]	NEC-1 [3]
Test Vehicle Type	1982 C20 Chevy Pickup	1982 Honda Civic	1980 Plymouth Gran Fury	1980 Chrysler Newport	1979 Chrysler Newport	1981 Plymouth Gran Fury	1985 Ford LTD	1991 GMC 2500 Pickup
Test Vehicle Gross Weight (kg)	2607	883	2100	2109	2124	2137	2043	1979
Impact Angle (deg)	20.0	20.0	25.0	25.0	26.0	25.0	25.1	24.5
Impact Speed (km/hr)	98.7	100.1	97.0	99.1	98.8	99.9	96.1	103.2
Installation Type	G4(1S)	G4(1S)	G4(1S)	G4(1S)	Stiffened G4(1S) with W-beam	G4(1S) with channel rubrail	G4(1S)	G4(1S)
Curb Type [4]	203-mm AASHTO IV-4A	152-mm AASHTO IV-4F	152-mm AASHTO IV-4F	102-mm AASHTO IV-4G	152-mm AASHTO IV-4F	152-mm AASHTO IV-4F	152-mm AASHTO IV-4A	203-mm AASHTO IV-4G
Curb Placement [5]	Front face of curb flush with front face of guardrail	Front face of dike flush with front face of guardrail	Front face of dike flush with front face of guardrail	Front face of curb 127-mm in front of front face of guardrail	Front face of dike flush with front face of guardrail	Front face of dike flush with front face of guardrail	Front face of curb flush with front face of guardrail	Front face of curb flush with front face of guardrail
Exit Angle (deg) and Speed (km/hr)	NA/NA	6.0/73.3	5.0/64.1	3.0/61.7	10.0/53.3	9.0/73.6	6.2/64.4	NA/NA
Long. OIV (m/s) and Ridedown Accel (g's)	5.05/2.9	7.07/2.4	6.73/4.7	6.54/5.4	8.18/9.2	5.83/4.0	5.77/3.2	NA/NA
Lateral OIV (m/s) and Ridedown Accel (g's)	3.16/5.5	7.35/12.5	5.33/9.8	4.59/10.0	5.67/8.8	5.24/9.4	4.90/8.5	NA/NA
Test Criteria	NCHRP 230	NCHRP 230	NCHRP 230	NCHRP 230	NCHRP 230	NCHRP 230	NCHRP 230	NCHRP 350
Test Results Conclusion	Failed due to vaulting	Meets all criteria	Vaulting occurred but criteria met	Meets all criteria	Meets all criteria	Meets all criteria	Meets all criteria	Failed due to system penetration

[1] ENSCO, Inc. (2)
[2] MwRSF (3)
[3] MwRSF (4)
[4] AASHTO (8)

[5] Part of curb that is detailed
NA - Not Available
OIV - Occupant Impact Velocity

Two tests performed by ENSCO, Inc., one with a pickup truck and one with a sedan, resulted in the vehicle vaulting over the guardrail. The 2,607-kg pickup truck, used in test no. 1862-1-88, vaulted over the guardrail with the front face in the same vertical plane as the front face of a 203-mm Type "A" concrete curb. For test no. 1862-5-89, the 2,100-kg sedan climbed on top of the guardrail used in conjunction with a 152-mm asphalt dike. The front of the dike was in the same vertical plane as the front face of the guardrail. In both tests, the guardrail deflected enough for the vehicle's wheels to impact the curb. The compression of the vehicle's suspension system produced upward forces on the vehicle, which in turn, caused the vehicle to vault over the guardrail (1-2). In test no. 1862-4-89, the guardrail flush with the front of a 152-mm asphalt dike successfully redirected the 883-kg small car. The small guardrail deflections did not allow the wheels to contact the curb (1-2).

ENSCO, Inc.'s test no. 1862-12-90 evaluated the effects of lowering the curb height to 102 mm. The guardrail over a 102-mm type "H" curb located with the front face of the curb 127-mm in front of the front face of the guardrail performed satisfactorily when impacted by a 2,109-kg sedan. Reducing the curb height was one solution to the prevention of vehicle vaulting; however, stiffening the guardrail to reduce the deflection produces a better performing system as seen in test nos. 1862-13-91 and 1862-14-91. In test no. 1862-13-91, the guardrail with the front face in the same vertical plane as the front of a 152-mm asphalt dike, which was stiffened by bolting an extra W-beam rail to the back of the steel posts, successfully redirected the 2,124-kg sedan. For test no. 1862-14-91, a channel rubrail was added to stiffen the guardrail which was used in combination with a 152-mm asphalt dike. The front of the dike was flush with the front face of the guardrail. During the crash test, the 2,137-kg sedan was successfully redirected, and in a more stable manner than observed in test no. 1862-12-90 where the curb height was reduced (1-2).

Previously, MwRSF also has conducted a test on a guardrail/curb combination system. The system consisted of a W-beam guardrail with its front face place in the same vertical plane as the front face of a 152-mm type "A" concrete curb. One crash test, test no. MO6C-1, was successfully performed on this system, resulting in the stable redirection of a 2,043-kg sedan (3).

In summary, previous sedan testing on guardrail/curb combinations have shown improvement in performance with the following modifications: (1) reducing the curb height from 152 to102 mm; (2) adding W-beam rail to the back side of the steel posts; and (3) adding a channel rubrail below the W-beam rail.

Recently, MwRSF completed the Phase I development effort for a guardrail/curb combination system (4). For this study, a 53.34-m long guardrail/curb combination was designed and unsuccessfully crash tested according to the NCHRP Report No. 350 criteria using a ¾-ton pickup truck which penetrated through the system. Following the analysis and redesign of the guardrail system, the system was retested. The results of this effort are reported herein.

3 TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1 Test Requirements

Longitudinal barriers, such as guardrails installed over curbs, must satisfy the safety performance criteria provided in NCHRP Report No. 350 to be accepted for use on new construction projects or as a replacement for existing designs not meeting current safety standards. According to TL-3 of NCHRP Report No. 350, guardrails over curbs must be subjected to two full-scale vehicle crash tests: (1) a 2,000-kg pickup truck impacting at a speed of 100.0 km/hr and at an angle of 25 degrees; and (2) an 820-kg small car impacting at a speed of 100.0 km/hr and at an angle of 20 degrees. However, W-beam guardrails perform satisfactorily when impacted by small cars, being essentially rigid (9-12), with no significant potential for occupant risk problems arising from vehicle pocketing or severe wheel snagging on the guardrail posts. Therefore, the 820-kg small car crash test was deemed unnecessary for this project.

3.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the barrier to contain, redirect, or allow controlled vehicle penetration in a predictable manner. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Vehicle trajectory after collision is a measure of the potential for the post-impact trajectory of the vehicle to cause subsequent multi-vehicle accidents. It is also an indicator for the potential safety hazard for the occupants of the other vehicles or the occupants of the impacting vehicle when subjected to secondary collisions with other fixed objects. These three evaluation criteria are defined in Table 2. The full-scale vehicle crash test was conducted and reported in accordance with the procedures provided in NCHRP Report No. 350.

Table 2. NCHRP Report No. 350 Evaluation Criteria for 2000P Pickup Truck Crash Test (7)

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. Deformations 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/sec 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 test impact angle, measured at time of vehicle loss of contact with test devise.

4 GUARDRAIL OVER CURB DESIGN

The total length of the test installation was 53.34 m long, as shown in Figure 1. Photographs of the test installation are shown in Figures 2 and 3. The test installation consisted of 26.67 m of nested 12-gauge W-beam rail supported by steel posts, standard 12-gauge W-beam guardrail supported by steel posts, an anchorage system replicating a Breakaway Cable Terminal (BCT) on both the upstream and downstream ends but installed tangent to the guardrail system and without the buffer head, and a concrete curb.

The entire system was constructed with twenty-nine guardrail posts. Post nos. 3 through 27 consisted of galvanized, ASTM A36 steel W152x13.4 sections measuring 1,830-mm long. Post nos. 1, 2, 28, and 29 were timber posts measuring 140-mm wide x 190-mm deep x 1,080-mm long and were placed in steel foundation tubes. The timber posts and foundation tubes were part of an anchor system, similar to a BCT but installed tangent to the system, used to develop the required tensile capacity of the guardrail. Lap-splice connections between the rail sections were configured to reduce vehicle snagging at the splice during the crash tests.

Post nos. 1 through 29 were spaced 1,905-mm on center. For post nos. 3 through 27, the soil embedment depth was 1,202 mm. In addition, 152-mm wide x 203-mm deep x 360-mm long routed wood spacer blockouts were used to block the rail away from post nos. 3 through 27.

Standard 2.66-mm (12-gauge) thick W-beam rail, measuring 11.43-m long, was placed between post nos. 1 and 7, as shown in Figure 1. Subsequently, two nested W-beam guardrails, measuring 2.66-mm thick, were used to span between post nos. 7 and 21 for a total nested length of 26.67m, as shown in Figure 1. This is in contrast to the system used for test no. NEC-1 previously tested with single standard 2.66-mm thick, W-beam rail spanning between post nos. 7 and 21 (4).

Standard 2.66-mm thick W-beam rail, measuring 15.24-m long, was placed between post nos. 21 and 29. Specific details regarding the lengths and positions of guardrail sections are provided in Figure 1. The mounting height of the W-beam rail was 706 mm, as measured from the gutterline to the top of the rail.

The concrete curb constructed underneath the W-beam guardrail was 19.05 m long, beginning at post no.19 to post no. 9, as shown in Figure 1. The curb was constructed so that the initial slope break-point of the curb and the front face of the guardrail were in the same vertical plane. The curb was a type "G" curb, sometimes referred to as a triangular-shape, wedge, or lip curb. The curb had an overall height and width of 102 mm and 203 mm, respectively. The details of the curb are shown in Figure 1.

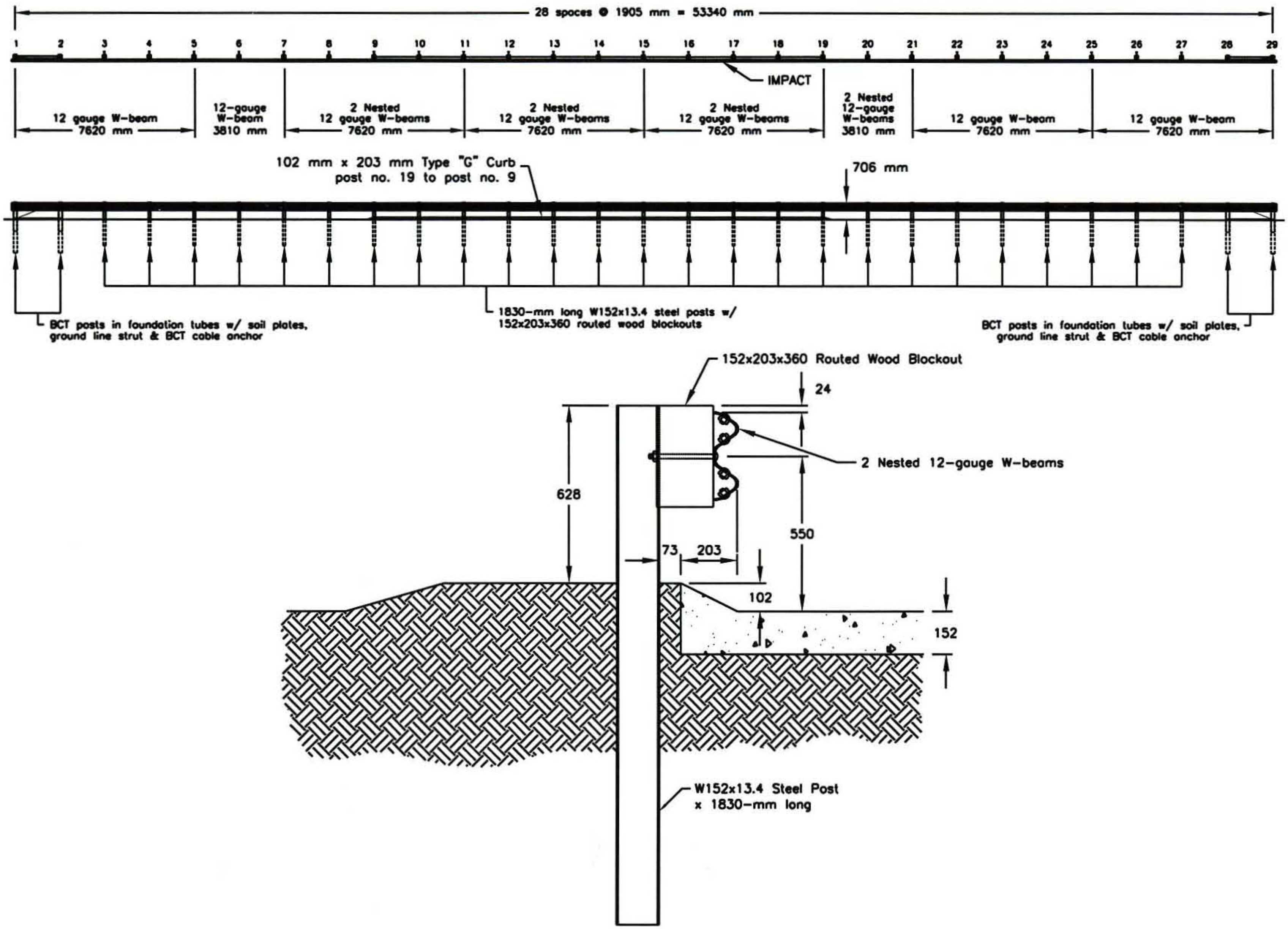


Figure 1. Test Installation Configuration

Figure 2. Guardrail Over Curb System

Figure 3. Post-to-Rail Attachment for the Guardrail Over Curb System

5 TEST CONDITIONS

5.1 Test Facility

The testing facility is located at the Lincoln Air-Park on the northwest (NW) end of the Lincoln Municipal Airport and is approximately 8.0 km NW of the University of Nebraska-Lincoln.

5.2 Vehicle Tow and Guidance System

A reverse cable tow system with a 1:2 mechanical advantage was used to propel the test vehicle. The distance traveled and the speed of the tow vehicle were one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the guardrail system. A digital speedometer in the tow vehicle was utilized to increase the accuracy of the test vehicle impact speed.

A vehicle guidance system developed by Hinch (13) was used to steer the test vehicle. A guide-flag, attached to the left-front wheel and the guide cable, was sheared off before impacting the guardrail. The 9.5-mm diameter guide cable was tensioned to approximately 13.3 kN, and supported by hinged stanchions in the lateral and vertical directions and spaced at 30.48 m initially and at 15.24 m toward the end of the guidance system. The hinged stanchions stood upright while holding up the guide cable, but as the vehicle was towed down the line, the guide-flag struck and knocked each stanchion to the ground. The vehicle guidance system was approximately 387.5-m long.

5.3 Test Vehicles

For test NEC-2, a 1994 GMC 2500 ¾-ton pickup truck was used as the test vehicle. The test inertial and gross static weights were 2,033 kg. The test vehicle is shown in Figure 4, and vehicle dimensions are shown in Figure 5.

The longitudinal component of the center of gravity was determined using the measured axle weights. The location of the final centers of gravity are shown in Figure 6.

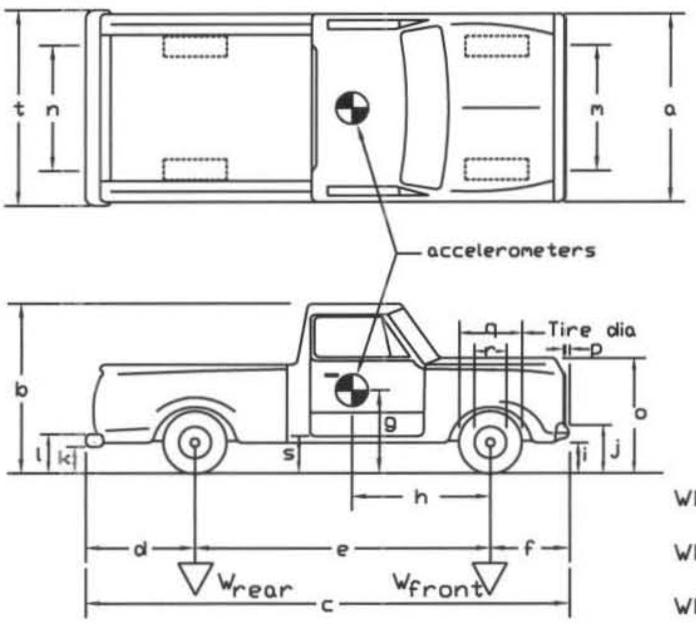
Figure 4. Test Vehicle, Test NEC-2

Date: 7/24/00 Test Number: NEC-2 Model: 2500

Make: GMC Vehicle I.D.#: 1GDGC24K9RE563346

Tire Size: LT245/75R16D Year: 1994 Odometer: 260998

*(All Measurements Refer to Impacting Side)



Vehicle Geometry - mm

a	1886	b	1829
c	5537	d	1302
e	3327	f	908
g	667	h	1392
i	457	j	667
k	603	l	781
m	1588	n	1622
o	1029	p	102
q	756	r	445
s	473	t	1842

Wheel Center Height Front 368

Wheel Center Height Rear 371

Wheel Well Clearance (FR) 892

Wheel Well Clearance (RR) 956

Engine Type V-8

Engine Size 350-5.7 L

Transmission Type:

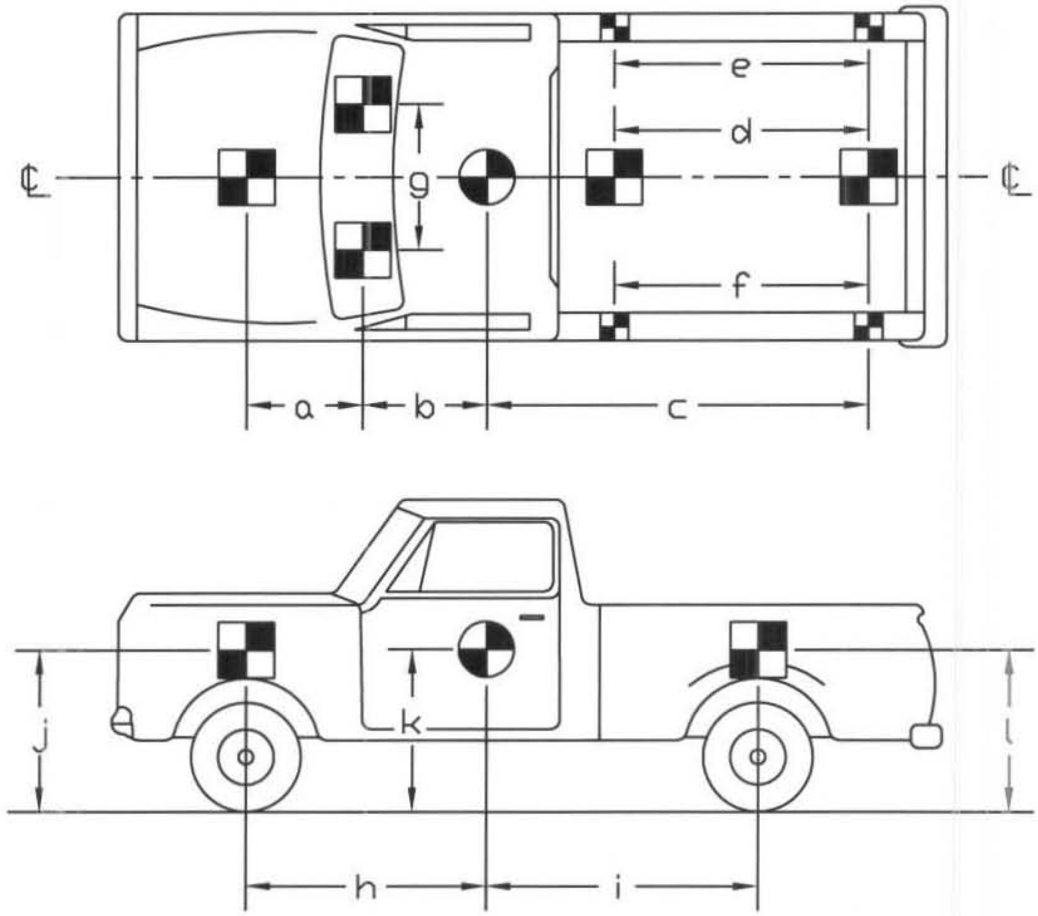
Automatic or (Manual)

FWD or (RWD) or 4WD

Weights - kg	Curb	Test Inertial	Gross Static
W_{front}	1170	1181	1181
W_{rear}	847	852	852
W_{total}	2017	2033	2033

Note any damage prior to test: few minor box dents

Figure 5. Vehicle Dimensions, Test NEC-2



TEST #: NEC-2

TARGET GEOMETRY (mm)

a	876	d	1791	g	1029	j	1003
b	749	e	2153	h	1392	k	667
c	2680	f	2153	i	1937	l	1060

Figure 6. Vehicle Target Locations, Test NEC-2

Square, black and white-checkered targets were placed on the vehicle to aid in the analysis of the high-speed film, as shown in Figure 6. Round, checkered targets were placed on the center of gravity on the driver's side door, the passenger's side door, and on the roof of the vehicle. The remaining targets were located for reference so that they could be viewed from the high-speed cameras for film analysis.

The front wheels of the test vehicle were aligned for camber, caster, and toe-in values of zero so that the vehicle would track properly along the guide cable. Two 5B flash bulbs were mounted on both the hood and roof of the vehicle to pinpoint the time of impact with the guardrail on the high-speed film. The flash bulbs were fired by a pressure tape switch mounted on the front face of the bumper. A remote controlled brake system was installed in the test vehicle so the vehicle could be brought safely to a stop after the test.

5.4 Data Acquisition Systems

5.4.1 Accelerometers

One triaxial piezoresistive accelerometer system with a range of ±200 G's was used to measure the acceleration in the longitudinal, lateral, and vertical directions at a sample rate of 10,000 Hz. The environmental shock and vibration sensor/recorder system, Model EDR-4M6, was developed by Instrumented Sensor Technology (IST) of Okemos, Michigan and includes three differential channels as well as three single-ended channels. The EDR-4 was configured with 6 Mb of RAM memory and a 1,500 Hz lowpass filter. Computer software, "DynaMax 1 (DM-1)" and "DADiSP" were used to analyze and plot the accelerometer data.

A backup triaxial piezoresistive accelerometer system with a range of ±200 G's was also used to measure the acceleration in the longitudinal, lateral, and vertical directions at a sample rate of

3,200 Hz. The environmental shock and vibration sensor/recorder system, Model EDR-3, was developed by Instrumented Sensor Technology (IST) of Okemos, Michigan. The EDR-3 was configured with 256 Kb of RAM memory and a 1,120 Hz lowpass filter. Computer software, "DynaMax 1 (DM-1)" and "DADiSP" were used to analyze and plot the accelerometer data.

5.4.2 Rate Transducer

A Humphrey 3-axis rate transducer with a range of 360 deg/sec in each of the three directions (pitch, roll, and yaw) was used to measure the rates of motion of the test vehicle. The rate transducer was rigidly attached to the vehicle near the center of gravity of the test vehicle. Rate transducer signals, excited by a 28 volt DC power source, were received through the three single-ended channels located externally on the EDR-4M6 and stored in the internal memory. The raw data measurements were then downloaded for analysis and plotted. Computer software, "DynaMax 1 (DM-1)" and "DADiSP" were used to analyze and plot the rate transducer data.

5.4.3 High-Speed Photography

For test NEC-2, five high-speed 16-mm Red Lake Locam cameras, with operating speeds of approximately 500 frames/sec, were used to film the crash test. A high-speed Red Lake E/cam digital video camera, with an operating speed 500 frames/sec, was used to film the crash test. A Locam, with a wide-angle 12.5-mm lens, was placed above the test installation to provide a field of view perpendicular to the ground. A Locam with a 76-mm lens, a SVHS video camera, and a 35-mm still camera were placed downstream from the impact point and had a field of view parallel to the barrier. A Locam and a SVHS video camera were placed on the traffic side of the barrier and had a field of view perpendicular to the barrier. A Locam and a SVHS video camera were placed downstream and behind the barrier. Another Locam was placed downstream and behind the barrier, but closer to the impact point. A Red Lake E/cam high-speed digital video camera was placed upstream and behind the barrier. A schematic of all ten camera locations for test NEC-2 is shown in Figure 7. The film was analyzed using the Vanguard Motion Analyzer. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed film.

5.4.4 Pressure Tape Switches

For test NEC-2, five pressure-activated tape switches, spaced at 2-m intervals, were used to determine the speed of the vehicle before impact. Each tape switch fired a strobe light which sent an electronic timing signal to the data acquisition system as the right-front tire of the test vehicle passed over it. Test vehicle speed was determined from electronic timing mark data recorded with "Test Point" software. Strobe lights and high-speed film analysis are used only as a backup in the event that vehicle speed cannot be determined from the electronic data.

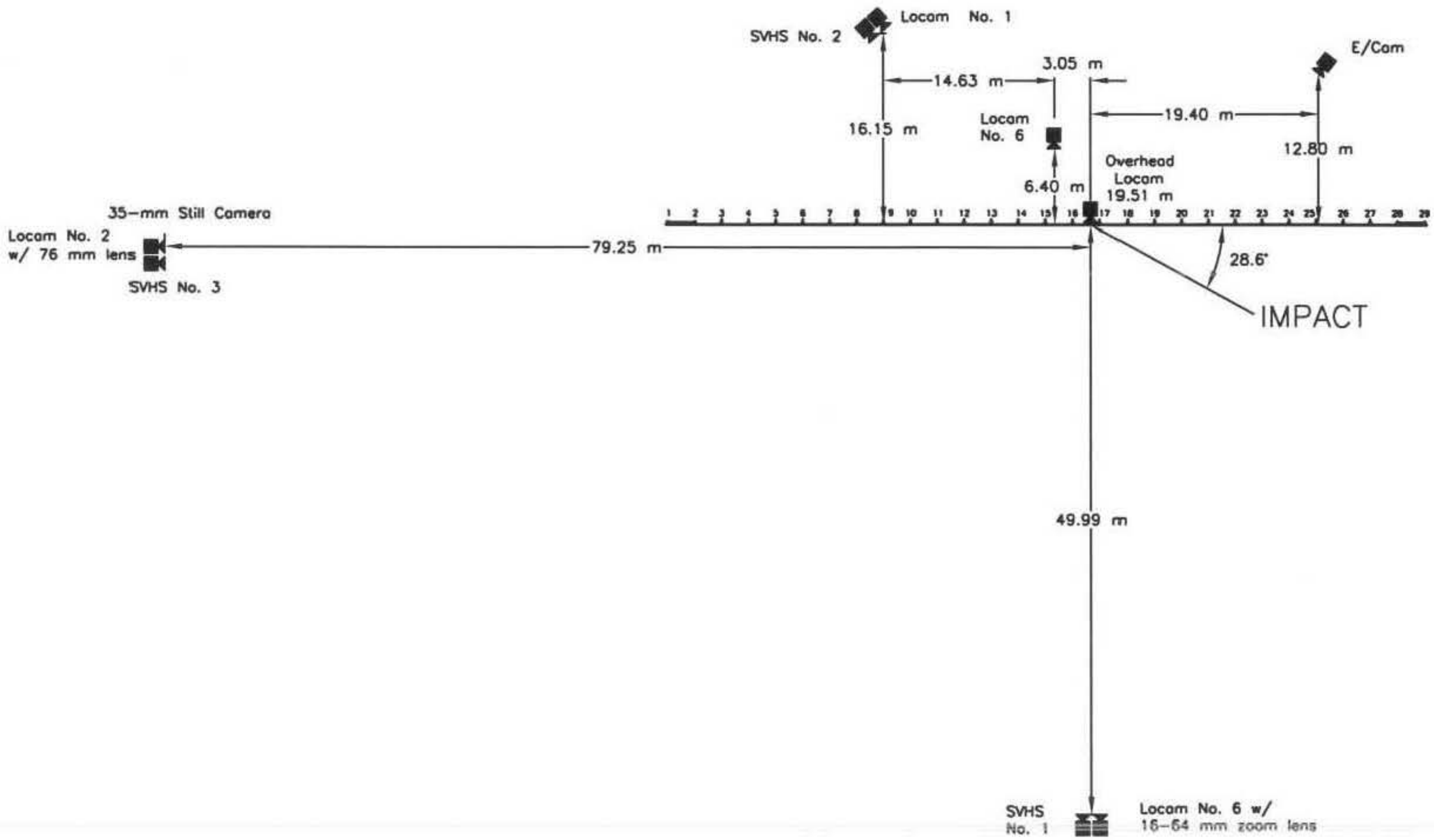


Figure 7. Location of High-Speed Cameras, Test NEC-2

6 CRASH TEST NO. 2

6.1 Test NEC-2

The 2,033-kg pickup truck impacted the guardrail over curb system at a speed of 100.3 km/hr and an angle of 28.6 degrees. A summary of the test results and the sequential photographs are shown in Figure 8. Additional sequential photographs are shown in Figures 9 and 10. Documentary photographs of the crash test are shown in Figures 11 through 13.

6.2 Test Description

Initial impact occurred between post nos. 16 and 17 or 660-mm downstream from the center of post no. 17, as shown in Figure 14. At 0.020 sec, post no. 16 began to rotate backward without significant twisting. At 0.028 sec after impact, the right-front corner of the vehicle was at the midspan between post nos. 16 and 17. At this same time, post nos. 16 and 17 were rotating equally, and the soil encountered significant movement. At 0.050 sec, post no. 15 began to rotate backwards. At 0.060 sec, the right-front corner of the vehicle was at post no. 16. At 0.074 sec, the right-front tire of the vehicle impacted post no. 16. At this same time, post nos. 15 and 18 began to rotate. At 0.100 sec, the right-front of the vehicle was at the midspan between post nos. 15 and 16, and post no. 16 was at its maximum deflection. At 0.109 sec, post no. 15 bent at the groundlevel. At 0.127 sec, the movement of post no. 16 ceased, and post nos. 13 and 14 began to move as the vehicle began to redirect. At this same time, the guardrail buckled at post no. 14 and twisted downward at post no. 15. At 0.140 sec, the right-front corner of the vehicle was at post no. 15 as the vehicle began to pitch upward. At 0.169 sec, the right-front tire passed over post no. 15, which was laying on the ground. At this same time, the right-front corner of the vehicle was located completely over the top of the rail near post no. 14, which was still relatively undeflected. At 0.184 sec, the right-front corner of the vehicle was at the midspan between post nos. 14 and 15. At 0.187 sec, the right-front tire impacted post no. 15. At 0.191 sec, the left-front tire became airborne as the vehicle did not encounter significant roll. At this same time, post no. 15 reached its maximum deflection. At 0.197 sec, the vehicle was extending over the top of the rail with the guardrail positioned near the center of the vehicle's front end. At 0.216 sec, the right-front corner of the vehicle was located at post no. 14. At 0.232 sec, the vehicle showed significant clockwise roll (CW) away from the rail. At 0.250 sec, the right-front corner of the vehicle was at the midspan between post nos. 13 and 14. At 0.262 sec, the rear bumper contacted the rail slightly upstream of post no. 14. At 0.278 sec, the right-rear wheel impacted the guardrail. At 0.286 sec, the front of the vehicle was located at post no. 13. At 0.302 sec, the rear bumper was located slightly past post no. 16 and over the top of the rail. At this same time, the front of the vehicle was located just downstream of post no. 13 with the right-rear tire climbing the rail span between post nos. 16 and 17. The vehicle became parallel to the guardrail at 0.311 sec after impact with a velocity of 63.4 km/hr. At 0.331 sec, the front of the vehicle was located at the midspan between post nos. 12 and 13. At 0.328 sec, the right-rear tire lost contact with the rail. At 0.348 sec, the right-rear tire deflated as it impacted the top of the rail near post no. 14. At 0.385 sec, the left-rear tire was airborne. At 0.428 sec, the rear of the vehicle to the midpoint of the vehicle's right side was positioned completely over the rail. At 0.449 sec, the left-rear tire impacted the rail. At 0.56 sec, the vehicle reached its maximum roll angle of 35.2 degrees away from the rail. At 0.60 sec, the vehicle reached its maximum pitch angle of 21.3 degrees upward. At 0.746 sec, the vehicle was completely airborne above the guardrail system. At 0.80 sec, the vehicle reached its maximum yaw angle of 42.8 degrees. At 0.907 sec, the vehicle's differential contacted the top of the rail. At 1.050 sec, the left-front tire contacted the ground. At 1.102 sec, the left-rear tire contacted the ground. At 1.118 sec, the right-front tire contacted the ground. At 1.362 sec, the left-front tire became airborne. At 1.725 sec, the left-front tire contacted the ground. At 1.916 sec, the left-rear tire contacted the ground. The vehicle's post-impact trajectory is shown in Figure 8. The vehicle came to rest behind the system, approximately 42.04-m downstream from impact and 3.11-m laterally behind a line projected parallel to the traffic-side face of the rail, as shown in Figure 8.

6.3 Barrier Damage

Damage to the barrier was moderate, as shown in Figures 15 through 25. Actual vehicle impact occurred 356-mm downstream from the center of post no. 17. Barrier damage consisted mostly of deformed guardrail posts, contact marks on a guardrail section, and deformed W-beam rail.

The guardrail damage consisted of moderate deformation and flattening of the W-beam rail between post nos. 13 and 17. Contact marks were found on the guardrail between post nos. 3 through 4 and 6 through 17. The top of the guardrail was buckled at post nos. 13 and 14. The lower edge of the guardrail at post no. 14 was also buckled. The W-beam was pulled off of post nos. 7, 8, 14, 16, and 22. No significant guardrail damage occurred upstream of post no. 18 nor downstream of post no. 5.

Steel posts, post nos. 14 through 19, were twisted and bent toward the ground. Five steel posts, post nos. 7 through 9, 12, and 13, were bent toward the ground without rotating. Seven other steel posts, post nos. 20, 21, and 23 through 27, were slightly rotated and moved in the soil. The wooden blockouts at post nos. 8 and 17 encountered heavy contact and were damaged. The downstream and upstream BCT posts, post nos. 1, 2, 28, and 29, remained undamaged except for movement in the soil. No significant post damage occurred to post nos. 10, 11, 22, nor downstream of post no. 6.

The permanent set of the guardrail and posts is shown in Figures 21 through 25. The cable anchor ends encountered slight permanent set deformations, as shown in Figure 25. The maximum lateral permanent set rail and post deflections were approximately 721 mm at the centerline of post no. 15 and 737 mm at post no. 16, respectively, as measured in the field. The maximum lateral dynamic rail and post deflections were approximately 1,072 mm at the centerline of post no. 15 and 802 mm at post no. 16, respectively, as determined from the high-speed film analysis.

6.4 Vehicle Damage

Exterior vehicle damage was moderate, as shown in Figures 26 and 27. Occupant compartment damage was negligible. The vehicle experienced moderate frontal crush, as shown in Figure 27. The front bumper buckled at the centerline of the bumper and the right side was pushed back into the engine compartment. The right-front fender was dented and deformed. The right-front wheel assembly was deformed to approximately a 90-degree bend. The right-front and right-rear tires were deflated. Minor damage was found on the right-front steel rim. In addition, the right-front tie-rod disengaged, the right-rear shock mounts tore, and the drive shaft shifted to the left. The right side of the grill disengaged from the front of the vehicle. The right-side headlight was disengaged. The lower-front portion of the left-side fender was slightly damaged. The box was shifted slightly to the left. Deformation occurred to the left-front, right-front, and right-rear quarter panels. The roof, the hood, the right-side and left-side doors, and all the window glass remained undamaged.

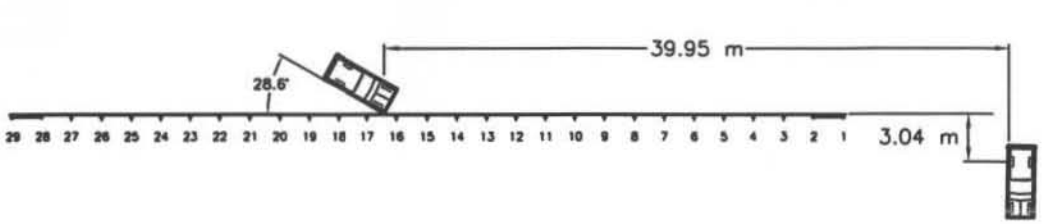
6.5 Occupant Risk Values

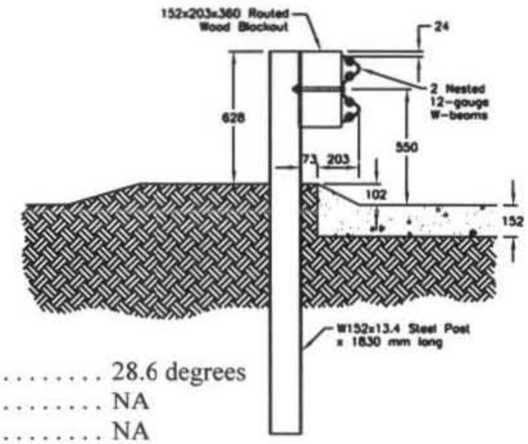
The longitudinal and lateral occupant impact velocities were determined to be 6.09 m/sec and 4.85 m/sec, respectively. The maximum 0.010-sec average occupant ridedown decelerations in the longitudinal and lateral directions were 6.72 g's and 5.75 g's, respectively. It is noted that the occupant impact velocities (OIV) and occupant ridedown decelerations (ORD) were within the suggested limits provided in NCHRP Report No. 350. The results of the occupant risk, as determined from the accelerometer data, are summarized in Figure 8. Results are shown graphically in Appendix A. The results from the rate transducer are shown graphically in Appendix B.

6.6 Discussion

The analysis of the test results for test NEC-2 showed that the guardrail installed over a curb adequately contained and redirected the vehicle with controlled lateral displacements of the guardrail. Detached elements and debris from the test article did not penetrate or show potential for penetrating the occupant compartment. Deformations of, or intrusion into, the occupant compartment that could have caused serious injury did not occur. The vehicle remained upright during and after collision. Vehicle roll, pitch, and yaw angular displacements were noted, but they were deemed acceptable because they did not adversely influence occupant risk safety criteria nor cause rollover. The vehicle's trajectory did not intrude into adjacent traffic lanes. In addition, the vehicle's exit angle was less than 60 percent of the impact angle. Therefore, test NEC-2 conducted on the guardrail/curb combination was determined to be acceptable according to the NCHRP Report No. 350 criteria.

0.000 sec | 0.062 sec | 0.171 sec | 0.197 sec | 0.302 sec





- Test Number NEC-2
- Date 7/24/00
- Appurtenance .... W-beam guardrail over curb system
- Total Length .... 53.34 m
- Steel Nested W-Beam
  - Thickness .... Two at 2.66 mm each
  - Top Mounting Height .... 706 mm
- Steel Posts
  - Post Nos. 3 - 27 .... W152x13.4 by 1,830-mm long
- Wood Posts
  - Post Nos. 1 - 2, 28 - 29 (BCT) . 140 mm x 190 mm by 1,080-mm long
- Routed Wood Spacer Blocks
  - Post Nos. 3 - 27 .... 152 mm x 203 mm by 360-mm long
- Curb .... AASHTO 102 mm x 203 mm Type "G" Curb
  - Curb Span .... Post no. 19 to post no. 9
  - Total Curb Length .... 19.05 m
- Soil Type .... Grading B - AASHTO M 147-65 (1990)
- Vehicle Model .... 1994 GMC 2500 ¾-Ton
  - Curb .... 2,017 kg
  - Test Inertial .... 2,033 kg
  - Gross Static .... 2,033 kg
- Vehicle Speed
  - Impact .... 100.3 km/hr
  - Exit .... NA
- Vehicle Angle
  - Impact .... 28.6 degrees
  - Exit .... NA
- Vehicle Snagging .... NA
- Vehicle Pocketing .... NA
- Vehicle Stability .... Satisfactory
- Occupant Ridedown Deceleration (10 msec avg.)
  - Longitudinal .... 6.72 < 20 G's
  - Lateral (not required) 5.75
- Occupant Impact Velocity
  - Longitudinal .... 6.09 < 12 m/s
  - Lateral (not required) 4.85
- Vehicle Damage .... Moderate
  - TAD[14] 1-RFQ-4
  - SAE[15] 1-RFEW5
- Vehicle Stopping Distance .... Behind the system
  - Left Rear Tire .... 42.04 m downstream 3.11 m behind
- Barrier Damage .... Moderate
- Maximum Deflections
  - Permanent Set .... 721 mm
  - Dynamic .... 1,072 mm

Figure 8. Summary of Test Results and Sequential Photographs, Test NEC-2

0.000 sec

0.101 sec

0.232 sec

0.385 sec

0.594 sec

1.050 sec

0.000 sec

0.109 sec

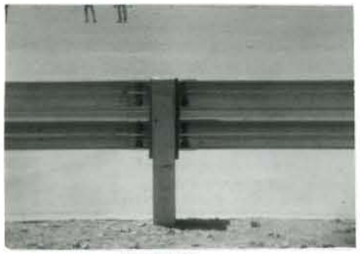
0.169 sec

0.259 sec

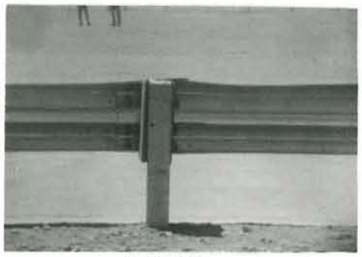
0.302 sec

0.416 sec

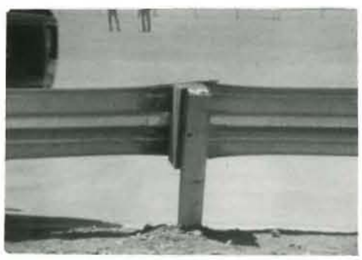
Figure 9. Additional Sequential Photographs, Test NEC-2



0.012 sec



0.050 sec



0.072 sec

0.176 sec

0.318 sec

0.000 sec

0.140 sec

0.216 sec

0.394 sec

Figure 10. Additional Sequential Photographs, Test NEC-2

Figure 11. Documentary Photographs, Test NEC-2

Figure 12. Documentary Photographs, Test NEC-2

Figure 13. Documentary Photographs, Test NEC-2

Figure 14. Impact Location, Test NEC-2

Figure 15. Guardrail Over Curb System Damage, Test NEC-2

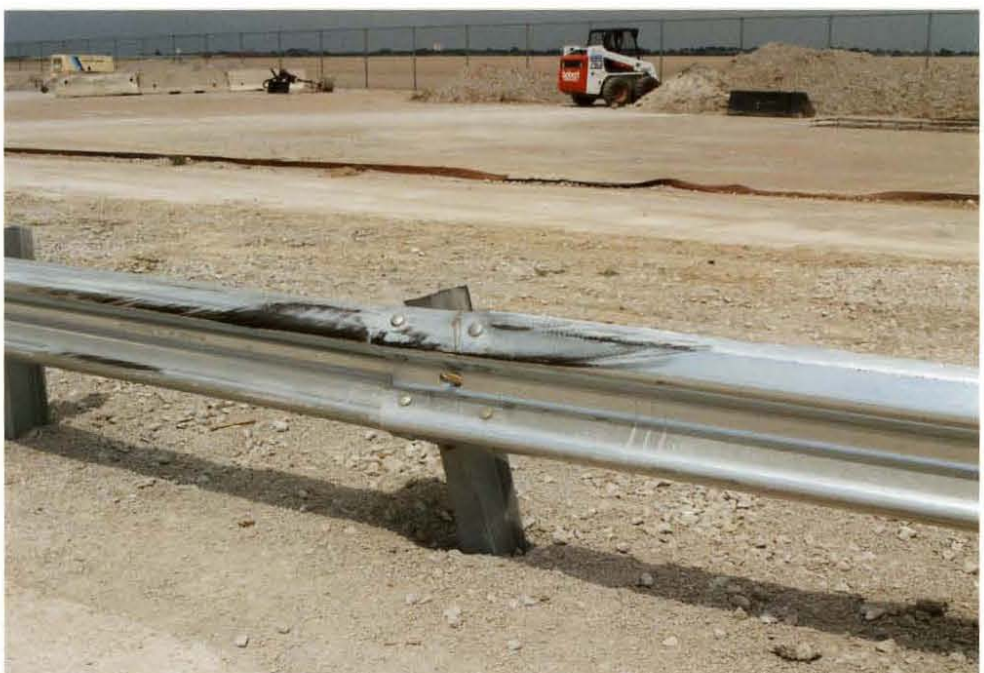


Figure 16. Guardrail Over Curb System Damage, Test NEC-2

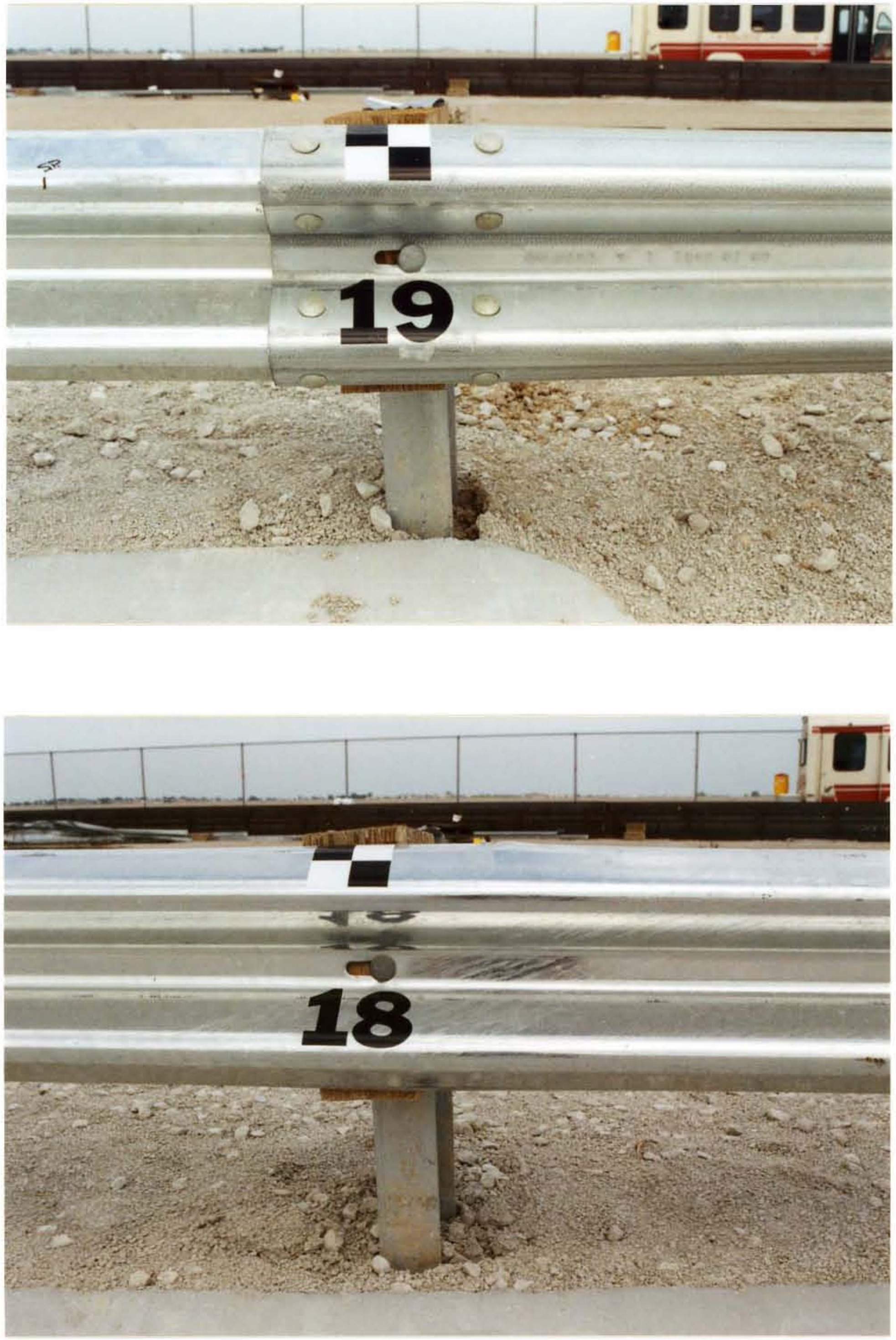


Figure 17. Guardrail Over Curb System Rail and Post Damage, Test NEC-2

Figure 18. Guardrail Over Curb System Rail and Post Damage, Test NEC-2

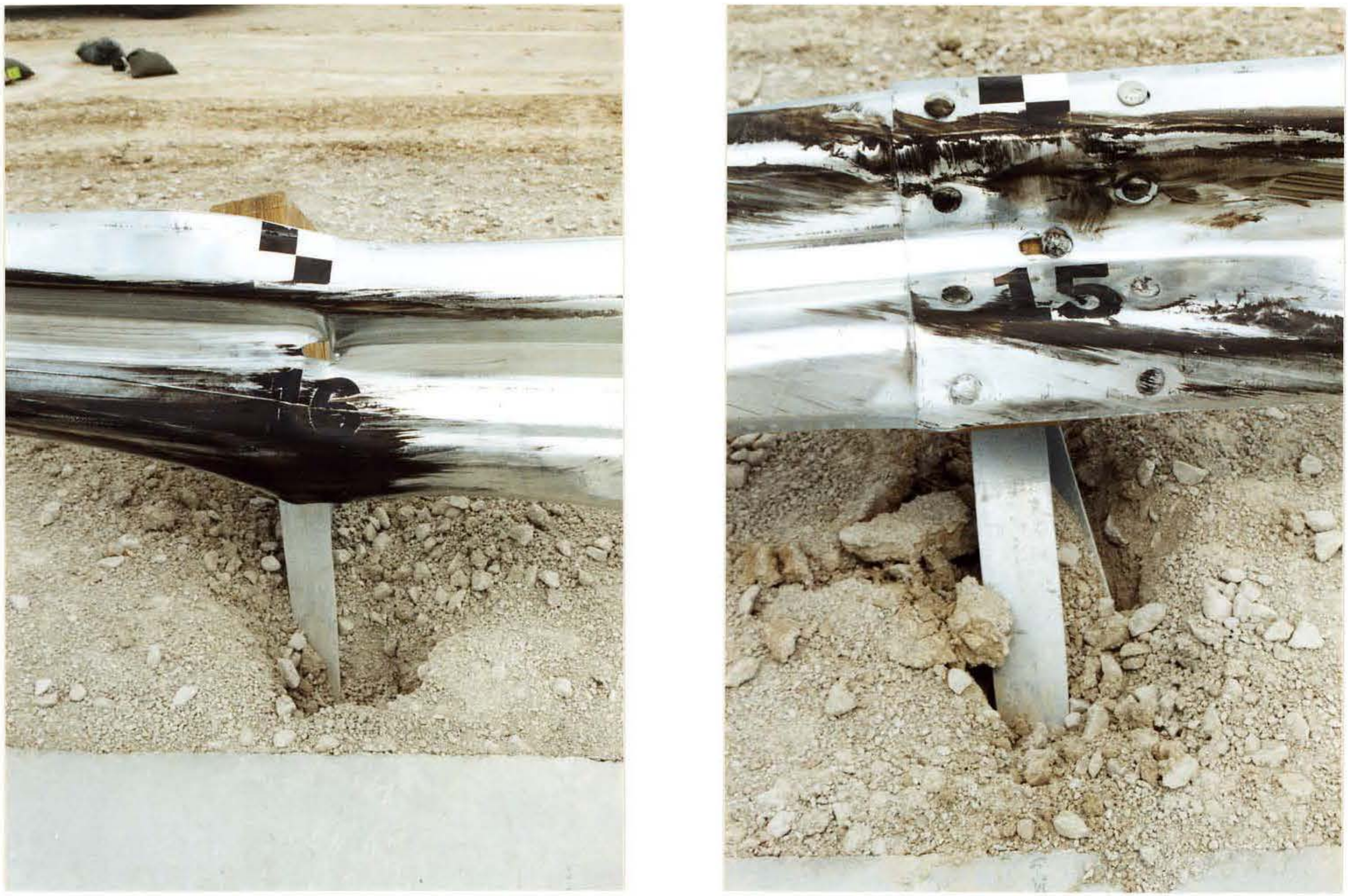


Figure 19. Guardrail Over Curb System Rail and Post Damage, Test NEC-2

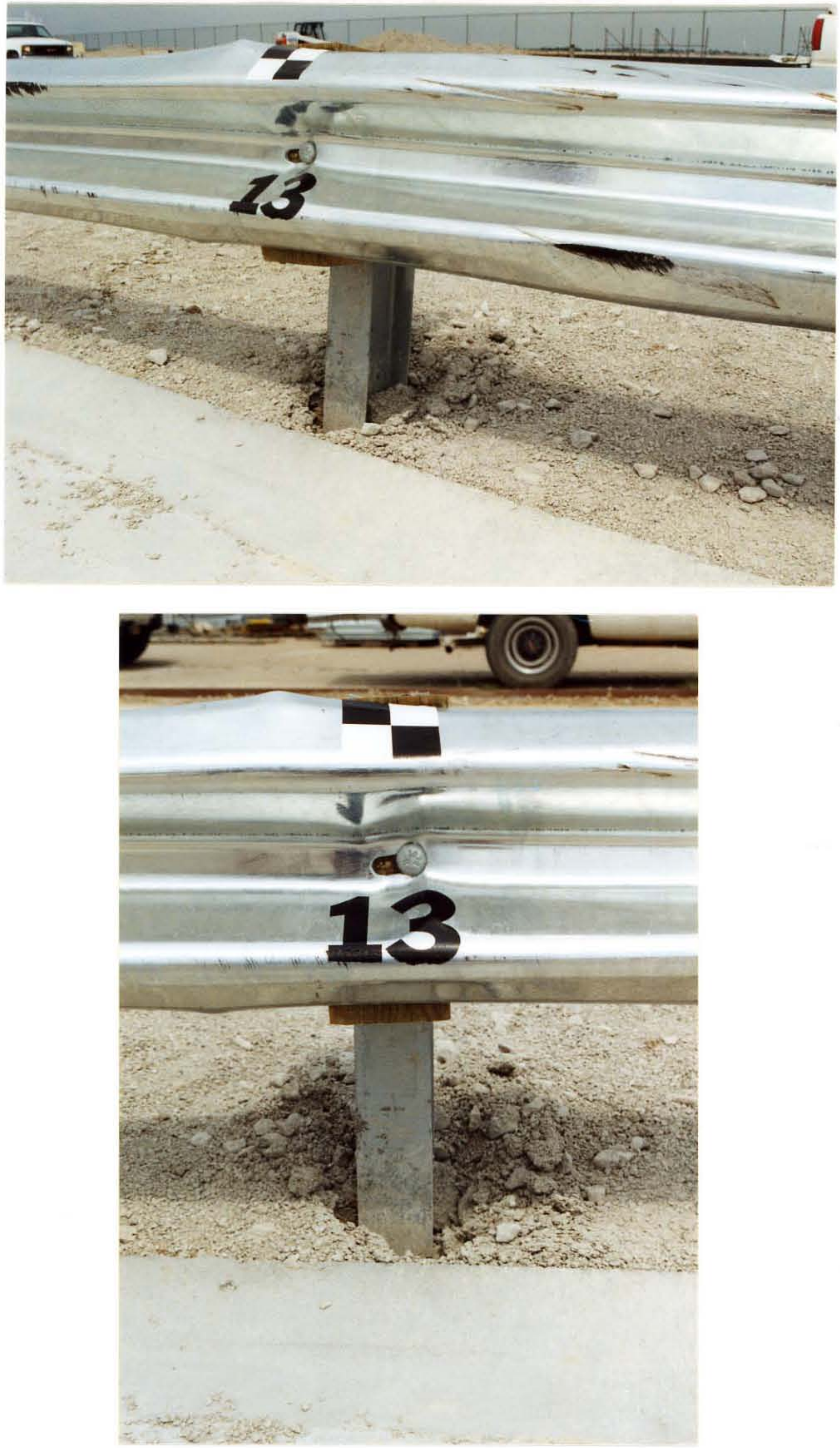


Figure 20. Guardrail Over Curb System Rail and Post Damage, Test NEC-2

Post No. 13

Post No. 14

Figure 21. Final Post Position – Post Nos. 13 and 14, Test NEC-2

Post No. 15

Post No. 16

Figure 22. Final Post Position – Post Nos. 15 and 16, Test NEC-2

Post No. 17

Post No. 18

Figure 23. Final Post Position – Post Nos. 17 and 18, Test NEC-2

Figure 24. Final Post Position – Post No. 19, Test NEC-2

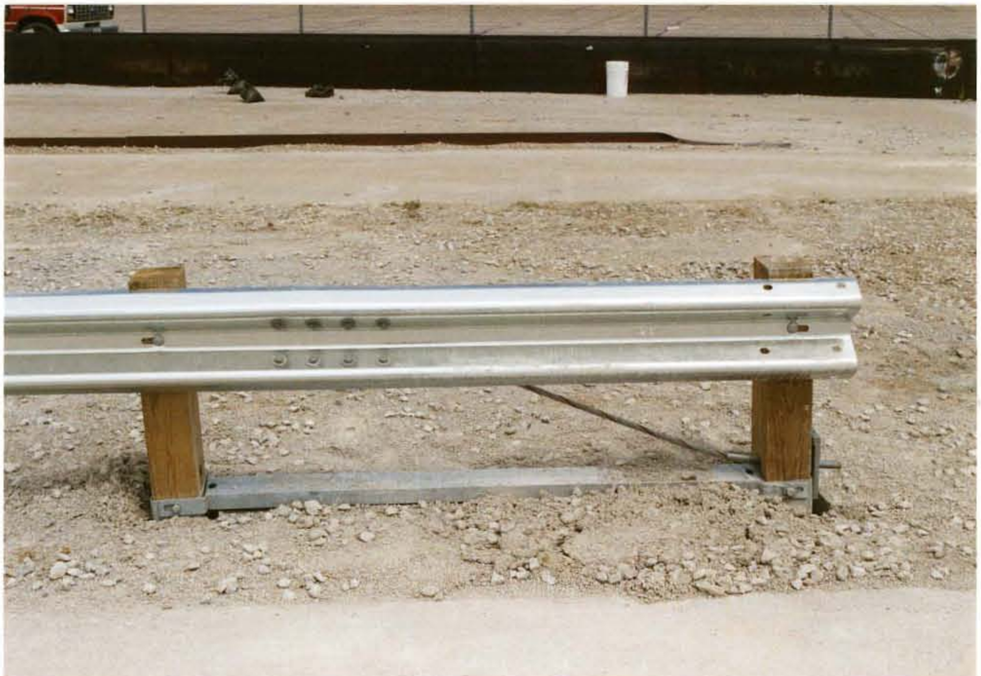


Figure 25. Permanent Set Deflections of End Anchorages, Test NEC-2

Figure 26. Vehicle Damage, Test NEC-2

Figure 27. Front-End Vehicle Damage, Test NEC-2

7 SUMMARY AND CONCLUSIONS

A guardrail/curb combination system was constructed and full-scale vehicle crash tested. The guardrail system was configured with steel posts supporting 53.34 m of nested W-beam rail and installed over a triangular-shape curb. A full-scale vehicle crash test was performed with a ¾-ton pickup truck on the guardrail system and was determined to be acceptable according to the TL-3 safety performance criteria presented in NCHRP Report No. 350. A summary of the safety performance evaluation is provided in Table 3.

Table 3. Summary of Safety Performance Evaluation Results - Guardrail over Curb System

Evaluation Factors		Evaluation Criteria	Test NEC-2
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.	M
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.	S
	F.	The vehicle should remain upright during and after collision although moderate roll, pitching and yawing are acceptable.	S
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	S
	L.	The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 G's.	S
	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 devise.	S

S - (Satisfactory)
M - (Marginal)
U - (Unsatisfactory)
NA - Not Available

8 RECOMMENDATIONS

A guardrail system designed for use over curbs, as described in this report, was successfully crash tested according to the criteria found in NCHRP Report No. 350. The results of this test indicate that this design is a suitable design for use on Federal-aid highways. However, any design modifications made to the guardrail/curb combination system can only be verified through the use of full-scale vehicle crash testing.

9 REFERENCES

1. *Memorandum on Performance of Guardrail/Curb Combinations*, February 28, 1992, File Designation HNG-14, Federal Highway Administration (FHWA), Washington, D.C., 1992.

2. Stout, D., Hughes, W., and McGee, H., *Traffic Barriers on Curves, Curbs, and Slopes*, Report No. FHWA/RD-93/082, Submitted to the Office of Safety and Traffic Operations, Federal Highway Administration, Performed by ENSCO, Inc., August 1993.

3. Holloway, J.C. and Rosson, B.T., *Performance Evaluation of Missouri's 6-in. Barrier Curb Under W-beam Guardrail*, Final Report to the Missouri Highway and Transportation Department, Transportation, Report No. TRP-03-40-94, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, April 1994.

4. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Reid, J.D., and Holloway, J.C., *Guardrail and Guardrail Terminals Installed Over Curbs*, Final Report to the Midwest State's Regional Pooled Fund Program, Transportation Record No. TRP-03-83-99, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, March 21, 2000.

5. Michie, J.D., *Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances*, National Cooperative Highway Research Program (NCHRP) Report No. 230, Transportation Research Board, Washington, D.C., March 1981.

6. *Guide Specifications for Bridge Railings*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 1989.

7. Ross, H.E., Sicking, D.L., Zimmer, R.A. and Michie, J.D., *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Research Program (NCHRP) Report No. 350, Transportation Research Board, Washington, D.C., 1993.

8. *A Policy on Geometric Design of Highways and Streets*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 1990.

9. Buth, C.E., Campise, W.L., Griffin, III, L.I., Love, M.L., and Sicking, D.L., *Performance Limits of Longitudinal Barrier Systems - Volume I - Summary Report*, Report No. FHWA/RD-86/153, Submitted to the Office of Safety and Traffic Operations, Federal Highway Administration, Performed by Texas Transportation Institute, May 1986.

10. Ivey, D.L., Robertson, R., and Buth, C.E., *Test and Evaluation of W-Beam and Thrie-Beam Guardrails*, Report No. FHWA/RD-82/071, Submitted to the Office of Research, Federal Highway Administration, Performed by Texas Transportation Institute, March 1986.

11. Ross, H.E., Jr., Perera, H.S., Sicking, D.L., and Bligh, R.P., *Roadside Safety Design for Small Vehicles*, National Cooperative Highway Research Program (NCHRP) Report No. 318, Transportation Research Board, Washington, D.C., May 1989.

12. Holloway, J.C., Bierman, M.G., Pfeifer, B.G., Rosson, B.T., and Sicking, D.L., *Performance Evaluation of KDOT W-Beam Systems Volume I: Full-Scale Crash Testing*, Final Report to the Nebraska Department of Roads, Transportation Report No. TRP-03-39-96, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, May 1996.

13. Hinch, J., Yang, T-L, and Owings, R., *Guidance Systems for Vehicle Testing*, ENSCO, Inc., Springfield, VA 1986.

14. *Vehicle Damage Scale for Traffic Investigators*, Second Edition, Technical Bulletin No. 1, Traffic Accident Data (TAD) Project, National Safety Council, Chicago, Illinois, 1971.

15. *Collision Deformation Classification - Recommended Practice J224 March 1980*, Handbook Volume 4, Society of Automotive Engineers (SAE), Warrendale, Pennsylvania, 1985.

10 APPENDICES

APPENDIX A

Accelerometer Data Analysis, Test NEC-2

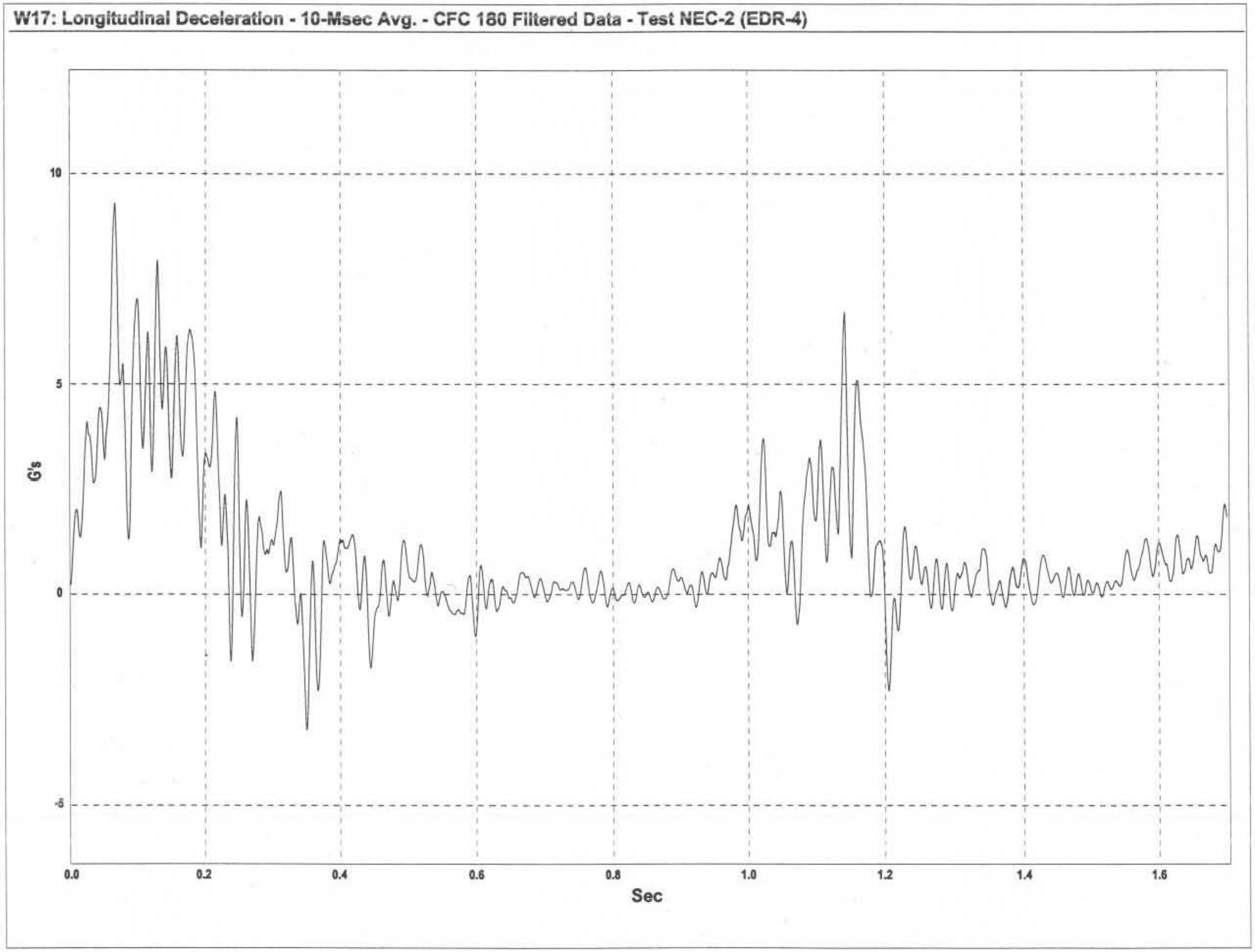


Figure A-1. Graph of Longitudinal Deceleration, Test NEC-2

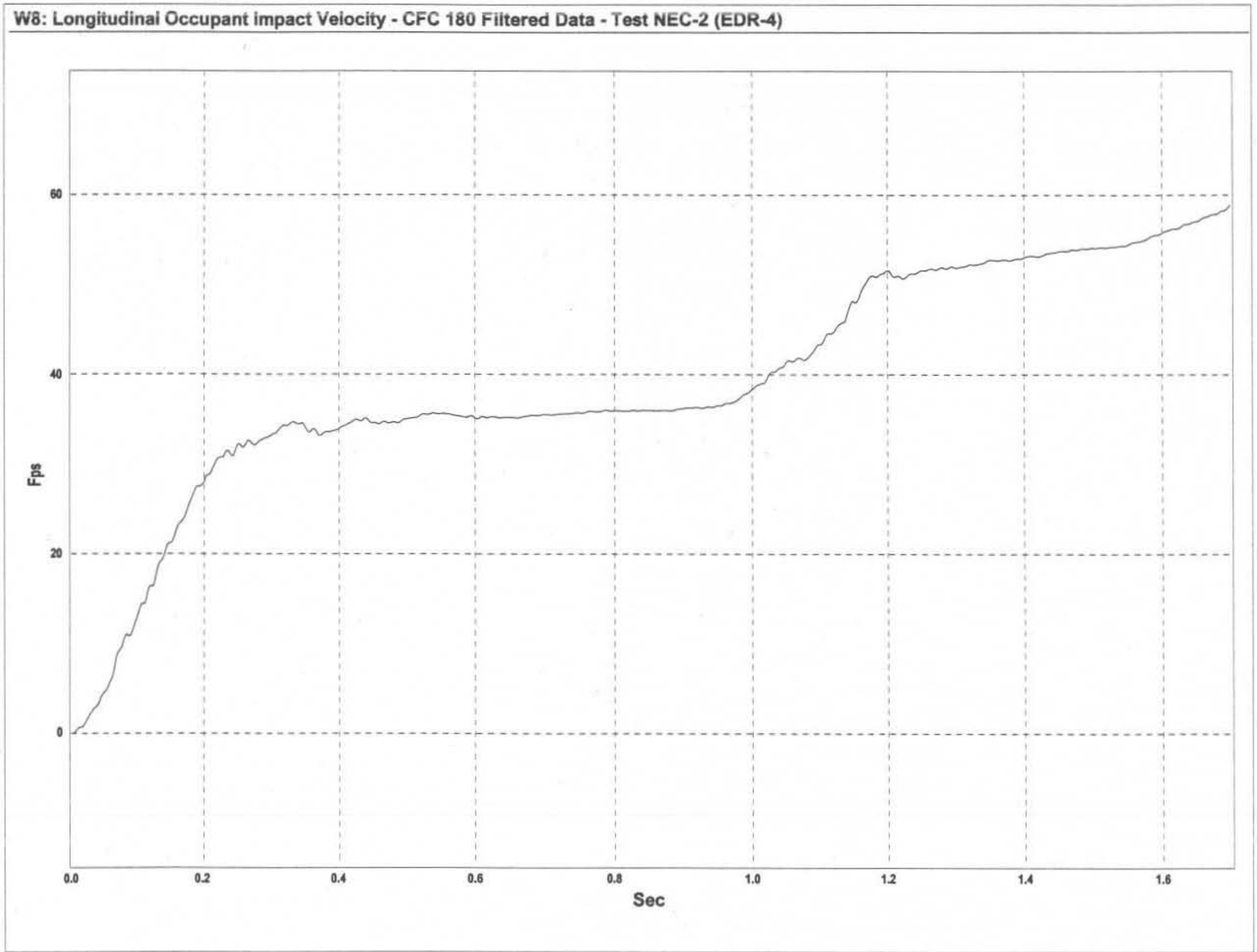


Figure A-2. Graph of Longitudinal Occupant Impact Velocity, Test NEC-2

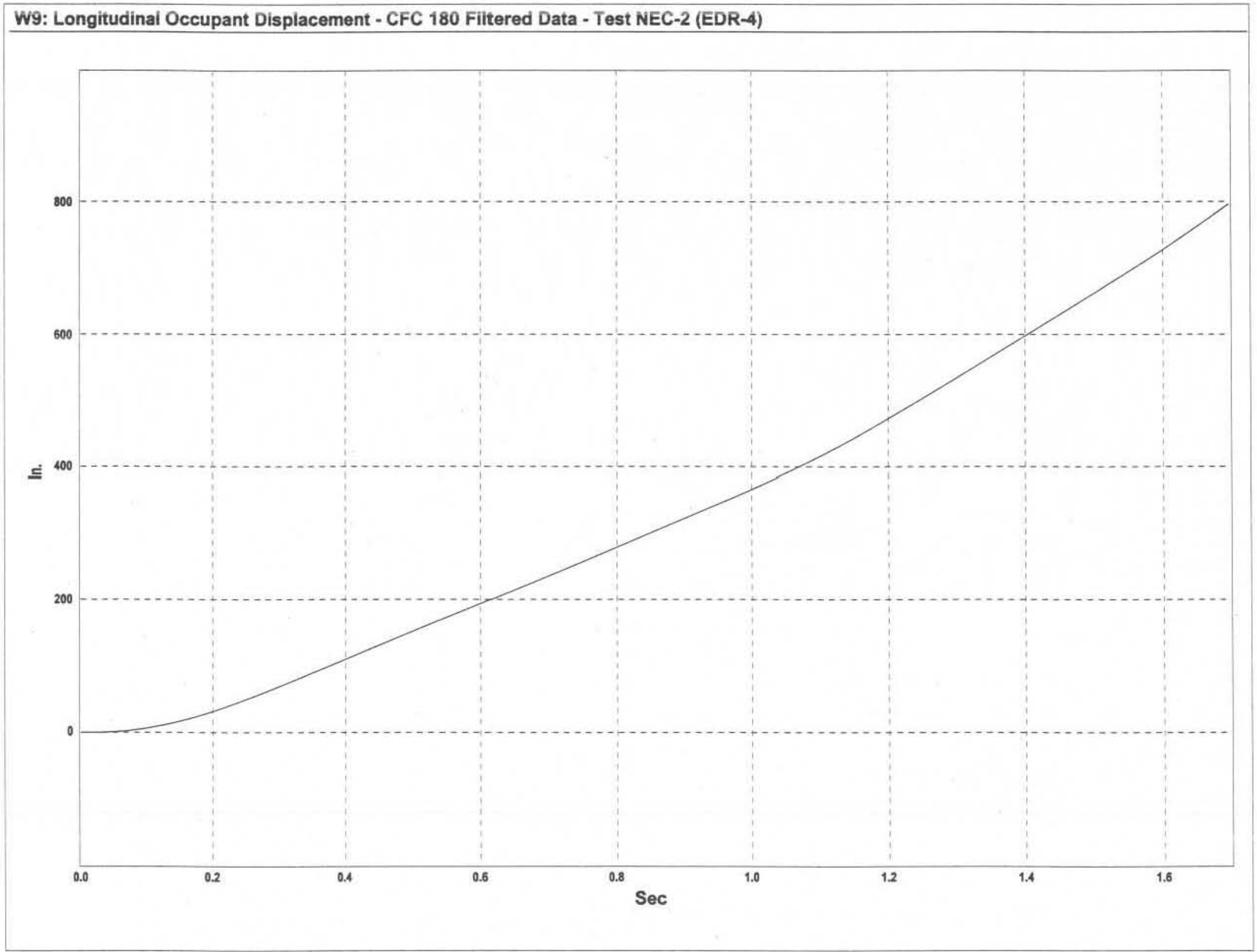


Figure A-3. Graph of Longitudinal Occupant Displacement, Test NEC-2

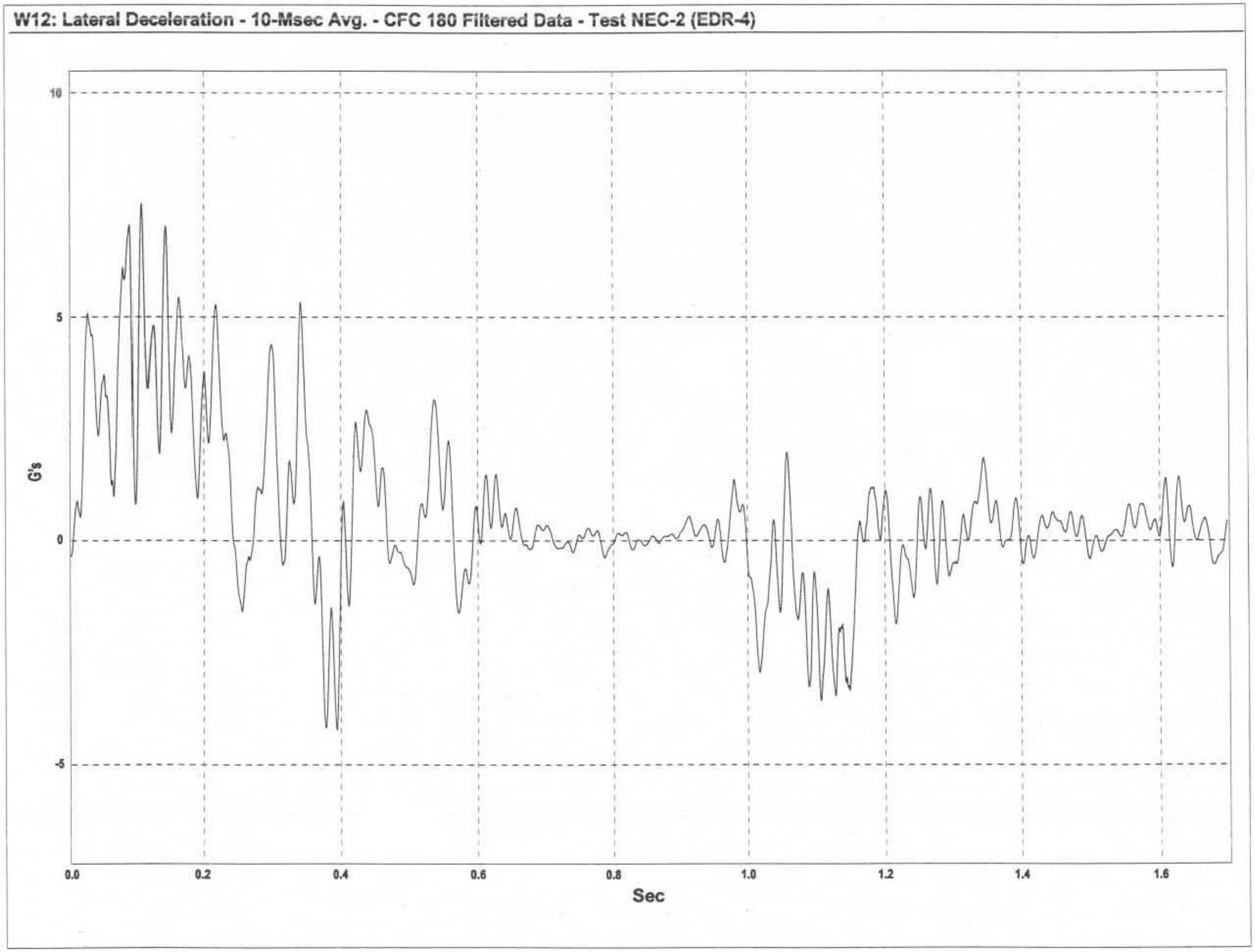


Figure A-4. Graph of Lateral Deceleration, Test NEC-2

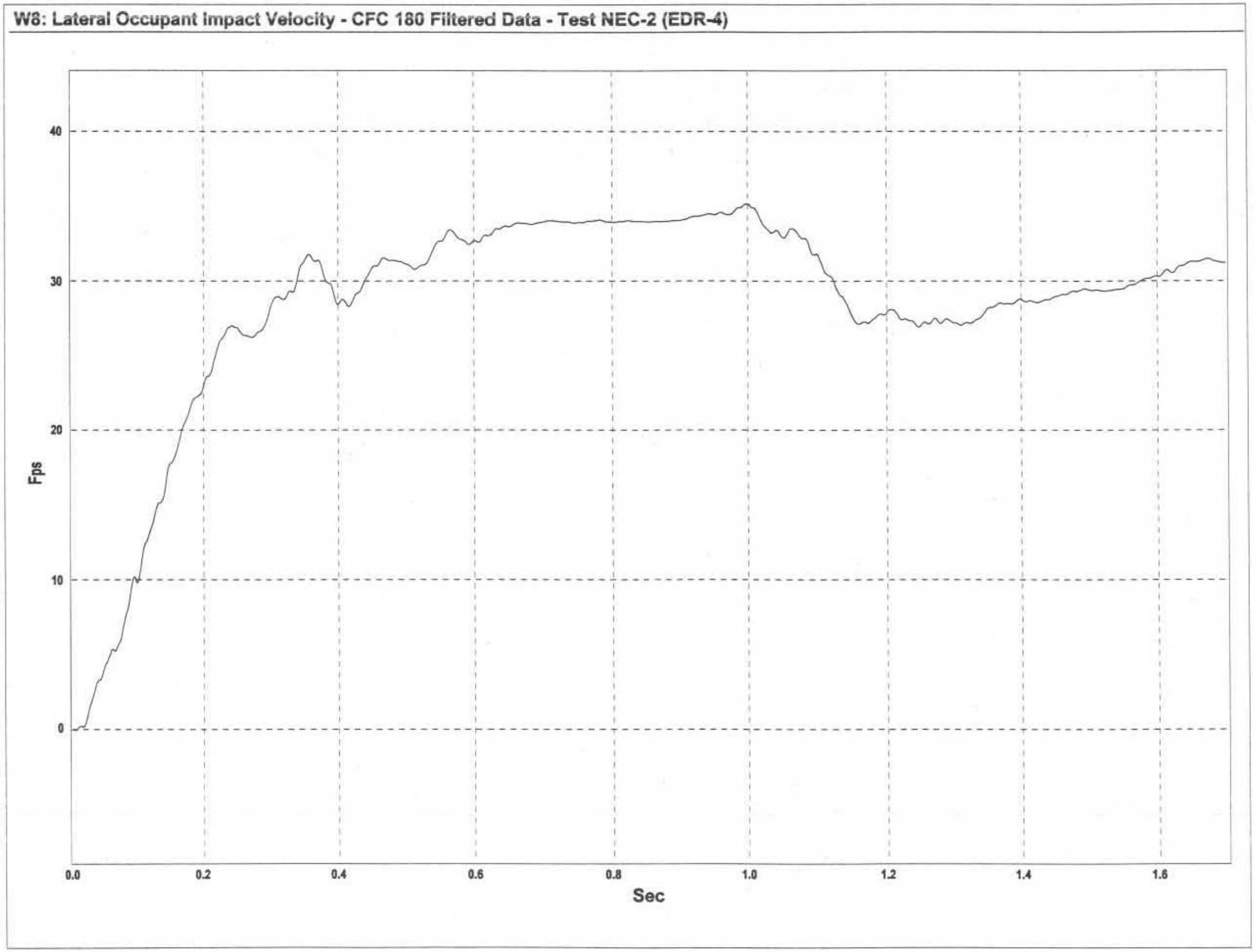


Figure A-5. Graph of Lateral Occupant Impact Velocity, Test NEC-2

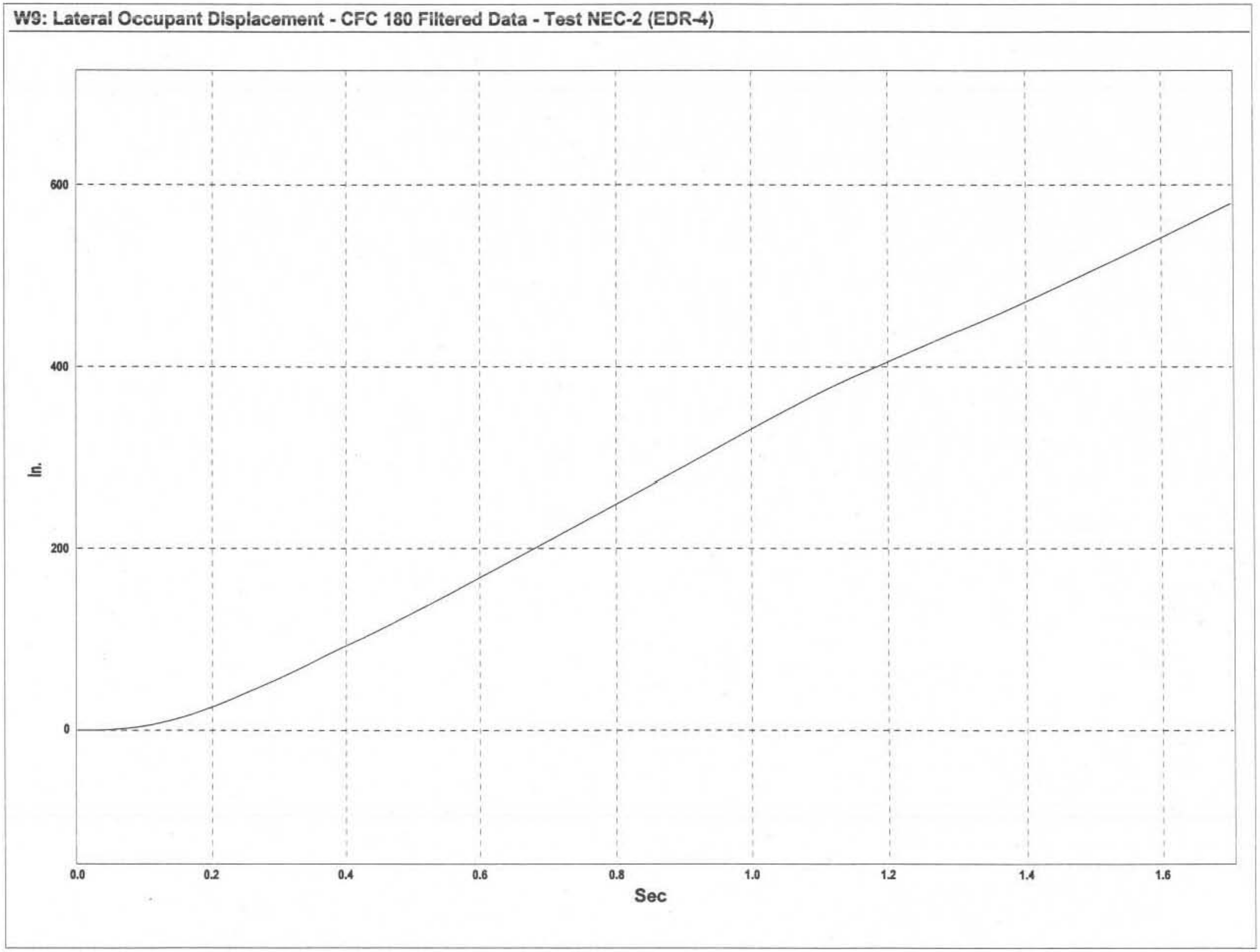


Figure A-6. Graph of Lateral Occupant Displacement, Test NEC-2

APPENDIX B

Rate Transducer Data Analysis, Test NEC-2

Figure B-1. Graph of Roll, Pitch, and Yaw Angular Displacements, Test NEC-2

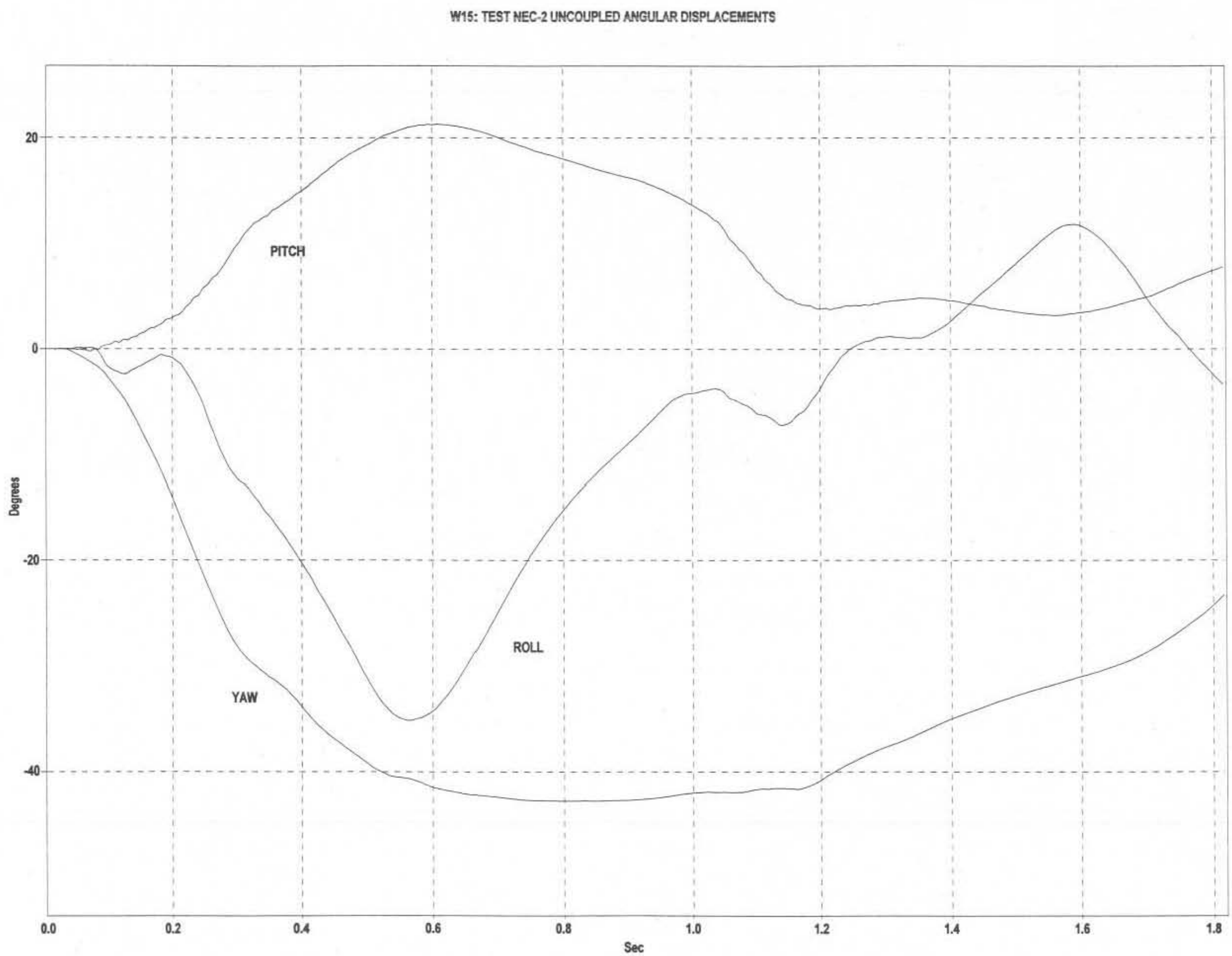


Figure B-1. Graph of Roll, Pitch, and Yaw Angular Displacements, Test NEC-2