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GUARDRAIL AND GUARDRAIL TERMINALS INSTALLED OVER CURBS

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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 a 2.66-mm (12-gauge) thick W-beam rail totaling 53.34 m in length. The W-beam rail was supported by twenty-five W150x13.5 steel posts, each measuring 1,830-mm long, and four standard BCT posts, each measuring 1,080-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 and live-driver curb testing, using a ¾-ton pickup trucks. The full-scale test, impacting at a speed of 103.2 km/hr and an angle of 24.5 degrees, was unsuccessful because the barrier system failed at the splice at post no. 12. The three live-driver curb tests, impacting at a speed of either 64 km/hr or 100 km/hr and an angle of 25 degrees, helped to determine the curb, tire, and suspension interaction to use in future simulation work. The safety performance of the long-span barrier system was determined to be unacceptable according to the Test Level 3 (TL-3) evaluation criteria specified in NCHRP Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features*.

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DISCLAIMER STATEMENT

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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 (1-3). 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* (4). However, one pickup truck crash test was performed unsuccessfully on a guardrail/curb combination according to the criteria provided in the American Association of State Highway and Transportation Official's (AASHTO's) *Guide Specifications for Bridge Railings* (5). Consequently, the performance of guardrails installed over curbs has not been evaluated using ¾-ton pickup trucks according to the guidelines presented in NCHRP Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features* (6). 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. If 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. Fourth, three live-driver vehicle tests were performed while traversing over a concrete curb using a ¾-ton pickup truck, weighing approximately 2,000 kg, with a target impact speed of either 64 km/hr or 100 km/hr and an angle of 25 degrees. 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 performance 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 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 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). Crash testing of guardrail/curb combinations previously conducted at ENSCO, Inc. and at MwRSF were evaluated according to the criteria provided in NCHRP Report No. 230 criteria as well as the AASHTO *Guide Specifications for Bridge Railings*.

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 in combination with 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. 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 with 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 with a 102-mm type "H" curb 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 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. During the crash test, the 2,137-kg sedan was successfully redirected, and in a more stable manner than observed iin 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 in combination with 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. 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]
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
Test Vehicle Gross Weight (kg)	2607	883	2100	2109	2124	2137	2043
Impact Angle (deg)	20.0	20.0	25.0	25.0	26.0	25.0	25.1
Impact Speed (km/hr)	98.7	100.1	97.0	99.1	98.8	99.9	96.1
Installation Type	G4(1S)	G4(1S)	G4(1S)	G4(1S)	Stiffened G4(1S) with W-beam	G4(1S) with channel rubrail	G4(1S)
Curb Type [3]	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
Curb Placement	Flush with guardrail face	Flush with guardrail face	Flush with guardrail face	In front of guardrail face	Flush with guardrail face	Flush with guardrail face	Flush with guardrail face
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
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
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
Test Results Conclusion According to NCHRP 230 (4) Criteria	Test article failed due to vaulting	Meets all criteria	Vaulting occurred but criteria met	Meets all criteria	Meets all criteria	Meets all criteria	Meets all criteria

[1] ENSCO, Inc. (2)
[2] MwRSF (3)
[3] AASHTO (7)
NA - Not Available
OIV - Occupant Impact Velocity

3 TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1 Test Requirements

Longitudinal barriers, such as guardrails installed over curbs, must satisfy the requirements 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 Test Level 3 (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 barriers struck by small cars have been shown to meet safety performance standards and to be essentially rigid (8-11), with no significant potential for occupant risk problems arising from vehicle pocketing or severe wheel snagging on the post at the downstream end of the long-span. 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 tests were conducted and reported in accordance with the procedures provided in NCHRP Report No. 350.

Table 2. NCHRP Report 350 Evaluation Criteria for 2000P Pickup Truck Crash Test (6)

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 Figure 2. The test installation consisted of 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 W150x13.5 sections measuring 1,830-mm long. Post nos. 1 through 2 and 28 through 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, 150-mm wide x 200-mm deep x 360-mm long routed wood spacer blockouts were used to block the rail away from post nos. 3 through 27.

All guardrail used throughout the installation consisted of 2.66-mm (12-gauge) thick W-beam rail. 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 533-mm downstream of post no.16 to 533-mm downstream of post no. 6, 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.

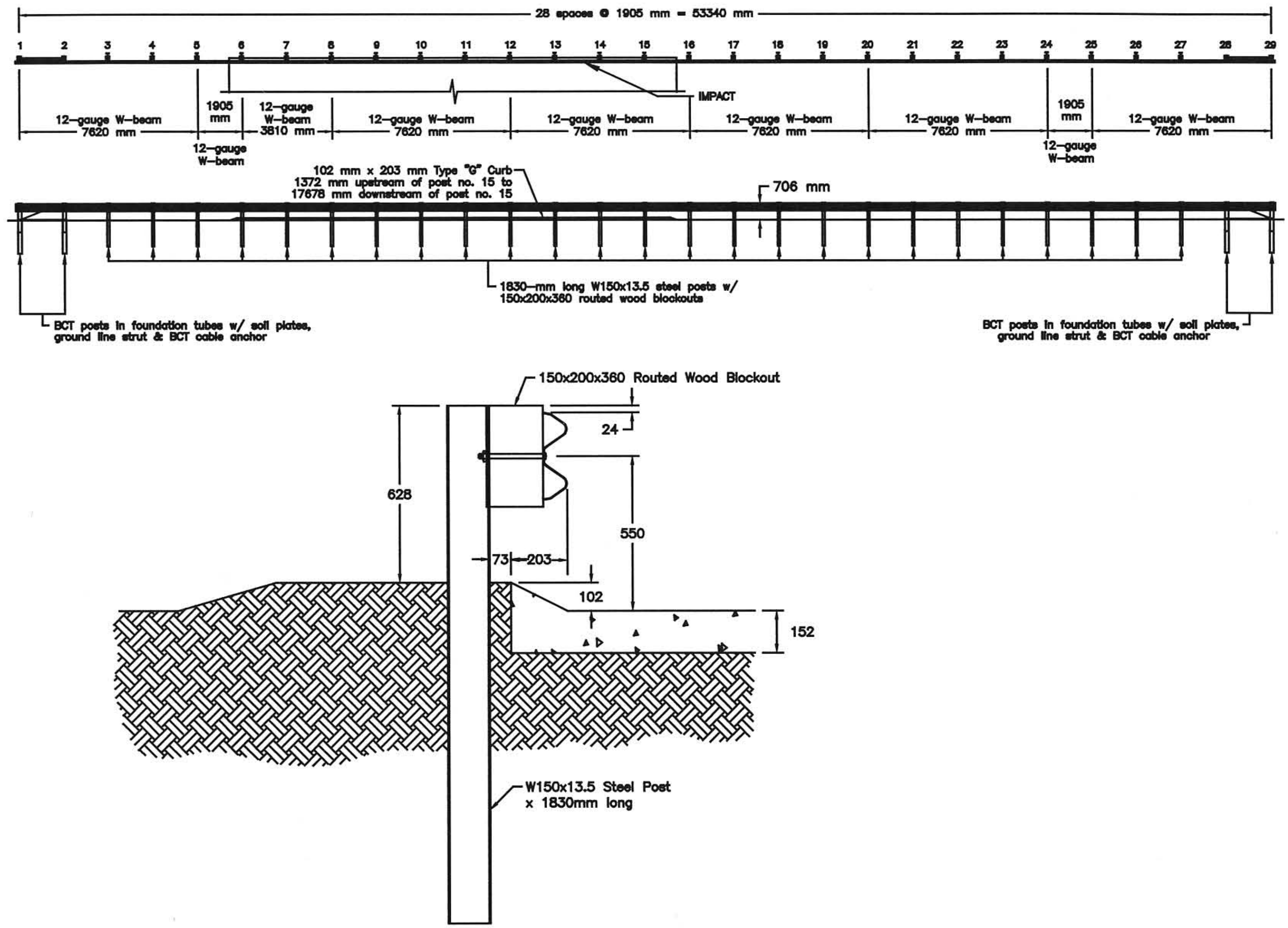


Figure 1. Test Installation Configuration

Figure 2. Guardrail Over Curb System

5 TEST CONDITIONS

5.1 Test Facility

The testing facility is located at the Lincoln Air-Park on the NW end of the Lincoln Municipal Airport and is approximately 8.0 km NW of the University of Nebraska-Lincoln. The site is protected by a 2.44-m high chain-link security fence.

5.2 Vehicle Tow and Guidance System

A reverse cable tow system with a 1:2 mechanical advantage was used to propel the test vehicles. 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 (12) was used to steer the test vehicle. A guide-flag, attached to the front-left wheel and the guide cable, was sheared off before impact. 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 365.8-m long.

5.3 Test Vehicles

For test NEC-1, a 1991 GMC 2500 ¾-ton pickup truck was used as the test vehicle. The test inertial and gross static weights were 1,979 kg. The test vehicle is shown in Figure 3, and vehicle dimensions are shown in Figure 4.

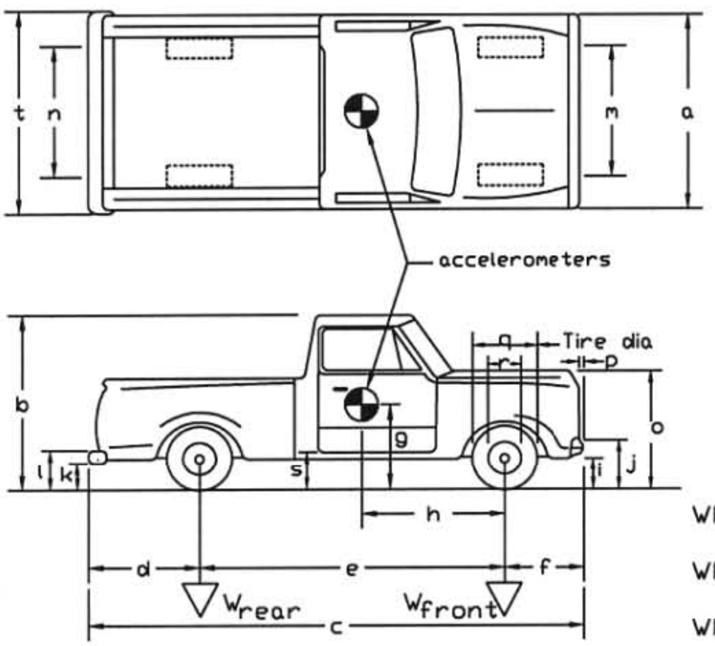
Figure 3. Test Vehicle, Test NEC-1

Date: 5/19/98 Test Number: NEC-1 Model: 2500

Make: GMC Vehicle I.D.#: 1GTFC24K3ME530562

Tire Size: LT225/75R16D Year: 1991 Odometer: 151,950

*(All Measurements Refer to Impacting Side)



Vehicle Geometry - mm

a	1867	b	1778
c	5575	d	1353
e	3327	f	895
g	737	h	1486
i	394	j	610
k	521	l	718
m	1575	n	1626
o	1029	p	83
q	749	r	445
s	406	t	1842

Wheel Center Height Front 362

Wheel Center Height Rear 368

Wheel Well Clearance (FR) 845

Wheel Well Clearance (RR) 902

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}	1038	1095	1095
W_{rear}	798	884	884
W_{total}	1836	1979	1979

Note any damage prior to test: right rear box, windshield cracks

Figure 4. Vehicle Dimensions, Test NEC-1

The Suspension Method (13) was used to determine the vertical component of the center of gravity for the test vehicles. This method is based on the principle that the center of gravity of any freely suspended body is in the vertical plane through the point of suspension. The vehicle was suspended successively in three positions, and the respective planes containing the center of gravity were established. The intersection of these planes pin-pointed the location of the center of gravity. 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 5.

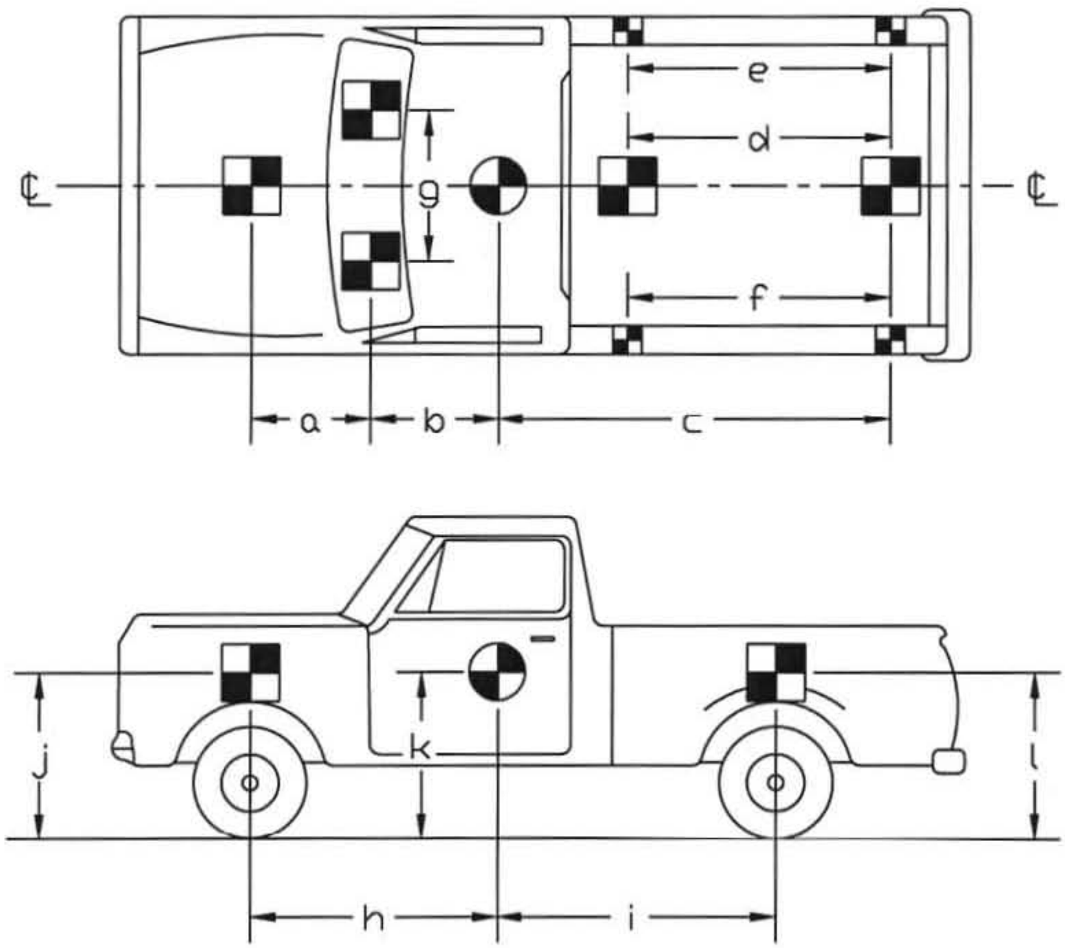
Square, black and white-checkered targets were placed on the vehicle to aid in the analysis of the high-speed film, as shown in Figure 5. One target was placed on the center of gravity on the driver's side door, the passenger's side door, and on the roof of the vehicle. The remaining targets were located 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



TEST #: NEC-1

TARGET GEOMETRY (mm)

a 1334	b 673	c 2629	d 1842
e 2146	f 2153	g 978	h 1486
i 1861	j 943	k 737	l 1006

Figure 5. Vehicle Target Locations, Test NEC-1

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 digitize, 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 digitize, analyze, and plot the accelerometer data.

5.4.2 Rate Transducer

A Humphrey 3-axis rate transducer with a range of 250 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 digitize, analyze, and plot the rate transducer data.

5.4.3 High-Speed Photography

For test NEC-1, 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 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 schematic of all nine camera locations for test NEC-1 is shown in Figure 6. 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-1, 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.

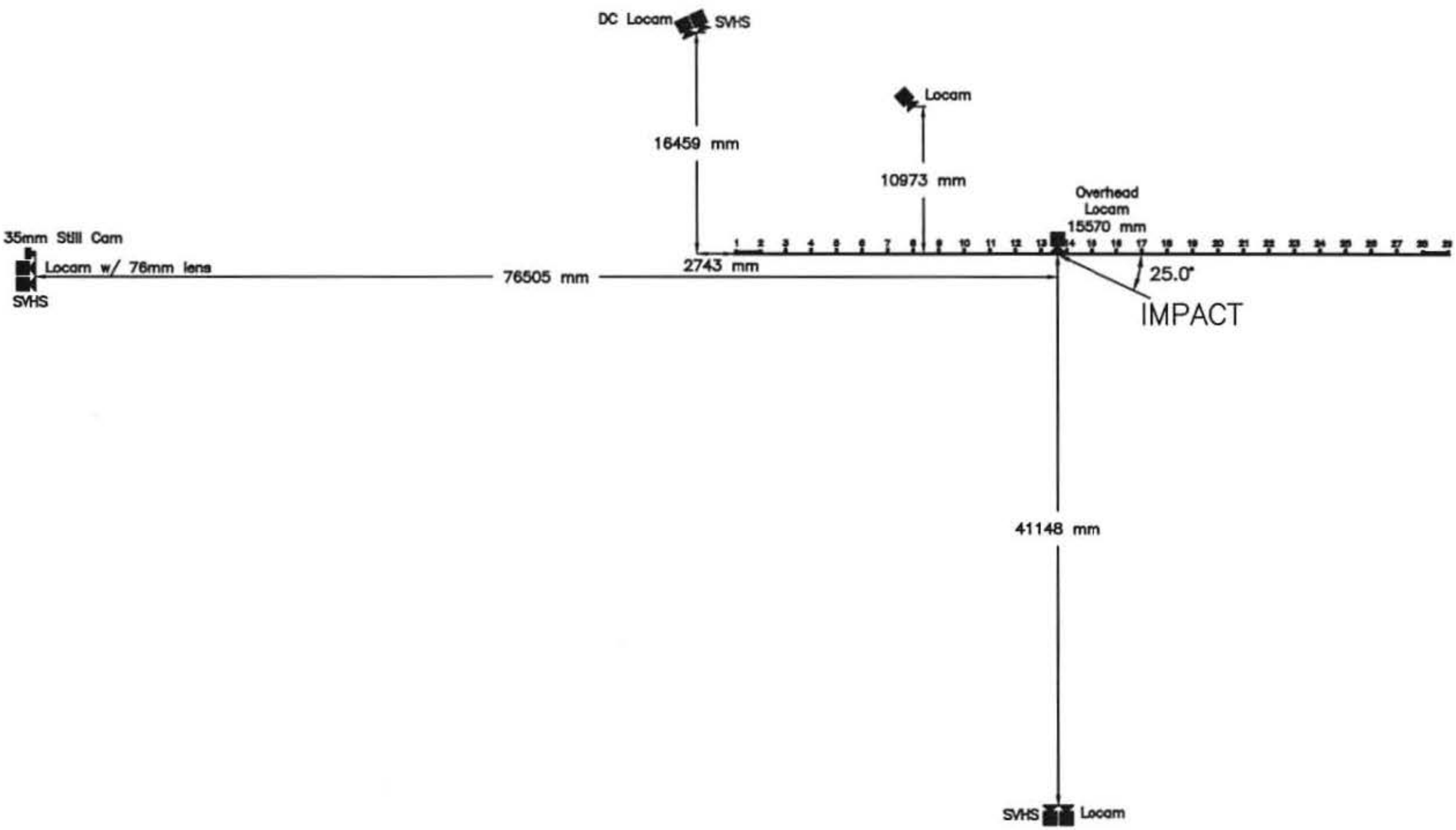


Figure 6. Location of High-Speed Cameras, Test NEC-1

6 CRASH TEST NO. 1

6.1 Test NEC-1

The 1,979-kg pickup truck impacted the guardrail over curb system at a speed of 103.2 km/hr and an angle of 24.5 degrees. A summary of the test results and the sequential photographs are shown in Figure 7. Additional sequential photographs are shown in Figure 8. Documentary photographs of the crash test are shown in Figures 9 and 10.

6.2 Test Description

Initial impact occurred between post nos. 13 and 14 or 660-mm downstream from the center of post no. 14, as shown in Figure 11. At 0.028 sec, post no. 13 was rotating backward without significant twisting. At 0.040 sec after impact, the right-front corner of the vehicle was at post no.13, while post nos. 13 and 14 deformed at 0.052 sec. At 0.078 sec, the vehicle was near the midspan between post nos. 12 and 13 and did not appear to be redirecting. At this same time, the right-front tire deformed outward. At 0.086 sec, the vehicle was upstream of post no. 12 when it began to significantly twist counter-clockwise (CCW) while being pushed to the ground. At 0.090 sec, the guardrail was positioned under the right-front corner of the vehicle. At 0.094 sec, post no. 12 was impacted by the right-front quarter-point of the vehicle. As post no. 12 was released from the W-beam rail and at 0.120 sec, the bottom downstream corner of the wood blockout was pushed up against the lower, flattened region of the W-beam rail splice. Shortly thereafter, a tear in the W-beam rail began at the bottom downstream bolt location and propagated upward through the bolt group. At 0.134 sec, the guardrail fractured at the splice located at post no. 12, allowing the vehicle to penetrate behind the system. At this same time, it was evident that the tearing began prior to the deformed right-front wheel reaching the rail rupture region . At 0.160 sec, the front midpoint of the vehicle was at post no. 11. At this same time, the remaining stub length of guardrail upstream of post no. 11 was deforming around the post and into the front of the vehicle. The guardrail between post nos. 12 and 13 was positioned along the right side of the vehicle at this same time. At 0.186 sec, the vehicle traveled over post no. 11. At 0.197 sec, the vehicle had redirected approximately 11 degrees. At this same time, the guardrail released from post no. 10, buckled at the point of release, and continued to wrap around post no. 11. The left quarter-point of the vehicle impacted post no. 10 at 0.245 sec. At 0.252 sec, the right-front tire deformed inward with the rim digging into the ground. At 0.270 sec, the vehicle's right-rear tire was off the ground, while the rear end of the vehicle reached its maximum position above the ground at 0.294 sec. At 0.306 sec, the vehicle yawed CCW while still moving forward. The vehicle's right-rear tire contacted the ground at 0.445 sec. At 0.538 sec, the vehicle became parallel to the system. At 0.553 sec, the right-front tire deformed to the point of the rim being parallel with the ground, and at this same time, the vehicle rolled toward the left. At 0.60 sec, the vehicle reached its maximum roll angle of 8.1 degrees. At 0.613 sec, the vehicle continued to yaw CCW and moved away from the backside of the system. At 0.866 sec, the vehicle reached its maximum pitch angle of 5.4 degrees. The vehicle's post-impact trajectory is shown in Figure 7. The vehicle came to rest behind the system, approximately 46.02-m downstream from impact and 12.19-m laterally behind a line projected parallel to the traffic-side face of the rail, as shown in Figure 7.

6.3 Barrier Damage

Damage to the barrier was extensive, as shown in Figures 12 through 16. Actual vehicle impact occurred midway between post nos. 13 and 14. Barrier damage consisted mostly of deformed guardrail posts, contact marks on a guardrail section, and deformed and fractured W-beam rail. As shown in Figures 12 through 15, the failure of the W-beam splice at post no. 12 caused significant damage to the posts and guardrail located downstream.

Three steel posts, post nos. 10 through 12, were twisted and bent toward the ground. Two other steel posts, post nos. 13 and 14 were rotated 102 mm and 51 mm at the ground, respectively. Both downstream BCT posts, post nos. 1 and 2, were partially split down the middle and remained standing. Post no. 3 through 8 twisted in the clockwise (CW) direction when looking at the traffic side of the rail. The slots in the guardrail at these post were also damaged. No significant post or guardrail damage occurred upstream of post no. 14.

Minor guardrail bucking occurred 102-mm downstream of post no. 14. The W-beam pulled off of post nos. 10 through 12. The W-beam fractured at post no.12 and folded about the location of post no. 10 with the final location of the W-beam behind post no. 9, as shown in Figures 12 and 13. Contact marks were found on the guardrail between post nos. 10 and 13. The W-beam's lower hump was flattened along the distance of 1600-mm downstream of post no. 14 through post no. 12.

6.4 Vehicle Damage

Exterior vehicle damage was moderate, as shown in Figures 17 and 18. Occupant compartment damage was negligible. The vehicle experienced extensive frontal crush, as shown in Figure 18. The radiator was crushed inward toward the engine, and the engine was displaced into the firewall. The front bumper was flattened and pushed inward toward the engine compartment. Deformation occurred to the left-front, right-front, and right-rear quarter panels. The right-front wheel assembly was deformed. The right-front wheel sustained tire holes and rim damage. The roof, the hood, and all the window glass remained undamaged.

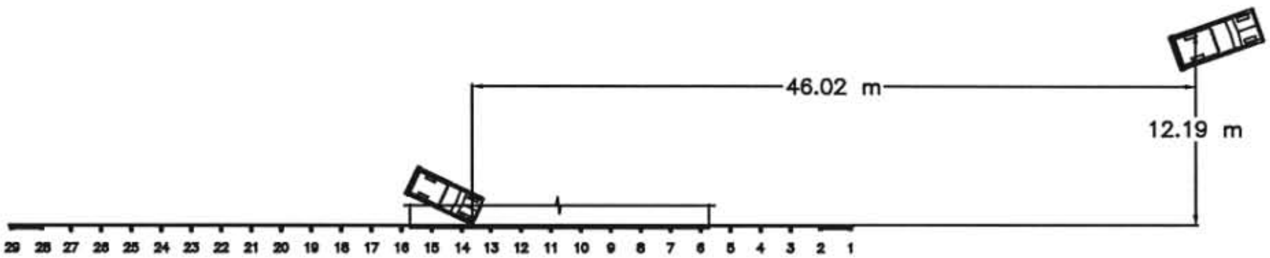
6.5 Occupant Risk Values

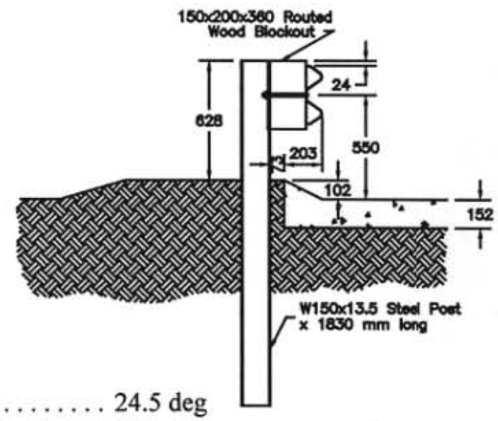
The normalized longitudinal and lateral occupant impact velocities were not determined due to the failure of the barrier system as the vehicle penetrated through the system. The maximum 0.010-sec average occupant ridedown decelerations in the longitudinal and lateral directions also were not calculated due to the failure of the system. However, these results are shown graphically in Appendix A for use in further analysis and system redesign. The results from the rate transducer are shown graphically in Appendix B.

6.6 Discussion

The analysis of the test results for test NEC-1 showed that the guardrail installed over a curb did not contain nor redirect 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. The vehicle's trajectory did not intrude into adjacent traffic lanes, but the penetration of the vehicle through the system was unacceptable. Therefore, test NEC-1 conducted on the guardrail/curb combination was determined to be unacceptable according to the NCHRP Report No. 350 criteria.

0.000 sec | 0.078 sec | 0.120 sec | 0.160 sec | 0.197 sec





- Test Number NEC-1
- Date 5/19/98
- Appurtenance . . . . W-beam guardrail over curb system
- Total Length . . . . 53.34 m
- Steel W-Beam
  - Thickness . . . . 2.66 mm
  - Top Mounting Height . . . . 706 mm
- Steel Posts
  - Post Nos. 3 - 27 . . . . W150x13.5 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 . . . . 150 mm x 200 mm by 360-mm long
- Curb . . . . AASHTO 102 mm x 203 mm Type "G" Curb
  - Curb Span . . . . 533-mm downstream post no. 16 to 533-mm downstream post no. 6
  - Total Curb Length . . . . 19.05 m
- Soil Type . . . . Grading B - AASHTO M 147-65 (1990)
- Vehicle Model . . . . 1991 GMC 2500 ¾-Ton
  - Curb . . . . 1,836 kg
  - Test Inertial . . . . 1,979 kg
  - Gross Static . . . . 1,979 kg
- Vehicle Speed
  - Impact . . . . 103.2 km/hr
  - Exit . . . . NA
- Vehicle Angle
  - Impact . . . . 24.5 deg
  - Exit . . . . NA
- Vehicle Snagging . . . . NA
- Vehicle Pocketing . . . . NA
- Vehicle Stability . . . . Satisfactory
- Occupant Ridedown Deceleration (10 msec avg.)
  - Longitudinal . . . . NA
  - Lateral (not required) . . . . NA
- Occupant Impact Velocity (Normalized)
  - Longitudinal . . . . NA
  - Lateral (not required) . . . . NA
- Vehicle Damage . . . . Moderate
  - TAD[14] 1-RFQ-3/1-FR-3
  - SAE[15] 1-FZEE2
- Vehicle Stopping Distance . . . . Behind the system
  - Left Rear Tire . . . . 46.02 m downstream 12.19 m behind
- Barrier Damage . . . . Extensive (W-beam splice failure at post no. 12)
- Maximum Deflections
  - Permanent Set . . . . NA
  - Dynamic . . . . NA

Figure 7. Summary of Test Results and Sequential Photographs, Test NEC-1


0.000 sec


0.000 sec


0.000 sec


0.122 sec


0.116 sec


0.072 sec


0.200 sec


0.163 sec


0.132 sec


0.258 sec


0.223 sec


0.170 sec


0.431 sec


0.306 sec


0.222 sec


0.613 sec


0.445 sec


0.252 sec

Figure 8. Additional Sequential Photographs, Test NEC-1

Figure 9. Documentary Photographs, Test NEC-1

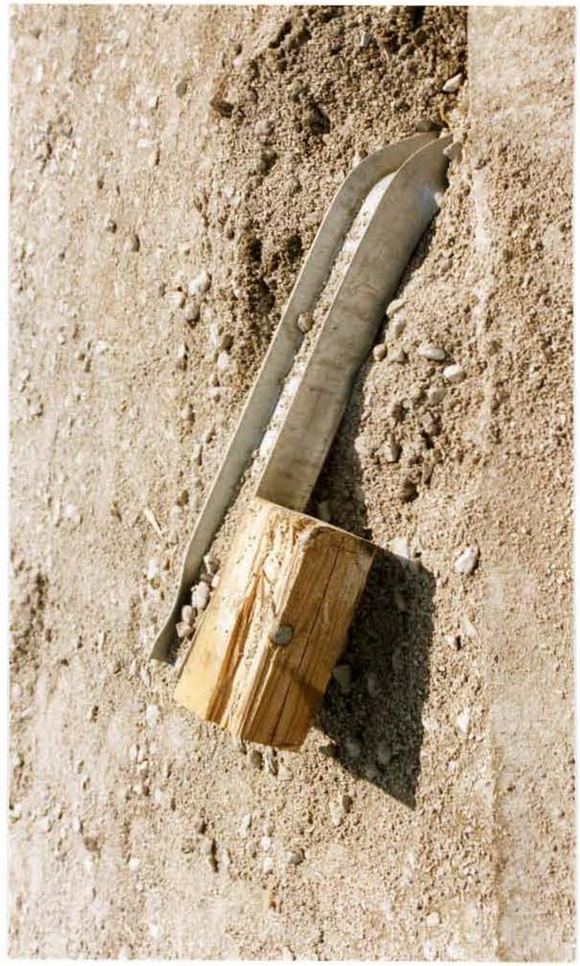
Figure 10. Documentary Photographs, Test NEC-1

Figure 11. Impact Location, Test NEC-1

Figure 12. Guardrail Over Curb System Damage, Test NEC-1

Figure 13. Guardrail Over Curb System Damage, Test NEC-1

Post No. 10



Post No. 11

Post No. 12

Figure 14. Post Damage, Test NEC-1

Figure 15. BCT Cable Anchor Post Nos. 1 and 2 Damage - Downstream End, Test NEC-1

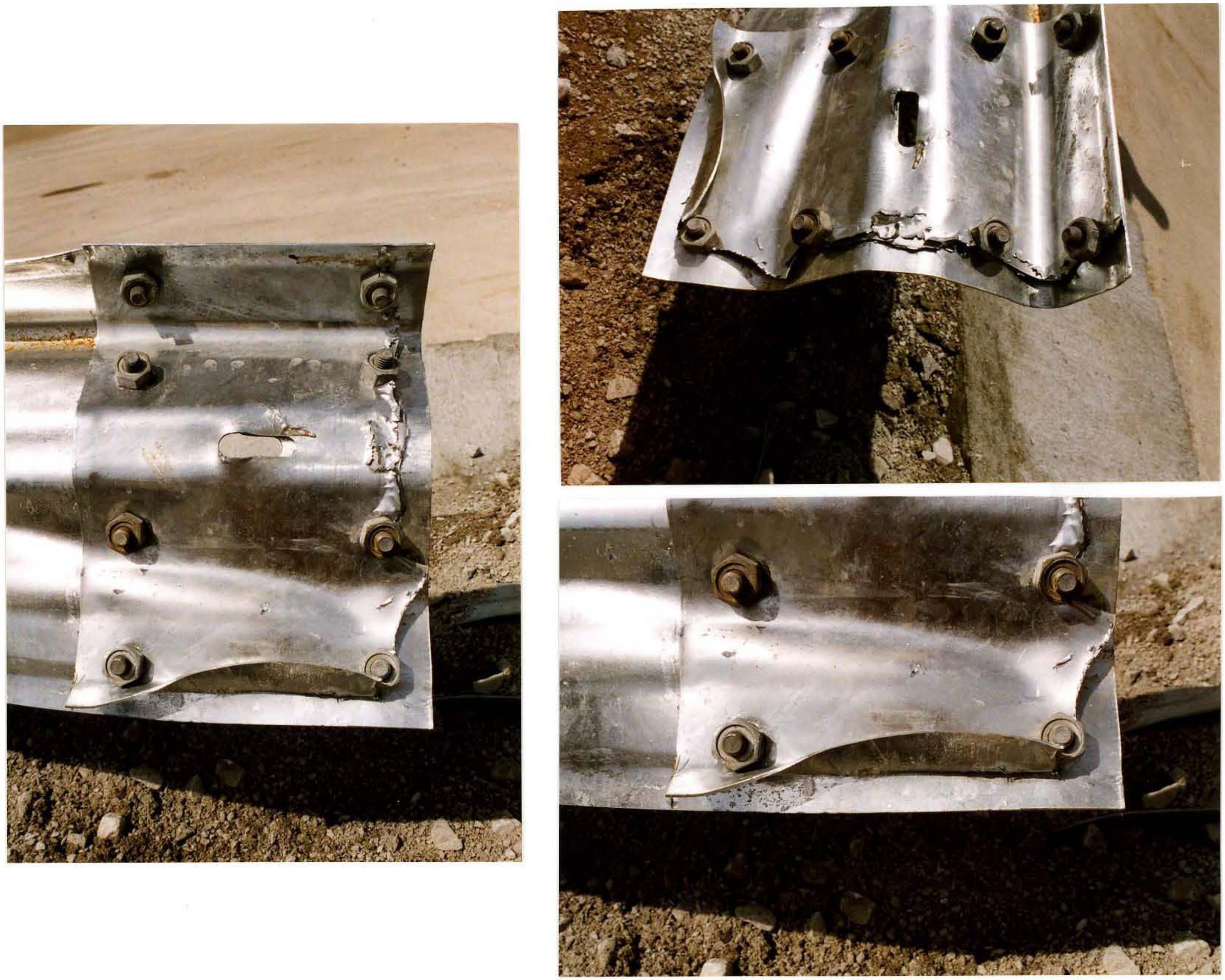


Figure 16. Damage to W-beam Rail Splice at Post No. 12, Test NEC-1

Figure 17. Vehicle Damage, Test NEC-1

Figure 18. Front-End Vehicle Damage, Test NEC-1

7 DISCUSSION

Following an analysis of the test results, a safety performance evaluation was conducted, and test no. NEC-1 was determined to be unacceptable according to the NCHRP Report No. 350 criteria. Due to the unsuccessful crash test of the guardrail/curb combination, it was necessary to determine the cause of the poor barrier performance so that design modifications could be made to the barrier system in order to improve its overall safety. An investigation of test results revealed that the vehicle did not override the guardrail system prior to the failure of the W-beam rail splice at post no. 12. In addition, no strong case for the influence of the curb on the vehicle's tire and suspension effecting the test can be made from evaluation of the film. The several factors that are likely to have contributed to the failure are discussed below.

First, although the AASHTO M180 steel used in W-beam guardrails is a relatively ductile material and can sustain significant plastic strain without failure, full-scale crash tests have indicated that guardrails tend to fail at relatively low plastic strains. Recall that the cross-section of a W-beam rail element is reduced by approximately 15 percent at the rail splice. This reduction in cross-section tends to localize strain in the splice region and leads to rail rupture near the point that the full cross-section begins to yield. Consequently, the critical impact location (CIP) was based upon the impact condition which produced the greatest potential for rail rupture; where rupture would occur at a rail splice.

Second, the guardrail post and blockout located at post no. 12 or the location of the W-beam rail splice encountered significant twisting as it was pushed back and toward the ground. This rotation and subsequent movement resulted in the bottom downstream corner of the wood blockout being pushed up against the lower, flattened region of the W-beam rail splice. Subsequently, a tear in the W-beam rail was observed at the bottom downstream bolt location of the rail splice which later propagated upward through the reduced-area cross-section. This tearing action occurred as the right-front corner of the vehicle was in contact with the rail splice region. In addition, this rail rupture resulted in the loss of all tensile capacity which led to the significant vehicle penetration into the guardrail system.

Finally, the guardrail/curb combination was constructed with an increased post embedment depth of 102 mm, resulting from the placement of soil fill on the back side of the concrete curb. As a result of the increased post embedment depth as well as the concrete pad positioned on the ground surface near traffic-side face of the posts, the post stiffness and strength behaviors evidenced during the crash test would likely have increased. With the increased post stiffness and strength, a slight increase in vehicle pocketing on the upstream side of a guardrail post may have occurred, as observed by the significantly twisting of post no. 12, resulting in localized strain in splice region.

Following this investigation, MwRSF researchers believed that the guardrail/curb combination could be significantly improved by incorporating only modest changes in the system, such as increasing the capacity of the W-beam rail. However, in order to more accurately investigate and study the vehicle interaction with combination guardrail/curb barrier systems, three-dimensional computer simulation modeling would likely be required in the future.

8 DEVELOPMENTAL TESTING – LIVE-DRIVER TESTS

8.1 Background and Test Conditions

Following the unsuccessful full-scale vehicle crash test on the guardrail installed over curb, developmental testing was used to determine the interaction between the curb and the vehicle's tire and suspension. The vehicular motions of the pickup truck components would be used for comparison to future simulation work.

Three impact tests were performed on a 102-mm high triangular-shape curb, as shown in Figure 19, and are summarized in Table 3. For test no. 1, 2, and 3, a 1994 Chevrolet ¾-ton pickup truck was driven into the curb with variations in the impact speed as well as the suspension of the vehicle. The vehicle dimensions are shown in Figure 20. For the tests, the vehicle impacted at a speed of either 64 km/hr or 100 km/hr and at an angle of 25 degrees. 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 21. Curb impact performance was evaluated in terms of the trajectories of vehicular components including: (1) the right-front wheel, (2) the right-rear wheel, (3) the right-front bumper, (4) the right-rear bumper, (5) the right-front fender, and (6) the right-rear fender.

Table 3. Summary of Developmental Testing – Live Driver Tests

Test No.	Speed (km/hr)	Angle (degrees)	Suspension Variation
1	64	25	None
2	100	25	None
3	100	25	Removal of sway bar

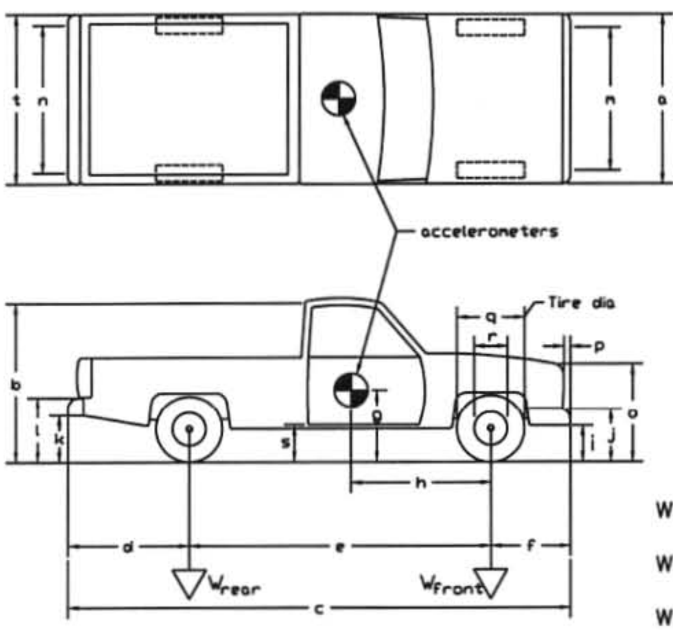
Figure 19. 102-mm High Triangular-Shape Curb

Date: 9/10/98 Test Number: Curb Test No. 1, 2, 3 Model: 2500

Make: GMC 2500 Vehicle I.D.#: 1GDGC24K2RE550535

Tire Size: LT245/75R16 Year: 1994 Odometer: 198,197

*(All Measurements Refer to Impacting Side)



Vehicle Geometry – mm

a	1899	b	1842
c	5531	d	1295
e	3327	f	908
g	737	h	1410
i	470	j	635
k	591	l	775
m	1600	n	1626
o	1003	p	89
q	749	r	445
s	489	t	1848

Wheel Center Height Front 365

Wheel Center Height Rear 362

Wheel Well Clearance (FR) 883

Wheel Well Clearance (RR) 953

Engine Type 8 cyl.

Engine Size 5.7L 350 CID

Transmission Type:

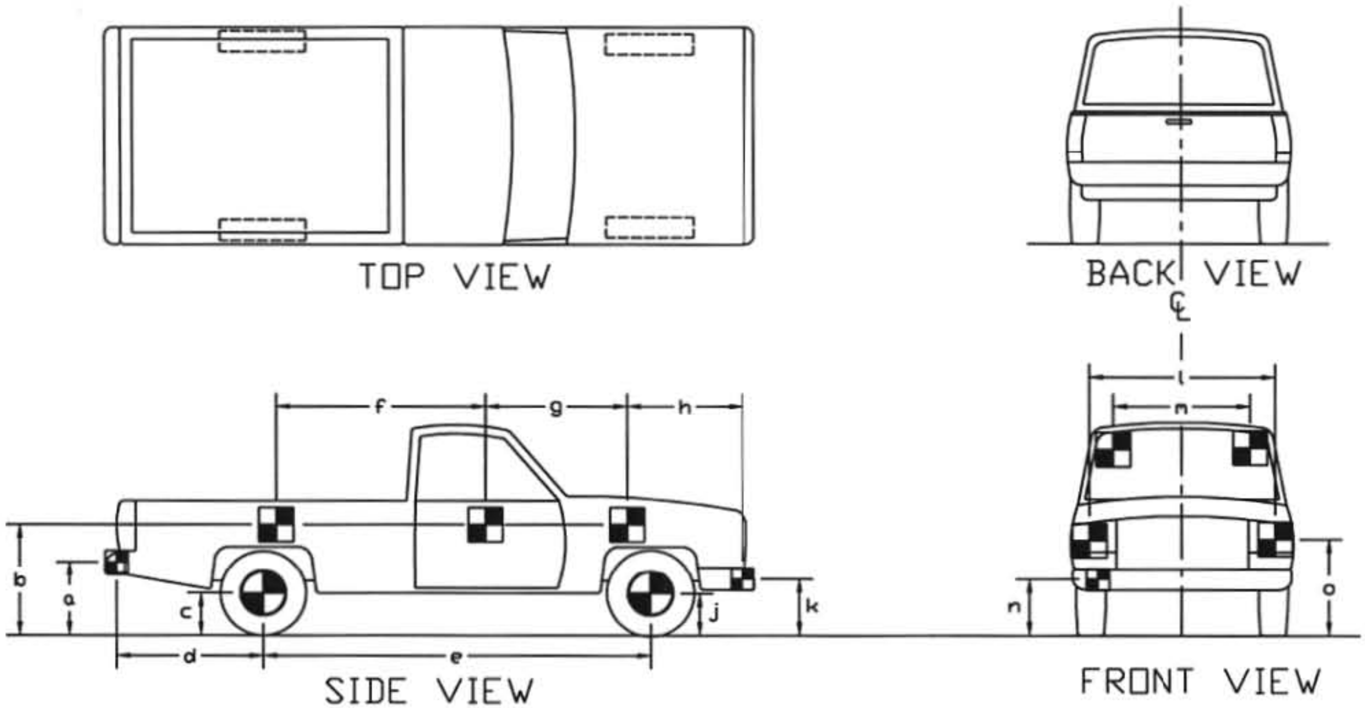
Automatic or Manual

FWD or RWD or 4WD

Weights – kg	Curb	Test Inertial	Gross Static
W_{front}	1182	---	---
W_{rear}	867	---	---
W_{total}	2049	---	---

Note any damage prior to test: NONE

Figure 20. Vehicle Dimensions, Curb Test Nos. 1, 2, and 3



TEST #: Curb Test No. 1, 2, 3

TARGET GEOMETRY (mm)

a	711	d	1226	g	1308	k	557	n	557
b	1003	e	3340	h	575	l	1419	o	---
c	371	f	2021	j	364	m	1213		

Figure 21. Vehicle Target Locations, Curb Test No. 1, 2, and 3

8.2 Test Results

8.2.1 Curb Test No. 1

The pickup truck was driven over the curb at a speed of 64 km/hr and an angle of 25 degrees. The suspension of the truck was not altered prior to testing. The trajectories of the front and rear wheels, the front and rear bumpers, and the front and rear fenders are shown in Figure 22.

8.2.2 Curb Test No. 2

The pickup truck was driven over the curb at a speed of 100 km/hr and an angle of 25 degrees. The suspension of the truck was not altered prior to testing. The trajectories of the front and rear wheels, the front and rear bumpers, and the front and rear fenders are shown in Figure 23.

8.2.3 Curb Test No. 3

The pickup truck was driven over the curb at a speed of 100 km/hr and an angle of 25 degrees. The sway bar of the suspension was removed from the truck prior to testing. The trajectories of the front and rear wheels, the front and rear bumpers, and the front and rear fenders are shown in Figure 24.

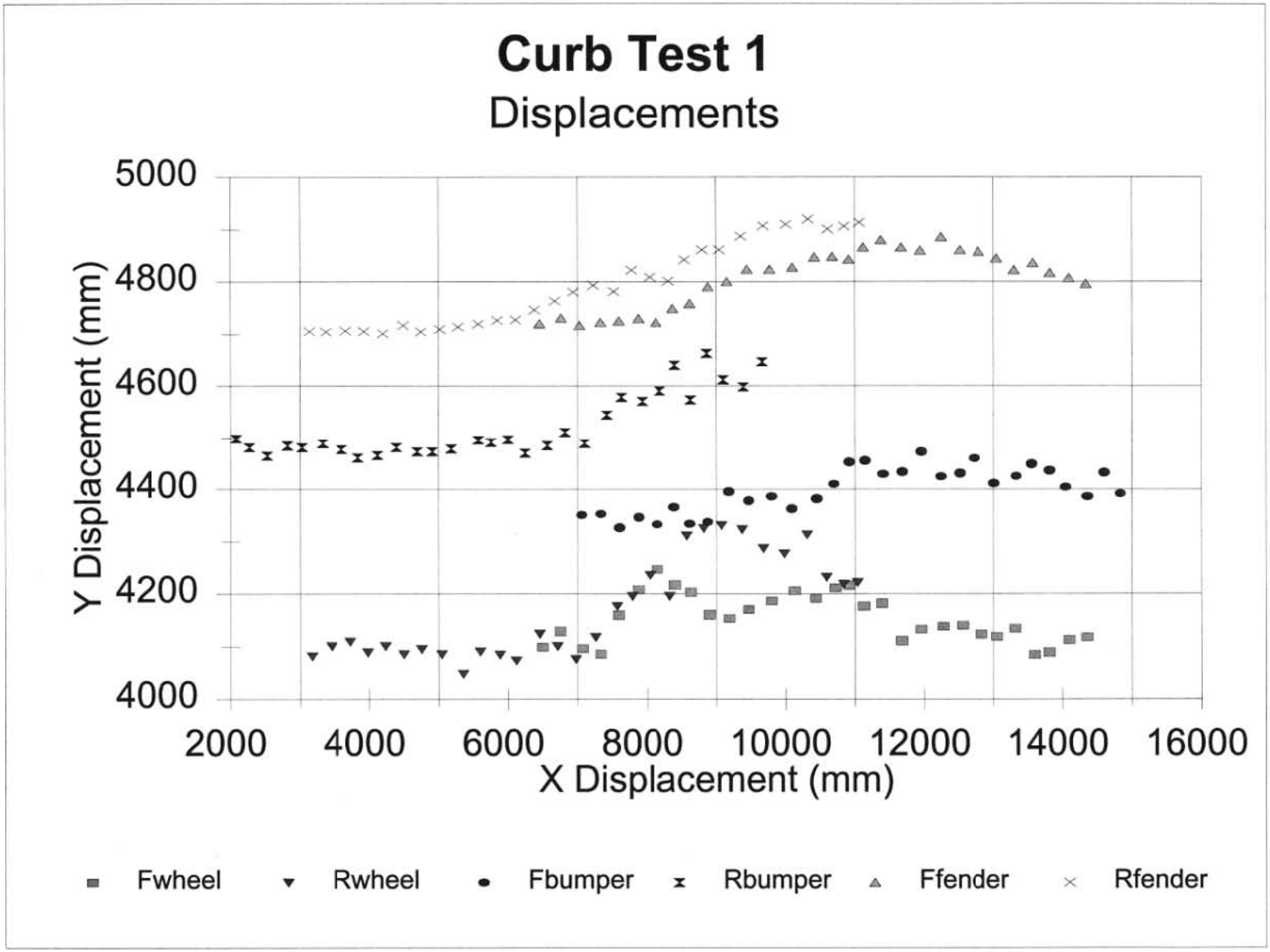


Figure 22. Vehicular Component Trajectories, Curb Test No. 1

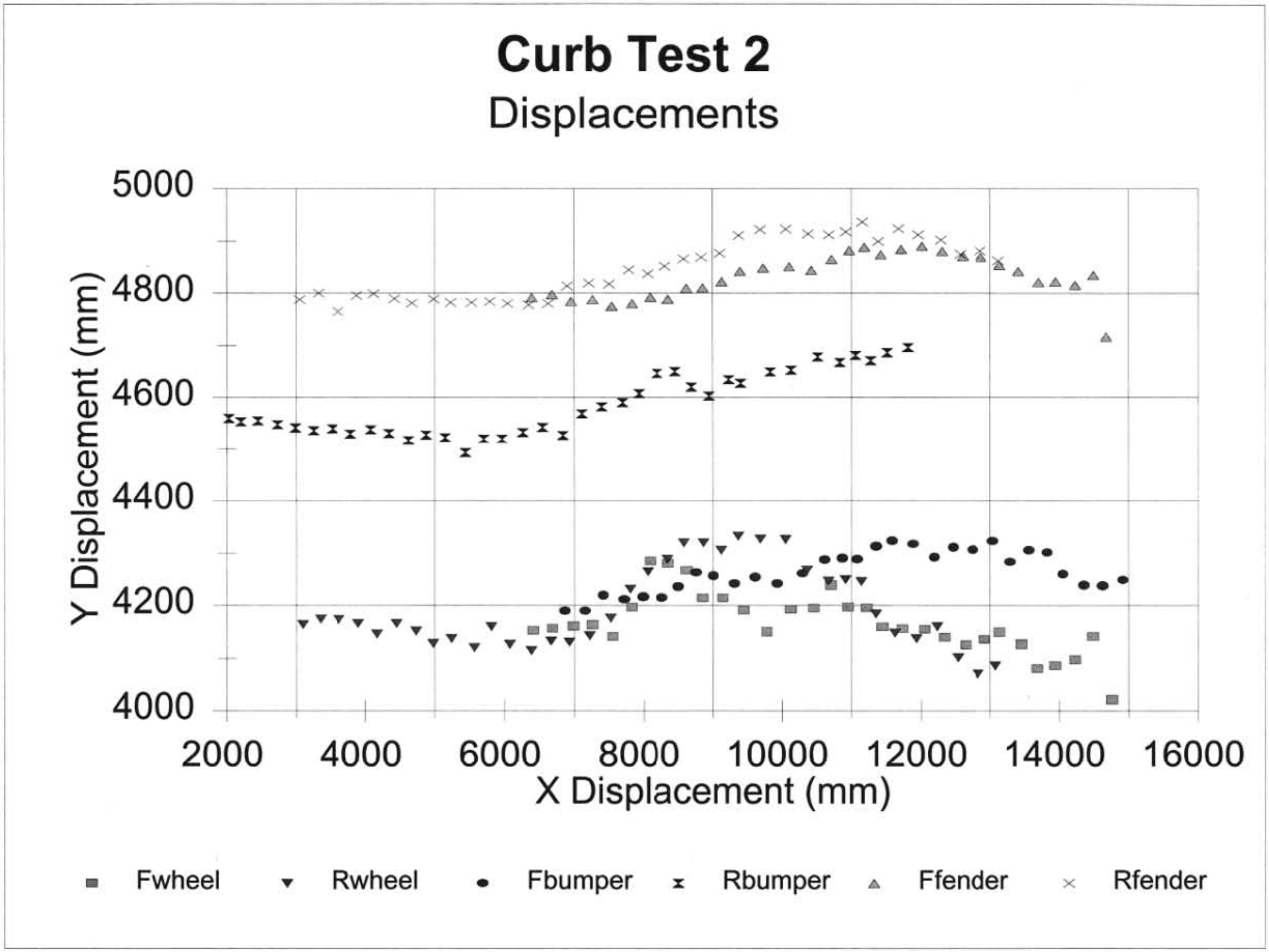


Figure 23. Vehicular Component Trajectories, Curb Test No. 2

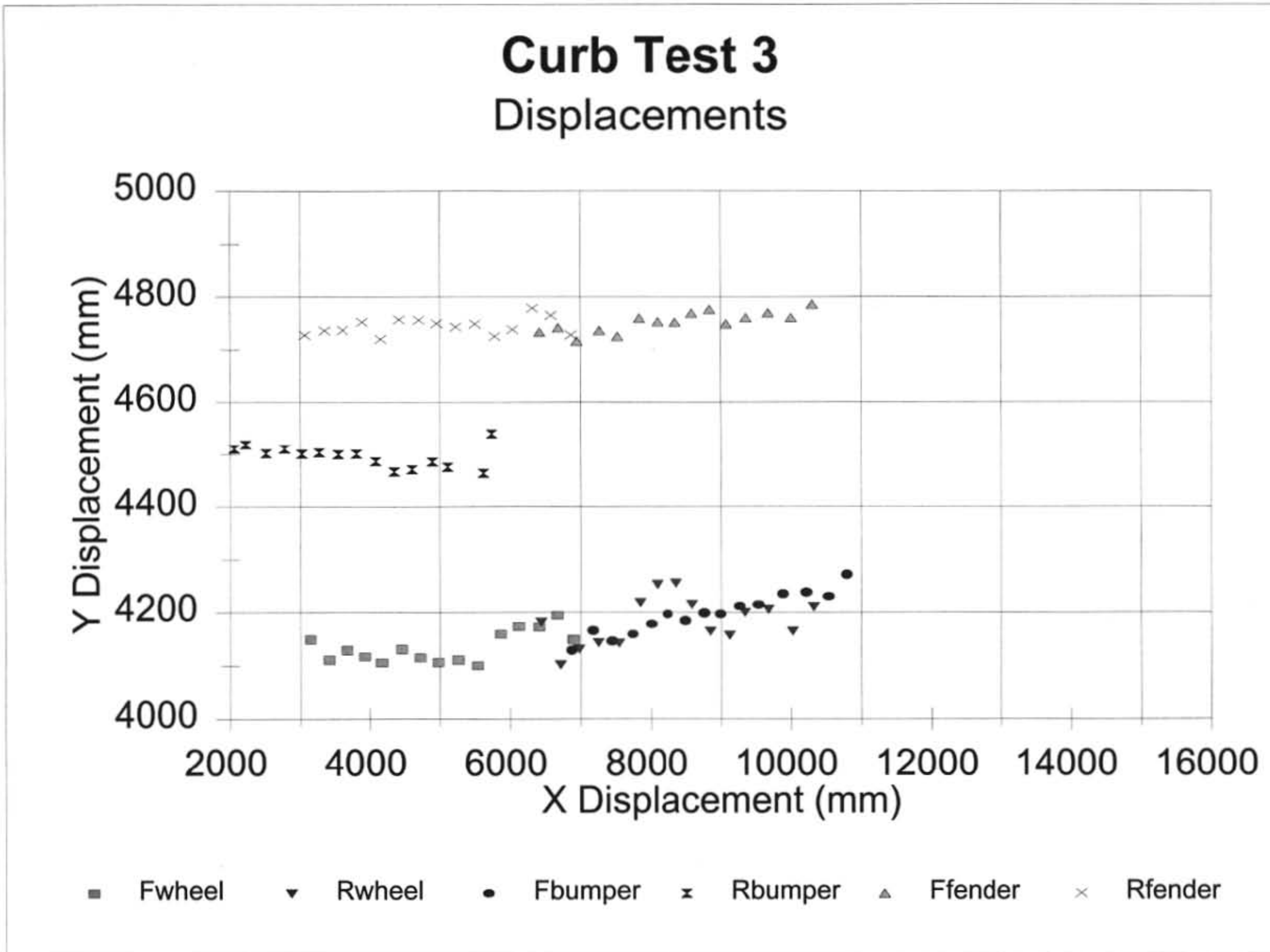


Figure 24. Vehicular Component Trajectories, Curb Test No. 3

9 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 W-beam rail and installed over a triangular-shape curb. One full-scale vehicle crash test was performed according to the TL-3 criteria found in NCHRP Report No. 350. The crash test, test no. NEC-1, failed due to severe vehicle penetration into the guardrail system. This vehicle penetration occurred as a result of a loss of rail tensile capacity during vehicle redirection. The loss of rail capacity was determined to have occurred with the rupture of the W-beam rail splice at post no. 12. A summary of the safety performance evaluation is provided in Table 4.

Table 4. Summary of Safety Performance Evaluation Results - Guardrail over Curb System

Evaluation Factors		Evaluation Criteria	Test NEC-1
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.	U
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.	NA
	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.	NA

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

10 RECOMMENDATIONS

A guardrail system designed for use over curbs, as described in this report, was unsuccessfully crash tested according to the criteria found in NCHRP Report No. 350. The results of this test indicate that this design is not suitable for use on Federal-aid highways due to the failure of the W-beam rail splice at post no. 12.

Although the guardrail/curb combination did not perform in an acceptable manner, there still exists the potential for W-beam guardrail/curb systems to meet the TL-3 safety standards. It is likely that simple modifications will greatly improve the system's performance. Examples of these design modifications include the following and/or combinations thereof: (1) incorporating nested 12-gauge W-beam rail; (2) replacing the single 12-gauge rail with 10-gauge material; (3) relocating the rail splice away from a post location; (4) reducing post spacing; and (5) replacing the steel posts with wood CRT posts. However, any design modifications made to the guardrail/curb combination system can only be verified through the use of full-scale vehicle crash testing.

11 REFERENCES

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12 APPENDICES

APPENDIX A

Accelerometer Data Analysis, Test NEC-1

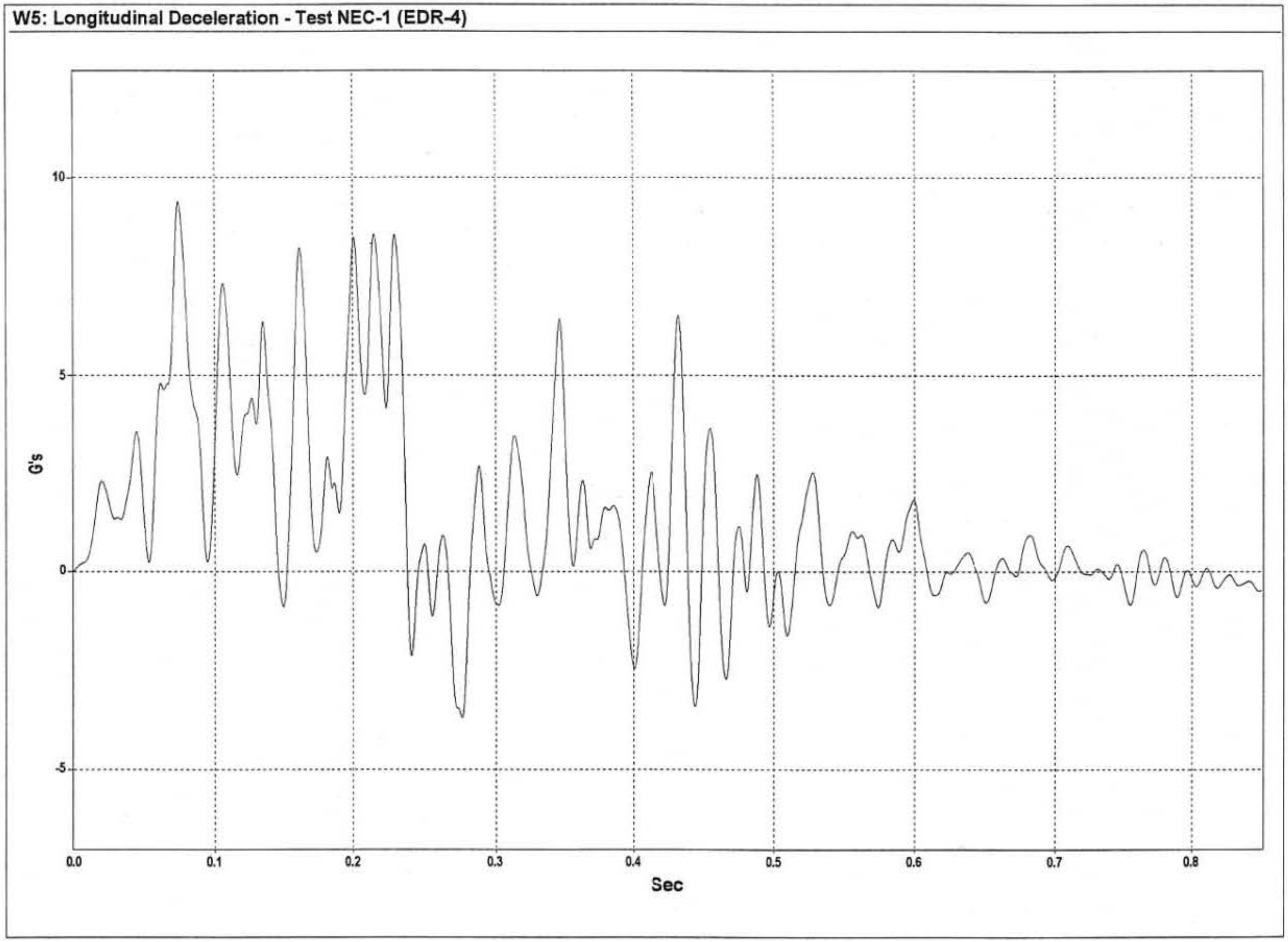

Figure A-1. Graph of Longitudinal Deceleration, Test NEC-1

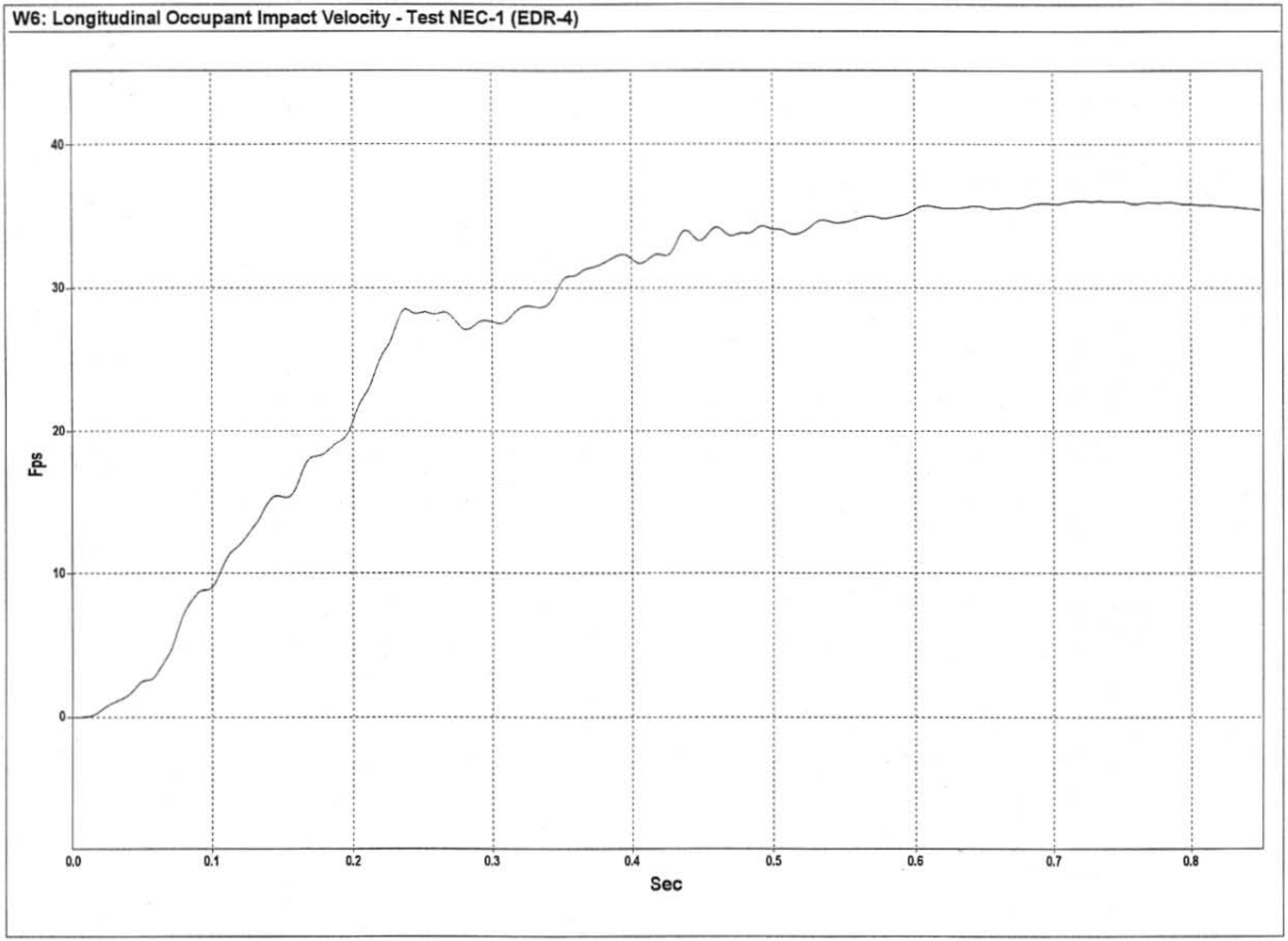

Figure A-2. Graph of Longitudinal Occupant Impact Velocity, Test NEC-1

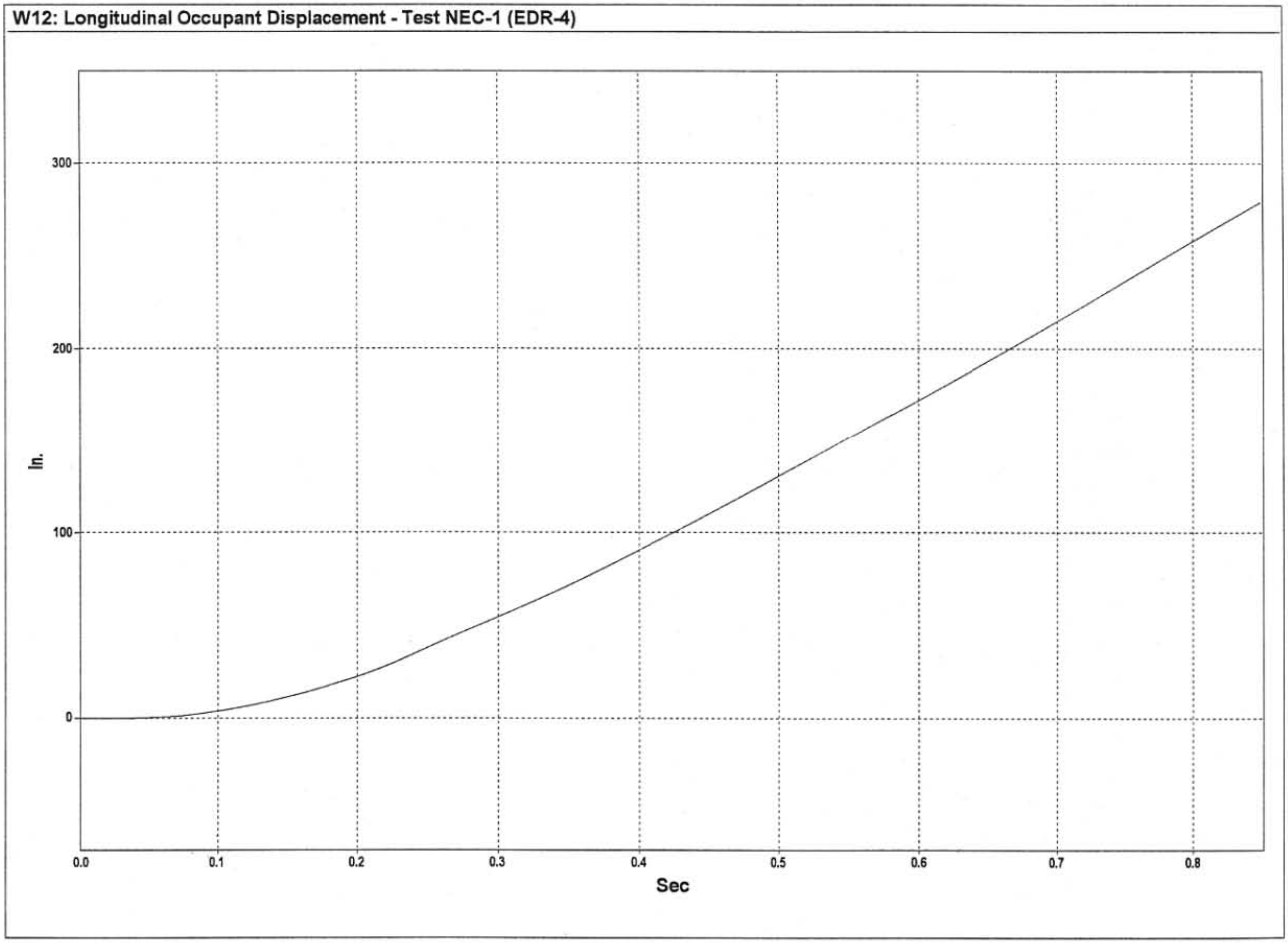

Figure A-3. Graph of Longitudinal Occupant Displacement, Test NEC-1

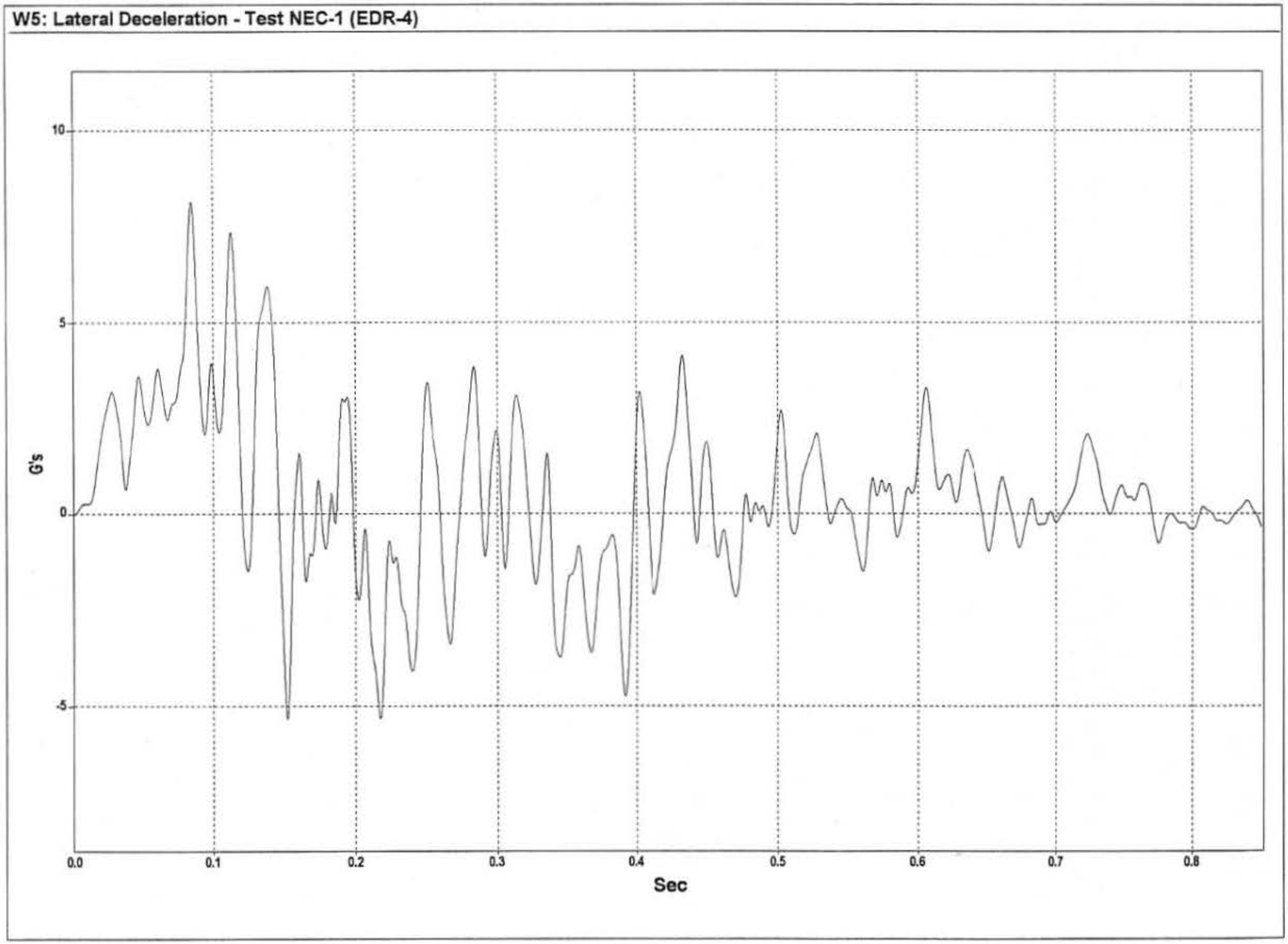

Figure A-4. Graph of Lateral Deceleration, Test NEC-1

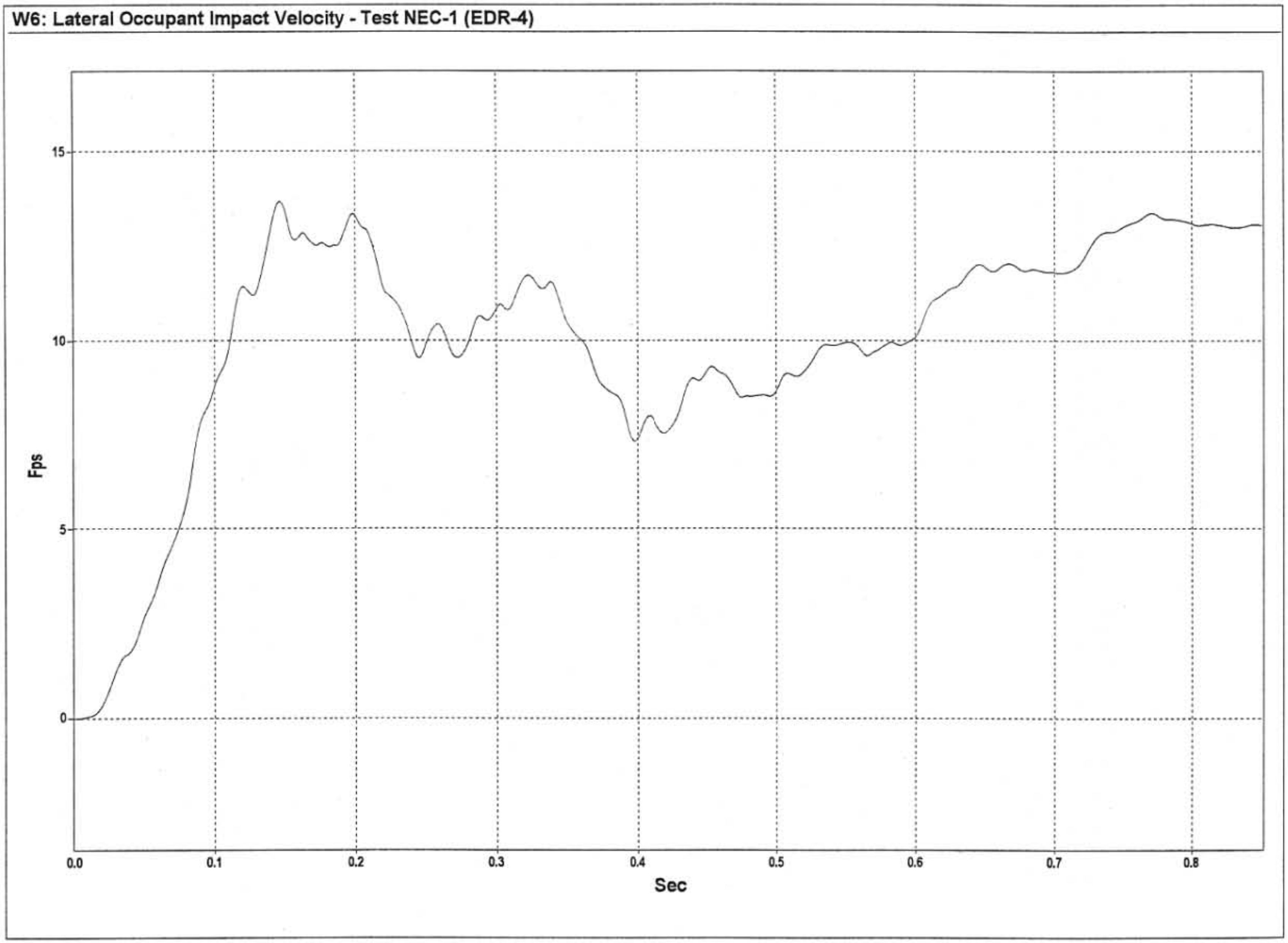

Figure A-5. Graph of Lateral Occupant Impact Velocity, Test NEC-1

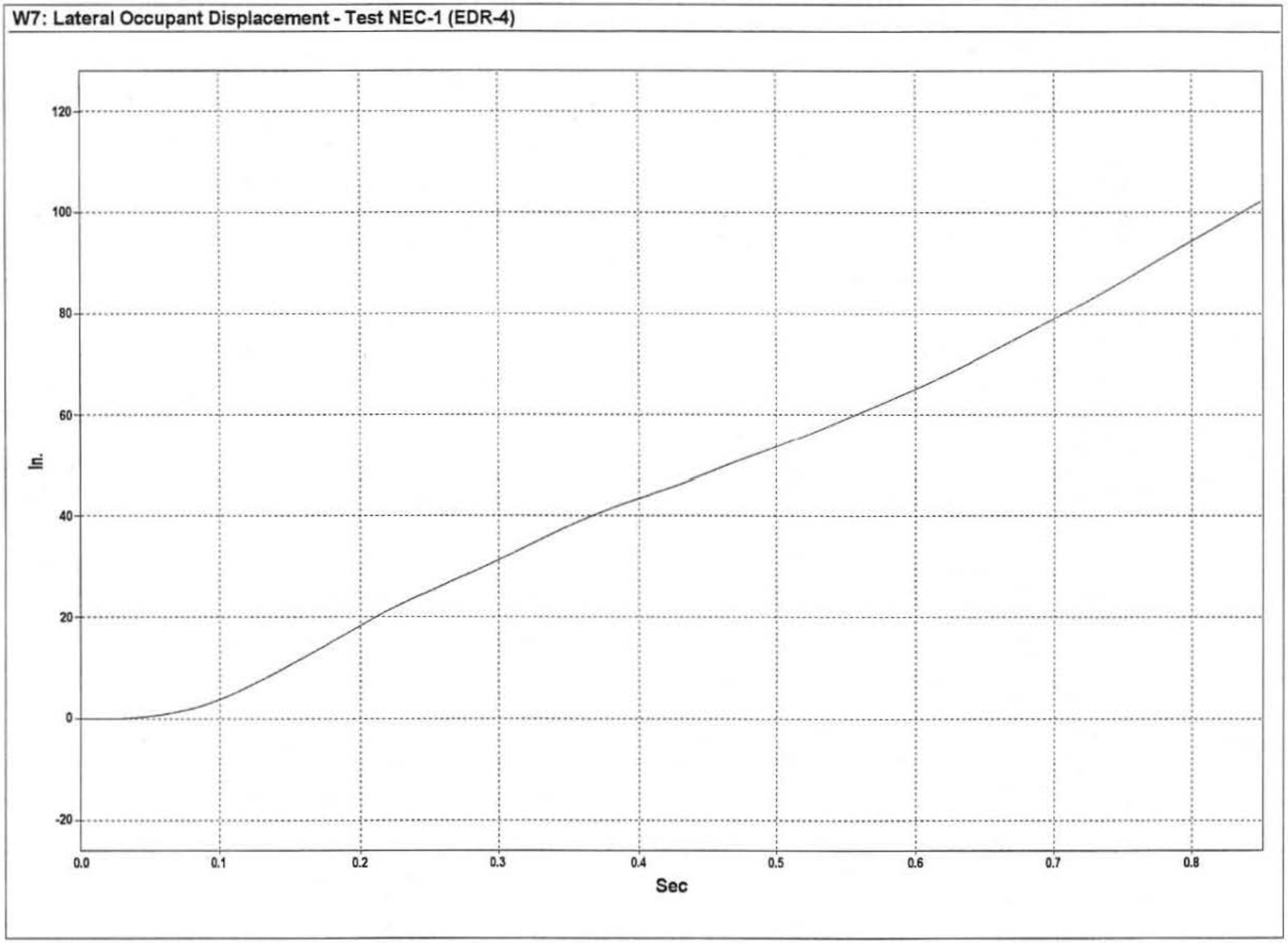

Figure A-6. Graph of Lateral Occupant Displacement, Test NEC-1

APPENDIX B

Rate Transducer Data Analysis, Test NEC-1

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

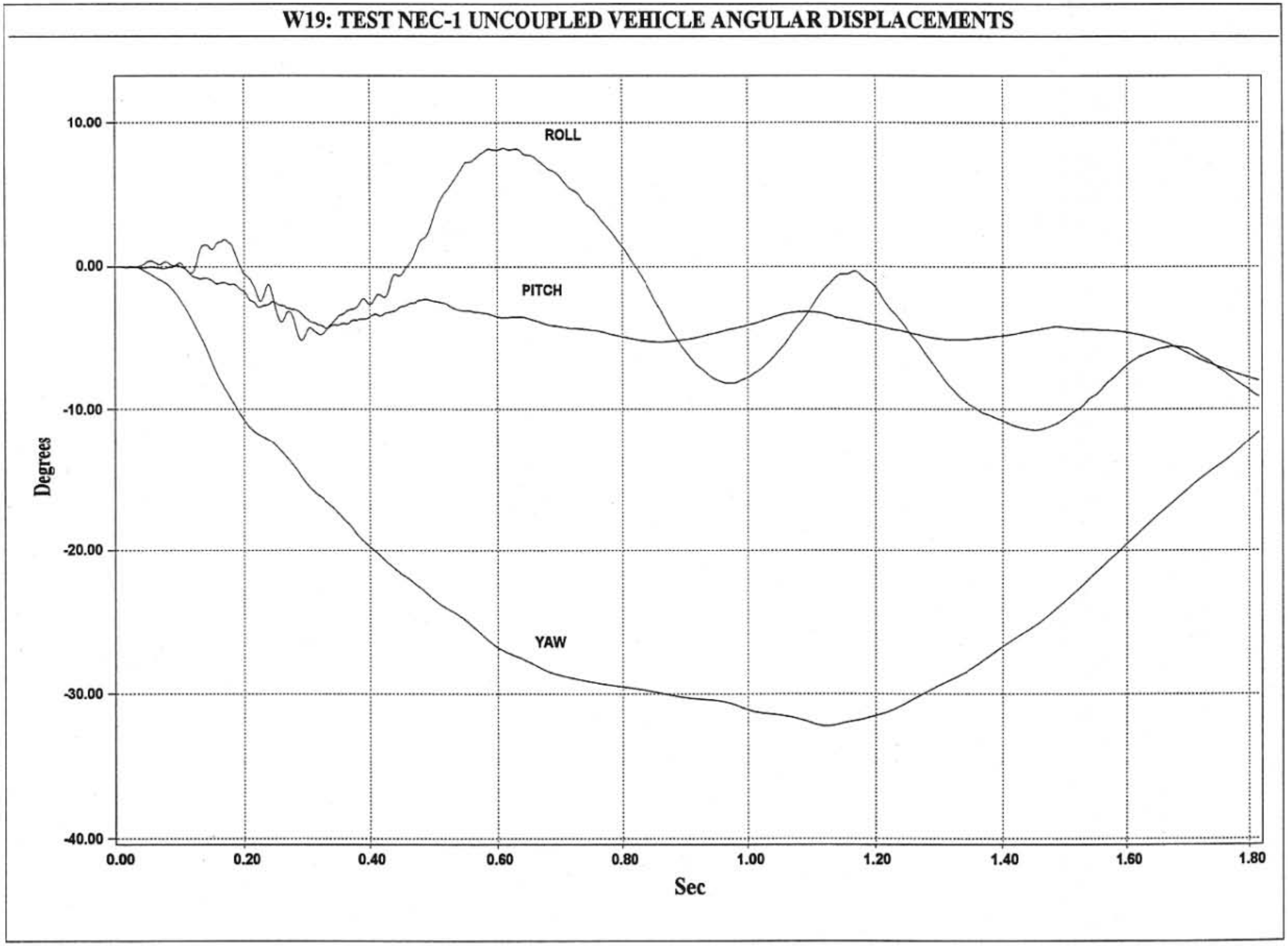

Figure B-1. Graph of Roll, Pitch, and Yaw Angular Displacements, Test NEC-1