

**PERFORMANCE EVALUATION OF THE
FREE-STANDING TEMPORARY BARRIER –
UPDATE TO NCHRP 350 TEST NO. 3-11
(2214TB-1)**

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16. Abstract (Limit: 200 words) Based on the proposed changes to the National Cooperative Highway Research Program (NCHRP) Report No. 350 guidelines, NCHRP Project 22-14(2) researchers deemed it appropriate to evaluate a free-standing temporary concrete barrier system prior to finalizing the new crash testing procedures and guidelines. For this effort, the free-standing temporary barrier system was selected for evaluation. One full-scale vehicle crash test was performed on the longitudinal barrier system in accordance with the Test Level 3 (TL-3) requirements presented in the Update to NCHRP Report No. 350. For the testing program, a 2270P pickup truck vehicle, which was a ¾-ton, two-door vehicle, was used. The free-standing temporary barrier system provided an acceptable safety performance when impacted by the ¾-ton, two-door pickup truck, thus meeting the proposed TL-3 requirements presented in the Update to NCHRP Report No. 350. This test vehicle was not ultimately recommended for inclusion in the Update to NCHRP Report No. 350.			
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1 INTRODUCTION

1.1 Problem Statement

In the late 1990s, roadside safety experts, State DOT representatives, Federal government officials, and industry personnel began discussions and preparations for updating the National Cooperative Highway Research Program (NCHRP) Report No. 350 safety performance guidelines (1). The new guidelines would improve upon existing test procedures, consider changes in the vehicle fleet, provide criteria for new roadside hardware categories and re-evaluate the appropriateness of the impact conditions.

In 1997, NCHRP Project 22-14, entitled *Improvement of the Procedures for the Safety Performance Evaluation of Roadside Features*, was initiated with the intent to: (1) evaluate the relevance and efficacy of the crash testing procedures, (2) assess the needs for updating NCHRP Report No. 350, and (3) provide recommended strategies for their implementation. Following the completion of this NCHRP study at the Texas Transportation Institute (TTI) in 2001, a follow-on research study was begun in 2002. NCHRP Project 22-14(2), entitled *Improved Procedures for Safety Performance Evaluation of Roadside Features*, was undertaken by Midwest Roadside Safety Facility (MwRSF) researchers with the objectives to: (1) prepare the revised crash testing guidelines, (2) assess the effects of any proposed guidelines, and (3) identify research needs for future improvements to the procedures.

Consequently, it was anticipated that a number of revisions would be incorporated into the Update of NCHRP Report No. 350 guidelines (2). For example, changes in the vehicle fleet have resulted in the need to reassess the small car and pickup truck test vehicles. Accordingly, new, heavier test vehicles have been selected for both the small car and light truck classes of vehicles.

Additionally, during the second study, researchers determined that the 100 km/h (62.1 mph) impact speed and 25 degree impact angle would remain the same as used in NCHRP Report No. 350 for the large passenger vehicle class impacting longitudinal barriers. However, the impact angle for the small car impact condition would increase from 20 to 25 degrees for evaluating longitudinal barriers and the length-of-need for guardrail terminals. The effects of any changes to vehicle specifications or impact conditions must be understood before the safety performance evaluation guidelines are finalized. Therefore, a series of full-scale crash tests on NCHRP Report No. 350 approved systems were to be conducted with the new test vehicles and impact conditions.

1.2 Objective

The objective of this research project was to evaluate the safety performance of the free-standing temporary barrier system when full-scale vehicle crash tested according to the test designation no. 3-11 criteria presented in the Update of NCHRP Report No. 350 guidelines (2).

1.3 Scope

The research objective was achieved through the completion of several tasks. First, a full-scale vehicle crash test was performed on the free-standing temporary barrier system. The crash test utilized a pickup truck, weighing approximately 2,270 kg (5,004 lbs). The target impact conditions for the test were an impact speed of 100.0 km/h (62.1 mph) and an impact angle of 25 degrees. Next, the test results were analyzed, evaluated, and documented. Finally, conclusions and recommendations were made that pertain to the safety performance of the free-standing temporary barrier system relative to the test performed.

2 TEST REQUIREMENTS AND EVALUATION CRITERIA

2.1 Test Requirements

Historically, longitudinal barriers, such as temporary barrier systems, have been required to satisfy impact safety standards in order to be accepted by the Federal Highway Administration (FHWA) for use on National Highway System (NHS) construction projects or as a replacement for existing designs not meeting current safety standards. In recent years, these safety standards have consisted of the guidelines and procedures published in NCHRP Report No. 350 (1). However, NCHRP Project 22-14(2) generated revised testing procedures and guidelines for use in the evaluation of roadside safety appurtenances and were presented in the draft report entitled, *NCHRP Report 350 Update* (2). Therefore, according to Test Level 3 (TL-3) of the Update to NCHRP Report No. 350, longitudinal barrier systems must be subjected to two full-scale vehicle crash tests. The two full-scale crash tests are as follows:

1. Test Designation 3-10. An 1,100-kg (2,425-lb) passenger car impacting at a nominal speed and angle of 100.0 km/h (62.1 mph) and 25 degrees, respectively.
2. Test Designation 3-11. A 2,270-kg (5,004-lb) pickup truck impacting at a nominal speed and angle of 100.0 km/h (62.1 mph) and 25 degrees, respectively.

The test conditions for TL-3 longitudinal barriers are summarized in Table 1. Test Designation 3-11 was conducted for the free-standing temporary barrier system described herein.

2.2 Evaluation Criteria

According to the Update to NCHRP Report No. 350, the 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. This criterion also indicates the potential safety hazard for the occupants of other vehicles or the occupants of the impacting vehicle when subjected secondary collisions with other fixed objects. These three evaluation criteria are summarized in Table 2 and defined in greater detail in the Update to NCHRP Report No. 350 report (2). The full-scale vehicle crash tests were conducted and reported in accordance with the procedures provided in the Update to NCHRP Report No. 350.

Table 1. Update to NCHRP Report No. 350 Test Level 3 Crash Test Conditions

Test Article	Test Designation	Test Vehicle	Impact Conditions			Evaluation Criteria ¹
			Speed		Angle (degrees)	
			(km/h)	(mph)		
Longitudinal Barrier	3-10	1100C	100	62.1	25	A,D,F,H,I,M
	3-11	2270P	100	62.1	25	A,D,F,H,I,M

¹ Evaluation criteria explained in Table 2.

Table 2. Update to NCHRP Report No. 350 Evaluation Criteria for Crash Tests

Structural Adequacy	A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; 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 should not exceed limits set forth in Section 5.3 and Appendix E of the Update to NCHRP Report No. 350.
	F. The vehicle should remain upright during and after collision.
	H. Longitudinal and lateral occupant impact velocities should fall below the preferred value of 9.0 m/s (29.5 ft/s), or at least below the maximum allowable value of 12.0 m/s (39.4 ft/s).
	I. Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15 Gs, or at least below the maximum allowable value of 20.0 Gs.
Vehicle Trajectory	M. After impact, the vehicle shall exit the barrier within the exit box.

3 TEST CONDITIONS

3.1 Test Facility

The testing facility is located at the Lincoln Air Park on the northwest side of the Lincoln Municipal Airport and is approximately 8.0 km (5 mi.) northwest of the University of Nebraska-Lincoln.

3.2 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 barrier system. A digital speedometer was located on the tow vehicle to increase the accuracy of the test vehicle impact speed.

A vehicle guidance system developed by Hinch (3) was used to steer the test vehicle. A guide-flag, attached to the front-right wheel and the guide cable, was sheared off before impact with the barrier system. The 9.5-mm (0.375-in.) diameter guide cable was tensioned to approximately 15.6 kN (3,500 lbf), and supported laterally and vertically every 30.48 m (100 ft) by hinged stanchions. 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. For test 2214TB-1, the vehicle guidance system was 328 m (1,075 ft) long.

3.3 Test Vehicles

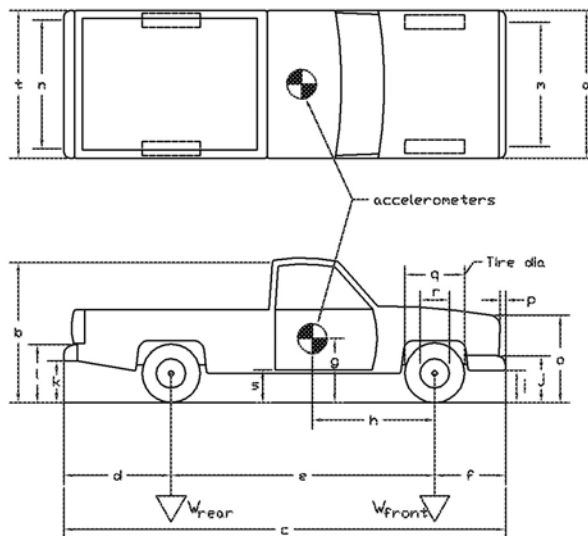
For test 2214TB-1, a 2002 GMC 2500 ¾-ton pickup truck was used as the test vehicle. The test inertial and gross static weights were 2,268 kg (5,000 lbs). The test vehicle is shown in Figure 1, and vehicle dimensions are shown in Figure 2.



Figure 1. Test Vehicle, Test 2214TB-1

Date: 5/4/04 Test Number: 2214TB-1 Model: 2500 P.U.
 Make: GMC Vehicle I.D.#: 1GDGC24U32Z135014
 Tire Size: LT245/75 R16 Year: 2002 Odometer: 260879

*(All Measurements Refer to Impacting Side)



Vehicle Geometry -- mm (in.)

a 1905 (75.0) b 1883 (74.125)
 c 5629 (221.625) d 1299 (51.125)
 e 3391 (133.5) f 940 (37.0)
 g 686 (27.0) h 1448 (57.0)
 i 584 (23) j 781 (30.75)
 k 584 (23.0) l 762 (30.0)
 m 1727 (68.0) n 1680 (66.125)
 o 1048 (41.25) p 89 (3.5)
 q 762 (30.0) r 438 (17.25)
 s 502 (19.75) t 1851 (72.875)
 Wheel Center Height Front 365 (14.375)
 Wheel Center Height Rear 370 (14.5625)
 Wheel Well Clearance (FR) 949 (37.375)
 Wheel Well Clearance (RR) 968 (38.125)

Weights	Curb	Test Inertial	Gross Static
W _{front}	<u>1213 (2674)</u>	<u>1299 (2864)</u>	<u>1299 (2864)</u>
W _{rear}	<u>855 (1886)</u>	<u>969 (2136)</u>	<u>9689 (2136)</u>
W _{total}	<u>2068 (4560)</u>	<u>2268(5000)</u>	<u>2268 (5000)</u>

Engine Type 8 CYL. GAS

Engine Size 6.0 L

Transmission Type:

Automatic or Manual

FWD or RWD or 4WD

Note any damage prior to test: No mirrors, Dent on passenger-side door

Figure 2. Vehicle Dimensions, Test 2214TB-1

The Suspension Method (4) was used to determine the vertical component of the center of gravity (c.g.) for the pickup truck. This method is based on the principle that the c.g. 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 c.g. were established. The intersection of these planes pinpointed the location of the center of gravity. The longitudinal component of the c.g. was determined using the measured axle weights. The location of the final center of gravity is shown in Figures 1 and 2.

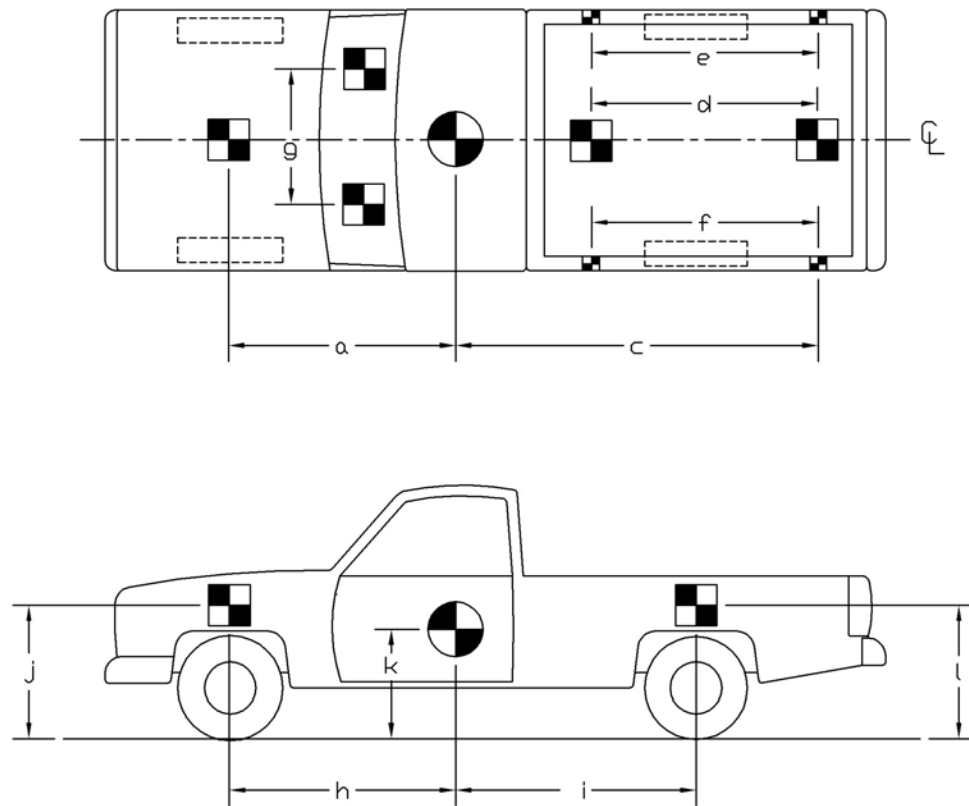
Square black and white-checkered targets were placed on the vehicle to aid in the analysis of the high-speed film and E/cam and Photron video, as shown in Figure 3. Checkered targets were placed on the center of gravity, on the driver's side door, on the passenger's side door, and on the roof of the 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 barrier on the high-speed film, E/cam video, and Photron video. 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.

3.4 Data Acquisition Systems

3.4.1 Accelerometers

One triaxial piezoresistive accelerometer system with a range of ± 200 Gs was used to measure the acceleration in the longitudinal, lateral, and vertical directions at a sample rate of 10,000



TEST #: 2214TB-1			
TARGET GEOMETRY -- mm (in.)			
a 1746 (68.75)	d 1749 (68.875)	g 1057 (41.625)	j 1159 (45.625)
b —	e 2076 (81.75)	h 1448 (57.0)	k 686 (27.0)
c 2657 (104.625)	f 20.75 (81.75)	i 1943 (76.5)	l 1187 (46.75)

Figure 3. Vehicle Target Locations, Test 2214TB-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”, was used to analyze and plot the accelerometer data.

Another triaxial piezoresistive accelerometer system with a range of ± 200 Gs 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 Instrumental 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”, was used to analyze and plot the accelerometer data.

3.4.2 Rate Transducers

An Analog Systems 3-axis rate transducer with a range of 1,200 degrees/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 mounted inside the body of the EDR-4M6 and recorded data at 10,000 Hz to a second data acquisition board inside the EDR-4M6 housing. The raw data measurements were then downloaded, converted to the appropriate Euler angles for analysis, and plotted. Computer software, “DynaMax 1 (DM-1)” and “DADiSP”, was used to analyze and plot the rate transducer data.

3.4.3 High-Speed Photography

For test 2214TB-1, two high-speed 16-mm Red Lake Locam cameras, with operating speeds of approximately 500 frames/sec, were used to film the crash test. Two high-speed Photron video

cameras and four high-speed Red Lake E/cam video cameras, all with operating speeds of 500 frames/sec, and five Canon digital video cameras, with a standard operating speed of 29.97 frames/sec, were also used to film the crash test. Camera details and a schematic of all thirteen camera locations for test 2214TB-1 is shown in Figure 4. The Locam films, Photron video, and E/cam videos were analyzed using the Vanguard Motion Analyzer, ImageExpress MotionPlus software, and Redlake Motion Scope software, respectively. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed film.

3.4.4 Pressure Tape Switches

For test 2214TB-1, five pressure-activated tape switches, spaced at 2-m (6.56-ft) 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 left-front tire of the test vehicle passed over it. Test vehicle speed was determined from electronic timing mark data recorded using 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.

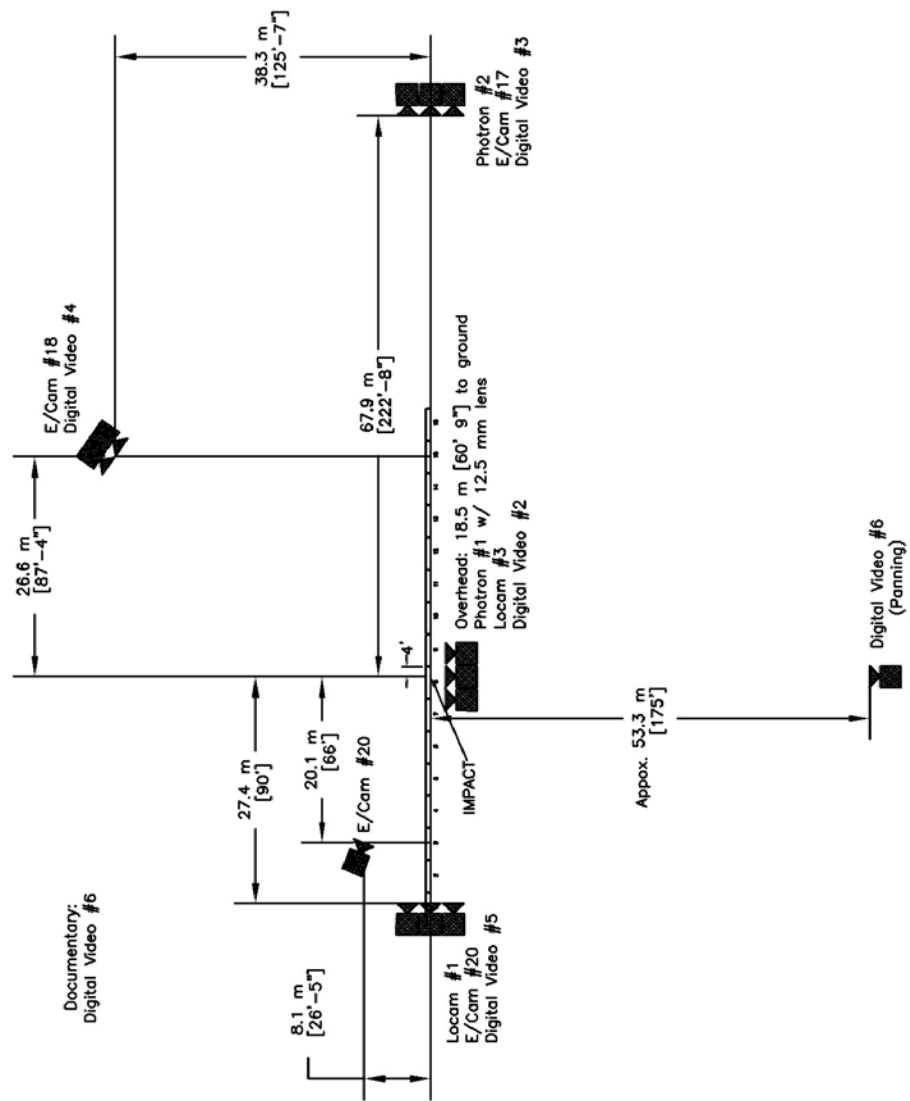


Figure 4. Location of High-Speed Cameras, Test 2214TB-1

4 DESIGN DETAILS

The 62.34-m (204.5-ft) long test installation consisted of temporary concrete barriers in a free-standing configuration, as shown in Figures 5 through 9. The sixteen 3,810-mm (12-ft 6-in.) long, F-shaped temporary concrete barriers were placed on the concrete tarmac without any attachment between the barriers and the tarmac. The corresponding English-unit drawings are shown in Appendix A. Photographs of the test installation are shown in Figures 10 through 12.

The concrete used for the barriers consisted of Iowa's Barrier Mix, with a minimum 28-day concrete compressive strength of 34.5 MPa (5,000 psi). The minimum concrete cover varied at different positions of rebar in the barrier. A minimum concrete cover of 51 mm (2 in.) was used along the top of the vertical stirrup rebar and the bottom longitudinal rebar. Minimum concrete cover of 44 mm (1.75 in.) and 25 mm (1 in.) were used along the sides of the vertical stirrup rebar and at the rebar around the anchor bolt block, respectively. All the steel reinforcement in the barrier was ASTM A615 Grade 60 rebar, except for the loop bars, which were ASTM A706 Grade 60 rebar. The barrier reinforcement details are shown in Figures 5 through 9.

Barrier reinforcement consisted of three No. 5 and two No. 4 longitudinal bars, twelve No. 4 bars for the vertical stirrups, and six No. 6 bars for the anchor bolt block reinforcement loops. Each of the five longitudinal rebar was 3.71 m (12 ft - 2 in.) long. The vertical spacings of the lower, middle, and upper longitudinal bars were 165 mm (6.5 in.), 368 mm (14.5 in.), and 780 mm (29.125 in.) from the ground to their centers, respectively. The 1,829-mm (72-in.) long, vertical stirrups were bent into the shape of the barrier. Their spacings varied longitudinally, as shown in Figure 6. The 889-mm (35-in.) long, anchor bolt block loops were bent into a U-shape and were used to reinforce the anchor bolt area, as shown in Figures 6 through 8.

The barriers used a pin and loop type connection comprised of two sets of rebar loops on each barrier interconnection. Each loop assembly was configured with three ASTM A706 Grade 60 No. 6 bars that were bent into a loop shape, as shown in Figure 8. The vertical pin used in the connection consisted of a 32-mm (1.25 in.) diameter x 711-mm (28-in.) long round bar composed of ASTM, A36 steel, as shown in Figure 9. The pin was held in place using one 64-mm wide x 102-mm long x 13-mm thick (2.5-in. x 4-in. x 0.5-in.) ASTM A36 steel plate with a 35-mm (1.375-in.) diameter hole centered on it. The plate was welded 64 mm (2.5 in.) below the top of the pin. A gap of 92 mm (3.625 in.) between the ends of two consecutive barriers was formed from the result of pulling the connection taut.

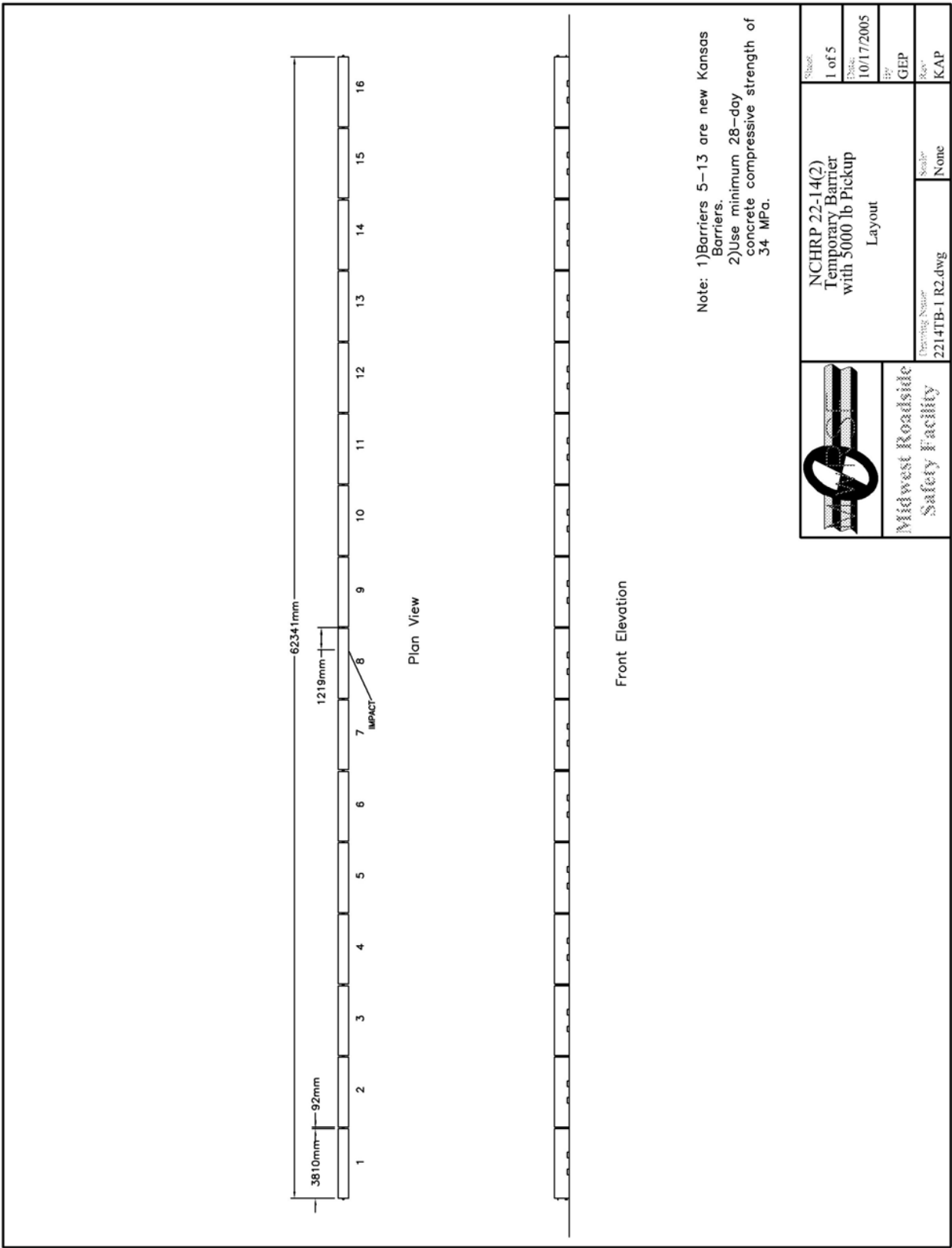
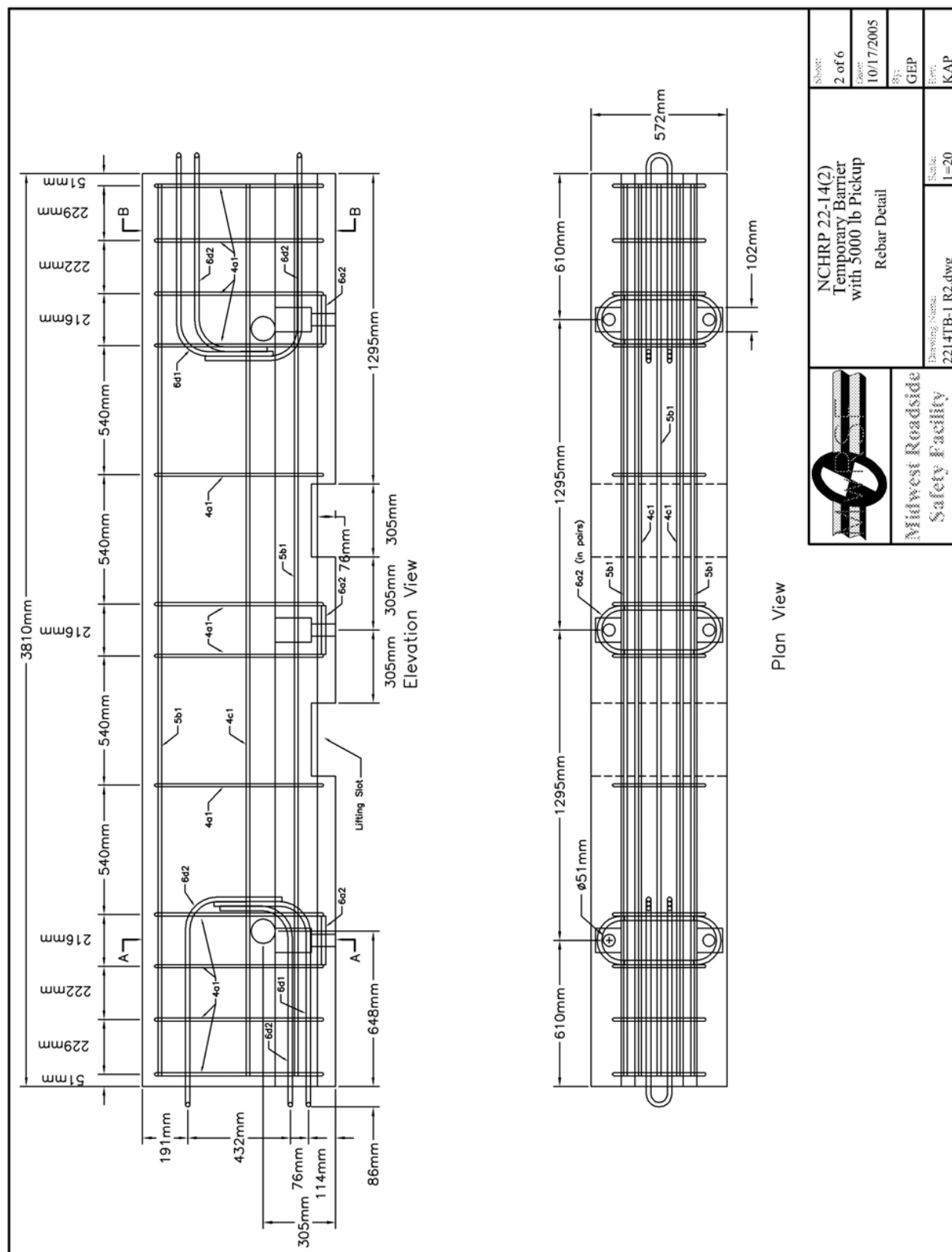


Figure 5. Layout for Free-Standing Temporary Barriers



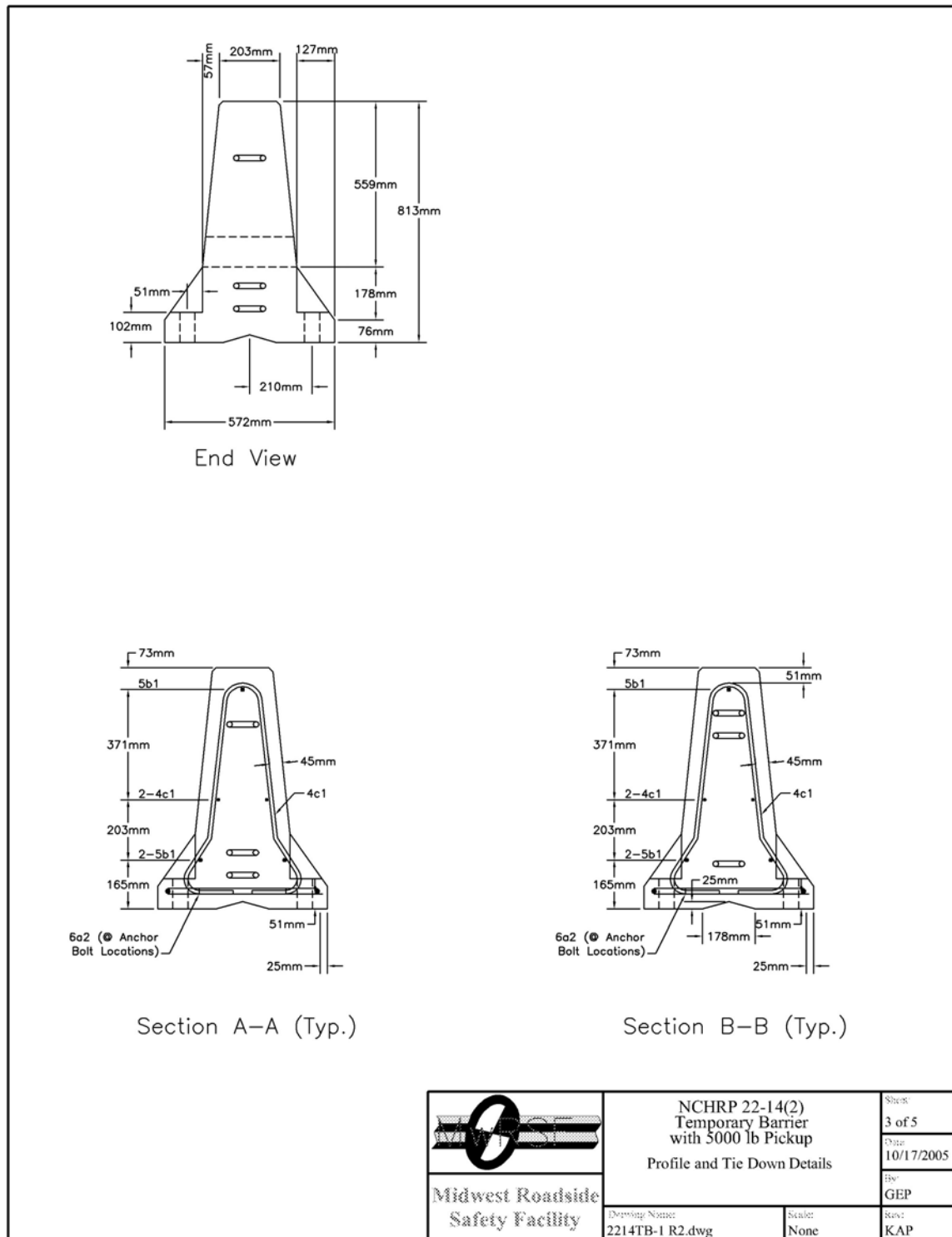


Figure 7. Temporary Barrier Profile Details

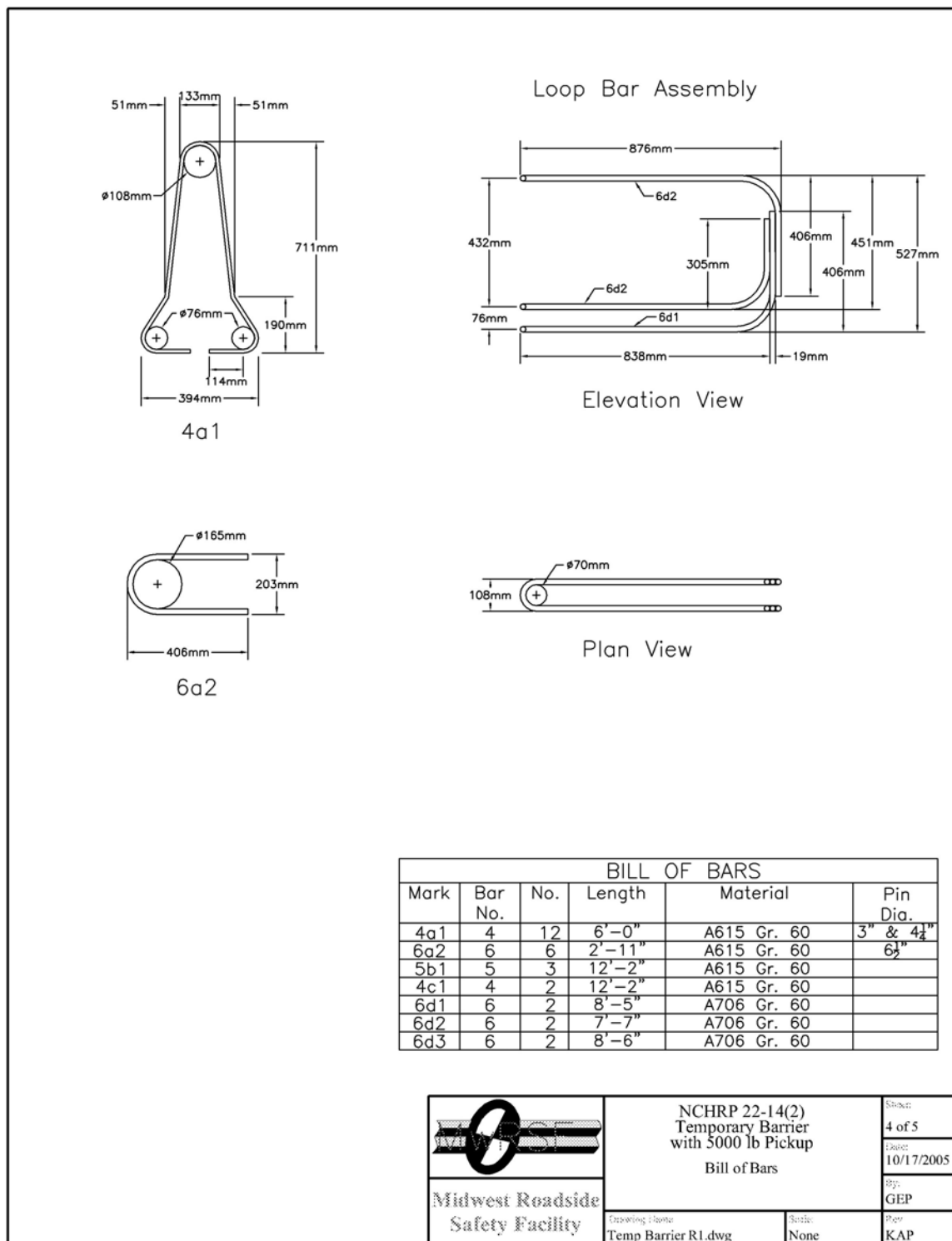


Figure 8. Temporary Barrier Bill of Bars

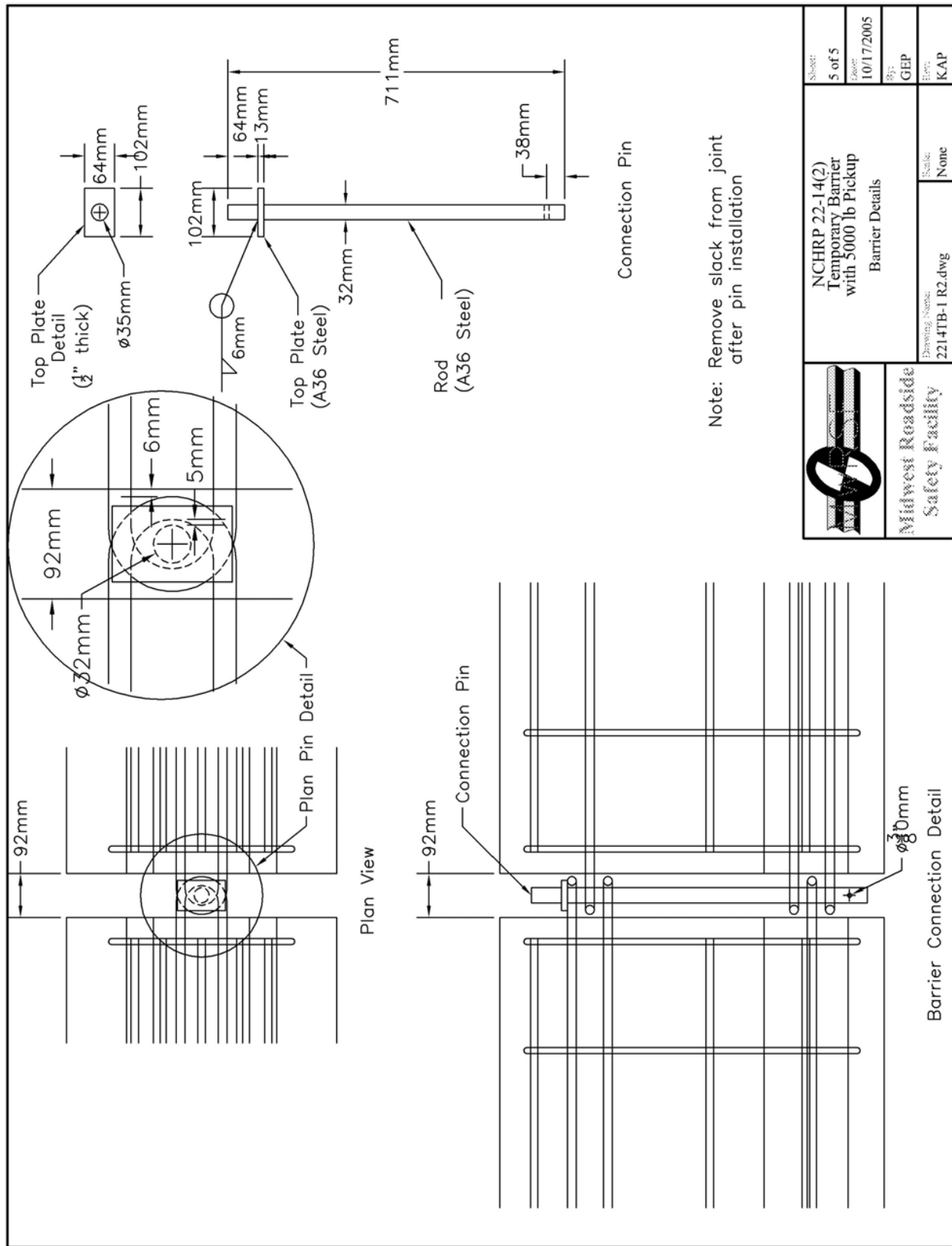


Figure 9. Temporary Barrier Connection Details



Figure 10. Temporary Barrier System



Figure 11. Temporary Barrier System



Figure 12. Barrier Connection Joints

5 CRASH TEST

5.1 Test 2214TB-1

The 2,268-kg (5,000-lb) pickup truck impacted the free-standing temporary barrier system at a speed of 99.5 km/h (61.9 mph) and at an angle of 25.7 degrees. A summary of the test results and sequential photographs are shown in Figure 13. The summary of the test results and sequential photographs in English units are shown in Appendix B. Additional sequential photographs are shown in Figures 14 through 17. Documentary photographs of the crash test are shown in Figures 18 and 19.

5.2 Test Description

Initial vehicle impact was to occur 1,219 mm (48 in.) upstream from the center of the gap between barrier nos. 8 and 9, as shown in Figure 20. Actual vehicle impact occurred 1,645 mm (64.75 in.) upstream from the center of the gap between barrier nos. 8 and 9. At 0.010 sec after initial impact, the left-front corner crushed inward as the left-front corner of the hood protruded over the top of barrier no. 8. At 0.028 sec, concrete dust appeared as barrier no. 8 encountered damage from impact with the left-front tire. At this same time, the left-front quarter panel crushed. At 0.040 sec, barrier no. 8 deflected backward as the hood continued to protrude over the top of the barrier. At 0.060 sec, the left-front corner of the hood was located at the joint between barrier nos. 8 and 9. At this same time, barrier no. 9 began deflecting backward and a gap formed between the top of the left-side door and the rest of the vehicle's cab. At 0.084 sec, the hood deformed up and away from the rest of the vehicle. At this same time, vertical cracks appeared on the back side of barrier no. 9. At 0.120 sec, the left-front corner of the hood was located at the middle of barrier no. 9 as barrier nos. 8 and 9 continued to deflect backwards. At 0.150 sec, the left-front side of vehicle was

positioned on top of barrier no. 9. At this same time, the cracks on the back side of barrier no. 9 increased in number and severity. At 0.180 sec, the left-front corner of the hood was located at the joint between barrier nos. 9 and 10 as barrier no. 10 began to deflect backward. At 0.246 sec after impact, the vehicle became parallel to the system with a resultant velocity of 71.7 km/h (44.5 mph). At this same time, the front half of the left side of the vehicle rode along the top of barrier nos. 9 and 10 with the left-rear tire airborne. At 0.272 sec, the vehicle redirected away from the system with the front of the vehicle located near the center of barrier no. 10. At this same time, the left side of the vehicle continued to travel on top of barrier nos. 9 and 10. At 0.294 sec, the left-rear tire contacted the middle of barrier no. 9 as the vehicle experienced clockwise (CW) roll away from the barrier. At this same time, chunks of concrete disengaged from the top of barrier no. 9. At 0.332 sec, barrier no. 10 continued to sustain significant deflection backward as the vehicle continued to roll CW away from the barrier. At 0.372 sec, the left-rear tire was on top of barrier no. 9, and the right-rear tire was airborne. At 0.396 sec, the vehicle rode along the top of barrier no. 10. At this same time, the right-front corner of the vehicle pitched downward as the vehicle continued to roll CW away from the barrier. At 0.484 sec, the vehicle continued to ride along the top of barrier nos. 10 and 11. At this same time, barrier nos. 7 through 10 continued to deflect backward. At 0.550 sec, the front of the vehicle continued to pitch downward with the rear of the vehicle rising higher into the air. At 0.706 sec, the left-front tire rotated outward and was compressed into the top of the barrier. At 0.712 sec, the vehicle's rear-end reached its maximum height in the air as its front end pitched downward. At 0.798 sec, the left-front tire disengaged from the axle. At 0.898 sec, the vehicle levels out with the rear of the vehicle still airborne. At 0.952 sec, the vehicle rolled counter-clockwise (CCW) toward the barrier system and pitched toward the left-front corner of the vehicle.

At 0.986 sec, the right-front tire was airborne. At 1.070 sec, the disengaged left-front tire contacted the left-side window, which shattered. At 1.172 sec, the disengaged left-front tire was lodged between the left-side door and the barrier. At 1.224 sec, the left side of the box contacted and rode along the top of the barrier system. At 1.372 sec, the vehicle exited the system at an approximate angle of 12 degrees and an approximate velocity of 60 km/h (37.3 mph). At 1.654 sec, the right side tires remained airborne with the vehicle rolling significantly CCW. At 1.788 sec, the truck was no longer in contact with the barrier. At 1.816 sec, the vehicle slid along as it remained rolled significantly CCW toward the left side of the vehicle, but began to roll back CW. At this same time, the vehicle yawed CW. At 2.390 sec, the vehicle continued to yaw CW as the vehicle leveled out and the right-front tire contacted the ground. At 2.572 sec, the right-rear tire contacted the ground. The vehicle came to rest 49.85 m (163 ft - 6.5 in.) downstream from impact and 6.24 m (20 ft - 5.5 in.) laterally away from the traffic-side face of the temporary barrier system. The trajectory and final position of the pickup truck are shown in Figures 13 and 21.

5.3 Barrier Damage

Damage to the barrier was moderate, as shown in Figures 22 through 26. Barrier damage consisted of contact and gouge marks, concrete barrier cracking, and spalling of the concrete. The length of vehicle contact along the temporary concrete barrier system was approximately 30 m (98 ft), which spanned from 1,600 mm (63 in.) upstream from the downstream end of barrier no. 8 through 864 mm (34 in.) downstream from the upstream end of barrier no. 16.

Tire marks were visible on the front face of barrier nos. 8 through 10. Contact marks were found on the top of barrier nos. 8, 9, and 12 through 16. Yellow contact marks began 483 mm (19 in.) upstream from the downstream end of barrier no. 8 and 152 mm (6 in.) from the top of the

barrier and continued through the downstream end of barrier no. 8.

Concrete spalling occurred at impact on barrier no. 8. The lower-front corner at the downstream end of barrier no. 8 was fractured and separated. The front upstream edge of barrier no. 9 encountered concrete spalling 305 mm (12 in.) from the top of the barrier and was approximately 76 mm (3 in.) long. Concrete spalling found on the backside of the upstream end of barrier no. 9 was 102 mm (4 in.) wide and 483 mm (19 in.) long starting at the top of the barrier. Concrete spalling was found on the bottom-front face 965 mm (38 in.) downstream from the upstream end of barrier no. 9 and was 330 mm (13 in.) wide by 203 mm (8 in.) tall. A 305-mm (12-in.) wide piece of concrete was separated from the top of barrier no. 9 and exposed the top rebar beginning 1,321 mm (52 in.) downstream from the upstream end of the barrier. Concrete spalling with an average width of 102 mm (4 in.) was located 2,540 mm (100 in.) downstream from the upstream end of barrier no. 9 and exposed the longitudinal rebar. Concrete spalling occurred from 1,803 mm (71 in.) to 2,540 mm (100 in.) downstream from the upstream end of barrier no. 9. A 191-mm (7.5-in.) long piece of concrete, with an average width of 279 mm (11 in.), was separated from barrier no. 9 beginning 2,540 mm (100 in.) downstream from the upstream end of the barrier and exposing the stirrup. The concrete on the backside of barrier no. 9 was completely fractured 1,422 mm (56 in.) downstream from the upstream end of the barrier. The backside of barrier no. 10 encountered significant spalling measuring 76 mm (3 in.) wide by 343 mm (13.5 in.) long starting at the top of the barrier. Minor concrete spalling was found 660 mm (26 in.) downstream from the upstream end of the barrier no. 10. An 89-mm (3.5-in.) wide by 203-mm (8-in.) long area of concrete spalling was found on barrier no. 10 beginning 1,829 mm (72 in.) downstream from the barrier's upstream end. Minor concrete spalling measuring 89 mm (3.5 in.) wide by 51 mm (2 in.) tall was found 114 mm (4.5 in.) upstream

from the downstream end of barrier no. 10. Minor spalling was also found on barrier no. 14.

Cracking was found on barrier no. 8 and began 1,372 mm (54 in.) upstream from the downstream end of the barrier and extended upward and slightly downstream along the front face of the barrier. This crack was also visible on the backside of barrier no. 8. Cracking occurred on both the front and back sides of barrier no. 9 beginning 686 mm (27 in.) downstream from the upstream end of the barrier. Two cracks were found 1,270 mm (50 in.) downstream from the upstream end of the barrier and began at the upper-left corner of the upstream lifting slot propagating up and around to the back side of the barrier. Another crack on barrier no. 9 occurred 1,562 mm (61.5 in.) downstream from the upstream end of the barrier at the upper-right corner of the upstream lifting slot. Minor cracking in barrier no. 9 occurred on the top and back side at 2,032 mm (80 in.) downstream from the upstream end of the barrier. Cracking was found on barrier no. 10 beginning at the upper-left corners of both lifting slots and propagating upward to the top of the barrier. Barrier no. 11 encountered a small crack which began at the upper-left corner of the downstream lifting slot and propagated to the midpoint of the top face of the barrier.

The connection pin between barrier nos. 8 and 9 was bent 102 mm (4 in.) from the top of the pin. The connection pin between barrier nos. 9 and 10 was bent approximately 127 mm (5 in.) from the bottom of the pin. The connection pins between barrier nos. 10 and 16 remained undamaged, but were lodged in the joints. No noticeable deformations were found on the barrier joint loops.

The permanent set of the barrier system is shown in Figure 22. Barrier nos. 6 through 16 encountered longitudinal and lateral movement. The maximum lateral permanent set barrier deflection was 1,441 mm (56.75 in.) at the upstream end of barrier no. 9, as measured in the field. The maximum lateral dynamic barrier deflection was 1,441 mm (56.75 in.) at the upstream end of

barrier no. 9, as determined from high-speed digital video analysis. The working width of the system was found to be 2,013 mm (79.25 in.).

5.4 Vehicle Damage

Exterior vehicle damage was moderate, as shown in Figures 27 through 29. Occupant compartment deformations to the left side and center of the floorboard were judged insufficient to cause serious injury to the vehicle occupants. Maximum longitudinal deflections of 146 mm (5.75 in.) were located near the front center of the left-side floor pan. Maximum lateral deflections of 32 mm (1.25 in.) were located near the left-front corner of the left-side floor pan. Maximum vertical deflections of 64 mm (2.5 in.) were located near the left-front corner of the left-side floor pan. Complete occupant compartment deformations and the corresponding locations are provided in Appendix C.

Damage was concentrated on the left-front corner of the vehicle. The left-front quarter panel was deformed inward and downward toward the engine compartment. The left side of the front bumper was flattened and bent back toward the engine compartment nearly contacting the lower frame rail. The left-side door encountered a large dent below the window. The top of the left door was ajar. The cab encountered two dents right behind the left-side door. The box encountered numerous dents along the entire right side. The left-front wheel assembly deformed and crushed inward toward the engine compartment. The left-side lower ball joint, top ball joint, and steering linkage were fractured. The left-side sway bar and lower control arm connection was bent. The left-front tire disengaged from the rest of the wheel assembly. The left-front and left-rear steel rims were deformed and dented. The left-front and left-rear tires' side walls were torn, and the tires deflated. The left-side park light disengaged from the vehicle. The left-side door's window glass was

fractured and missing. The lower-right side of the windshield encountered minor cracking. All other window glass remained undamaged. The right side and rear of the vehicle remained undamaged.

5.5 Occupant Risk Values

The longitudinal and lateral occupant impact velocities were determined to be 5.63 m/s (18.46 ft/s) and 5.75 m/s (18.88 ft/s), respectively. The maximum 0.010-sec average occupant ridedown decelerations in the longitudinal and lateral directions were 11.93 Gs and 6.52 Gs, respectively. It is noted that the occupant impact velocities (OIVs) and occupant ridedown decelerations (ORDs) were within the suggested limits provided in NCHRP Report No. 350. The THIV and PHD values were determined to be 8.50 m/s (27.89 ft/s) and 12.07 Gs, respectively. The results of the occupant risk, as determined from the accelerometer data, are summarized in Figure 13. Results are shown graphically in Appendix D. The results from the rate transducer are shown graphically in Appendix D.

5.6 Discussion

The analysis of the test results for test no. 2214TB-1 showed that the free-standing temporary concrete barrier system impacted with the with the 2270P vehicle of the Update to NCHRP Report No. 350 adequately contained and redirected the vehicle with controlled lateral displacements of the barrier system. There were no detached elements nor fragments which showed potential for penetrating the occupant compartment nor presented undue hazard to other traffic. Deformations of, or intrusion into, the occupant compartment that could have caused serious injury did not occur. However, it should be noted that the left-front wheel assembly disengaged from the vehicle and impacted the left-side door's window and fractured it. The test vehicle did not penetrate nor ride over the temporary concrete barrier system and remained upright during and after the 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. After collision, the vehicle's trajectory revealed minimum intrusion into adjacent traffic lanes. In addition, the vehicle exited the barrier within the exit box. Therefore, test no. 2214TB-1 conducted on the free-standing temporary concrete barrier system was determined to be acceptable according to the TL-3 safety performance criteria found in the Update to NCHRP Report No. 350.

It should be noted that the center of gravity of 686 mm (27 in.) of the pickup tested was determined to be at the low end of the c.g. height range of the large passenger vehicle class (i.e., light trucks) currently on the roadways. Consequently, this vehicle was judged to not be an accurate representation of the light trucks on the roadways, which accounts for approximately half of all vehicles sold in the United States. Since it was desired that the test vehicle represented the taller vehicles in this class, a minimum c.g. height of 710 mm (28 in.) was set.

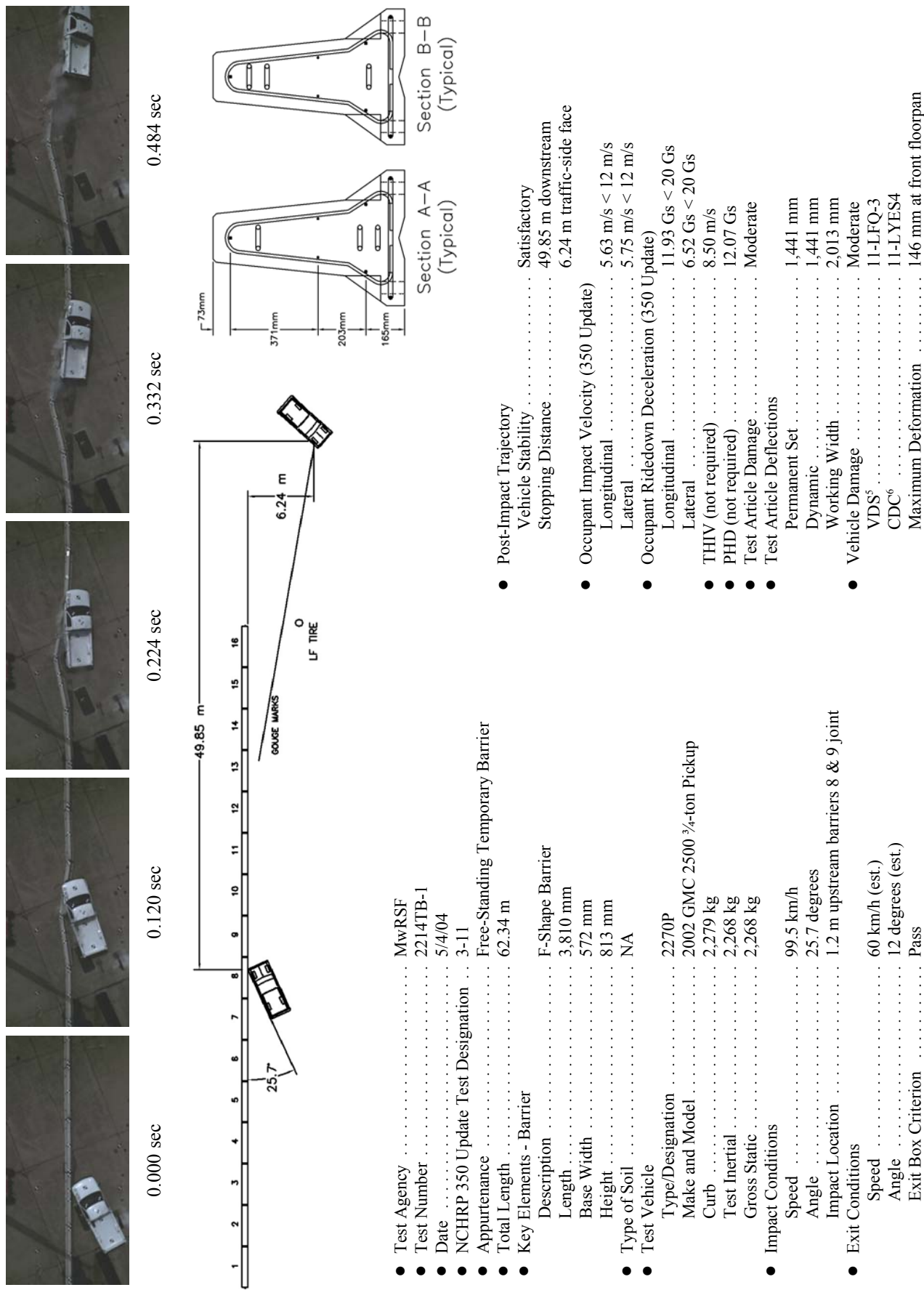


Figure 13. Summary of Test Results and Sequential Photographs, Test 2214TB-1



0.000 sec



0.798 sec



0.142 sec



0.938 sec



0.254 sec



1.070 sec



0.466 sec



1.352 sec



0.706 sec



1.602 sec

Figure 14. Additional Sequential Photographs, Test 2214TB-1



0.000 sec



0.434 sec



0.024 sec



0.712 sec



0.084 sec



1.204 sec



0.172 sec



1.816 sec



0.296 sec



2.572 sec

Figure 15. Additional Sequential Photographs, Test 2214TB-1



0.000 sec



0.076 sec



0.162 sec



0.296 sec



0.380 sec



0.000 sec



0.070 sec



0.192 sec



0.292 sec



0.374 sec

Figure 16. Additional Sequential Photographs, Test 2214TB-1



0.000 sec



0.200 sec



0.334 sec



0.667 sec



0.868 sec



1.101 sec



0.000 sec



0.133 sec



0.234 sec



0.334 sec



0.400 sec



0.734 sec

Figure 17. Additional Sequential Photographs, Test 2214TB-1



Figure 18. Documentary Photographs, Test 2214TB-1



Figure 19. Documentary Photographs, Test 2214TB-1



Figure 20. Impact Location, Test 2214TB-1



Figure 21. Vehicle Final Position and Trajectory Marks, Test 2214TB-1



Figure 22. Temporary Barrier Damage, Test 2214TB-1



Figure 23. Temporary Barrier Damage, Test 2214TB-1



Figure 24. Temporary Barrier Damage, Test 2214TB-1



Figure 25. Temporary Barrier Damage, Test 2214TB-1



Figure 26. Temporary Barrier Damage, Test 2214TB-1



Figure 27. Vehicle Damage, Test 2214TB-1



Figure 28. Vehicle Damage, Test 2214TB-1



Figure 29. Vehicle Damage, Test 2214TB-1

6 SUMMARY AND CONCLUSIONS

A free-standing temporary barrier system was constructed and full-scale vehicle crash tested. One full-scale vehicle crash test, using a pickup truck vehicle, was performed on the longitudinal barrier system and was determined to be acceptable according to the TL-3 safety performance criteria presented in the Update to NCHRP Report No. 350. A summary of the safety performance evaluation is provided in Table 3. While the vehicle mass and impact conditions are included in the proposed Update to NCHRP Report No. 350, the $\frac{3}{4}$ -ton, 2-door pickup truck utilized in this test was ultimately not recommended in the Update to NCHRP Report No. 350.

Table 3. Summary of Safety Performance Evaluation Results

Evaluation Factors	Evaluation Criteria	Test 2214TB-1
Structural Adequacy	A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underide, or override the installation although controlled lateral deflection of the test article is acceptable.	S
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 should not exceed limits set forth in Section 5.3 and Appendix E of the Update to NCHRP Report No. 350.	S
	F. The vehicle should remain upright during and after collision.	S
	H. Longitudinal and lateral occupant impact velocities should fall below the preferred value of 9.0 m/s (29.5 ft/s), or at least below the maximum allowable value of 12.0 m/s (39.4 ft/s).	S
	I. Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15 Gs, or at least below the maximum allowable value of 20.0 Gs.	S
Vehicle Trajectory	M. After impact, the vehicle shall exit the barrier within the exit box.	S

S - Satisfactory
U - Unsatisfactory
NA - Not Available

7 REFERENCES

1. 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.
2. Sicking, D.L., Mak, K.K., and Rohde, J.R., *NCHRP Report No. 350 Update - Chapters 1 through 7, Draft Report*, Presented to the Transportation Research Board, Prepared by the Midwest Roadside Safety Facility, University of Nebraska-Lincoln, July 2005 [Privileged Document].
3. Hinch, J., Yang, T.L., and Owings, R., *Guidance Systems for Vehicle Testing*, ENSCO, Inc., Springfield, VA, 1986.
4. *Center of Gravity Test Code - SAE J874 March 1981*, SAE Handbook Vol. 4, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, 1986.
5. *Vehicle Damage Scale for Traffic Investigators*, Second Edition, Technical Bulletin No. 1, Traffic Accident Data (TAD) Project, National Safety Council, Chicago, Illinois, 1971.
6. *Collision Deformation Classification - Recommended Practice J224 March 1980*, Handbook Volume 4, Society of Automotive Engineers (SAE), Warrendale, Pennsylvania, 1985.

8 APPENDICES

APPENDIX A

English-Unit System Drawings

Figure A-1. Layout for Free-Standing Temporary Barriers (English)

Figure A-2. Temporary Barrier Design Details (English)

Figure A-3. Temporary Barrier Profile Details (English)

Figure A-4. Temporary Barrier Bill of Bars (English)

Figure A-5. Temporary Barrier Connection Details (English)

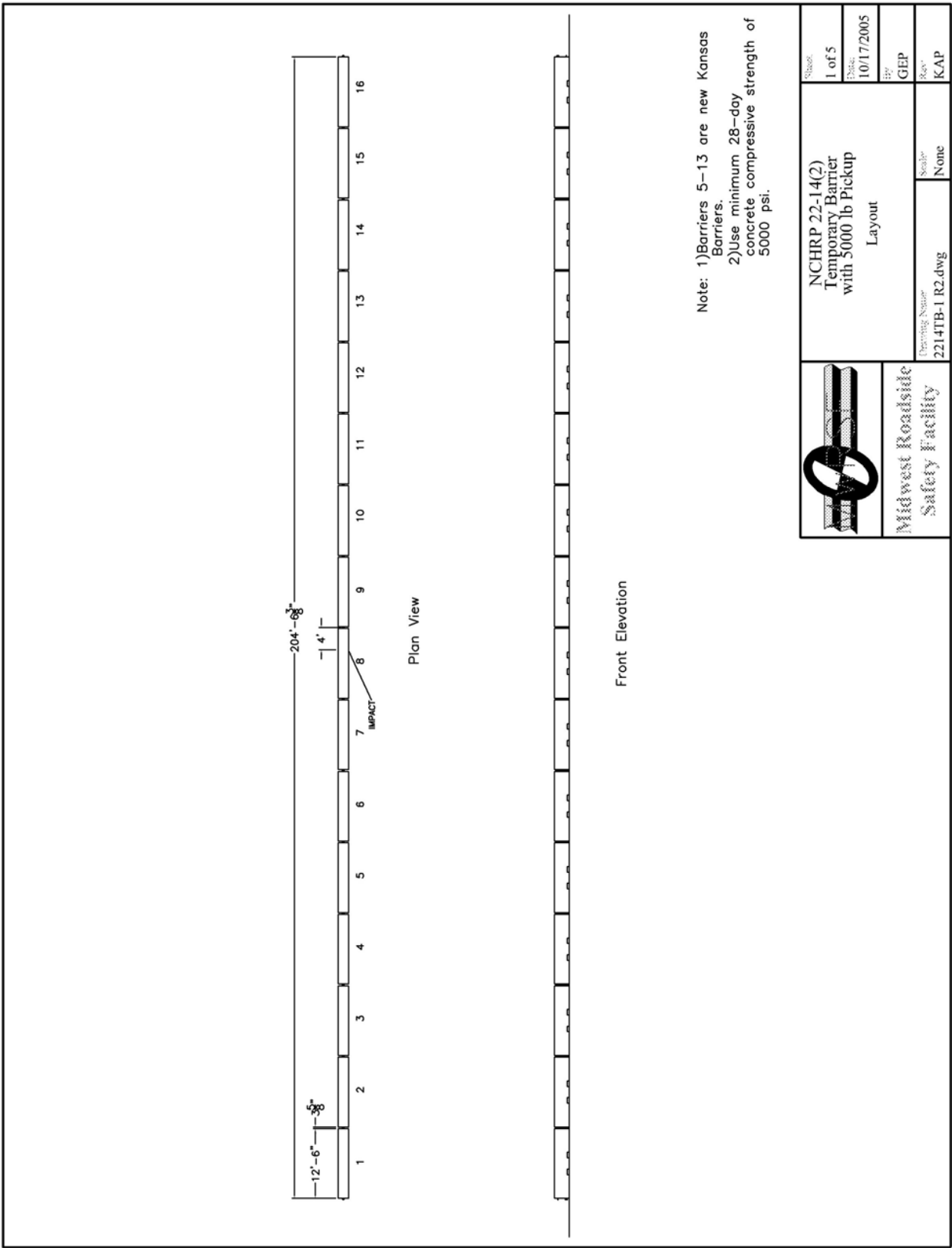


Figure A-1. Layout for Free-Standing Temporary Barriers (English)

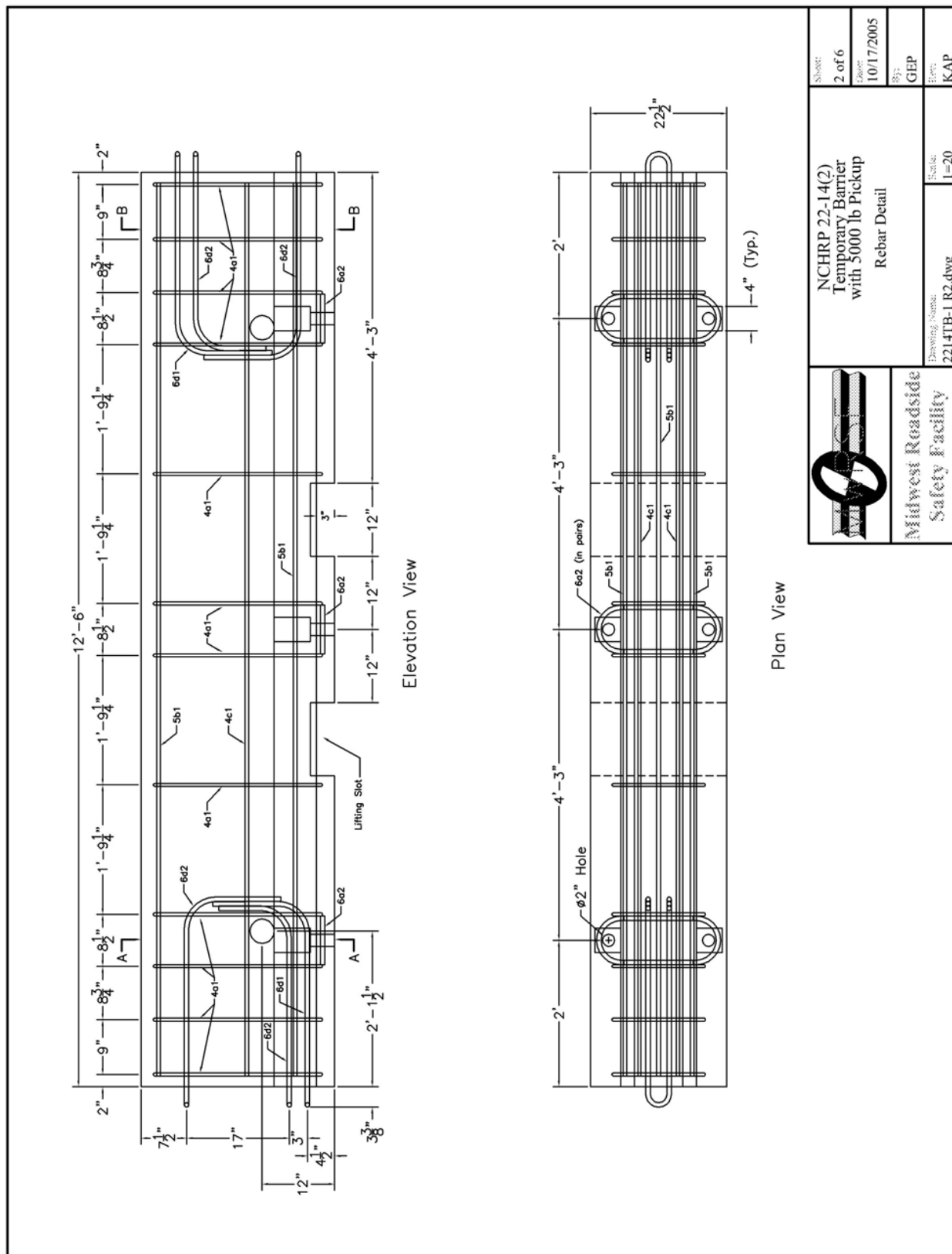


Figure A-2. Temporary Barrier Design Details (English)

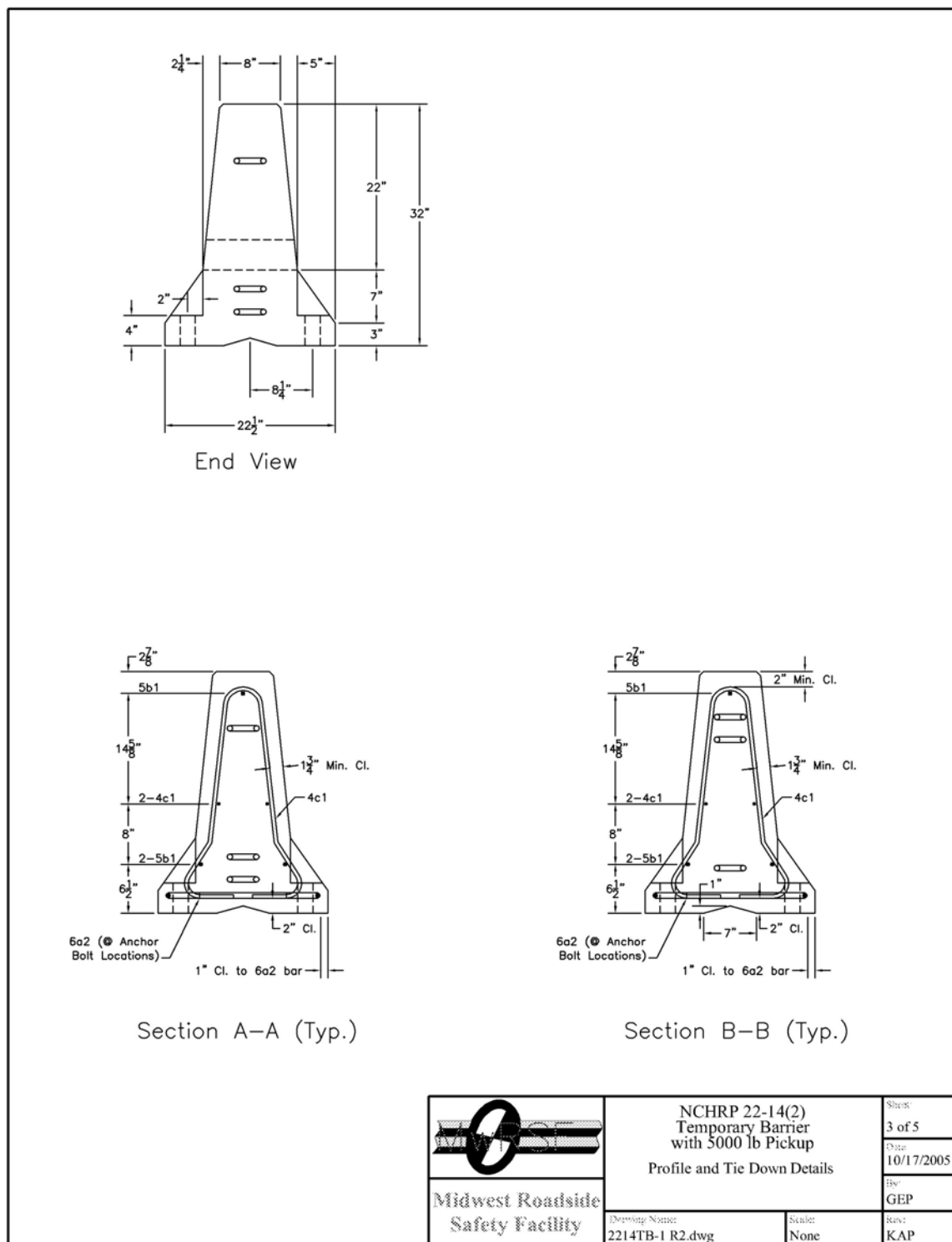


Figure A-3. Temporary Barrier Profile Details (English)

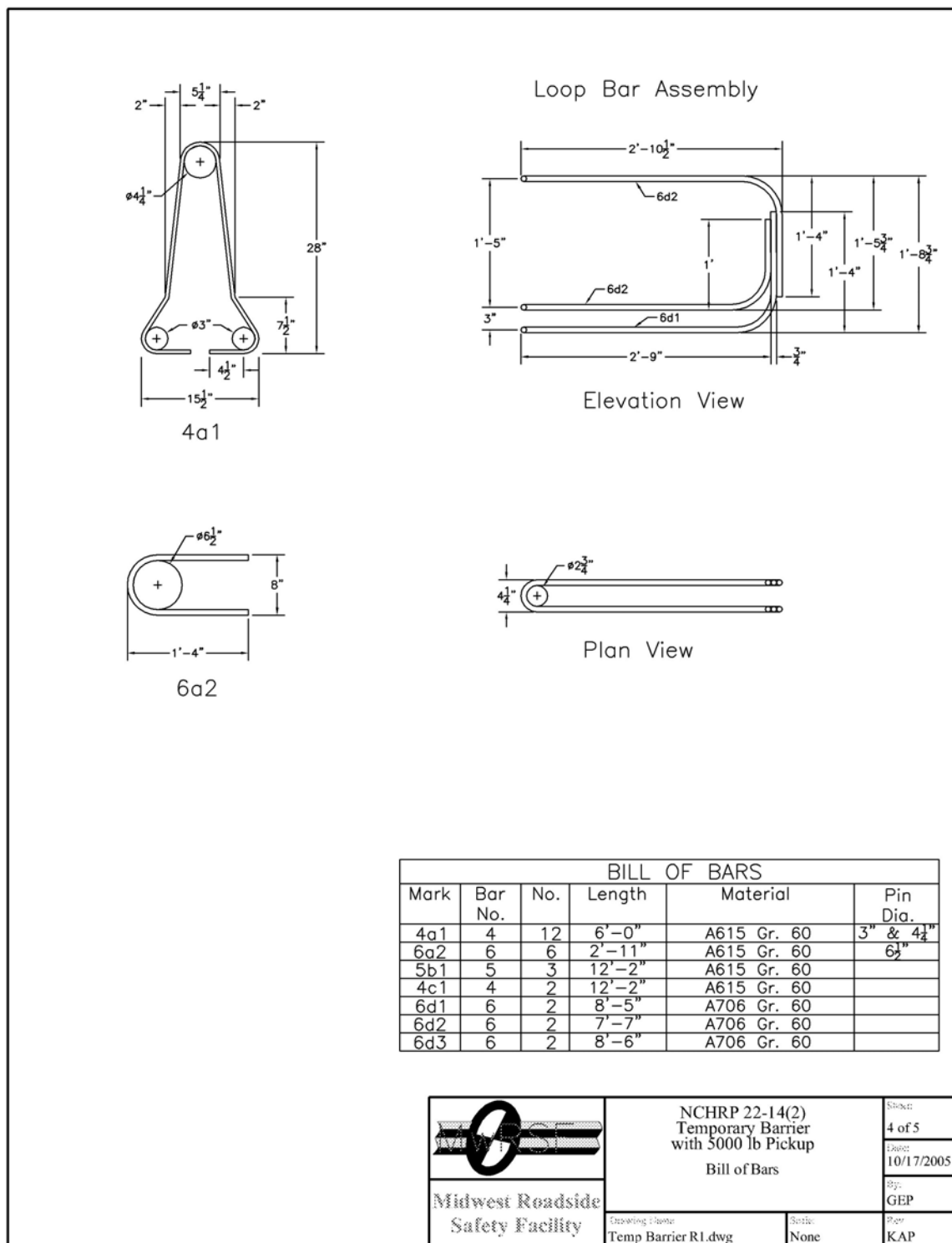
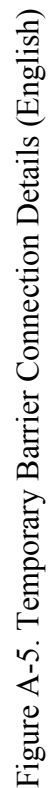


Figure A-4. Temporary Barrier Bill of Bars (English)



APPENDIX B

Test Summary Sheet in English Units

Figure B-1. Summary of Test Results and Sequential Photographs (English), Test 2214TB-1

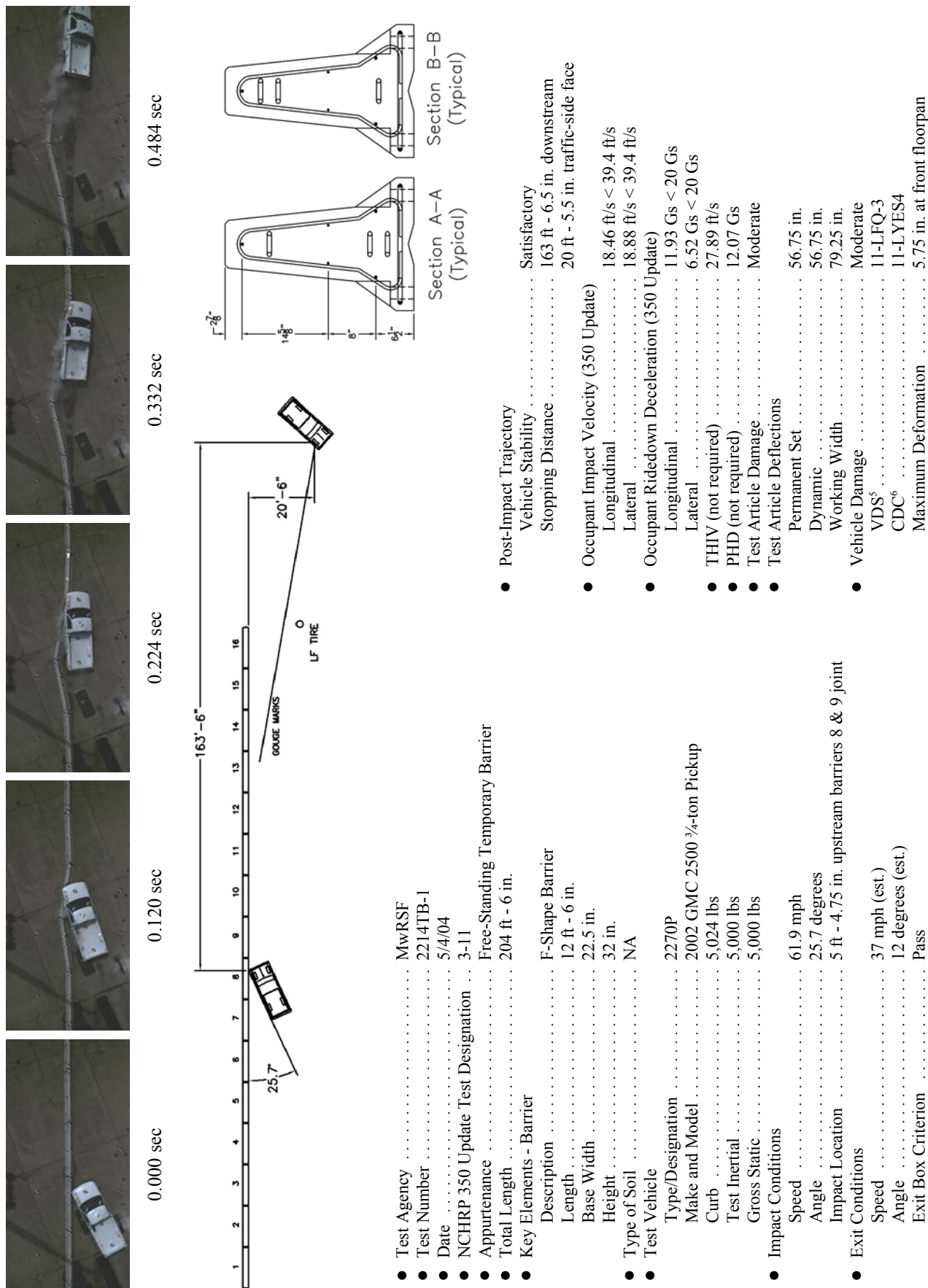


Figure B-1. Summary of Test Results and Sequential Photographs (English), Test 2214TB-1

APPENDIX C

Occupant Compartment Deformation Data, Test 2214TB-1

Figure C-1. Occupant Compartment Deformation Data, Test 2214TB-1

Figure C-2. Occupant Compartment Deformation Index (OCDI), Test 2214TB-1

Figure C-3. NASS Crush Data, Test 2214TB-1

VEHICLE PRE/POST CRUSH INFO

TEST: 2214TB-1
VEHICLE: 2002/GMC/2500/VWHITE

POINT	X	Y	Z	X'	Y'	Z'	DEL X	DEL Y	DEL Z	Secondary points					
										Y2	Z2	Y2'	Z2'	Del Y2	Del Z2
1	59.25	-28.75	-3	58.25	-27.5	-2.5	-1	1.25	0.5			-3	-1.75		-1.25
2	61.25	-23.75	-3	57	-22.75	-0.5	-4.25	1	2.5			-3	-0.5		-2.5
3	65.25	-18.5	-1.25	59.5	-18.25	-1.25	-5.75	0.25	0			-1.75	-1.25		-0.5
4	62.25	-12	-3.75	61.75	-13	-3.75	-0.5	-1	0			-4	-3.25		-0.75
5	59	-5.5	-1.25	59.75	-6.25	-1.5	0.75	-0.75	-0.25			-1.25	-0.75		-0.5
6	55.25	-1.25	-1	55.5	-1.5	-1	0.25	-0.25	0			-1	-0.75		-0.25
7	58.25	-27.25	-8	56.25	-26.75	-6	-2	0.5	2			-8.25	-6		-2.25
8	59	-20.25	-7.75	55.5	-19.75	-6	-3.5	0.5	1.75			-8	-6		-2
9	58.5	-13	-7.75	57.25	-13	-7.25	-1.25	0	0.5			-8	-7.25		-0.75
10	53	-6.25	-4.75	53	-6	-4.5	0	0.25	0.25			-4.5	-4.75		0.25
11	50.25	-0.25	-3	50.25	-0.25	-2.75	0	0	0.25			-2.75	-2.5		-0.25
12	50	-30	-10.5	50	-29.5	-10.5	0	0.5	0			-10.75	-9.75		-1
13	48.75	-23.5	-10.75	48.5	-23	-10.25	-0.25	0.5	0.5			-11	-9.5		-1.5
14	52	-18	-10.5	51.5	-17.5	-10.25	-0.5	0.5	0.25			-10.75	-9.5		-1.25
15	48	-12	-10.75	48	-11.25	-10.75	0	0.75	0			-10.75	-10.25		-0.5
16	45.5	-5.5	-4.5	45.25	-5.5	-4.25	-0.25	0	0.25			-4.5	-4		-0.5
17	39.25	-29.5	-11	40	-29.5	-11	0.75	0	0			-11.25	-10.25		-1
18	40	-23.25	-11	40.5	-23.25	-11.5	0.5	0	-0.5			-11.25	-10.75		-0.5
19	40.75	-18	-11	40.75	-18	-11.25	0	0	-0.25			-11.25	-10.75		-0.5
20	40.5	-11.75	-11	40.75	-11	-11	0.25	0.75	0			-11	-10.75		-0.25
21	40	-7	-7.5	40	-6.75	-7.5	0	0.25	0			-7.25	-7.25		0
22	27.75	-27.75	-9.25	27.5	-27.5	-9.75	-0.25	0.25	-0.5			-9.75	-9		-0.75
23	29	-14.25	-9.75	28.75	-14.25	-9.5	-0.25	0	0.25			-9.5	-9.25		-0.25
24	18.25	-27.25	-9.25	18.25	-27.5	-10	0	-0.25	-0.75			-10	-9		-1
25	19.5	-12.75	-10	19.25	-12.5	-9.5	-0.25	0.25	0.5			-9.5	-9.75		0.25
26	43	-29.25	-22	43.25	-29	-22	0.25	0.25	0			-22.25	-22.5		0.25
27	45	-16.25	-23	45.25	-16.25	-23	0.25	0	0			-22.75	-23		0.25
28	43.25	-0.25	-22.5	43.5	-0.25	-23.25	0.25	0	-0.75			-23	-23		0
29															
30															

ORIENTATION AND REFERENCE INFO

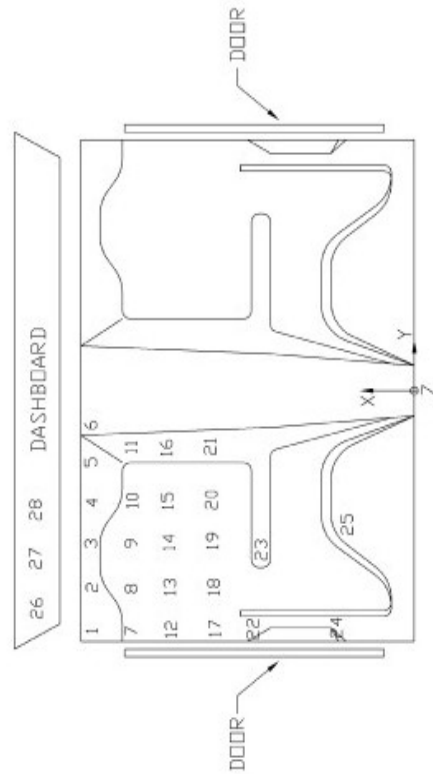


Figure C-1. Occupant Compartment Deformation Data, Test 2214TB-1

Occupant Compartment Deformation Index (OCDI)

Test No. 2214TB-1
Vehicle Type: 2002 GMC 2500

OCDI = XXABCDEFGHI

XX = location of occupant compartment deformation

A = distance between the dashboard and a reference point at the rear of the occupant compartment, such as the top of the rear seat or the rear of the cab on a pickup

B = distance between the roof and the floor panel

C = distance between a reference point at the rear of the occupant compartment and the motor panel

D = distance between the lower dashboard and the floor panel

E = interior width

F = distance between the lower edge of right window and the upper edge of left window

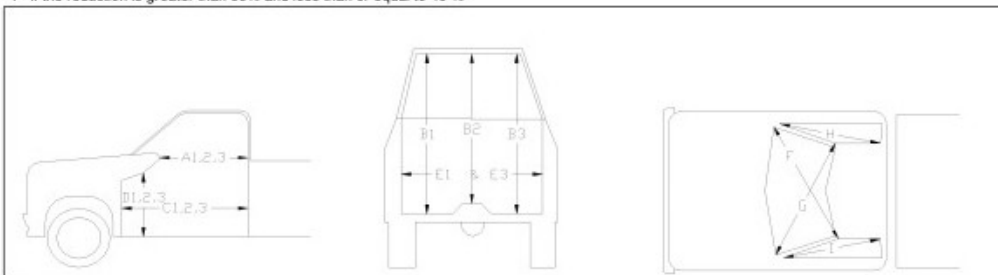
G = distance between the lower edge of left window and the upper edge of right window

H = distance between bottom front corner and top rear corner of the passenger side window

I = distance between bottom front corner and top rear corner of the driver side window

Severity Indices

- 0 - if the reduction is less than 3%
- 1 - if the reduction is greater than 3% and less than or equal to 10 %
- 2 - if the reduction is greater than 10% and less than or equal to 20 %
- 3 - if the reduction is greater than 20% and less than or equal to 30 %
- 4 - if the reduction is greater than 30% and less than or equal to 40 %



where,
1 = Passenger Side
2 = Middle
3 = Driver Side

Location:

Measurement	Pre-Test (in.)	Post-Test (in.)	Change (in.)	% Difference	Severity Index
A1	41.00	41.25	0.25	0.61	0
A2	41.50	41.75	0.25	0.60	0
A3	41.25	41.25	0.00	0.00	0
B1	47.75	48.00	0.25	0.52	0
B2	44.50	44.50	0.00	0.00	0
B3	47.75	48.00	0.25	0.52	0
C1	60.00	57.50	-2.50	-4.17	1
C2	55.00	55.00	0.00	0.00	0
C3	59.00	59.00	0.00	0.00	0
D1	16.50	16.50	0.00	0.00	0
D2	9.25	9.00	-0.25	-2.70	0
D3	16.00	16.00	0.00	0.00	0
E1	63.00	62.75	-0.25	-0.40	0
E3	64.13	64.25	0.13	0.19	0
F	61.25	61.00	-0.25	-0.41	0
G	61.00	61.00	0.00	0.00	0
H	37.50	37.50	0.00	0.00	0
I	36.25	36.25	0.00	0.00	0

Note: Maximum severity index for each variable (A-I) is used for determination of final OCDI value

Final OCDI: RF A B C D E F G H I
RF 0 0 1 0 0 0 0 0 0

Figure C-2. Occupant Compartment Deformation Index (OCDI), Test 2214TB-1

Date: 5/4/04 Test Number: 2214TB-1 Model: 2500 P.U.
 Make: GMC Vehicle I.D.#: 1GDGC24U32Z135014
 Tire Size: LT 245/75 R16 Year: 2002 Odometer: 250879

*(All Measurements Refer to Impacting Side)

Vehicle Geometry -- mm (in.)

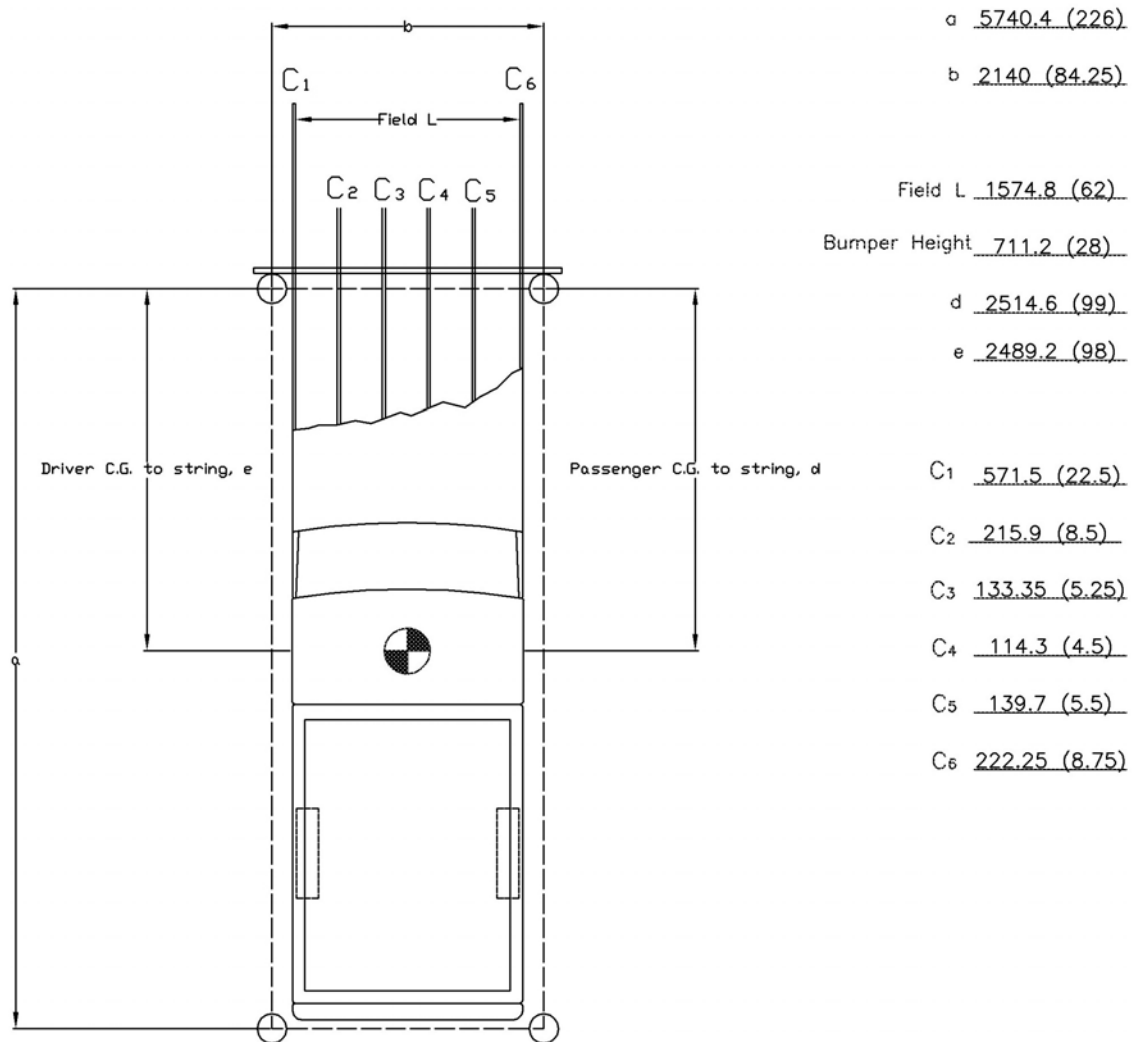


Figure C-3. NASS Crush Data, Test 2214TB-1

APPENDIX D

Accelerometer and Rate Transducer Data Analysis, Test 2214TB-1

Figure D-1. Graph of Longitudinal Deceleration, Test 2214TB-1

Figure D-2. Graph of Longitudinal Occupant Impact Velocity, Test 2214TB-1

Figure D-3. Graph of Longitudinal Occupant Displacement, Test 2214TB-1

Figure D-4. Graph of Lateral Deceleration, Test 2214TB-1

Figure D-5. Graph of Lateral Occupant Impact Velocity, Test 2214TB-1

Figure D-6. Graph of Lateral Occupant Displacement, Test 2214TB-1

Figure D-7. Graph of Yaw Angular Displacements, Test 2214TB-1

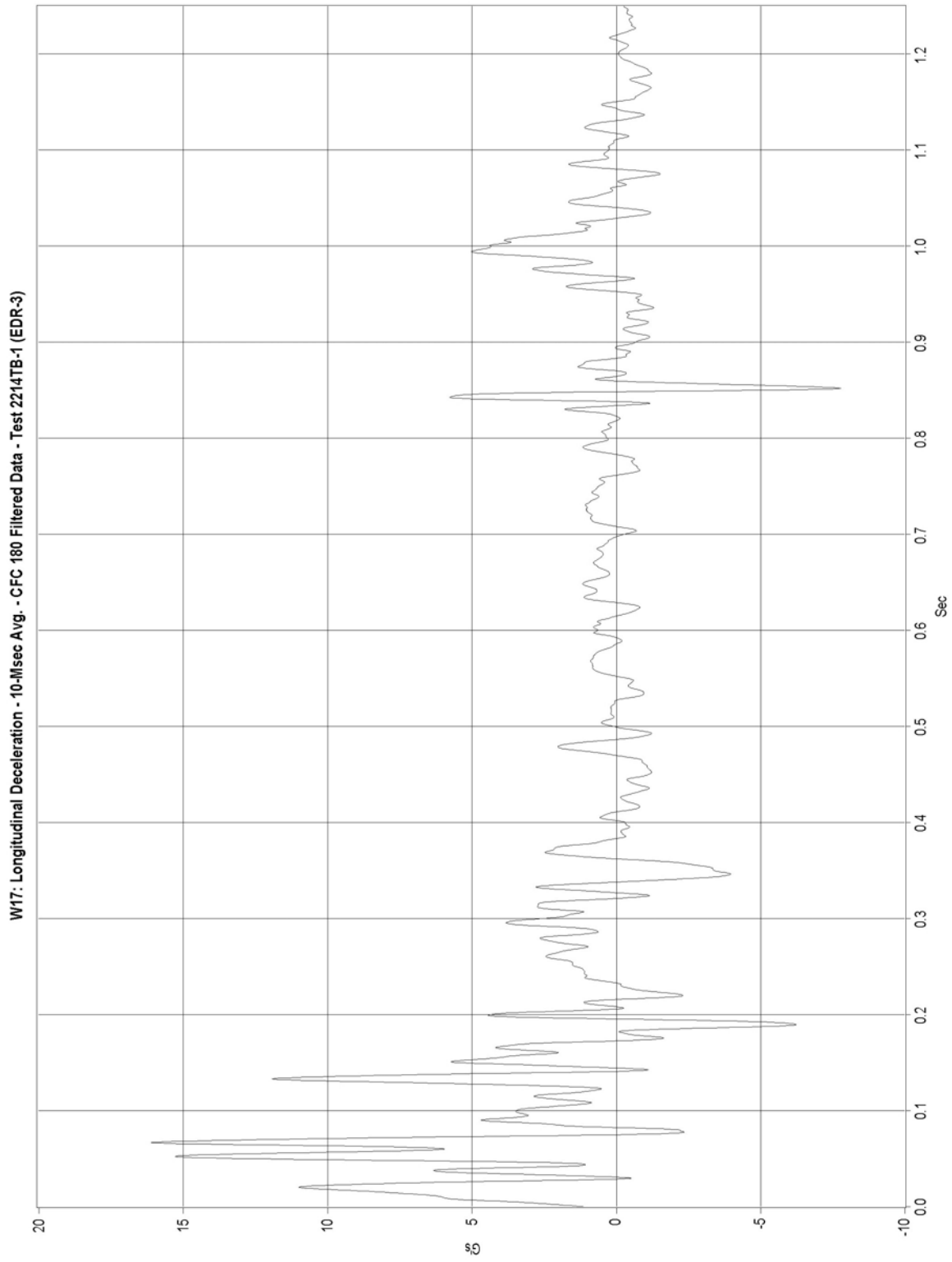


Figure D-1. Graph of Longitudinal Deceleration, Test 2214TB-1

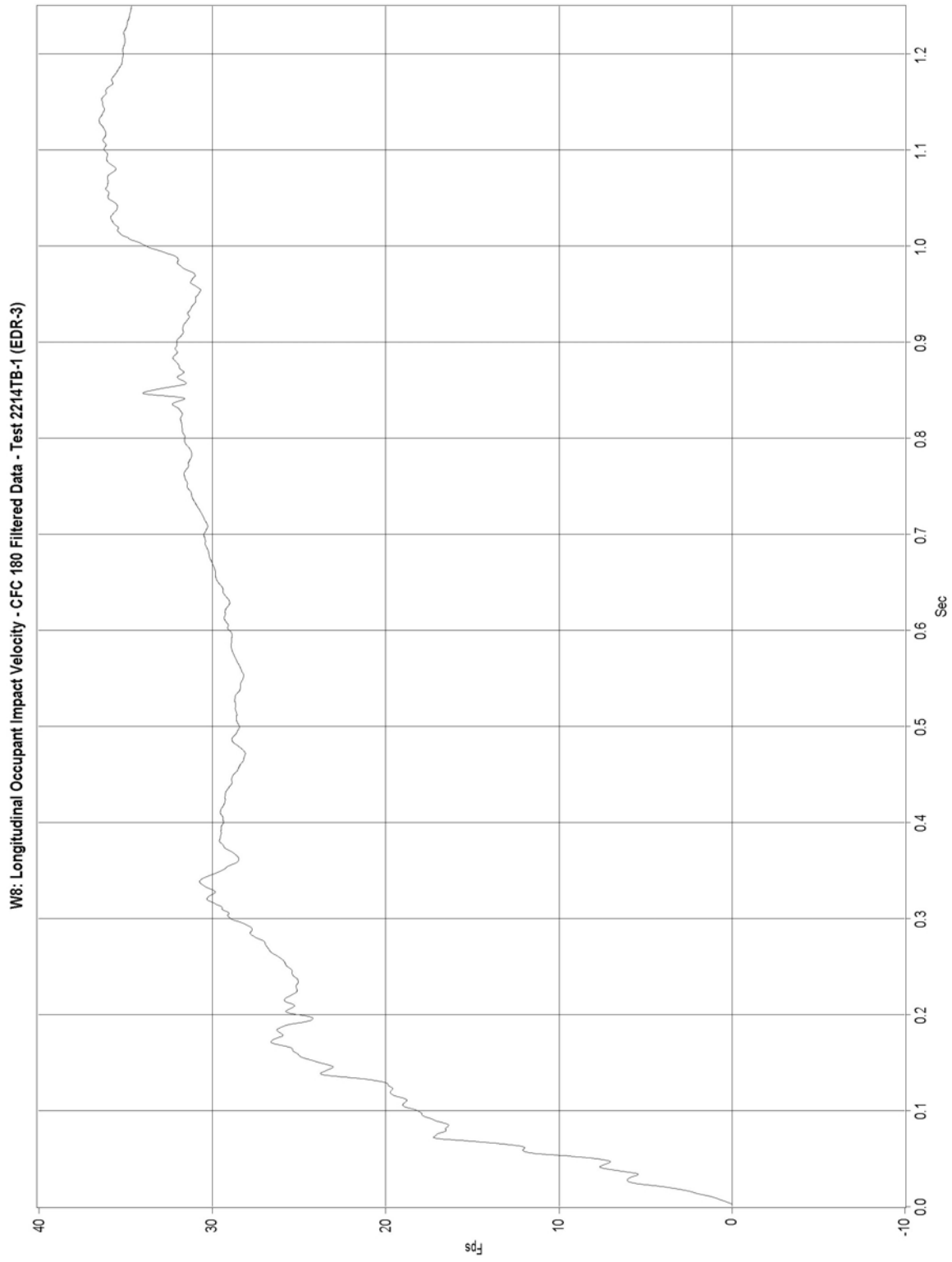


Figure D-2. Graph of Longitudinal Occupant Impact Velocity, Test 2214TB-1

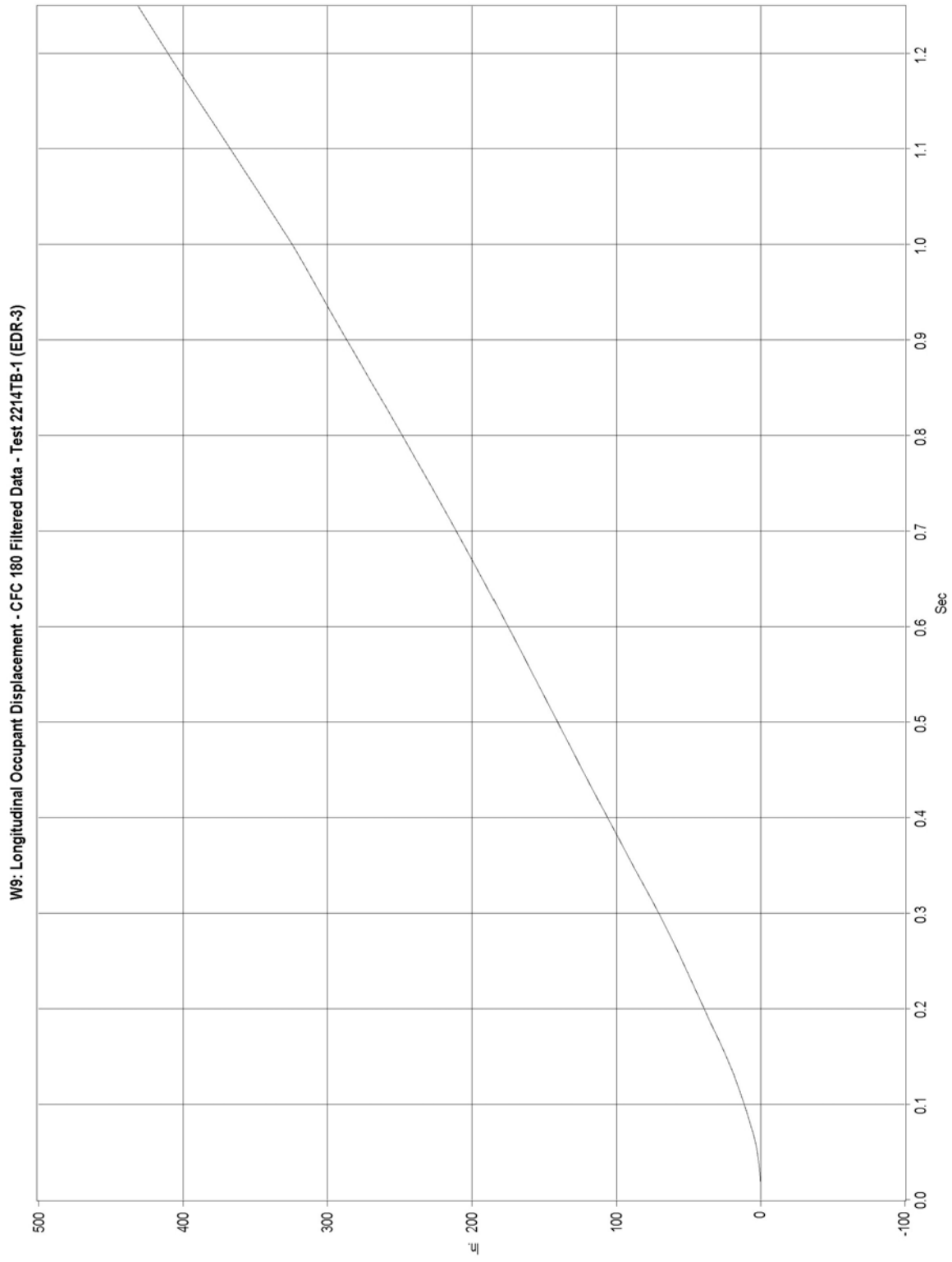


Figure D-3. Graph of Longitudinal Occupant Displacement, Test 2214TB-1

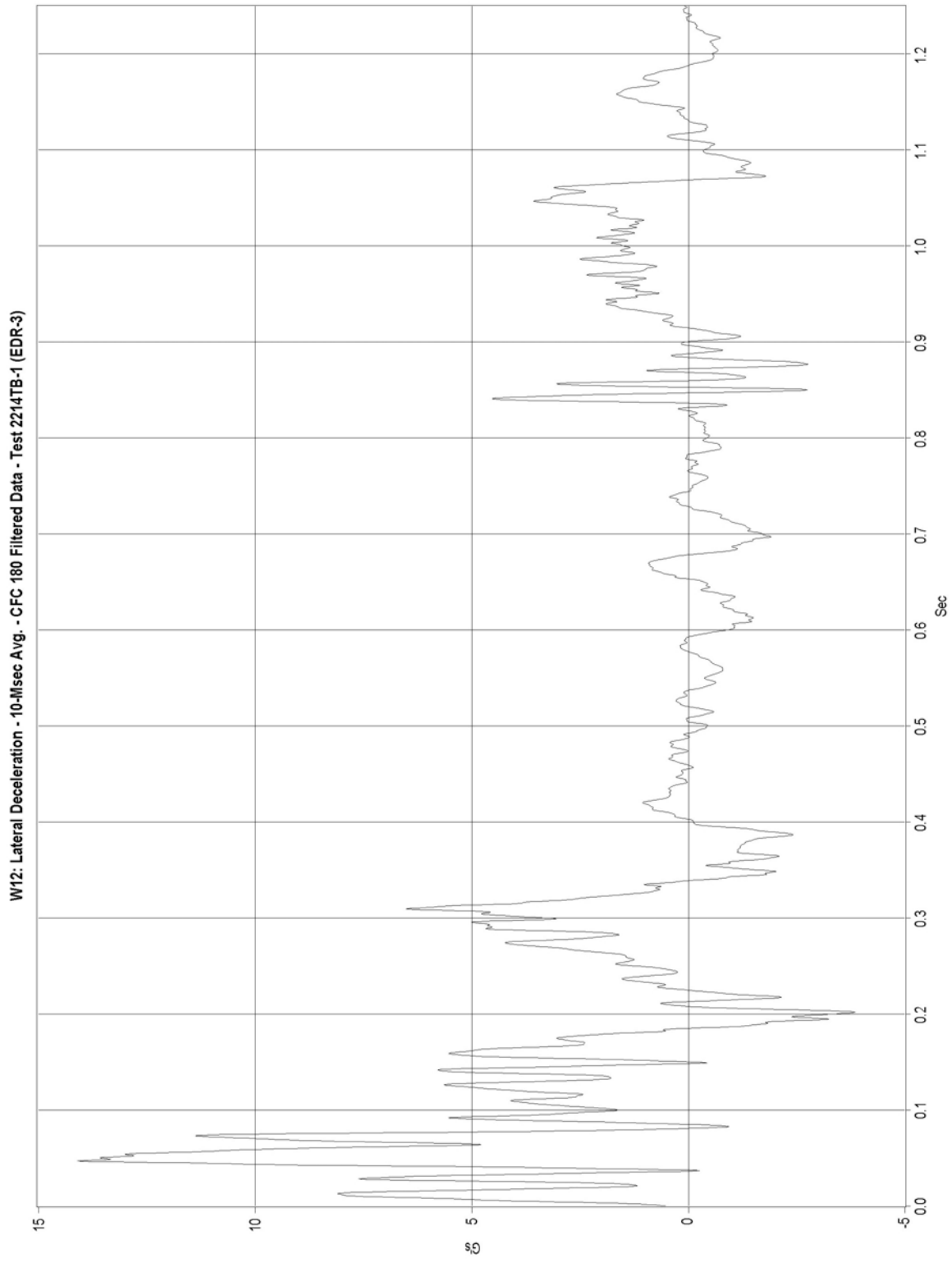


Figure D-4. Graph of Lateral Deceleration, Test 2214TB-1

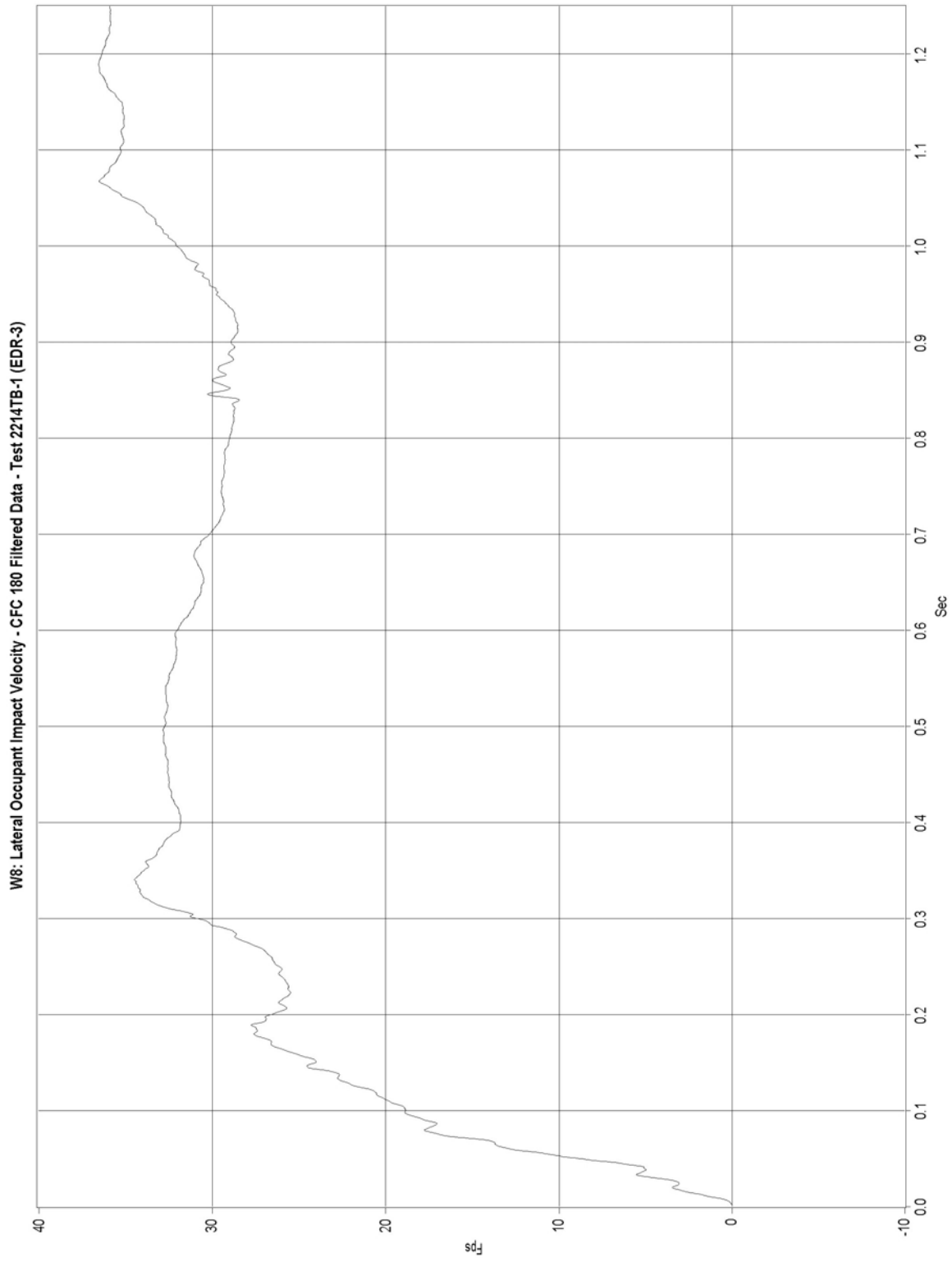


Figure D-5. Graph of Lateral Occupant Impact Velocity, Test 2214TB-1

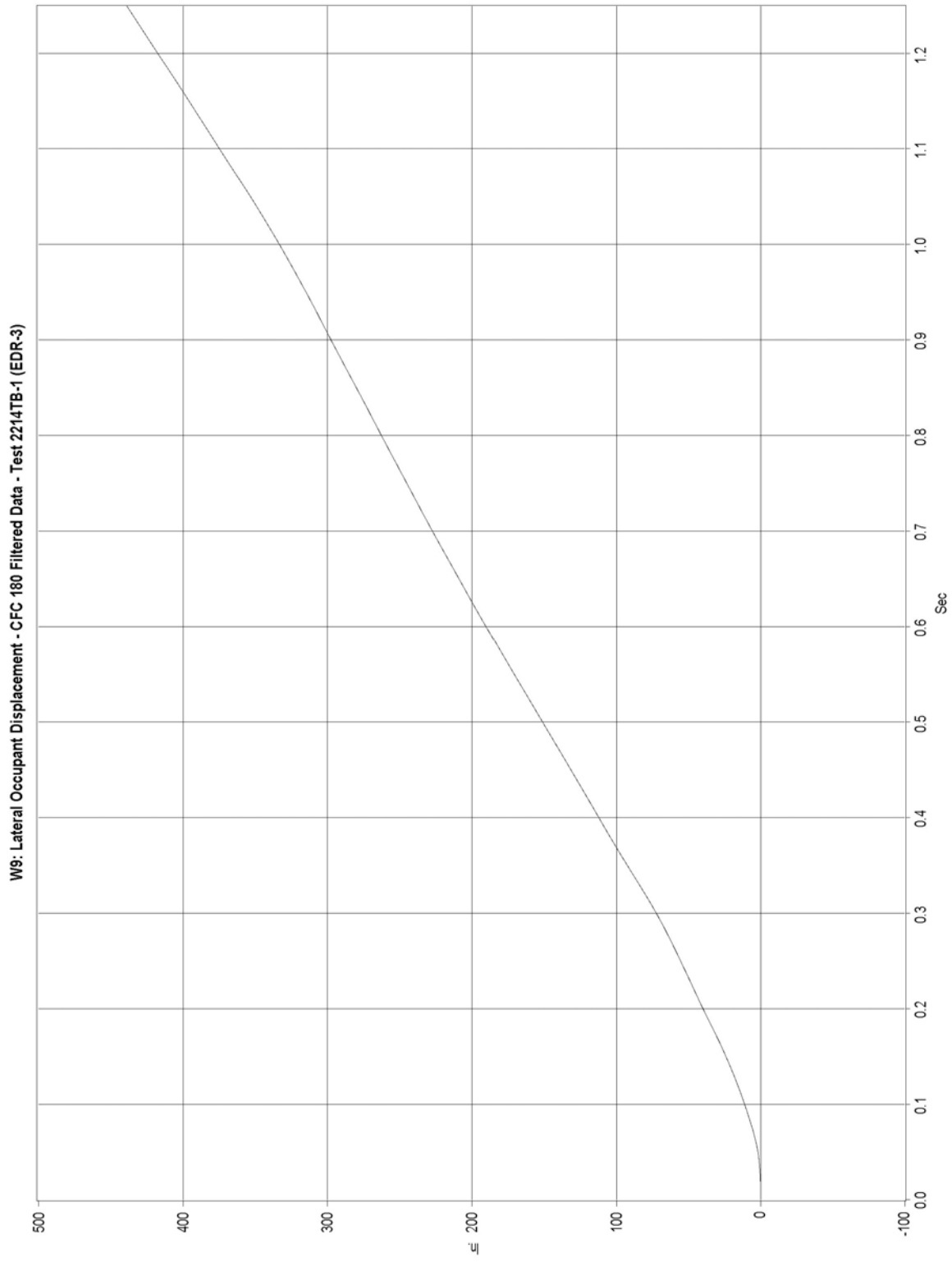


Figure D-6. Graph of Lateral Occupant Displacement, Test 2214TB-1

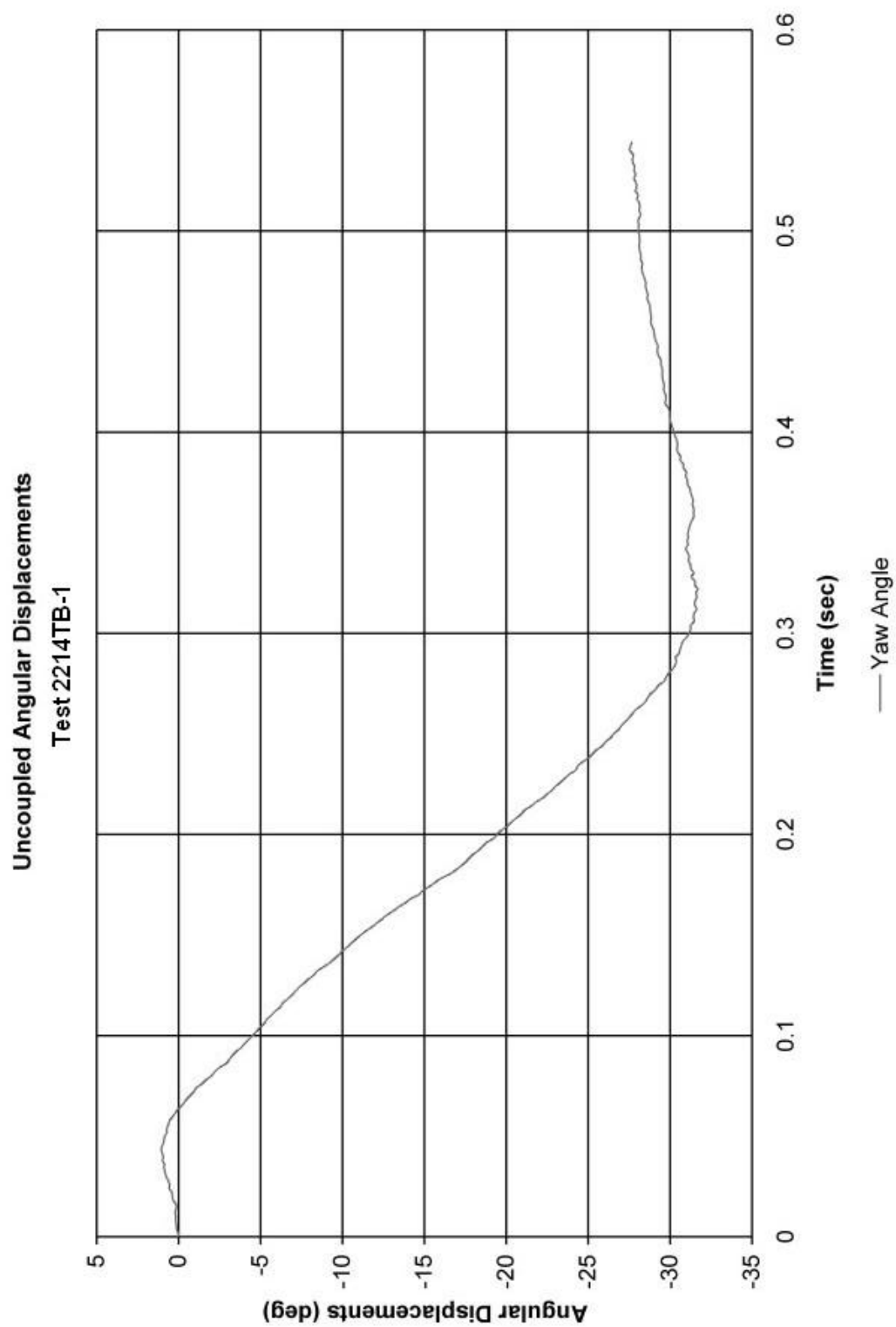


Figure D-7. Graph of Yaw Angular Displacements, Test 2214TB-1