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Design and Evaluation of an Open Combination Traffic/Bicycle Bridge Railing System

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DESIGN AND EVALUATION OF AN OPEN COMBINATION TRAFFIC/BICYCLE BRIDGE RAILING SYSTEM

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16. Abstract (Limit: 200 words)

Two Open Traffic/Bicycle Bridge Railing Systems were designed and tested for use on a rigid, single-slope, concrete barrier. The test installations consisted of 36.3 m (119 ft - 2 7/8 in.) of the railing mounted to a 36.58-m (120-ft) long section of standard single-slope concrete barrier.

For each system, one full-scale crash test was conducted and reported in accordance with the requirements set forth in the National Cooperative Highway Research Program (NCHRP) Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features*. The first test consisted of a 2,015-kg (4,442-lb) 1998 GMC C2500 pickup truck impacting at an angle of 25.6 degrees and at a speed of 101.5 km/h (63.1 mph). The pickup snagged on the longitudinal rails during climb and eventually rolled, resulting in test failure. For the second test, modifications were made to the system in an attempt to reduce vehicle penetration and prevent rolling. The second test was also conducted with a 1998 GMC C2500 pickup truck. The pickup weighed 2,029 kg (4,473 lbs), and impacted the system at an angle of 25.6 degrees and at a speed of 102.7 km/h (63.8 mph). Once again, the pickup snagged as it climbed the barrier, resulting in vehicle roll and unsatisfactory results.

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DISCLAIMER STATEMENT

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TABLE OF CONTENTS

List of Figures

Page

List of Tables

Page

1 INTRODUCTION

1.1 Background and Problem Statement

When constructing new bridges, local communities often consider the addition of sidewalks for pedestrian or bicycle use. With the exception of the Minnesota Combination Rail [1], no Federal Highway Administration (FHWA) approved designs incorporate an open railing mounted on top of a standard 813-mm (32-in.) New Jersey or single-sloped concrete barrier that meet the Test Level (TL-4) criteria in National Cooperative Highway Research Program (NCHRP) Report No. 350 [2] for bicycle traffic and vehicular impacts.

Open bicycle rail systems must meet many rigorous standards. First, the height of the railing must be 1,067 mm (42 in.) for pedestrian walkways and 1,372 mm (54 in.) for bicycle paths. Second, the American Association of State Highway and Transportation Officials' (AASHTO) *Standard Specifications for Highway Bridges* [3] allows a 203-mm (8-in.) maximum opening between the railings above the concrete. In addition, the rail must be capable of supporting a static load, while being able to break away under impact conditions where the box of a single-axle truck rides on top of the rail during redirection.

1.2 Objective

The main objective of the research project was to develop an open combination traffic/bicycle bridge rail for use with concrete parapets. The bridge railing was to meet the Test Level 4 (TL-4) safety performance criteria set forth in NCHRP Report No. 350, *Recommended Procedures for the Safety Performance Evaluation of Highway Features*. The design was to address the salient bicycle specifications, minimize the potential for snag, and provide tensile capacity throughout the system, as well as be economically feasible to construct.

1.3 Scope

Although the research objective was never completed, several tasks were performed in an attempt to reach the objective. First, a literature search was performed to review similar bridge rails, including identifying key features of each design that would provide insight into how the bridge rail would perform. Second, the existing design was analyzed and designed to prevent the snagging potential. After final design and fabrication, two full-scale vehicle crash tests were performed. The first test was conducted on a design which utilized three longitudinal rails, and the second test was conducted on a modified design utilizing four longitudinal rails. Both full-scale vehicle crash tests were performed with a 3/4-ton pickup truck, weighing approximately 2,000 kg (4,409 lbs), at a target impact speed and angle of 100.0 km/h (62.1 mph) and 25 degrees, respectively. Test results were analyzed, evaluated, and documented. From these results, conclusions were drawn and recommendations were made concerning the safety performance and use of the traffic/bicycle bridge rail.

2 LITERATURE REVIEW

Historically, little research has been completed on the development and crash testing of traffic/bicycle railings. Specifically, only four pedestrian/bicycle railings are known to have been evaluated by full-scale crash testing.

The first of those railings is the BR27D system, which consisted of two horizontal, tubular steel rails supported by vertical, tubular steel posts [5]. The system was attached to a rectangular concrete barrier. It was constructed in two distinct configurations, one with a raised concrete sidewalk and one without. Two full-scale crash tests were utilized to evaluate each configuration of the system, and the system was deemed acceptable according to the Performance Level 1 (PL-1) criteria established in the AASHTO's *Guide Specifications for Bridge Railings* [6].

The second tested system was BR27C, which consisted of a single horizontal, tubular steel rail supported by vertical, tubular steel posts and was attached to a rectangular concrete barrier [7]. The system was also constructed with and without a raised sidewalk. BR27C was determined to be acceptable according to the AASHTO PL-2 criteria based on a total of six full-scale tests, three for each configuration [6].

The third design again consisted of two horizontal, tubular steel rails and vertical, tubular steel posts attached to the Illinois 2399-1 traffic railing system [8]. The system was determined to be acceptable according to the AASHTO PL-1 criteria based on one full-scale crash test.

The final traffic/pedestrian railing was designed for use with the standard New Jersey safety shape bridge rail [1]. The system utilized two longitudinal, tubular steel rails with tubular, breakaway steel posts as vertical supports. One wire rope cable was strung through each longitudinal tube to prevent the railing from falling below the concrete barrier after impact. In addition, solid vertical spindles, spaced 168 mm (6.61 in.) on center, ran between the upper and lower longitudinal rails. The system successfully met the NCHRP Report No. 350 TL-4 criteria by passing full-scale crash tests with both a pickup truck and a single-unit truck.

3 TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1 Test Requirements

Longitudinal barriers, such as combination traffic/bicycle bridge railings, must satisfy the requirements provided in NCHRP Report No. 350 to be accepted for use on National Highway System (NHS) construction projects or as a replacement for existing systems not meeting current safety standards. According to TL-4 of NCHRP Report No. 350, longitudinal barriers must be subjected to three full-scale vehicle crash tests. The three crash tests are as follows:

1. Test Designation 4-10 consisting of an 820-kg (1,808-lb) small car impacting the bicycle/pedestrian rail system at a nominal speed and angle of 100.0 km/h (62.1 mph) and 20 degrees, respectively.

2. Test Designation 4-11 consisting of a 2,000-kg (4,409-lb) pickup truck impacting the bicycle/pedestrian rail system at a nominal speed and angle of 100.0 km/h (62.1 mph) and 25 degrees, respectively.

3. Test Designation 4-12 consisting of an 8,000-kg (17,637-lb) single-unit truck impacting the bicycle/pedestrian rail system at a nominal speed and angle of 80.0 km/h (49.7 mph) and 15 degrees, respectively.

During the design phase of the barrier system, special attention was given to prevent geometric features of the bicycle/pedestrian rail design that would cause the small car test to fail due to excessive snagging resulting from the small car's lateral extent over the concrete parapet. Therefore, due to the prior successful small car testing on concrete parapets and the attention given to the geometric features in the design, the 820-kg (1,808-lb) small car crash test was deemed unnecessary for the project. The test conditions for the TL-4 barriers are summarized in Table 1.

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 the collision. Criteria for structural adequacy are intended to evaluate the ability of the bicycle/pedestrian rail 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 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 1. NCHRP Report No. 350 Test Level 4 Crash Test Conditions

Test Article	Test Designation	Test Vehicle	Impact Conditions			Evaluation Criteria
			Speed		Angle (degrees)	
			(km/h)	(mph)		
Longitudinal Barrier	4-10	820C	100	62.1	20	A,D,F,H,I,K,M
	4-11	2000P	100	62.1	25	A,D,F,K,L,M
	4-12	8000S	80	49.7	15	A,D,G,K,M

Table 2. NCHRP Report No. 350 Evaluation Criteria for Crash Tests [2]

Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.
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.
	G	It is preferable, although not essential, that the vehicle remain upright during and after collision..
	F.	The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.
	H.	Longitudinal and lateral occupant impact velocities should fall below the preferred value of 9 m/s (29.5 ft/s), or at least below the maximum allowable value of 12 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 Gs.
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.
	L.	The occupant impact velocity in the longitudinal direction should not exceed 12 m/s (39.4 ft/s) and the occupant ridedown acceleration in the longitudinal direction.
	M.	The exit angle from the test article preferably should be less than 60 percent of test impact angle measured at time of vehicle loss of contact with test device.

4 DESIGN DETAILS – SYSTEM NO. 1

The test installation consisted of 36.3 m (119 ft - 2 7/8 in.) of bicycle rail mounted to a 36.58-m (120-ft) long, standard single-slope concrete barrier. Design details are shown in Figures 1 through 7. The corresponding English-unit drawings are shown in Appendix A. Photographs of the test installation are shown in Figure 8.

The bicycle rail consisted of longitudinal rails, steel posts, and sloped end sections. The longitudinal rails were fabricated with TS 76-mm x 51-mm x 3.2-mm (3-in. x 2-in. x 1/8-in.) ASTM A500 Grade B structural steel tubing. Each of the three longitudinal rails consisted of 6,096-mm (20-ft) long sections spliced at the midspan between two posts. The rails were attached to 51-mm x 51-mm x 6.4-mm (2-in. x 2-in. x 1/4-in.) steel angles welded to the posts with a 10-mm (3/8-in.) diameter, 76-mm (3-in.) long bolt.

The expansion tubes for the rail splices were fabricated with 616-mm (24 1/4-in.) long, TS 64-mm x 38-mm x 6.4-mm (2 ½-in. x 1 ½-in. x 1/4-in.) ASTM A500 Grade B structural steel tubing. The expansion tubes were inserted into the bicycle tubes with four 13-mm (1/2-in.) diameter, 70-mm (2 3/4-in.) long bolts placed vertically with two in the upstream tube section and two in the downstream tube section. To fill the gap between the longitudinal rail and the expansion tube, a steel plate shim was used on both the long and short faces of the tube. The shim on the long side was a 356-mm (14-in.) long, 38-mm x 3.2-mm thick (1 1/2-in. x 1/8-in.) steel plate, while the shim on the short side was a 356-mm (14-in.) long, 19-mm x 3.2-mm thick (3/4-in. x 1/8-in.) steel plate.

The top mounting heights of the lower, middle, and upper rails from the ground were 1,006 mm (39 5/8 in.), 1,194 mm (47 in.), and 1,381 mm (54 3/8 in.), respectively. The system was terminated by sloping the ends of the three longitudinal tubes down to the top of the barrier. The lower sloped end rail was 448-mm (17 5/8-in.) long and ended 478 mm (1 ft - 6 13/16 in.) away from the centerline of the first and last posts. The middle sloped end rail was 918-mm (36 1/8-in.) long and ended 910 mm (2 ft - 11 13/16 in.) away from the centerline of the first and last posts. The top sloped end rail was 1,389-mm (54 11/16-in.) long and ended 1,341 mm (4 ft - 4 13/16 in.) away from the centerline of the first and last posts. The sloped end rails were bolted to both the top and back sides of the concrete parapet, as shown in Figures 1 and 3.

The 927-mm (3-ft 1/2-in.) long steel posts were fabricated with TS 102-mm x 51-mm x 4.8-mm (4-in. x 2-in. x 1/8-in.) ASTM A500 Grade B structural steel tubing. A 178-mm x 254-mm x 12.7-mm (7-in. x 10-in. x 1/2-in.) steel plate was welded to each post in order to attach it to the barrier with four 19-mm (3/4-in.) diameter, 102-mm (4-in.) long Grade 5 bolts. The posts were attached to the barrier with a rectangular pattern of bolts spaced 102-mm (4-in.) vertically and 152-mm (6-in.) horizontally. The posts were spaced 3,048 mm (10 ft) on center. The top of the post was located 1,375-mm (54 1/8-in.) from the ground and was capped with a 4.8-mm (3/16-in.) thick, A36 steel plate. The overall height of the system was 1,380 mm (54 5/16 in.).

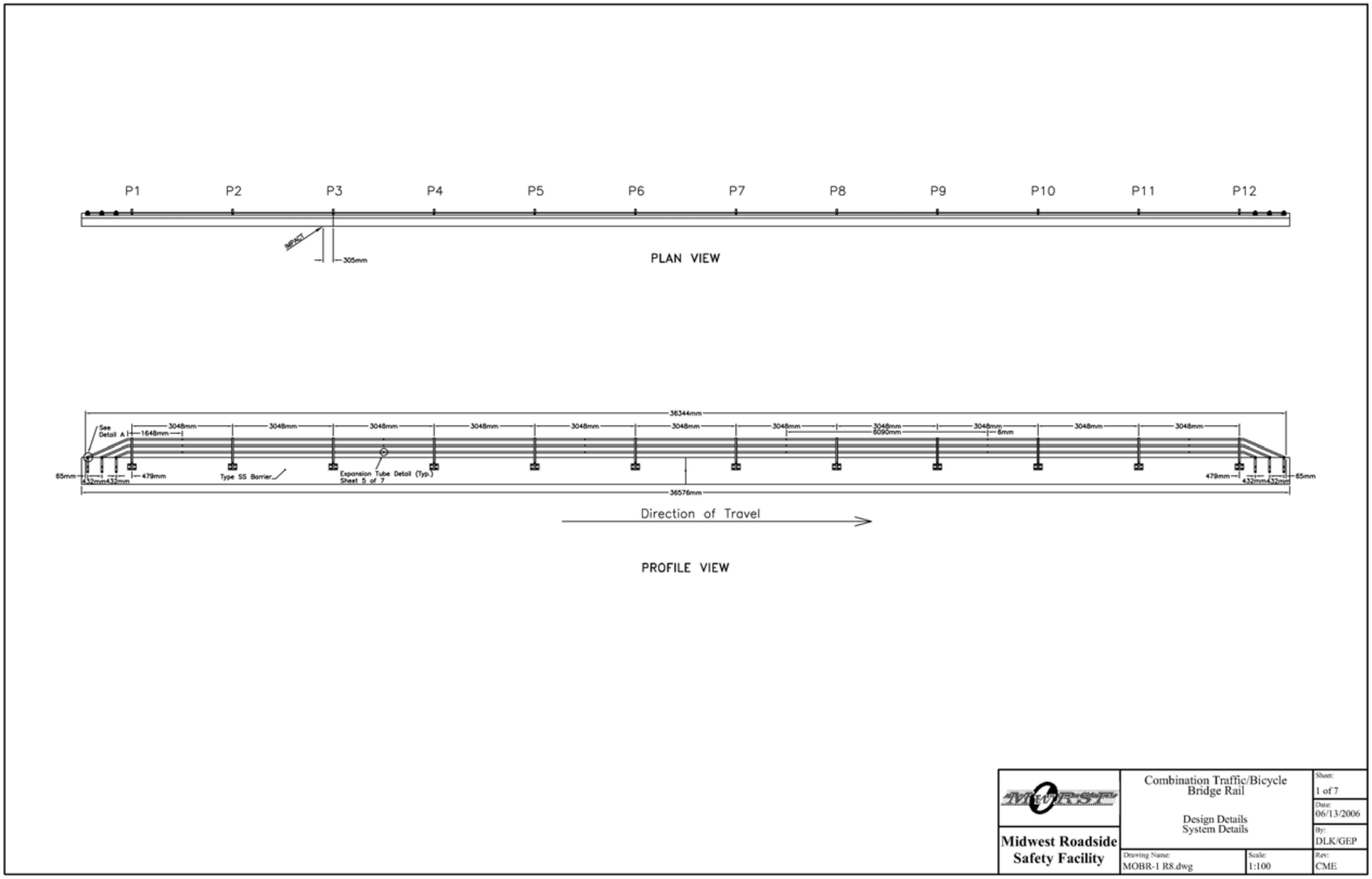


Figure 1. Combination Traffic/Bicycle Bridge Rail - System Details

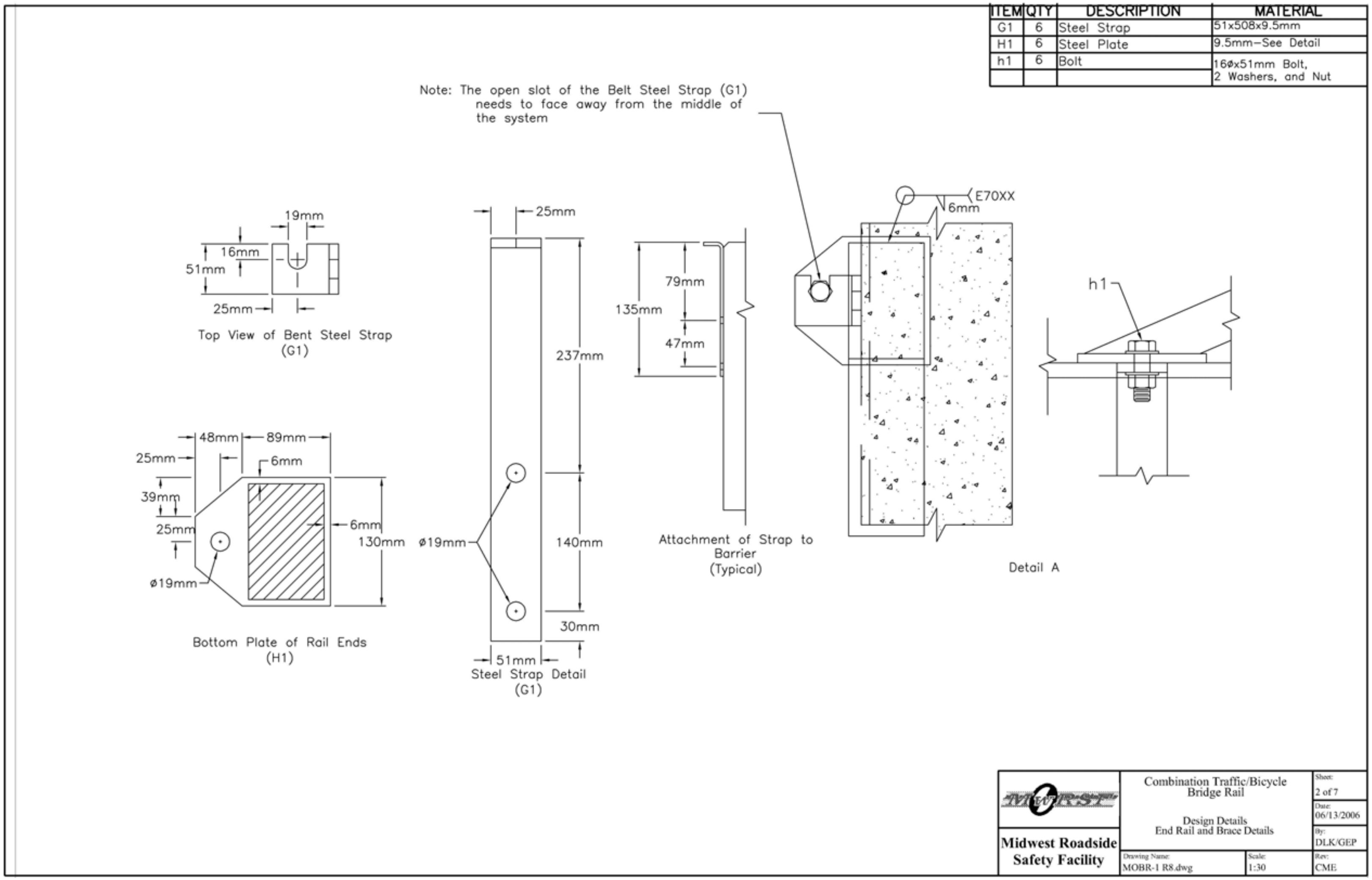


Figure 2. Combination Traffic/Bicycle Bridge Rail - End Rail and Brace Details

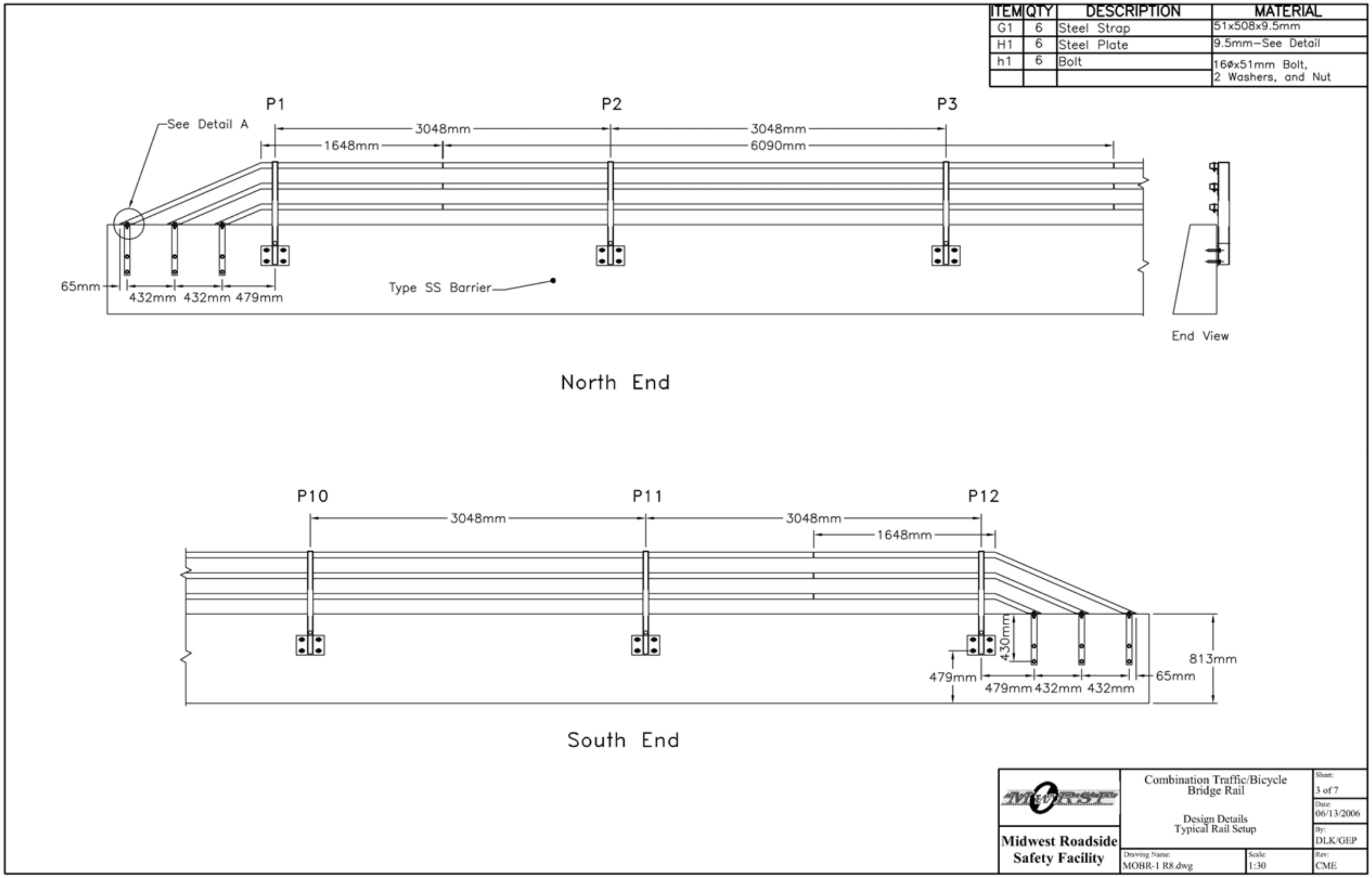


Figure 3. Combination Traffic/Bicycle Bridge Rail - Typical Rail Setup

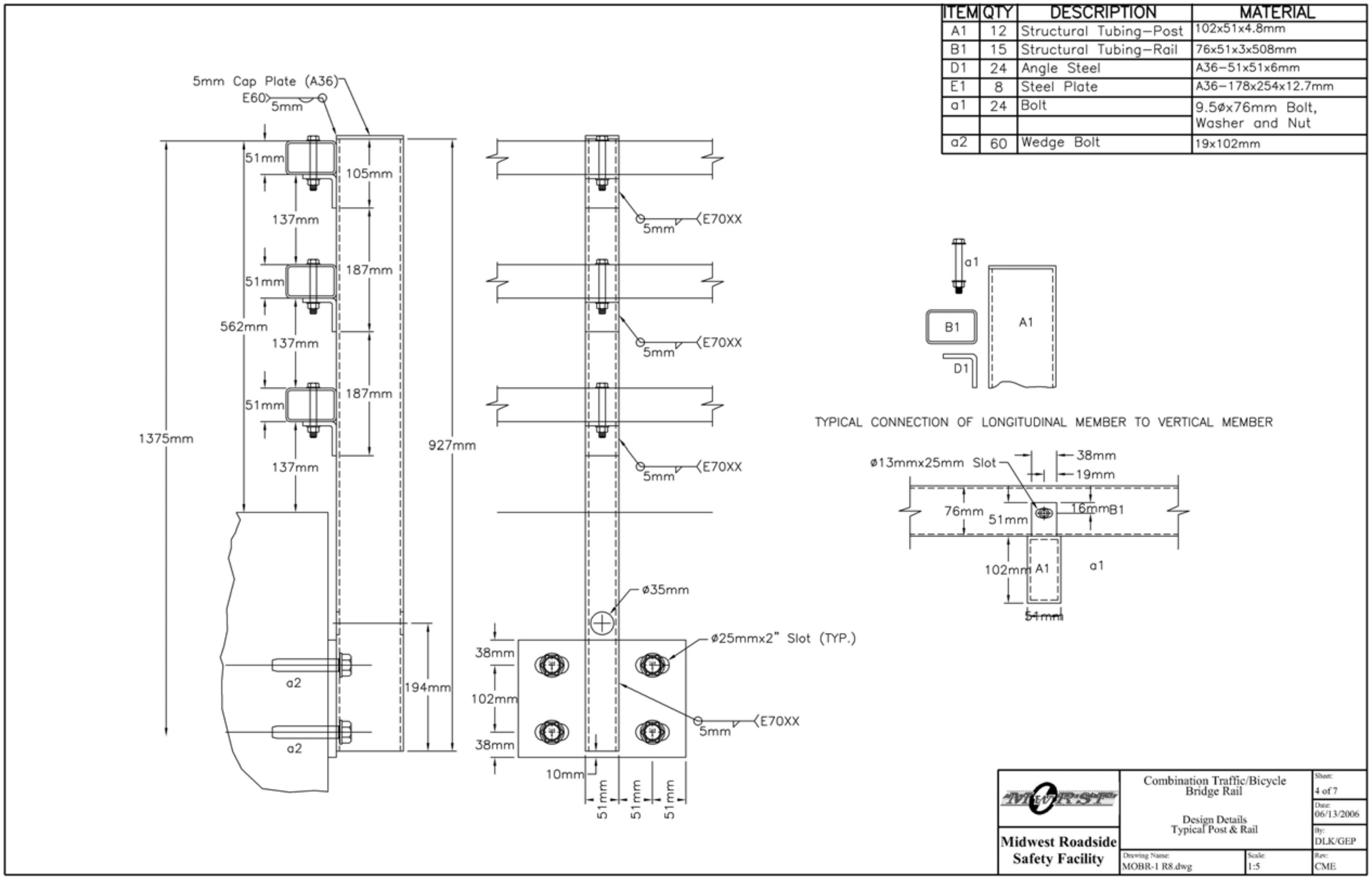


Figure 4. Combination Traffic/Bicycle Bridge Rail - Typical Post and Rail Details

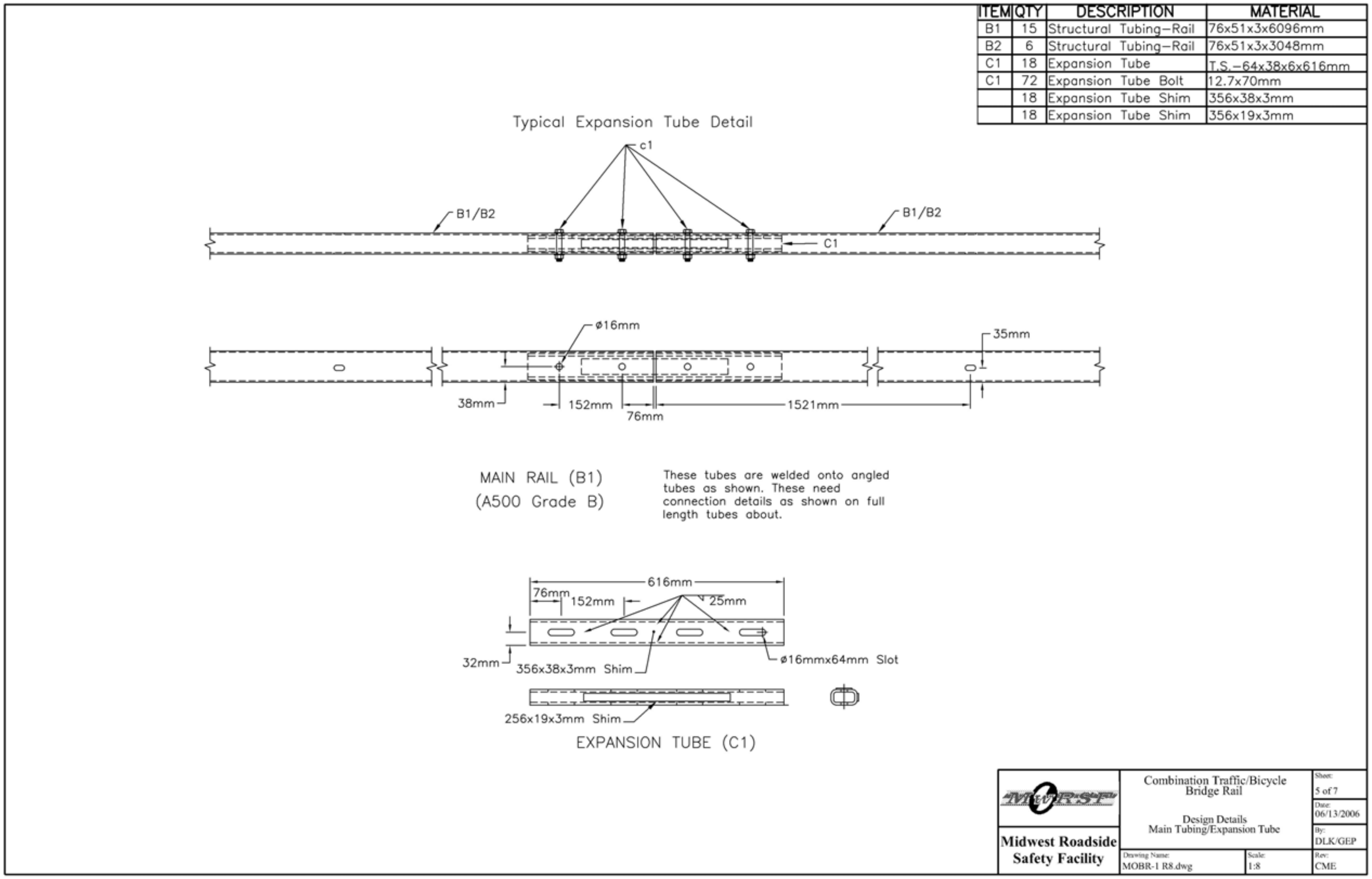


Figure 5. Combination Traffic/Bicycle Bridge Rail - Main Tubing and Expansion Tube Details

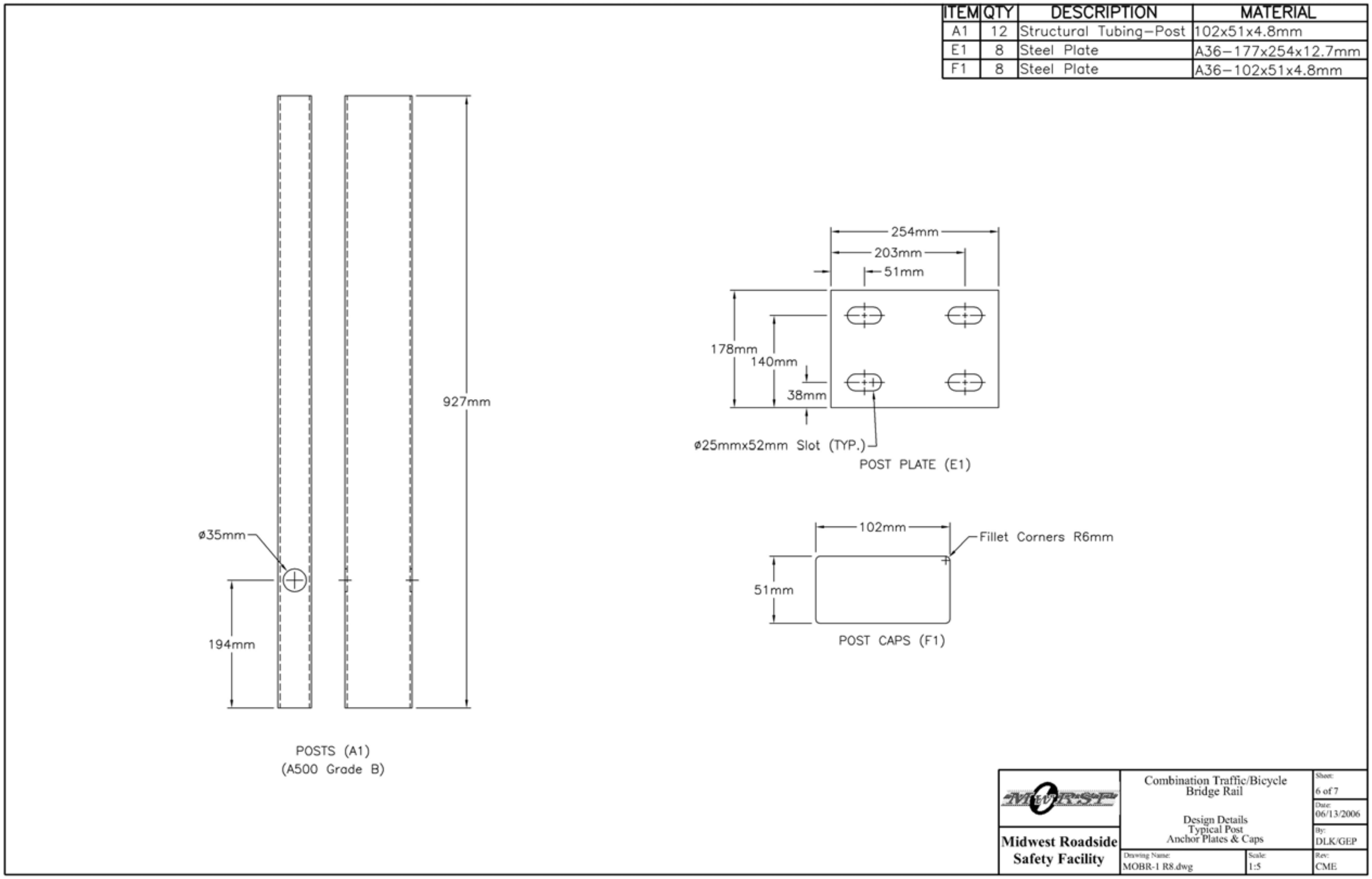


Figure 6. Combination Traffic/Bicycle Bridge Rail, Post, Anchor Plates, and Caps Details

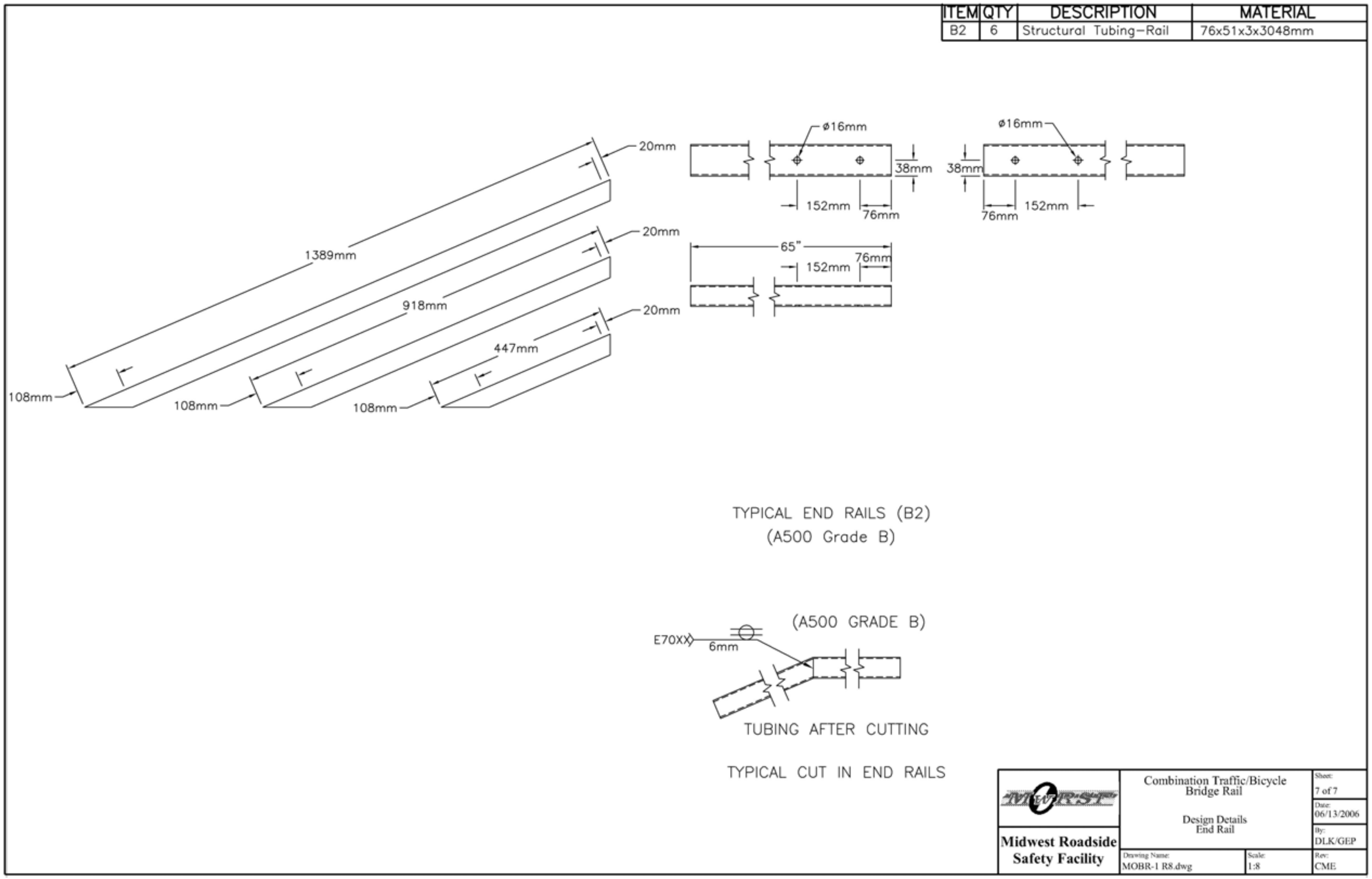


Figure 7. Combination Traffic/Bicycle Bridge Rail - End Rail Details

Figure 8. Combination Traffic/Bicycle Bridge Rail

5 TEST CONDITIONS

5.1 Test Facility

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

5.2 Vehicle Tow and Guidance System

A reverse cable tow system with a 1:2 mechanical advantage was used to propel the test vehicle. The distance traveled and the speed of the tow vehicle were one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the 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 [10] was used to steer the test vehicle. A guide-flag, which was attached to both 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 lbs), 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 tests MOBR-1 and MOBR-2, the vehicle guidance systems were approximately 335 m (1,100 ft) long.

5.3 Test Vehicles

For test MOBR-1, a 1998 GMC C2500 3/4-ton pickup truck was used as the test vehicle. The test inertial and gross static weights were 2,015 kg (4,443 lbs). Photographs of the test vehicle are shown in Figure 9, and vehicle dimensions are provided in Figure 10.

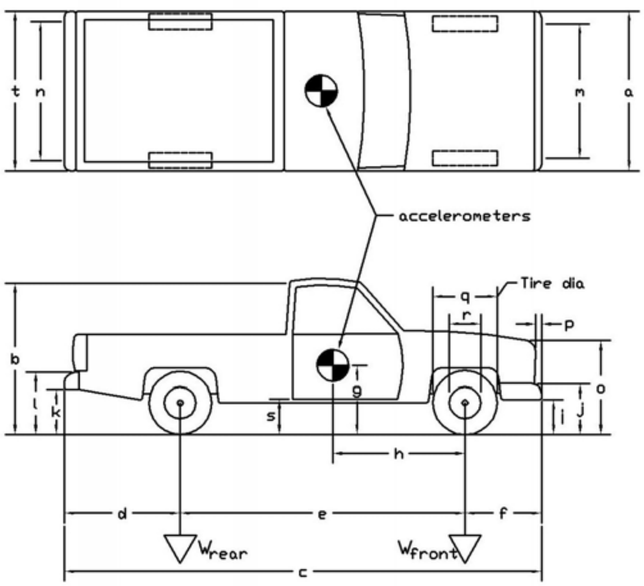
Figure 9. Test Vehicle, Test MOBR-1

Date: 3/27/04 Test Number: MOBR-1 Model: 2000P

Make: GMC Vehicle I.D.#: 1GDGC24R3WZ541957

Tire Size: LT 245/75 R16 Year: 1998 Odometer: 271487

*(All Measurements Refer to Impacting Side)



Vehicle Geometry – mm (in.)

a	1880 (74.0)	b	1829 (72.0)
c	5537 (218.0)	d	1295 (51.0)
e	3346 (131.75)	f	895 (35.25)
g	667 (26.25)	h	1394 (54.875)
i	457 (18.0)	j	749 (29.5)
k	610 (24.0)	l	806 (31.75)
m	1594 (62.75)	n	1575 (62.0)
o	1035 (40.75)	p	89 (3.5)
q	756 (29.75)	r	445 (17.5)
s	483 (19.0)	t	1892 (74.5)

Wheel Center Height Front 362 (14.25)

Wheel Center Height Rear 365 (14.375)

Wheel Well Clearance (FR) 908 (35.75)

Wheel Well Clearance (RR) 946 (37.25)

Engine Type 8 CYL. GAS

Engine Size 5.7 L 350 CID

Transmission Type:

Automatic or Manual

FWD or RWD or 4WD

Weights kg (lbs)	Curb	Test Inertial	Gross Static
W_{front}	1140 (2513)	1171 (2581)	1171 (2581)
W_{rear}	842 (1857)	845 (1862)	845 (1862)
W_{total}	1982 (4370)	2015 (4443)	2015 (4443)

Note any damage prior to test: None

Figure 10. Vehicle Dimensions, Test MOBR-1

For test MOBR-2, a 1998 GMC C2500 3/4-ton pickup truck was used as the test vehicle. The test inertial and gross static weights were 2,029 kg (4,473 lb). The test vehicle is shown in Figure 11, and vehicle dimensions are shown in Figure 12.

The longitudinal components of the center of gravity was determined using the measured axle weights. The location of the final centers of gravity are shown in Figures 1 and 12.

Square black and white-checkered targets were placed on the vehicles to aid in the analysis of the high-speed film and E/cam and Photron video, as shown in Figures 13 and 14. Round, checkered targets were placed at the center of gravity on the driver's side door, the passenger's side door, and the roof of the vehicles. The remaining targets were located for reference in strategic locations on the vehicles so they could be viewed from the high-speed cameras for film analysis.

The front wheels of the test vehicles were aligned for camber, caster, and toe-in values of zero so 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 to a stop safely after the test.

5.4 Data Acquisition Systems

5.4.1 Accelerometers

For tests MOBR-1 and MOBR-2, a 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 3,200 Hz. The environmental shock and vibration sensor/recorder

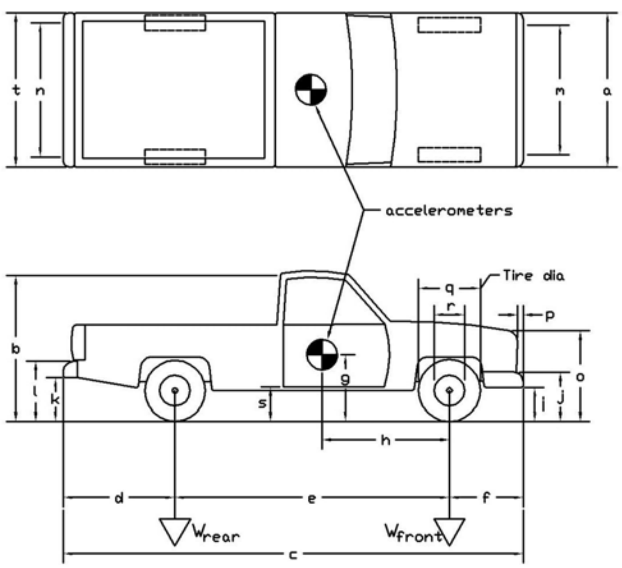
Figure 11. Test Vehicle, Test MOBR-2

Date: 6/24/04 Test Number: MOBR-2 Model: 2000P

Make: GMC Vehicle I.D.#: 1GDC24R3W2542297

Tire Size: LT 245/75 R16 Year: 1998 Odometer: 223447

*(All Measurements Refer to Impacting Side)



Vehicle Geometry – mm (in.)

a	1886 (74.25)	b	1965 (77.375)
c	5537 (218.0)	d	1295 (51.0)
e	3346 (131.75)	f	895 (35.25)
g	667 (26.25)	h	1394 (54.875)
i	457 (18.0)	j	667 (26.25)
k	610 (24.0)	l	787 (31.0)
m	1588 (62.5)	n	1632 (64.25)
o	1035 (40.75)	p	89 (3.5)
q	756 (29.75)	r	441 (17.375)
s	486 (19.125)	t	1848 (72.75)

Wheel Center Height Front 368 (14.5)

Wheel Center Height Rear 371 (14.625)

Wheel Well Clearance (FR) 908 (35.75)

Wheel Well Clearance (RR) 953 (37.5)

Frame Height (FR) 413 (16.25)

Frame Height (RR) 559 (22.0)

Engine Type 8 CYL. GAS

Engine Size 5.7 L 350 CID

Transmission Type:

Automatic or Manual

FWD or RWD or 4WD

Weights kg (lbs)	Curb	Test Inertial	Gross Static
W_{front}	1148 (67.125)	1183 (2608)	1183 (2608)
W_{rear}	889 (1961)	846 (1865)	846 (1865)
W_{total}	2038 (4493)	2029 (4473)	2029 (4473)

Note any damage prior to test: Minor Cosmetic

Figure 12. Vehicle Dimensions, Test MOBR-2

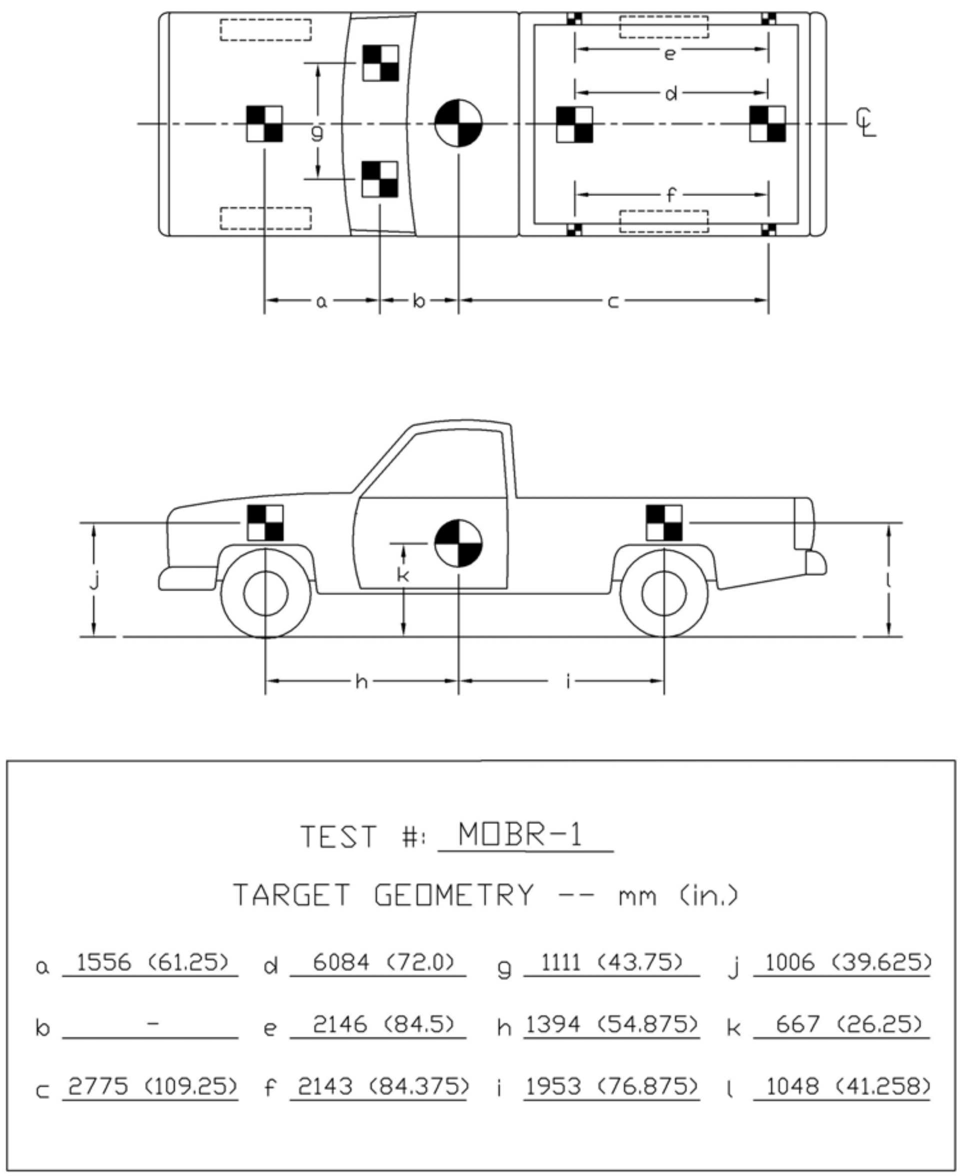
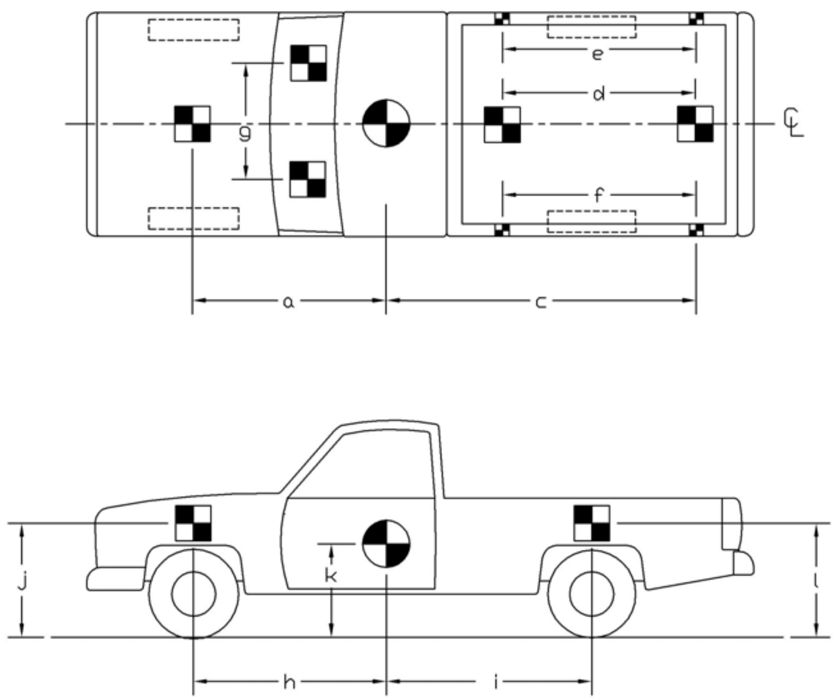


Figure 13. Vehicle Target Locations, Test MOBR-1



TEST #: MOBR-2

TARGET GEOMETRY -- mm (in.)

a	1705 (67.125)	d	1965 (77.375)	g	883 (34.75)	j	1054 (41.5)
b	-	e	2153 (84.75)	h	1394 (54.875)	k	667 (26.25)
c	2651 (104.375)	f	2153 (84.75)	i	1953 (76.875)	l	1006 (39.625)

Figure 14. Vehicle Target Locations, Test MOBR-2

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.

For test MOBR-2, a second 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 10,000 Hz. The environmental shock and vibration sensor/recorder system, Model EDR-4M6, was developed by Instrumented Sensor Technology (IST) of Okemos, Michigan and includes three differential channels as well as three single-ended channels. The EDR-4 was configured with 6 Mb of RAM memory and a 1,500 Hz lowpass filter. Computer software, “DynaMax 1 (DM-1)” and “DADiSP”, was used to analyze and plot the accelerometer data.

5.4.2 Rate Transducers

For test MOBR-2, a Humphrey 3-axis rate transducer with a range of 360 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 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”, was used to analyze and plot the rate transducer data.

5.4.3 High-Speed Photography

For test MOBR-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. One Photron high-speed video camera and four high-speed Red Lake E/cam video cameras, all with operating speeds of 500 frames/sec, were also used to film the crash test. In addition, five Canon digital video cameras, with a standard operating speed of 29.97 frames/sec, were also used to film the crash test. A Locam (with a wide-angle 12.5-mm lens), a high-speed Photron video camera (with a 12.5-mm lens), and one Canon digital video camera were placed above the test installation to provide a field of view perpendicular from the ground. One Locam, a high-speed E/cam video camera, and a Canon digital video camera were placed downstream from the impact point and had a field of view parallel to the barrier. A high-speed E/cam video camera and a Canon digital video camera were placed downstream from the impact point and behind the barrier. Another high-speed E/cam video camera and Canon digital video camera were placed upstream from impact and had a field of view parallel to the barrier. Another high-speed E/cam video camera was placed upstream from the impact point, but at a shorter distance behind the barrier. A Canon digital video camera, with a panning view, was placed on the traffic side of the barrier and had a field of view perpendicular to the barrier. A schematic of all twelve camera locations for test MOBR-1 is shown in Figure 15.

For test MOBR-2, one high-speed 16-mm Red Lake Locam camera, with operating speeds of approximately 500 frames/sec, was used to film the crash test. Two Photron high-speed video cameras and three high-speed Red Lake E/cam video cameras, all with operating speeds of 500 frames/sec, were also used to film the crash test. In addition, six Canon digital video cameras, with a standard operating speed of 29.97 frames/sec, were also used to film the crash test. A Locam (with a wide-angle 12.5-mm lens), a high-speed Photron video camera (with a 12.5-mm lens), and one Canon digital video camera were placed above the test installation to provide a field of view perpendicular from the ground. One Nikon 8700 still digital camera, a high-speed E/cam video camera, and a Canon digital video camera were placed downstream from the impact point and had a field of view parallel to the barrier. A high-speed E/cam video camera and a Canon digital video camera were placed downstream from the impact point and behind the barrier. Another high-speed E/cam video camera and Canon digital video camera were placed upstream from impact and had a field of view parallel to the barrier. A high-speed Photron video camera with a 17-102-mm lens and a Canon digital video camera were placed upstream from the impact point, but at a shorter distance behind the barrier. A Canon digital video camera, with a panning view, was placed on the traffic side of the barrier and had a field of view perpendicular to the barrier. A schematic of all twelve camera locations for test MOBR-2 is shown in Figure 16.

The Locam film, Photron videos, 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.

5.4.4 Pressure Tape Switches

For tests MOBR-1 and MOBR-2, 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 right-front tire of the test vehicle passed over it. Test vehicle speed was determined from electronic timing mark data recorded using the “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.

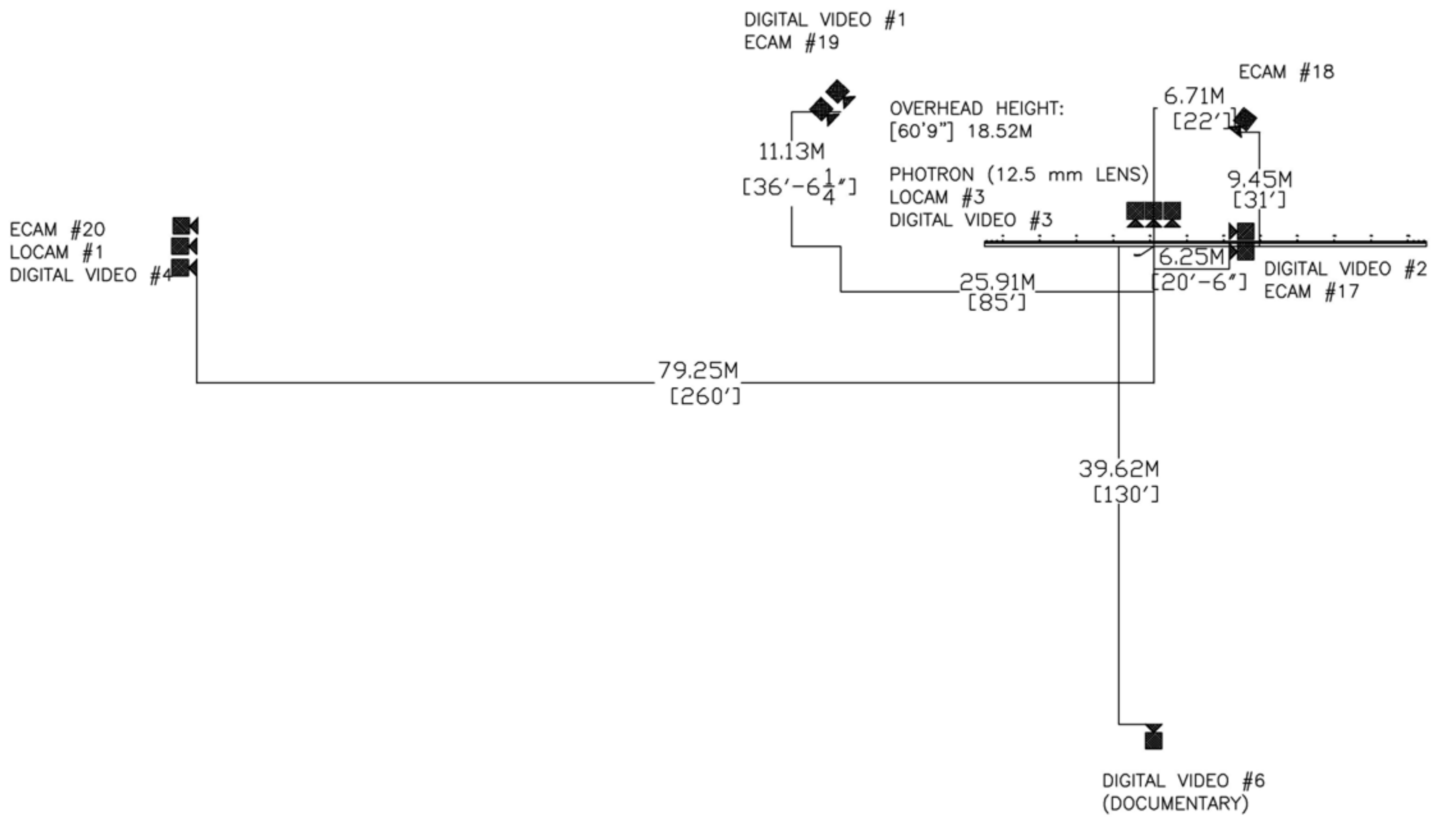


Figure 15. Location of High-Speed Video Cameras, Test MOBR-1

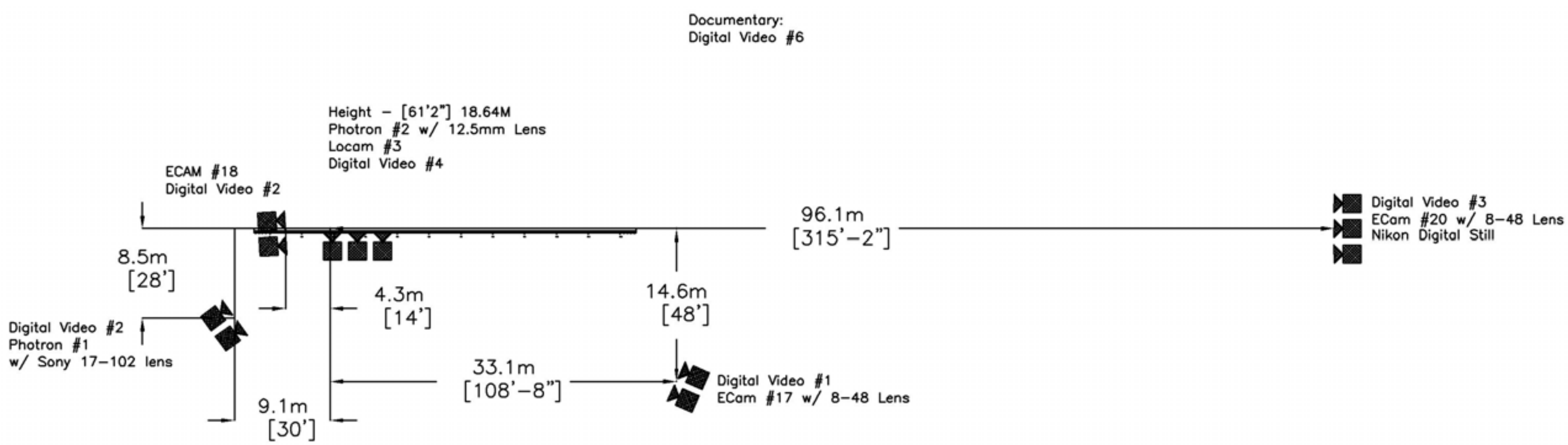


Figure 16. Location of High-Speed Video Cameras, Test MOBR-2

6 CRASH TEST NO. 1

6.1 Test MOBR-1

The 2,015-kg (4,442-lb) pickup truck impacted the combination traffic/bicycle bridge rail (System No. 1) at a speed of 101.5 km/h (63.1 mph) and at an angle of 25.6 degrees. A summary of the test results including sequential photographs is shown in Figure 17. The summary of the test results and sequential photographs in English units are shown in Appendix B. Additional sequential photographs are shown in Figures 18 through 23. Documentary photographs of the crash test are shown in Figure 24.

6.2 Test Description

Initial impact was to occur 305 mm (12 in.) upstream from the centerline of post no. 3, as shown in Figure 1. Actual vehicle impact occurred 533 mm (21 in.) upstream from the centerline of post no. 3. At 0.010 sec, the right-front corner of the hood protruded over the top of the concrete barrier, and the right side of the front bumper crushed inward, forming a buckle point at the center of the bumper. At 0.014 sec after impact, the right-front tire contacted the wall. At this same time, the right-front quarter panel crushed inward. At 0.024 sec, the test vehicle began to redirect as the lower right-front corner of the vehicle continued to crush inward. At this same time, the hood began to lift up and away from the right-front corner of the vehicle. At 0.036 sec, the right-front corner protruded over the top of the barrier system. At 0.038 sec, the truck climbed the concrete barrier slightly, with the right-front wheel deformed to a position of being pressed flat against the front face of the concrete barrier. After 0.042 sec, the right-front corner of the hood had protruded behind the bicycle rail, and the right-front quarter panel crushed inward as the lower and middle longitudinal rails deflected downward and upward, respectively. At this same time, the right-front wheel well impacted post no. 2, and the hood continued to lift upward. At 0.056 sec after impact, the top of the right-side door became ajar. Upward lift of the hood continued until 0.058 sec after impact, at which time the vehicle pitched downward toward its right-front corner. Post nos. 2 and 3 deflected backward as the lower and middle longitudinal rails reached their maximum separation. As the vehicle traveled downstream, the largest post deflection occurred at post no. 3, and the deflection of the lower and middle rails between post nos. 3 and 4 increased while the deflection of the lower and middle rails between post nos. 2 and 3 decreased. The vehicle continued to roll clockwise, and at 0.096 sec, the left-front tire became airborne. Around 0.132 sec, the vehicle lost contact with the bicycle rail, but remained in contact with the concrete barrier. This vehicle contact caused significant damage to the surface of the concrete barrier as the vehicle continued to move downstream. The vehicle continued to roll clockwise, with the right side of the vehicle riding along the top of the concrete barrier. By 0.158 sec, the left-rear tire became airborne, and the vehicle recontacted the bicycle rail. At this same time, post no. 2 deflected backwards and the lower and middle rails between post nos. 2 and 3 deflect toward each other. At 0.180 sec, the vehicle became parallel to the system with a resultant velocity of 85.9 km/h (53.4 mph). At this same time, the vehicle continued to roll clockwise with the upper portion of the vehicle in contact with the bicycle rail. As the vehicle redirected and continued to roll clockwise, the right-rear corner of the vehicle contacted the top of the concrete barrier. At 0.580 sec, the vehicle exited the barrier at an angle of 2.2 degrees and at a resultant velocity of 84.5 km/h (52.5 mph). After this time, the vehicle continued to roll clockwise with a trajectory nearly parallel to the system. By 1.734 sec, the vehicle had rolled onto its right side and slid downstream. The vehicle came to rest back on its tires, 68.6 m (225 ft) downstream from impact and 9.25 m (30 ft - 4 in.) laterally away from the traffic-side face of the barrier. The trajectory and final position of the vehicle are shown in Figures 17 and 26.

6.3 System Damage

Damage to the combination traffic/bicycle bridge rail was minimal, as shown in Figures 27 through 28. Barrier damage consisted of contact and gouge marks on the concrete parapet, contact marks on the bicycle rail, and pull out of attachment bolts. The length of vehicle contact along the combination bridge rail was approximately 3 m (10 ft - 5 in.), which spanned from 533 mm (21 in.) upstream from post no. 3 through 460 mm (16 in.) upstream from the centerline of post no. 4.

Heavy scrapes from the wheel or bumper were located at 356 mm (14 in.) upstream from the centerline of post no. 3. A heavily-defined circular wheel mark was found on the front face of the concrete barrier at 610 mm (24 in.) downstream from the centerline of post no. 3. A 152-mm (6-in.) long gouge in the front face of the concrete barrier was found 152 mm (6 in.) upstream from post no. 3.

Contact marks were found on the upper rail of the bicycle rail beginning at the splice between post nos. 3 and 4 and ending 1,270 mm (50 in.) upstream from post no. 5. Contact marks were found on the front face of the lower and middle rails, starting at the splice between post nos. 3 and 4 to 914 mm (36 in.) downstream from the splice. Light contact marks were found on the bottom and top faces of all three rails. The top two bolts attaching post nos. 2 and 3 to the concrete barrier pulled 6 mm to 13 mm (1/4 in. to 1/2 in.) out of the concrete.

The permanent set of the combination traffic/bicycle bridge rail was negligible. The maximum lateral dynamic rail and post deflections were 65 mm (2.6 in.) at 464 mm (18.25 in.) downstream of post no. 2 and 42 mm (1.65 in.) at the centerline of post no. 2, respectively, as determined from high-speed video analysis. The working width of the system was found to be 507 mm (20.0 in.).

6.4 Vehicle Damage

Exterior vehicle damage was extensive, as shown in Figures 29 through 33. Extensive occupant compartment deformations occurred due to vehicle rollover. Moderate deformations occurred near the center of the right-side floor pan. The majority of the vehicle damage was concentrated on the passenger side and front of the vehicle. The front bumper buckled at the centerline. The headlight assemblies were detached. The right side of the grill encountered significant damage and deformation. The right side of the front bumper was deformed and encountered white paint marks from the barrier. The right-front quarter panel was crushed inward and downward. The right-side wheel assembly was deformed severely backward into the frame. The right-side upper A-frame disengaged. The transmission housing and the starter housing were fractured. The frame encountered heavy tire marks due to rubbing from the deformed right-front wheel assembly. Heavy scraping and contact marks were found on the right-side door, front-right quarter panel, box, and right-front steel rim. The right-front wheel hub was ground down due to heavy scraping on the barrier. The seal between the right-front tire and rim was broken, and the tire was deflated. The left side of the roof was crushed extensively with the maximum crush occurring near the outside of the left side of the roof. The tailgate was disengaged from the vehicle. The right-side and rear windows were shattered. The windshield was heavily cracked on the left side.

6.5 Occupant Risk Values

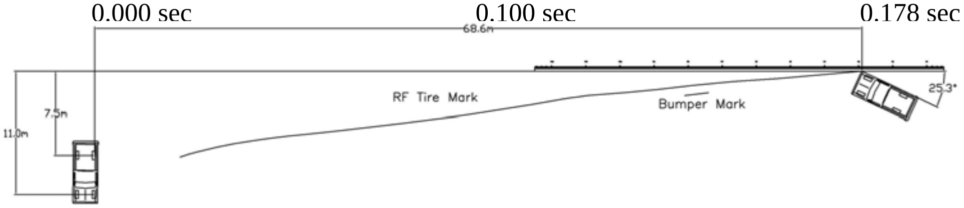
The longitudinal and lateral components of the occupant impact velocities (OIVs) were determined as 5.36 m/s (17.66 ft/s) and 8.43 m/s (27.65 ft/s), respectively. The maximum 0.010-sec average lateral and longitudinal occupant ridedown decelerations (ORDs) were 6.23 Gs and 12.89

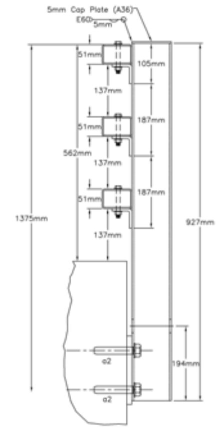
Gs, respectively. The OIVs and the ORDs were within the suggested limits provided in NCHRP Report No. 350. The detailed summary of the results of the occupant risk, as determined from the accelerometer data, are shown in Figure 17. The results are shown graphically in Appendix C.

6.6 Discussion

The analysis of the results for test no. MOBR-1 showed that the traffic/bicycle rail adequately contained, but did not safely redirect the vehicle since the vehicle did not remain upright after collision with the barrier. The rollover was caused by the right-front corner of the vehicle protruding under the longitudinal rails and preventing the vehicle from climbing the barrier. 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 intrusions into, the occupant compartment that could have caused serious injury did occur with the deformation of vehicle's roof. After collision, the vehicle's trajectory appeared to intrude into adjacent traffic lanes. Therefore, test no. MOBR-1 conducted on the combination traffic/bicycle rail was determined to be unacceptable according to the safety performance criteria of test designation no. 4-11 found in NCHRP Report No. 350 due to vehicle rollover.

0.000 sec 0.100 sec 0.178 sec 0.318 sec 0.455 sec





• Test Number	MOBR-1 (4-11)
• Date	3/27/04
• Test Article	Combination Trafic/Bicycle Bridge Rail
Total Length	36.34 m
Overall Height	1,380 mm
• Bicycle Rail Tubes	ASTM A500 Grade B Steel
Section	TS 76 mm x 51 mm x 3.2 mm thick
Length	6,096 mm and 3,048 mm
Top Mounting Height	Lower Tube . . . . 924 mm
	Middle Tube . . . 1,187 mm
	Upper Tube . . . . 1,374 mm
• Post Nos. 1-12	ASTM A500 Grade B Steel
Section	TS 102 mm x 51 mm x 5 mm thick
Center-to-Center Spacing	3,048 mm
• Soil Type	NA
• Vehicle Model	1998 GMC C2500 3/4-ton pickup
Curb	1,982 kg
Test Inertial	2,015 kg
Gross Static	2,015 kg
• Impact Location	305 mm upstream of post no. 3
• Vehicle Speed	
Impact	101.5 km/h
Exit	84.5 km/h
• Vehicle Angle	
Impact (trajectory)	25.6 degrees
Exit (trajectory)	2.2 degrees

• Vehicle Snagging	Moderate
• Vehicle Pocketing	None
• Vehicle Stability	Unsatisfactory
• Occupant Ridedown Deceleration (10 msec avg.)	
Longitudinal	6.23 Gs/-5.74 Gs < 20 Gs
Lateral	12.89 Gs < 20 Gs
• Occupant Impact Velocity	
Longitudinal	5.38 m/s < 12 m/s
Lateral (not required)	8.43 m/s < 12 m/s
• Vehicle Damage	Extensive
TAD[12]	1-RFQ-5
SAE[13]	01RYAO5
• Vehicle Stopping Distance	69.4 m downstream
	11.0 m laterally
• Test Article Damage	Minimal
• Maximum Deflection	
Permanent Set	None
Dynamic	65 mm
• Working Width	507 mm

Figure 17. Summary of Test Results and Sequential Photographs, Test MOBR-1

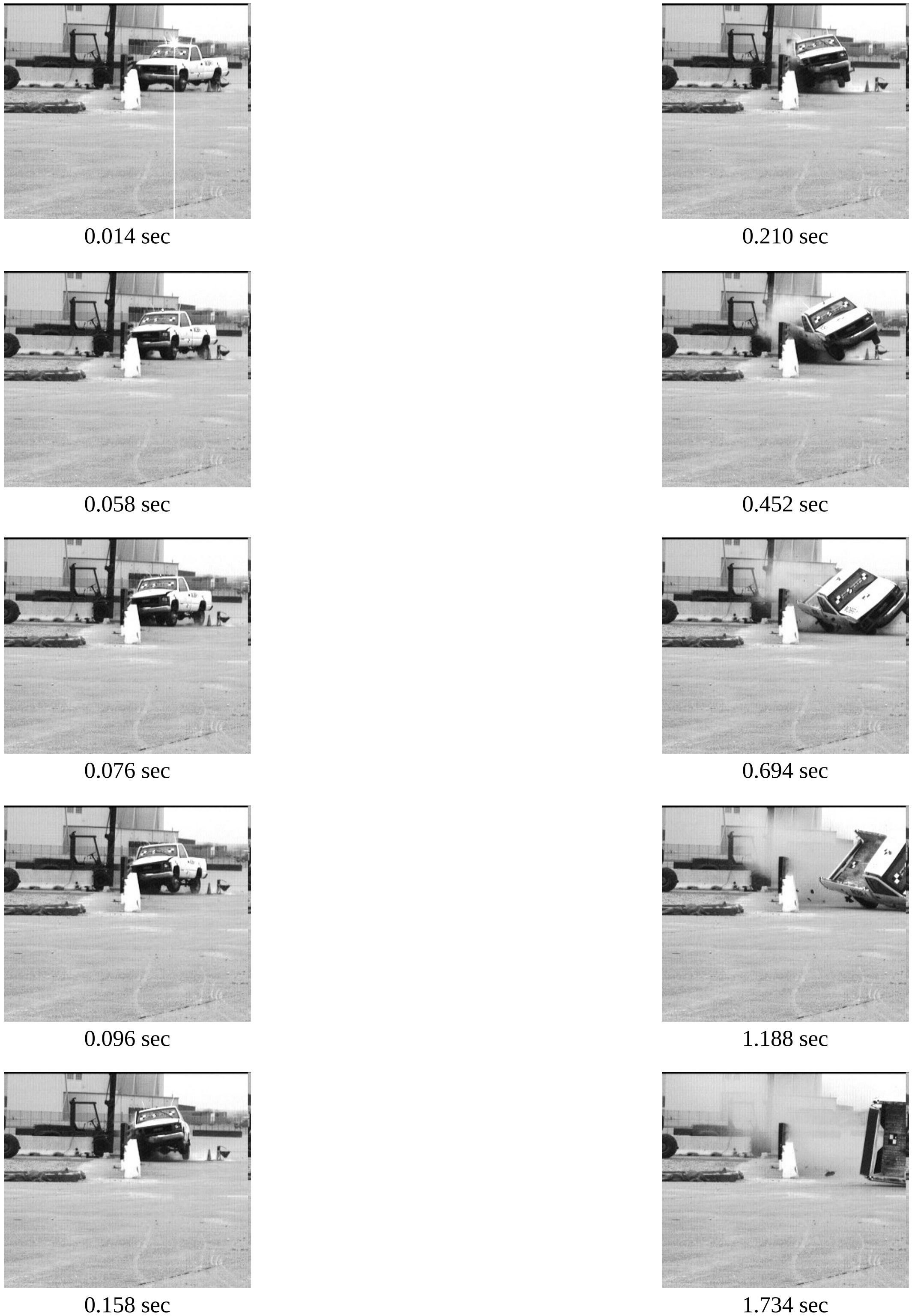


Figure 18. Additional Sequential Photographs, Test MOBR-1

0.000 sec

0.067 sec

0.133 sec

0.234 sec

0.501 sec

1.168 sec

1.835 sec

Figure 19. Additional Sequential Photographs, Test MOBR-1


0.000 sec


0.067 sec

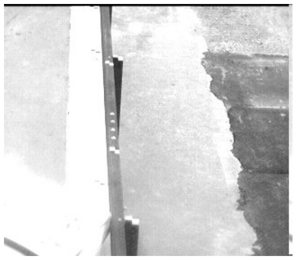

0.133 sec


0.200 sec


0.334 sec


0.634 sec

Figure 20. Additional Sequential Photographs, Test MOBR-1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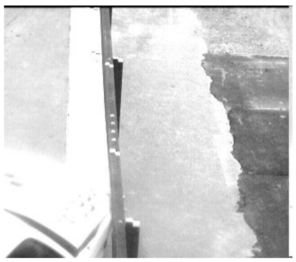

0.036 sec


0.060 sec

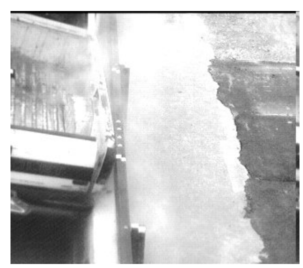

0.094 sec


0.134 sec


0.174 sec


0.184 sec


0.190 sec


0.248 sec


0.316 sec

Figure 21. Additional Sequential Photographs, Test MOBR-1

0.028 sec

0.042 sec

0.086 sec

0.132 sec

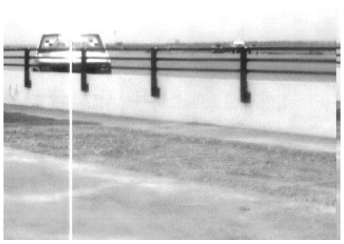
0.154 sec

0.182 sec

0.214 sec

0.354 sec

Figure 22. Additional Sequential Photographs, Test MOBR-1



0.000 sec

0.074 sec

0.106 sec

0.126 sec

0.184 sec

0.246 sec

0.350 sec

0.438 sec

Figure 23. Additional Sequential Photographs, Test MOBR-1

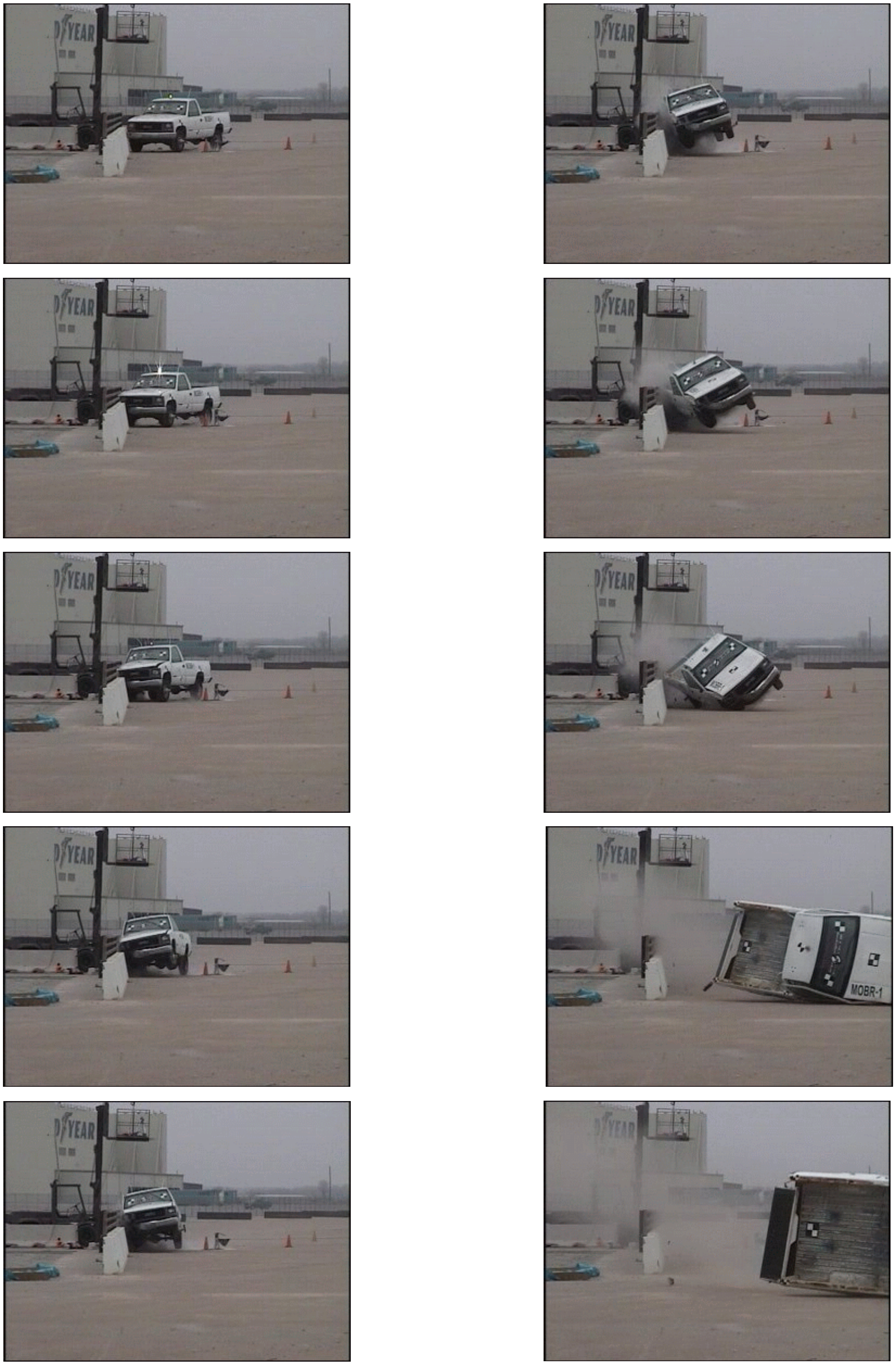


Figure 24. Documentary Photographs, Test MOBR-1

Figure 25. Impact Location, Test MOBR-1

Figure 26. Vehicle Final Position, Test MOBR-1

Figure 27. System Damage, Test MOBR-1

Figure 28. System Damage, Test MOBR-1

Figure 29. Vehicle Damage, Test MOBR-1

Figure 30. Vehicle Damage, Test MOBR-1

Figure 31. Vehicle Damage, Test MOBR-1

Figure 32. Vehicle Undercarriage Damage, Test MOBR-1

Figure 33. Windshield and Occupant Compartment Damage, Test MOBR-1

7 DESIGN MODIFICATION DETAILS – SYSTEM NO. 2

After the initial design was deemed unsuccessful, modifications were made to the system in an attempt to improve the impact performance. From the film analysis, the deflection of the rails and subsequent protrusion of the right-front corner of the vehicle held the vehicle from experiencing the normal vaulting behavior shown previously with impacts on a single slope barrier, in turn causing the vehicle to roll. It was then determined that reducing the space between the rails and repositioning the rail would potentially reduce the amount of vehicle intrusion between the rails. Therefore, in the modified system, the number of longitudinal rails was increased from three to four, with the top of the tops of the rails mounted at 1,375 mm (54 1/8 in.), 1,235 mm (48 5/8 in.), 1,095 mm (43 1/8 in.), and 995 mm (39 1/8 in.) from the ground. System details are shown in Figures 34 through 40 with photographs shown in Figure 41. Corresponding English-unit system details are presented in Appendix D.

Again, the system was terminated by sloping the ends of the four longitudinal tubes down to the top of the barrier. The bottom sloped end rail was 335 mm (13 3/16 in.) long and ended 376 mm (14 7/8 in.) away from the centerline of the first and last posts. The lower-middle sloped end rail was 686 mm (27 in.) long and ended 699 mm (2 ft - 3 1/2 in.) away from the centerline of the first and last posts. The upper-middle sloped end rail was 1,038 mm (40 7/8 in.) long and ended 1,021 mm (3 ft - 4 3/16 in.) away from the centerline of the first and last posts. The top sloped end rail was 1,389 mm (54 11/16 in.) long and ended 1,343 mm (4 ft 4 7/8 in.) away from the centerline of the first and last posts. The sloped end rails were bolted to both the top and back sides of the concrete parapet, as shown in Figures 34 and 36.

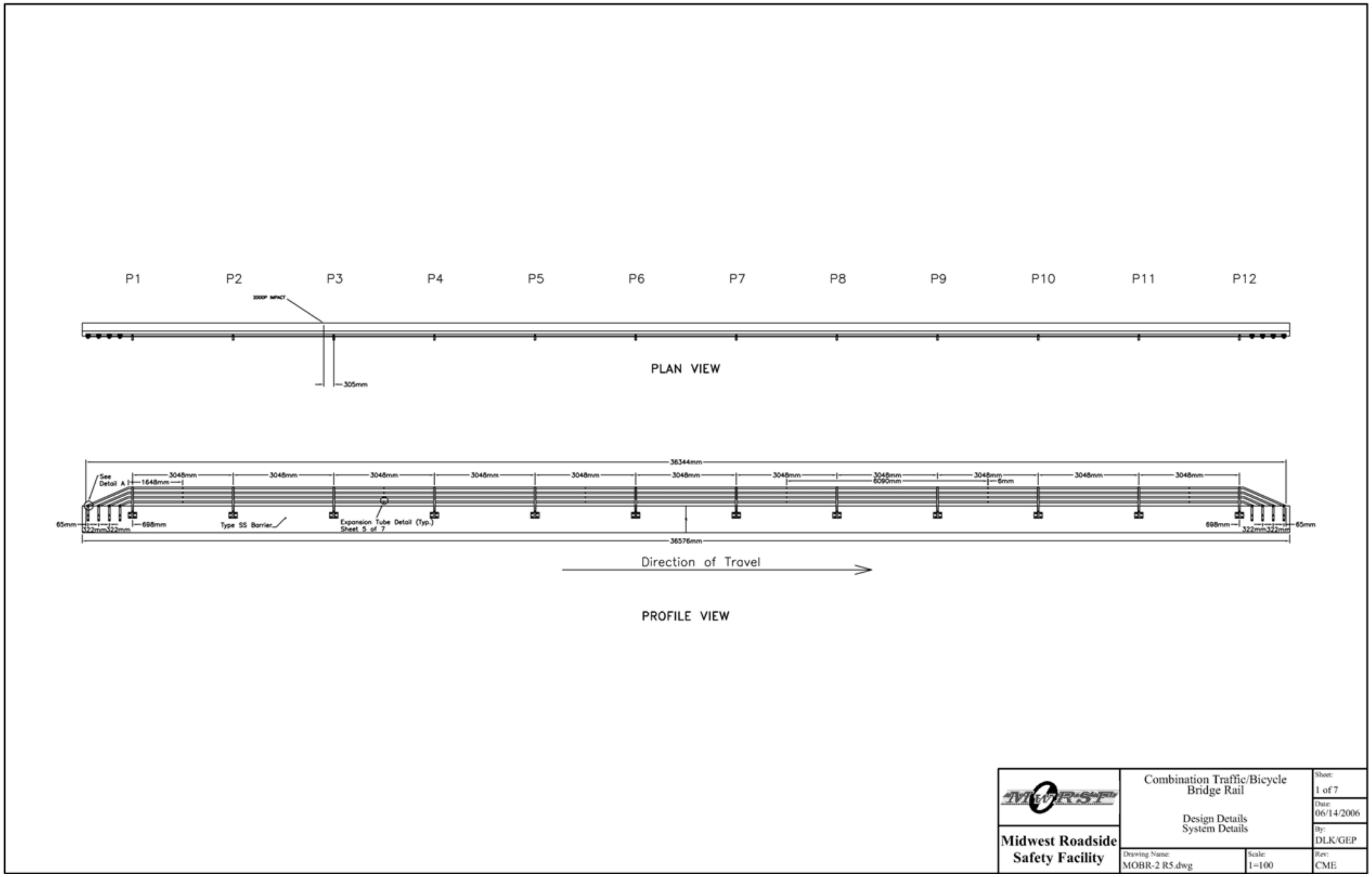


Figure 34. Modified Combination Traffic/Bicycle Bridge Rail - System Details

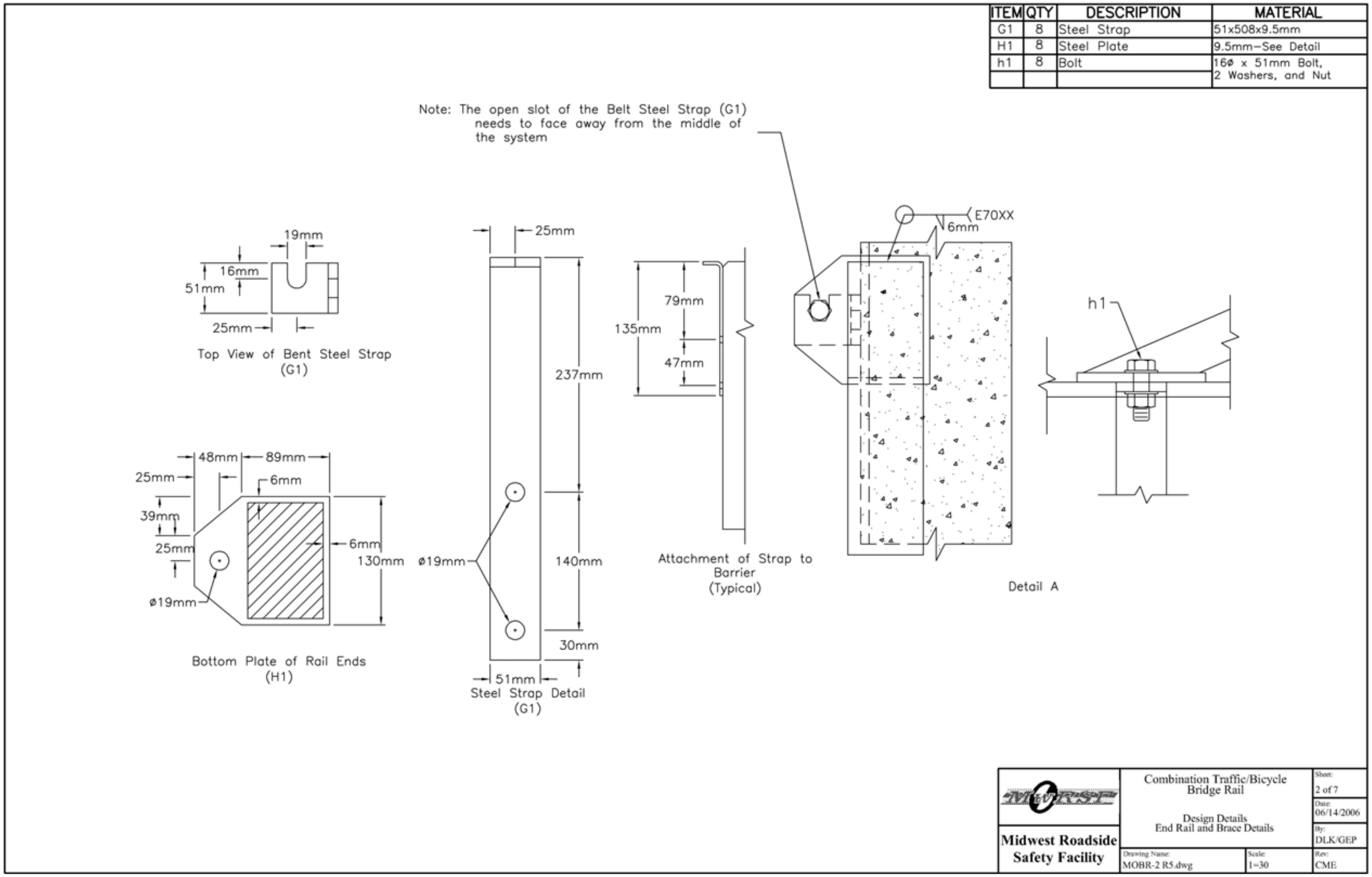


Figure 35. Modified Combination Traffic/Bicycle Bridge Rail - End Rail and Brace Details

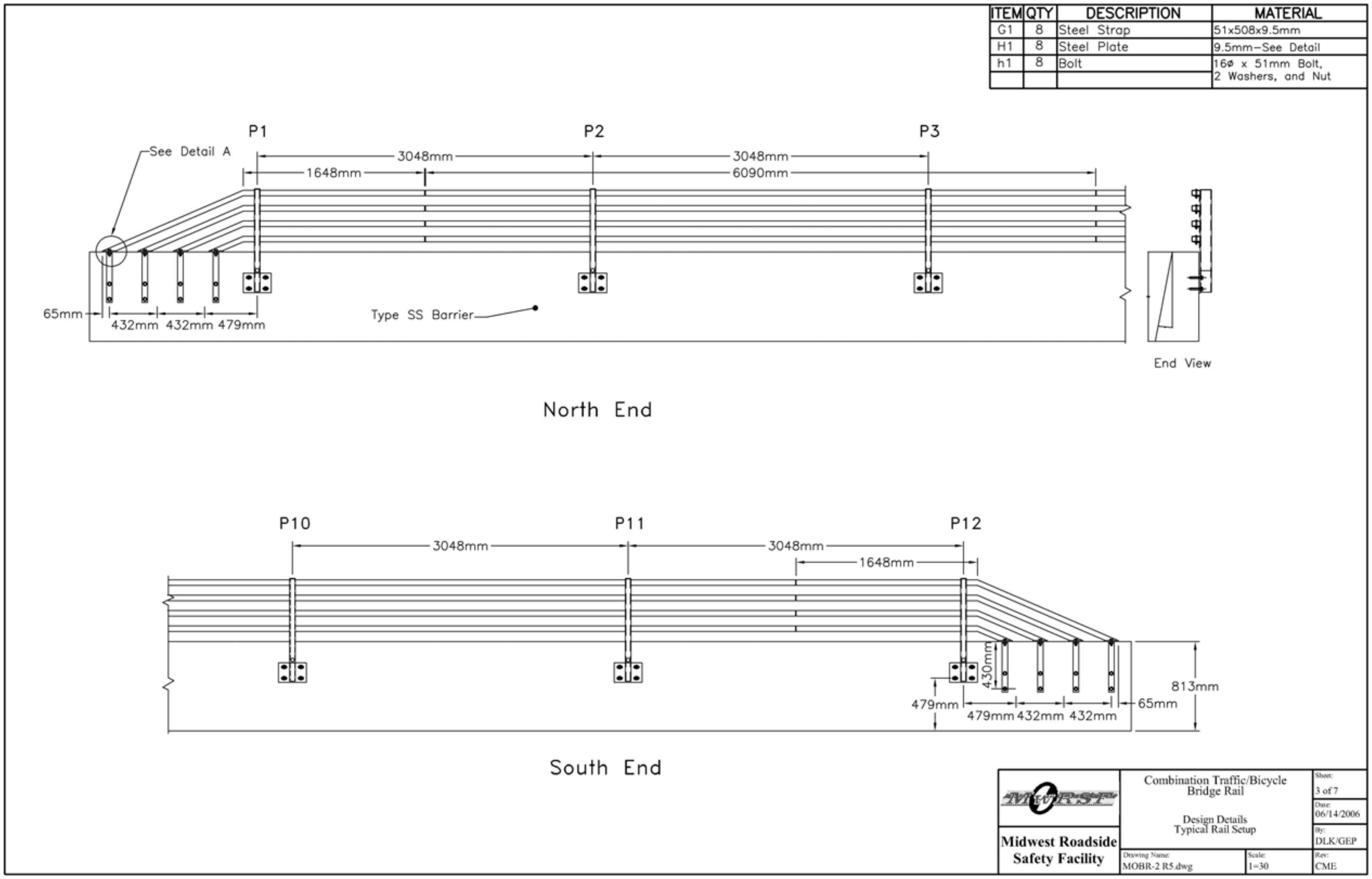


Figure 36. Modified Combination Traffic/Bicycle Bridge Rail - Typical Rail Setup

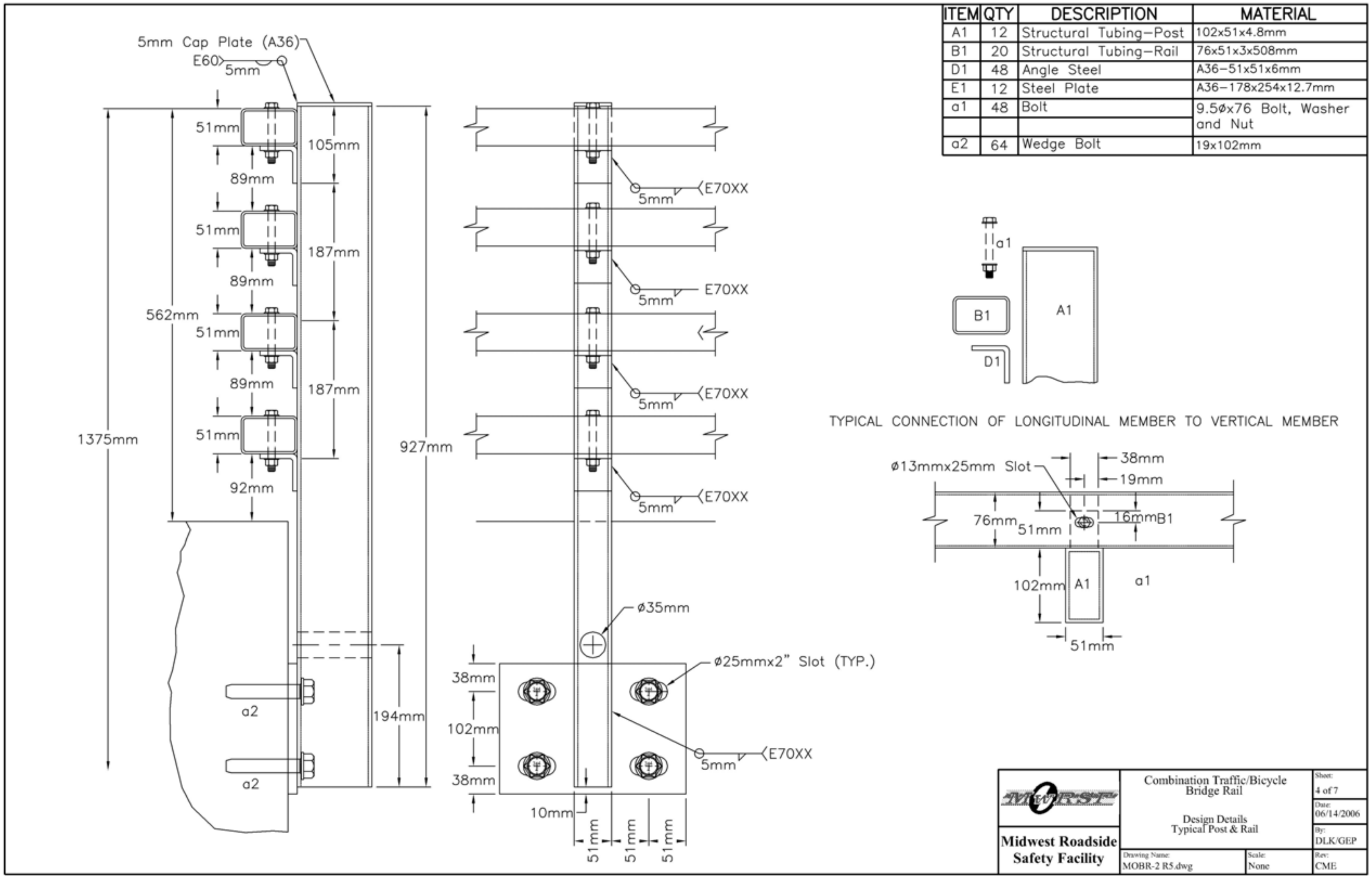
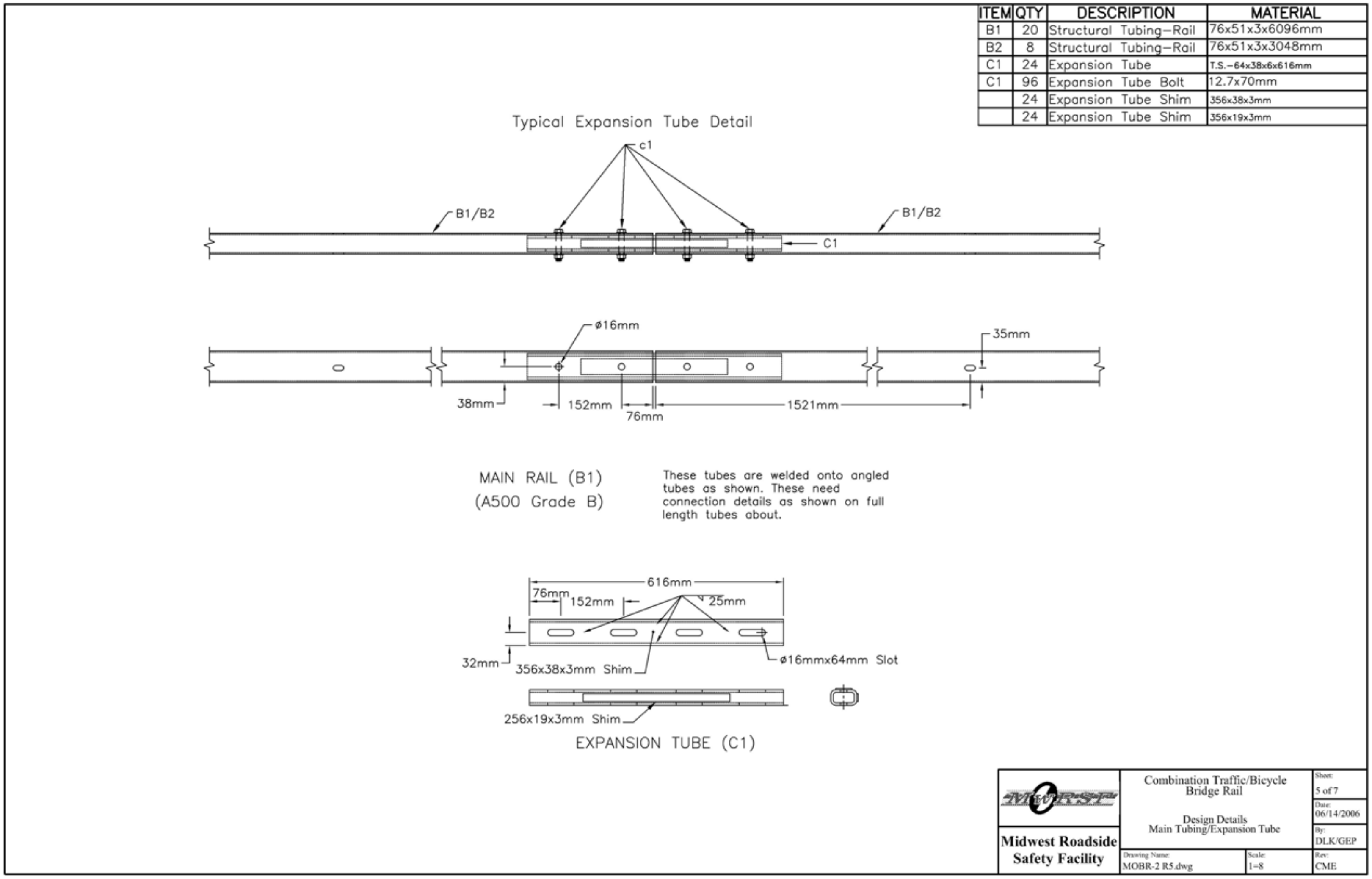


Figure 37. Modified Combination Traffic/Bicycle Bridge Rail - Typical Post and Rail Details



ITEM	QTY	DESCRIPTION	MATERIAL
B1	20	Structural Tubing–Rail	76x51x3x6096mm
B2	8	Structural Tubing–Rail	76x51x3x3048mm
C1	24	Expansion Tube	T.S.–64x38x6x616mm
C1	96	Expansion Tube Bolt	12.7x70mm
	24	Expansion Tube Shim	356x38x3mm
	24	Expansion Tube Shim	356x19x3mm

Figure 38. Modified Combination Traffic/Bicycle Bridge Rail - Main Tubing and Expansion Tube Details

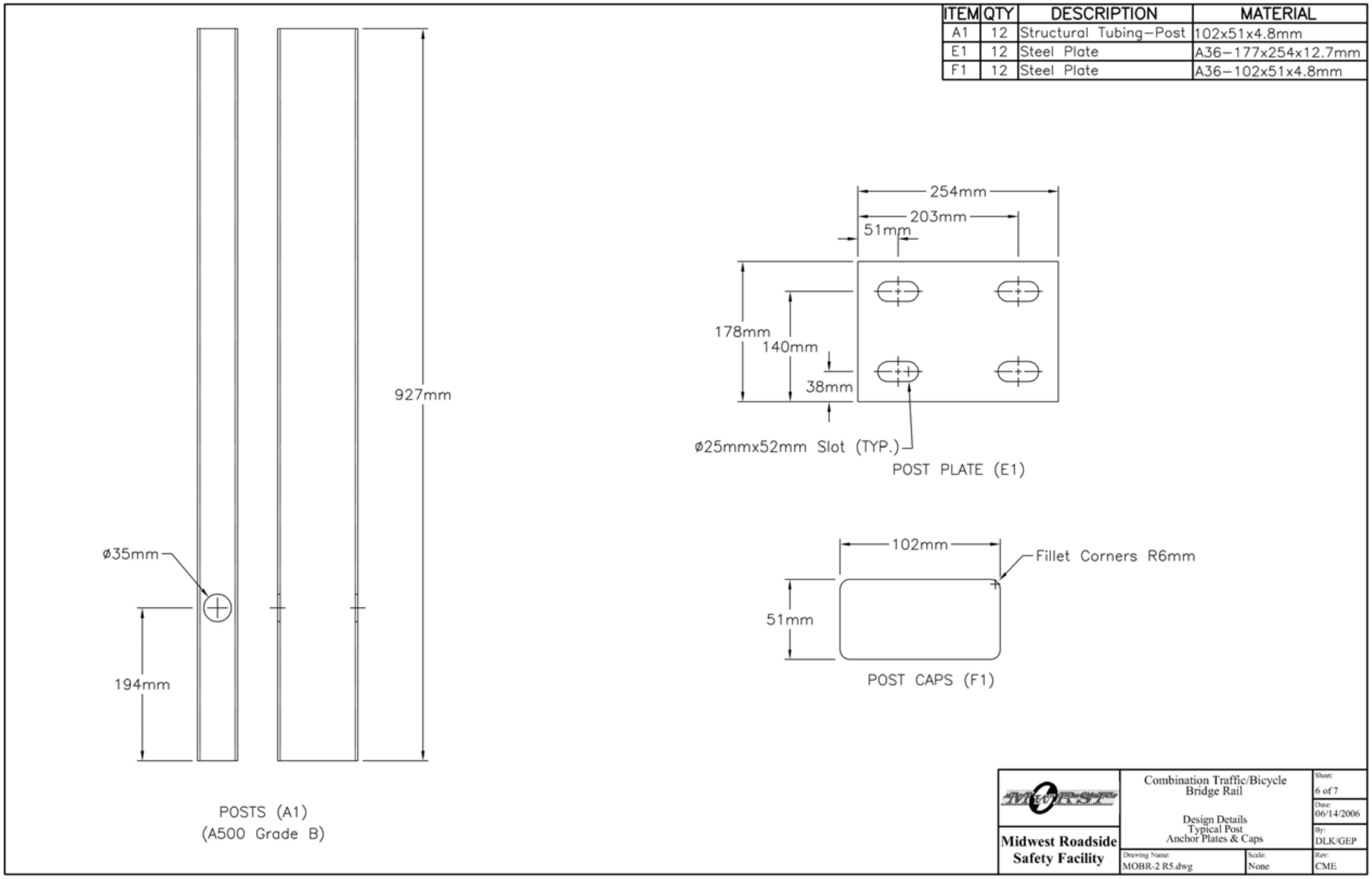


Figure 39. Modified Combination Traffic/Bicycle Bridge Rail - Post, Anchor Plate, and Cap Details

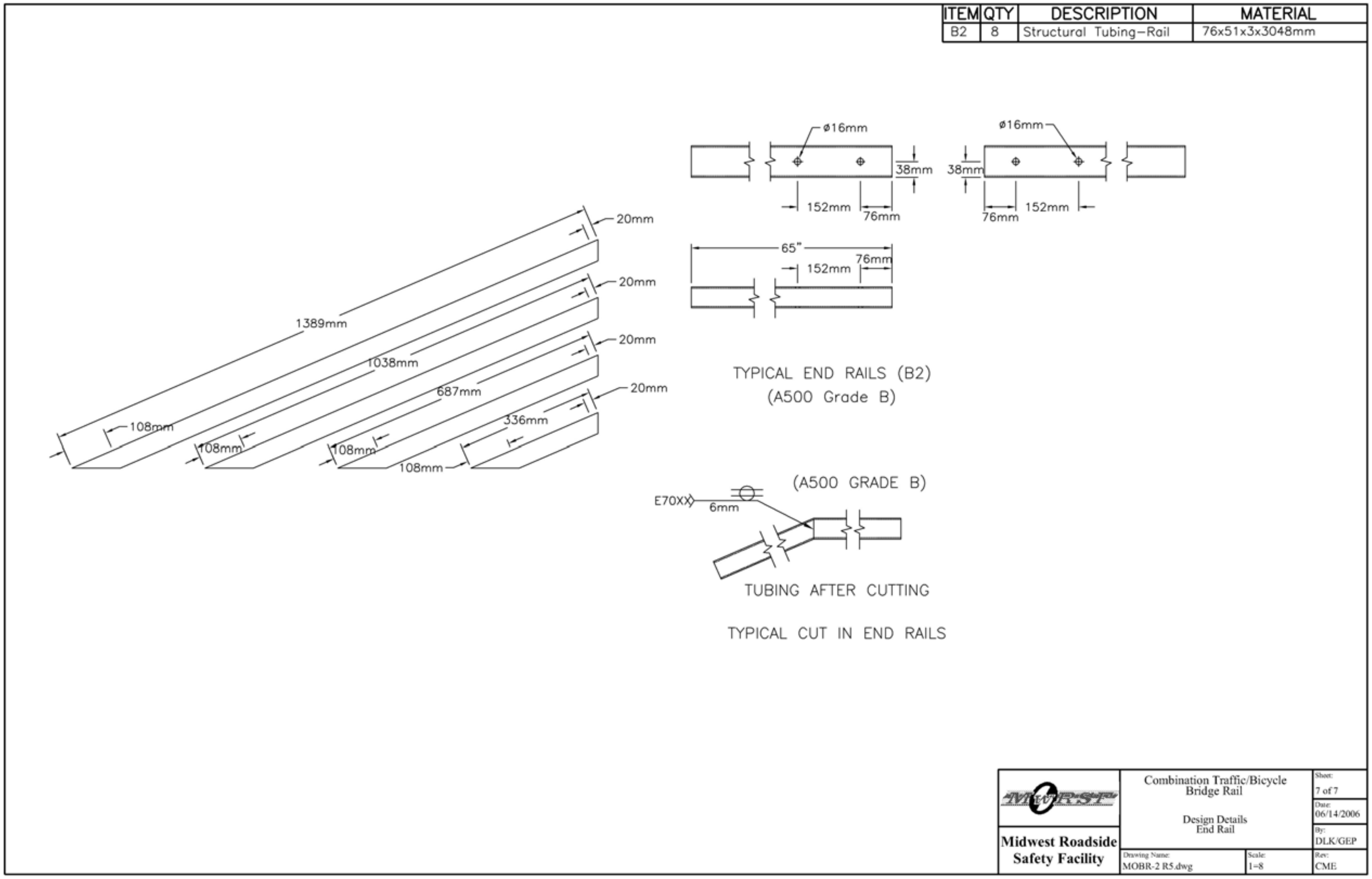


Figure 40. Modified Combination Traffic/Bicycle Bridge Rail - End Rail Details

Figure 41. Modified Combination Traffic/Bicycle Bridge Rail

8 CRASH TEST NO. 2

8.1 Test MOBR-2

The 2,029-kg (4,473-lb) pickup truck impacted the combination traffic/bicycle bridge rail (System No. 2) at a speed of 102.7 km/h (63.8 mph) and at an angle of 25.6 degrees. A summary of the test results and sequential photographs are shown in Figure 42. The summary of the test results and sequential photographs in English units are shown in Appendix B. Additional sequential photographs are shown in Figures 43 through 48. Documentary and damage photographs of the crash test are shown in Figures 49 through 50.

8.2 Test Description

Initial impact was to occur 305 mm (12 in.) upstream from the centerline of post no. 3, as shown in Figure 1. Actual vehicle impact occurred 559 mm (22.0 in.) upstream from the centerline of post no. 3. At 0.015 sec after impact, the right-front corner of the vehicle, including the bumper and the front-quarter panel, crushed inward. The hood also crumpled inward but not as severe. As the vehicle continued to contact the barrier, the hood began to lift up off the frame. At 0.030 sec, the hood protruded over and behind the concrete barrier. At 0.034 sec after impact, the longitudinal rails exhibited visible deflection. At this same time, the right-front quarter panel continued to crush inward and contacted the right-front tire, with the hood protruding farther beyond the back side of the barrier. The longitudinal rails' lateral deflection increased while the two middle rails separated vertically due to the intrusion of the right-front corner of the vehicle. The right-side door became ajar.

At 0.046 sec, the vehicle began to redirect as the hood buckled and the left-front bumper shifted due to the right side of the bumper deforming. At 0.058 sec after impact, the vehicle rolled clockwise toward the barrier. At this same time, the two middle rails continued to separate. Shortly after, the lower-middle rail returned to its original position. However, the upper-middle rail continued to deflect upward until it nearly contacted the upper rail. The vehicle continued to redirect, and by 0.126 sec, the vehicle was no longer in contact with the upper-middle rail which returned to its original position. By this time, the right-side door and right side of the vehicle was in contact with the concrete barrier. At 0.216 sec, the vehicle became parallel to the system with a resultant velocity of 85.9 km/h (53.4 mph). As the clockwise rolling motion continued, the front and rear of the vehicle twisted with respect to each other.

At 0.240 sec after impact, the right-front quarter-panel lost contact with the barrier. At this same time, the tailgate disengaged from the vehicle. At 0.490 sec, the vehicle exited the barrier at an angle of 9 degrees and at a resultant velocity of 86.3 km/h (53.6 mph). After the vehicle was no longer in contact with the barrier, the rear of the vehicle pitched upward. The vehicle continued onto its right side and slid downstream. The vehicle came to rest, back on its tires, 70.9 m (232 ft - 7 3/8 in.) downstream from impact and 5.4 m (17 ft - 8 5/8 in.) laterally away from the traffic-side face of the barrier. The trajectory and final position of the vehicle are shown in Figures 42 and 52.

8.3 Barrier Damage

Damage to the combination traffic/bicycle bridge rail was minimal, as shown in Figures 53 and 54. Damage to the combination traffic/bicycle bridge rail consisted of contact marks and gouges on the concrete parapet and contact marks on the bicycle rail. Vehicle contact along the combination bridge rail was approximately 5.4 m (17 ft - 10 in.), which spanned 864 mm (34 in.) upstream from the centerline of post no. 3 through 1,524 mm (60 in.) downstream from the centerline of post no. 4. Tire marks began 559 mm (22 in.) upstream from the centerline of post no. 3, with a maximum width of 660 mm (26 in.), and continued downstream 2,515 mm (99 in.) along the bottom of the marks, and 2,997 mm (118 in.) along the top of the marks. One gouge in the concrete barrier began with the tire marks and extended downstream for 3,302 mm (130 in.). This gouge had a width of 102 mm (4 in.) which began 737 mm (29 in.) above the ground and tapered to a width of 6.4 mm (1/4 in.) at 819 mm (32.25 in.) above the ground. A second gouge was 343 mm (13.5 in.) long and 178 mm (7 in.) wide at its widest point and began 394 mm (15 ½ in.) upstream from the centerline of post no. 3. A third gouge was approximately 25-mm (1-in.) thick and 365-mm (14-in.) long with a semicircular shape and began 343 mm (13 ½ in.) upstream from the centerline of post no. 3. Numerous small gouges were found in the region with the tire marks near post no. 3.

White paint marks were found on the front face of the bottom rail between 356 mm (14 in.) and 660 mm (26 in.) downstream from the centerline of post no. 3. Black rubber or plastic marks were also found on the bottom rail between 1,537 mm (60.5 in.) and 2,642 mm (104 in.) downstream from the centerline of post no. 3. Two distinct white paint marks were found on the front, bottom, and top faces of the lower-middle rail. The first mark began 330 mm (13 in.) downstream from the centerline of post no. 3 and continued for 2,007 mm (79 in.). A 6.4-mm (1/4-in.) wide by 1,384-mm (54.5-in.) long mark on the bottom face of the lower-middle rail, began 1,524 mm (60 in.) downstream from the centerline of post no. 3. The upper-middle rail encountered the most markings, with white paint on the front and bottom faces. The contact marks began 102 mm (4 in.) downstream from the centerline of post no. 3 and ended 3,327 mm (131 in.) downstream from the centerline of post no. 3. The width of these marks ranged from 6.4 mm (1/4 in.) to 51 mm (2 in.). The top rail also contained white paint and black tire marks on its front face. Six distinct marks, ranging in width from 6.4 mm (1/4 in.) to 38 mm (1 ½ in.), began 114 mm (4.5 in.) downstream from the centerline of post no. 3 and ended 4,572 mm (180 in.) downstream from the centerline of post no. 3.

The permanent set of the combination traffic/bicycle bridge rail was negligible. The maximum lateral dynamic rail and post deflections were 30 mm (1 1/8 in.) and 25 mm (15/16 in.) at the centerline of post no. 4, respectively, as determined from high-speed video analysis. The working width of the system was found to be 333 mm (13 in.).

8.4 Vehicle Damage

Exterior vehicle damage was moderate, as shown in Figures 55 through 59. Moderate deformation occurred near the center of the right-side floorboard, and the right side was shifted backward and inward. The majority of the vehicle damage was concentrated on the right side and the front of the vehicle. The front-right tire was pushed backward into the wheel well. The front-quarter panel was severely scratched at random locations, with concentrated scratches at the door hinge and hood joint. The right-front quarter panel was dented and buckled. The headlight housing was cracked, and the lights were pushed backward and downward into the wheel well. The front bumper was dented, scratched, and pushed back into the vehicle on the right side, and encountered a buckle point near the center.

The outside steel rim of the right-front wheel was scratched, and the hub cap in the center was torn apart. The right-front tire's seal was broken, and the tire was deflated. The wheel bearing was severely scratched.

The right-side lower and upper A-arms were bent and buckled, with the lower arm more severely damaged than the upper. The right-side sway bar and tie rod were bent. The right-front end of the frame buckled at the front of the transmission mount and the cross frame buckled between the two front wheels. The right-side steering arm frame pivot was bent backward. The right-side bumper mounting bracket was deformed inward and backward.

The left side encountered only minor damage including a dent in the front quarter panel. The rear bumper was severely scratched and dented on the right side. The tailgate was detached from the vehicle. The roof suffered no damage.

The hood was latched but deformed upward on the left side and bent downward and backward on the right-front corner. The hood's hinges were severely deformed, but the hood could still be opened. The plastic grill and light housing assembly were cracked and pushed back into the wheel well. The air filter housing was cracked in half. The right-side door encountered random scratches with a high concentration at the handle height near the rear of the cab. The top of the right-side door was ajar, and the door could not be opened. The A-pillar had random scratches throughout its length and a severe dent at the bottom end. The box of the vehicle was severely scratched and dented, with minor scratches on the wheel well trim. The right-rear tire was scratched along the steel rim, and the hub cap was broken and collapsed. The right-rear tire was deflated, but the attachment and position of the wheel remained normal. The windshield showed cracks radiating outward from the bottom-center. All other glass remained undamaged.

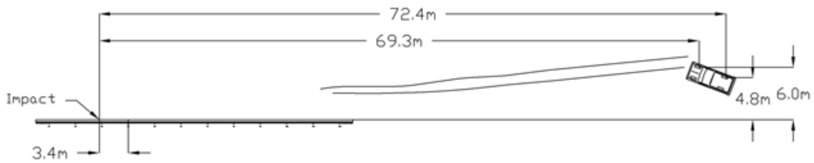
8.5 Occupant Risk Values

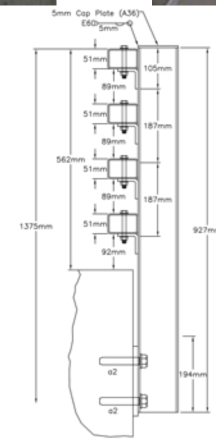
The longitudinal and lateral occupant impact velocities (OIVs) were determined to be 6.19 m/sec (20.31 ft/sec) and 8.42 m/sec (27.62 ft/sec), respectively. The maximum 10-msec occupant ridedown decelerations (ORDs) in the longitudinal and lateral directions were 5.11/-9.28 Gs and 14.22 Gs, respectively. The OIVs and ORDs were within the suggested limits provided in NCHRP Report No. 350. These results of the occupant risk, determined from the accelerometer data, are summarized in Figure 42. Results are shown graphically in Appendix E.

8.6 Discussion

The analysis of the results for test no. MOBR-2 showed that the traffic/bicycle rail adequately contained, but did not safely redirect the vehicle since the vehicle did not remain upright after collision with the barrier. 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 occur with the damage to the vehicle's windshield. It should be noted that the right-front corner of the vehicle protruded under the longitudinal rails and prevented the vehicle from climbing the barrier and subsequently the vehicle rolled over onto its side. After collision, the vehicle's trajectory appeared to intrude slightly into adjacent traffic lanes. Therefore, test no. MOBR-2 conducted on the combination traffic/bicycle rail was determined to be unacceptable according to the safety performance criteria of test designation no. 4-11 found in NCHRP Report No. 350 due to vehicle rollover.

0.000 sec 0.086 sec 0.168 sec 0.338 sec 0.514 sec





- Test Number MOBR-2 (4-11)
- Date 3/27/04
- Test Article . . . . Comb. Traffic/Bicycle Bridge Rail
  - Total Length . . . . 36.34 m
  - Overall Height . . . . 1,380 mm
- Bicycle Rail Tubes . . . . ASTM A500 Grade B Steel
  - Section . . . . TS 76 mm x 51 mm x 3.2 mm thick
  - Length . . . . 6,096 mm and 3,048 mm
  - Top Mounting Height . . . . . Lower Tube . . . . 955 mm
    - Lower Middle Tube 1,095 mm
    - Upper Middle Tube . 1,235 mm
    - Upper Tube . . . . 1,375 mm
- Post Nos. 1-12 . . . . ASTM A500 Grade B Steel
  - Section . . . . TS 102 mm x 51 mm x 5 mm thick
  - Center-to-Center Spacing . . 3,048 mm
- Soil Type . . . . NA
- Vehicle Model . . . . 1998 GMC C2500 3/4-ton pickup
  - Curb . . . . 2,038 kg
  - Test Inertial . . . . 2,029 kg
  - Gross Static . . . . 2,029 kg
- Impact Location . . . . 305 mm upstream of post no. 3
- Vehicle Speed
  - Impact . . . . 102.7 km/h
  - Exit . . . . 86.3 km/h
- Vehicle Angle
  - Impact (trajectory) . . . . 25.6 degrees
  - Exit (trajectory) . . . . 9.0 degrees

- Vehicle Snagging . . . . Moderate
- Vehicle Pocketing . . . . None
- Vehicle Stability . . . . Unsatisfactory
- Occupant Ridedown Deceleration (10 msec avg.)
  - Longitudinal . . . . 5.11 Gs/-9.29 Gs < 20 Gs
  - Lateral . . . . 14.22 Gs < 20 Gs
- Occupant Impact Velocity
  - Longitudinal . . . . 6.19 m/s < 12 m/s
  - Lateral (not required) . . . . . 8.42 m/s < 12 m/s
- Vehicle Damage . . . . Extensive
  - TAD[12] 1-RFQ-5
  - SAE[13] 01RDAO5
- Vehicle Stopping Distance . . . . . 69.3 m downstream
  - 11.0 m laterally
- Test Article Damage . . . . Minimal
- Maximum Deflection
  - Permanent Set . . . . None
  - Dynamic . . . . 29.5 mm
- Working Width . . . . 333 mm

Figure 42. Summary of Test Results and Sequential Photographs, Test MOBR-2


0.000 sec


0.033 sec


0.100 sec


0.167 sec


0.234 sec


0.367 sec


0.501 sec


0.701 sec


0.968 sec


1.301 sec

Figure 43. Additional Sequential Photographs, Test MOBR-2

0.05 sec

0.183 sec

0.317 sec

0.484 sec

0.617 sec

0.784 sec

Figure 44. Additional Sequential Photographs, Test MOBR-2

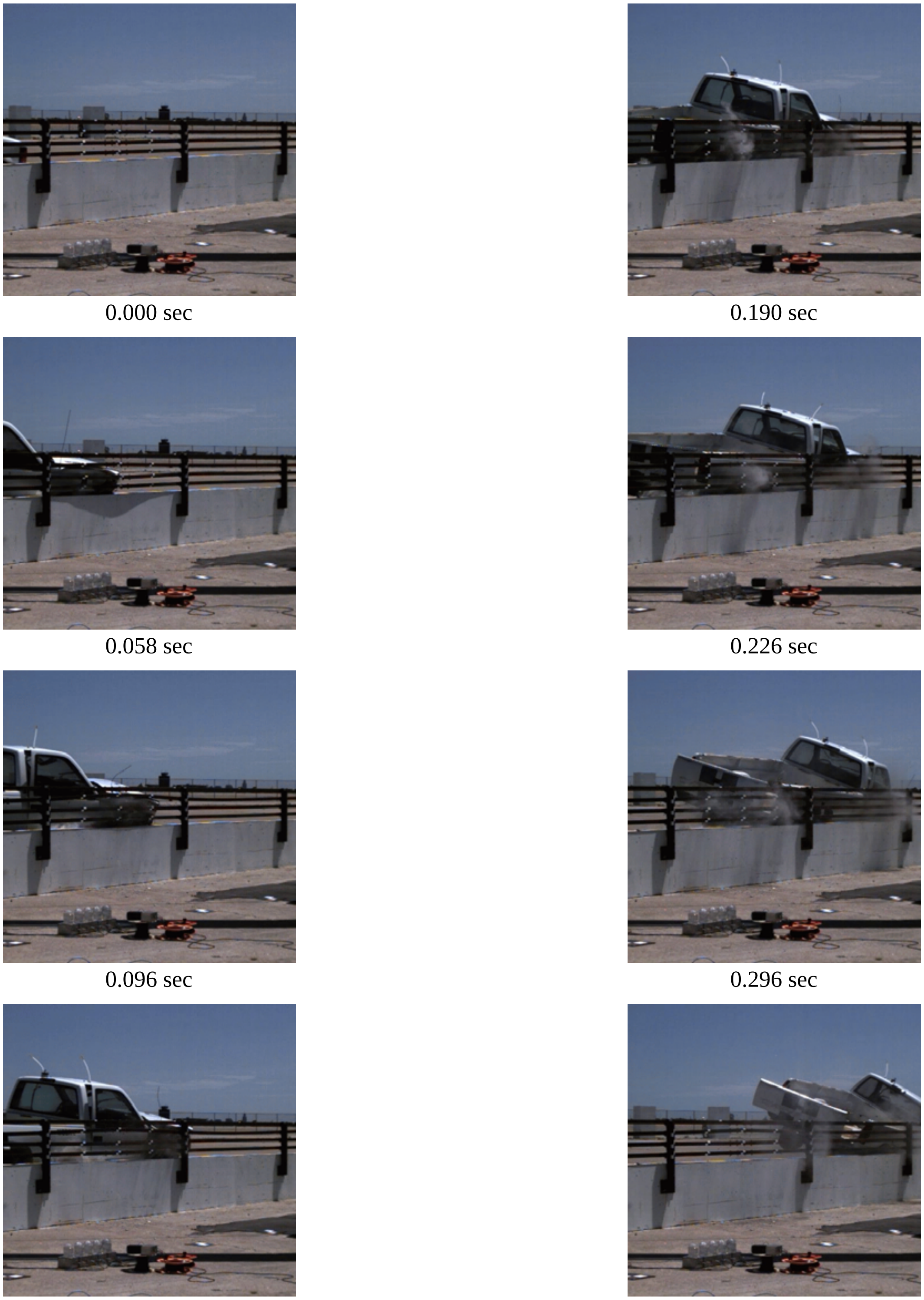
0.000 sec

0.234 sec

0.133 sec

0.367 sec

Figure 45. Additional Sequential Photographs, Test MOBR-2



0.000 sec
0.190 sec
0.058 sec
0.226 sec
0.096 sec
0.296 sec
0.136 sec
0.396 sec

Figure 46. Additional Sequential Photographs, Test MOBR-2

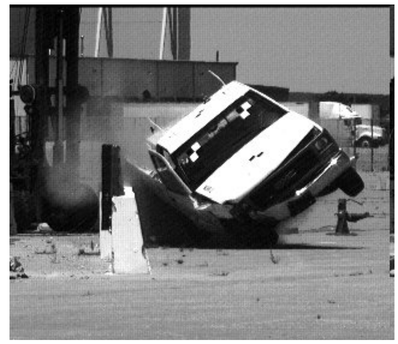
0.000 sec

0.060 sec

0.130 sec

0.160 sec

0.282 sec



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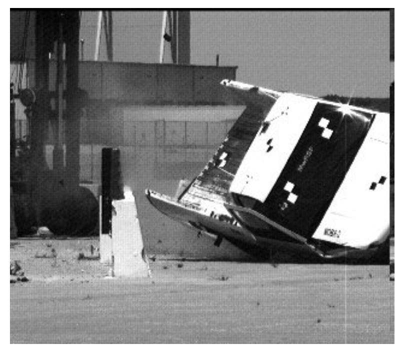

0.932 sec

1.424 sec

Figure 47. Additional Sequential Photographs, Test MOBR-2

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0.126 sec

0.214 sec

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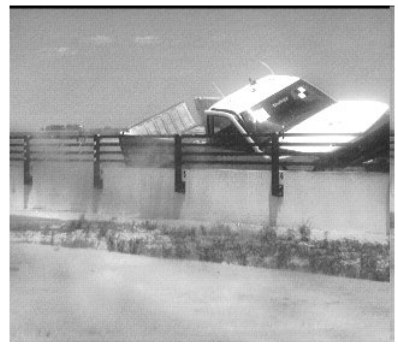

0.332 sec

0.432 sec

0.582 sec

Figure 48. Additional Sequential Photographs, Test MOBR-2

Figure 49. Documentary Photographs, Test MOBR-2

Figure 50. Documentary Photographs, Test MOBR-2

Figure 51. Impact Location, Test MOBR-2

Figure 52. Vehicle Final Position, Test MOBR-2

Figure 53. System Damage, Test MOBR-2

Figure 54. System Damage, Test MOBR-2

Figure 55. Vehicle Damage, Test MOBR-2

Figure 56. Vehicle Damage, Test MOBR-2

Figure 57. Vehicle Damage, Test MOBR-2

Figure 58. Vehicle Undercarriage Damage, Test MOBR-2

Figure 59. Vehicle Undercarriage Damage, Test MOBR-2

9 SUMMARY AND CONCLUSIONS

Two combination traffic/bicycle bridge railings were designed, constructed, and full-scale vehicle crash tested. A total of two full-scale pickup truck crash tests were conducted on the system according to the NCHRP Report No. 350 TL-4 requirements. A summary of the safety performance evaluation for both tests is provided in Table 3.

The first crash test on the traffic/bicycle rail was test no. MOBR-1, which incorporated a three-rail design. Although the rail contained the vehicle, it did not safely redirect the vehicle as it rolled over during exit. The addition of the open railing on top of the single-slope concrete barrier prevented the test vehicle from climbing the barrier as seen previously with single-slope concrete barriers. The vehicle climb restriction caused the vehicle to encounter significant roll as it exited the system, and subsequently it rolled over.

The second crash test was test no. MOBR-2 on the modified railing design that incorporated four rails instead of three. The barrier system contained the vehicle, but it did not safely redirect the vehicle as it rolled over during exit. The open railing on the top of the concrete barrier once again prevented the test vehicle from climbing the barrier. This restricted climb, caused excessive vehicle roll, thus allowing the vehicle to roll onto its side.

Both crash tests met the requirements for structural adequacy, debris and detached elements, exit angles, occupant impact velocities, and occupant ridedown accelerations. However, neither vehicle remained upright after the collision, causing the two systems to fail to meet the evaluation criteria.

Table 3. Summary of Safety Performance Evaluation Results

Evaluation Factor	Evaluation Criteria		Test MOBR-1	Test MOBR-2
Structural Adequacy	A.	Test article should contain and redirect the vehicle; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	S	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 that could cause serious injuries should not be permitted.	S	S
	F.	The vehicle should remain upright during and after collision although moderate roll, pitching, and yawing are acceptable.	U	U
	G.	It is preferable, although not essential, that the vehicle remain upright during and after collision.	NA	NA
	H.	Longitudinal and lateral occupant impact velocities should fall below the preferred value of 9 m/s (29.5 ft/s), or at least below the maximum allowable value of 12 m/s (39.4 ft/s).	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 Gs.	S	S
Vehicle Trajectory	K.	After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.	M	M
	L.	The occupant impact velocity in the longitudinal direction should not exceed 12 m/sec (39.4 ft/s) and the occupant ridedown acceleration in the longitudinal direction should not exceed 20 Gs	S	S
	M.	The exit angle from the test article preferably should be less than 60 percent of test impact angle measured at time of vehicle loss of contact with test device.	S	S

S - Satisfactory
M - Marginal
U - Unsatisfactory
NA - Not Applicable

10 RECOMMENDATIONS

A combination traffic/bicycle bridge rail, as described within this report, was designed to be mounted to the top of a concrete parapet barrier. The system was unsuccessfully tested according to the NCHRP Report No. 350 TL-4 requirements. The results indicated that the barrier system is not suitable for use on Federal-aid highways.

However, modifications could be made to the system in order to increase its chances of successfully meeting the requirements specified by NCHRP Report No. 350. One change may include the use of an increased lateral offset for positioning the posts and rail farther away from the back side of the concrete barrier. This modification would prevent the vehicle's engine hood and right-front quarter panel from protruding between the rails and consequentially prevent the vehicle to encounter the normal barrier climb. Another modification would include the attachment of either of the two bicycle railings to a vertical parapet in lieu of the single-slope barrier used for this study. This second change would reduce vehicle climb up the barrier face as well as the resulting instability which occurred when the rails restrained vertical movement of the pickup truck. However, any modifications would require additional testing.

11 REFERENCES

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12 APPENDICES

APPENDIX A

English-Unit System Details, Test MOBR-1

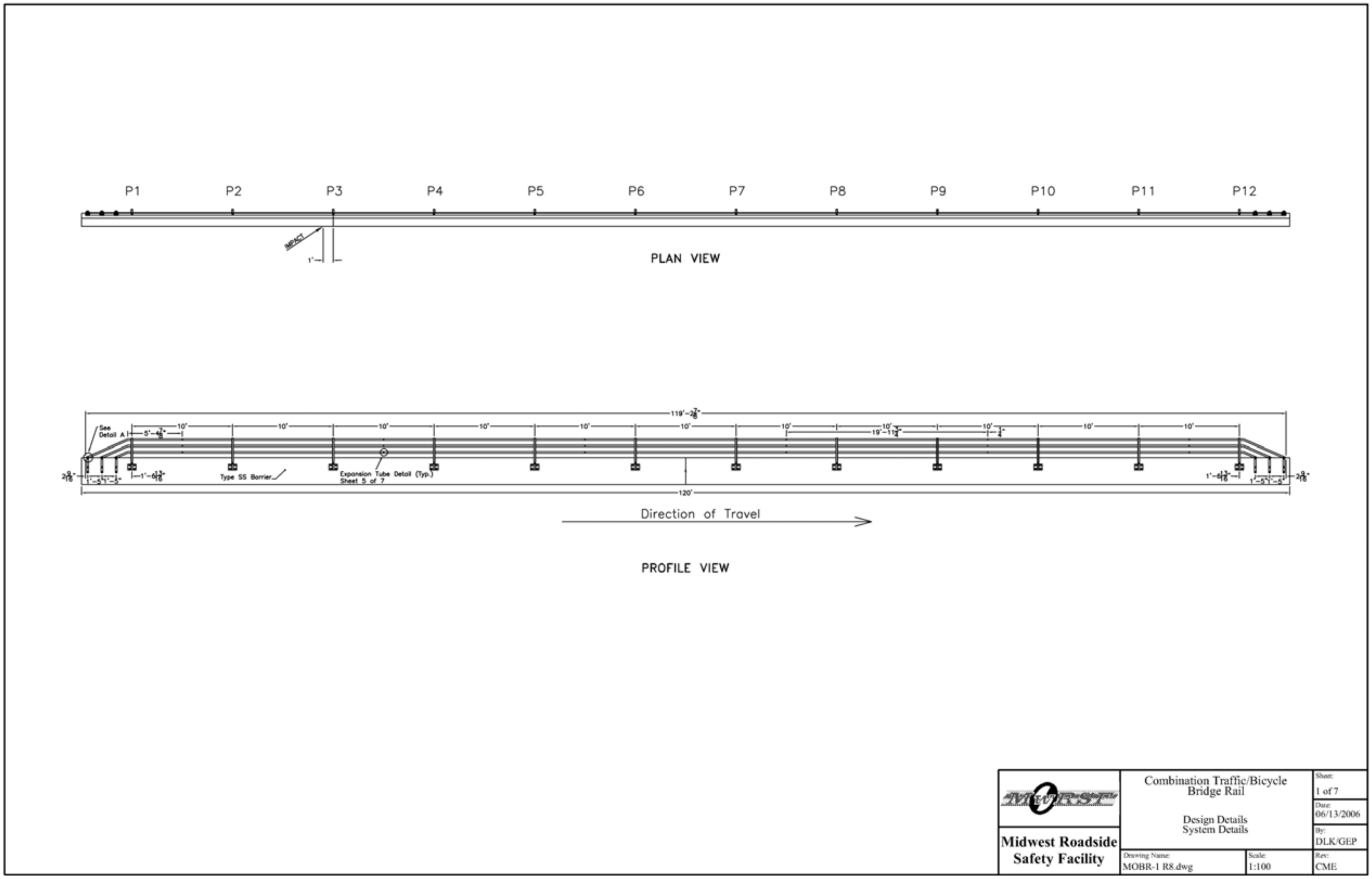


Figure A-1. Combination Traffic/Bicycle Bridge Rail - System Details

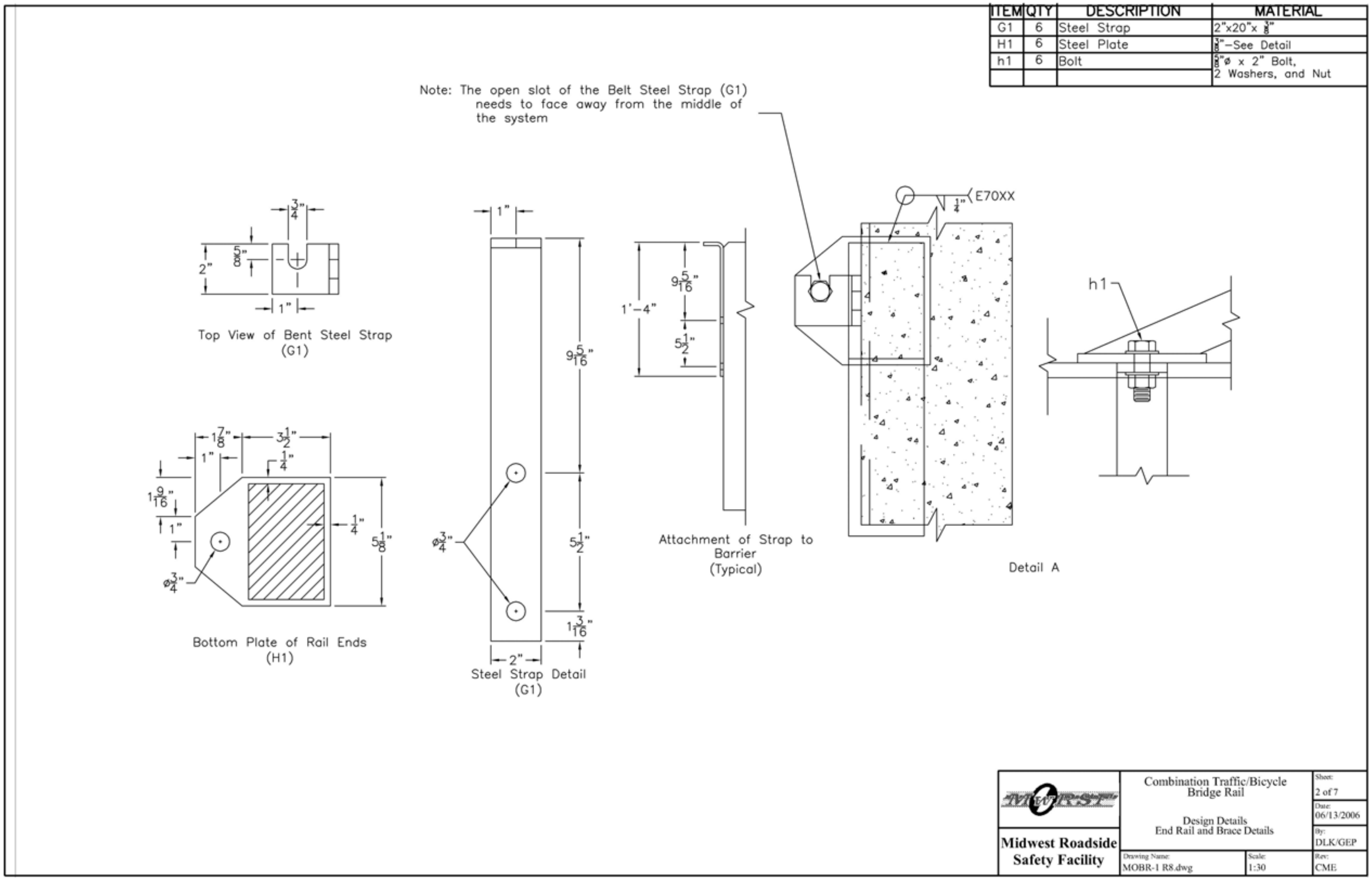


Figure A-2. Combination Traffic/Bicycle Bridge Rail - End Rail and Brace Details

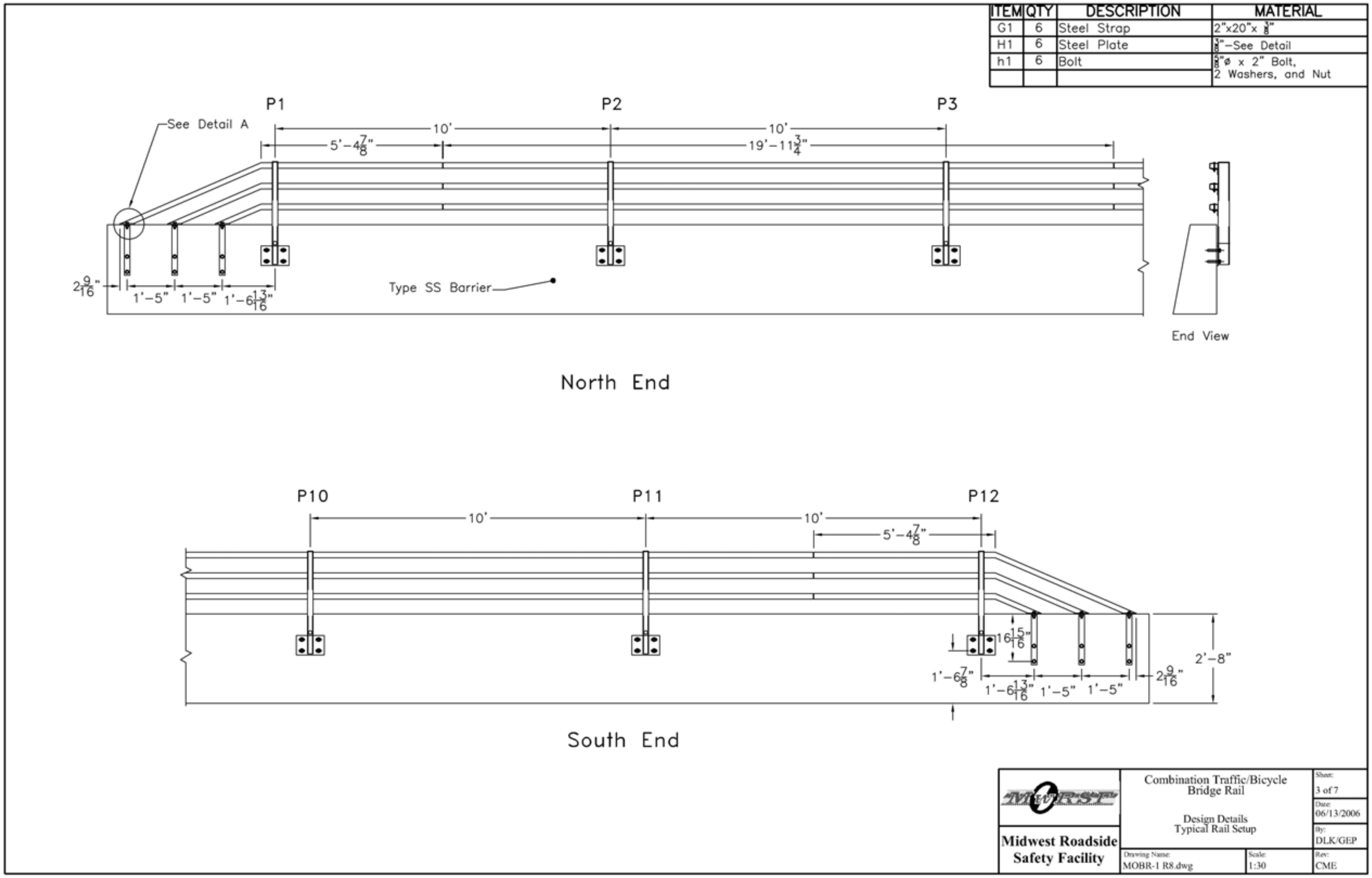
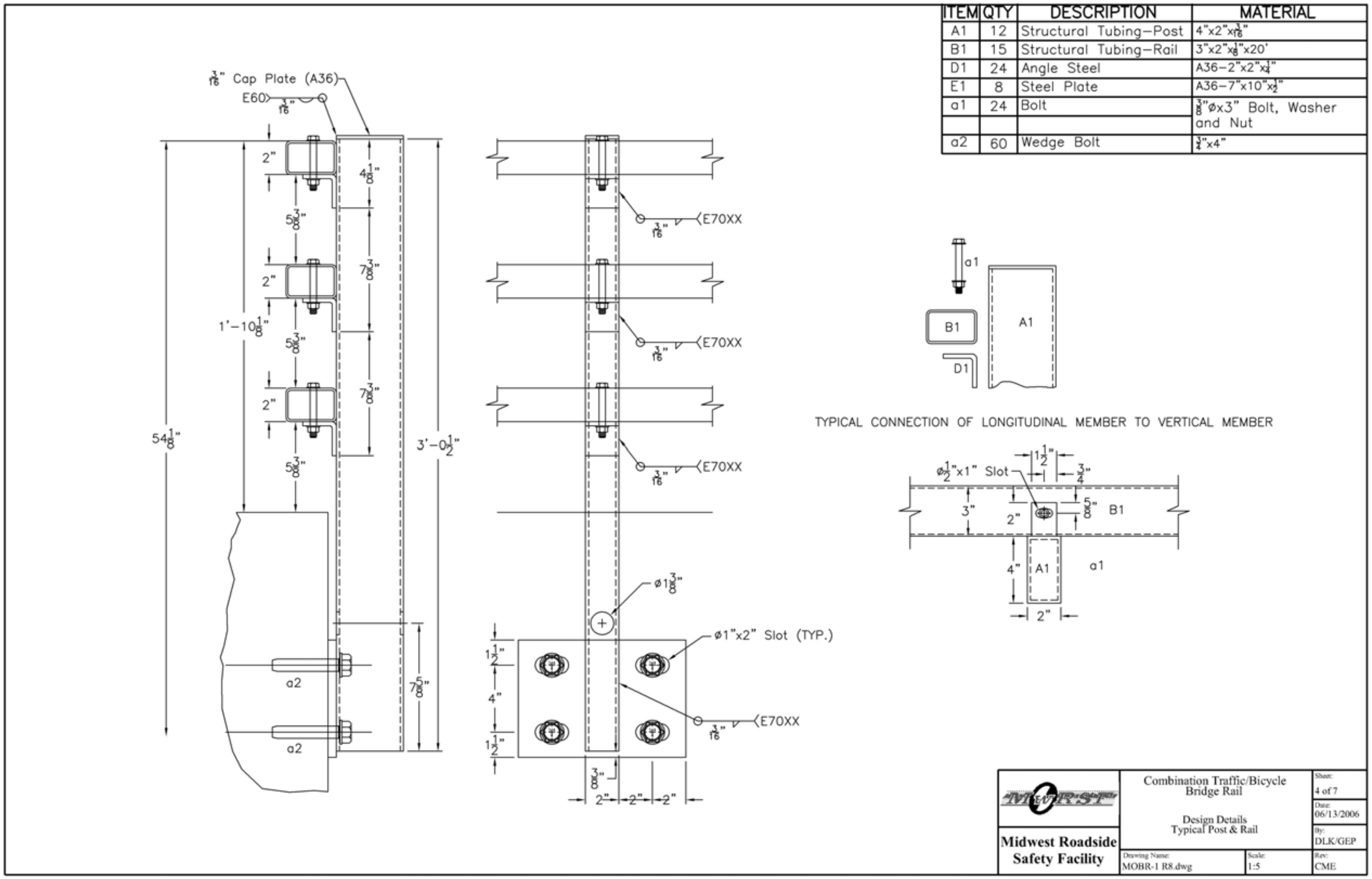
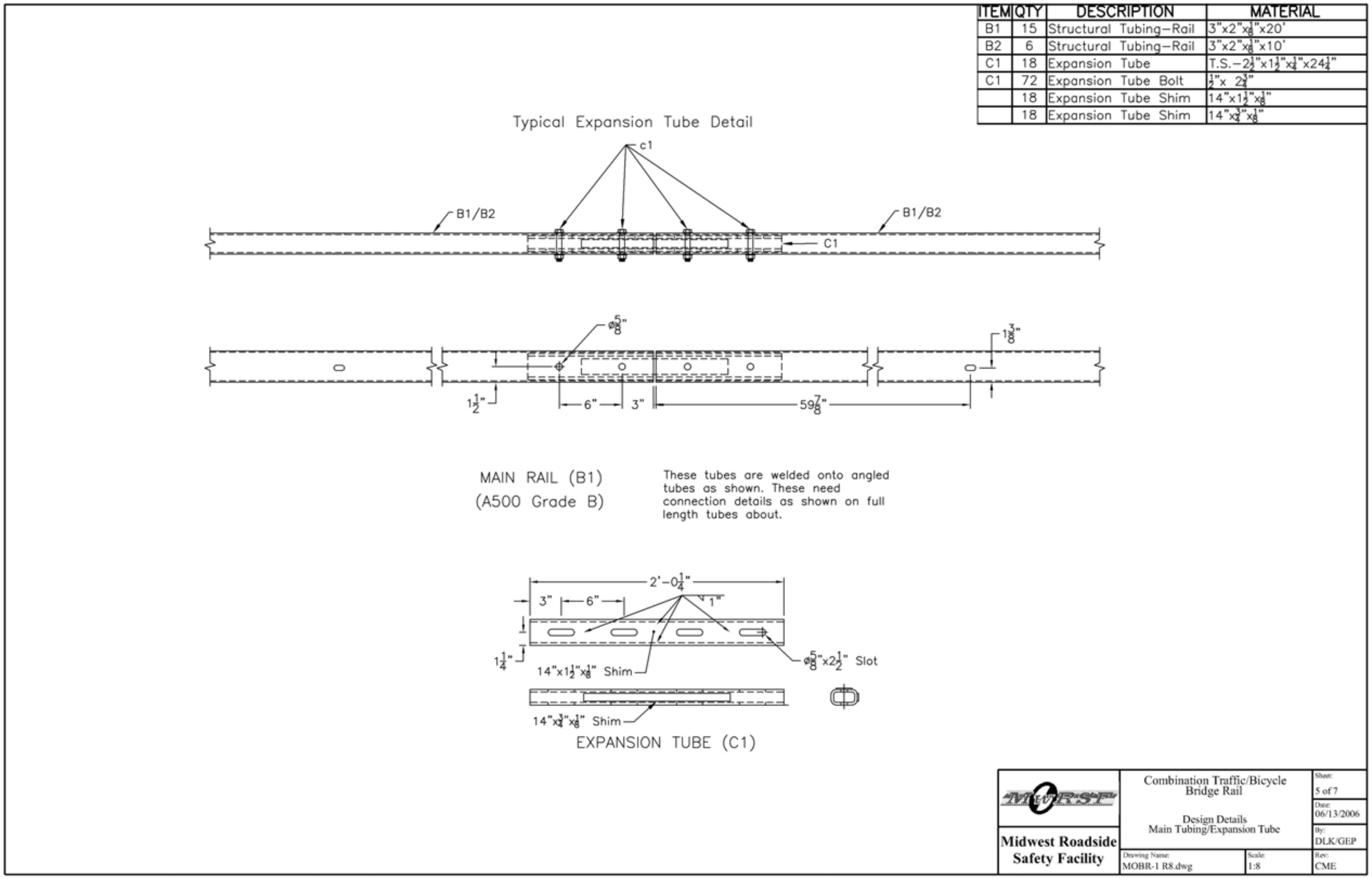


Figure A-3. Combination Traffic/Bicycle Bridge Rail - Typical Rail Setup



ITEM	QTY	DESCRIPTION	MATERIAL
A1	12	Structural Tubing–Post	4"x2"x3/16"
B1	15	Structural Tubing–Rail	3"x2"x1/8"x20'
D1	24	Angle Steel	A36–2"x2"x1/4"
E1	8	Steel Plate	A36–7"x10"x1/2"
a1	24	Bolt	3/8"øx3" Bolt, Washer and Nut
a2	60	Wedge Bolt	1/4"x4"

Figure A-4. Combination Traffic/Bicycle Bridge Rail - Typical Post and Rail Details



ITEM	QTY	DESCRIPTION	MATERIAL
B1	15	Structural Tubing–Rail	3"x2"x1/8"x20'
B2	6	Structural Tubing–Rail	3"x2"x1/8"x10'
C1	18	Expansion Tube	T.S.–2 1/2"x1 1/2"x1/4"x24 1/4"
C1	72	Expansion Tube Bolt	1/2"x 2 3/4"
	18	Expansion Tube Shim	14"x1 1/2"x1/8"
	18	Expansion Tube Shim	14"x3/4"x1/8"

Figure A-5. Combination Traffic/Bicycle Bridge Rail - Main Tubing and Expansion Tube Details

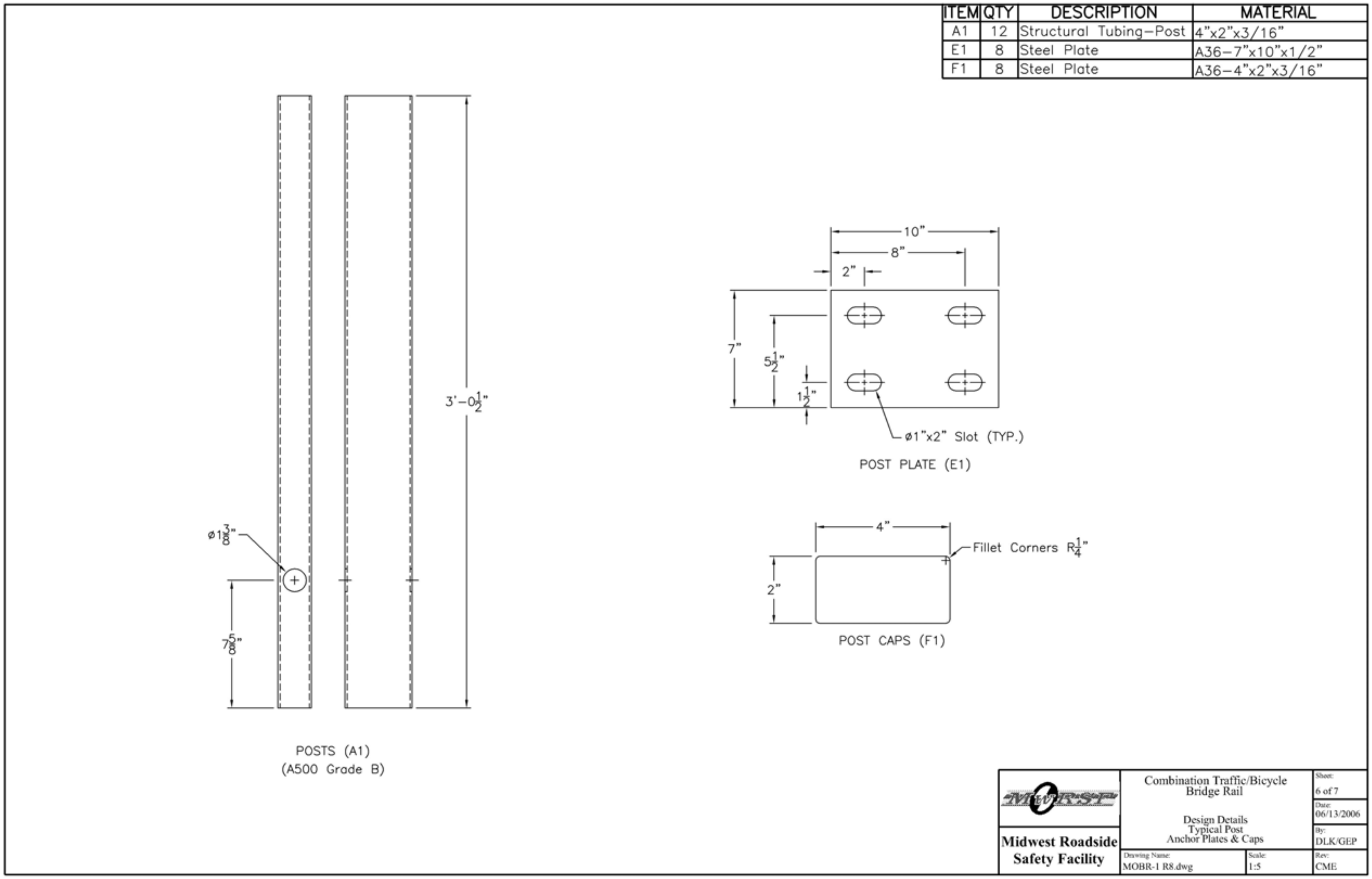


Figure A-6. Combination Traffic/Bicycle Bridge Rail - Typical Post, Anchor Plate, and Caps Details

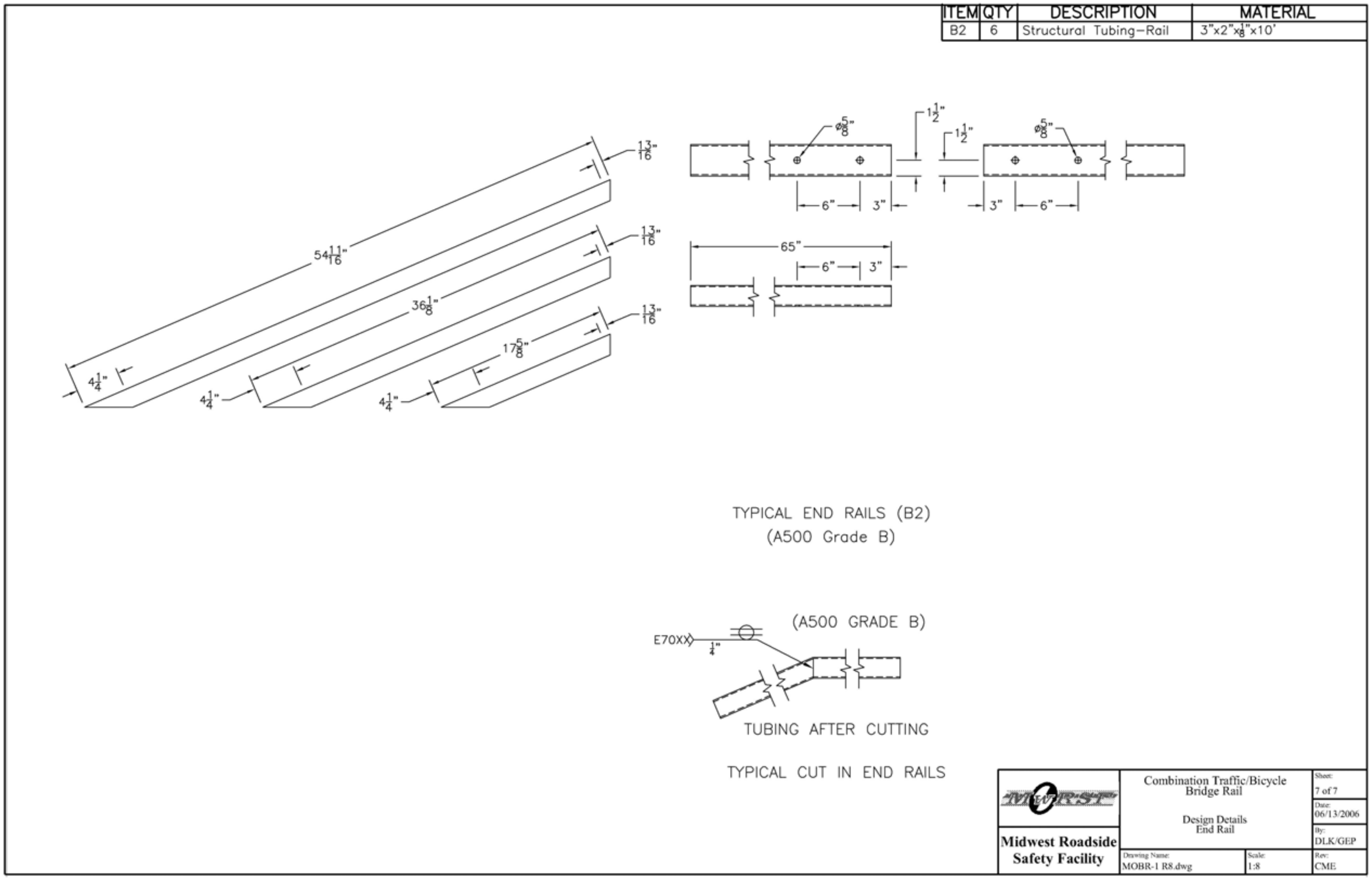


Figure A-7. Combination Traffic/Bicycle Bridge Rail - End Rail Details

APPENDIX B

Test Summary Sheets in English Units

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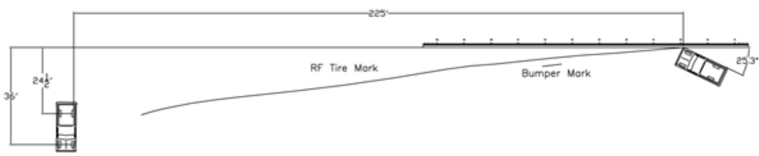
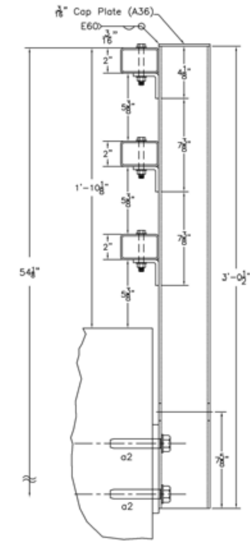
0.178 sec

0.318 sec

0.455 sec





- Test Number MOBR-1 (4-11)
- Date 3/27/04
- Test Article . . . . Comb. Traffic/Bicycle Bridge Rail
  - Total Length . . . . 119 ft 2 3/4 in.
  - Overall Height . . . . 54 3/8 in.
- Bicycle Rail Tubes . . . . ASTM A500 Grade B Steel
  - Section . . . . TS 3 in. x 2 in. x 1/8 in. thick
  - Length . . . . 240 in. and 120 in.
  - Top Mounting Height . . . . . Lower Tube . . . . 39 3/8 in.
    Middle Tube . . . 46 3/4 in.
    Upper Tube . . . . 54 1/8 in.
- Post Nos. 1-12 . . . . ASTM A500 Grade B Steel
  - Section . . . . TS 4 in. x 2 in. x 3/16 in. thick
  - Center to Center Spacing . . 120 in.
- Soil Type . . . . NA
- Vehicle Model . . . . 1998 GMC C2500 3/4-ton pickup
  - Curb . . . . 4,370 lbs
  - Test Inertial . . . . 4,443 lbs
  - Gross Static . . . . 4,443 lbs
- Impact Location . . . . 12 in. upstream of post no. 3
- Vehicle Speed
  - Impact . . . . 63.1 mph
  - Exit . . . . 52.5 mph
- Vehicle Angle
  - Impact (trajectory) . . . . 25.6 degrees
  - Exit (trajectory) . . . . 2.20 degrees
- Vehicle Snagging . . . . Moderate
- Vehicle Pocketing . . . . None
- Vehicle Stability . . . . Unsatisfactory
- Occupant Ridedown Deceleration (10 msec avg.)
  - Longitudinal . . . . 6.23 Gs/-5.74 Gs < 20 Gs
  - Lateral . . . . 12.89 Gs < 20 Gs
- Occupant Impact Velocity
  - Longitudinal . . . . 17.65 fps < 39.37 fps
  - Lateral (not required) . . . . . 27.66 fps < 39.37 fps
- Vehicle Damage . . . . Extensive
  - TAD[12] 1-RFQ-5
  - SAE[13] 01RYAO5
- Vehicle Stopping Distance . . . . . 227.7 ft downstream
  36.1 ft laterally
- Test Article Damage . . . . Minimal
- Maximum Deflection
  - Permanent Set . . . . None
  - Dynamic . . . . 2 9/16 in.
- Working Width . . . . 19 15/16 in.

Figure B-1. Summary of Test Results and Sequential Photographs, Test MOBR-1

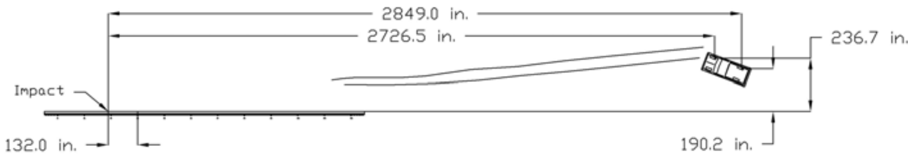

0.000 sec

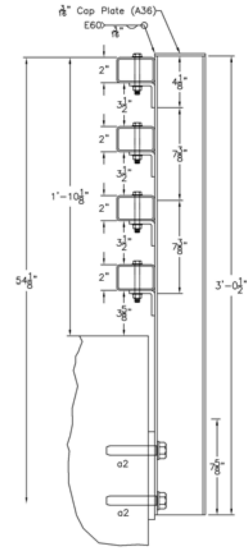

0.086 sec


0.168 sec


0.338 sec


0.514 sec





- Test Number MOBR-2 (4-11)
- Date 3/27/04
- Test Article . . . . Combination Bic./Ped./Veh. Rail
    - Total Length . . . . 119 ft 2 3/4 in.
    - Overall Height . . . . 54 3/8 in.
- Bicycle Rail Tubes . . . . ASTM A500 Grade B Steel
    - Section . . . . TS 3 in. x 2 in. x 1/8 in. thick
    - Length . . . . 240 in. and 120 in.
    - Top Mounting Height . . . . . Lower Tube . . . . 37 5/8 in.; Lower Middle Tube 43 1/8 in.; Upper Middle Tube . 48 5/8 in.; Upper Tube . . . . 54 1/8 in.
- Post Nos. 1-12 . . . . ASTM A500 Grade B Steel
    - Section . . . . TS 4 in. x 2 in. x 3/16 in. thick
    - Center to Center Spacing . . 120 in.
- Soil Type . . . . NA
- Vehicle Model . . . . 1998 GMC C2500 3/4-ton pickup
    - Curb . . . . 4,493 lbs
    - Test Inertial . . . . 4,473 lbs
    - Gross Static . . . . 4,473 lbs
- Impact Location . . . . 12 in. upstream of post no. 3
- Vehicle Speed
    - Impact . . . . 63.8 mph
    - Exit . . . . 53.6 mph
- Vehicle Angle
    - Impact (trajectory) . . . . 25.6 degrees
    - Exit (trajectory) . . . . 9.0 degrees
- Vehicle Snagging . . . . Moderate
- Vehicle Pocketing . . . . None
- Vehicle Stability . . . . Unsatisfactory
- Occupant Ridedown Deceleration (10 msec avg.)
    - Longitudinal . . . . 5.11 Gs/-9.29 Gs < 20 Gs
    - Lateral . . . . 14.22 Gs < 20 Gs
- Occupant Impact Velocity
    - Longitudinal . . . . 20.3 fps < 39.37 fps
    - Lateral (not required) . . . . . 27.6 fps < 39.37 fps
- Vehicle Damage . . . . Extensive
    - TAD[12] 1-RFQ-5
    - SAE[13] 01RDAO5
- Vehicle Stopping Distance . . . . . 227.4 ft downstream, 36.1 ft laterally
- Test Article Damage . . . . Minimal
- Maximum Deflection
    - Permanent Set . . . . None
    - Dynamic . . . . 1 1/8 in.
- Working Width . . . . 13 in.

Figure B-2. Summary of Test Results and Sequential Photographs, Test MOBR-2

APPENDIX C

Accelerometer Data Analysis, Test MOBR-1

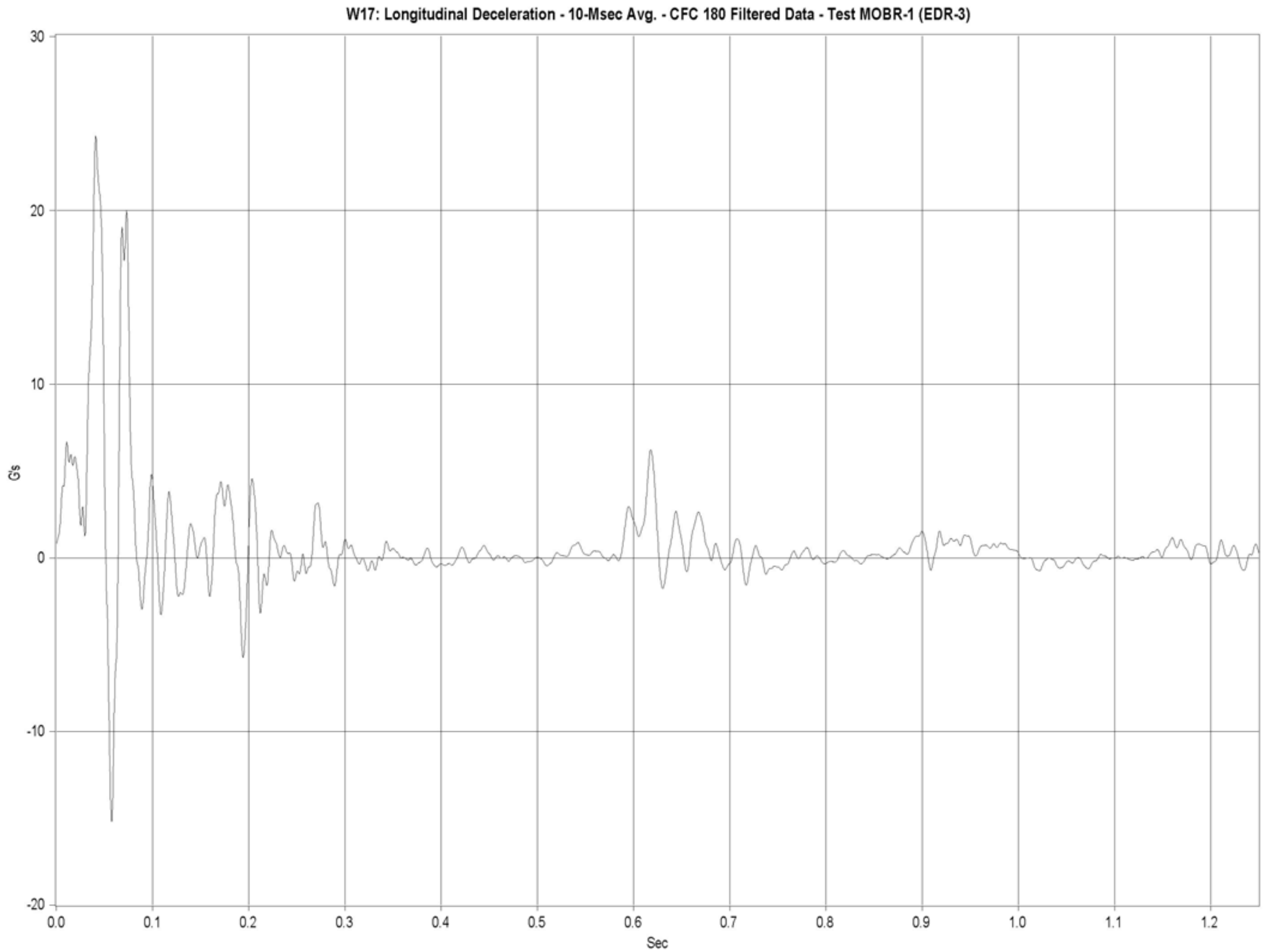


Figure C-1. Graph of Longitudinal Deceleration, Test MOBR-1

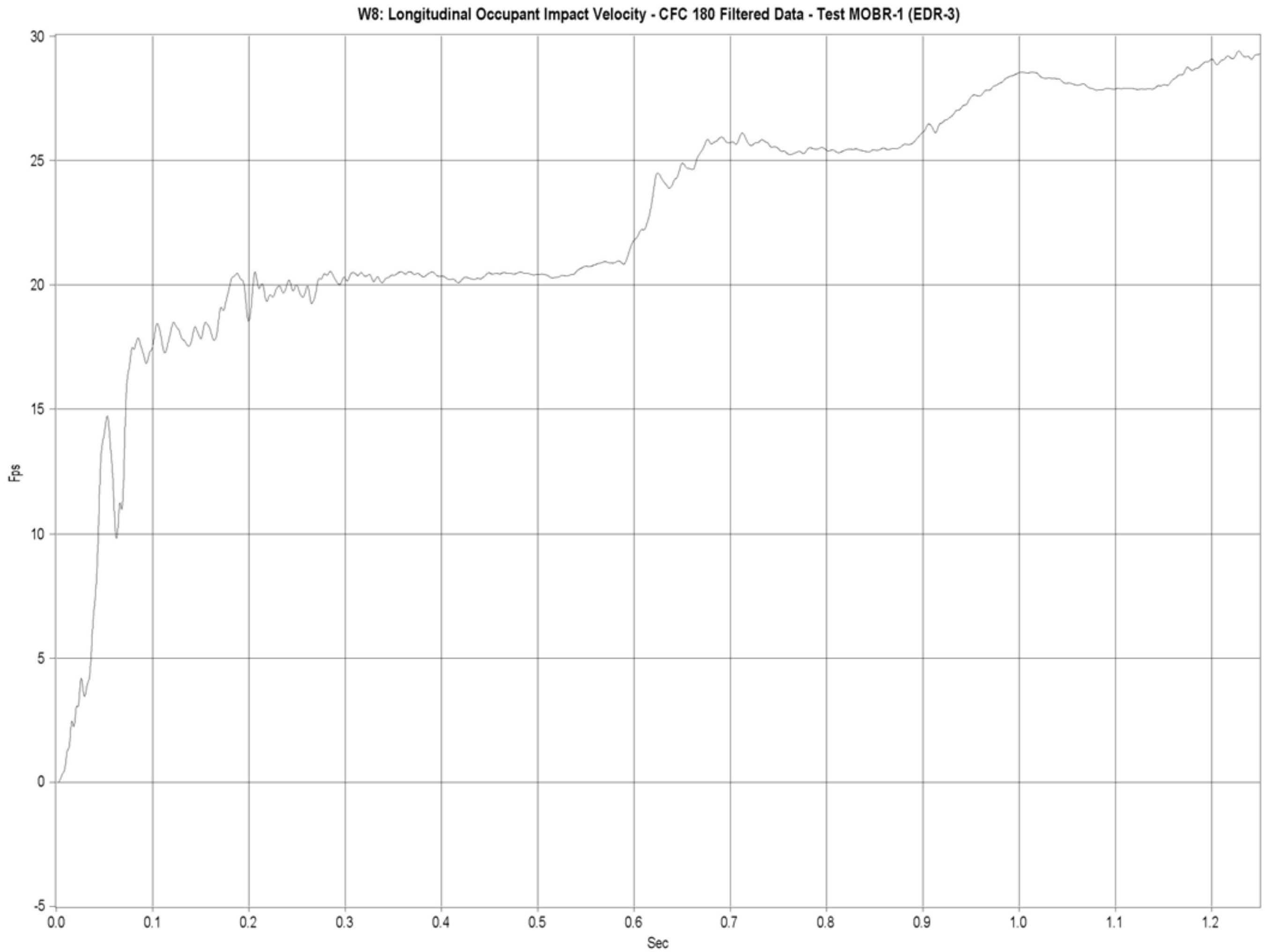


Figure C-2. Graph of Longitudinal Occupant Impact Velocity, Test MOBR-1

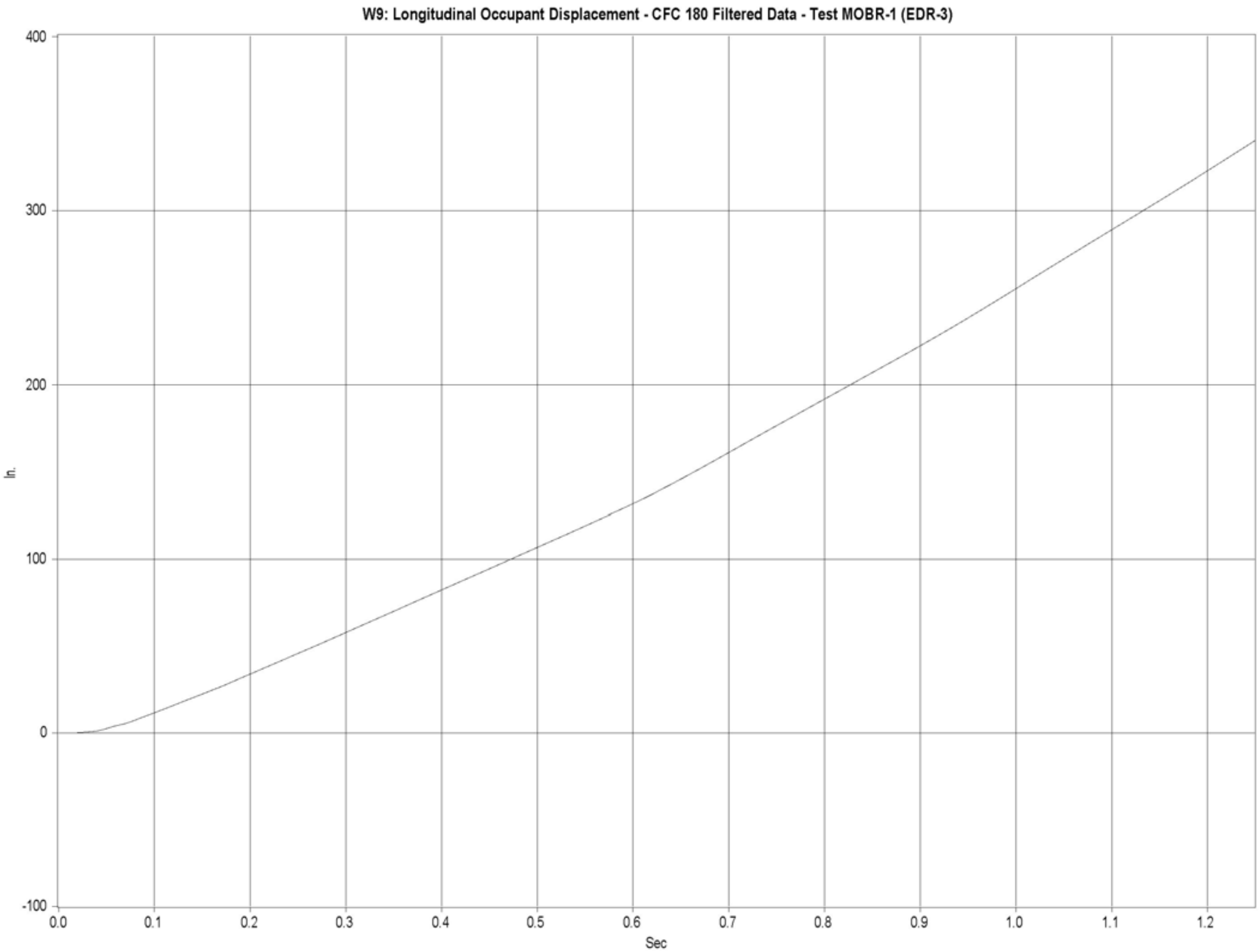


Figure C-3. Graph of Longitudinal Displacement, Test MOBR-1

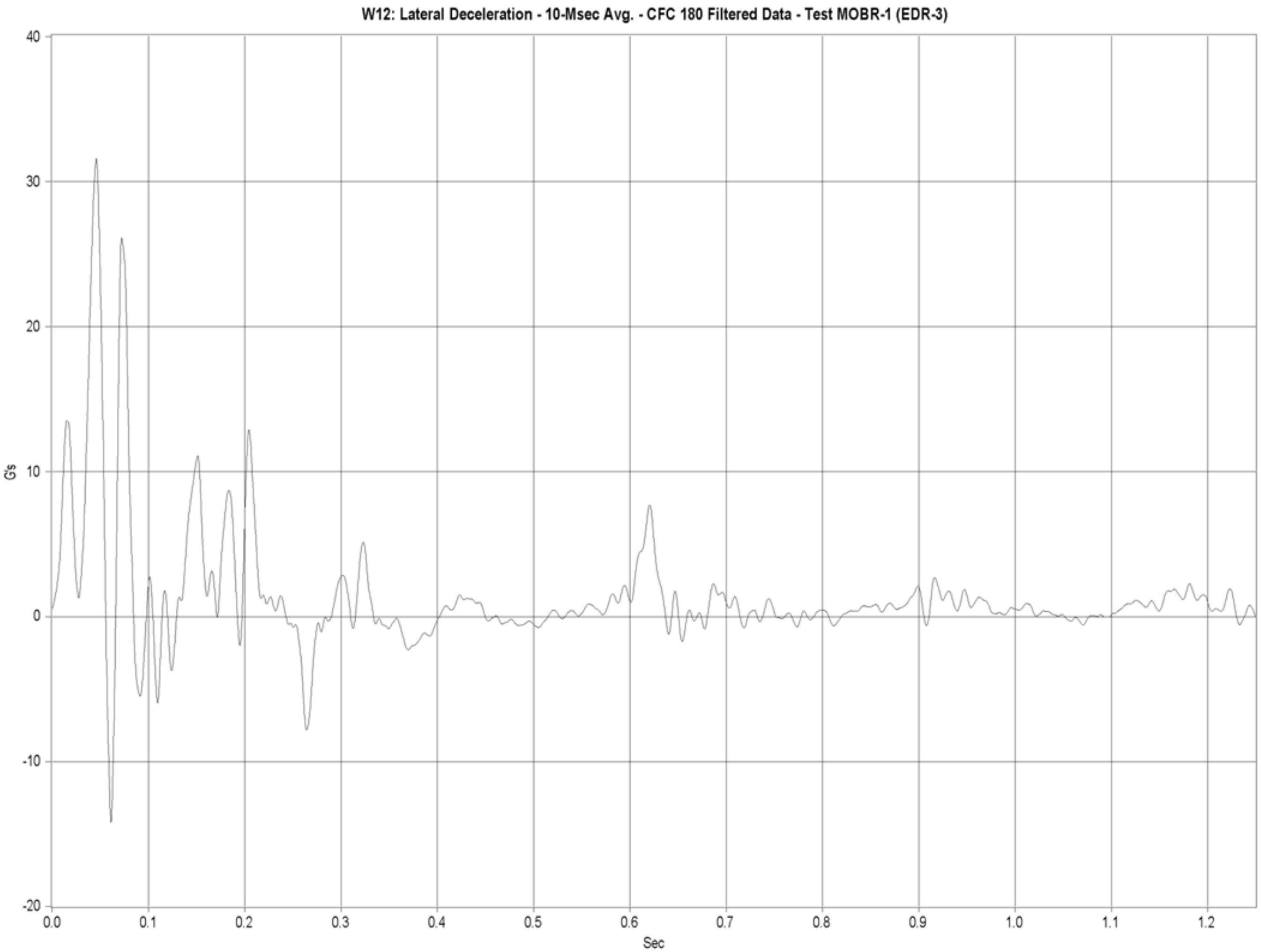


Figure C-4. Graph of Lateral Deceleration, Test MOBR-1

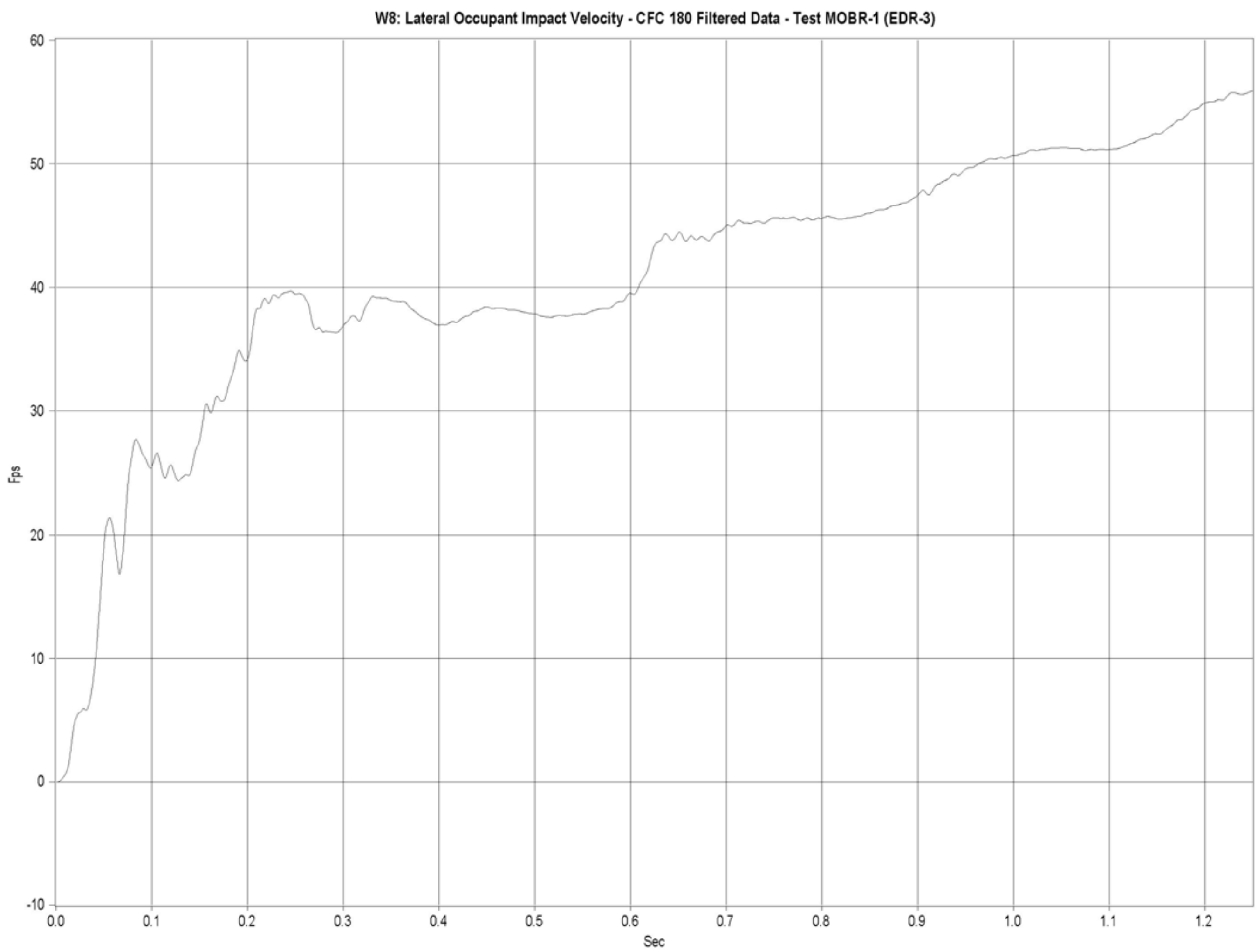


Figure C-5. Graph of Lateral Occupant Impact Velocity, Test MOBR-1

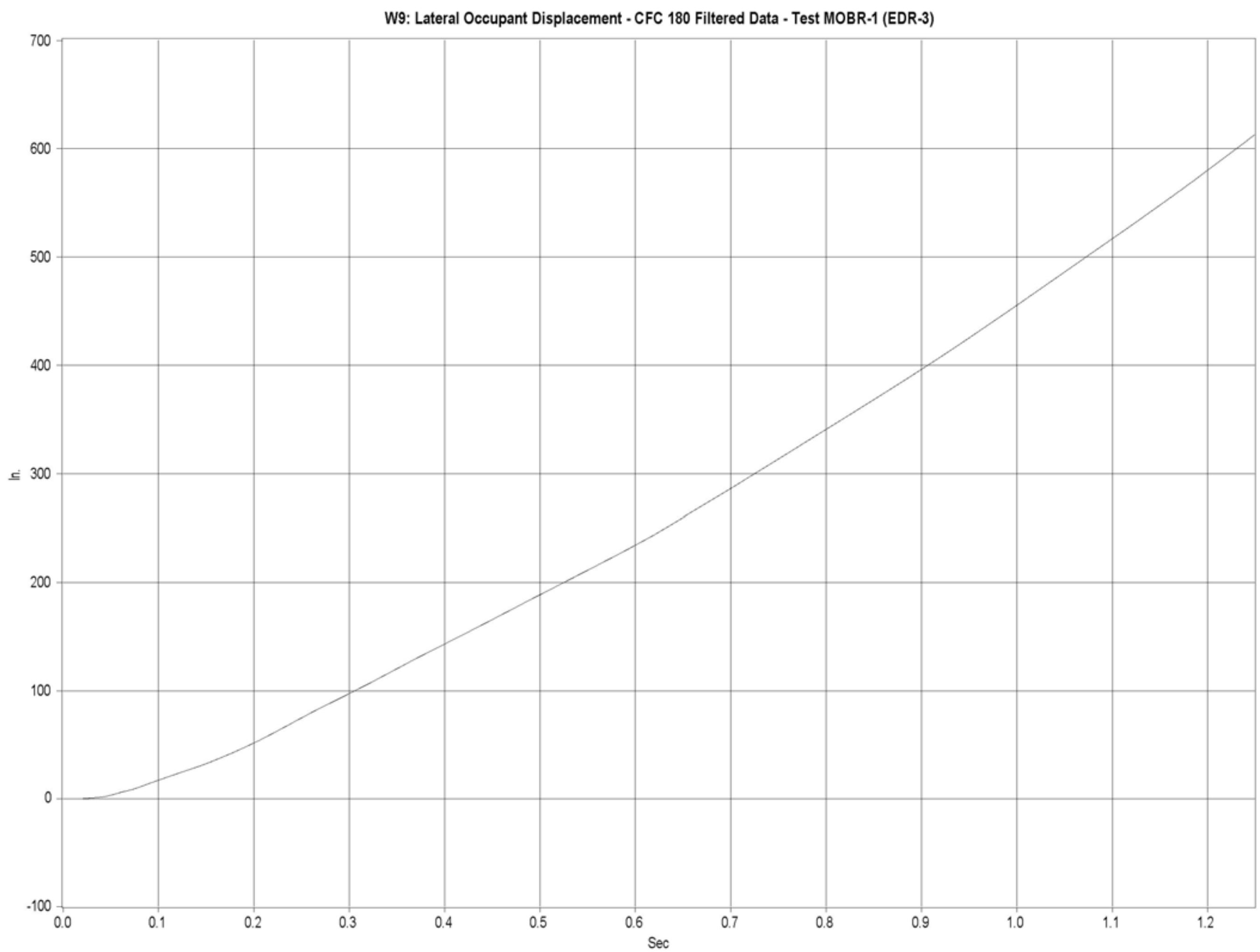


Figure C-6. Graph of Lateral Displacement, Test MOBR-1

APPENDIX D

English-Unit System Details, Test MOBR-2

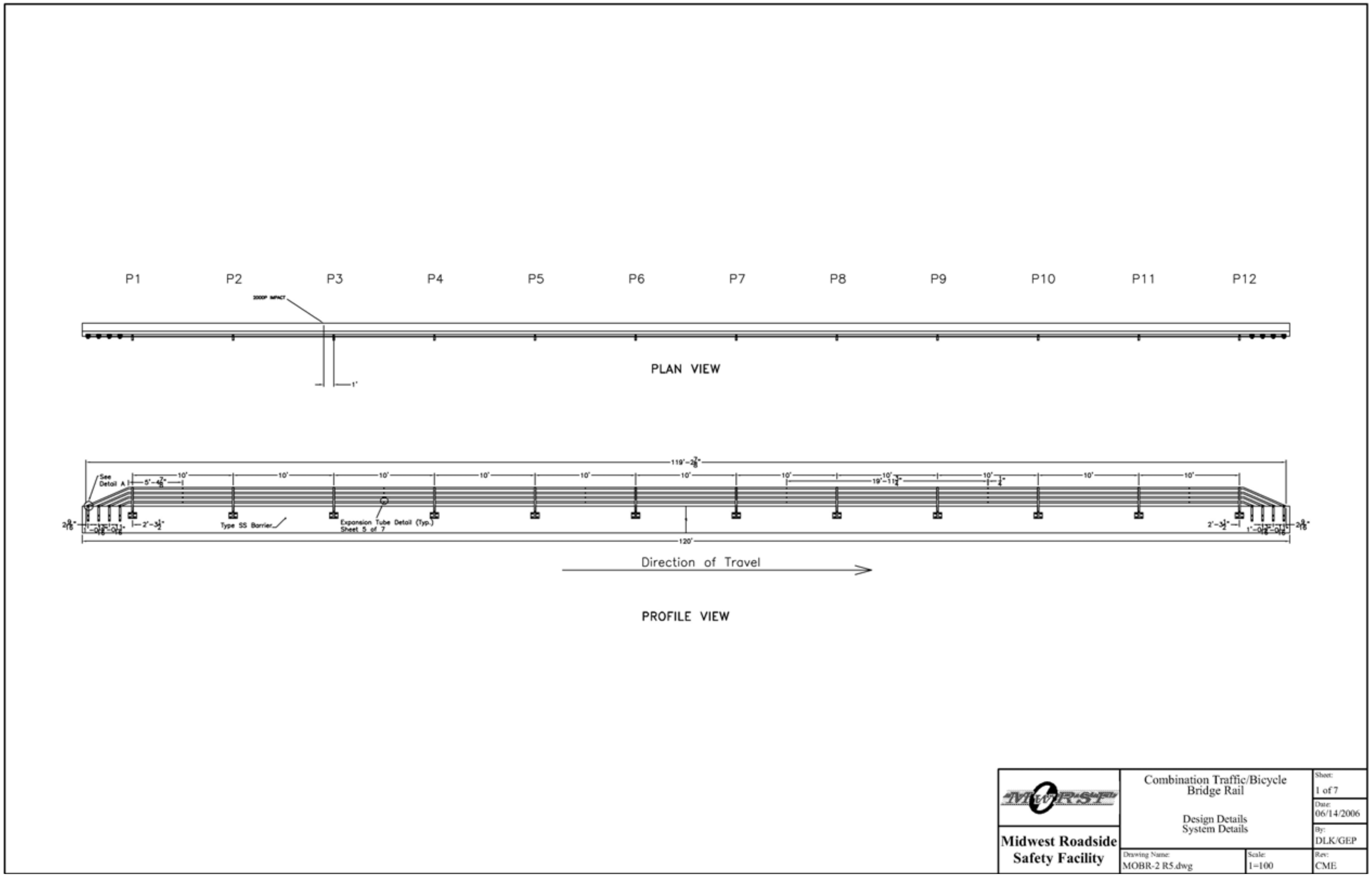


Figure D-1. Modified Combination Traffic/Bicycle Bridge Rail - System Details

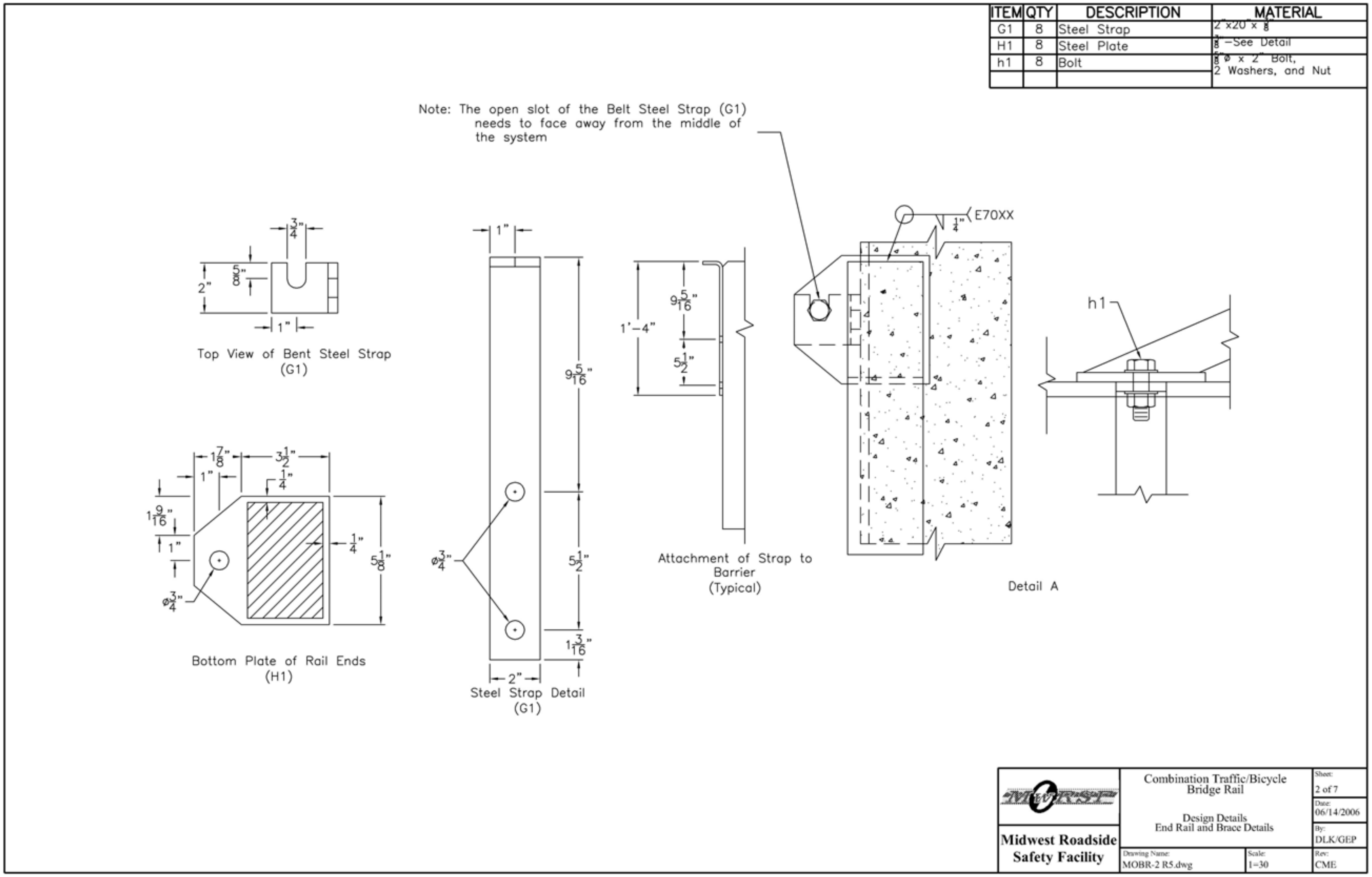


Figure D-2. Modified Combination Traffic/Bicycle Bridge Rail - End Rail and Brace Details

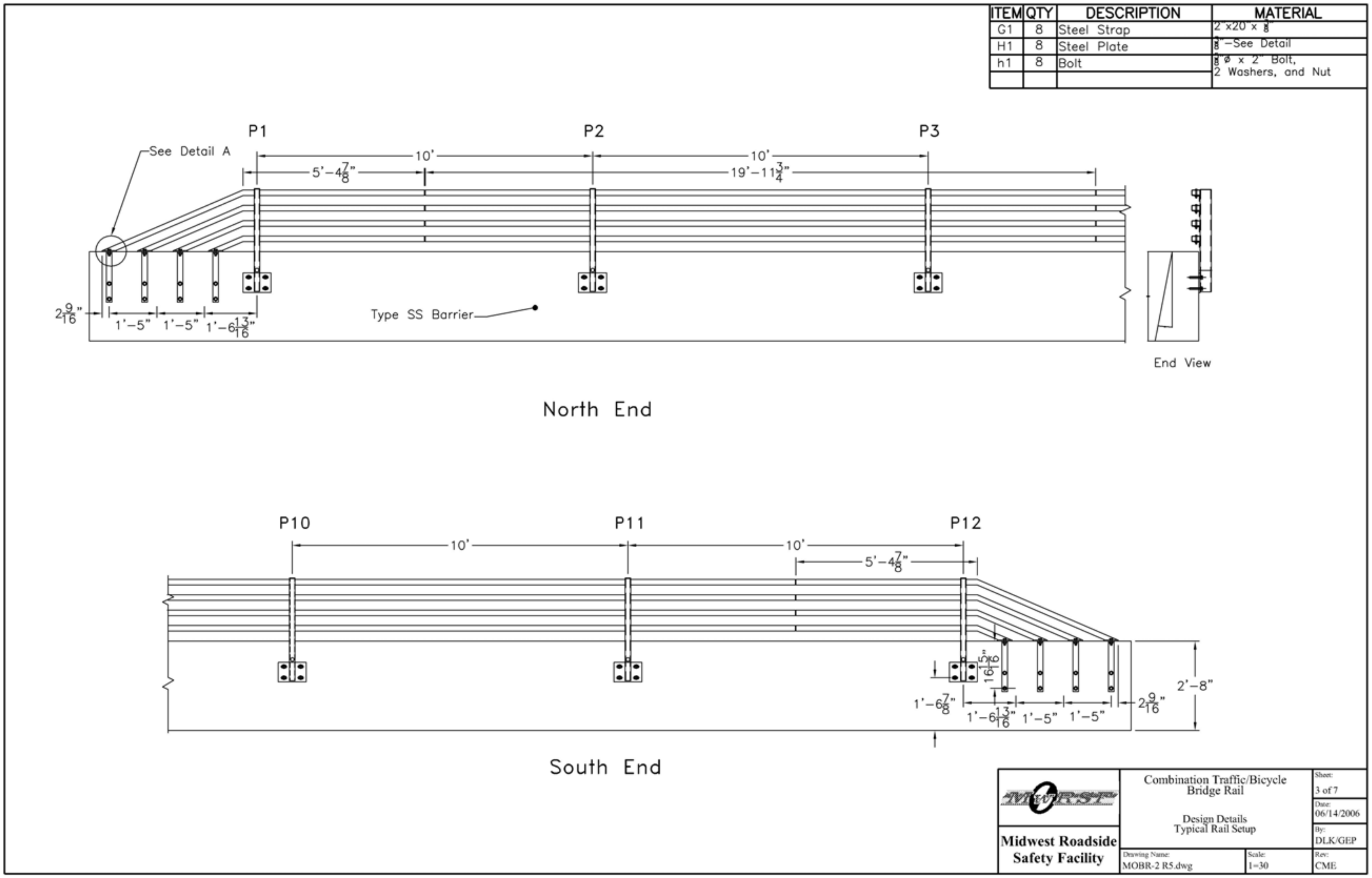
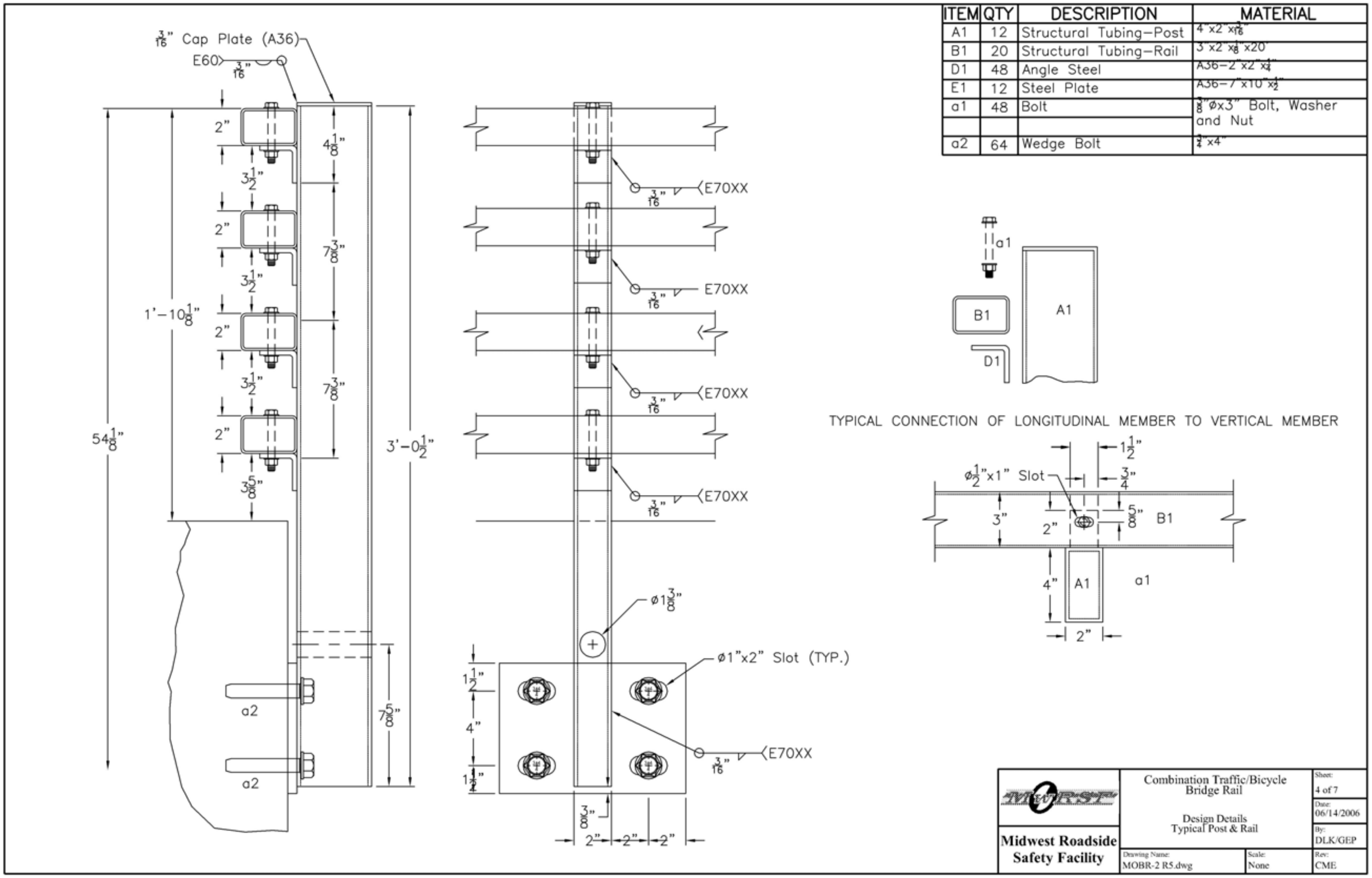


Figure D-3. Modified Combination Traffic/Bicycle Bridge Rail - Typical Rail Setup



ITEM	QTY	DESCRIPTION	MATERIAL
A1	12	Structural Tubing–Post	4"x2"x3/16"
B1	20	Structural Tubing–Rail	3"x2"x1/8"x20'
D1	48	Angle Steel	A36–2"x2"x1/4"
E1	12	Steel Plate	A36–7"x10"x1/2"
a1	48	Bolt	3/8"øx3" Bolt, Washer and Nut
a2	64	Wedge Bolt	3/4"x4"

Figure D-4. Modified Combination Traffic/Bicycle Bridge Rail - Typical Post and Rail Details

ITEM	QTY	DESCRIPTION	MATERIAL
B1	20	Structural Tubing–Rail	3"x2"x 1/8"x20'
B2	8	Structural Tubing–Rail	3"x2"x 1/8"x10'
C1	24	Expansion Tube	T.S.–2 1/2"x1 1/2"x1/4"x24 1/4"
C1	96	Expansion Tube Bolt	1/2" x 2 3/4"
	24	Expansion Tube Shim	14"x1 1/2"x1/8"
	24	Expansion Tube Shim	14"x3/4"x1/8"

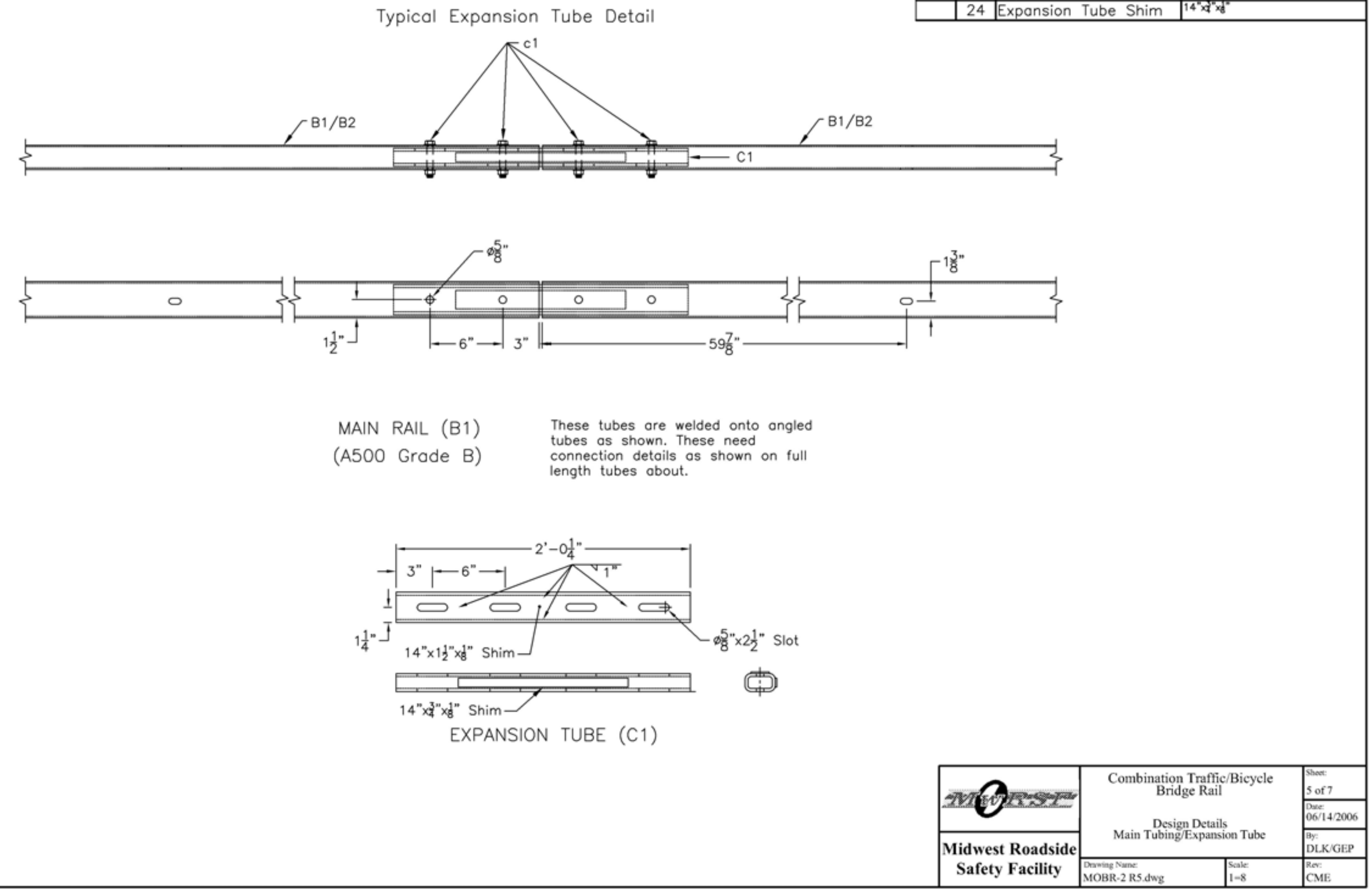
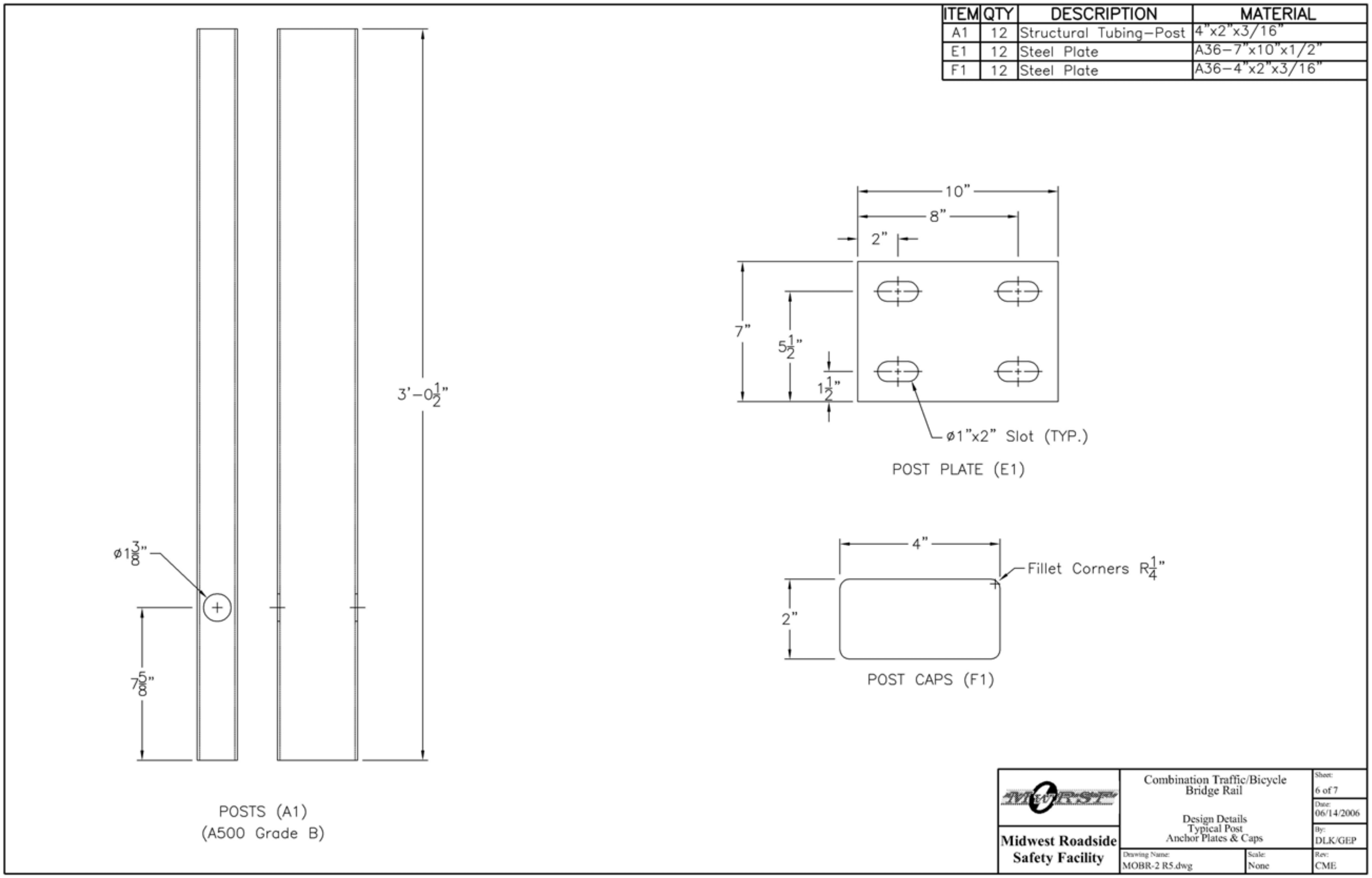


Figure D-5. Modified Combination Traffic/Bicycle Bridge Rail - Main Tubing and Expansion Tube Details



ITEM	QTY	DESCRIPTION	MATERIAL
A1	12	Structural Tubing–Post	4"x2"x3/16"
E1	12	Steel Plate	A36–7"x10"x1/2"
F1	12	Steel Plate	A36–4"x2"x3/16"

Figure D-6. Modified Combination Traffic/Bicycle Bridge Rail - Typical Post, Anchor Plate, and Cap Details

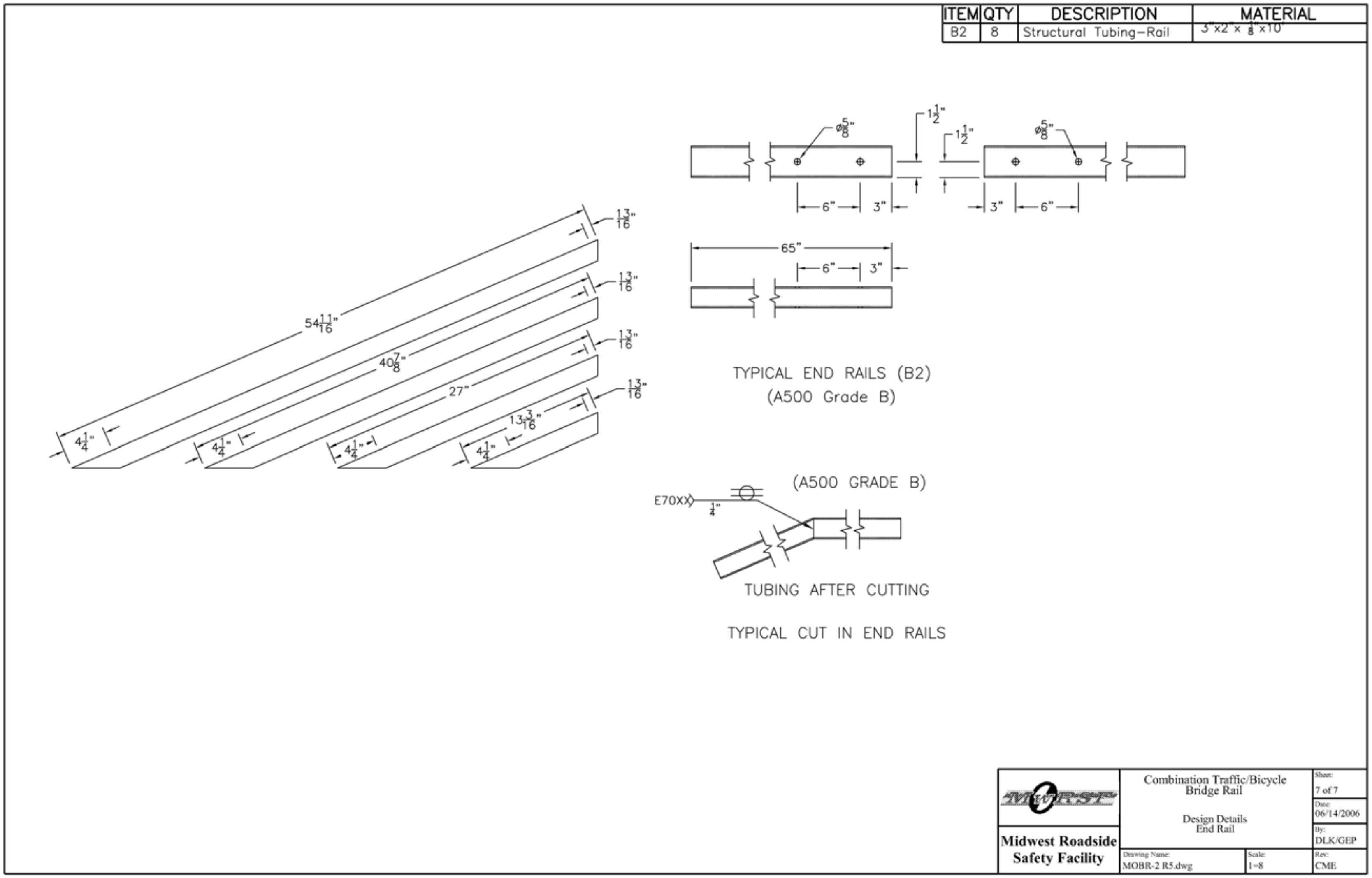


Figure D-7. Modified Combination Traffic/Bicycle Bridge Rail - End Rail Details

APPENDIX E

Accelerometer Data Analysis, Test MOBR-2

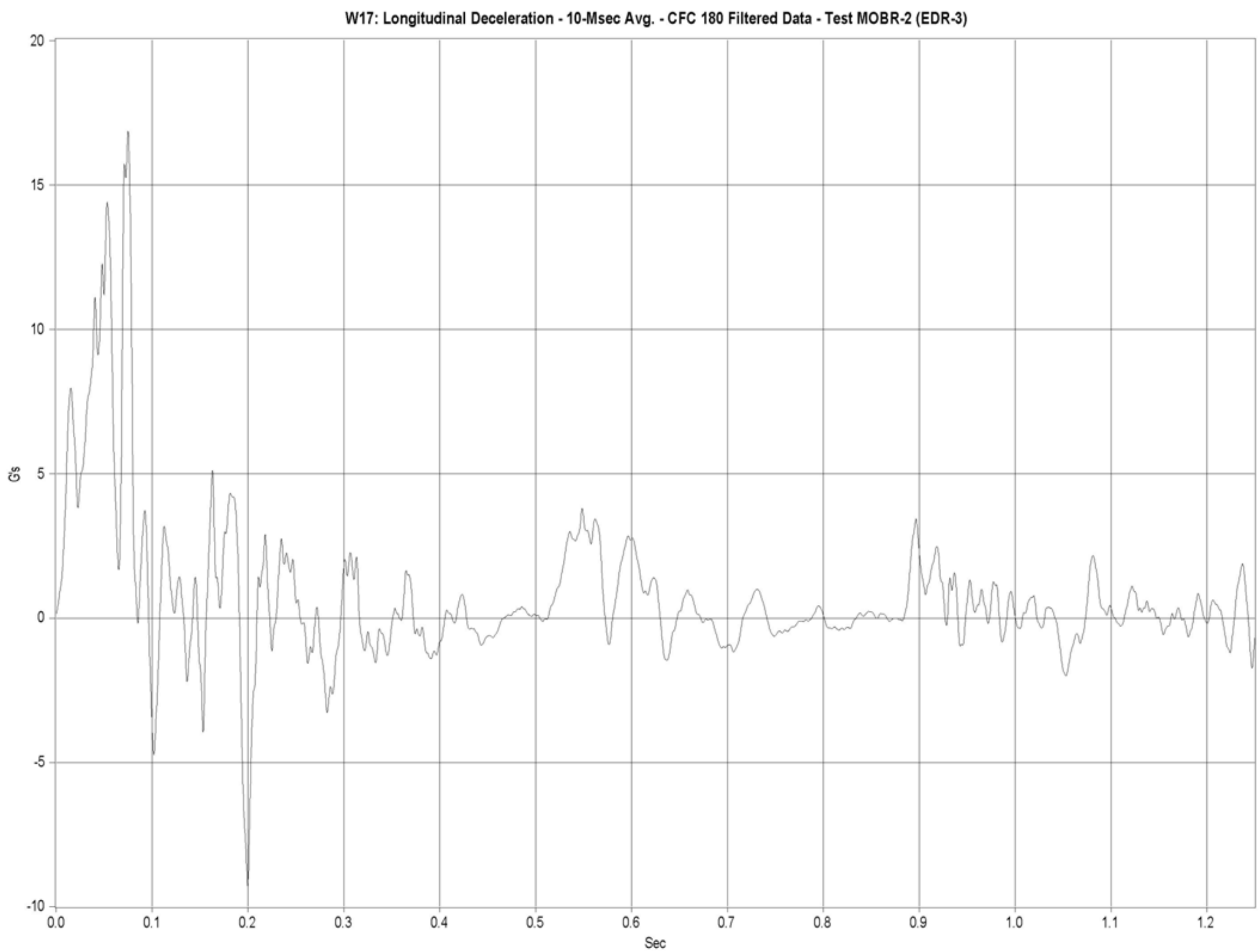


Figure E-1. Graph of Longitudinal Deceleration, Test MOBR-2

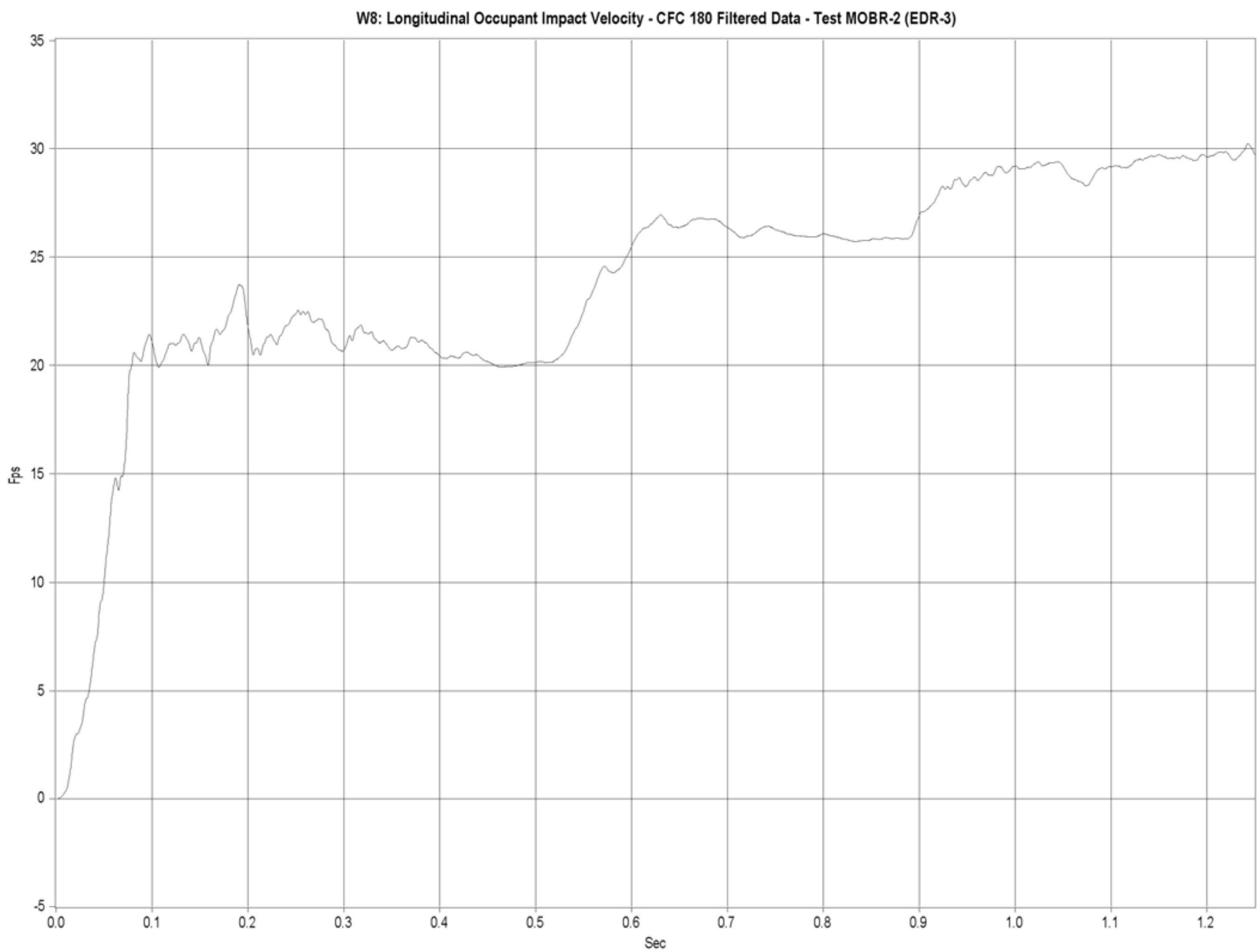


Figure E-2. Graph of Longitudinal Occupant Impact Velocity, Test MOBR-2

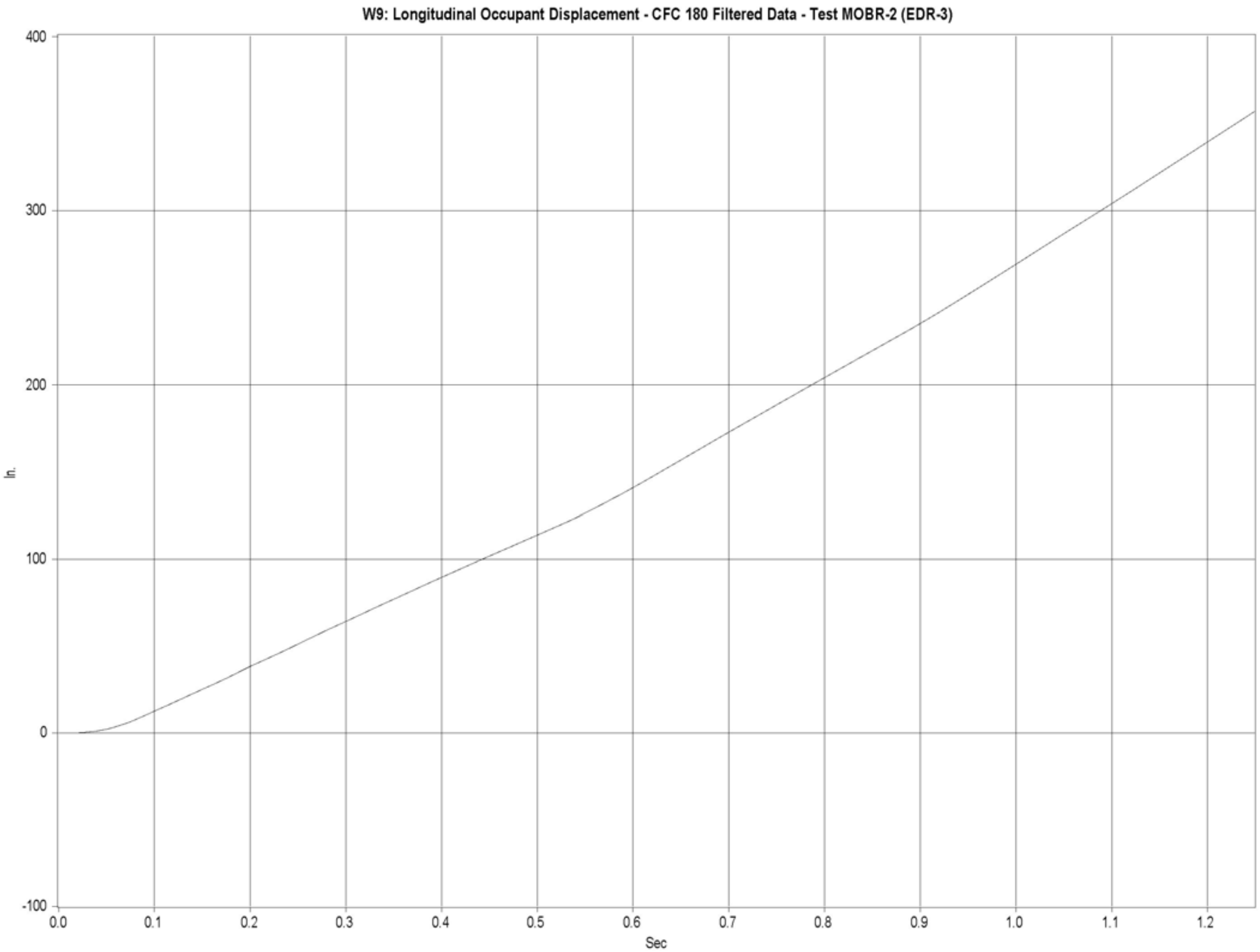


Figure E-3. Graph of Longitudinal Displacement, Test MOBR-2

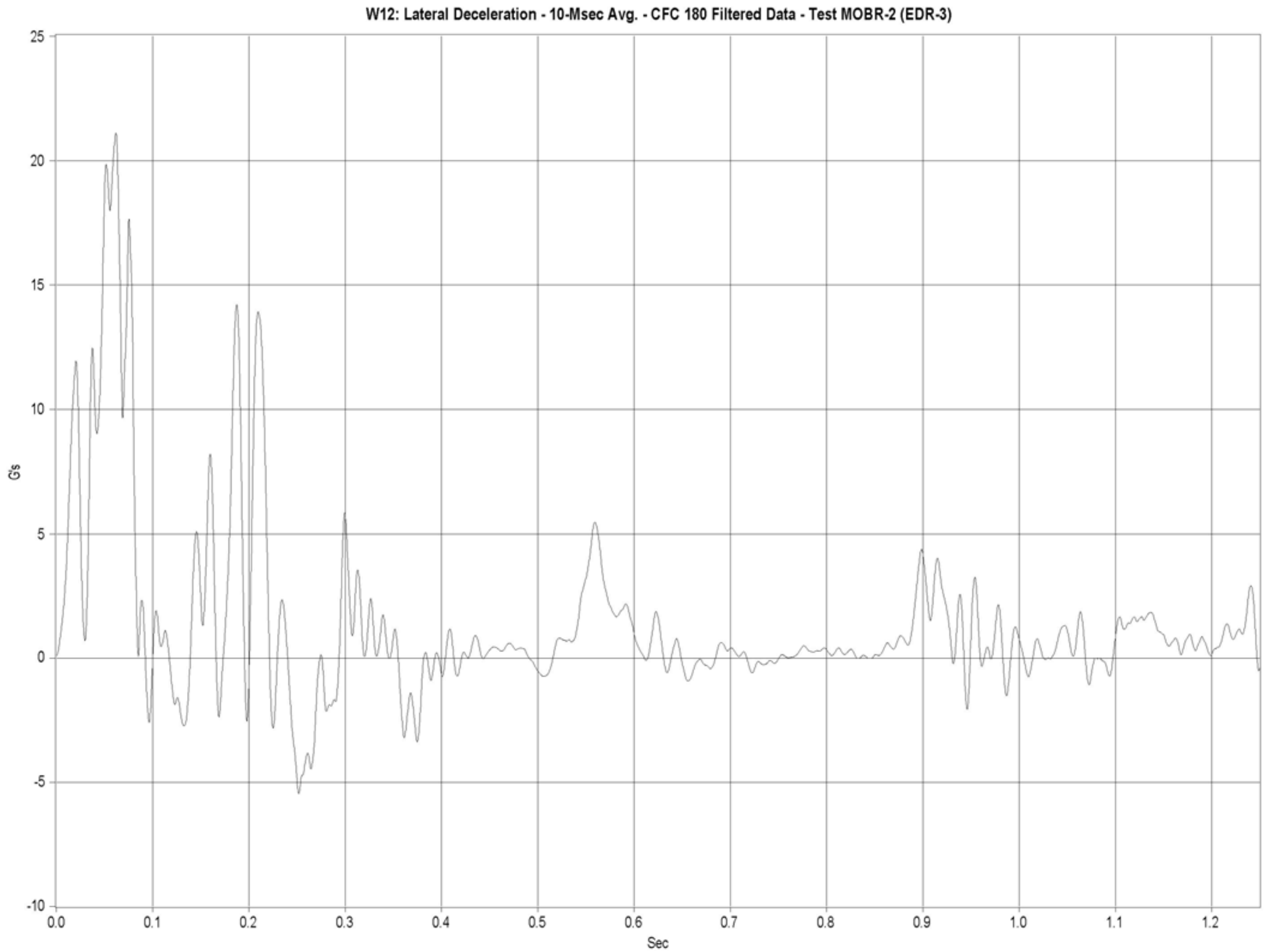


Figure E-4. Graph of Lateral Deceleration, Test MOBR-2

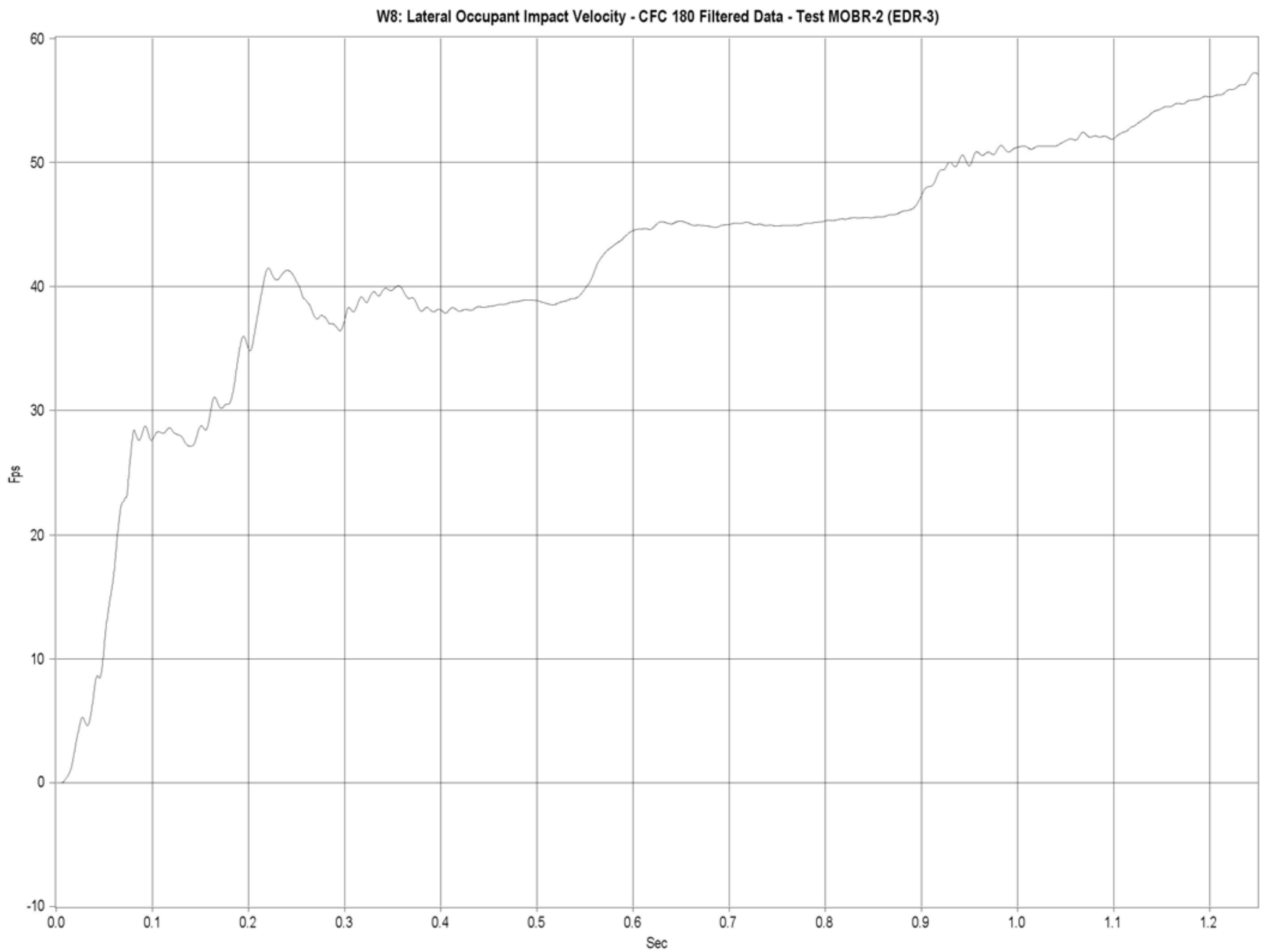


Figure E-5. Graph of Lateral Occupant Impact Velocity, Test MOBR-2

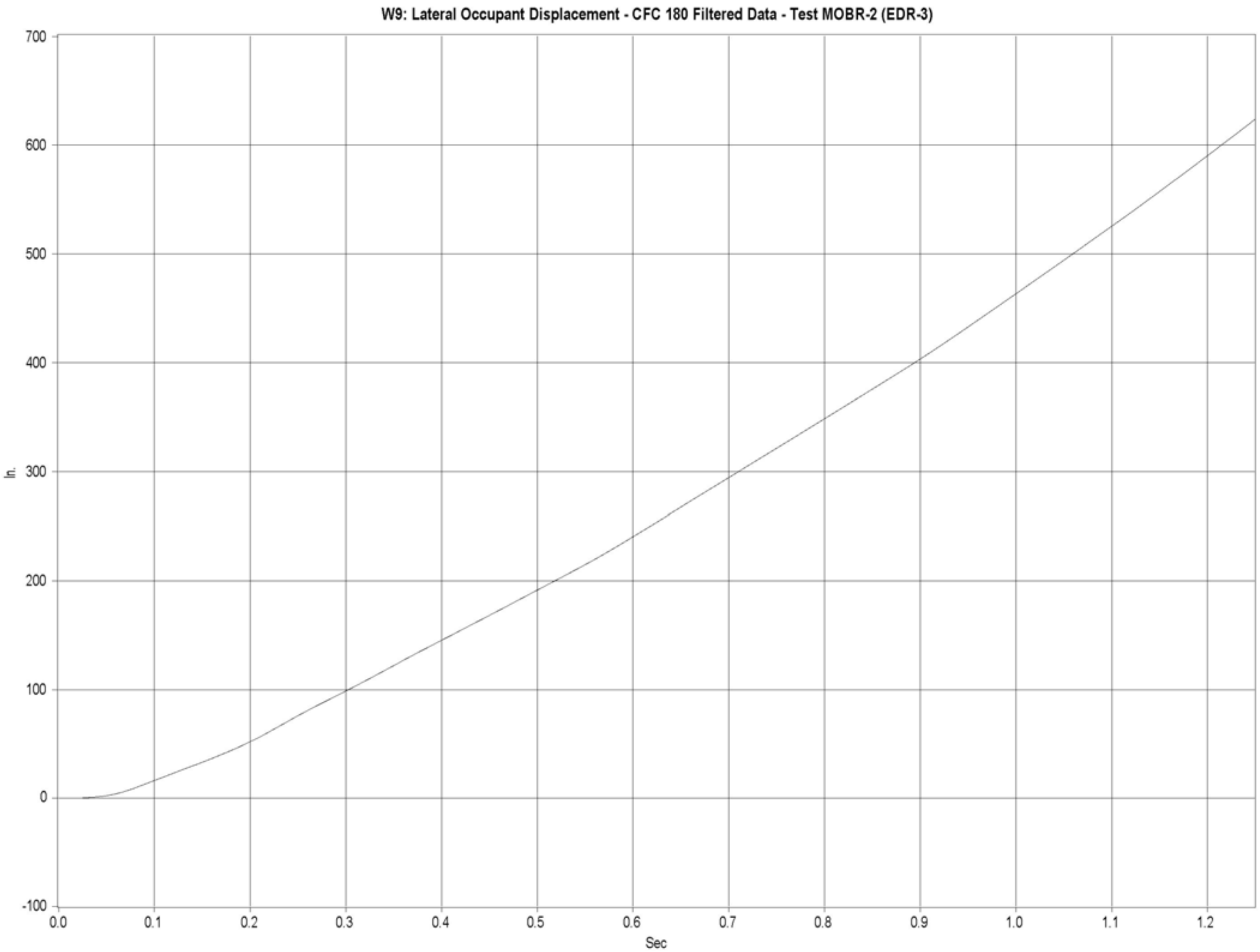


Figure E-6. Graph of Lateral Displacement, Test MOBR-2

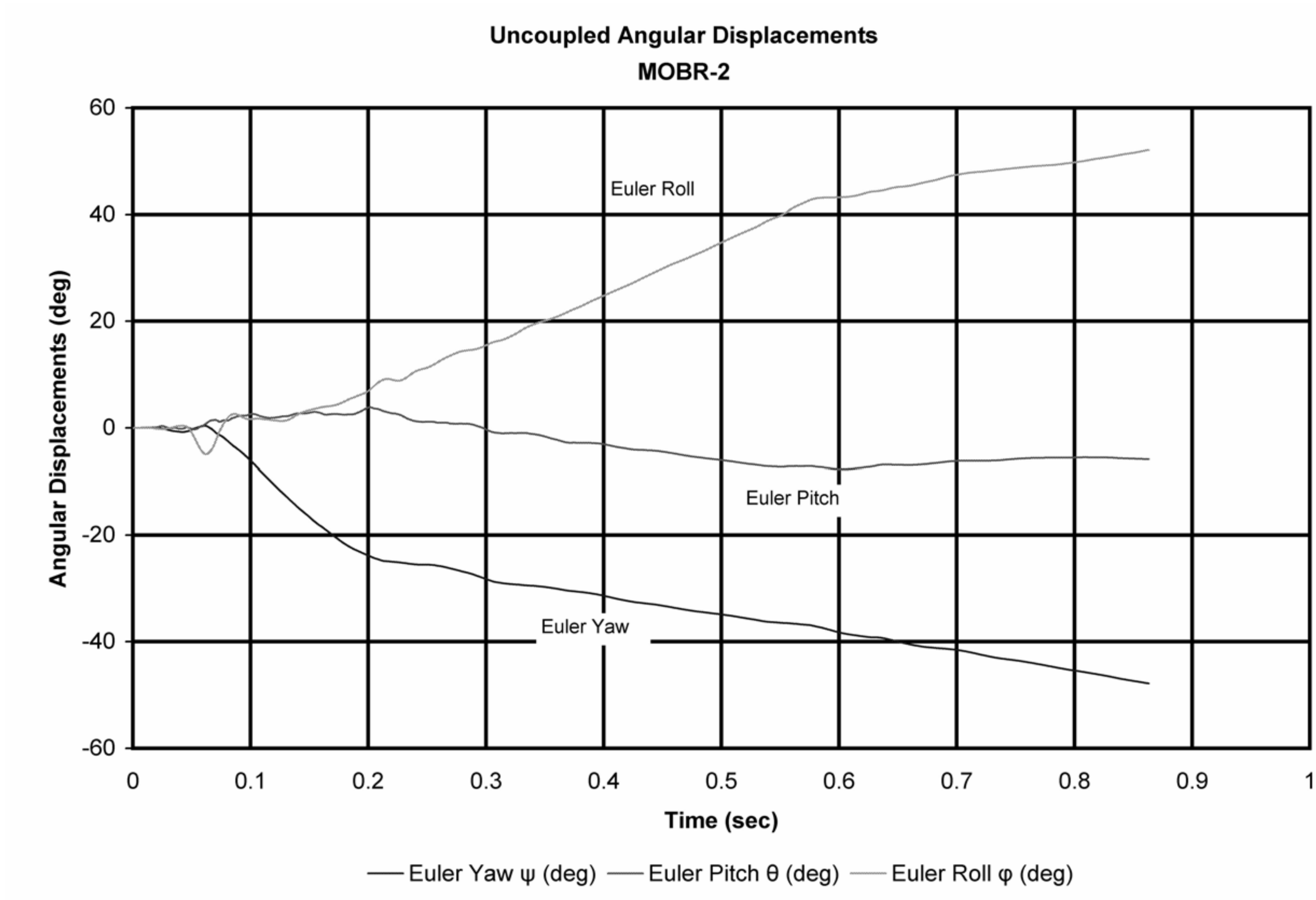


Figure E-7. Graph of Roll, Pitch, and Yaw Angular Displacements, Test MOBR-2