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MASH TL-3 EVALUATION OF THE UNREINFORCED, SINGLE-SLOPE CONCRETE MEDIAN BARRIER

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16. Abstract

The Ohio Department of Transportation (ODOT) requested an evaluation of an unreinforced, single-slope concrete median barrier capable of satisfying Test Level 3 (TL-3) safety requirements found in the *Manual for Assessing Safety Hardware, Second Edition* (MASH 2016). The barrier was designed with a height of 42 in. (1,067 mm), a base width of 28 in. (711 mm), and top width of 12 in. (305 mm). The tarmac surface was milled down 1 in. (25 mm) to accommodate the barrier and asphalt pad. The barrier was cast in place using concrete with a minimum compressive strength of 4,000 psi (27.6 MPa). Expansion joints were installed in 20-ft (6.1-m) intervals to simulate cracking and potential barrier discontinuities. An asphalt pad, installed on the milled surface using a tack coat, functioned as the barrier keyway and extended 96 in. (2,438 mm) from the traffic and back sides of the barrier.

Previous testing of similar single-slope concrete barriers indicated that only one full-scale crash test (MASH test designation no. 3-11) was needed to satisfy TL-3 criteria. During the test, the 5,001-lb (2,268-kg) pickup impacted the installation at a speed of 62.8 mph (101.0 km/h) and at an angle of 24.9 degrees for an impact severity of 116.3 kip-ft (157.7 kJ). The vehicle was safely contained and redirected, and the test satisfied safety performance evaluation criteria of test designation no. 3-11 found in MASH 2016.

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DISCLAIMER STATEMENT

This report was completed with funding from the Ohio Department of Transportation and the United States Department of Transportation. The contents of this report reflect the views and opinions of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Ohio Department of Transportation nor the United States Department of Transportation. This report does not constitute a standard, specification, regulation, product endorsement, or an endorsement of manufacturers.

UNCERTAINTY OF MEASUREMENT STATEMENT

The Midwest Roadside Safety Facility (MwRSF) has determined the uncertainty of measurements for several parameters involved in standard full-scale crash testing and non-standard testing of roadside safety features. Information regarding the uncertainty of measurements for critical parameters is available upon request by the sponsor and the Federal Highway Administration.

INDEPENDENT APPROVING AUTHORITY

The Independent Approving Authority (IAA) for the data contained herein was Dr. Jennifer Schmidt, Research Assistant Professor.

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1 INTRODUCTION

1.1 Background

The Ohio Department of Transportation (ODOT) employs an unreinforced, single-slope, concrete median barrier that is based on previously crash tested single-slope barrier geometries and the Ontario Tall Wall barrier [1]. However, this barrier design has not been evaluated to the updated crash safety standards found in the American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware*, *Second Edition* (MASH 2016) [2]. Additionally, the lack of reinforcement in the concrete median barrier may pose concerns with respect to the safety performance of the barrier system. Therefore, the ODOT unreinforced, single-slope, concrete barrier needed to be evaluated to the Test Level 3 (TL-3) criteria of MASH 2016.

The ODOT unreinforced, single-slope, concrete barrier consists of a 42-in. (1,067-mm) tall single-slope face geometry with a slope of 10.9 degrees from vertical. The top width of the barrier is 12 in. (305 mm) and the base width is 28 in. (711 mm). ODOT employs a variety of asphalt and concrete keyways, soil fill adjacent to the barrier, and dowel bar options for anchoring the base of the barrier. Reinforced and anchored end sections are used near barrier ends and/or expansion joints. ODOT also employs contraction joints at a minimum of every 20 ft (6.1 m) throughout the barrier.

ODOT's use of an unreinforced, single-slope, concrete barrier was based on the unreinforced Ontario Tall Wall [1]. The Ontario Tall Wall test installation consisted of a 328-ft (100-m) long, unreinforced, New Jersey shape, concrete median barrier embedded in 3 in. (76 mm) of Type "D" hot-mix, hot-laid asphaltic concrete, as shown in Figure 1. The total height of the barrier was 41.3 in. (1,050 mm) above the roadway surface. The base width of the barrier was 31.5 in. (800 mm) and the top width was 11.4 in. (290 mm). The barrier was slip-formed continuously without construction joints and was placed on a 29.5-in. (750-mm) thick granular base that extended from the front edge of the barrier to 3 ft (914 mm) beyond the back of the barrier. The layout of the as-tested Ontario Tall Wall is shown in Figure 1.

In the full-scale crash testing of the Ontario Tall Wall, an 80,000-lb (36,287-kg) tractor trailer impacted the barrier 87 ft (26.5 m) from the upstream end of the test installation at a speed of 49.6 mph (79.8 km/h) and an angle of 15.1 degrees. The tractor trailer was contained and redirected. However, the ballast used in the trailer of the test vehicle impacted and ruptured the side of the trailer as the tractor trailer rolled, resulting in some of the ballast exiting the trailer during impact. The Ontario Tall Wall barrier performed satisfactorily, meeting the guidelines set forth in NCHRP Report 230 [3] and the 1989 AASHTO *Guide Specifications for Bridge Railings* [4]. The results also demonstrated that the unreinforced, concrete Ontario Tall Wall barrier was structurally adequate to contain and redirect an 80,000-lb (36,287-kg) tractor trailer with the caveat that some of the ballast mass was lost during testing.

While the Ontario Tall Wall testing indicated that an unreinforced concrete barrier could redirect heavy vehicles, concerns about the performance of unreinforced concrete barriers remain. Unreinforced barriers may crack over time, even to the point where visual gaps may exist throughout the cross section. In this scenario, no rail continuity would exist and vehicle redirection would be dependent upon a combination of several factors, including the inertial resistance of the thick concrete barrier, the bond between the barrier and support surface and/or asphalt keyway, and the limited structural capacity of the concrete cross section (shear, tension, torsion, bending, etc.) away from the gap location.

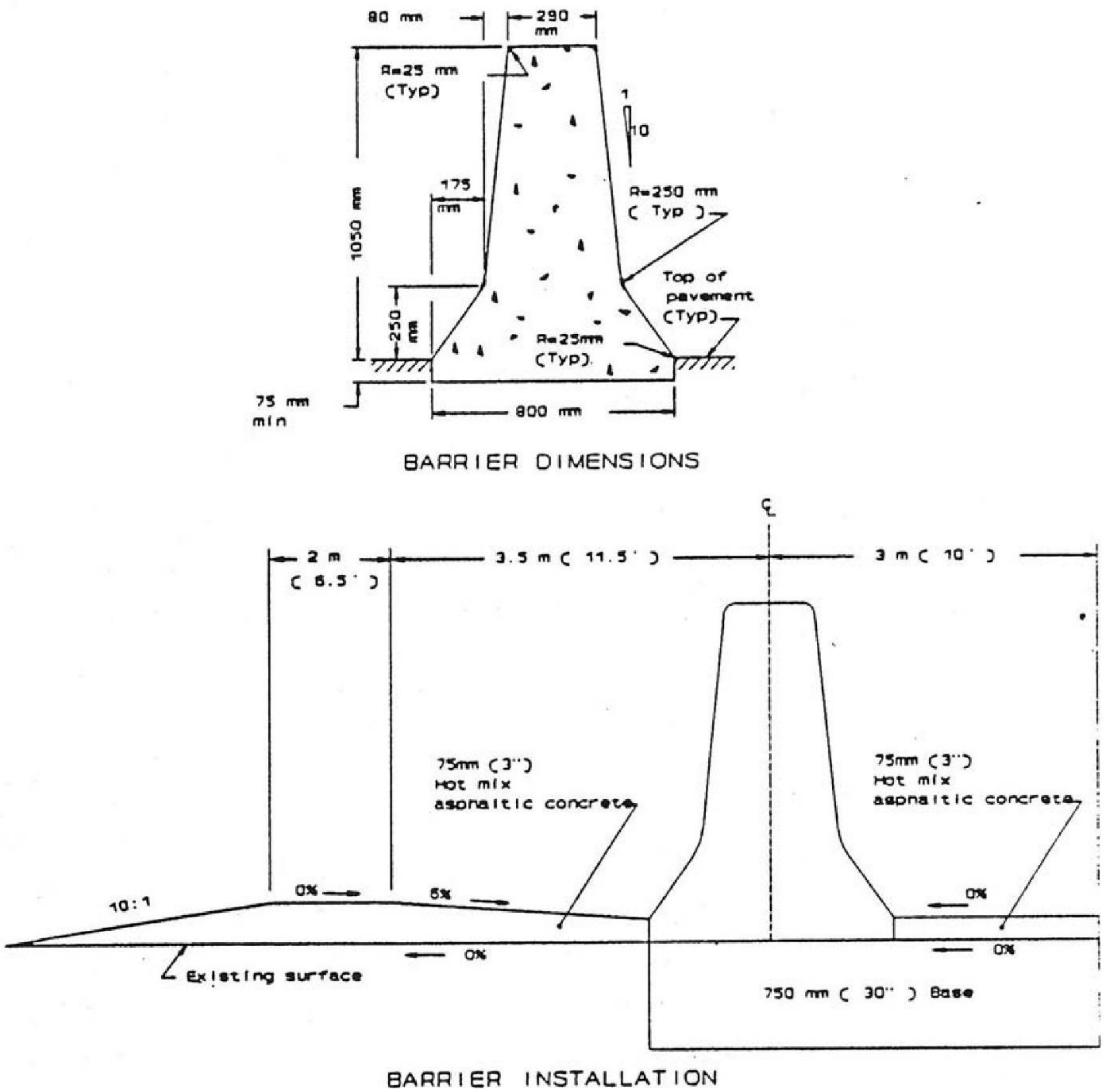


Figure 1. Ontario Tall Wall [1]

The geometry of the single-slope face concrete barrier was previously evaluated under MASH TL-3 using a shorter barrier, the TxDOT Type SSTR (Single-Slope Traffic Rail) bridge rail, as shown in Figure 2 [5]. The barrier had a 36-in. (914-mm) height and was impacted by a 2270P vehicle at 63.8 mph (102.7 km/h) and at an angle of 24.8 degrees. The vehicle was successfully contained and redirected, and performed acceptably to safety criteria established in MASH.

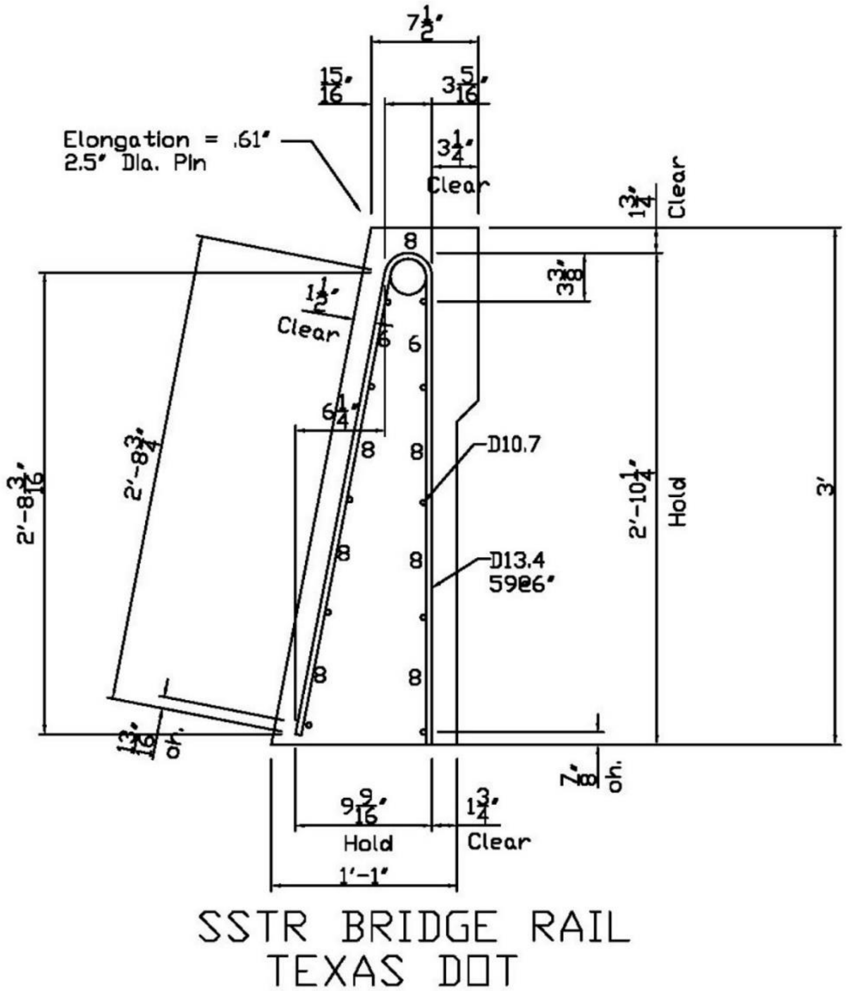


Figure 2. TxDOT Type SSTR Bridge Rail

1.2 Objective

The objective of this research effort was to evaluate ODOT's unreinforced, single-slope, concrete barrier according to the TL-3 criteria of MASH 2016.

1.3 Scope

The research objective was achieved through the completion of several tasks. One full-scale crash test was conducted on the unreinforced, single-slope, concrete median barrier according to MASH 2016 test designation no. 3-11. Next, the full-scale vehicle crash test results were analyzed, evaluated, and documented. Conclusions and recommendations were then made pertaining to the safety performance of the unreinforced, single-slope, concrete median barrier.

2 TEST REQUIREMENTS AND EVALUATION CRITERIA

2.1 Test Requirements

Longitudinal barriers such as the unreinforced, single-slope, concrete median barrier must satisfy impact safety standards in order to be declared eligible for federal reimbursement by the Federal Highway Administration (FHWA) for use on the National Highway System (NHS). For new hardware, these safety standards consist of the guidelines and procedures published in MASH 2016 [2]. Note that there is no difference between MASH 2009 [6] and MASH 2016 for longitudinal concrete barriers such as the system tested in this project, except that additional occupant compartment deformation measurements are required by MASH 2016.

According to TL-3 of MASH 2016, longitudinal barrier systems must be subjected to two full-scale vehicle crash tests, as summarized in Table 1. However, only test designation no. 3-11 was deemed critical for evaluation of the ODOT unreinforced, single-slope, concrete barrier. Test designation no. 3-10 with the 1100C vehicle is typically required to evaluate vehicle capture, vehicle stability, and occupant risk concerns for the small car. Previous testing was conducted according to MASH 2016 test designation no. 3-10 on the CALTRANS Type 60 single-slope concrete median barrier with a 36-in. (914-mm) height and 9.1-degree sloped face [7]. This test indicated that the capture, stability, and occupant risk values were acceptable for a TL-3 1100C vehicle impact on a single-slope concrete barrier with a sloped face only 1.7 degrees steeper than that of the ODOT unreinforced single-slope barrier. It was believed that the similar barrier geometry of the ODOT single-slope barrier would provide similar vehicle redirection and stability characteristics. Additionally, structural loading of the barrier in test designation no. 3-10 with the 1100C vehicle would be significantly less than that of test designation no. 3-11 with the 2270P vehicle. Thus, test designation no. 3-11 with the 2270P vehicle was considered the most critical test to evaluate vehicle capture, vehicle stability, vehicle snag, and maximal structural loading of the barrier. Thus, only test designation no. 3-11 was conducted and reported herein.

Table 1. MASH 2016 TL-3 Crash Test Conditions for Longitudinal Barriers

Test Article	Test Designation No.	Test Vehicle	Vehicle Weight, lb (kg)	Impact Conditions		Evaluation Criteria [1]
				Speed, mph (km/h)	Angle, deg.	
Longitudinal Barrier	3-10	1100C	2,420 (1,100)	62 (100)	25	A,D,F,H,I
	3-11	2270P	5,000 (2,270)	62 (100)	25	A,D,F,H,I

[1] Evaluation criteria explained in Table 2.

MASH and its predecessor, NCHRP Report No. 350 [8], have both operated under the philosophy to evaluate hardware under the “worst practical condition” and the “state of the possible.” Under the “worst practical condition” and the “state of the possible” philosophies, hardware evaluation should make an effort to evaluate barriers in their worst or most critical conditions and in realistic scenarios. Due to concerns for the loss of continuity in an unreinforced barrier resulting from temperature and shrinkage cracking, it was recommended that the ODOT unreinforced, single-slope, concrete barrier be tested with discontinuities in the barrier and that the barrier be impacted in critical locations near those discontinuities.

It should be noted that the test matrix detailed herein represents the researchers' best engineering judgement with respect to the MASH 2016 safety requirements and their internal evaluation of critical tests necessary to evaluate the crashworthiness of the barrier system. However, the recent switch to new vehicle types as part of the implementation of the MASH 2016 criteria and the lack of experience and knowledge regarding the performance of the new vehicle types with certain types of hardware could result in unanticipated barrier performance. Thus, any tests within the evaluation matrix deemed non-critical may eventually need to be evaluated based on additional knowledge gained over time or revisions to the MASH 2016 criteria.

2.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the unreinforced single-slope concrete barrier to contain and redirect impacting vehicles. In addition, controlled lateral deflection of the test article is acceptable. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Post-impact vehicle trajectory is a measure of the potential of the vehicle to result in a secondary collision with other vehicles and/or fixed objects, thereby increasing the risk of injury to the occupants of the impacting vehicle and/or other vehicles. These evaluation criteria are summarized in Table 2 and defined in greater detail in MASH 2016. The full-scale vehicle crash test documented herein was conducted and reported in accordance with the procedures provided in MASH 2016.

In addition to the standard occupant risk measures, the Post-Impact Head Deceleration (PHD), the Theoretical Head Impact Velocity (THIV), and the Acceleration Severity Index (ASI) were determined and reported. Additional discussion on PHD, THIV and ASI is provided in MASH 2016.

Table 2. MASH 2016 Evaluation Criteria for Longitudinal Barrier

<table>
<tr><td>Structural Adequacy</td><td>A.</td><td colspan="3">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.</td></tr>
<tr><td rowspan="10">Occupant Risk</td><td>D.</td><td colspan="3">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 5.2.2 and Appendix E of MASH 2016.</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td></tr>
<tr><td rowspan="4">H.</td><td colspan="3">Occupant Impact Velocity (OIV) (see Appendix A, Section A5.2.2 of MASH 2016 for calculation procedure) should satisfy the following limits:</td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30 ft/s
(9.1 m/s)</td><td>40 ft/s
(12.2 m/s)</td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.2.2 of MASH 2016 for calculation procedure) should satisfy the following limits:</td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15.0 g’s</td><td>20.49 g’s</td></tr>
</table>

3 DESIGN DETAILS

The ODOT unreinforced, single-slope, concrete barrier is used in various installation layouts, as shown in Figures 3 and 4. The Midwest Roadside Safety Facility (MwRSF) discussed the various barrier configurations with ODOT to select a critical barrier configuration for full-scale crash testing. The selected configuration was as follows.

1. The barrier consisted of the ODOT Type B, 42-in. (1,067-mm) tall, unreinforced, single-slope concrete barrier with a 12-in. (305-mm) wide top, a 28-in. (711-mm) wide base, and a 10.9-degree constant-slope face. A 119-ft 11¾-in. (36.6-m) long barrier section was constructed for the crash testing utilizing 4,000-psi (27.6-MPa) concrete, as specified in the ODOT standard plans.

2. In order to simulate cracking and potential barrier discontinuities in the unreinforced barrier, MwRSF placed ¼-in. (6-mm) wide separator plates, which spanned the entire barrier cross section, at 20-ft (6.1-m) intervals along the barrier when the system was constructed. This spacing matched the minimum spacing of the contraction joints in the ODOT standard plans. After forming, the separator plates were removed such that a simulated vertical crack through the barrier was created. MwRSF selected a critical impact point (CIP) upstream from one of these cracks to maximize the potential for barrier loading adjacent to the discontinuity and evaluate potential for vehicle snag at the discontinuity.

3. The as-tested barrier test installation did not include the ODOT end section details as the barrier was to be evaluated along the length of need and the discontinuities built into the barrier section noted above prevented loading of the ends of the barrier.

4. Various ODOT barrier anchorage methods were reviewed with the sponsor, and a critical installation design was selected for the full-scale crash testing. This installation used an asphalt keyway consisting of a continuous layer of 1-in. (25-mm) thick by 8-ft (2.4-m) wide asphalt on the front and back of the barrier. The barrier was installed on the concrete tarmac at the MwRSF Outdoor Test Site.

5. The asphalt used for the barrier keyway is specified in the ODOT standard as a Superpave, surface course, asphaltic concrete with a tack coat. Due to the difficulty in obtaining the exact asphalt mixes used by ODOT at MwRSF's test facility, ODOT agreed to use a similar Superpave mix available in Nebraska. A tack coat similar to that used by ODOT was installed beneath the asphalt.

The test installation consisted of an unreinforced, single-slope, concrete median barrier, as shown in Figures 5 through 8. Photographs of the test installation are shown in Figures 9 through 11. Material specifications, mill certifications, and certificates of conformity for the system materials are shown in Appendix A. The system design was based on the ODOT standard details for their barrier, as discussed previously. The tarmac surface around the system was milled down 1 in. (25 mm) to accommodate an asphalt pad on the front and back sides of the barrier. Following milling and prior to barrier casting, a thin coating of concrete grout was applied over the middle 40 ft (12.2 m) of concrete beneath the barrier to provide a smooth surface and prevent excessive bonding of the barrier to the milled surface. The barrier installation was 119 ft – 11¾ in. (36.6 m) long and 43 in. (1,092 mm) tall, and consisted of a 10.9-degree slope, which resulted in a base thickness of 28⅜ in. (721 mm) and top width of 12 in. (305 mm). A 1-in. (25-mm) deep asphalt keyway was installed on each side of the barrier that made the effective top height and base width of the of the barrier system 42 in. (1,067 mm) and 28 in. (711 mm), respectively. The top corners had a ¾-in. (19-mm) chamfer. A ¼-in. (6-mm) gap was placed every 20 ft (6.1 m) along the barrier installation to simulate cracking at expansion joint locations, which created six barrier segments, denoted barrier no. 1 through barrier no. 6.

Construction photographs of the system are shown in Figure 9. Each barrier was cast using wooden forms and a ¼-in. (6-mm) thick steel plate was used to maintain even gap spacing between barrier segments. Concrete cylinders from each segment were tested, as shown in Appendix A, and only barrier segment no. 4 failed to meet the required strength of 4,000 psi (27.6 MPa) prior to the date of the test. However, barrier segment no. 4 was downstream from the main impact region and was not considered critical to vehicle impact. Thus, the test was conducted with barrier segment no. 4 having a 45-day compressive strength of 3,680 psi (25.4 MPa).

Several imperfections in the barriers naturally occurred when removing the formwork. Thermal hairline cracks extended vertically through barriers nos. 1, 2, and 5, as shown in Figure 11. Several gouges resulting from removal of the forms can also be seen on the barrier segments. The gouges vary in size and are generally present along the vertical center of each of the barriers. Additionally, small and limited spalling on the edges of some of the gaps between barriers occurred when removing the steel plate due to the large amount of force needed to remove the plate.

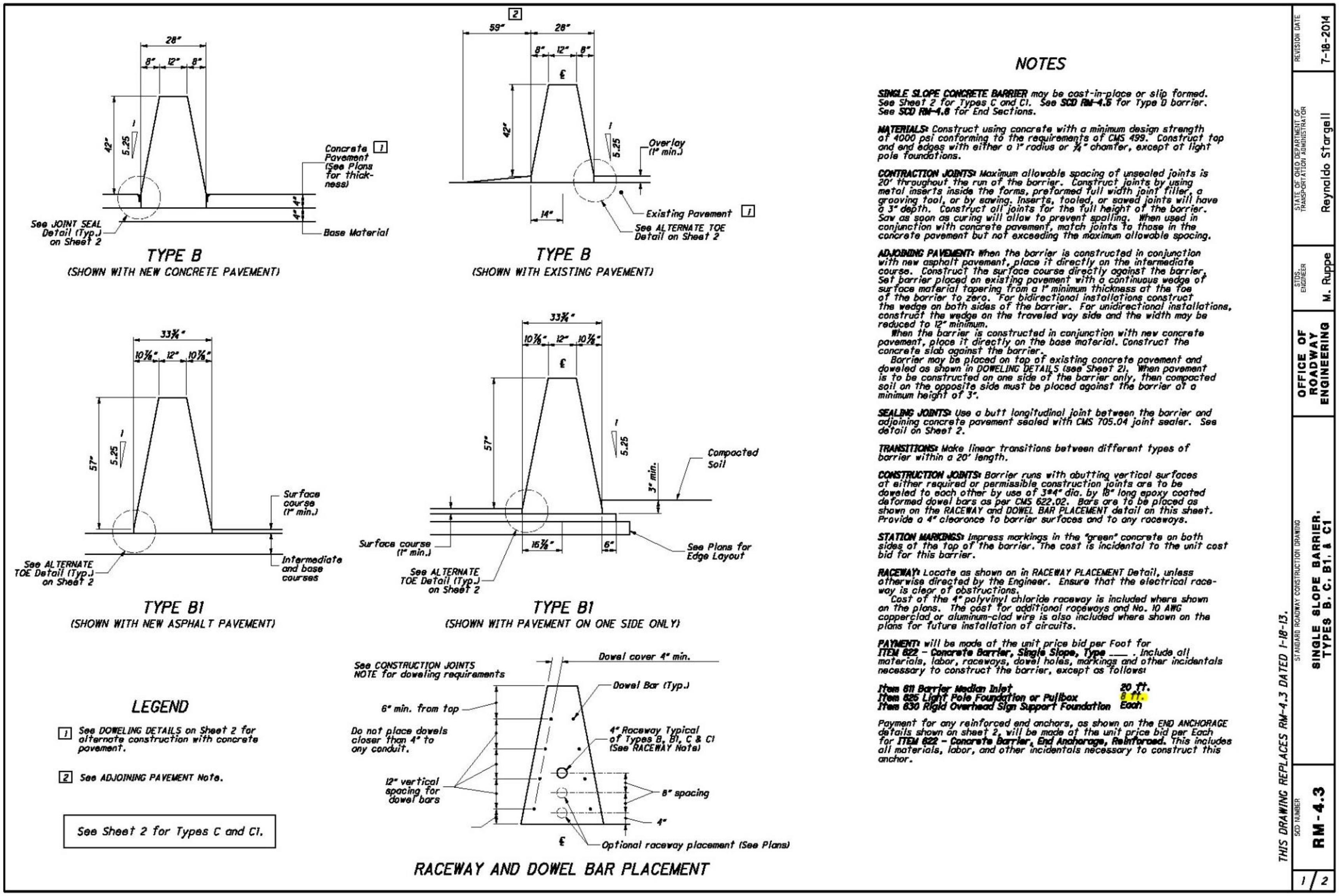


Figure 3. ODOT Single-Slope Median Barrier Details

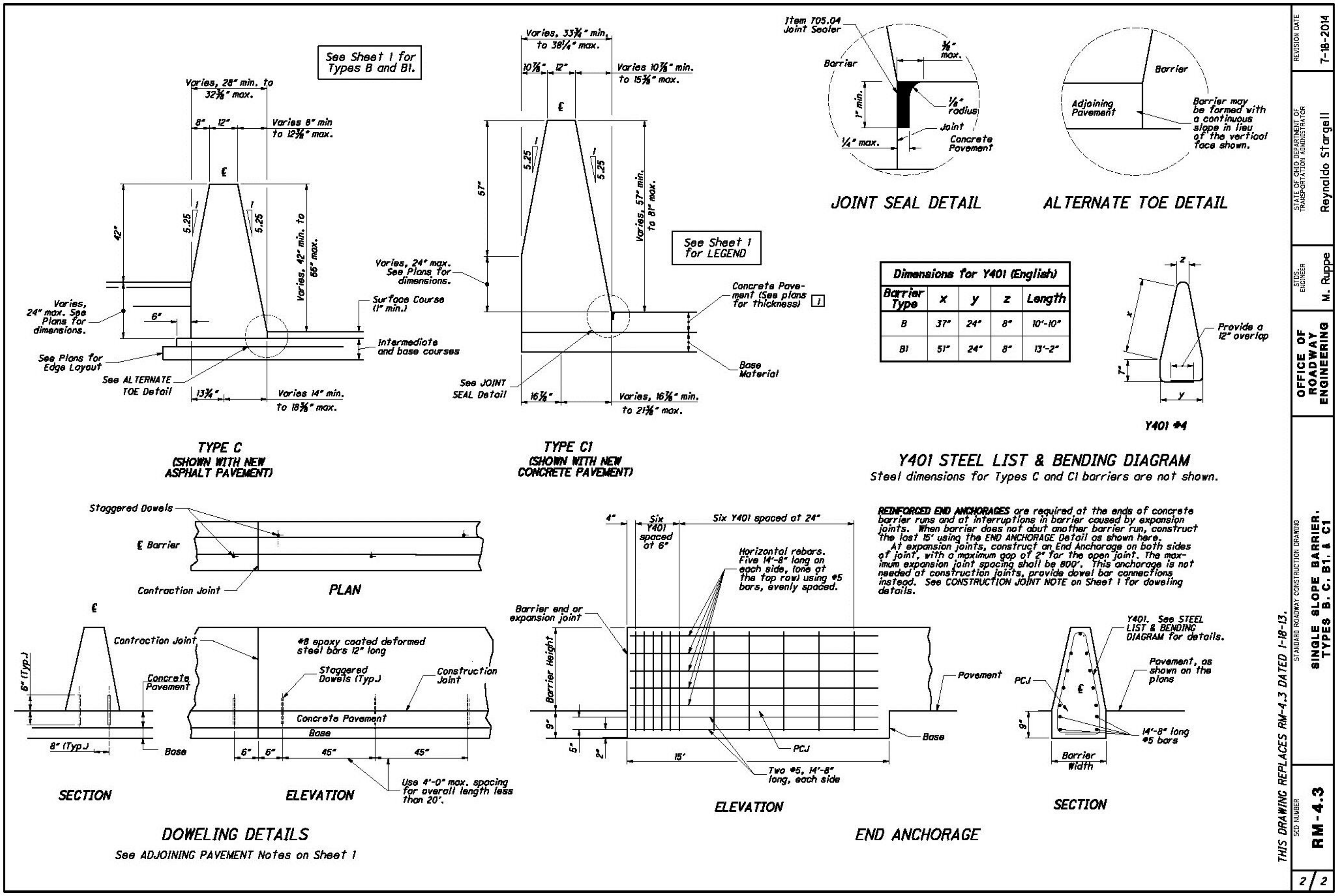


Figure 4. ODOT Single-Slope Median Barrier Details

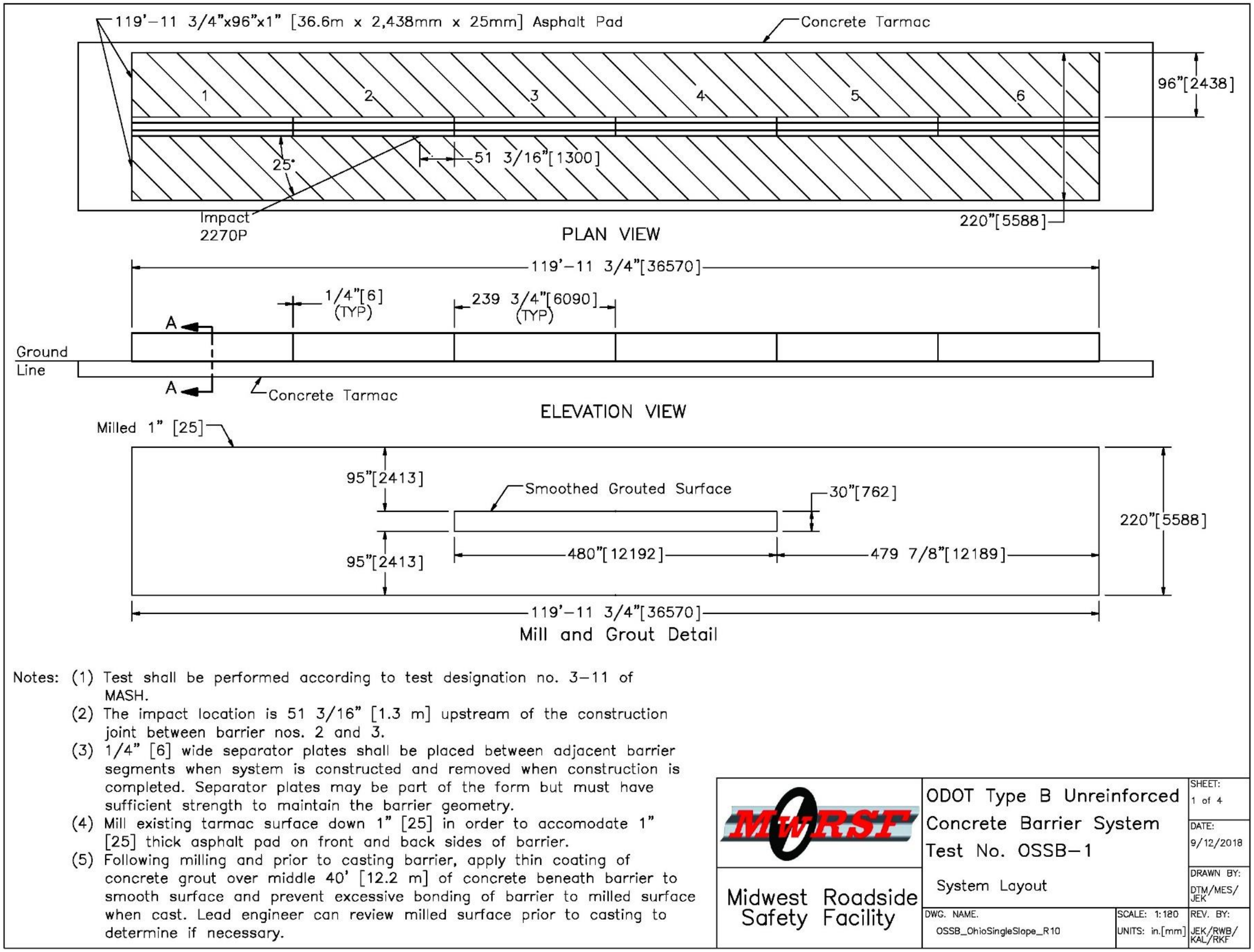


Figure 5. Test Installation Layout, Test No. OSSB-1

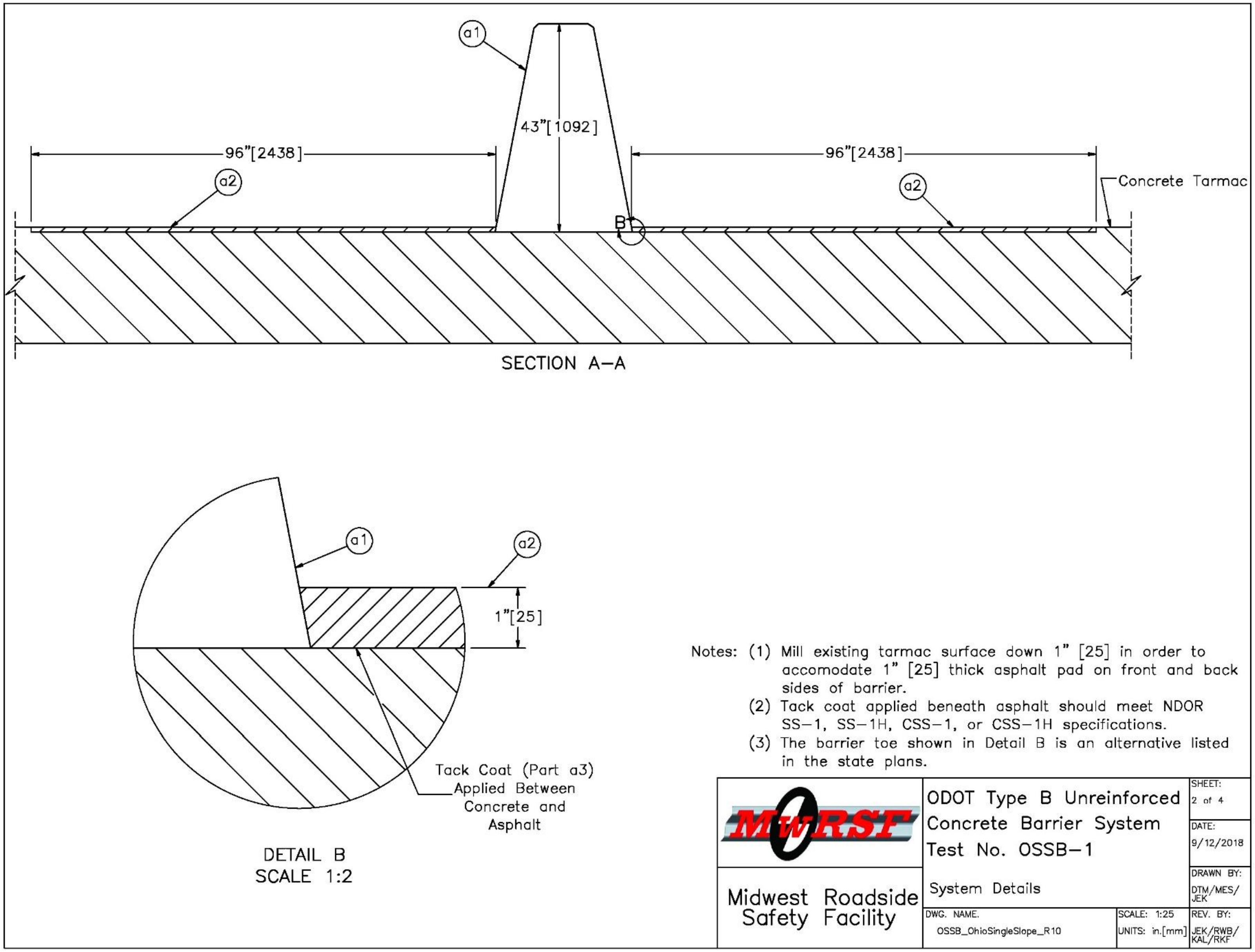


Figure 6. System Details, Test No. OSSB-1

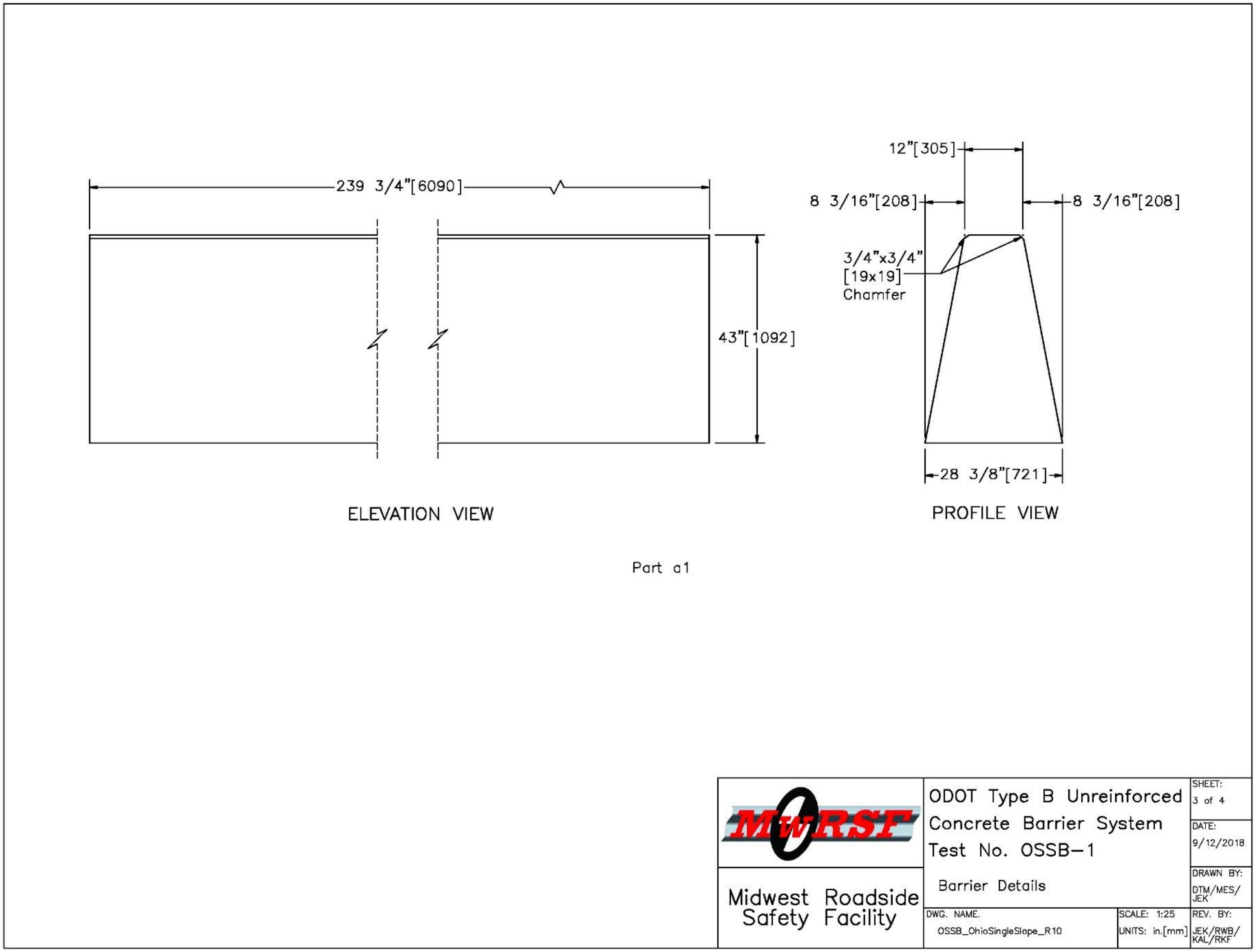


Figure 7. Barrier Details, Test No. OSSB-1

Item No.	Quantity	Description	Material Specification
a1	1	42" [1,067] Tall, 1,439 3/4" [35.6 m] Long, Unreinforced Single Slope Concrete Barrier	Min. f'c = 4,000 psi [27.6 MPa] NE 47BD Mix
a2	–	Asphalt	NDOR Superpave SPH Mix Binder PG 64–34
a3	–	Tack Coat	NDOR SS–1, SS–1H, CSS–1, or CSS–1H

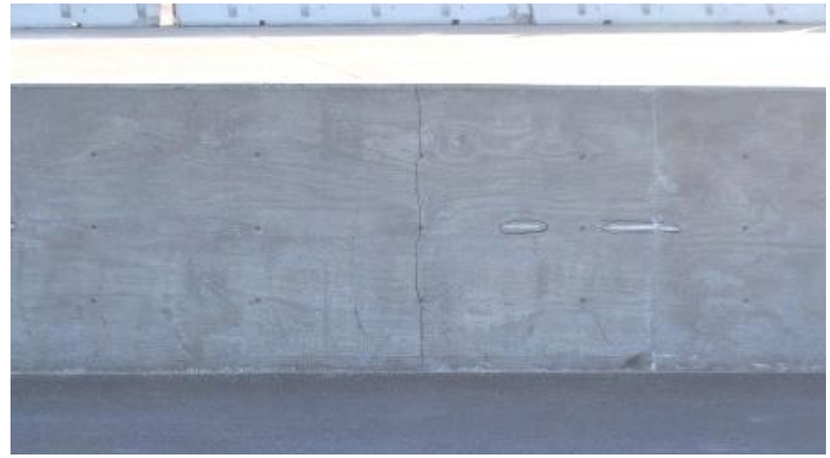
Midwest Roadside Safety Facility	ODOT Type B Unreinforced Concrete Barrier System Test No. OSSB–1		SHEET: 4 of 4
			DATE: 9/12/2018
	Bill of Materials		DRAWN BY: DTM/MES/JEK
	DWG. NAME. OSSB_OhioSingleSlope_R10	SCALE: None UNITS: in.[mm]	REV. BY: JEK/RWB/KAL/RKF

Figure 8. Bill of Materials, Test No. OSSB-1

Figure 9. Test Article Construction Photographs, Test No. OSSB-1

Figure 10. Test Installation Photographs, Test No. OSSB-1

Barrier No. 1 Thermal Hairline Crack



Barrier No. 5 Thermal Hairline Crack

Barrier No. 2 Thermal Hairline Crack

Spalling of Barrier Gap

Figure 11. Barrier Imperfections, Test No. OSSB-1

4 TEST CONDITIONS

4.1 Test Facility

The Outdoor Test Site is located at the Lincoln Air Park on the northwest side of the Lincoln Municipal Airport and is approximately 5 miles (8.0 km) northwest of the University of Nebraska-Lincoln.

4.2 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 on the tow vehicle increased the accuracy of the test vehicle impact speed.

A vehicle guidance system developed by Hinch [9] was used to steer the test vehicle. A guide flag, attached to the right-front wheel and the guide cable, was sheared off before impact with the barrier system. The ⅜-in. (9.5-mm) diameter guide cable was tensioned to approximately 3,500 lb (15.6 kN) and supported both laterally and vertically every 100 ft (30.5 m) 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.

4.3 Test Vehicles

For test no. OSSB-1, a 2011 Dodge Ram 1500 crew cab pickup truck was used as the test vehicle. The curb, test inertial, and gross static vehicle weights were 5,122 lb (2,323 kg), 5,001 lb (2,268 kg), and 5,163 lb (2,342 kg), respectively. The test vehicle is shown in Figures 12 and 13, and vehicle dimensions are shown in Figure 14.

The longitudinal component of the center of gravity (c.g.) was determined using the measured axle weights. The Suspension Method [10] was used to determine the vertical component of the 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 final c.g. location for the test inertial condition. The location of the final c.g. is shown in Figures 14 and 15. Data used to calculate the location of the c.g. and ballast information are shown in Appendix B.

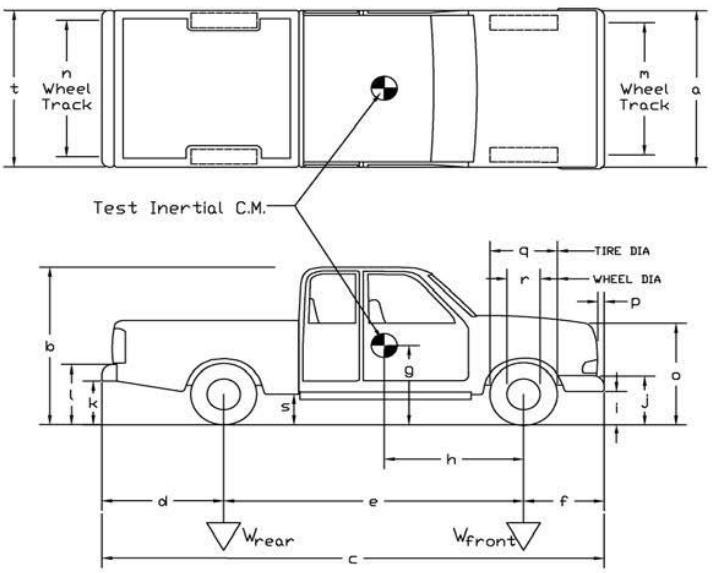
Square, black- and white-checkered targets were placed on the vehicle for reference to be viewed from the high-speed digital video cameras and aid in the video analysis, as shown in Figure 15. Round, checkered targets were placed on the c.g. on the left-side door, the right-side door, and the roof of the vehicle.

The front wheels of the test vehicle were aligned to vehicle standards except the toe-in value was adjusted to zero such that the vehicles would track properly along the guide cable. A 5B flash bulb was mounted under the vehicle's left-side windshield wiper and was fired by a pressure tape switch mounted at the impact corner of the bumper. The flash bulb was fired upon initial impact with the test article to create a visual indicator of the precise time of impact on the high-speed digital videos. A remote-controlled brake system was installed in the test vehicle so the vehicle could be brought safely to a stop after the test.

Figure 12. Test Vehicle, Test No. OSSB-1

Figure 13. Test Vehicle’s Interior Floorboards and Undercarriage, Test No. OSSB-1

Date:	12/13/2017	Test Name:	OSSB-1	VIN No:	1D7RB1CP0BS685744
Year:	2011	Make:	Dodge Ram 1500	Model:	1500 Crew Cab
Tire Size:	265/70 R17	Tire Inflation Pressure:	40 Psi	Odometer:	127742



Vehicle Geometry - in. (mm)
Target Ranges listed below

a: 73 (1854) 78±2 (1950±50)	b: 74 3/8 (1889)		
c: 229 3/4 (5836) 237±13 (6020±325)	d: 47 1/2 (1207)		
e: 140 1/4 (3562) 148±12 (3760±300)	f: 42 (1067) 39±3 (1000±75)		
g: 28 5/16 (719) min: 28 (710)	h: 61 1/4 (1556) 63±4 (1575±100)		
i: 12 5/8 (321)	j: 25 (635)		
k: 21 (533)	l: 29 3/4 (756)		
m: 67 1/8 (1705) 67±1.5 (1700±38)	n: 67 5/8 (1718) 67±1.5 (1700±38)		
o: 44 (1118) 43±4 (1100±75)	p: 4 1/2 (114)		
q: 31 1/2 (800)	r: 18 1/4 (464)		
s: 15 1/4 (387)	t: 76 1/2 (1943)		

Wheel Center Height (Front):	15	(381)
Wheel Center Height (Rear):	15 3/8	(391)
Wheel Well Clearance (Front):	34 3/4	(883)
Wheel Well Clearance (Rear):	38	(965)
Bottom Frame Height (Front):	17 3/4	(451)
Bottom Frame Height (Rear):	25 3/4	(654)
Engine Type:	8cyl. Gas	
Engine Size:	4.7L	
Transmission Type:	Auto	
Drive Type:	RWD	
Cab Style:	Crew Cab	
Bed Length:	67"	

Mass Distribution lb (kg)

Gross Static	LF	1503 (682)	RF	1412 (640)
	LR	1091 (495)	RR	1157 (525)

Weights lb (kg)	Curb	Test Inertial	Gross Static
W-front	2885 (1309)	2818 (1278)	2915 (1322)
W-rear	2237 (1015)	2183 (990)	2248 (1020)
W-total	5122 (2323)	5001 (2268) 5000±110 (2270±50)	5163 (2342) 5165±110 (2343±50)

GVWR Ratings lb

Front	3700
Rear	3900
Total	6800

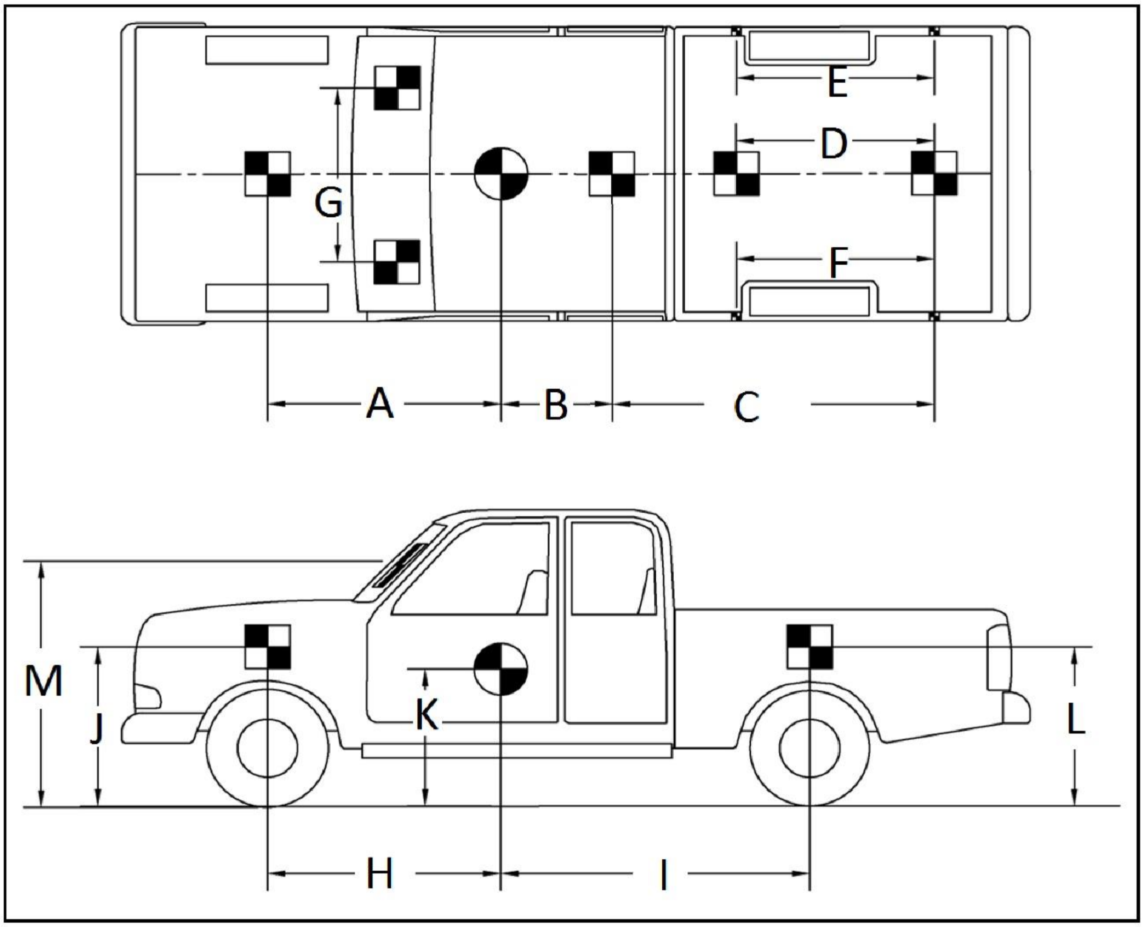
Dummy Data

Type:	Hybrid II
Mass:	162 lb
Seat Position:	Left/Driver

Note any damage prior to test: Small dent right of center of bumper. Right side scrape/dent along lower center of rear door in to the box side.

Figure 14. Vehicle Dimensions, Test No. OSSB-1

Date:	12/13/2017	Test Name:	OSSB-1	VIN:	1D7RB1CP0BS685744
Year:	2011	Make:	Dodge Ram 1500	Model:	1500 Crew Cab



TARGET GEOMETRY-- in. (mm)

A:	72 1/4	(1835)	E:	54 3/8	(1381)	J:	38 7/8	(987)
B:	36 3/4	(933)	F:	54 1/2	(1384)	K:	28 1/4	(718)
C:	63 5/8	(1616)	G:	29 1/2	(749)	L:	32 1/4	(819)
D:	31 3/4	(806)	H:	61 1/4	(1556)	M:	65 1/8	(1654)
			I:	79	(2007)			

Figure 15. Target Geometry, Test No. OSSB-1

4.4 Simulated Occupant

For test no. OSSB-1, A Hybrid II 50th-Percentile, Adult Male Dummy, equipped with clothing and footwear was placed in the left-front seat of the test vehicle with the seat belt fastened. The dummy, which had a final weight of 162 lb (73 kg), was represented by model no. 572, and was manufactured by Android Systems of Carson, California. As recommended by MASH 2016, the dummy was not included in calculating the c.g. location.

4.5 Data Acquisition Systems

4.5.1 Accelerometers

Two environmental shock and vibration sensor/recorder systems were used to measure the accelerations in the longitudinal, lateral, and vertical directions. Both accelerometer systems were mounted near the c.g. of the test vehicle. The electronic accelerometer data obtained in dynamic testing was filtered using the SAE Class 60 and the SAE Class 180 Butterworth filter conforming to the SAE J211/1 specifications [11].

The two accelerometer systems, the SLICE-1 and SLICE-2 units, were modular data acquisition systems manufactured by Diversified Technical Systems, Inc. (DTS) of Seal Beach, California. The SLICE-2 unit was designated as the primary system as it was closest to the vehicle c.g. The acceleration sensors were mounted inside the bodies of custom-built, SLICE 6DX event data recorders and recorded data at 10,000 Hz to the onboard microprocessor. Each SLICE 6DX was configured with 7 GB of non-volatile flash memory, a range of ±500 g's, a sample rate of 10,000 Hz, and a 1,650 Hz (CFC 1000) anti-aliasing filter. The "SLICEWare" computer software programs and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

4.5.2 Rate Transducers

Two identical angle rate sensor systems mounted inside the bodies of the SLICE-1 and SLICE-2 event data recorders were used to measure the rates of rotation of the test vehicle. Each SLICE MICRO Triax ARS had a range of 1,500 degrees/sec in each of the three directions (roll, pitch, and yaw) and recorded data at 10,000 Hz to the onboard microprocessors. The raw data measurements were then downloaded, converted to the proper Euler angles for analysis, and plotted. The "SLICEWare" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the angular rate sensor data.

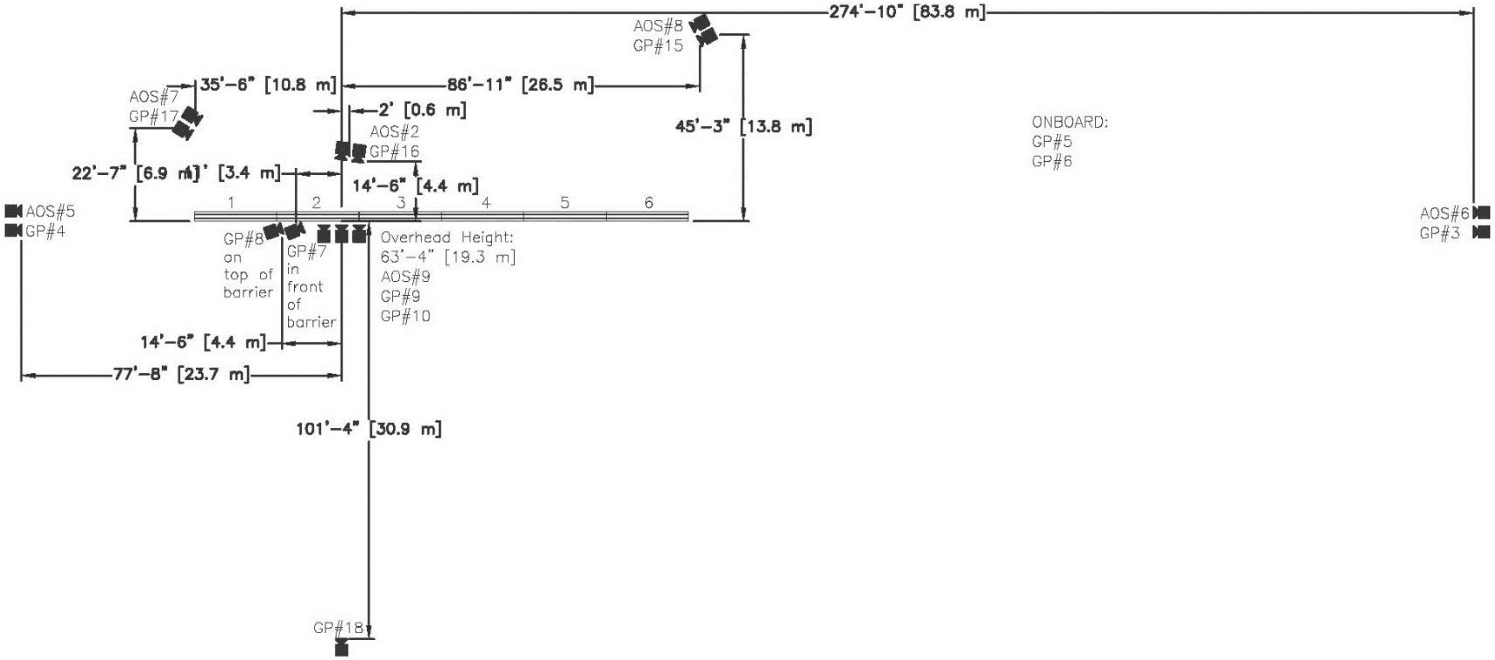
4.5.3 Retroreflective Optic Speed Trap

The retroreflective optic speed trap was used to determine the speed of the test vehicle before impact. Five retroreflective targets, spaced at approximately 18-in. (457-mm) intervals, were applied to the side of the vehicle. When the emitted beam of light was reflected by the targets and returned to the Emitter/Receiver, a signal was sent to the data acquisition computer, recording at 10,000 Hz, as well as the external LED box activating the LED flashes. The speed was then calculated using the spacing between the retroreflective targets and the time between the signals. LED lights and high-speed digital video analysis are only used as a backup in the event that vehicle speeds cannot be determined from the electronic data.

4.5.4 Digital Photography

Six AOS high-speed digital video cameras and twelve GoPro digital video cameras were utilized to film test no. OSSB-1. Camera details, camera operating speeds, lens information, and a schematic of the camera locations relative to the system are shown in Figure 16.

The high-speed videos were analyzed using TEMA Motion and RedLake MotionScope software programs. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed videos. A Nikon digital still camera was also used to document pre- and post-test conditions for the test.



No.	Type	Operating Speed (frames/sec)	Lens	Lens Setting
AOS-2	AOS Vitcam	500	Kowa 16mm	-
AOS-5	AOS X-PRI	500	Telesar 135 mm Fixed	-
AOS-6	AOS X-PRI	500	Sigma 28-70 #2	35
AOS-7	AOS X-PRI	500	Fujinon 35mm	-
AOS-8	AOS S-VIT 1531	500	Sigma 28-70 #1	35
AOS-9	AOS TRI-VIT 2236	1000	Kowa 12mm Fixed	-
GP-3	GoPro Hero 3+ w/ Cosmicar 12.5mm	120		
GP-4	GoPro Hero 3+ w/ Computar 12.5mm	120		
GP-5	GoPro Hero 3+	120		
GP-6	GoPro Hero 3+	120		
GP-7	GoPro Hero 4	240		
GP-8	GoPro Hero 4	240		
GP-9	GoPro Hero 4	120		
GP-10	GoPro Hero 4	240		
GP-15	GoPro Hero 4	240		
GP-16	GoPro Hero 4	240		
GP-17	GoPro Hero 4	240		
GP-18	GoPro Hero 4	120		

Figure 16. Camera Locations, Speeds, and Lens Settings, Test No. OSSB-1

5 FULL-SCALE CRASH TEST NO. OSSB-1

5.1 Weather Conditions

Test no. OSSB-1 was conducted on December 17, 2017 at approximately 1:45 p.m. The weather conditions as per the National Oceanic and Atmospheric Administration (station 14939/LNK) were reported and are shown in Table 3.

Table 3. Weather Conditions, Test No. OSSB-1

Temperature	42° F
Humidity	62%
Wind Speed	8 mph
Wind Direction	10° from True North
Sky Conditions	Scattered Cloud Coverage
Visibility	8.0 Statute Miles
Pavement Surface	Dry
Previous 3-Day Precipitation	0.1 in.
Previous 7-Day Precipitation	0.1 in.

5.2 Test Description

The 5,001-lb (2,268-kg) crew cab pickup truck impacted the unreinforced, single-slope barrier system at a speed of 62.8 mph (101.0 km/h) and at an angle of 24.9 degrees. A summary of the test results and sequential photographs are shown in Figure 18. Additional sequential photographs are shown in Figure 19 through Figure 20. Documentary photographs of the crash test are shown in Figures 21 and 22.

Initial vehicle impact was to occur $51^{3}/_{16}$ in. (1,300 mm) upstream from the construction joint between barrier nos. 2 and 3, as shown in Figure 23, which was selected using Table 2.7 of MASH 2016 to maximize structural loading adjacent to the simulated joint and the probability of vehicle snag. The actual point of impact was 52.0 in. (1,322 mm) upstream from the construction joint between barrier nos. 2 and 3. A sequential description of the impact events is contained in Table 4. The vehicle came to rest 232 ft – 6 in. (70.9 m) downstream from the impact location and 14 ft – 5 in. (4.4 m) laterally away from the traffic side of the barrier system after the brakes were applied. The vehicle remained stable and upright throughout vehicle redirection, and the vehicle trajectory and final position are shown in Figures 18 and 24.

Table 4. Sequential Description of Impact Events, Test No. OSSB-1

TIME (sec)	EVENT
0.000	Vehicle’s left-front bumper impacted barrier no. 2 at a location 52 in. (1,322 mm) upstream from construction joint of barrier nos. 2 and 3.
0.004	Vehicle’s left-front tire contacted barrier no. 2.
0.006	Vehicle’s left fender and grille contacted barrier no. 2.

0.010	Vehicle’s left fender deformed. Vehicle’s left headlight contacted barrier no. 2.
0.022	Vehicle’s left-front tire rode up barrier no. 2.
0.040	Vehicle’s left-front bumper and grille contacted barrier no. 3. Vehicle pitched upward.
0.044	Vehicle’s left and right airbags deployed.
0.050	Vehicle’s left-front door contacted barrier no. 2.
0.062	Barrier no. 2 rolled away from traffic-side of system.
0.066	Vehicle’s grille disengaged and windshield cracked.
0.096	Vehicle’s right-front tire became airborne.
0.098	Vehicle’s left-front door contacted barrier no. 3.
0.134	Barrier no. 2 rolled toward traffic-side of system.
0.154	Vehicle’s left-front tire became airborne.
0.168	Vehicle’s left-rear quarter panel contacted barrier no. 2.
0.184	Vehicle’s right headlight disengaged.
0.188	Vehicle was parallel to system at a speed of 47.8 mph (76.9 km/h).
0.199	Vehicle’s rear bumper contacted barrier no. 2.
0.208	Vehicle rolled toward system.
0.210	Vehicle’s left headlight disengaged.
0.212	Barrier no. 2 rolled away from traffic-side of system.
0.221	Vehicle’s tailgate deformed.
0.228	Vehicle’s right-rear tire became airborne.
0.248	Vehicle pitched downward.
0.254	Vehicle’s rear bumper contacted barrier no. 3.
0.272	Barrier no. 2 rolled toward traffic-side of system.
0.367	Vehicle exited system at a speed of 46.6 mph (75.0 km/h) with a c.g. exit angle of −3.0 degrees and a vehicle orientation exit angle of 3.8 degrees.
0.562	Vehicle’s left-front tire regained contact with ground.
0.680	Vehicle rolled away from system.
0.720	Vehicle’s right-rear tire regained contact with ground.
0.724	Vehicle pitched upward.
0.740	Vehicle’s right-front tire regained contact with ground.
0.942	Vehicle rolled toward system.
1.000	Vehicle was stable and traveling downstream on all four wheels.

5.3 Barrier Damage

Damage to the test installation was minimal, as shown in Figures 25 through 28. Barrier damage consisted of contact marks, gouging and spalling of the concrete, and minor concrete cracking. The length of vehicle contact along the barrier was approximately 11 ft – 6⅜ in. (3.5 m), which spanned from 5 ft – 5⅞ in. (1.7 m) upstream from the center of the joint between barrier nos. 2 and 3 to 6 ft – ½ in. (1.8 m) downstream from the center of the joint between barrier nos. 2 and 3.

A 59-in. (1,499-mm) long gouge was found on the downstream end of barrier no. 2. The downstream edge of barrier no. 2 and upstream edge of barrier no. 3 were spalled on the traffic side. Minor spider web cracks stemmed from the thermal crack that resulted during construction near the center of barrier no. 2. One such crack occurred on the top of barrier no. 2 for a length of 4 in. (102 mm). Additionally, a 3½-in. (89-mm) long crack was located on the front face of barrier no. 2, 3 in. (76 mm) below the top plane of the barrier.

The maximum lateral permanent set deflection of the system was negligible as no displacement of the base of the barrier was observed in the asphalt. The maximum lateral dynamic barrier deflection, including tipping of the barrier along the top surface, was 1.0 in. (25 mm) near the downstream end of barrier no. 2, as determined from high-speed digital video analysis. The working width of the system was found to be 28.0 in. (711 mm), also determined from the high-speed digital video analysis. A schematic demonstrating permanent set deflection, dynamic deflection, and working width is shown in Figure 17.

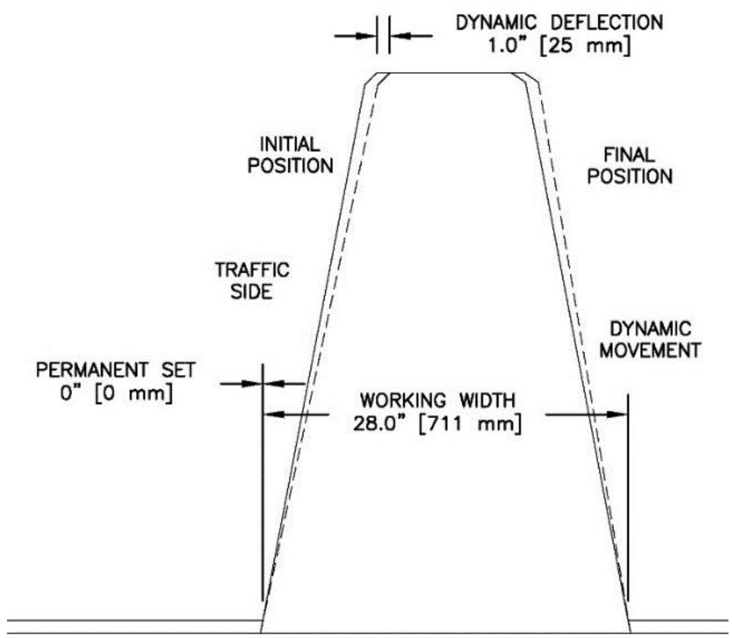


Figure 17. Permanent Set Deflection, Dynamic Deflection, and Working Width, Test No. OSSB-1

5.4 Vehicle Damage

The damage to the vehicle was moderate, as shown in Figures 29 through 34. The maximum occupant compartment deformations are listed in Table 5 along with the deformation limits established in MASH 2016 for various areas of the occupant compartment. None of the established MASH 2016 deformation limits were violated. Complete occupant compartment and vehicle deformations and the corresponding locations are provided in Appendix C. Note that floor pan deformation and occupant compartment deformation data for reference set 2 have been omitted from Appendix C due to errors in data acquisition.

The majority of the vehicle damage was concentrated on the left-front corner and left side of the vehicle where the impact had occurred. Two buckles occurred on the left-front frame, one in front of the wheel and the other just behind the wheel. The left frame horn buckled near the suspension and the left-front bumper mount plate was bent. The front cab mounts were slightly bent in a counter-clockwise direction. The left side of the bumper cover was bent in toward the engine compartment, and the crush extended to the height of the headlight. The grille and both headlights were disengaged from the vehicle. Additionally, the bottom of the front bumper was twisted in toward the engine from the centerline to the left side. The left-front quarter panel was crushed inward and buckled under the left-front door. The left-front door was scraped and deformed inward. The left-rear door was dented and scratched. The left-rear quarter panel was scratched and bent inward. The left-rear bumper was dented and shifted toward the right side of the vehicle as a result of impact deformation. The tailgate became disconnected on the right side of the vehicle, and both brake lights were shattered.

The front anti-roll bar was bent inward on the left-front side. Both links of the roll bar were bent forward. The front-left shock was bent forward, and the spring pushed off center. The left-rear brake line and caliper were bent and in slight contact with the rim. The left-rear side spring became dislodged and was wedged between the axle and the rim. The rear anti-roll bar was shifted to the passenger side. The lower control arm of the left-front suspension was folded back and disengaged off the frame mounts. The steering gear box was shattered, and the left-front tie rod was bent approximately 45 degrees forward. The transmission was shifted on its rear mounts, and the rear axle was shifted toward the right side about ½ in. (13 mm). The left-front engine mount had three bolts sheared off, and the right-front mount was undamaged.

The left-front tire was torn and in contact with the fender, but was not disengaged from the rim. The left-front tire rim and hubcap were crushed, and the hubcap was disengaged from the tire. No engine damage occurred, and the windshield was cracked extending from its bottom-left and right corners. The remaining windows were undamaged.

Table 5. Maximum Occupant Compartment Deformations by Location

LOCATION	MAXIMUM DEFORMATION in. (mm)	MASH 2016 ALLOWABLE DEFORMATION in. (mm)
Wheel Well & Toe Pan	1⅞ (48)	≤ 9 (229)
Floor Pan & Transmission Tunnel	1¼ (32)	≤ 12 (305)
A- and B-Pillars	1¼ (32)	≤ 5 (127)
A- and B-Pillars (Lateral)	⅞ (22)	≤ 3 (76)
Side Front Panel (in Front of A-Pillar)	1⅝ (41)	≤ 12 (305)
Side Door (Above Seat)	1½ (38)	≤ 9 (229)
Side Door (Below Seat)	⅞ (22)	≤ 12 (305)
Roof	⅝ (16)	≤ 4 (102)
Windshield	0 (0)	≤ 3 (76)
Side Window	Intact	No shattering resulting from contact with structural member of test article
Dash	⅞ (22)	N/A

N/A – Not applicable

5.5 Occupant Risk

The calculated occupant impact velocities (OIVs) and maximum 0.010-sec average occupant ridedown accelerations (ORAs) in both the longitudinal and lateral directions are shown in Table 6. Note that the OIVs and ORAs were within suggested limits, as provided in MASH 2016. The calculated THIV, PHD, and ASI values are also shown in Table 6. The results of the occupant risk analysis, as determined from the accelerometer data, are summarized in Figure 18. The recorded data from the accelerometers and the rate transducers are shown graphically in Appendix D.

Table 6. Summary of OIV, ORA, THIV, PHD, and ASI Values, Test No. OSSB-1

Evaluation Criteria		Transducer		MASH 2016 Limits
		SLICE-1	SLICE-2 (primary)	
OIV ft/s (m/s)	Longitudinal	-21.29 (-6.49)	-19.26 (-5.87)	±40 (12.2)
	Lateral	24.82 (7.56)	26.90 (8.20)	±40 (12.2)
ORA g's	Longitudinal	7.33	-9.35	±20.49
	Lateral	12.36	10.40	±20.49
MAX. ANGULAR DISPL. deg.	Roll	-24.2	-20.0	±75
	Pitch	5.8	6.6	±75
	Yaw	30.4	29.3	not required
THIV ft/s (m/s)		31.50 (9.60)	32.78 (9.99)	not required
PHD g's		12.49	12.21	not required
ASI		1.63	1.81	not required

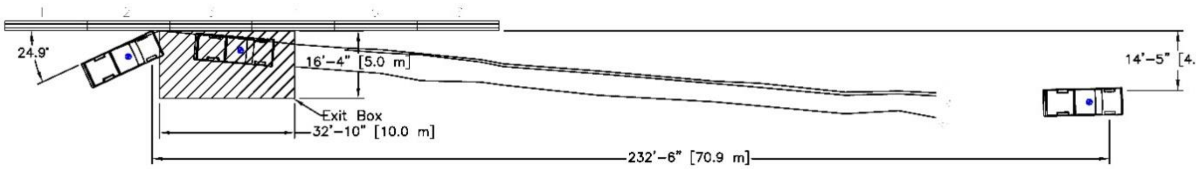
5.6 2270P Peak Force Calculation

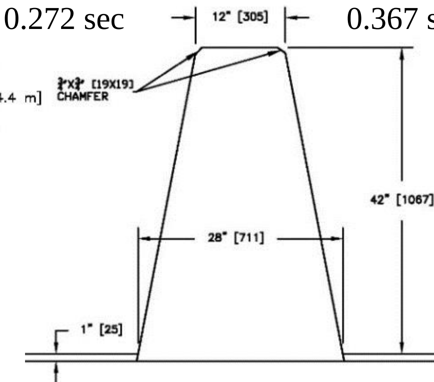
The longitudinal and lateral vehicle accelerations, as measured at the vehicle's c.g., were also processed using a CFC 60, 50-msec moving average. The 50-msec moving average vehicle accelerations were then combined with the uncoupled yaw angle versus time data in order to estimate the vehicular loading applied to the barrier system. From the data analysis, the perpendicular impact force was determined for test no. OSSB-1, as shown in Appendix E. The maximum perpendicular, or lateral, load imparted to the barrier was estimated to be 84.5 kips (376.0 kN), and the maximum parallel, or longitudinal, load imparted to the barrier was estimated to be 20.0 kips (89.1 kN) as determined by SLICE-2.

5.7 Discussion

The analysis of the test results for test no. OSSB-1 showed that the system adequately contained and redirected the 2270P vehicle with controlled lateral displacements of the barrier. Detached elements, fragments, or other debris from the test article did not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic pedestrians, or work-zone personnel. Deformations of, or intrusions into, the occupant compartment that could have caused serious injury did not occur. The test vehicle did not penetrate nor ride over the barrier and remained upright during and after the collision. Vehicle roll, pitch, and yaw angular displacements, as shown in Appendix D, were deemed acceptable because they did not adversely influence occupant risk nor cause rollover. After impact, the vehicle c.g. was measured to exit the barrier at an angle of −3.0 degrees, and the vehicle orientation angle during exit measured 3.8 degrees. The difference in exit angle values can be attributed to the vehicle rolling toward the test article as it exited the system. As the vehicle exited the system, vehicle roll toward the barrier altered the c.g. target alignment relative to the orientation of the single-slope barrier, which resulted in a negative c.g. exit angle even though the vehicle was exiting the system at a low trajectory angle. The vehicle's exit trajectory did not violate the bounds of the exit box. Therefore, test no. OSSB-1 was determined to be acceptable according to the MASH 2016 safety performance criteria for test designation no. 3-11.

0.000 sec 0.050 sec 0.178 sec 0.272 sec 0.367 sec





- Test Agency .... MwRSF
- Test Number OSSB-1
- Date 12/17/17
- MASH 2016 Test Designation No. 3-11
- Test Article .... Longitudinal Concrete Barrier
  - Total Length .... 119 ft – 11¾ in. (36.6 m)
- Key Component – Unreinforced Concrete Barrier
  - Length .... 239¾ in. (6,090 mm)
  - Height .... 42 in. (1,067 mm)
  - Width .... 28 in. (711 mm)
  - Number of Barrier Segments 6
- Vehicle Make /Model .... 2011 Dodge Ram 1500 Crew Cab Pickup Truck
  - Curb .... 5,122 lb (2,323 kg)
  - Test Inertial .... 5,001 lb (2,268 kg)
  - Gross Static .... 5,163 lb (2,342 kg)
- Impact Conditions
  - Speed .... 62.8 mph (101.0 km/h)
  - Angle .... 24.9 deg.
  - Impact Location .... 52 in. (1,321 mm) US from Joint 2-3
- Impact Severity ......116.3 kip-ft (157.7 kJ) > 106 kip-ft (144 kJ) limit from MASH 2016
- Exit Conditions
  - Speed .... 46.6 mph (75.0 km/h)
  - C.G. Exit Angle .... −3.0 deg.
  - Vehicle Orientation Exit Angle .... 3.8 deg.
- Exit Box Criterion .... Pass
- Vehicle Stability .... Satisfactory
- Vehicle Stopping Distance .... 232 ft – 6 in. (70.9 m)
  14 ft – 5 in. (4.4 m) laterally in front
- Vehicle Damage .... Moderate
  - VDS [12] 11-LFQ-4
  - CDC [13] 11-LYEW-3
  - Maximum Interior Deformation .... 1⅞ in. (48 mm)
- Test Article Damage .... Minimal
- Maximum Test Article Deflections
  - Permanent Set .... 0 in. (0 mm)
  - Dynamic .... 1.0 in. (25 mm)
  - Working Width .... 28.0 in. (711 mm)
- Transducer Data

Evaluation Criteria		Transducer		MASH 2016 Limit
		SLICE-1	SLICE-2 (primary)	
OIV ft/s (m/s)	Longitudinal	-21.29 (-6.49)	-19.26 (-5.87)	±40 (12.2)
	Lateral	24.82 (7.56)	26.90 (8.20)	±40 (12.2)
ORA g's	Longitudinal	7.33	-9.35	±20.49
	Lateral	12.36	10.40	±20.49
MAX ANGULAR DISP. deg.	Roll	-24.2	-20.0	±75
	Pitch	5.8	6.6	±75
	Yaw	30.4	29.3	not required
THIV – ft/s (m/s)		31.50 (9.60)	32.78 (9.99)	not required
PHD – g's		12.49	12.21	not required
ASI		1.63	1.81	not required

Figure 18. Summary of Test Results and Sequential Photographs, Test No. OSSB-1

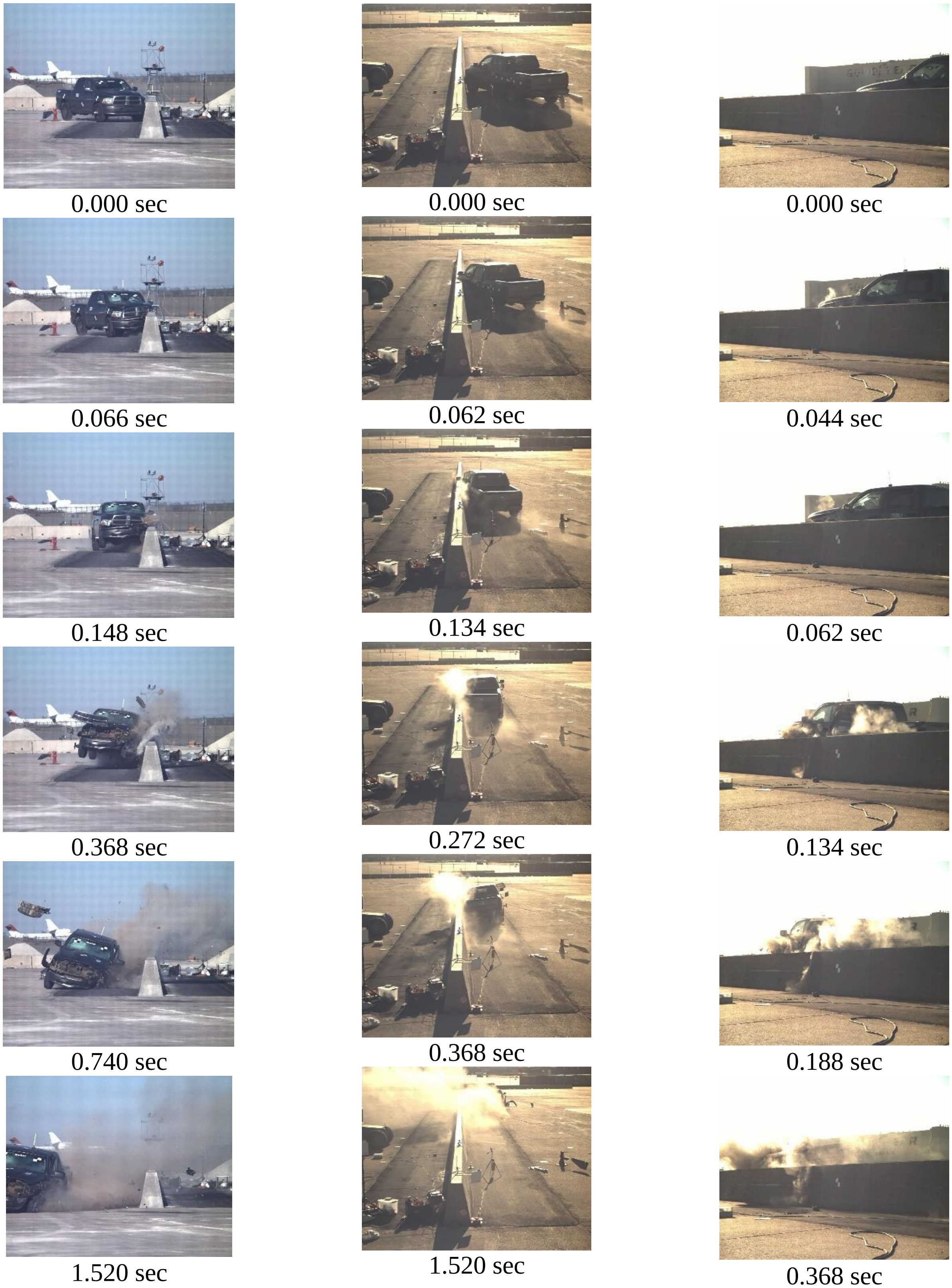


Figure 19. Additional Sequential Photographs, Test No. OSSB-1

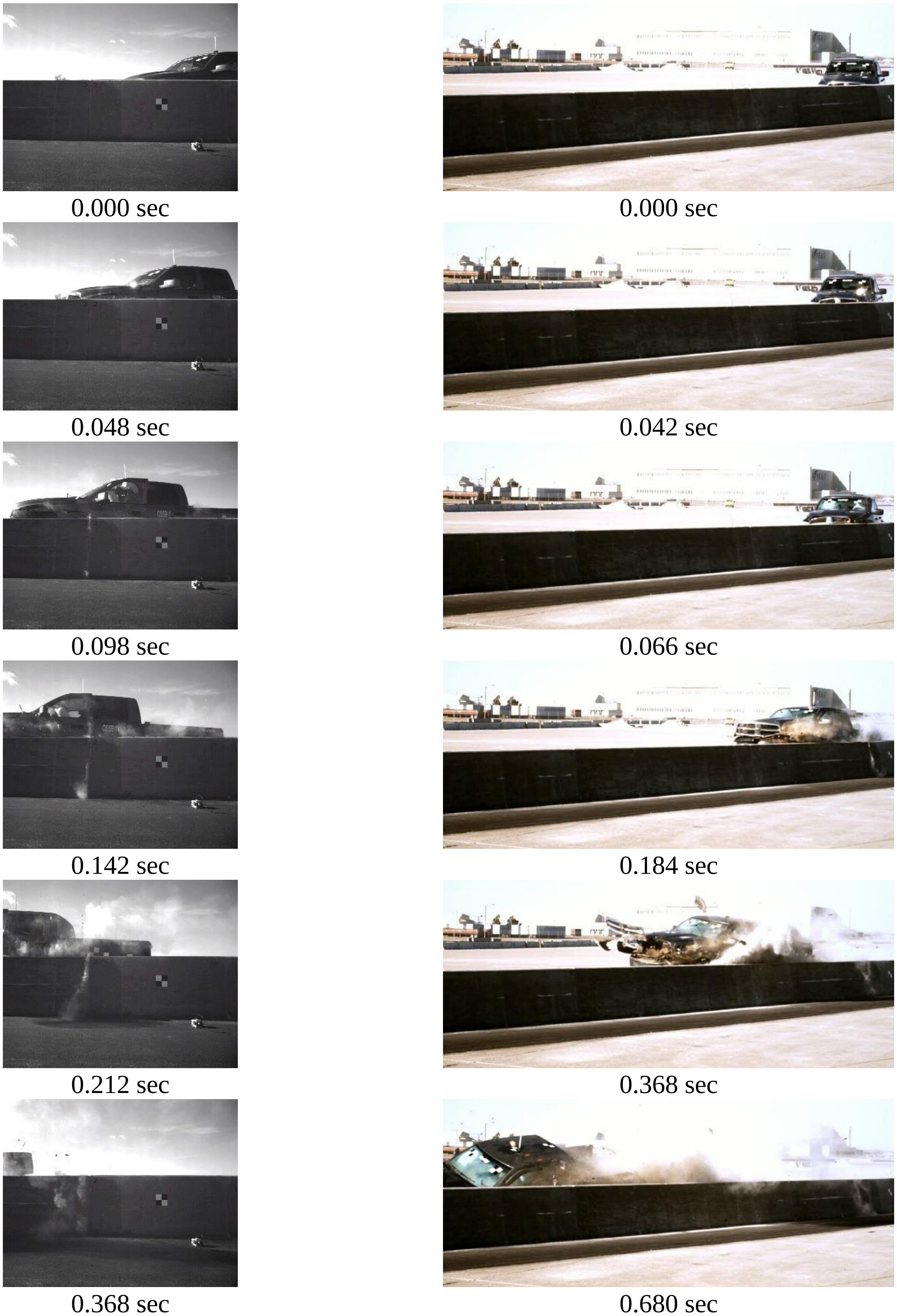


Figure 20. Additional Sequential Photographs, Test No. OSSB-1

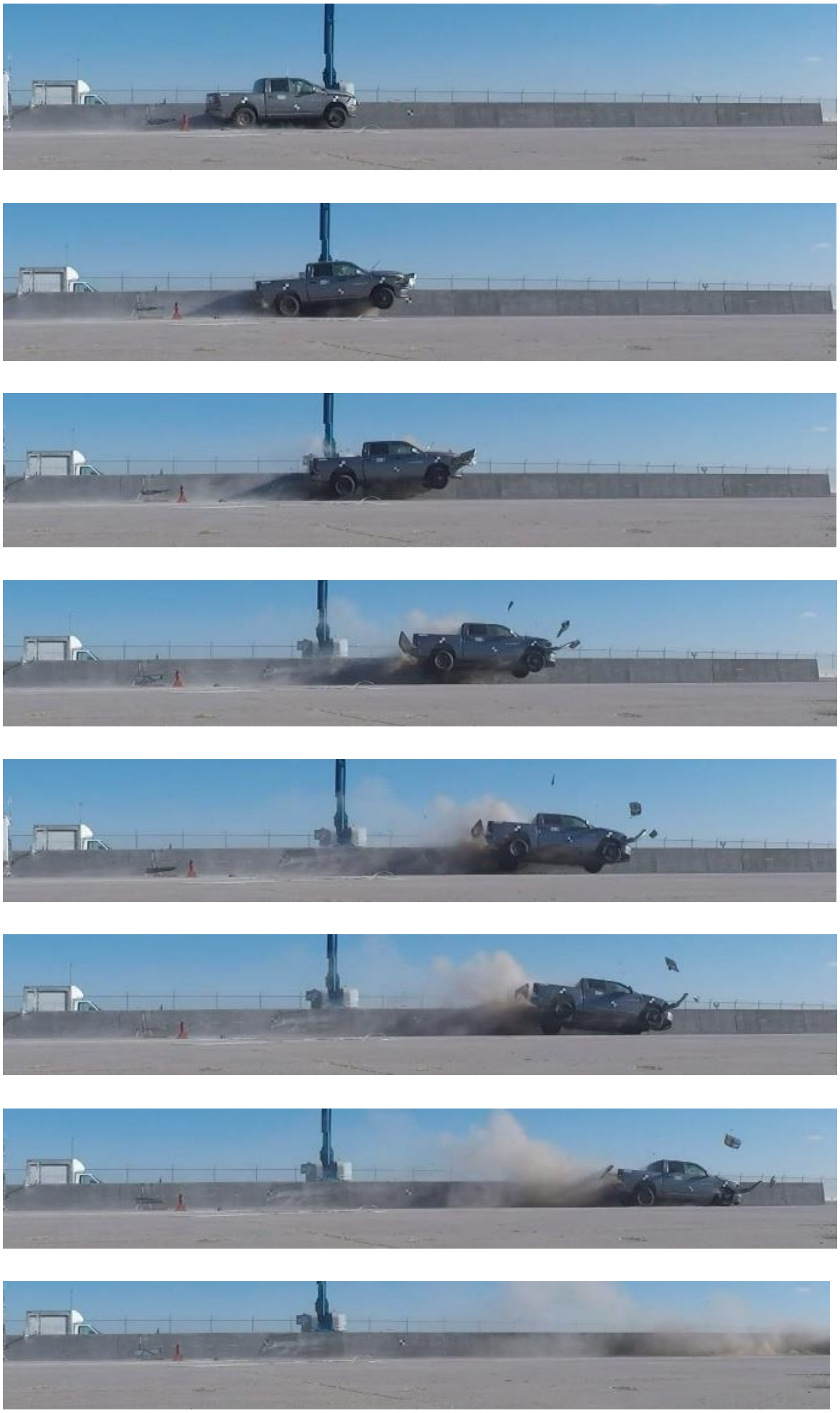


Figure 21. Documentary Photographs, Test No. OSSB-1

Figure 22. Documentary Photographs, Test No. OSSB-1

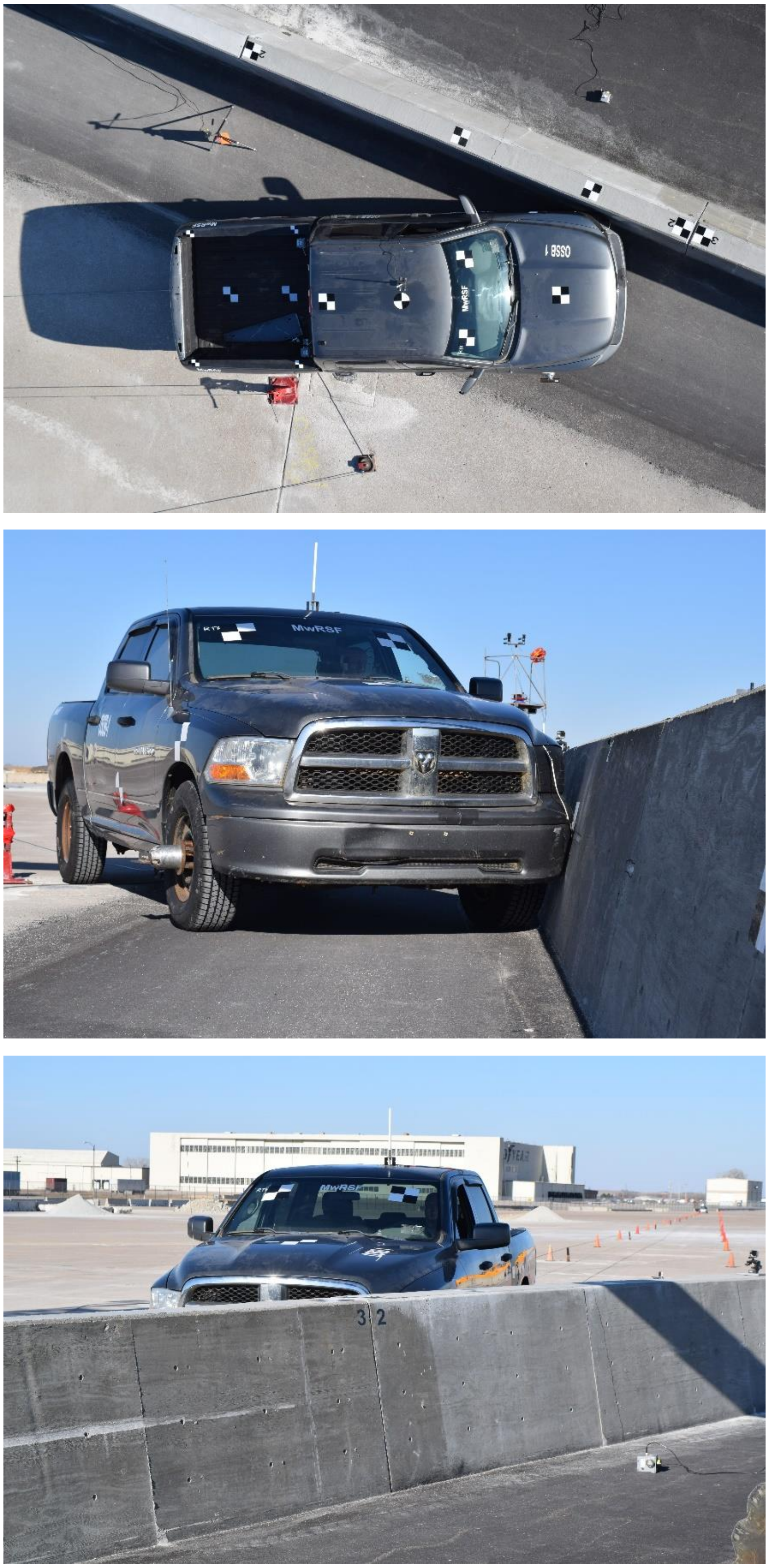


Figure 23. Impact Location, Test No. OSSB-1

Figure 24. Vehicle Final Position and Trajectory Marks, Test No. OSSB-1

Figure 25. System Damage, Test No. OSSB-1

Front Barrier Segment No. 2

Front Barrier Segment No. 3

Back Barrier Segment No. 2

Back Barrier Segment No. 3

Figure 26. Front- and Back-Side Barrier Damage, Test No. OSSB-1

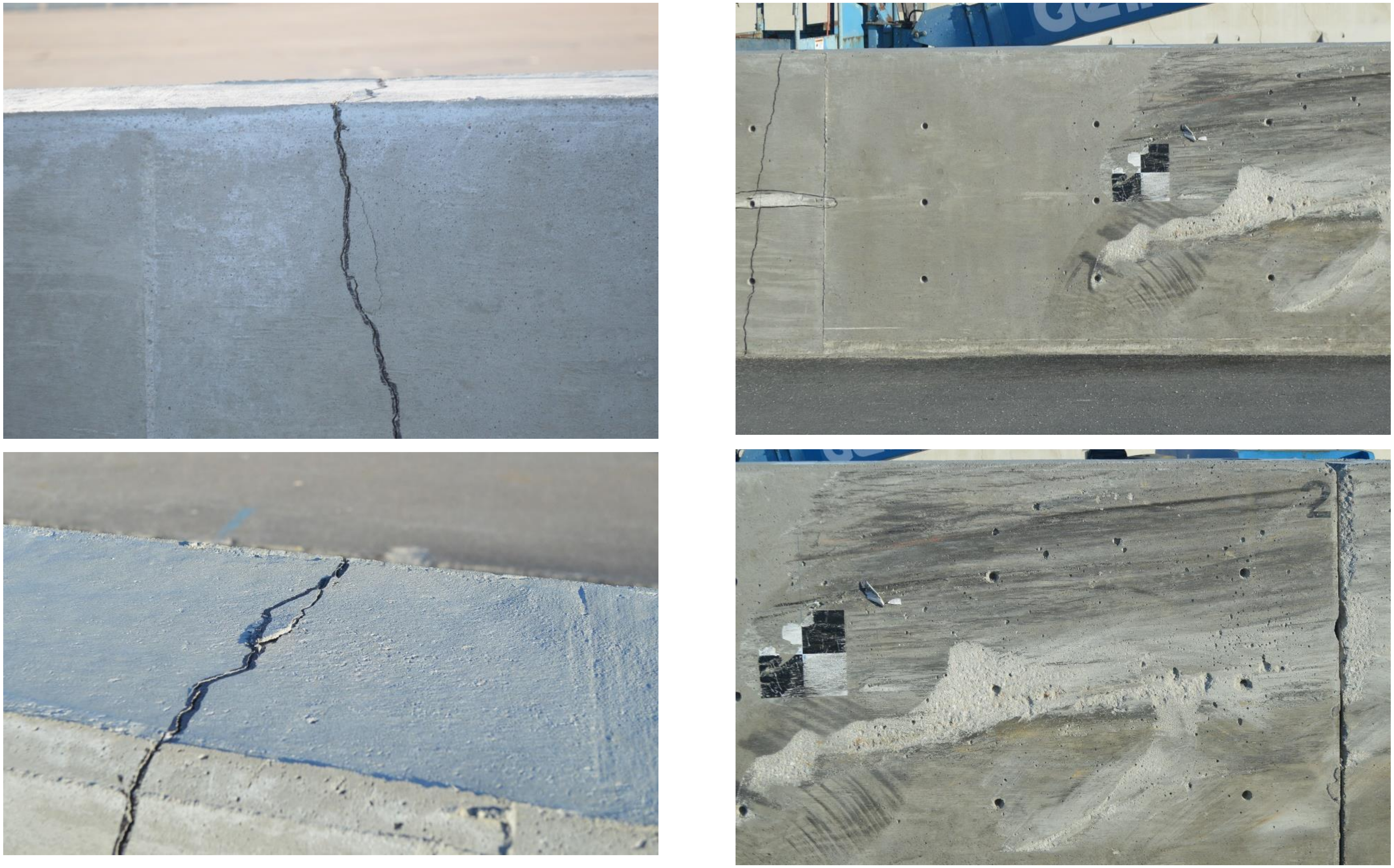


Figure 27. Barrier No. 2 Damage, Test No. OSSB-1

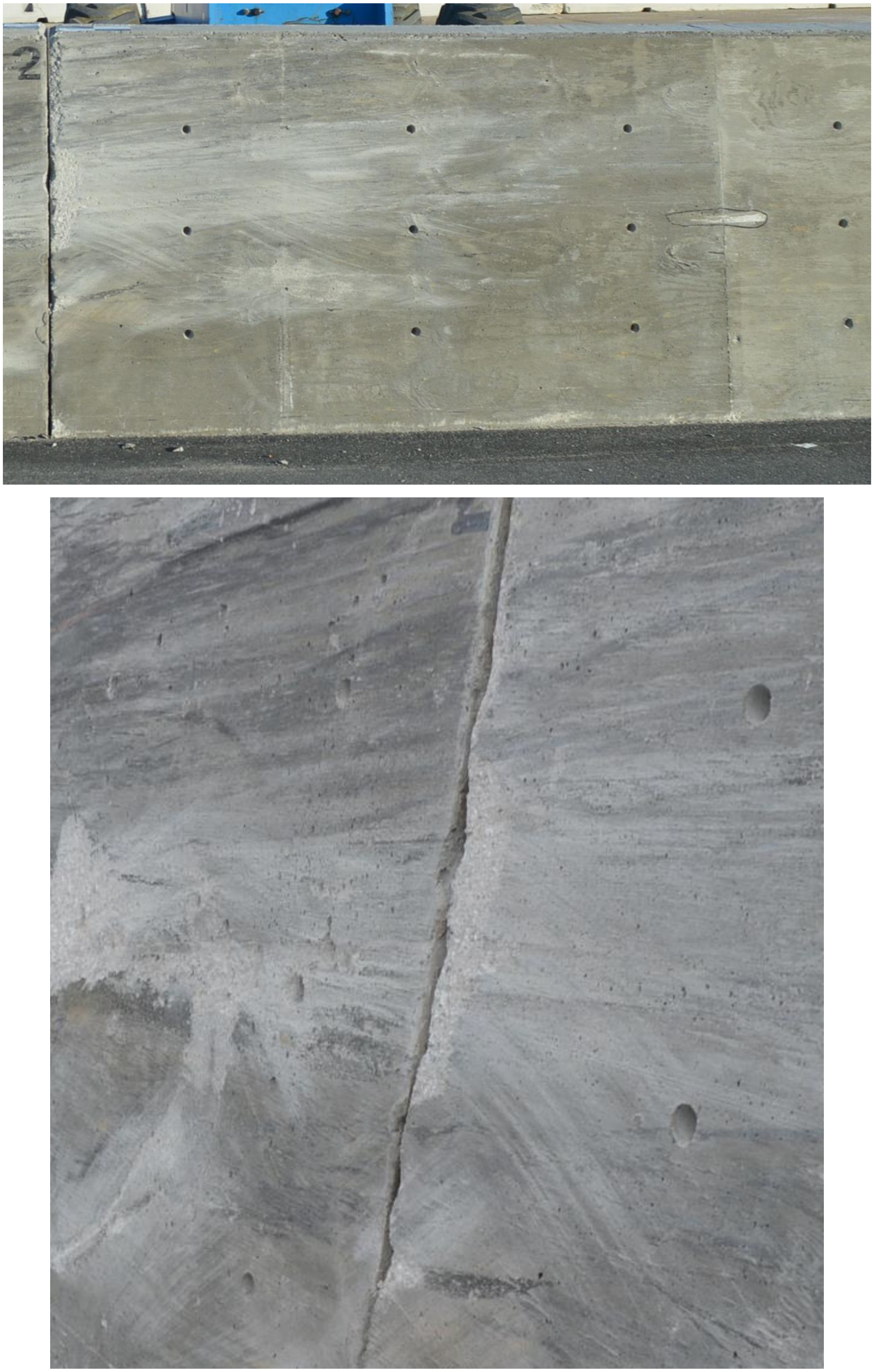


Figure 28. Barrier No. 3 Damage, Test No. OSSB-1

Figure 29. Vehicle Damage, Test No. OSSB-1

Figure 30. Additional Vehicle Damage, Test No. OSSB-1

Figure 31. Additional Vehicle Damage, Test No. OSSB-1

Figure 32. Vehicle Windshield Damage, Test No. OSSB-1

Figure 33. Occupant Compartment Damage, Test No. OSSB-1

Figure 34. Undercarriage Vehicle Damage, Test No. OSSB-1

6 SUMMARY AND CONCLUSIONS

This research effort assessed the crashworthiness of the ODOT unreinforced, single-slope, median barrier system in accordance with MASH 2016 TL-3 evaluation criteria. The ODOT unreinforced, single-slope, median barrier had a height of 43 in. (1,092 in.), a top width of 12 in. (305 mm), and a bottom width of 28⅜ in. (721 in.). The base of the barrier was surrounded by a 1-in. (25-mm) thick asphalt pad that extended 96 in. (2,438 mm) from the traffic and back sides of the system. The asphalt pad gave the barrier an effective height of 42 in. (1,067 mm) and base width of 28 in. (711 mm). The system was fabricated with ¼-in. (6-mm) gaps in the barrier section every 20 ft (6.1 m) in order to simulate potential cracking that can form in unreinforced concrete barriers. MASH 2016 test designation no. 3-11 was conducted on the barrier in order to evaluate its performance.

During test no. OSSB-1, the 5,001-lb (2,268-kg) crew cab pickup truck impacted the unreinforced barrier system at a speed of 62.8 mph (101.0 km/h) and at an angle of 24.9 degrees, resulting in an impact severity of 116.3 kip-ft (157.7 kJ). The vehicle was successfully contained and redirected by the system. The vehicle exited the system at a speed of 46.6 mph (75.0 km/h) with a vehicle c.g. exit angle of −3.0 degrees. The vehicle's orientation as it exited the system was 3.8 degrees. The difference in exit angle values can be attributed to the vehicle rolling toward the test article as it exited the system. As the vehicle exited the system, vehicle roll toward the barrier altered the c.g. target alignment relative to the orientation of the single-slope barrier, which resulted in a negative c.g. exit angle. Thus, the vehicle orientation angle during exit is a more accurate measurement of the vehicle's exit angle as it was redirected by the system. Barrier nos. 2 and 3 experienced spalling and scraping near impact, and several cracks extended from the existing thermal hairline cracks in barrier no. 2 as a result of impact. A dynamic deflection of 1.0 in. (25 mm) and a working width of 28.0 in. (711 mm) were observed during the test. All occupant risk values were found to be within limits, and the occupant compartment deformations were also deemed acceptable. Subsequently, test no. OSSB-1 was determined to satisfy the safety performance criteria for MASH 2016 test designation no. 3-11. A summary of the test evaluation is shown in Table 7.

It should be noted that the ODOT unreinforced concrete barrier was evaluated with a 1-in. (25-mm) thick asphalt keyway that represented the lowest capacity anchorage system used by ODOT with this type of barrier. Therefore, it is believed that the other, more robust anchorage methods in the ODOT standard details would also provide adequate barrier anchorage under MASH 2016 TL-3 impact conditions. Additionally, ODOT has provisions for installation of the single-slope barrier tested herein on concrete paving, asphalt paving, and compacted aggregate bases. It is believed that the performance of the barrier system will not be affected by the base type as long as the asphalt keyway anchoring the barrier system is present. ODOT also uses a dowel bar anchorage for the single-slope barrier. This system is only intended for use with a concrete base.

ODOT also has provisions in their details for the single-slope barrier evaluated herein that allow for a 4-in. (102-mm) diameter electrical raceway in the middle of the barrier section. This minimal loss of section near the center of the barrier section would not be expected to have a significant effect on the overall barrier capacity. This fact combined with the minimal barrier damage observed in test no. OSSB-1 would suggest that the use of the 4-in. (102-mm) diameter electrical raceway would be acceptable.

The performance and redirective capacity of the unreinforced concrete barrier evaluated herein were believed to be largely related to the size of the barrier cross-section and the mass of the barrier. Thus, it is not recommended to utilize unreinforced concrete barriers with a reduced cross-section geometry and/or mass without further research and evaluation.

Finally, it was noted previously that the ODOT unreinforced, single-slope, median barrier was evaluated with ¼-in. (6-mm) gaps or through cracks every 20 ft (6.1 m) along the barrier length to represent a worst practical condition for evaluation of the barrier system. Evaluation of the barrier under MASH 2016 TL-3 impact conditions indicated that the barrier had sufficient capacity even with the presence of these through cracks. However, additional intermediate cracking could develop over the service life of the barrier due to thermal cycling and other factors that could create additional rail discontinuities. If these discontinuities form in close proximity to one another or other existing cracks, the barrier capacity could be reduced, and the performance of the barrier may become less effective than what was observed in the testing detailed in this report. Based on this concern, it is recommended that end users of the unreinforced barrier periodically inspect the barrier over time to ensure that closely-spaced through-cracking that could alter performance does not occur.

Table 7. Summary of Safety Performance Evaluation

<table>
<tr><th>Evaluation Factors</th><th colspan="4">Evaluation Criteria</th><th>Test No. OSSB-1</th></tr>
<tr><td>Structural Adequacy</td><td>A.</td><td colspan="3">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.</td><td>S</td></tr>
<tr><td rowspan="11">Occupant Risk</td><td rowspan="2">D.</td><td colspan="3">1. 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.</td><td>S</td></tr>
<tr><td colspan="3">2. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH 2016.</td><td>S</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td><td>S</td></tr>
<tr><td rowspan="4">H.</td><td colspan="3">Occupant Impact Velocity (OIV) (see Appendix A, Section A5.2.2 of MASH 2016 for calculation procedure) should satisfy the following limits:</td><td rowspan="4">S</td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30 ft/s (9.1 m/s)</td><td>40 ft/s
(12.2 m/s)</td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.2.2 of MASH 2016 for calculation procedure) should satisfy the following limits:</td><td rowspan="4">S</td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15.0 g’s</td><td>20.49 g’s</td></tr>
<tr><td colspan="5">MASH 2016 Test Designation No.</td><td>3-11</td></tr>
<tr><td colspan="5">Final Evaluation (Pass or Fail)</td><td>Pass</td></tr>
</table>

S – Satisfactory U – Unsatisfactory NA - Not Applicable

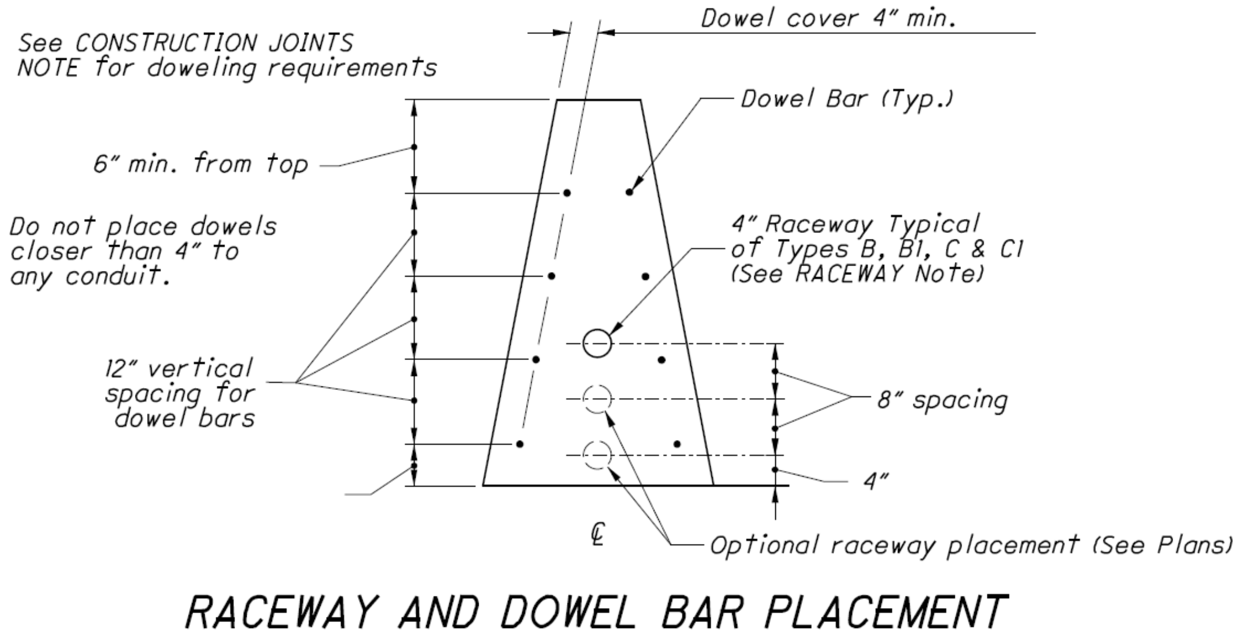


Figure 35. ODOT Single-Slope Barrier Electrical Raceway Detail

7 MASH EVALUATION

The ODOT unreinforced, single-slope, concrete median barrier was evaluated to determine its compliance with MASH 2016 TL-3 evaluation criteria. This barrier system consisted of an unreinforced concrete barrier section with a 12-in. (305-mm) top width and a 28-in. (711-mm) bottom width that was anchored with a 1-in. (25-mm) thick asphalt keyway. The 1-in. (25-mm) thick asphalt keyway was considered the weakest, and therefore, most critical configuration for testing. The barrier system was evaluated with vertical asperities or through-cracks every 20 ft (6.1 m) along the barrier length to represent a worst practical condition for evaluation of the barrier system.

MASH 2016 currently requires two full-scale crash tests for evaluation of longitudinal barrier systems to TL-3. Only test designation no. 3-11 was deemed critical for evaluation of the ODOT unreinforced, single-slope, concrete median barrier. Test designation no. 3-10 with the 1100C vehicle is typically required to evaluate vehicle capture, vehicle stability, and occupant risk concerns for the small car vehicle. Previous testing was conducted according to MASH test designation no. 3-10 on the CALTRANS Type 60 single-slope concrete median barrier with a 36-in. (914-mm) height and 9.1-degree sloped face [7]. This test indicated that the capture, stability, and occupant risk values were acceptable for a TL-3 1100C vehicle impact on a single-slope concrete barrier with a sloped face only 1.7 degrees steeper than that of the ODOT unreinforced single-slope barrier. It was believed that the similar barrier geometry of the ODOT single-slope barrier would provide for similar vehicle redirection and stability. Additionally, structural loading of the barrier in test designation no. 3-10 with the 1100C vehicle would be significantly less than that of test designation no. 3-11 with the 2270P vehicle. Thus, test designation no. 3-11 with the 2270P vehicle was considered the most critical test to evaluate vehicle capture, vehicle stability, vehicle snag, and maximize structural loading of the barrier, and only test designation no. 3-11 was deemed necessary to evaluate the barrier system.

Test no. OSSB-1 was conducted to evaluate the crashworthiness of the barrier system to MASH 2016 TL-3 evaluation criteria. During test no. OSSB-1, the 5,001-lb (2,268-kg) crew cab pickup truck impacted the unreinforced barrier system at a speed of 62.8 mph (101.0 km/h) and at an angle of 24.9 degrees, resulting in an impact severity of 116.3 kip-ft (157.7 kJ). The vehicle exited the system at a speed of 46.6 mph (75.0 km/h) with a vehicle c.g. exit angle of −3.0 degrees. The vehicle orientation as it exited the system was 3.8 degrees. The difference in exit angle values can be attributed to the vehicle rolling toward the test article as it exited the system. As the vehicle exited the system, vehicle roll toward the barrier altered the c.g. target alignment relative to the orientation of the single-slope barrier, which resulted in a negative c.g. exit angle. Thus, the vehicle orientation angle during exit is a more accurate measurement of the vehicle's exit angle as it was redirected by the system. The vehicle was successfully contained and redirected by the system. Barrier nos. 2 and 3 experienced spalling and scraping near impact, and several cracks extended from the thermal hairline cracks in barrier no. 2 as a result of impact. A dynamic deflection of 1.0 in. (25 mm) and a working width of 28.0 in. (711 mm) were observed during the test. All occupant risk values were found to be within limits, and the occupant compartment deformations were also deemed acceptable. Subsequently, test no. OSSB-1 was determined to satisfy the safety performance criteria for MASH 2016 test designation no. 3-11.

Based on the evaluation of the successful full-scale crash testing in test no. OSSB-1 and the review of previous MASH crash testing of single-slope barriers with a small car vehicle, it is believed that the ODOT unreinforced, single-slope concrete median barrier meets all of the requirements for compliance with MASH 2016 TL-3. The ODOT barrier configurations previously shown in Figures 3 and 4 would have similar performance to that of the unreinforced, single-slope concrete barrier and would also be crashworthy.

8 REFERENCES

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9 APPENDICES

Appendix A. Material Specifications

Table A-1. Bill of Materials, Test No. OSSB-1

Item No.	Description	Material Specification	Reference
a1	42" [1,067] Tall, 1,439¾" [36.6 m] Long, Unreinforced, Single-Slope, Concrete Barrier	Min. f’c = 4,000 psi [27.6 MPa] NE 47BD Mix	Cylinder Testing Matrix
a2	Asphalt	NDOR Superpave SPH Mix Binder PG 64-34	Project #540624
a3	Tack Coat	NDOR SS-1, SS-1H, CSS-1, or CSS-1H	N/A

N/A – Not Applicable

Table A-2. Concrete Compressive Strength Data, Test No. OSSB-1

OSSB-1 CONCRETE TEST SCHEDULE

Cylinder Label	Cast Date	Breaking Date	Breaking Strength (psi)	Cure Days	Mix Design and Target f'c	Notes:
A	10/9/2017	11/6/2017	4710	28	47BD f'c = 4000psi	Barrier Segment 1
B	10/9/2017	11/30/2017	5100	52		Cyl B is partial size
C	10/11/2017	11/15/2017	3630	35	47BD f'c = 4000psi	Barrier Segment 2
D	10/11/2017	11/15/2017	3600	35		
D2	10/11/2017	12/5/2017	4554	62		U.S. Core
E	10/13/2017	11/15/2017	3750	33	47BD f'c = 4000psi	Barrier Segment 3
F	10/13/2017	11/15/2017	3720	33		Impact Barrier
G	10/13/2017	11/30/2017	4400	48		
G2	10/13/2017	12/5/2017	4586	60		D.S. Core
H	10/16/2017	11/15/2017	3050	30	47BD f'c = 4000psi	Barrier Segment 4
I	10/16/2017	11/15/2017	2980	30		
J	10/16/2017	11/30/2017	3680	45		
K	10/18/2017	11/15/2017	4180	28	47BD f'c = 4000psi	Barrier Segment 5
L	10/18/2017	11/15/2017	3880	28		
M	10/18/2017	11/30/2017	5140	43		
N	10/20/2017	11/15/2017	2790	26	47BD f'c = 4000psi	Barrier Segment 6
O	10/20/2017	11/15/2017	2830	26		
P	10/20/2017	11/30/2017	3870	41		
P2	10/20/2017	12/5/2017	4287	53		Practice Core

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COMPRESSION TEST OF CYLINDRICAL CONCRETE SPECIMENS - 6x12

ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility **Date** 06-Nov-17
Project Name: Miscellaneous Concrete Testing
Placement Location: Project Ohio Single Slope Cylinder A

Mix Designation: **Required Strength:**

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area, sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 29	A	10/9/2017	11/6/2017	11/6/2017	28	0	28	12	5.98	28.06	132,053	4,710		5	C 1231

1 cc: Ms. Karla Lechtenberg
Midwest Roadside Safety Facility

Remarks:

Concrete test specimens along with documentation and test data were submitted by Midwest Roadside Safety Facility.

Test results presented relate only to the concrete specimens as received from Midwest Roadside Safety

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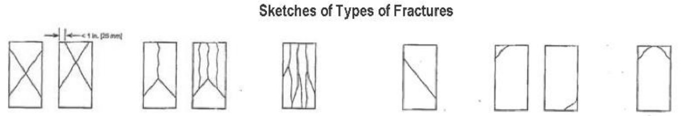
Sketches of Types of Fractures



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By__________
Brant Wells, Field/Lab Operations Manager

Figure A-1. Concrete Compression Testing Data, Cylinder A, 28 Cure Days, Test No. OSSB-1

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COMPRESSION TEST OF CYLINDRICAL CONCRETE SPECIMENS - 6x12

ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility **Date** 30-Nov-17
Project Name: Miscellaneous Concrete Testing
Placement Location: Ohio Single Slope

Mix Designation: **Required Strength:**

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area, sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 41	B	10/9/2017	11/30/2017	11/30/2017	52	0	52	12	5.97	27.95	142,534	5,100		5	C 1231

1 cc: Ms. Karla Lechtenberg
Midwest Roadside Safety Facility

Remarks:

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Sketches of Types of Fractures

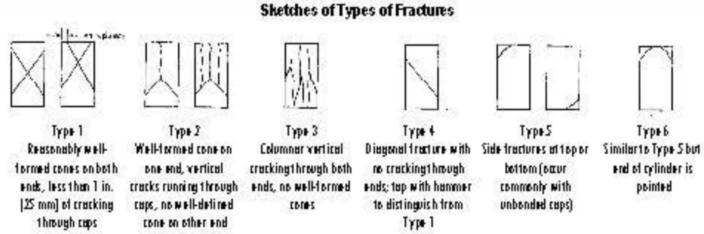

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Figure A-2. Concrete Compression Testing Data, Cylinder B, 52 Cure Days, Test No. OSSB-1

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ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility **Date** 20-Nov-17
Project Name: Miscellaneous Concrete Testing
Placement Location: Ohio Single Slope

Mix Designation: **Required Strength:** 4000

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area, sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 30	C	10/11/2017	11/15/2017	11/15/2017	35	0	35	12	5.99	28.15	102,277	3,630	4,000	6	C 1231
URR- 31	D	10/11/2017	11/15/2017	11/15/2017	35	0	35	12	5.99	28.18	101,405	3,600	4,000	6	C 1231

1 cc: Ms. Karla Lechtenberg
Midwest Roadside Safety Facility

Remarks:

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Sketches of Types of Fractures

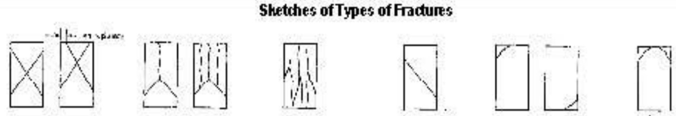

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Figure A-3. Concrete Compression Testing Data, Cylinders C and D, 35 Cure Days, Test No. OSSB-1

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ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility **Date** 20-Nov-17
Project Name: Miscellaneous Concrete Testing
Placement Location: Ohio Single Slope

Mix Designation: **Required Strength:** 4000

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area, sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 32	E	10/13/2017	11/15/2017	11/15/2017	33	0	33	12	5.99	28.13	105,566	3,750	4,000	6	C 1231
URR- 33	F	10/13/2017	11/15/2017	11/15/2017	33	0	33	12	5.99	28.20	104,915	3,720	4,000	6	C 1231

1 cc: Ms. Karla Lechtenberg
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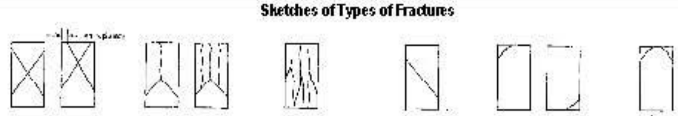
Sketches of Types of Fractures



Type 1: Reasonably well-formed cones on both ends, less than 1 in. [25 mm] of cracking through caps
Type 2: Well-formed cone on one end, vertical cracks running through caps, no well-defined cone on other end
Type 3: Columnar vertical cracking through both ends, no well-formed cones
Type 4: Diagonal fracture with no cracking through ends; tap with hammer to distinguish from Type 1
Type 5: Side fractures at top or bottom (occur commonly with unbonded caps)
Type 6: Similar to Type 5 but end of cylinder is pointed

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Brant Wells, Field/Lab Operations Manager

Figure A-4. Concrete Compression Testing Data, Cylinders E and F, 33 Cure Days, Test No. OSSB-1

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COMPRESSION TEST OF CYLINDRICAL CONCRETE SPECIMENS - 6x12

ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility **Date** 30-Nov-17
Project Name: Miscellaneous Concrete Testing
Placement Location: Ohio Single Slope

Mix Designation: **Required Strength:**

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area, sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 42	G	10/13/2017	11/30/2017	11/30/2017	48	0	48	12	5.99	28.13	124,997	4,440		5	C 1231

1 cc: Ms. Karla Lechtenberg
Midwest Roadside Safety Facility

Remarks:

All concrete test data in this report was produced by Benesch personnel using ASTM Standard Methods and Practices unless otherwise noted.

Test results presented relate only to the concrete sampled by Benesch personnel as referenced above.

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Sketches of Types of Fractures

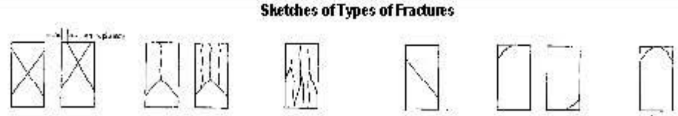

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Figure A-5. Concrete Compression Testing Data, Cylinder G, 48 Cure Days, Test No. OSSB-1

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COMPRESSION TEST OF CYLINDRICAL CONCRETE SPECIMENS - 6x12

ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility **Date** 20-Nov-17
Project Name: Miscellaneous Concrete Testing
Placement Location: Ohio Single Slope

Mix Designation: **Required Strength:** 4000

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area, sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 34	H	10/16/2017	11/15/2017	11/15/2017	30	0	30	12	5.99	28.19	86,084	3,050	4,000	6	C 1231
URR- 35	I	10/16/2017	11/15/2017	11/15/2017	30	0	30	12	6.01	28.37	84,432	2,980	4,000	6	C 1231

1 cc: Ms. Karla Lechtenberg
Midwest Roadside Safety Facility

Remarks:

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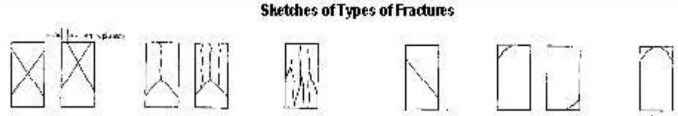
Page 1

Sketches of Types of Fractures



Type 1: Reasonably well-formed cones on both ends, less than 1 in. [25 mm] of cracking through caps
Type 2: Well-formed cone on one end, vertical cracks running through caps, no well-defined cone on other end
Type 3: Columnar vertical cracking through both ends, no well-formed cones
Type 4: Diagonal fracture with no cracking through ends; tap with hammer to distinguish from Type 1
Type 5: Side fractures at top or bottom (occur commonly with unbonded caps)
Type 6: Similar to Type 5 but end of cylinder is pointed

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By
Brant Wells, Field/Lab Operations Manager

Figure A-6. Concrete Compression Testing Data, Cylinders H and I, 30 Cure Days, Test No. OSSB-1

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COMPRESSION TEST OF CYLINDRICAL CONCRETE SPECIMENS - 6x12

ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility **Date** 30-Nov-17
Project Name: Miscellaneous Concrete Testing
Placement Location: Ohio Single Slope

Mix Designation: **Required Strength:**

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area, sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 43	J	10/16/2017	11/30/2017	11/30/2017	45	0	45	12	5.99	28.18	103,771	3,680		5	C 1231

1 cc: Ms. Karla Lechtenberg
Midwest Roadside Safety Facility

Remarks:

All concrete test data in this report was produced by Benesch personnel using ASTM Standard Methods and Practices unless otherwise noted.

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Sketches of Types of Fractures

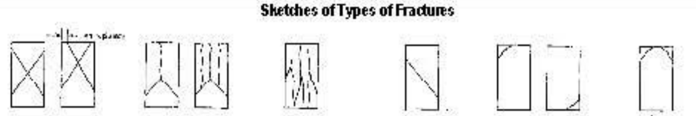

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Figure A-7. Concrete Compression Testing Data, Cylinder J, 45 Cure Days, Test No. OSSB-1

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COMPRESSION TEST OF CYLINDRICAL CONCRETE SPECIMENS - 6x12

ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility **Date** 20-Nov-17
Project Name: Miscellaneous Concrete Testing
Placement Location: Ohio Single Slope

Mix Designation: **Required Strength:** 4000

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area, sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 36	K	10/18/2017	11/15/2017	11/15/2017	28	0	28	12	5.97	27.96	116,776	4,180	4,000	6	C 1231
URR- 37	L	10/18/2017	11/15/2017	11/15/2017	28	0	28	12	5.99	28.20	109,326	3,880	4,000	6	C 1231

1 cc: Ms. Karla Lechtenberg
Midwest Roadside Safety Facility

Remarks:

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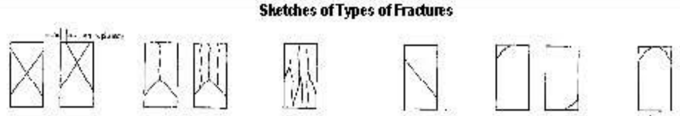
Sketches of Types of Fractures



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By____________________
Brant Wells, Field/Lab Operations Manager

Figure A-8. Concrete Compression Testing Data, Cylinders K and L, 28 Cure Days, Test No. OSSB-1

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COMPRESSION TEST OF CYLINDRICAL CONCRETE SPECIMENS - 6x12

ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility **Date** 30-Nov-17
Project Name: Miscellaneous Concrete Testing
Placement Location: Ohio Single Slope

Mix Designation: **Required Strength:**

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area, sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 44	M	10/18/2017	11/30/2017	11/30/2017	43	0	43	12	5.99	28.22	145,072	5,140		5	C 1231

1 cc: Ms. Karla Lechtenberg
Midwest Roadside Safety Facility

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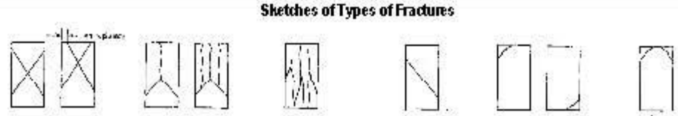
Sketches of Types of Fractures



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Brant Wells, Field/Lab Operations Manager

Report Number 2147369869
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Figure A-9. Concrete Compression Testing Data, Cylinder M, 43 Cure Days, Test No. OSSB-1

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COMPRESSION TEST OF CYLINDRICAL CONCRETE SPECIMENS - 6x12

ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility **Date** 20-Nov-17
Project Name: Miscellaneous Concrete Testing
Placement Location: Ohio Single Slope

Mix Designation: **Required Strength:** 4000

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area, sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 38	N	10/20/2017	11/15/2017	11/15/2017	26	0	26	12	6.00	28.28	78,842	2,790	4,000	6	C 1231
URR- 39	O	10/20/2017	11/15/2017	11/15/2017	26	0	26	12	5.98	28.10	79,528	2,830	4,000	6	C 1231

1 cc: Ms. Karla Lechtenberg
Midwest Roadside Safety Facility

Remarks:

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Test results presented relate only to the concrete specimens as received from Midwest Roadside Safety

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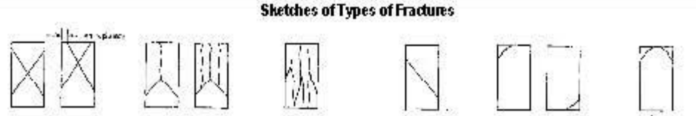
Sketches of Types of Fractures



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Brant Wells, Field/Lab Operations Manager

Figure A-10. Concrete Compression Testing Data, Cylinders N and O, 26 Cure Days, Test No. OSSB-1

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COMPRESSION TEST OF CYLINDRICAL CONCRETE SPECIMENS - 6x12

ASTM Designation: C 39

Client Name: Midwest Roadside Safety Facility **Date** 30-Nov-17
Project Name: Miscellaneous Concrete Testing
Placement Location: Ohio Single Slope

Mix Designation: **Required Strength:**

Laboratory Test Data

Laboratory Identification	Field Identification	Date Cast	Date Received	Date Tested	Days Cured in Field	Days Cured in Laboratory	Age of Test, Days	Length of Specimen, in.	Diameter of Specimen, in.	Cross-Sectional Area, sq.in.	Maximum Load, lbf	Compressive Strength, psi.	Required Strength, psi.	Type of Fracture	ASTM Practice for Capping Specimen
URR- 45	P	10/20/2017	11/30/2017	11/30/2017	41	0	41	12	5.98	28.11	108,883	3,870		5	C 1231

1 cc: Ms. Karla Lechtenberg
Midwest Roadside Safety Facility

Remarks:

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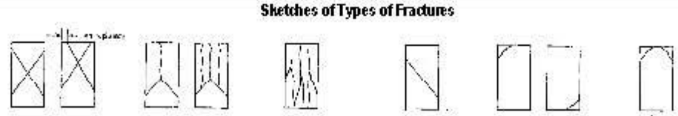
Report Number 2147369870
Page 1

Sketches of Types of Fractures



Type 1
Reasonably well-formed cones on both ends, less than 1 in. [25 mm] of cracking through caps

Type 2
Well-formed cone on one end, vertical cracks running through caps, no well-defined cone on other end

Type 3
Columnar vertical cracking through both ends, no well-formed cones

Type 4
Diagonal fracture with no cracking through ends; tap with hammer to distinguish from Type 1

Type 5
Side fractures at top or bottom (occur commonly with unbonded caps)

Type 6
Similar to Type 5 but end of cylinder is pointed

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By
Brant Wells, Field/Lab Operations Manager

Figure A-11. Concrete Compression Testing Data, Cylinder P, 41 Cure Days, Test No. OSSB-1

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COMPRESSION TEST OF CONCRETE CORES
ASTM Designation: C39

Project: Midwest Roadside Safety Cores — Project No.: 00110546.00
Placement Location: — Date: 12/5/2017

Mix Type:		Cement Factor, Sks/Yd:	
Mix Number:		Water-Cement Ratio:	
Type of Forms:		Slump (in):	
Number of Units Used:	N/A	Unit Wt (lbs/ft^3):	
Admixture Type:		Air Content (%):	
Admixture Quantity:		Batch Volume (yd^3):	
Average Field Temp.:		Ticket Number:	

Sample Identification	P2	D2	G2			
Date Cast						
Date Received in Lab	12/1/2017	12/1/2017	12/1/2017			
Date Tested	12/5/2017	12/5/2017	12/5/2017			
Days Cured in Field						
Days Cured in Laboratory	5	5	5			
Age of Specimen (Days)						
Length (in)	7.726	7.293	7.278			
Average Diameter (in)	3.908	3.906	3.909			
Cross-Sectional Area (in^2)	12	12	12			
Maximum Load (lbf)	51424	54570	55042			
Compressive Strength (psi)	4290	4550	4590			
Length/Diameter Ratio	2	1.9	1.9			
Correction	1	1	1			
Corrected Comp. Strength (psi)	4290	4550	4590			
Type of Fracture	4	6	4			
Required Strength (Mpa)						

Midwest Roadside Safety — Alfred Benesch & Company
Jim Holloway — Brant Wells

Remarks:

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By: bwells@benesch.com Digitally signed by bwells@benesch.com DN: cn=bwells@benesch.com Date: 2017.12.06 15:00:32 -06'00'

Brant Wells, Field/Lab Operations Manager

Figure A-12. Concrete Compression Testing Data, Cylinders D2 (62 Cure Days), G2 (60 Cure Days), and P2 (53 Cure Days), Test No. OSSB-1

CITY OF LINCOLN MATERIALS TESTING LAB
ASPHALT AGGREGATE WORKSHEET

CONTRACTOR		Cather Const.		Specific Gravity of Coarse Aggregate (AASHTO T 85)	
SUPERPAVE LEVEL		SPR			GsbC (Coarse)
MIX TYPE		NON-ARTERIAL		Oven Dry Weight (A)	2086.4
JOBMIX		2017-01		SSD Weight (B)	2107.7
DATE REC'D.		02/06/17		Weight in Water (C)	1315.3
PROJECT NUMBER		540624		Bulk S.G. (A/(B-C))	2.633
Wt. of Sample (Wtt)	9995.0	Wt.	%	Absorption ((B-A)/A)*100	1.0
Wt. of +#4 (Wtc)	%C (100(Wtc/Wtt))	2126.6	21.3	Date Ran	02/15/17
Wt. of -#4 (Wtf)	%F (100(Wtf/Wtt))	7868.4	78.7	Ran By	JEB

Fine Aggregate Angularity (AASHTO T 304)			Specific Gravity of Fine Aggregate (AASHTO T 84)	FAA	GsbF(Fine)
Volume of Measure (V)	100.0		SSD Weight (S)	500.0	500.0
Mass of Empty Measure (E)	190.0		Oven Dry Weight (A)	493.8	490.3
RUN	1	2	Flask Number	1	1
Gross Mass (D)	334.5	334.4	Flask Weight+Water to Line (B)	672.8	672.8
Net Mass, (F=D-E)	144.5	144.4	Flask+SSD Weight+Water to Line (C)	982.8	981.2
U=[(V-(F/G))/V]*100			Volume of Sample (S-(C-B))	190.0	191.6
FINE AGG. ANGULARITY (U)	44.4	44.4	Bulk S.G. (A/(B+S-C))	2.599	2.559
FAA, Average of two runs	44.4		Absorption ((S-A)/A)*100	1.3	2.0
Date Ran	02/21/17		Date Ran	02/17/17	02/14/17
Ran By	JEB		Ran By	AJR	AJR
			GsB (100/((%C/GsbC)+(%F/GsbF)))	2.574	

Coarse Aggregate Angularity (ASTM D 5821-95)	
Total weight of sample (A)	500.0
Mass or count of particles with one fractured face (B)	57.0
Mass or count of particles with at least two fractured faces (C)	422.0
Mass or count of particles in the uncrushed category not meeting the fractured particle criteria (A-(B+C))	21.0
Percentage with one or more fractured faces. ((B+C)/A*100)	96
Percentage of particles with at least two fractured faces ((C/A)*100)	84
Date Ran	02/21/17
Ran By	JEB

Flat and Elongated Particles (ASTM D 4791)				
Sieve Size	Total Wt.	Fail Wt.	% Flat and Elongated Particles	
1.0 in. (25.0 mm)			0.0%	
3/4 in. (19.0 mm)			0.0%	
1/2 in. (12.5 mm)	222.4	0.0	0.0%	
3/8 in. (9.5 mm)	187.2	0.0	0.0%	
			Total % Flat and Elongated Particles	0%
			Date Ran	02/21/17
			Ran By	JEB

Sand Equivalent (AASHTO T 176)					
Soaking Start	Sedimentation Start	Clay	Sand	Sand Equivalent	
				0.0	
				0.0	
				0.0	
				Sand Equivalent Average	0
				Date Ran	
				Ran By	

Figure A-13. Asphalt Material Specifications, Test No. OSSB-1

CATHER CONST. TYPE 2 (SPR) 2017

CATHER CONST. TYPE 2 (SPR) 2017-01		CONTRACTOR TESTS AGGREGATE GRADATIONS											
%	MATERIAL	S.G.	1"	3/4	1/2	3/8	#4	#8	#16	#30	#50	#200	SOURCE
0	2A GRAVEL-LR												
0	QTZ. MAN SAND-EVERIST												
0	QTZ. 3/4" ROCK												
0	QTZ. 3/16" DOWN												
0	5/8" SPECIAL-KER.												
15	3/8" LS CHIPS-MM		100.0	100.0	100.0	99.0	33.0	3.0	2.0	1.0	1.0	1.0	02/06/17
0	SCREENINGS-KER.												
5	3/4" LS-MM		100.0	100.0	40.0	12.0	6.0	5.0	4.0	3.0	2.0	1.0	02/06/17
0	1/4" LS CHIPS												
0	47B GRAVEL-LR												
0	WASH SAND-WSG												
15	LS MAN SAND-MM		100.0	100.0	100.0	100.0	94.0	64.0	32.0	12.0	3.0	1.5	02/06/17
25	3A CSG-VONTZ CONST.		100.0	100.0	100.0	100.0	93.0	56.0	34.0	20.0	12.0	5.5	02/06/17
5	RAS		100.0	100.0	100.0	100.0	99.0	95.0	79.0	61.0	53.0	32.0	02/06/17
35	RAP		100.0	100.0	97.0	94.0	83.0	64.0	47.0	34.0	22.0	9.0	02/06/17
100	BLEND		100.0	100.0	96.0	93.4	76.6	51.5	34.2	22.1	14.1	6.6	
								*				*	* INDEPENDENT ADJ.

GRADATION BAND % PASSING

SIEVE	"SPR" BAND	
200	4.0	9.0
50	12.0	21.0
30		
16		
8	46.0	56.0
4		
3/8"	81.0	96.0
1/2"		
3/4"		
1"		

TEST COMPARISON

	CAL. BLEND	CITY LAB		IGNITION
#200	6.6	5.9	7.9	7.0
#50	14.1	13.1	14.9	14.7
#30	22.1	20.8	23.6	23.2
#16	34.2	32.4	35.5	35.6
#8	51.5	51.0	56.0	53.6
#4	76.6	77.4	80.3	76.2
3/8"	93.4	94.5	95.1	92.7
1/2"	96.0	96.8	97.2	94.4
3/4"	100.0	99.9	100.0	100.0
1"	100.0	100.0	100.0	100.0

POWER

	.45
0	0.000
	0.312
	0.582
	0.795
	1.077
	1.472
	2.016
	2.754
100	3.116
	3.762
	4.257

CATHER CONST. TYPE 2 (SPR) 2017-01		CITY LAB TESTS AGGREGATE GRADATIONS											
%	MATERIAL	S.G.	1"	3/4	1/2	3/8	#4	#8	#16	#30	#50	#200	SOURCE
0	2A GRAVEL-LR												
0	QTZ. MAN SAND-EVERIST												
0	QTZ. 3/4" ROCK												
0	QTZ. 3/16" DOWN												
0	5/8" SPECIAL-KER.												
15	3/8" LS CHIPS-MM		100.0	100.0	100.0	99.3	35.9	3.2	1.6	1.2	1.1	1.0	02/13/17
0	SCREENINGS-KER.												
5	3/4" LS-MM		100.0	98.9	43.0	12.6	6.3	4.6	3.1	2.2	1.7	1.4	02/13/17
0	1/4" LS CHIPS												
0	47B GRAVEL-LR												
0	WASH SAND-WSG												
15	LS MAN SAND-MM		100.0	100.0	100.0	100.0	92.1	59.3	27.0	9.8	2.8	1.2	02/13/17
25	3A CSG-VONTZ CONST.		100.0	100.0	100.0	100.0	92.0	53.1	29.6	16.7	9.6	3.8	02/13/17
5	RAS		100.0	100.0	100.0	100.0	98.2	94.3	76.3	59.0	50.2	29.4	02/13/17
35	RAP		100.0	100.0	98.9	97.1	85.5	66.9	47.8	34.0	21.4	8.8	02/13/17
100	BLEND		100.0	99.9	96.8	94.5	77.4	51.0	32.4	20.8	13.1	5.9	
								*				*	* INDEPENDENT ADJ.

Figure A-14. Asphalt Material Specifications, Test No. OSSB-1

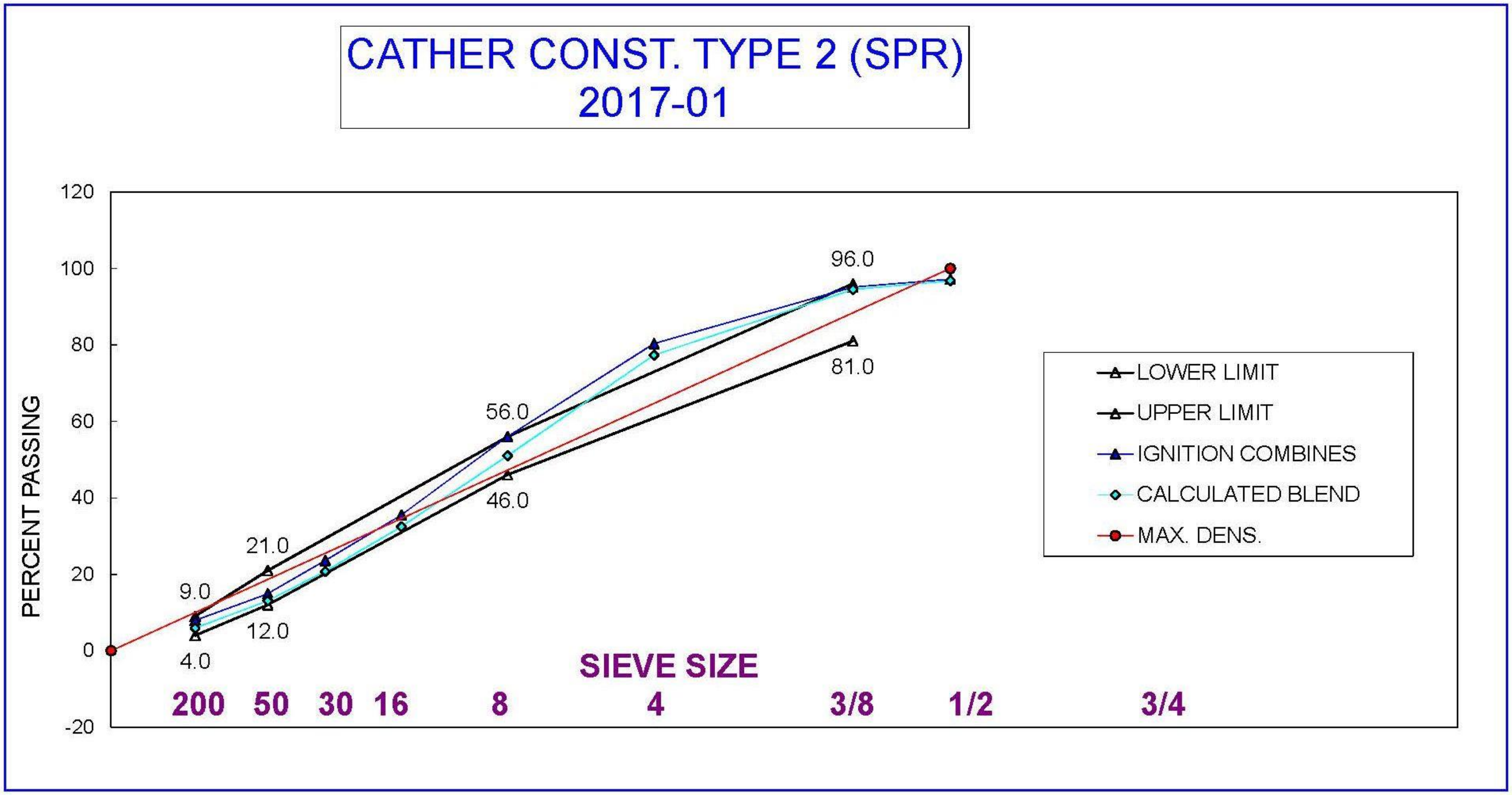


Figure A-15. Asphalt Material Specifications, Test No. OSSB-1

03/13/17

SUPERPAVE TESTING RESULTS

SAMPLE NUM.:	2017-005	DATE:	03/03/17	LOT :	TON :
PLANT:	CATHER CONST.	PROJECT NUM.:	540624	LANE :	LIFT :
MIX TYPE:	2 NON-ARTERIAL	LOCATION:	2017-01 MIX DESIGN VERIFY		
PLACED BY:	CATHER CONST.	JOBMIX:	2017-01	AC SOURCE	MONARCH
TARGET Pb	5.20	35%-RAP		AC GRADE	64-34
Pb (Ignition)	5.39	25%-3A CSG		Gb @ 60 F	1.0370
Pbe	3.95	15%-LS MAN SAND		Gb @ 77 F	1.0309
Gmm (Rice)	2.464	15%-3/8" LS CHIPS			DESIGN
Gsb (Agg.)	2.574	05%-3/4" LS ROCK		FAA	44.4
Gse	2.676	05%-RAS		CAA	96/84

GYRATORY VOLUMETRICS

Superpave: SPR			
Level	Nini	Ndes	Nmax
Gyrations	7	65	100
Gmb	2.201	2.393	2.416
%Gmm	89.3	97.1	98.1
Spec.	N/A	96.0-98.0	N/A
	Va	2.9	3 +/- 1
	VMA	12.0	12 Min.
	VFA	76.1	70-80
Mix Adjusted to 3.0 % Air Voids			
	Pb (Est.)	5.35	

IGNITION COMBINES

	BAND	SPR
1"	100.0	
3/4"	100.0	
5/8"		
1/2"	97.2	
3/8"	95.1	81/96
#4	80.3	
#8	56.0	46/56
#10		
#16	35.5	
#30	23.5	
#50	14.9	12/21
#200	7.9	4/9
DP	1.5	0.7-1.7

DENSITY CORE RESULTS

CORE NUM.	THICKNESS (in.)	SG CORE	COMPACTION (%)	DATE (MM/DD/YY) RECD.	TESTED	DAYS
1					N/A	
2					N/A	
3				AVG. COMPACT. (%)		

Figure A-16. Asphalt Material Specifications, Test No. OSSB-1

Appendix B. Vehicle Center of Gravity Determination

Date:	**12/13/2017**	**Test Name:**	**OSSB-1**	**VIN:**	**1D7RB1CP0BS685744**
Year:	**2011**	**Make:**	**Dodge Ram 1500**	**Model:**	**1500 Crew Cab**

Vehicle CG Determination

VEHICLE	Equipment	Weight (lb.)	Vertical CG (in.)	Vertical M (lb.-in.)
+	Unballasted Truck (Curb)	5122	28 1/4	144696.5
+	Hub	19	15	285
+	Brake activation cylinder & frame	7	26	182
+	Pneumatic tank (Nitrogen)	22	27	594
+	Strobe/Brake Battery	6	26	156
+	Brake Receiver/Wires	6	51	306
+	CG Plate including DAS	50	31 1/2	1575
-	Battery	-37	42	-1554
-	Oil	-9	16 1/2	-148.5
-	Interior	-82	27	-2214
-	Fuel	-160	19 1/2	-3120
-	Coolant	-11	35	-385
-	Washer fluid	-4	35	-140
+	Water Ballast (In Fuel Tank)	64	17	1088
+	Onboard Supplemental Battery	13	26	338
				0
				141659

Note: (+) is added equipment to vehicle, (-) is removed equipment from vehicle

Estimated Total Weight (lb.) 5006
Vertical CG Location (in.) 28.2978

Vehicle Dimensions for C.G. Calculations

Wheel Base: 140 1/4 in.
Front Track Width: 67 1/8 in.
Rear Track Width: 67 5/8 in.

Center of Gravity	2270P MASH Targets	Test Inertial	Difference
Test Inertial Weight (lb.)	5000 ± 110	5001	1.0
Longitudinal CG (in.)	63 ± 4	61.220906	-1.77909
Lateral CG (in.)	NA	0.4109053	NA
Vertical CG (in.)	28 or greater	28.30	0.29784

Note: Long. CG is measured from front axle of test vehicle

Note: Lateral CG measured from centerline - positive to vehicle right (passenger) side

CURB WEIGHT (lb.)

	Left	Right
Front	1514	1371
Rear	1085	1152

FRONT	2885	lb.
REAR	2237	lb.
TOTAL	5122	lb.

TEST INERTIAL WEIGHT (lb.)

	Left	Right
Front	1421	1397
Rear	1049	1134

FRONT	2818	lb.
REAR	2183	lb.
TOTAL	5001	lb.

Figure B-1. Vehicle Mass Distribution, Test No. OSSB-1

Appendix C. Vehicle Deformation Records

Date: 1/22/2018 Test Name: OSSB-1 VIN: 1D7RB1CP0BS685744
Year: 2011 Make: Dodge Ram 1500 Model: 1500 Crew Cab

VEHICLE PRE/POST CRUSH
FLOORPAN - SET 1

POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)	Total Δ (in.)
1	58.453	-34.992	-2.511	bad data	bad data	bad data	bad data	bad data	bad data	bad data
2	58.802	-29.950	-2.391	57.087	-29.419	-1.682	-1.715	0.531	0.710	1.931
3	58.941	-24.593	-2.413	58.475	-24.438	-2.980	-0.466	0.155	-0.566	0.749
4	59.023	-20.902	-2.395	58.965	-20.858	-3.131	-0.059	0.044	-0.736	0.740
5	54.854	-34.497	-4.134	53.660	-34.024	-4.072	-1.194	0.473	0.062	1.285
6	55.559	-29.739	-4.097	54.961	-29.480	-4.518	-0.597	0.259	-0.422	0.776
7	55.944	-24.481	-3.981	55.764	-24.295	-4.830	-0.180	0.185	-0.849	0.887
8	56.132	-21.011	-3.959	55.928	-20.907	-4.562	-0.204	0.103	-0.602	0.644
9	52.199	-34.252	-4.804	51.916	-33.961	-5.919	-0.283	0.290	-1.115	1.187
10	52.451	-29.469	-4.816	52.159	-29.209	-5.616	-0.292	0.260	-0.800	0.890
11	52.741	-23.984	-4.838	52.538	-23.769	-5.486	-0.203	0.215	-0.648	0.712
12	52.446	-20.087	-4.860	52.218	-19.862	-5.189	-0.229	0.225	-0.329	0.460
13	49.211	-34.236	-4.818	48.981	-34.023	-6.049	-0.230	0.213	-1.232	1.271
14	49.335	-29.556	-4.821	49.119	-29.359	-5.782	-0.216	0.196	-0.961	1.004
15	49.522	-24.148	-4.837	49.252	-23.969	-5.433	-0.270	0.179	-0.596	0.678
16	49.642	-20.105	-4.862	49.430	-19.877	-5.175	-0.211	0.228	-0.314	0.442
17	45.746	-33.958	-4.802	45.563	-33.763	-6.082	-0.184	0.195	-1.280	1.308
18	46.205	-29.495	-4.807	45.990	-29.302	-5.768	-0.215	0.194	-0.961	1.003
19	46.292	-24.128	-4.829	46.090	-23.892	-5.361	-0.201	0.236	-0.532	0.616
20	46.421	-20.125	-4.858	46.242	-19.943	-5.117	-0.178	0.182	-0.259	0.363
21	41.291	-33.787	-4.887	41.154	-33.646	-5.634	-0.137	0.141	-0.748	0.773
22	41.578	-29.358	-4.859	41.439	-29.195	-5.578	-0.139	0.163	-0.719	0.751
23	41.742	-24.237	-4.886	41.498	-24.083	-5.278	-0.244	0.154	-0.392	0.486
24	41.994	-20.167	-4.925	41.694	-19.978	-5.128	-0.300	0.190	-0.203	0.409
25	34.203	-33.642	-0.911	34.203	-33.674	-1.189	0.000	-0.033	-0.278	0.280
26	34.419	-29.539	-0.888	34.362	-29.527	-1.112	-0.057	0.012	-0.224	0.232
27	34.434	-24.212	-0.918	34.365	-24.190	-1.072	-0.069	0.022	-0.154	0.170
28	34.446	-20.251	-0.944	34.327	-20.198	-1.091	-0.119	0.053	-0.147	0.197

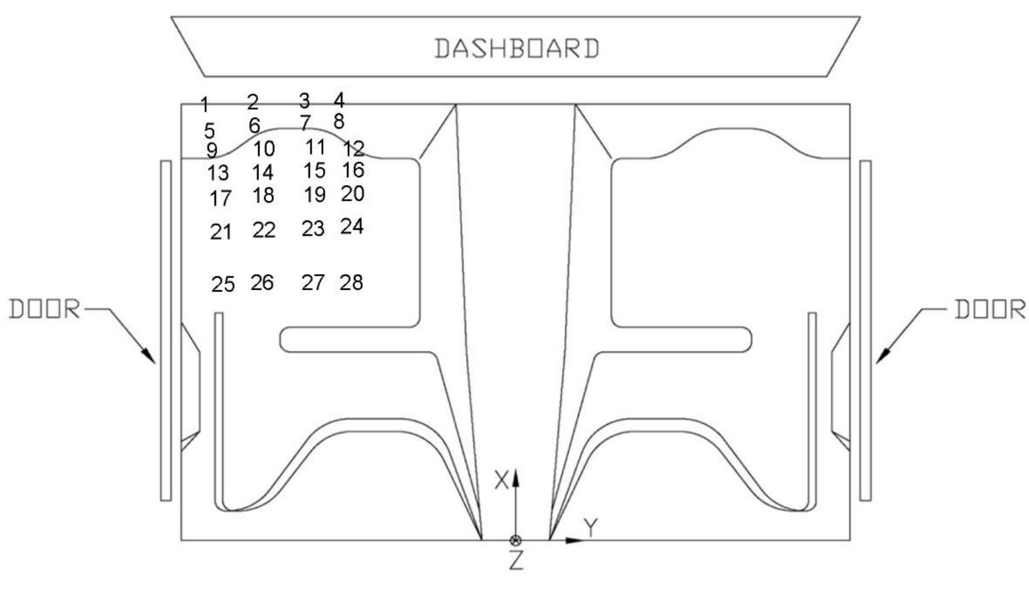


Figure C-1. Floor Pan Deformation Data – Set 1, Test No. OSSB-1

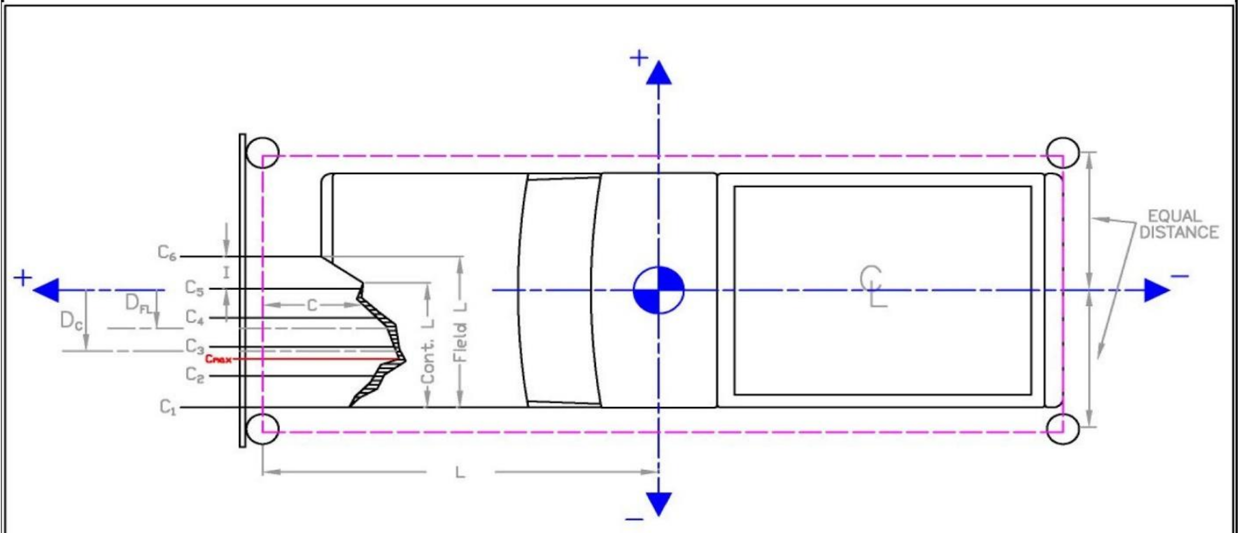
Date: 1/22/2018 Test Name: OSSB-1 VIN: 1D7RB1CP0BS685744
Year: 2011 Make: Dodge Ram 1500 Model: 1500 Crew Cab

VEHICLE PRE/POST CRUSH
INTERIOR CRUSH - SET 1

	POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)	Total Δ (in.)
DASH	1	50.384	-36.835	27.177	49.971	-37.030	27.624	-0.413	-0.194	0.447	0.638
	2	47.353	-26.117	30.087	47.162	-26.312	30.450	-0.192	-0.195	0.363	0.454
	3	49.664	-8.345	28.073	49.459	-8.619	27.990	-0.205	-0.274	-0.083	0.352
	4	45.571	-36.069	16.440	44.979	-36.246	17.062	-0.592	-0.177	0.622	0.877
	5	44.459	-25.889	23.799	bad data	bad data	bad data	bad data	bad data	bad data	bad data
	6	43.349	-7.355	15.459	43.074	-7.632	15.550	-0.275	-0.277	0.092	0.401
SIDE PANEL	7	57.209	-39.772	4.959	56.305	-38.797	5.446	-0.904	0.975	0.487	1.416
	8	54.262	-39.596	6.062	53.398	-38.357	6.528	-0.863	1.239	0.466	1.580
	9	54.214	-39.585	3.008	53.394	-38.223	3.431	-0.820	1.362	0.423	1.645
IMPACT SIDE DOOR	10	22.724	-41.728	16.599	21.871	-42.920	16.693	-0.853	-1.192	0.094	1.469
	11	30.874	-41.642	17.124	29.979	-42.767	17.357	-0.895	-1.125	0.233	1.457
	12	41.904	-41.610	15.551	41.030	-42.256	15.866	-0.875	-0.646	0.315	1.132
	13	24.713	-41.162	1.466	24.063	-41.613	1.589	-0.650	-0.451	0.123	0.801
	14	32.004	-41.802	0.719	31.297	-42.217	0.921	-0.707	-0.415	0.202	0.844
	15	39.946	-42.306	1.304	39.237	-42.650	1.656	-0.709	-0.344	0.352	0.863
ROOF	16	38.385	-29.202	42.608	38.109	-29.539	42.983	-0.277	-0.337	0.375	0.575
	17	39.455	-25.589	42.793	39.221	-25.949	43.114	-0.234	-0.359	0.321	0.536
	18	40.758	-20.532	42.873	40.608	-20.826	43.124	-0.150	-0.294	0.251	0.415
	19	41.562	-15.171	43.004	41.388	-15.518	43.205	-0.174	-0.347	0.201	0.437
	20	42.021	-8.291	43.107	41.914	-8.622	43.208	-0.107	-0.331	0.101	0.362
	21	32.284	-27.264	45.515	32.077	-27.560	45.766	-0.206	-0.296	0.251	0.440
	22	33.443	-22.758	45.713	33.204	-23.087	45.942	-0.239	-0.329	0.229	0.467
	23	34.497	-17.190	45.871	34.354	-17.469	46.043	-0.143	-0.279	0.172	0.358
	24	35.002	-12.108	45.972	34.853	-12.424	46.073	-0.149	-0.316	0.102	0.364
	25	35.330	-7.440	45.984	35.231	-7.682	46.062	-0.100	-0.243	0.079	0.274
	26	28.945	-26.573	46.114	28.757	-26.851	46.335	-0.189	-0.278	0.221	0.402
	27	29.732	-22.189	46.362	29.513	-22.495	46.562	-0.220	-0.306	0.200	0.427
	28	30.438	-16.888	46.561	30.327	-17.150	46.702	-0.111	-0.262	0.141	0.317
	29	30.765	-11.941	46.671	30.659	-12.186	46.794	-0.105	-0.245	0.122	0.294
	30	30.860	-7.158	46.719	30.793	-7.395	46.793	-0.067	-0.236	0.074	0.257
A PILLAR	31	52.351	-37.935	29.446	52.795	-38.823	28.765	0.443	-0.888	-0.682	1.204
	32	50.137	-37.447	31.098	49.807	-37.990	31.432	-0.330	-0.543	0.334	0.718
	33	46.669	-35.706	32.884	46.390	-36.115	33.298	-0.280	-0.409	0.414	0.646
	34	42.678	-35.236	36.017	42.372	-35.601	36.468	-0.307	-0.365	0.452	0.657
B PILLAR	35	10.918	-38.414	20.342	10.673	-38.629	20.561	-0.245	-0.215	0.219	0.393
	36	14.835	-38.487	20.466	14.581	-38.767	20.676	-0.254	-0.280	0.210	0.433
	37	10.742	-37.496	30.036	10.483	-37.729	30.193	-0.259	-0.234	0.156	0.382
	38	13.915	-37.507	30.167	13.620	-37.751	30.350	-0.295	-0.243	0.183	0.424
	39	9.841	-33.507	41.676	9.560	-33.669	41.845	-0.280	-0.163	0.169	0.366
	40	12.951	-33.629	41.446	12.757	-33.840	41.562	-0.194	-0.211	0.116	0.309

Figure C-2. Occupant Compartment Deformation Data – Set 1, Test No. OSSB-1

Date:	1/22/2018	**Test Name:**	OSSB-1	**VIN:**	1D7RB1CP0BS685744
Year:	2011	**Make:**	Dodge Ram 1500	**Model:**	1500 Crew Cab



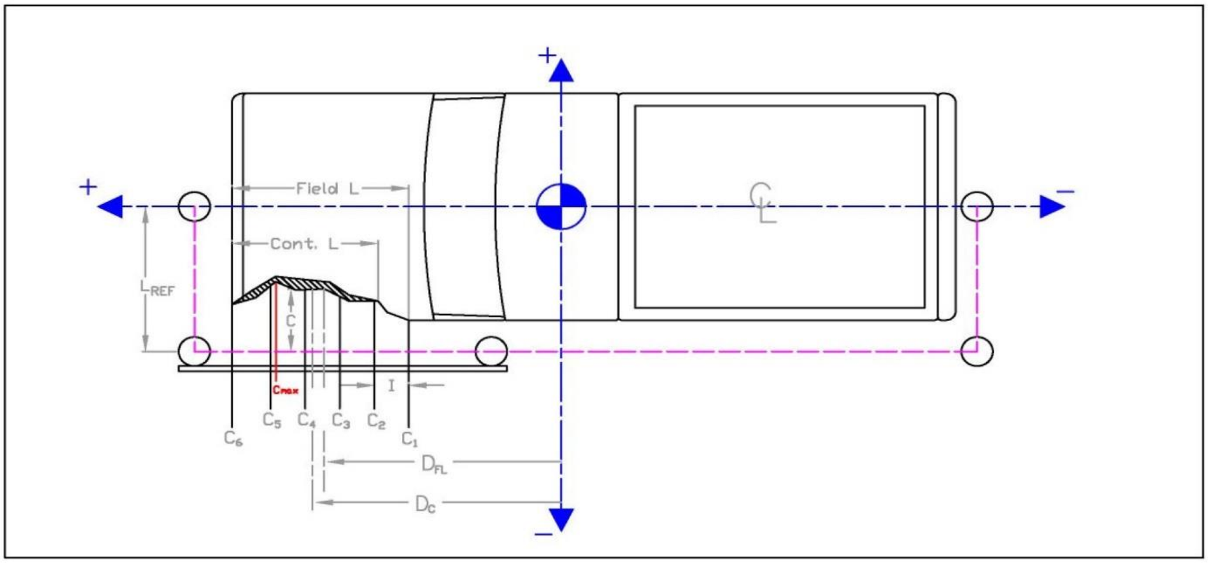
	in.	(mm)
Distance from C.G. to reference line - L_{REF}:	116 1/8	(2950)
Total Vehicle Width:	73	(1854)
Width of contact and induced crush - Field L:	54 1/4	(1378)
Crush measurement spacing interval (L/5) - I:	10 7/8	(276)
Distance from center of vehicle to center of Field L - D_{FL}:	0	()
Width of Contact Damage:	19 3/4	(502)
Distance from center of vehicle to center of contact damage - D_C:	-27	-(686)

NOTE: Enter "NA" for crush measurement if distance can not be measured (i.e., side of vehicle has been pushed inward)
NOTE: All values must be filled out above before crush measurements are filled out.

	Crush Measurement		Lateral Location		Original Profile Measurement		Dist. Between Ref. Lines		Actual Crush	
	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)
C_1	N/A	#VALUE!	-27 1/8	-(689)	7 5/8	(194)	10 5/8	(270)	#VALUE!	#VALUE!
C_2	19	(483)	-16 1/4	-(413)	5	(127)			3 3/8	(86)
C_3	15 1/4	(387)	-5 3/8	-(137)	4 1/8	(105)			1/2	(13)
C_4	14 3/8	(365)	5 1/2	(140)	4 1/8	(105)			- 3/8	-(10)
C_5	15 1/4	(387)	16 3/8	(416)	5	(127)			- 3/8	-(10)
C_6	20	(508)	27 1/4	(692)	7 5/8	(194)			1 3/4	(44)
C_{MAX}	37	(940)	-25 1/2	-(648)	7	(178)			19 3/8	(492)

Figure C-3. Exterior Vehicle Crush (NASS) - Front, Test No. OSSB-1

Date:	1/22/2018	Test Name:	OSSB-1	VIN:	1D7RB1CP0BS685744
Year:	2011	Make:	Dodge Ram 1500	Model:	1500 Crew Cab



	in.	(mm)
Distance from centerline to reference line - L_{REF}:	-54	-(1372)
Total Vehicle Length:	229 3/4	(5836)
Distance from vehicle c.g. to 1/2 of Vehicle total length:	-11 5/8	-(295)
Width of contact and induced crush - Field L:	229 3/4	(5836)
Crush measurement spacing interval (L/5) - I:	46	(1168)
Distance from vehicle c.g. to center of Field L - D_{FL}:	-36	-(913)
Width of Contact Damage:	229 3/4	(5836)
Distance from vehicle c.g. to center of contact damage - D_C:	-36	-(913)

NOTE: Enter "NA" for crush measurement if distance can not be measured (i.e., front of vehicle has been pushed inward or tire has been removed)

NOTE: All values must be filled out above before crush measurements are filled out.

	Crush Measurement		Longitudinal Location		Original Profile Measurement		Dist. Between Ref. Lines		Actual Crush	
	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)
C_1	N/A	#VALUE!	-150 7/8	-(3832)	33 1/2	(851)	-98	-(2489)	#VALUE!	#VALUE!
C_2	18	(457)	-104 7/8	-(2664)	6	(152)			110	(2794)
C_3	15 1/8	(384)	-58 7/8	-(1495)	5 1/2	(140)			107 5/8	(2734)
C_4	13 1/8	(333)	-12 7/8	-(327)	5	(127)			106 1/8	(2696)
C_5	14 1/4	(362)	33 1/8	(841)	5 1/8	(130)			107 1/8	(2721)
C_6	29 5/8	(752)	79 1/8	(2010)	5 3/4	(146)			121 7/8	(3096)
C_{MAX}	29 5/8	(752)	79 1/8	(2010)	5 3/4	(146)			121 7/8	(3096)

Figure C-4. Exterior Vehicle Crush (NASS) - Side, Test No. OSSB-1

Appendix D. Accelerometer and Rate Transducer Data Plots, Test No. OSSB-1

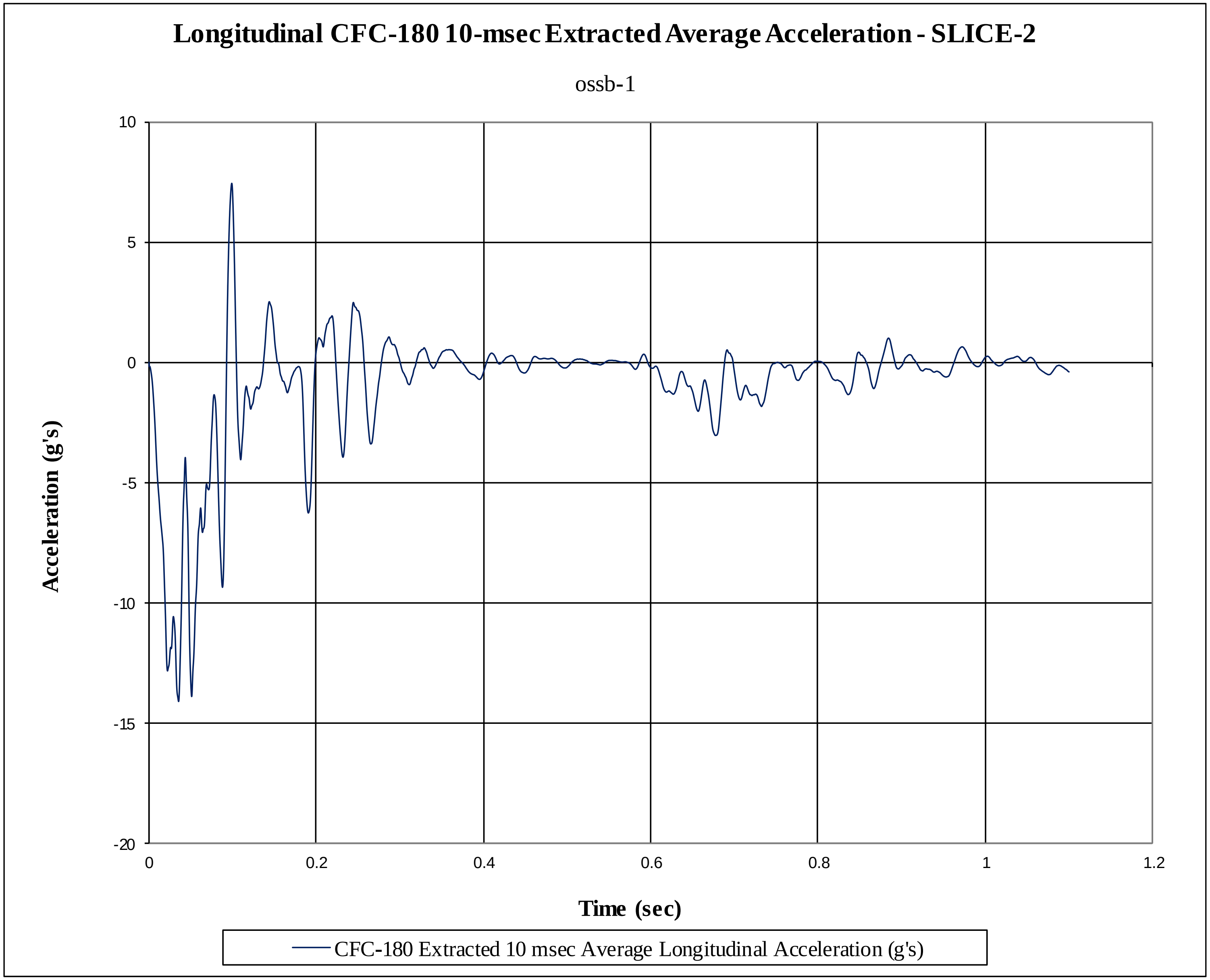


Figure D-1. 10-ms Average Longitudinal Acceleration (SLICE-2), Test No. OSSB-1

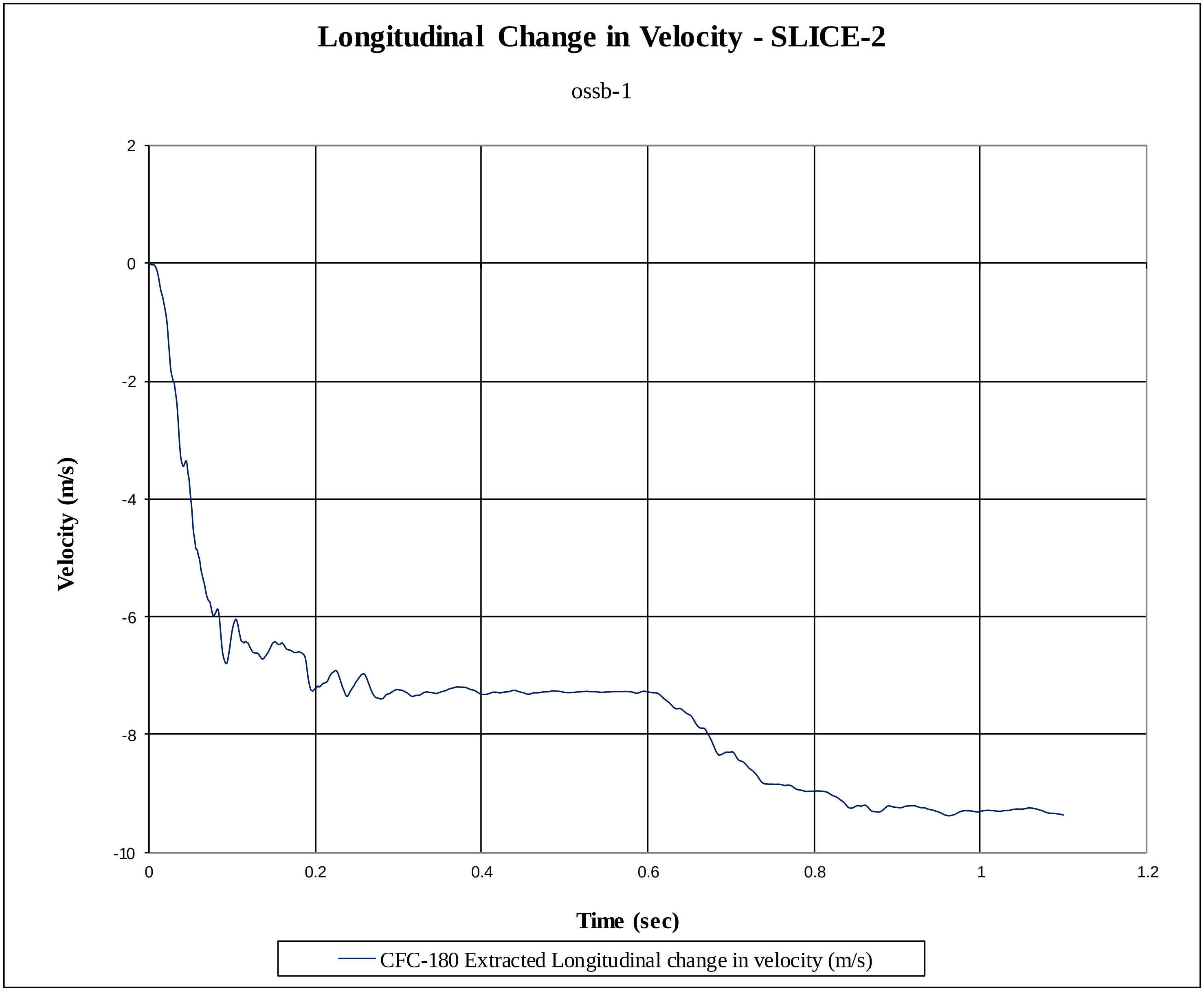


Figure D-2. Longitudinal Occupant Velocity (SLICE-2), Test No. OSSB-1

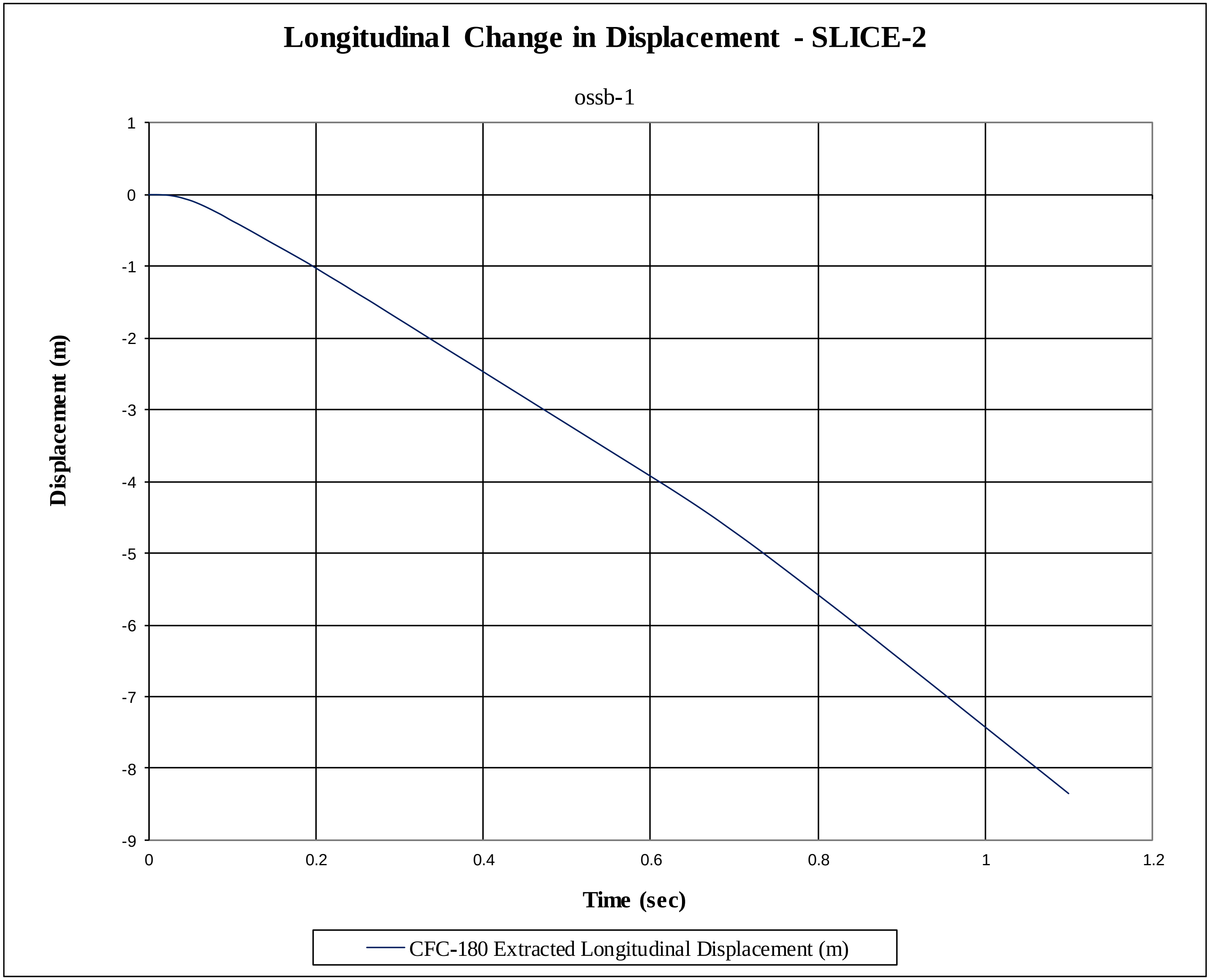


Figure D-3. Longitudinal Occupant Displacement (SLICE-2), Test No. OSSB-1

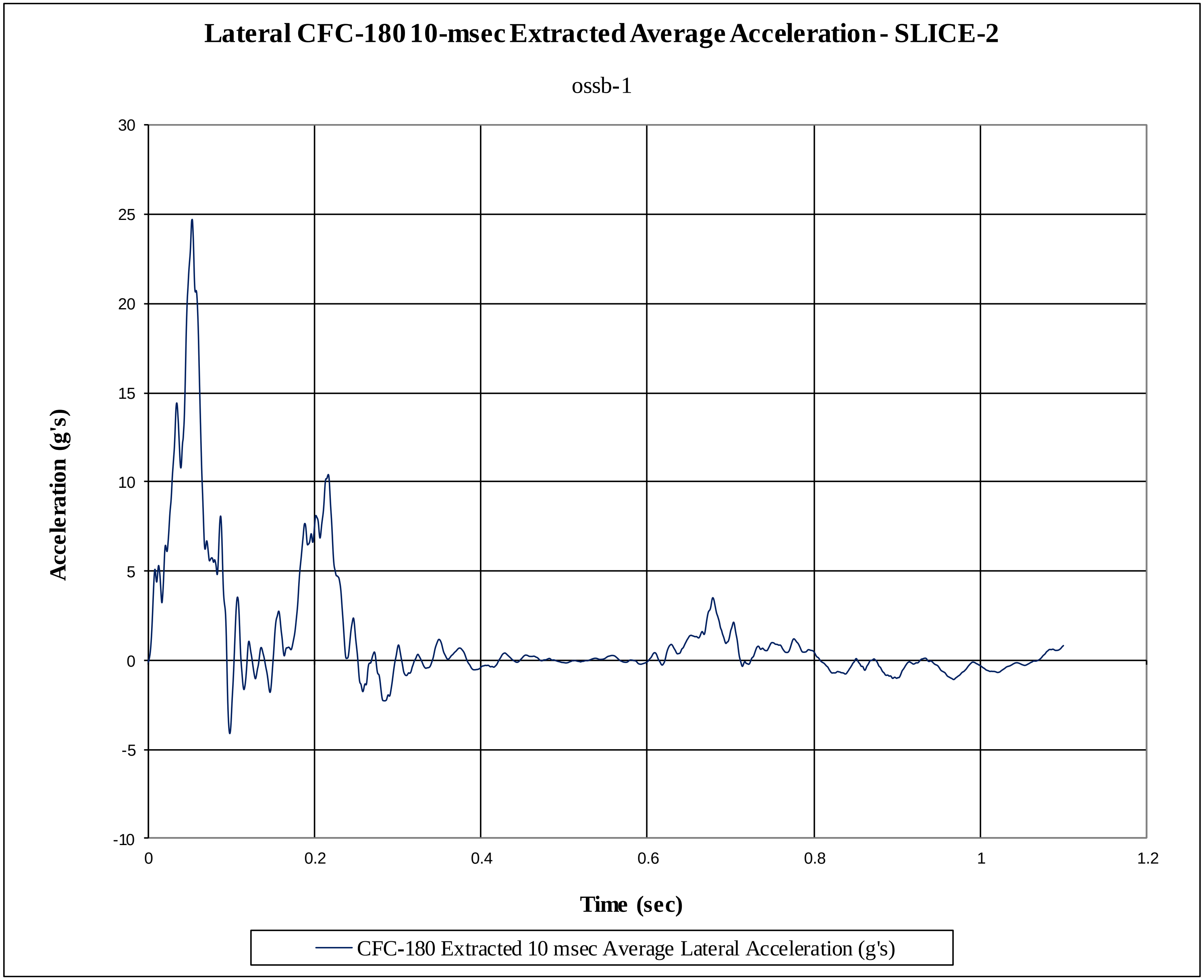


Figure D-4. 10-ms Average Lateral Acceleration (SLICE-2), Test No. OSSB-1

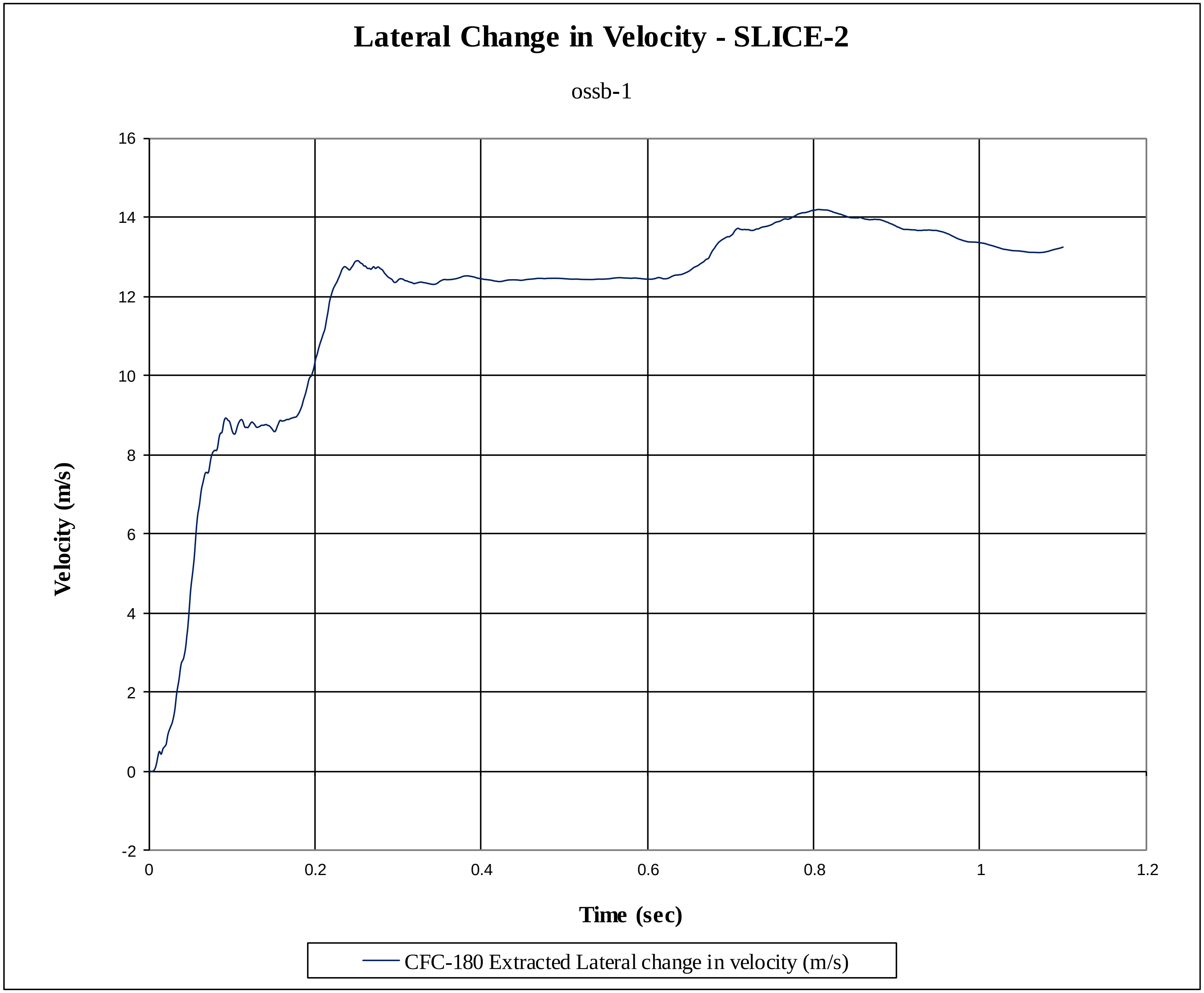


Figure D-5. Lateral Occupant Velocity (SLICE-2), Test No. OSSB-1

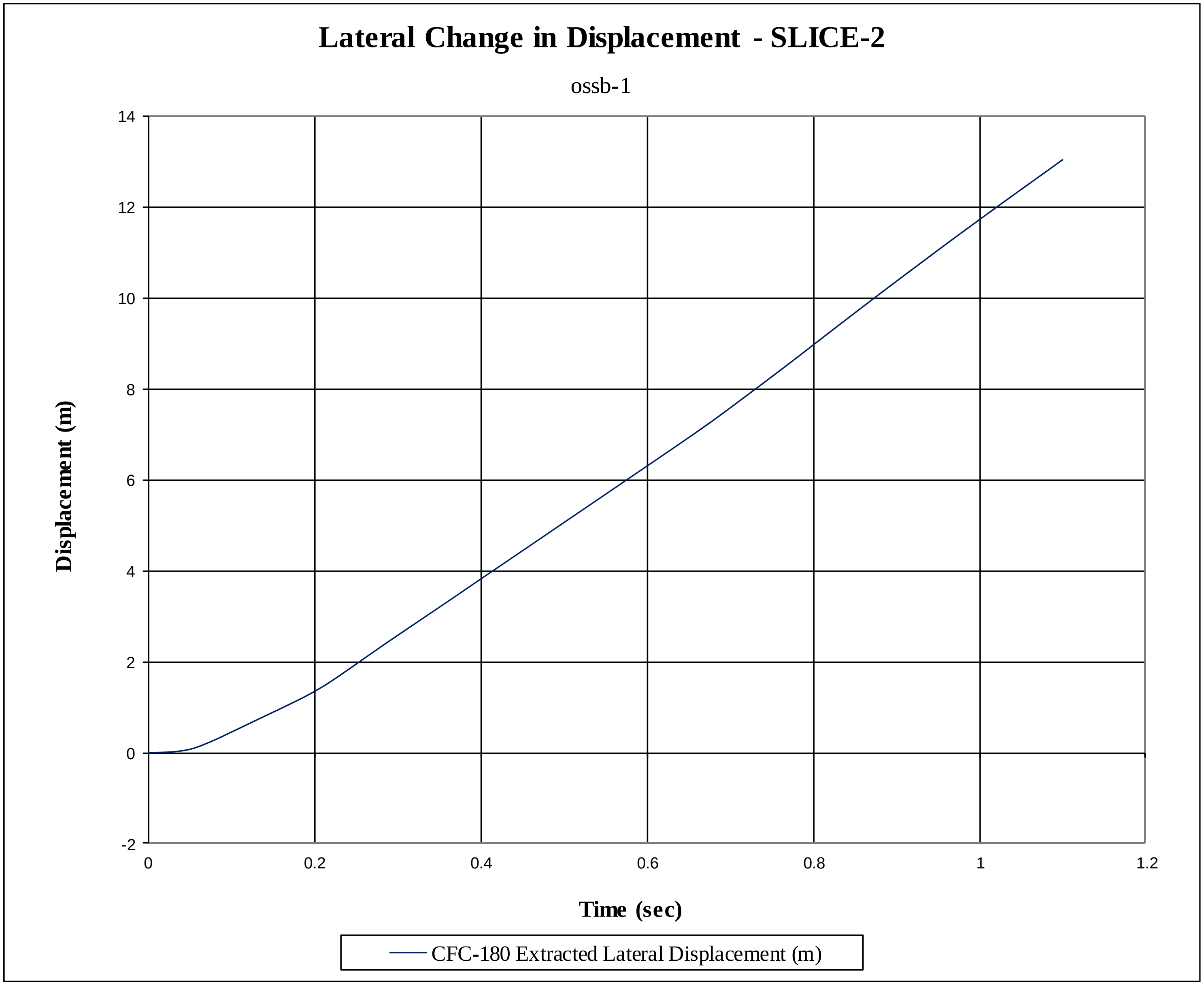


Figure D-6. Lateral Occupant Displacement (SLICE-2), Test No. OSSB-1

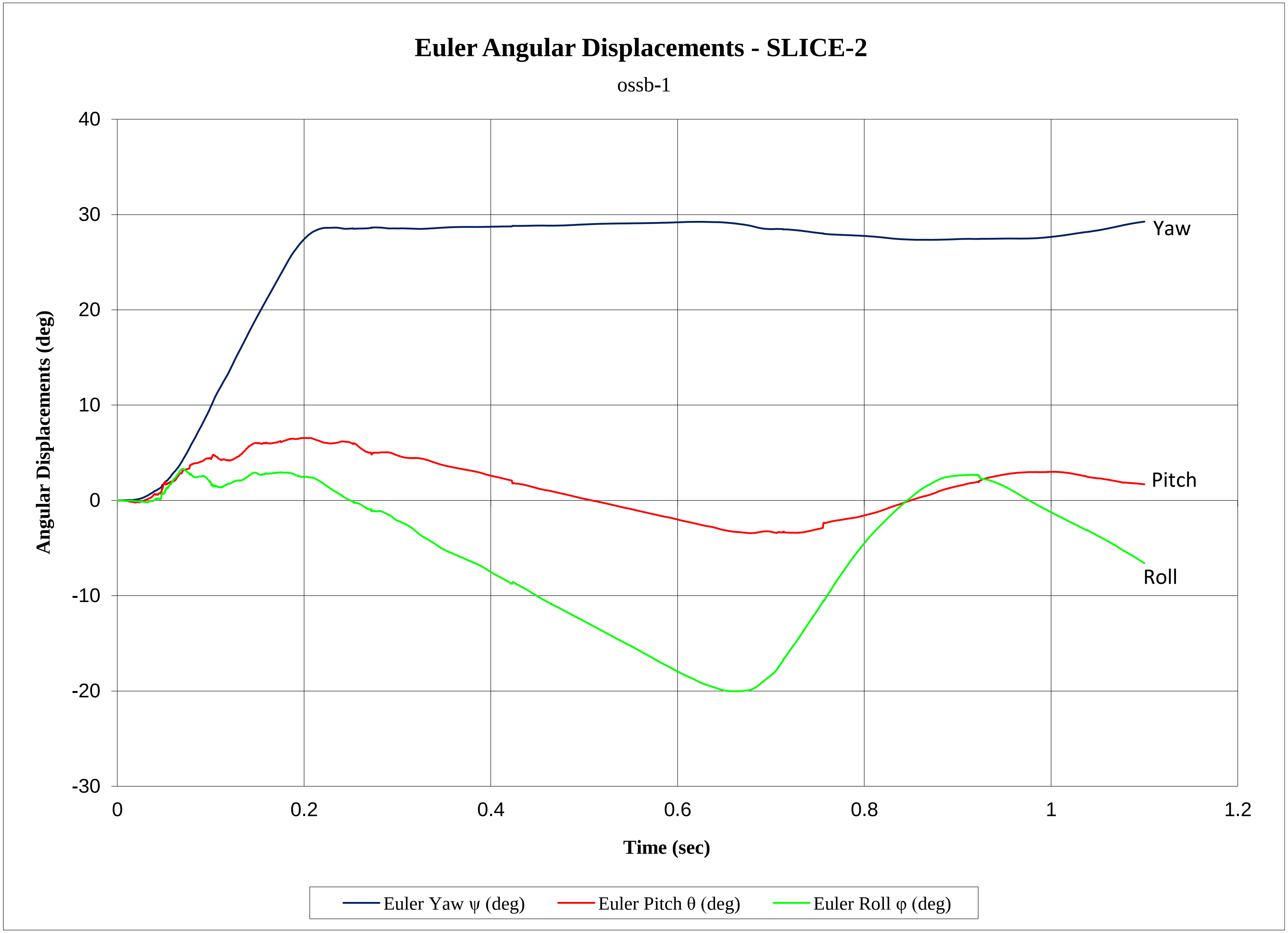


Figure D-7. Vehicle Angular Displacements (SLICE-2), Test No. OSSB-1

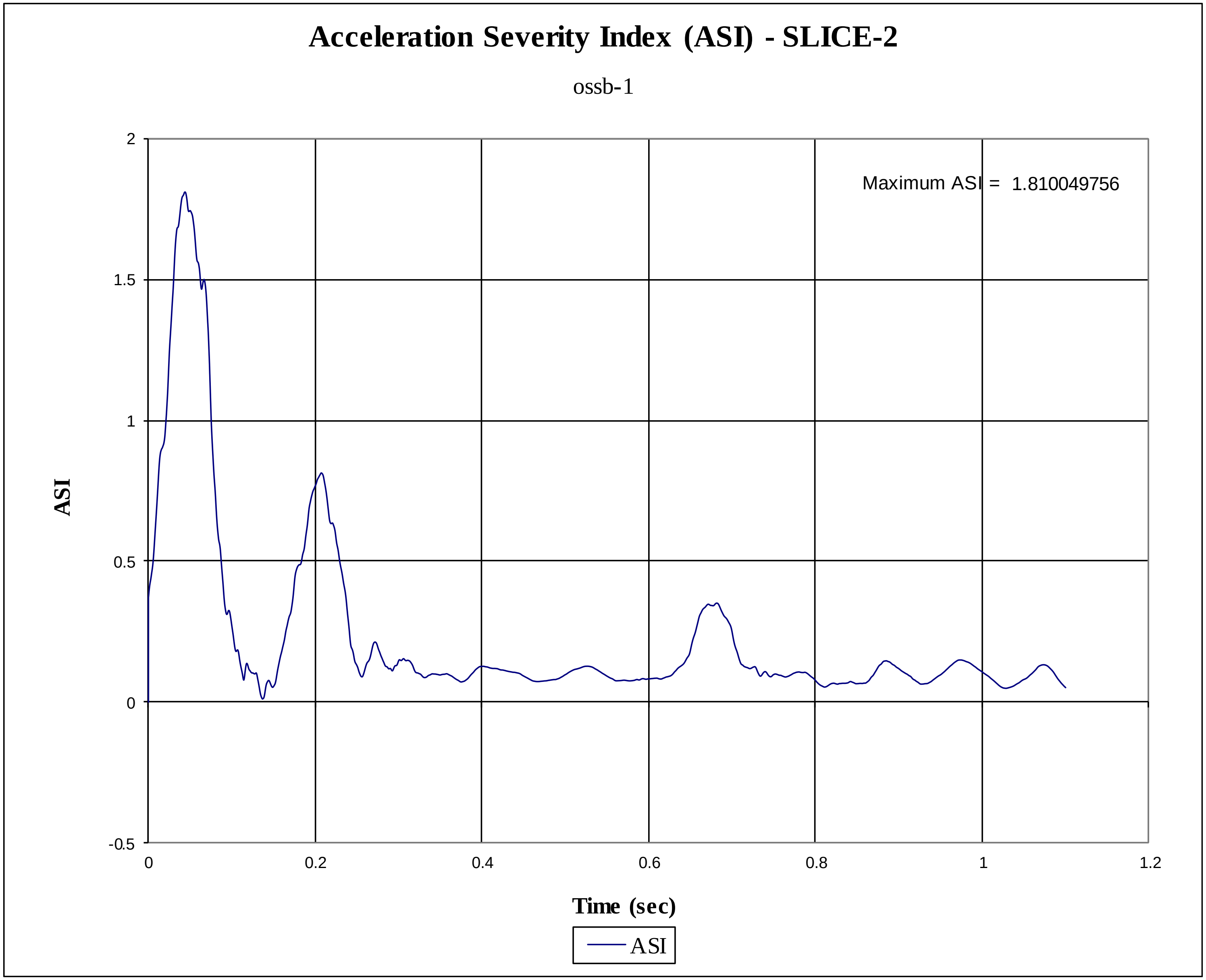


Figure D-8. Acceleration Severity Index (SLICE-2), Test No. OSSB-1

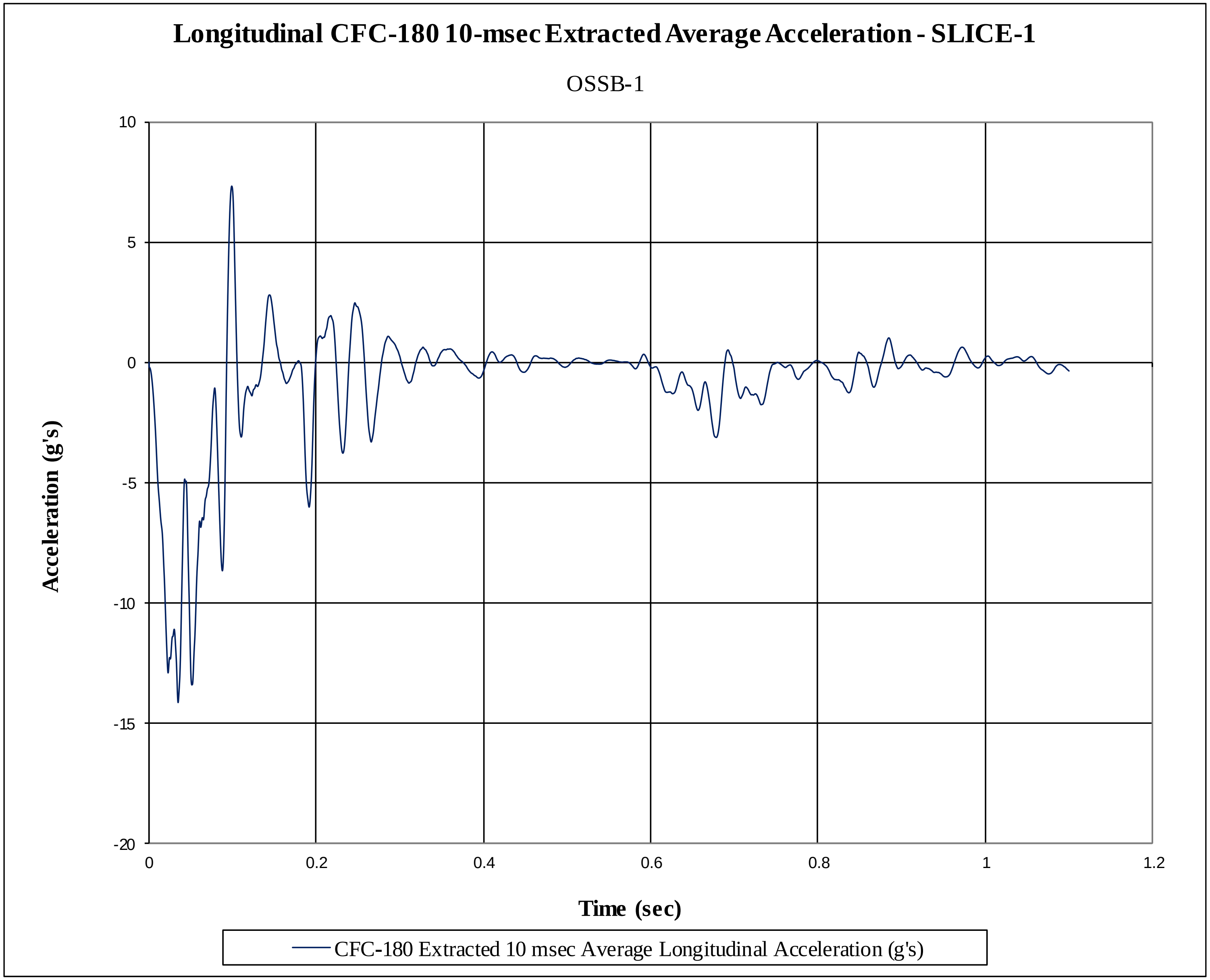


Figure D-9. 10-ms Average Longitudinal Deceleration (SLICE-1), Test No. OSSB-1

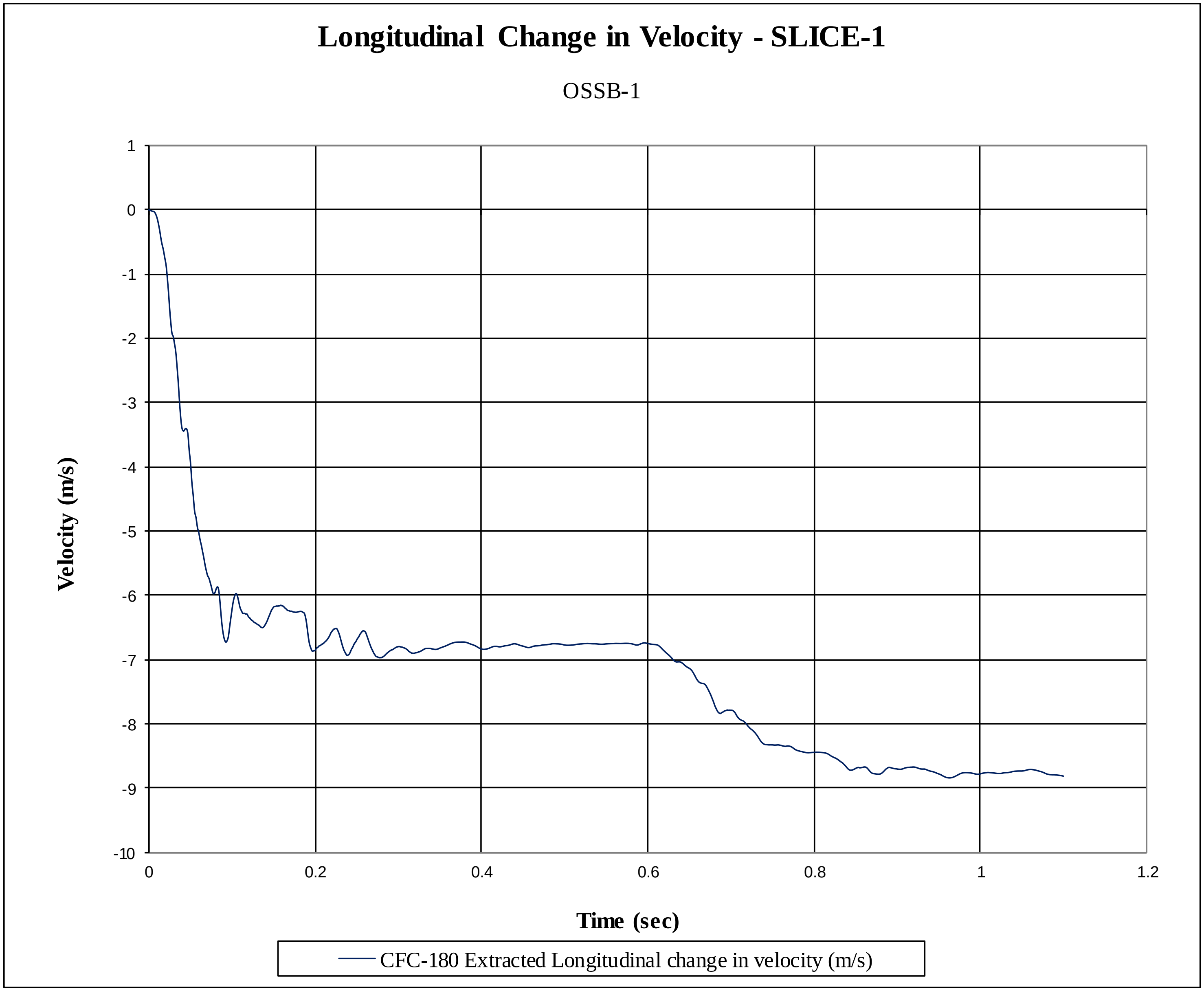


Figure D-10. Longitudinal Occupant Impact Velocity (SLICE-1), Test No. OSSB-1

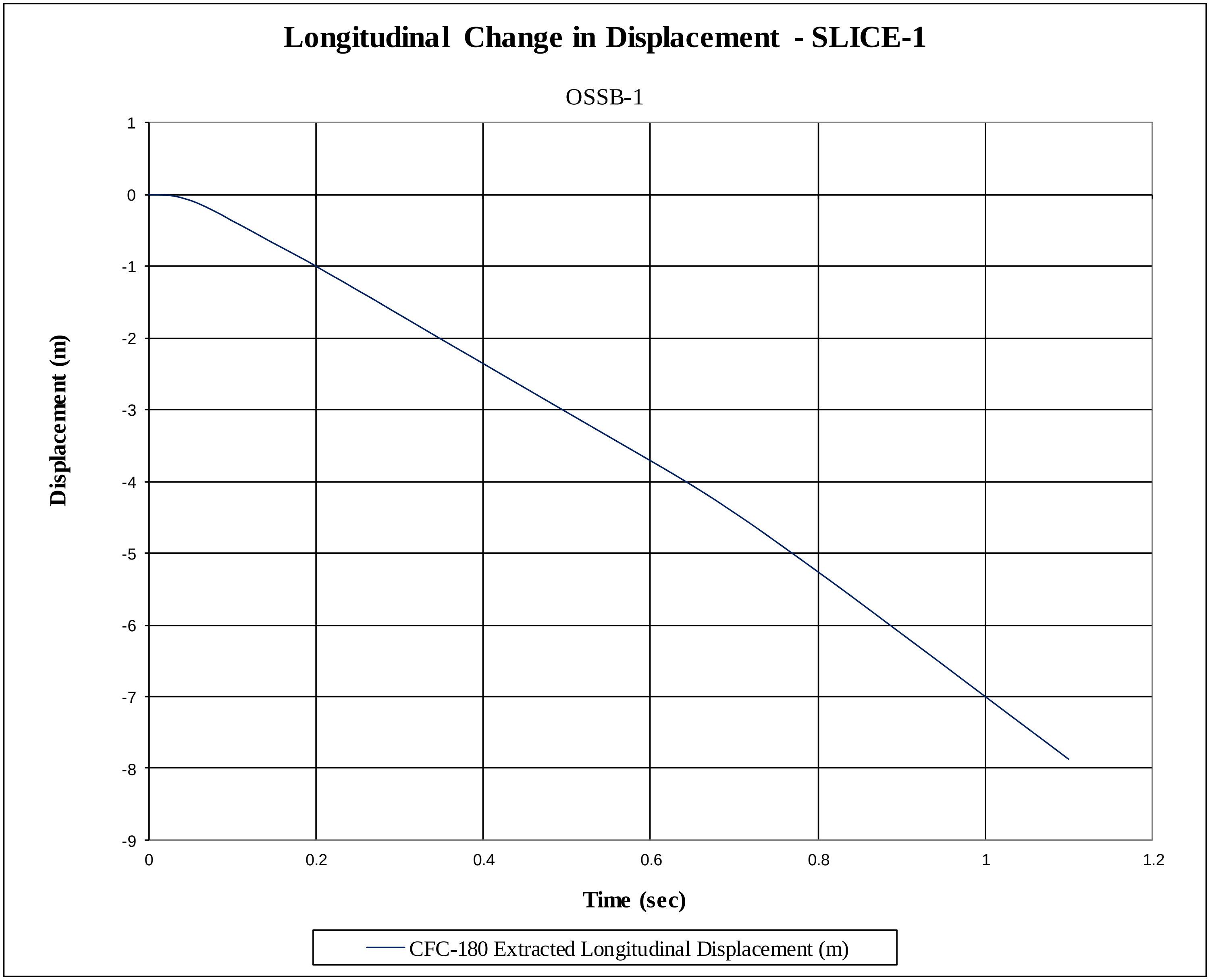


Figure D-11. Longitudinal Occupant Displacement (SLICE-1), Test No. OSSB-1

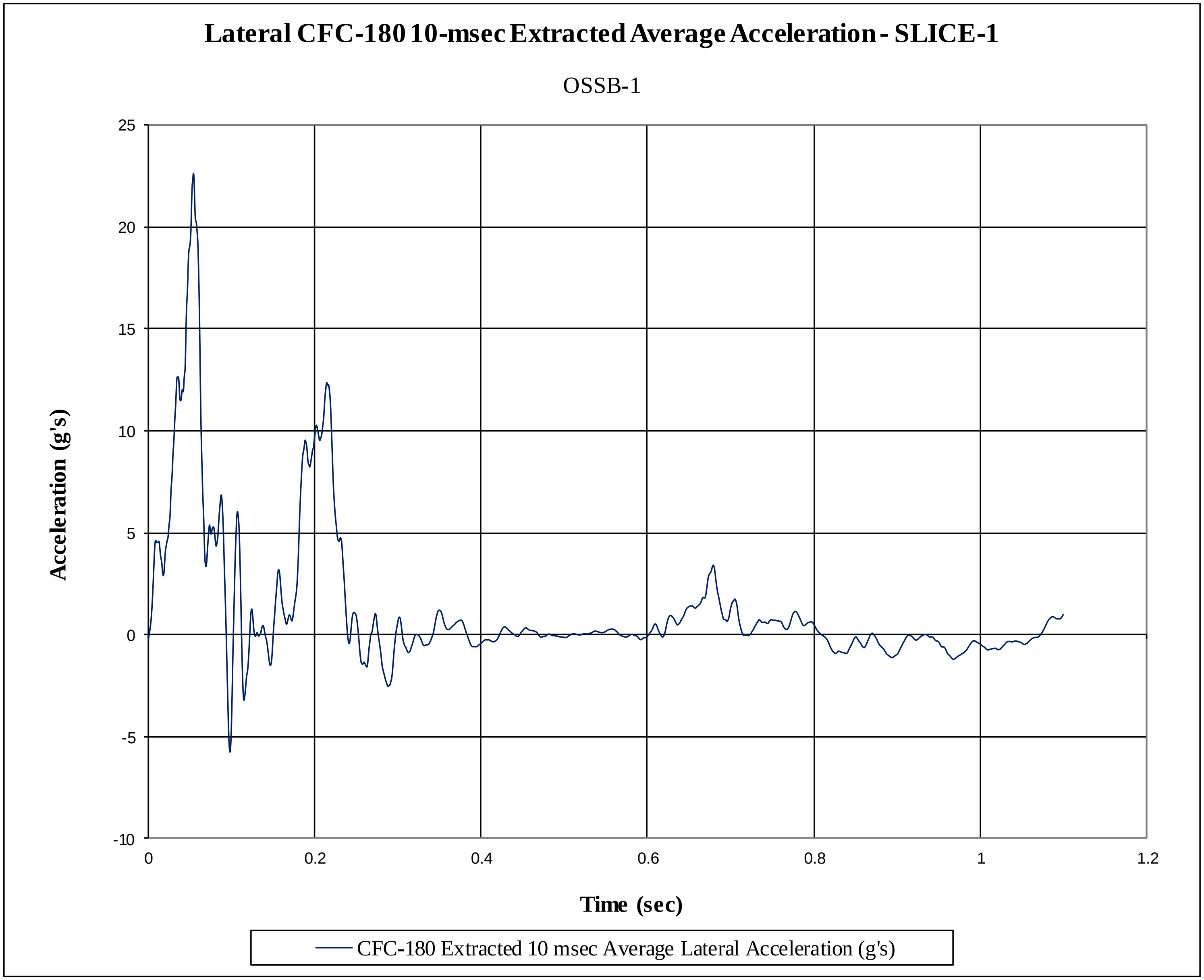


Figure D-12. 10-ms Average Lateral Deceleration (SLICE-1), Test No. OSSB-1

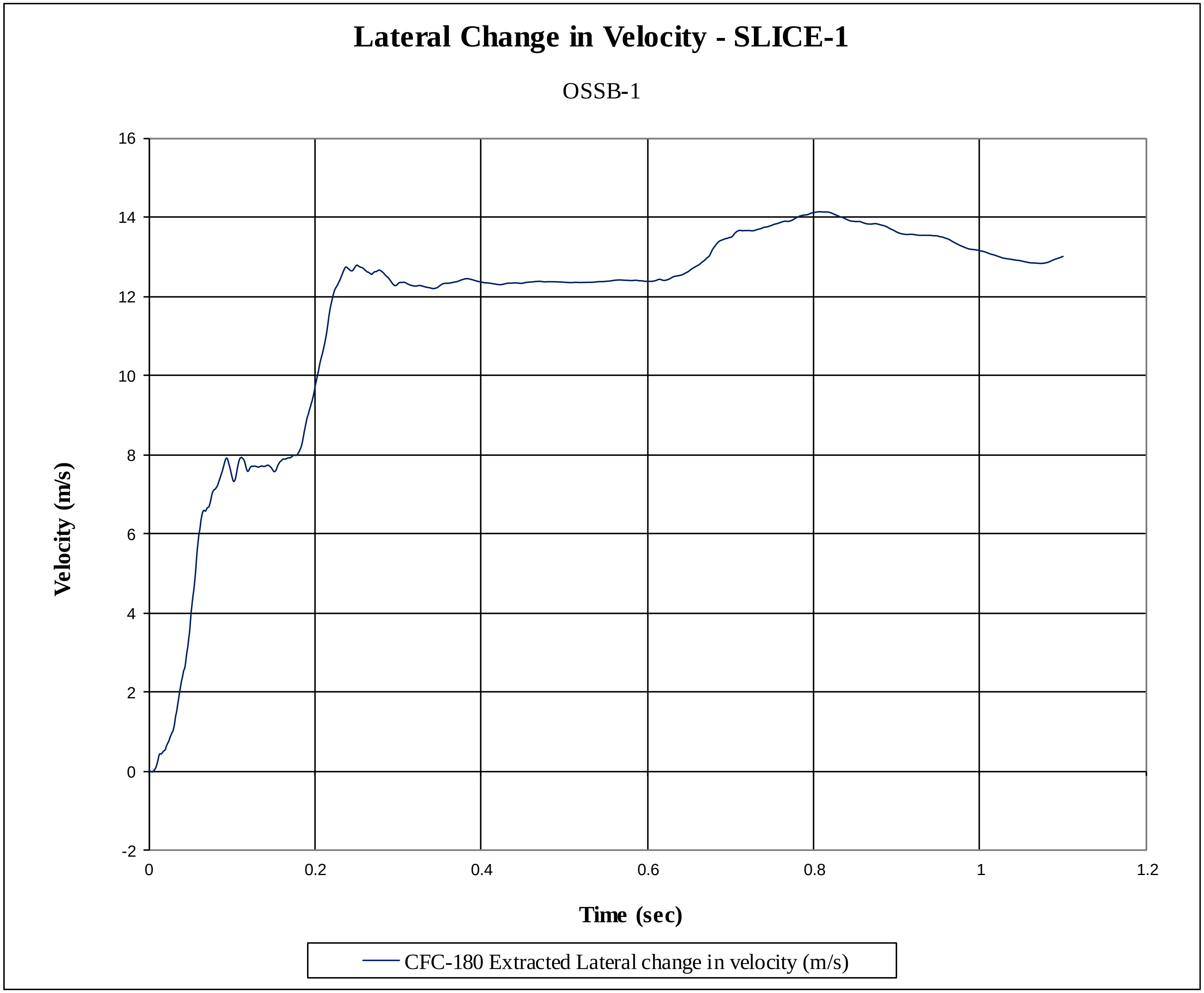


Figure D-13. Lateral Occupant Velocity (SLICE-1), Test No. OSSB-1

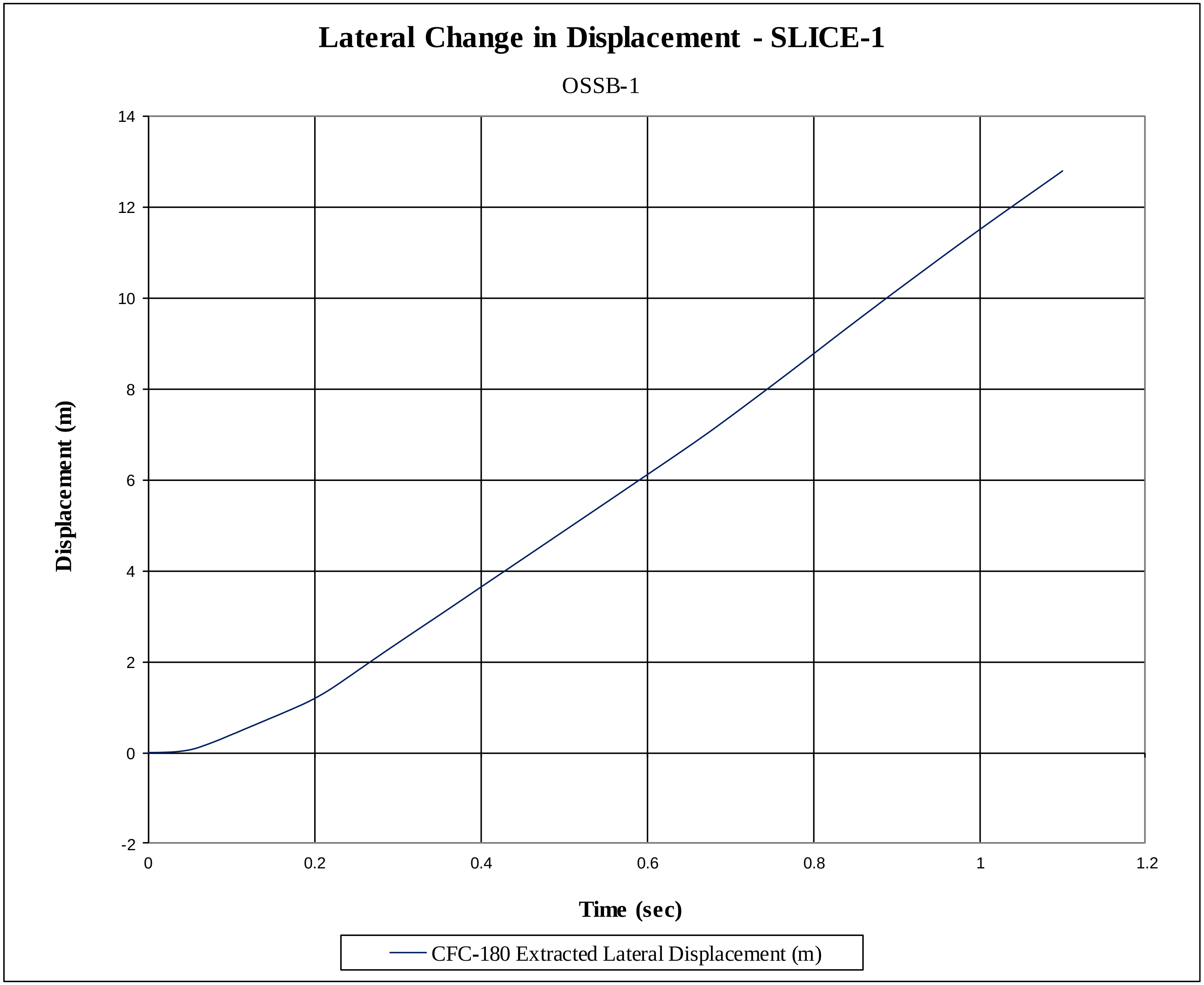


Figure D-14. Lateral Occupant Displacement (SLICE-1), Test No. OSSB-1

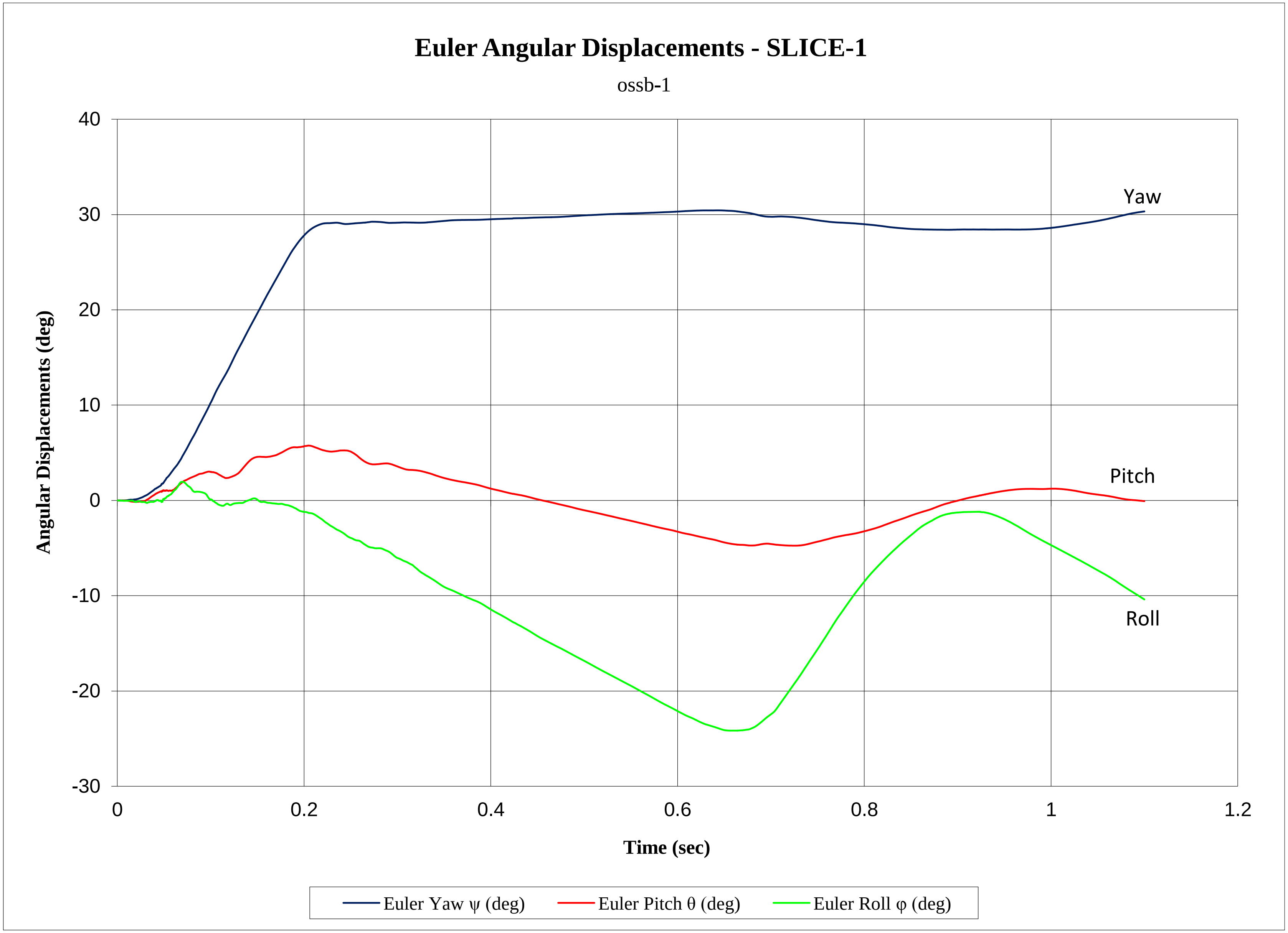


Figure D-15. Vehicle Angular Displacements (SLICE-1), Test No. OSSB-1

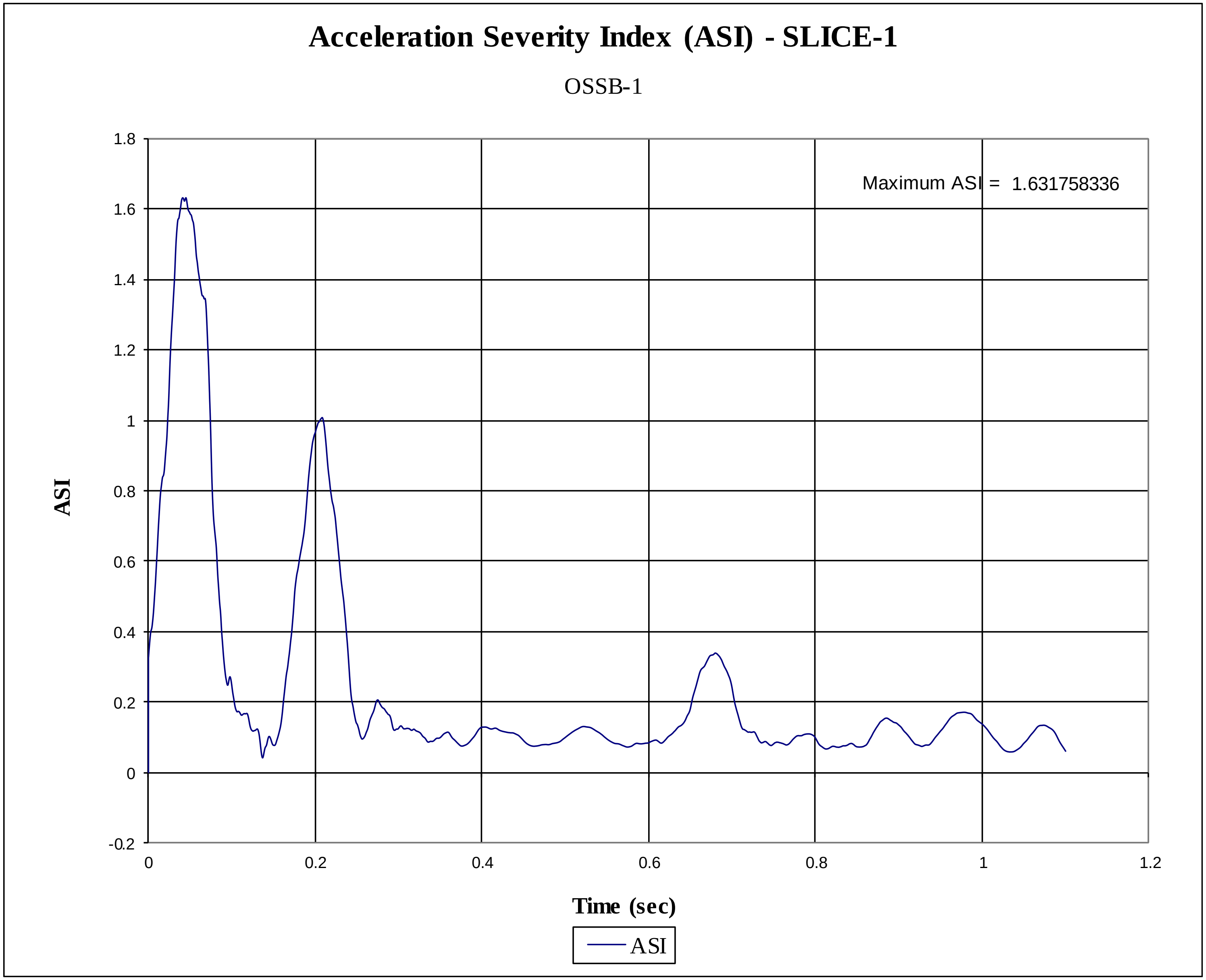


Figure D-16. Acceleration Severity Index (SLICE-1), Test No. OSSB-1

Appendix E. Perpendicular Force Calculation, Test No. OSSB-1

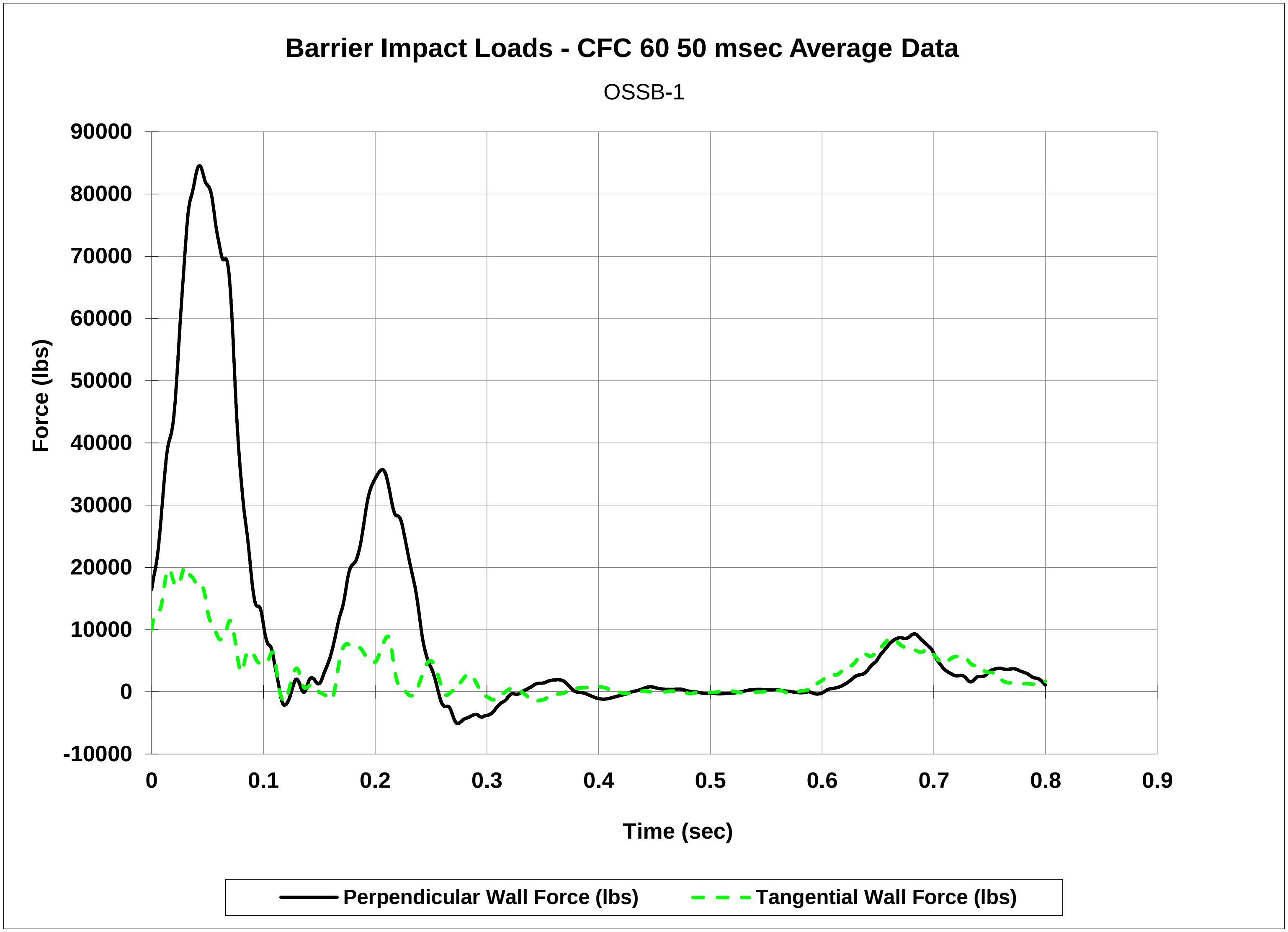


Figure E-1. Perpendicular Forces Imparted to the Barrier System (SLICE-2), Test No. OSSB-1

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