TTI: 0-6968

DEVELOPMENT OF *MASH* TL-3 TRANSITIONS FOR CAST IN PLACE CONCRETE BARRIERS

ACCREDITED
ISO 17025 Laboratory
Testing Certificate # 2821.01

Crash testing performed at:
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Bryan, TX 77807

Test Report 0-6968-R8

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS

TEXAS DEPARTMENT OF TRANSPORTATION

in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
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16. Abstract

The objective of this project was to develop transition designs for three cast in place concrete barrier combinations. These included transitions for connecting (a) TxDOT's 36-inch tall Single Slope Traffic Rail (SSTR) to 42-inch tall Single Slope Concrete Barrier (SSCB), (b) 32-inch tall F-shape concrete barrier to SSCB, and (c) TxDOT's 32-inch tall T221 vertical concrete wall to SSCB. The designs were required to meet AASHTO *MASH* Test Level 3 (TL-3) criteria, and their compliance was to be evaluated using a combination of past testing results, impact simulation analyses, and limited full scale testing. Researchers developed designs and reinforcement details for all three transitions.

The transition from SSTR to SSCB was comprised of a single slope barrier profile on the traffic side. This design did not require simulation or testing due to the known *MASH* compliance of the single slope barrier profile. Researchers developed designs of the other two transitions by performing dynamic vehicular impact simulations using *MASH* TL-3 impact conditions. Using results of these simulations, researchers selected the most critical cases for performance of full scale crash tests. The design selected for full scale testing was the transition between T221 and SSCB. *MASH* requires performing Test 3-20 (small car) and Test 3-21 (pickup) to evaluate transition designs. Both tests were performed on the transition between T221 and SSCB. The direction of vehicle impact in both tests was from the side of the SSCB to T221, which was selected based on simulation results. The transition performed acceptably in both tests for *MASH* TL-3 criteria.

Based on the results of the simulations for F-shape to SSCB transition, and the fact that the more critical design of T221 to SSCB transition passed *MASH* testing, the F-shape to SSCB transition was also considered a *MASH* compliant design. This report provides details of the transition designs, simulation analyses, reinforcement details, and a detailed documentation of the *MASH* crash testing.

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views 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 view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer(researcher) in charge of the project was Nauman M. Sheikh, P.E. #105155.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

TTI PROVING GROUND DISCLAIMER

The results of the crash testing reported herein apply only to the article tested.

REPORT AUTHORIZATION

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5(F-32)/9 or (F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	Square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lb/in^2

*SI is the symbol for the International System of Units

CHAPTER 1:
INTRODUCTION

1.1 BACKGROUND AND PROBLEM STATEMENT

TxDOT has various cast in place concrete barrier designs that occasionally need to be connected to each other in the field. Since the cross-sectional profiles and heights of these barriers differ significantly, they cannot be connected without using proper barrier transition sections that smoothly transition from one barrier shape to the other. Currently there are no transition designs that have been evaluated for compliance with American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (*MASH*) guidelines (***Error! Reference source not found.***).

1.2 OBJECTIVES AND SCOPE OF RESEARCH

The objective of this project was to develop transition designs for three cast in place concrete barrier combinations. These included transitions for connecting (a) TxDOT's 36-inch tall Single Slope Traffic Rail (SSTR) to 42-inch tall Single Slope Concrete Barrier (SSCB), (b) 32-inch tall F-shape concrete barrier to SSCB, and (c) TxDOT's 32-inch tall T221 vertical concrete wall to SSCB. The designs were required to meet AASHTO *MASH* Test Level 3 (TL-3) criteria, and researchers were to evaluate their compliance using a combination of past testing results, impact simulation analyses, and limited full scale testing.

Researchers were also required to develop concrete reinforcement details for each transition system. Based on the results of simulation analyses, researchers selected the most critical design for full-scale crash testing. A total of two crash tests were incorporated in the scope of this project. These were *MASH* Test 3-20 and Test 3-21 for evaluating barrier transitions for *MASH* TL-3.

Chapter 2 of this report provides details of the research approach, transition designs, simulation analyses, and reinforcement details. Detailed documentation of the crash tests and results, and an assessment of the crash tested transition for *MASH* TL-3 evaluation criteria is presented in Chapters 3 to 8. Chapter 9 presents key findings of this project and recommendations on implementation of the results by TxDOT.

CHAPTER 2: DESIGN AND SIMULATION

This chapter presents details of the various transitions designed under this project, and the results of simulations performed to evaluate the performance of these designs. TxDOT selected the following three cast in place concrete barrier combinations for developing the transitions.

- 36-inch tall SSTR to 42-inch tall SSCB, which has a symmetric profile about the vertical axis.
- 32-inch tall F-shape median barrier to 42-inch tall SSCB.
- 32-inch tall T221 vertical rail to 42-inch tall SSCB.

Researchers developed preliminary transition design concepts for TxDOT's review and approval. Once approved, researchers developed full-scale finite element (FE) models of the preliminary transition designs and performed vehicle impact simulations with *MASH* Test 3-20 and Test 3-21 impact conditions. Both test conditions involve impacting the barrier transition at an impact speed and angle of 62 mi/h and 25 degrees, respectively. Test 3-20 involves impacting with a 2,420-lb small passenger sedan, and Test 3-21 involves impacting with a 5,000-lb pickup truck.

All simulations were performed using LS-DYNA, which is a commercially available general-purpose FE analysis software (*2*). The barrier and the transition sections were modeled using rigid material representation. Since LS-DYNA is a dynamic analysis code that makes use of explicit time-integration methodology, loads from the vehicle impact were transferred to the barrier in a dynamic manner (*3*). Vehicle models used in the simulations were originally developed by Center for Collision Safety and Analysis and were further improved by TTI over the course of use under various projects.

2.1 SSTR TO SSCB TRANSITION

Simulation analysis was not performed in the case of the transition between the 36-inch tall SSTR and the 42-inch tall SSCB. Both barriers have a single slope profile on the traffic-side face and the only transition is in the height of the barriers. Since this was not a significant change from the already known *MASH* compliant crash performance of the single slope barriers, only the geometric design and the reinforcement details were developed for this transition (*2, 3*).

Figures 2.1 and 2.2 show the details of the transition between the 36-inch tall SSTR and the 42-inch tall SSCB. The transition section is 6-ft long. The traffic side face of this transition has a single slope profile that matches the SSTR and the SSCB profile. The top of the transition tapers from 36 inches on the side of the SSTR to 42 inches on the side of the SSCB. The width and the field side face of the transition section varies geometrically to match the SSTR and SSCB profiles at each end.

Reinforcement details of the transition are also shown in Figures 2.1 and 2.2, which accommodate TxDOT's standard reinforcement for SSTR and SSCB at each end of the transition section.

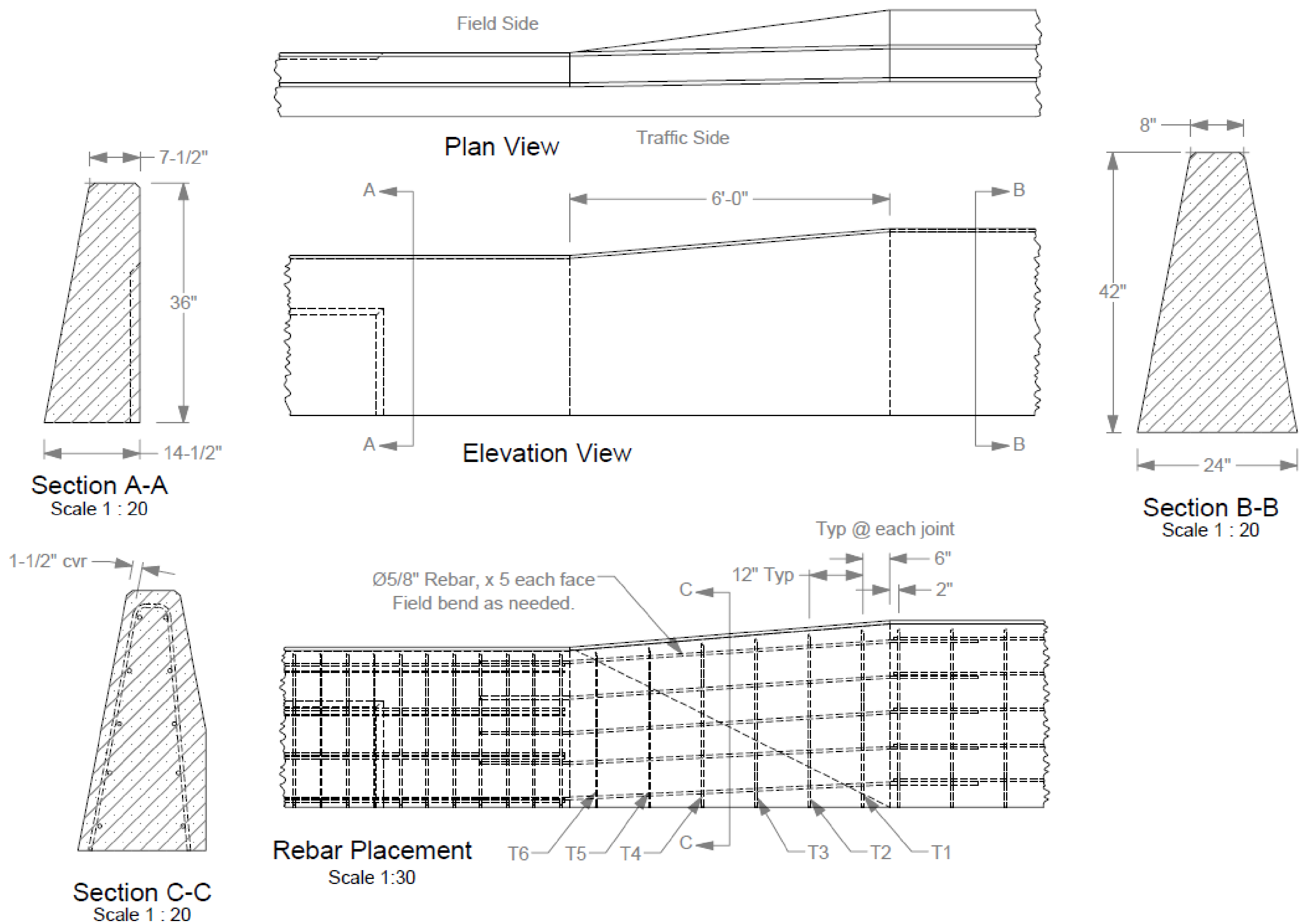

Figure 2.1. Transition between SSTR and SSCB.

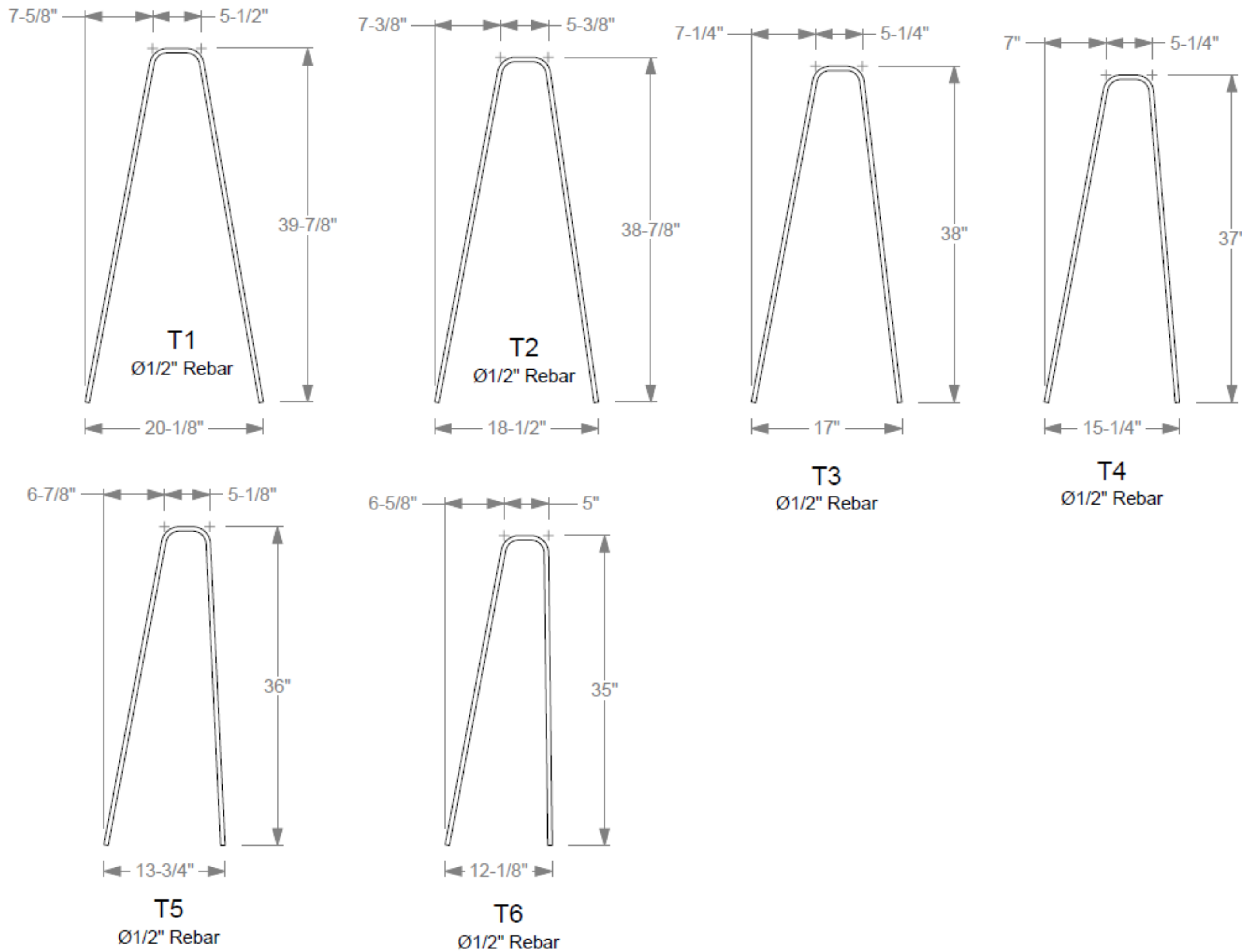

Figure 2.2. Rebar for Transition between SSTR and SSCB.

2.2 F-SHAPE TO SSCB TRANSITION

The transition from 32-inch tall F-shape to 42-inch tall SSCB was comprised of a 6-ft long barrier section that transitions the geometric profiles of the two barriers and the 10-inch difference in their height. The transition segment was symmetric about the vertical axis to allow use in a median application (see Figure 2.3).

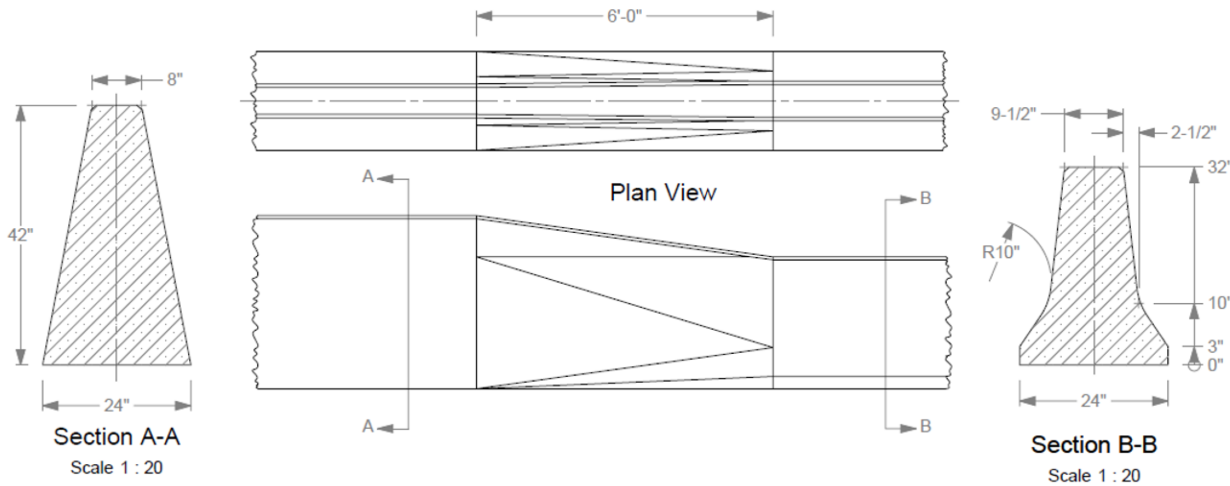

Figure 2.3. F-shape to SSCB Transition Concept.

Impact simulations were performed with the vehicle traveling in the direction from the F-shape to the SSCB, and in the direction from the SSCB to the F-shape barrier. Results of the impact simulations for *MASH* Test 3-20 (small car) and 3-21 (pickup truck) are shown in Figure 2.4 for the impact in the direction from the F-shape to SSCB. The results of the impact simulations for *MASH* Test 3-20 and 3-21 for the direction from the SSCB to the F-shape are shown in Figure 2.5. The impact points were 3.6 ft and 4.3 ft upstream of the start of the transition section in simulations of Test 3-20 and Test 3-21, respectively.

In all four simulations cases, the vehicle was contained and redirected in a stable manner. Table 2.1 presents key results from the simulations. All occupant risk metrics were within *MASH* thresholds, and the transition design was considered suitable for further development of reinforcement details.

Reinforcement details of the transition are shown in Figures 2.6 and 2.7, which accommodate TxDOT's standard reinforcement for F-shape concrete barrier and the SSCB at each end of the transition.

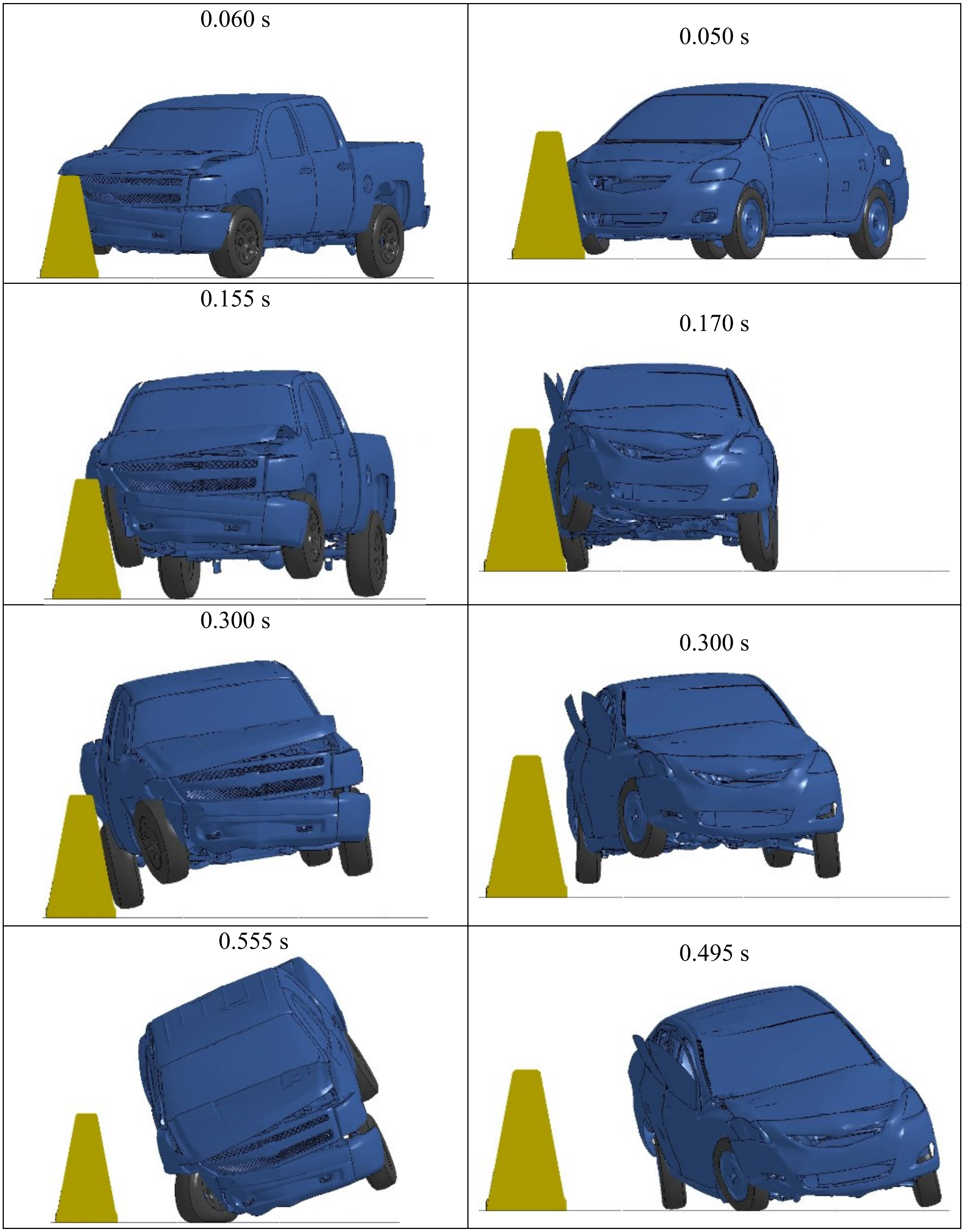

Figure 2.4. Simulations of *MASH* Tests 3-21 (Left) and 3-20 (Right) with F-shape to SSCB Transition (F-shape to SSCB Direction).

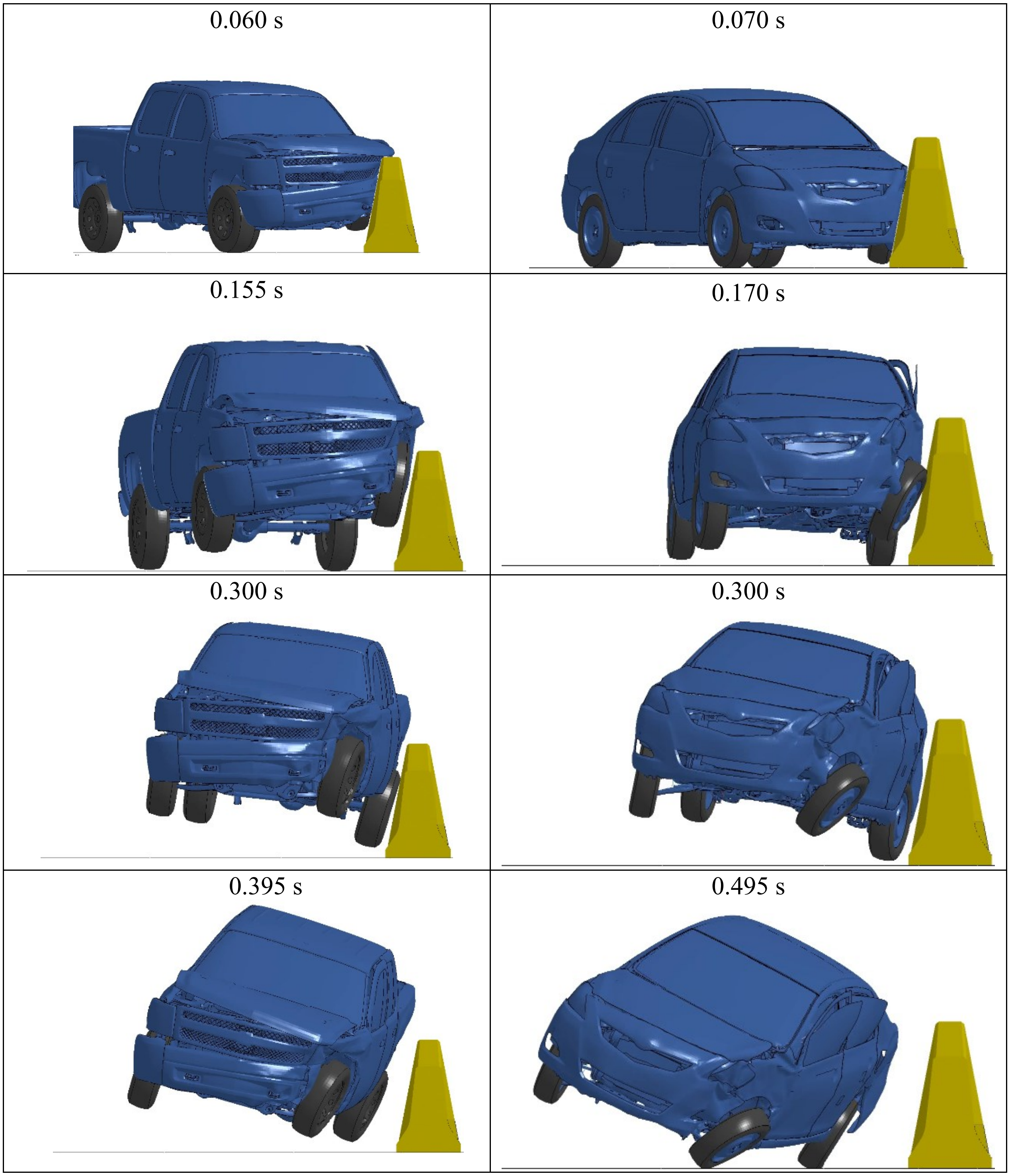

Figure 2.5. Simulations of *MASH* Tests 3-21 (Left) and 3-20 (Right) with F-shape to SSCB Transition (SSCB to F-shape Direction).

Table 2.1. Results of MASH Impact Simulations with F-shape to SSCB Transition.

		Test 3-21 (Pickup)		Test 3-20 (Small Car)	
		SS-F	F-SS	SS-F	F-SS
OIV (ft/s)	x	20.34	17.06	18.37	17.39
	y	25.59	26.25	30.51	29.20
Ridedown Acceleration (g)	x	8.0	4.7	4.7	3.5
	y	17.9	16.3	13.1	13.5
Maximum Vehicle Angles (degree)	Roll	−28.5	28.1	−33.2	13.1
	Pitch	−11.3	−13.5	−6.1	−8.7
	Yaw	35.1	−30.0	47.5	−37.8

SS-F: Direction of impact from SSCB to F-shape
F-SS: Direction of impact from F-shape to SSCB

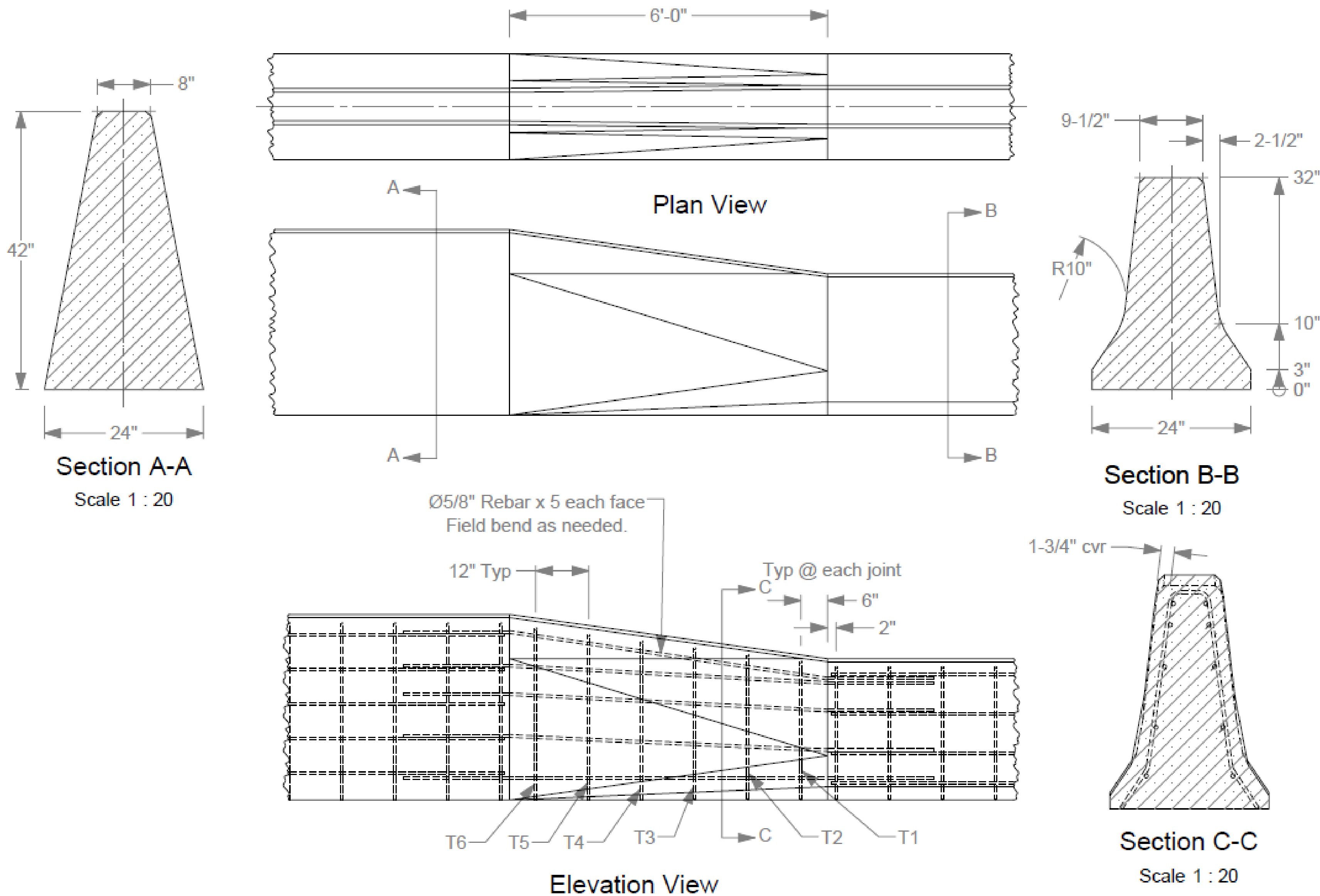

Figure 2.6. Transition between F-shape and SSCB.

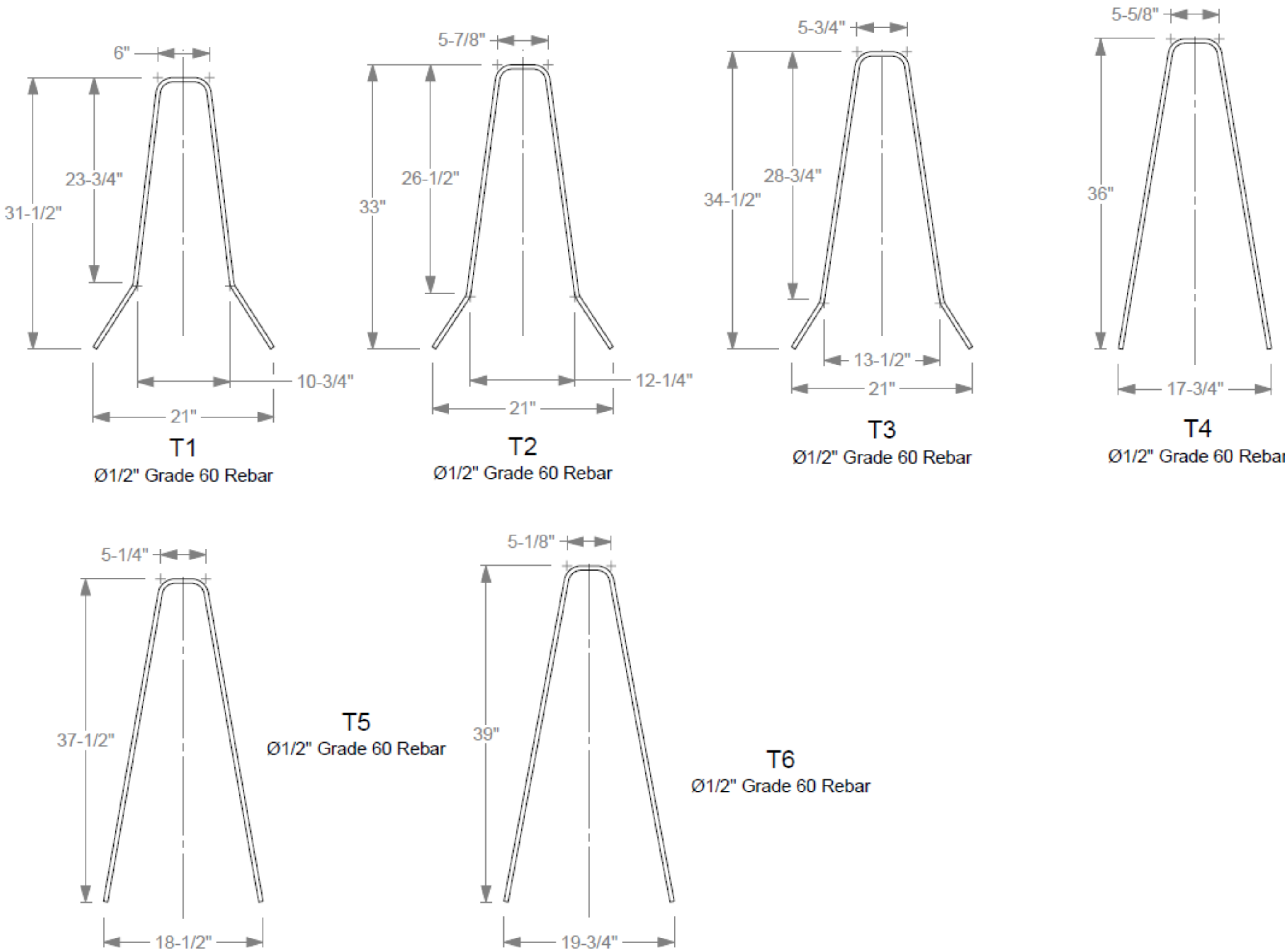

Figure 2.7. Transition between F-shape and SSCB (Continued).

2.3 T221 TO SSCB TRANSITION

The transition from 32-inch tall T221 vertical wall parapet to 42-inch tall SSCB was designed to transition the geometric profiles of the two barriers and the 10-inch difference in their height. A 6-ft long transition section was initially proposed and simulated. However, the results of the simulations showed high ridedown acceleration in the case of the pickup truck impact. To reduce the ridedown accelerations and improve vehicle stability during redirection, the length of the transition section was increased to 15 ft (see Figure 2.8).

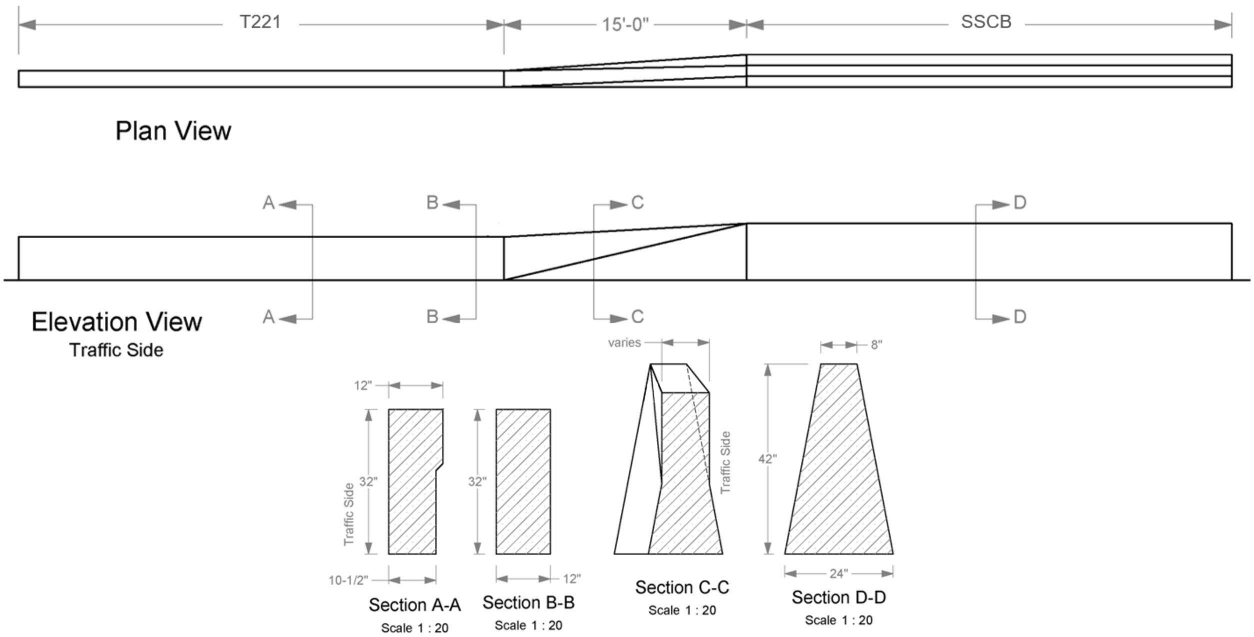

Figure 2.8. T221 to SSCB Transition Concept.

Impact simulations were performed with the vehicle traveling in the direction from T221 to SSCB, and in the direction from SSCB to T221 barriers. Results of the impact simulations for *MASH* Test 3-20 and 3-21 are shown in Figure 2.9 for the impact in the direction from SSCB to T221. For the direction from the T221 to SSCB, results of the impact simulations for *MASH* Test 3-20 and 3-21 are shown in Figure 2.10. In simulations of Test 3-20 and Test 3-21, the impact points were 3.6 ft and 4.3 ft upstream of the start of the transition section, respectively.

In all four simulations cases, the vehicle was contained and redirected in a stable manner. Table 2.2 presents key results from the simulations. All occupant risk metrics were within *MASH* thresholds, and the transition design was considered suitable for further development of reinforcement details.

Since this transition was selected for crash testing (explained in the next section), reinforcement details of the transition are presented in the following chapter, along with details of the crash test installation.

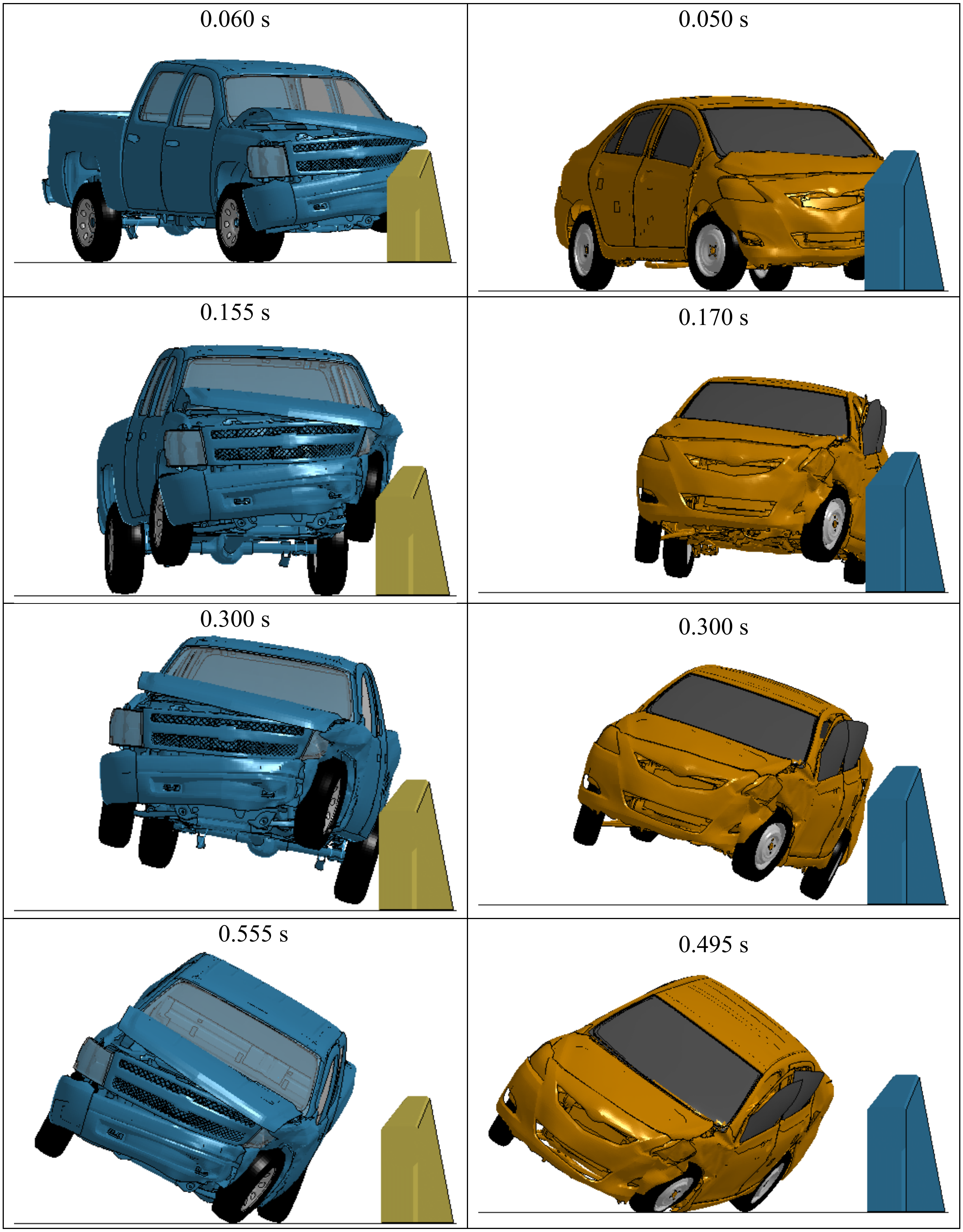

Figure 2.9. Simulations of *MASH* Tests 3-21 (Left) and 3-20 (Right) with T221 to SSCB Transition (SSCB to T221 Direction).

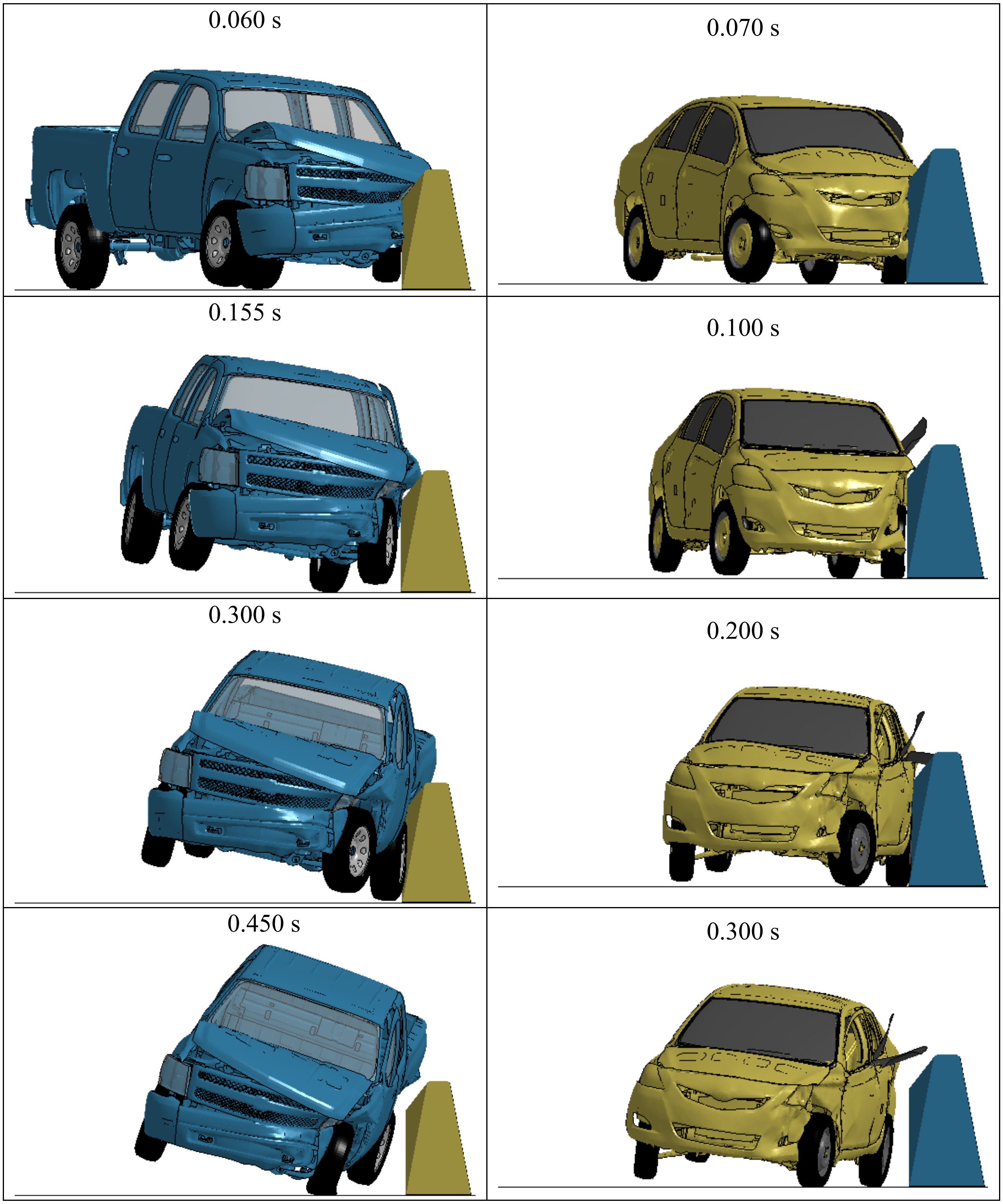

Figure 2.10. Simulations of *MASH* Tests 3-21 (Left) and 3-20 (Right) with T221 to SSCB Transition (T221 to SSCB Direction).

Table 2.2. Results of MASH Impact Simulations with T221 to SSCB Transition.

		Test 3-21 (Pickup)		Test 3-20 (Small Car)	
		T-SS	SS-T	T-SS	SS-T
OIV (ft/s)	x	26.25	24.93	21.65	18.37
	y	24.28	25.59	31.17	30.51
Ridedown Acceleration (g)	x	5.8	6.9	3.6	4.2
	y	6.5	18.7	13.2	15.9
Maximum Vehicle Angles (degree)	Roll	−19.6	−10.7	7.0	−34.1
	Pitch	29.1	30.3	38.0	36.0
	Yaw	−23.2	36.3	6.7	−44.1

SS-T: Direction of impact from SSCB to T221
T-SS: Direction of impact from T221 to SSCB

2.4 DESIGN SELECTION FOR CRASH TESTING

The scope of this project was to perform two crash tests on the design determined to be most critical based on the results of the simulation analyses. By comparing simulation results of the F-shape to SSCB transition (Table 2.1) and the T221 to SSCB transition (Table 2.2), it can be determined that the latter is the more critical of the two. For this design, the impact direction from SSCB to T221 is the most critical case in terms of ridedown acceleration for Test 3-21. This design and direction are also the most critical for Test 3-20 with regard to OIV, ridedown acceleration, and maximum vehicle roll, pitch, and yaw angles.

The transition between T221 and SSCB was thus selected for full scale crash testing, and *MASH* Tests 3-20 and 3-21 were performed on the transition. The direction of impact in both tests was from SSCB to T221 barrier. Details of the test installation and the crash tests are presented in the following chapters.

CHAPTER 3:
SYSTEM DETAILS

3.1 TEST ARTICLE AND INSTALLATION DETAILS

The T221 vertical wall to SSCB transition test installation was 75 ft long. It consisted of 30 ft of T221 vertical wall and 30 ft of SSCB, with a 15 ft long transition section between them. The entire length of the test installation consisted of steel reinforced concrete. The transition section joined the two adjacent barriers and gradually transitioned from one profile to the other. The T221 shape was 32 inches tall and 12 inches wide at top, with vertical sides for the first 42 linear inches from the joint with the transition section. The remainder of the T221 contained a 1½-inch deep, 19-inch tall relief on the field side face. The SSCB was 42 inches tall, 8 inches wide at top, and 24 inches wide at bottom. It had the same slope on the traffic and field sides.

Figure 3.1 presents overall information on the T221 vertical wall to SSCB transition, and Figure 3.2 provides photographs of the installation. Appendix A provides further details of the T221 vertical wall to SSCB transition, along with the details of the steel reinforcement.

The test installation was anchored to existing concrete pavement with ¾-inch × 21-inch rebar, embedded 6 inches deep into the pavement, and secured with Hilti HIT-RE 500 V3 epoxy. Figure 3.3 shows spacing of these anchors.

3.2 DESIGN MODIFICATIONS DURING TESTS

No modifications were made to the installation during the testing phase.

3.3 MATERIAL SPECIFICATIONS

The concrete was installed in two pours, and was specified to be TxDOT Class C (3600 psi minimum strength). Compressive strength of the concrete on the date of the first test, at 34 days of age, was 6626 psi for the bottom half of the installation and 6119 psi for the top half of the installation.

Appendix B provides material certification documents for the materials used to construct the T221 vertical wall to SSCB transition.

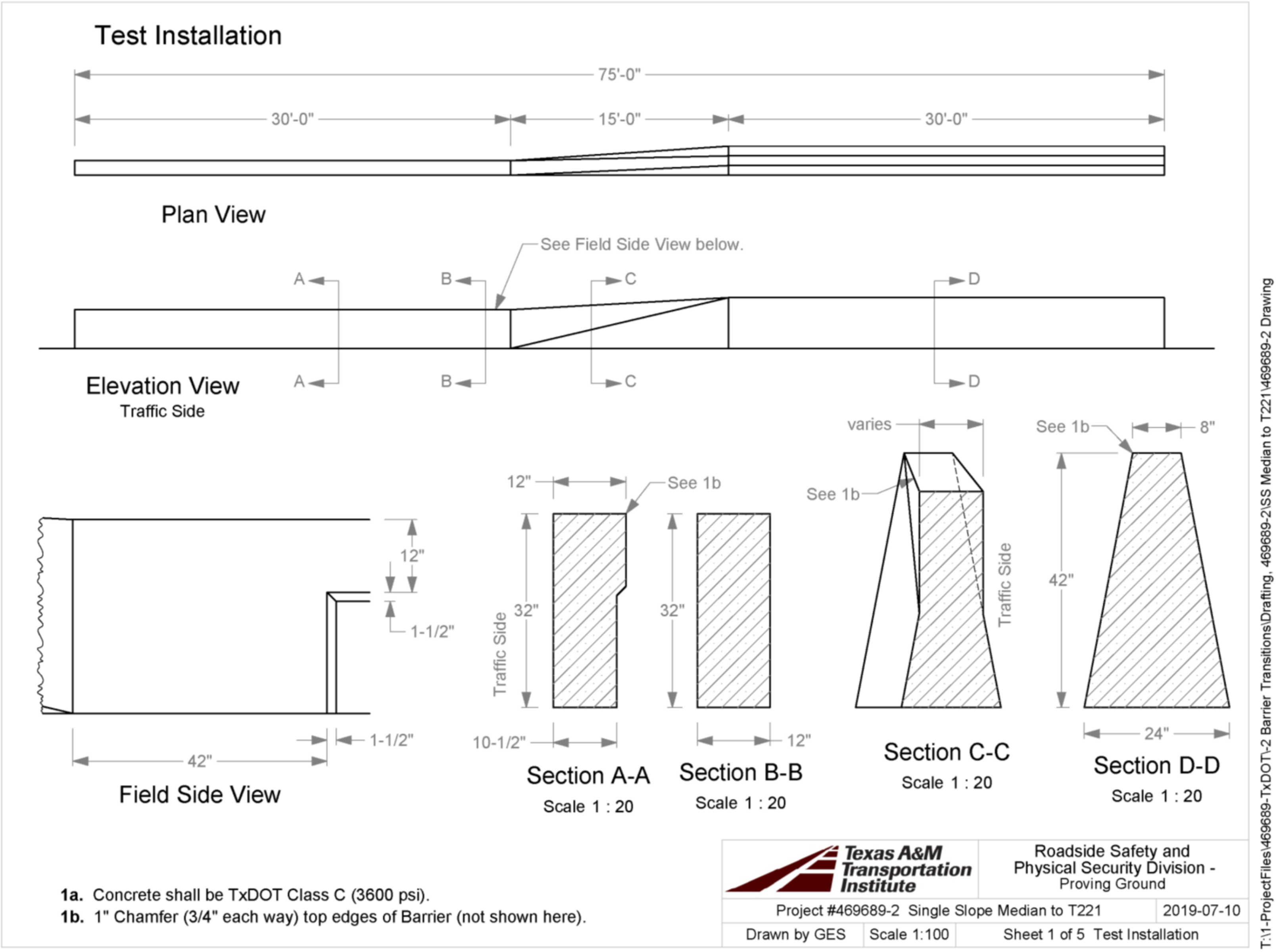

Figure 3.1. Overall Details of T221 Vertical Wall to SSCB Transition.

Figure 3.2. T221 Vertical Wall to SSCB Transition Prior to Testing.

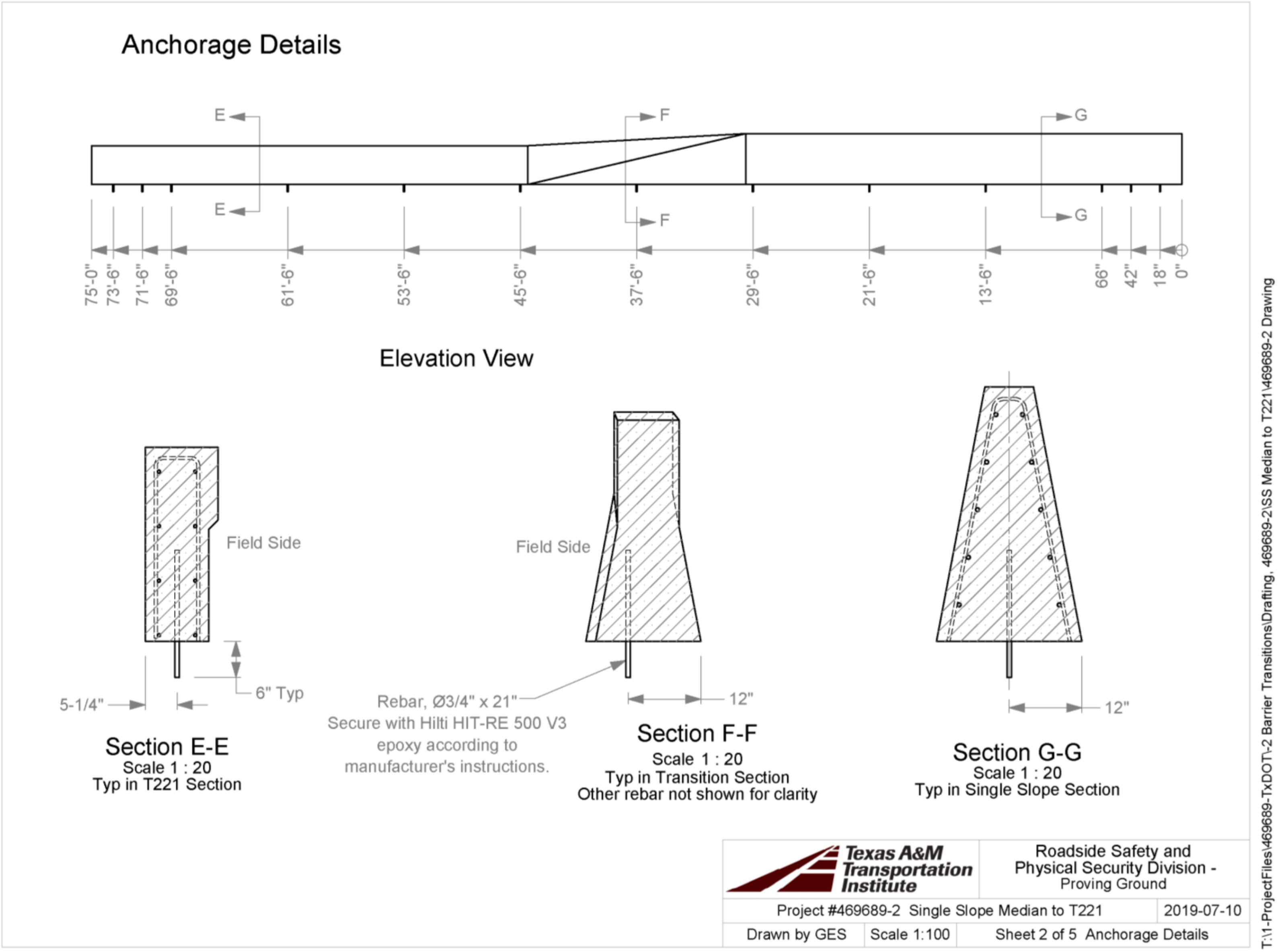

Figure 3.3. Anchor Details of T221 Vertical Wall to SSCB transition.

CHAPTER 4:
TEST REQUIREMENTS AND EVALUATION CRITERIA

4.1 CRASH TEST MATRIX

Table 4.1 shows the test conditions and evaluation criteria for *MASH* TL-3 for transitions. The critical impact point (CIP) for each test was determined using the information provided in *MASH* Section 2.3.2 and *MASH* Figure 2-1. Figures 4.1 and 4.2 show the target CIPs for each test. The crash tests and data analysis procedures were in accordance with guidelines presented in *MASH*. Chapter 5 presents brief descriptions of these procedures.

Table 4.1. Test Conditions and Evaluation Criteria Specified for *MASH* TL-3 Transitions.

Test Article	Test Designation	Test Vehicle	Impact Conditions		Evaluation Criteria
			Speed	Angle	
Transition	3-20	1100C	62 mi/h	25	A, D, F, H, I
	3-21	2270P	62 mi/h	25	A, D, F, H, I

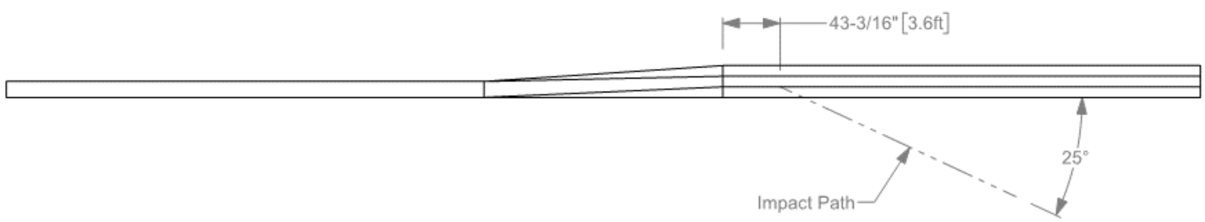

Figure 4.1. Target CIP for *MASH* Test 3-20 on the T221 Vertical Wall to SSCB Transition.

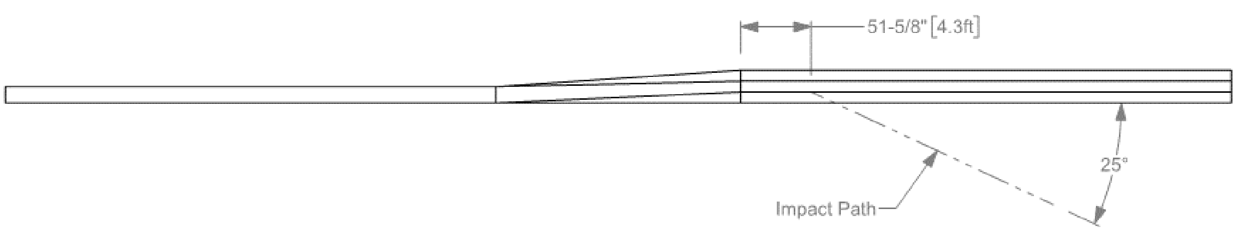

Figure 4.2. Target CIP for *MASH* Test 3-21 on the T221 Vertical Wall to SSCB Transition.

4.2 EVALUATION CRITERIA

The appropriate safety evaluation criteria from Tables 2-2A and 5-1 of *MASH* were used to evaluate the crash tests reported herein. The test conditions and evaluation criteria required for *MASH* TL-3 are listed in Table 4.1, and the substance of the evaluation criteria in Table 4.2. An evaluation of each crash test is presented in detail under the section Assessment of Test Results.

Table 4.2. Evaluation Criteria Required for *MASH* TL-3 Transitions.

Evaluation Factors	Evaluation Criteria
Structural Adequacy	*A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.*
Occupant Risk	*D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present 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.*
	F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.
	H. Occupant impact velocities (OIV) should satisfy the following limits: Preferred value of 30 ft/s, or maximum allowable value of 40 ft/s.
	I. The occupant ridedown accelerations should satisfy the following: Preferred value of 15.0 g, or maximum allowable value of 20.49 g.

CHAPTER 5:
TEST CONDITIONS

5.1 TEST FACILITY

The full-scale crash tests reported herein were performed at Texas A&M Transportation Institute (TTI) Proving Ground, an International Standards Organization (ISO)/International Electrotechnical Commission (IEC) 17025-accredited laboratory with American Association for Laboratory Accreditation (A2LA) Mechanical Testing Certificate 2821.01. The full-scale crash tests were performed according to TTI Proving Ground quality procedures and according to the *MASH* guidelines and standards.

The test facilities of the TTI Proving Ground are located on the Texas A&M University System RELLIS Campus, which consists of a 2000-acre complex of research and training facilities situated 10 miles northwest of the flagship campus of Texas A&M University. The site, formerly a United States Army Air Corps base, has large expanses of concrete runways and parking aprons well suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, durability and efficacy of highway pavements, and evaluation of roadside safety hardware and perimeter protective devices. The site selected for construction and testing of the T221 vertical wall to SSCB transition on an out-of-service apron. The apron consists of an unreinforced jointed-concrete pavement in 12.5-ft × 15-ft blocks nominally 6 inches deep. The aprons were built in 1942, and the joints have some displacement, but are otherwise flat and level.

5.2 VEHICLE TOW AND GUIDANCE SYSTEM

Each test vehicle was towed into the test installation using a steel cable guidance and reverse tow system. A steel cable for guiding the test vehicle was tensioned along the path, anchored at each end, and threaded through an attachment to the front wheel of the test vehicle. An additional steel cable was connected to the test vehicle, passed around a pulley near the impact point, through a pulley on the tow vehicle, and then anchored to the ground such that the tow vehicle moved away from the test site. A 2:1 speed ratio between the test and tow vehicle existed with this system. Just prior to impact with the installation, the test vehicle was released and ran unrestrained. The vehicle remained freewheeling (i.e., no steering or braking inputs) until it cleared the immediate area of the test site (no sooner than 2 s after impact), after which the brakes were activated, if needed, to bring the test vehicle to a safe and controlled stop.

5.3 DATA ACQUISITION SYSTEMS

5.3.1 Vehicle Instrumentation and Data Processing

Each test vehicle was instrumented with a self-contained, on-board data acquisition system. The signal conditioning and acquisition system is a 16-channel, Tiny Data Acquisition System (TDAS) Pro produced by Diversified Technical Systems, Inc. The accelerometers, which measure the x, y, and z axis of vehicle acceleration, are strain gauge type with linear millivolt output proportional to acceleration. Angular rate sensors, measuring vehicle roll, pitch, and yaw rates, are ultra-small, solid state units designed for crash test service. The TDAS Pro hardware and software conform to the latest SAE J211, Instrumentation for Impact Test. Each of the 16 channels can provide precision amplification, scaling, and filtering based on transducer specifications and calibrations. During the test, data are recorded from each channel at a rate of 10,000 values per second with a resolution of one part in 65,536. Once data are recorded, internal batteries back these up inside the unit should the primary battery cable be severed. Initial contact of the pressure switch on the vehicle bumper provides a time zero mark and initiates the recording process. After each test, the data are downloaded from the TDAS Pro unit into a laptop computer at the test site. The Test Risk Assessment Program (TRAP) software then processes the raw data to produce detailed reports of the test results.

Each of the TDAS Pro units is returned to the factory annually for complete recalibration, and all instrumentation used in the vehicle conforms to all specifications outlined by SAE J211. All accelerometers are calibrated annually by means of an ENDEVCO® 2901, precision primary vibration standard. This standard and its support instruments are checked annually and receive a National Institute of Standards Technology (NIST) traceable calibration. The rate transducers used in the data acquisition system receive a calibration via a Genisco Rate-of-Turn table. The subsystems of each data channel are also evaluated annually, using instruments with current NIST traceability, and the results are factored into the accuracy of the total data channel, per SAE J211. Calibrations and evaluations are also made any time data are suspect. Acceleration data are measured with an expanded uncertainty of ±1.7 percent at a confidence factor of 95 percent (k=2).

TRAP uses the data from the TDAS Pro to compute occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and the highest 10-millisecond (ms) average ridedown acceleration. TRAP calculates change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms intervals in each of the three directions are computed. For reporting purposes, the data from the vehicle-mounted accelerometers are filtered with a SAE Class 180-Hz low-pass digital filter, and acceleration versus time curves for the longitudinal, lateral, and vertical directions are plotted using TRAP.

TRAP uses the data from the yaw, pitch, and roll rate transducers to compute angular displacement in degrees at 0.0001-s intervals, then plots yaw, pitch, and roll versus time. These displacements are in reference to the vehicle-fixed coordinate system with the initial position and orientation of the vehicle-fixed coordinate systems being initial impact. Rate of rotation data is measured with an expanded uncertainty of ±0.7 percent at a confidence factor of 95 percent (k=2).

5.3.2 Anthropomorphic Dummy Instrumentation

An Alderson Research Laboratories Hybrid II, 50th percentile male anthropomorphic dummy, restrained with lap and shoulder belts, was placed in the front seat on the impact side of the 1100C vehicle. The dummy was not instrumented.

According to *MASH*, use of a dummy in the 2270P vehicle is optional, and no dummy was used in the test.

5.3.3 Photographic Instrumentation and Data Processing

Photographic coverage of each test included three digital high-speed cameras:

- One overhead with a field of view perpendicular to the ground and directly over the impact point.
- One placed upstream of the impact on the traffic side of the barrier.
- A third placed to have a field of view parallel to and aligned with the installation at the downstream end.

A flashbulb on the impacting vehicle was activated by a pressure-sensitive tape switch to indicate the instant of contact with the T221 vertical wall to SSCB transition. The flashbulb was visible from each camera. The video files from these digital high-speed cameras were analyzed to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A digital camera recorded and documented conditions of each test vehicle and the installation before and after the test.

CHAPTER 6:
MASH TEST 3-20 (CRASH TEST NO. 469689-2-1)

6.1 TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH Test 3-20 involves an 1100C vehicle weighing 2420 lb ±55 lb impacting the CIP of the transition at an impact speed of 62 mi/h ±2.5 mi/h and an angle of 25° ±1.5°. The target CIP for *MASH* Test 3-20 on the T221 vertical wall to SSCB transition was 3.6 ft ±1 ft upstream of the start of the transition section adjacent to the SSCB, as shown in Figure 4.1.

The 2011 Kia Rio* used in the test weighed 2416 lb, and the actual impact speed and angle were 61.6 mi/h and 24.6°, respectively. The actual impact point was 3.5 ft upstream of the start of the transition section adjacent to SSCB. Minimum target impact severity (IS) was 51 kip-ft, and actual IS was 53 kip-ft.

6.2 WEATHER CONDITIONS

The test was performed on the morning of August 19, 2019. Weather conditions at the time of testing were as follows: wind speed: 5 mi/h; wind direction: 205° (vehicle was traveling at magnetic heading of 205°); temperature: 88°F; relative humidity: 76 percent.

6.3 TEST VEHICLE

Figures 6.1 and 6.2 show the 2011 Kia Rio used for the crash test. The vehicle's test inertia weight was 2416 lb, and its gross static weight was 2581 lb. The height to the lower edge of the vehicle bumper was 7.75 inches, and height to the upper edge of the bumper was 21.5 inches. Table C.1 and in Appendix C.1 gives additional dimensions and information on the vehicle. The vehicle was directed into the installation using a cable reverse tow and guidance system, and was released to be freewheeling and unrestrained just prior to impact.

Figure 6.1. Transition and Test Vehicle Geometrics for Test No. 469689-2-1.

* The 2011 model vehicle used was older than the 6-year age noted in *MASH*, and was selected based upon availability. An older model vehicle is permitted by AASHTO as long as it is otherwise *MASH* compliant. Other than the vehicle's year model, this 2011 model vehicle met *MASH* requirements.

Figure 6.2. Test Vehicle before Test No. 469689-2-1.

6.4 TEST DESCRIPTION

The test vehicle was traveling at an impact speed of 61.6 mi/h when it contacted the T221 vertical wall to SSCB transition 3.5 ft upstream of the beginning of the transition section adjacent to SSCB. The impact angle was 24.6°. Table 6.1 lists events that occurred during Test No. 469689-2-1. Figures C.1 and C.2 in Appendix C.2 present sequential photographs during the test.

Table 6.1. Events during Test No. 469689-2-1.

TIME (s)	EVENTS
0.000	Vehicle contacts the barrier
0.037	Vehicle begins to redirect
0.093	Left front tire lifts up from pavement
0.167	Vehicle is traveling parallel with transition
0.186	Right rear corner of vehicle contacts transition
0.203	Left rear tire lifts up from pavement
0.298	Vehicle loses contact with transition while traveling at 50.1 mi/h, exit trajectory of 4.1°, and heading of 11.3°
0.4360	Right front tire contacts pavement
0.502	Right rear tire contacts pavement
0.548	Left front tire contacts pavement

For transitions, it is desirable that the vehicle redirects and exits the barrier within the exit box criteria (not less than 32.8 ft downstream from loss of contact for cars and pickups). The test vehicle exited within the exit box criteria defined in *MASH*. After loss of contact with the barrier, the vehicle came to rest 237 ft downstream of the impact and 114 ft toward traffic lanes.

6.5 DAMAGE TO TEST INSTALLATION

Figure 6.3 shows the damage to the T221 vertical wall to SSCB transition. The SSCB barrier and the transition sustained cosmetic damage only. Working width* was 24.0 inches. The height of the working width was 0.0 inch. No dynamic deflection or permanent deformation of the barrier or the transition were observed.

Figure 6.3. T221 vertical wall to SSCB transition after Test No. 469689-2-1.

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* Working width is defined as the total barrier width plus the maximum intrusion of any portion of the barrier or test vehicle past the pre-impact field side edge of the barrier.

6.6 DAMAGE TO TEST VEHICLE

Figure 6.4 shows the damage sustained by the vehicle. The front bumper, hood, right front fender, right strut and tower, right front tire and rim, right front door and window glass, right rear door right rear rim, right rear exterior bed, and rear bumper were damaged. The windshield sustained stress cracks radiating up and out from the right A-post. Maximum exterior crush to the vehicle was 8.0 inches in the front and side planes at the right front corner at bumper height. Maximum occupant compartment deformation was 3.5 inches in the right front floor pan. Figure 6.5 shows the interior of the vehicle. Tables C.2 and C.3 in Appendix C.1 provide exterior crush and occupant compartment measurements.

Figure 6.4. Test Vehicle after Test No. 469689-2-1.

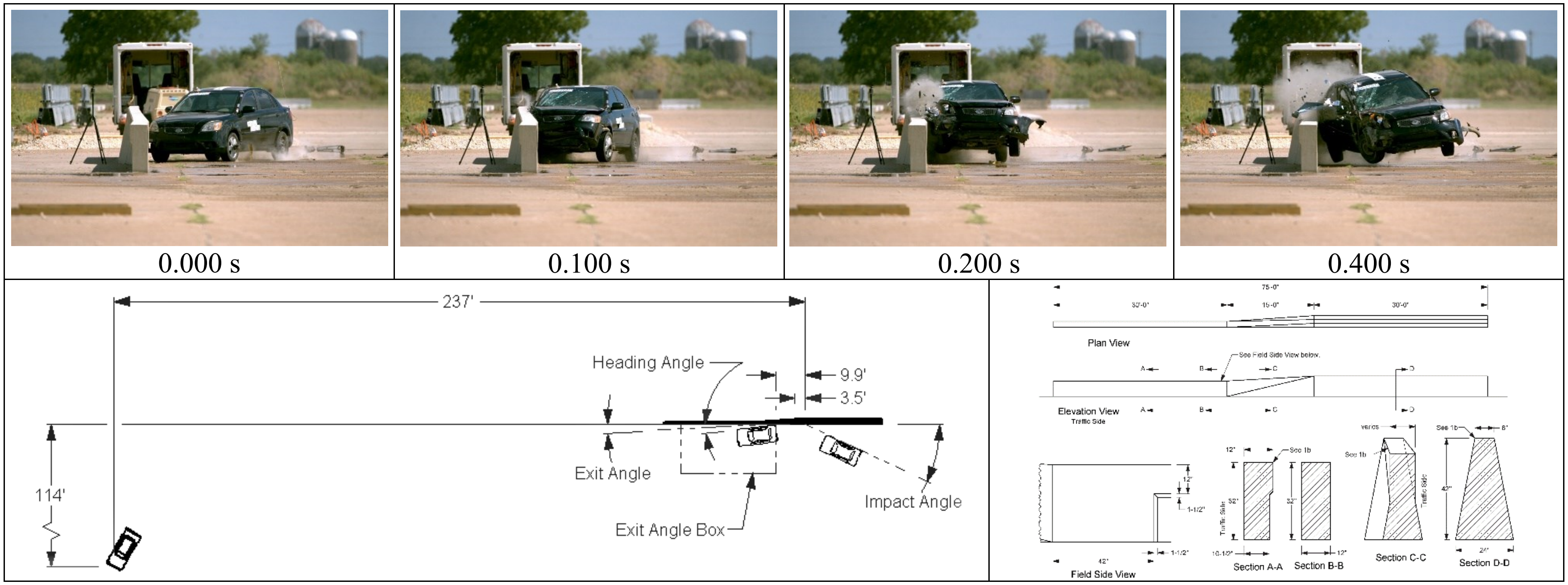
Figure 6.5. Interior of Test Vehicle after Test No. 469689-2-1.

6.7 OCCUPANT RISK FACTORS

Data from the accelerometer, located at the vehicle's center of gravity, were digitized for evaluation of occupant risk and are shown in Table 6.2. Figure 6.6 summarizes these data and other pertinent information from the test. Figure C.3 in Appendix C.3 shows the vehicle angular displacements, and Figures C.4 through C.6 in Appendix C.4 show accelerations versus time traces.

Table 6.2. Occupant Risk Factors for Test No. 469689-2-1.

Occupant Risk Factor	Value	Time
Occupant Impact Velocity (OIV)		
Longitudinal	**19.4 ft/s**	at 0.1114 s on right side of interior
Lateral	**30.8 ft/s**	
Occupant Ridedown Accelerations		
Longitudinal	**3.5 g**	0.0825–0.0925 s
Lateral	**7.0 g**	0.1853–0.1953 s
Theoretical Head Impact Velocity (THIV)	**11.1 m/s**	at 0.0717 s on right side of interior
Post Head Deceleration (PHD)	**7.1 g**	0.1853–0.1953 s
Acceleration Severity Index (ASI)	**2.43**	0.0426–0.0926 s
Maximum 50-ms Moving Average		
Longitudinal	**−10.5 g**	0.0194–0.0694 s
Lateral	**−18.6 g**	0.0223–0.0723 s
Vertical	**−4.4 g**	0.0197–0.0697 s
Maximum Roll, Pitch, and Yaw Angles		
Roll	**23°**	1.9997 s
Pitch	**7°**	0.5539 s
Yaw	**74°**	1.5583 s



General Information
- Test Agency ...... Texas A&M Transportation Institute (TTI)
- Test Standard Test No. ...... MASH Test 3-20
- TTI Test No. 469689-2-1
- Test Date 2019-08-19

Test Article
- Type ...... Transition
- Name ...... T221 to SSCB Transition
- Installation Length ...... 75 ft
- Material or Key Elements ... 30 ft of single slope steel reinforced concrete,15 ft long steel reinforced concrete transition, 30 ft of T221 shape steel reinforced concrete anchored to concrete pavement

Test Vehicle
- Type/Designation 1100C
- Make and Model ...... 2011 Kia Rio
- Curb ...... 2477 lb
- Test Inertial ...... 2416 lb
- Dummy ...... 165 lb
- Gross Static ...... 2581 lb

Impact Conditions
- Speed ...... 61.6 mi/h
- Angle ...... 24.6°
- Location/Orientation ...... 3.5 ft upstream of start of transition

Impact Severity ...... 53 kip-ft

Exit Conditions
- Speed ...... 50.1 mi/h
- Trajectory/Heading Angle ... 4.1° / 11.3°

Occupant Risk Values
- Longitudinal OIV ...... 19.4 ft/s
- Lateral OIV ...... 30.8 ft/s
- Longitudinal Ridedown ...... 3.5 g
- Lateral Ridedown ...... 7.0 g
- THIV ...... 40.0 km/h
- PHD ...... 7.1 g
- ASI 2.43
- Max. 0.050-s Average
  - Longitudinal ...... −10.5 g
  - Lateral ...... −18.6 g
  - Vertical ...... −4.4 g

Post-Impact Trajectory
- Stopping Distance ...... 237 ft downstream 114 ft twd traffic

Vehicle Stability
- Maximum Yaw Angle ...... 74°
- Maximum Pitch Angle ...... 7°
- Maximum Roll Angle ...... 23°
- Vehicle Snagging ...... No
- Vehicle Pocketing ...... No

Test Article Deflections
- Dynamic ...... None
- Permanent ...... None
- Working Width ...... 24.0 inches
- Height of Working Width ...... At base

Vehicle Damage
- VDS 01RFQ6
- CDC 01FREW4
- Max. Exterior Deformation ...... 8.0 inches
- OCDI RF0110000
- Max. Occupant Compartment Deformation ...... 3.5 inches

Figure 6.6. Summary of Results for *MASH* Test 3-20 on the T221 Vertical Wall to SSCB Transition.

CHAPTER 7:
MASH TEST 3-21 (CRASH TEST NO. 469689-2-2)

7.1 TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH Test 3-21 involves a 2270P vehicle weighing 5000 lb ±110 lb impacting the CIP of the transition at an impact speed of 62 mi/h ±2.5 mi/h and an angle of 25° ±1.5°. The target CIP for *MASH* Test 3-11 on the T221 vertical wall to SSCB transition was 4.3 ft ±1 ft upstream of the start of the transition section adjacent to SSCB.

The 2013 RAM 1500 pickup truck used in the test weighed 5035 lb. The actual impact speed and angle were 61.9 mi/h and 26.2°, respectively. The actual impact point was 4.1 ft upstream of the start of the transition section adjacent to SSCB. Minimum target IS was 106 kip-ft, and actual IS was 126 kip-ft.

7.2 WEATHER CONDITIONS

The test was performed on the morning of August 21, 2019. Weather conditions at the time of testing were as follows: wind speed: 5 mi/h; wind direction: 194° (vehicle was traveling at magnetic heading of 205°); temperature: 88°F; relative humidity: 72 percent.

7.3 TEST VEHICLE

Figures 7.1 and 7.2 show the 2013 Dodge RAM 1500 pickup truck used for the crash test. The vehicle's test inertia weight was 5035 lb and its gross static weight was 5035 lb. The height to the lower edge of the vehicle bumper was 11.75 inches, and the height to the upper edge of the bumper was 27.0 inches. The height to the vehicle's center of gravity was 28.4 inches. Tables D.1 and D.2 in Appendix D.1 give additional dimensions and information on the vehicle. The vehicle was directed into the installation using the cable reverse tow and guidance system, and was released to be freewheeling and unrestrained just prior to impact.

Figure 7.1. Transition and Test Vehicle Geometrics for Test No. 469689-2-2.

Figure 7.2. Test Vehicle before Test No. 469689-2-2.

7.4 TEST DESCRIPTION

The test vehicle was traveling at an impact speed of 61.9 mi/h when it contacted the T221 vertical wall to SSCB transition 4.1 ft upstream of the beginning of the transition adjacent to SSCB. The impact angle was 26.2°. Table 7.1 lists events that occurred during Test No. 469689-2-2. Figures D.1 and D.2 in Appendix D.2 present sequential photographs during the test.

Table 7.1. Events during Test No. 469689-2-2.

TIME (s)	EVENTS
0.000	Vehicle contacts transition
0.044	Vehicle begins to redirect
0.097	Left front tire lifts off pavement
0.181	Vehicle traveling parallel with transition
0.183	Right rear bumper contacts transition
0.203	Left rear tire lifts off pavement
0.291	Vehicle loses contact with transition while traveling at 51.3 mi/h, trajectory of 5.0°, and heading of 3.1°
0.498	Right rear tire contacts pavement
0.591	Right front tire contacts pavement
0.626	Left front tire contacts pavement

For longitudinal barriers, it is desirable that the vehicle redirects and exits the barrier within the exit box criteria (not less than 32.8 ft downstream from loss of contact for cars and pickups). The test vehicle exited within the exit box criteria defined in *MASH*. After loss of contact with the barrier, the vehicle came to rest 280 ft downstream of the impact and 23 ft toward the field side.

7.5 DAMAGE TO TEST INSTALLATION

Figure 7.3 shows the damage to the T221 vertical wall to SSCB transition. The barrier sustained cosmetic damage only. Working width* was 24.0 inches. The height of the working width was 0.0 inch. No dynamic deflection or permanent deformation were observed.

Figure 7.3. Transition after Test No. 469689-2-2.

* Working width is defined as the total barrier width plus the maximum intrusion of any portion of the barrier or test vehicle past the pre-impact field side edge of the barrier.

7.6 DAMAGE TO TEST VEHICLE

Figure 7.4 shows the damage sustained by the vehicle. The front bumper, hood, grill, radiator and support, right front fender, right front tire and rim, right front door, right rear door, right rear cab corner, right rear exterior bed, right rear spring, and rear bumper were damaged. Maximum exterior crush to the vehicle was 14.0 inches in the side plane at the right front corner at bumper height. Maximum occupant compartment deformation was 4.0 inches in the right front firewall area. Figure 7.5 shows the interior of the vehicle. Tables D.3 and D.4 in Appendix D.1 provide exterior crush and occupant compartment measurements.

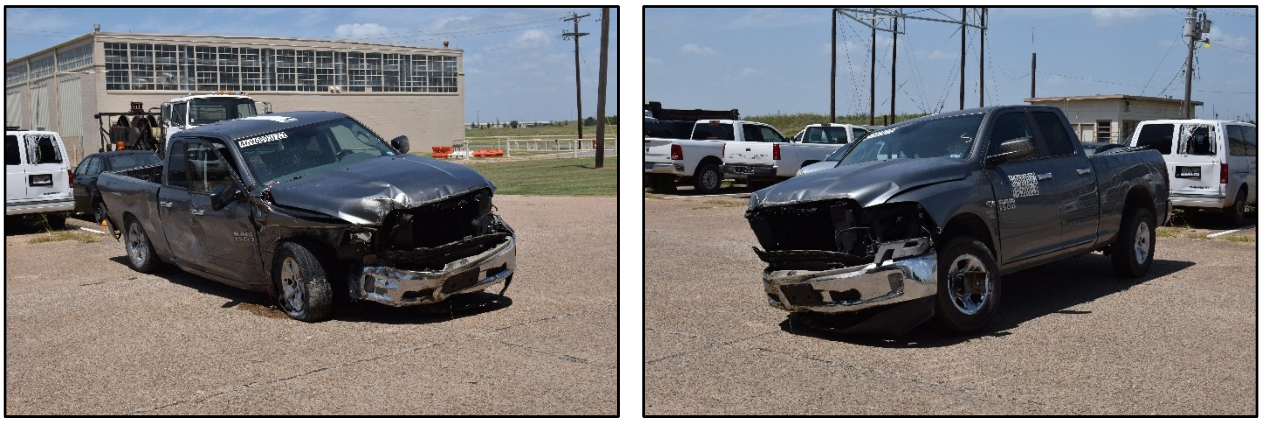


Figure 7.4. Test Vehicle after Test No. 469689-2-2.

Figure 7.5. Interior of Test Vehicle after Test No. 469689-2-2.

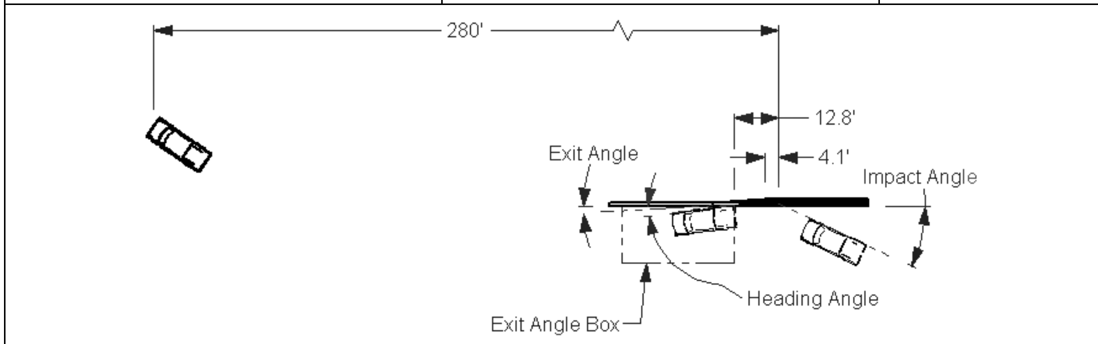
7.7 OCCUPANT RISK FACTORS

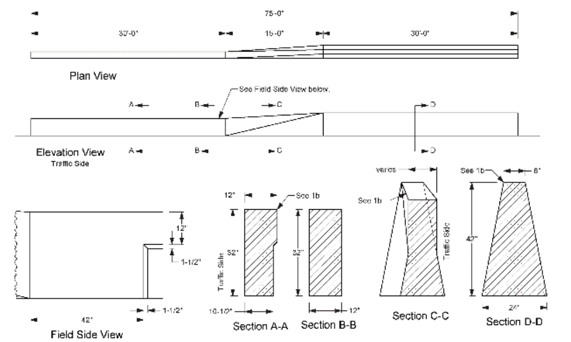
Data from the accelerometer, located at the vehicle's center of gravity, were digitized for evaluation of occupant risk and are shown in Table 7.2. Figure 7.6 summarizes these data and other pertinent information from the test. Figure D.3 in Appendix D.3 shows the vehicle angular displacements, and Figures D.4 through D.9 in Appendix D.4 show accelerations versus time traces.

Table 7.2. Occupant Risk Factors for Test No. 469689-2-2.

Occupant Risk Factor	Value	Time
OIV		
Longitudinal	**15.7 ft/s**	at 0.0937 s on right side of interior
Lateral	**28.2 ft/s**	
Ridedown Accelerations		
Longitudinal	**4.2 g**	0.1880–0.1980 s
Lateral	**12.2 g**	0.1793–0.1893 s
THIV	**9.9 m/s**	at 0.0917 s on right side of interior
PHD	**12.4 g**	0.1794–0.1894 s
ASI	**1.88**	0.0596–0.1096 s
Maximum 50-ms Moving Average		
Longitudinal	**−7.5 g**	0.0205–0.0705 s
Lateral	**−14.5 g**	0.0407–0.0907 s
Vertical	**−4.9 g**	0.6611–0.7111 s
Maximum Roll, Pitch, and Yaw Angles		
Roll	**6°**	0.6437 s
Pitch	**9°**	2.0000 s
Yaw	**43°**	0.7721 s

0.000 s | 0.200 s | 0.400 s | 0.600 s





General Information

Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	MASH Test 3-21
TTI Test No.	469689-2-2
Test Date	2019-08-21

Test Article

Type	Transition
Name	T221 to SSCB Transition
Installation Length	75 ft
Material or Key Elements	30 ft of single slope steel reinforced concrete,15 ft long steel reinforced concrete transition, 30 ft of T221 shape steel reinforced concrete anchored to concrete pavement

Test Vehicle

Type/Designation	2270P
Make and Model	2013 Dodge RAM 1500 Pickup
Curb	4974 lb
Test Inertial	5035 lb
Dummy	No dummy
Gross Static	5035 lb

Impact Conditions

Speed	61.9 mi/h
Angle	26.2°
Location/Orientation	4.1 ft ft upstream of transition joint

Impact Severity

Exit Conditions

Speed	51.3 mi/h
Angle	5.0° / 3.1°

Occupant Risk Values

Longitudinal OIV	15.7 ft/s
Lateral OIV	28.2 ft/s
Longitudinal Ridedown	4.2 g
Lateral Ridedown	12.2 g
THIV	35.7 km/h
PHD	12.4 g
ASI	1.88
Max. 0.050-s Average	
Longitudinal	−7.5 g
Lateral	−14.5 g
Vertical	−4.9 g

Post-Impact Trajectory

Stopping Distance	280 ft downstream 23 ft twd field side

Vehicle Stability

Maximum Yaw Angle	43°
Maximum Pitch Angle	9°
Maximum Roll Angle	6°
Vehicle Snagging	No
Vehicle Pocketing	No

Test Article Deflections

Dynamic	None
Permanent	None
Working Width	24.0 inches
Height of Working Width	At base

Vehicle Damage

VDS	01RFQ5
CDC	01FREW4
Max. Exterior Deformation	14.0 inches
OCDI	RF0010000
Max. Occupant Compartment Deformation	4.0 inches

Figure 7.6. Summary of Results for *MASH* Test 3-21 on the T221 Vertical Wall to SSCB Transition.

CHAPTER 8:
CRASH TESTING SUMMARY AND CONCLUSIONS

8.1 ASSESSMENT OF TEST RESULTS

Tables 8.1 and 8.2 provide an assessment for each test based on the applicable safety evaluation criteria for *MASH* Test 3-20 and 3-21, respectively.

8.2 CONCLUSIONS

Table 8.3 shows that the T221 vertical wall to SSCB transition performed acceptably as a *MASH* TL-3 transition.

Table 8.1. Performance Evaluation Summary for *MASH* Test 3-20 on T221 Vertical Wall to SSCB Transition.

Test Agency: Texas A&M Transportation Institute — Test No.: 469689-2-1 — Test Date: 2019-08-19

***MASH* Test Evaluation Criteria**	**Test Results**	**Assessment**
Structural Adequacy		
A. *Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable*	The transition contained and redirected the 1100C vehicle. The vehicle did not penetrate, override, or underride the installation. No dynamic deflection or permanent deformation was observed.	Pass
Occupant Risk		
D. *Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.*	No detached elements, fragments, or other debris were present to penetrate or show potential for penetrating the occupant compartment or to present hazard to others in the area.	Pass
Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.	Maximum occupant compartment deformation was 3.5 inches in the right front floor pan.	
F. *The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.*	The 1100C vehicle remained upright during and after the collision period. Maximum roll and pitch angles were 23° and 7°, respectively.	Pass
H. *Longitudinal and lateral occupant impact velocities (OIV) should fall below the preferred value of 30 ft/s, or at least below the maximum allowable value of 40 ft/s.*	Longitudinal OIV was 19.4 ft/s and lateral OIV was 30.8 ft/s.	Pass
I. *Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15.0 Gs, or at least below the maximum allowable value of 20.49 Gs.*	Longitudinal occupant ridedown acceleration was 3.5 g and lateral occupant ridedown acceleration was 7.0 g.	Pass
Vehicle Trajectory		
For redirective devices, it is preferable that the vehicle be smoothly redirected and leave the barrier within the “exit box” criteria (not less than 32.8 ft for the 1100C and 2270P vehicles), and should be documented.	The 1100C vehicle exited within the exit box.	Documentation only

Table 8.2. Performance Evaluation Summary for *MASH* Test 3-21 on T221 Vertical Wall to SSCB Transition.

Test Agency: Texas A&M Transportation Institute | Test No.: 469689-2-2 | Test Date: 2019-08-21

***MASH* Test Evaluation Criteria**	**Test Results**	**Assessment**
<u>Structural Adequacy</u> *A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable*	The transition contained and redirected the 2270P vehicle. The vehicle did not penetrate, override, or underride the installation. No dynamic deflection or permanent deformation was observed.	Pass
<u>Occupant Risk</u> *D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.*	No detached elements, fragments, or other debris were present to penetrate or show potential for penetrating the occupant compartment or to present hazard to others in the area.	Pass
Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.	Maximum occupant compartment deformation was 4.0 inches in the right front firewall area.	
F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.	The 2270P vehicle remained upright during and after the collision period. Maximum roll and pitch angles were 6° and 9°, respectively.	Pass
H. Longitudinal and lateral occupant impact velocities should fall below the preferred value of 30 ft/s, or at least below the maximum allowable value of 40 ft/s.	Longitudinal OIV was 15.7 ft/s and lateral OIV was 28.2 ft/s.	Pass
I. Longitudinal and lateral occupant ridedown accelerations should fall below the preferred value of 15.0 Gs, or at least below the maximum allowable value of 20.49 Gs.	Longitudinal occupant ridedown acceleration was 4.2 g and lateral occupant ridedown acceleration was 12.2 g.	Pass
<u>Vehicle Trajectory</u>		
For redirective devices, it is preferable that the vehicle be smoothly redirected and leave the barrier within the “exit box” criteria (not less than 32.8 ft for the 1100C and 2270P vehicles), and should be documented.	The 2270P vehicle exited within the exit box.	Documentation only

Table 8.3. Assessment Summary for *MASH* TL-3 Tests on T221 Vertical Wall to SSCB Transition.

Evaluation Factors	Evaluation Criteria	Test No. 469468-2-1	Test No. 169468-2-2
Structural Adequacy	A	S	S
Occupant Risk	D	S	S
	F	S	S
	H	S	S
	I	S	S
	Test No.	***MASH* Test 3-20**	***MASH* Test 3-21**
	Pass/Fail	Pass	Pass

S = Satisfactory
U = Unsatisfactory
N/A = Not Applicable

CHAPTER 9: IMPLEMENTATION*

Based on *MASH* compliant performance of single slope barrier in past testing, the design of cast in place SSTR to SSCB transition developed in this project is considered suitable for implementation as a *MASH* TL-3 transition system (*4, 5*).

Based on the results of the testing and evaluation reported herein, the design of cast in place T221 vertical wall to SSCB transition is considered suitable for implementation as a *MASH* TL-3 transition system.

Testing was only performed in the direction from SSCB to T221. Simulation results of these impact conditions were more conservative than the test results with regard to vehicle stability and occupant risk. The direction of impact from T221 to SSCB was determined to be less critical in the simulation analyses, so Tests 3-20 and 3-21 were not performed in this direction. However, based on successful performance in the simulation analyses, the transition system is expected to perform acceptably in the direction from T221 to SSCB as well.

Similarly, results of simulations performed with the F-shape to SSCB transition were less critical than the T221 to SSCB transition simulations. Thus, even though full scale crash testing was not performed for the F-shape to SSCB transition, it is expected to perform acceptably as a *MASH* TL-3 transition based on simulation results and is considered suitable for implementation.

Statewide implementation of the transition designs developed in this project can be achieved by TxDOT's Design Division through the development and issuance of new standard detail sheets. Transition details provided in Appendix A and in Figures 2.1, 2.2, 2.6, and 2.7 can be used for this purpose.

* The opinions/interpretations identified/expressed in this section of the report are outside the scope of TTI Proving Ground's A2LA Accreditation.

REFERENCES

1. AASHTO. *Manual for Assessing Roadside Safety Hardware.* Second Edition, 2016, American Association of State Highway and Transportation Officials: Washington, D.C.

2. Livermore Software Technology Corporation, *LS-DYNA Keyword User's Manual*, 2016, Livermore, California.

3. Livermore Software Technology Corporation, *LS-DYNA Theory Manual*, 2019, Livermore, California.

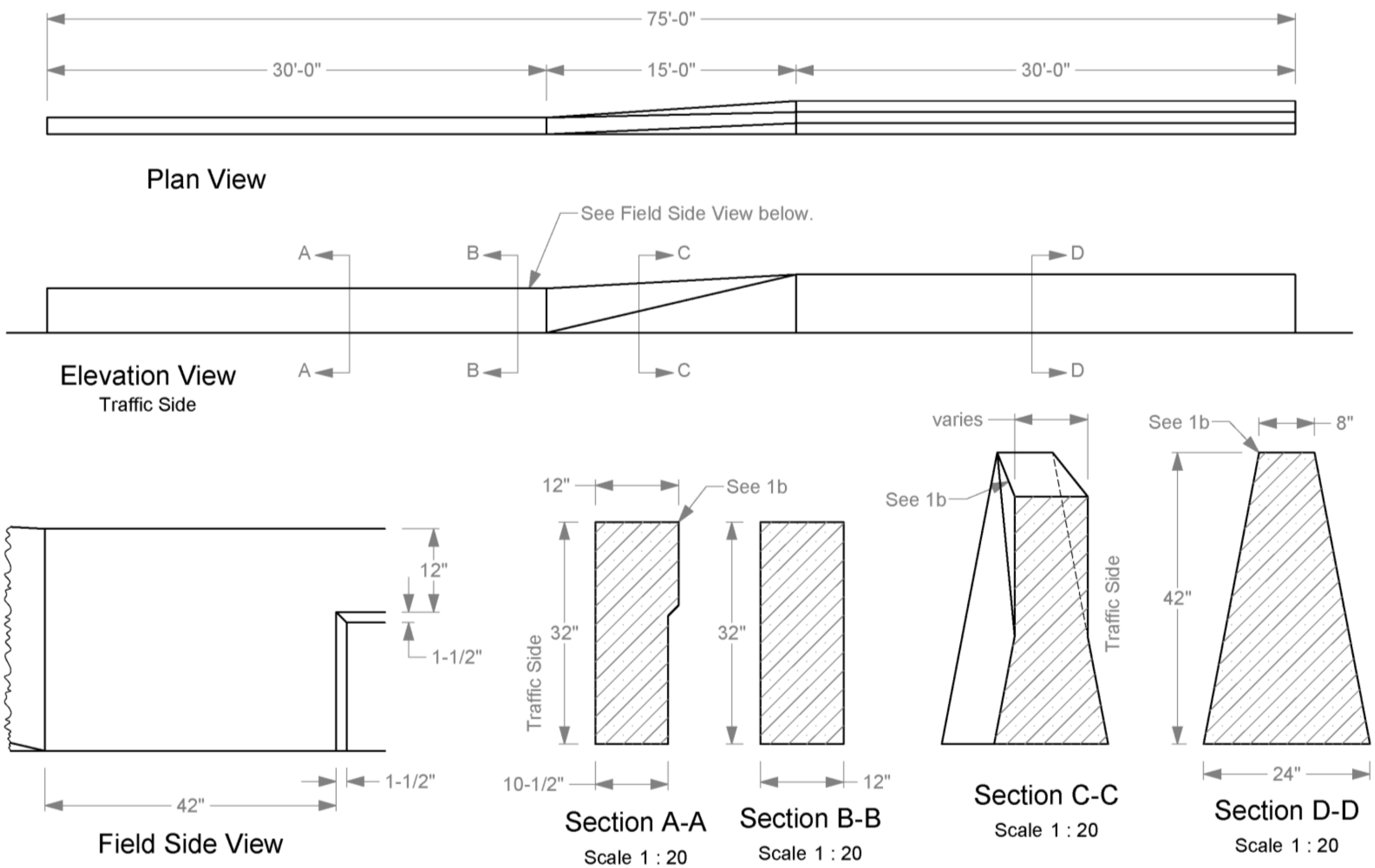
4. W.F. Williams, R.P. Bligh, and W.L. Menges, *Mash Test 3-11 of the TxDOT Single Slope Bridge Rail (Type SSTR) on Pan-Formed Bridge Deck.* Report 9-1002-3. Texas A&M Transportation Institute, College Station, TX, 2011.

5. D. Whitesel, J. Jewell, and R. Meline, *Compliance Crash Testing of the Type 60 Median Barrier, Test 140MASH3C16-04.* Research Report FHWA/CA17-2654, Roadside Safety Research Group, California Department of Transportation, Sacramento, CA, May 2018.

APPENDIX A. DETAILS OF T221 VERTICAL WALL TO SSCB TRANSITION

T:\1-ProjectFiles\469689-TxDOT\-2 Barrier Transitions\Drafting, 469689-2\SS Median to T221\469689-2 Drawing

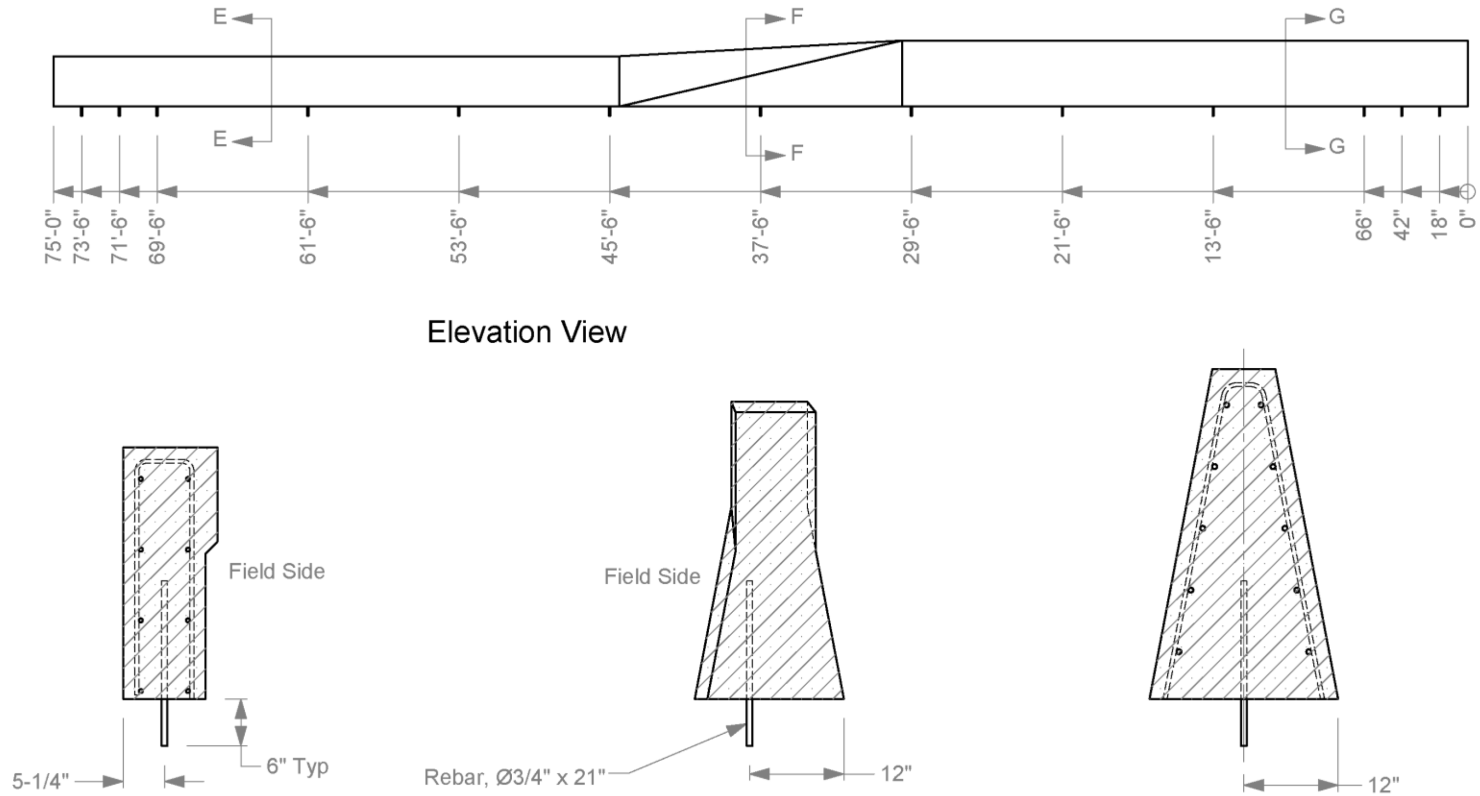
Test Installation



1a. Concrete shall be TxDOT Class C (3600 psi).
1b. 1" Chamfer (3/4" each way) top edges of Barrier (not shown here).

Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Project #469689-2 Single Slope Median to T221		2019-07-10
Drawn by GES	Scale 1:100	Sheet 1 of 5 Test Installation

Anchorage Details



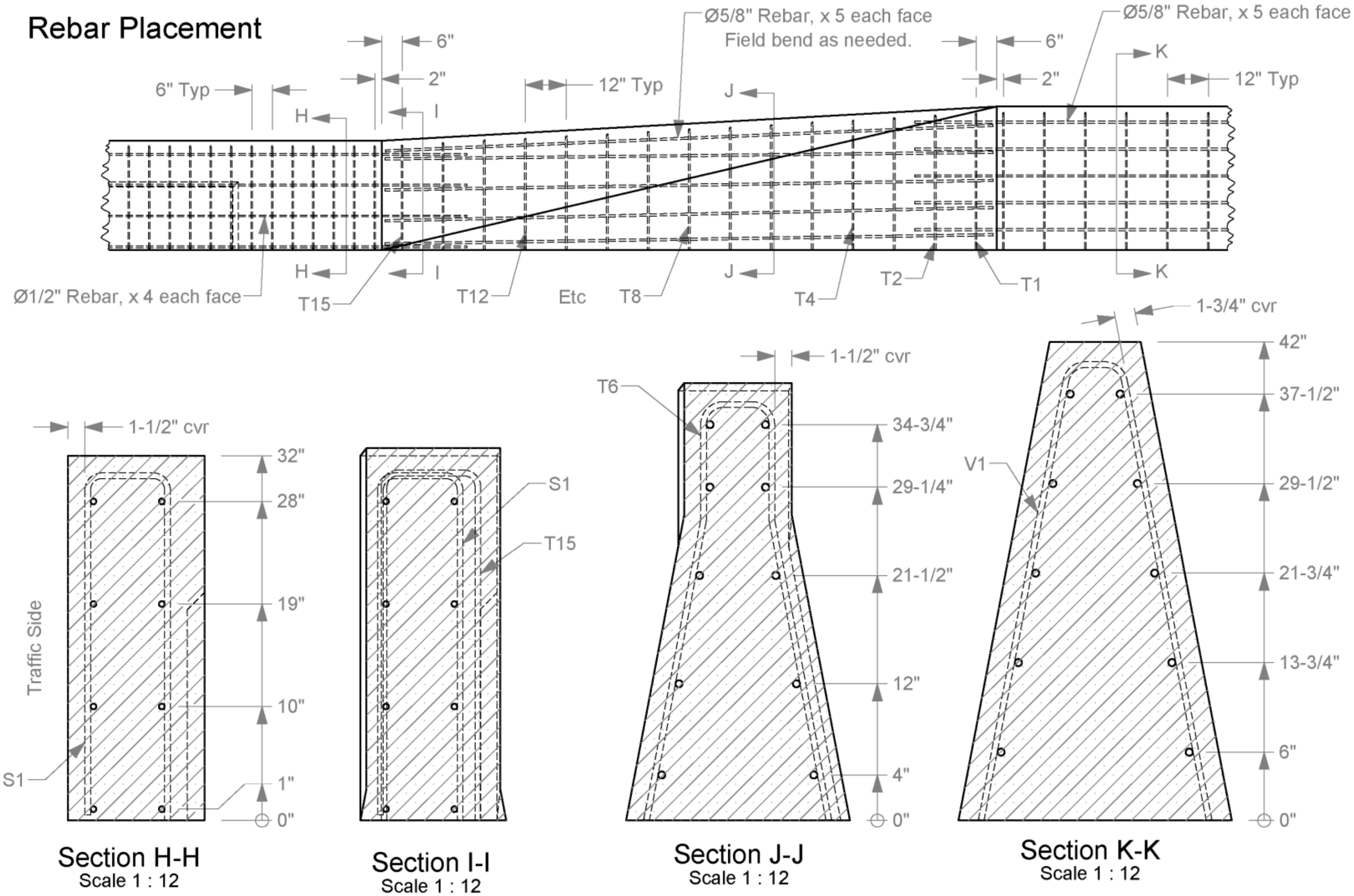
Section E-E
Scale 1 : 20
Typ in T221 Section

Section F-F
Scale 1 : 20
Typ in Transition Section
Other rebar not shown for clarity

Section G-G
Scale 1 : 20
Typ in Single Slope Section

Texas A&M Transportation Institute		Roadside Safety and Physical Security Division - Proving Ground
Project #469689-2 Single Slope Median to T221		2019-07-10
Drawn by GES	Scale 1:100	Sheet 2 of 5 Anchorage Details

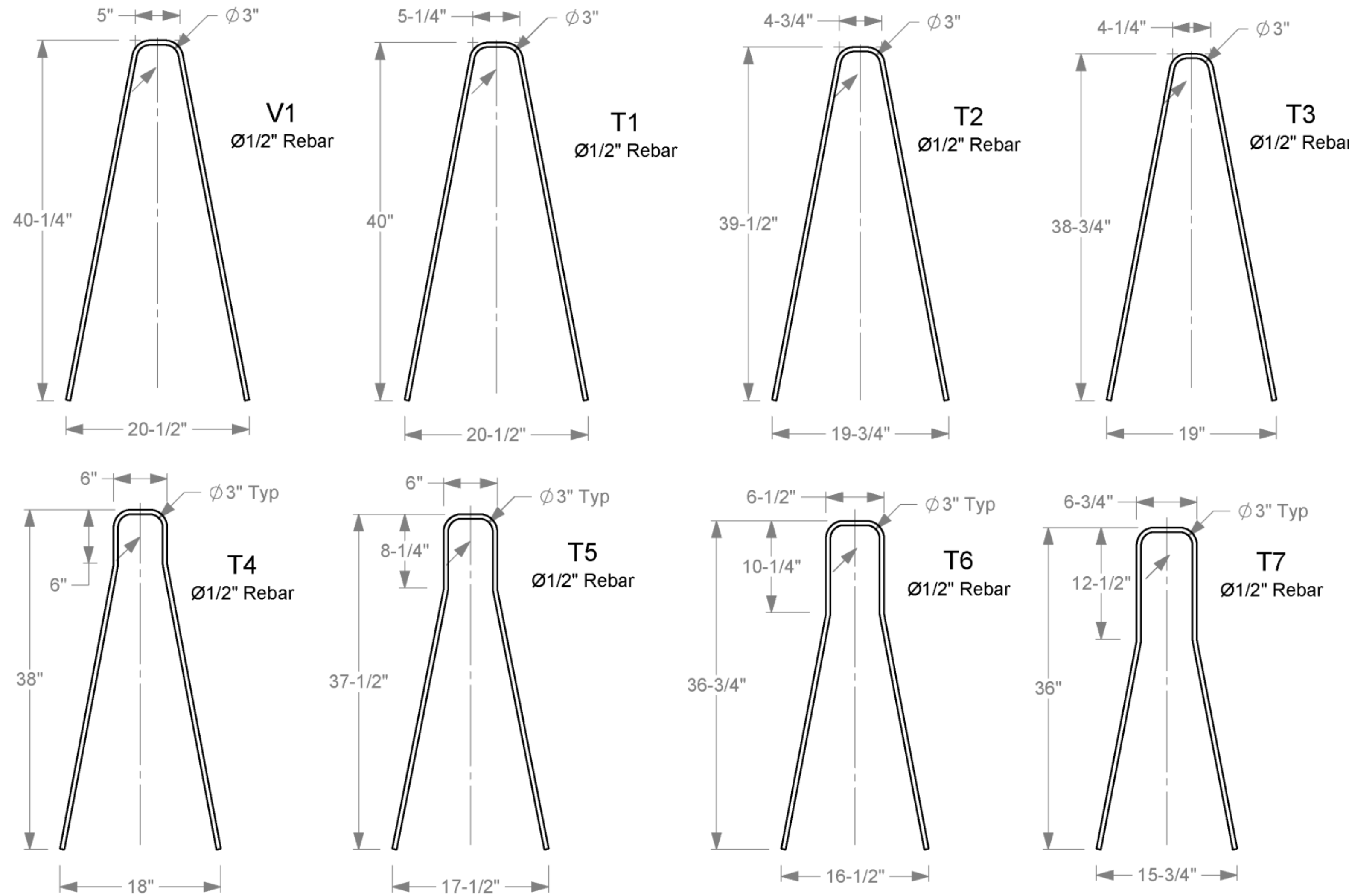
Rebar Placement



3a. All rebar dimensions are to center of bar unless otherwise indicated by "cvr" (cover).
3b. Minimum rebar lap is 17" for #4 bars and 24" for #5 bars. All rebar is grade 60.

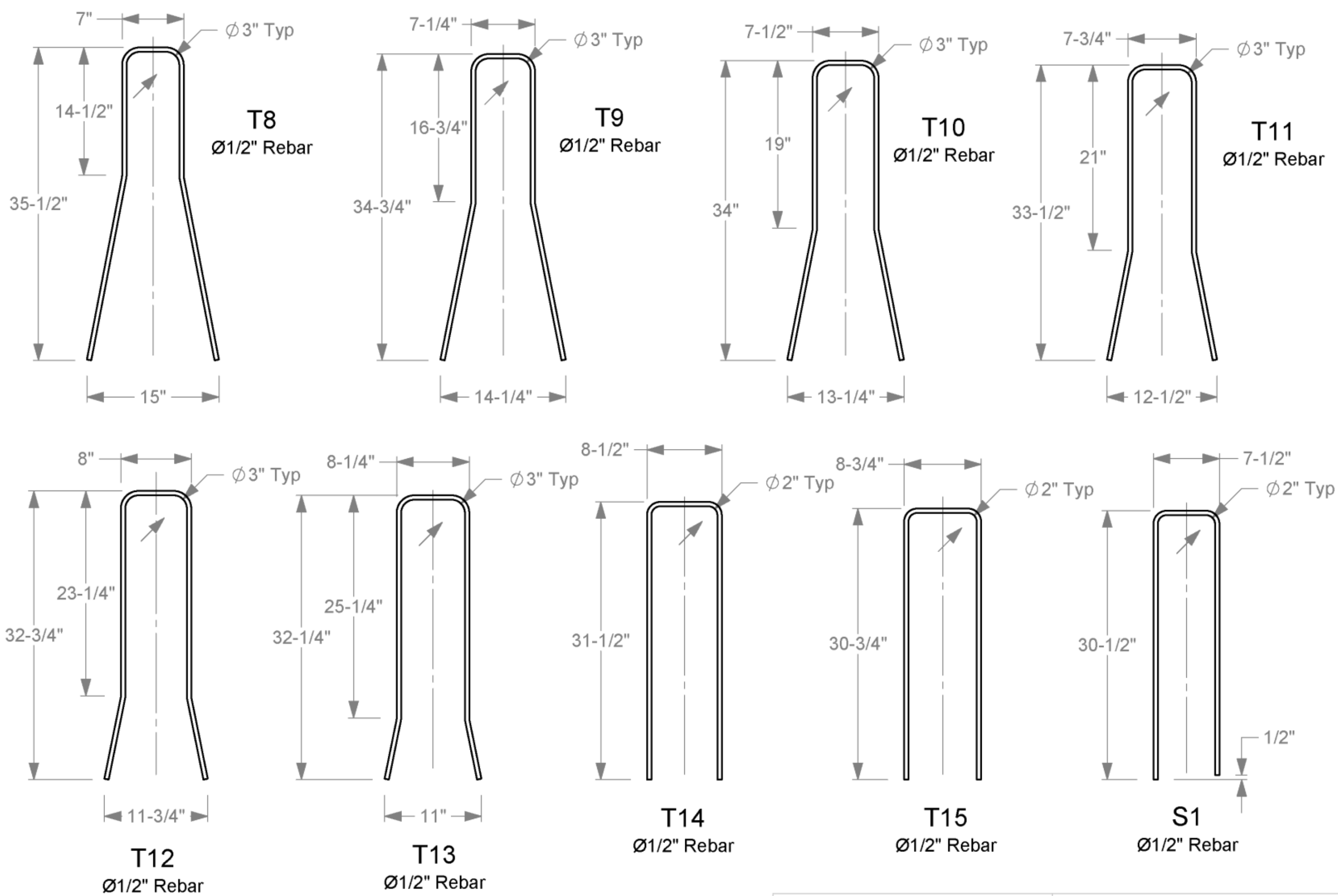
Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Project #469689-2 Single Slope Median to T221		2019-07-10
Drawn by GES	Scale 1:40	Sheet 3 of 5 Rebar Placement

T:\1-ProjectFiles\469689-TxDOT\-2 Barrier Transitions\Drafting, 469689-2\SS Median to T221\469689-2 Drawing



Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Project #469689-2 Single Slope Median to T221		2019-07-10
Drawn by GES	Scale 1:15	Sheet 4 of 5 V1 & T1 - T7

T:\1-ProjectFiles\469689-TxDOT\-2 Barrier Transitions\Drafting, 469689-2\SS Median to T221\469689-2 Drawing



Texas A&M Transportation Institute	Roadside Safety and Physical Security Division - Proving Ground	
Project #469689-2 Single Slope Median to T221		2019-07-10
Drawn by GES	Scale 1:15	Sheet 5 of 5 T8 - T13 & S1

T:\1-ProjectFiles\469689-TxDOT\-2 Barrier Transitions\Drafting, 469689-2\SS Median to T221\469689-2 Drawing

APPENDIX B. SUPPORTING CERTIFICATION DOCUMENTS

Texas A&M Transportation Institute Proving Ground 3100 SH 47, Bldg 7091 Bryan, TX 77807 Texas A&M University College Station, TX 77843 Phone 979-845-6375	QF 7.3-01 Concrete Sampling	Doc. No. QF 7.3-01	Issue Date: 2018-06-18
Quality Form	Prepared by: Wanda L. Menges Approved by: Darrell L. Kuhn	Revision: 6	Page: 1 of 1

The information contained in this document is confidential to TTI Proving Ground.

Project No: 469688-2 **Casting Date:** 2019-7-16 **Mix Design (psi):** CLASS C

9 3/2019-08-19

Name of Technician Taking Sample: GREG FRITZ

Name of Technician Breaking Sample: Bill Griffith

Signature of Technician Taking Sample: [signature]

Signature of Technician Breaking Sample: [signature]

Load No.	Truck No.	Ticket No.	Location (from concrete map)
T1	7110	5526601	BOTTOM HALF OF RAIL
T2	8120	5526684	TOP HALF OF RAIL

Load No.	Break Date	Cylinder Age	Total Load (lbs)	Break (psi)	Average
T1	2019-08-19	34 days	186000	6579	
			191000	6756	6626
			185000	6544	
T2	2019-08-19	34 days	174000	6154	
			184000	6508	6119
			161000	5695	

CUSTOMER'S COPY

TICKET NO. 5526601

T1

Martin Marietta

1503 LBJ Freeway
Suite 400
Dallas, Tx 75234

5526601

LOAD TIME	TO JOB	ARRIVE JOB SITE	BEGIN POUR	FINISH POUR	LEAVE JOB SITE	ARRIVE PLANT
8:36	8:50	9:11	:	:	:	:

WATER ADDED ON JOB AT CUSTOMER'S REQUEST ________ GAL.
ALLOWABLE WATER (withheld from batch) ________ GAL.
TEST CYLINDER TAKEN ❑ YES ❑ NO BY ________
CYLINDER TAKEN ❑ BEFORE ❑ AFTER WATER

ADDITIONAL WATER ADDED TO THIS CONCRETE WILL REDUCE ITS STRENGTH. ANY WATER ADDED IN EXCESS OF SPECIFIED SLUMP IS AT CUSTOMER'S RISK.

CUSTOMER SIGNATURE
X

DELIVERY OF THESE MATERIALS IS SUBJECT TO THE TERMS AND CONDITIONS ON THE REVERSE SIDE HEREOF AS ACCEPTED BY SIGNATURE ABOVE.

CUSTOMER NAME AND DELIVERY ADDRESS
TTI-Riverside Campus

PLANT 617 TRUCK 7110 ORDER NO. 2033 SLUMP 5.00 P.O. #/JOB/LOT GRID
DRIVER NAME [illegible]MOND ORTIZ DATE 7/16/19
CUSTOMER NUMBER PROJECT 79546 CUM. QTY 6.00 ORDERED QTY 12.00

LOAD QUANTITY	PRODUCT CODE	DESCRIPTION		UNIT PRICE	AMOUNT
6.00	CYDS	DBCC00	DOT, CLASS C, T1		
1.00	ea	12987	FREIGHT CHARGE		

SPECIAL DELIVERY INSTRUCTIONS [illegible] RIGHT LEONARD RD, RIGHT ON HWY 47, LEFT INTO RELLISTHEY WILL MEET YOU AT THE ROUNDA BOUT

SALES TAX

TOTAL

DANGER! MAY CAUSE ALKALI BURNS.
SEE WARNINGS ON REVERSE SIDE.

FOR OFFICE USE ONLY **FORM:**

Truck	Driver	User	Disp Ticket Num	Ticket ID	Time	Date
7110	940107	user	5526601	77559	8:36	7/16/19

Load Size	Mix Code	Returned	Qty	Mix Age	Seq	Load ID
6.00 CYDS	DBCC00				D	78594

Material	Design Qty	Required	Batched	% Var	% Moisture	Actual Wat
1"CS	1920 lb	11555 lb	11640 lb	* 0.74%	0.30% M	4 gl
SAND-1	1292 lb	8033 lb	8000 lb	-0.41%	3.50% M	34 gl
CMT-I/II	360 lb	2160 lb	2170 lb	0.46%		
FLYASH-C	240 lb	1440 lb	1430 lb	-0.69%		
H2O	267 lb	1151 lb	1152 lb	0.09%		138 gl
ZY-610	14 oz	130 oz	129 oz	-0.46%		

Actual Num Batches: 1
Load Total: 24400 lb Design 0.445 Water/Cement 0.445 T Design 192.0 gl Actual 175.8 gl To Add: 10.2 gl
Slump: 5.00 in # Water in Truck: 6.0 gl Adjust Water: 0.0 gl / Load Trim Water: -1.7 gl/ CYD

CUSTOMER'S COPY

TICKET NO. 5526684 Y2

Martin Marietta

1503 LBJ Freeway
Suite 400
Dallas, Tx 75234

* 5 5 2 6 6 8 4 *

LOAD TIME	TO JOB	ARRIVE JOB SITE	BEGIN POUR	FINISH POUR	LEAVE JOB SITE	ARRIVE PLANT
8:52	9:03	9:25	:	:	:	:

WATER ADDED ON JOB AT CUSTOMER'S REQUEST ________ GAL.
ALLOWABLE WATER (withheld from batch) ________ GAL.
TEST CYLINDER TAKEN ❑ YES ❑ NO BY ________
CYLINDER TAKEN ❑ BEFORE ❑ AFTER WATER

ADDITIONAL WATER ADDED TO THIS CONCRETE WILL REDUCE ITS STRENGTH. ANY WATER ADDED IN EXCESS OF SPECIFIED SLUMP IS AT CUSTOMER'S RISK.

CUSTOMER SIGNATURE
X

DELIVERY OF THESE MATERIALS IS SUBJECT TO THE TERMS AN CONDITIONS ON THE REVERSE SIDE HEREOF AS ACCEPTED B SIGNATURE ABOVE .

CUSTOMER NAME AND DELIVERY ADDRESS
TEXAS A & M UNIVERSI
TTI-Riverside Campus

PLANT	TRUCK	ORDER NO.	SLUMP	P.O. #/JOB/LOT	GRID
617	8120	2033	5.0	469689-2	

DRIVER NAME	DATE
Matthew Wenzel	7/16/19

CUSTOMER NUMBER	PROJECT	CUM. QTY	ORDERED QTY
783659	79546	12.00	12.00

LOAD QUANTITY	PRODUCT CODE		DESCRIPTION	UNIT PRICE	AMOUNT
6.00	CYDS	DBCC00	DOT, CLASS C, T1		
1.00	ea	12987	FREIGHT CHARGE		

SPECIAL DELIVERY INSTRUCTIONS
SOUTH 2818, RIGHT LEONARD RD, RIGHT ON HWY 47, LEFT
INTO RELLISTHEY WILL MEET YOU AT THE ROUNDA BOUT

SALES TAX

TOTAL

DANGER! MAY CAUSE ALKALI BURNS.
SEE WARNINGS ON REVERSE SIDE.

FOR OFFICE USE ONLY **FORM:**

Truck	Driver	User	Disp Ticket Num	Ticket ID	Time	Date
8120	946451	user	5526684	77560	8:52	7/16/19

Load Size	Mix Code	Returned	Qty	Mix Age	Seq	Load ID
6.00 CYDS	DBCC00				D	78595

Material	Design Qty	Required	Batched	% Var	% Moisture	Actual Wat
1"CS	1920 lb	11555 lb	11560 lb	* 0.05%	0.30% M	4 gl
SAND-1	1292 lb	8033 lb	8040 lb	0.09%	3.50% M	34 gl
CMT-I/II	360 lb	2160 lb	2180 lb	0.93%		
FLYASH-C	240 lb	1440 lb	1430 lb	-0.69%		
H20	267 lb	1134 lb	1137 lb	0.24%		136 gl
ZY-610	14 oz	130 oz	130 oz	0.31%		

Actual Num Batches: 1
Load Total: 24355 lb Design 0.445 Water/Cement 0.444 T Design 192.0 gl Actual 174.1 gl To Add: 9.8 gl
Slump: 5.00 in # Water in Truck: 8.0 gl Adjust Water: 0.0 gl / Load Trim Water: -1.7 gl/ CYD

APPENDIX C. *MASH* TEST 3-20 (CRASH TEST NO. 469689-2-1)

C.1 VEHICLE PROPERTIES AND INFORMATION

Table C.1. Vehicle Properties for Test No. 469689-2-1.

Date: 2019-08-19 Test No.: 469689-02-1 VIN No.: KNADH4A35B6916812

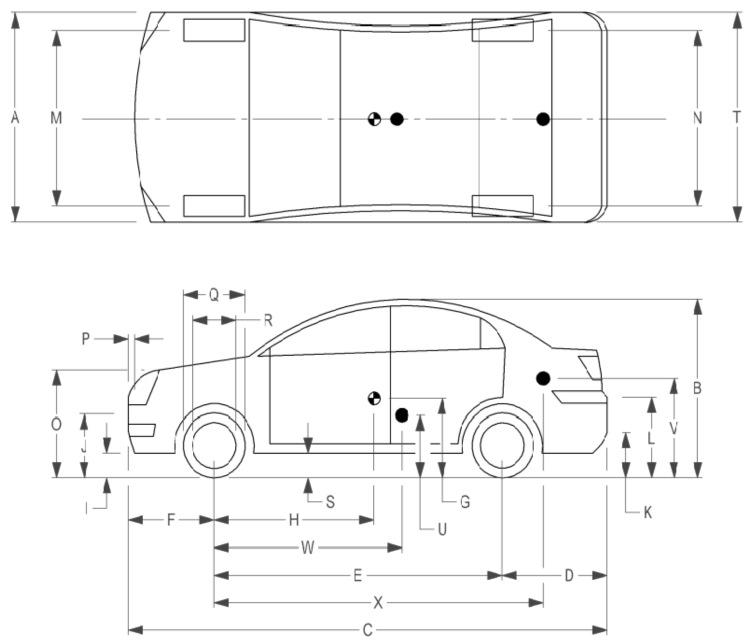
Year: 2011 Make: Kia Model: Rio

Tire Inflation Pressure: 32 PSI Odometer: 95134 Tire Size: 185/65R14

Describe any damage to the vehicle prior to test: None

● Denotes accelerometer location.

NOTES: None



Engine Type: 4 CYL
Engine CID: 1.6 L
Transmission Type:
☑ Auto or ☐ Manual
☑ FWD ☐ RWD ☐ 4WD
Optional Equipment:
None

Dummy Data:
Type: 50th Percentile Male
Mass: 165 lb
Seat Position: IMPACT SIDE

Geometry: inches

A	66.38	F	33.00	K	12.25	P	4.12	U	14.75
B	51.50	G		L	25.25	Q	22.50	V	20.75
C	165.75	H	36.05	M	57.75	R	15.50	W	36.00
D	34.00	I	7.75	N	57.70	S	8.25	X	71.50
E	98.75	J	21.50	O	27.00	T	66.20		

Wheel Center Ht Front 11.00 Wheel Center Ht Rear 11.00 W-H 0.00

RANGE LIMIT: A = 65 ±3 inches; C = 169 ±8 inches; E = 98 ±5 inches; F = 35 ±4 inches; H = 39 ±4 inches; O (Bottom of Hood Lip) = 24 ±4 inches
TOP OF RADIATOR SUPPORT = 28.25 inches; (M+N)/2 = 56 ±2 inches; W-H < 2 inches or use MASH Paragraph A4.3.2

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	1718	M_{front}	1584	1534	1619
Back	1874	M_{rear}	893	882	962
Total	3638	M_{Total}	2477	2416	2581

Allowable TIM = 2420 lb ±55 lb | Allowable GSM = 2585 lb ± 55 lb

Mass Distribution:
lb LF: 832 RF: 702 LR: 402 RR: 480

Table C.2. Exterior Crush Measurements of Vehicle for Test No. 469689-2-1.

Date:	2019-08-19	Test No.:	469689-02-1	VIN No.:	KNADH4A35B6916812
Year:	2011	Make:	Kia	Model:	Rio

VEHICLE CRUSH MEASUREMENT SHEET[1]

Complete When Applicable	
End Damage	Side Damage
Undeformed end width ________	Bowing: B1 _____ X1 _____
Corner shift: A1 ________	B2 _____ X2 _____
A2 ________	
End shift at frame (CDC)	Bowing constant
(check one)	$\frac{X1+X2}{2}$ = ______
< 4 inches ________	
≥ 4 inches ________	

Note: Measure C_1 to C_6 from Driver to Passenger Side in Front or Rear Impacts – Rear to Front in Side Impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage Width** (CDC)	Direct Damage Max*** Crush	Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
1	Front plane at bumper ht	18	8	18	2	6	8	-	-	-	+24.5
2	Side plane at bumper ht	18	8	40	0	1	2.5	4	6	8	+62
	Measurements recorded										
	☑ **inches** **or** ☐ **mm**										

[1]Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

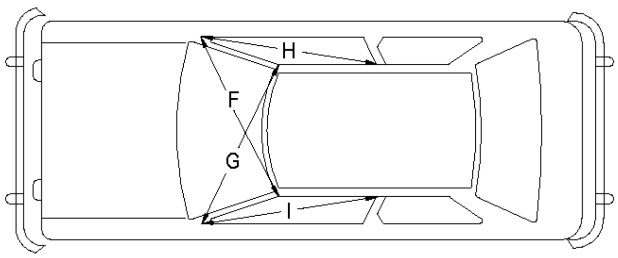
***Measure and document on the vehicle diagram the location of the maximum crush.

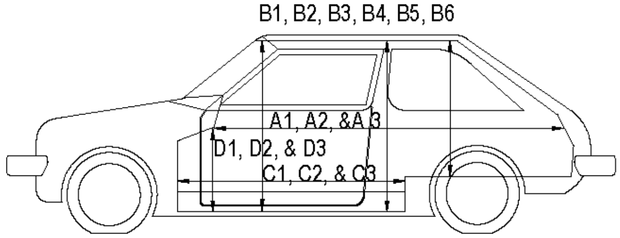
Note: Use as many lines/columns as necessary to describe each damage profile.

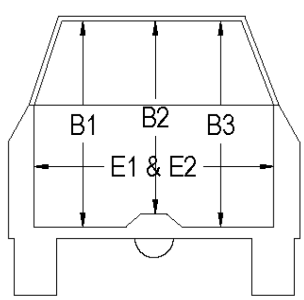
Table C.3. Occupant Compartment Measurements of Vehicle for Test No. 469689-2-1.

Date: 2019-08-19 Test No.: 469689-02-1 VIN No.: KNADH4A35B6916812

Year: 2011 Make: Kia Model: Rio







*Lateral area across the cab from
driver's side kick panel to passenger's side kick panel.

OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before	After (inches)	Differ.
A1	67.50	67.50	0.00
A2	67.25	67.25	0.00
A3	67.75	67.75	0.00
B1	40.50	40.50	0.00
B2	39.00	39.00	0.00
B3	40.50	37.00	-3.50
B4	36.25	36.25	0.00
B5	36.00	36.00	0.00
B6	36.25	36.25	0.00
C1	26.00	26.00	0.00
C2	0.00	0.00	0.00
C3	26.00	24.00	-2.00
D1	9.50	9.50	0.00
D2	0.00	0.00	0.00
D3	9.50	7.50	-2.00
E1	51.50	51.50	0.00
E2	51.00	51.00	0.00
F	51.00	51.00	0.00
G	51.00	51.00	0.00
H	37.50	37.50	0.00
I	37.50	37.50	0.00
J*	51.00	50.00	-1.00

C.2 SEQUENTIAL PHOTOGRAPHS

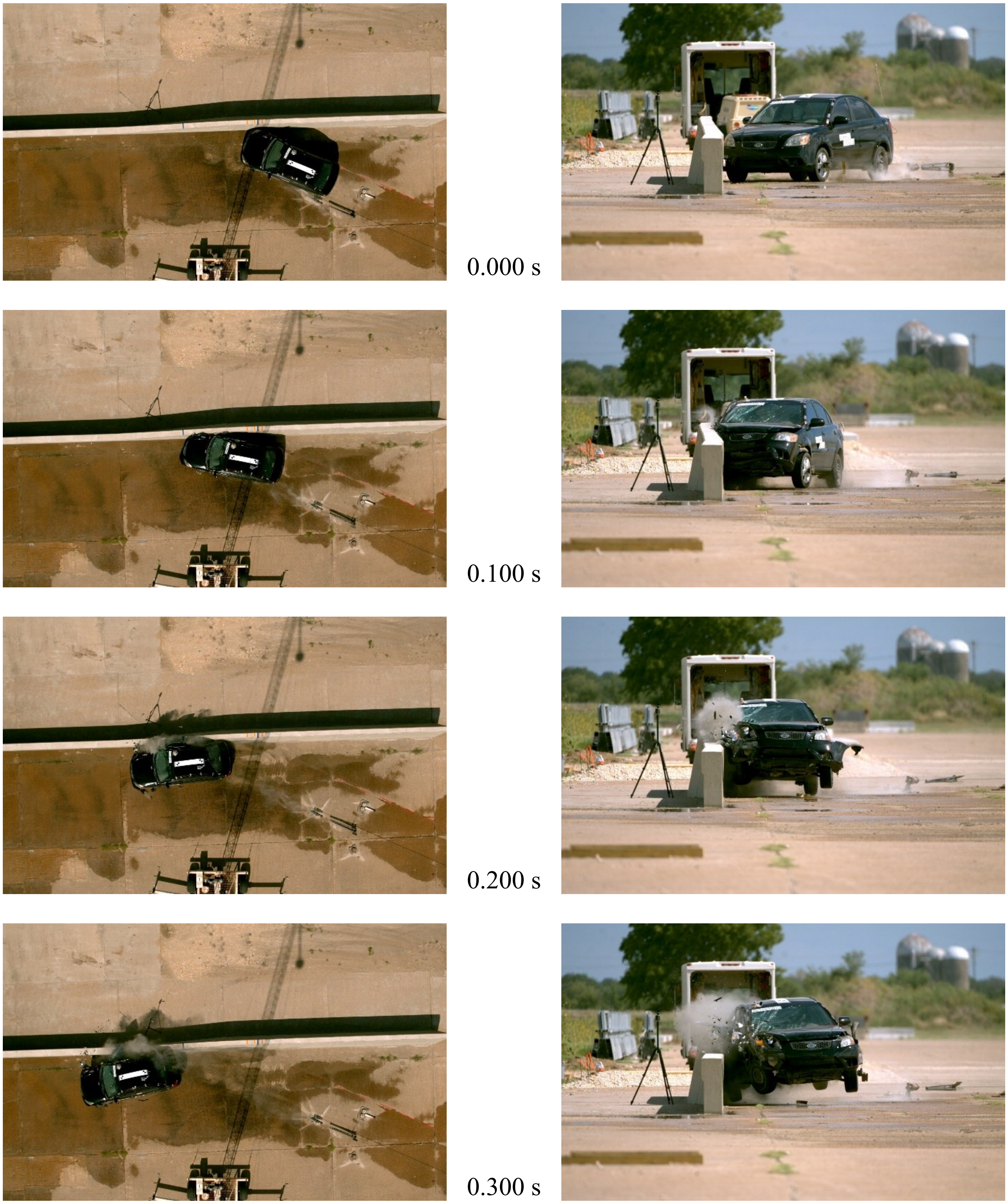


Figure C.1. Sequential Photographs for Test No. 469689-2-1 (Overhead and Frontal Views).


0.400 s



0.500 s



0.600 s



0.700 s


Figure C.1. Sequential Photographs for Test No. 469689-2-1 (Overhead and Frontal Views) (Continued).

0.000 s

0.100 s

0.200 s

0.300 s

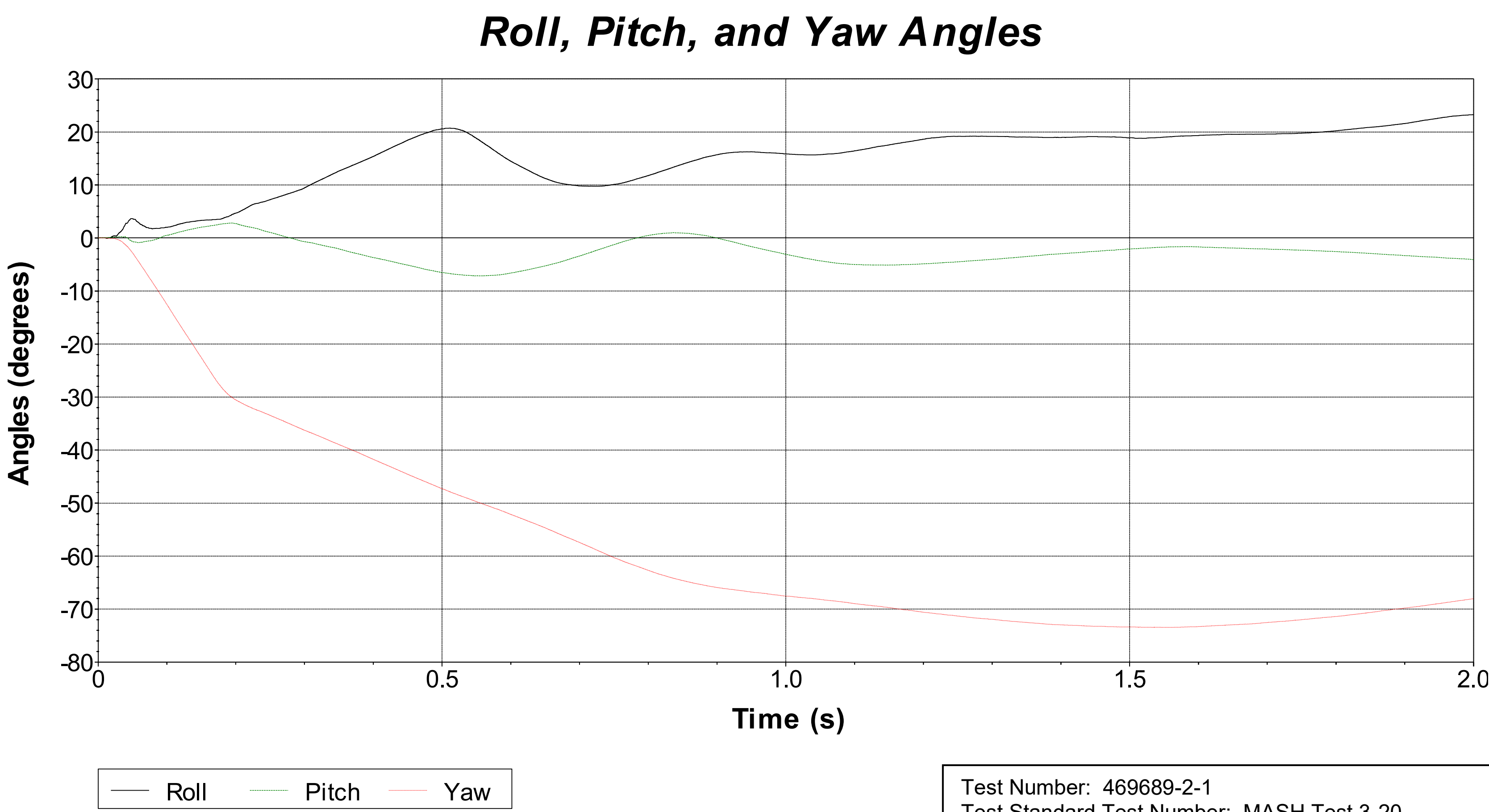
0.400 s

0.500 s

0.600 s

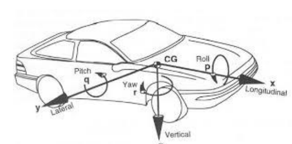
0.700 s

Figure C.2. Sequential Photographs for Test No. 469689-2-1 (Rear View).



Axes are vehicle-fixed.
Sequence for determining orientation:

1. Yaw.
2. Pitch.
3. Roll.



Test Number: 469689-2-1
Test Standard Test Number: MASH Test 3-20
Test Article: T221 vertical wall to SSCB transition
Test Vehicle: 2011 Kia Rio
Inertial Mass: 2416 lb
Gross Mass: 2581 lb
Impact Speed: 61.6 mi/h
Impact Angle: 24.6°

Figure C.3. Vehicle Angular Displacements for Test No. 469689-2-1.

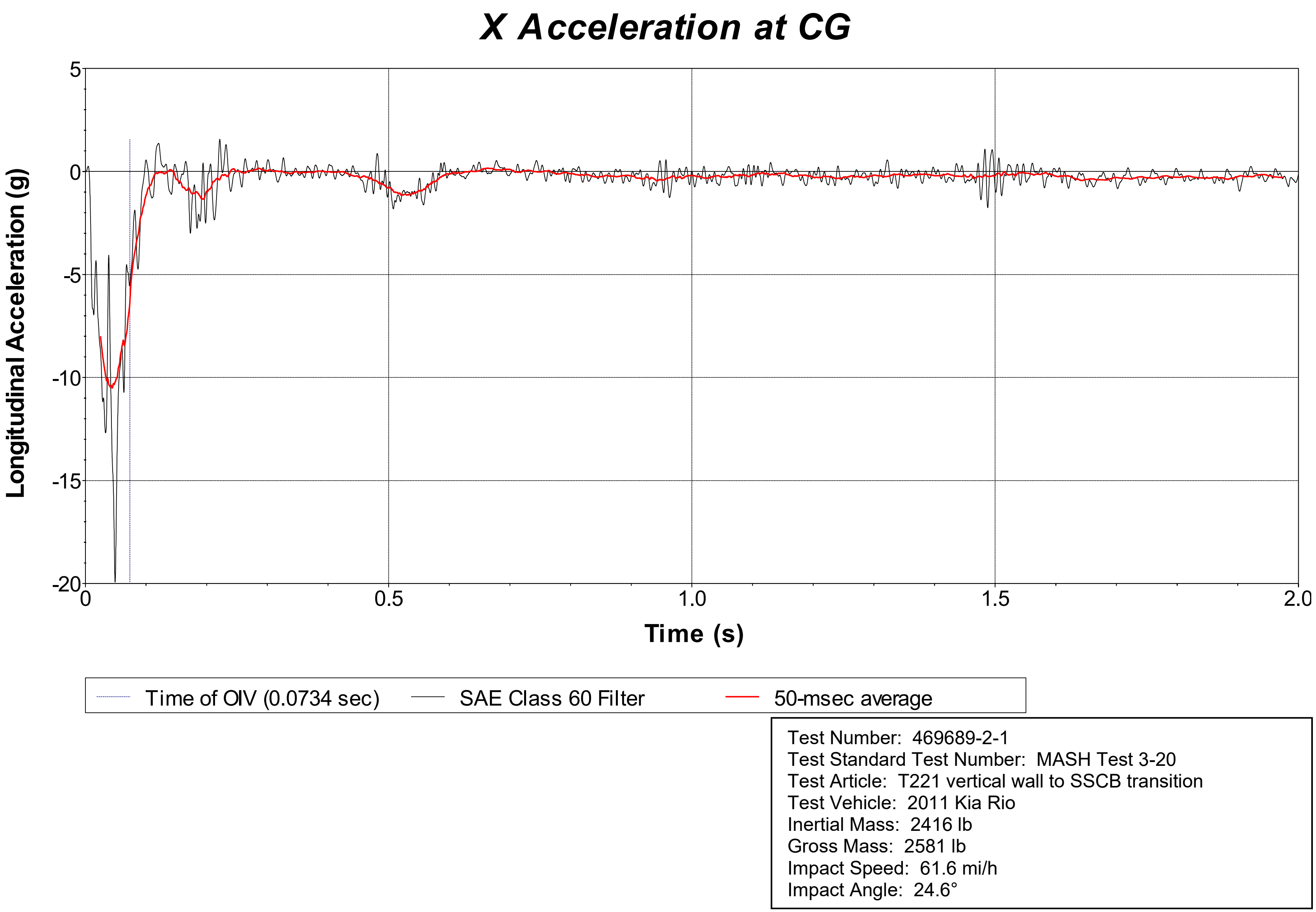


Figure C.4. Vehicle Longitudinal Accelerometer Trace for Test No. 469689-2-1 (Accelerometer Located at Center of Gravity).

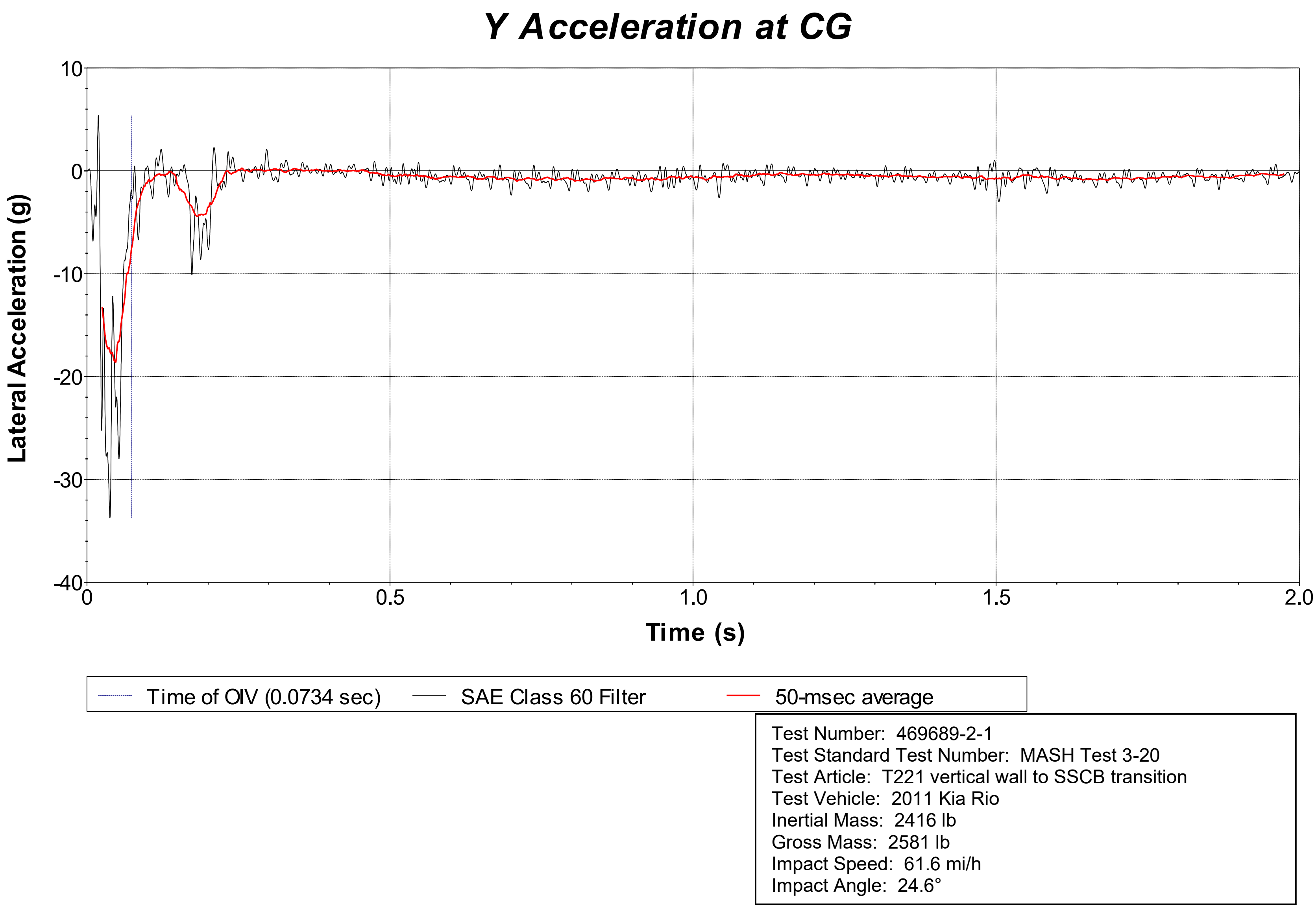
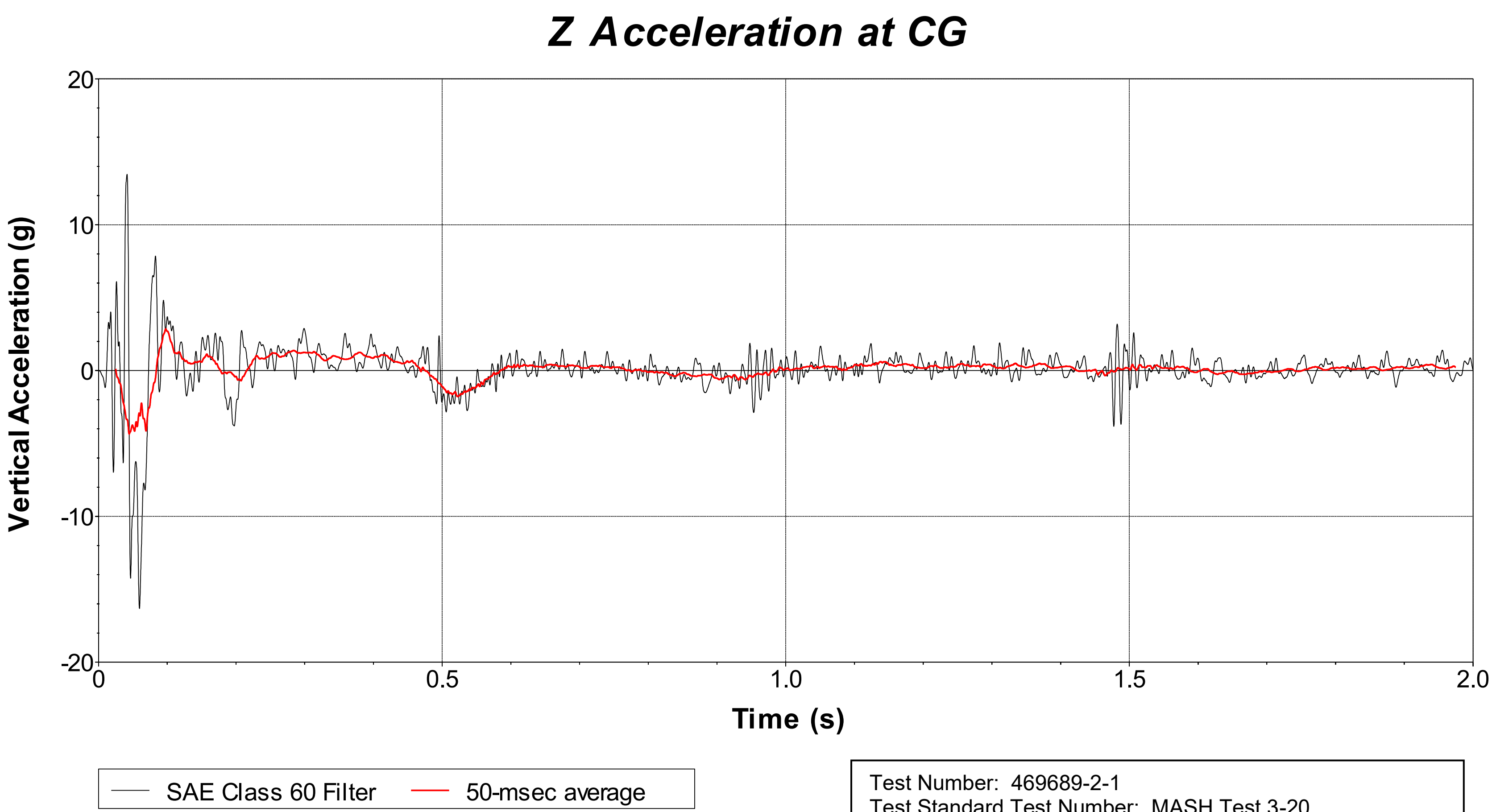


Figure C.5. Vehicle Lateral Accelerometer Trace for Test No. 469689-2-1 (Accelerometer Located at Center of Gravity).



Test Number: 469689-2-1
Test Standard Test Number: MASH Test 3-20
Test Article: T221 vertical wall to SSCB transition
Test Vehicle: 2011 Kia Rio
Inertial Mass: 2416 lb
Gross Mass: 2581 lb
Impact Speed: 61.6 mi/h
Impact Angle: 24.6°

Figure C.6. Vehicle Vertical Accelerometer Trace for Test No. 469689-2-1 (Accelerometer Located at Center of Gravity).

APPENDIX D. *MASH* TEST 3-21 (CRASH TEST NO. 469689-2-2)

D.1 VEHICLE PROPERTIES AND INFORMATION

Table D.1. Vehicle Properties for Test No. 469689-2-2.

Date:	2019-08-21	Test No.:	469689-02-2	VIN No.:	1C6RR6GT17DS693697
Year:	2013	Make:	RAM	Model:	1500

Tire Size: 265/70 R 17 — Tire Inflation Pressure: 35 psi

Tread Type: Highway — Odometer: 153103

Note any damage to the vehicle prior to test: None

● Denotes accelerometer location.

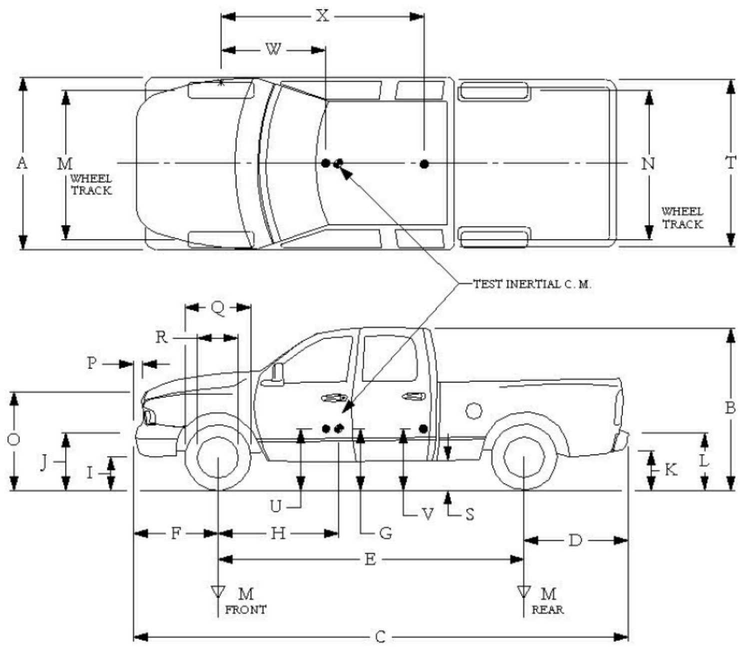
NOTES: None

Engine Type: V-8
Engine CID: 4.7 liter

Transmission Type:
☑ Auto or ☐ Manual
☐ FWD ☑ RWD ☐ 4WD

Optional Equipment:
None

Dummy Data:
Type: No dummy
Mass: 0 lb
Seat Position: NA



Geometry: inches

A	78.50	F	40.00	K	20.00	P	3.00	U	26.75
B	74.00	G	28.40	L	30.00	Q	30.50	V	30.25
C	227.50	H	61.94	M	68.50	R	18.00	W	61.90
D	44.00	I	11.75	N	68.00	S	13.00	X	79.00
E	140.50	J	27.00	O	46.00	T	77.00		

Wheel Center Height Front	14.75	Wheel Well Clearance (Front)	6.00	Bottom Frame Height - Front	12.50
Wheel Center Height Rear	14.75	Wheel Well Clearance (Rear)	9.25	Bottom Frame Height - Rear	22.50

RANGE LIMIT: A=78 ±2 inches; C=237 ±13 inches; E=148 ±12 inches; F=39 ±3 inches; G = > 28 inches; H = 63 ±4 inches; O=43 ±4 inches; (M+N)/2=67 ±1.5 inches

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	3700	M_{front}	2875	2815	2815
Back	3900	M_{rear}	2099	2220	2220
Total	6700	M_{Total}	4974	5035	5035

(Allowable Range for TIM and GSM = 5000 lb ±110 lb)

Mass Distribution:
lb — LF: 1375 — RF: 1440 — LR: 1080 — RR: 1140

Table D.2. Measurements of Vehicle Vertical CG for Test No. 469689-2-2.

Date: 2019-08-21 Test No.: 469689-02-2 VIN: 1C6RR6GT17DS693697

Year: 2013 Make: RAM Model: 1500

Body Style: Quad Cab Mileage: 153103

Engine: 4.7 liter V-8 Transmission: Automatic

Fuel Level: Empty Ballast: 100 (440 lb max)

Tire Pressure: Front: 35 psi Rear: 35 psi Size: 265/70 R 17

Measured Vehicle Weights: (lb)

LF:	1375	RF:	1440	Front Axle:	2815
LR:	1080	RR:	1140	Rear Axle:	2220
Left:	2455	Right:	2580	Total:	5035
					5000 ±110 lb allowed

Wheel Base: 140.50 inches Track: F: 68.50 inches R: 68.00 inches

148 ±12 inches allowed Track = (F+R)/2 = 67 ±1.5 inches allowed

Center of Gravity, SAE J874 Suspension Method

X:	61.95	inches	Rear of Front Axle	(63 ±4 inches allowed)
Y:	0.85	inches	Left - Right +	of Vehicle Centerline
Z:	28.40	inches	Above Ground	(minumum 28.0 inches allowed)

Hood Height: 46.00 inches Front Bumper Height: 27.00 inches

43 ±4 inches allowed

Front Overhang: 40.00 inches Rear Bumper Height: 30.00 inches

39 ±3 inches allowed

Overall Length: 227.50 inches

237 ±13 inches allowed

Table D.3. Exterior Crush Measurements of Vehicle for Test No. 469689-2-2.

Date:	2019-08-21	Test No.:	469689-02-2	VIN No.:	1C6RR6GT17DS693697
Year:	2013	Make:	RAM	Model:	1500

VEHICLE CRUSH MEASUREMENT SHEET[1]

Complete When Applicable	
End Damage	**Side Damage**
Undeformed end width ________	Bowing: B1 _____ X1 _____
Corner shift: A1 ________	B2 _____ X2 _____
A2 ________	
End shift at frame (CDC)	Bowing constant
(check one)	$\frac{X1+X2}{2}$ = _______
< 4 inches ________	
≥ 4 inches ________	

Note: Measure C_1 to C_6 from Driver to Passenger Side in Front or Rear Impacts – Rear to Front in Side Impacts.

Specific Impact Number	Plane* of C-Measurements	Direct Damage		Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
		Width** (CDC)	Max*** Crush								
1	Front plane at bmp ht	18	12	32	0	1	3	4	7	12	+19
2	Side plane at bmp ht	18	14	64	4	6	-	-	12	14	+72
	Measurements recorded										
	☑ inches or ☐ mm										

[1]Table taken from National Accident Sampling System (NASS).

*Identify the plane at which the C-measurements are taken (e.g., at bumper, above bumper, at sill, above sill, at beltline, etc.) or label adjustments (e.g., free space).

Free space value is defined as the distance between the baseline and the original body contour taken at the individual C locations. This may include the following: bumper lead, bumper taper, side protrusion, side taper, etc. Record the value for each C-measurement and maximum crush.

**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

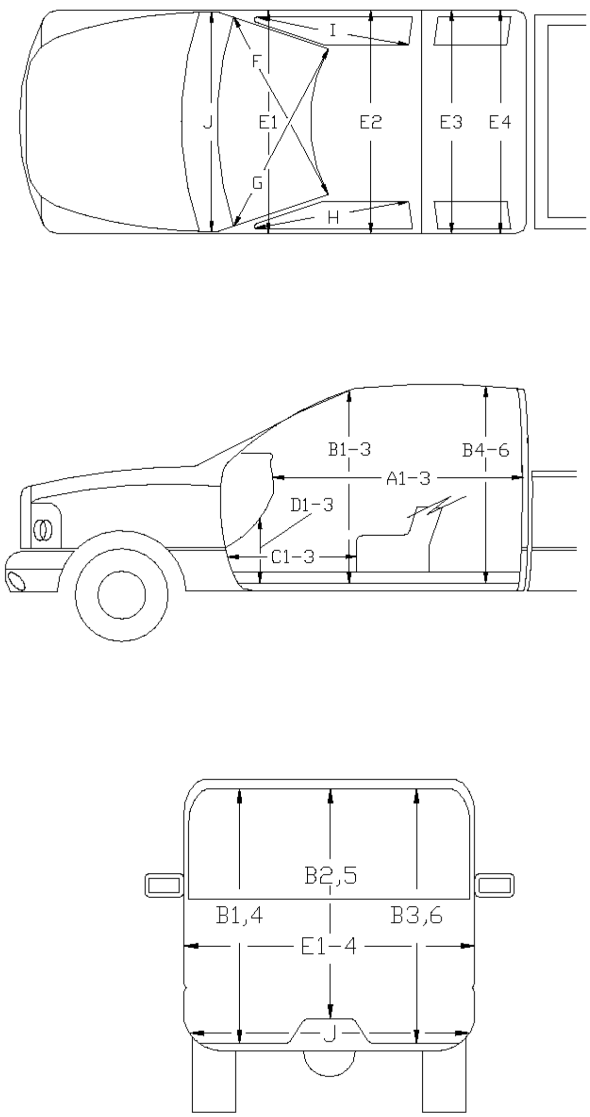
***Measure and document on the vehicle diagram the location of the maximum crush.

Note: Use as many lines/columns as necessary to describe each damage profile.

Table D.4. Occupant Compartment Measurements of Vehicle for Test No. 469689-2-2.

Date: 2019-08-21 Test No.: 469689-02-2 VIN No.: 1C6RR6GT17DS693697

Year: 2013 Make: RAM Model: 1500



*Lateral area across the cab from driver's side kickpanel to passenger's side kickpanel.

OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before	After (inches)	Differ.
A1	65.00	65.00	0.00
A2	63.00	63.00	0.00
A3	65.50	65.50	0.00
B1	45.00	45.00	0.00
B2	38.00	38.00	0.00
B3	45.00	45.00	0.00
B4	39.50	39.50	0.00
B5	43.00	43.00	0.00
B6	39.50	39.50	0.00
C1	26.00	26.00	0.00
C2	0.00	0.00	0.00
C3	26.00	22.00	-4.00
D1	11.00	11.00	0.00
D2	0.00	0.00	0.00
D3	11.50	11.50	0.00
E1	58.50	57.50	-1.00
E2	63.50	65.50	2.00
E3	63.50	63.50	0.00
E4	63.50	63.50	0.00
F	59.00	59.00	0.00
G	59.00	59.00	0.00
H	37.50	37.50	0.00
I	37.50	37.50	0.00
J*	25.00	21.50	-3.50

D.2 SEQUENTIAL PHOTOGRAPHS

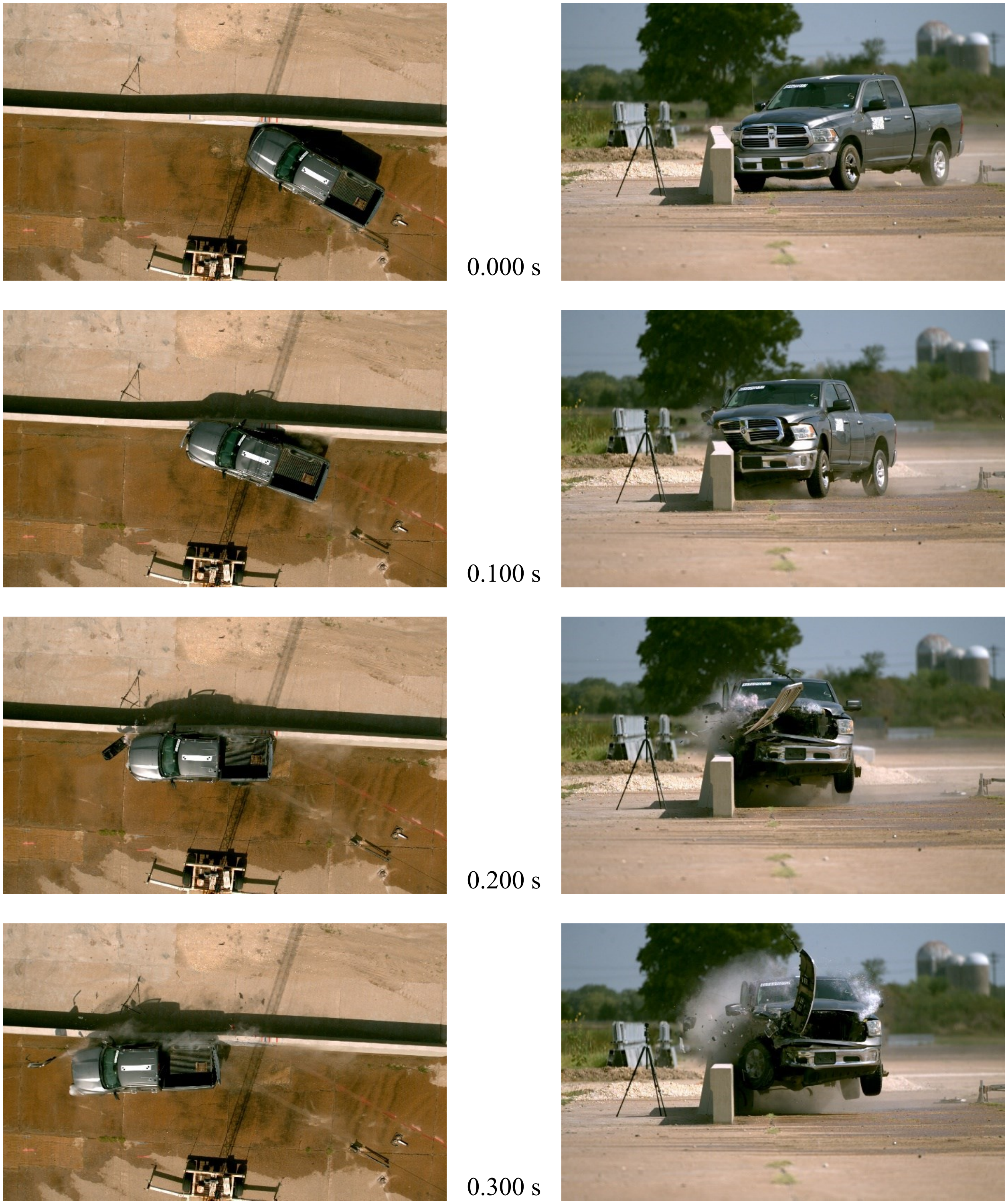


Figure D.1. Sequential Photographs for Test No. 469689-2-2 (Overhead and Frontal Views).

0.400 s

0.500 s

0.600 s

0.700 s

Figure D.1. Sequential Photographs for Test No. 469689-2-2 (Overhead and Frontal Views) (Continued).

0.000 s

0.100 s

0.200 s

0.300 s

0.400 s

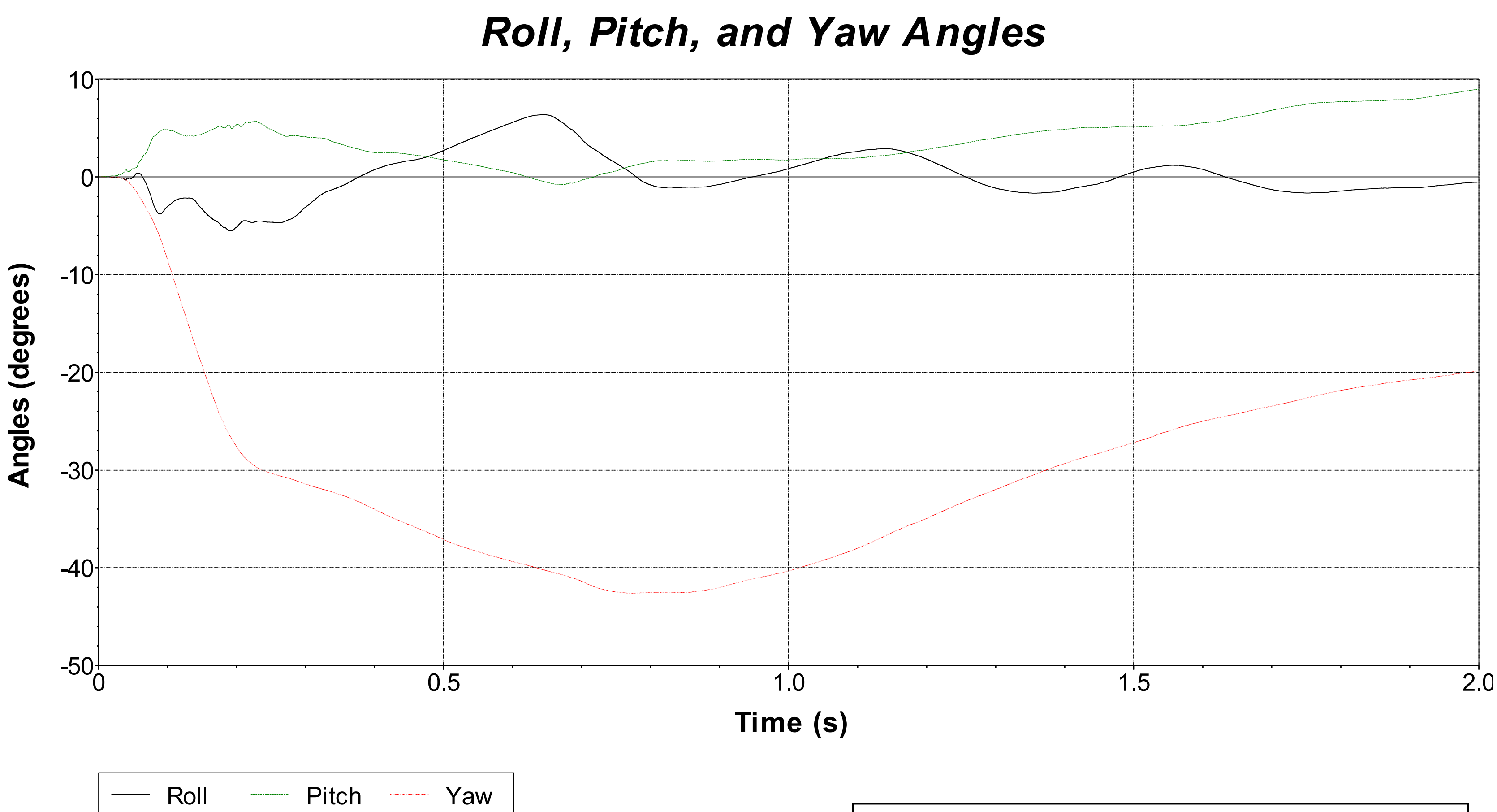
0.500 s

0.600 s

0.700 s

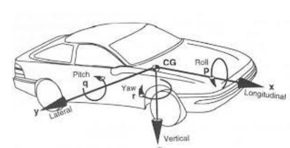
Figure D.2. Sequential Photographs for Test No. 469689-2-2 (Rear View).

D.3 VEHICLE ANGULAR DISPLACEMENT



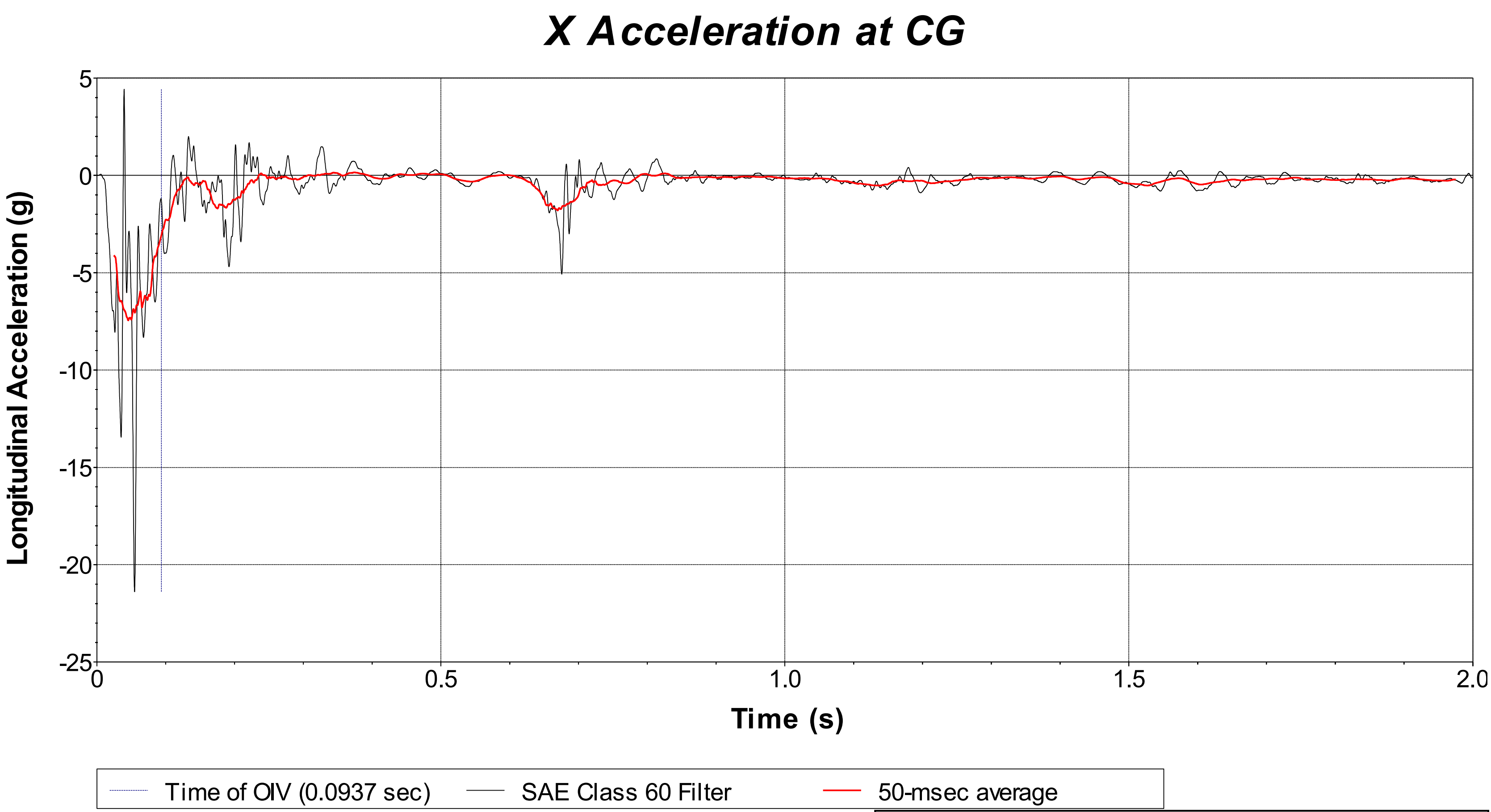
Axes are vehicle-fixed.
Sequence for determining orientation:

1. Yaw.
2. Pitch.
3. Roll.



Test Number: 469689-2-2
Test Standard Test Number: MASH Test 3-21
Test Article: T221 vertical wall to SSCB transition
Test Vehicle: 2013 RAM 1500 Pickup
Inertial Mass: 5035 lb
Gross Mass: 5035 lb
Impact Speed: 61.9 mi/h
Impact Angle: 26.2°

Figure D.3. Vehicle Angular Displacements for Test No. 469689-2-2.



Test Number: 469689-2-2
Test Standard Test Number: MASH Test 3-21
Test Article: T221 vertical wall to SSCB transition
Test Vehicle: 2013 RAM 1500 Pickup
Inertial Mass: 5035 lb
Gross Mass: 5035 lb
Impact Speed: 61.9 mi/h
Impact Angle: 26.2°

Figure D.4. Vehicle Longitudinal Accelerometer Trace for Test No. 469689-2-2 (Accelerometer Located at Center of Gravity).

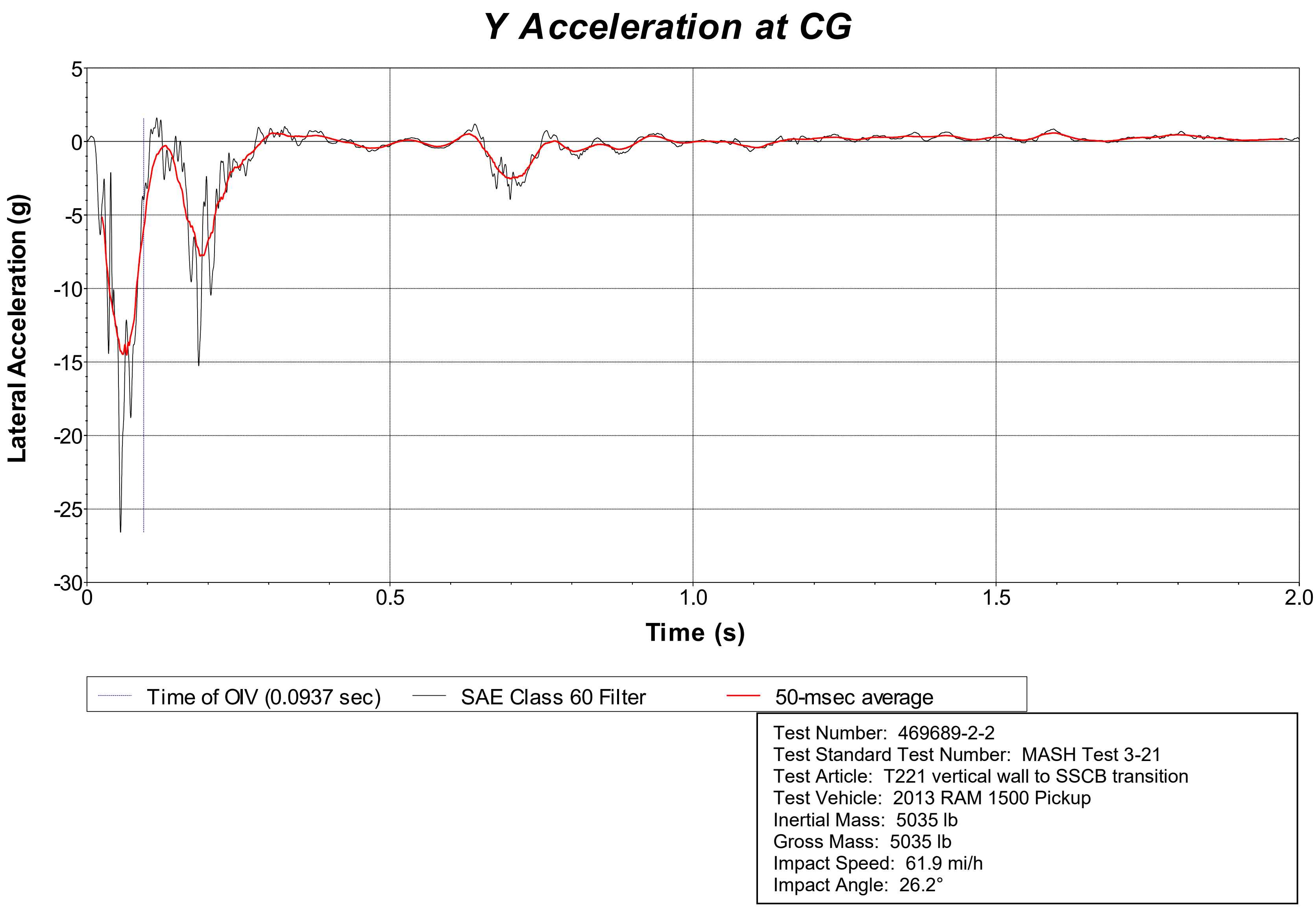


Figure D.5. Vehicle Lateral Accelerometer Trace for Test No. 469689-2-2 (Accelerometer Located at Center of Gravity).

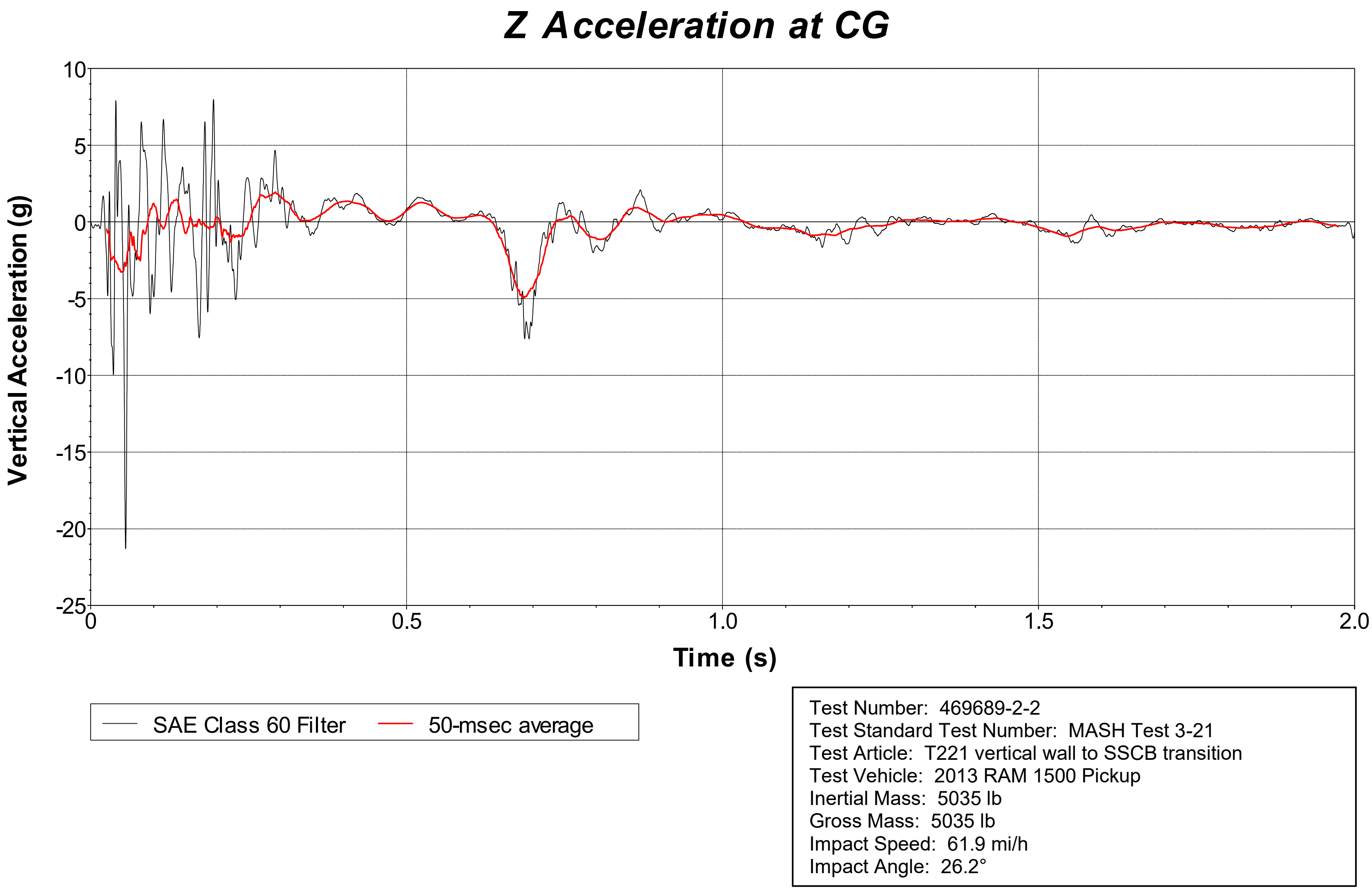


Figure D.6. Vehicle Vertical Accelerometer Trace for Test No. 469689-2-2 (Accelerometer Located at Center of Gravity).