TTI: 9-1002

DEVELOPMENT OF A *MASH* TL-2 GUARDRAIL-TO-BRIDGE RAIL TRANSITION COMPATIBLE WITH 31-INCH GUARDRAIL

ISO 17025 Laboratory
Testing Certificate # 2821.01
Crash testing performed at:
TTI Proving Ground
3100 SH 47, Building 7091
Bryan, TX 77807

Test Report 9-1002-8

Cooperative Research Program

TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM
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 TxDOT Design Division is in the process of developing new guardrail standards that comply with the AASHTO *Manual for Assessing Safety Hardware* (*MASH*). The new guardrail system will provide increased capacity and improved impact performance relative to the current design. A key feature of the new system is an increased in rail mounting height from 27 inches to 31 inches.

TxDOT's current TL-2 metal beam transition is 27 inches tall and is not compatible with the new 31 inch guardrail system. While the high-speed, nested thrie beam transition system meets *MASH* guidelines and is compatible with a 31-inch guardrail, it would be cost-prohibitive to use it on all roadways.

The objective of this research was to develop a transition that is suitable for use on lower speed roadways, less expensive and complex than the current high-speed (i.e., TL-3) transition design, and is compatible with a 31-inch guardrail. A low-cost guardrail-to-bridge rail transition was successfully developed and tested under *MASH* Test Level 2 conditions. It is compatible with a 31-inch guardrail and can connect to rigid concrete bridge rails. It is considered suitable for implementation on roadways that have traffic conditions appropriate for the use of TL-2 safety hardware. Use of this system provides significant savings in material and installation cost compared to the high speed transition system.

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DEVELOPMENT OF A *MASH* TL-2 GUARDRAIL-TO-BRIDGE RAIL TRANSITION COMPATIBLE WITH 31-INCH GUARDRAIL

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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 here. 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, and its contents are not intended for construction, bidding, or permit purposes. In addition, the above listed agencies assume no liability for its contents or use thereof. The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear here solely because they are considered essential to the object of this report. The engineer in charge of the project was Roger P. Bligh, P.E. (Texas, #78550).

TTI PROVING GROUND DISCLAIMER

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

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ISO 17025 Laboratory
Testing Certificate # 2821.01

Crash testing performed at:
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CHAPTER 1. INTRODUCTION

1.1 INTRODUCTION

This project was set up to provide Texas Department of Transportation (TxDOT) with a mechanism to quickly and effectively evaluate high priority issues related to roadside safety devices. Roadside safety devices shield motorists from roadside hazards such as non-traversable terrain and fixed objects. To maintain the desired level of safety for the motoring public, these safety devices must be designed to accommodate a variety of site conditions, placement locations, and a changing vehicle fleet. Periodically, there is a need to assess the compliance of existing safety devices with current vehicle testing criteria and develop new devices that address identified needs.

Under this project, roadside safety issues are identified and prioritized for investigation. Each roadside safety issue is addressed with a separate work plan, and the results are summarized in an individual test report.

1.2 BACKGROUND

The American Association of State Highway Transportation Officials (AASHTO) published the *Manual for Assessing Safety Hardware (MASH)* in October 2009 (*1*). *MASH* supersedes *National Cooperative Highway Research Program (NCHRP) Report 350* (*2*) as the recommended guidance for the safety performance evaluation of roadside safety features.

Recent testing under *MASH* has demonstrated that these strong-post W-beam guardrail systems are at or near their performance limits. Under NCHRP Projects 22-14(02) and 22-14(03), a series of crash tests were performed to assess the impact performance of commonly used barrier systems when impacted by the new ½-ton, four-door, pickup truck design vehicle (designated 2270P) under the AASHTO *MASH* guidelines. The increase in the weight of the new pickup truck from approximately 4400 lb to 5000 lb (2000 kg to 2270 kg) increases the impact severity of the structural adequacy test (Test 3-11) for longitudinal barriers by 13 percent.

A 27⅝-inch tall, modified G4(1S) steel post W-beam guardrail failed due to rail rupture when impacted by a 5000-lb, ¾-ton pickup truck (*3*). In a subsequent test of the same system with the 5000-lb, ½-ton, 4-door *MASH* pickup truck, the guardrail successfully contained and redirected the vehicle (*4*). However, the rail had a vertical tear through approximately half of its cross section, indicating that the modified G4(1S) guardrail is at its performance limits with no factor of safety. In a test of the G4(2W) wood post W-beam guardrail, the rail ruptured and failed to contain the heavier *MASH* pickup truck (*5*).

On May 17, 2010, the Federal Highway Administration issued a technical memorandum to provide guidance to state Departments of Transportation (DOTs) on height of guardrail for new installations on the National Highway System (NHS) (*6*). The memorandum discusses performance issues with the modified G4(1S) guardrail and details the minimum mounting heights of steel post guardrail systems successfully crash tested under both *NCHRP Report 350* and *MASH*.

In regard to *MASH*, the memorandum recommends that transportation agencies consider adopting generic or proprietary 31-inch high guardrail designs (instead of the modified G4(1S) system) as standard for all new installations. It states that these systems offer improved crash-test performance and increased capacity to safely contain and redirect higher center-of-gravity vehicles such as pickup trucks and SUVs.

TxDOT initiated a review of their guardrail standards based on the outcome of these recent studies and the FHWA technical memorandum. TxDOT expressed interest in the use of a generic 31-inch tall guardrail with conventional 8-inch deep offset blocks to provide enhanced containment capacity and stability for light trucks. *MASH* test 3-10 was performed on this system to verify its impact performance. This test sought to assess occupant risk associated with the potential for increased vehicle-post interaction resulting from the increased rail height. The 31-inch W-beam guardrail with standard offset blocks met all required *MASH* performance criteria for test 3-10.

The TxDOT Design Division is in the process of developing new standards for the 31 inch guardrail. The guardrail system includes not only the guardrail length of need, but also consideration of end terminals and guardrail-to-bridge rail transitions. TxDOT's current TL-2 metal beam transition, which is detailed on standard sheet MBGF(TL2)-09, is 27 inches tall and is not compatible with the new 31-inch guardrail. While the high-speed, nested thrie beam transition system (MBGF(TR)-09) meets *MASH* guidelines and is compatible with the 31-inch guardrail, it would be cost prohibitive to use it on all roadways.

The need exists to develop a new TL-2 transition that meets *MASH* impact performance requirements and is compatible with the proposed TxDOT 31-inch guardrail system. Additionally, the transition should be low-cost and easy to install.

1.3 OBJECTIVES/SCOPE OF RESEARCH

The researchers sought to develop a guardrail-to-concrete bridge rail transition that is compatible with 31-inch guardrails and suitable for use on lower speed roadways. The transition should also have a shorter length and be less expensive than the current high-speed (i.e., TL-3) nested thrie beam transition design.

The performance of a new transition design was evaluated both analytically and experimentally through full-scale crash testing to assess compliance with *MASH* performance criteria. The testing was conducted at an impact speed of 44 mi/h, which conforms to *MASH* test level 2 (TL-2) conditions. Reported here are the details of the *MASH* TL-2 transition, test conditions, description of the tests performed, and an assessment of the test results.

CHAPTER 2. TRANSITION DESIGN

The researchers met with TxDOT personnel and discussed design requirements and constraints associated with the development of a TL-2 transition from a 31-inch tall strong-post W-beam approach guardrail to a rigid concrete bridge parapet. Emphasis was placed on the development of a system that is low-cost, simple to install and maintain, and would incorporate standard hardware items to the fullest extent possible.

The researchers performed analyses using computer simulation techniques to assess the ability of selected design concepts to meet *MASH* impact performance criteria prior to conducting any full scale crash tests. For the computer modeling effort, they used the BARRIER VII (*7*) program, a two-dimensional code that models vehicular impacts with deformable barriers. The program models a barrier as an assemblage of discrete structural members possessing geometric and material nonlinearities. It has been used successfully to simulate impacts with a variety of flexible roadside barriers, including transitions from flexible to rigid barriers (*8,9,10,11,12*).

Several transition designs were evaluated as part of the computer simulation effort. For each case, the approach guardrail was assumed to be a strong-post W-beam guardrail. The 12 gauge W-beam rail was mounted to 6-ft long, W6 × 9 steel posts at a height of 31 inches to the top of the rail, providing a post embedment depth of 40 inches. The posts were spaced on 6 ft-3 inch centers, and 8-inch deep offset blocks were incorporated between the rail and posts. The concrete bridge rail parapet was modeled as a rigid barrier to represent the worst-case condition. The current TxDOT TL-2 metal beam transition system was modeled as a point of reference for comparison to the new design concepts.

The simulated impacts involved a 5000-lb pickup truck impacting the transition at a speed of 44 mph and an angle of 25 degrees. Several simulations were conducted for each transition system. The impact location was incrementally varied along the transition to determine the location that maximizes the wheel contact with the end of the rigid bridge parapet. This point was defined to be the critical impact point (CIP) for the transition.

Most existing transition systems, including the current TxDOT TL-2 metal beam transition, incorporate a nested rail element to provide additional bending strength across the end of the concrete bridge rail. This practice is effective in reducing the effects of localized rail deformation at the edge of the concrete parapet. However, installation of nested rail sections is difficult. The lap splices connecting the nested transition rail to the W-beam guardrail at the upstream end and a terminal connector or end shoe on the downstream bridge rail end require connection of three rail sections rather than two as in the case of a standard guardrail lap splice. The geometry of the corrugated W-beam and thrie beam rails does not permit the splice bolt holes in the three rail sections to fully align, even with the use of drift pins. Physical modification of one or more rail sections through grinding or torch cutting is typically required in order to obtain sufficient clearance to insert the splice bolts through the three rail sections. Depending on their extent, these field modifications can compromise the strength of the rail.

To simplify installation and avoid the need for rail alteration, the design concepts for the new TxDOT *MASH* TL-2 metal beam transition focused on the use of single thickness rail elements. The initial transition concept was to use a single 12-gauge, non-symmetric W-beam-to-thrie beam transition section as the rail element for the TL-2 transition. The W-beam end was attached directly to the 31-inch W-beam guardrail and the thrie beam end was attached directly to the concrete bridge rail. The non-symmetric W-beam-to-thrie beam transition section is 6.25 ft long. The post spacing immediately upstream of the concrete bridge rail was reduced to 37.5 inches over a distance of 12.5 ft to help increase the stiffness and reduce dynamic deflection.

Table 1 summarizes the results of the simulation. Both the dynamic deflection and wheel snagging on the end of the concrete bridge rail exceeded the values associated with the current TL-2 metal beam transition system by almost 1 inch. The wheel snagging reported in Table 1 should be compared on a relative rather than absolute basis. The values correspond to an undeformed wheel path as the vehicle is redirected. In an actual crash test, the wheel and suspension system will displace inward and rearward on the vehicle, resulting in less absolute snagging on the end of the concrete bridge rail. Nonetheless, the undeformed wheel snagging provides a good basis for a relative comparison of design concepts to one another and to the existing TL-2 metal beam transition system, which is known to comply with *NCHRP Report 350* performance criteria.

Table 2.1. Barrier VII Simulation Results for *MASH* TL-2 Transition Concepts.

Description	Deflection (inches)	Snagging[1] (inches)
MBGF(TL2)-09[2] (Existing)	4.9	6.5
6.25 ft W-Beam to Thrie Transition (12 gauge) (Option 1)	5.8	7.4
6.25 ft W-Beam to Thrie Transition (10 gauge) (Option 2)	5.5	7.1
37.5 in. Thrie + 9.375ft W-Beam to Thrie Transition (10 gauge) (Option 3)	5.3	6.9

[1] Wheel overlap on end of bridge parapet (undeformed position)
[2] Existing TL-2 metal beam transition system with 27-inch rail height

The results of the simulation with the 12-gauge transition section raised concern about localized bending of the rail at the end of the parapet. This behavior can increase the dynamic deflection and wheel snagging on the end of the parapet. Design option 2 used the same layout as design option 1, but the thickness of the W-beam-to-thrie beam transition section was increased from 12 gauge to 10 gauge. Table 1 shows that both the dynamic deflection and the wheel snagging decreased for this option, but they were still greater than the values obtained for the existing TL-2 metal beam transition.

The researchers were concerned that the tapered geometry of the transition section increased the clear opening between the ground and the rail in advance of the parapet, and provided the opportunity for the small passenger car to snag on the end of the concrete parapet. Design option 3 incorporated a short 37.5-inch long, 10-gauge thrie beam section between the W-beam-to-thrie beam transition section and the end of the concrete parapet. This reduced the clear opening to a constant 11 inches in the critical region immediately upstream of the concrete bridge rail, which reduce the probability of vehicle snagging. The overall length of the transition rail was 9 ft-4.5 inches. This permits the splices of the approach guardrail to be offset between posts without the need for a special length W-beam rail section. The midspan rail splices is a feature of the proposed 31-inch guardrail system that effectively increases the rail capacity.

Table 1 shows that the dynamic deflection and wheel snagging were only slightly greater for design option 3 than the existing TL-2 metal beam transition. Some increase was to be expected due to the increased impact severity associated with the heavier *MASH* pickup truck compared to *NCHRP Report 350*. Since the performance of the existing TL-2 metal beam transition was well within the thresholds for occupant risk and occupant compartment deformation, the slight increase in dynamic deflection and wheel snagging was considered tolerable.

Option 1 was selected for full-scale crash testing in consultation with TxDOT personnel. This option was believed to have a high probability of meeting TL-2 impact conditions. The thrie beam rail section decreases the rail deformation around the end of the rigid concrete parapet and reduces the probability of severe wheel snagging. All of the components of the transition are standard hardware items that are readily available from guardrail manufacturers. The use of 10 gauge rail eliminated the need for a nested rail section, thereby reducing installation cost and complexity.

Details of the selected design were finalized and presented to the Project Monitoring Committee (PMC) for review and approval. Upon approval of the design details, a prototype transition installation was constructed and subjected to full-scale crash tests in accordance with *MASH* guidelines. Details of the crash tests are provided in the following chapters.

CHAPTER 3. SYSTEM DETAILS

3.1 TEST ARTICLE DESIGN AND CONSTRUCTION

TxDOT permits the use of three different post types in its guardrail systems: W6×8.5 steel posts, 7-inch diameter round wood posts, and 6-inch × 8-inch rectangular wood posts. The researchers concluded that the W6×8.5 steel post would constitute the most critical condition in regard to post snagging and would, therefore, be used in the full-scale crash test. By using the most critical post type, a successful result would also be applicable to the other post types.

Upon selection of the post type, a prototype transition installation was constructed to include an appropriate length of bridge parapet and approach guardrail. The bridge parapet utilized for the test was an existing 36-inch tall single slope traffic rail (SSTR). The upstream end of the SSTR was modified to include a vertical taper over the last 3 ft of the parapet to help reduce wheel contact.

A 37.5-inch long section of 10-gauge thrie beam rail was attached to the face of the SSTR using a 10-gauge thrie beam terminal connector. The thrie beam rail was twisted into the sloped traffic face of the parapet and the terminal connector was attached to the parapet using five 0.825-inch diameter, A325 hex head through bolts.

The 10-gauge thrie beam section connected to a 10-gauge, non-symmetric W-beam-to-thrie beam transition section. The non-symmetric transition section was 6 ft-3 inches long and maintained a 31-inch rail height from the thrie beam to the W-beam approach guardrail.

The first W6×8.5 steel post was located 29 inches upstream from the end of the bridge rail end. The next three posts comprising the transition were spaced 37.5 inches on center. All of the posts in the transition and approach guardrail were 6 ft long and embedded 40 inches in a crushed limestone road base material.

A 25-ft length of strong-post W-beam guardrail was attached to the upstream end of the transition. It consisted of a single, 12-gauge W-beam rail supported on W6×9 steel posts spaced 6 ft-3 inches apart. The W-beam rail was offset from the posts using 6-inch × 8-inch × 14-inch routered wood blockouts. The rail was mounted at a height of 31 inches and the rail splices were located midspan between posts. The installation was terminated using a 25-ft long, TL-2 ET-PLUS guardrail terminal.

Figure 3.1 shows the layout of the test installation, and Figure 3.2 has the photographs of the completed test installation. Additional details of the test installation can be found in Appendix A.

3.2 MATERIAL SPECIFICATIONS

The W-beam guardrail, thrie beam guardrail, and W-beam-to-thrie beam transition section conformed to AASHTO M180. The W6×8.5 steel guardrail posts were ASTM A36. The routered wood offset blocks were grade 1 southern yellow pine. The guardrail post bolts and rail splice bolts complied with ASTM A307 and were galvanized in accordance with ASTM A153. The nuts complied with ASTM A563 and were galvanized in accordance with ASTM A153. The terminal connector anchor bolts were ASTM A325. The posts were installed in soil meeting AASHTO standard specifications for "Materials for Aggregate and Soil Aggregate Subbase, Base and Surface Courses," designated M147-65(2004), grading B. Certification documents for all three tests performed are on file at Texas Transportation Institute Proving Ground.

3.3 SOIL STRENGTH

In accordance with Appendix B of *MASH*, soil strength was measured on the day of each crash test (see Appendix B, Figure B1 through B3). During installation of the *MASH* TL-2 transition, two standard W6×16 posts were installed in the immediate vicinity of the transition, utilizing the same fill materials and installation procedures followed for the guardrail system and used in the reference tests (see Appendix B, Figure B4).

As the reference tests in Appendix B, Figure B4 show, the minimum post loads required for deflections at 5 inches, 10 inches, and 15 inches, measured at a height of 25 inches, are 3940 lb, 5500 lb, and 6540 lb, respectively (90 percent of static load for the initial standard installation).

On the day of test 420021-4, July 22, 2011, load on the test post at deflections of 5 inches, 10 inches, and 15 inches was 5091 lbf, 6606 lbf, and 7636 lbf, respectively. The strength of the backfill material met minimum requirements.

On the day of test 420021-6, August 4, 2011, load on the test post at deflections of 5 inches, 10 inches, and 15 inches was 5485 lbf, 6606 lbf, and 6909 lbf, respectively. The strength of the backfill material met minimum requirements.

On the day of test 420021-7, August 23, 2011, load on the test post at deflections of 5 inches, 10 inches, and 15 inches was 8151 lbf, 8939 lbf, and 8515 lbf, respectively. The strength of the backfill material met minimum requirements.

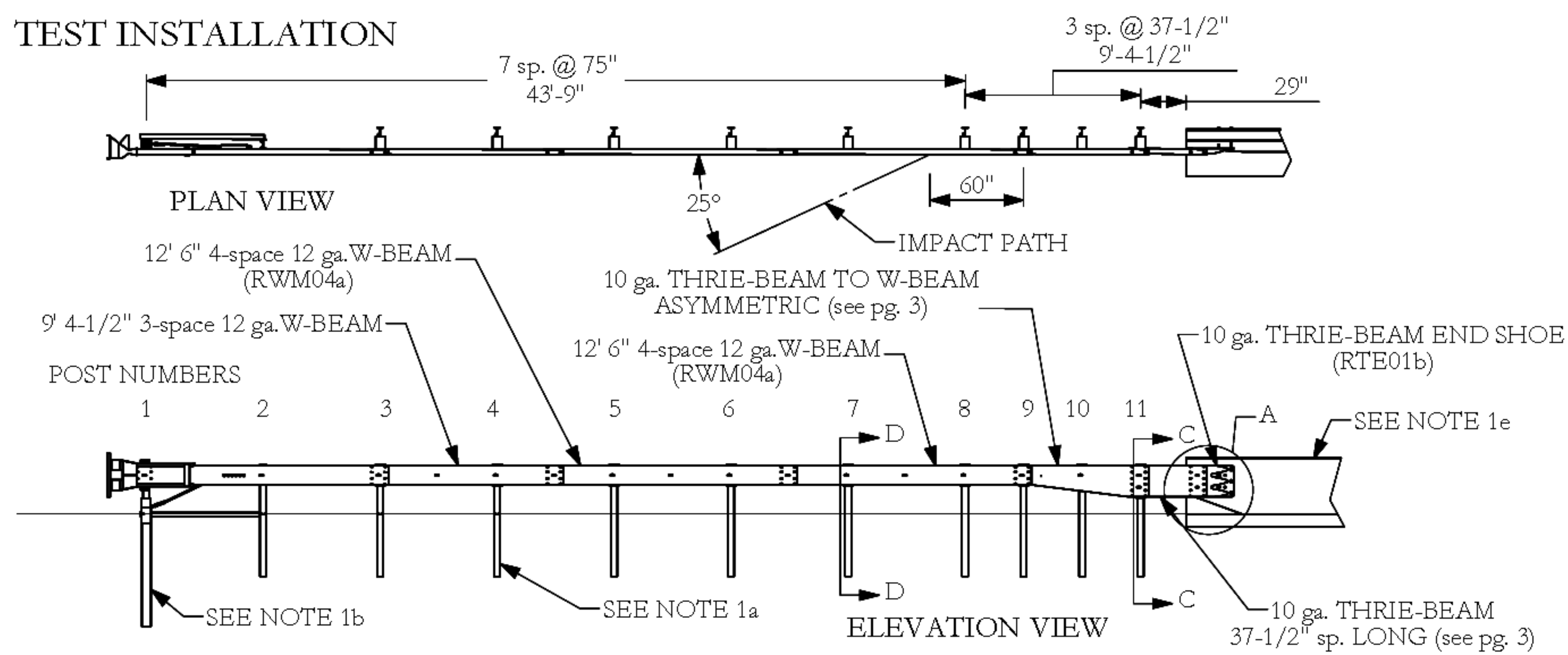


Figure 3.1. Details of the *MASH* TL-2 Transition Installation.

Figure 3.2. ***MASH*** **TL-2 Transition before Test No. 420021-4.**

CHAPTER 4. TEST REQUIREMENTS AND EVALUATION CRITERIA

4.1 CRASH TEST MATRIX

MASH test 21 is the recommended test for evaluating the impact performance of a transition section. This test involves a 5000-lb pickup truck impacting the critical impact point (CIP) of the transition section at an angle of 25 degrees. The test is intended to evaluate the strength of the transition section (i.e., its ability to contain and redirect the 5000-lb vehicle), vehicle stability, and occupant risk (e.g., extent of occupant compartment deformation).

The relevant *MASH* test designation for TL-2 is test 2-21, which has a nominal impact speed of 44 mi/h. In accordance with the recommendations of *MASH,* the BARRIER VII simulation program was used to select the CIP. The CIP for the selected transition design was determined to be 4 ft upstream of the end of the bridge parapet.

An optional test for evaluating transitions to TL-2 is *MASH* test 2-20. This test involves a 2425 lb passenger car impacting the CIP of the transition at a nominal impact speed and angle of 44 mi/h and 25 degrees, respectively. The primary purpose of this test is to assess occupant risk associated with vehicle snagging and post-impact trajectory of the vehicle. *MASH* states that this test should be conducted if there is reasonable uncertainty regarding the impact performance of the system for impacts with small passenger vehicles.

The TxDOT *MASH* TL-2 metal beam transition has two distinct transition points: an upstream transition from the approach guardrail to the transition section and a downstream transition from the transition section to the concrete bridge rail. Both transition points should be tested to fully evaluate a transition system. If the optional test is included, the matrix could include up to four tests.

Test 2-21 with the pickup truck was run on the downstream transition point. This test was considered the most critical for evaluating strength of the transition and vehicle stability. The optional small car test was also run at this transition point because of snagging concerns related to the increase in impact angle for test 2-20 from 20 degrees to 25 degrees under *MASH*.

The most critical test for the upstream transition point was determined to be test 2-20 with the small passenger car. This was due to the possibility of the vehicle underriding the 31 inch approach guardrail and wedging under the tapered non-symmetric W-beam-to-thrie beam transition section. The CIP for this test was determined to be 5 ft upstream of the upstream end of the non-symmetric transition piece. Test 2-21 was not performed at the upstream transition location because it was not considered critical based on the documented performance of the 31-inch guardrail systems.

The crash test and data analysis procedures were in accordance with guidelines presented in *MASH*. Chapter 5 presents brief descriptions of these procedures.

4.2 EVALUATION CRITERIA

The crash test was evaluated in accordance with the relevant criteria presented in *MASH*. The performance of the *MASH* TL-2 transition was judged on the basis of three factors: structural adequacy, occupant risk, and post impact vehicle trajectory. Structural adequacy is judged on the ability of the transition to contain and redirect the vehicle. Occupant risk criteria evaluate the potential risk of hazard to occupants in the impacting vehicle and, to some extent, other traffic, pedestrians, or workers in construction zones, if applicable. Post-impact vehicle trajectory is assessed to determine potential for secondary impact with other vehicles or fixed objects, creating further risk of injury to occupants of the impacting vehicle and/or risk of injury to occupants in other vehicles. The appropriate safety evaluation criteria from Table 5-1 of *MASH* were used to evaluate the crash test reported herein. These criteria are listed in further detail under the assessment of each crash test.

CHAPTER 5. CRASH TEST PROCEDURES

5.1 TEST FACILITY

The full-scale crash test reported here was performed at the Texas Transportation Institute (TTI) Proving Ground. The TTI Proving Ground is an International Standards Organization (ISO) 17025 accredited laboratory with American Association for Laboratory Accreditation (A2LA) Mechanical Testing certificate 2821.01. The full-scale crash test was performed according to TTI Proving Ground quality procedures and according to the *MASH* guidelines and standards.

The TTI Proving Ground is a 2000-acre complex of research and training facilities located 10 miles northwest of the main campus of Texas A&M University. Formerly an Air Force base, the site 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 safety evaluation of roadside safety hardware. The site selected for construction and testing of the *MASH* TL-2 transition evaluated under this project was along the edge of an out-of-service apron. The apron consists of an unreinforced jointed-concrete pavement in 12.5 ft by 15 ft blocks nominally 8 to 12 inches deep. The apron is over 50 years old, and the joints have some displacement, but are otherwise flat and level.

5.2 VEHICLE TOW AND GUIDANCE PROCEDURES

The 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 two-to-one speed ratio between the test and tow vehicle existed with this system. Just prior to impact with the installation, the test vehicle was released to be free-wheeling and unrestrained. The vehicle remained free-wheeling, i.e., no steering or braking inputs, until the vehicle cleared the immediate area of the test site, at which time brakes on the vehicle were activated to bring it to a safe and controlled stop.

5.3 DATA ACQUISITION SYSTEMS

5.3.1 Vehicle Instrumentation and Data Processing

The 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. Measuring the x, y, and z axis of vehicle acceleration, the accelerometers are strain gauge type with linear millivolt output proportional to acceleration. Angular rate sensors, measuring vehicle roll, pitch, and yaw rates, are ultra small size, solid state units designs 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 is capable of providing 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 the data are recorded, the 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 as well as initiating 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. Accelerometers and rate transducers are also calibrated annually with traceability to the National Institute for Standards and Technology.

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 60-Hz 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 and 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 that of initial impact.

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 driver's position in the tests with the 1100C passenger car. The dummy was uninstrumented. Use of a dummy in the 2270P pickup truck is optional according to *MASH*, and there was no dummy used in the test with the 2270P vehicle.

5.3.3 Photographic Instrumentation and Data Processing

Photographic coverage of the test included three high-speed cameras: one overhead with a field of view perpendicular to the ground and directly over the impact point; one placed behind the installation at an angle; and a third placed to have a field of view parallel to and aligned with the installation at the downstream end. A flashbulb activated by pressure-sensitive tape switches was positioned on the impacting vehicle to indicate the moment of contact with the installation and was visible from each camera. The films from these high-speed cameras were analyzed on a computer-linked motion analyzer to observe phenomena occurring during the collision and to obtain time-event, displacement, and angular data. A mini-DV camera and still cameras recorded and documented conditions of the test vehicle and installation before and after the test.

CHAPTER 6. *MASH* TEST 3-21 (TEST NO. 420021-4)

6.1 TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

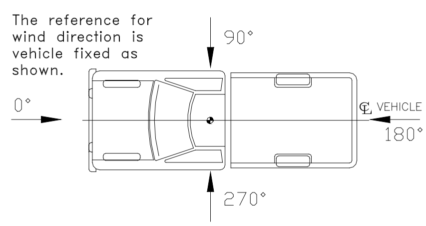
MASH test 2-21 involves a 2270P pickup truck weighing 5000 lb ±100 lb impacting the transition at an impact speed of 44 mi/h ±2.5 mi/h and an angle of 25 degrees ±1.5 degrees. The target impact point was 48 inches upstream of end of concrete parapet. The 2004 Dodge Ram 1500 pickup truck used in the test weighed 5089 lb, and the actual impact speed and angle were 43.7 mi/h and 25.8 degrees, respectively. The actual impact point was 55 inches upstream of the end of the concrete parapet.

6.2 TEST VEHICLE

The 2004 Dodge Ram 1500 pickup truck (shown in Figures 6.1 and 6.2) for the crash test. Test inertia weight of the vehicle was 5089 lb, and its gross static weight was 5089 lb. The height to the lower edge of the vehicle bumper was 13.5 inches, and the height to the upper edge of the vehicle bumper was 26.0 inches. Height to the vehicle center-of-gravity was 28.6 inches. Tables C1 and C2 in Appendix C 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 free-wheeling and unrestrained just prior to impact.

6.3 WEATHER CONDITIONS

The test was performed on the morning of July 22, 2011. Weather conditions at the time of testing were: Wind speed: 9 mi/h; Wind direction: 220 degrees with respect to the vehicle (vehicle was traveling in a northwesterly direction); Temperature: 90°F, Relative humidity: 62 percent.



6.4 TEST DESCRIPTION

The 2004 Dodge Ram 1500 pickup truck, traveling at an impact speed of 43.7 mi/h, impacted the *MASH* TL-2 transition 55 inches upstream of the end of the concrete parapet at an impact angle of 25.8 degrees. At 0.017, post 11 began to deflect toward the field side, and at 0.021 s, the vehicle began to redirect. The vehicle reached the end of the concrete parapet at 0.061 s, and the concrete parapet began to deflect toward the field side at 0.071 s. At 0.225 s, the vehicle was traveling parallel with the transition at a speed of 36.0 mi/h. The rear of the vehicle contacted the transition at 0.282 s, and the maximum dynamic deflection of 5.7 inches occurred at 0.324 s. At 0.331 s, the soil behind the posts began to displace towards the field side. At 0.423 s, the vehicle lost contact with the transition traveling at an exit speed and angle of 32.6 mi/h and 8.2 degrees, respectively. Brakes on the vehicle were not applied, and the vehicle came to rest 173 ft downstream of impact and adjacent to the traffic face of the concrete parapet. Figures D1 and D2 in Appendix D show sequential photographs of the test period.

Figure 6.1. Vehicle/Installation Geometrics for Test No. 420021-4.

Figure 6.2. Vehicle before Test No. 420021-4.

6.5 DAMAGE TO TEST INSTALLATION

Figures 6.3 and 6.4 show damage to the *MASH* TL-2 transition. Posts 9, 10, and 11 were pushed toward the field side 0.4 inch, 1.1 inches, and 2.1 inches, respectively. The end of the concrete deck was cracked and the end of the concrete parapet was cracked near the anchor bolts attaching the rail to the parapet. Length of contact of the vehicle with the transition was 13.4 ft; working width was 15.8 inches. Maximum dynamic deflection during the test was 5.7 inches, and maximum permanent deformation was 2.9 inches.

6.6 VEHICLE DAMAGE

Figure 6.5 shows damage to the 2004 Dodge Ram 1500. The left upper and lower A-arm, left upper and lower ball joint, sway bar, tie rod, and left frame rail were damaged. Also damaged were the front bumper, left front fender, left front door, left front tire and wheel rim, left rear exterior bed, left rear wheel rim, and rear bumper. Maximum exterior crush to the vehicle was 16 inches in the front plane at the left front corner at bumper height. Maximum occupant compartment deformation was 2.0 inches in the left side firewall. Figure 6.6 shows photographs of the interior of the vehicle. Exterior crush and occupant compartment deformations are provided in Appendix C, Tables C3 and C4.

6.7 OCCUPANT RISK FACTORS

Data from the accelerometer, located at the vehicle center of gravity, were digitized for evaluation of occupant risk. In the longitudinal direction, the occupant impact velocity was 18.4 ft/s at 0.120 s, the highest 0.010-s occupant ridedown acceleration was 5.9 Gs from 0.124 to 0.134 s, and the maximum 0.050-s average acceleration was −7.9 Gs between 0.060 and 0.110 s. In the lateral direction, the occupant impact velocity was 19.7 ft/s at 0.120 s, the highest 0.010-s occupant ridedown acceleration was 8.0 Gs from 0.337 to 0.347 s, and the maximum 0.050-s average was 9.1 Gs between 0.049 and 0.099 s. Theoretical Head Impact Velocity (THIV) was 28.9 km/h or 8.0 m/s at 0.116 s; Post-Impact Head Decelerations (PHD) was 8.1 Gs between 0.330 and 0.340 s; and Acceleration Severity Index (ASI) was 1.15 between 0.054 and 0.104 s. Figure 6.7 summarizes these data and other pertinent information from the test. Figure E1 in Appendix E presents angular displacements versus time, and Figures F1 through F6 in Appendix F present data on accelerations versus time.

Figure 6.3. Position of Vehicle/Installation after Test No. 420021-4.

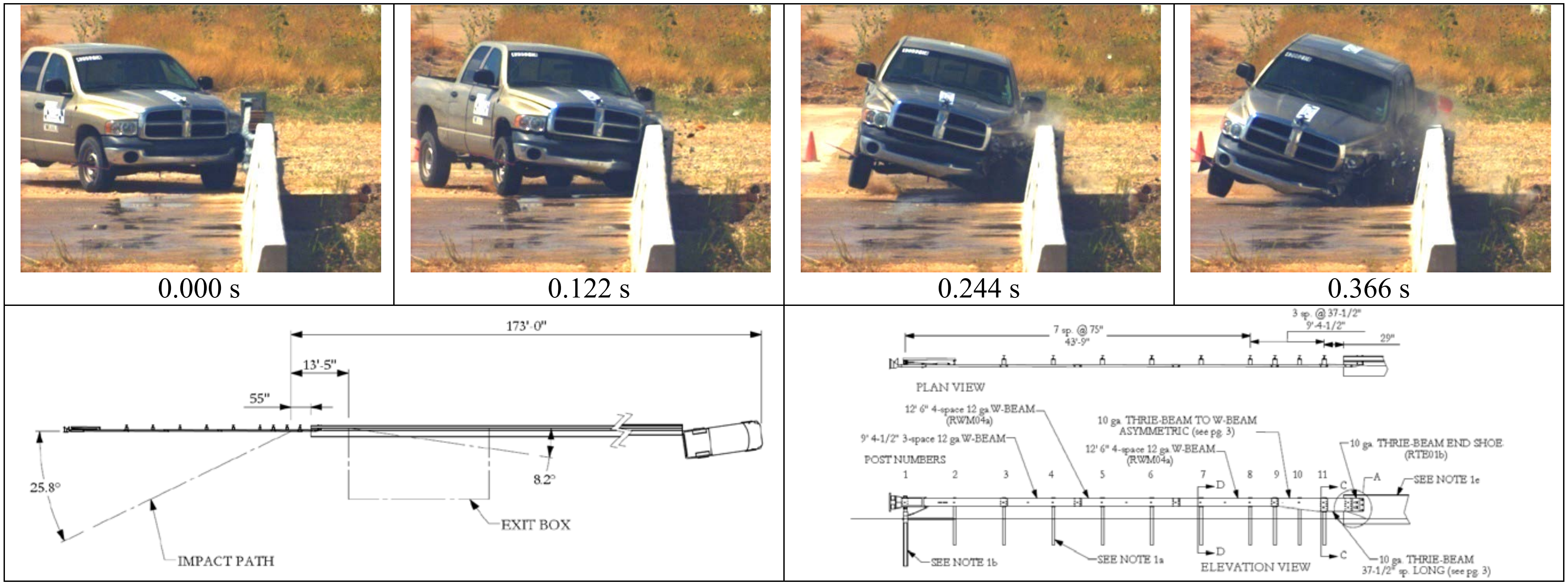
Figure 6.4. Installation after Test No. 420021-4.

Figure 6.5. Vehicle after Test No. 420021-4.

Before
Test

After Test

Figure 6.6. Interior of Vehicle for Test No. 420021-4.



General Information
Test Agency: Texas Transportation Institute (TTI)
Test Standard Test No.: MASH Test 2-21
TTI Test No.: 420021-4
Test Date: 2011-07-22

Test Article
Type: Transition
Name: *MASH* TL-2 transition
Installation Length: 210.5 ft (terminal, transition and SSTR)
Material or Key Elements: 10-gauge thrie beam rail on face of SSTR using 10-gauge thrie beam terminal connector and 10-gauge thrie beam section to 10-gauge, non-symmetric W-beam-to-thrie beam transition section

Soil Type and Condition: Standard soil, dry

Test Vehicle
Type/Designation: 2270P
Make and Model: 2004 Dodge Ram 1500
Curb: 4879 lb
Test Inertial: 5089 lb
Dummy: No dummy
Gross Static: 5089 lb

Impact Conditions
Speed: 43.7 mi/h
Angle: 25.8 degrees
Location/Orientation: 55 inches upstrm of end of parapet

Exit Conditions
Speed: 32.6 mi/h
Angle: 8.2 degrees

Occupant Risk Values
Impact Velocity
Longitudinal: 18.4 ft/s
Lateral: 19.7 ft/s
Ridedown Accelerations
Longitudinal: 5.9 Gs
Lateral: 8.0 Gs
THIV: 28.9 km/h
PHD: 8.1 Gs
ASI: 1.15
Max. 0.050-s Average
Longitudinal: −7.9 Gs
Lateral: 9.1 Gs
Vertical: 2.4 Gs

Post-Impact Trajectory
Stopping Distance: 173.0 ft

Vehicle Stability
Maximum Yaw Angle: 35 degrees
Maximum Pitch Angle: 9 degrees
Maximum Roll Angle: 18 degrees
Vehicle Snagging: No
Vehicle Pocketing: No

Test Article Deflections
Dynamic: 5.7 inches
Permanent: 2.9 inches
Working Width: 15.8 inches

Vehicle Damage
VDS: 11LFQ6
CDC: 11FREW4
Max. Exterior Deformation: 16.0 inches
OCDI: LF0010000
Max. Occupant Compartment Deformation: 2.0 inches

Figure 6.7. Summary of Results for *MASH* Test 2-21 on the *MASH* TL-2 Transition.

6.8 ASSESSMENT OF TEST RESULTS

An assessment of the test based on the applicable *MASH* safety evaluation criteria is provided below.

6.8.1 Structural Adequacy

A. *Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.*

Results: The *MASH* TL-2 transition contained and redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection was 5.8 inches. (PASS)

6.8.2 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.*
Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH. (roof ≤4.0 inches; windshield = ≤3.0 inches; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 inches; forward of Apillar ≤12.0 inches; front side door area above seat ≤9.0 inches; front side door below seat ≤12.0 inches; floor pan/transmission tunnel area ≤12.0 inches.

Results: No detached elements, fragments, or other debris from the transition were present to penetrate the occupant compartment, show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. (PASS)
Maximum occupant compartment deformation was 2.0 inches. (PASS)

F. *The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.*

Results: The 2270P vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 18 degrees and 9 degrees, respectively. (PASS)

H. *Occupant impact velocities should satisfy the following:*

Longitudinal and Lateral Occupant Impact Velocity

Preferred	*Maximum*
30 ft/s	*40 ft/s*

Results: Longitudinal occupant impact velocity was 18.4 ft/s, and lateral occupant impact velocity was 19.7 ft/s. (PASS)

I. Occupant ridedown accelerations should satisfy the following:

Longitudinal and Lateral Occupant Ridedown Accelerations

Preferred	*Maximum*
15.0 Gs	*20.49 Gs*

Results: Longitudinal occupant ridedown acceleration was 5.9 Gs, and lateral occupant ridedown acceleration was 8.0 Gs. (PASS)

6.8.3 Vehicle Trajectory

For redirective devices, the vehicle shall exit the barrier within the exit box.

Result: The 2270P vehicle exited within the exit box. (PASS)

CHAPTER 7. *MASH* TEST 2-20 AT THE DOWNSTREAM END (TEST NO. 420021-6)

7.1 TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

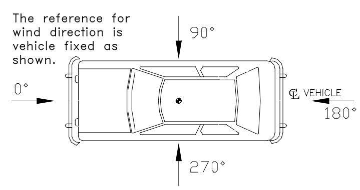
MASH test 2-20 involves an 1100C passenger car weighing 2425 lb ±55 lb impacting the transition at an impact speed of 44 mi/h ±2.5 mi/h and an angle of 25 degrees ±1.5 degrees. The target impact point was 5 ft upstream of post 9 (post 9 is at upstream end of the non-symmetric W-beam-to-thrie beam transition section). The 2004 Kia Rio used in the test weighed 2418 lb and the actual impact speed and angle were 43.5 mi/h and 26.4 degrees, respectively. The actual impact point was 5.9 ft upstream of post 9.

7.2 TEST VEHICLE

A 2004 Kia Rio, (shown in Figures 7.1 and 7.2) was used for the crash test. Test inertia weight of the vehicle was 2418 lb, and its gross static weight was 2586 lb. The height to the lower edge of the vehicle bumper was 8.50 inches, and the height to the upper edge of the bumper was 22.75 inches. Table C5 in Appendix C gives 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 free-wheeling and unrestrained just prior to impact.

7.3 WEATHER CONDITIONS

The test was performed on the morning of August 4, 2011. Weather conditions at the time of testing were: Wind speed: 5 mi/h; Wind direction: 254 degrees with respect to the vehicle (vehicle was traveling in a northwesterly direction); Temperature: 93°F, Relative humidity: 49 percent.



7.4 TEST DESCRIPTION

The 2004 Kia Rio, traveling at an impact speed of 43.5 mi/h, impacted the *MASH* TL-2 transition 5.9 ft upstream of post 9 at an impact angle of 26.4 degrees. At 0.039 s, the vehicle began to redirect, and at 0.041 s, the bumper of the vehicle protruded under the rail element and contacted the traffic side flange of post 8. The left front tire of the vehicle contacted the flange of post 8 at 0.079 s, and the roof of the vehicle began to deform at 0.086 s. At 0.102 s, the windshield sustained stress cracks at the left lower corner, and at 0.104 s, the parts of the vehicle protruding under the rail contacted the traffic side flange of post 9. The bumper of the vehicle separated from the vehicle and the right side tire blew out at 0.147 s. The vehicle contacted post 10 at 0.169 s, and the vehicle began to yaw counterclockwise at 0.240 s. At 0.535 s, the vehicle lost contact with the transition. The exit speed and angle were not obtainable because the vehicle yawed counterclockwise (101 degrees) as it lost contact with the transition. Brakes on the vehicle were not applied, and the vehicle subsequently came to rest 54 ft toward traffic lanes in front of post 10. Figures D3 and D4 in Appendix D show sequential photographs of the test period.

Figure 7.1. Vehicle/Installation Geometrics for Test No. 420021-6.

Figure 7.2. Vehicle before Test No. 420021-6.

7.5 DAMAGE TO TEST INSTALLATION

Figures 7.3 and 7.4 show damage to the *MASH* TL-2 transition. Post 1 was pulled downstream 0.38 inch at ground level and post 7 was leaning toward the field side at 2 degrees. Posts 8 and 9 were leaning toward the field side 30 degrees and downstream 50-55 degrees. Post 10 was leaning toward the field side 10 degrees and downstream 20 degrees. The rail element released from post 8 through 10, and the blockouts at posts 8 and 9 were shattered. Length of contact of the vehicle with the rail element was 12.3 ft; working width was 2.6 ft. Maximum dynamic deflection during the test was 14.4 inches, and maximum permanent deformation was 8.0 inches at post 8.

7.6 VEHICLE DAMAGE

Figure 7.5 shows that the 1100C vehicle sustained damage to the left front corner. The left front strut and strut tower, front bumper, hood, radiator, fan, radiator support, left front fender, left front wheel rim, left door, and right front tire and wheel rim were damaged. The windshield sustained stress cracks in the left lower corner. Maximum exterior crush to the vehicle was 15 inches in the side plane at the left front corner at bumper height. Maximum occupant compartment deformation was 0.25 inch in the lateral area across the cab at the kick panel near the driver's feet. Figure 7.6 has pictures of the interior of the vehicle. Tables C4 and C5 in Appendix C provide the exterior crush and occupant compartment deformation measurements.

7.7 OCCUPANT RISK FACTORS

Data from the accelerometer, which is located at the vehicle center of gravity, were digitized for evaluation of occupant risk. In the longitudinal direction, the occupant impact velocity was 29.5 ft/s at 0.148 s, the highest 0.010-s occupant ridedown acceleration was 9.0 Gs from 0.173 to 0.183 s, and the maximum 0.050-s average acceleration was −10.7 Gs between 0.081 s and 0.131 s. In the lateral direction, the occupant impact velocity was 14.1 ft/s at 0.148 s, the highest 0.010-s occupant ridedown acceleration was 5.9 Gs from 0.153 to 0.163 s, and the maximum 0.050-s average was 4.4 Gs between 0.048 and 0.098 s. THIV was 35.0 km/h or 9.7 m/s at 0.145 s; PHD was 9.2 Gs between 0.172 and 0.182 s; and ASI was 0.97 between 0.079 and 0.129 s. Figure 7.7 summarizes these data and other pertinent information from the test. Figure E2 in Appendix E has data on vehicle angular displacements versus time traces; and Figures F7 through F12 in Appendix F present the accelerations versus time traces.

Figure 7.3. Position of Vehicle/Installation after Test No. 420021-6.

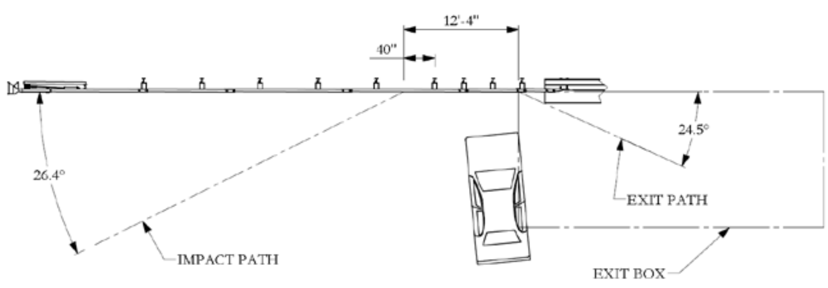
Figure 7.4. Installation after Test No. 420021-6.

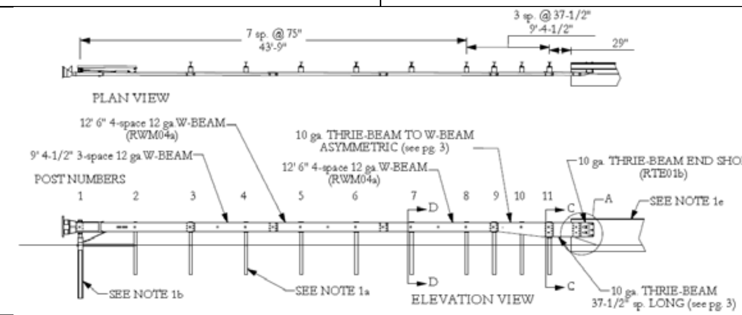
Figure 7.5. Vehicle after Test No. 420021-6.

Before Test

After Test

Figure 7.6. Interior of Vehicle for Test No. 420021-6.





General Information	
Test Agency	Texas Transportation Institute (TTI)
Test Standard Test No.	MASH Test 2-20
TTI Test No.	420021-6
Test Date	2011-08-04
Test Article	
Type	Transition
Name	*MASH* TL-2 transition
Installation Length	210.5 ft (terminal, transition and SSTR)
Material or Key Elements	10-gauge thrie beam rail on face of SSTR using 10-gauge thrie beam terminal connector and 10-gauge thrie beam section to 10-gauge, non-symmetric W-beam-to-thrie beam transition section
Soil Type and Condition	Standard Soil, Dry
Test Vehicle	
Type/Designation	1100C
Make and Model	2004 Kia Rio
Curb	2395 lb
Test Inertial	2418 lb
Dummy	168 lb
Gross Static	2586 lb

Impact Conditions	
Speed	43.5 mi/h
Angle	26.4 degrees
Location/Orientation	5.9 ft upstrm of post 9
Exit Conditions	
Speed	Not Obtainable
Angle	Not Obtainable
Occupant Risk Values	
Impact Velocity	
Longitudinal	29.5 ft/s
Lateral	14.1 ft/s
Ridedown Accelerations	
Longitudinal	9.0 G
Lateral	5.9 G
THIV	35.0 km/h
PHD	9.2 G
ASI	0.97
Max. 0.050-s Average	
Longitudinal	−10.7 G
Lateral	4.4 G
Vertical	−1.7 G

Post-Impact Trajectory	
Stopping Distance	12.7 ft dwnstrm
Vehicle Stability	
Maximum Yaw Angle	-77 degrees
Maximum Pitch Angle	−14 degrees
Maximum Roll Angle	10 degrees
Vehicle Snagging	Yes
Vehicle Pocketing	No
Test Article Deflections	
Dynamic	14.4 inches
Permanent	8.0 inches
Working Width	2.6 ft
Vehicle Damage	
VDS	11LFQ6
CDC	11FDEW5
Max. Exterior Deformation	15.0 inches
OCDI	LF0000000
Max. Occupant Compartment Deformation	2.0 inches

Figure 7.7. Summary of Results for *MASH* Test 2-20 at the Downstream End of the *MASH* TL-2 Transition.

7.8 ASSESSMENT OF TEST RESULTS

An assessment of the test based on the applicable *MASH* safety evaluation criteria is provided below.

7.8.1 Structural Adequacy

B. 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.

Results: The *MASH* TL-2 transition contained and redirected the 1100C vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 14.4 inches. (PASS)

7.8.2 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.

Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH. (roof ≤4.0 inches; windshield = ≤3.0 inches; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 inches; forward of A-pillar ≤12.0 inches; front side door area above seat ≤9.0 inches; front side door below seat ≤12.0 inches; floor pan/transmission tunnel area ≤12.0 inches.

Results: No detached elements, fragments, or other debris were present to penetrate or show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. (PASS)
Maximum occupant compartment deformation was 2.0 inches in the lateral area across the occupant compartment at the kick panel on the driver's side. (PASS)

F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.

Results: The 1100C vehicle remained upright during and after the collision event. (PASS)

I. Occupant impact velocities should satisfy the following:

Longitudinal and Lateral Occupant Impact Velocity

Preferred	*Maximum*
30 ft/s	*40 ft/s*

Results: Longitudinal occupant impact velocity was 29.5 ft/s, and lateral occupant impact velocity was 14.1 ft/s. (PASS)

I. Occupant ridedown accelerations should satisfy the following:

Longitudinal and Lateral Occupant Ridedown Accelerations	
Preferred	*Maximum*
15.0 Gs	*20.49 Gs*

Results: Longitudinal ridedown acceleration was 9.0 G, and lateral ridedown was 5.9 G. (PASS)

7.8.3 Vehicle Trajectory

For redirective devices, the vehicle shall exit the barrier within the exit box.

Result: The 1100C vehicle did not cross the exit box. (PASS)

CHAPTER 8. *MASH* TEST 2-20 AT THE UPSTREAM END (TEST NO. 420021-7)

8.1 TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

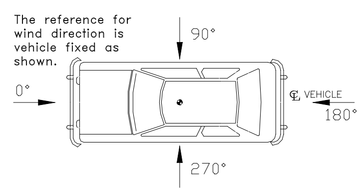
MASH test 2-20 involves an 1100C vehicle weighing 2425 lb ±55 lb impacting the transition at an impact speed of 44 mi/h ±2.5 mi/h and an angle of 25 degrees ±1.5 degrees. The target impact point was 4 ft upstream of the end of the concrete parapet. The 2004 Kia Rio used in the test weighed 2416 lb and the actual impact speed and angle were 43.5 mi/h and 24.4 degrees, respectively. The actual impact point was 54 inches upstream of the end of the concrete parapet.

8.2 TEST VEHICLE

The 2004 Kia Rio (shown in Figures 8.1 and 8.2) was used for the crash test. Test inertia weight of the vehicle was 2416 lb, and its gross static weight was 2581 lb. The height to the lower edge of the vehicle bumper was 8.50 inches, and the height to the upper edge of the bumper was 22.75 inches. Table C8 in Appendix C gives 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 free-wheeling and unrestrained just prior to impact.

8.3 WEATHER CONDITIONS

The test was performed on the morning of August 23, 2011. Weather conditions at the time of testing were: Wind speed: 7 mi/h; Wind direction: 205 degrees with respect to the vehicle (vehicle was traveling in a northwesterly direction); Temperature: 91°F, Relative humidity: 57 percent.



8.4 TEST DESCRIPTION

The 2004 Kia Rio, traveling at an impact speed of 43.5 mi/h, impacted the *MASH* TL-2 transition 54 inches upstream of the end of the concrete parapet at an impact angle of 24.4 degrees. At approximately 0.008 s, post 10 began to deflect toward impact, and at 0.012 s, post 11 began to deflect toward impact. Post 9 began to deflect toward the field side at 0.024 s, and the vehicle began to redirect at 0.029 s. The window in the driver's side front door shattered at 0.103 s. At 0.203 s, the vehicle was traveling parallel with the transition at a speed of 31.5 mi/h. The rear of the vehicle contacted the transition at 0.294 s. At 0.351 s, the vehicle lost contact with the transition traveling at an exit speed and angle of 30.7 mi/h and 17.1 degrees, respectively. Brakes on the vehicle were not applied, and the vehicle subsequently came to rest 141 ft downstream of impact and 75 ft toward traffic lanes. Figures D5 and D6 in Appendix D show sequential photographs of the test period.

Figure 8.1. Vehicle/Installation Geometrics for Test No. 420021-7.

Figure 8.2. Vehicle before Test No. 420021-7.

8.5 DAMAGE TO TEST INSTALLATION

Figures 8.3 and 8.4 show damage to the *MASH* TL-2 transition. The wheel of the vehicle contacted the traffic face of post 11. Posts 10 and 9 deflected toward the field side 0.5 inch and 0.25 inch, respectively, measured at ground level. Post 8 was disturbed. No movement was noted in the remaining posts. Length of contact of the vehicle with the rail element was 6.4 ft. Working width was 11.7 inches. Maximum dynamic deflection during the test was 3.4 inches, and maximum permanent deformation was 3.0 inches.

8.6 VEHICLE DAMAGE

Figure 8.5 shows the 1100C vehicle sustained damage to the left front corner. The left front strut and strut tower were deformed. Also damaged were the front bumper, hood, radiator and support, left front fender, left front tire and wheel rim, left front door and door glass, left rear quarter panel and rear bumper. The windshield sustained stress cracks, and the roof was buckled over an area measuring 3 inches × 5 inches × 0.5 inch deep. Maximum external crush of the vehicle was 13.0 inches in the front plane at the left front corner at bumper height. Maximum occupant compartment deformation was 0.5 inch in the lateral area across the occupant compartment at the level of the kick panel on the driver side. Figure 8.6 shows pictures of the interior of the vehicle. Tables C9 and C10 in Appendix C have data on the exterior crush and occupant compartment deformation measurements.

8.7 OCCUPANT RISK FACTORS

Data from the accelerometer, which was located at the vehicle center of gravity, were digitized for evaluation of occupant risk. In the longitudinal direction, the occupant impact velocity was 19.7 ft/s at 0.100 s, the highest 0.010-s occupant ridedown acceleration was 11.9 Gs from 0.101 to 0.111 s, and the maximum 0.050-s average acceleration was −9.6 Gs between 0.060 s and 0.110 s. In the lateral direction, the occupant impact velocity was 24.6 ft/s at 0.100 s, the highest 0.010-s occupant ridedown acceleration was 3.8 Gs from 0.298 to 0.308 s, and the maximum 0.050-s average was 12.0 Gs between 0.041 and 0.091 s. THIV was 34.3 km/h or 9.5 m/s at 0.097 s; PHD was 12.1 Gs between 0.101 and 0.110 s; and ASI was 1.52 between 0.041 and 0.091 s. Figure 8.7 summarizes these data and other pertinent information from the test. Appendix E, Figure E3 present the vehicle angular displacements versus time trace, and Figures F13 through F18 in Appendix F have data on accelerations versus time traces.

Figure 8.3. Position of Vehicle/Installation after Test No. 420021-7.

Figure 8.4. Installation after Test No. 420021-7.

Figure 8.5. Vehicle after Test No. 420021-7.

Before Test
After Test

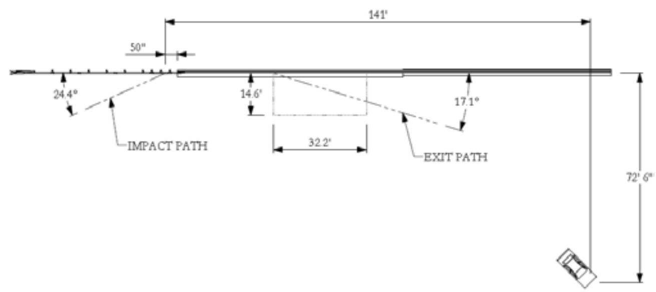
Figure 8.6. Interior of Vehicle for Test No. 420021-7.

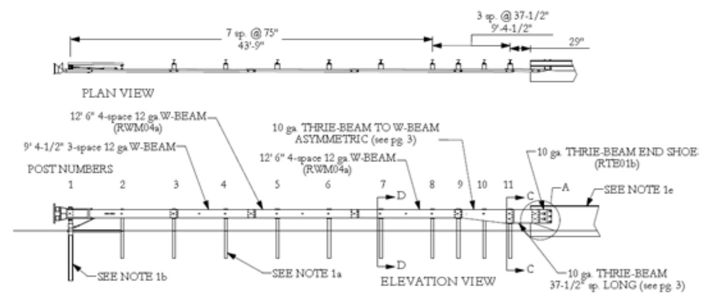
0.000 s

0.102 s

0.204 s

0.3060 s





General Information
Test Agency .... Texas Transportation Institute (TTI)
Test Standard Test No. .... MASH Test 2-20
TTI Test No. 420021-7
Test Date 2011-08-23

Test Article
Type .... Transition
Name .... *MASH* TL-2 transition
Installation Length .... 210.5 ft (terminal, transition and SSTR)
Material or Key Elements .... 10-gauge thrie beam rail on face of SSTR using 10-gauge thrie beam terminal connector and 10-gauge thrie beam section to 10-gauge, non-symmetric W-beam-to-thrie beam transition section

Soil Type and Condition .... Standard Soil, Dry

Test Vehicle
Type/Designation 1100C
Make and Model .... 2004 Kia Rio
Curb .... 2444 lb
Test Inertial .... 2416 lb
Dummy .... 165 lb
Gross Static .... 2581 lb

Impact Conditions
Speed .... 43.5 mi/h
Angle .... 24.4 degrees
Location/Orientation .... 4 ft upstrm of bridge rail end

Exit Conditions
Speed .... 30.7 mi/h
Angle .... 17.1 degrees

Occupant Risk Values
Impact Velocity
Longitudinal .... 19.7 ft/s
Lateral .... 24.6 ft/s
Ridedown Accelerations
Longitudinal .... 11.9 G
Lateral .... 3.8 G
THIV .... 34.3 km/h
PHD .... 12.1 G
ASI 1.52
Max. 0.050-s Average
Longitudinal .... −9.6 G
Lateral .... 12.0 G
Vertical .... −2.6 G

Post-Impact Trajectory
Stopping Distance .... 141 ft dwnstrm

Vehicle Stability
Maximum Yaw Angle .... 53 degrees
Maximum Pitch Angle .... 2 degrees
Maximum Roll Angle .... 5 degrees
Vehicle Snagging .... Yes
Vehicle Pocketing .... No

Test Article Deflections
Dynamic .... 3.4 inches
Permanent .... 3.0 inches
Working Width .... 11.7 inches

Vehicle Damage
VDS 11LFQ3
CDC 11FDEW3
Max. Exterior Deformation .... 13.0 inches
OCDI LF0000000
Max. Occupant Compartment Deformation .... 0.5 inches

Figure 8.7. Summary of Results for *MASH* Test 2-20 at Upstream End of the *MASH* TL-2 Transition.

8.8 ASSESSMENT OF TEST RESULTS

An assessment of the test based on the applicable *MASH* safety evaluation criteria is provided below.

8.8.1 Structural Adequacy

C. 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.

Results: The *MASH* TL-2 transition contained and redirected the 1100C vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 3.4 inches. (PASS)

8.8.2 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.
Deformation of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH. (roof ≤4.0 inches; windshield = ≤3.0 inches; side windows = no shattering by test article structural member; wheel/foot well/toe pan ≤9.0 inches; forward of A-pillar ≤12.0 inches; front side door area above seat ≤9.0 inches; front side door below seat ≤12.0 inches; floor pan/transmission tunnel area ≤12.0 inches).

Results: No detached elements, fragments, or other debris were present to penetrate or show potential for penetrating the occupant compartment, or to present undue hazard to others in the area. (PASS)
Maximum occupant compartment deformation was 0.5 inch in the lateral area across the occupant compartment at the level of the kick panel on the driver side. (PASS)

F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.

Results: The 1100C vehicle remained upright during and after the collision event. Maximum roll and pitch were 5 degrees and 2 degrees, respectively. (PASS)

J. Occupant impact velocities should satisfy the following:

Longitudinal and Lateral Occupant Impact Velocity

Preferred	*Maximum*
30 ft/s	*40 ft/s*

Results: Longitudinal occupant impact velocity was 19.7 ft/s, and lateral occupant impact velocity was 24.6 ft/s. (PASS)

I. Occupant ridedown accelerations should satisfy the following:

Longitudinal and Lateral Occupant Ridedown Accelerations

Preferred	*Maximum*
15.0 Gs	*20.49 Gs*

Results: Longitudinal ridedown acceleration was 11.9 G, and lateral ridedown was 3.8 G. (PASS)

8.8.3 Vehicle Trajectory

For redirective devices, the vehicle shall exit the barrier within the exit box.

Result: The 1100C vehicle did not cross the exit box. (PASS)

CHAPTER 9. SUMMARY AND CONCLUSIONS

The TxDOT Design Division is in the process of developing new standards for the 31-inch guardrail. The guardrail system includes not only the guardrail length of need, but also consideration of end terminals and guardrail-to-bridge rail transitions. TxDOT's current TL-2 metal beam transition (MBGF(TL2)-09) is not compatible with the new 31-inch guardrail, and the high-speed, nested thrie beam transition system (MBGF(TR)-09) would be cost-prohibitive to use at all locations on all roadways.

A new *MASH* TL-2 transition was developed and successfully crash tested. The system uses a short thrie beam section for attachment to a concrete bridge parapet and a non-symmetrical W-beam-to-thrie beam transition section to attach to a 31-inch tall approach guardrail.

Three critical test conditions were identified for evaluation of the *MASH* TL-2 transition. The downstream transition point was tested with both a pickup truck (test 2-21) and a small passenger car (test 2-20). Additionally, the impact performance of the upstream transition point was evaluated with a small passenger car. Tables 9.1 through 9.3 show that the new *MASH* TL-2 transition met all the requirements of *MASH* for all three tests. In each test, the vehicle remained stable and the occupant risk indices were below the preferred limits recommended in *MASH*.

Table 9.1. Performance Evaluation Summary for *MASH* Test 2-21 on the *MASH* TL-2 Transition.

Test Agency: Texas Transportation Institute | Test No.: 420021-4 | Test Date: 2011-07-22

***MASH* Test 2-21 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 *MASH* TL-2 Transition contained and redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection was 5.8 inches.	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 from the transition were present to penetrate the occupant compartment or to show potential for penetrating the occupant compartment, or to present undue 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 2.0 inches.	Pass
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 event. Maximum roll and pitch angles were 18 degrees and 9 degrees, 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 occupant impact velocity was 18.4 ft/s, and lateral occupant impact velocity was 19.7 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 5.9 Gs, and lateral occupant ridedown acceleration was 8.0 Gs.	Pass
Vehicle Trajectory *For redirective devices, the vehicle shall exit the barrier within the exit box.*	The 2270P vehicle exited within the exit box.	Pass

Table 9.2. Performance Evaluation Summary for *MASH* Test 2-10 on the *MASH* TL-2 Transition.

Test Agency: Texas Transportation Institute | Test No.: 420021-6 | Test Date: 2011-08-04

***MASH* Test 2-10 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 *MASH* TL-2 Transition contained and redirected the 1100C vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 14.4 inches.	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 undue 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 2.0 inches in the lateral area at the kick panel on the driver's side.	Pass
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 event.	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 occupant impact velocity was 29.5 ft/s, and lateral occupant impact velocity was 14.1 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 ridedown acceleration was 9.0 G, and lateral ridedown was 5.9 G.	Pass
Vehicle Trajectory *For redirective devices, the vehicle shall exit the barrier within the exit box.*	The 1100C vehicle did not cross the exit box.	Pass

Table 9.3. Performance Evaluation Summary for *MASH* Test 2-20 on the *MASH* TL-2 Transition.

Test Agency: Texas Transportation Institute | Test No.: 420021-7 | Test Date: 2011-08-23

***MASH* Test 2-20 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 *MASH* TL-2 Transition contained and redirected the 1100C vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 3.4 inches.	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 undue 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 0.5 inch in the lateral area across the occupant compartment at the level of the kick panel on the driver side	Pass
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 event.	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 occupant impact velocity was 19.7 ft/s, and lateral occupant impact velocity was 24.6 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 ridedown acceleration was 11.9 G, and lateral ridedown was 3.8 G.	Pass
Vehicle Trajectory *For redirective devices, the vehicle shall exit the barrier within the exit box.*	The 1100C vehicle did not cross the exit box.	Pass

CHAPTER 10. IMPLEMENTATION STATEMENT

A new TL-2 W-beam transition was successfully developed and found to meet the impact performance requirements of *MASH*. The new *MASH* TL-2 W-beam transition system can be implemented statewide through the development of a new standard detail sheet by TxDOT's Design Division. It is considered suitable for roadways that have traffic conditions appropriate for the use of TL-2 safety hardware.

The transition is comprised of standard hardware components and represents significant savings in terms of both material and installation cost compared to the high-speed nested thrie beam transition. The use of single, 10-gauge rail components simplifies installation and avoids the need for rail alteration at splice locations that can potentially weaken the rail strength.

The 31-inch mounting height is compatible with the proposed 31-inch guardrail system. The transition can be attached to F-shape, single slope, and vertical concrete barrier profiles. When attached to F-shape and single slope barriers, the bottom upstream edge of the barrier should be tapered to vertical over a distance of 3 ft to help reduce the severity of wheel snagging on the end of the parapet. The minor damage sustained by the system during the design crash tests near the parapet end suggests that the transition should be inexpensive to maintain.

REFERENCES

1. AASHTO, *Manual for Assessing Safety Hardware*, American Association of State Highway and Transportation Officials, Washington, D.C., 2009.

2. H. E. Ross, Jr., D. L. Sicking, R. A. Zimmer and J. D. Michie. *Recommended Procedures for the Safety Performance Evaluation of Highway Features*, National Cooperative Highway Research Program Report 350, Transportation Research Board, National Research Council, Washington, D.C., 1993.

3. K. A. Polivka, R. K. Faller, D. L. Sicking, J. R. Rohde, B. W. Bielenberg, and J. D. Reid, *Performance Evaluation of the Modified G4(1S) Guardrail – Update to NCHRP 350 Test No. 3-11 (2214-WB-1)*, Research Report TRP-03-168-06, Midwest Roadside Safety Facility, Lincoln, NE, October 2006.

4. K. A. Polivka, R. K. Faller, D. L. Sicking, J. R. Rohde, B. W. Bielenberg, and J. D. Reid, *Performance Evaluation of the Modified G4(1S) Guardrail—Update to NCHRP 350 Test No. 3-11 with 28" C.G. Height (2214-WB-2)*, Research Report TRP-03-169-06, Midwest Roadside Safety Facility, Lincoln, NE, October 2006.

5. D. L. Bullard, Jr., R. P. Bligh, and W. L. Menges, *Appendix D: MASH TL-3 Testing and Evaluation of the G4(2W) W-Beam Guardrail*, Research Report 476460-1-5, Texas Transportation Institute, College Station, TX, March 2010.

6. Roadside Design: Steel Strong-Post W-beam Guardrail, May 17, 2010 Memorandum, Office of Safety Design, Federal Highway Administration, U.S. Department of Transportation.

7. G. H. Powell, *Barrier VII: A Computer Program for Evaluation of Automobile Barrier Systems*, Report No. FHWA-RD-73-51, Federal Highway Administration, Washington, D.C., April 1973.

8. M. E. Bronstad, M. H. Calcote, M. H. Ray, and J. B. Mayer, *Guardrail-Bridge Rail Transition Design—Volume 1, Research Report*, Report No. FHWA/RD-86/178, Federal Highway Administration, Washington, D. C., April 1988.

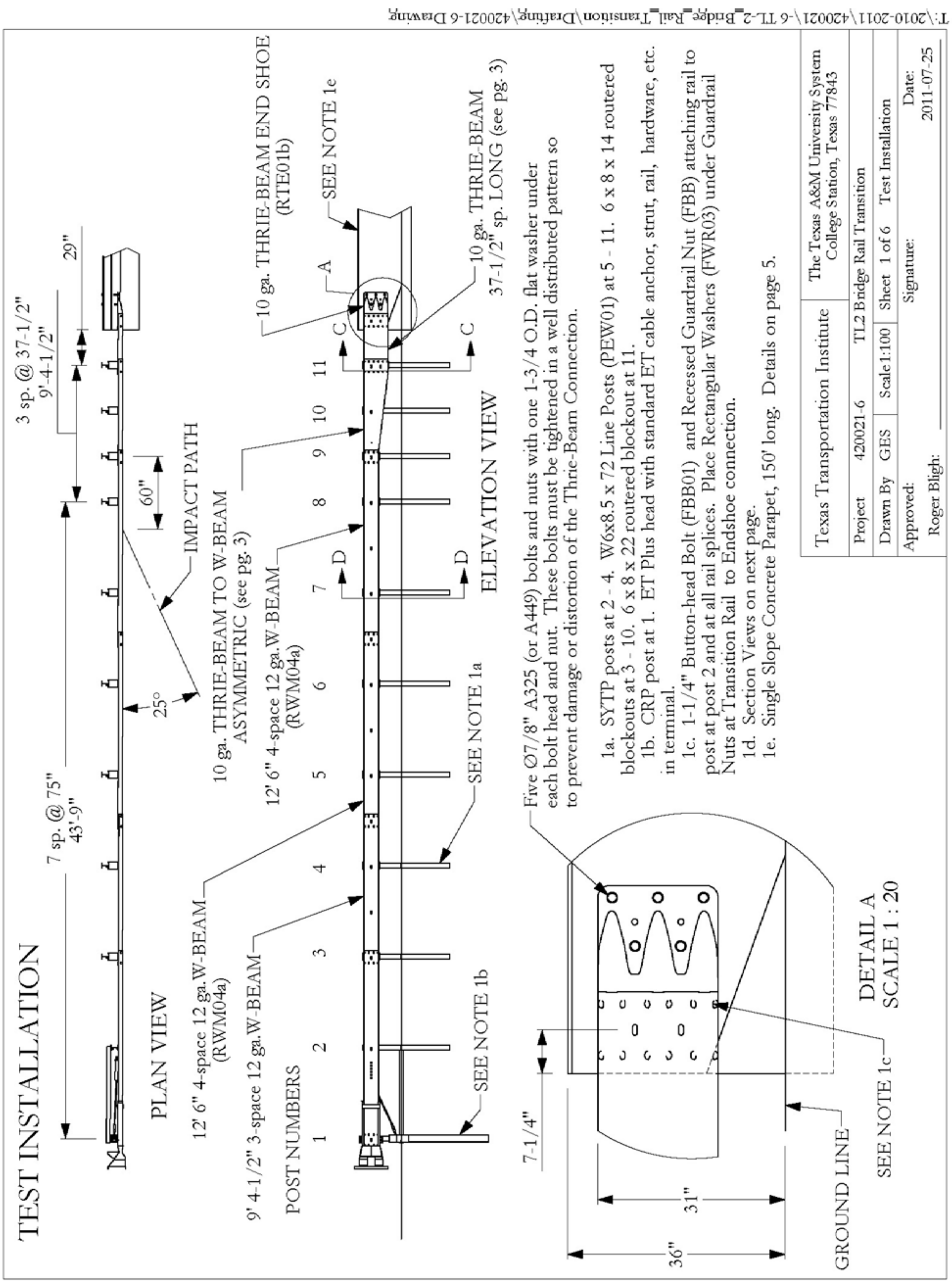
9. R. P. Bligh, D. L. Sicking, and H. E. Ross, Jr., *Development of a Guardrail to Bridge Rail Transition*, Research Report 461-1F, Texas Transportation Institute, Texas A&M University, College Station, Texas, June 1988.

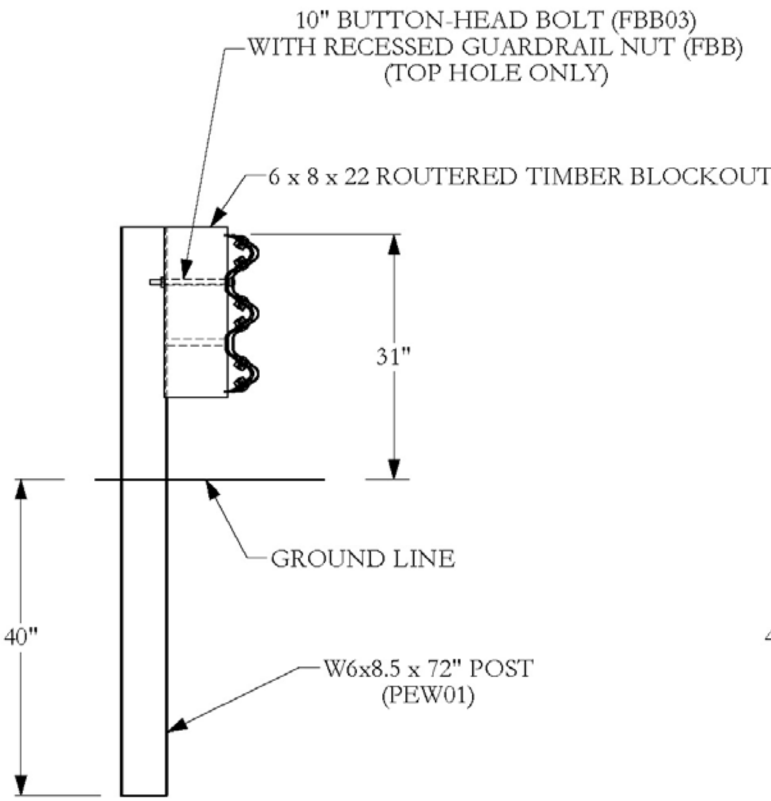
10. K. K. Mak, R. P. Bligh, C. E. Buth, and D. L. Bullard, Jr., *Development of a Box-Beam Guardrail Retrofit Transition to the Wyoming Steel Tube-Type Bridge Railing*, Research Report 0382-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, October 1989.

11. R. P. Bligh, and D. L Sicking, *Evaluation of Bridge Approach Rails*, Research Report 7155-1F, Texas Transportation Institute, College Station, Texas, March 1991.

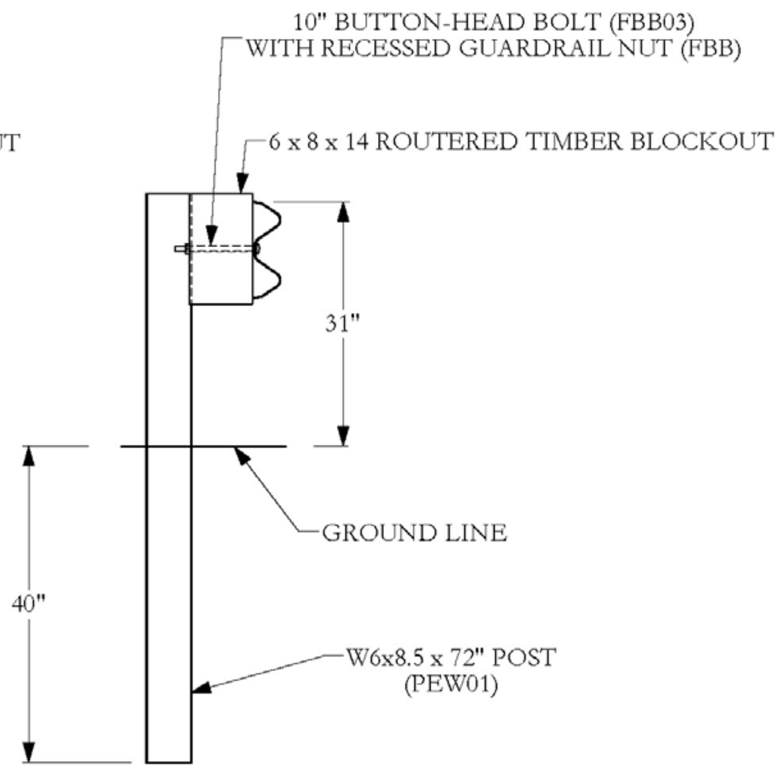
12. R. P. Bligh, W. L. Menges, and R. R. Haug, *Evaluation of Guardrail to Bridge Rail Transitions*, Research Report 4564-1, Texas Transportation Institute, College Station, Texas, October 2003.

APPENDIX A. DETAILS OF THE *MASH* TL-2 TRANSITION





SECTION C-C
SCALE 1 : 20



SECTION D-D
SCALE 1 : 20

Texas Transportation Institute		The Texas A&M University System College Station, Texas 77843	
Project 420021-6	TL2 Bridge Rail Transition		
Drawn By GES	Scale 1:20	Sheet 2 of 6	Section Views

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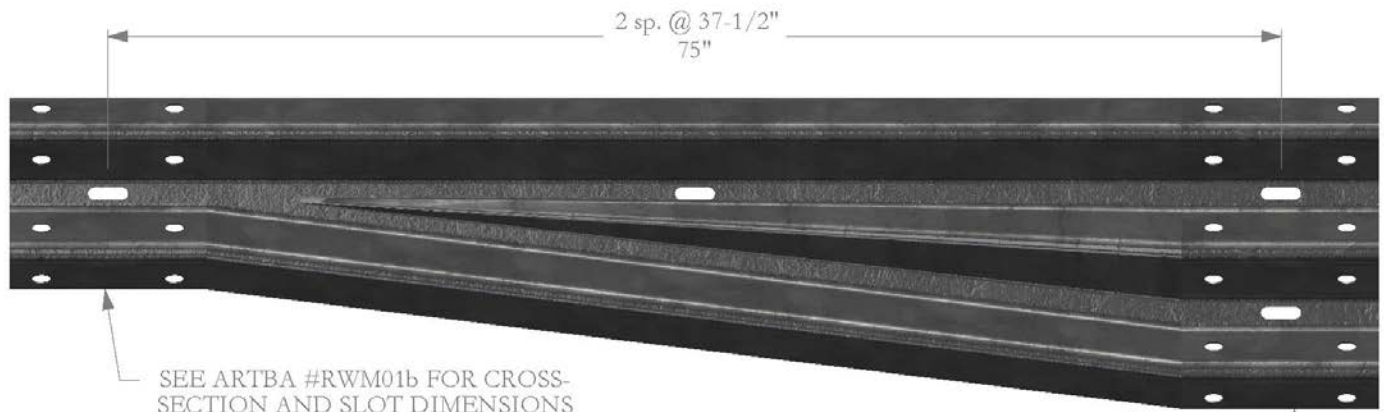

SEE ARTBA #RWM01b FOR CROSS-SECTION AND SLOT DIMENSIONS

SEE ARTBA #RTM01b FOR CROSS-SECTION AND SLOT DIMENSIONS

10 ga. THRIE-BEAM TO W-BEAM
ASYMMETRIC

10 ga. THRIE-BEAM
37-1/2" sp. LONG
SEE ARTBA #RTM01b FOR CROSS-SECTION AND SLOT DIMENSIONS

Texas Transportation Institute		The Texas A&M University System College Station, Texas 77843
Project 420021-6	TL2 Bridge Rail Transition	
Drawn By GES	Scale 1:10	Sheet 3 of 6 Rails

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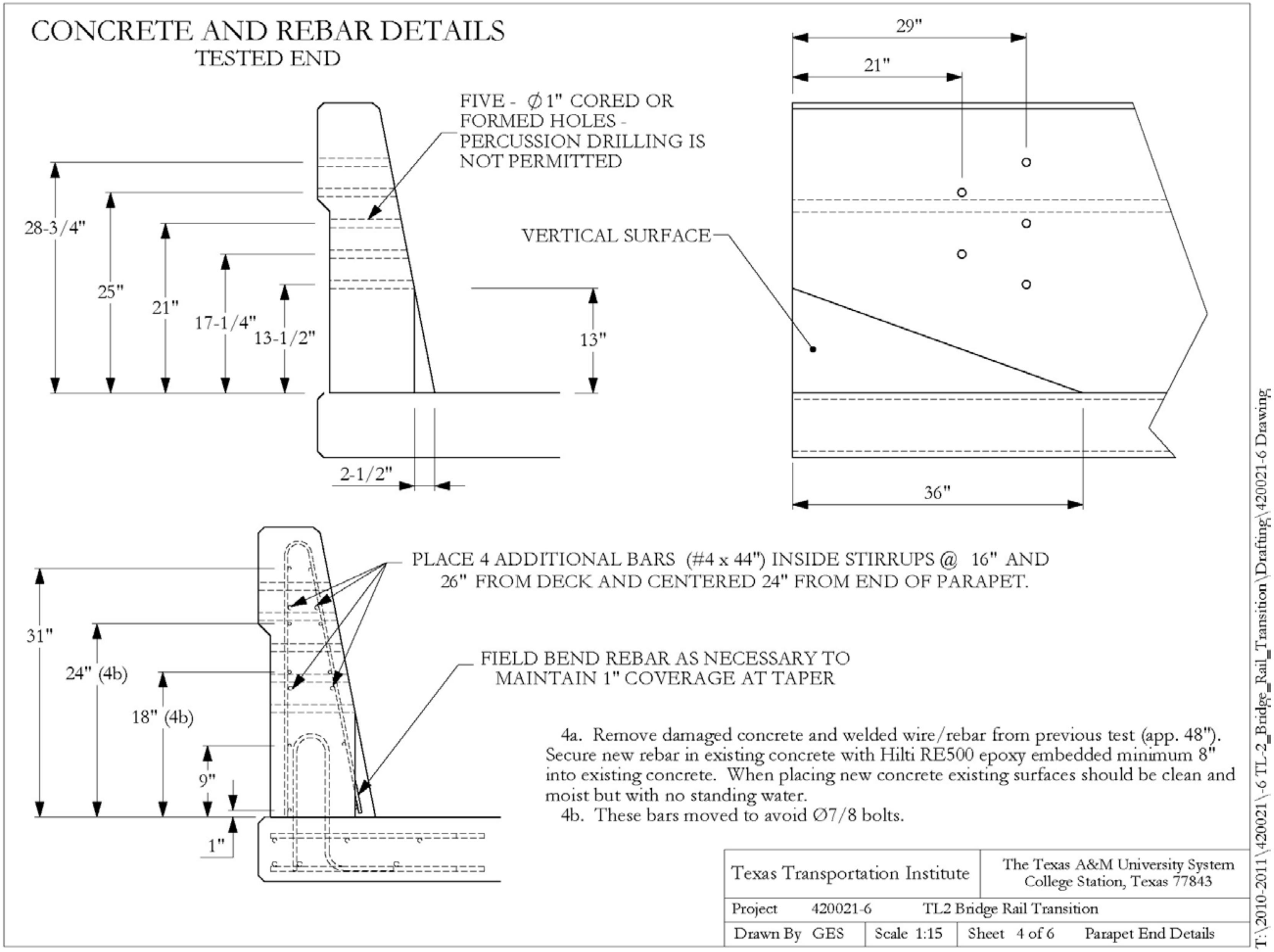
2011-07-25


CONCRETE AND REBAR DETAILS
TESTED END
FIVE - Ø1" CORED OR FORMED HOLES - PERCUSSION DRILLING IS NOT PERMITTED
VERTICAL SURFACE
28-3/4"
25"
21"
17-1/4"
13-1/2"
13"
2-1/2"
29"
21"
36"
PLACE 4 ADDITIONAL BARS (#4 x 44") INSIDE STIRRUPS @ 16" AND 26" FROM DECK AND CENTERED 24" FROM END OF PARAPET.
FIELD BEND REBAR AS NECESSARY TO MAINTAIN 1" COVERAGE AT TAPER
31"
24" (4b)
18" (4b)
9"
1"
4a. Remove damaged concrete and welded wire/rebar from previous test (app. 48"). Secure new rebar in existing concrete with Hilti RE500 epoxy embedded minimum 8" into existing concrete. When placing new concrete existing surfaces should be clean and moist but with no standing water.
4b. These bars moved to avoid Ø7/8 bolts.
Texas Transportation Institute
The Texas A&M University System
College Station, Texas 77843
Project 420021-6
TL2 Bridge Rail Transition
Drawn By GES
Scale 1:15
Sheet 4 of 6
Parapet End Details
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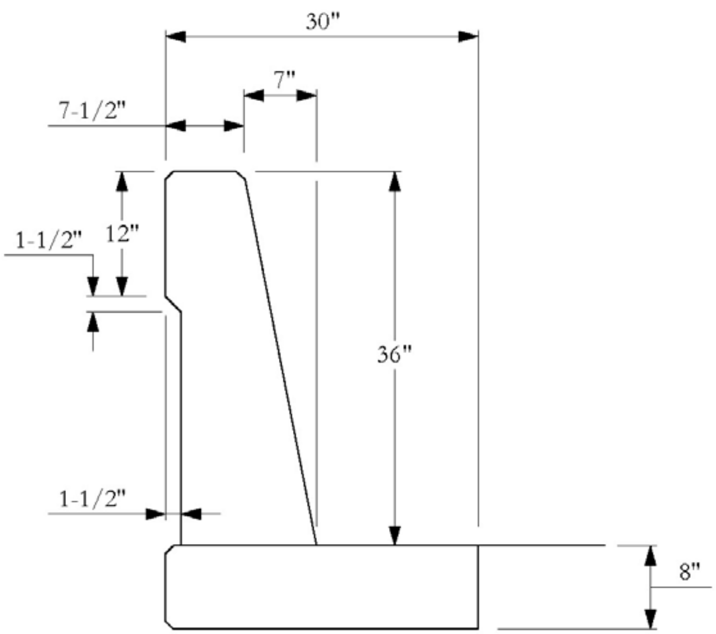
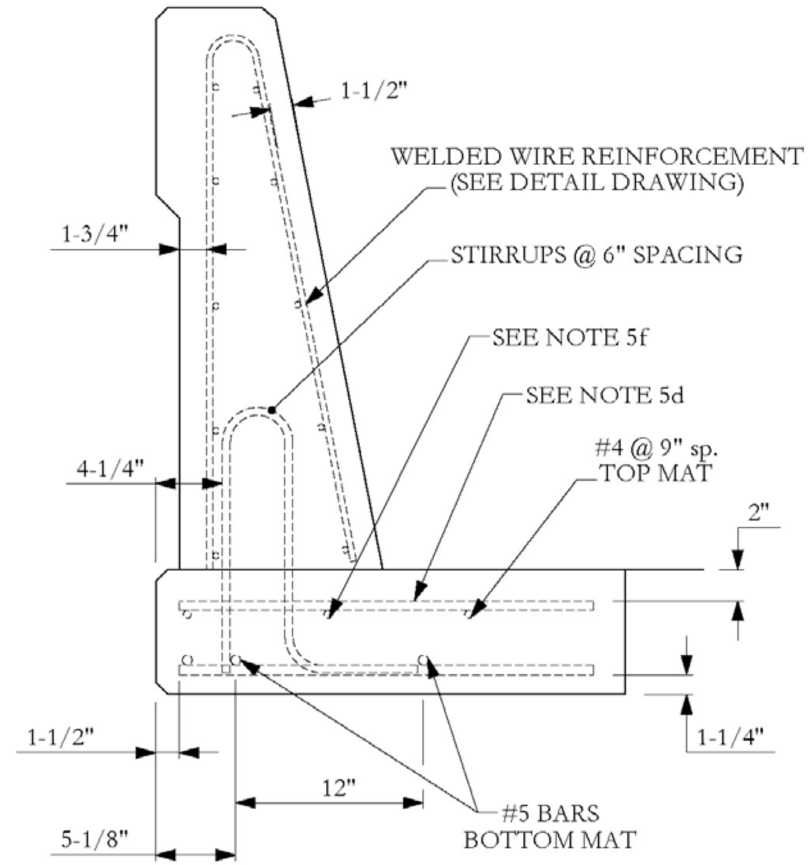


CONCRETE CROSS-SECTION
SCALE 1:15



REBAR PLACEMENT
CROSS-SECTION

5a. Concrete is Class S (4000 psi) for the deck, and Class C (3600 psi) for the parapet.
5b. Transverse bars in deck weld to existing rebar (not shown) protruding from runway.
5c. Deck is canti-levered from runway.
5d. Transverse bars at 6" spacing in top mat, 18" at bottom.
5e. Rebar lap splices are 17" for #4's and 21" for #5's.
5f. This bar may be adjusted laterally +/- 3" to allow tying to stirrup.

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Project 420021-6	TL2 Bridge Rail Transition
Drawn By GES · Scale 1:10	Sheet 5 of 6 · Concrete Details

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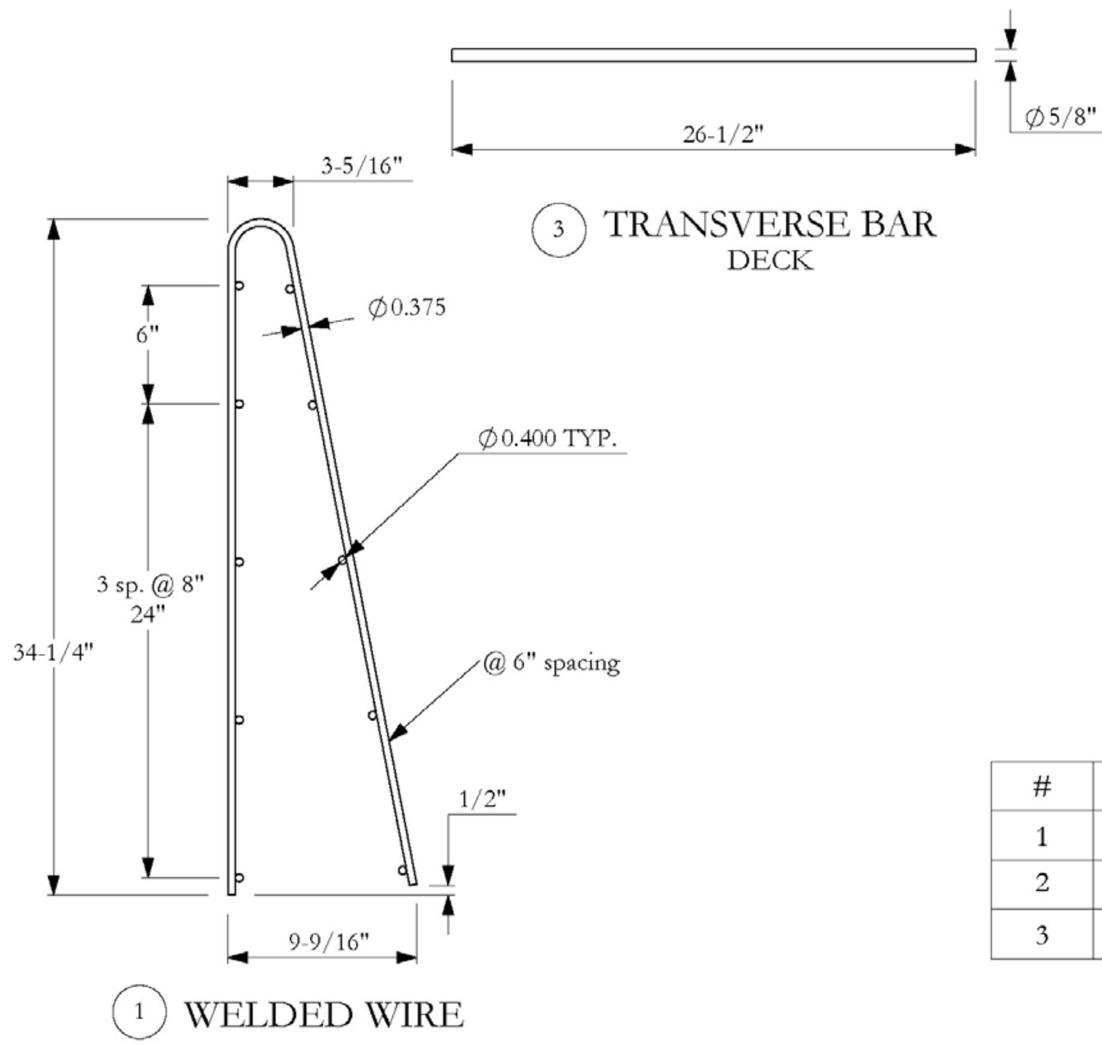

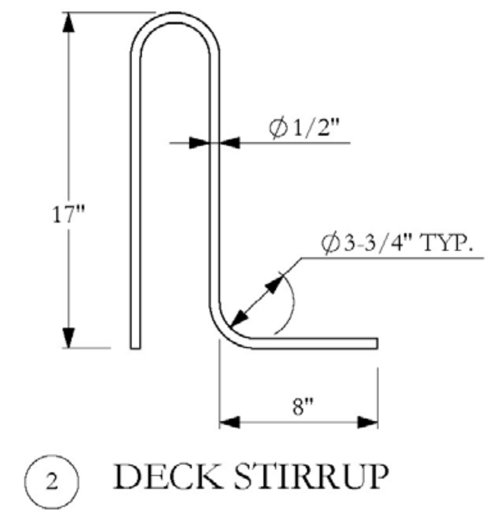

#	PART NAME
1	Welded Wire reinforcement
2	Parapet Stirrup
3	Transverse Bar-Deck

6a. Welded Wire reinforcement is grade 70. All other rebar is grade 60.
6b. Where welded wire is removed to patch concrete for this test replace welded wire with #4 bars. Adjust spacing of longitudinal bars to avoid holes for Ø7/8" bolts.

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Project 420021-6	TL2 Bridge Rail Transition	
Drawn By GES	Scale 1:8	Sheet 6 of 6 Rebar Details

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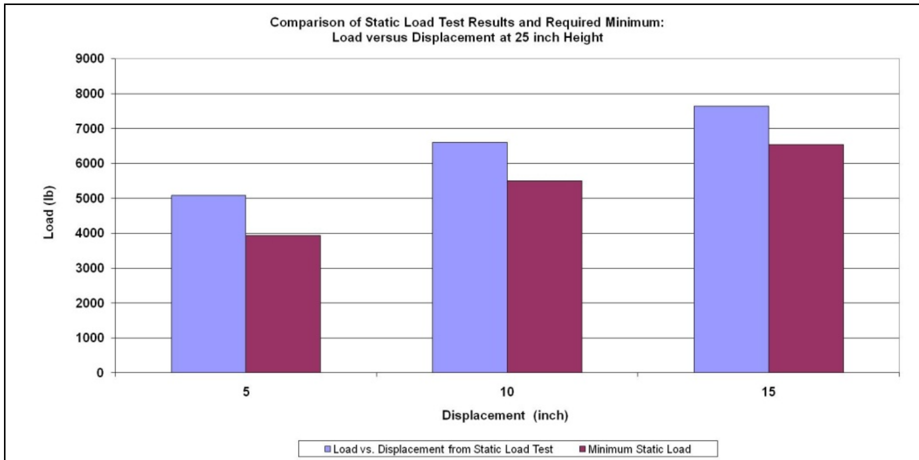
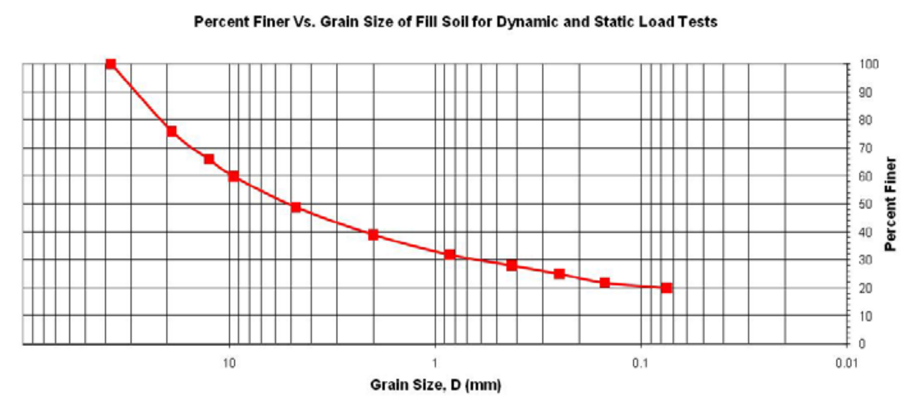
APPENDIX B. SOIL STRENGTH DOCUMENTATION



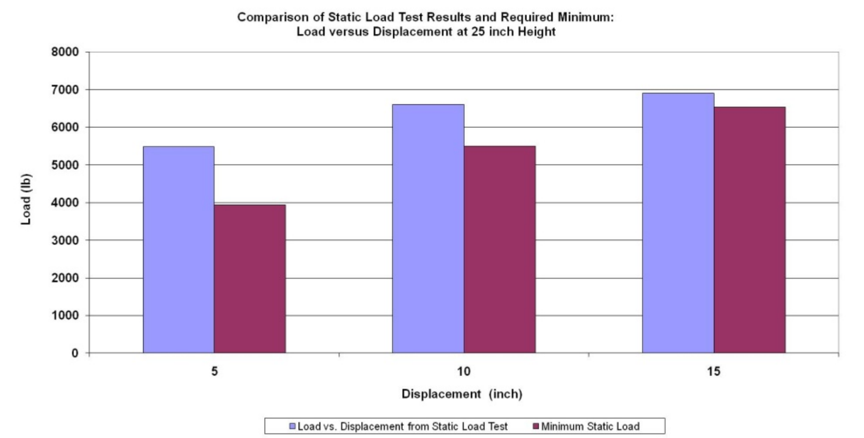
Static Load Setup



Post-Test Photo of Post

Date	2011-07-22
Test Facility and Site Location	TTI Proving Ground, 3100 SH 47, Bryan, TX
In Situ Soil Description (ASTM D2487)	Sandy gravel with silty fines
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO Grade B Soil-Aggregate (see sieve analysis)
Description of Fill Placement Procedure	6-inch lifts tamped with a pneumatic compactor

Figure B1. Test Day Static Soil Strength Documentation for Test No. 420021-4.



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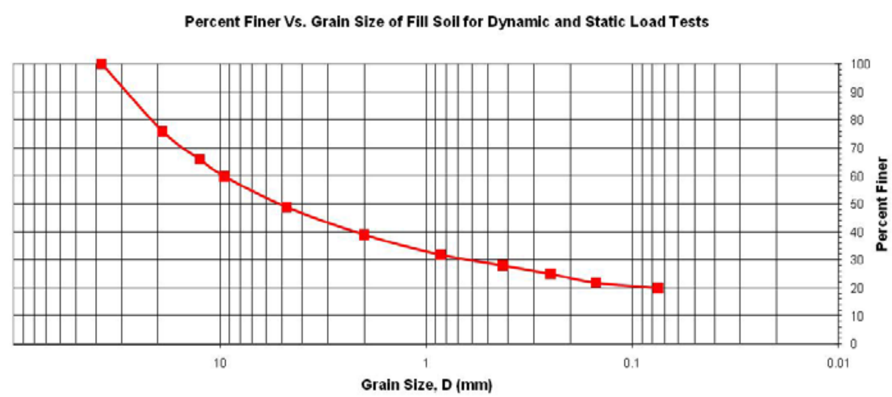
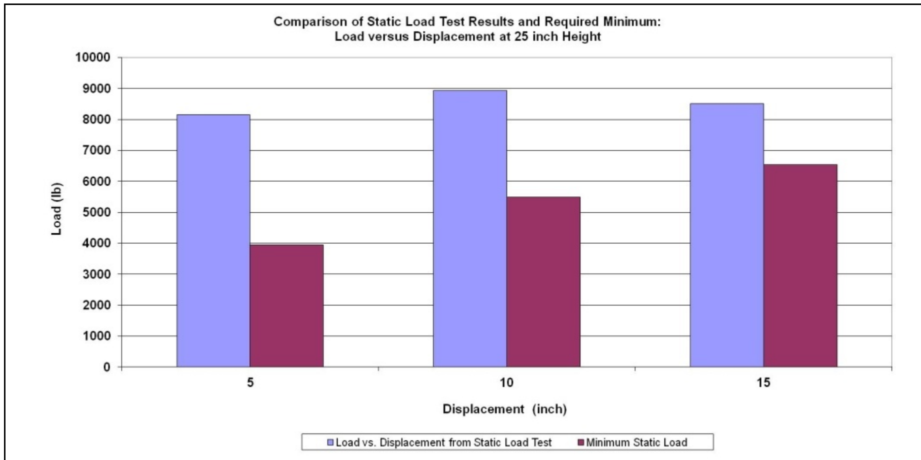


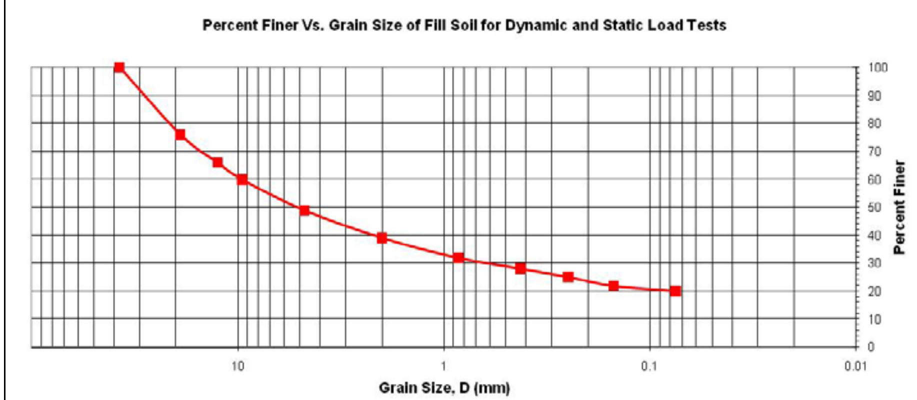
Post-Test Photo of Post

Date	2011-08-04
Test Facility and Site Location	TTI Proving Ground, 3100 SH 47, Bryan, TX
In Situ Soil Description (ASTM D2487)	Sandy gravel with silty fines
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO Grade B Soil-Aggregate (see sieve analysis)
Description of Fill Placement Procedure	6-inch lifts tamped with a pneumatic compactor

Figure B2. Test Day Static Soil Strength Documentation for Test No. 420021-6.



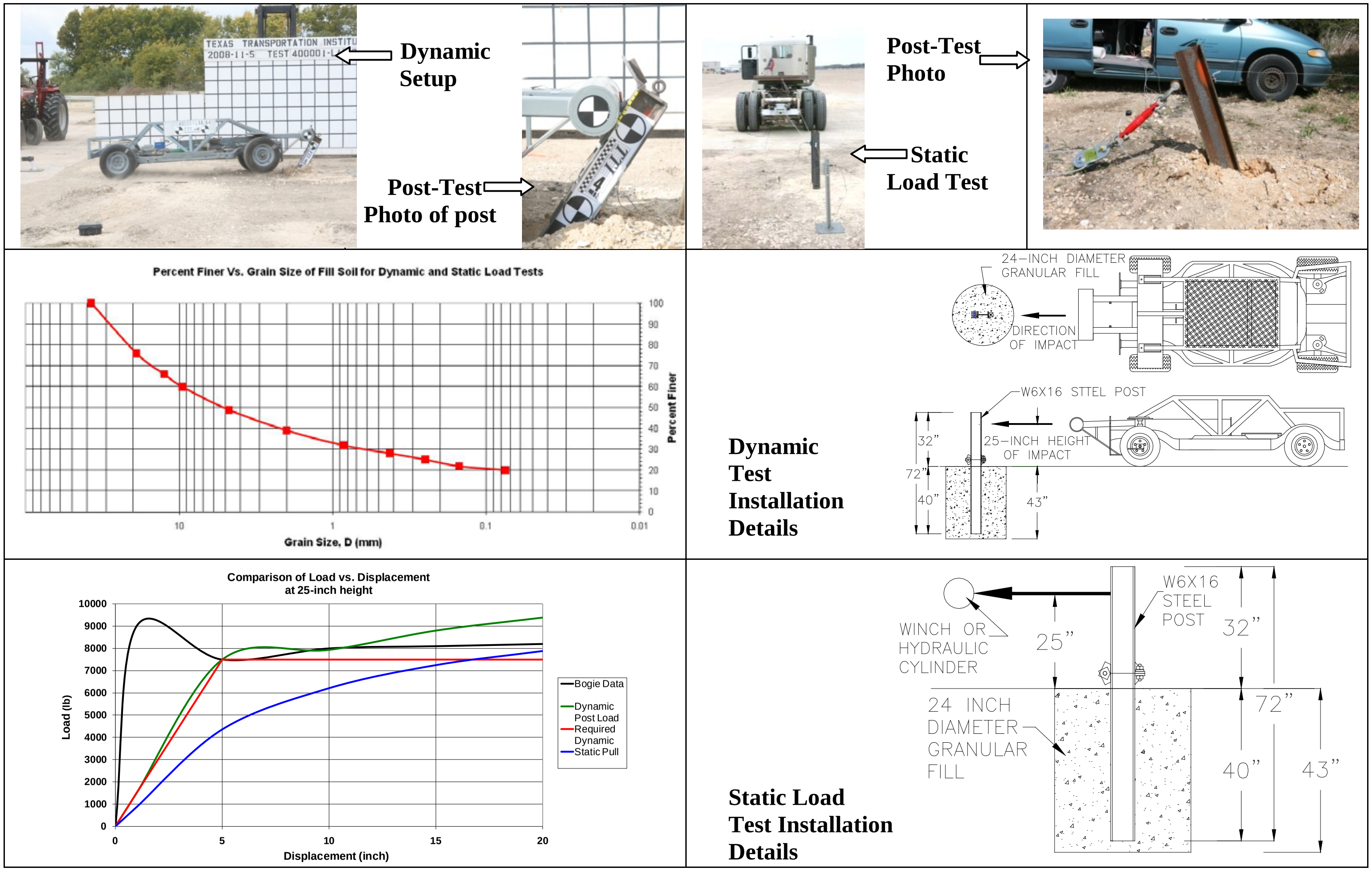
Static Load Setup



Post-Test Photo of Post

Date	2011-08-23
Test Facility and Site Location	TTI Proving Ground, 3100 SH 47, Bryan, TX
In Situ Soil Description (ASTM D2487)	Sandy gravel with silty fines
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO Grade B Soil-Aggregate (see sieve analysis)
Description of Fill Placement Procedure	6-inch lifts tamped with a pneumatic compactor

Figure B3. Test Day Static Soil Strength Documentation for Test No. 420021-7.



Date	2008-11-05
Test Facility and Site Location	TTI Proving Ground, 3100 SH 47, Bryan, TX 77807
In Situ Soil Description (ASTM D2487	Sandy gravel with silty fines
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO Grade B Soil-Aggregate (see sieve analysis above)
Description of Fill Placement Procedure	6-inch lifts tamped with a pneumatic compactor
Bogie Weight	5009 lb
Impact Velocity	20.5 mph

Figure B4. Summary of Strong Soil Test Results for Establishing Installation Procedure.

APPENDIX C. TEST VEHICLE PROPERTIES AND INFORMATION

Table C1. Vehicle Properties for Test No. 420021-4.

Date: 2011-07-22 Test No.: 420021-4 VIN No.: 1D7HA18N44S545897

Year: 2004 Make: Dodge Model: Ram 1500

Tire Size: 245/75R19 Tire Inflation Pressure: 35 psi

Tread Type: Highway Odometer: 150341

Note any damage to the vehicle prior to test: ______

● Denotes accelerometer location.

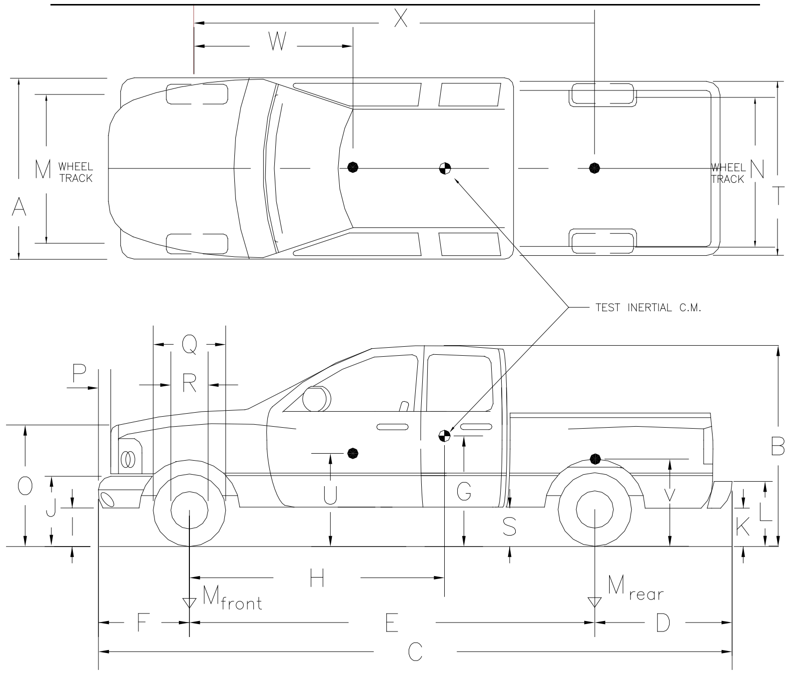
NOTES: ______

Engine Type: V-8
Engine CID: 4.7 liter

Transmission Type:
x Auto or ____ Manual
____ FWD x RWD ____ 4WD

Optional Equipment:
______

Dummy Data:
Type: None
Mass: ______
Seat Position: ______



Geometry: inches

A	77.00	F	39.00	K	20.50	P	3.00	U	27.50
B	73.25	G	28.62	L	28.75	Q	29.50	V	30.00
C	227.00	H	63.91	M	68.25	R	18.50	W	63.00
D	47.50	I	13.50	N	67.25	S	14.25	X	99.00
E	140.50	J	26.00	O	44.75	T	75.50		
Wheel Center Ht Front	14.125	Wheel Well Clearance (FR)	6.125	Frame Ht (FR)	16.625				
Wheel Center Ht Rear	14.25	Wheel Well Clearance (RR)	11.25	Frame Ht (RR)	24.25				

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	3650	M_{front}	2785	2774	Allowable		Allowable
Back	3900	M_{rear}	2094	2315	Range		Range
Total	6650	M_{Total}	4879	5089	5000 ±110 lb		5000 ±110 lb

Mass Distribution:
lb LF: 1403 RF: 1371 LR: 1132 RR: 1183

Table C2. Parametric Measurement for Vertical CG on 2270P Vehicle for Test No. 420021-6.

Date: 2011-07-22 Test No.: 420021-4 VIN: 1D7HA18N44S545897

Year: 2004 Make: Dodge Model: 1500 Ram

Body Style: Quad Cab Mileage: 150341

Engine: 4.7 liter Transmission: Automatic

Fuel Level: Empty Ballast: 241 lb front of bed (440 lb max)

Tire Pressure: Front: 35 psi Rear: 35 psi Size: 248/75R17

Measured Vehicle Weights: (lb)								
LF:	1424		RF:	1375		Front Axle:	2799	
LR:	1089		RR:	1139		Rear Axle:	2228	
Left:	2513		Right:	2514		Total:	5027	
							5000 ±110 lb allowed	
Wheel Base:	140.5	inches	Track: F:	68.25	inches	R:	67.25	inches
	148 ±12 inches allowed			Track = (F+R)/2 = 67 ±1.5 inches allowed				
Center of Gravity, SAE J874 Suspension Method								
X:	62.27	in	Rear of Front Axle	(63 ±4 inches allowed)				
Y:	0.01	in	Left - Right +	of Vehicle Centerline				
Z:	28.625	in	Above Ground	(minumum 28.0 inches allowed)				

Hood Height: 44.75 inches
43 ±4 inches allowed

Front Bumper Height: 26.00 inches

Front Overhang: 39.00 inches
39 ±3 inches allowed

Rear Bumper Height: 28.75 inches

Overall Length: 227.00 inches
237 ±13 inches allowed

Table C3. Exterior Crush Measurements for Test No. 420021-4.

Date: 2011-07-22 Test No.: 420021-4 VIN No.: 1D7HA18N44S545897

Year: 2004 Make: Dodge Model: Ram 1500

VEHICLE CRUSH MEASUREMENT SHEET[1]

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

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	18.0	16.0	24.0	16.0	11.0	4.5	2.0	1.0	0	-12
2	Side plane at bumper ht	18.0	10.0	0	2.0	---	---	8.5	10.0	+70	
	Measurements recorded										
	in inches										

[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).

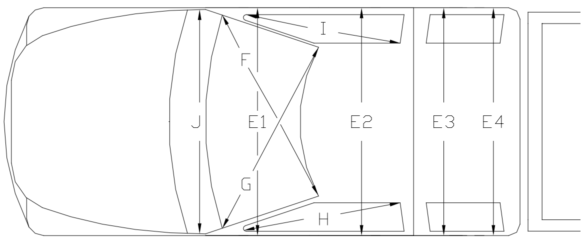
***Measure and document on the vehicle diagram the location of the maximum crush.

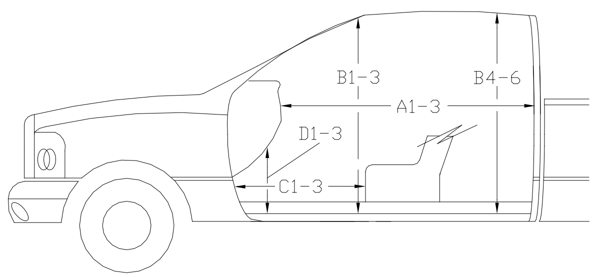
Note: Use as many lines/columns as necessary to describe each damage profile.

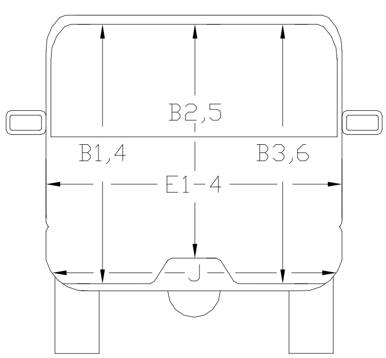
Table C4. Occupant Compartment Measurements for Test No. 420021-4.

Date: 2011-07-22 Test No.: 420021-4 VIN No.: 1D7HA18N44S545897

Year: 2004 Make: Dodge Model: Ram 1500







OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before (inches)	After (inches)
A1	64.25	64.25
A2	64.50	64.50
A3	65.25	65.25
B1	45.50	45.50
B2	39.12	39.12
B3	45.50	45.50
B4	42.00	42.00
B5	42.75	42.75
B6	42.00	42.00
C1	29.75	27.75
C2	---	---
C3	27.25	27.25
D1	12.75	13.12
D2	2.50	2.50
D3	11.50	11.50
E1	62.50	62.50
E2	64.25	64.25
E3	64.00	64.00
E4	64.00	64.00
F	60.50	60.50
G	62.00	62.00
H	39.50	39.50
I	39.50	39.50
J*	62.25	61.75

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

Table C5. Vehicle Properties for Test No. 420021-6.

Date: 2011-08-04 Test No.: 420021-6 VIN No.: KNADC125646331124

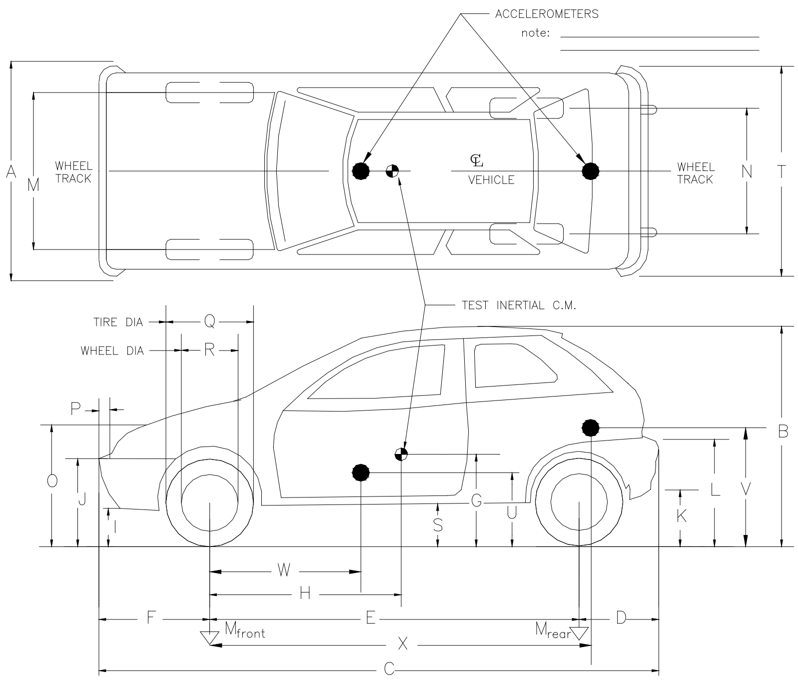
Year: 2004 Make: Kia Model: Rio

Tire Inflation Pressure: 32 psi Odometer: 67522 Tire Size: 185/65R14

Describe any damage to the vehicle prior to test: __________

● Denotes accelerometer location.

NOTES: __________



Engine Type: 4 cylinder
Engine CID: 1.5 liter
Transmission Type:
x Auto or ____ Manual
x FWD ____ RWD ____ 4WD
Optional Equipment: __________

Dummy Data:
Type: 50th percentile male
Mass: 168 lb
Seat Position: Driver side

Geometry: inches

A	62.50	F	32.00	K	12.00	P	3.25	U	15.50
B	56.12	G		L	24.25	Q	22.50	V	21.50
C	164.25	H	33.96	M	56.50	R	15.50	W	35.00
D	37.00	I	8.50	N	57.00	S	8.62	X	104.50
E	95.25	J	22.75	O	28.00	T	63.00		

Wheel Center Ht Front 10.75 Wheel Center Ht Rear 11.125

RANGE LIMIT: A = 65 ±3 inches; C = 168 ±8 inches; E = 98 ±5 inches; F = 35 ±4 inches; G = 39 ±4 inches; O = 24 ±4 inches; M+N/2 = 56 ±2 inches

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial		Gross Static	
Front	1691	M_{front}	1535	1556	Allowable	1629	Allowable
Back	1559	M_{rear}	860	862	Range	957	Range =
Total	3250	M_{Total}	2395	2418	2420 ±55 lb	2586	2585 ±55 lb

Mass Distribution:
lb LF: 800 RF: 756 LR: 418 RR: 444

Table C6. Exterior Crush Measurements for Test No. 420021-6.

Date: 2011-08-04 Test No.: 420021-6 VIN No.: KNADC125646331124

Year: 2004 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		Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
		Width** (CDC)	Max*** Crush								
1	Front plane at bumper ht	19.0	7.0	30.0	7.0	5.0	3.5	2.5	1.0	0	-12
2	Side plane at bumper ht	19.0	15.0	34.0	0	3.75	9.0	11.0	13.0	15.0	+4.5
	Measurements recorded										
	in inches										

[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).

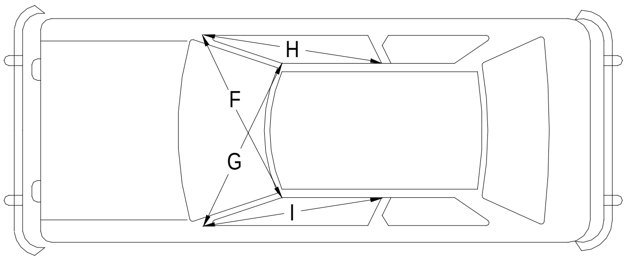
***Measure and document on the vehicle diagram the location of the maximum crush.

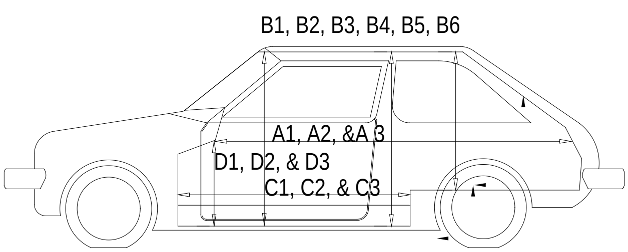
Note: Use as many lines/columns as necessary to describe each damage profile.

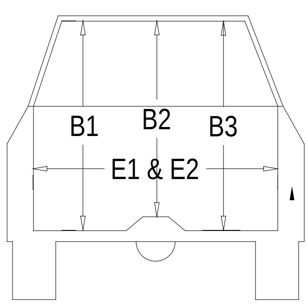
Table C7. Occupant Compartment Measurements for Test No. 420021-6.

Date: 2011-08-04 Test No.: 420021-6 VIN No.: KNADC125646331124

Year: 2004 Make: Kia Model: Rio







OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before (inches)	After (inches)
A1	67.25	67.25
A2	65.00	65.00
A3	37.25	37.25
B1	39.50	39.50
B2	35.50	35.50
B3	39.50	39.50
B4	34.75	34.75
B5	35.00	35.00
B6	34.75	34.75
C1	27.00	27.00
C2	----	----
C3	27.00	27.00
D1	9.75	9.75
D2	----	----
D3	9.25	9.25
E1	48.50	48.50
E2	50.50	50.50
F	49.00	49.00
G	49.00	49.00
H	36.50	36.50
I	36.50	36.50
J*	50.25	50.00

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

Table C8. Vehicle Properties for Test No. 420021-7.

Date: 2011-08-23 Test No.: 420021-7 VIN No.: KNADC125X46319834

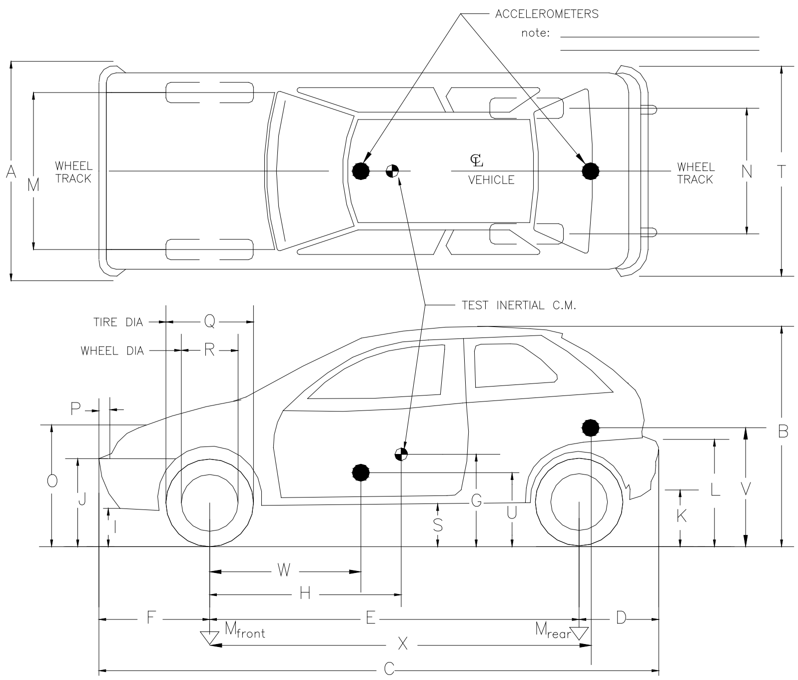
Year: 2004 Make: Kia Model: Rio

Tire Inflation Pressure: 32 psi Odometer: 115760 Tire Size: 185/65R14

Describe any damage to the vehicle prior to test: ______

● Denotes accelerometer location.

NOTES: ______



Engine Type: 4 cylinder
Engine CID: 1.5 liter
Transmission Type:
x Auto or ____ Manual
x FWD ____ RWD ____ 4WD
Optional Equipment: ______

Dummy Data:
Type: 50th percentile male
Mass: 165 lb
Seat Position: Driver side

Geometry: inches

A	62.50	F	32.00	K	12.00	P	3.25	U	15.50
B	56.12	G		L	24.25	Q	22.50	V	21.50
C	164.25	H	34.38	M	56.50	R	15.50	W	35.00
D	37.00	I	8.50	N	57.00	S	8.62	X	106.00
E	95.25	J	22.75	O	28.00	T	63.00		

Wheel Center Ht Front 10.75 Wheel Center Ht Rear 11.125

RANGE LIMIT: A = 65 ±3 inches; C = 168 ±8 inches; E = 98 ±5 inches; F = 35 ±4 inches; G = 39 ±4 inches; O = 24 ±4 inches; M+N/2 = 56 ±2 inches

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial		Gross Static	
Front	1691	M_{front}	1559	1544	Allowable	1620	Allowable
Back	1559	M_{rear}	835	872	Range	961	Range =
Total	3250	M_{Total}	2444	2416	2420 ±55 lb	2581	2585 ±55 lb

Mass Distribution:
lb LF: 776 RF: 768 LR: 432 RR: 440

Table C9. Exterior Crush Measurements for Test No. 420021-7.

Date: 2011-08-23 Test No.: 420021-7 VIN No.: KNADC125X46319834

Year: 2004 Make: Kia Model: Rio

VEHICLE CRUSH MEASUREMENT SHEET[1]

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

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 bumper ht	12.0	13.0	24.0	13.0	8.5	6.0	4.0	2.25	0	-12.0
2	Side plane at bumper ht	12.0	10.5	40.0	0	2.25	4.0	7.5	9.5	10.5	+50.0
	Measurements recorded										
	in inches										

[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.

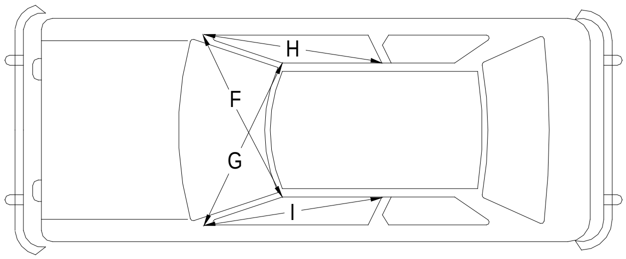
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

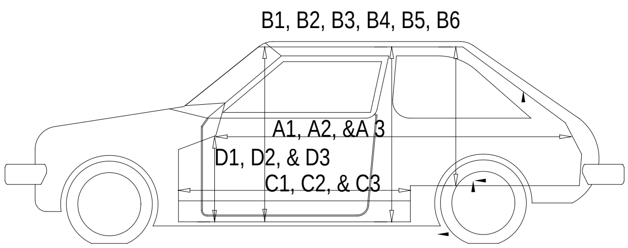
***Measure and document on the vehicle diagram the location of the maximum crush.

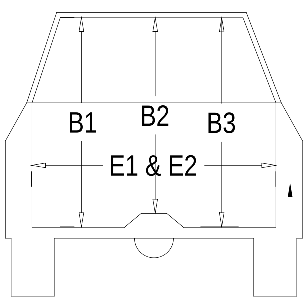
Note: Use as many lines/columns as necessary to describe each damage profile.

Table C10. Occupant Compartment Measurements for Test No. 420021-7.

Date:	2011-08-23	Test No.:	420021-7	VIN No.:	KNADC125X46319834
Year:	2004	Make:	Kia	Model:	Rio





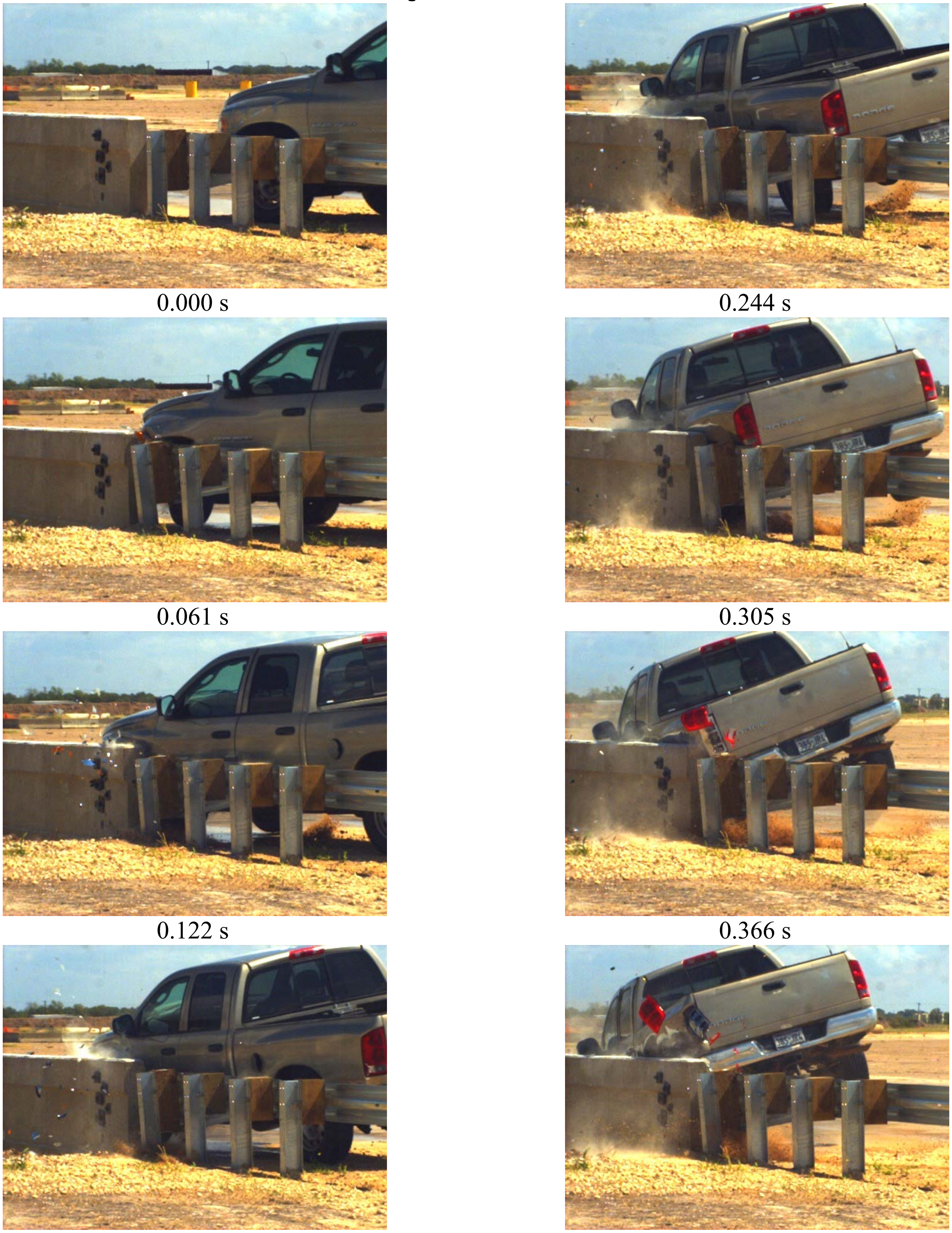


OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before (inches)	After (inches)
A1	67.00	67.00
A2	65.25	65.25
A3	67.00	67.00
B1	39.50	39.50
B2	35.50	35.50
B3	39.50	39.50
B4	34.50	34.50
B5	34.75	34.75
B6	34.50	34.50
C1	26.25	26.25
C2	----	----
C3	26.25	26.25
D1	9.75	9.75
D2	-----	-----
D3	9.50	9.50
E1	48.50	49.00
E2	50.50	51.75
F	49.00	49.00
G	49.00	49.00
H	36.50	36.50
I	36.50	36.50
J*	20.25	49.75

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

APPENDIX D. SEQUENTIAL PHOTOGRAPHS



0.000 s

0.061 s

0.122 s

0.183 s

0.244 s

0.305 s

0.366 s

0.427 s

Figure D1. Sequential Photographs for Test No. 420021-4 (Rear View).

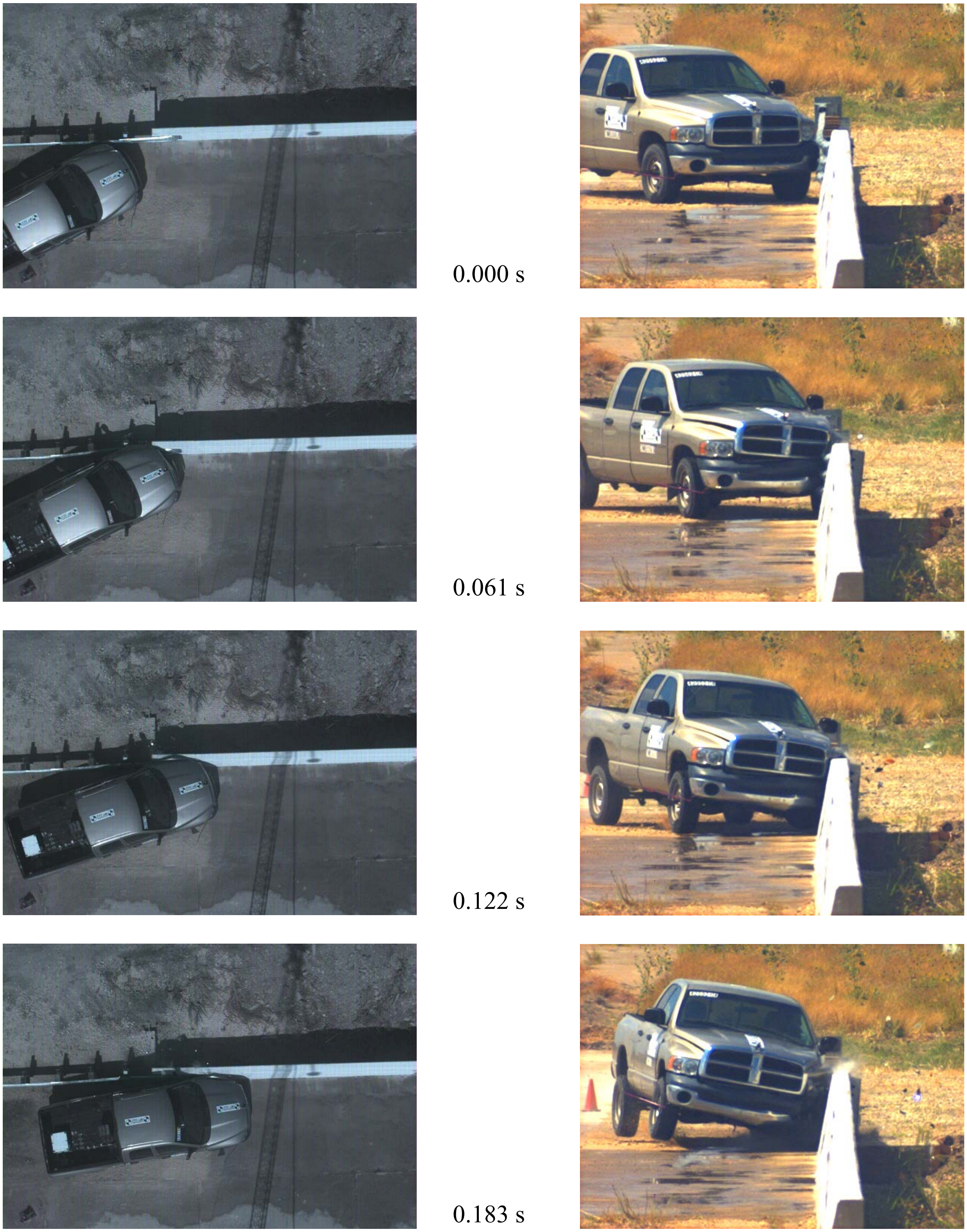


Figure D2. Sequential Photographs for Test No. 420021-4 (Overhead and Frontal Views).

0.244s

0.305 s

0.366 s

0.427 s

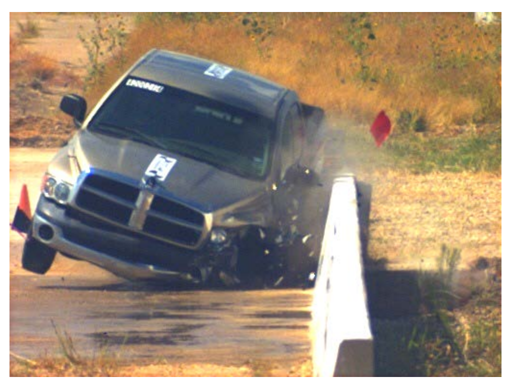


Figure D2. Sequential Photographs for Test No. 420021-4 (Overhead and Frontal Views) (continued).

0.000 s

0.040 s

0.080 s

0.120 s

Figure D3. Sequential Photographs for Test No. 420021-6 (Overhead and Frontal Views).

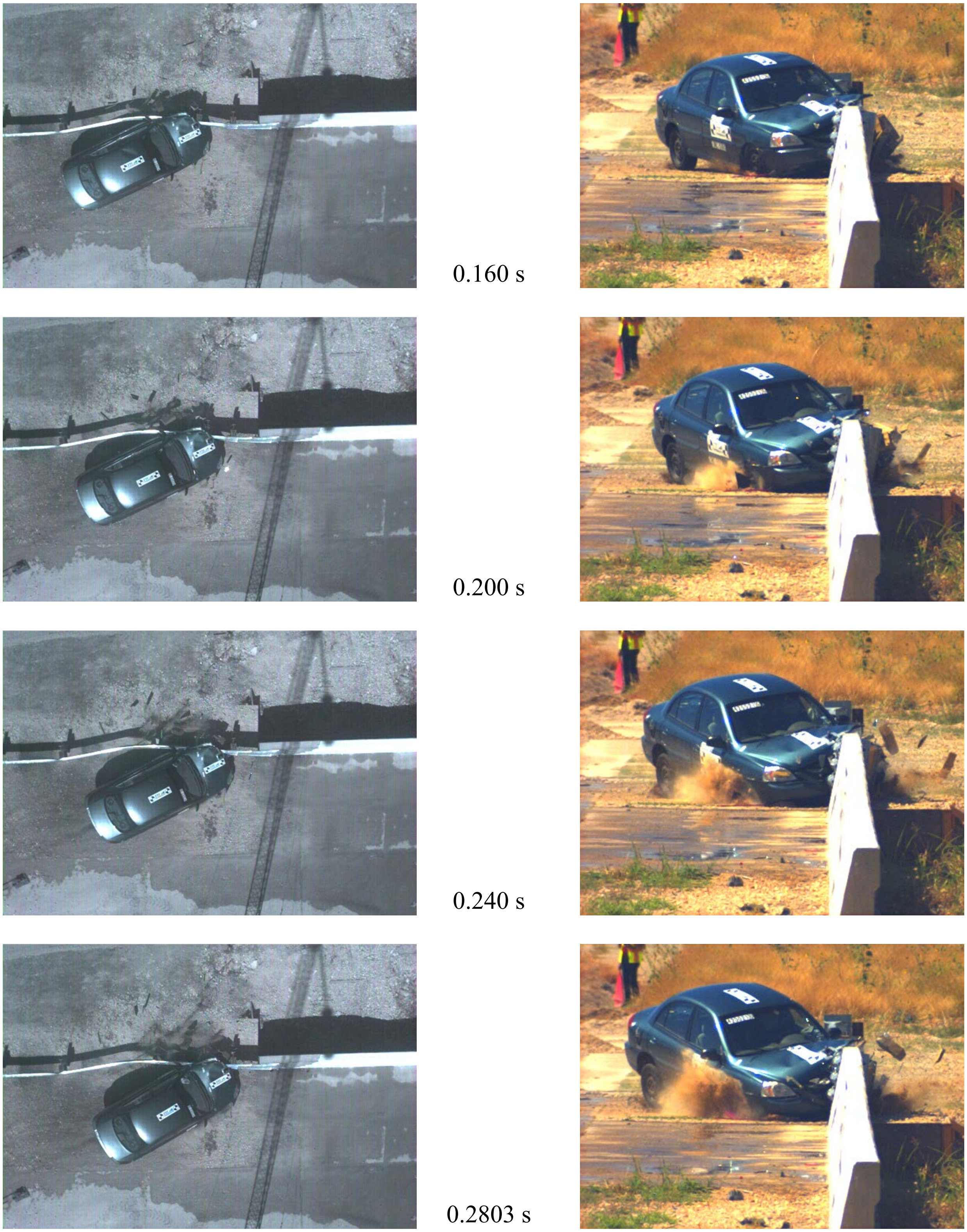


Figure D3. Sequential Photographs for Test No. 420021-6 (Overhead and Frontal Views) (continued).

0.000 s

0.040 s

0.080 s

0.120 s

0.160 s

0.200 s

0.240 s

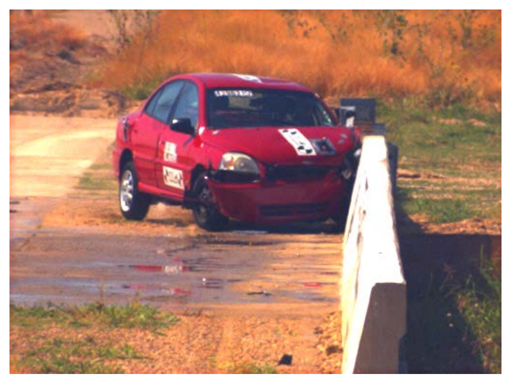
0.280 s

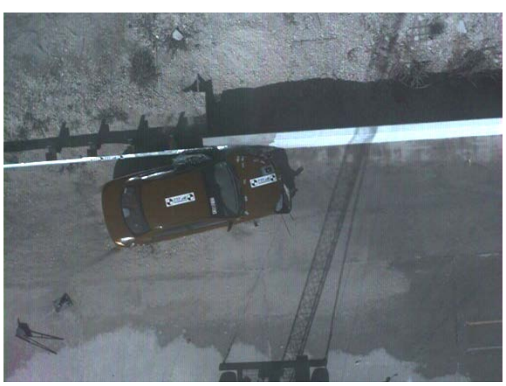
Figure D4. Sequential Photographs for Test No.420021-6 (Rear View).

0.000 s

0.056 s

0.102 s





0.153 s

Figure D5. Sequential Photographs for Test No. 420021-7 (Overhead and Frontal Views).

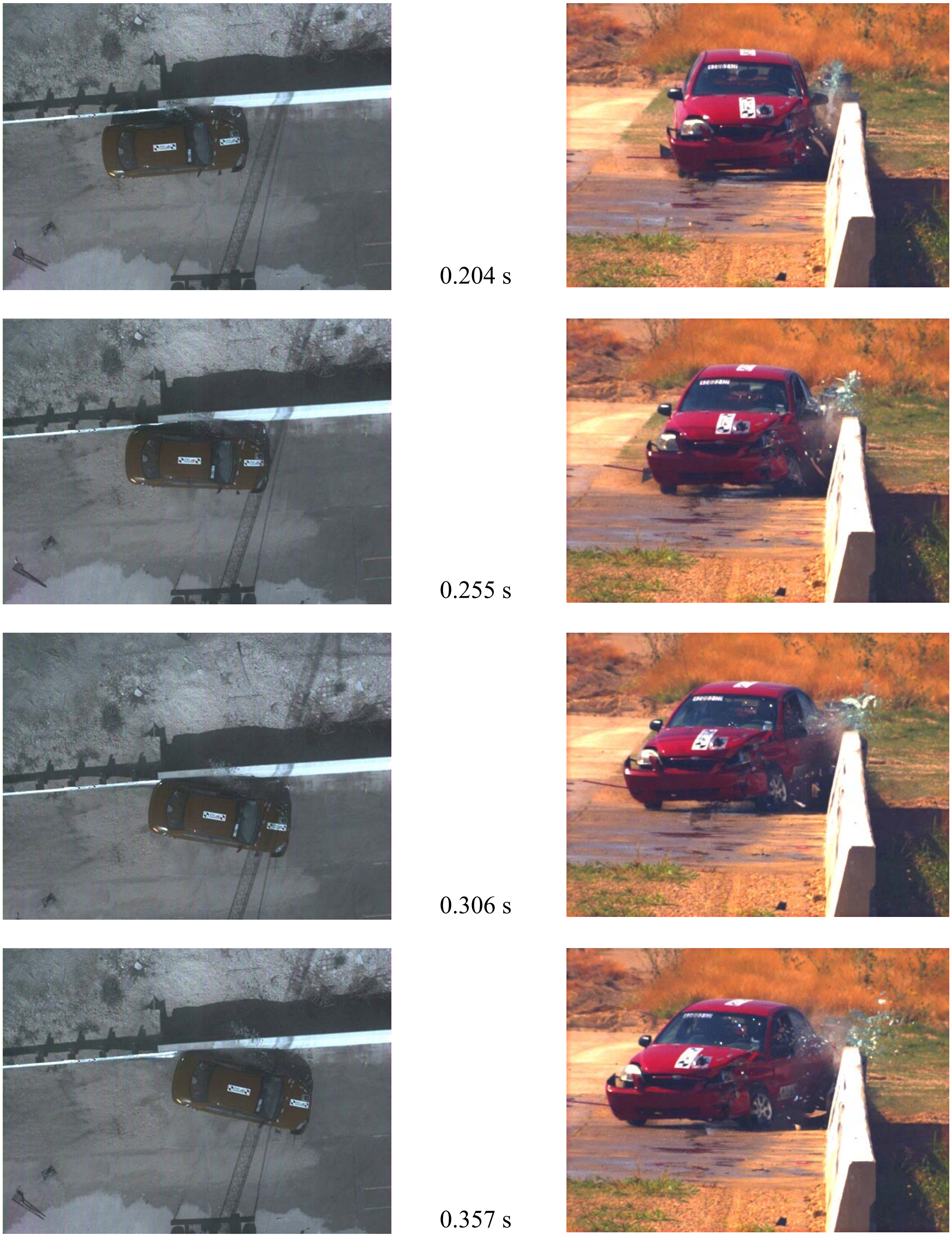


Figure D5. Sequential Photographs for Test No. 420021-7 (Overhead and Frontal Views) (continued).


0.000 s


0.204 s


0.051 s


0.255 s


0.102 s


0.306 s


0.153 s

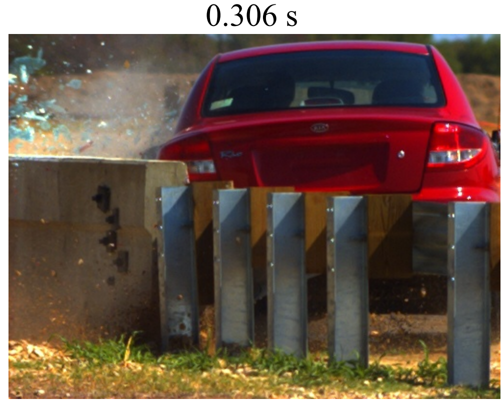

0.357 s

Figure D6. Sequential Photographs for Test No.420021-7 (Rear View).

APPENDIX E. VEHICLE ANGULAR DISPLACEMENTS

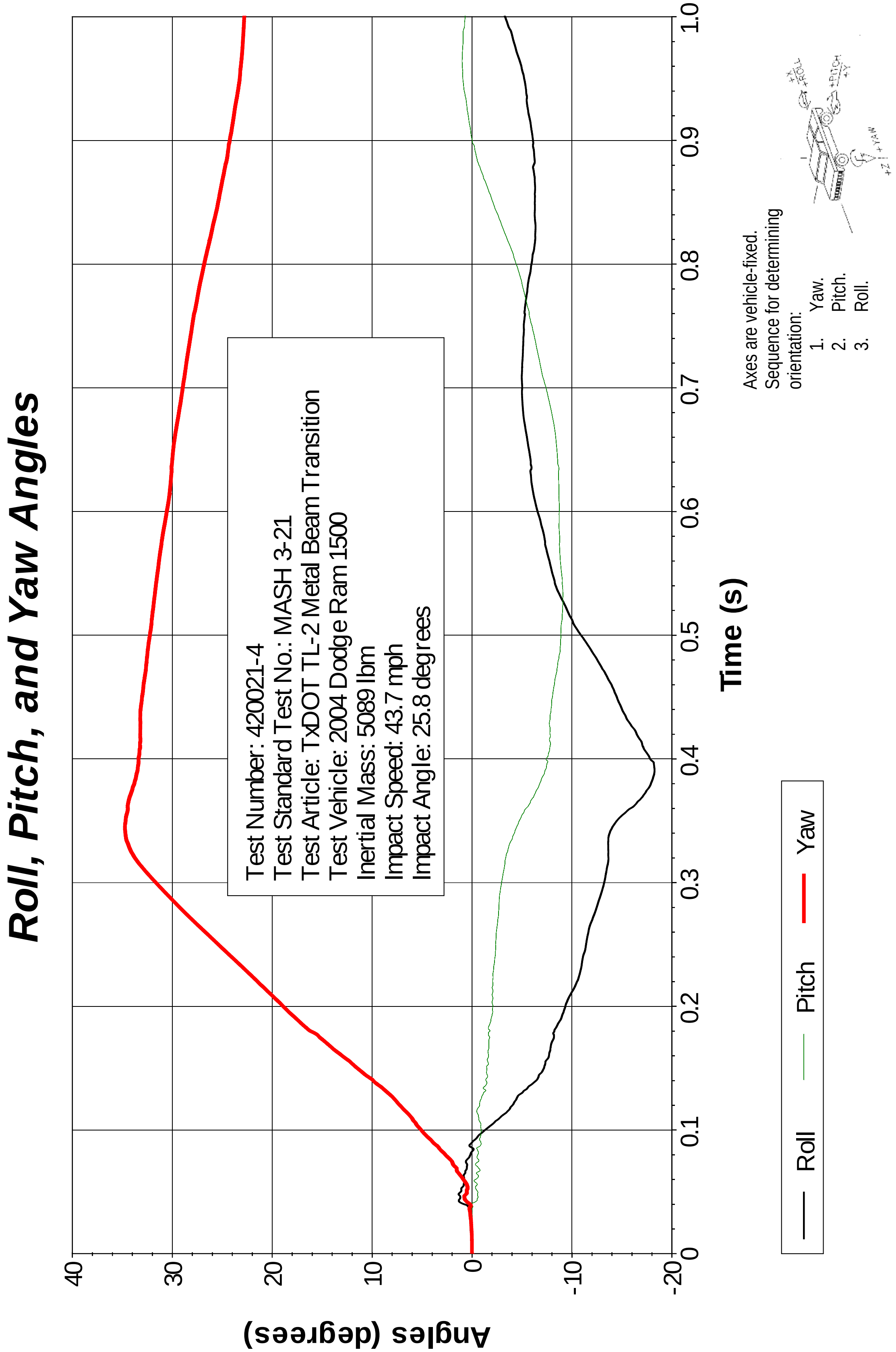


Figure E1. Vehicle Angular Displacements for Test No. 420021-4.

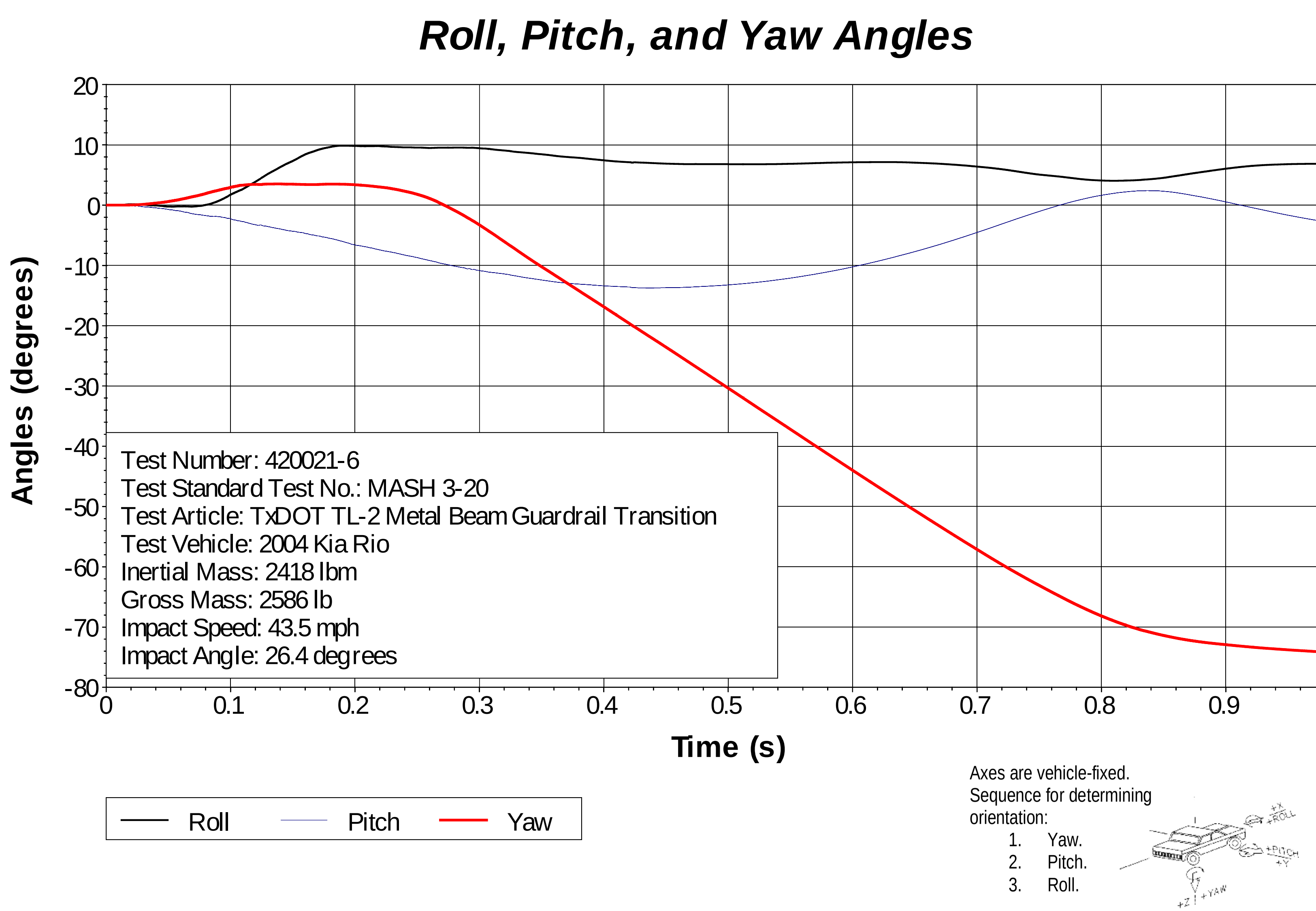


Figure E2. Vehicle Angular Displacements for Test No. 420021-6.

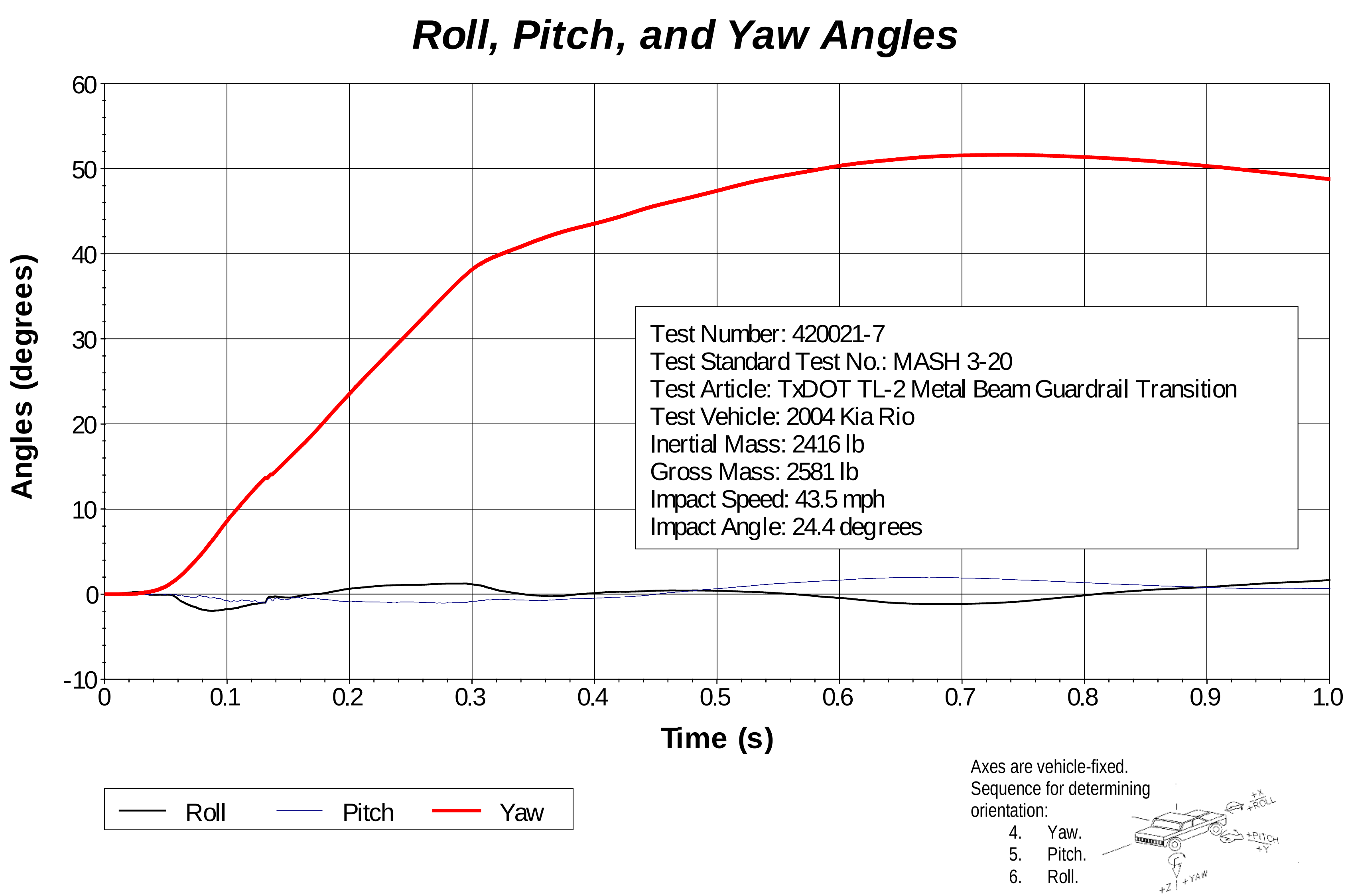


Figure E3. Vehicle Angular Displacements for Test No. 420021-7.

APPENDIX F. VEHICLE ACCELERATIONS

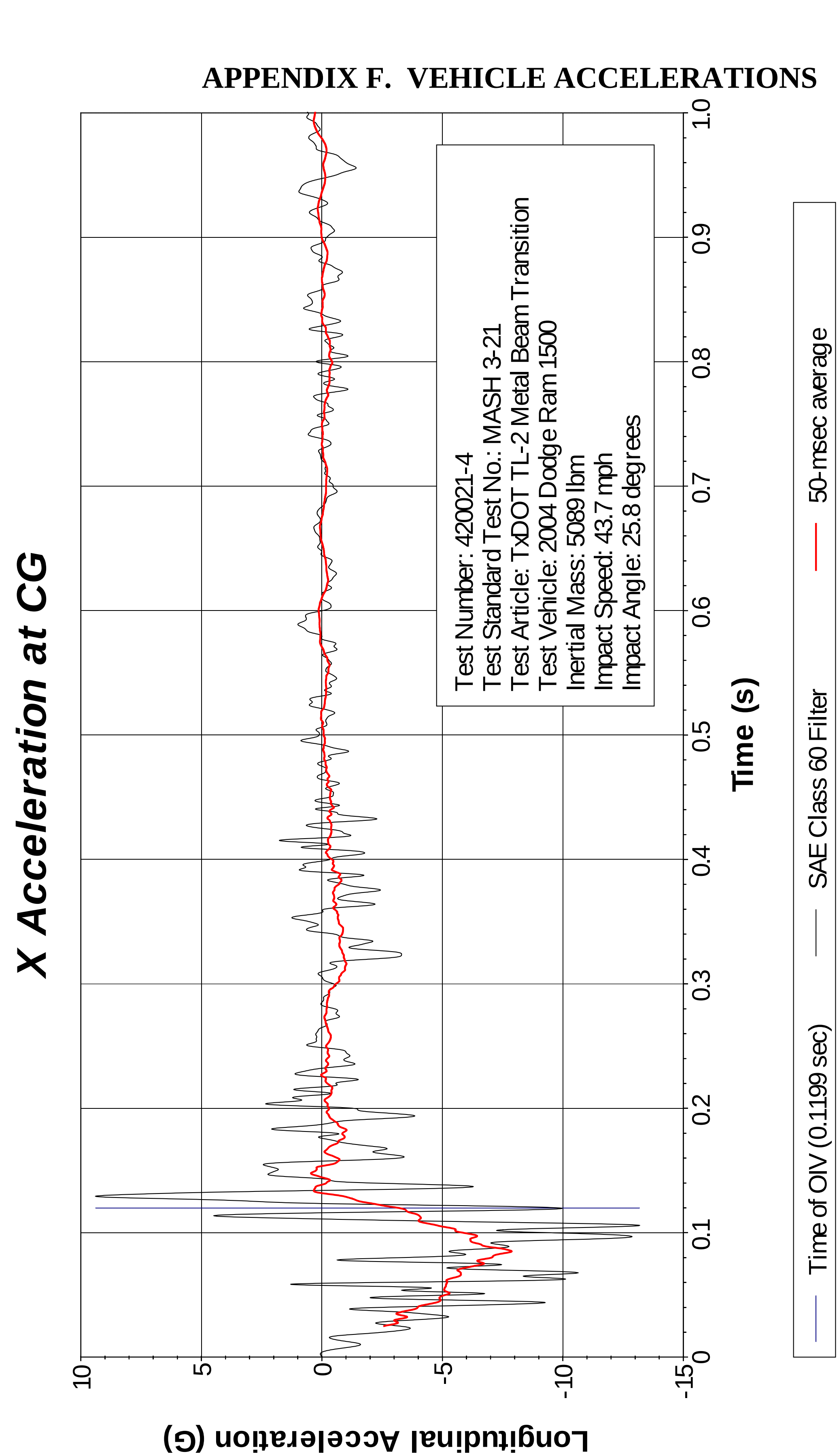


Figure F1. Vehicle Longitudinal Accelerometer Trace for Test No. 420021-4 (Accelerometer Located at Center of Gravity).

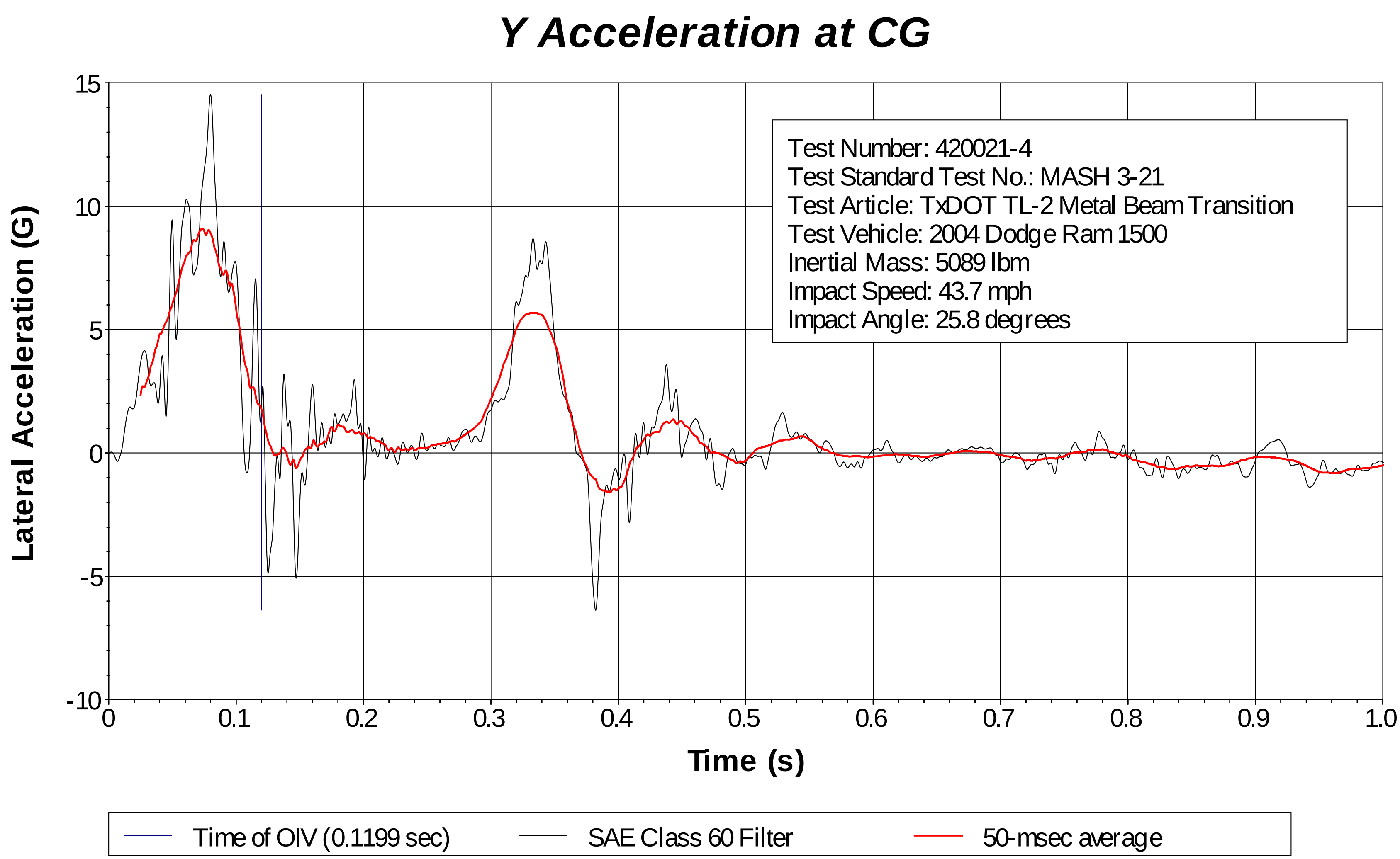


Figure F2. Vehicle Lateral Accelerometer Trace for Test No. 420021-4 (Accelerometer Located at Center of Gravity).

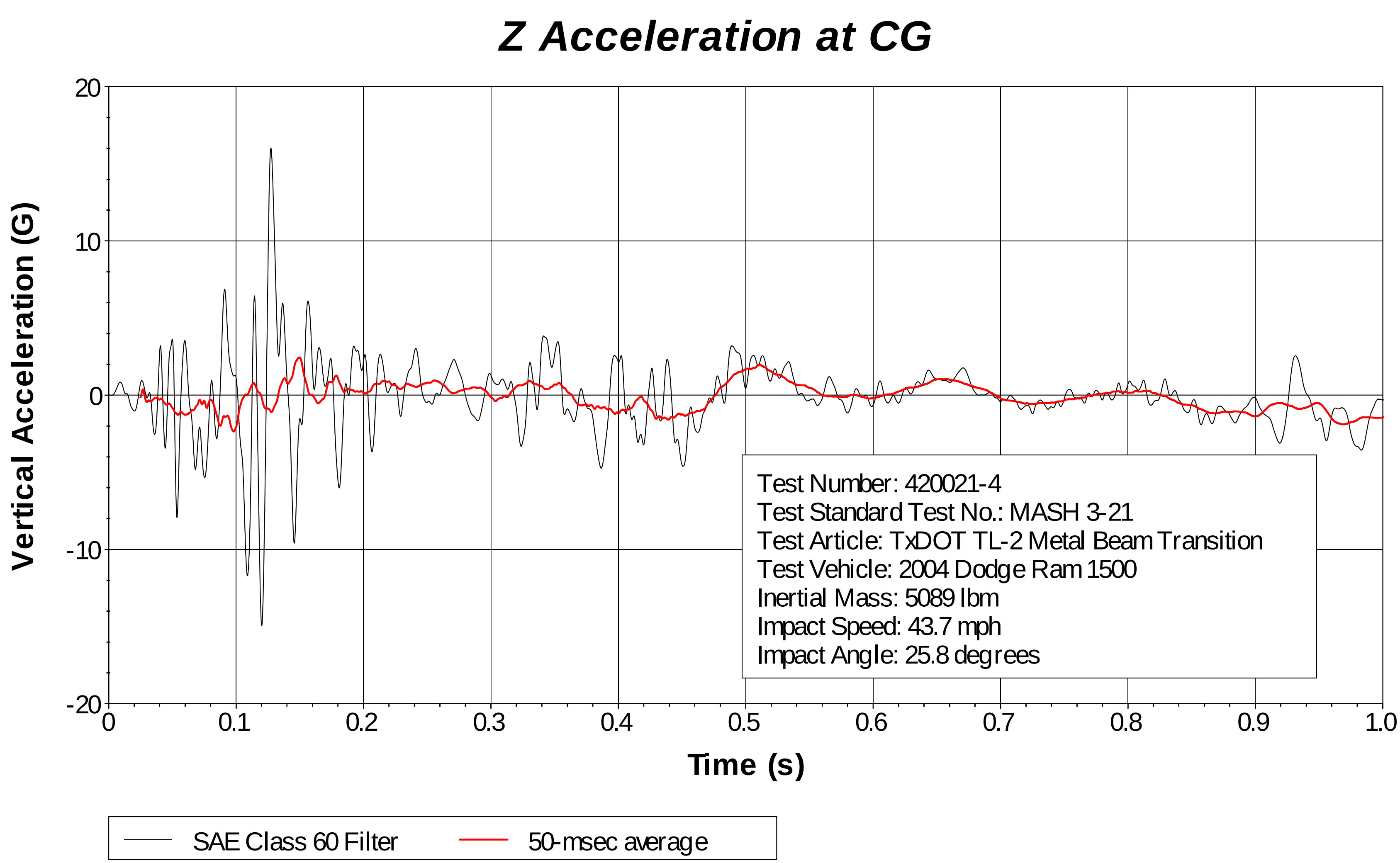


Figure F3. Vehicle Vertical Accelerometer Trace for Test No. 420021-4 (Accelerometer Located at Center of Gravity).

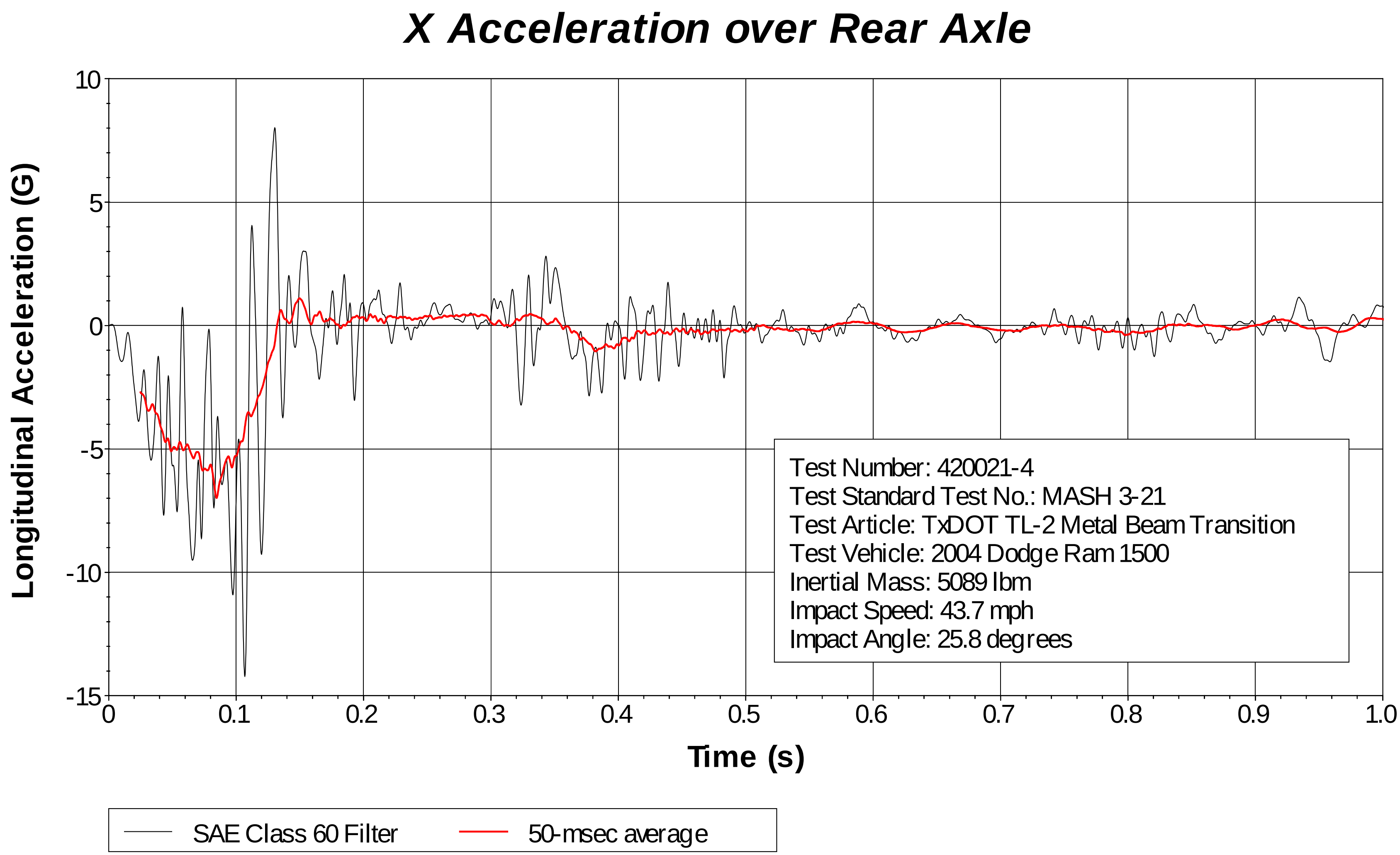


Figure F4. Vehicle Longitudinal Accelerometer Trace for Test No. 420021-4 (Accelerometer Located over Rear Axle).

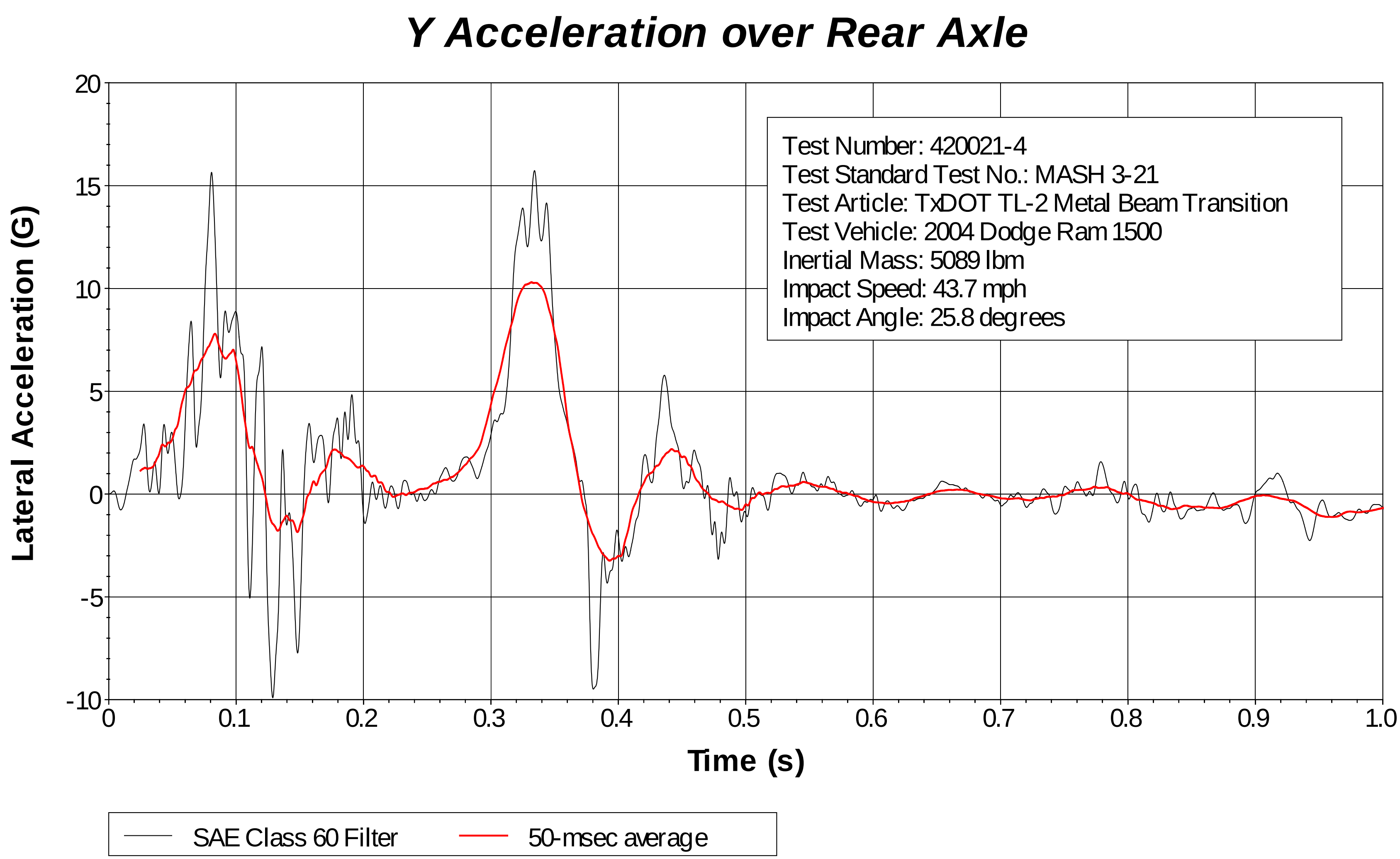


Figure F5. Vehicle Lateral Accelerometer Trace for Test No. 420021-4 (Accelerometer Located over Rear Axle).

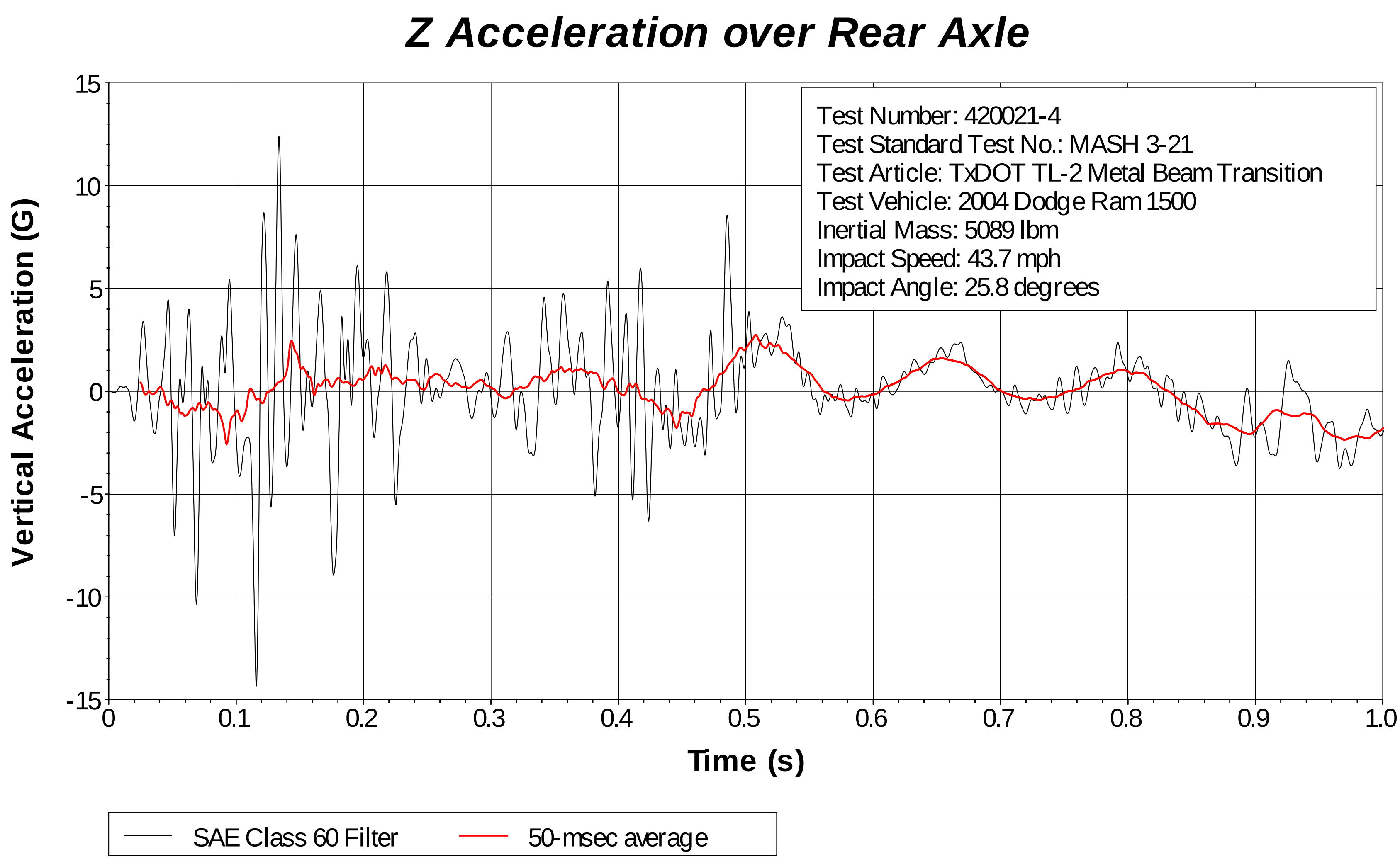


Figure F6. Vehicle Vertical Accelerometer Trace for Test No. 420021-4 (Accelerometer Located over Rear Axle).

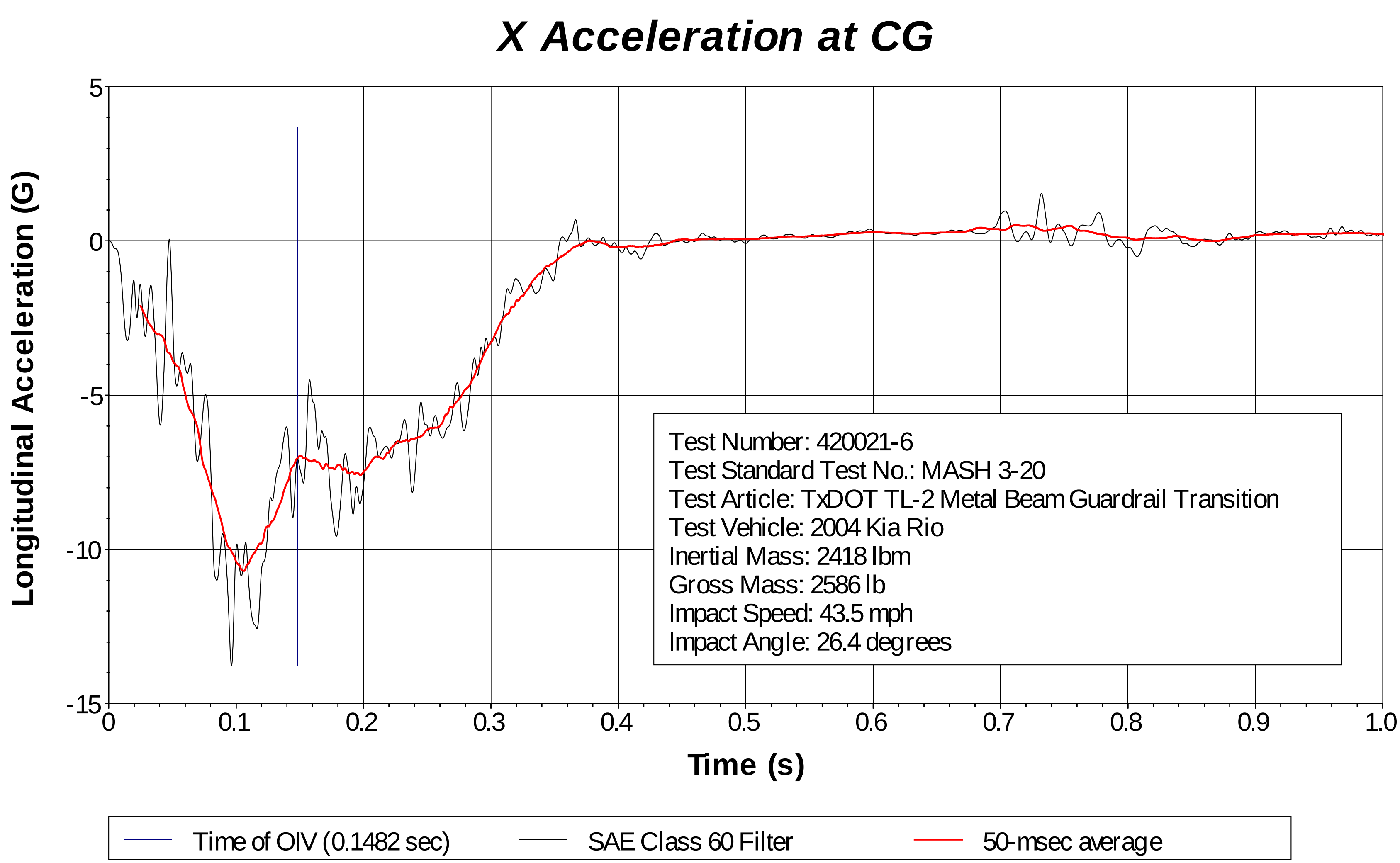


Figure F7. Vehicle Longitudinal Accelerometer Trace for Test No. 420021-6 (Accelerometer Located at Center of Gravity).

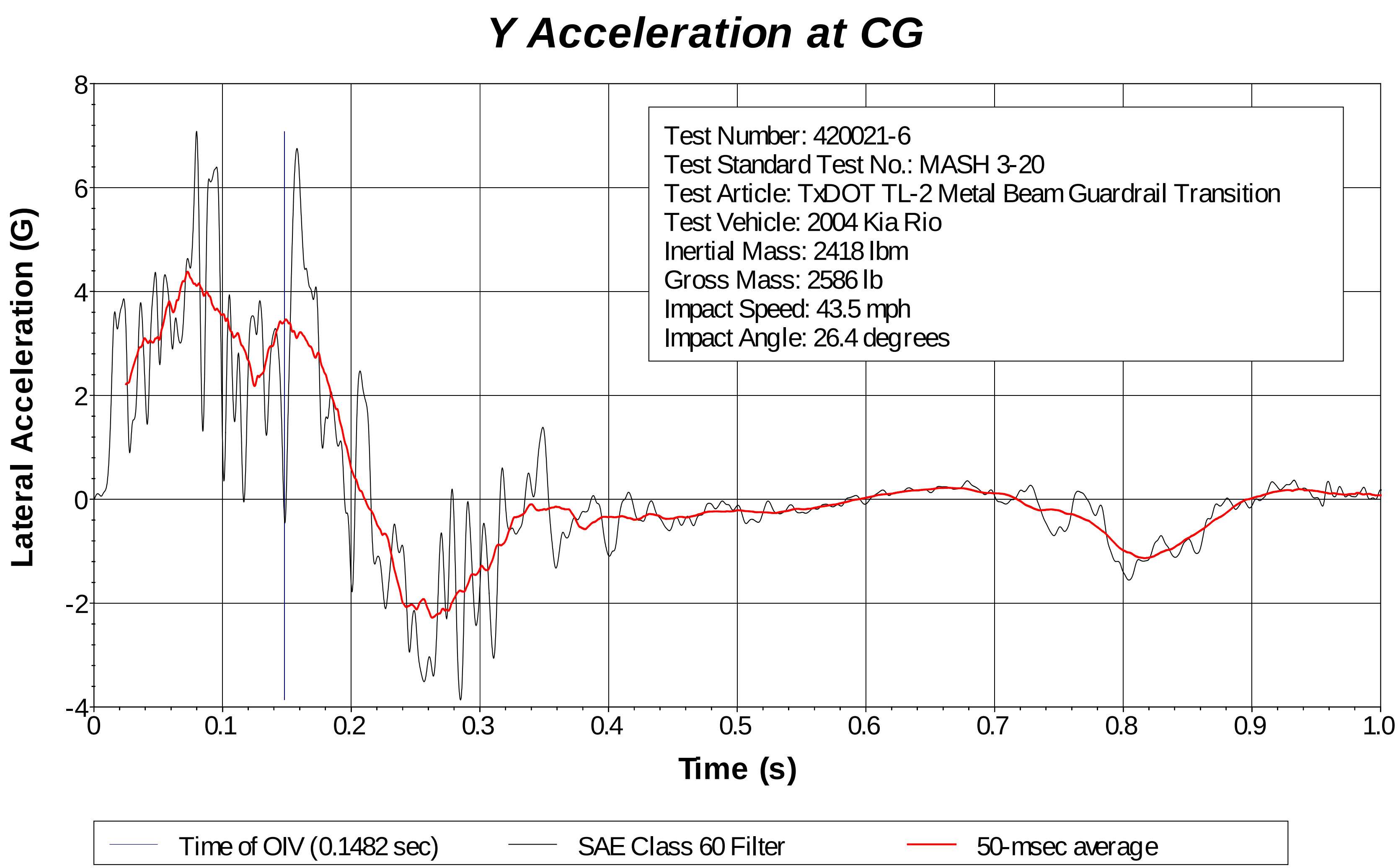


Figure F8. Vehicle Lateral Accelerometer Trace for Test No. 420021-6 (Accelerometer Located at Center of Gravity).

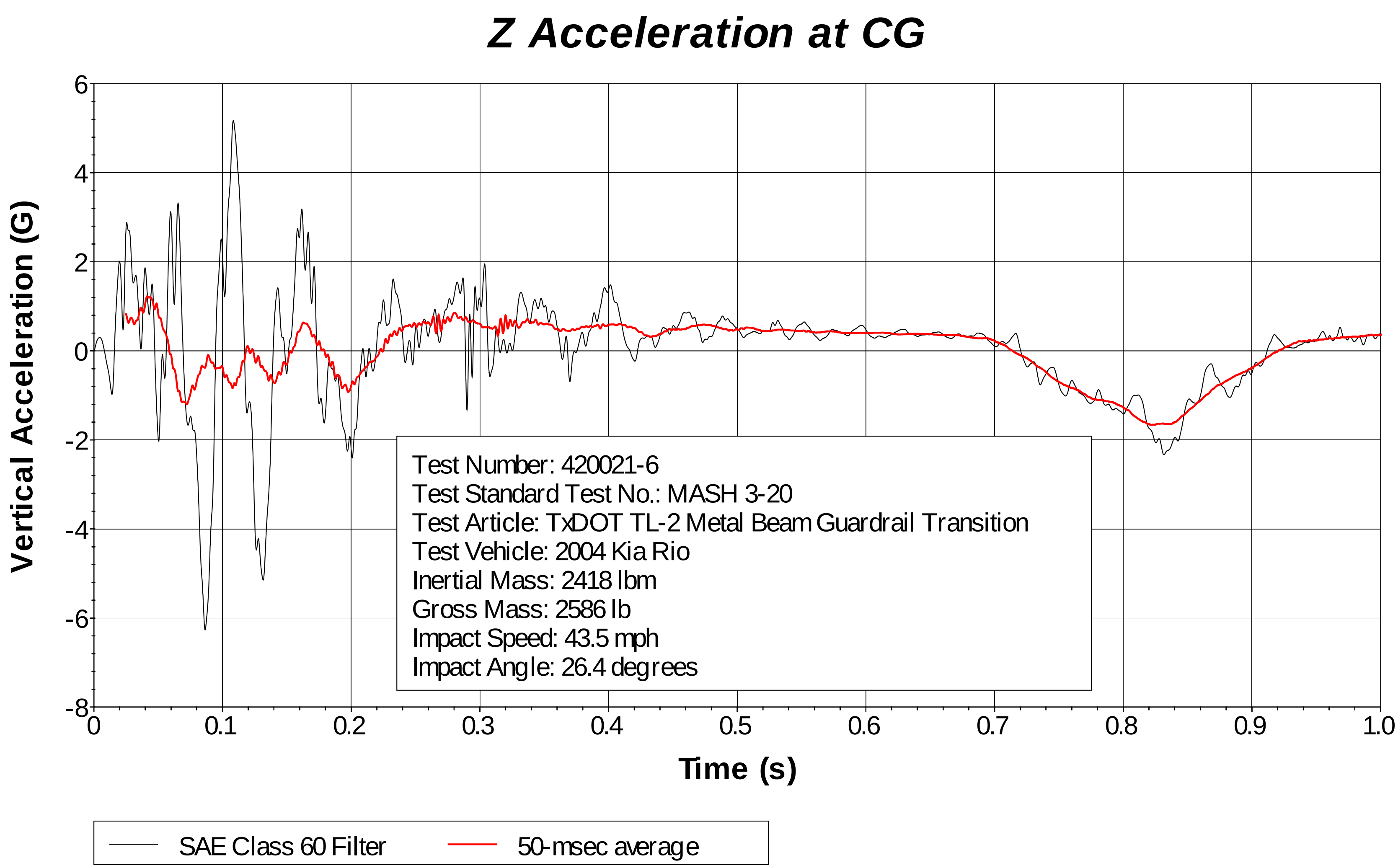


Figure F9. Vehicle Vertical Accelerometer Trace for Test No. 420021-6 (Accelerometer Located at Center of Gravity).

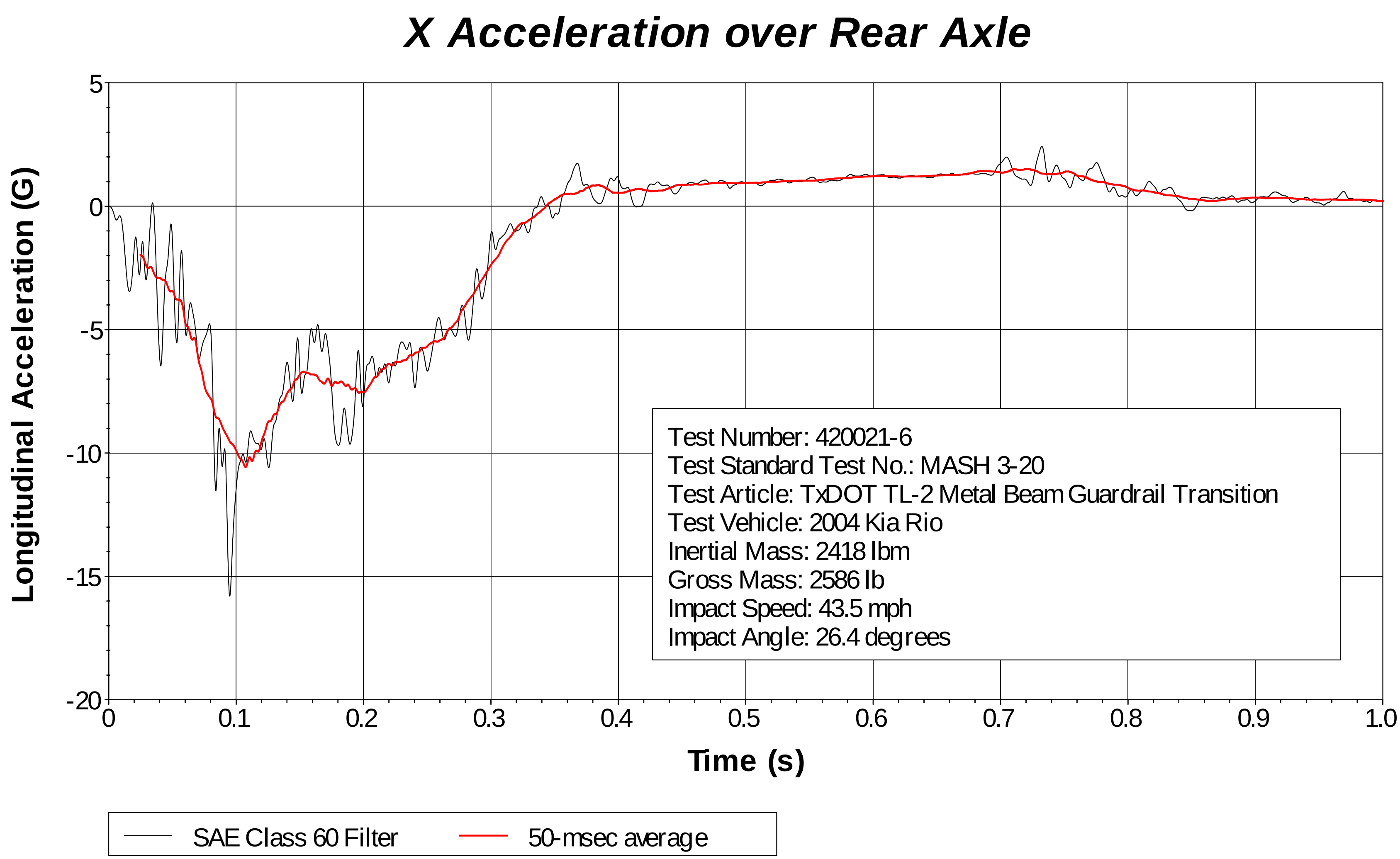


Figure F10. Vehicle Longitudinal Accelerometer Trace for Test No. 420021-6 (Accelerometer Located over Rear Axle).

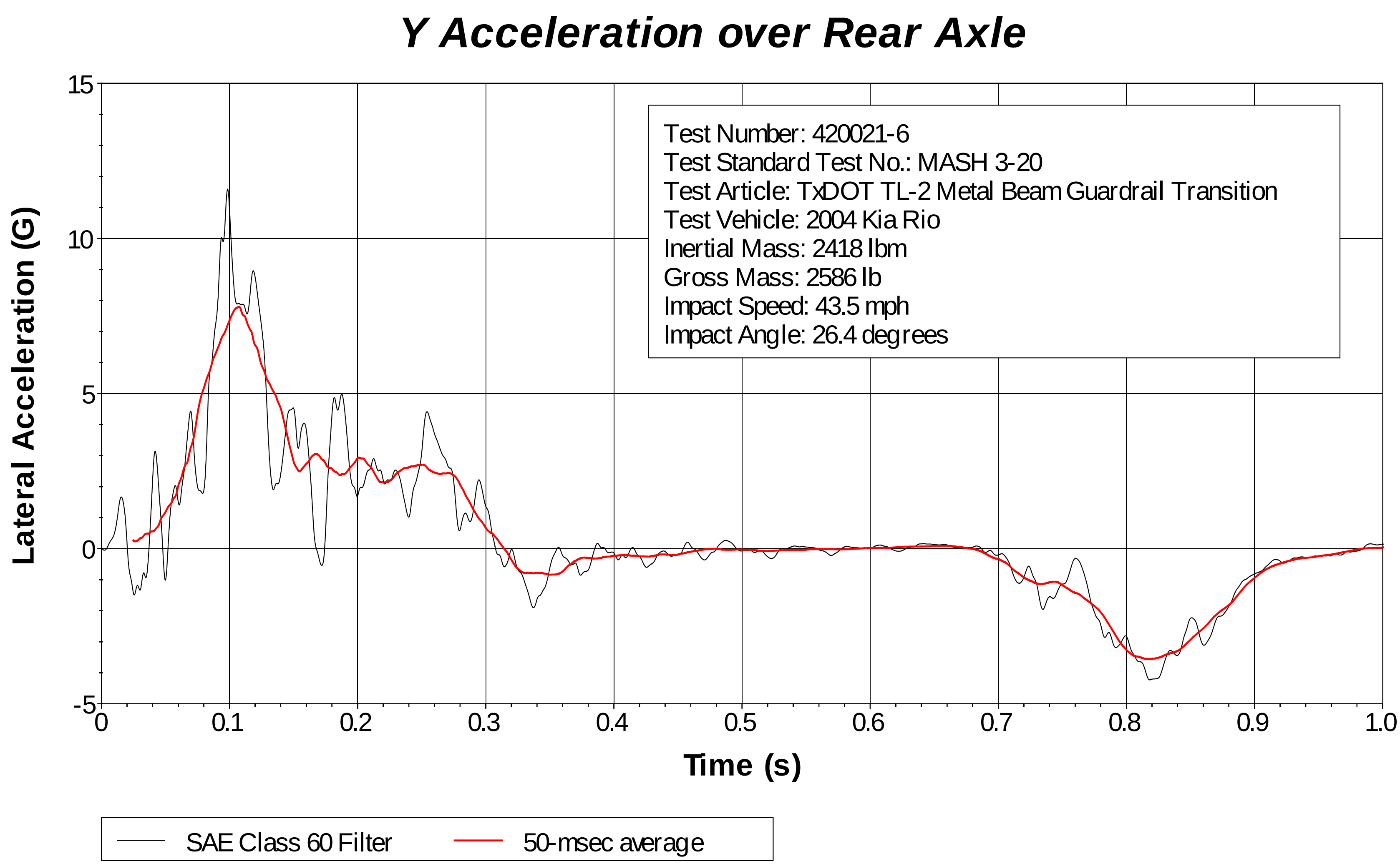


Figure F11. Vehicle Lateral Accelerometer Trace for Test No. 420021-6 (Accelerometer Located over Rear Axle).

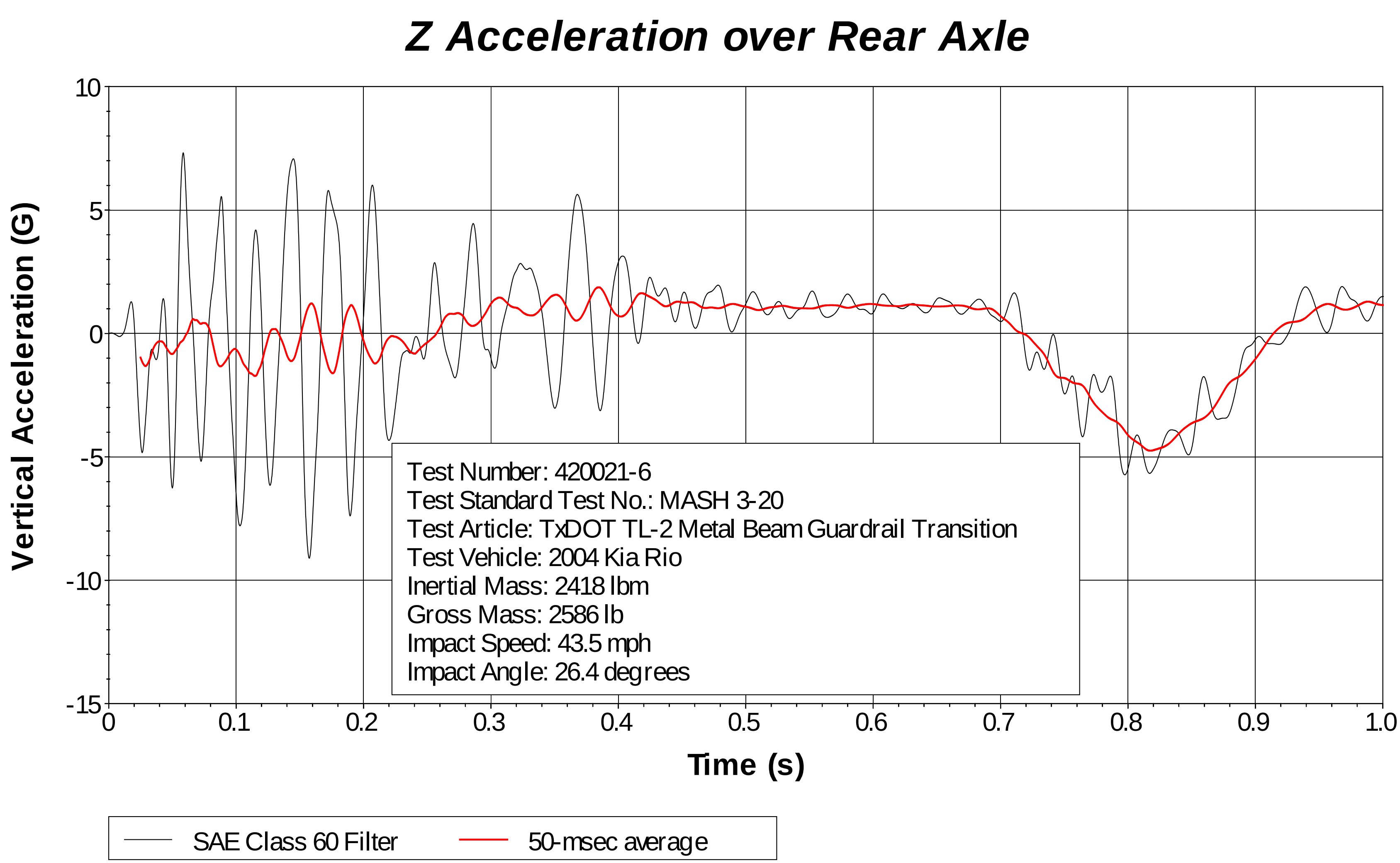


Figure F12. Vehicle Vertical Accelerometer Trace for Test No. 420021-6 (Accelerometer Located over Rear Axle).

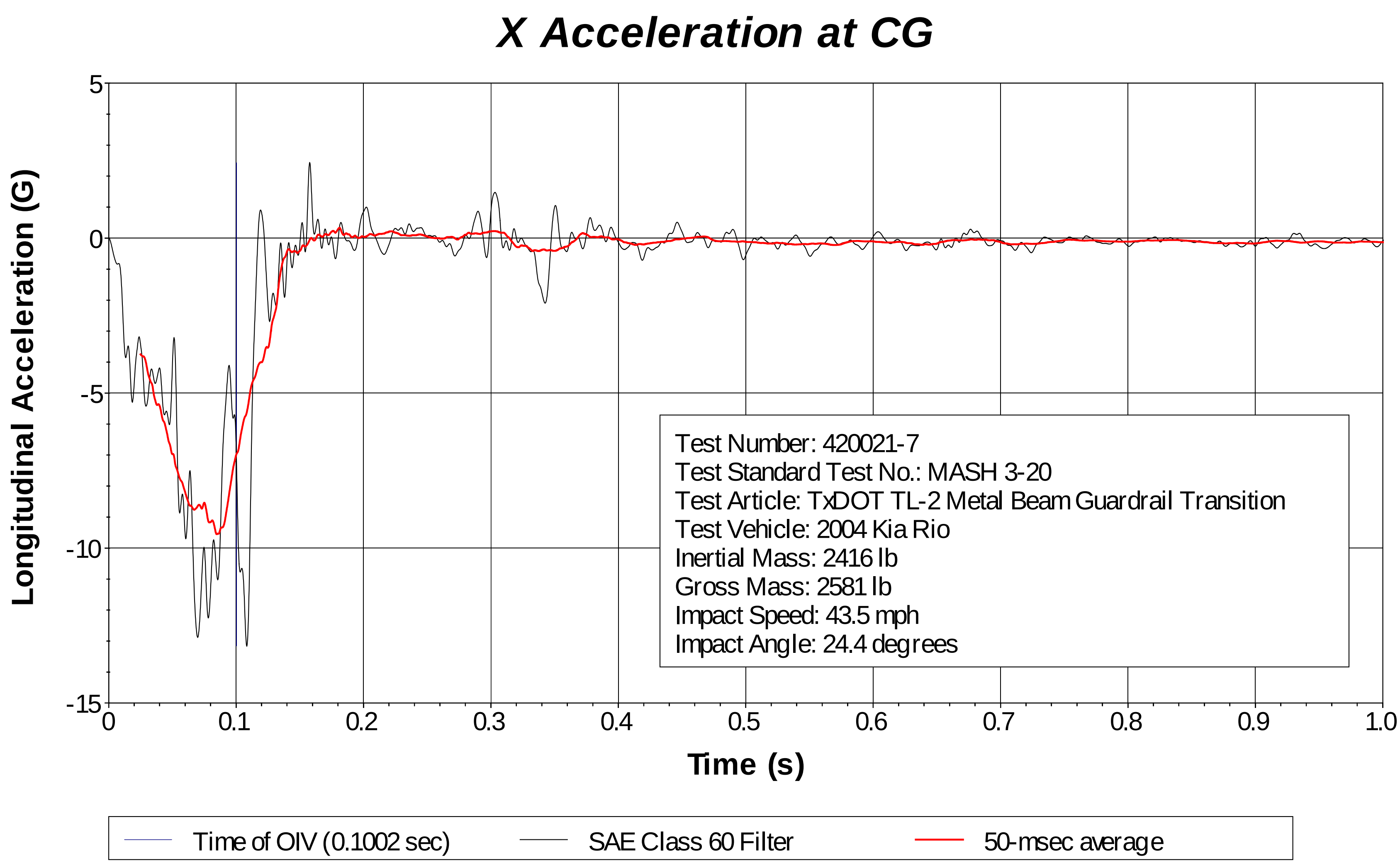


Figure F13. Vehicle Longitudinal Accelerometer Trace for Test No. 420021-7 (Accelerometer Located at Center of Gravity).

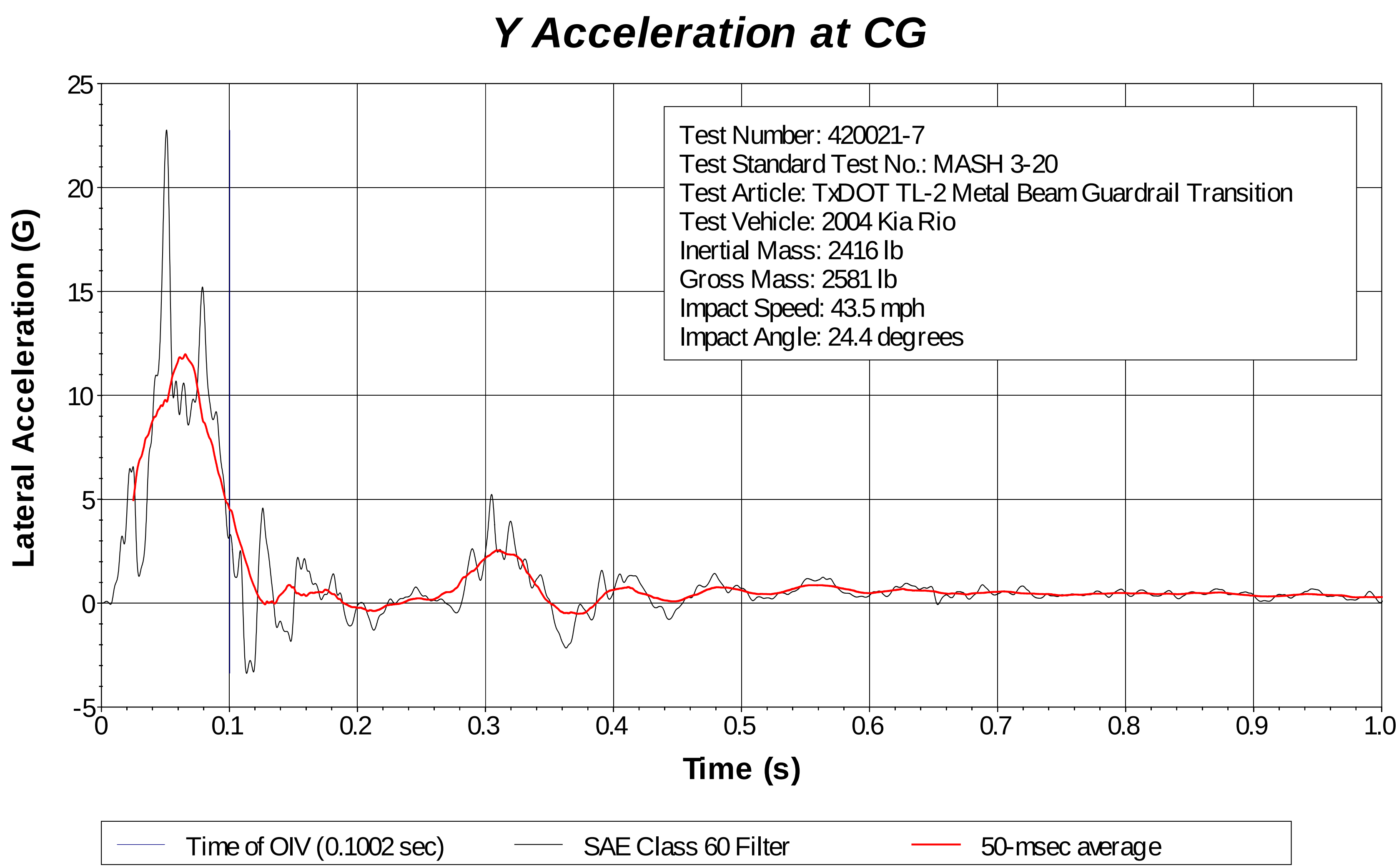


Figure F14. Vehicle Lateral Accelerometer Trace for Test No. 420021-7 (Accelerometer Located at Center of Gravity).

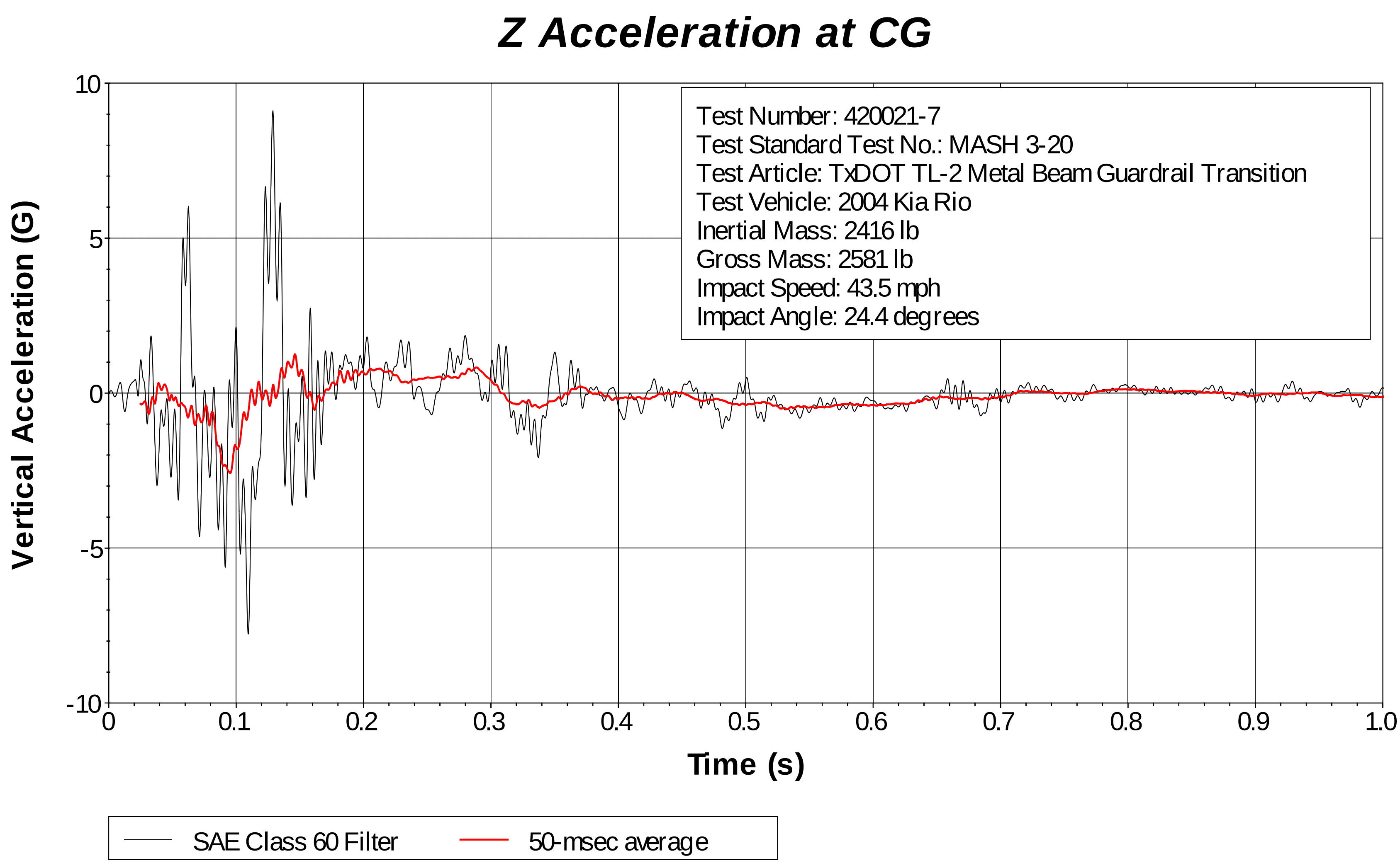


Figure F15. Vehicle Vertical Accelerometer Trace for Test No. 420021-7 (Accelerometer Located at Center of Gravity).

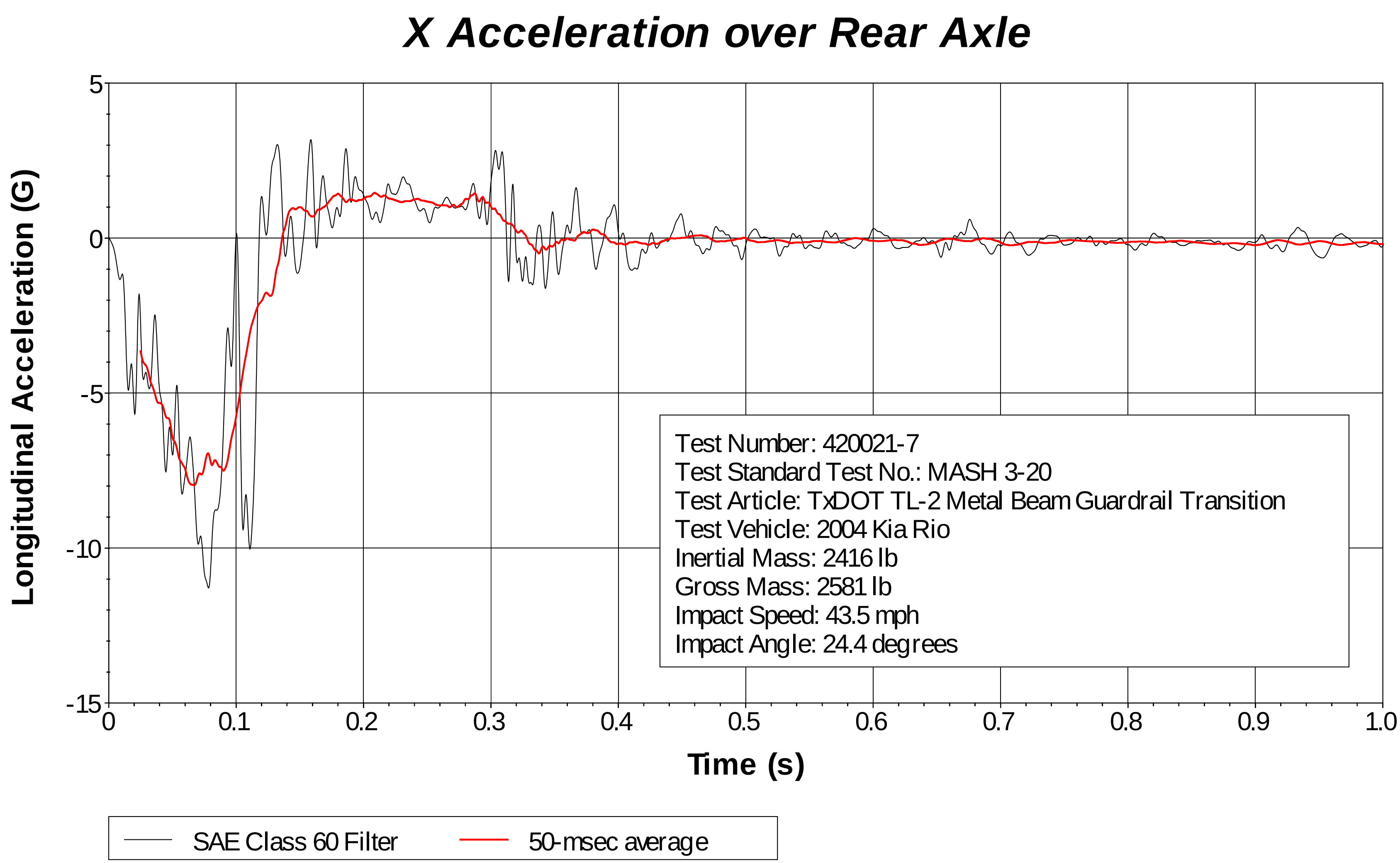


Figure F16. Vehicle Longitudinal Accelerometer Trace for Test No. 420021-7 (Accelerometer Located over Rear Axle).

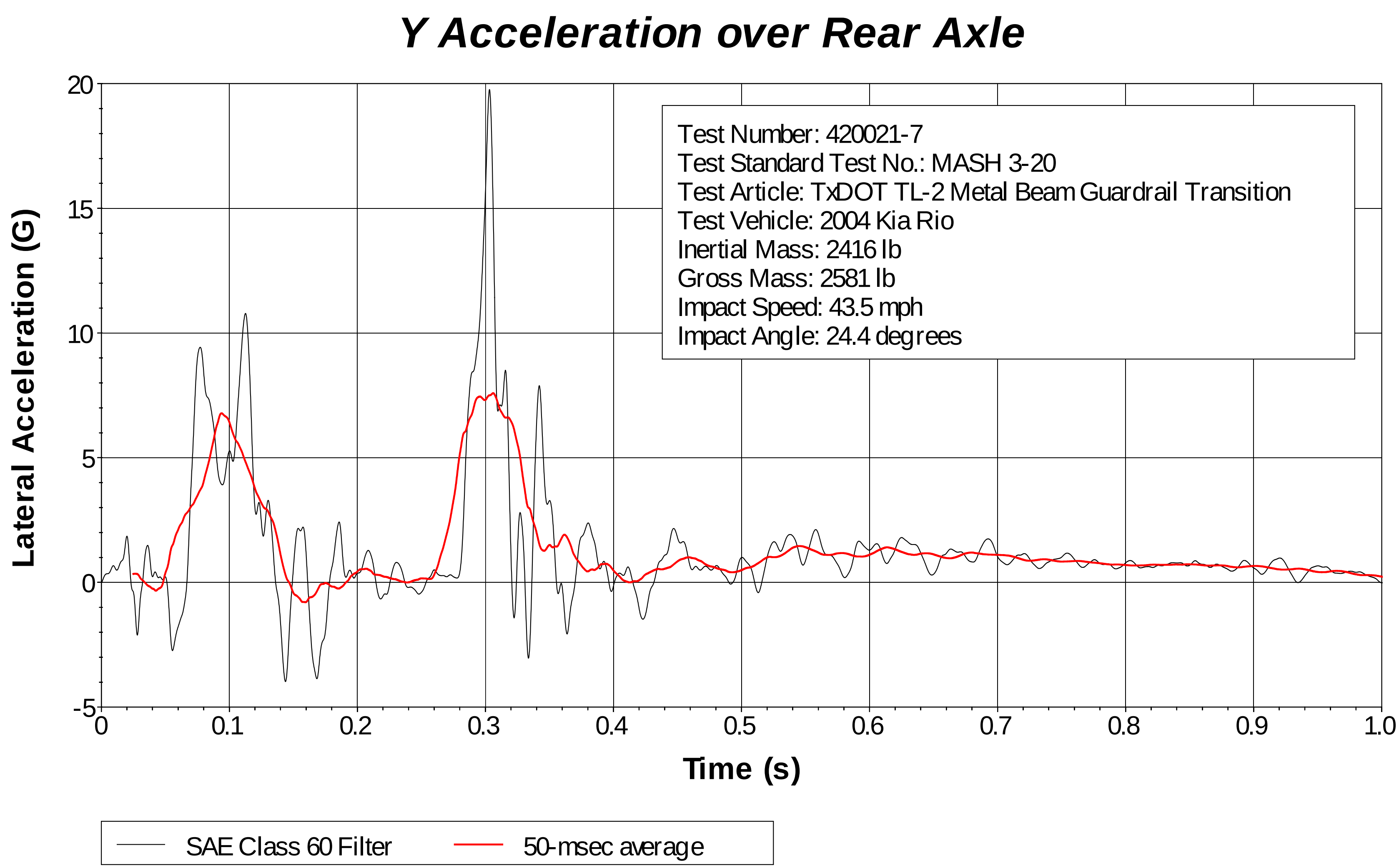


Figure F17. Vehicle Lateral Accelerometer Trace for Test No. 420021-7 (Accelerometer Located over Rear Axle).

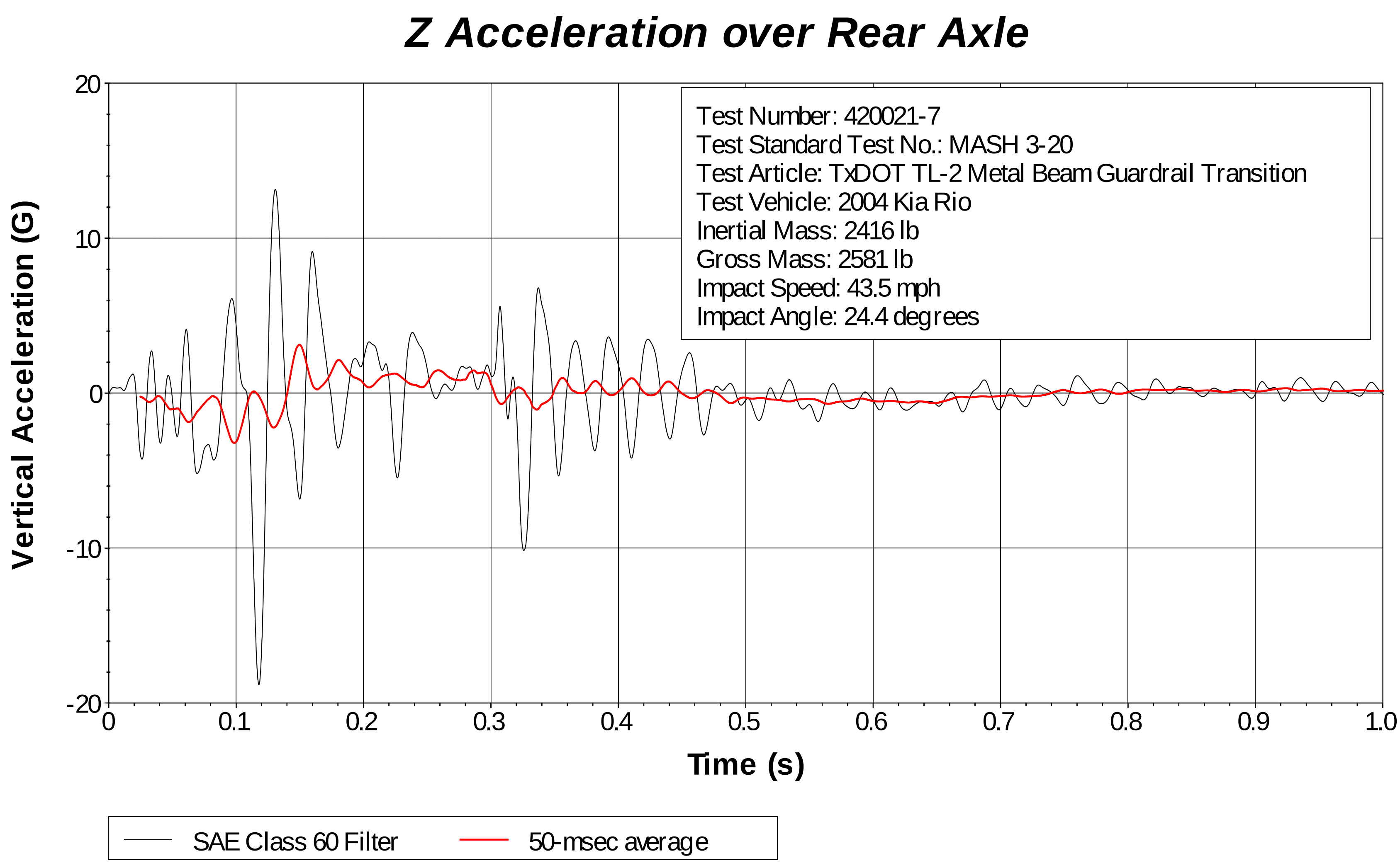


Figure F18. Vehicle Vertical Accelerometer Trace for Test No. 420021-7 (Accelerometer Located over Rear Axle).