



DEVELOPMENT AND TESTING OF A NON-PINNED LOW-PROFILE END TREATMENT



Crash testing performed at:
TTI Proving Ground
3100 SH 47, Building 7091
Bryan, TX 77807

Test Report 9-1002-12-7

Cooperative Research Program

**TEXAS A&M TRANSPORTATION INSTITUTE
COLLEGE STATION, TEXAS**

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

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16. Abstract The Low-Profile barrier was crash tested in the 1990s to assure that a previously developed Low-Profile barrier end treatment complied with Test Level 2 (TL-2) criteria for terminals and redirective crash cushions as presented in National Cooperative Highway Research Program (NCHRP) <i>Report 350</i> . Together, the sloped end treatment and the low-profile barrier provide an innovative barrier system acceptable for use on most local and collector roads, and many work zones, depending upon applicable guidelines. The primary advantage of the low-profile barrier system is that the 20-inch height of the system is less than the traditional concrete barrier height of 32 inches. The reduced height provides enhanced driver visibility in highway work zones and other appropriate locations. The Federal Highway Administration (FHWA) deemed acceptable the complete Low-Profile barrier system, including the sloped end treatment, for use in situations consistent with <i>NCHRP Report 350</i> TL-2 applications in 2009. The original Low-Profile end treatment was designed and tested under the assumption that it would be attached to the pavement or subgrade using vertical steel pins spaced at equal intervals along the centerline of the end treatment. The purpose of the steel pins was to control the lateral deflection of the end treatment during impact. While the steel pins do an excellent job of controlling the lateral deflection of the end treatment during impact, the introduction of holes into the pavement or subgrade may not be desirable in many applications. The purpose of the research presented was to determine if a non-pinned Low-Profile end treatment can comply with applicable crash test standards. The unpinned Low-Profile end treatment performed acceptably for <i>MASH</i> Tests 2-34 and 2-35.					
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by

W. Lynn Beason, Ph.D., P.E.
Associate Research Engineer
Texas A&M Transportation Institute

Michael S. Brackin, M.S.C.E., E.I.T.
Associate Transportation Researcher
Texas A&M Transportation Institute

Roger P. Bligh, Ph.D., P.E.
Research Engineer
Texas A&M Transportation Institute

and

Wanda L. Menges
Research Specialist
Texas A&M Transportation Institute

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TEXAS A&M TRANSPORTATION INSTITUTE
College Station, Texas 77843-3135

DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation, 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 herein 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 herein apply only to the article being tested.



Wanda L. Menges, Research Specialist
Deputy Quality Manager

Richard A. Zimmer, Senior Research Specialist
Test Facility Manager
Quality Manager
Technical Manager

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CHAPTER 1. INTRODUCTION

1.1 INTRODUCTION

The project under which the current research was conducted was set up to provide the 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 were identified and prioritized for investigation. Each roadside safety issue was addressed with a separate work plan, and the results are summarized in individual test reports.

TxDOT engineers identified a modification to the Low-Profile barrier system that would make the system much easier to deploy in many work zone applications. Specifically, it was suggested that it would greatly improve the utility of the Low-Profile barrier system if it was not always necessary to employ the steel anchor pins used to connect the Low-Profile end treatment to the existing pavement or subgrade. This is particularly an issue when the Low-Profile barrier system is being used in applications where the introduction of drilled holes into existing pavement could affect its local integrity. While the pin holes introduced into the pavements can ultimately be patched, the utility of the Low-Profile barrier would greatly increase if it could be deployed without the introduction of holes in the supporting pavement.

The purpose of the research presented in this report was to evaluate the performance of the Low-Profile barrier system without the end treatment anchor pins and, if necessary, make changes to the system hardware that would allow it to be deployed without the pins. This report describes the effort and presents results of full-scale crash tests to verify the proposed changes to the Low-Profile barrier system that allow it to be safely deployed without the use of the end treatment anchor pins. Finally, recommendations are presented for the immediate implementation of the non-pinned Low-Profile barrier system.

1.2 BACKGROUND

Researchers at the Texas Transportation Institute (TTI) originally developed the Low-Profile barrier system for use in low-speed (45 mi/h or less) applications (1, 2). One of the primary advantages of the Low-Profile barrier system is that it has a maximum height of only 20 inches. When the Low-Profile barrier system is deployed in work zones, driver visibility is greatly increased when compared to more conventional work zone barriers with a typical height of 32 inches. This increased driver visibility leads to safer work zone conditions.

The Low-Profile barrier system consists of two major elements: the Low-Profile portable concrete barrier (PCB) segment and the Low-Profile end treatment. The Low-Profile PCB segment is a 20-ft-long prismatic concrete barrier with a 20-inch height and a negatively sloped impact face. Low-Profile PCB segments have no positive attachments to the pavement or subgrade. The Low-Profile end treatment is a 20-ft-long concrete barrier segment that tapers linearly from a height of 4 inches at the free end to a height of 20 inches at the end that connects with the Low-Profile PCB segment. Both the Low-Profile PCB segments and the Low-Profile end treatments incorporate a unique double bolt connection that provides significant axial, shear, and moment resistance so that the lateral deflection of the system is minimized when it is impacted by an errant vehicle.

Unlike the Low-Profile PCB segments, the Low-Profile end treatment incorporates seven vertical holes spaced on 24-inch centers along the longitudinal center line of the end treatment. These vertical holes accept 1.25-inch diameter steel pins drilled or driven into the underlying pavement or subgrade. The purpose of the pins is to control lateral deflection of the end treatment during vehicle impact. While explicit pin installation instructions were not developed for different types of pavements and subgrades, simplified analyses performed at the time of the original design suggested that seven steel pins would be sufficient to control lateral deflections of the Low-Profile end treatment under the specified design conditions. Complete details of the original design and development of the Low-Profile barrier system are well-documented elsewhere and are not duplicated in this report (1, 2).

At the time of the development of the original Low-Profile barrier system, highway safety appurtenances were evaluated according to procedures and specifications presented in National Cooperative Highway Research Program (NCHRP) *Report 230* (3). While testing recommendations presented in *NCHRP Report 230* were not sufficient for a thorough evaluation of low-speed highway safety appurtenances, TTI researchers used the general *NCHRP Report 230* framework and engineering judgment to develop what was believed to be a reasonable test criteria to certify the performance of the new Low-Profile barrier system. In 1992, the Low-Profile barrier system was recommended for use (1, 2).

Shortly after the introduction of the Low-Profile barrier system, new full-scale crash test recommendations for the evaluation of highway safety hardware were presented in the form of *NCHRP Report 350* (4). *NCHRP Report 350* presented more comprehensive test guidelines than those originally presented in *NCHRP Report 230*. Unlike *NCHRP Report 230*, *NCHRP Report 350* introduced explicit test criteria to fully evaluate highway safety appurtenances intended for use in low-speed applications. These new criteria were referred to as Test Level 2 (TL-2) criteria in *NCHRP Report 350*. Once the Federal Highway Administration (FHWA) accepted the new TL-2 criteria, it became necessary to reevaluate the Low-Profile barrier system in light of the new criteria.

Based on a comprehensive review of the original testing conducted with the Low-Profile PCB segment, the researchers have determined that the original test results were sufficient to be deemed compliant with the new *NCHRP Report 350* criteria. However, a review of the original test results for the Low-Profile end treatment suggested additional crash testing was required to ensure that it was compatible with *NCHRP Report 350* TL-2 criteria (5).

Under *NCHRP Report 350*, the Low-Profile end treatment was classified as a gating terminal or device. Gating devices are “designed to allow controlled penetration of the vehicle when impacted between the end and the beginning of the length of need of the device.” The length of need for the Low-Profile end treatment was originally defined to coincide with the interface between the Low-Profile end treatment and the first downstream Low-Profile PCB segment. *NCHRP Report 350* presents seven different sets of crash test conditions for the evaluation of TL-2 gating end treatments. These test conditions are referred to as test designations 2-30 to 2-35 and test designation 2-39. In 1998, TTI researchers presented additional test results and justifications to show that the Low-Profile barrier system complied with *NCHRP Report 350* criteria (5).

1.3 OBJECTIVES/SCOPE OF RESEARCH

The original Low-Profile end treatment is anchored to the pavement by inserting seven steel pins through precast holes spaced at 24-inch intervals along the centerline of the end treatment. These pins were originally designed to control the lateral deflection of the Low-Profile end treatment since it is otherwise supported only at the end that connects to the Low-Profile PCB. TTI and TxDOT engineers involved with the project had originally recognized that if the steel anchor pins were not employed, there would be significant rotation of the connection between the Low-Profile end treatment and the upstream Low-Profile PCB if the large vehicle mandated in the TL 2 test criteria has impacted them. This rotation, of course, would lead to significant lateral deflection at the nose of the Low-Profile end treatment. TTI and TxDOT engineers have fully discussed and analyzed this issue early in the development of the Low-Profile end treatment. Since one of the primary applications for the Low-Profile barrier system is to protect work zones associated with vertical cuts along the edges of pavement, a decision was made to use the steel anchor pins so that the lateral deflection of the Low-Profile end treatment would be controlled. Use of the pins prevents the Low-Profile end treatment from being pushed over the edge of a vertical cut and rolling the entire barrier system into the work zone.

Recent discussions with TxDOT engineers suggest there are also many applications for the Low-Profile barrier system where there is room for substantial displacement of the Low-Profile end treatment. In such applications the acceptability of the Low-Profile barrier system is controlled only by its compliance with TL 2 criteria.

TTI engineers reviewed the existing Low-Profile barrier system in an effort to estimate the consequences associated with removing the steel support pins from the Low-Profile end treatment. The primary conclusion of this review was the steel pins provide the primary mechanism for controlling the lateral deflections of the end treatment during large vehicle impacts. If the steel anchor pins were removed, then three remaining factors would control the lateral displacement of the Low-Profile end treatment:

- Mass of the end treatment.
- Frictional forces between the end treatment and the supporting surface.
- The flexural rigidity of the connection between the end treatment and the Low-Profile PCB.

Of these three factors, only the flexural rigidity of the connection can be addressed without a major redesign of the system.

In the current research, it was proposed that the Low-Profile barrier system be modified by removing the steel anchor pins from the Low-Profile end treatment so there will not be any positive attachment of the system to the pavement or subgrade. The proposed modification only affects the Low-Profile end treatment because Low-Profile PCB segments never employed positive anchorage devices (1). The original testing of the Low-Profile PCB segments was performed before the development of the Low-Profile end treatment so it is clear that the performance of Low-Profile PCB segments is not affected by removal of the end treatment anchor pins. Therefore, the research focused on the performance of the non-pinned Low-Profile end treatment.

In 2009, the American Association of State Highway and Transportation Officials (AASHTO), *Manual for Assessing Safety Hardware (MASH)*, was published as the new crash testing standard (6). This document supersedes *NCHRP Report 350* testing procedures previously used to justify the performance of the Low-Profile barrier system. Changes incorporated into the new *MASH* guidelines include new design test vehicles, revised test matrices, and revised impact conditions. In general, the *MASH* testing framework is equal to or more severe than *NCHRP Report 350* testing. The objective of the testing performed under this study is not to requalify the non-pinned Low-Profile barrier system under the new *MASH* criteria, but rather, to extend the *NCHRP Report 350* certification for the Low-Profile barrier system to include deployments with non-pinned end treatments. In pursuing this objective, all new testing presented in this report was conducted under the equal, or more stringent, criteria presented in *MASH*.

CHAPTER 2. SYSTEM DETAILS

2.1 TEST ARTICLE DESIGN AND CONSTRUCTION

The Low-Profile end treatment is constructed in 20-ft lengths so that it has the same length as the Low-Profile PCB segment. The connection end of the Low-Profile end treatment is 20 inches high so its height matches the Low-Profile PCB. In addition, the connection end incorporates the same bolted connection developed for use with the Low-Profile PCB so it can be connected directly to this PCB. The height of 20 inches is maintained for a distance of 5 ft along the length of the Low-Profile end treatment from the connection end. Then, the height of the end treatment is reduced linearly from 20 inches to 4 inches at the nose of the Low-Profile end treatment. In addition to a reduction of barrier height in the remaining 15 ft of the end treatment, the widths of the barrier top and bottom are symmetrically tapered to 14.5 inches and 14.0 inches respectively so the negative slope of the impact face (1:20) of the end treatment is maintained throughout its length. The Low-Profile end treatment is reinforced appropriately so the flexural capacity throughout its length is sufficient to minimize cracking during transport and handling.

The connection between the Low-Profile end treatment and the Low-Profile PCB is accomplished by inserting two steel bolts that pass through two precast holes in the mating barrier ends. Appendix A shows complete details of the end treatment, while [Figure 2.1](#) presents general details of the specific arrangement used in the testing reported here. Specifications require these two bolts be secured in place using standard washers and nuts. The bolts provide a centric tensile force in the connection that couples with compressive forces on the barrier faces in contact to develop a moment that resists rotation at this connection. Complete details of the mechanics of this connection are discussed elsewhere ([1](#), [2](#)).

The key to development of the tensile forces in the bolts and hence the flexural rigidity of the joint is the ability of the nuts and washers to transfer the tensile force in the bolts to the barrier face. While standard bolts and washers have been shown to be adequate when the Low-Profile end treatment is anchored to the pavement with the steel pins, a concern develops when the lateral displacement is entirely controlled by the stiffness of this connection. Evaluation of the connection shows that the weak link is the structural integrity of the standard steel washers that transfer the force from the nuts to the concrete. In some cases, these washers underwent a significant deformation during testing. While this does not present a problem when the anchor pins are used, it raises some level of concern when the anchor pins are excluded.

An engineering review of the connection resulted in the addition of a 5 × 10-inch steel plate washer that is fabricated using $\frac{3}{8}$ -inch thick steel flat strap. The rectangular plate washer has two symmetrically placed holes spaced to fit over both of the two steel bolts that provide the connection. These steel plate washers are slipped over both ends of the connection bolts. The two standard steel washers were then installed between the plate washers and the standard nuts. [Figure 2.2](#) presents a sketch of the new plate washer. It is required that the new plate washer be used on both sides of the end treatment to Low-Profile PCB connection and the next two PCB to

PCB connections. After that, the new plate washer can be incorporated or not at the discretion of the specifier.

Figure 2.1 presents details of the Low-Profile barrier system as it was deployed for testing, and Figure 2.2 presents details of the new steel plate washer. Figure 2.3 provides two photographs of the Low-Profile barrier system as deployed for testing. In addition, Figure 2.3 presents a photograph of a typical plate washer installation.

In summary, two modifications were made to the Low-Profile barrier system:

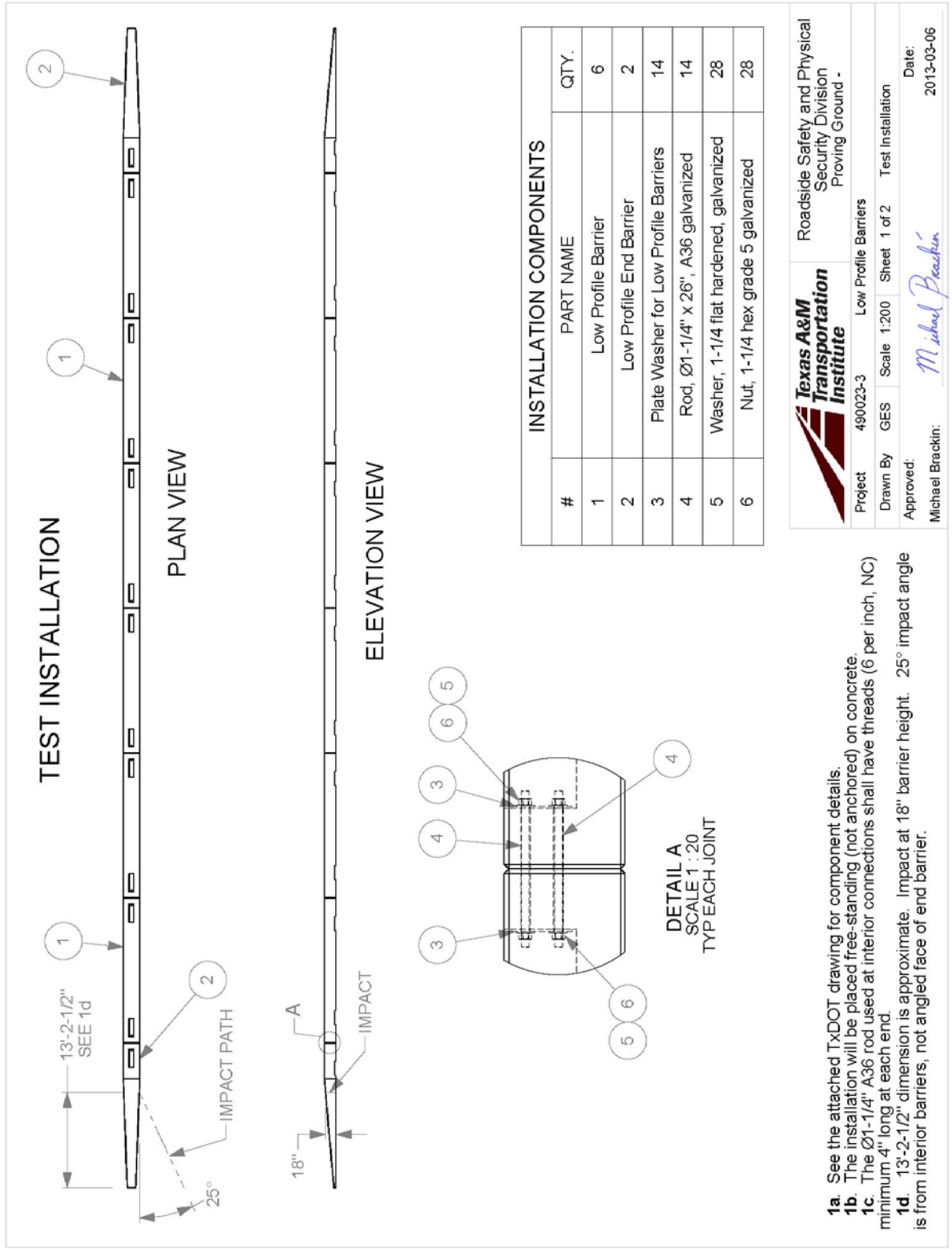
- The steel anchor pins that were previously used to control lateral deflection of the end treatment were removed.
- The three end connections in the barrier deployment were reinforced through the use of a new steel plate washer as discussed above.

2.2 MATERIAL SPECIFICATIONS

The Low-Profile barrier system consisted of two major elements: the Low-Profile PCB segment and the Low-Profile end treatment. Each of these elements was a pre-cast reinforced concrete member. All concrete material was specified to meet Class C or H specifications for Portland cement concrete. Unless otherwise specified, the reinforcing bars met the minimum requirements for Grade 40 according to American Standard for Testing and Materials (ASTM) A615. Reinforcing bars designated “H2 Bar” met the minimum requirements for Grade 60 according to ASTM A615.

The connection between two Low-Profile PCBs or a Low-Profile end treatment and Low-Profile PCB was accomplished by inserting two bolts through two precast holes in the mating barrier ends. These 1.25-inch diameter bolts were fabricated using ASTM A36 material with threads cut with Class 2A tolerances according to American National Standards Institute (ANSI B1.1). Standard USS washers and hex nuts were used. These nuts and washers met the requirements for Grade 5 according to Society of Automobile Engineers (SAE J429). These hex nuts met Class 2B tolerances for threads according to ANSI B1.1. All bolts, nuts, and washers were hot-dip galvanized according to ASTM A153.

To enhance the flexural rigidity of these connections, special plate washers with two symmetrically placed holes spaced to fit over both bolts were installed. These plate washers met the minimum specifications according to ASTM A36 material. For the tests presented herein, these plate washers were not hot-dip galvanized.



T:2012-2013W90023 TXDOT-5-LowProfileDrafting490023-5 Drawing

Figure 2.1. Layout of the Non-pinned Low-Profile PCB Installation.

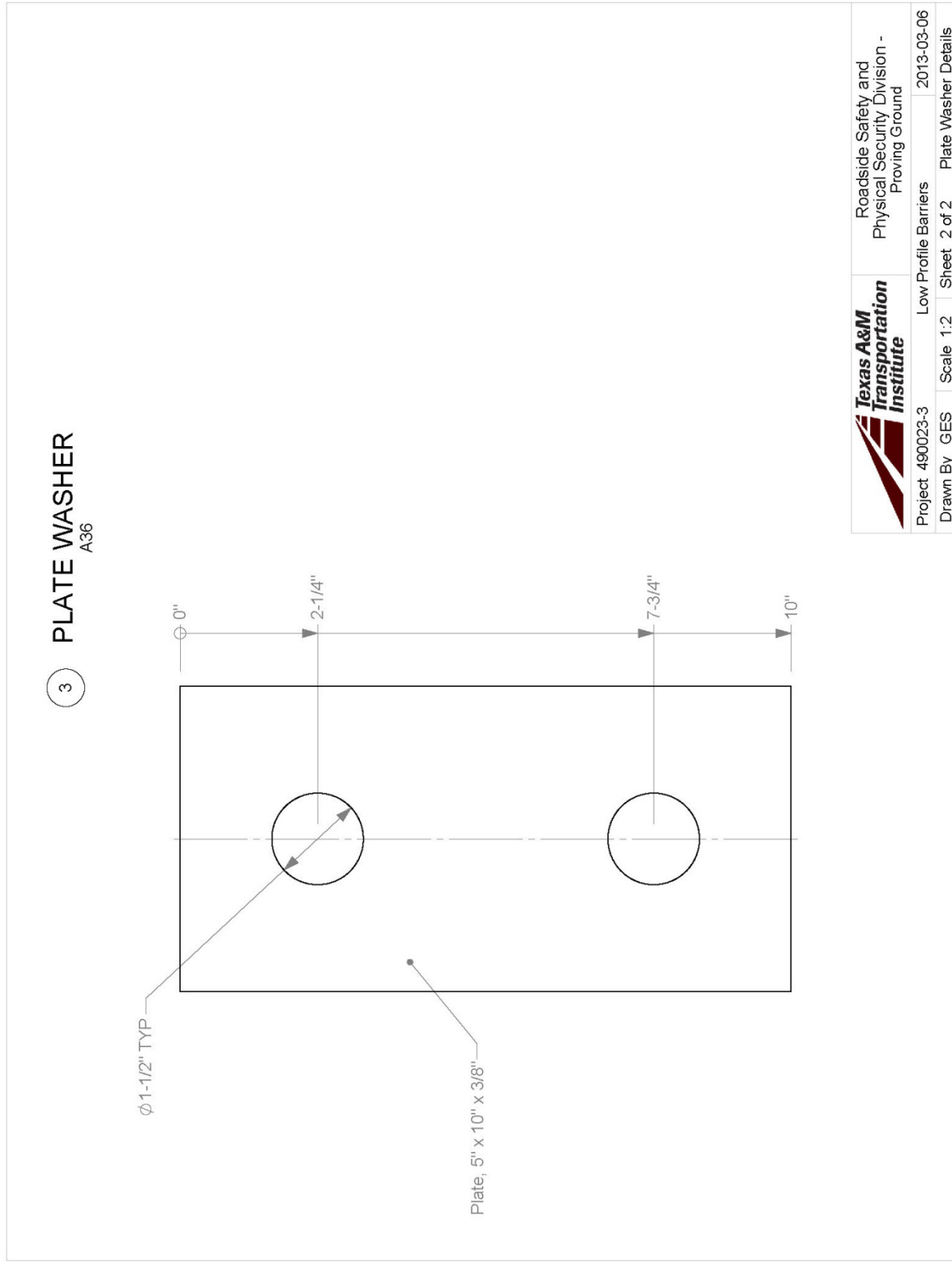


Figure 2.2. Details of the Plate Washer Used with the Non-pinned Low-Profile PCB.



Figure 2.3. Non-pinned Low-Profile End Treatment before Test No. 490023-7.

CHAPTER 3. TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1 CRASH TEST MATRIX

The Low-Profile barrier system, including the Low-Profile PCB and the Low-Profile end treatment, has previously been found to be in compliance with TL-2 requirements presented in *NCHRP Report 350* (5). As stated previously, this acceptance was for the Low-Profile barrier system that incorporates a pinned Low-Profile end treatment. In the current effort, it is desired to extend the *NCHRP Report 350* acceptance of the Low-Profile barrier system to include the case where the end treatment is not pinned to the pavement.

Seven tests were considered in the original *NCHRP Report 350* testing of the Low-Profile barrier system: three small passenger vehicle tests and four full-size pickup tests. TTI and TxDOT engineers reviewed the previous test matrix and concluded that it is necessary to repeat two tests from the original test matrix to demonstrate that a Low-Profile barrier system with a non-pinned end treatment complies with *NCHRP Report 350* criteria.

As stated above, a review of the original *NCHRP Report 350* crash test documentation shows that three small passenger vehicle tests were originally considered. These include Tests 2-30, 2-32, and 2-34. The impact angle for Test 2-30 is 0 degrees. It is clear that removal of the end treatment support pins will have no influence on tests involving an impact angle of 0 degrees. Therefore, Test 2-30 was waived for the current situation. Test 2-32 involves an impact angle of 15 degrees with the centerline of the vehicle aligned with that of the nose of the end treatment. This test is intended to evaluate occupant risk and vehicle trajectory. Because the nose of the Low-Profile end treatment has a height of only 4 inches, this test is much less severe than Test 2-34 that involves the same speed and angle but is conducted at the critical impact point. Test 2-32 is very close to an errant vehicle crossing a curb at a shallow angle. The vehicle will simply gate with much less of a disturbance than will occur with Test 2-34. This observation is borne out in previous testing of the pinned end-treatment where Test 2-32 was conducted. Therefore, Test 2-32 was waived for the current situation.

Test 2-34 is clearly the most critical small passenger vehicle test of the original test matrix. Because this test involves an impact angle of 15 degrees, it is possible that removal of the pins from the end treatment will result in lateral displacements that would influence the outcome. Moreover, a review of previous testing on the Low-Profile barrier system clearly shows that this is the most likely test condition to cause failure. Therefore, TTI and TxDOT engineers agreed that Test 2-34 must be repeated with the pins removed from the end treatment. *NCHRP Report 350* Test 2-34 is formally described as follows:

***NCHRP Report 350* test designation 2-34:** This test involves an 820-kg (1808-lb) passenger vehicle impacting the end treatment at a nominal speed and angle of 70 km/h (43.6 mi/h) and 15 degrees with the front corner of the vehicle aligned with the critical impact point (CIP) of the end treatment. The test is intended primarily to evaluate occupant risk and vehicle trajectory.

Four full-size pickup tests were originally considered for *NCHRP Report 350* testing of the pinned Low-Profile end treatment. These include Tests 2-31, 2-33, 2-35, and 2-39. Test 2-31 involves an impact angle of 0 degrees. As stated above, crash test results involving impact angles of 0 degrees will not be influenced by removal of the steel anchor pins. Therefore, Test 2-31 is waived for the current situation. Test 2-33 is essentially the same test as Test 2-32 except that it involves a pickup instead of a small passenger vehicle. This test involves the centerline of the pickup impacting the centerline nose of the end treatment with an angle of 15 degrees. It is clear a full-size pickup will be much more stable in these conditions than the small passenger vehicle. Therefore, for the same reasons discussed above, Test 2-33 is waived for the current situation. *NCHRP Report 350* Test 2-39 involves a full-size pickup impacting the end treatment from the reverse direction with an angle of 20 degrees. This test was originally waived because it was clear that the pinned end treatment would easily pass this test. It is even more clear that the test would be successful with a non-pinned end treatment because any lateral displacement of the end treatment would lessen the severity of the impact. Test 2-35 involved the full-size pickup impacting at the beginning of the length of need. In validation of the original Low-Profile end treatment, the beginning of the length of need was defined to be the point where the end treatment connects to the Low-Profile PCB. Therefore, this test was originally waived because the length of need did not involve the end treatment. That was the correct decision for evaluating the pinned Low-Profile barrier system. However, it is not the correct decision for evaluating the non-pinned end treatment as discussed below.

If a full-size pickup impacts the nose of the non-pinned end treatment with an angle of 20 degrees, it would simply gate as discussed above with respect to Test 2-33. There would be a relatively small lateral load placed on the end treatment. If a full-size pickup impacted the system exactly at the connection between the non-pinned end treatment and the Low-Profile PCB, it would make little difference whether the end treatment was pinned or not. However, there is a critical point between the nose and the connection end of the Low-Profile end treatment where the full-size pickup will just begin to be redirected. At this critical point, the connection between the non-pinned end treatment and the Low-Profile PCB will receive the maximum moment. This is where the effects of the end treatment not being pinned to the pavement will be most critical. This point was estimated to be 13.2 ft from the nose of the non-pinned end treatment using well-accepted finite element procedures. For purposes of running the most critical strength test on the non-pinned end treatment, this point was defined to be the beginning of the length of need in the context of Test 2-35. *NCHRP Report 350* Test 2-35 is formally described below

***NCHRP Report 350* Test designation 2-35:** This test involves a 2000-kg (4409-lb) pickup truck impacting the end treatment at a nominal speed and angle of 70 km/h (43.6 mi/h) and 20 degrees with the front corner of the vehicle impacting at the beginning of the length of need (LON). Test 2-35 is intended primarily to evaluate the ability of the end treatment to contain and redirect (structural adequacy) the pickup truck within vehicle trajectory criteria.

While the non-pinned end treatment will continue to be used as an *NCHRP Report 350* device, the actual tests that were used to examine the behavior of the non-pinned end treatment were conducted and evaluated in accordance with analogous *MASH* test procedures. The formal descriptions of the two tests that were conducted on the non-pinned end treatment are as follows:

1. ***MASH Test 2-34***: An 1100C (2425-lb) passenger car impacting the terminal at a nominal impact speed and angle of 44 mi/h and 15 degrees, respectively, with the corner of the bumper aligned with the CIP of the LON of the terminal. The test is primarily intended to evaluate occupant risk and vehicle trajectory criteria.
2. ***MASH Test 2-35***: A 2270P (5000-lb) pickup truck impacting the terminal at a nominal impact speed and angle of 44 mi/h and 25 degrees, respectively, with the corner of the bumper aligned with the beginning of the LON of the terminal. The test is primarily intended to evaluate structural adequacy and vehicle trajectory criteria.

MASH Test 2-35 is substantially more severe than *NCHRP Report 350 Test 2-35*. The impact angle is increased from 20 to 25 degrees, the vehicle mass is increased from 2000 kg to 2270 kg, and the impact speed is increased slightly from 43.5 mi/h to 44 mi/h. This test is referred to in the TTI data system as Test No. 490023-7. The target impact point was located 13.2 ft from the nose of the end treatment as described later. This point is believed to be the closest point to the nose of the end treatment that will result in a redirection rather than gating. Therefore, this impact point should serve as the beginning of the length of need and should also result in the most severe loading on the non-pinned end treatment connection. Hence, impact at this point will assure the worst-case situation for evaluating the lateral deflection and structural adequacy of the non-pinned end treatment. Location of this critical impact point was based on the results of well-established finite element techniques described in the next section.

MASH Test 2-34 is more severe than *NCHRP Report 350 Test 2-34*. While the impact angle remains the same, the vehicle mass is increased substantially from 820 kg to 1100 kg, and the impact speed is increased slightly from 43.5 to 44 mi/h. The non-pinned Low-Profile end treatment was subjected to the *MASH* version of Test 2-35. This test is referred to in the TTI data system as Test No. 490023-5. As described above, this test involved a small passenger vehicle impacting the non-pinned end treatment at the critical impact that was established to be 3 ft from the nose of the end treatment in work leading to the original certification of the Low-Profile end treatment.

The crash test and data analysis procedures were in accordance with guidelines presented in *MASH*. [Chapter 4](#) presents brief descriptions of these procedures.

3.2 CRITICAL IMPACT POINT FOR MASH TEST 2-35

MASH defines the location at which the test vehicle first contacts the test article as the impact point. The impact point that maximizes the risk for failure of the test according to the criteria set forth in *MASH* is known as the critical impact point (CIP). Furthermore, *MASH* recommends the use of finite element (FE) analyses to determine the CIP of redirective barriers whenever possible.

A matrix of FE analyses was performed to determine the CIP of the Low-Profile end treatment. These analyses were performed using LS-DYNA, a general purpose explicit FE code used to solve non-linear, dynamic responses of complex three-dimensional problems. LS-DYNA is capable of simulating the interaction and providing dynamic load-time history data for a vehicular-barrier impact.

For each FE analysis, a single Low-Profile end treatment was modeled using rigid material. These elements had no material failure or deformation capabilities. The end treatment was restrained from translational and rotational movements. It was the authors' intent to limit displacement and deformation of the end treatment to determine the CIP. It is reasonable to assume limiting displacement and deformation provides the worst case scenario to determine the CIP. The vehicle model used in the FE analyses was a Chevrolet Silverado that the National Crash Analysis Center (NCAC) developed. This model is available in the public domain and meets the specification criteria for the *MASH* 2270P design vehicle. Additionally, this vehicle model incorporated various modifications that TTI made to improve its performance and fidelity. [Figure 3.1](#) shows the FE model described.

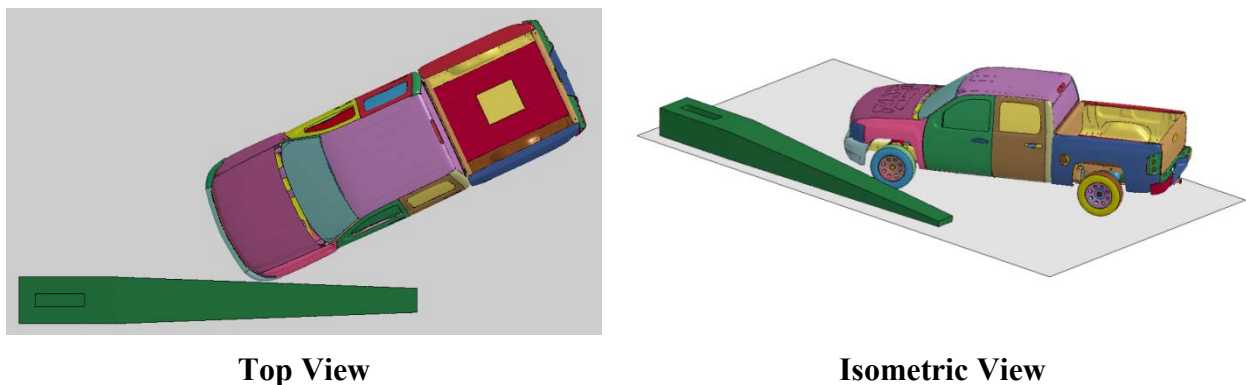


Figure 3.1. FE Model of Non-pinned Low-Profile End Treatment for Determining CIP.

The research team selected impact points at four locations along the length of the Low-Profile end treatment for FE analyses. These points were located where the end treatment was 12, 14, 16, and 18 inches in height. These locations were selected to determine the location at which an impacting vehicle would just begin to redirect and travel upstream along the barrier rather than gate over the end treatment. Impacting the end treatment at this critical point will provide the maximum moment possible in the connection between the end treatment and Low-Profile PCB. This critical point defines the beginning length of need.

All FE analyses were performed according to the criteria for *MASH* Test 2-35 involving the 2270P design vehicle impacting the end treatment at 25 degrees and 44 mi/h at the aforementioned impact points. [Figure 3.2](#) below shows the result of this FE matrix.

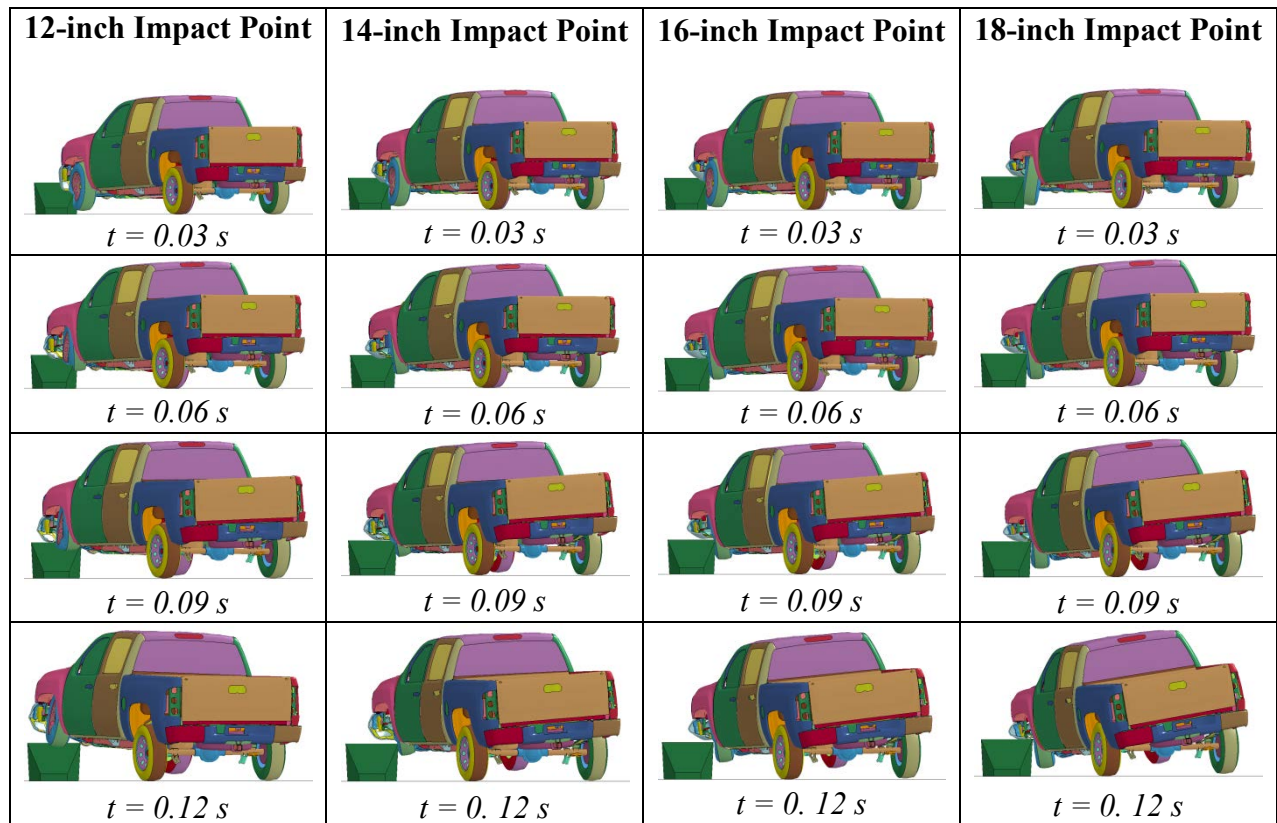
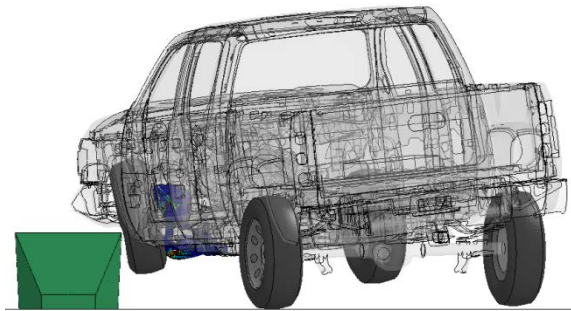


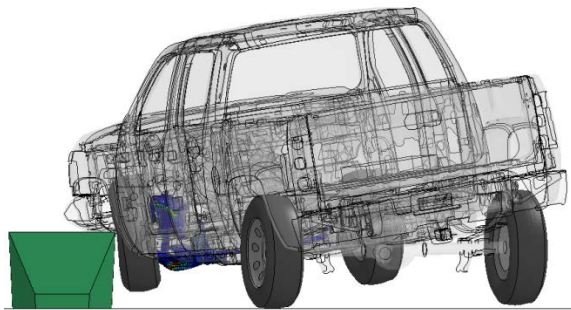
Figure 3.2. Sequential Results from FE Analyses for Different Impact Points.

As seen in [Figure 3.2](#), a vehicle that impacts the Low-Profile end treatment at 12 or 14 inches in height will gate.

While both the 16- and 18-inch high impact points appear to redirect the vehicle (see [Figure 3.3](#)), the latter maximizes the opportunity to redirect the vehicle and thus provides the maximum load condition on the end treatment-PCB connection. This impact point was selected as the CIP and located approximately 13 ft 2.5 inches upstream from the tip of the end treatment. A full-scale crash test was subsequently performed at this impact point, and the details are presented in the following chapters.



16-inch Impact Point at $t = 0.125$ s



18-inch Impact Point at $t = 0.115$ s

Figure 3.3. FE Results as the Vehicle's Front Wheel Loses Initial Contact with the End Treatment.

3.3 EVALUATION CRITERIA

The crash tests were evaluated in accordance with the criteria presented in *MASH*. The performance of the Low-Profile Barrier Terminal is 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 Low-Profile Barrier Terminal to contain and redirect the vehicle, or bring the vehicle to a controlled stop in a predictable manner. 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 here, and are listed in further detail under the assessment of the crash test.

CHAPTER 4. CRASH TEST PROCEDURES

4.1 TEST FACILITY

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

The Texas A&M Transportation Institute 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. The site, formerly an Air Force base, has large expanses of concrete runways and parking aprons well-suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, durability and efficacy of highway pavements, and evaluation of roadside safety hardware. The site selected for construction and testing of the Low-Profile end treatment evaluated under this project was along the surface of an out-of-service apron. The apron consists of an unreinforced jointed-concrete pavement in 12.5-ft × 15-ft blocks nominally 6 inches deep. The apron is over 60 years old, and the joints have some displacement, but are otherwise flat and level.

4.2 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 unrestrained. The vehicle remained freewheeling (i.e., no steering or braking inputs) until it cleared the immediate area of the test site, after which the brakes are activated, only if needed, to bring it to a safe and controlled stop.

4.3 DATA ACQUISITION SYSTEMS

4.3.1 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 that Diversified Technical Systems, Inc. produced. The accelerometers, which measure the x, y, and z axis of vehicle acceleration, are strain gauge type with linear millivolt output proportional to acceleration. Angular rate sensors, measuring vehicle roll, pitch, and yaw rates, are ultra-small, solid state units designed for crash test service. The TDAS Pro hardware and software conform to the latest SAE J211, Instrumentation for Impact Test. Each of the 16

channels 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 data are recorded, internal batteries back these up inside the unit should the primary battery cable be severed. Initial contact of the pressure switch on the vehicle bumper provides a time zero mark as well as initiates the recording process. After each test, the data are downloaded from the TDAS Pro unit into a laptop computer at the test site. The Test Risk Assessment Program (TRAP) software then processes the raw data to produce detailed reports of the test results. Each of the TDAS Pro units is returned to the factory annually for complete recalibration. Accelerometers and rate transducers are also calibrated annually with traceability to the National Institute for Standards and Technology. Acceleration data is measured with an expanded uncertainty of ± 1.7 percent at a confidence factor of 95 percent ($k=2$).

TRAP uses the data from the TDAS Pro to compute occupant/compartment impact velocities, time of occupant/compartment impact after vehicle impact, and the highest 10-millisecond (ms) average ridedown acceleration. TRAP calculates change in vehicle velocity at the end of a given impulse period. In addition, maximum average accelerations over 50-ms intervals in each of the three directions are computed. For reporting purposes, the data from the vehicle-mounted accelerometers are filtered with a 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, then plots yaw, pitch, and roll versus time. These displacements are in reference to the vehicle-fixed coordinate system with the initial position and orientation of the vehicle-fixed coordinate systems being initial impact. Rate of rotation data is measured with an expanded uncertainty of ± 0.7 percent at a confidence factor of 95 percent ($k=2$).

4.3.2 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 of the 1100C vehicle. The dummy was uninstrumented. Use of a dummy in the 2270P vehicle is optional according to *MASH*, and no dummy was used in the tests with the 2270P vehicle.

4.3.3 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 instant 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 5. RESULTS FOR *MASH* TEST NO. 2-35 (CRASH TEST NO. 490023-7)

5.1 TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH Test 2-35 involves a 2270P vehicle weighing 5000 lb \pm 100 lb and impacting the non-pinned Low-Profile end treatment at an impact speed of 44 mi/h \pm 2.5 mi/h and an angle of 25 degrees \pm 1.5 degrees. The target impact point was the height when the end treatment reached 18 inches (81.5 inches upstream of the splice). The 2006 Dodge Ram 1500 pickup truck used in the test weighed 5016 lb, and the actual impact speed and angle were 45.0 mi/h and 25.3 degrees, respectively. The actual impact point was 78.0 inches upstream of the splice. The target impact severity (IS) was 57.8 kip-ft, and actual IS was 62.0 kip-ft.

5.2 TEST VEHICLE

Figures 5.1 and 5.2 show the 2006 Dodge Ram 1500 pickup truck used for the crash test. Test inertia weight of the vehicle was 5016 lb, and its gross static weight was 5016 lb. The height to the lower edge of the vehicle bumper was 15.25 inches, and it was 28.00 inches to the upper edge of the bumper. The height to the vehicle's center of gravity was 28.00 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 freewheeling and unrestrained just prior to impact.

5.3 WEATHER CONDITIONS

The test was performed on the morning of March 22, 2013. Weather conditions at the time of testing were as follows: wind speed: 6 mi/h; wind direction: 219 degrees with respect to the vehicle (vehicle was traveling in a northwesterly direction); temperature: 75°F; relative humidity: 80 percent.

5.4 TEST DESCRIPTION

The 2006 Dodge Ram 1500 pickup truck, traveling at an impact speed of 45.0 mi/h, impacted the non-pinned Low-Profile end treatment 78 inches upstream of the splice at an impact angle of 25.3 degrees. At approximately 0.013 s, the vehicle began to redirect, and at 0.036 s, the end of the terminal began to deflect toward the field side. The vehicle was traveling parallel with the barrier at 0.297 s, and the rear of the vehicle contacted the barrier at 0.348 s. As the vehicle continued forward, it left the view of the overhead high-speed camera, and exit speed and angle were not obtainable. However, judging from tire tracks, the vehicle exited the barrier at approximately 10 degrees, and came to rest 160 ft downstream of impact and 171 ft toward traffic lanes. Figures C1 and C2 in Appendix C show sequential photographs of the test period.



Figure 5.1. Vehicle/Installation Geometrics for Test No. 490023-7.



Figure 5.2. Vehicle before Test No. 490023-7.

5.5 DAMAGE TO TEST INSTALLATION

Figures 5.3 and 5.4 show damage to the installation, with tire marks and concrete spalling along the impact area on the traffic side and concrete spalling at joint 2-3 on the field side. Movement of the end treatment was 44 inches toward the field side at the upstream end, 25 inches toward the field side at joint 1-2, 9 inches toward the field side at joint 2-3, 2 inches toward the field side at joint 3-4 and 1 inch toward traffic lanes at joint 4-5. The 2270P vehicle remained in contact with the barrier for 29 ft-3 inches. Working width during the test was 55.0 inches, and vehicle intrusion was 27.7 inches. Maximum dynamic deflection during the test was 42.4 inches toward the field side, and maximum permanent movement was 42.4 inches toward the field side at the upstream end of the terminal section.

5.6 VEHICLE DAMAGE

Figure 5.5 shows damage to the vehicle. The left lower control arm was deformed. The front bumper, left front fender, left front tire and wheel rim, left front and rear doors, left rear of the cab, left exterior bed, left rear front tire and wheel rim, left front and rear doors, left lower corner of the cab, left rear exterior bed, left rear wheel rim, and the rear bumper were damaged. Maximum exterior crush to the vehicle was 14.0 inches in the front plane at the left front corner at bumper height. No occupant compartment deformation occurred. Figure 5.6 has photographs of the interior of the vehicle. Appendix C, Tables C3 and C4 show details of the exterior crush and occupant compartment.

5.7 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 12.1 ft/s at 0.121 s, the highest 0.010-s occupant ridedown acceleration was 4.3 Gs from 0.352 to 0.362 s, and the maximum 0.050-s average acceleration was -6.3 Gs between 0.034 and 0.084 s. In the lateral direction, the occupant impact velocity was 15.4 ft/s at 0.121 s, the highest 0.010-s occupant ridedown acceleration was 5.3 Gs from 0.323 to 0.333 s, and the maximum 0.050-s average was 9.0 Gs between 0.040 and 0.090 s. Theoretical Head Impact Velocity (THIV) was 21.8 km/h or 6.1 m/s at 0.116 s; Post-Impact Head Decelerations (PHD) was 6.3 Gs between 0.352 and 0.362 s; and Acceleration Severity Index (ASI) was 1.13 between 0.035 and 0.085 s. Figure 5.7 summarized these data and other pertinent information from the test. Appendix C, Figures C3 through C9 show the vehicle angular displacements and accelerations versus time traces.



Figure 5.3. Installation/Vehicle Positions after Test No. 490023-7.



Figure 5.4. Installation after Test No. 490023-7.



Figure 5.5. Vehicle after Test No. 490023-7.



Figure 5.6. Interior of Vehicle for Test No. 490023-7.

5.8 ASSESSMENT OF TEST RESULTS

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

5.8.1 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 non-pinned Low-Profile end treatment contained and redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection of the barrier during the crash test was 42.4 inches. (PASS)

5.8.2 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 was present to penetrate or to show potential for penetrating the occupant compartment, or to present hazard to others in the area. (PASS)
No deformation or intrusion into the occupant compartment occurred. (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 15 degrees and 4 degrees, respectively. (PASS)

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

Longitudinal and Lateral Occupant Impact Velocity

<u>Preferred</u>	<u>Maximum</u>
30 ft/s	40 ft/s

Results: Longitudinal occupant impact velocity was 12.1 ft/s, and lateral occupant impact velocity was 15.4 ft/s. (PASS)

I. *Occupant ridedown accelerations should satisfy the following:*

Longitudinal and Lateral Occupant Ridedown Accelerations

<u><i>Preferred</i></u>	<u><i>Maximum</i></u>
<i>15.0 Gs</i>	<i>20.49 Gs</i>

Results: Longitudinal ridedown acceleration was 4.3 G, and lateral ridedown acceleration was 5.3 G. (PASS)

5.8.3 Vehicle Trajectory

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

Result: The 2270P vehicle came to rest 171 ft downstream of impact and 14 ft toward traffic lanes. (PASS)

CHAPTER 6. RESULTS FOR *MASH* TEST NO. 2-34 (CRASH TEST NO. 490023-5)

6.1 TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH Test 2-34 involves a 1100C vehicle weighing 2420 lb \pm 55 lb and impacting the non-pinned Low-Profile end treatment at an impact speed of 44 mi/h \pm 2.5 mi/h and an angle of 15 degrees \pm 1.5 degrees. The target impact point was 3 ft downstream from the tip end of the terminal. The 2008 Kia Rio used in the test weighed 2425 lb, and the actual impact speed and angle were 43.9 mi/h and 15.2 degrees, respectively. The actual impact point was 33.0 inches downstream from the tip. Target impact severity (IS) was 10.5 kip-ft, and actual IS was 10.7 kip-ft.

6.2 TEST VEHICLE

Figures 6.1 and 6.2 show the 2008 Kia Rio that was used for the crash test. Test inertia weight of the vehicle was 2425 lb, and its gross static weight was 2614 lb. The height to the lower edge of the vehicle bumper was 7.12 inches, and it was 21.00 inches to the upper edge of the bumper. 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 freewheeling and unrestrained just prior to impact.

6.3 WEATHER CONDITIONS

The test was performed on the morning of March 26, 2013. Weather conditions at the time of testing were as follows: wind speed: 4 mi/h; wind direction: 336 degrees with respect to the vehicle (vehicle was traveling in a northwesterly direction); temperature: 50°F; relative humidity: 38 percent.

6.4 TEST DESCRIPTION

The 2008 Kia Rio, traveling at an impact speed of 43.9 mi/h, impacted the non-pinned Low-Profile end treatment 33.0 inches downstream from the tip at an impact angle of 15.2 degrees. At approximately 0.020 s, the left front tire began to ride up the traffic face of the end treatment, and at 0.029 s, air began to escape from the tire around the edge of the wheel rim. The left front wheel rim reached the top of the end treatment at 0.042 s, and the vehicle began to redirect at 0.048 s. At 0.084 s, the left front tire was on top the end treatment, and at 0.095 s, the left rear tire contacted the end treatment. The left rear tire climbed on top the end treatment at 0.178 s, and the vehicle was traveling parallel with the barrier at 0.576 s. As the vehicle continued forward, the vehicle rode over the end treatment and came to rest on the field side of the barrier. Figures C1 and C2 in Appendix C show sequential photographs of the test period.



Figure 6.1. Vehicle/Installation Geometrics for Test No. 490023-5.



Figure 6.2. Vehicle before Test No. 490023-5.

6.5 DAMAGE TO TEST INSTALLATION

Figures 6.3 and 6.4 show damage to the installation, which was mostly cosmetic in nature with tire marks and concrete spalling along the impact area and tire marks only on the top surface of the barrier. Working width during the test was 28.75 inches, and vehicle intrusion was 32.3 ft. Maximum dynamic deflection during the test was 0.75 inch toward the field side, and maximum permanent movement was 0.75 inch toward the field side at the upstream end of the terminal section.

6.6 VEHICLE DAMAGE

Figure 6.5 shows damage to the vehicle. The left and right ends of the tie rod and the right lower control arm were deformed. Also, the left front tire and wheel rim and left rear wheel rim were damaged. No measureable exterior crush to the vehicle was noted, nor was there evidence of occupant compartment deformation or intrusion. Photographs of the interior of the vehicle are shown in Figure 6.6. Appendix C, Tables C3 and C4 show the details of the exterior crush and occupant compartment.

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 4.6 ft/s at 0.355 s, the highest 0.010-s occupant ridedown acceleration was 2.5 Gs from 0.664 to 0.674 s, and the maximum 0.050-s average acceleration was -1.9 Gs between 0.007 and 0.057 s. In the lateral direction, the occupant impact velocity was 4.9 ft/s at 0.355 s, the highest 0.010-s occupant ridedown acceleration was 3.7 Gs from 0.408 to 0.418 s, and the maximum 0.050-s average was 1.8 Gs between 0.372 and 0.422 s. THIV was 6.4 km/h or 1.8 m/s at 0.338 s; PHD was 3.8 Gs between 0.408 and 0.418 s; and ASI was 0.38 between 0.024 and 0.074 s. Figure 6.7 summarized these data and other pertinent information from the test. Appendix C, Figures C3 through C9 present the vehicle angular displacements and accelerations versus time traces.

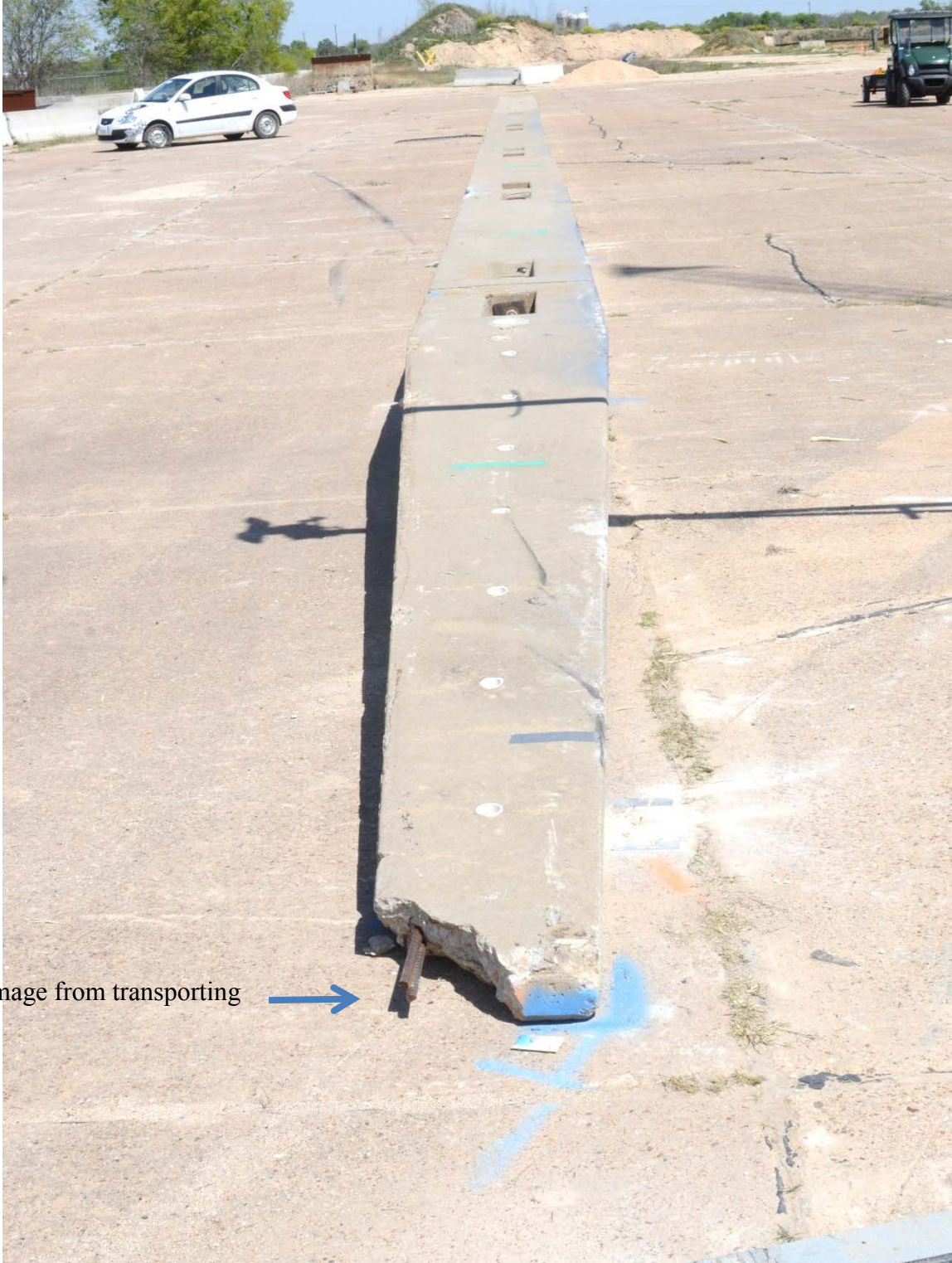


Figure 6.3. Installation/Vehicle Positions after Test No. 490023-5.



Figure 6.4. Installation after Test No. 490023-5.



Figure 6.5. Vehicle after Test No. 490023-5.

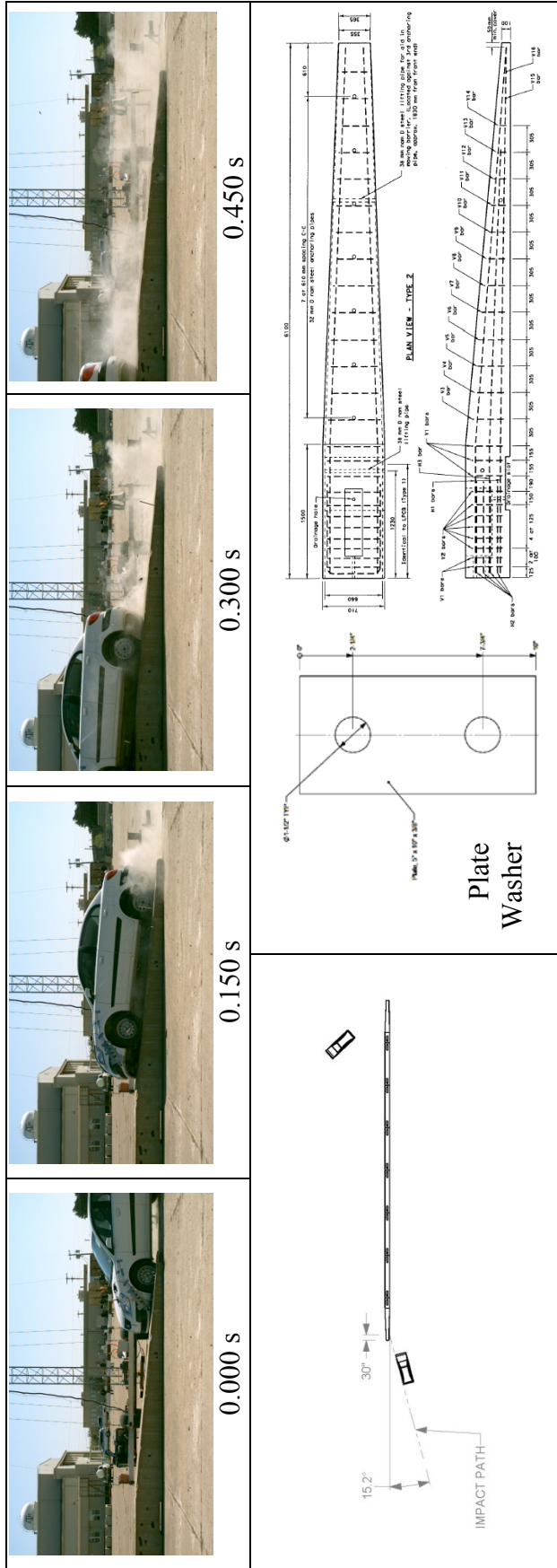


Before Test



After Test

Figure 6.6. Interior of Vehicle for Test No. 490023-5.



General Information	
Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	MASH Test 2-35
TTI Test No.	490023-5
Test Date	2013-03-26
Test Article	
Type	Terminal
Name	Non-pinned Low-Profile Barrier
Installation Length	160 ft
Material or Key Elements	20 ft reinforced concrete ranging in height from 20 inches to 4 inches
Soil Type and Condition	
Placed on Concrete Surface, Dry	
Test Vehicle	
Type/Designation	1100C
Make and Model	2008 Kia Rio
Curb	2289 lb
Test Inertial	2425 lb
Dummy	189 lb
Gross Static	2614 lb
Impact Conditions	
Speed	43.9 mi/h
Angle	15.2 degrees
Location/Orientation	33 inches from end
Impact Severity	
10.7 kip-ft	
Exit Conditions	
Speed	Not obtainable
Angle	Not obtainable
Occupant Risk Values	
Impact Velocity	
Longitudinal	4.6 ft/s
Lateral	4.9 ft/s
Ridedown Accelerations	
Longitudinal	2.5 G
Lateral	3.7 G
THIV	1.8 m/s
PHI	3.8 G
ASI	0.38
Max. 0.050-s Average	
Longitudinal	-1.9 G
Lateral	1.8 G
Vertical	3.4 G
Post-Impact Trajectory	
Stopping Distance	146 ft downstrm
	20 ft twd field side
Vehicle Stability	
Maximum Yaw Angle	26 degrees
Maximum Pitch Angle	9 degrees
Maximum Roll Angle	51 degrees
Vehicle Snagging	No
Vehicle Pocketing	No
Test Article Deflections	
Dynamic	0.75 inch
Permanent	0.75 inch
Vehicle Intrusion	32.3 ft
Working Width	28.75 inches
Vehicle Damage	
VDS	11FL1
CDC	11FLWN1
Max. Exterior Deformation	None
OCDI	None
Max. Occupant Compartment Deformation	LF0000000

Figure 6.7. Summary of Results for MASH Test 2-35 on the Non-pinned Low-Profile End Treatment.

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

C. *Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.*

Results: The non-pinned Low-Profile end treatment slowed the 1100C vehicle allowing the vehicle to override the end. (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 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 was present to penetrate or to show potential for penetrating the occupant compartment, or to present hazard to others in the area. (PASS)
No deformation or intrusion into the occupant compartment occurred. (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 angles were 51 degrees and 9 degrees, respectively. (PASS)

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

Longitudinal and Lateral Occupant Impact Velocity

<u>Preferred</u>	<u>Maximum</u>
30 ft/s	40 ft/s

Results: Longitudinal occupant impact velocity was 4.6 ft/s, and lateral occupant impact velocity was 4.9 ft/s. (PASS)

I. *Occupant ridedown accelerations should satisfy the following:*
Longitudinal and Lateral Occupant Ridedown Accelerations

<u>Preferred</u>	<u>Maximum</u>
15.0 Gs	20.49 Gs

Results: Longitudinal ridedown acceleration was 2.5 G, and lateral ridedown acceleration was 3.7 G. (PASS)

6.8.3 Vehicle Trajectory

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

Result: The 1100C vehicle exited toward the field side of the barrier. (PASS)

CHAPTER 7. SUMMARY AND CONCLUSIONS

7.1 ASSESSMENT OF TEST RESULTS

7.1.1 *MASH* Test 2-35 – Crash Test No. 490023-7

The non-pinned Low-Profile end treatment contained and redirected the 2270P vehicle. The vehicle did not penetrate, underide, or override the installation. Maximum dynamic deflection of the barrier was 42.4 inches measured at the end treatment nose. No detached elements, fragments, or other debris from the barrier were present to penetrate or show potential for penetrating the occupant compartment, or to present hazard to others in the area. No deformation or intrusion of the occupant compartment occurred. The 2270P vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 15 degrees and 4 degrees, respectively. Occupant risk factors were within the preferred limits specified in *MASH*. The 2270P vehicle came to rest 171 ft downstream of impact and 14 ft toward traffic lanes.

7.1.2 *MASH* Test 2-34 – Crash Test No. 490023-5

The non-pinned Low-Profile end treatment slowed the 1100C vehicle by allowing the vehicle to gate over the end. Maximum dynamic deflection of the barrier was 0.75 inches measured at the end treatment nose. No detached elements, fragments, or other debris was present to penetrate or to show potential for penetrating the occupant compartment, or to present hazard to others in the area. No deformation or intrusion into the occupant compartment occurred. The 1100C vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 51 degrees and 9 degrees, respectively. Occupant risk factors were within the preferred limits specified in *MASH*.

7.2 CONCLUSIONS

The non-pinned Low-Profile end treatment performed acceptably for *MASH* Tests 2-34 and 2-35 (see [Tables 7.1](#) and [7.2](#)).

Table 7.1. Performance Evaluation Summary for MASH Test 2-35 on the Low-Profile End Treatment.

Test Agency: Texas A&M Transportation Institute		Test No.: 490023-7	Test Date: 2013-03-22
MASH Test 2-35 Evaluation Criteria		Test Results	Assessment
Structural Adequacy <i>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.</i>		The non-pinned Low-Profile end treatment contained and redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection of the barrier was 42.4 inches.	Pass
Occupant Risk <i>D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant undue hazard to other traffic, pedestrians, or personnel in a work zone.</i> <i>Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.</i>		No detached elements, fragments, or other debris from the barrier were present to penetrate or show potential for penetrating the occupant compartment, or to present hazard to others in the area. No deformation or intrusion of the occupant compartment occurred.	Pass
<i>F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</i>		The 2270P vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 15 degrees and 4 degrees, respectively.	Pass
<i>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.</i>		Longitudinal occupant impact velocity was 12.1 ft/s, and lateral occupant impact velocity was 15.4 ft/s.	Pass
<i>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.</i>		Longitudinal ridedown acceleration was 4.3 G, and lateral ridedown acceleration was 4.7 G.	Pass
Vehicle Trajectory <i>For redirective devices, the vehicle shall exit the barrier within the exit box.</i>		The 2270P vehicle came to rest 171 ft downstream of impact and 14 ft toward traffic lanes.	Pass

Table 7.2. Performance Evaluation Summary for MASH Test 2-34 on the Low-Profile End Treatment.

Test Agency: Texas A&M Transportation Institute		Test No.: 490023-5	Test Date: 2013-03-26
MASH Test 2-34 Evaluation Criteria		Test Results	Assessment
Structural Adequacy <i>C. Acceptable test article performance may be by redirection, controlled penetration, or controlled stopping of the vehicle.</i>		The non-pinned Low-Profile end treatment slowed the 1100C vehicle by allowing the vehicle to gate over the end.	Pass
Occupant Risk <i>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.</i>		No detached elements, fragments, or other debris was present to penetrate or to show potential for penetrating the occupant compartment, or to present hazard to others in the area.	Pass
<i>E. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.</i>		No deformation or intrusion into the occupant compartment occurred.	Pass
<i>F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</i>		The 1100C vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 51 degrees and 9 degrees, respectively.	Pass
<i>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.</i>		Longitudinal occupant impact velocity was 4.6 ft/s, and lateral occupant impact velocity was 4.9 ft/s.	Pass
<i>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.</i>		Longitudinal ridedown acceleration was 2.5 G, and lateral ridedown acceleration was 3.7 G.	Pass
Vehicle Trajectory <i>For redirective devices, the vehicle shall exit the barrier within the exit box.</i>		The 1100C vehicle exited toward the field side of the barrier.	Pass

CHAPTER 8. IMPLEMENTATION STATEMENT

This research report presents the results of two full-scale crash tests that show the previously developed Low-Profile portable concrete barrier (PCB) system can be safely deployed without using the vertical steel pins that were previously specified to anchor the end treatment to the pavement/subgrade. These tests show that the non-pinned Low-Profile PCB system exceeds test criteria presented in *NCHRP Report 350*. Deployment of the barrier in this configuration requires that the immediate area surrounding the end treatment is smooth and flat so that the 42.4 inches of lateral displacement can be accommodated. The non-pinned Low-Profile barrier system is considered acceptable for use on roadways and in work zones suitable for TL-2 design impact conditions, and can accommodate approximately 4 ft of lateral displacement of the end treatment. Furthermore, the use of non-pinned end treatments does not affect the impact performance or design deflections for the Low-Profile barrier itself. The barrier was previously successfully tested without end treatments and had a maximum dynamic deflection of 5 inches (*1*).

Based on guidelines presented in *NCHRP Report 350*, the non-pinned Low-Profile barrier is also suitable for other applications depending upon traffic conditions, site conditions, traffic volume and mix, and the cost-effectiveness of safety alternatives. Therefore, the researchers recommend use of the non-pinned Low-Profile barrier system where applicable.

By using these guidelines for the non-pinned Low Profile end treatment, TxDOT has a cost-saving alternative to the previously pinned Low-Profile end treatment. Installation of the pinned Low-Profile end treatment requires increased labor efforts and worker exposure during both barrier placement and removal. Thus, the elimination of these pins reduces costs and improves worker safety. In addition, materials and labor necessary to fabricate these pins are not required. The drilling necessary to insert these pins can disrupt the integrity of the pavement (concrete and asphalt). The non-pinned Low-Profile end treatment helps maintain the integrity of the pavement and removes the need for post-installation repairs of the pavement.

REFERENCES

1. T. R. Guidry and W. Lynn Beason, "Development of a Low-Profile Portable Concrete Barrier," Final Report No. 1949-2, Texas Department of Highways and Public Transportation, November 1991.
2. W. Lynn Beason, "Development of an End Treatment for a Low-Profile Portable Concrete Barrier," Final Report No. 990-4F, Texas Department of Highways and Public Transportation, November 1992.
3. J. D. Michie, "Recommended Procedures for the Safety Performance Evaluation of Highway Appurtenances," *NCHRP Report 230*, Transportation Research Board, Washington, D. C., 1980.
4. 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.
5. W. Lynn Beason, W. L. Menges, and D. L. Ivey, "Compliance Testing of an End Treatment for a Low-Profile Portable Concrete Barrier," Final Report No. 1403-S, Texas Department of Highways and Public Transportation, April 1998.
6. AASHTO, *Manual for Assessing Safety Hardware*, American Association of State Highway and Transportation Officials, Washington, D. C., 2009.

APPENDIX B. CERTIFICATION DOCUMENTATION

MATERIAL USED

TEST NUMBER 490023-5
TEST NAME Low Profile Barriers
DATE 2013-03-22

The Ø1-1/4" nuts used on the connection bolts were received from Mack Bolt and Steel on 2013-03-20. No cert papers for them have been received as of test date.

All other material was supplied by TxDOT with no accompanying paperwork.

APPENDIX C. INFORMATION FOR CRASH TEST 490023-7

Table C1. Vehicle Properties for Test No. 490023-7.

Date: 2013-03-22 Test No.: 490023-7 VIN No.: 1D7HA18No65693242
 Year: 2006 Make: Dodge Model: Ram 1500
 Tire Size: P265/70R17 Tire Inflation Pressure: 35 psi
 Tread Type: Highway Odometer: 124208

Note any damage to the vehicle prior to test: _____

• Denotes accelerometer location.

NOTES: _____

Engine Type: V8
 Engine CID: 4.7 liter

Transmission Type:
 Auto or _____ Manual
 FWD RWD 4WD

Optional Equipment: _____

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

Geometry: Inches

A	<u>78.25</u>	F	<u>36.00</u>	K	<u>21.50</u>	P	<u>2.88</u>	U	<u>28.50</u>
B	<u>75.50</u>	G	<u>28.00</u>	L	<u>30.25</u>	Q	<u>30.50</u>	V	<u>30.50</u>
C	<u>223.75</u>	H	<u>62.52</u>	M	<u>68.50</u>	R	<u>18.38</u>	W	<u>61.50</u>
D	<u>47.25</u>	I	<u>15.25</u>	N	<u>68.00</u>	S	<u>16.00</u>	X	<u>80.00</u>
E	<u>140.50</u>	J	<u>28.00</u>	O	<u>45.50</u>	T	<u>77.50</u>		
Wheel Center Height Front	<u>14.75</u>	Wheel Well Clearance (Front)	<u>6.00</u>	Bottom Frame Height - Front	<u>11.75</u>				
Wheel Center Height Rear	<u>14.75</u>	Wheel Well Clearance (Rear)	<u>10.25</u>	Bottom Frame Height - Rear	<u>26.00</u>				

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	<u>3700</u>	<u>M_{front}</u>	<u>2862</u>	<u>2784</u>
Back	<u>3900</u>	<u>M_{rear}</u>	<u>2053</u>	<u>2232</u>
Total	<u>6700</u>	<u>M_{Total}</u>	<u>4915</u>	<u>5016</u>

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

Mass Distribution:

lb LF: 1401 RF: 1383 LR: 1109 RR: 1173

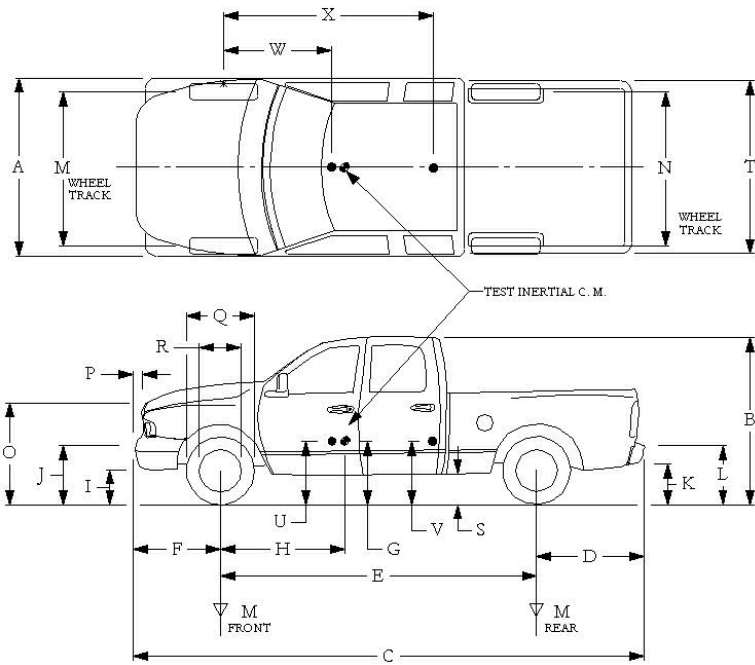


Table C2. Measurement of Vehicle CG for Test No. 490023-7.

Date: 2013-03-22 Test No.: 490023-7 VIN: 1D7HA18No65693242
 Year: 2006 Make: Dodge Model: Ram 1500
 Body Style: Quad Cab Mileage: 124208
 Engine: 4.7 liter V8 Transmission: Automatic
 Fuel Level: Empty Ballast: 214 lb (440 lb max)
 Tire Pressure: Front: 35 psi Rear: 35 psi Size: P265/70R17

Measured Vehicle Weights: (lb)			
LF:	<u>1401</u>	RF:	<u>1383</u>
Front Axle:		<u>2784</u>	
LR:	<u>1109</u>	RR:	<u>1123</u>
Rear Axle:		<u>2232</u>	
Left:	<u>2510</u>	Right:	<u>2506</u>
Total:		<u>5016</u>	
5000 ±110 lb allow ed			
Wheel Base:	<u>140.5</u> inches	Track: F:	<u>68.5</u> inches
148 ±12 inches allow ed		R:	<u>68</u> inches
		Track = (F+R)/2 = 67 ±1.5 inches allow ed	
Center of Gravity, SAE J874 Suspension Method			
X:	<u>62.52</u> inches	Rear of Front Axle	(63 ±4 inches allow ed)
Y:	<u>-0.03</u> inches	Left - Right +	of Vehicle Centerline
Z:	<u>28</u> inches	Above Ground	(minumum 28.0 inches allow ed)

Hood Height: 44.50 inches Front Bumper Height: 28.00 inches
 43 ±4 inches allowed

Front Overhang: 36.00 inches Rear Bumper Height: 30.25 inches
 39 ±3 inches allowed

Overall Length: 223.75 inches
 237 ±13 inches allowed

Table C3. Exterior Crush Measurements for Test No. 490023-7.

Date: 2013-03-22 Test No.: 490023-7 VIN No.: 1D7HA18No65693242
 Year: 2006 Make: Dodge Model: Ram 1500

VEHICLE CRUSH MEASUREMENT SHEET¹

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 $\frac{X1 + X2}{2} = \underline{\hspace{2cm}}$

Note: Measure C₁ to C₆ 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	17	14	24	14	12	8	3	1	0	-17.5
2	Side plane at bumper ht	17	12	48	0	1/2	---	---	10	12	+76
	Measurements recorded										
	in inches										

¹Table 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).

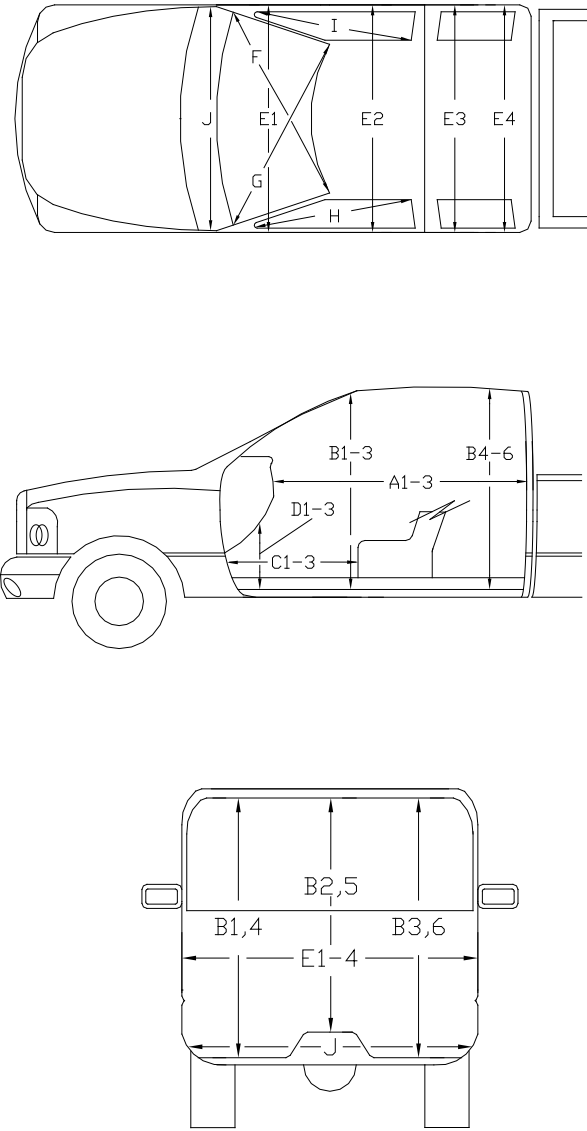
***Measure and document on the vehicle diagram the location of the maximum crush.

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

Table C4. Occupant Compartment Measurements for Test No. 490023-7.

Date: 2013-03-22 Test No.: 490023-7 VIN No.: 1D7HA18No65693242
 Year: 2006 Make: Dodge Model: Ram 1500

OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT



	Before (inches)	After (inches)
A1	65.00	65.00
A2	64.50	64.50
A3	65.25	65.25
B1	45.25	45.25
B2	39.50	39.50
B3	45.25	45.25
B4	42.00	42.00
B5	45.00	45.00
B6	42.00	42.00
C1	30.00	30.00
C2	----	----
C3	27.00	27.00
D1	12.75	12.75
D2	----	----
D3	11.50	11.50
E1	62.75	62.75
E2	64.25	64.25
E3	64.00	64.00
E4	64.50	64.50
F	60.00	60.00
G	60.00	60.00
H	39.00	39.00
I	39.00	39.00
J*	62.25	62.25

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



0.000 s



0.202 s



0.404 s



0.606 s



Figure C1. Sequential Photographs for Test No. 490023-7 (Overhead and Side Views).



0.808 s



Vehicle out of view

Vehicle out of view

1.010 s

Vehicle out of view

Vehicle out of view

1.212 s

Vehicle out of view

Vehicle out of view

1.414 s

**Figure C1. Sequential Photographs for Test No. 490023-7
(Overhead and Side Views) (continued).**



0.000 s



0.808 s



0.202 s



1.010 s



0.404 s



1.212 s



0.606 s



1.414 s

Figure C2. Sequential Photographs for Test No. 490023-7 (Rear View).

Roll, Pitch, and Yaw Angles

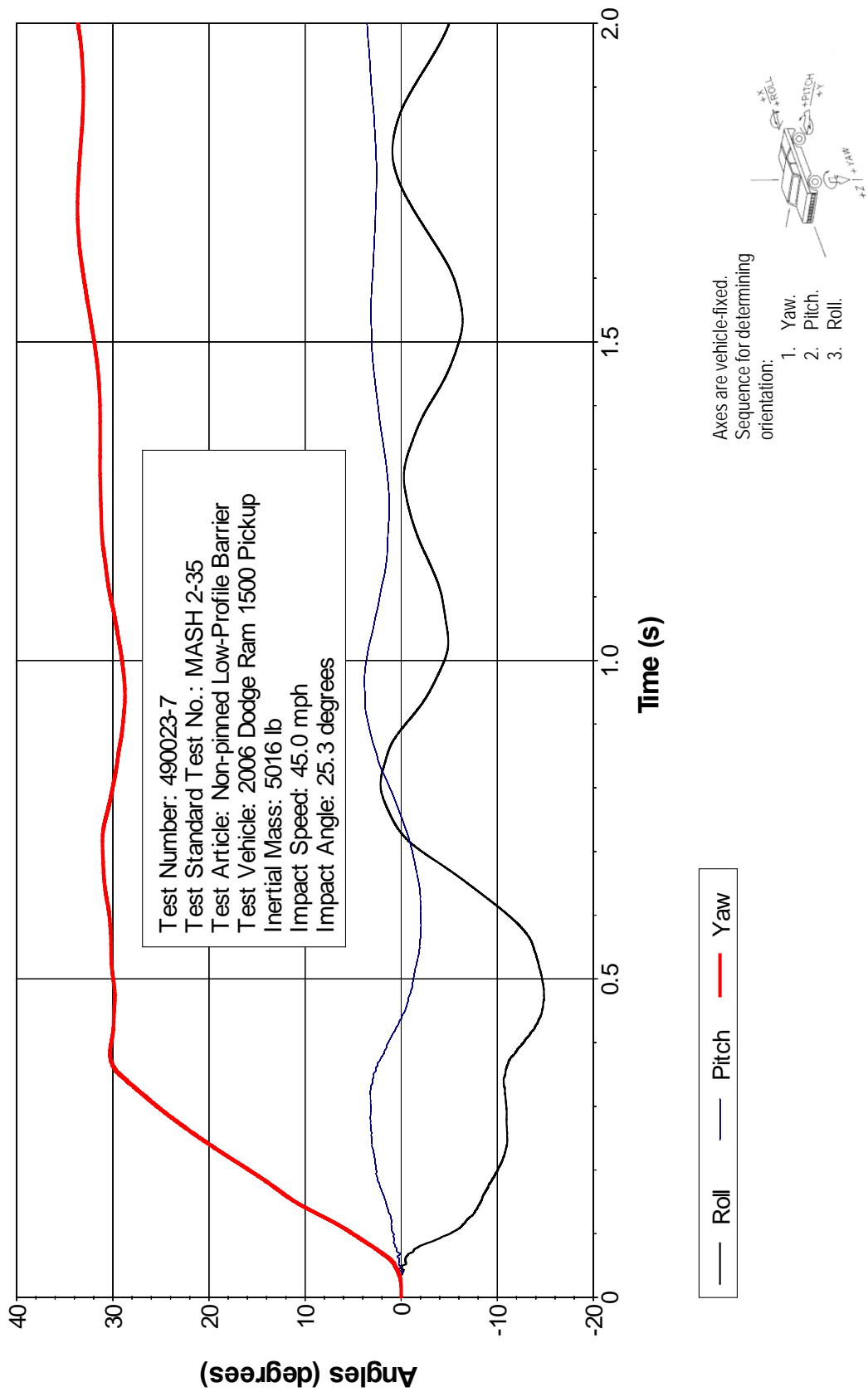


Figure C3. Vehicle Angular Displacements for Test No. 490023-7.

X Acceleration at CG

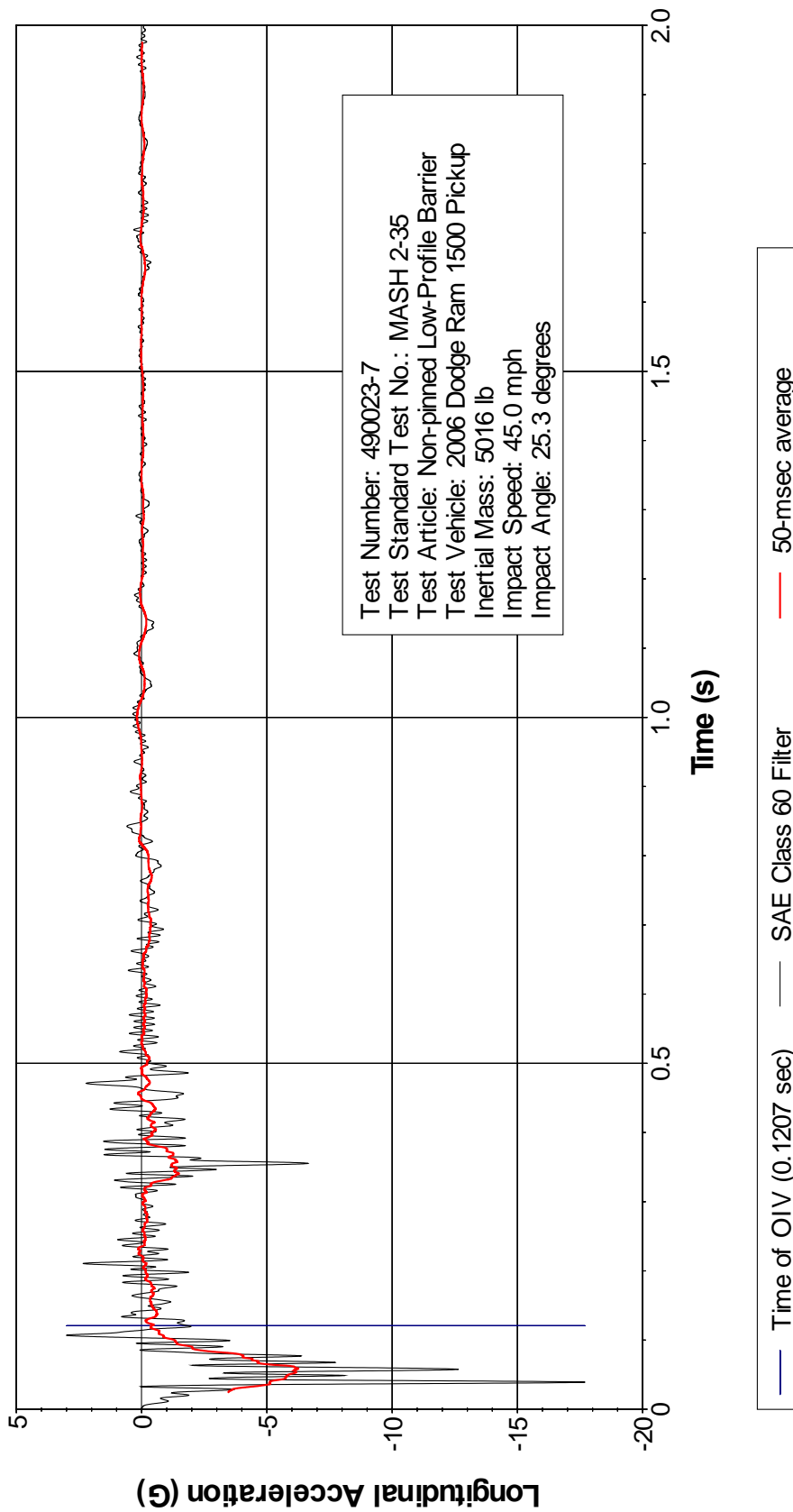


Figure C4. Vehicle Longitudinal Accelerometer Trace for Test No. 490023-7 (Accelerometer Located at Center of Gravity).

Y Acceleration at CG

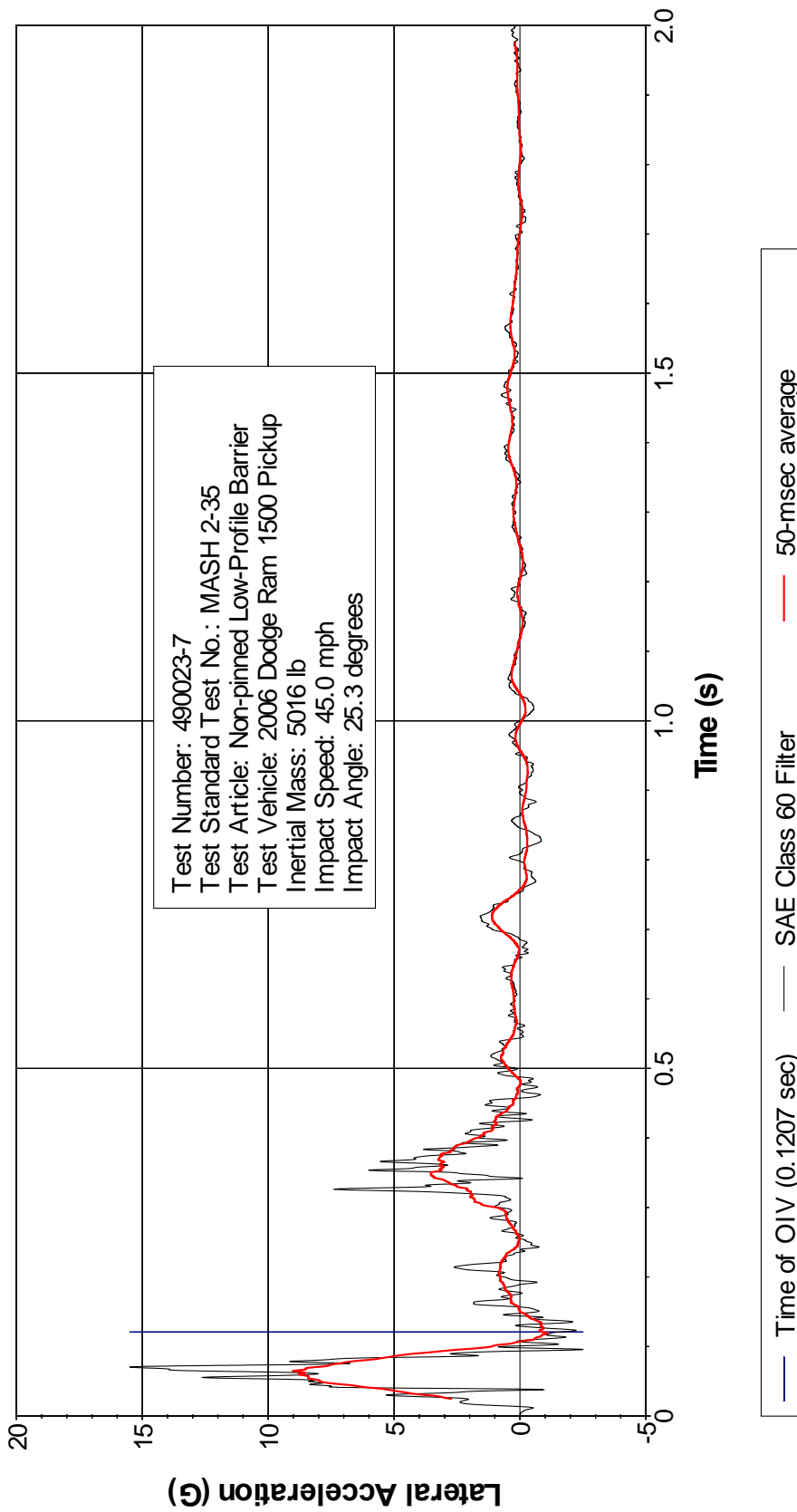


Figure C5. Vehicle Lateral Accelerometer Trace for Test No. 490023-7 (Accelerometer Located at Center of Gravity).

Z Acceleration at CG

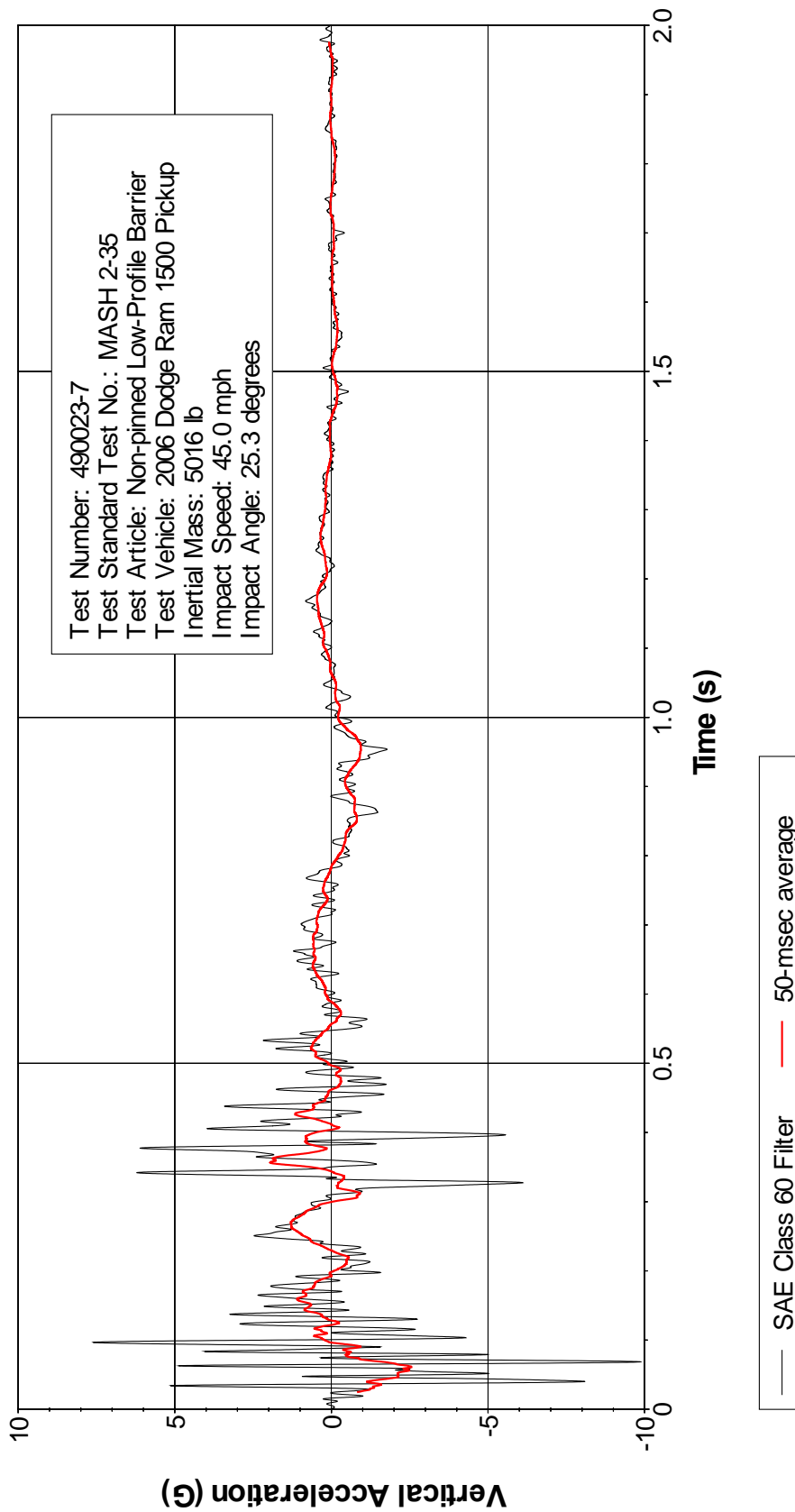


Figure C6. Vehicle Vertical Accelerometer Trace for Test No. 490023-7 (Accelerometer Located at Center of Gravity).

X Acceleration Rear of CG

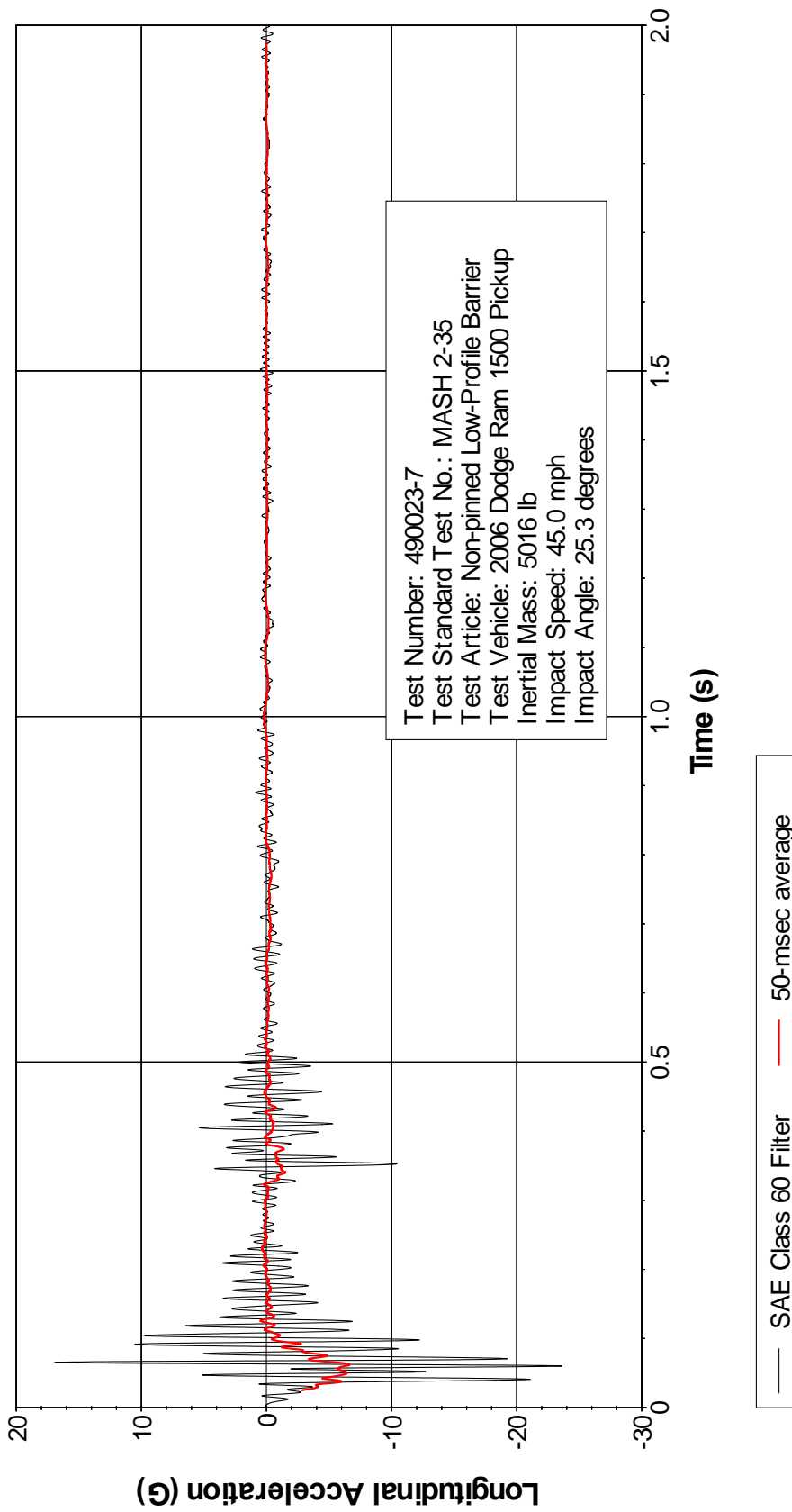


Figure C7. Vehicle Longitudinal Accelerometer Trace for Test No. 490023-7 (Accelerometer Located Rear of Center of Gravity).

Y Acceleration Rear of CG

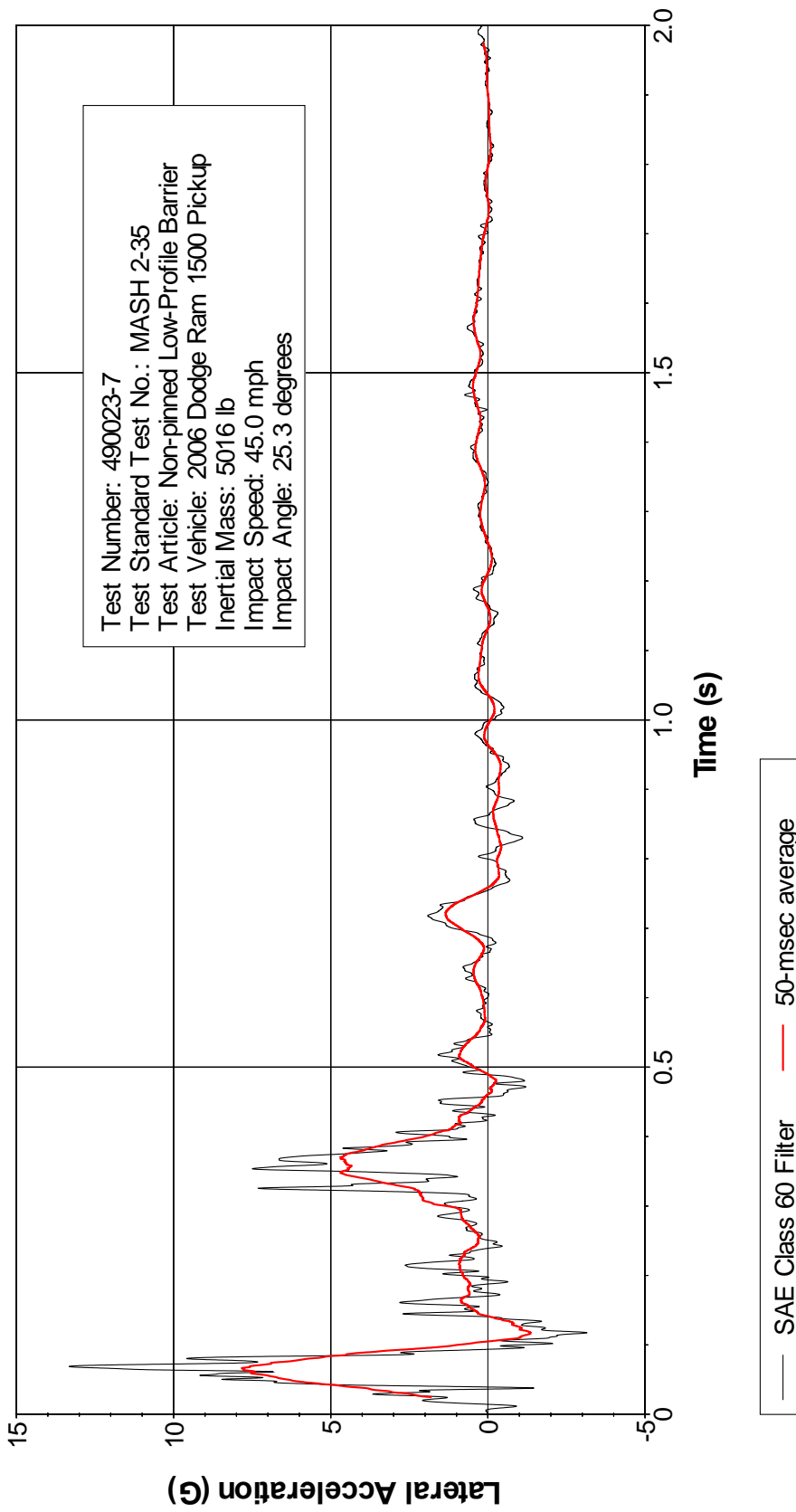


Figure C8. Vehicle Lateral Accelerometer Trace for Test No. 490023-7 (Accelerometer Located Rear of Center of Gravity).

Z Acceleration Rear of CG

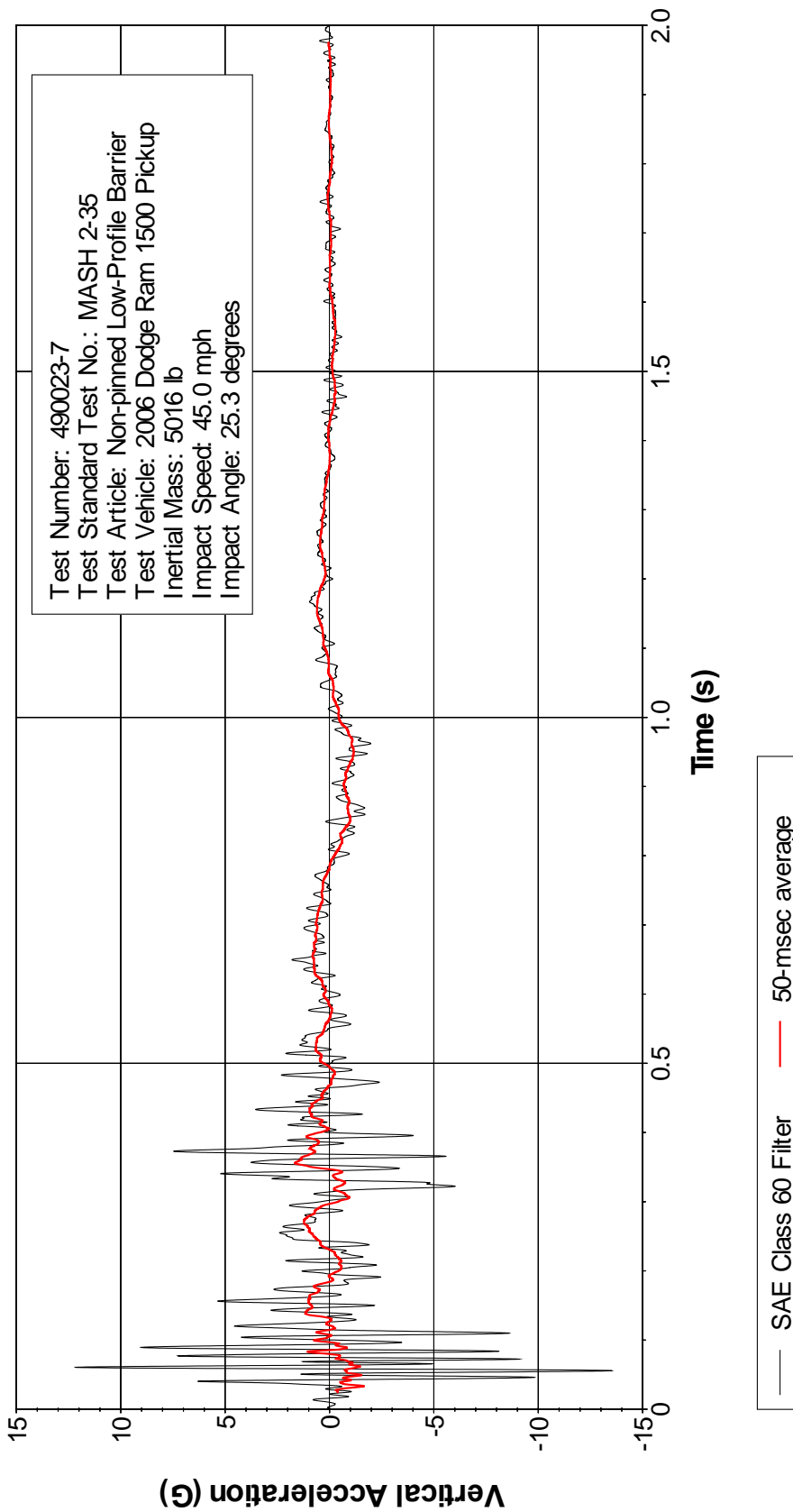


Figure C9. Vehicle Vertical Accelerometer Trace for Test No. 490023-7 (Accelerometer Located Rear of Center of Gravity).

APPENDIX D. INFORMATION FOR CRASH TEST 490023-5

Table D1. Vehicle Properties for Test No. 490023-5.

Date: 2013-03-26 Test No.: 490023-5 VIN No.: KNADE123X86369048
 Year: 2008 Make: Kia Model: Rio
 Tire Inflation Pressure: 32 psi Odometer: 94640 Tire Size: 175/70R14

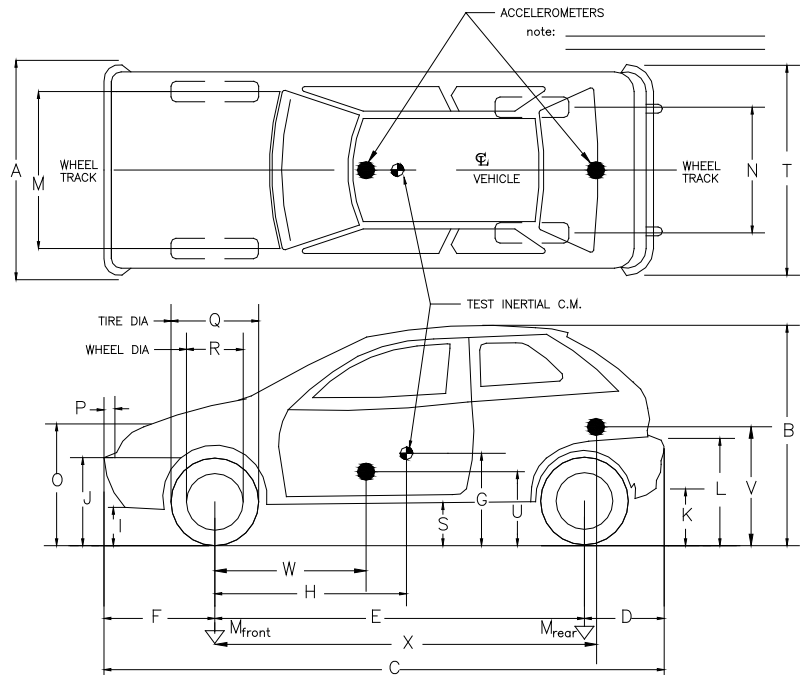
Describe any damage to the vehicle prior to test: _____

● Denotes accelerometer location.

NOTES: _____

Engine Type: 4 cylinder
 Engine CID: 1.6 liter
 Transmission Type:
 ___ Auto or x Manual
x FWD ___ RWD ___ 4WD
 Optional Equipment:

Dummy Data:
 Type: 50th percentile male
 Mass: 189 lb
 Seat Position: Driver Side



Geometry: inches

A	<u>66.38</u>	F	<u>33.00</u>	K	<u>11.00</u>	P	<u>4.12</u>	U	<u>14.00</u>
B	<u>57.75</u>	G	<u>---</u>	L	<u>24.12</u>	Q	<u>22.19</u>	V	<u>22.00</u>
C	<u>165.75</u>	H	<u>37.18</u>	M	<u>57.75</u>	R	<u>15.38</u>	W	<u>45.00</u>
D	<u>34.00</u>	I	<u>7.12</u>	N	<u>57.12</u>	S	<u>7.62</u>	X	<u>107.00</u>
E	<u>98.75</u>	J	<u>21.00</u>	O	<u>30.62</u>	T	<u>66.12</u>		

Wheel Center Ht Front _____ Wheel Center Ht Rear _____

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	<u>1918</u>	M_{front}	<u>1512</u>	<u>1610</u>
Back	<u>1874</u>	M_{rear}	<u>913</u>	<u>1004</u>
Total	<u>3638</u>	M_{Total}	<u>2425</u>	<u>2614</u>

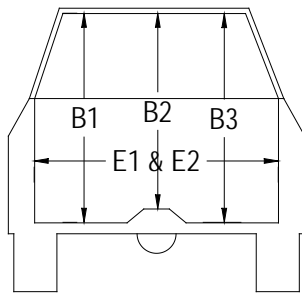
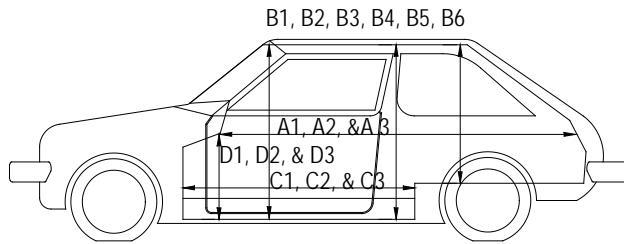
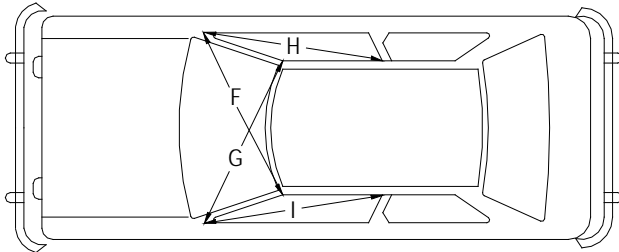
Allowable TIM = 2420 lb ±55 lb | Allowable GSM = 2585 lb ± 55 lb

Mass Distribution:

lb LF: 771 RF: 741 LR: 473 RR: 440

Table D3. Occupant Compartment Measurements for Test No. 490023-5.

Date: 2013-03-26 Test No.: 490023-5 VIN No.: KNADE123X86369048
 Year: 2008 Make: Kia Model: Rio



OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

	Before (inches)	After (inches)
A1	68.00	68.00
A2	66.25	66.25
A3	68.00	68.00
B1	40.50	40.50
B2	39.50	39.50
B3	40.50	40.50
B4	36.25	36.25
B5	35.50	35.50
B6	36.25	36.25
C1	26.00	26.00
C2	-----	-----
C3	26.00	26.00
D1	9.50	9.50
D2	-----	-----
D3	9.50	9.50
E1	51.75	51.75
E2	51.00	51.00
F	50.50	50.50
G	50.50	50.50
H	37.00	37.00
I	37.00	37.00
J*	51.00	51.00

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



0.000 s



0.075 s



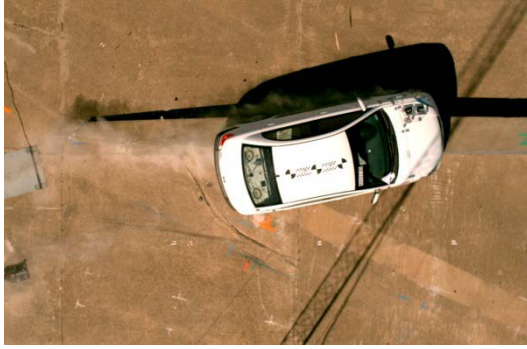
0.150 s



0.225 s



Figure D1. Sequential Photographs for Test No. 490023-5 (Overhead and Side Views).



0.300s



0.375 s



0.450 s



0.576 s



**Figure D1. Sequential Photographs for Test No. 490023-5
(Overhead and Side Views) (continued).**



0.000 s



0.075 s



0.150 s



0.225 s



0.300 s



0.375 s



0.450 s



0.576 s

Figure D2. Sequential Photographs for Test No. 490023-5 (Rear View).

Roll, Pitch, and Yaw Angles

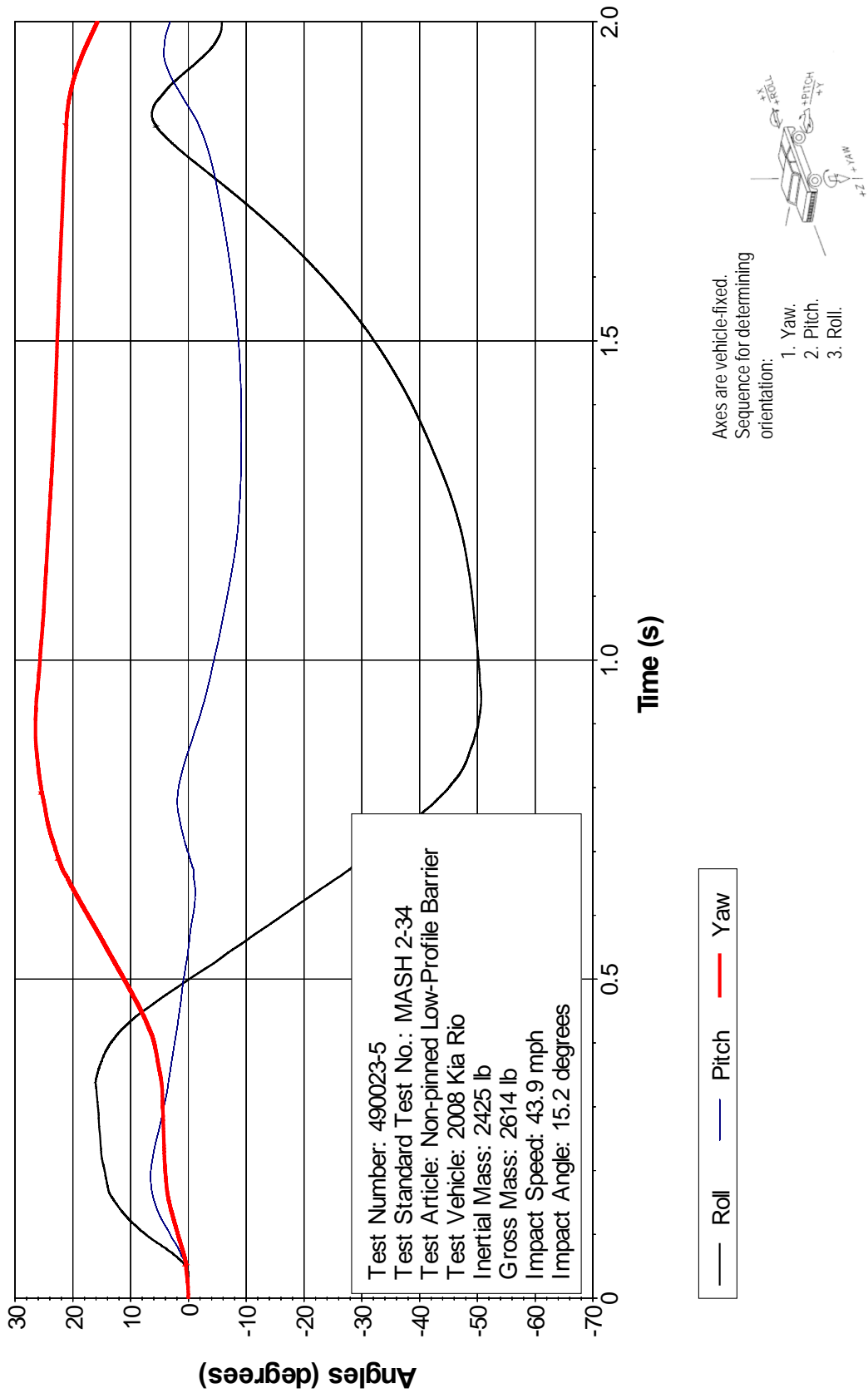


Figure D3. Vehicle Angular Displacements for Test No. 490023-5.

X Acceleration at CG

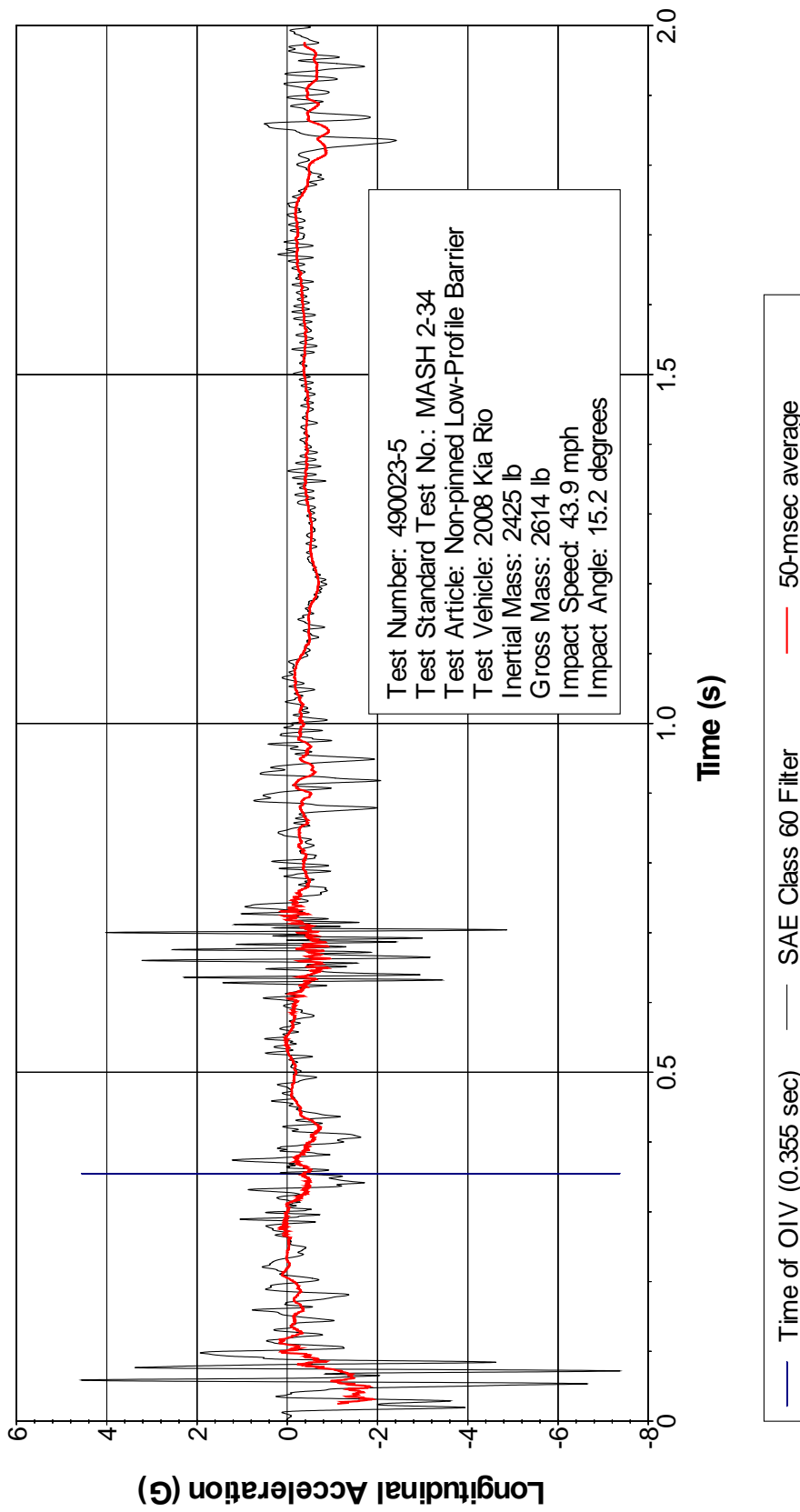


Figure D4. Vehicle Longitudinal Accelerometer Trace for Test No. 490023-5 (Accelerometer Located at Center of Gravity).

Y Acceleration at CG

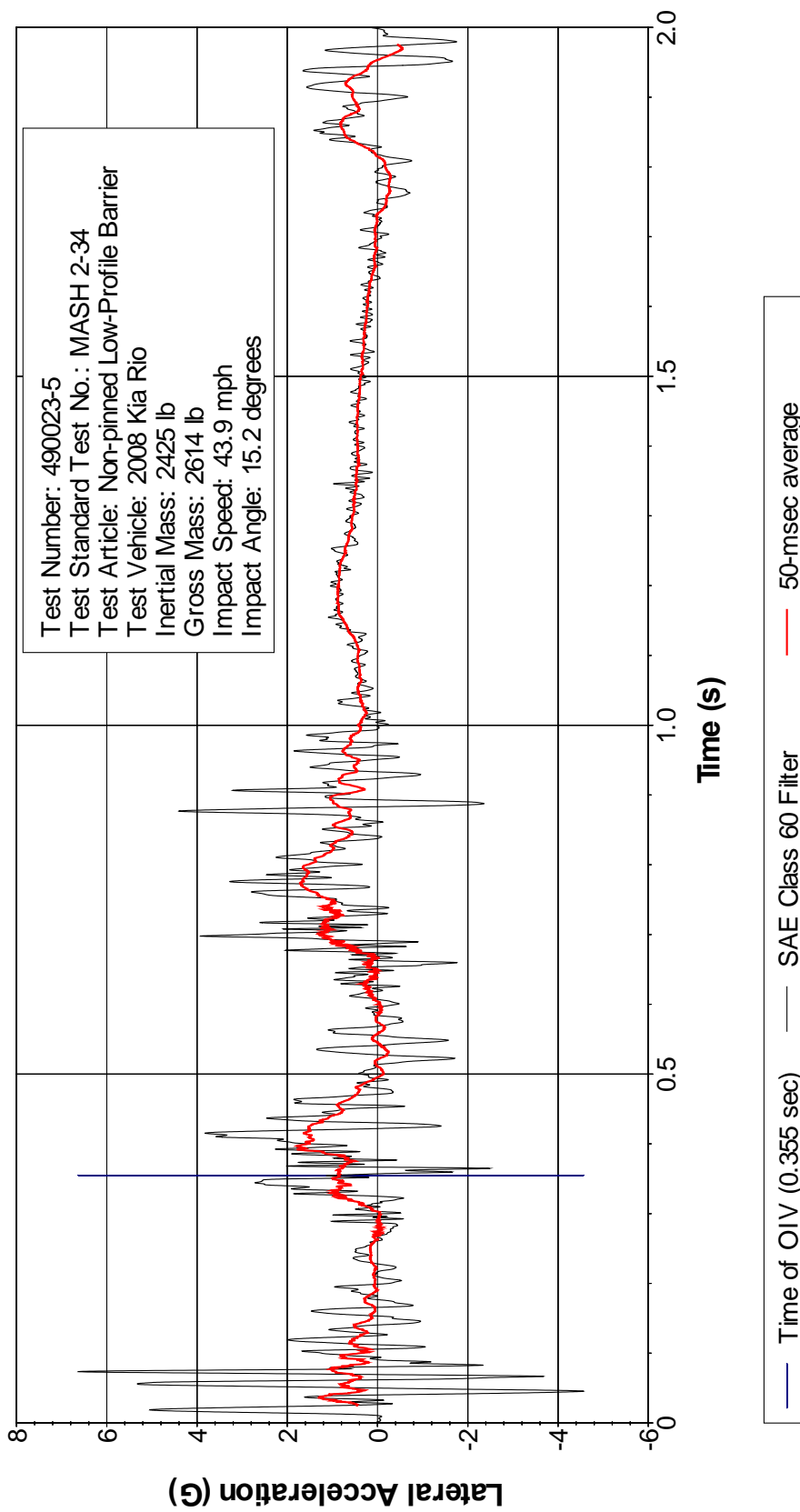


Figure D5. Vehicle Lateral Accelerometer Trace for Test No. 490023-5 (Accelerometer Located at Center of Gravity).

Z Acceleration at CG

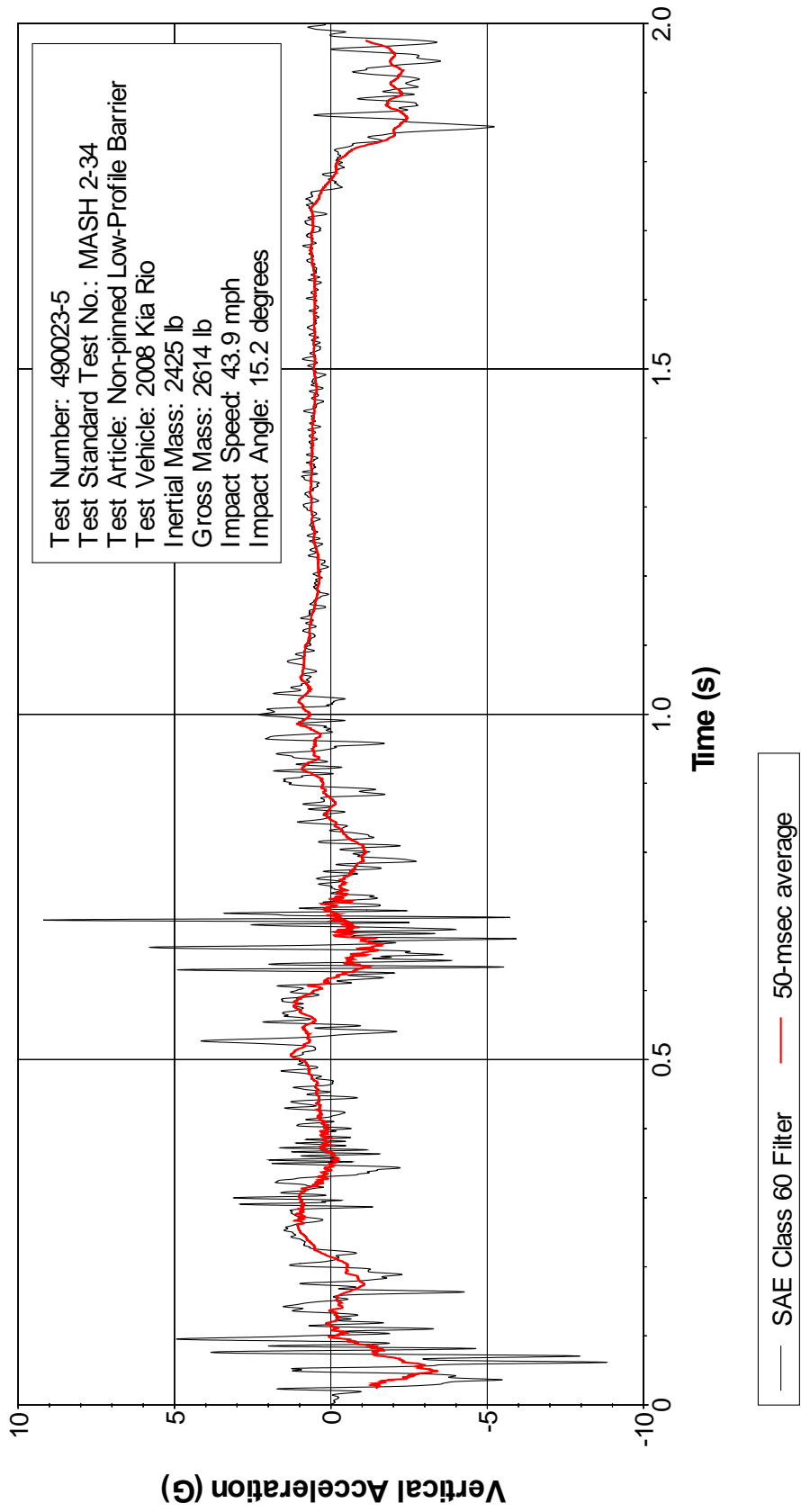


Figure D6. Vehicle Vertical Accelerometer Trace for Test No. 490023-5 (Accelerometer Located at Center of Gravity).

X Acceleration Rear of CG

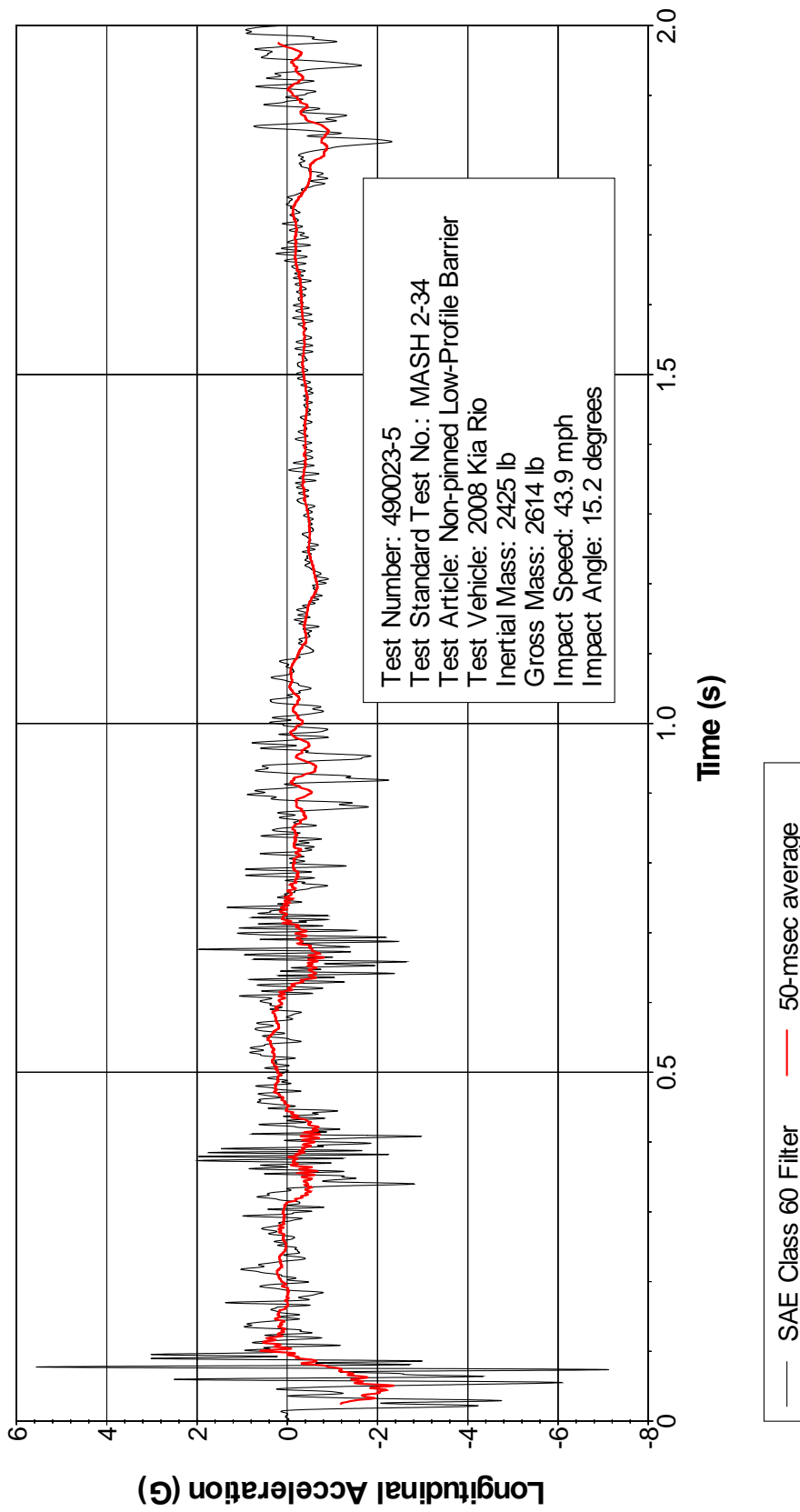


Figure D7. Vehicle Longitudinal Accelerometer Trace for Test No. 490023-5 (Accelerometer Located Rear of Center of Gravity).

Y Acceleration Rear of CG

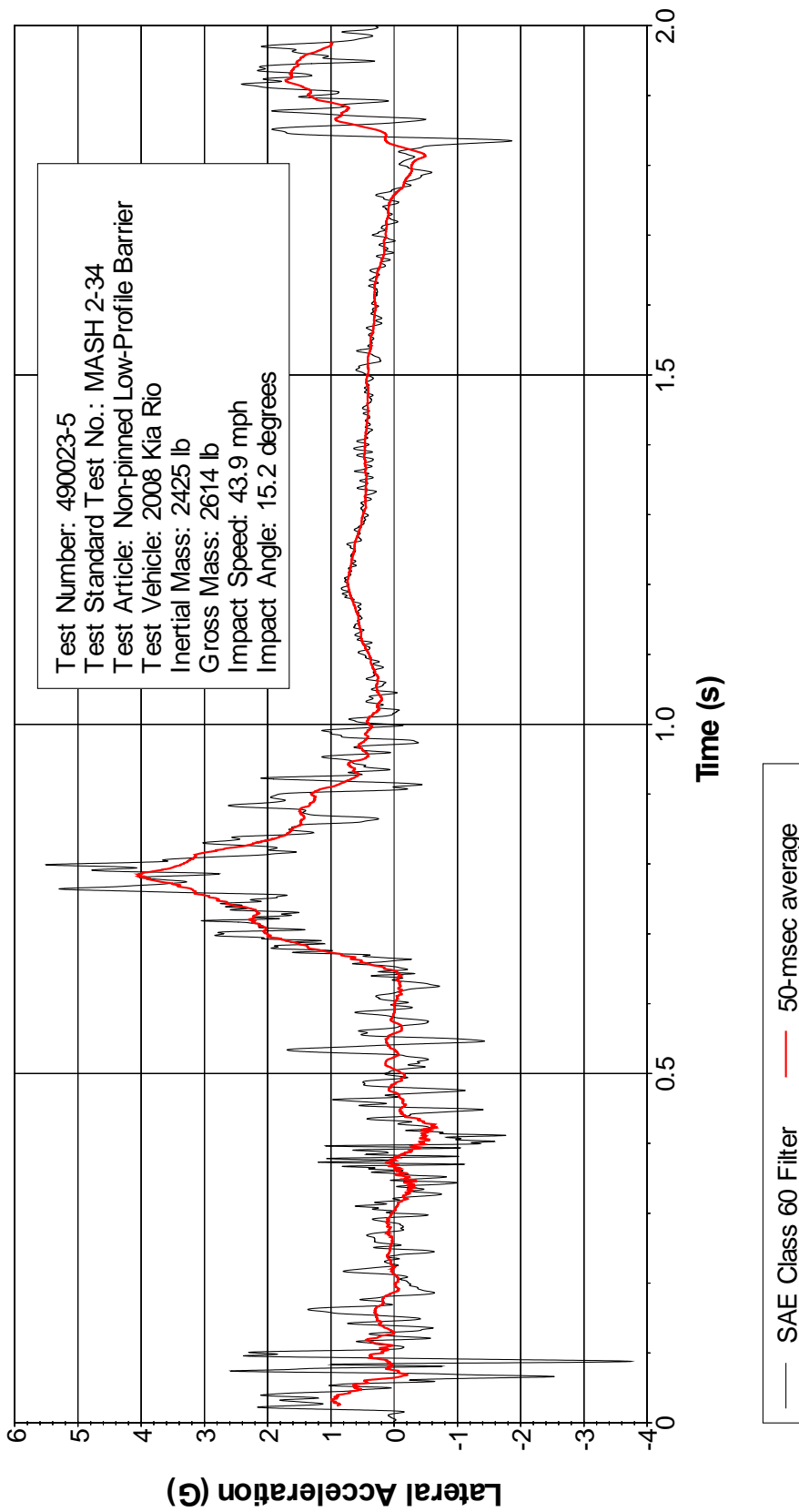


Figure D8. Vehicle Lateral Accelerometer Trace for Test No. 490023-5 (Accelerometer Located Rear of Center of Gravity).

Z Acceleration Rear of CG

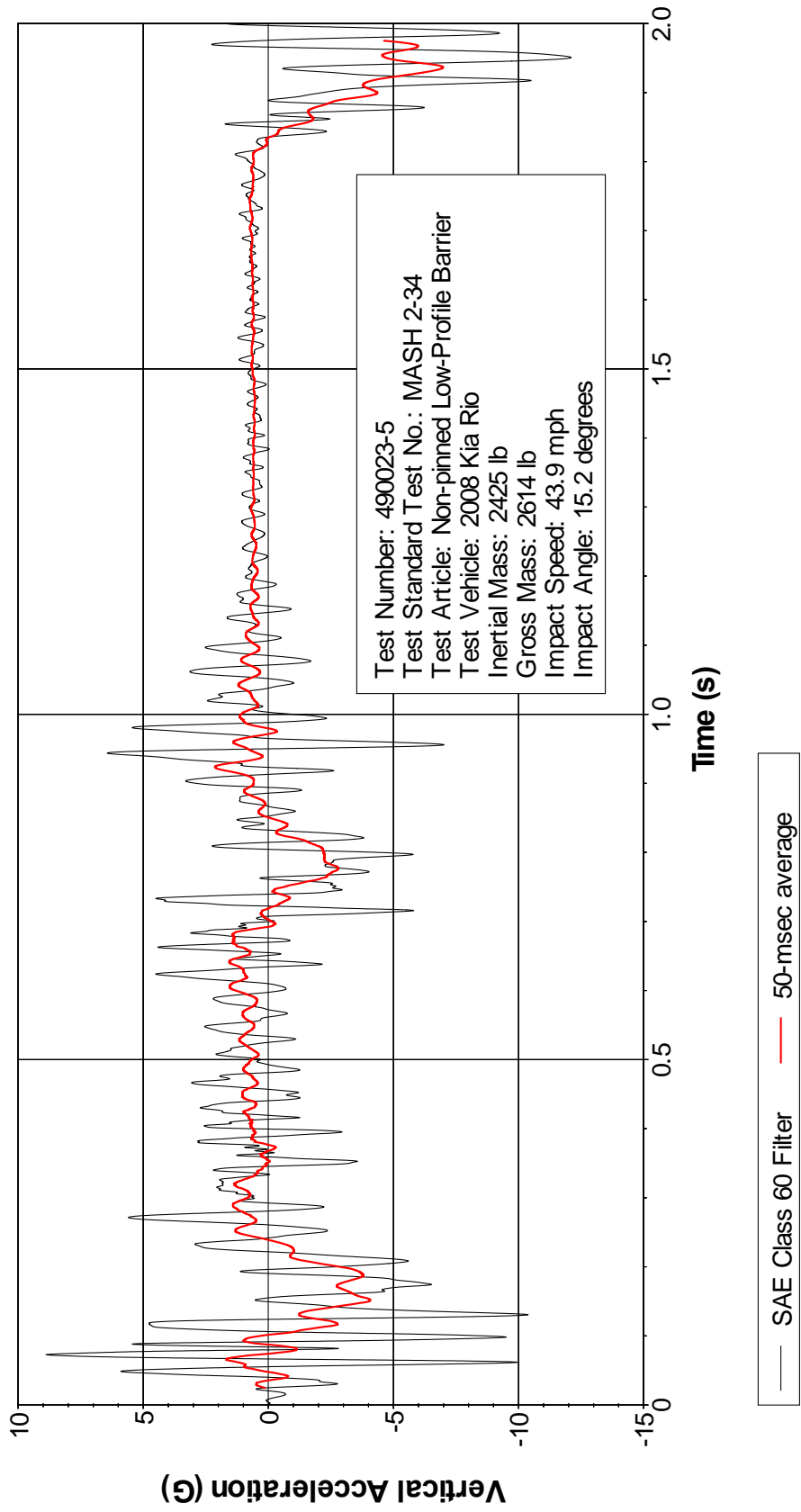


Figure D9. Vehicle Vertical Accelerometer Trace for Test No. 490023-5 (Accelerometer Located Rear of Center of Gravity).

