TESTING CERT # 2937.01

Research Project Number TPF-5(193) Supplement #29

MINIMUM EFFECTIVE GUARDRAIL LENGTH FOR THE MGS

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Madison, Wisconsin 53707

MwRSF Research Report No. TRP-03-276-13

August 12, 2013

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. TRP-03-276-13	2.	3. Recipient's Accession No.	
4. Title and Subtitle Minimum Effective Guardrail Length for the MGS		5. Report Date August 12, 2013	
		6.	
7. Author(s) Weiland, N.A., Reid, J.D., Faller, R.K., Sicking, D.L., Bielenberg, R.W., and Lechtenberg, K.A.		8. Performing Organization Report No. TRP-03-276-13	
9. Performing Organization Name and Address Midwest Roadside Safety Facility (MwRSF) Nebraska Transportation Center University of Nebraska-Lincoln 130 Whittier Research Center 2200 Vine Street Lincoln, Nebraska 68583-0853		10. Project/Task/Work Unit No.	
		11. Contract © or Grant (G) No. TPF-5(193) Supplement #29	
12. Sponsoring Organization Name and Address Wisconsin Department of Transportation 4802 Sheboygan Avenue Madison, Wisconsin 53707		13. Type of Report and Period Covered Final Report: 2010 – 2013	
		14. Sponsoring Agency Code TPF-5(193) Supp.#29	
15. Supplementary Notes Prepared in cooperation with U.S. Department of Transportation, Federal Highway Administration.			

16. Abstract (Limit: 200 words)

Varying roadside hazards and roadway geometries can result in a calculated length-of-need for a W-beam guardrail system to be shorter than the currently-tested minimum length. The recommended minimum length for the standard Midwest Guardrail System (MGS) has been 175 ft (55.3 m) based on crash testing according to the NCHRP Report No. 350 and MASH testing specifications.

The primary objective of this research study was to evaluate the effects of reducing the system length of the MGS. The research study included one full-scale crash test with a Dodge Ram pickup truck impacting a 75-ft (22.9-m) long MGS system. The 75-ft (22.9-m) long system satisfied the MASH Test Level 3 (TL-3) evaluation criteria for test designation no. 3-11. A comparison of the 75-ft (22.9-m) and 175-ft (55.3-m) long systems demonstrated that the reduced system length did not adversely affect the overall system performance or deflections.

A detailed analysis was then performed using BARRIER VII and LS-DYNA to analyze system performance with lengths of 62 ft – 6 in. (19.1 m) and 50 ft (15.2 m). The 62-ft 6-in. (19.1-m) MGS produced similar rail forces, deflections, anchor forces, and anchor deflections as the 75-ft (22.9-m) MGS. The 50-ft (15.2-m) and 62-ft 6-in. (19.1-m) MGS systems indicated successful redirection of the vehicle and shielding of the hazard. However, full-scale crash testing is recommended for both the 62-ft 6-in. (19.1-m) and 50-ft (15.2-m) MGS. This research was conducted to evaluate the strength of the shortened MGS system and not to recommend real world installations of the MGS at these reduced lengths.

17. Document Analysis/Descriptors Highway Safety, Crash Test, Roadside Appurtenances, Compliance Test, MASH, MGS, Guardrail, TL-3, Minimum Length		18. Availability Statement No restrictions. Document available from: National Technical Information Services, Springfield, Virginia 22161	
19. Security Class (this report) Unclassified	20. Security Class (this page) Unclassified	21. No. of Pages 218	22. Price

DISCLAIMER STATEMENT

This report was completed with funding from the Wisconsin Department of Transportation (WisDOT). The contents of this report reflect the views and opinions of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the WisDOT nor the Federal Highway Administration, U.S. Department of Transportation. This report does not constitute a standard, specification, regulation, product endorsement, or an endorsement of manufacturers.

UNCERTAINTY OF MEASUREMENT STATEMENT

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

INDEPENDENT APPROVING AUTHORITY

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

ACKNOWLEDGEMENTS

The authors wish to acknowledge the Wisconsin Department of Transportation for sponsoring this project and MwRSF personnel for constructing the barriers and conducting the crash tests.

Acknowledgement is also given to the following individuals who made a contribution to the completion of this research project.

Midwest Roadside Safety Facility

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S.K. Rosenbaugh, M.S.C.E., E.I.T., Research Associate Engineer
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1 INTRODUCTION

1.1 Problem Statement

Certain types of roadside hazards, combined with varying roadway and roadside geometries, can cause the calculated length-of-need (LON) for guardrail systems to be shorter than 175 ft (53.3 m). As a result, the following question periodically arises, "Is there a minimum length of guardrail that is required to ensure that the guardrail system adequately contains and redirects an impacting vehicle?"

The Midwest Guardrail System (MGS) is a post-and-rail system which was originally developed according to the Test Level 3 (TL-3) standards set forth by the National Cooperative Highway Research Program (NCHRP) Report No. 350 [1] to provide a reliable W-beam guardrail system capable of capturing and redirecting higher center-of-mass vehicles [2]. The MGS has also been successfully crash tested and evaluated according to the TL-3 procedures provided in the *Manual for Assessing Safety Hardware* (MASH) [3] for both the 1100C passenger car and 2270P pickup truck [4-6].

In general, W-beam guardrail systems, including the MGS, have been crash tested using a system length of approximately 175 ft (53.3 m). The primary basis for crash testing a W-beam guardrail system at a minimum length of 175 ft (53.3 m) is to accurately predict the working width and dynamic deflection for the barrier system at a location where end effects are eliminated. It is unknown whether the safety performance of the MGS, or its dynamic deflection, is adversely affected by using an installed length shorter than the tested length of 175 ft (53.3 m). As the guardrail system gets shorter, a larger portion of a barrier's redirective force must be carried by the end anchors. Higher anchor loads correspond to larger longitudinal anchor movement. In general, terminal testing has shown that longitudinal increases in anchor motion can lead to increases in lateral barrier deflection. Thus, dynamic deflections will likely increase as the impact location approaches the ends of the barrier. It is imperative to understand how system shortening effects anchor movement and barrier deflection.

Due to the increase in effective impact angle, vehicular impacts into flared systems result in higher impact severity ratings and impose higher loads on the end anchors. Successful testing of the MGS on a flare rate of up to 5:1 illustrated the robustness of the system [7-9]. Therefore, it was speculated that tangential guardrail systems at lengths shorter than 175 ft (53.3 m) with standard impact severity ratings could withstand the increased anchor loads and successfully redirect 2270P vehicles at the MASH TL-3 test conditions. However, no crash test data existed to support or recommend the use of shorter guardrail lengths.

Shortening the barrier length also increases the likelihood of vehicles interacting with the downstream end anchor. Full-scale crashing testing has shown successful redirection of a 2270P vehicle impacting the MGS at a location six posts upstream of the downstream end terminal [10]. However, crash testing with the 2270P vehicle has not been conducted at locations closer to the downstream end terminal, and it is possible that the vehicle could gate through the barrier system. Therefore, systems shorter than 175 ft (53.3 m) may have a significantly reduced zone of containment and redirection. The length of the zone of containment and redirection must also be evaluated for short barrier installations.

1.2 Objectives

The objective of this research project was to evaluate and determine the overall safety performance, dynamic deflection, and effective working width of the Midwest Guardrail System at lengths shorter than the current, 175-ft (53.3-m) minimum recommended length. The guardrail system lengths were to be evaluated according to the TL-3 safety performance criteria set forth by the American Association of State Highway and Transportation Officials (AASHTO) in MASH [3].

1.3 Scope

The proposed research began by performing a limited, LS-DYNA computer simulation effort on a 75-ft (22.9-m) long MGS to determine the impact location for the proposed crash test. The computer analysis was used to identify the range of impact locations for which the barrier could contain and redirect without allowing the vehicle to gate through or destroy the downstream end anchorage system. A full-scale crash test was then conducted on a 75-ft (22.9-m) long MGS with a 2270P vehicle according to test designation no. 3-11 of MASH.

In addition to full-scale crash testing, computer simulations were performed to investigate shorter system lengths below 175 ft (53.3 m). A BARRIER VII model was validated with the full-scale crash test, then adjusted to model system lengths at 62 ft – 6 in. (19.1 m) and 50 ft (15.2 m). LS-DYNA simulations were conducted to further investigate a 50-ft (15.2-m) long MGS at various impact locations. Finally, conclusions were made that pertain to the overall performance of the 75-ft (22.9-m) long MGS, and recommendations were provided for MGS lengths of 62 ft – 6 in. (19.1 m) and 50 ft (15.2 m). This research study was conducted to evaluate the strength and performance of MGS guardrail systems with reduced lengths and to analyze the loads into the end anchorages, however, the research performed was not to encourage real world installations of these shortened system lengths.

2 LITERATURE REVIEW

Limited research on short sections of guardrail has been published by the Highway Research Board from the 1960's. Cichowski, Skeels, and Hawkins observed that adhering to a minimum length of guardrail was critical [11]. During their study, an unanchored, 37-ft 6-in. (11.4-m) long section of guardrail, consisting of three 12-ft 6-in. (3.8-m) long segments, was impacted by a 3,963-lb (1,798-kg) sedan at an impact speed and angle of 65 mph (104.6 km/h) and 25 degrees, respectively. A total of four 6-ft 2-in. (1.9-m) long posts of two different types were utilized. The end posts were 8-in. x 8-in. (203-mm x 203-mm) wood posts, and 6-in. x 8-in. (152-mm x 203-mm) wood posts were spaced evenly through the center section of the rail. This crash test resulted in the vehicle completely penetrating through the guardrail. From these findings, it was concluded that for a 35-mph (56.3-km/h), 20-degree vehicular impact, the minimum installation length was 100 ft (30.5 m), otherwise a collapse toward the center of the rail would occur. Further, a 65-mph (104.6 km/h), 20-degree crash test required a minimum installation length of 250 ft (76.2 m). For additional security, the researchers recommended that both ends be ramped and anchored into the ground to develop the full ribbon tensile strength across the entire installation. It was also concluded that without end anchors, full ribboning would be impossible with short barrier lengths.

Beaton et al. provided the most in-depth research on the effects of guardrail length [12]. Long lengths of guardrail permit load transfer to posts at substantial distances away from the impact location in either direction. In short system installations, individual connections to the post are forced to withstand greater loads than those in longer guardrail systems. There must be a sufficient quantity of posts in any beam and post system to develop the axial strength of the beam. Test no. 131 consisted of a 37 ft – 6 in. (11.4 m) unanchored section of 12-gauge galvanized steel, corrugated-beam guardrail with seven 8-in. x 8-in. x 64-in. (203-mm x 203-mm x 1,626-mm) Douglas Fir posts spaced 6 ft – 3 in. (1.9 m) on center with a 36-in. (914-mm) post embedment. Machine bolts, 5/8-in. (16-mm) diameter, with round cut washers under the head and nut were used to fasten the rails. The test article was subjected to a 63-mph (101.4-km/h), 25-degree impact near the center post with a 4,540-lb (2,059-kg) large passenger sedan. The test was unsuccessful as the vehicle penetrated through the barrier, and the guardrail snagged on the vehicle and was drug away. This failure led to a second test, test no. 132, with a total system length of 62 ft – 6 in. (19.1 m) under similar impact conditions. In an attempt to increase end rigidity, a slight flare was formed by modifying the blockouts at each end of the guardrail. No blockouts were placed on the end posts and 4-in. (102-mm) deep blockouts were placed on the second posts from each end. Impact occurred 2 ft (0.6 m) downstream of post no. 4. As before, the section was unanchored, and the test failed. Again, the vehicle penetrated through the barrier, and the guardrail snagged on the vehicle.

Based on test nos. 131 and 132, it was concluded that any unanchored guardrail section was vulnerable to severe impacts, such as at the test conditions of 60 mph (96.5 km/h) and 25 degress, when struck within 30 ft (9.1 m) of either end, regardless of the length of the section. It was determined that loads must be transferred to the soil by some other means than through inline posts for short sections [13]. In addition to test nos. 131 and 132, Nordlin et al.. conducted six full-scale crash tests on short sections of blocked-out, corrugated metal beam guardrail systems. Three of these tests were performed on freestanding sections using two different end anchorage systems. The other three tests were performed on simulated bridge approach guardrail flares using a cable anchor assembly on the upstream end and a rigid attachment to the concrete bridge rail parapet at the other end.

One end anchorage system, known as the “Texas Twist” design, was developed by the Texas Highway Department. The results of test nos. 133 and 134 indicated that short guardrail sections utilizing the "Texas Twist" performed adequately when impacted near the center of the guardrail [13]. However, system performance was poor with regard to impacts onto the ramped ends. The installations for these two tests were 62 ft – 6 in. (19.1 m) long with 18-ft 9-in. (5.7-m) sections of beam at each end, twisted 90 degrees axially and bent down. The ends were bolted to a fabricated steel post encased in an 18-in. diameter by 5-ft (457-mm x 1.5-m) deep concrete footing. In test no. 133, the impact occurred near the center of the guardrail system at a speed of 56 mph (90.1 km/h) and an angle of 30 degrees. The vehicle was redirected, and the barrier proved effective. Test no. 134 was conducted on the sloped end region of the barrier. The sedan impacted at 63 mph (101.4 km/h) and 24 degrees approximately 4 ft – 11 in. (1.5 m) from the concrete footing. The vehicle vaulted the barrier and ultimately rolled over.

Further attempts to provide end anchorages were investigated with the development of a cable end anchor [13]. Test no. 135 utilized a 50-ft (15.2-m) section of blocked-out guardrail constructed on a parabolic flare. No blockouts were placed on the end posts, and 4-in. (102-mm) deep blockouts were placed on the second posts from each end. Round cut washers were used under all bolt heads. A ¾-in. (19-mm) steel cable with a 21.4-ton (213-kN) tensile capacity was attached to the barrier end with a custom fitting between the first and second posts. The opposite end was clamped to a 1¼-in. (32-mm) eye bolt attached to a steel section cast in an 18-in. diameter by 5-ft (457-mm x 1.5-m) deep concrete footing. The vehicle in test no. 135 impacted the barrier at 59 mph (95 km/h) and 28 degrees and remained in contact for 22 ft (6.7 m) before being redirected and exiting the system at an angle of 24 degrees. The vehicle sustained moderate front-end damage, but the test passed. The success of this test prompted further evaluation into the short section of a flared guardrail, bridge approach as indicated by test nos. 135 through 138. As a result of test nos. 135 through 138, an effective cable anchoring device was developed for short, free-standing sections of guardrail. In addition, an efficient bridge approach guardrail flare design was developed, which provided a relatively smooth transition from the semi-flexible, blocked-out beam barrier (8-in. x 8-in. (203-mm x 203-mm) posts at 6 ft-3 in. (1.9 m) on center) through a semi-rigid system barrier (10-in. x 10-in. (254-mm x 254-mm) posts at 3 ft-1½ in. (1.0 m) on center) to a rigid reinforced concrete bridge rail.

The guardrail design was a common factor in each of these tests. At the time of the research in the 1960's, the California Division of Highways standard metal beam guardrail consisted of a 12-gauge (0.105 in.) corrugated steel beam mounted 27 in. (686 mm) above groundline with 8-in. x 8-in. x 64-in. (203-mm x 203-mm x 1,626-mm) treated Douglas Fir posts spaced 6 ft-3 in. (1.9 m) on center [11-13]. The test installation summaries, conditions and results have been tabulated in Tables 1 and 2.

Table 1. Test Installation Summary

Test Information				System Information				
No.	Reference	Date	Organization	Length	Brief System Description	End Conditions	No. of Posts	Soil Conditions
601	[11]	7/20/1960	General Motors	37 ft - 6 in. (11.4 m)	(3) 12 ft - 6 in. (3.8-m) sections at 37 ft - 6 in. (11.4 m) total	Both ends ramped and anchored	4	Dry
131	[12]	11/30/1965	California Dept of Public Works	37 ft - 6 in. (11.4 m)	37 ft - 6 in. (11.4 m) free standing section of unanchored guardrail.	Unanchored	7	Damp
132	[12]	6/15/1966	California Dept of Public Works	62 ft - 6 in. (19.1 m)	62 ft - 6 in. (19.1 m) unanchored (in an attempt to increase end rigidity, a slight flare was formed by modifying the blockouts at each end of the installation, no blocks on end posts)	Unanchored	11	Dry
133	[13]	12/15/1966	California Dept of Public Works	62 ft - 6 in. (19.1 m)	62 ft - 6 in. (19.1 m) section of guardrail with 18-ft 9-in. (5.7 m) of the beam section at each end twisted 90 deg axially, bent down and bolted to fabricated steel posts cast in 18-in. diameter by 5-ft (457-mm x 1.5-m) deep cylindrical concrete footings.	Texas Twist	5	Damp
134	[13]	1/18/1967	California Dept of Public Works	62 ft - 6 in. (19.1 m)	62 ft - 6 in. (19.1 m) section of guardrail with 18-ft 9-in. (5.7 m) of the beam section at each end twisted 90 deg axially, bent down and bolted to fabricated steel posts cast in 18-in. diameter by 5-ft (457-mm x 1.5-m) deep cylindrical concrete footings.	Texas Twist	5	Damp
135	[13]	8/10/1967	California Dept of Public Works	50 ft (15.2 m)	50 ft (15.2 m) of corrugated metal beam guardrail constructed with a parabolic flare. No block out blocks on end posts/4-in. (102-mm) blocks on second to end. Secured with 3/4-in. (19-mm) steel cable attached with special fitting to beam between first and second posts. Other end was clamped to a 1-1/4-in. (32-mm) eye bolt attached to a steel 8 WF 17 section cast in an 18-in. diameter by 5-ft (457-mm x 1.5-m) deep concrete footing.	Cable Anchor	8	Dry
136	[13]	9/28/1967	California Dept of Public Works	53 ft (16.2 m)	Success of Test 135 prompted Test 136 which anchored upstream end of bridge guardrail. 53-ft (16.2-m) section with initial 12 ft (3.7 m) installed with enough curvature that remaining 41 ft (12.5 m) was installed in a straight line.	Cable Anchor to Concete Bridge End Post	9	Dry
137	[13]	2/28/1968	California Dept of Public Works	50 ft (15.2 m)	To correct deficiencies noted in Test 136. 50 ft (15.2 m) section with end offset 4 ft (1.2 m) from projected face of bridge. Blockout block between guardrail beam and the concrete was fabricated of 1/4-in. (6-mm) steel plate rather than the wood vlock post spacing near concrete bridge decreased to 3 ft-1½ in. (1.0 m). Three timber rail posts were changed to 10-in. x 10-in. (254-mm x 254-mm)	Cable Anchor to Concete Bridge End Post (with changes noted)	9	Damp
138	[13]	5/2/1968	California Dept of Public Works	50 ft (15.2 m)	Identical setup to Test 137	Cable Anchor to Concete Bridge End Post	9	Dry

Table 2. Test Conditions and Results

Test No.	Reference No.	Impact Speed mph (km/h)	Impact Angle degrees	Impact Location	Vehicle Weight/Mass lb (kg)	Exit Angle degrees	Pass/Fail
601	[11]	65 (104.6)	25	Near Center	3,963 (1,798)	NA	Fail
131	[12]	63 (101.4)	25	Near Center Post	4,540 (2,059)	NA	Fail
132	[12]	61 (98.2)	25	2 ft (0.6 m) downstream of Post 4	4,540 (2,059)	NA	Fail
133	[13]	56 (90.1)	30	2 ft (0.6 m) downstream of Post 2	4,540 (2,059)	7	Pass
134	[13]	63 (101.4)	24	4 ft – 11 in. (1.5 m) upstream from the concrete footing	4,540 (2,059)	NA	Fail
135	[13]	59 (95)	28	Between Post nos. 2 and 3	4,540 (2,059)	24	Pass
136	[13]	60 (96.6)	33	18 ft (5.5 m) upstream of the simulated bridge end post	4,540 (2,059)	NA	Fail
137	[13]	61 (98.2)	27	Near center of guardrail	4,540 (2,059)	16	Pass
138	[13]	61 (98.2)	25	Upstream of the end anchor cable attachment	4,670 (2,118)	NA	Fail

3 CRITICAL LENGTH AND IMPACT POINT

3.1 Critical Length

A finite element simulation using LS-DYNA was performed in order to determine the impact point for full-scale crash testing [14]. The LS-DYNA simulation of the 2270P model impacting the standard MGS guardrail system was validated with prior full-scale crash testing [15]. Based on previous testing and knowledge of longitudinal guardrail systems, the researchers at Midwest Roadside Safety Facility (MwRSF) had determined that the MGS could potentially be reduced in length, maybe as short as 75 ft (22.9 m). Therefore, the MGS model for this study was reduced to 75 ft (22.9 m). Simulations of a 2270P vehicle impacting at 62 mph (100 km/h) and 25 degrees were conducted on the 75-ft (22.9-m) long MGS to determine the range of impacts for which a vehicle could possibly be contained and redirected without gating through or destroying the end anchorage.

The basic end anchorage system used at MwRSF for crash testing the MGS and other W-beam guardrail systems was constructed from standard end terminal hardware which originated in the modified Breakaway Cable Terminal (BCT) end anchor but is now installed tangent. However, steel foundation tubes with soil plates have been replaced with longer steel foundation tubes. Although the MwRSF end anchorage system is not a crashworthy upstream end terminal, it does provide adequate and representative tensile anchorage to corrugated beam guardrail systems. This anchorage hardware has also undergone successful full-scale crash testing when configured as a trail-end terminal [10,16].

Standard testing for the MGS was conducted with system lengths of 175 ft (53.3 m). Although not quantifiable at this time, it is believed that a considerable amount of longitudinal loading is absorbed by the posts that are not directly in the impact region, which reduces the loading at the anchors. Due to a reduced barrier length, crash testing on a 75-ft (22.9-m) long

MGS may increase loading to both end anchors regardless of the impact location. According to MASH, post no. 3 is usually considered the length-of-need (LON) impact location for guardrail end terminals. As such, energy-absorbing guardrail end terminals are required to redirect an impacting vehicle at this point.

3.2 Impact Point

LS-DYNA simulations were performed along the system length of the shortened MGS. These simulations were not an evaluation of the overall safety performance of the barrier and end terminals. Rather, the initial simulations were conducted to investigate an impact point which, when full-scale crash tested, would successfully evaluate the shortened MGS system. A full-scale crash test at the upstream LON, post no. 3, tested the basic upstream impact location for the 75-ft (22.9-m) MGS and also tested the actual strength of the end anchorages used at MwRSF, as shown in Figure 1. Simulations indicated that impacting at post no. 8 would result in successful redirection; but the downstream end anchorage would be destroyed. Similarly, an impact at post no. 7 would provide successful redirection and, although the end anchorage was damaged, it would not be completely destroyed, as shown in Figure 2. Thus, the range of impacts that would result in a vehicle redirection was determined to be between post no. 3 and post no. 7 for the 75-ft (22.9-m) long MGS at TL-3 conditions.

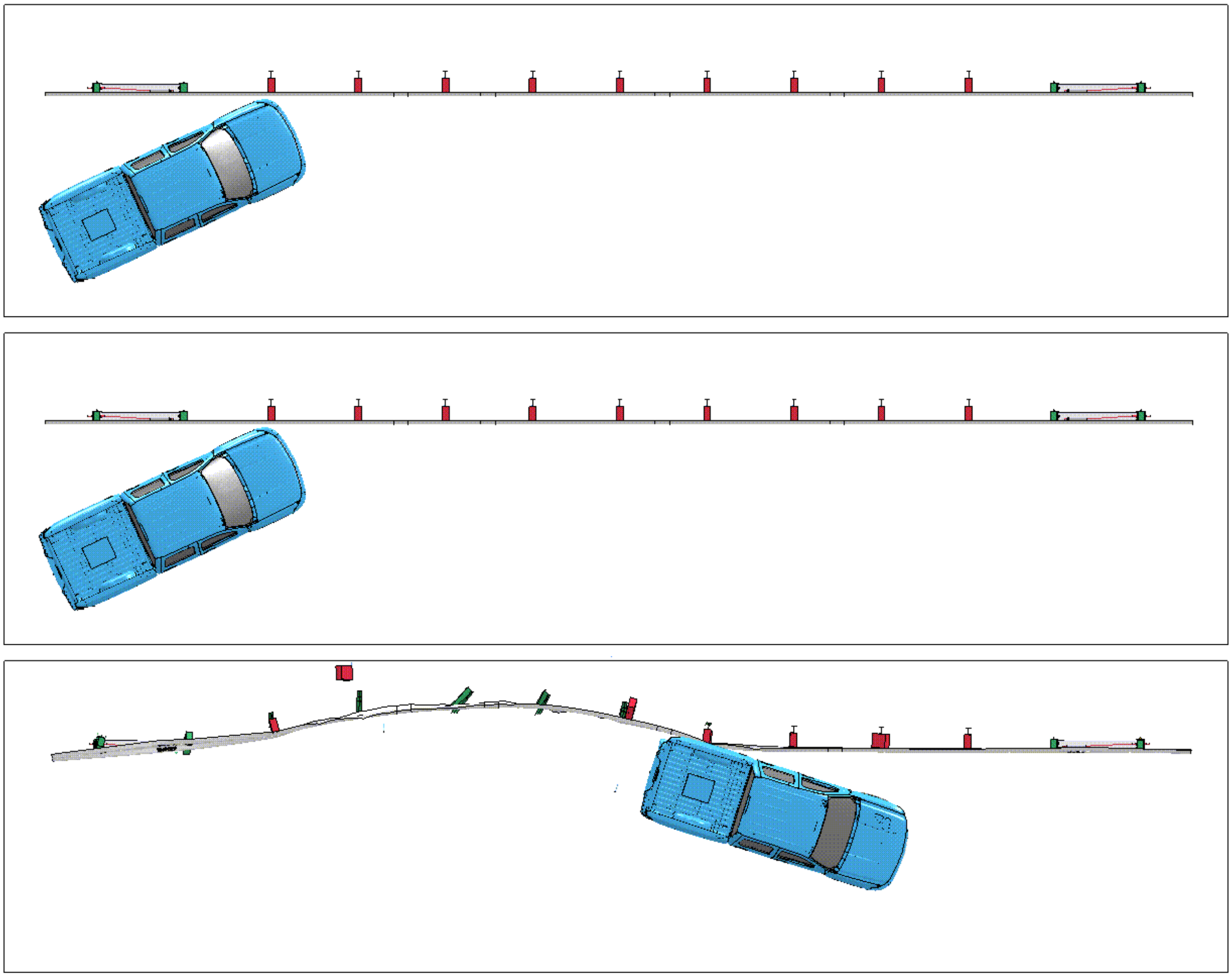


Figure 1. LS-DYNA Simulation, 2270P Impacting 75-ft (22.9-m) MSG at Post no. 3

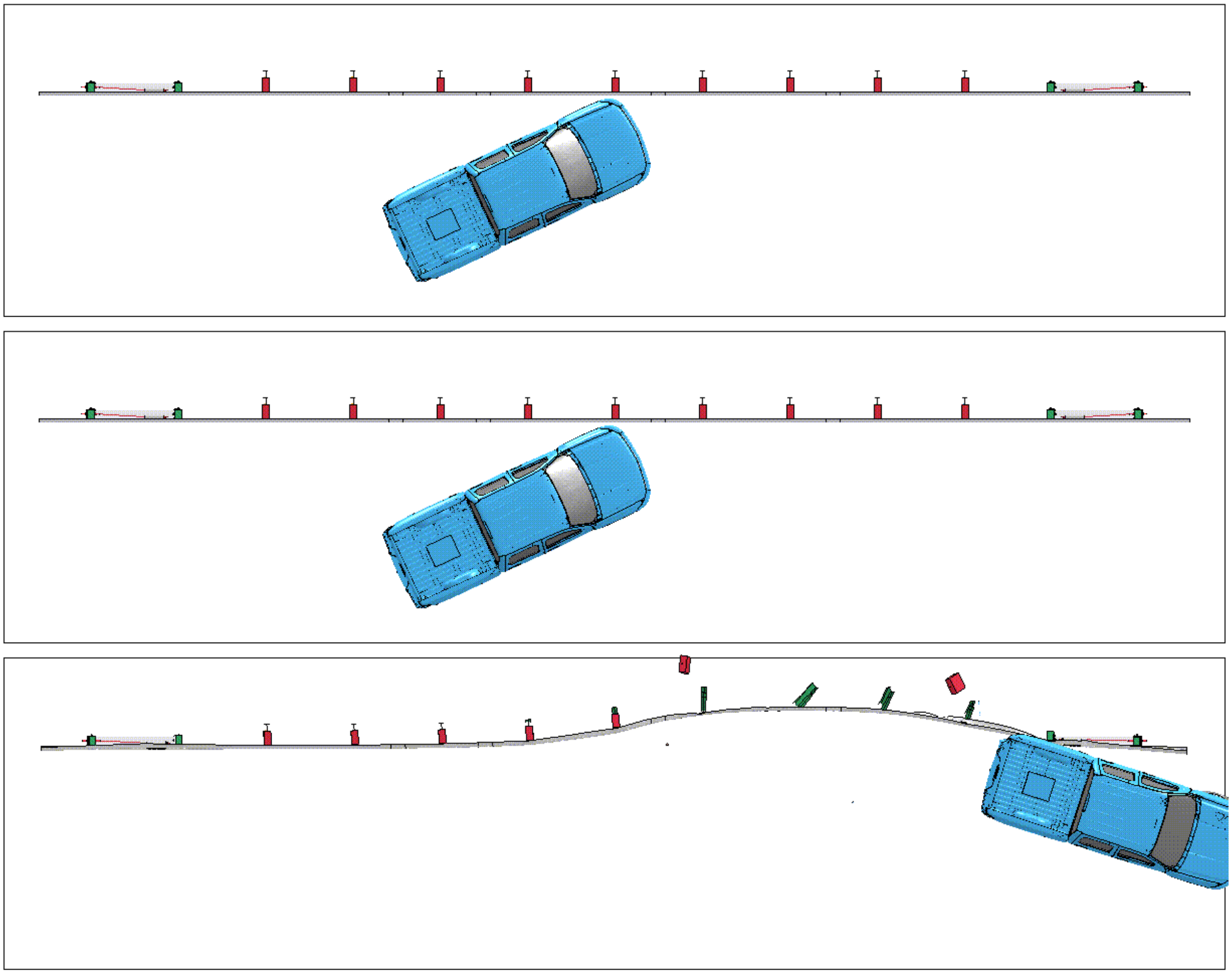


Figure 2.LS-DYNA Simulation, 2270P Impacting 75-ft (22.9-m) MSG at Post no. 7

Although LS-DYNA simulations indicated that impacts within this range may provide redirection capabilities, there are significant simplifications in the model that prevent complete confidence in using it as a predictive tool. Specifically, breaking of the wood posts at the anchors and the steel post's motion through the soil are very difficult to model with current technology. The project included only one full-scale crash test, so an impact point was desired that would evaluate the shortened MGS and not the end anchorages. Due to the uncertainties associated with the simulations, it was determined that impact on the 75-ft (22.9-m) MGS would occur at post no. 4 versus post no. 3. This shift in impact location was believed to appropriately distribute the load between both the upstream and downstream end anchors and provide a basis for achieving the objectives of this minimum effective length MGS project.

4 DESIGN DETAILS

The test installation consisted of 75 ft (22.9 m) of 12-gauge (2.66-mm thick) W-beam guardrail with a top rail mounting height of 31 in. (787 mm) supported by steel posts, as shown in Figure 3. End anchorage systems, similar to those used on tangent guardrail terminals, were utilized on both the upstream and downstream ends of the guardrail system. Design details are shown in Figures 3 through 14. Photographs of the test installation are shown in Figures 15 and 16. Material specifications, mill certifications, and certificates of conformity for the system materials are shown in Appendix A.

The system was constructed with 13 guardrail posts. Post nos. 3 through 11 were galvanized, ASTM A992, W6x8.5 (W152x12.6) steel sections measuring 72 in. (1,829 mm) long. Post nos. 1, 2, 12, and 13 were 5½-in. wide x 7½-in. deep x 46-in. long (140-mm x 191-mm x 1,168-mm) BCT timber posts. The anchor posts were placed 16 in. (406 mm) into 6-in. wide x 8-in. deep x 72-in. long (152-mm x 203-mm x 1,829-mm), ASTM A53 Grade B, steel foundation tube, as shown in Figures 5 and 6. Post nos. 1, 2, 12, and 13 were placed such that the top of the BCT post was 32 in. (813 mm) above the ground line.

All posts were spaced 75 in. (1,905 mm) on center and placed in a compacted, coarse, crushed limestone material, as recommended by MASH [3]. Post nos. 3 through 11 had an embedment depth of 40 in. (1,016 mm). A 6-in. wide x 12-in. deep x 14½-in. long (152-mm x 305-mm x 368-mm) Southern Yellow Pine wood blockout was used to block the rail away from the front face of each steel post, as shown in Figure 10. A 16D double head nail was also driven through a hole in the front flange of the post into the top of the blockout assembly to prevent rotation of the blockout.

Standard 12-gauge (2.66-mm thick) W-beam rails with additional post bolt slots at half-post spacing intervals were mounted on post nos. 1 through 13, as shown in Figures 3, 4, and 13.

The W-beam had a 24⅞-in. (632-mm) center mounting height, such that the center of the rail was mounted 7⅛ in. (181 mm) from the top of the BCT timber post. Rail splices were located at midspans between posts, as shown in Figures 3 and 4. The lap splice connections between the rail sections were configured to reduce vehicle snag potential at the splice during the crash test.

Load cell assemblies were spliced into the anchor cables in the upstream and downstream anchorages to measure the loads experienced during full-scale crash testing. The use of these load cell assemblies were purely research orientated with the purpose of analyzing the anchors' performance. These load cell assemblies would not be implemented in the field for use with real-world installations.

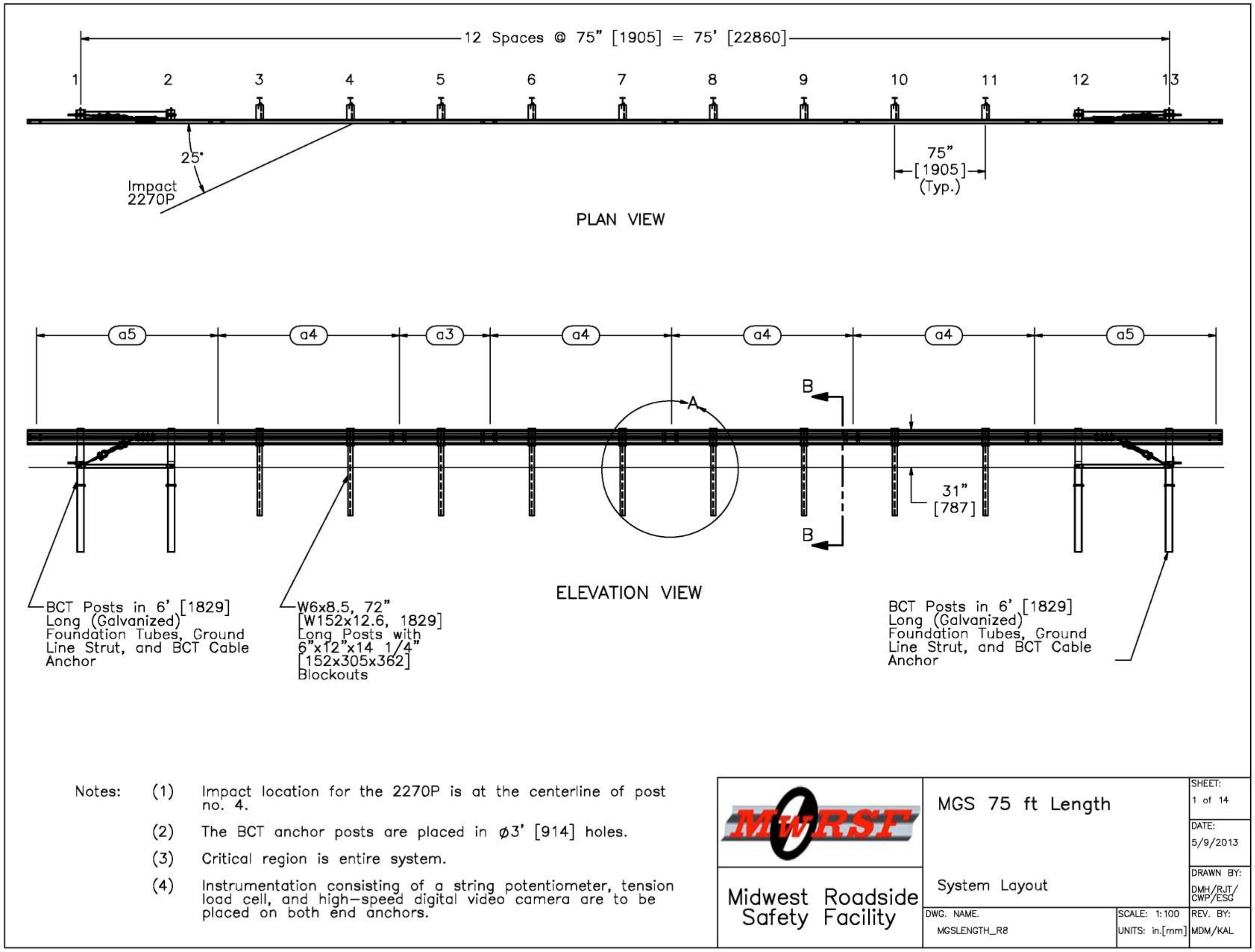


Figure 3. Test Installation Layout, Test No. MGSMIN-1

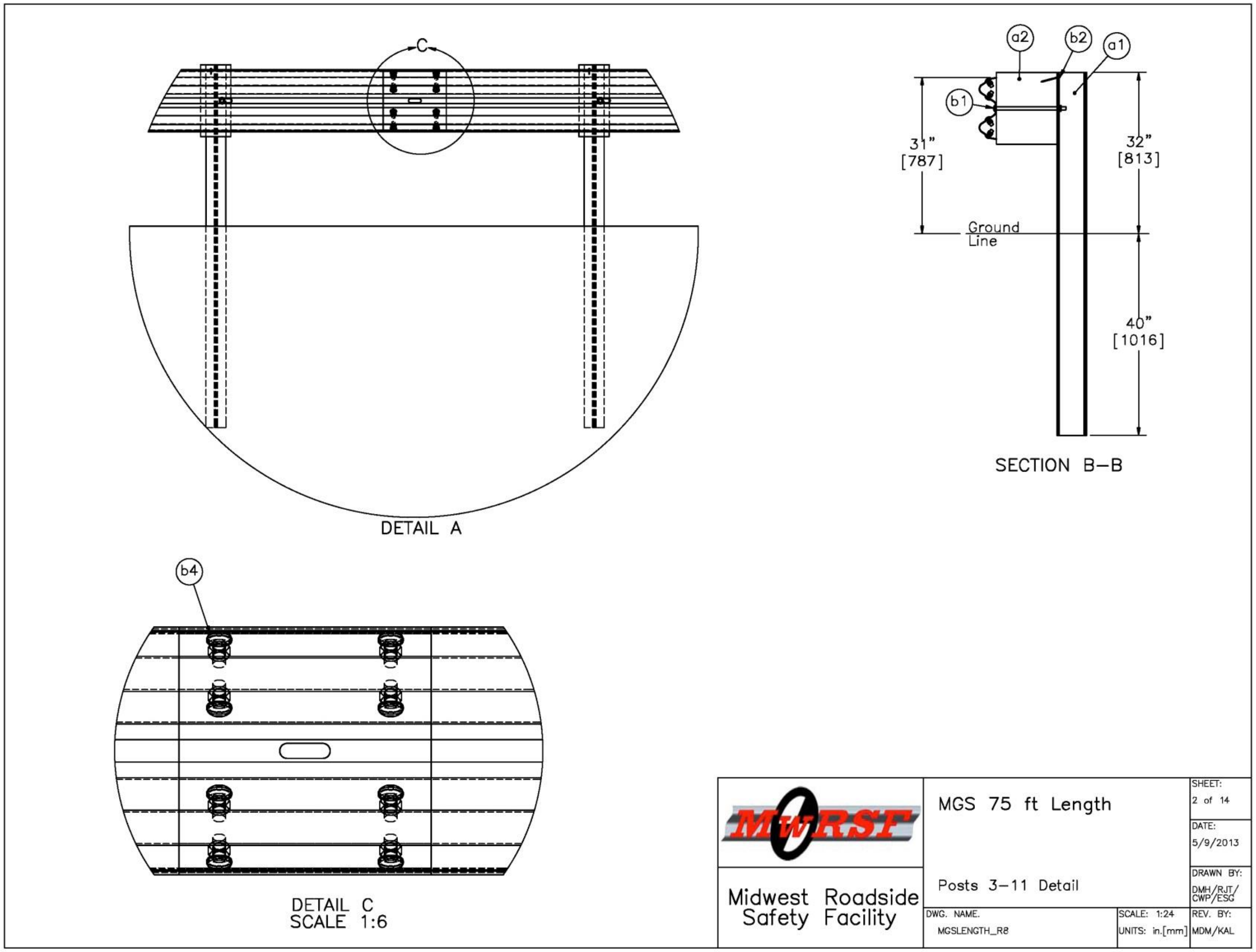


Figure 4. 31-in. (787-mm) Tall MGS Details, Test No. MGSMIN-1

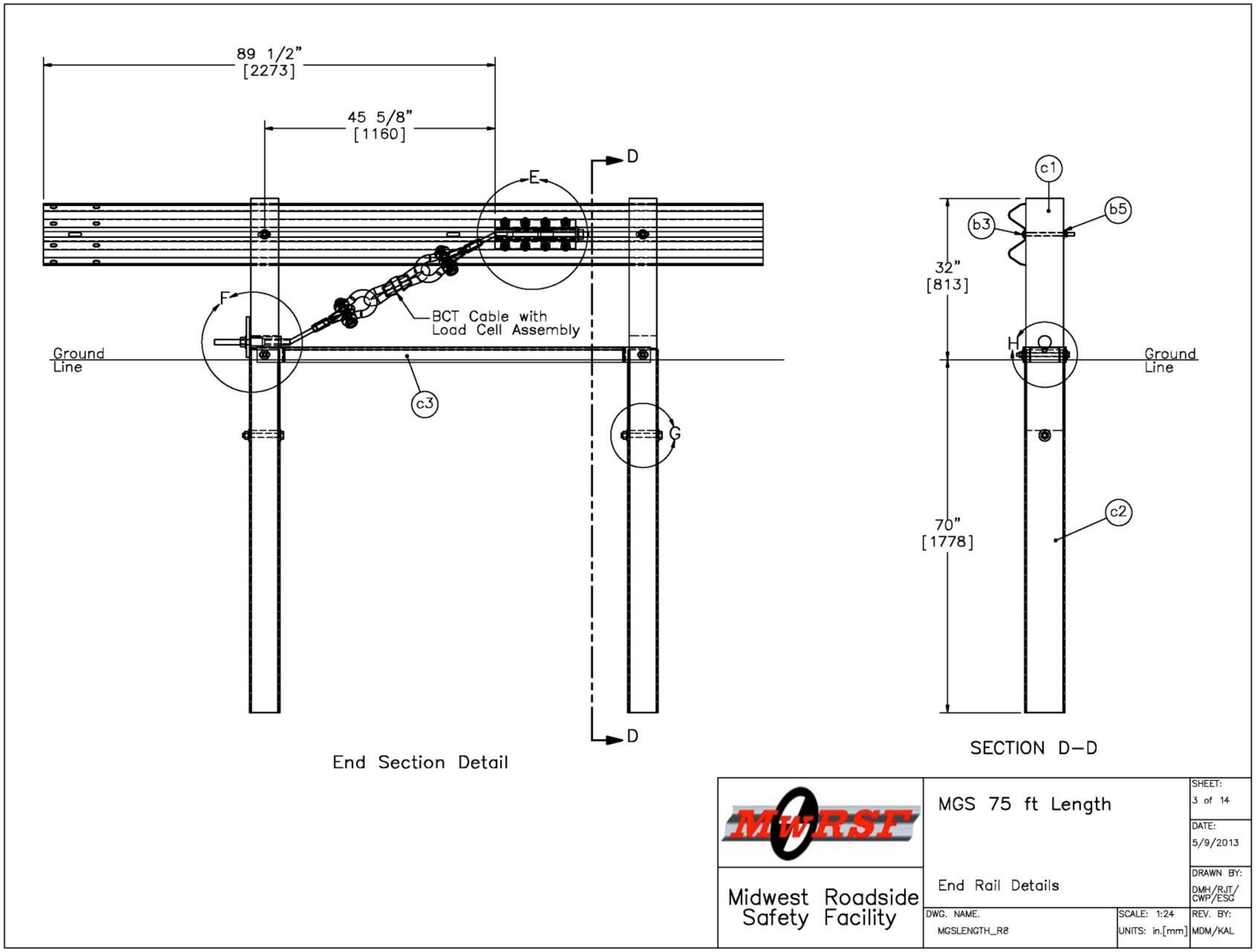


Figure 5. BCT End Anchor Details, Test No. MGSMIN-1

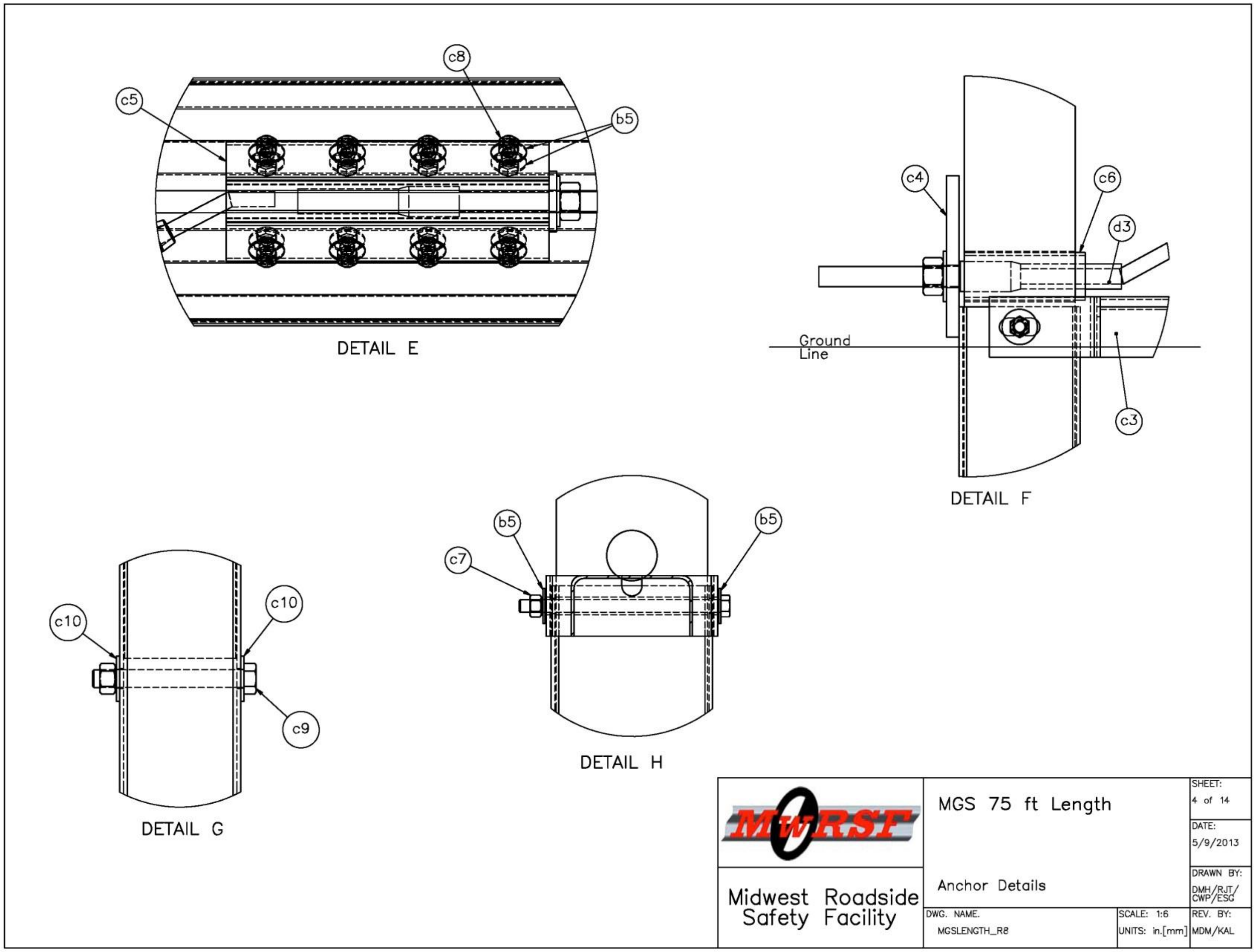


Figure 6. BCT End Anchor Details, Test No. MGSMIN-1

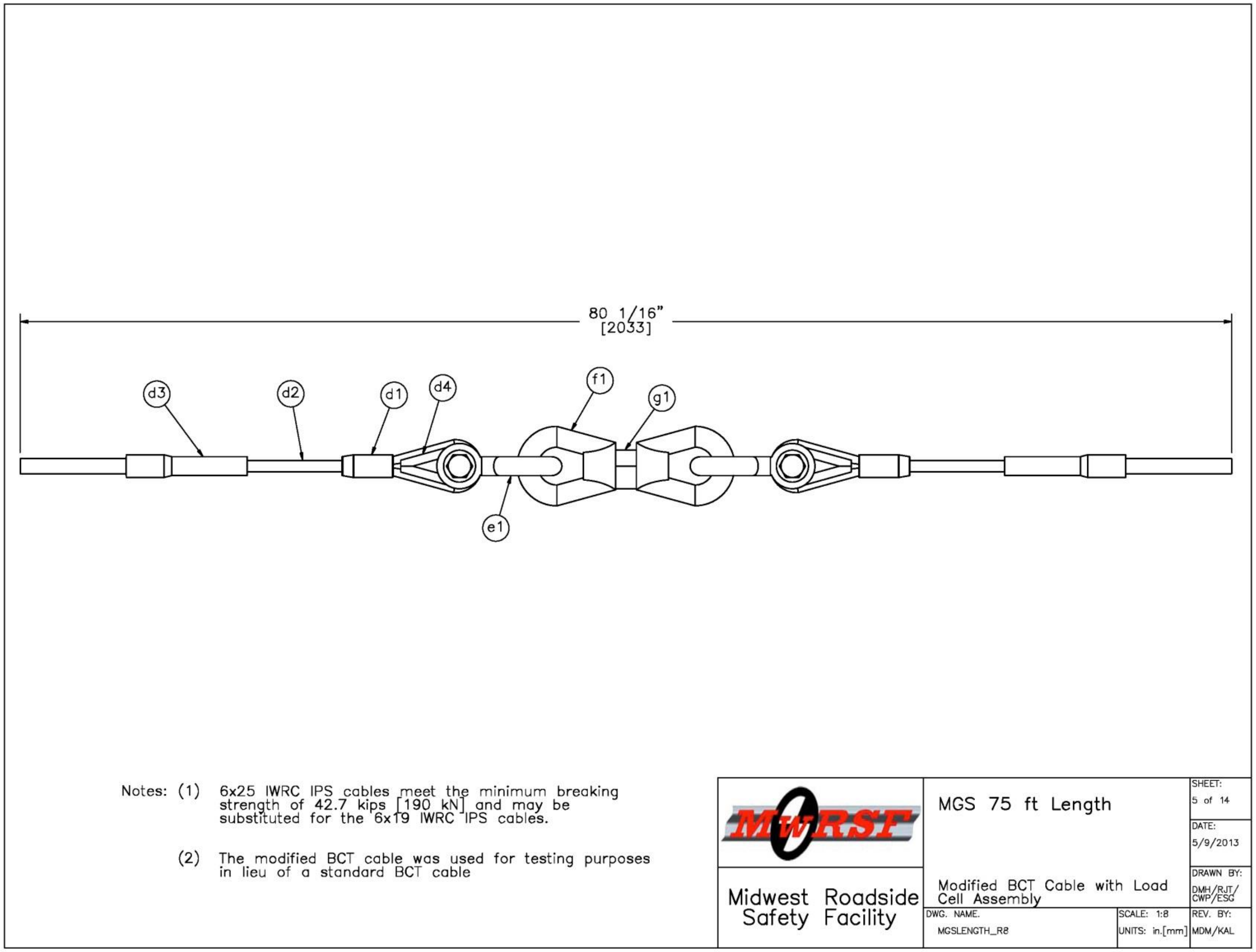


Figure 7. Modified BCT Cable with Load Cell Details, Test No. MGSMIN-1

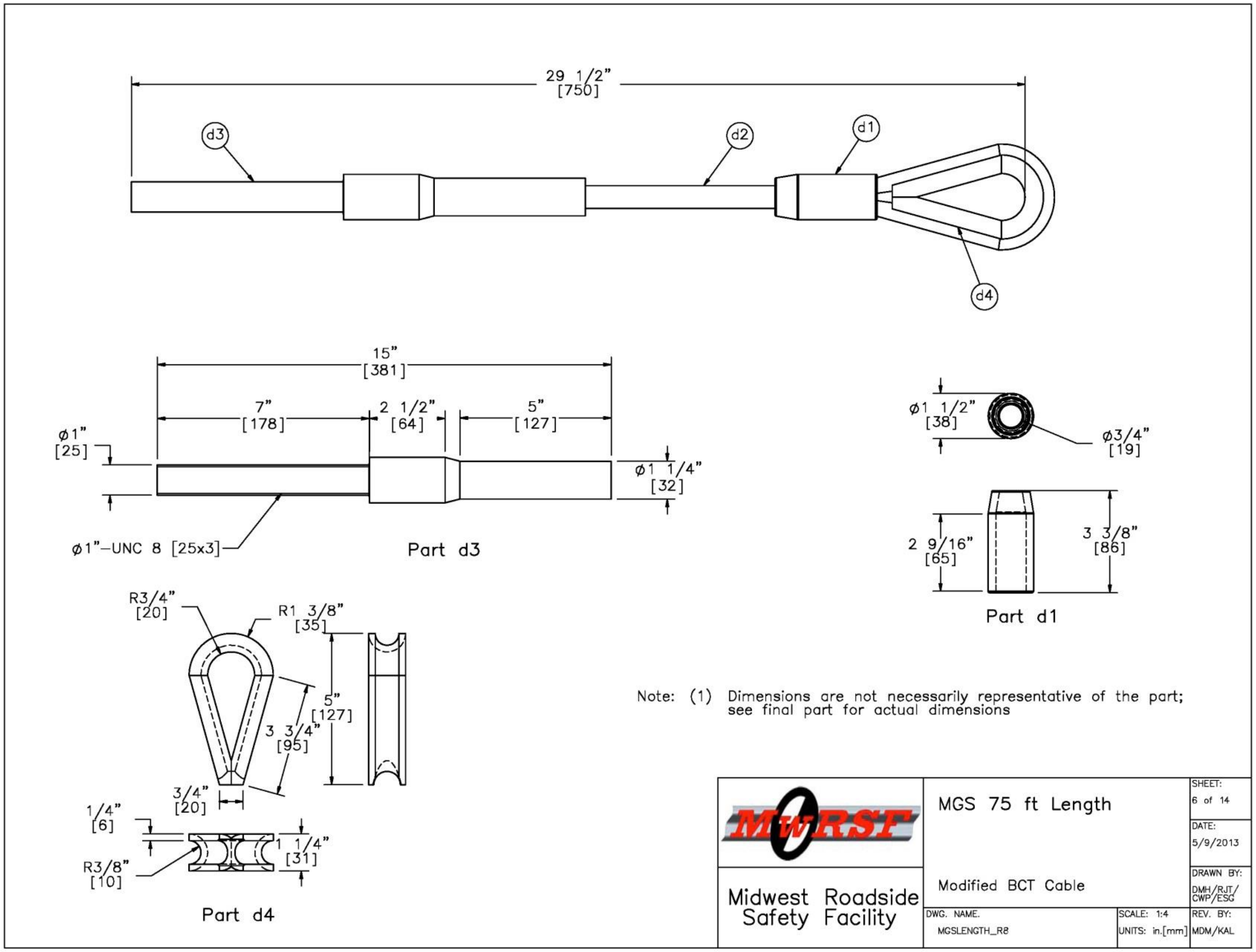


Figure 8. Modified BCT Cable Details, Test No. MGSMIN-1

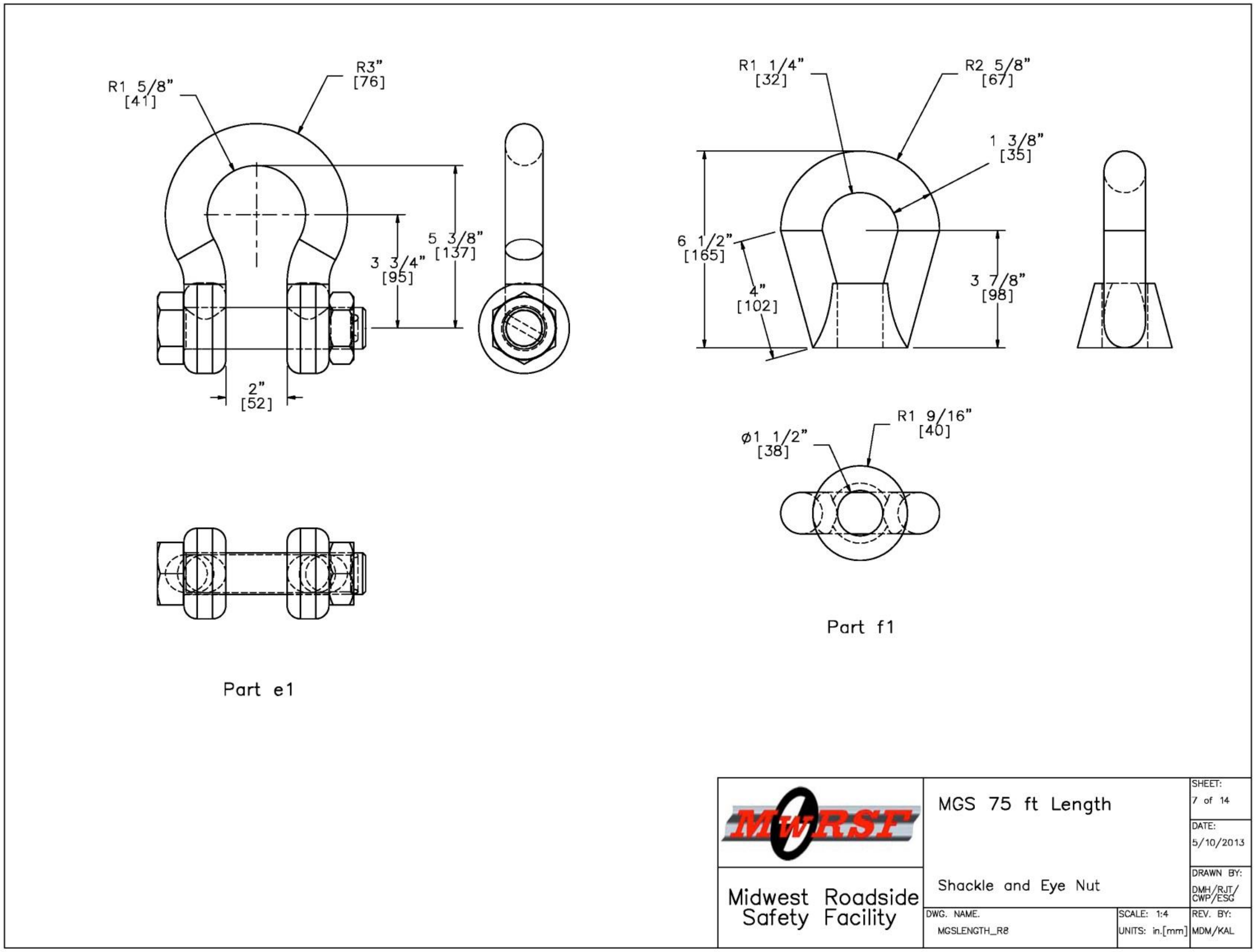


Figure 9. Shackle and Eye Nut Details, Test No. MGSMIN-1

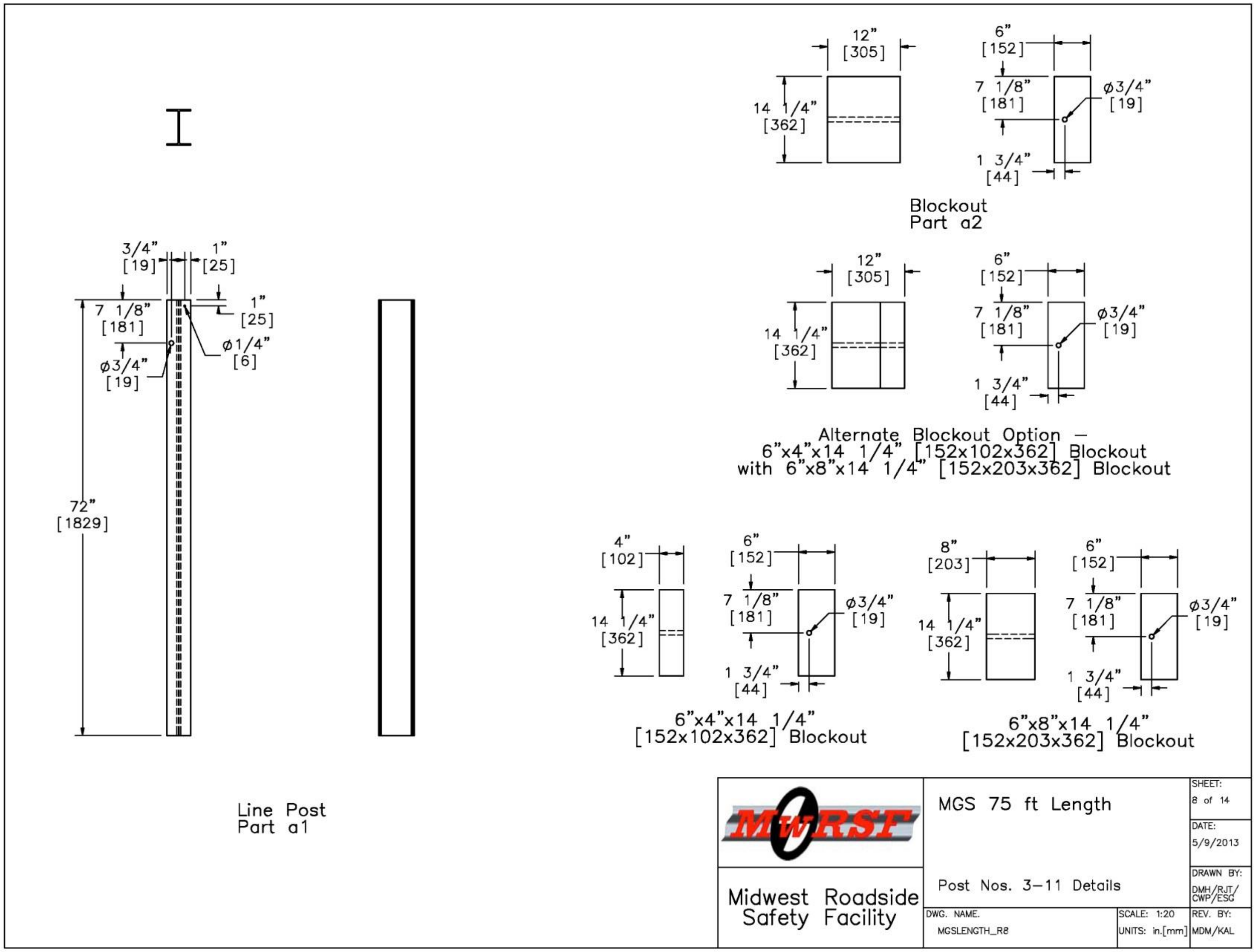


Figure 10. Line Post and Blockout Details, Test No. MGSMIN-1

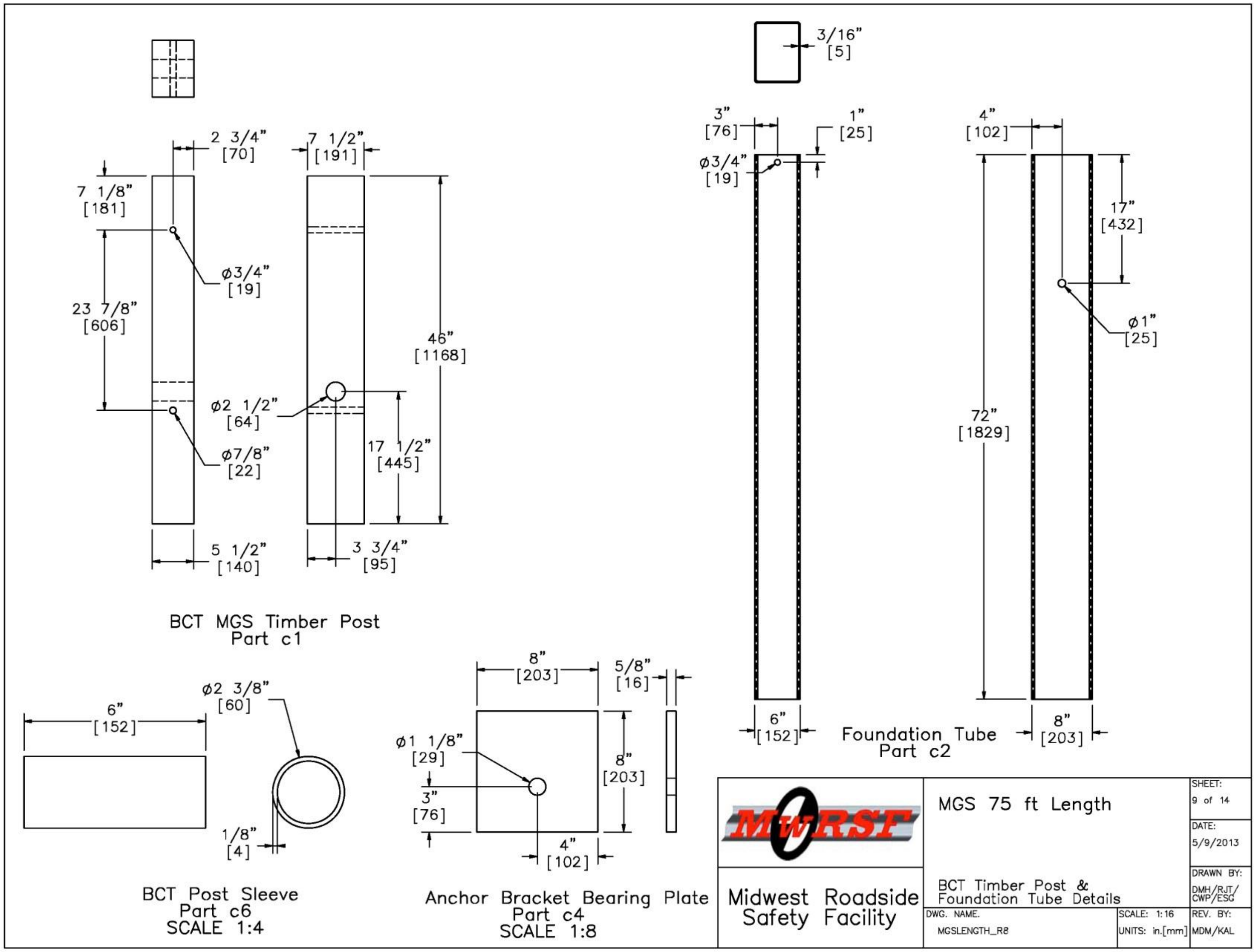


Figure 11. BCT Post and Foundation Tube Details, Test No. MGSMIN-1

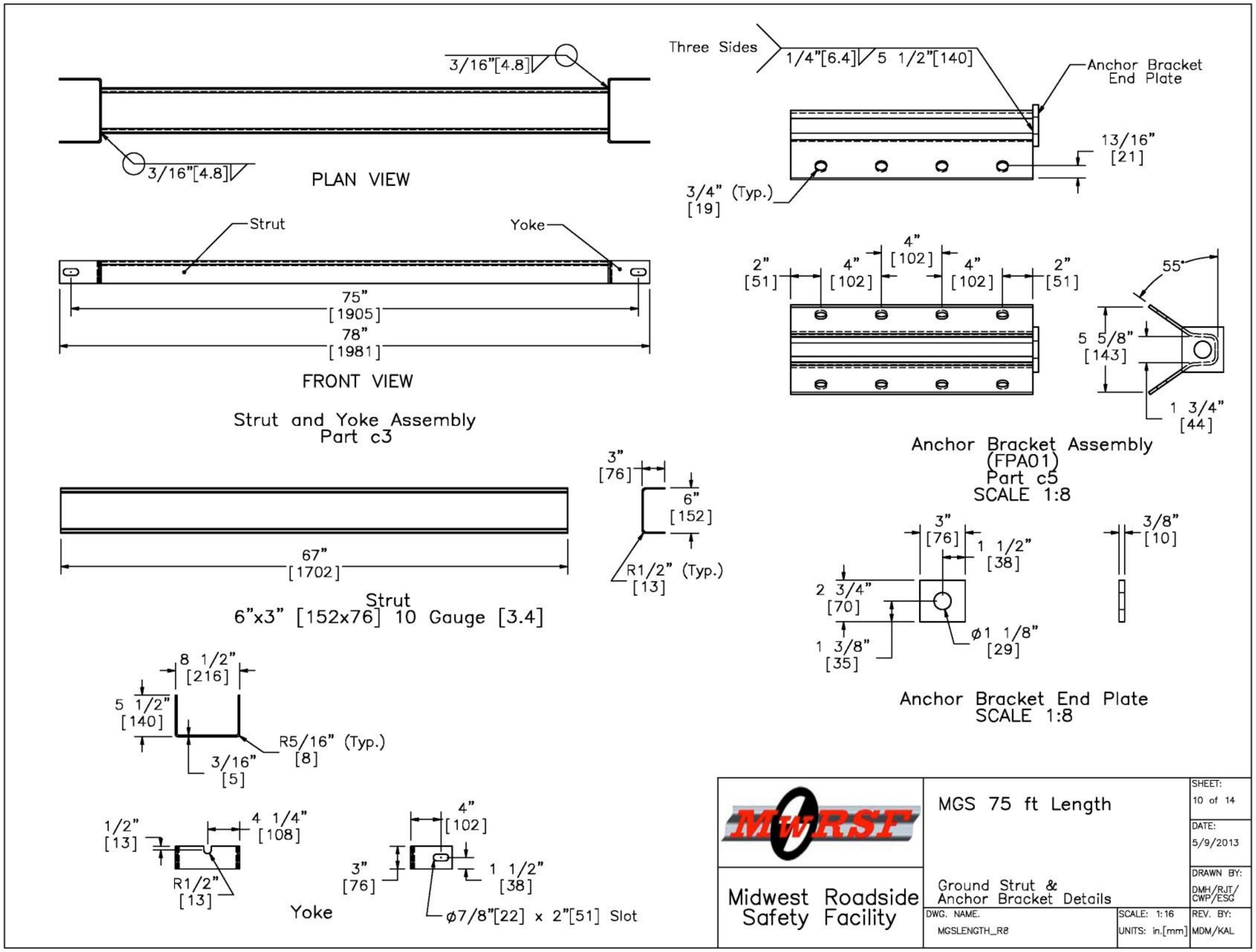


Figure 12. Ground Strut and Anchor Bracket Details, Test No. MGSMIN-1

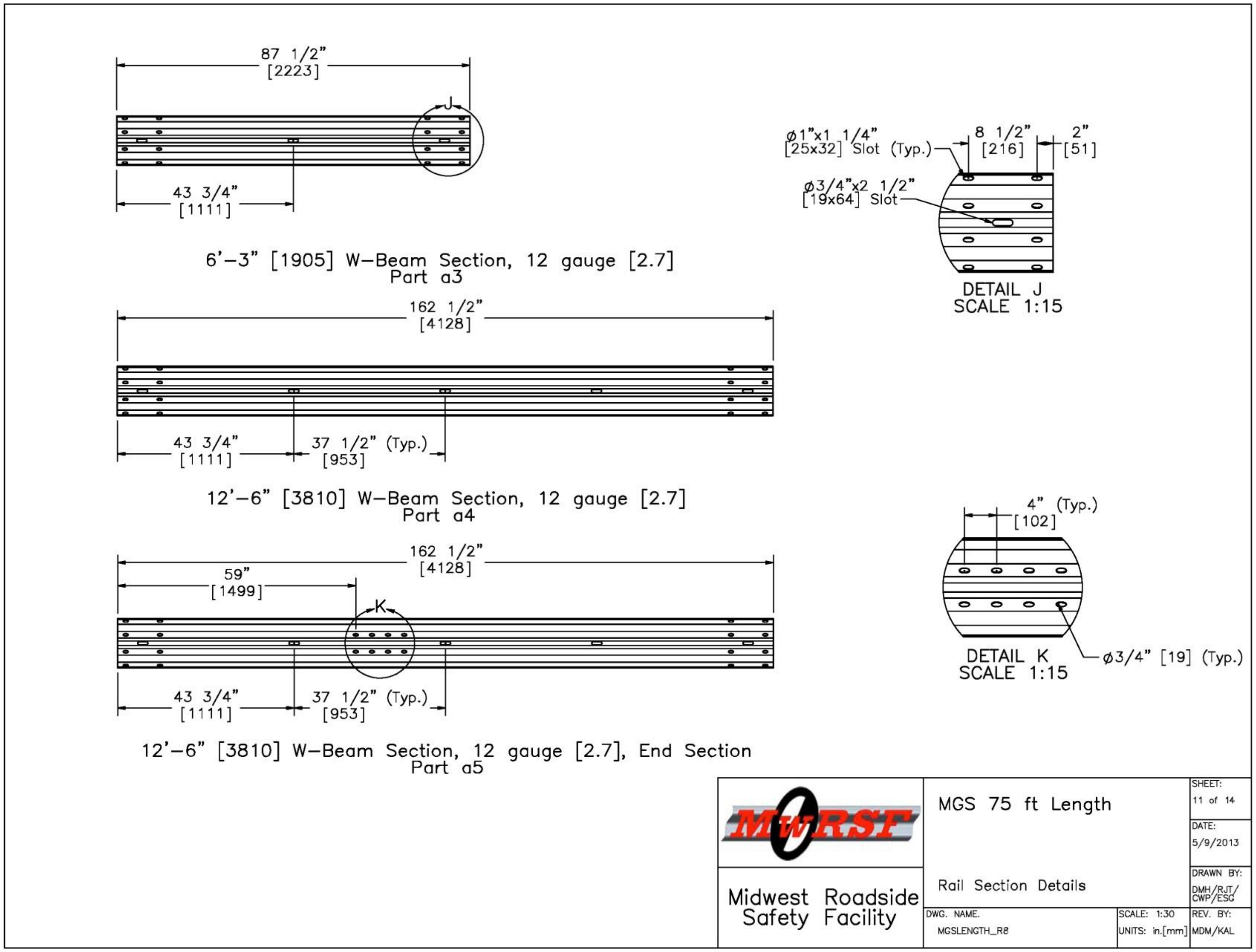


Figure 13. W-Beam Guardrail Details, Test No. MGSMIN-1

Item No.	QTY.	Description	Material Specifications	Hardware Guide
a1	9	W6x8.5 6' Long [W152x12.6 1829] Steel Post	ASTM A992 Min. 50 ksi [345 MPa] (W6x9 ASTM A36 Min. 36 ksi [248 MPa])	PWE06
a2	9	6x12x14 1/4" [152x305x362] Blockout	SYP Grade No. 1 or better	PDB10a–b
a3	1	6'–3" [1905] W–Beam MGS Section	12 gauge [2.7] AASHTO M180	RWM01a
a4	4	12'–6" [3810] W–Beam MGS Section	12 gauge [2.7] AASHTO M180	RWM04a
a5	2	12'–6" [3810] W–Beam MGS End Section	12 gauge [2.7] AASHTO M180	RWM14a
b1	9	5/8" Dia. x 14" Long [M16x356] Guardrail Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	FBB06
b2	9	16D Double Head Nail	–	–
b3	4	5/8" Dia. x 10" Long [M16x254] Guardrail Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	FBB03
b4	48	5/8" Dia. x 1 1/2" Long [M16x38] Guardrail Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	FBB01
b5	44	5/8" [16] Dia. Flat Washer	Grade 2	FWC16a
c1	4	BCT Timber Post – MGS Height	SYP Grade No. 1 or better	PDF01
c2	4	72" [1829] Long Foundation Tube	ASTM A53 Grade B	PTE06
c3	2	Strut and Yoke Assembly	ASTM A36 Steel Galvanized	–
c4	2	8x8x5/8" [203x203x15.9] Anchor Bearing Plate	ASTM A36 Steel	FPB01
c5	2	Anchor Bracket Assembly	ASTM A36 Steel	FPA01
c6	2	2 3/8" [60] O.D. x 6" [152] Long BCT Post Sleeve	ASTM A53 Grade B Schedule 40	FMM02
c7	4	5/8" Dia. x 10" Long [M16x254] Hex Head Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	FBX16a
c8	16	5/8" Dia. x 1 1/2" Long [M16x38] Hex Head Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	FBX16a
c9	4	7/8" Dia. x 7 1/2" Long [M22x191] Hex Head Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	FBX22a
c10	8	7/8" [22] Dia. Flat Washer	Grade 2	FWC22a

Midwest Roadside Safety Facility	MGS 75 ft Length		SHEET: 12 of 14
			DATE: 5/9/2013
	Bill of Materials		DRAWN BY: DMH/RJT/CWP/ESG
	DWG. NAME. MGSLENGTH_R8	SCALE: NONE UNITS: in.[mm]	REV. BY: MDM/KAL

Figure 14. Bill of Materials, Test No. MGSMIN-1

Item No.	QTY.	Description	Material Specifications
d1	4	115–HT Mechanical Splice – 3/4" [19] Dia.	As Supplied
d2	4	3/4" [190] Dia. 6x19 IWRC IPS Wire Rope	IPS Galvanized
d3	4	BCT Anchor Cable End Swage Fitting	Grade 5 – Galvanized
d4	4	Crosby Heavy Duty HT–3/4" [19] Dia. Cable Thimble	Stock No. 1037773 – Galvanized
e1	4	Crosby G2130 or S2130 Bolt Type Shackle – 1 1/4" [32] Dia. with thin head bolt, nut, and cotter pin, Grade A, Class 3	Stock Nos. 1019597 and 1019604 – As Supplied
f1	4	Chicago Hardware Drop Forged Heavy Duty Eye Nut – Drilled and Tapped 1 1/2" [38] Dia. – UNF 12 [M36]	As Supplied, Stock No. 107
g1	2	TLL–50K–PTB Load Cell	NA

Midwest Roadside Safety Facility	MGS 75 ft Length	SHEET: 13 of 14	DATE: 5/9/2013
	Bill of Materials	DRAWN BY: DMH/RJT/CWP/ESG	
DWG. NAME. MGSLENGTH_R8	SCALE: NONE UNITS: in.[mm]	REV. BY: MDM/KAL	

Figure 14. Bill of Materials, Test No. MGSMIN-1

Figure 15. Test Installation Photographs, Test No. MGSMIN-1

Figure 16. Test Installation Photographs, Test No. MGSMIN-1

5 TEST REQUIREMENTS AND EVALUATION CRITERIA

5.1 Test Requirements

Longitudinal barriers, such as W-beam guardrails, must satisfy impact safety standards in order to be declared eligible for federal reimbursement by the Federal Highway Administration (FHWA) for use on the National Highway System (NHS). For new hardware, these safety standards consist of the guidelines and procedures published in MASH [3]. According to TL-3 of MASH, longitudinal barrier systems must be subjected to two full-scale vehicle crash tests. The two full-scale crash tests are noted below:

1. Test Designation No. 3-10 consists of a 2,425-lb (1,100-kg) passenger car impacting the system at a nominal speed and angle of 62 mph (100 km/h) and 25 degrees, respectively.

2. Test Designation No. 3-11 consists of a 5,000-lb (2,268-kg) pickup truck impacting the system at a nominal speed and angle of 62 mph (100 km/h) and 25 degrees, respectively.

Prior research has shown successful safety performance for small cars impacting the Midwest Guardrail System [2,4]. These small car tests resulted in no significant potential for occupant risk problems arising from vehicle pocketing, wheel snagging on the guardrail posts, potential for rail rupture, or vehicular instabilities due to vaulting or climbing the rail. The rail deflections and loads experienced by the barrier during these 1100C tests were significantly lower than the rail deflections and loads resulting from 2270P impacts. Since this project sought to evaluate short system performance in relation to deflections and anchor loading, the 2270P test was identified as the critical test. Therefore, the 1100C small car test, MASH test designation 3-10, was deemed unnecessary for evaluation on the 75-ft (22.9-m) MGS. The test conditions for TL-3 longitudinal barriers are summarized in Table 3.

Table 3. MASH TL-3 Crash Test Conditions

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

[1] Evaluation criteria explained in Table 4.

5.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the guardrail system to contain and redirect impacting vehicles. In addition, controlled lateral deflection of the test article is acceptable. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle.

The full-scale vehicle crash test was conducted and reported in accordance with the procedures provided in MASH. For longitudinal barriers, only the evaluation criteria pertaining to the structural adequacy and occupant risk are required. Although not required, the post-impact vehicle trajectory provides important information about the manner in which the barrier redirects the vehicle during an impact event. Post-impact vehicle trajectory is a measure of the potential of the vehicle to result in a secondary collision with other vehicles and/or fixed objects, thereby increasing the risk of injury to the occupants of the impacting vehicle and/or other vehicles. These evaluation criteria are summarized in Table 4 and defined in greater detail in MASH.

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

5.3 Soil Strength Requirements

In order to limit the variation of soil strength among testing agencies, foundation soil must satisfy the recommended performance characteristics set forth in Chapter 3 and Appendix B of MASH. Testing facilities must first subject the designated soil to a dynamic post test to demonstrate a minimum dynamic load of 7.5 kips (33.4 kN) at deflections between 5 and 20 in. (127 and 508 mm). If satisfactory results are observed, a static test is conducted using an identical test installation. The results from this static test become the baseline requirement for soil strength in future full-scale crash testing in which the designated soil is used. An additional post installed near the impact point is statically tested on the day of the full-scale crash test in the same manner as used in the baseline static test. The full-scale crash test can be conducted only if the static test results show a soil resistance equal to or greater than 90 percent of the baseline test at deflections of 5, 10, and 15 in. (127, 254, and 381 mm). Otherwise, the crash test must be postponed until the soil demonstrates adequate post-soil strength. Of course, a dynamic soil test could also be used to verify that a minimum dynamic load of 7.5 kips (33.4 kN) at deflections between 5 and 20 in. (127 and 508 mm) is achieved.

Table 4. MASH Evaluation Criteria for Longitudinal Barrier

<table>
<tr><td>Structural Adequacy</td><td>A.</td><td colspan="3">Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td></tr>
<tr><td rowspan="11">Occupant Risk</td><td>D.</td><td colspan="3">Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td></tr>
<tr><td rowspan="4">H.</td><td colspan="3">Occupant Impact Velocity (OIV) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:</td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30 ft/s
(9.1 m/s)</td><td>40 ft/s
(12.2 m/s)</td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:</td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15.0 g’s</td><td>20.49 g’s</td></tr>
</table>

6 TEST CONDITIONS

6.1 Test Facility

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

6.2 Vehicle Tow and Guidance System

A reverse cable tow system with a 1:2 mechanical advantage was used to propel the test vehicle. The distance traveled and the speed of the tow vehicle were one-half that of the test vehicle. The test vehicle was released from the tow cable before impact with the barrier system. A digital speedometer on the tow vehicle increased the accuracy of the test vehicle impact speed.

A vehicle guidance system developed by Hinch [17] was used to steer the test vehicle. A guide flag, attached to the right-front wheel and the guide cable, was sheared off before impact with the barrier system. The ⅜-in. (9.5-mm) diameter guide cable was tensioned to approximately 3,500 lb (15.6 kN) and supported both laterally and vertically every 100 ft (30.5 m) by hinged stanchions. The hinged stanchions stood upright while holding up the guide cable, but as the vehicle was towed down the line, the guide flag struck and knocked each stanchion to the ground.

6.3 Test Vehicle

For test no. MGSMIN-1, a 2005 Dodge Ram 1500 Quad Cab pickup truck was used as the test vehicle. The curb, test inertial, and gross static vehicle weights were 4,913 lb (2,228 kg), 4,956 lb (2,248 kg), and 5,126 lb (2,325 kg), respectively. The test vehicle is shown in Figure 17, and vehicle dimensions are shown in Figure 18.

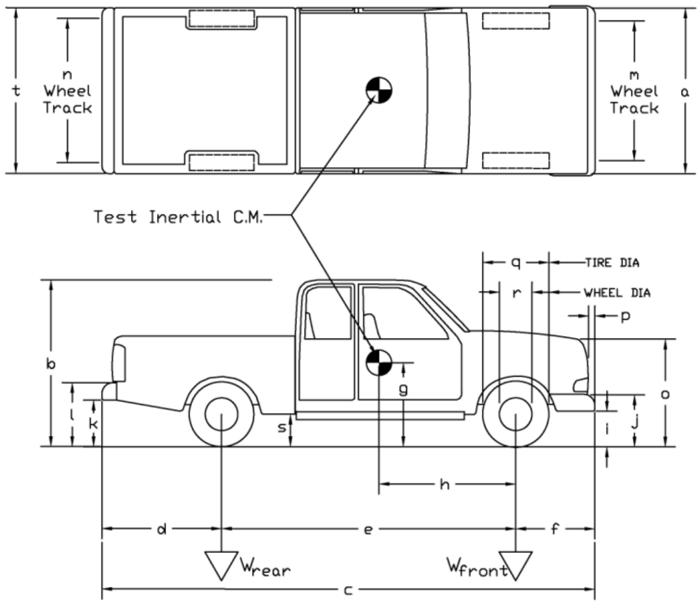
The longitudinal component of the center of gravity (c.g.) was determined using the measured axle weights. The Suspension Method [18] was used to determine the vertical

Figure 17. Test Vehicle, Test No. MGSMIN-1

Date:	**4/5/2012**	**Test Number:**	**MGSMIN-1**	**Model:**	**2270P**
Make:	**Dodge Ram**	**Vehicle I.D.#:**	**1D7HA18N95S293291**		
Tire Size:	**265/70 R17**	**Year:**	**2005**	**Odometer:**	**143810**

Tire Inflation Pressure: **35psi**

***(All Measurements Refer to Impacting Side)**



Vehicle Geometry -- in. (mm)

a	**78 1/4**	**(1988)**	**b**	**74 1/2**	**(1892)**
c	**227 3/4**	**(5785)**	**d**	**47 1/2**	**(1207)**
e	**140 1/4**	**(3562)**	**f**	**40**	**(1016)**
g	**28 1/6**	**(716)**	**h**	**62 7/8**	**(1597)**
i	**15 3/4**	**(400)**	**j**	**25 3/4**	**(654)**
k	**21 1/2**	**(546)**	**l**	**29 1/2**	**(749)**
m	**68**	**(1727)**	**n**	**67 3/4**	**(1721)**
o	**43 3/4**	**(1111)**	**p**	**3 1/4**	**(83)**
q	**31**	**(787)**	**r**	**18 1/2**	**(470)**
s	**15 3/4**	**(400)**	**t**	**75 1/2**	**(1918)**

Wheel Center Height Front	**15**	**(381)**
Wheel Center Height Rear	**15**	**(381)**
Wheel Well Clearance (F)	**35 5/8**	**(905)**
Wheel Well Clearance (R)	**38 1/8**	**(968)**
Frame Height (F)	**18**	**(457)**
Frame Height (R)	**25 3/8**	**(645)**
Engine Type	**8cyl Gas**	
Engine Size	**4.7L**	

Transmition Type:

Automatic **Manual**

FWD **RWD** **4WD**

Mass Distribution lb (kg)

Gross Static	**LF**	**1471 (667)**	**RF**	**1367 (620)**
	LR	**1145 (519)**	**RR**	**1143 (518)**

Weights lb (kg)	**Curb**	**Test Inertial**	**Gross Static**
W-front	**2781 (1261)**	**2734 (1240)**	**2838 (1287)**
W-rear	**2132 (967)**	**2222 (1008)**	**2288 (1038)**
W-total	**4913 (2228)**	**4956 (2248)**	**5126 (2325)**

GVWR Ratings

Front	**3650**
Rear	**3900**
Total	**6650**

Dummy Data

Type: **Hybrid II**

Mass: **170 lbs**

Seat Position: **Driver**

Note any damage prior to test: **Small dent in driver's side box (lower rear) very minor hail damage**

Figure 18. Vehicle Dimensions, Test No. MGSMIN-1

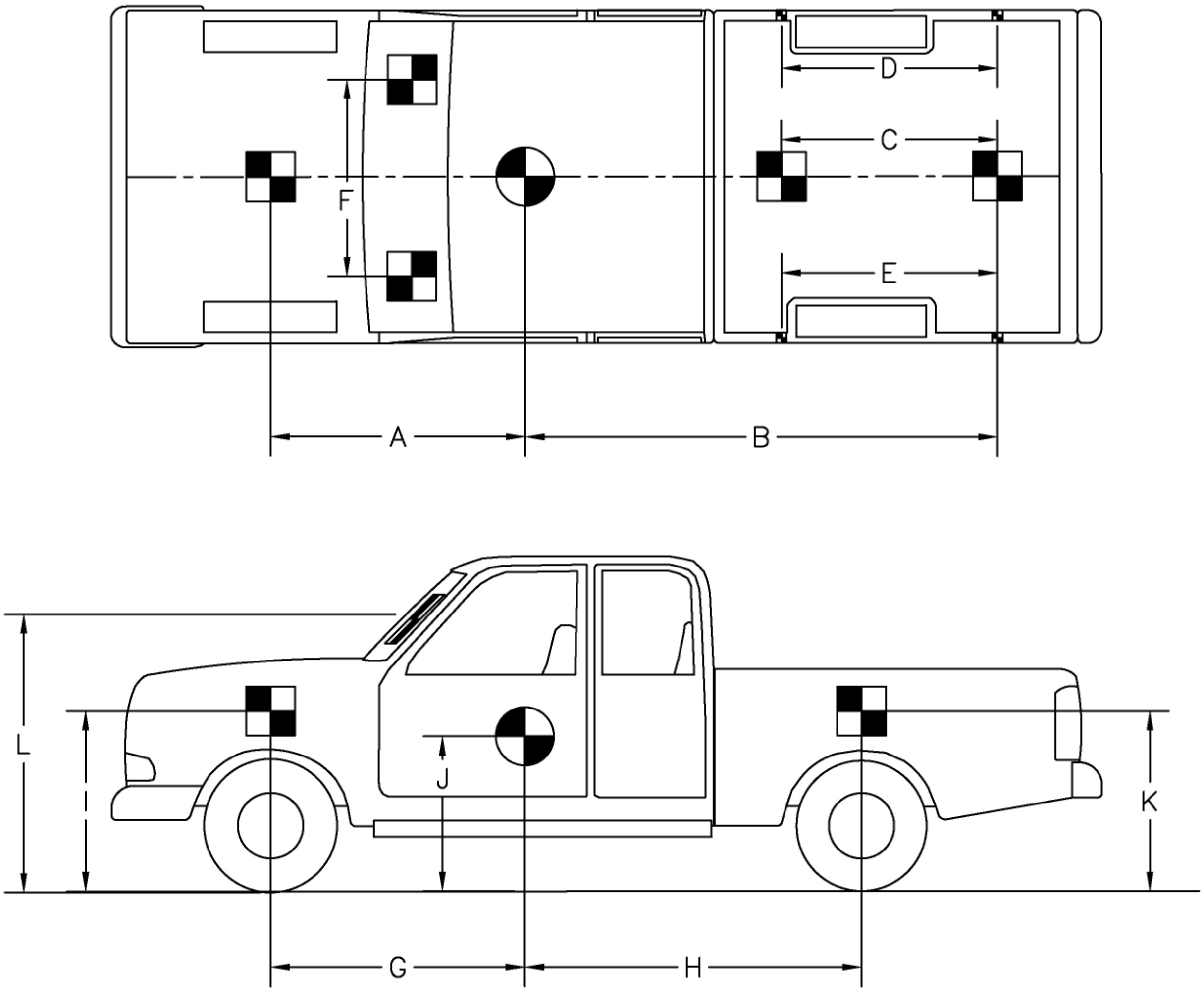
component of the c.g. for the pickup truck. This method is based on the principle that the c.g. of any freely suspended body is in the vertical plane through the point of suspension. The vehicle was suspended successively in three positions, and the respective planes containing the c.g. were established. The intersection of these planes pinpointed the final c.g. location for the test inertial condition. The location of the final c.g. is shown in Figures 18 and 19. Data used to calculate the location of the c.g. and ballast information are shown in Appendix B.

Square, black- and white-checkered targets were placed on the vehicle for reference to be viewed from the high-speed digital video cameras and aid in the video analysis, as shown in Figure 19. Round, checkered targets were placed on the center of gravity on the left-side door, the right-side door, and the roof of the vehicle.

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

6.4 Simulated Occupant

For test no. MGSMIN-1, a Hybrid II 50th-Percentile, Adult Male Dummy, equipped with clothing and footwear, was placed in the left-front seat of the test vehicle with the seat belt fastened. The dummy, which had a final weight of 170 lb (77 kg), was represented by model no. 572, serial no. 451, and was manufactured by Android Systems of Carson, California. As recommended by MASH, the dummy was not included in calculating the c.g location.



TEST #: MGSMIN-1

TARGET GEOMETRY-- in. (mm)

A	**77**	**(1956)**	**E**	**64**	**(1626)**	**I**	**40**	**(1016)**
B	**103 3/8**	**(2626)**	**F**	**40 3/4**	**(1035)**	**J**	**28 1/8**	**(714)**
C	**48**	**(1219)**	**G**	**62 7/8**	**(1597)**	**K**	**42 3/8**	**(1076)**
D	**64**	**(1626)**	**H**	**77 3/8**	**(1965)**	**L**	**59 3/4**	**(1518)**

Figure 19. Target Geometry, Test No. MGSMIN-1

6.5 Data Acquisition Systems

6.5.1 Accelerometers

Three environmental shock and vibration sensor/recorder systems were used to measure the accelerations in the longitudinal, lateral, and vertical directions. All of the accelerometers were mounted near the center of gravity of the test vehicles. The electronic accelerometer data obtained in dynamic testing was filtered using the SAE Class 60 and the SAE Class 180 Butterworth filter conforming to the SAE J211/1 specifications [19].

The first accelerometer system, the DTS, was three piezoresistive accelerometers manufactured by Endevco of San Juan Capistrano, California. The three accelerometers were used to measure each of the longitudinal, lateral, and vertical accelerations independently at a sample rate of 10,000 Hz. The accelerometers were configured with a range of ±500 g's and controlled using a DTS Sensor Input Module (SIM), Model TDAS3-SIM-16M manufactured by Diversified Technical Systems, Inc. (DTS) of Seal Beach, California. The SIM was configured with 16 MB SRAM and 8 sensor input channels with 250 kB SRAM/channel. The SIM was mounted on a TDAS3-R4 module rack which was configured with isolated power/event/communications, 10BaseT Ethernet and RS232 communication, and an internal backup battery. The "DTS TDAS Control" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

The second system, SLICE 6DX, was a modular data acquisition system manufactured by DTS of Seal Beach, California. The acceleration sensors were mounted inside the body of the custom built SLICE 6DX event data recorder and recorded data at 10,000 Hz to the onboard microprocessor. The SLICE 6DX was configured with 7 GB of non-volatile flash memory, a range of ±500 g's, a sample rate of 10,000 Hz, and a 1,650 Hz (CFC 1000) anti-aliasing filter.

The "SLICEWare" computer software programs and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

The third system, Model EDR-3, was a triaxial piezoresistive accelerometer system manufactured by Instrumented Sensor Technology (IST) of Okemos, Michigan. The EDR-3 was configured with 256 kB of RAM, a range of ±200 g's, a sample rate of 3,200 Hz, and a 1,120 Hz low-pass filter. The "DynaMax 1 (DM-1)" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

6.5.2 Rate Transducers

An angle rate sensor, the ARS-1500, with a range of 1,500 degrees/sec in each of the three directions (roll, pitch, and yaw) was used to measure the rates of rotation of the test vehicle. The angular rate sensor was mounted on an aluminum block inside the test vehicle near the center of gravity and recorded data at 10,000 Hz to the SIM. The raw data measurements were then downloaded, converted to the proper Euler angles for analysis, and plotted. The "DTS TDAS Control" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the angular rate sensor data.

A second angle rate sensor system, the SLICE MICRO Triax ARS, with a range of 1,500 degrees/sec in each of the three directions (roll, pitch, and yaw) was used to measure the rates of rotation of the test vehicle. The angular rate sensors were mounted inside the body of the custom built SLICE 6DX event data recorder and recorded data at 10,000 Hz to the onboard microprocessor. The raw data measurements were then downloaded, converted to the proper Euler angles for analysis, and plotted. The "SLICEWare" computer software program and a customized Microsoft Excel worksheet were used to analyze and plot the angular rate sensor data.

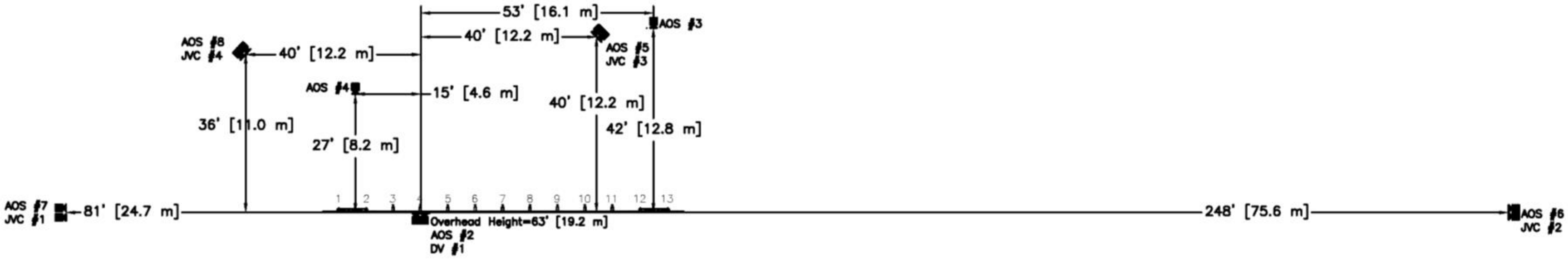
6.5.3 Pressure Tape Switches

For test no. MGSMIN-1, three pressure-activated tape switches, spaced at approximately 6.56-ft (2-m) intervals, were used to determine the speed of the vehicle before impact. Each tape switch fired a strobe light which sent an electronic timing signal to the data acquisition system as the left-front tire of the test vehicle passed over it. Test vehicle speeds were determined from electronic timing mark data recorded using TestPoint and LabVIEW computer software programs. Strobe lights and high-speed video analysis are used only as a backup in the event that vehicle speed cannot be determined from the electronic data.

6.5.4 Digital Photography

Three AOS VITcam high-speed digital video cameras, three AOS X-PRI high-speed digital video cameras, one AOS S-VIT high-speed digital video camera, four JVC digital video cameras, and two Canon digital video cameras were utilized to film test no. MGSMIN-1. Camera details, camera operating speeds, lens information, and a schematic of the camera locations relative to the system are shown in Figure 20.

The high-speed videos were analyzed using ImageExpress MotionPlus and RedLake MotionScope software programs. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed videos. A Nikon D50 digital still camera was also used to document pre- and post-test conditions for all tests.



	No.	Type	Operating Speed (frames/sec)	Lens	Lens Setting
High-Speed Video	2	AOS Vitcam CTM	500	Cosmicar 12.5mm Fixed	NA
	3	AOS Vitcam CTM	500	Osawa 28-80	60
	4	AOS Vitcam CTM	500	Sigma 24-135	35
	5	AOS X-PRI Gigabit	500	Sigma 24-70	35
	6	AOS X-PRI Gigabit	500	Canon 17-102	102
	7	AOS X-PRI Gigabit	500	Fujinon 50mm Fixed	NA
	8	AOS S-VIT	500	Sigma 50mm Fixed	NA
Digital Video	1	JVC – GZ-MC500 (Everio)	29.97		
	2	JVC – GZ-MG27u (Everio)	29.97		
	3	JVC – GZ-MG27u (Everio)	29.97		
	4	JVC – GZ-MG27u (Everio)	29.97		
	1	Canon ZR90	29.97		
	2	Canon ZR10	29.97		

Figure 20. Camera Locations, Speeds, and Lens Settings, Test No. MGSMIN-1

August 12, 2013

7 FULL-SCALE CRASH TEST NO. MGSMIN-1

7.1 Static Soil Test

Before full-scale crash test no. MGSMIN-1 was conducted, the strength of the foundation soil was evaluated with a static test, as described in MASH. The static test results, as shown in Appendix C, demonstrated a soil resistance above the baseline test limits. Thus, the soil provided adequate strength, and full-scale crash testing could be conducted on the barrier system.

7.2 Test No. MGSMIN-1

The 5,126-lb (2,325-kg) pickup truck impacted the 75-ft (22.9-m) long, 31-in. (787-mm) tall MGS at a speed of 63.1 mph (101.6 km/h) and at an angle of 24.9 degrees. A summary of the test results and sequential photographs are shown in Figure 23. Additional sequential photographs are shown in Figures 24 through 26. Documentary photographs of the crash test are shown in Figure 27.

7.3 Weather Conditions

Test no. MGSMIN-1 was conducted on April 5, 2012 at approximately 3:45 pm. The weather conditions as per the National Oceanic and Atmospheric Administration (station 14939/LNK) were reported and are shown in Table 5 [20].

Table 5. Weather Conditions, Test No. MGSMIN-1

Temperature	67° F
Humidity	32%
Wind Speed	9 mph
Wind Direction	120° from True North
Sky Conditions	Sunny
Visibility	10 Statute Miles
Pavement Surface	Dry
Previous 3-Day Precipitation	0.00 in.
Previous 7-Day Precipitation	0.00 in.

7.4 Test Description

Initial vehicle impact was to occur at the center line of post no. 4, as shown in Figure 28, which was selected using LS-DYNA simulation to test the upstream impact location for the 75-ft (22.9-m) MGS system. The actual point of impact was 4 in. (102 mm) downstream of post no. 4. A sequential description of the impact events is contained in Table 6. The vehicle came to rest facing downstream at 138 ft (42.1 m) downstream of the initial impact point and 17 ft – 6in. (5.3 m) laterally away from the front of the rail. The vehicle trajectory and final position are shown in Figures 23 and 29.

Table 6. Sequential Description of Impact Events, Test No. MGSMIN-1

TIME (sec)	EVENT
0.000	The left side of the front bumper impacted the guardrail 4 in. (102 mm) downstream of the intended impact location.
0.006	Post no. 4 deflected laterally away from the traffic side.
0.024	Post no. 5 deflected away from the traffic side and post no. 3 deflected downstream.
0.028	Upstream anchors, post nos. 1 and 2, started to deflect downstream.
0.034	The left-front headlight shattered. Kinks began to form in the top corrugation of the rail, upstream of post no. 6, while post no. 4 started to twist downstream.
0.040	A dent formed in the vehicle’s left-front fender, and kinks formed in the rail at the midspan between post nos. 4 and 5.
0.046	The downstream anchors, post nos. 12 and 13, began deflecting upstream.
0.062	The left side of the front bumper contacted the front face of post no. 5. Post no. 6 began to deflect backward.
0.064	Rail disengaged from post no. 5, and post no. 6 twisted upstream.
0.078	Vehicle began to redirect downstream. Post nos. 6 through 9 twisted upstream. Vehicle’s left-front tire overrode post no. 5.
0.098	Post no. 7 deflected laterally away from the traffic side.
0.108	Rail disengaged from post no. 6. Kinking and flattening continued to occur along the rail.
0.120	The blockout disengaged from post no. 6.
0.148	Post no. 9 twisted downstream and post no. 8 deflected away from the traffic side. Vehicle’s left-front fender crushed further inward and due to the left-front tire’s orientation, it was apparent that the steering link had disengaged.
0.174	Rail disengaged from post no. 7.

0.180	The blockout disengaged from post no. 7.
0.218	The left-front tire overrode post no. 7.
0.288	Post no. 9 deflected away from the traffic side, and the vehicle overrode post no. 8.
0.314	The vehicle became parallel with the system at a speed of 42.3 mph (68.1 km/h).
0.376	Post no. 10 deflected away from the traffic side, while post no. 4 deflected toward the traffic side.
0.408	Vehicle overrode post no. 9 and began to roll away from barrier. The left-front tire disengaged from the vehicle.
0.488	Vehicle began to pitch downward and post nos. 12 and 13 deflected upstream.
0.594	Vehicle continued to pitch downward and yaw away from the barrier.
0.700	The vehicle exited the system at 32.9 mph (52.9km/h).
0.798	Vehicle began to roll toward the system.
0.898	Rail disengaged from post no. 13.
1.070	Vehicle pitched upward.
1.188	Right-rear tire contacted the ground.

7.5 Barrier Damage

Damage to the barrier was moderate, as shown in Figures 30 through 37. Barrier damage consisted of deformed W-beam rail, contact marks on sections of guardrail and posts, deformed steel posts, and cracked wood BCT anchor posts. The length of vehicle contact along the barrier was approximately 37 ft – 2 in. (11.3 m), which spanned from 4 in. (102 mm) downstream of the centerline of post no. 4 through the centerline of post no. 10.

Numerous kinks in the top and bottom corrugations of the rail were found 8 in. (203 mm) upstream of post no. 3 through 2 in. (51 mm) downstream of post no. 11, as shown in Figures 30 and 31. Flattening of the guardrail occurred at the splice between post nos. 4 and 5 and extended to post no. 8. The bottom corrugation was folded back at post nos. 5 and 6 as well as from the splice between post nos. 7 and 8 to post no. 9. The W-beam guardrail detached from post nos. 5 through 11 and 13. A ¼-in. (6-mm) vertical tear was found at the downstream end of the slot at post no. 6. Buckles were found 2 in. (51 mm) upstream of post no. 4 near the post bolt and at post no. 10. A dent in the rail occurred slightly upstream and above the bolt slot at post no. 5, as shown in Figure 34.

Post no. 2 cracked in multiple places: (1) across the top of the post, 3½ in. (89 mm) from the front; (2) a 7-in. (178-mm) long vertical crack on the upstream side near the hole; and (3) a 10-in. (254-mm) long crack on the downstream side, measured from the ground up. The front of post nos. 3 and 4 twisted slightly downstream and both blockouts cracked. Furthermore, the top of the blockout at post no. 4 contained gouging from the rail. Post nos. 5 through 8 bent backward and downstream nearly to the ground, while the front flanges twisted to face upstream and the blockouts were disengaged. There were 7-in. (178-mm) long dents in the upstream front flange of post nos. 6 and 7 at locations 12 in. (305 mm) and 8 in. (203 mm) from the top, respectively. Post no. 8 had gouging of the upstream front flange between 11 in. (279 mm) and 19 in. (483 mm) from the top of the post. Additionally, post no. 8 had a 3-in. (76-mm) dent on the upstream back flange, 6½ in. (165 mm) from the top. Post no. 9 bent downstream and backwards, the front flange twisted slightly upstream, and the majority of the blockout disengaged. Post no. 10 twisted slightly downstream with splitting and cracking located throughout the blockout. The blockout of post no. 11 rotated downstream. Post no. 12 cracked significantly near the ground line. The portion between the hole and back face of post no. 12 fractured and the crack continued downward on the front side of the hole as shown in Figure 37.

A ¾-in. (19-mm) soil gap was present at the upstream edge of post no. 1, as shown in Figure 32. Soil gaps of ⅜ in. (10 mm) and 3½ in. (89 mm) were present at the front face of post nos. 3 and 4, respectively. There was a ½-in. (13-mm) soil gap present at the downstream edge on post no. 13, as shown in Figure 37. Large soil displacements were present around the bases of post nos. 5 through 10.

The slippage between adjacent rail segments was measured at every splice location, as shown in Table 7. Slippage at each splice location is shown in Figures 38 and 39. The maximum slippage was found to be ⅜ in. (10 mm) at the splice location between post nos. 5 and 6. A complete summary of the splice separations together with details of the slippage for each of the splice bolts is provided in Appendix D.

Table 7. Slippage at Guardrail Splices

Splice Location	Measured Slippage in. (mm)	
Post nos.	Front of Rail	Back of rail
2-3	5/16 (8)	1/4 (6)
4-5	1/4 (6)	1/4 (6)
5-6	5/16 (8)	3/8 (10)
7-8	1/2 (13)	1/2 (13)
9-10	5/16 (8)	5/16 (8)
11-12	1/8 (3)	1/16 (2)

The maximum permanent set rail and post deflections were 36⅜ in. (924 mm) at post no. 7 and 21¼ in.(540 mm) at post no. 5, respectively, as measured in the field. The maximum lateral dynamic set rail and post deflections were 42.2 in. (1,072 mm) at post no. 6 and 20.0 in. (508 mm) at post no. 5, respectively, as determined from high-speed digital video analysis. The working width of the system was found to be 48.8 in. (1,240 mm), also determined from high-speed digital video analysis.

7.6 Vehicle Damage

The damage to the vehicle was moderate, as shown in Figures 40 through 43. The maximum occupant compartment deformations are listed in Table 8 along with the deformation limits established in MASH for various areas of the occupant compartment. It should be noted that none of the MASH established deformation limits were violated. Complete occupant compartment and vehicle deformations and the corresponding locations are provided in Appendix E.

Table 8. Maximum Occupant Compartment Deformations by Location

LOCATION	MAXIMUM DEFORMATION in. (mm)	MASH ALLOWABLE DEFORMATION in. (mm)
Wheel Well & Toe Pan	3/8 (10)	≤ 9 (229)
Floor Pan & Transmission Tunnel	¼ (6)	≤ 12 (305)
Side Front Panel (in Front of A-Pillar)	¼ (6)	≤ 12 (305)
Side Door (Above Seat)	¼ (6)	≤ 9 (229)
Side Door (Below Seat)	¼ (6)	≤ 12 (305)
Roof	0 (0)	≤ 4 (102)
Windshield	0 (0)	≤ 3 (76)

A majority of the damage was concentrated on the left-front corner and left side of the vehicle where the impact occurred. A ¾-in. (19-mm) gap was present between the bumper and right-front headlight, and the hood was ajar 1½ in. (38 mm). The left-front bumper kinked, dented inward, and folded into the wheel well, and the bottom of the grill cover fractured. The left-front headlight fractured, and the fender folded under at the headlight. The left-front wheel disengaged, and the tie rod fractured. Similarly, the control arm and shock bent, and the brake line was cut. The disengaged wheel contained several 2-in. (51-mm) long dents and gouges along the rim. Contact marks and denting, 20 in. (508 mm) from the bottom of the door, occurred along the length of the vehicle. The top of the left-front fender separated from the door, and the door was slightly ajar. Both gaps were approximately a ½ in. (13 mm) wide. A 5-in. (127-mm) wide by 1½-in. (38-mm) deep dent was located in the fender behind the left-rear tire. Contact marks were present on the left-rear bumper, which bent inwards. No visible damage to the interior compartment or undercarriage was observed.

7.7 Occupant Risk

The calculated occupant impact velocities (OIVs) and maximum 0.010-sec occupant ridedown accelerations (ORAs) in both the longitudinal and lateral directions are shown in Table 9. Note that the OIVs and ORAs were within the suggested limits provided in MASH. The calculated THIV, PHD, and ASI values are also shown in Table 9. The results of the occupant risk analysis, as determined from the accelerometer data, are summarized in Figure 23. The recorded data from the accelerometers and the rate transducers are shown graphically in Appendix F.

Table 9. Summary of OIV, ORA, THIV, PHD, and ASI Values, Test No. MGSMIN-1

Evaluation Criteria		Transducer			MASH Limits
		DTS	**DTS-SLICE**	**EDR-3**	
OIV ft/s (m/s)	Longitudinal	-15.50 (-4.72)	-14.48 (-4.41)	-15.88 (-4.84)	≤ 40 (12.2)
	Lateral	14.15 (4.31)	14.66 (4.47)	14.02 (4.27)	≤40 (12.2)
ORA g's	Longitudinal	-8.95	-8.70	-8.12	≤ 20.49
	Lateral	6.94	6.16	5.71	≤ 20.49
THIV ft/s (m/s)		19.82 (6.04)	20.18 (6.15)	NA	not required
PHD g's		9.89	9.62	NA	not required
ASI		0.61	0.59	0.57	not required

7.8 Anchor Forces and Displacements

Forces through the upstream and downstream anchors were measured with load cells placed in the modified BCT cable assembly, as shown in Figure 7. Similarly, string pots were attached to post no. 1, on the upstream end, and post no. 13, on the downstream end, at ground level to measure the dynamic displacements of the anchors in the longitudinal direction. The forces and displacements through the upstream and downstream anchors are presented in Figures 21 and 22. The 75-ft (22.9-m) MGS experienced similar forces and longitudinal displacements at both end terminals. The peak forces experienced in the upstream and downstream anchors were 25.9 kips (115.2 kN) and 25.2 kips (112.1 kN), respectively. Similarly, the maximum longitudinal displacements in the upstream and downstream anchors were 1.54 in. (39 mm) and 1.70 in. (43 mm), respectively.

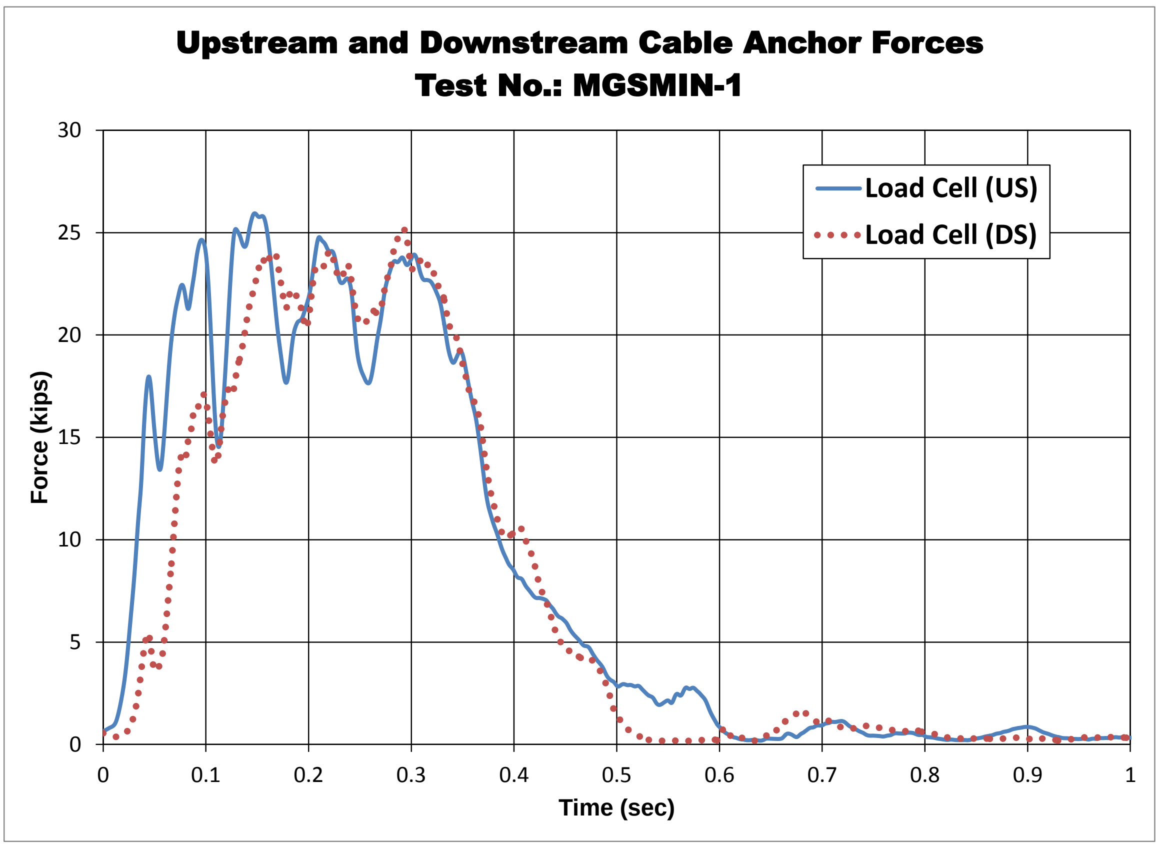


Figure 21. Upstream and Downstream Cable Anchor Forces

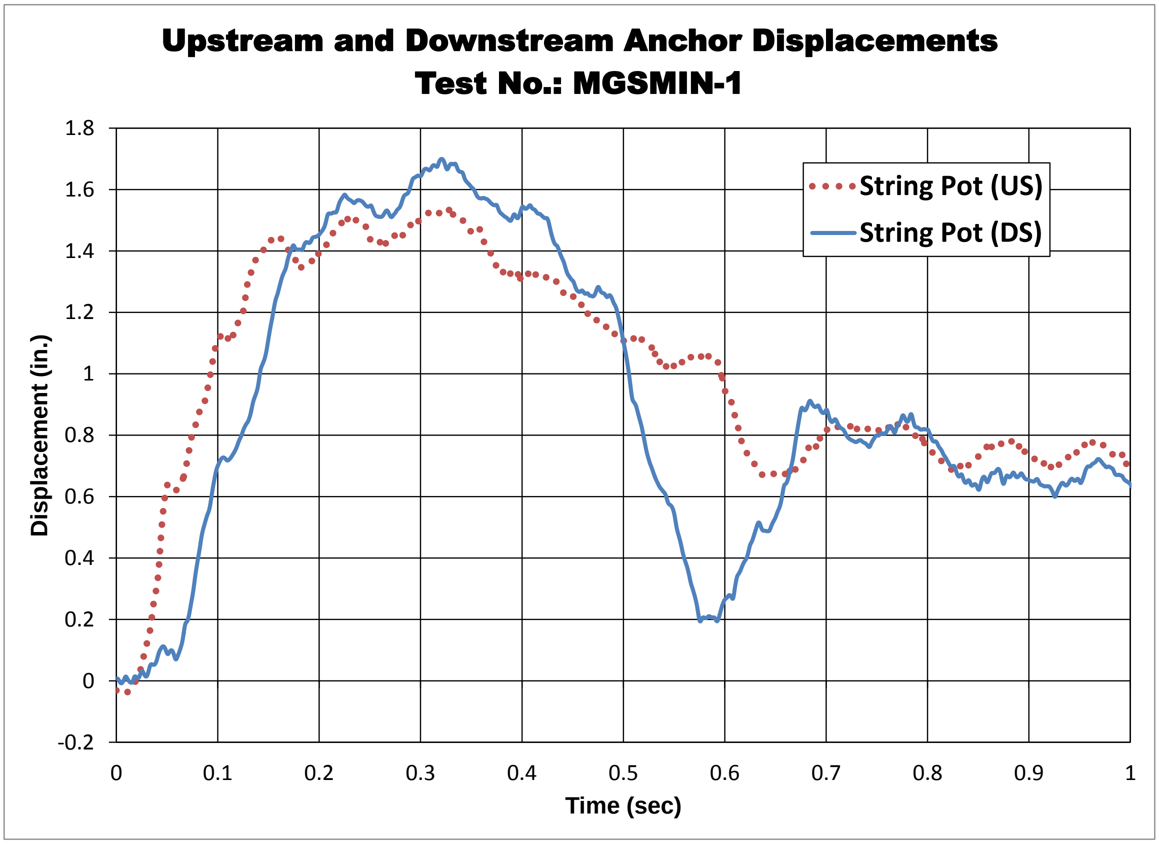
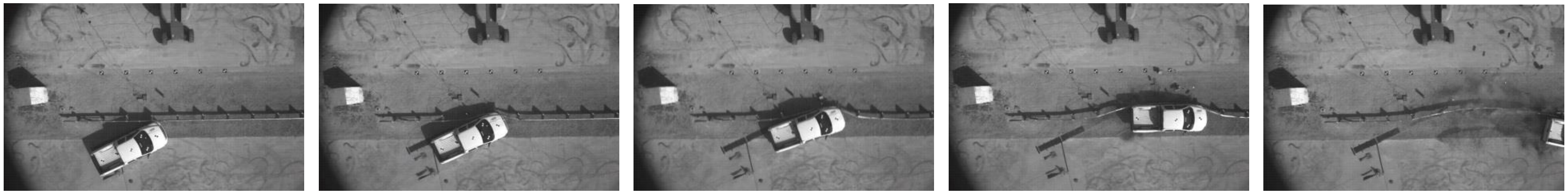


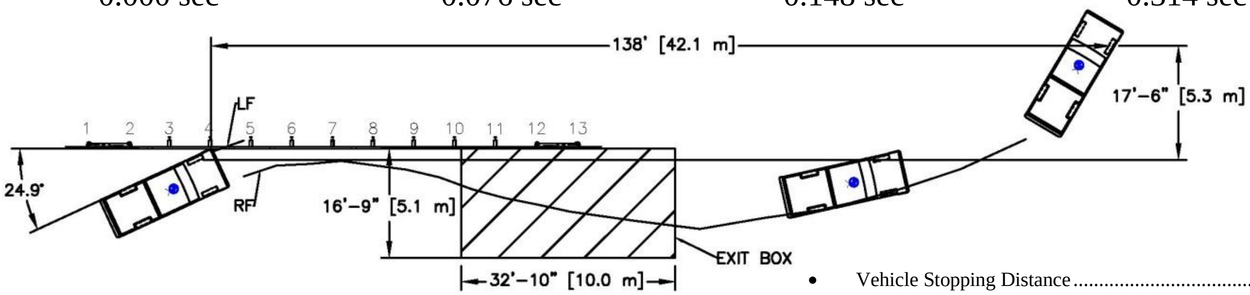
Figure 22. Upstream and Downstream Anchor Displacements

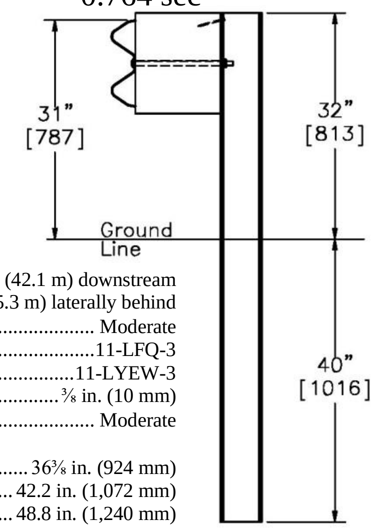
7.9 Discussion

The analysis of the test results for test no. MGSMIN-1 showed that the 75-ft (22.9-m) long MGS adequately contained and redirected the 2270P vehicle with controlled lateral displacements of the barrier. There were no detached elements or fragments that showed potential for penetrating the occupant compartment or presented undue hazard to other traffic. Deformations of, or intrusions into, the occupant compartment that could have caused serious injury did not occur. The test vehicle did not penetrate nor ride over the barrier and remained upright during and after the collision. Forces were evenly distributed amongst the upstream and downstream anchors, which produced similar longitudinal displacements. Vehicle roll, pitch, and yaw angular displacements, as shown in Appendix F, were deemed acceptable because they did not adversely influence occupant risk safety criteria nor cause rollover. It was determined that the vehicle's trajectory after impact did not violate the bounds of the exit box. Therefore, test no. MGSMIN-1 was determined to be acceptable according to the MASH safety performance criteria for test designation no. 3-11.



0.000 sec 0.076 sec 0.148 sec 0.314 sec 0.764 sec

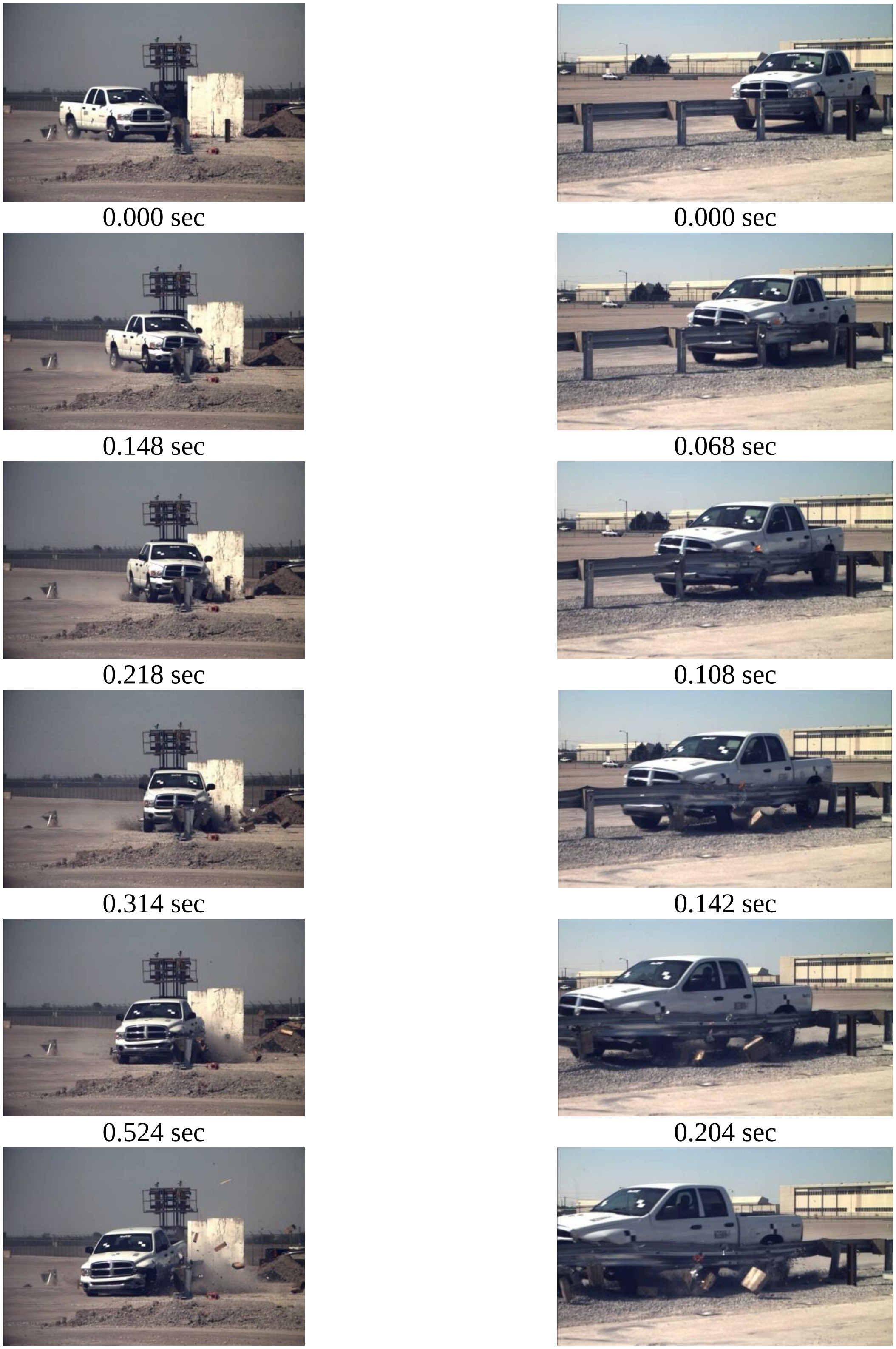




- Test Agency .... MwRSF
- Test Number MGSMIN-1
- Date 4/5/2012
- MASH Test Designation No. 3-11
- Test Article .... MGS Guardrail
- Total Length .... 75 ft (22.9 m)
- Key Component – Steel MGS Rail
  - Thickness .... 12 gauge (2.66 mm)
  - Top Mounting Height .... 31 in. (787 mm)
- Key Component - Steel Posts
  - Post Spacing .... 75 in. (1,905 mm)
  - Dimensions .... W6x8.5 x 72 in. long (W152x12.6 x 1,829 mm)
  - Embedment Depth .... 40 in. (1,016 mm)
- Key Component – Wood Spacer Blocks
  - Dimensions.. .... 6 x 12 x 14¼ in. (152 x 305 x 362 mm)
- Soil Type .... Coarse, Crushed Limestone Material
- Vehicle Make /Model .... 2005 Dodge Ram 1500 Quad Cab
  - Curb .... 4,913 lb (2,228 kg)
  - Test Inertial .... 4,956 lb (2,248 kg)
  - Gross Static .... 5,126 lb (2,325 kg)
- Impact Conditions
  - Speed .... 63.1 mph (101.6 km/h)
  - Angle (Trajectory) .... 24.9 deg
  - Angle (Orientation) .... 25.3 deg
  - Impact Location .... 4 in. (102 mm) downstream of post no. 4
- Exit Conditions
  - Speed .... 32.9 mph (52.9 km/h)
  - Angle (Trajectory) .... NA – exits overhead video before exiting the system
  - Angle (Orientation) .... 11.2 deg
- Exit Box Criterion .... Pass
- Vehicle Stability .... Satisfactory
- Vehicle Stopping Distance .... 138 ft (42.1 m) downstream
  .... 17 ft – 6 in. (5.3 m) laterally behind
- Vehicle Damage .... Moderate
  VDS[21] 11-LFQ-3
  CDC[22] 11-LYEW-3
  Maximum Interior Deformation .... ⅜ in. (10 mm)
- Test Article Damage .... Moderate
- Maximum Test Article Deflections
  - Permanent Set .... 36⅜ in. (924 mm)
  - Dynamic .... 42.2 in. (1,072 mm)
  - Working Width .... 48.8 in. (1,240 mm)
- Impact Severity (IS) .... 116.8 kip-ft (158.4 kJ) > 106 kip-ft (144 kJ) MASH limit
- Transducer Data and Maximum Angular Displacment

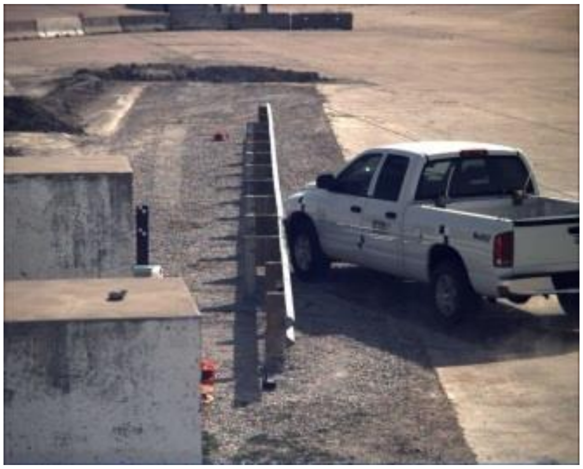
Evaluation Criteria		Transducer			MASH Limit
		DTS	DTS-SLICE	EDR-3	
OIV ft/s (m/s)	Longitudinal	-15.50 (-4.72)	-14.48 (-4.41)	-15.88 (-4.84)	≤ 40 (12.2)
	Lateral	14.15 (4.31)	14.66 (4.47)	14.02 (4.27)	≤ 40 (12.2)
ORA g's	Longitudinal	-8.95	-8.70	-8.12	≤ 20.49
	Lateral	6.94	6.16	5.71	≤ 20.49
THIV – ft/s (m/s)		19.82 (6.04)	20.18 (6.15)	NA	Not required
PHD – g's		9.89	9.62	NA	Not required
ASI		0.61	0.59	0.57	Not required
Roll (deg)		-6.5	-7.4	NA	<75°
Pitch (deg)		-5.0	-3.9	NA	<75°
Yaw (deg)		38.9	38.4	NA	Not required

Figure 23. Summary of Test Results and Sequential Photographs, Test No. MGSMIN-1



0.000 sec | 0.000 sec
0.148 sec | 0.068 sec
0.218 sec | 0.108 sec
0.314 sec | 0.142 sec
0.524 sec | 0.204 sec
0.700 sec | 0.228 sec

Figure 24. Additional Sequential Photographs, Test No. MGSMIN-1



0.000 sec

0.076 sec

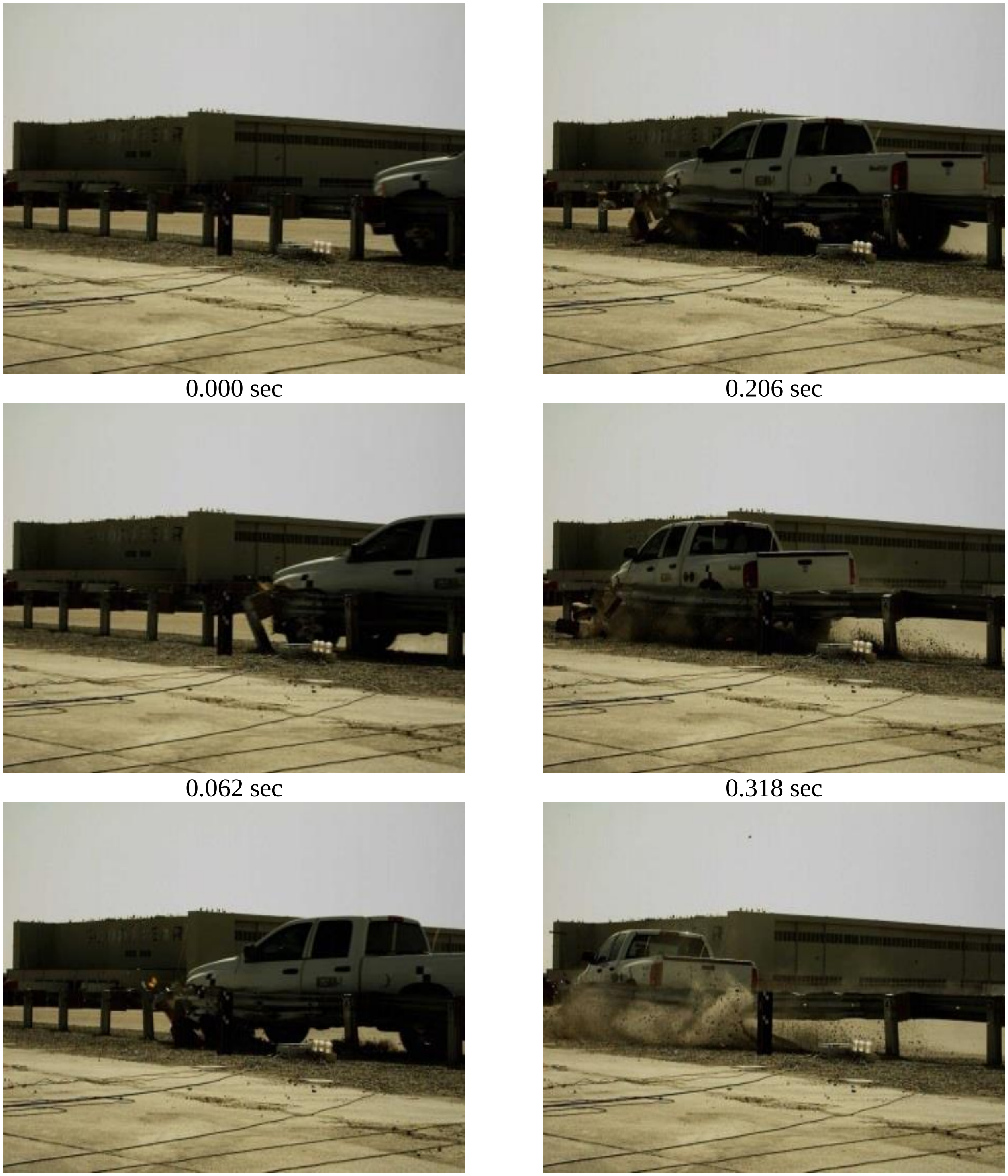
0.146 sec

0.200 sec

0.314 sec

0.700 sec

Figure 25. Additional Sequential Photographs, Test No. MGSMIN-1



0.000 sec 0.206 sec

0.062 sec 0.318 sec

0.130 sec 0.488 sec

Figure 26. Additional Sequential Photographs, Test No. MGSMIN-1

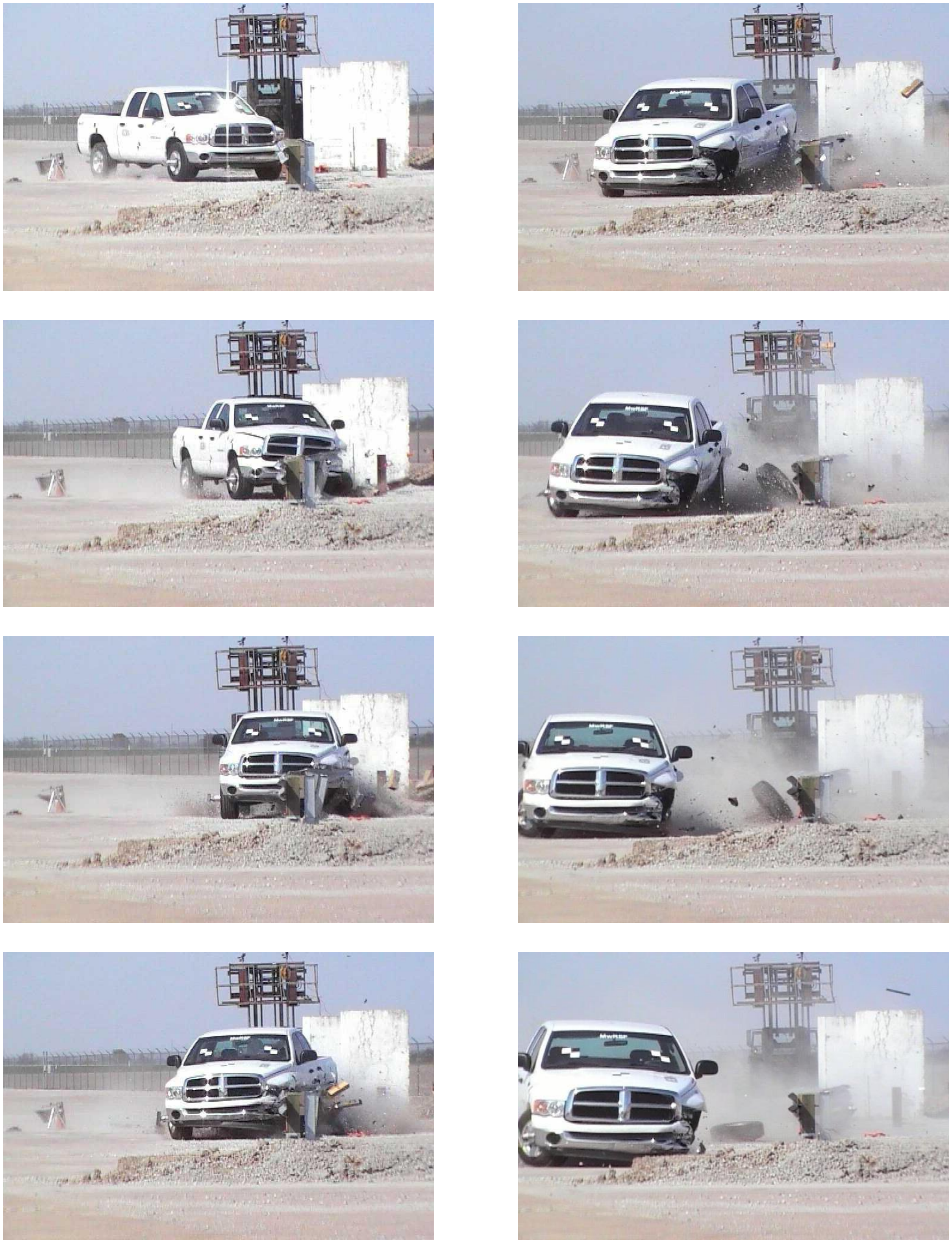


Figure 27. Documentary Photographs, Test No. MGSMIN-1

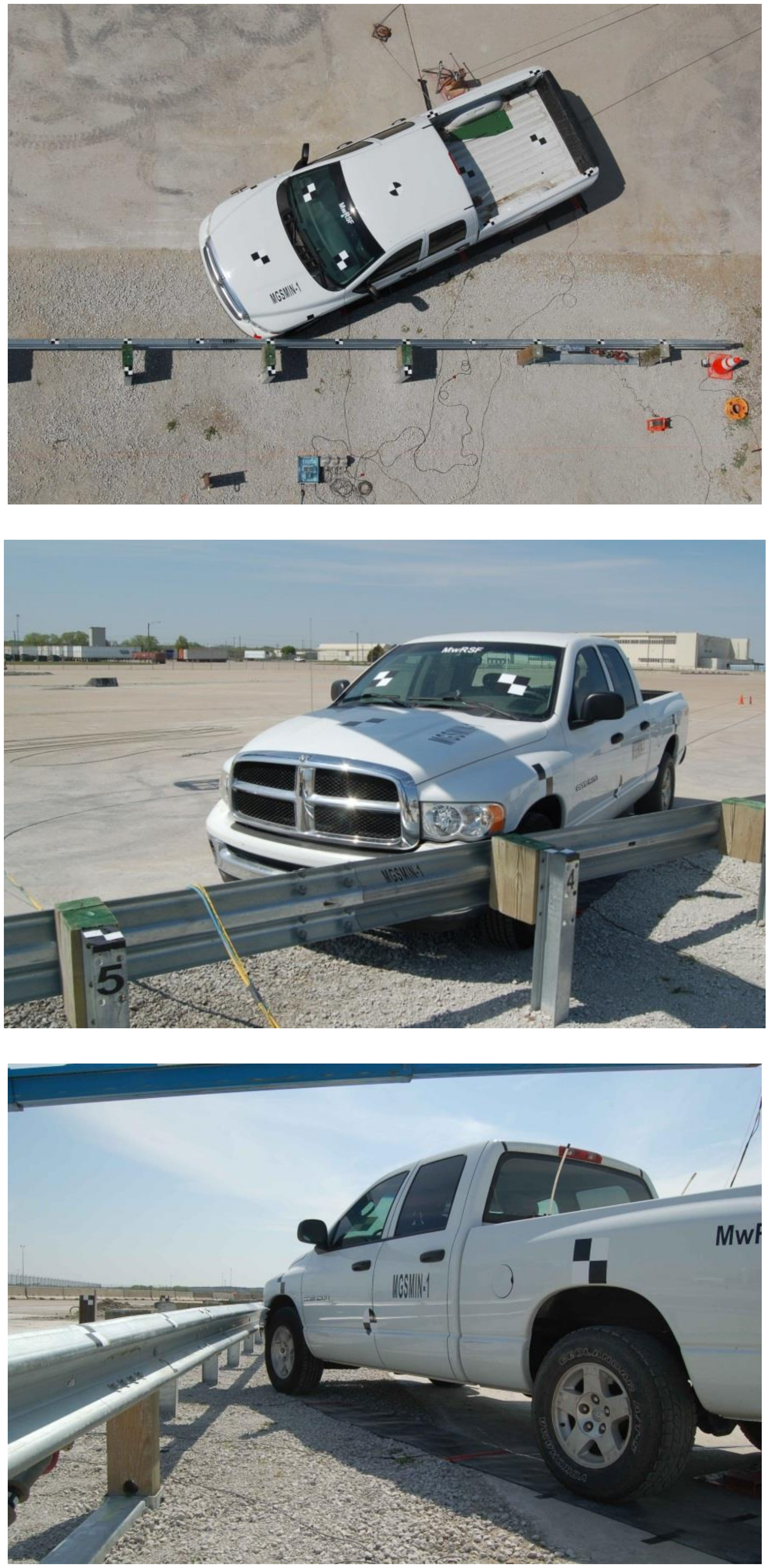


Figure 28. Impact Location, Test No. MGSMIN-1

Figure 29. Vehicle Final Position and Trajectory Marks, Test No. MGSMIN-1

Figure 30. System Damage, Test No. MGSMIN-1

Figure 31. System Damage, Test No. MGSMIN-1

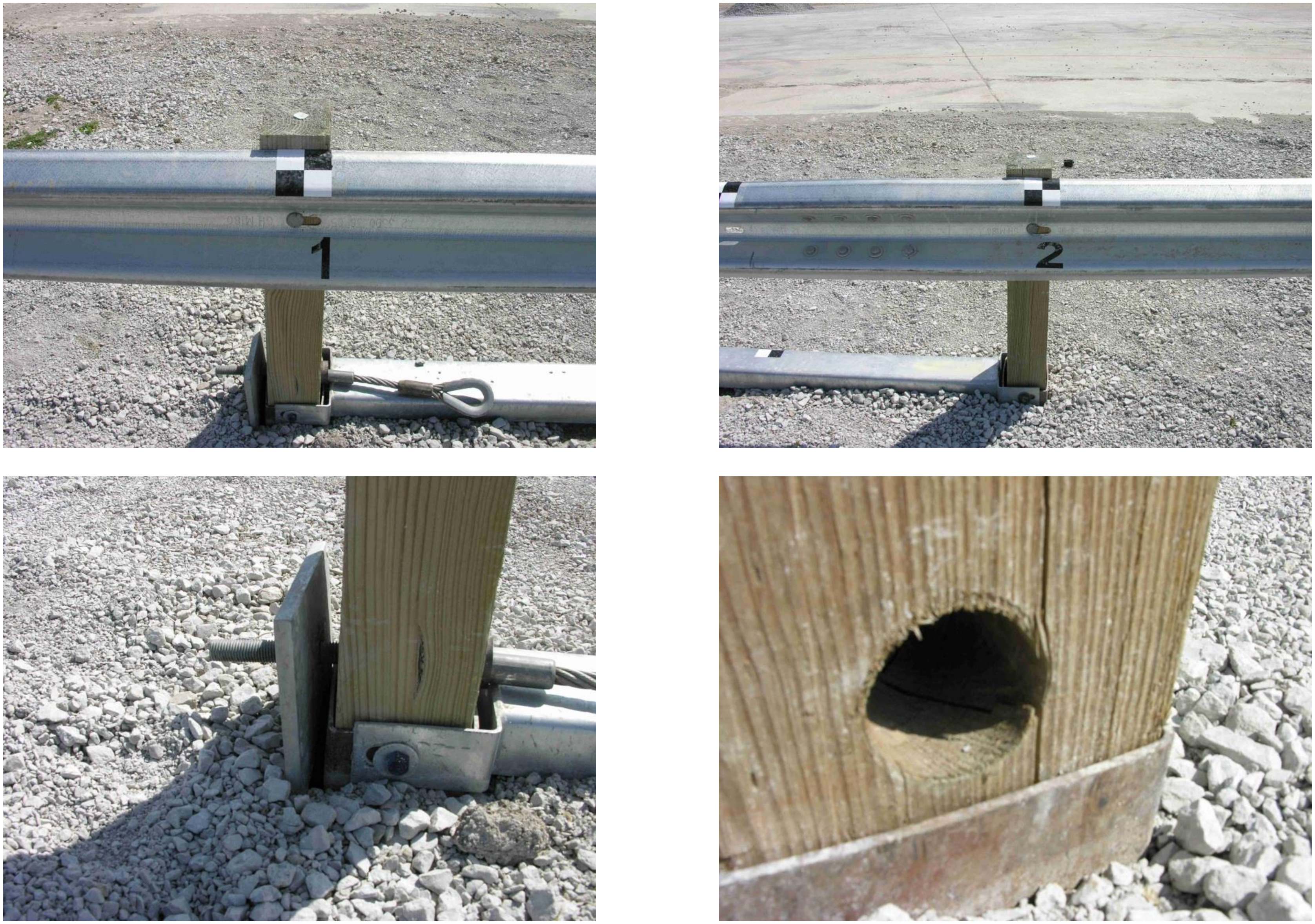


Figure 32. System Damage, Upstream Anchors, Post nos. 1 and 2, Test No. MGSMIN-1

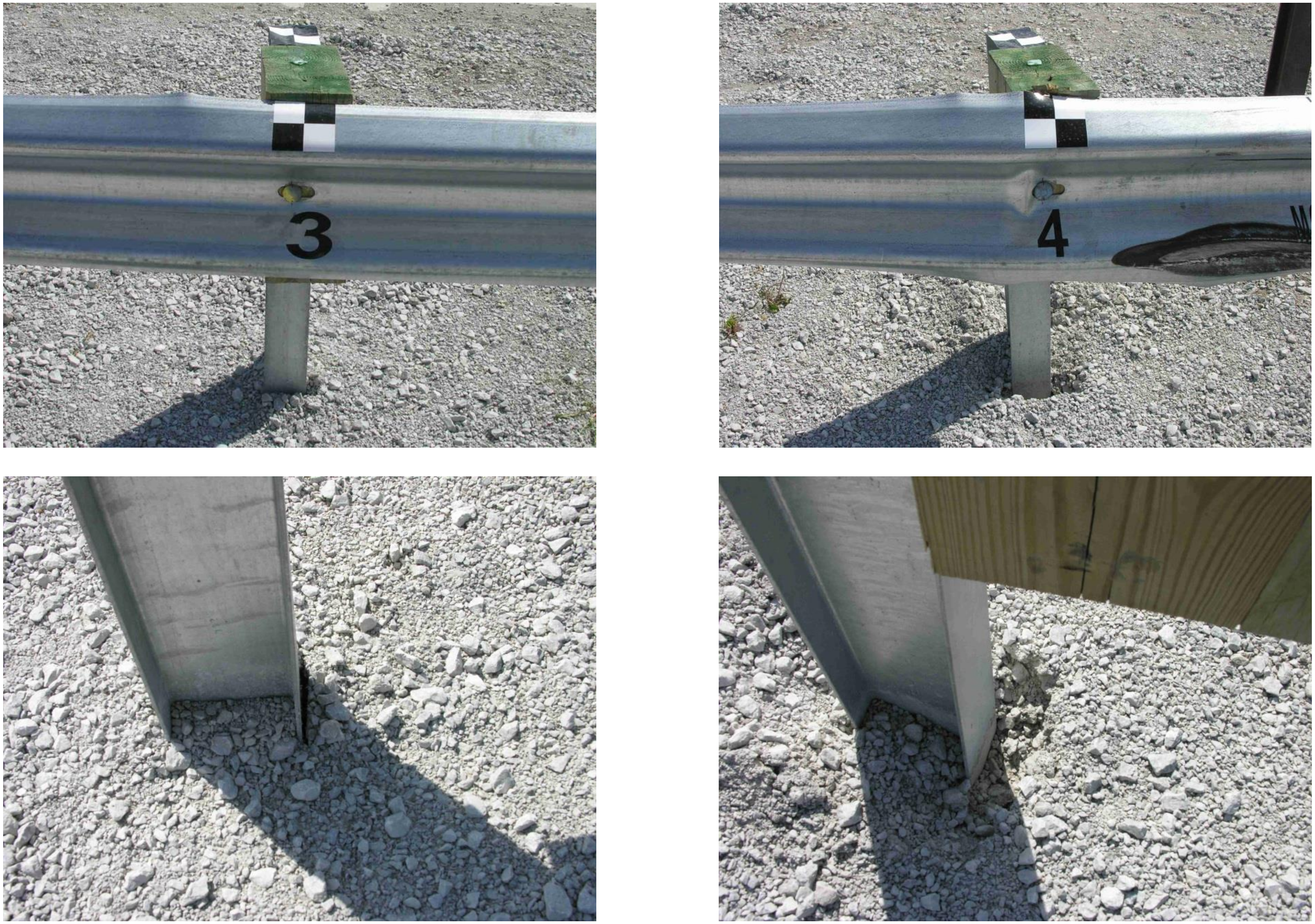


Figure 33. System Damage, Post nos. 3 and 4, Test No. MGSMIN-1

Figure 34. System Damage, Post nos. 5 and 6, Test No. MGSMIN-1

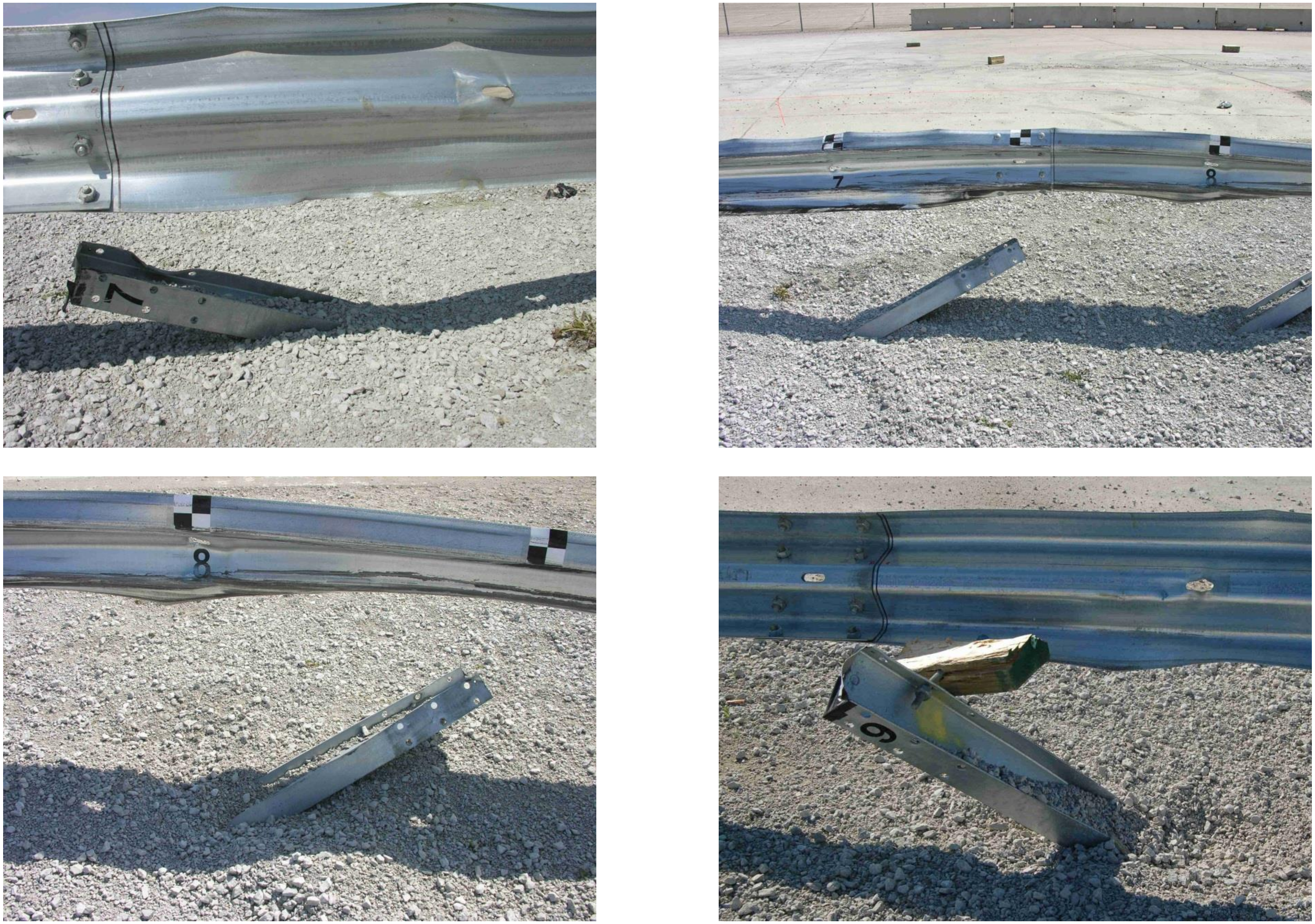


Figure 35. System Damage, Post nos. 7 through 9, Test No. MGSMIN-1

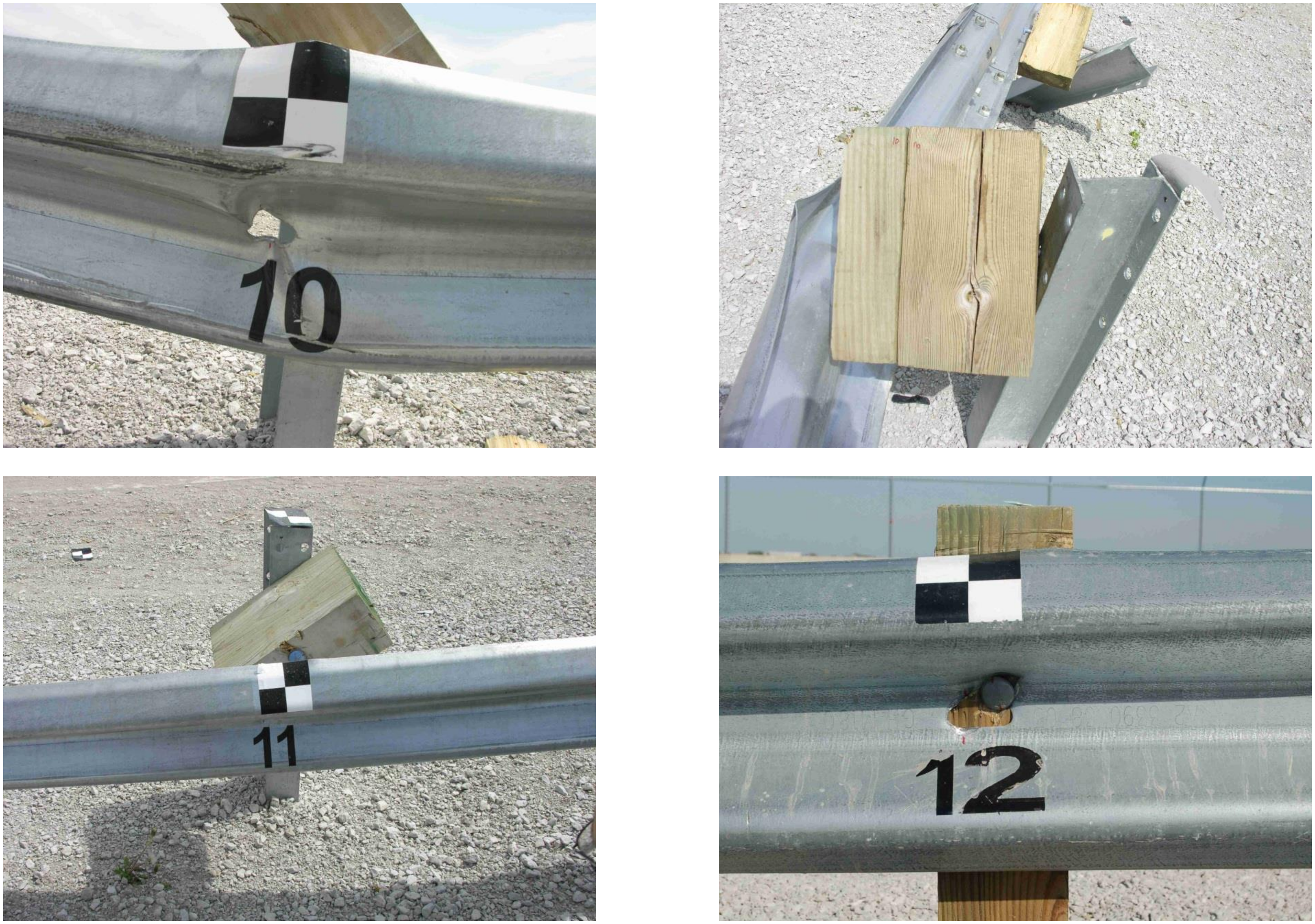


Figure 36. System Damage, Post nos. 10 through 12, Test No. MGSMIN-1

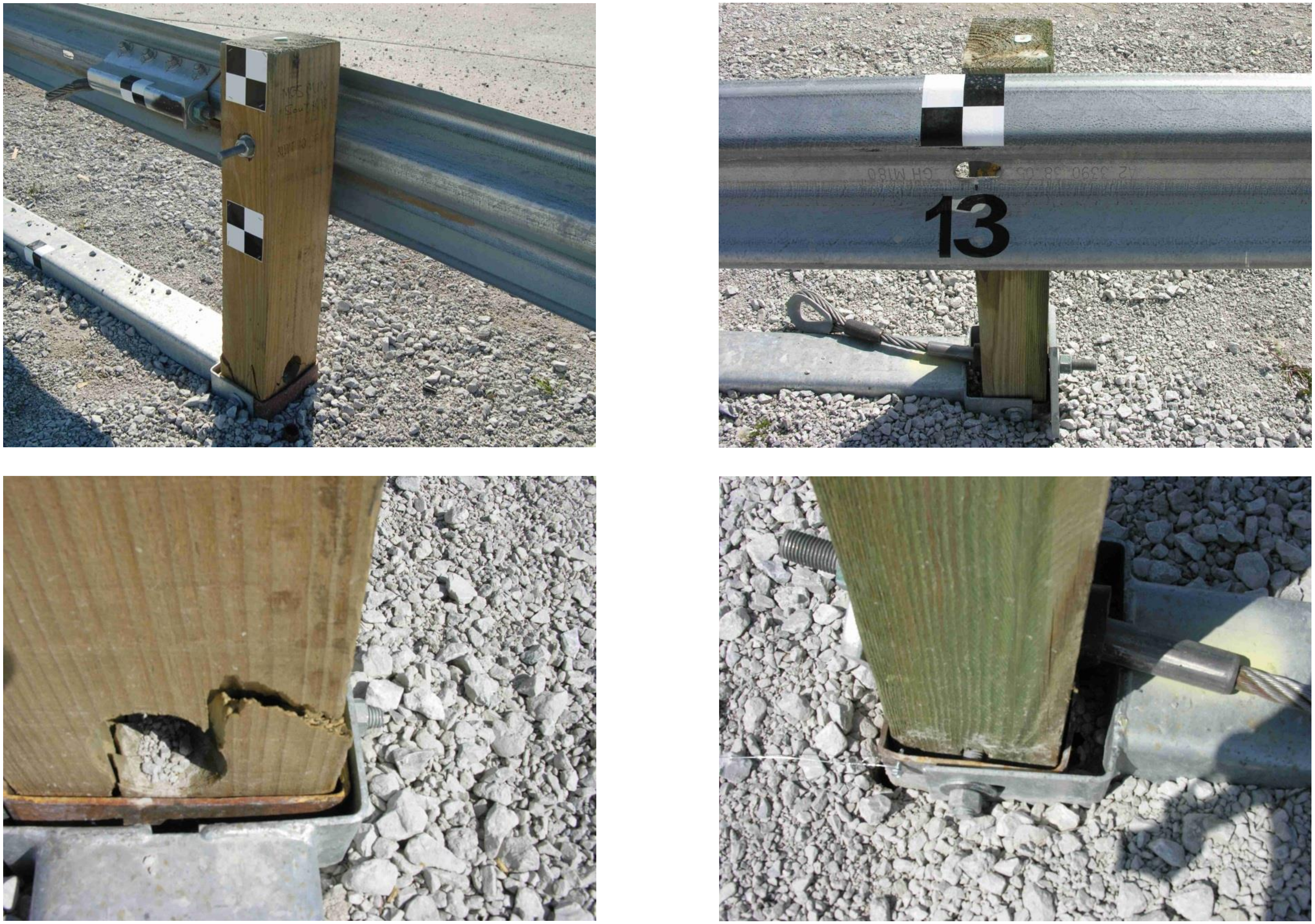
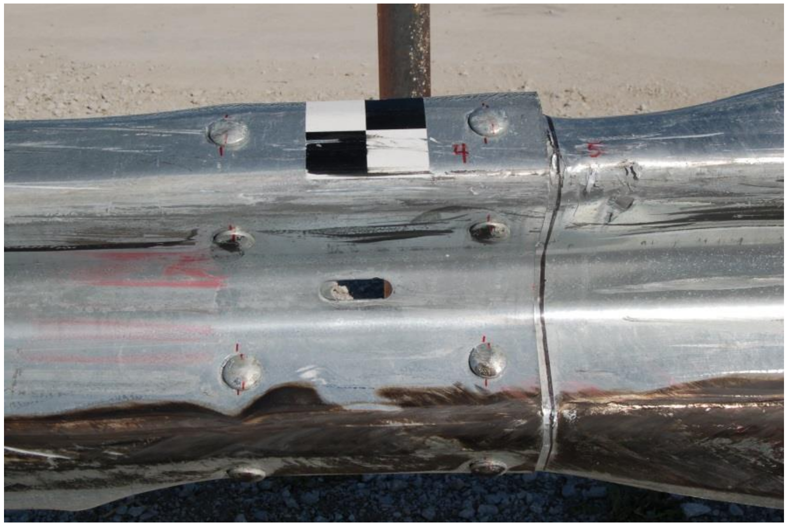
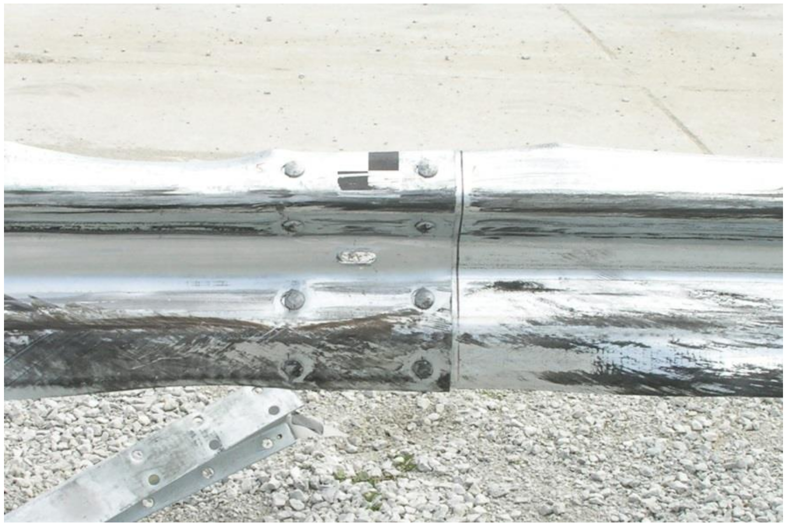


Figure 37. System Damage, Downstream Anchors, Post nos. 12 and 13, Test No. MGSMIN-1

Splice 2-3



Splice 4-5



Splice 5-6

Splice 7-8

Figure 38. System Damage, Splice Slippage, Test No. MGSMIN-1

Splice 9-10

Splice 11-12

Figure 39. System Damage, Splice Slippage, Test No. MGSMIN-1

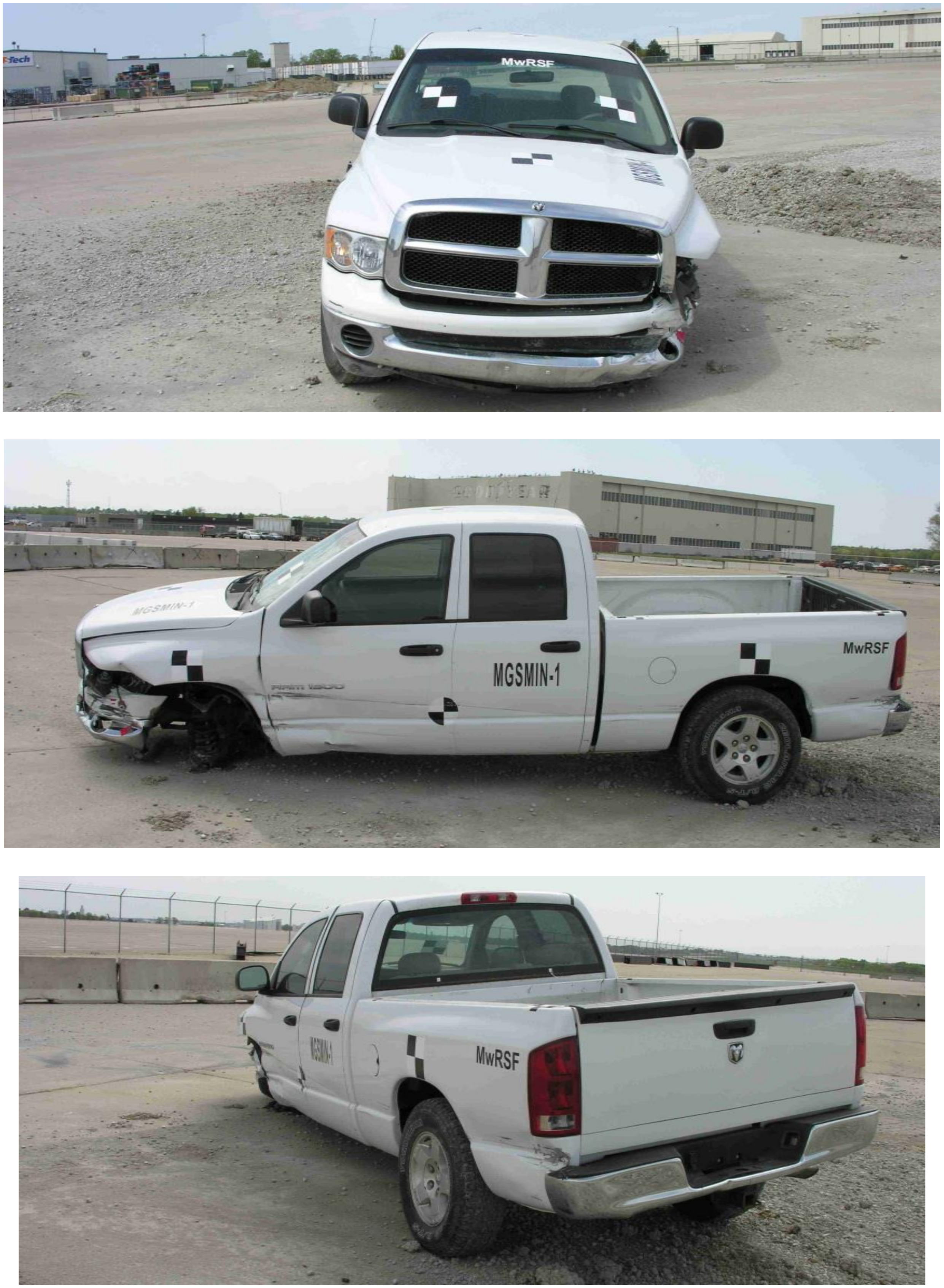


Figure 40. Vehicle Damage, Test No. MGSMIN-1

Figure 41. Vehicle Damage, Test No. MGSMIN-1

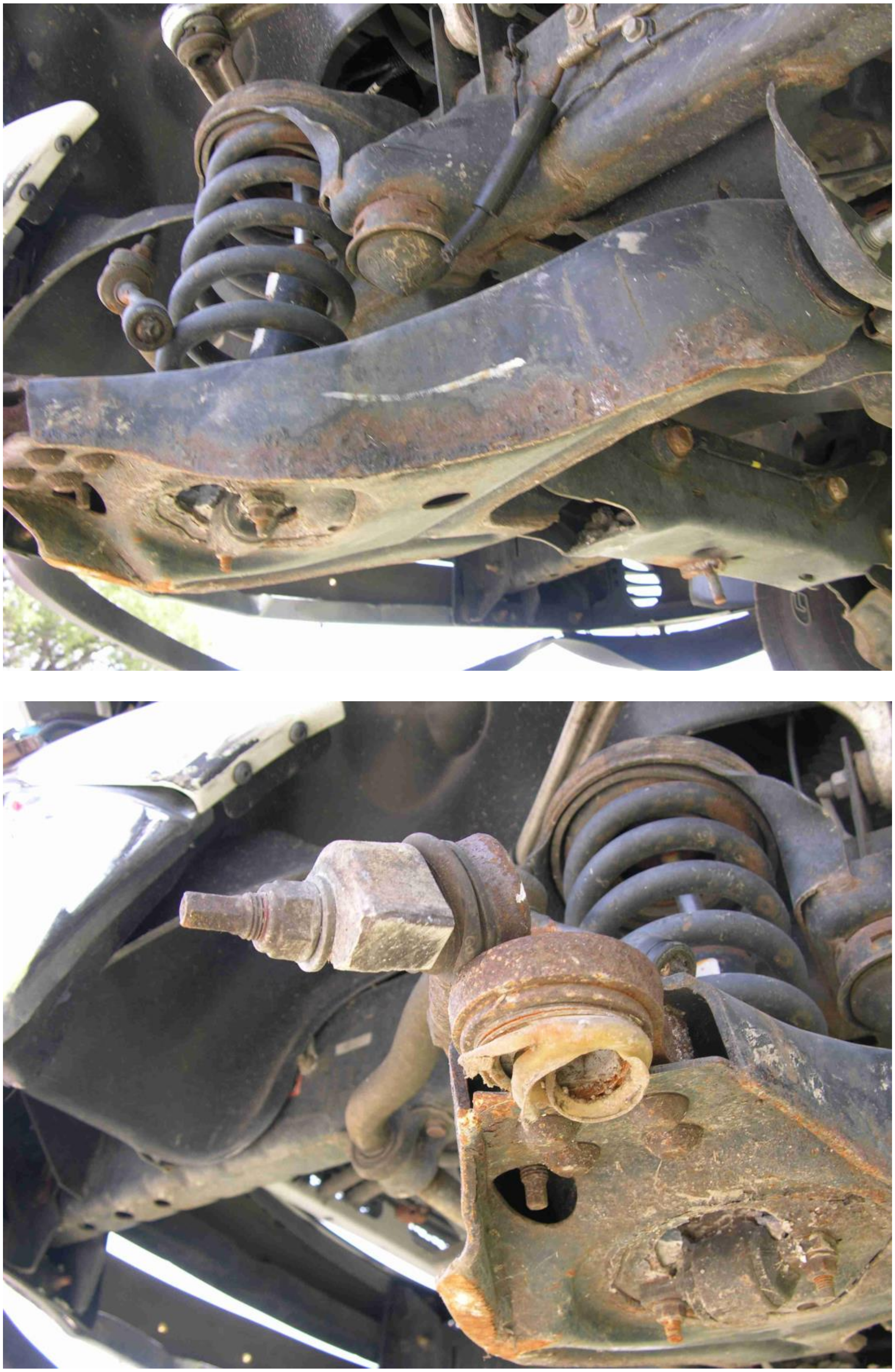


Figure 42. Vehicle Damage, Test No. MGSMIN-1

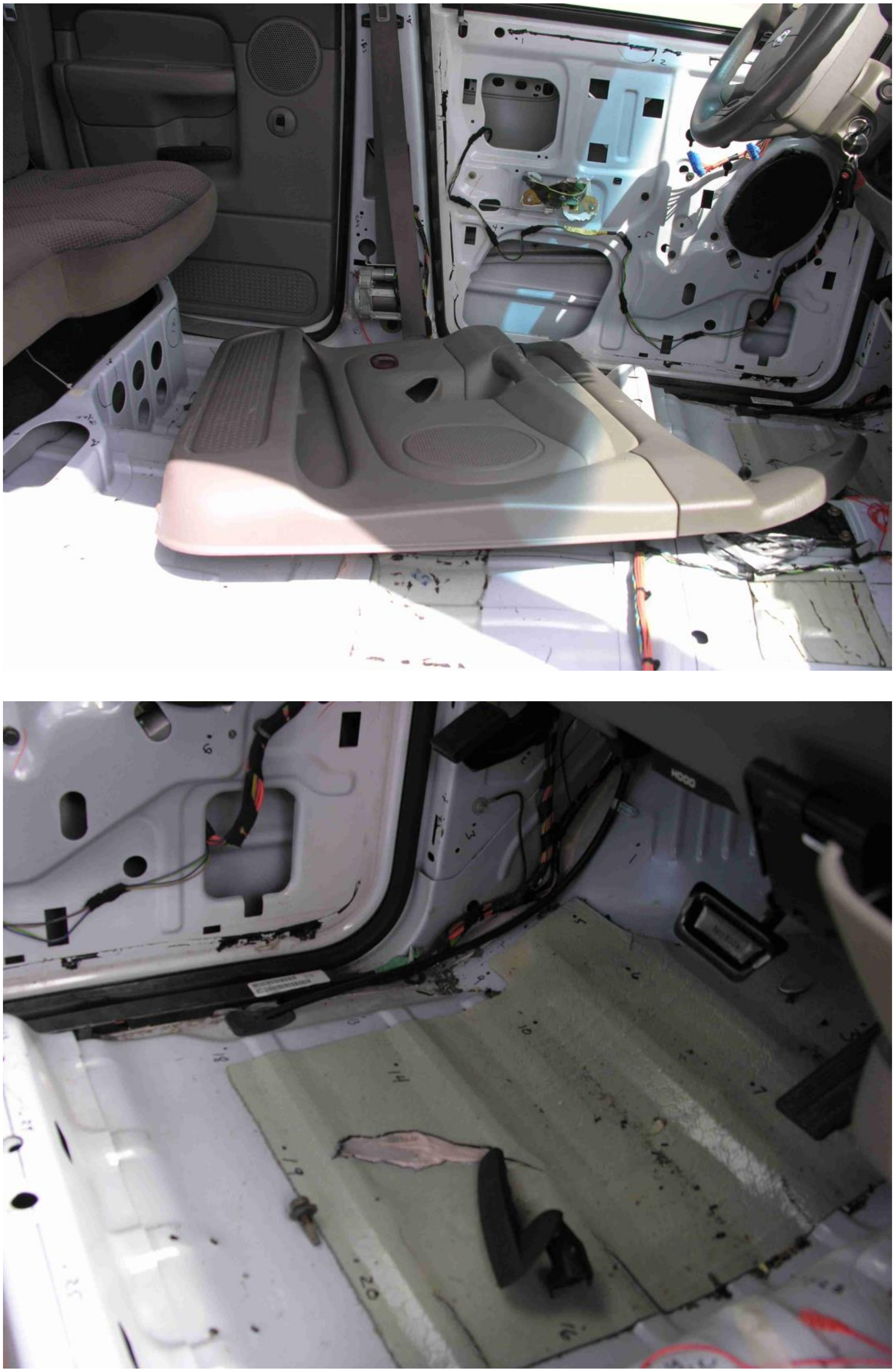


Figure 43. Occupant Compartment Deformation, Test No. MGSMIN-1

8 COMPARISON BETWEEN 175-FT AND 75-FT MGS

A comparison of test results between the standard MGS measuring 175 ft (53.3 m) long and the reduced 75-ft (22.9-m) system is presented in Table 10. Both tests were conducted under MASH TL-3 conditions with the 2270P vehicle. Rear view sequential photos along with barrier damage and vehicle damage are shown in Figures 44 through 46, respectively.

Table 10. Comparison of Test Results – Test Nos. 2214MG-2 and MGSMIN-1

Comparison of Results		MASH Test Designation No. 3-11	
		175-ft (53.3-m) MGS	75-ft (22.9-m) MGS
Test Number		2214MG-2	MGSMIN-1
Reference Number		[5]	NA
Vehicle	Designation	2270P	2270P
	Test Inertial, lb (kg)	5,000 (2,268)	4,956 (2,248)
Impact Conditions	Speed, mph (km/h)	62.8 (101.1)	63.1 (101.6)
	Angle, deg	25.5	24.9
Impact Severity, kip-ft (kN-m)		122 (166)	116 (158)
Exit Conditions	Speed, mph (km/h)	39.6 (63.7)	32.9 (52.9)
	Trajectory Angle, deg	13.5	NA
ORA, g's	Longitudinal	-8.2	-8.1
	Lateral	-6.9	5.7
OIV, ft/s (m/s)	Longitudinal	-15.3 (4.7)	-15.9 (4.8)
	Lateral	-15.6 (4.8)	14.0 (4.3)
Test Article Deflections, in. (mm)	Dynamic	43.9 (1,115)	42.2 (1,072)
	Permanent	31⅝ (803)	36⅜ (924)
	Working Width	48.6 (1,234)	48.8 (1,240)
Max. Occupant Compart. Deformation, in. (mm)		0.8 (19)	0.4 (9.5)
Max. Yaw Angle, deg.		-46	38.9
Max. Roll Angle, deg.		-5	6.5
Max. Pitch Angle, deg.		-2	-5
Impact Point		18" upstream post 12	4" downstream post 4
Posts detached from rail during impact		13-16	5-9,11,13
Posts hit by leading tire (wheel snag)		13-15	5-8
Leading tire/wheel disengaged		partially	yes

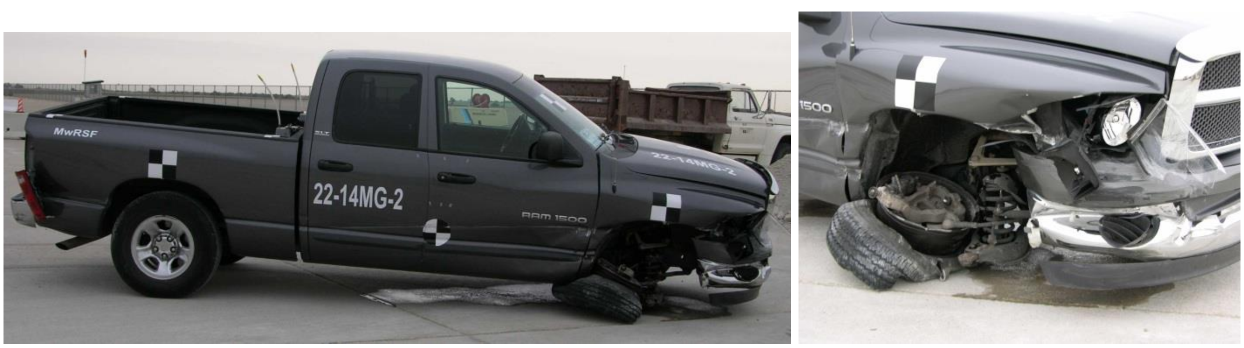
75-ft System | 175-ft System

Figure 44. Rear View 2270P Tests - MGSMIN-1 (left) and 2214MG-2 (right)

75-ft System 175-ft System

Figure 45. Barrier Damage – MGSMIN-1 (left) and 2214MG-2 (right)

75-ft System



175-ft System

Figure 46. Vehicle Damage - MGSMIN-1 (top) and 2214MG-2 (bottom)

Each test successfully passed all criteria set forth by MASH. Longitudinal and lateral change in velocity plots are shown in Figures 47 and 48. An EDR-4 accelerometer, used during test no. 2214MG-2, and a DTS system, used during test no. MGSMIN-1, recorded the pitch, roll, and yaw motions throughout impact and redirection sequentials, as shown in Figures 49 through 51. Test no. 2214MG-2 impacted the barrier on the right side of the vehicle compared to test no. MGSMIN-1, which impacted the barrier on the left side of the vehicle. As shown in Table 10, this produced negative roll and yaw angles for test no. 2214MG-2, according to the orientation angles in MASH [3]. This difference also affected the occupant ridedown accelerations (ORA) and the occupant impact velocity (OIV) values. However, the roll and yaw values were inverted to correspond with the orientation from test no. MGSMIN-1 and are compared in Figures 50 and 51. These comparisons now indicate roll into the barrier and yaw away from the barrier. In addition, the barrier profiles throughout the impact zone at 850 ms are plotted in Figure 52.

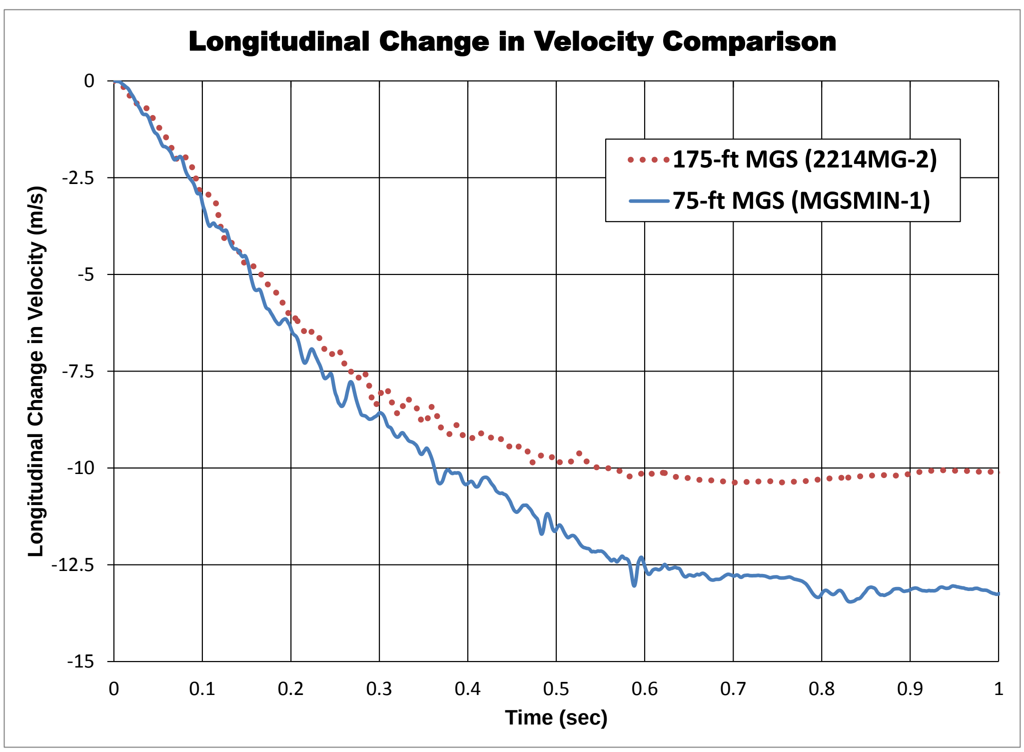


Figure 47. Longitudinal Change in Velocity Comparison

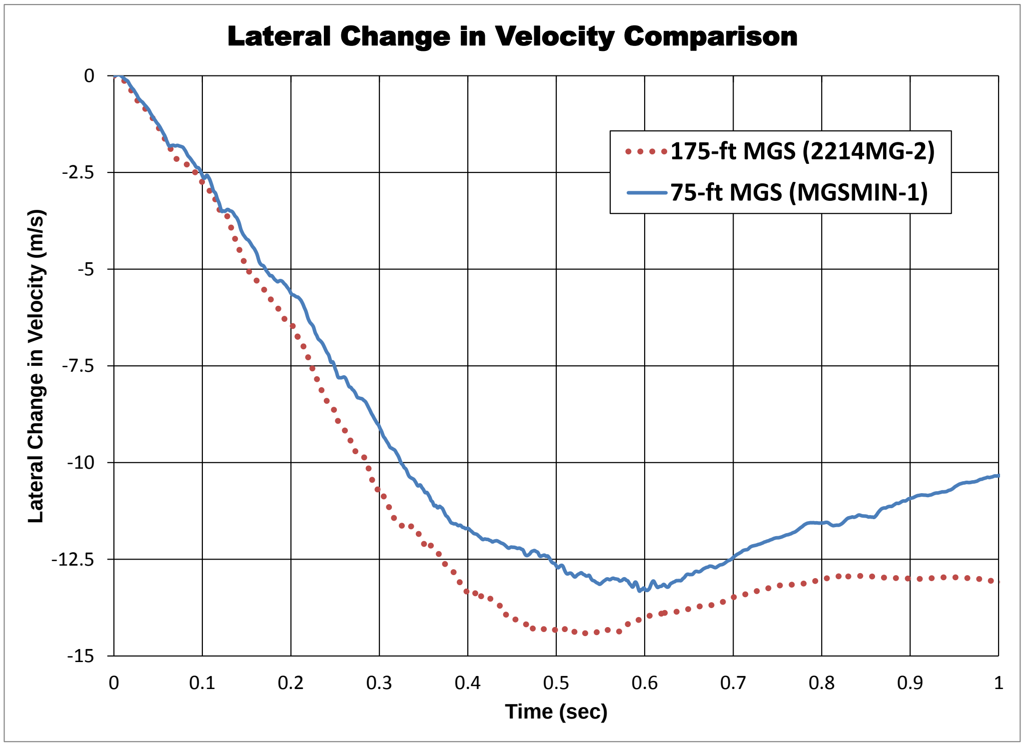


Figure 48. Lateral Change in Velocity Comparison

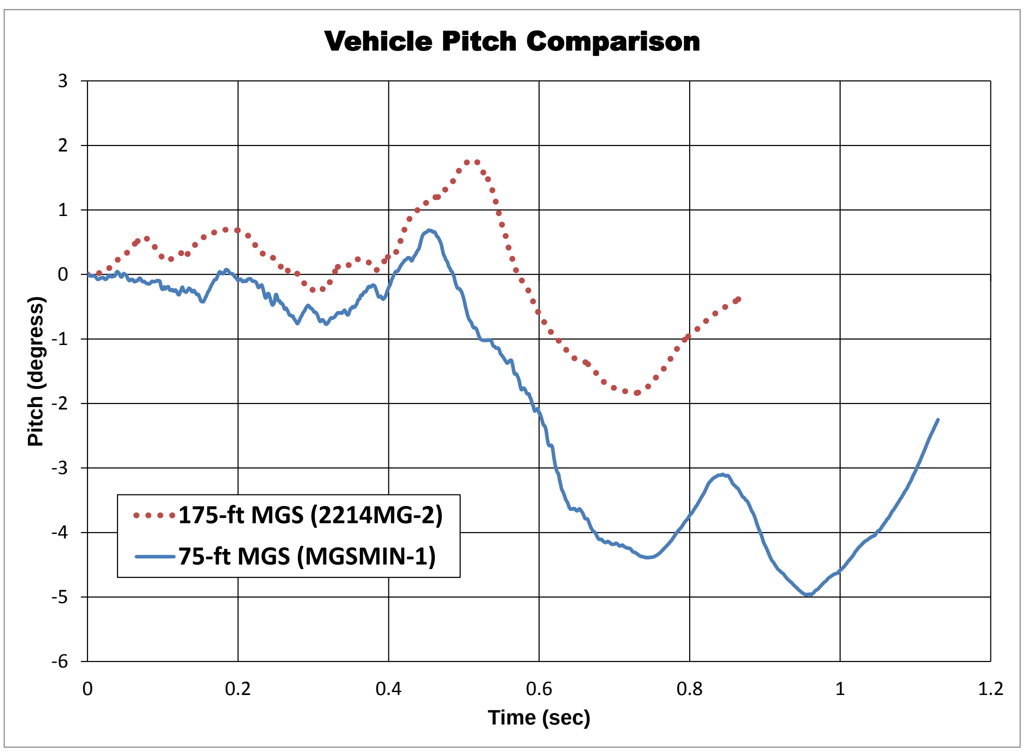


Figure 49. Vehicle Pitch Comparison

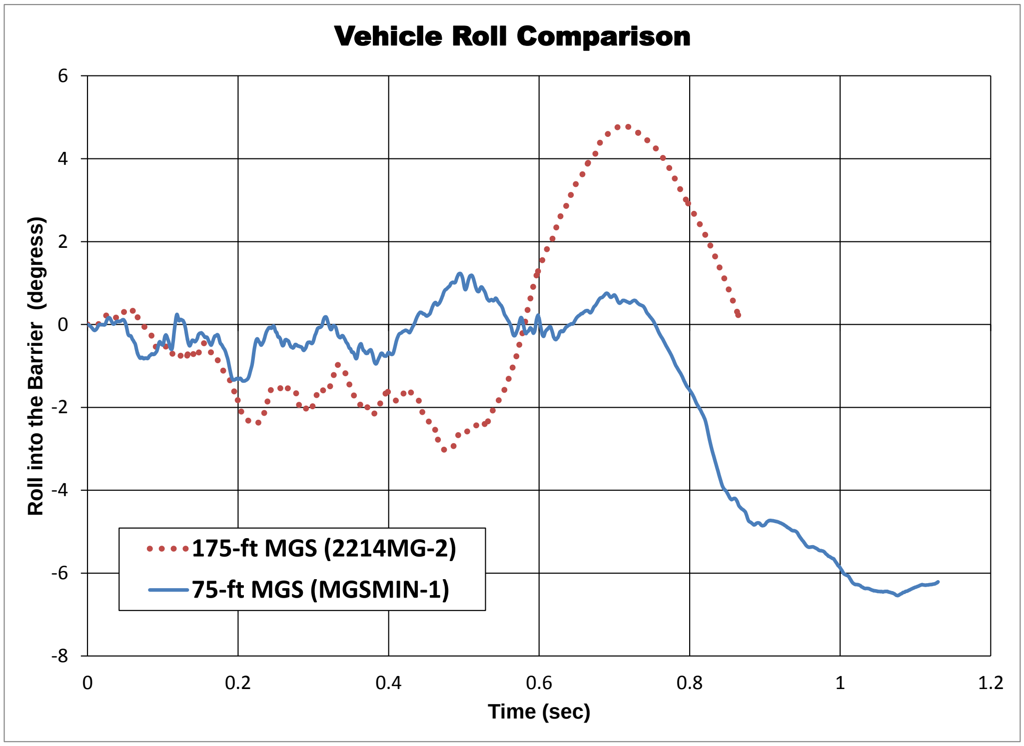


Figure 50. Vehicle Roll Comparison

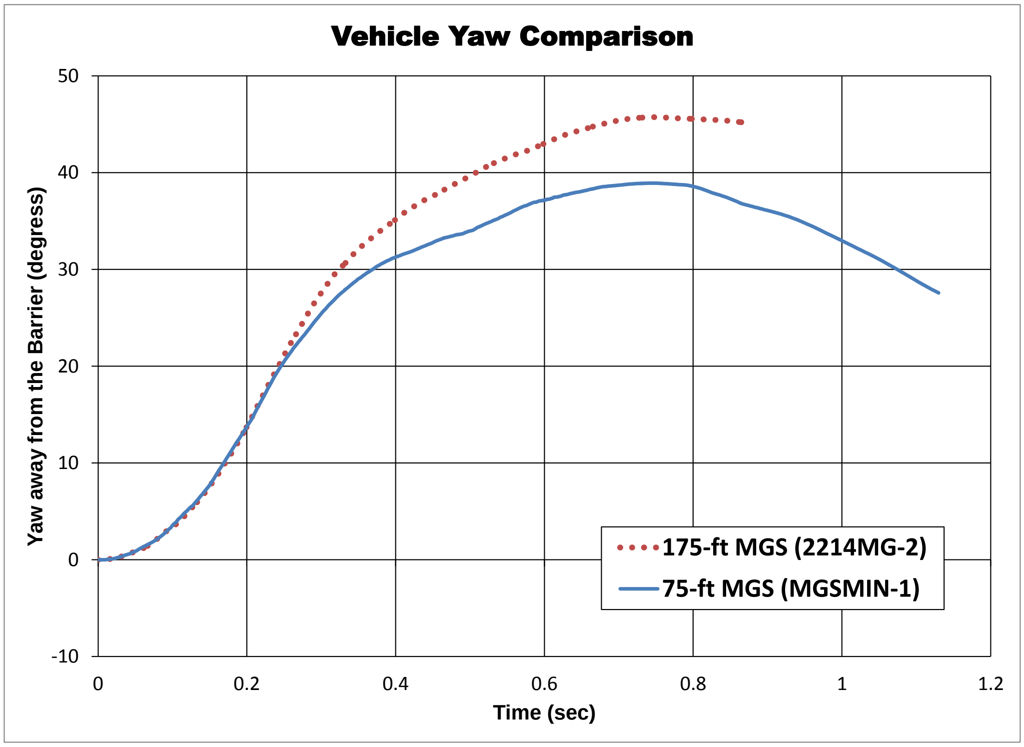


Figure 51. Vehicle Yaw Comparison

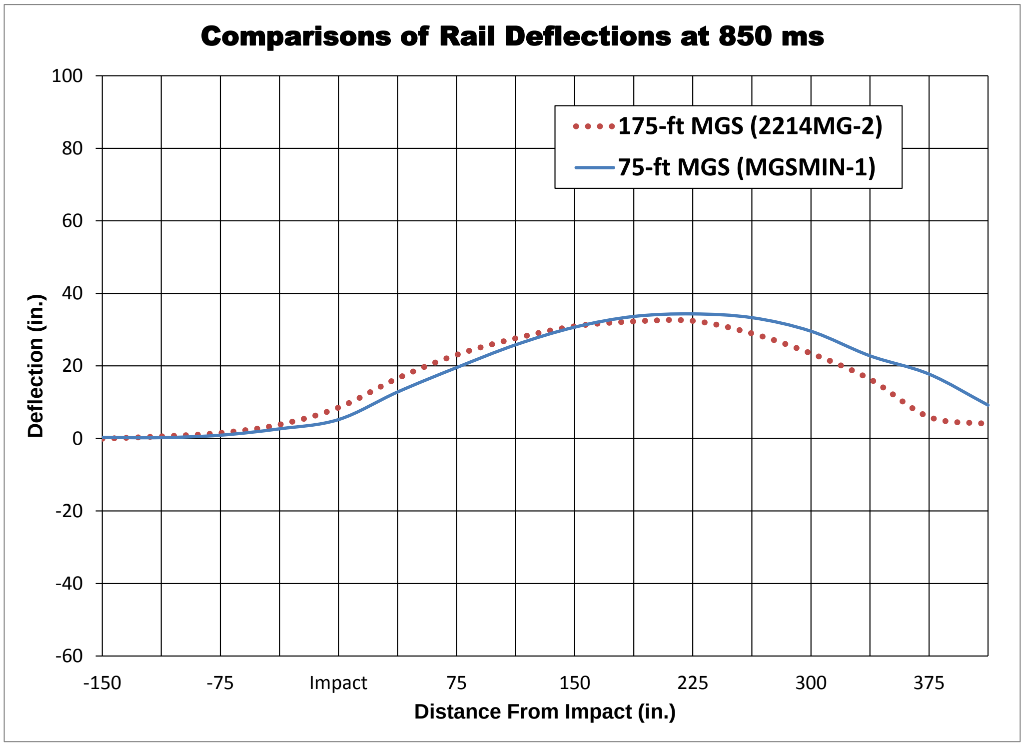


Figure 52. Rail Deflection Comparisons

The 175-ft (53.3-m) MGS and the 75-ft (22.9-m) MGS had similar results across the board. In general, rail deflections of the 75-ft (22.9-m) MGS closely resembled those of the 175-ft (53.3-m) MGS. There was less than a 3 percent difference in the maximum dynamic deflections and no considerable difference in the working widths. In addition, there was a 13 percent difference between the permanent rail deflections. However, three additional posts were detached from the rail, and an extra post was impacted by the leading tire in the 75-ft (22.9-m) MGS test. The ORA's and OIV's were slightly lower in the lateral direction for the 75-ft (22.9-m) system. These differences are also somewhat evident by examining the change in velocity plots. The pitch and yaw motions followed similar trends for both systems, and the minute change in roll motion was considered insignificant.

Some differences in the rail deflection may be attributed to the soil conditions. The more recent 75-ft (22.9-m) MGS crash test was performed in soil that used a relatively new compaction method. However, soil conditions for both tests met the minimum standards set in MASH. The 75-ft (53.3-m) MGS had a higher number of posts yield in the impact region, which resulted in a slightly longer contact length. Although the shorter system contained 16 less posts than the standard MGS, both systems exhibited similar maximum barrier deflections. The vehicle in the 75-ft (22.9-m) system experienced roll, pitch, and yaw angular displacements which closely matched those observed in the 175-ft (53.3-m) system. In addition, there were no considerable differences in the ORA or OIV values between the two tests. Thus, the reduction in system length from 175 ft (53.3 m) to 75 ft (22.9 m) did not adversely affect the overall performance of the MGS system.

9 BARRIER VII BASELINE MODEL

9.1 Background and Scope

To determine the minimum effective lengths for the MGS, additional computer simulations were performed to further investigate system lengths other than those tested. BARRIER VII is a computer program used extensively to model and analyze vehicle crashes into guardrail systems [23]. In this program, the barrier and vehicle are idealized as two-dimensional structures in the horizontal plane, meaning that vertical displacements of the barrier or the vehicle are not considered. BARRIER VII models post and beam systems using a rail that yields only at nodal locations and elastic, perfectly-plastic posts. Thus, component models of W6x9 (W152x13.4) posts, anchor posts, and 12-gauge (2.66-mm) W-beam guardrail were required to perform the analysis. The vehicle was idealized as a rigid body of prescribed shape surrounded by a cushion of discrete springs.

A baseline BARRIER VII model was developed to study the performance of the MGS guardrail with specifically the end anchorages using a 75-ft (22.9-m) system length. The model was validated with the corresponding full-scale crash test, test no. MGSMIN-1. This model was used for parametric studies to determine the effect that length had on guardrail post capacity and safety performance, to obtain maximum dynamic deflections, and to determine a minimum MGS system length.

9.2 Development and Calibration of the Baseline BARRIER VII Model

A BARRIER VII model was originally developed to represent a 175-ft (53.3-m) MGS system and was validated with full-scale testing [15]. This model was then modified to represent the 75-ft (22.9-m) MGS and calibrated using the data acquired during test no. MGSMIN-1 from the overhead high-speed film, onboard vehicle accelerometers, and speed traps based on previous calibration methods [24]. The BARRIER VII model was constructed from a single beam type and three different post types. The model had a total length of 75 ft (22.9 m) with W6x9 (W152x13.4) line posts. The first two and last two posts represented the modified Breakaway Cable Terminal (BCT) anchor posts on both the upstream and downstream ends but installed tangent. A layout of the 75-ft (22.9-m) MGS baseline BARRIER VII model is shown in Figure 53.

9.2.1 W-Beam Guardrail Model

The W-beam guardrail model was based on 50-ksi (345-MPa) steel and the geometry of standard 12-gauge (2.66-mm thick) guardrail. Other required properties were determined using elastic bending equations. A uniform mesh density was used across the entire length of all simulated systems. For the 75-ft (22.9-m) long MGS system, a total of 97 nodes were used, which resulted in a node spacing of 9⅜ in. (238 mm).

9.2.2 Coefficient of Friction

Contact interfaces between the vehicle and barrier were defined within BARRIER VII with a coefficient of friction. This global coefficient of friction was utilized to account for vehicle-rail friction, vehicle-post friction, and wheel snag during this impact event. The kinetic friction value was calibrated according to the physical test's exit time, parallel time and length of contact in order to provide the most accurate results. The coefficient of friction had a final value of 0.30.

9.2.3 W6x9 (W152x13.4) Post Models

The line-posts were simulated as 6-ft (1.83-m) long, W6x9 (W152x13.4) posts embedded in soil. Force versus deflection characteristics observed from previous bogie tests provided the basis for the post model. Calibrating the post input parameters began with comparisons of the deflected barrier profile during impacts. Additionally, due to the reduced system length, it was crucial to capture the longitudinal load transfer to end anchors as seen in full-scale crash testing.

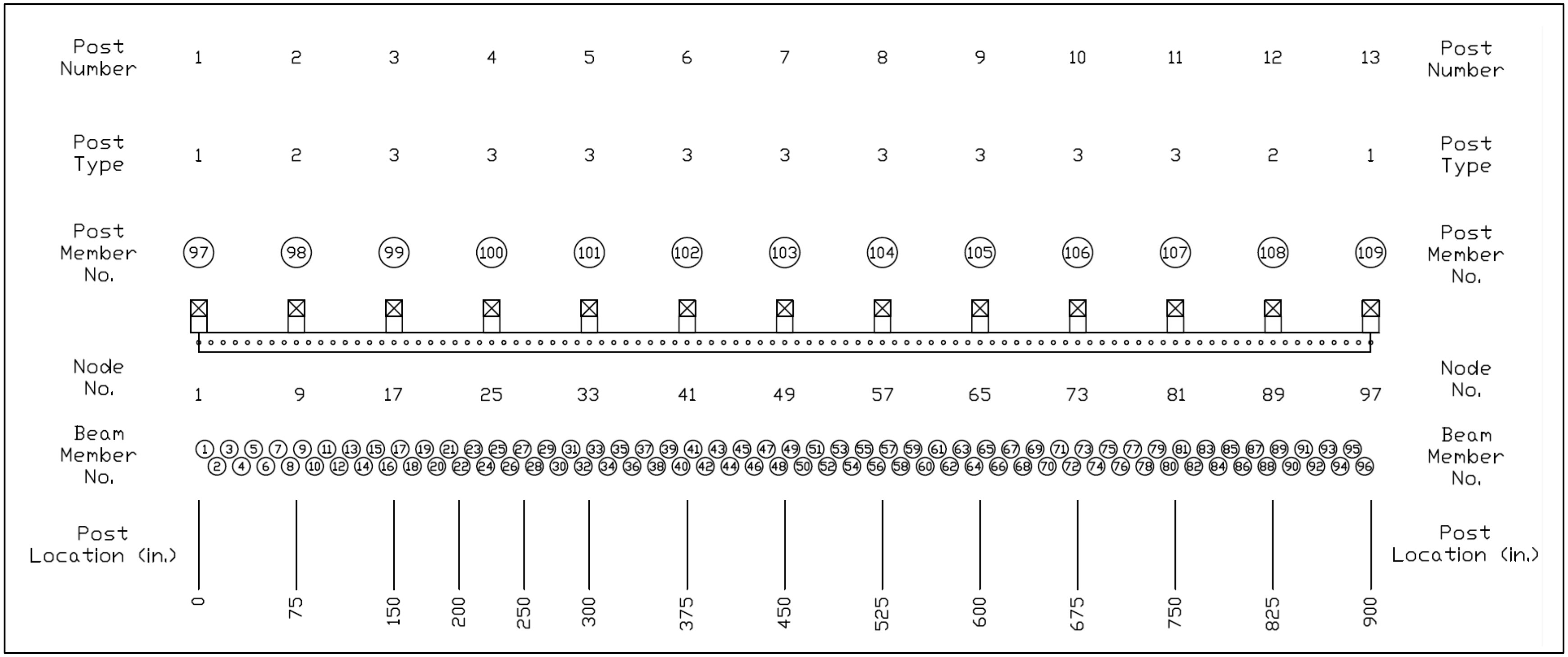


Figure 53. BARRIER VII Model Details, 75-ft MGS

Thus, in addition to matching the deflected barrier profiles during redirection, the calibration effort included matching the loads and deflections experienced by the end anchorages.

The calibrated post parameters for the W6x9 (W152x13.4) line posts used in the BARRIER VII simulations are shown in Table 11. In order to match the barrier profile and longitudinal load transfer to the end anchors observed during full-scale testing, some of the post parameters, such as the moment about the weak axis, had to be reduced and, thus, may not be truly indicative of physical posts. However, it was later determined that once the entire model was calibrated, the reduction in the line-post parameters did not adversely affect the results.

Table 11. BARRIER VII Line Post and Friction Parameters

BARRIER VII Parameters	Units	Input Values
K_B – Post Stiffness Along B (strong axis)	kip/in. (kN/m)	3.00 (525.38)
K_A – Post Stiffness Along A (weak axis)	kip/in. (kN/m)	2.00 (350.25)
M_A – Moment About A (strong axis)	kip-in. (kN-m)	180.65 (20.41)
M_B – Moment About B (weak axis)	kip-in. (kN-m)	30.90 (3.49)
δ_F – Failure Deflection Along A & B	in. (mm)	15 (381)
μ_k – Kinetic Friction Coefficient	Vehicle to Barrier	0.30

9.2.4 Anchor Models

In full-scale barrier systems used in MwRSF crash tests, two modified BCT posts are positioned at each end of the guardrail and housed within 6-ft (1.83-m) long steel foundation tubes. A ground line strut is positioned between the anchor posts, and a cable anchor is attached between the end post and the guardrail section.

In BARRIER VII, the ground-line strut and cable were not modeled for simplicity. Thus, to accommodate for this, the two end anchor posts were modeled with significantly stiffer post parameters to compensate for the lack of the ground line strut and cable [25-26].

Previous BARRIER VII MGS models contained anchorages which were developed and calibrated to replicate longitudinal force versus deflection characteristics due to rail loads. However, short system lengths increase the propensity for vehicle contact with the anchorage posts. The previous end anchorage models were not developed with breakaway characteristics, and had failure criterion which was too high to properly release when impacted by the vehicle. Thus, new end anchorages had to be developed to allow for fracture when impacted by the errant vehicle while maintaining the tensile strength of the rail.

The new anchor post models were calibrated with a separate full-scale crash test which focused specifically on impacts near the downstream end terminal. Full-scale crash test no. WIDA-1 involved a 2270P pickup impacting six posts upstream of the downstream end of a 175-ft (53.3-m) MGS system at 63 mph (101.4 km/h) and 26.4 degrees [10]. Simulations with the 175-ft (53.3-m) BARRIER VII model were conducted with the vehicle impacting the barrier, six posts upstream of the downstream end. Both the strong- and weak-axis modified BCT anchor post parameters were adjusted to match the fracture characteristics and conditions observed during test no. WIDA-1. The modified BCT anchor parameters are tabulated in Table 12 and the corresponding input deck for the BARRIER VII simulation is located in Appendix G.

Table 12. BARRIER VII BCT Anchor Post Parameters

BARRIER VII Parameters	Units	Input Values
K_1 – Post Stiffness - Strong BCT Anchor Along A and B (strong and weak axes)	kip/in. (kN/m)	6.00 (1050.76)
K_2 – Post Stiffness – Second BCT Anchor Along A and B (strong and weak axes)	kip/in. (kN/m)	3.00 (525.38)
M_1 – Moment - Strong BCT Anchor Along A and B (strong and weak axes)	kip-in. (kN-m)	675.0 (76.26)
M_2 – Moment – Second BCT Anchor Along A and B (strong and weak axes)	kip-in. (kN-m)	350.0 (39.54)
δ_F – Failure Deflection – Strong BCT Anchor Along A and B (strong and weak axes)	in. (mm)	11 (279)
δ_F – Failure Deflection– Second BCT Anchor Along A and B (strong and weak axes)	in. (mm)	9 (229)

The calibrated BCT post parameters and failure criterion were then placed into the 75-ft (22.9-m) MGS baseline model. Simulated impacts at post no. 4 were once again compared to the full-scale crash test, test no. MGSMIN-1. This effort was conducted to ensure that the new anchors: (1) maintained the necessary rail tension and (2) did not affect the line post calibration. The baseline model containing the new end anchors continued to accurately predict the deflected barrier profile as well as the longitudinal load transfer to the end anchors.

9.3 Validation of the MGSMIN-1 BARRIER VII Model

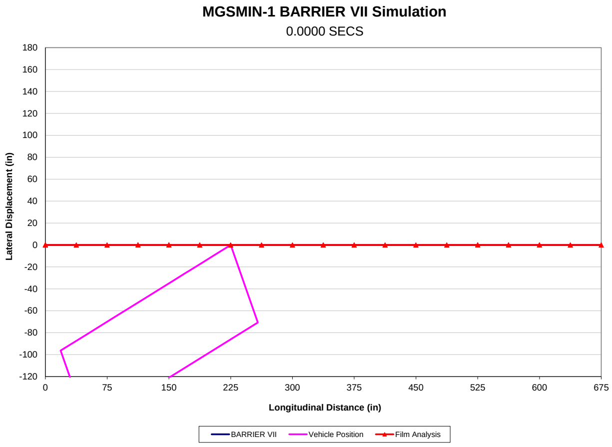
Validation of the 75-ft (22.9-m) MGS BARRIER VII model was completed by comparing the simulation results to those results observed in full-scale crash test no. MGSMIN-1 using three metrics: (1) vehicle kinematics; (2) barrier deflection profile; and (3) anchor load and displacement. The first validation method incorporated different evaluation parameters which were measured in the full-scale test and calculated using BARRIER VII. The vehicle kinematic parameters are shown Table 13. BARRIER VII calculated both the parallel time and parallel velocity exceptionally well with only 7.4 percent and 0.7 percent differences, respectively. However, the 88-ms difference in exit time between the BARRIER VII and the full-scale crash test was attributed to the differences in film analysis and computer simulation. BARRIER VII was able to exactly detect any loss of contact from the barrier, while this behavior was very difficult to observe during film analysis.

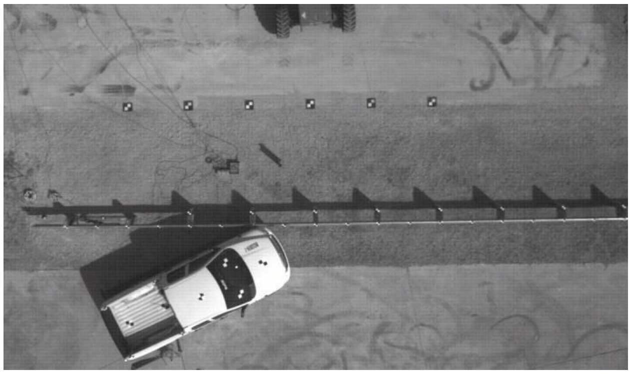
Table 13. Vehicle Kinematics from Test and BARRIER VII Simulation

Evaluation Parameters	Units	Test No. MGSMIN-1	BARRIER VII Simulation
Parallel Time	ms	314	339
Parallel Velocity	mph (km/h)	42.3 (68.1)	42.6 (68.6)
Exit Time	ms	700	612
Exit Angle	deg	NA	-15.4
Resultant Velocity at Exit	mph (km/h)	32.9 (52.9)	38.6 (62.1)

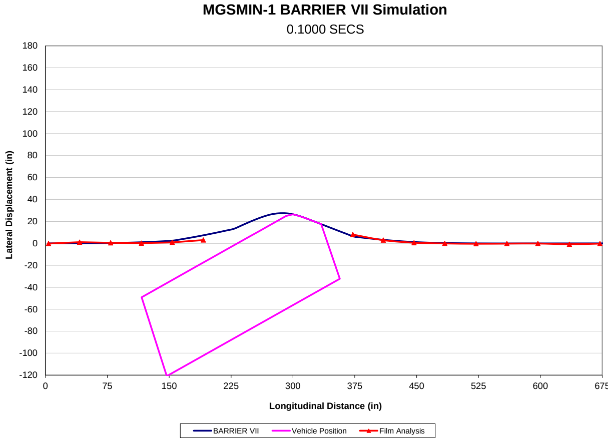
In addition to vehicle kinematics, the BARRIER VII model was validated against the deflected shape of the barrier. A graphical comparison between the calibrated baseline model and the overhead video from full-scale crash test no. MGSMIN-1 is shown in Figure 54. The comparison shows the barrier profiles from impact through exit at 100 ms intervals. There was a 13 percent difference observed in the dynamic rail deflections between the full-scale test and simulation with maximum deflections of 42.2 in. (1,072 mm) and 48.6 in. (1,234 mm), respectively. However, the BARRIER VII baseline model accurately estimated the system deflections through 600 ms of impact. After 600 ms, the simulation under-predicted the deflection of the rail; but, by this time, the vehicle had already been redirected and was exiting the system. Thus, only the permanent set deflections were inaccurate, under-estimating the permanent rail deflection by approximately 10¾ in. (273 mm). This difference may be attributed to the fact that BARRIER VII is not known for accurately predicting the rebound of the rail after redirection.

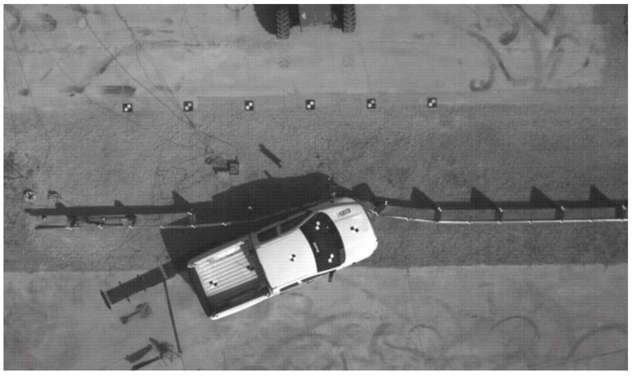
The vehicle kinematics and barrier deflections were also evaluated using the Roadside Safety Verification and Validation Program (RSVVP) [27]. RSVVP has the ability to quantitatively compare the similarity between multiple curves by computing comparison metrics. These comparison metrics can be used specifically to validate computer simulation results against experimental data. The data compared in this analysis were vehicle accelerations in the longitudinal and lateral directions as well as the vehicle yaw. Additional comparisons were made for the vehicle's parallel and exit times and corresponding velocities, barrier deflections, and barrier damage. Since BARRIER VII is limited to planar motion, the vertical accelerations and vehicle pitch and roll were not able to be assessed. The results indicated that the BARRIER VII simulation was validated against the full-scale crash test. The complete RSVVP analysis is provided in Appendix G.



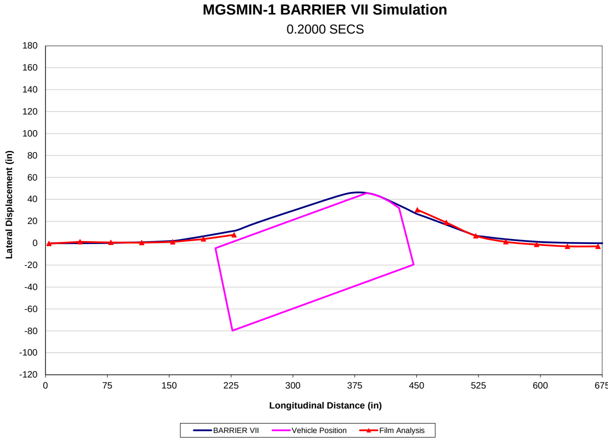


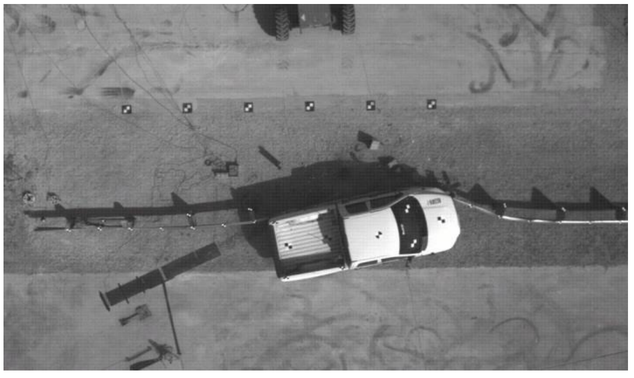
t = 0 ms





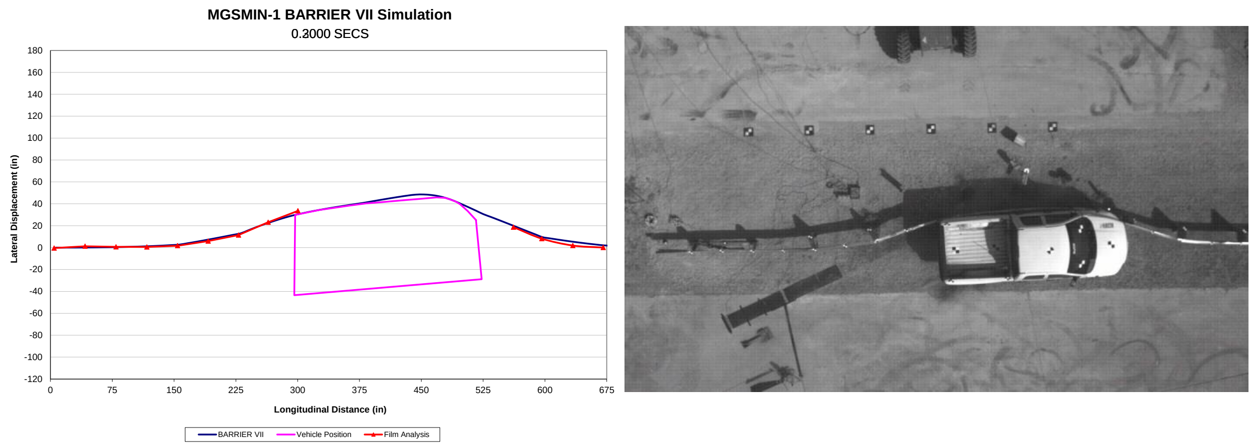
t = 100 ms



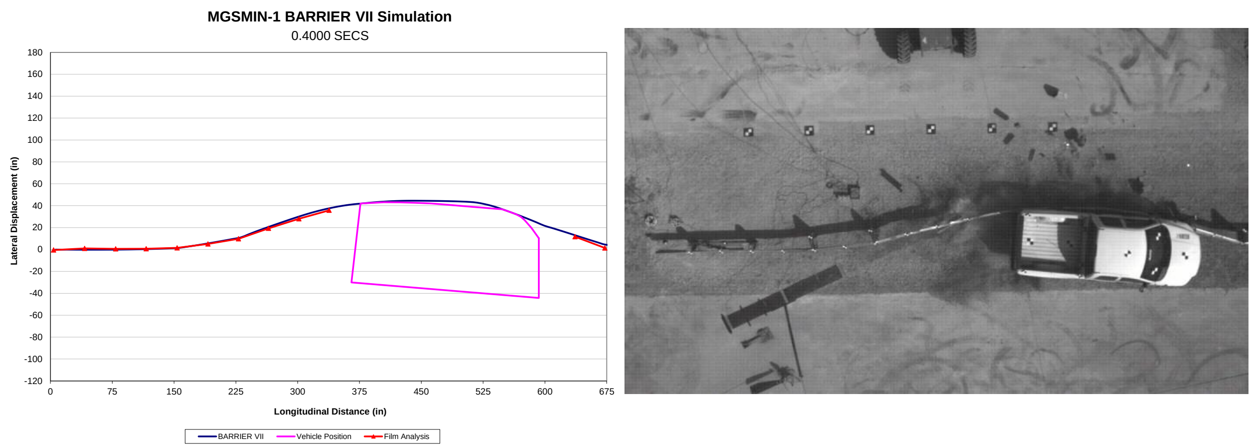


t = 200 ms

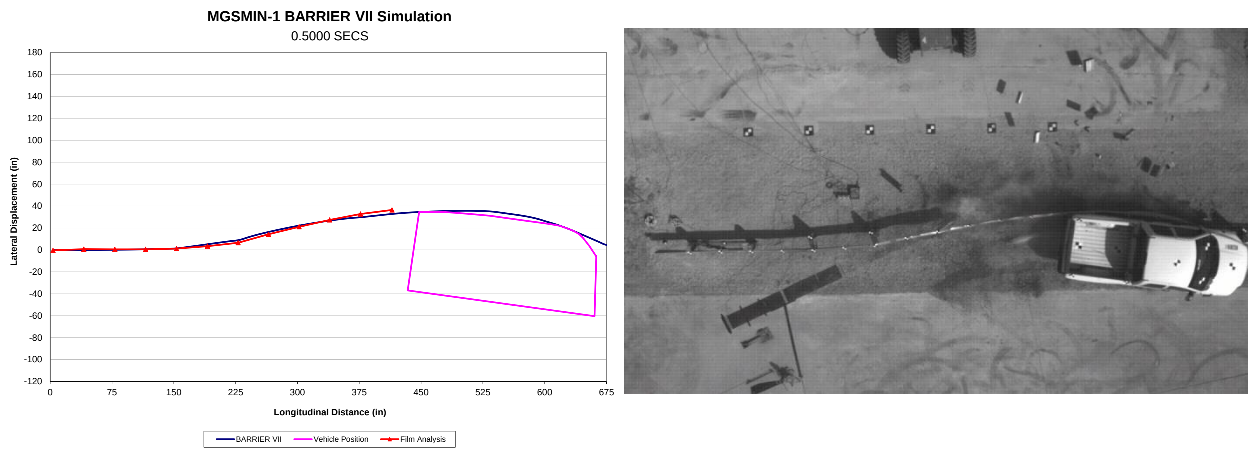
Figure 54. Sequential Figures from Simulation and Test No. MGSMIN-1



t = 300 ms

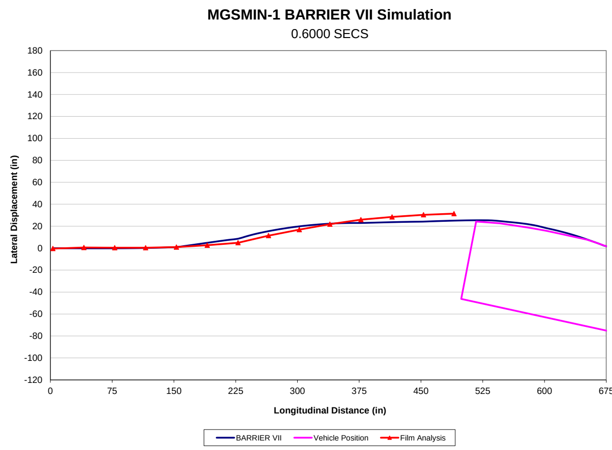


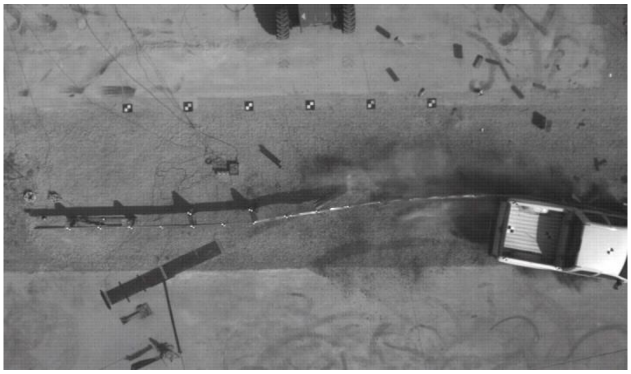
t = 400 ms



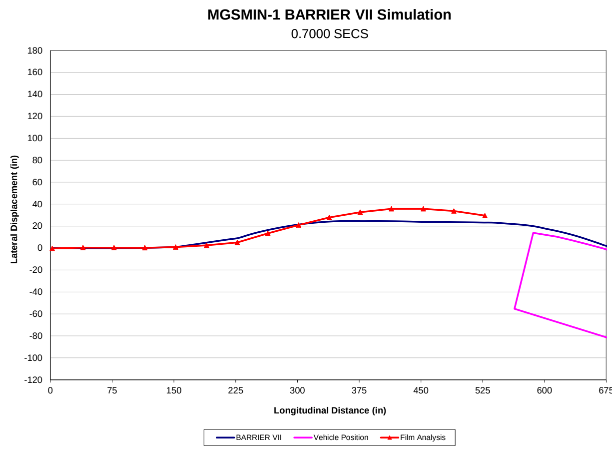
t = 500 ms

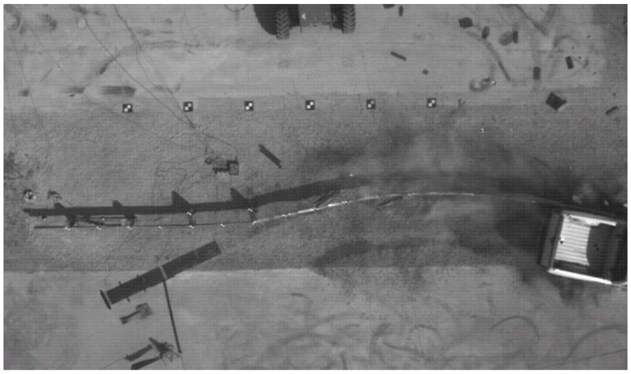
Figure 52. Sequential Figures from Simulation and Test No. MGSMIN-1 (continued)



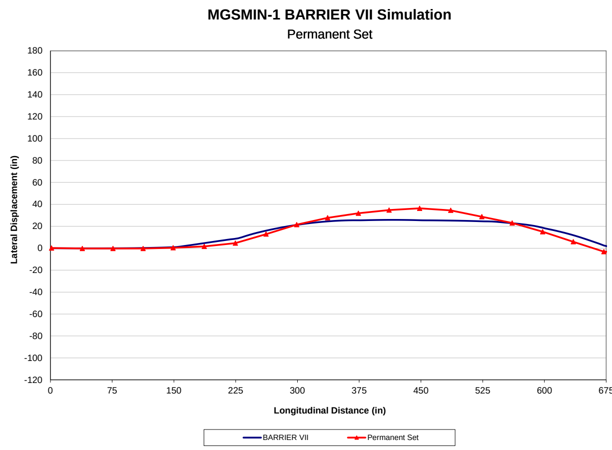


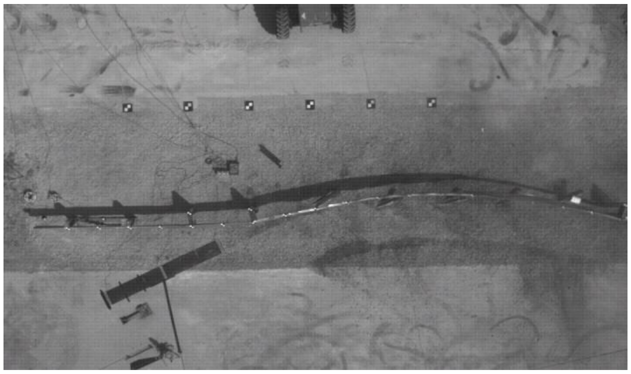
t = 600 ms





t = 700 ms





Permanent Set

Figure 52. Sequential Figures from Simulation and Test No. MGSMIN-1 (continued)

In the full-scale crash test, load cells were placed in the modified BCT anchor cables, and string pots were attached at the base of the end posts to measure the longitudinal displacements. Thus, anchor post displacements and tensile rail loads applied to the anchors could be directly compared between the full-scale crash test and the BARRIER VII simulation, as shown in Table 14. It should be noted that the string pots used in the full-scale crash test measured the anchor displacements at ground level, while BARRIER VII measured the post deflection at a rail height of 24.875 in. (632 mm). Thus, the BARRIER VII deflections had to be interpolated at groundline using the deflection at rail height and assuming a post rotation point at ⅔ of the embedment depth.

Table 14. MGSMIN-1 and Simulation Anchor Values

Measurement	Units	U.S. End Anchor		D.S. End Anchor	
		MGSMIN-1	B. VII	MGSMIN-1	B. VII
Maximum Displacement	in. (mm)	1.7 (43)	2.4 (61)	-1.5 (-38)	-1.2 (-30)
Maximum Force	kip (kN)	25.94 (115.39)	26.91 (130.73)	25.16 (111.92)	20.75 (98.97)

The BARRIER VII model reasonably predicted both the longitudinal anchor loads and the anchor post displacements. Simulated maximum rail forces in the upstream and downstream end anchorage were overestimated by 4 percent and underestimated by 17 percent, respectively. Interestingly, the anchor deflections were also slightly overestimated at the upstream end and slightly underestimated at the downstream end. This result was attributed to how vehicle-to-barrier friction was applied in BARRIER VII. BARRIER VII applies all friction forces to the rail and ignores contact with the posts. However, post contact is a significant contributor to the overall vehicle-to-barrier friction. Thus, the friction coefficient in BARRIER VII must account for post contact in order to match vehicle speeds, parallel times, and exit times. The extra friction applied to the rail would result in higher upstream loads and lower downstream loads.

Further validation of the anchors was performed by comparing the anchor loads and displacements throughout the entire event. The electronic accelerometer data obtained in dynamic testing was filtered using the SAE Class 60 and the SAE Class 180 Butterworth filter conforming to the SAE J211/1 specifications [19]. The load versus time histories from both the upstream and downstream anchor load assemblies were compared against the anchor loads calculated in BARRIER VII, as shown in Figure 55. BARRIER VII calculated anchor loads at a sampling rate of 1,000 Hz. Therefore, the anchor load data from the computer simulation was filtered using the SAE Class 60 Butterworth filter, similar to the crash test data, for this comparison. The simulation slightly over predicts the upstream anchor loads and under predicts the downstream anchor loads on average.

Overall, the simulation predicted the general trend of the anchor load versus time history with 18 percent accuracy for the upstream anchor loads and 9.9 percent accuracy for the downstream anchor loads. The accuracy percentages are based on the Sprague and Geers metrics which assess the magnitude and phase between two curves and combines them into a single comprehensive metric [28]. The differences in the time shift between the full-scale crash test data and simulation results can be attributed to the post-processing of the crash test data. The initial timing for the physical crash test data was determined to be at the first sign of loading whereas the simulation timing was relative to impact.

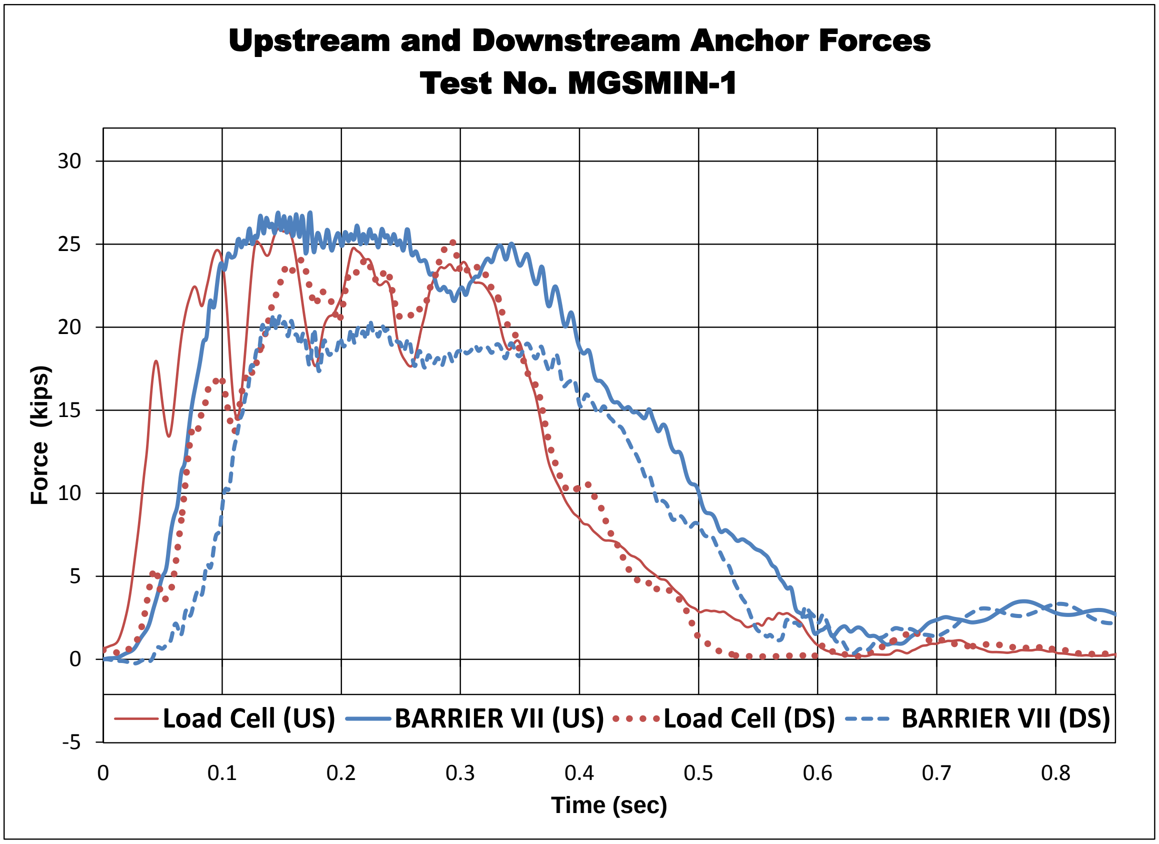


Figure 55. Time History of Anchor Loads

Similarly, the anchor displacements between the full-scale crash test and computer simulation were compared. Again, BARRIER VII calculated the post deflection at a height of 24.875 in. (632 mm), which was then interpolated down to the groundline. BARRIER VII over predicted the maximum upstream, longitudinal, anchor displacement by 0.7 in. (18 mm), as shown in Figure 56. The maximum downstream, longitudinal, anchor displacement was underestimated by only 0.3 in. (8 mm). The full-scale crash test had nearly equal loading on the end anchors followed by similar anchor displacements at both the upstream and downstream ends. However, BARRIER VII over-predicted the upstream anchor loads, which corresponded to an over-prediction in the anchor displacement. A similar correlation is evident in the under-prediction of the downstream anchor loading and displacement.

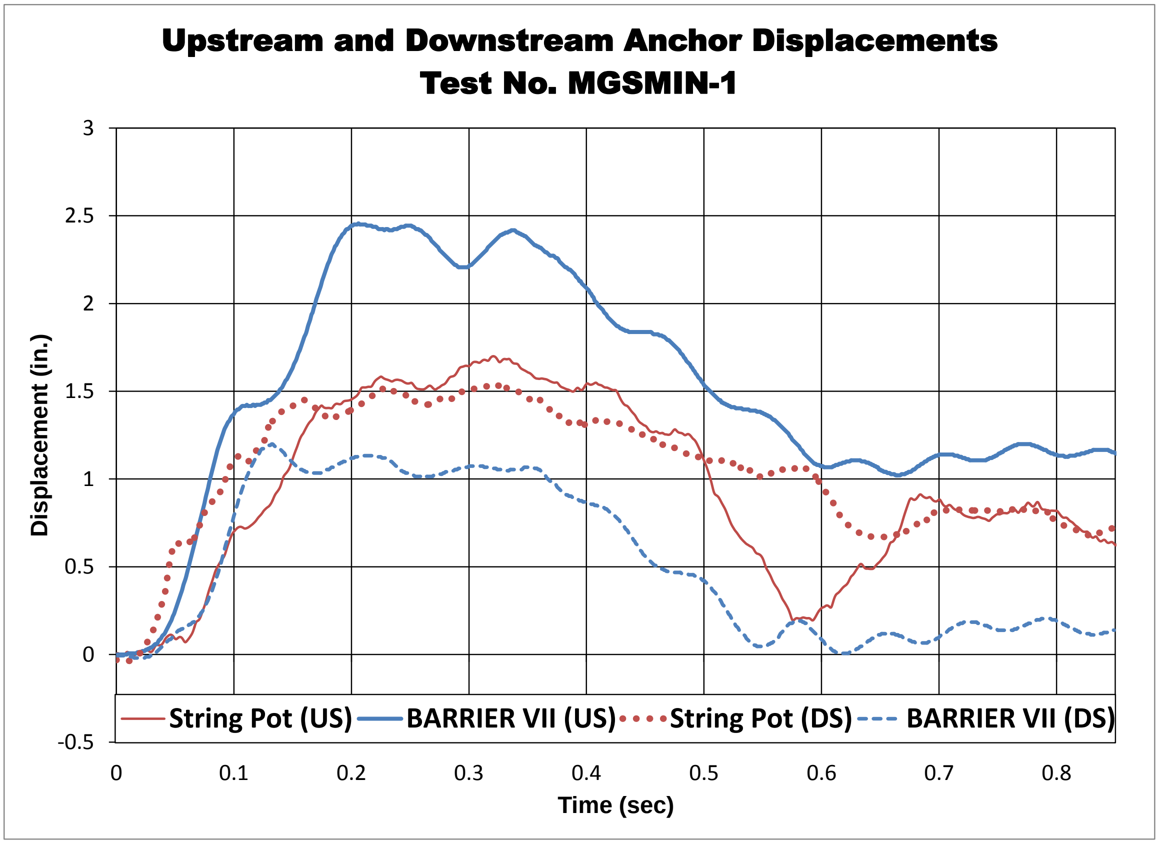


Figure 56. Time History of Longitudinal Anchor Displacements

Interestingly, the string pot data shows the downstream end anchor displacing before the upstream anchor, within the first 50 ms. This time discrepancy can be attributed to the post-processing of the string pot data. Since there is currently no way of determining when impact occurs, the string pot data was truncated up until the first sign of displacement at which point that corresponding time was used for both string pots. Although BARRIER VII over-predicted the upstream anchor displacement and slightly under-predicted the downstream anchor displacement, it accurately predicted the overall trend of the anchor displacement versus time histories.

All of the metrics used in evaluating the 75-ft (22.9-m) MGS BARRIER VII model against the full-scale crash test no. MGSMIN-1 were satisfied. Thus, the baseline BARRIER VII model was deemed validated. The full BARRIER VII input deck of the validated model is located in Appendix I.

10 SHORTER MGS SYSTEMS AND ZONE OF REDIRECTION

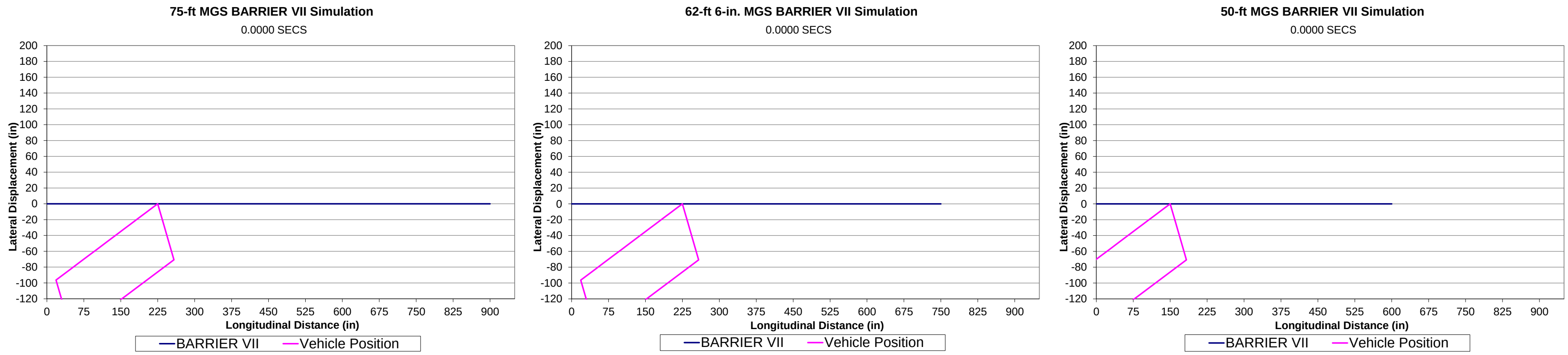
10.1 BARRIER VII Simulations

Once the baseline BARRIER VII model was calibrated and validated, it was then modified to simulate similar impacts into system lengths shorter than 75 ft (22.9 m) and to determine the minimum effective guardrail length required to adequately contain and redirect vehicles. Subsequent systems were shortened by two post spacings, and simulations were conducted to determine whether those barriers could successfully redirect an errant vehicle at the Test Level 3 (TL-3) impact conditions. Reductions by two post spacings were chosen because it was determined that there was not a significant difference between systems reduced by only a single post spacing, and a common W-beam guardrail section measures 12 ft – 6 in (3.8 m) long. Thus, system lengths at 62 ft – 6 in. (19.1 m) and 50 ft (15.2 m) were modeled, and the results of those simulations are presented hereafter. The BARRIER VII input decks for the 75-ft (22.9-m), 62-ft 6-in. (19.1-m), and 50-ft (15.2-m) systems are located in Appendices I through K, respectively.

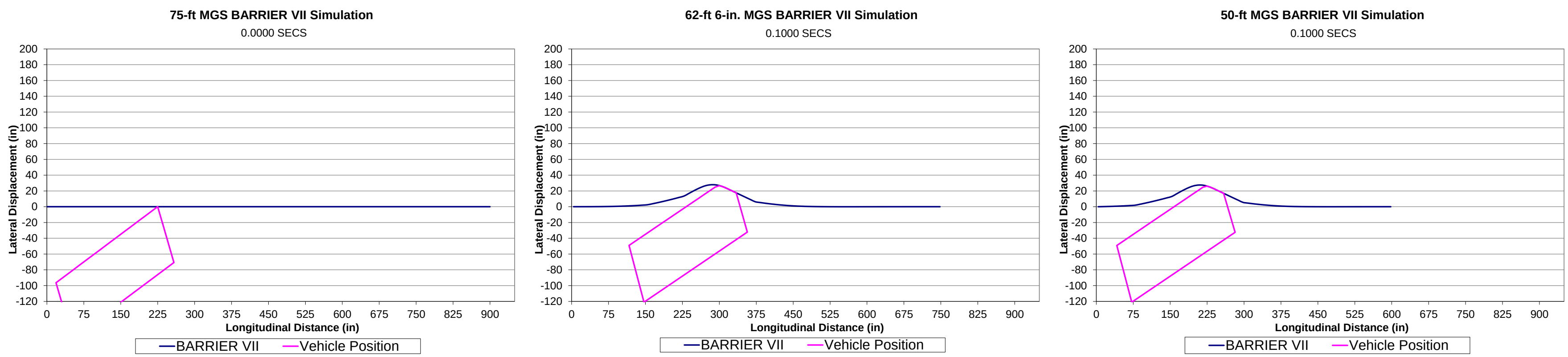
Impact conditions were at 63 mph (101.4 km/h) and 25 degrees to maintain similar conditions to those performed in the baseline model. A comparison of vehicle behavior, barrier loads and deflections, and anchor loads and deflections for the various system lengths are shown in Table 15. For system lengths of 75 ft (22.9 m) and 62 ft – 6 in. (19.1 m), impact occurred at post no. 4, similar to test no. MGSMIN-1. However, impacts to the 50-ft (15.2-m) system at post no. 4 resulted in the vehicle fracturing and overriding the downstream wood BCT anchor posts during redirection. The vehicle was captured and exited the system at an angle nearly parallel to the system, similar to the downstream end anchorage test, test no. WIDA-1. In order to avoid contact with the BCT posts and to allow for a better comparison between system performances, the impact point for the 50-ft (15.2-m) long MGS system was moved to post no. 3. A graphical comparison of the barrier deflections for all three system lengths are shown in Figure 57.

Table 15. Performance Comparison of Shorter Systems

Total System Length ft (m)	75 (22.9)	62.5 (19.1)	50 (15.2)
Total No. of Posts	13	11	9
Impact Location (Post No.)	4	4	3
Parallel Time ms	339	340	341
Parallel Velocity mph (km/h)	42.6 (68.6)	42.4 (68.2)	41.3 mph (66.5)
Exit Time ms	612	605	460
Exit Velocity mph (km/h)	38.6 (62.1)	37.9 (61.0)	36.5 (58.7)
Exit Angle Degrees	-15.4	-17.3	-15.4
Length of Redirective Zone (Post Nos.)	3-8	3-5	3
Contact Length (Post Nos.)	4-10	4-10	3-8
Post Failure (Post Nos.)	5-9	5-9	4-7
Max. US Anchor Deflection in. (mm) [x-dir.]	3.73 (95)	3.84 (98)	5.56 (141)
Max. DS Anchor Deflection in. (mm) [x-dir.]	1.82 (46)	1.80 (46)	1.85 (47)
Max. Dynamic Deflection in. (mm) [y-dir.]	48.72 (1,237)	49.00 (1,245)	48.57 (1,234)
Max. Rail Load kips (kN)	47.42 (210.9)	48.25 (214.6)	48.35 (215.1)
Max. US Anchor Load kips (kN)	26.91 (119.7)	29.20 (129.9)	27.99 (124.5)
Max. DS Anchor Load kips (kN)	20.75 (92.3)	21.85 (97.2)	21.11 (93.9)
Anchor Contact	No	Partial	Yes

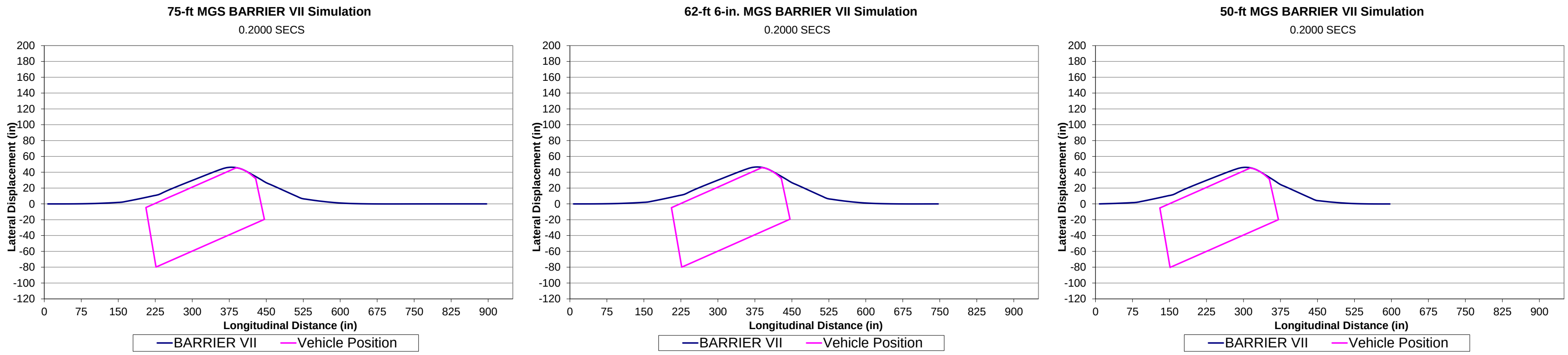


t = 0 ms

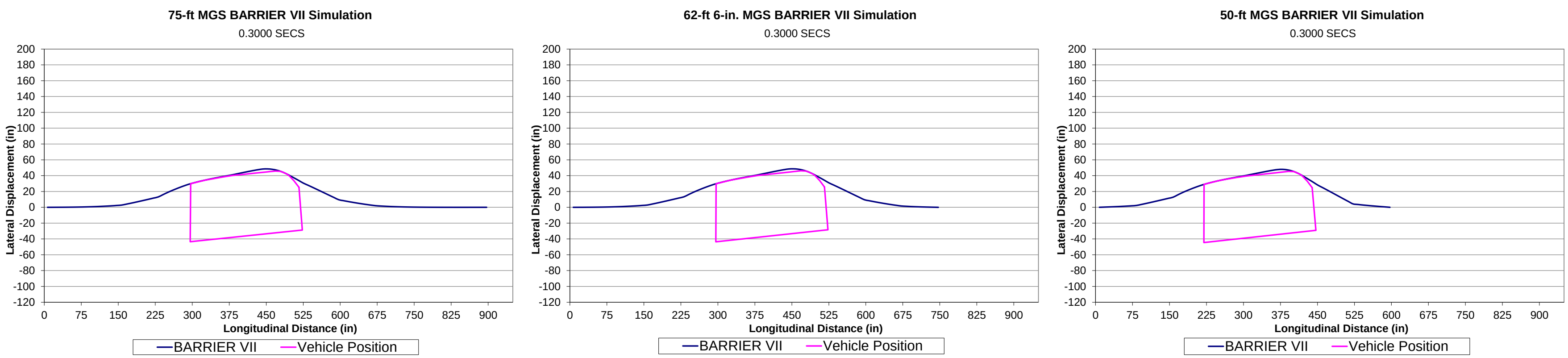


t = 100 ms

Figure 57. Sequential Figures from Simulation: 75-ft (22.9-m), 62-ft 6-in.(19.1-m) and 50-ft (15.2-m) MGS

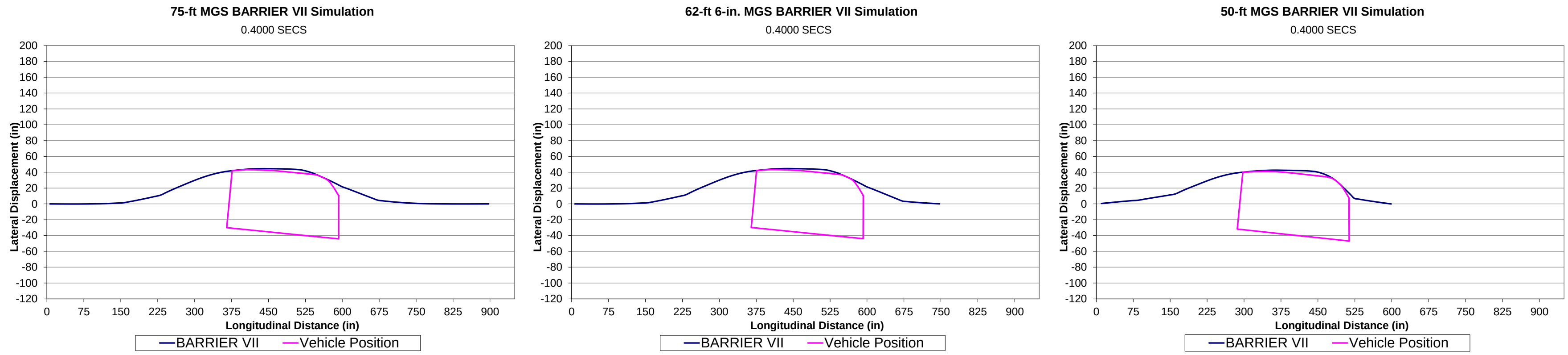


t = 200 ms

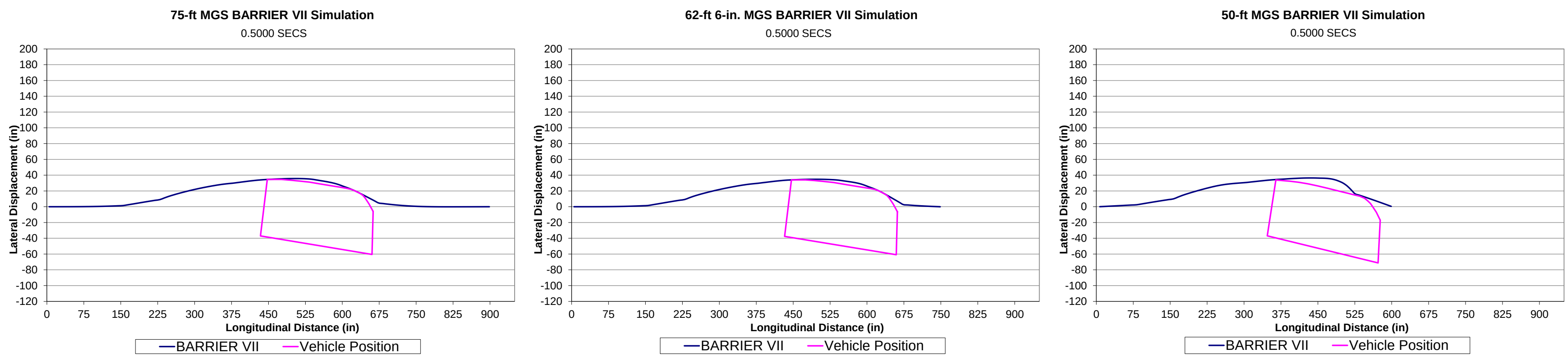


t = 300 ms

Figure 57. Sequential Figures from Simulation: 75-ft (22.9-m), 62-ft 6-in.(19.1-m) and 50-ft (15.2-m) MGS (continued)

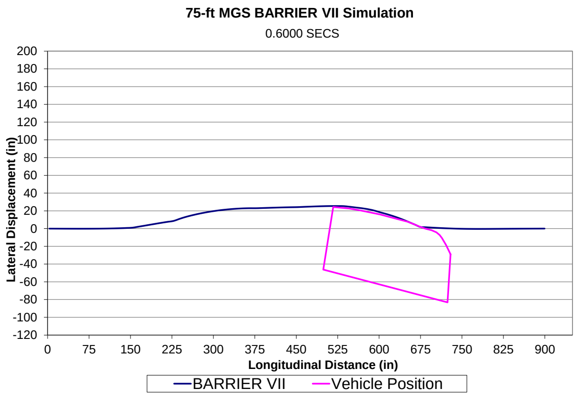


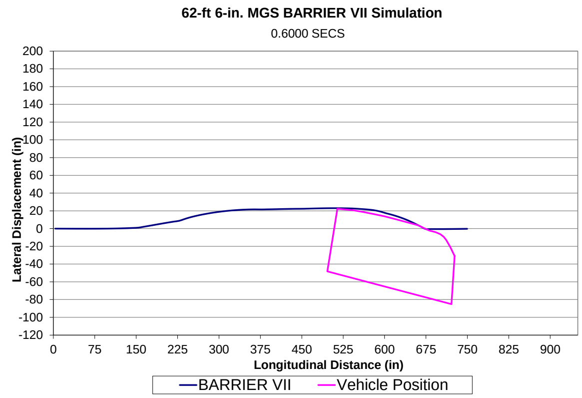
t = 400 ms

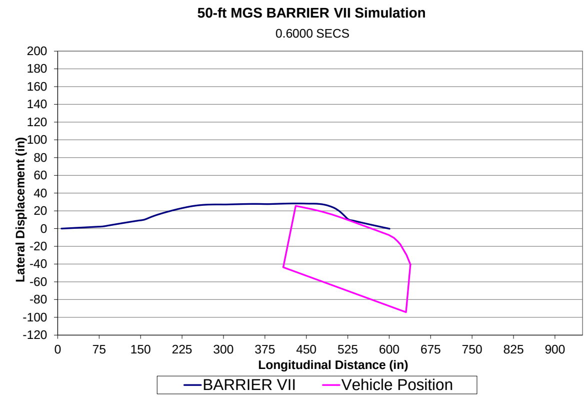


t = 500 ms

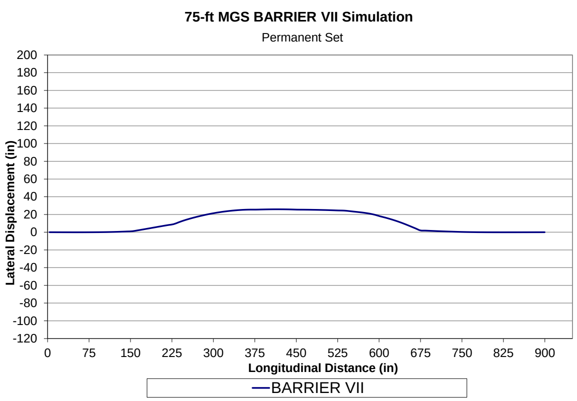
Figure 57. Sequential Figures from Simulation: 75-ft (22.9-m), 62-ft 6-in.(19.1-m) and 50-ft (15.2-m) MGS (continued)

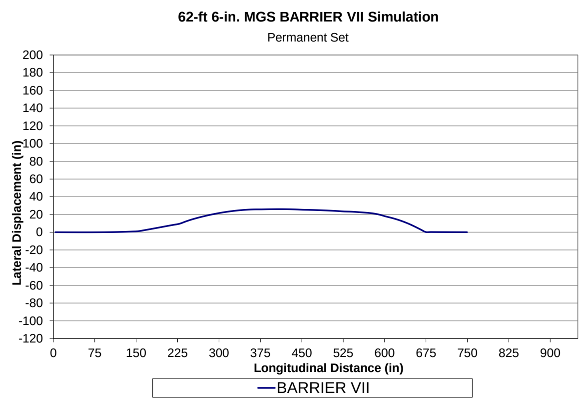


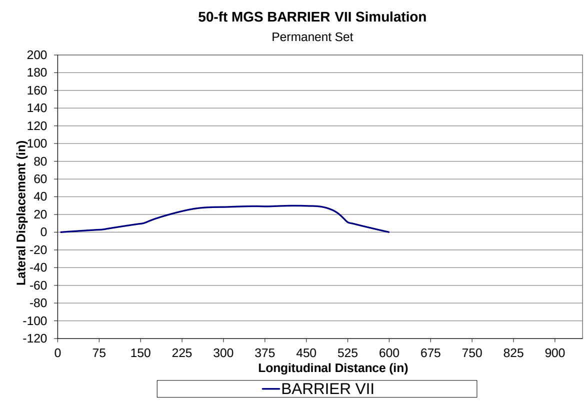




t = 600 ms







Final Barrier Deformations

Figure 57. Sequential Figures from Simulation: 75-ft (22.9-m), 62-ft 6-in.(19.1-m) and 50-ft (15.2-m) MGS (continued)

Based on BARRIER VII simulations, the shorter systems successfully captured and redirected the 2270P pickup at TL-3 conditions. The 75-ft (22.9-m) and 62 ft – 6 in. (19.1 m) systems had nearly identical barrier profiles, maximum deflections, and similar vehicle kinematic parameters throughout impact. The major differences between the 75-ft (22.9-m) and 62-ft 6-in. (19.1-m) MGS were the increased loads experienced through the rail and at the anchors. The 50-ft (15.2-m) MGS exhibited similar vehicle kinematic parameters as the previous two systems, except for a 24 percent difference in the exit time. The 50-ft (15.2-m) MGS barrier profile comparison showed the vehicle interacting with the downstream anchor shortly after 400 ms. Interaction with the downstream end anchor produced significantly differenced results in the anchor loads and deflections when compared to the 75-ft (22.9-m) and 62-ft 6-in. (19.1-m) MGS systems. The BARRIER VII input decks for the 62-ft 6-in. (19.1-m) and 50-ft (15.2-m) systems are located in Appendix J and K, respectively. The maximum rail forces, anchor deflections, and anchor forces calculated in BARRIER VII for the shortened MGS systems, are shown in Figures 58 through 60, respectively.

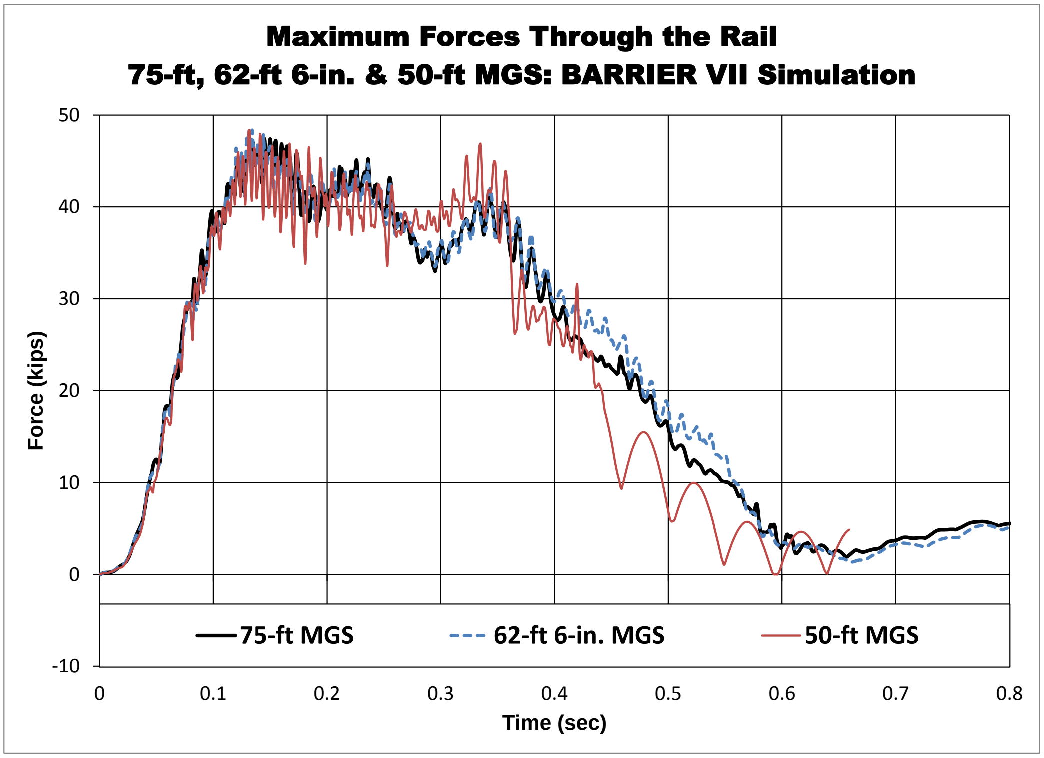


Figure 58. Maximum Forces through the Rail

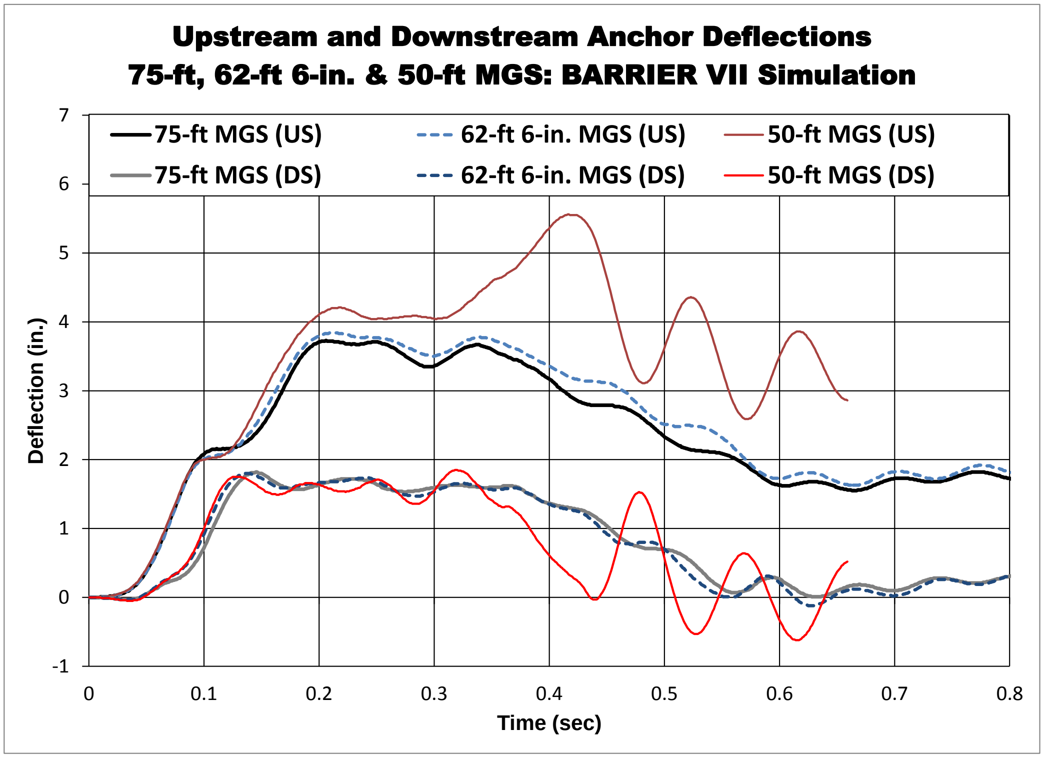


Figure 59. Upstream and Downstream Anchor Deflections

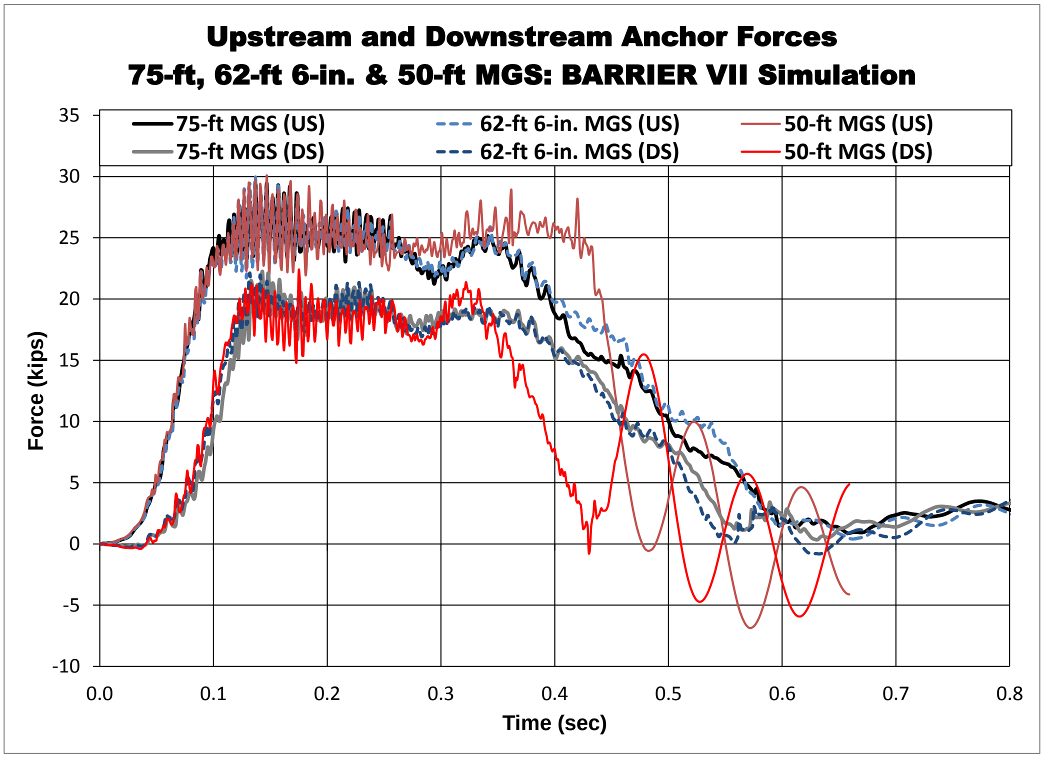


Figure 60. Upstream and Downstream Anchor Forces

The maximum forces through the rail show a similar trend for each of the system lengths evaluated. The initial peak forces at impact were nearly the same in each case. Both the 75-ft (22.9-m) and 62-ft 6-in. (19.1-m) models followed similar curves exceptionally well throughout the entire simulation. The 50-ft (15.2-m) model exhibited much more noise within the data and the system experienced higher forces from 250 ms to 350 ms as compared to the other two system lengths. The 75-ft (22.9-m) and 62-ft 6-in. (19.1-m) systems had similar anchor loads and deflections with slightly higher deflections observed in the 62-ft 6-in. (19.1-m) system, as expected. The 50-ft (15.2-m) system exhibited erratic deflection behavior in the anchors after approximately 350 ms. This behavior is more evident in the anchor forces after approximately 450 ms. This time frame corresponds to the vehicle impacting the second BCT post, located at 525 in., as illustrated in the sequentials shown in Figure 57.

Although the 50-ft (15.2-m) system successfully redirected the 2270P vehicle, the rail force and anchor responses shown in Figures 58 through 60 suggested that vehicle contact with the anchor posts produced unreliable results in the simulation. The inconsistencies present in the 50-ft (15.2-m) model may be a consequence of attempting to model a complex, 3-dimensional anchorage system within the 2-dimensional space of BARRIER VII. Therefore, a more sophisticated simulation was needed.

10.2 LS-DYNA Simulations

Due to the limitations in modeling the MGS anchorage with BARRIER VII, a brief LS-DYNA analysis was performed on the 50-ft (15.2-m) MGS to further evaluate the barrier's dynamic performance. In addition to vehicle-anchor interactions, the LS-DYNA simulations were used to investigate the vehicle's 3-dimensional response during impact and redirection. A 175-ft (53.3-m) MGS model, which was previously validated against full-scale crash testing [15], was reduced to create a 50-ft (15.2-m) MGS model. Simulations were performed with the 2270P impacting at approximately 62 mph (100 km/h) and 25 degrees into post nos. 3 through 8, from upstream to downstream. The results of these simulations are described in the following sections.

10.2.1 2270P Impacting 50-ft (15.2-m) MGS at Post No. 3

The first simulation impacted the 50-ft (15.2-m) system at post no. 3, as shown in Figure 61, replicating the BARRIER VII simulation impact point. There were similar results between the LS-DYNA and BARRIER VII simulations in terms of vehicle response, particularly, the yaw, parallel time, and total contact with the barrier. Also, the deformed barrier profile from LS-DYNA mimicked the predicted barrier deflections produced by BARRIER VII. However, one major difference between the simulations occurred at 400 ms where the LS-DYNA model predicted fracture of the downstream end terminal posts. This fracture correlates well with the results of the downstream anchorage full-scale crash test, test no. WIDA-1 [10]. Although the 50-ft (15.2-m) MGS LS-DYNA simulation showed distinct pitch and roll, these angular displacements did not adversely affect the vehicle during redirection. The LS-DYNA simulation results showed a successful redirection of the 2270P vehicle impacting post no. 3 of the 50-ft (15.2-m) MGS.

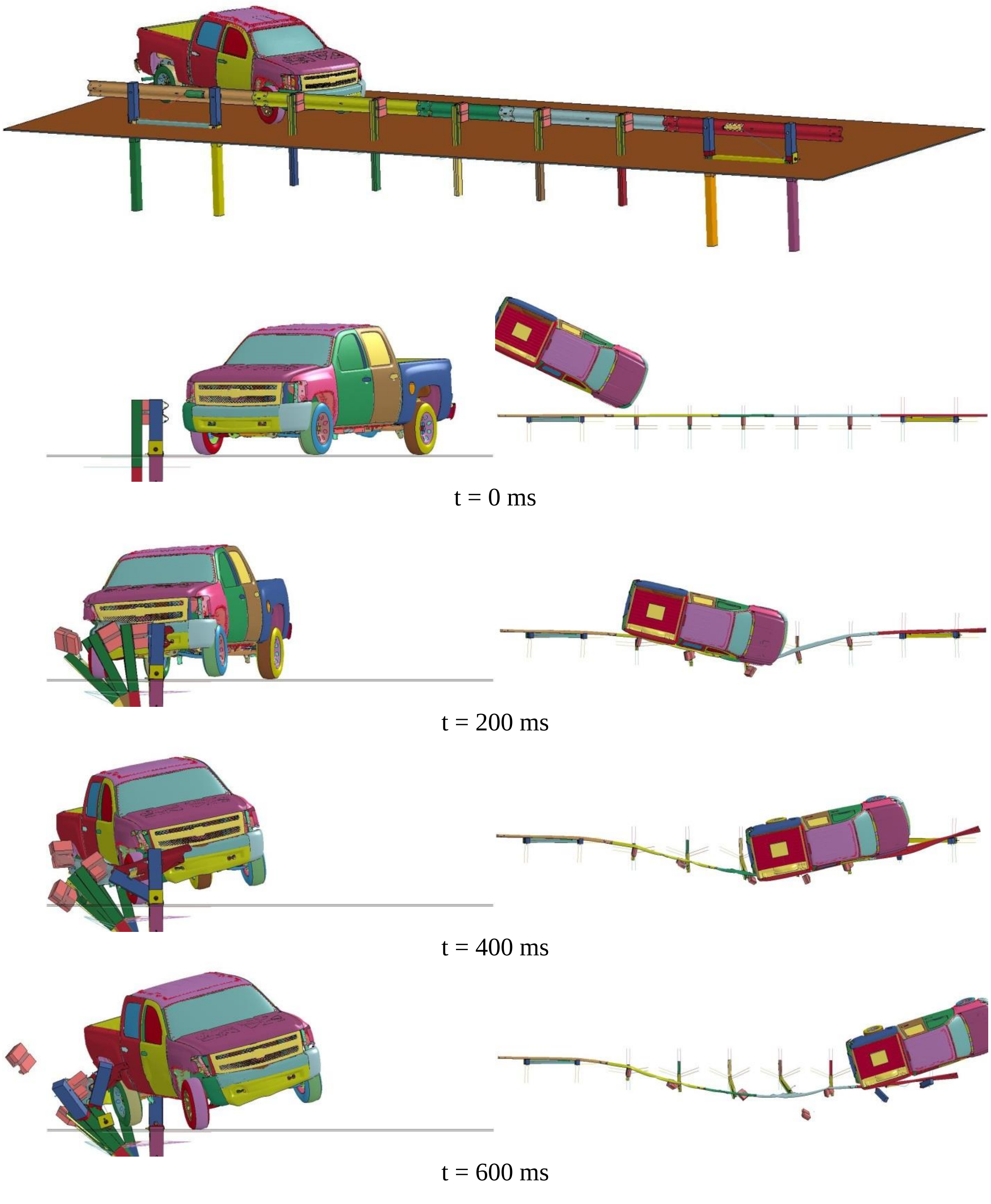


Figure 61. LS-DYNA Simulation, 2270P Impacting 50-ft (15.2-m) MGS at Post No. 3

10.2.2 2270P Impacting 50-ft (15.2-m) MGS at Post No. 4

Impact at post no. 4 of the 50-ft (15.2-m) MGS showed successful redirection of the 2270P vehicle. However, as opposed to the impact at post no. 3, the downstream end of the barrier gated at approximately 400 ms, as shown in Figure 62. Impact at post no. 4 predicted less vehicle roll then before, but the vehicle exhibited significantly more yaw as it passed over the end terminal at 600 ms. The parallel time matched well with the previous simulation, but the exit angle was reduced to nearly parallel with the barrier system. The LS-DYNA simulation did not show significant pocketing, which was present in the 50-ft (15.2-m) BARRIER VII simulation with an impact point at post no. 4. The results from LS-DYNA showed a successful redirection of the 2270P vehicle impacting post no. 4 of the 50-ft (15.2-m) MGS.

10.2.3 2270P Impacting 50-ft (15.2-m) MGS at Post No. 5

Impact at post no. 5 showed similar results to the previous simulation at post no. 4, as shown in Figure 63. The downstream anchor posts fractured at approximately 200 ms, and the system gated. The vehicle became parallel to the system at around 400 ms, although its trajectory was still aimed slightly away from traffic. There was little pitch and roll throughout the impact, but the vehicle experienced moderate yawing after it lost contact with the system. As impact locations progressed down the system, it was apparent that the vehicle would penetrate farther behind the barrier and continue at a higher trajectory angle.

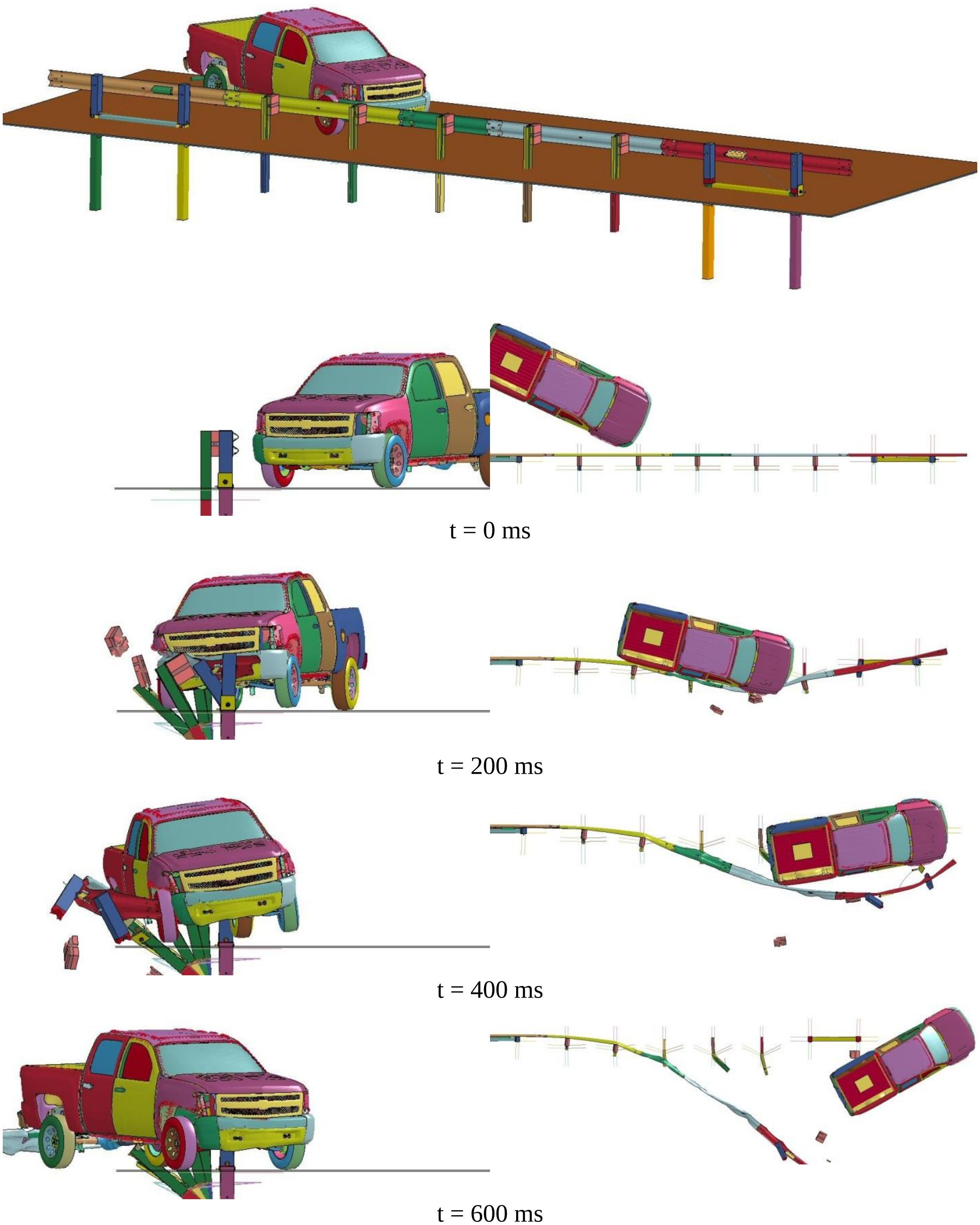


Figure 62. LS-DYNA Simulation, 2270P Impacting 50-ft (15.2-m) MGS at Post No. 4

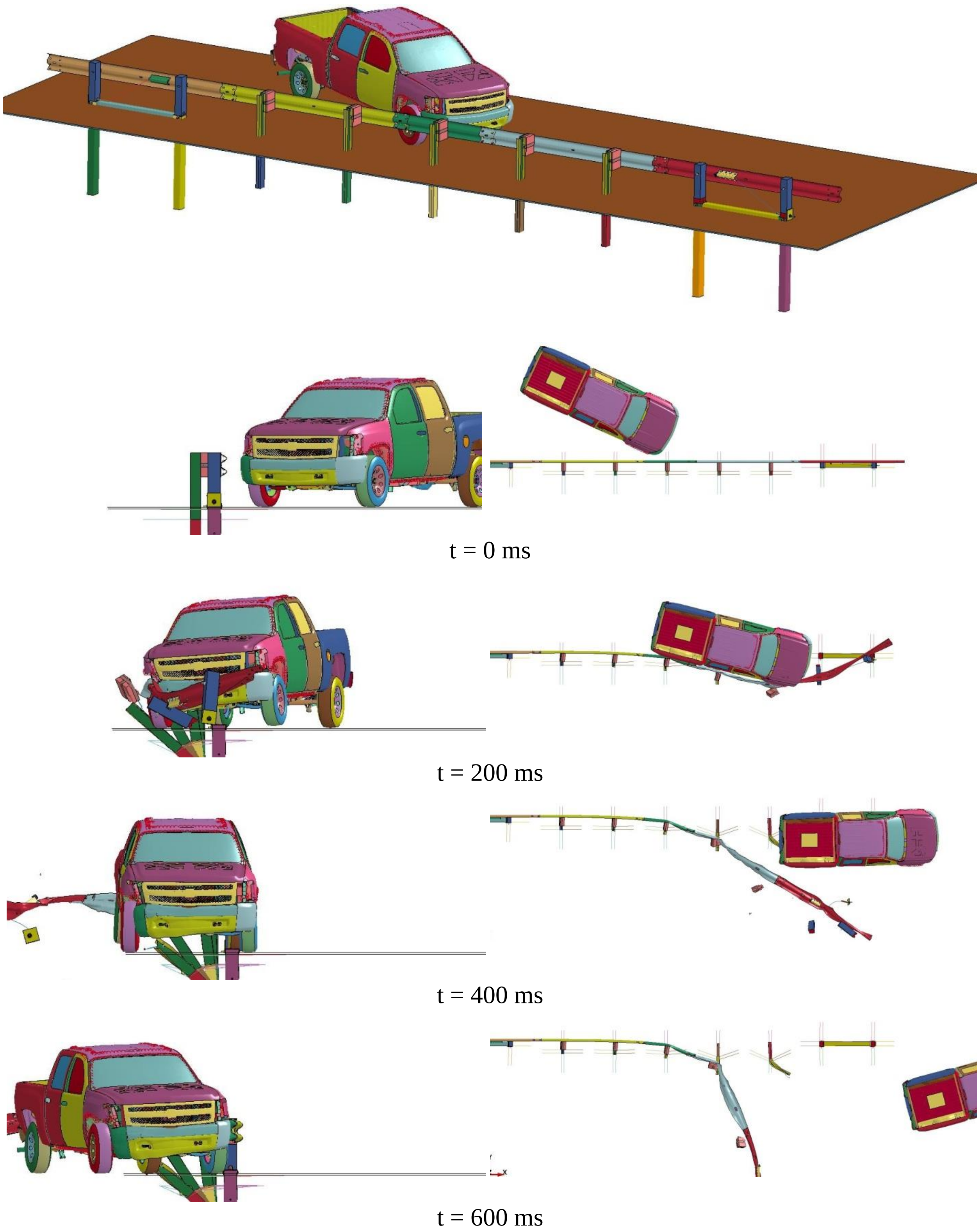


Figure 63. LS-DYNA Simulation, 2270P Impacting 50-ft (15.2-m) MGS at Post No. 5

10.2.4 2270P Impacting 50-ft (15.2-m) MGS at Post No. 6

Impact at post no. 6 showed the vehicle traveling through the system as shown in Figure 64. By 200 ms, the downstream anchorage had fractured, the system was gating, and the vehicle was penetrating the barrier. A parallel time was not observed because the vehicle never redirected. There was little roll, pitch, and yaw experienced during the event. Rail rupture occurred around 300 ms, possibly due to anchorage components snagging on the vehicle. It is unclear whether this would happen in a real full-scale impact, but since the system was gating, it was not deemed critical nor explored further.

10.2.5 2270P Impacting 50-ft (15.2-m) MGS at Post No. 7

Impact at post no. 7 showed almost immediate gating of the barrier system, as shown in Figure 65. The downstream end terminal posts fractured early in the event. The vehicle experienced very little roll, pitch, or yaw angular displacements. The rail did not fracture as seen during the impact at post no. 6.

10.2.6 2270P Impacting 50-ft (15.2-m) MGS at Post no. 8

Impact at post no. 8 showed similar trends to the impact events at post no. 7. The system gated as the vehicle immediately traveled through the barrier, as shown in Figure 66. The vehicle experienced very minor roll and pitch during the event and did not appear to show any traces of redirection.

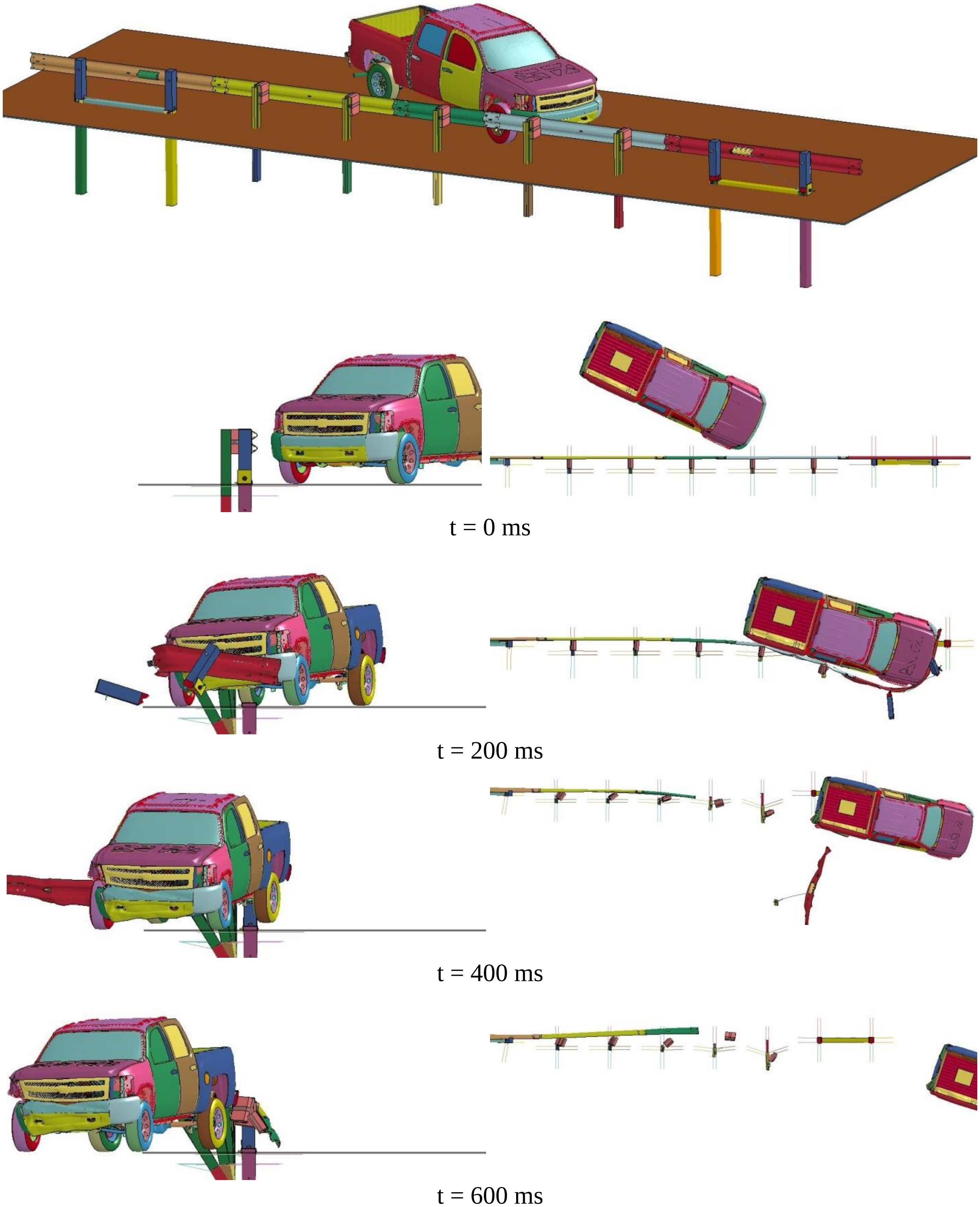
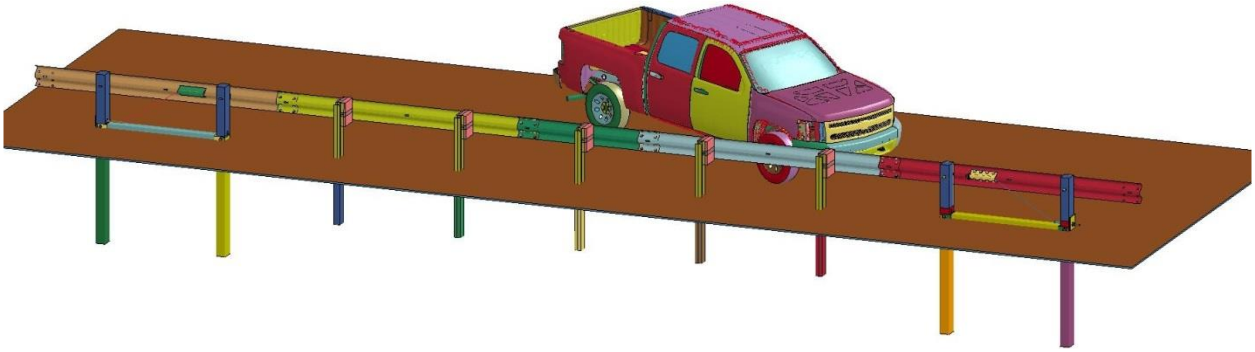
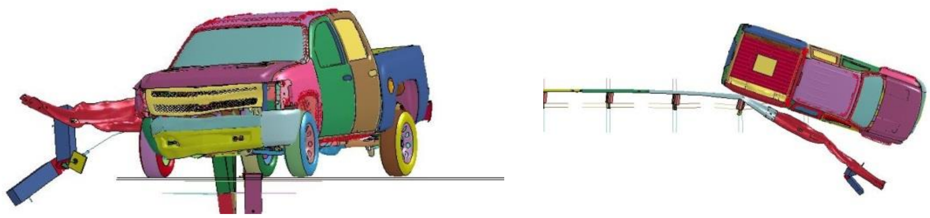


Figure 64. LS-DYNA Simulation, 2270P Impacting 50-ft (15.2-m) MGS at Post No. 6

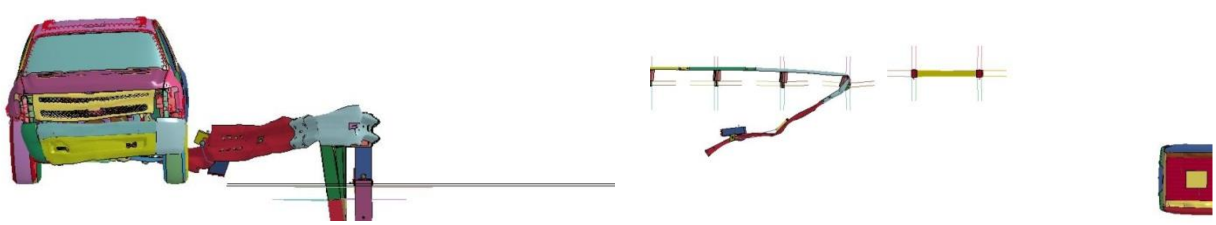


t = 0 ms



t = 200 ms

t = 400 ms



t = 600 ms

Figure 65. LS-DYNA Simulation, 2270P Impacting 50-ft (15.2-m) MGS at Post No. 7

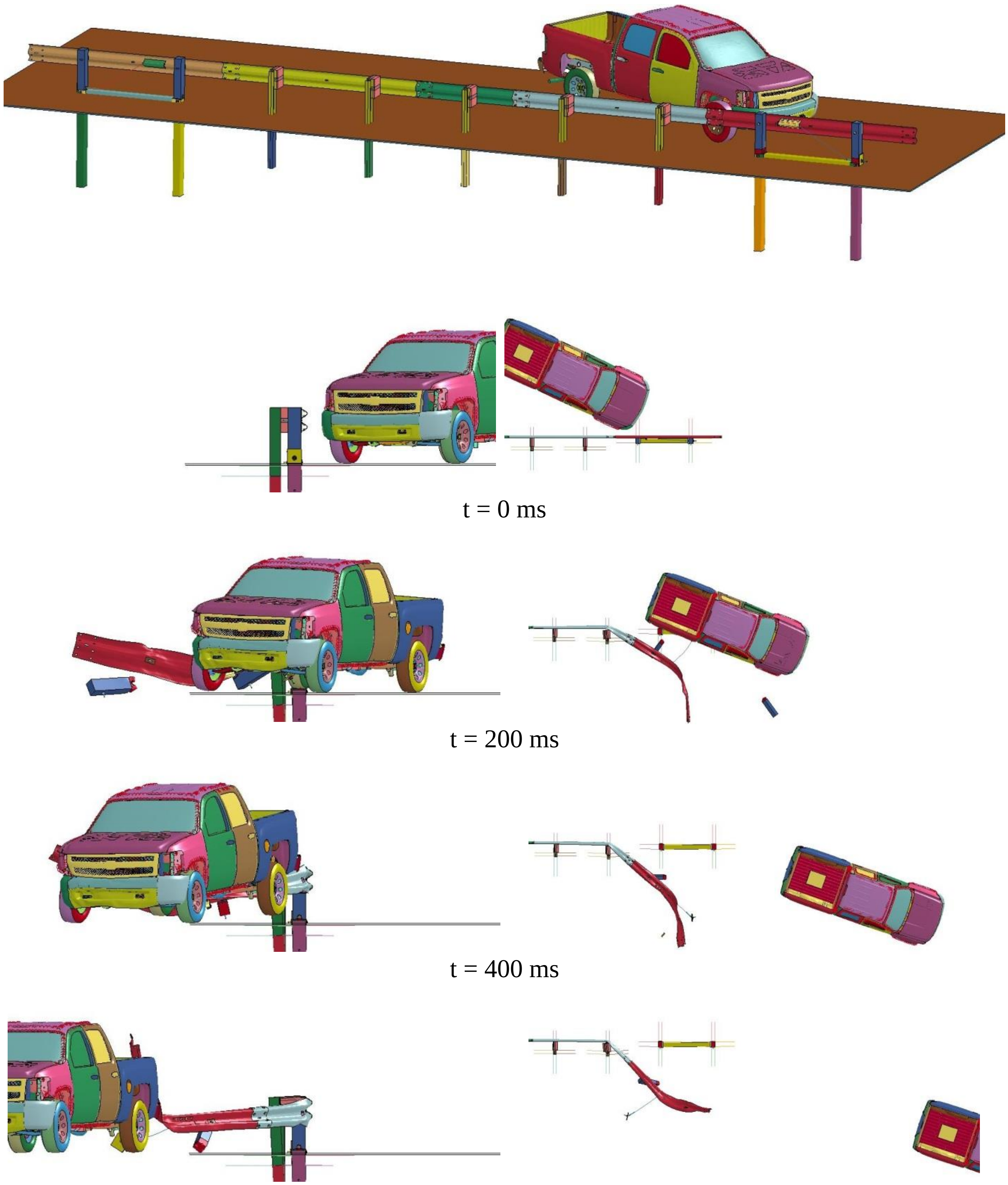


Figure 66. LS-DYNA Simulation, 2270P Impacting 50-ft (15.2-m) MGS at Post No. 8

10.3 Simulation Analysis and Discussion

10.3.1 BARRIER VII Analysis

The 62-ft 6-in. (19.1-m) system length produced results that were consistent with trends seen in the 75-ft (22.9-m) model, and the full-scale crash test, test no. MGSMIN-1. The 62-ft 6-in. (19.1-m) system produced a smooth redirection of the 2270P vehicle with similar barrier deflections. The parallel time, parallel velocity, exit time, and exit velocity were within 2 percent of the values for the 75-ft (22.9-m) system and the exit angles were within 2 degrees. However, as the guardrail system length decreased, a larger portion of the barrier's redirective force was expected to be carried by rail tension and the end anchors. The peak forces in the 62-ft 6-in. (19.1-m) system were slighter higher than the 75-ft (22.9-m) system, but the overall force versus time history curves for the two systems were similar. The 62-ft 6-in. (19.1-m) and 75-ft (19.9-m) systems exhibited similar anchor load and deflection behavior throughout impact. There was no data to suggest any irregularities in the 62-ft 6-in. (19.1-m) model. Therefore, based on BARRIER VII simulations, this system length was a valid candidate for a reduced MGS guardrail length.

The 50-ft (15.2-m) MGS simulation initially showed similar behavior in vehicle response compared to the 75-ft (22.9-m) results. However, at approximately 400 ms the vehicle began to contact post no. 8, the second BCT post of the downstream end terminal. This produced instabilities within the simulation as the anchor posts did not fail as expected based on full-scale crash testing [10]. The contact with the downstream end anchorage produced erratic results in the rail loads, anchor loads, and anchor deflection comparisons. Recall, the impact locations differed by one post spacing and therefore, direct comparisons between the 50-ft (15.2-m) system and the longer systems even prior to contact with post no. 8 should be taken with caution.

Initially, the impact produced the same peak forces in the 50-ft (15.2-m) system as the 62-ft 6-in. (19.1-m) and 75-ft (22.9-m) systems. At 350 ms all three systems experienced a spike in rail forces, but the 50-ft (15.2-m) system had a 16 percent increase in force over the other systems during this event. After 350 ms, the rail forces in the 50-ft (15.2-m) system diverged from the other two system lengths, dropping much quicker. Similar trends were observed when comparing the anchor forces and deflections in the 50-ft (15.2-m) system to the longer systems. Initially, the anchor loads and deflection curves followed the same trends but were slightly higher at times. However, after 350 ms, the 50-ft (15.2-m) system produced erratic fluctuations in data results due to the contact with the downstream end anchor.

The anchors were calibrated with the full-scale downstream anchor test to improve the overall barrier performance correlation between the simulation and full-scale testing. However, due to the 2-dimensional limitations of BARRIER VII, the anchor components, such as the groundline strut and anchor cable, had to be simplified. Thus, it was difficult for BARRIER VII to simulate both the rail anchorage and breakaway characteristics of these posts accurately. Due to these limitations of BARRIER VII, vehicle contact with the end terminal posts was not producing realistic results.

10.3.2 LS-DYNA Analysis

Since BARRIER VII was unable to accurately evaluate the 50-ft (15.2-m) system, limited LS-DYNA simulations were conducted at various impact locations to gain a better understanding of the vehicle behavior during impact and the behavior of the downstream terminal as it broke away. Impacts occurred between post no. 3, the determined length of need, through post no. 8. The analysis showed that at impacts between post nos. 3 and 4 the 2270P vehicle was successfully redirected. Impacts at post no. 5 and further downstream resulted in system gating. As the impact point moved closer to the downstream end, the anchor posts fractured quicker and the vehicle experienced less redirection prior to traversing over the anchorage and behind the system. Although LS-DYNA indicated the 50-ft (15.2-m) system could adequately redirect the 2270P vehicle for a few impact points, there are limitations present in these models as well. The wood posts and soil in LS-DYNA are not exact models of the physical system. The high variability associated with both of these factors limits LS-DYNA as a predictive tool and full-scale testing should be conducted before shorter lengths are recommended for implementation.

11 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This study set out to evaluate the overall performance of the Midwest Guardrail System at lengths shorter than the current 175-ft (53.3-m) test length. All safety performance evaluations were performed using the TL-3 criteria found in MASH. A full-scale crash test with the 2270P vehicle impacting the steel-post MGS with an installation length of 75 ft (22.9 m) was successful. A summary of the safety performance evaluation of the full-scale crash test is provided in Table 16.

The full-scale crash test, test no. MGSMIN-1, was performed on the MGS with a top rail mounting height of 31 in. (787 mm). The system incorporated 72-in. (1,829-mm) long, W6x8.5 (W152x12.6) steel posts with an embedment depth of 40 in. (1,016 mm). The test consisted of a 4,956-lb (2,248 kg) pickup truck impacting the barrier system at a speed of 63.1 mph (101.6 km/h) and at an angle of 24.9 degrees. During the test, the vehicle was contained and smoothly redirected without any significant snagging or pocketing. The maximum permanent set and dynamic deflections were 36⅜ in. (924 mm) and 42.2 in. (1,072 mm), respectively. The working width of the system was found to be 48.8 in. (1,240 mm). The test results were found to meet all of the MASH safety requirements for test designation no. 3-11.

The basic end anchorage system used at Midwest Roadside Safety Facility for MGS testing was adapted from the modified BCT and used in a tangent configuration. This system provides the adequate tensile strength for corrugated beam guardrails and has been successfully tested as upstream and downstream end anchorages. During the test no. MGSMIN-1, both end anchorages successfully withstood the impact loading, but the degree of fracture at the base of post nos. 12 and 13 suggest that this test length is approaching the limitations of the BCT wood anchor posts.

Table 16. Summary of Safety Performance Evaluation Results – Test No. MGSMIN-1

<table>
<tr><th>Evaluation Factors</th><th colspan="4">Evaluation Criteria</th><th>Test No. MGSMIN-1</th></tr>
<tr><td>Structural Adequacy</td><td>A.</td><td colspan="3">Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>S</td></tr>
<tr><td rowspan="11">Occupant Risk</td><td>D.</td><td colspan="3">Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.</td><td>S</td></tr>
<tr><td>F.</td><td colspan="3">The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td><td>S</td></tr>
<tr><td rowspan="4">H.</td><td colspan="3">Occupant Impact Velocity (OIV) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:</td><td rowspan="4">S</td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>30 ft/s (9.1 m/s)</td><td>40 ft/s (12.2 m/s)</td></tr>
<tr><td rowspan="4">I.</td><td colspan="3">The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:</td><td rowspan="4">S</td></tr>
<tr><td colspan="3">Occupant Risk Occupant Ridedown Acceleration Limits</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15.0 g’s</td><td>20.49 g’s</td></tr>
<tr><td colspan="5">MASH Test Designation No.</td><td>3-11</td></tr>
<tr><td colspan="5">Pass / Fail</td><td>Pass</td></tr>
</table>

S – Satisfactory U – Unsatisfactory NA - Not Applicable

It should be noted that the research detailed herein was limited to evaluation of the minimum system length for redirecting vehicles along the length of need for the MGS system. The scope of the research did not include evaluation of the performance of end terminals on a reduced length guardrail system. Further study may be warranted to investigate the effect of shorter system length on the performance of end terminals used in conjunction with minimal guardrail system lengths.

A comparison between the shortened 75-ft (22.9-m) MGS (test no. MGSMIN-1) and the standard 175-ft (53.3-m) MGS (test no. 2214MG-2) was performed to evaluate how the system length affects the barrier's performance and deflection. The dynamic deflection for the 175-ft (53.3-m) MGS was slightly higher than observed for the shortened system, but this difference could be contributed to variations in soil compaction between the tests. The working width was nearly indistinguishable, and the difference between permanent deflections was only 4.5-in. (114-mm). The 75-ft (22.9-m) MGS had a larger number of posts yield in the impact region as compared to the standard 175-ft (53.3-m) long MGS system. This increased post yielding resulted in a slightly longer contact length. In general, the 75-ft (22.9-m) MGS in test no. MGSMIN-1 performed as desired, closely resembling the standard 175-ft (53.3-m) MGS, and it successfully passed all MASH criteria for test designation no. 3-11. However, it should be noted that although the 75-ft MGS performed successfully, a system of this length may not be suited for all desired applications. Several factors including the Lateral Extent of the Area of Concern and the Runout Length must be considered when determining if the overall system length for a roadside barrier is sufficient for shielding a particular hazard. Failure to consider such factors could result in a vehicle gating through an end terminal and interacting with the hazard or object being protected.

To determine the minimum effective lengths for the MGS, computer simulations were used to investigate lengths shorter than 75 ft (22.9 m). A baseline 75-ft (22.9-m) BARRIER VII model was calibrated and validated with the full-scale crash test, test no. MGSMIN-1. Special attention was given to calibrating the end anchors, which were validated with full-scale crash testing on the downstream anchors in test no. WIDA-1 [10]. The model was then adjusted to simulate system lengths at 62 ft – 6 in. (19.1 m) and 50 ft (15.2 m).

The 62-ft 6-in. (19.2-m) model showed promising results with similar rail forces, barrier deflections, vehicle behavior, and anchor forces and deflections as the validated 75-ft (22.9-m) MGS model. Thus, a 62-ft 6-in. (19.2-m) MGS has the potential for a successful performance with MASH TL-3 standards. BARRIER VII simulations of the 50-ft (15.2-m) system produced erratic results and model instabilities once the vehicle contacted the end anchorage posts. It was concluded that the simplified BARRIER VII models of the end anchorages were limited in their ability to accurately simulate the modified BCT breakaway characteristics associated with vehicle contact.

Due to the limitations of modeling the end terminals in BARRIER VII, further investigations into the 50-ft (15.2-m) MGS were conducted with LS-DYNA. The LS-DYNA simulations provided more realistic anchorage post fracturing and insight into the vehicle roll and pitch tendencies. The simulations showed successful redirection of the 2270P vehicle for impacts between post nos. 3 and 4, while the system gated for impacts at post nos. 5 through 8. The farther downstream the impact occurred, the quicker the anchor posts failed and the less the vehicle's trajectory was altered. However, the high variability associated with wood and soil materials limit LS-DYNA as a comprehensive predictive tool. None the less, the 50-ft (15.2-m) long MGS has the potential for a successful performance with MASH TL-3 standards.

The 62-ft 6-in. (19.2-m) and 50-ft (15.2-m) models both exhibited the potential for successfully redirecting an errant vehicle at the MASH TL-3 test conditions. However, due to the limitations associated with the finite element models, full-scale crash testing is recommended for the 62-ft 6-in. (19.2-m) or 50-ft (15.2-m) MGS system lengths. Further, it should be noted that these systems would have a narrow window of impact points which would result in redirection. The downstream end anchorage testing concluded that vehicles would be redirected if impact occurred upstream from or at the sixth post from the downstream end, a minimum of 31.25 ft (9.5 m) (five post spacings) [10]. Recall, the beginning of the length of need is typically identified as post no. 3, or 12.5 ft (3.8 m) from the upstream end. Thus, the effective length of the impact region which could redirect the vehicle would be 6.25 ft (1.9 m) and 18.75 ft (5.7 m) for 50-ft (15.2-m) and 62-ft 6-in. (19.2-m) long MGS systems, respectively. With such a small effective impact region, these shorter system lengths may not be cost effective.

12 REFERENCES

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

2. Polivka, K.A., Faller, R.K., Sicking, D.L., Reid, J.D., Rohde, J.R., Holloway, J.C., Bielenberg, R.W., and Kuipers, B.D., *Development of the Midwest Guardrail System (MGS) for Standard and Reduced Post Spacing and in Combination with Curbs*, Final Report to the Midwest States' Regional Pooled Fund Program, Report No. TRP-03-139-04, Project No. SPR-3(017)-Years 10, 12-13, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, September 1, 2004.

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

4. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Bielenberg, R.W., and Reid, J.D., *Performance Evaluation of the Midwest Guardrail System – Update to NCHRP 350 Test No. 3-10 (2214MG-3)*, Final Report to the National Cooperative Highway Research Program (NCHRP), Transportation Research Report No. TRP-03-172-06, Project No. 22-14(2), Midwest Roadside Safety Facility, University of Nebraska-Lincoln, October 11, 2006.

5. Polivka, K.A., Faller, R.K., Sicking, D.L., Rohde, J.R., Bielenberg, B.W., and Reid, J.D., *Performance Evaluation of the Midwest Guardrail System - Update to NCHRP 350 Test No. 3-11 with 28" C.G. Height (2214MG-2)*, Final Report to the National Cooperative Highway Research Program (NCHRP), Transportation Research Board, Transportation Research Report No. TRP‑03‑171‑06, Midwest Roadside Safety Facility, University of Nebraska‑Lincoln, October 11, 2006.

6. Faller, R. K., Sicking, D. L., Bielenberg, R.W., Rohde, J. R., Polivka, K.A., and Reid, J. D., *Performance of Steel-Post, W-beam Guardrail Systems (Paper No. 07-2642)*, Paper No. 07-2642, Transportation Research Record No. 2025, Transportation Research Board, Washington, D.C., 2007.

7. Reid, J.D., Kuipers, B.D., Sicking, D.L., and Faller, R.K., *Impact Performance of W-Beam Guardrail Installed at Various Flare Rates*, International Journal of Impact Engineering, Volume 36, Issue 3, March 2009.

8. Kuipers, B.D., Faller, R.K., and Reid, J.D., Critical Flare Rates for W-Beam Guardrail - *Determining Maximum Capacity Using Computer Simulation*, Project NCHRP 17-20(3), Final Report to the National Cooperative Highway Research Program (NCHRP), Transportation Research Report No. TRP-03-157-04, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, January 24, 2005.

9. Stolle, C.S, Polivka, K.A., Reid, J.D., Faller, R.K., Sicking, D.L., Bielenberg, R.W., and Rohde, J.R., *Evaluation of Critical Flare Rates for the Midwest Guardrail System (MGS)*,

Final Report to the Midwest States' Regional Pooled Fund Program, Report No. TRP-03-191-08, Project No. SPR-3(017)-Years 14-15, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, July 15, 2008.

10. Mongiardini, M., Faller, R.K., Reid, J.D., and Sicking, D.L., *Downstream Anchoring Requirements for the Midwest Guardrail System*, Draft Report to Wisconsin Department of Transportation, Transportation Research Report No. TRP-03-279-12, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, In Progress.

11. Cichowski, W.G., Skeels, P.C., and Hawkins, W.R., *Appraisal of Guardrail Installations by Car Impact and Laboratory Tests*, Experimental Engineering Dept., General Motors Proving Ground, Milford, MI. Presented at the Highway Research Board 40th Annual Meeting. January 1961.

12. Beaton, J.L., Nordlin, E.F., Ames, W.H., and Field, R.N., *Dynamic Tests of Corrugated Metal Beam Guardrail*, State of California, Department of Public Works, Division of Highways, Materials and Research Department. January 1967.

13. Nordlin, E.F., Ames, W.H., Field, R.N., and Folsom, J.J., *Dynamic Tests of Short Sections of Corrugated Metal Beam Guardrail*, State of California, Department of Public Works, Division of Highways, Materials and Research Department. Research Report 636392-4. October 1968.

14. Halquist, J.O., *LS-DYNA Keyword User's Manual*, Version 971, Livermore SoftwareTechnology Corporation, Livermore, California, May 2007.

15. Julin, R.D., Reid, J.D., Faller, R.K., and Mongiardini, M., *Determination of the Maximum MGS Mounting Height – Phase II Detailed Analysis with LS-DYNA*, Final Report to the Midwest States' Regional Pooled Fund Program, Report No. TRP-03-274-12, Project No. TPF-5(193)-Year 20, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, December 5, 2012.

16. Mongiardini, M., Faller, R.K., Reid, J.D., and Sicking, D.L., *Dynamic Evaluation and Implementation Guidelines for a Non-Proprietary W-Beam Guardrail Trailing-End Terminal*, Paper No. 13-5277, Accepted for publication and presentation to the Transportation Research Board, TRB AFB20 Committee on Roadside Safety Design, Transportation Research Board, Washington D.C., January 2013.

17. Hinch, J., Yang, T.L., and Owings, R., *Guidance Systems for Vehicle Testing*, ENSCO, Inc., Springfield, Virginia, 1986.

18. *Center of Gravity Test Code* - SAE J874 March 1981, SAE Handbook Vol. 4, Society of Automotive Engineers, Inc., Warrendale, Pennsylvania, 1986.

19. Society of Automotive Engineers (SAE), *Instrumentation for Impact Test – Part 1 – Electronic Instrumentation*, SAE J211/1 MAR95, New York City, NY, July 2007.

20. Quality Controlled Local Climatological Data, Available: <http://cdo.ncdc.noaa/gov/qclcd/QCLCD>, [2012, July 18].

21. *Vehicle Damage Scale for Traffic Investigators*, Second Edition, Technical Bulletin No. 1, Traffic Accident Data (TAD) Project, National Safety Council, Chicago, Illinois, 1971.

22. *Collision Deformation Classification – Recommended Practice J224 March 1980*, Handbook Volume 4, Society of Automotive Engineers (SAE), Warrendale, Pennsylvania, 1985.

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

24. Julin, R.D., *Midwest Guardrail System BARRIER VII Analysis*, MwRSF Internal Report, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, October 6, 2011.

25. Herr, J.E., Rohde, J.R., Sicking, D.L., Reid, J.D., Faller, R.K., Holloway, J.C., Coon, B.A., and Polivka, K.A., *Development of Standards for Placement of Steel Guardrail Posts in Rock*, Final Report to the Midwest States' Regional Pooled Fund Program, Report No. TRP-03-119-03, Project No. SPR-3(017)-Year 9, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, May 30, 2003.

26. Kuipers, B.D., Faller, R.K. and Reid, J.D., *Critical Flare Rates for W-beam Guardrail – Determining Maximum Capacity using Computer Simulation*, Final Report to the National Academy of Sciences, Report No. TRP-03-157-04, NCHRP 17-20(3), Midwest Roadside Safety Facility, University of Nebraska-Lincoln, January 24, 2005.

27. Mongiardini, M., Ray, M.H., *Roadside Safety Verification and Validation Program (RSVVP)*, User's Manual, Rev. 1.4, December 2009.

28. M.A. Sprague and T.L. Geers, *Spectral Elements and Field Separation for an Acoustic Fluid Subject to Cavitation*, J Comput. Phys., pp. 184:149, Vol. 162, (2003).

13 APPENDICES

Appendix A. Material Specifications

Table A-1. Material Certification Listing for Test No. MGSMIN-1

Description	Material Specifications	Reference	Heat No.
W6x8.5 6' [W152x12.6 1829] Long Steel Post	ASTM A992 [345 MPa] (W6x9 A36 [248 MPa])	Requisitions: 10-0142(Posts4,5,7-11) and 002(Posts3&6)	22479790 / G802202
6x12x14 1/4" [152x305x362] Blockout	SYP Grade No. 1 or better	Tags painted with GREEN	C.O.C.:0 3/12/09
6'-3" [1905] W-Beam MGS Section	12 gauge [2.7] AASHTO M180	Requisition: 10-0142-5	C.O.C.: 08/04/09
12'-6" [3810] W-Beam MGS Section	12 gauge [2.7] AASHTO M180	HEAT# 4614	4614
12'-6" [3810] W-Beam MGS End Section	12 gauge [2.7] AASHTO M180	HEAT# 3390	3390
5/8" Dia. x 14" [M16x356] long Guardrail Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	REQUISITION: 09-0453-3 /and a Rollform Group Bolt (yellow paint)	7366618
16D Double Head Nail	-	SCAN: 16d-1 LABELED BOX ITEM	-
5/8" Dia. x 10" [M16x254] long Guardrail Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	GLOSS HUNTER GREEN PAINT	20131470
5/8" Dia. x 1 1/2" [M16x38] Guardrail Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	REQUISITION: 10-0144-1 (BOLT)/12-0098	5074645 /5072014 5072080 /20131470
5/8" [16] Dia. Flat Washer	ASTM A153	REQUISITION: 090453 and 12-0019	06/30/08
BCT Timber Post - MGS Height	SYP Grade No. 1 or better	TAGS PAINTED WHITE	C.O.C.: 04/13/2010
72" [1829] Long Foundation Tube	ASTM A53 Grade B	REQUISITIONS: 090453-7 and 090458	Y85912 / 722564
Strut and Yoke Assembly	ASTM A36 Steel Galvanized	REQUISITION: 090453-8	C.O.C.: 06/30/2008
8x8x5/8" [127x203x16] Anchor Cable Bearing Plate	ASTM A36 Steel	BLACK PAINT AND STAMPED WITH "A3"	18486
BCT Anchor Cable Assembly	n3/4" [19] 6x19 IWRC IPS Galvanized Wire Rope	BLACK PAINT AND STAMPED WITH"A1"	A57723
Anchor Bracket Assembly	ASTM A36 Steel	BLACK PAINT AND STAMPED WITH"A2"	V911470
2 3/8" [60] O.D. x 6" [152] Long BCT Post Sleeve	ASTM A53 Grade B Schedule 40	REQUISITION: 09-0458 HEAT# 280638	280638
5/8" Dia. x 10" [M16x254] Long Hex Head Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	BLACK PAINT LABELED CYLINDER IN CERT SHED	10101333405
5/8" Dia. x 1 1/2" [M16x38] Long Hex Head Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	HEX BOLT REQUISITION: 11-0006-3	7367052
7/8" Dia. x 7 1/2" [M22x191] Long Hex Head Bolt and Nut	Bolt ASTM A307, Nut ASTM A563 DH	12-0037	LOT: 17071802
7/8" [22] Dia. Flat Washer	ASTM A153	12-0037	8280072
SOIL	Compacted, coarse, crushed limestone	1192012	

PAGE 01/01

Certified Analysis

Trinity Highway Products, LLC
2548 N.E. 28th St.
Ft Worth, TX

Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 81097

LINCOLN, NE 68501-1097

Order Number: 1104828
Customer PO: 2095
BOL Number: 26405
Document #: 1
Shipped To: NE
Use State: KS

As of: 2/2/09

Project: RESALE

MIDWEST MACHINERY

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat #	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
634	545G	6'0 POST/DB:DDR	A-709			22479790	49,600	69,100	23.8	0.100	0.790	0.033	0.032	0.200	0.440	0.00	0.200	0.002	4
100	901G	12/FLARE/8 HOLE	M-180	A		583168	71,200	77,900	27.0	0.061	0.750	0.016	0.015	0.012	0.071	0.00	0.051	0.000	4

24 Posts purchased 3/24/09
#002

Upon delivery, all materials subject to Trinity Highway Products, LLC Storage Stain Policy No. LG-002.

ALL STEEL USED WAS MELTED AND MANUFACTURED IN USA AND COMPLIES WITH THE BUY AMERICA ACT.
ALL GUARDRAIL MEETS AASHTO M-180, ALL STRUCTURAL STEEL MEETS ASTM A36
ALL GALVANIZED MATERIAL CONFORMS WITH ASTM-123, UNLESS OTHERWISE STATED.
BOLTS COMPLY WITH ASTM A-307 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
NUTS COMPLY WITH ASTM A-563 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.

3/4" DIA CABLE 6X19 ZINC COATED SWAGED END AISI C-1035 STEEL ANNEALED STUD 1" DIA ASTM 449 AASHTO M30, TYPE II BREAKING STRENGTH -- 49100 LB

State of Texas, County of Tarrant. Sworn and subscribed before me this 2nd day of February, 2009
Notary Public:
Commission Expires:

RACHEL R. MEDINA
Notary Public
STATE OF TEXAS
My Comm. Exp. 07/19/2009

Trinity Highway Products, LLC
Certified By: Stefanie Englet
Quality Assurance

03/24/2009 15:00 402-761-3288

Figure A-1. W6x8.5 (W152x12.6) Steel Post Material Specifications, Test No. MGSMIN-1

GREGORY HIGHWAY PRODUCTS, INC.
4100 13th St. P.O. Box 80508
Canton, Ohio 44708

Customer: MIDWEST MACHINERY & SUPPLY CO.
2200 Y STREET

LINCOLN, NE. 68501

Test Report
B.O.L # 34259
Customer P.O. 2042
Shipped to: MIDWEST MACHINERY & SUPPLY CO.
Project : STOCK
GHP Order No 2456AB

DATE SHIPPED: 06/20/08

HT # code	C.	Mn.	P.	S.	Si.	Tensile	Yield	Elong.	Quantity	Class	Type	Description
G802202	0.14	0.74	0.014	0.027	0.21	78300	60600	22.5	750	A		6IN WF AT 8.5 X 6FT 0IN GR POST
G802217	0.12	0.8	0.014	0.029	0.26	76400	58300	26.6		A		6IN WF AT 8.5 X 6FT 0IN GR POST
G802213	0.13	0.7	0.014	0.03	0.23	76700	60000	24.6		A		6IN WF AT 8.5 X 6FT 0IN GR POST
G802203	0.13	0.74	0.014	0.027	0.2	76600	69600	22.9		A		6IN WF AT 8.5 X 6FT 0IN GR POST
13715	0.14	0.81	0.026	0.031	0.23	71000	49000	24.7		A		6IN WF AT 8.5 X 6FT 0IN GR POST
25267	0.14	0.71	0.026	0.027	0.17	69000	49000	24.4		A		6IN WF AT 8.5 X 6FT 0IN GR POST
56632	0.09	0.83	0.011	0.028	0.2	78790	64860	24		A		6IN WF AT 8.5 X 6FT 0IN GR POST
56F33	0.09	0.79	0.01	0.031	0.18	79480	66600	23		A		6IN WF AT 8.5 X 6FT 0IN GR POST
56632	0.09	0.83	0.011	0.028	0.2	78790	64860	24		A		6IN WF AT 8.5 X 6FT 0IN GR POST
25105	0.12	0.66	0.012	0.02	0.22	66000	45000	23.5		A		6IN WF AT 8.5 X 6FT 0IN GR POST
44330	0.12	0.69	0.012	0.026	0.23	63000	44000	20.4		A		6IN WF AT 8.5 X 6FT 0IN GR POST
44261	0.16	0.61	0.01	0.025	0.19	68000	45000	27.2		A		6IN WF AT 8.5 X 6FT 0IN GR POST

Bolts comply with ASTM A-307 specifications and are galvanized in accordance with ASTM A-153, unless otherwise stated.
Nuts comply with ASTM A-563 specifications and are galvanized in accordance with ASTM A-153, unless otherwise stated.
All other galvanized material conforms with ASTM-123 & ASTM-525
All steel used in the manufacture is of Domestic Origin, "Made and Melted in the United States"
All Guardrail and Terminal Sections meets AASHTO M-180, All structural steel meets AASHTO M-183 & M270
All Bolts and Nuts are of Domestic Origin
All material fabricated in accordance with Nebraska Department of Transportation

By: ______
Andrew Artar
Vice President of Sales and Marketing
Gregory Highway Products, Inc.

STATE OF OHIO: COUNTY OF STARK
Sworn to and subscribed before me, a Notary Public, by
Andrew Artar this 23th day of June, 2008.
______
Notary Public, State of Ohio

NOTARIAL SEAL STATE OF OHIO

CYNTHIA K. CRAWFORD
Notary Public, State of Ohio
My Commission Expires 09-16-2012

Figure A-2. W6x8.5 (W152x12.6) Steel Post Material Specifications, Test No. MGSMIN-1

S.L. Storey
LUMBER COMPANY, INC.

CERTIFICATE OF COMPLIANCE

MARCH 12, 2009

MIDWEST MACHINERY & SUPPLY
P O BOX 81097
LINCOLN, NE 68501

THE FOLLOWING MATERIAL DELIVERED ON 3/12/09 ON BILL OF LADING NUMBER 19216 HAS BEEN INSPECTED BEFORE AND AFTER TREATMENT AND IS IN FULL COMPLIANCE WITH APPLICABLE NEBRASKA DEPARTMENT OF ROADS REQUIREMENTS FOR SOUTHERN YELLOW PINE TIMBER GUARDRAIL COMPONENTS, PRESERVATIVE TREATED WITH CHROMATED-COPPER-ARSENATE (CCA-C) TO A MINIMUM RETENTION OF .60 LBS/CU.FT. THE ACCEPTANCE OF EACH PIECE BY COMPANY QUALITY CONTROL IS INDICATED BY A HAMMER BRAND ON THE END OF EACH PIECE.

MATERIAL		CHARGE #	DATE	RETENTION	QUANTITY
6x8x14"	Blockout (CD)	09-26	1/29/09	0.66	70
6x8x14"	Blockout (CD)	09-67	2/19/09	0.60	70
6x8x14"	OCD Blockout	09-95	3/5/09	0.62	140
6x8x6'	CRT Post	09-94	3/5/09	0.69	70
6x8x6'	Line Post	09-94	3/5/08	0.69	70
5½X7½X42½"	BCT Post	08-74	1/29/08	0.67	48
6x8x18"	Blockout	09-95	3/5/00	0.62	70
6x8x18"	Blockout	09-95	3/5/09	0.62	70

THIS CERTIFICATE APPLIES TO MATERIAL ORDERED FOR your order no.: 2117

FOR ANY INQUIRIES, PLEASE RETAIN THIS DOCUMENT FOR FUTURE REFERENCE.

THANK YOU FOR YOUR ORDER.

SINCERELY,

Karen L Storey

Karen Storey

SIGNED BEFORE ME THIS 12 DAY OF MARCH 2009.

Notary: William S. Houston
Notary Public Floyd County Georgia
My Commission Expires Oct. 15, 2010

WILLIAM S. HOUSTON NOTARY PUBLIC FLOYD COUNTY, GA

11/02/2009 09:59 402-761-3288 MIDWEST MACHINERY

Figure A-3. Wood Blockout Material Specifications, Test No. MGSMIN-1

Trinity Highw :oducts , LLC
25-:8 N.E. 28th St.
Ft Worth, TX

Customer:	MIDWEST MACH.& SUPPLY CO.	Sales Order:	1112249	Print Date:	8/4/09
	P. O. BOX 81097	Customer PO:	2188	Project:	RESALE
		BOL #	28104	Shipped To:	NE
		Document #	1	Use State:	KS
	LINCOLN, NE 68501-1097				

Trinity Highway Products, LLC
Certificate Of Compliance For Trinity Industries, Inc.
NCHRP Report 350 Compliant

Pieces	Description
X 40	12/6'3/S

Upon delivery, all materials subject to Trinity Highway Products , LLC Storage Stain Policy No. LG-002.

ALL STEEL USED WAS MELTED AND MANUFACTURED IN USA AND COMPLIES WITH THE BUY AMERICA ACT
ALL GUARDRAIL MEETS AASHTO M-180, ALL STRUCTURAL STEEL MEETS ASTM A36
ALL OTHER GALVANIZED MATERIAL CONFORMS WITH ASTM-123.
BOLTS COMPLY WITH ASTM A-307 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
NUTS COMPLY WITH ASTM A-563 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
3/4" DIA CABLE 6X19 ZINC COATED SWAGED END AISI C-1035 STEEL ANNEALED STUD 1" DIA ASTM 449 AASHTO M30, TYPE II BREAKING STRENGTH – 49100 LB

State of Texas, County of Tarrant. Sworn and subscribed before me this 4th day of August, 2009

RACHEL MEDINA
Notary Public, State of Texas
My Commission Expires
July 13, 2013

Notary Public:
Commission Expires: / /

Trinity Highway Products, LLC
Certified By: Stefanie Inglet
Quality Assurance

1 of 1

Figure A-4. 6-ft 3-in. (1.9-m) Long W-Beam Section Material Specifications, Test No. MGSMIN-1

GREGORY HIGHWAY PRODUCTS, INC.
4100 13th St. P.O. Box 80508
Canton, Ohio 44708

MAY 14 2009

Customer: UNIVERSITY OF NEBRASKA-LINCOLN
401 CANFIELD ADMIN BLDG
P O BOX 880439
LINCOLN, NE. 68588-0439

Test Report
B.O.L. # 39963
Customer P.O. 4500204081/ 04/06/2009
Shipped to: UNIVERSITY OF NEBRASKA-LINCOLN
Project : TEST PANELS
GHP Order No 105271

DATE SHIPPED: 05/07/09

HT # code	C.	Mn.	P.	S.	Si.	Tensile	Yield	Elong.	Quantity	Class	Type	Description
4614	0.21	0.84	0.011	0.003	0.03	89432	67993	19.8	160	A	2	12GA 12FT6IN/3FT1 1/2IN WB T2

Bolts comply with ASTM A-307 specifications and are galvanized in accordance with ASTM A-153, unless otherwise stated.
Nuts comply with ASTM A-563 specifications and are galvanized in accordance with ASTM A-153, unless otherwise stated.
All other galvanized material conforms with ASTM-123 & ASTM-525
All steel used in the manufacture is of Domestic Origin, "Made and Melted in the United States"
All Guardrail and Terminal Sections meets AASHTO M-180, All structural steel meets AASHTO M-183 & M270
All Bolts and Nuts are of Domestic Origin
All material fabricated in accordance with Nebraska Department of Transportation
All controlled oxidized/corrosion resistant Guardrail and terminal sections meet ASTM A606, Type 4.

By: Andrew Artar
Andrew Artar
Vice President of Sales & Marketing
Gregory Highway Products, Inc.

STATE OF OHIO: COUNTY OF STARK
Sworn to and subscribed before me, a Notary Public, by Andrew Artar this 8th day of May, 2009.
Cynthia K Crawford
Notary Public, State of Ohio

NOTARIAL SEAL STATE OF OHIO

CYNTHIA K. CRAWFORD
Notary Public, State of Ohio
My Commission Expires 09-16-2012

Figure A-5. 12-ft 6-in. (3.8-m) Long W-Beam Section Material Specifications, Test No. MGSMIN-1

RECEIVED
OCT 0 5 2005
UNL FMP

GREGORY HIGHWAY PRODUCTS, INC.
4100 13th St. P.O. Box 80508
Canton, Ohio 44708

Customer: UNIVERSITY OF NEBRASKA-LINCOLN
401 CANFIELD ADMIN BLDG
P O BOX 880439
LINCOLN, NE. 68588-0439

Test Report
B.O.L. # 15808 DATE SHIPPED: 09/27/05
Customer P.O.: VERBAL JOHN ROHDE
Shipped to: UNIVERSITY OF NEBRASKA-LINCOLN
Project : STOCK
GHP Order No.: 44822

HEAT #	C.	Mn.	P.	S.	Si.	Tensile	Yield	Elong.	Quantity	Class	Type	Description
3390	0.21	0.8	0.013	0.007	0.01	81660	62520	20.76	160		2	12GA 12FT6IN/3FT1 1/2IN WB T2

Bolts comply with ASTM A-307 specifications and are galvanized in accordance with ASTM A-153, unless otherwise stated.
Nuts comply with ASTM A-563 specifications and are galvanized in accordance with ASTM A-153, unless otherwise stated.
All other galvanized material conforms with ASTM-123 & ASTM-525
All steel used in the manufacture is of Domestic Origin, "Made and Melted in the United States"
All Guardrail and Terminal Sections meets AASHTO M-180, All structural steel meets AASHTO M-183 & M270
All Bolts and Nuts are of Domestic Origin

RECEIVED
OCT - 3 2005
UNL ACCOUNTING

By:
Andrew Artar
Vice President of Sales and Marketing
Gregory Highway Products, Inc.

STATE OF OHIO: COUNTY OF STARK
Sworn to and subscribed before me, a Notary Public, by Andrew Artar this 28th day of September, 2005

Dawn R. Batton
Notary Public, State of Ohio
My Commission Expires February 24, 2008

Figure A-6. 12-ft 6-in. (3.8-m) Long W-Beam End Section Material Specifications, Test No. MGSMIN-1

05/04/2009 16:36 402-761-3288 MIDWEST MACHINERY PAGE 15/52

55 04/14/2009 10:14 FAX 740 681 4433 MID WEST FAB: ROCKMILL 002 35406

MID WEST
FABRICATING CO.

CERTIFICATE OF COMPLIANCE

WE CERTIFY THAT ALL BOLTS ARE MADE AND MANUFACTURED IN THE USA.

TO: TRINITY INDUSTRIES INC.
Plant #55
550 East Robb Ave. 419-222-7398
Lima, Ohio 45801
SHIP DATE: 4/13/2009
MANUFACTURER: MID WEST FABRICATING CO.
ASTM: A307A
GALVANIZERS: Bristol/Pilot/Columbus TO A-153 CLASS C

QTY	PART NO.	HEAT NO.	LOT NO.	P.O.NO.
5,250	5/8 X 10-6"	20060370	95055	130236BR25
2,625	5/8 X 10-6"	20060370	95062	130236BR25
28,500	5/8 X14-6"	7366818	85199	126266BR114

Signature D. Smith D. Smith
TITLE: QUALITY CONTROL
DATE: 4/13/2009

313 North Johns Street • Amanda, Ohio 43102 • 740/969-4411 • FAX: 740/969-4433

Figure A-7. ⅝-in.x14-in. Guardrail Bolt Material Specifications, Test No. MGSMIN-1

Figure A-8. 16D Double Head Nail Material Specifications, Test No. MGSMIN-1

06/04/2009 16:36 402-761-3288 MIDWEST MACHINERY

MID WEST
FABRICATING CO.

CERTIFICATE OF COMPLIANCE

WE CERTIFY THAT ALL BOLTS ARE MADE AND MANUFACTURED IN THE USA.

TO: TRINITY INDUSTRIES INC.
Plant #55
425 E. O'Connor 419-222-7398
Lima,Ohio 45801
SHIP DATE:.11/6/2008
MANUFACTURER: MID WEST FABRICATING CO.
ASTM: A307A
GALVANIZERS: Columbus/Piolt TO A-153 CLASS C

QTY	PART NO.	HEAT NO.	LOT NO.	P.O.NO.
3,524	5/8 X 10-6"	7261134	85204	126266BR80
1,076	5/8 X 10-6"	7261134	85204	126266BR78
8,900	5/8 X 10-6"	7261134	85204	126266BR74
YUG 4,500	5/8 X 10-6"	7261611	85217	126266BR74
2,550	5/8 X 10W-6"	7261286	85180	126266BR84
4,500	5/8 X 14-6"	7366618	85199	126266BR68
6,000	5/8 X 18-6"	7366618	85157	126266BR84
1,536	5/8 X 18-6"	7366618	85157	126266BR74
130	5/8 X 18-6"	7366618	85156	126266BR74
2,964	5/8 X 18-6"	7366618	85149	126266BR74
4,370	5/8 X 18-6"	7261611	85146	126266BR74
400	5/8 X 3.5"	5978691	85016	126266BR82

Signature D. Smith D. Smith
TITLE: QUALITY CONTROL
DATE: 11/6/2008

313 North Johns Street • Amanda, Ohio 43102 • 740/969-4411 • FAX: 740/969-4433

Figure A-9. ⅝-in.x10-in. Guardrail Bolt Material Specifications, Test No. MGSMIN-1

TRINITY HIGHWAY PRODUCTS, LLC.
Plant #55
425 E. O' CONNOR AVENUE
Lima, OH 45801
419-227-1296

MATERIAL CERTIFICATION

CUSTOMER: STOCK	DATE: AUGUST 31, 2010
	INVOICE #
	LOT NUMBER 100730B2
PART NUMBER: 3360G	QUANTITY: 108,081
DESCRIPTION: 5/8"x 1 ¼" GR BOLT	DATE SHIPPED:
SPECIFICATIONS: ASTM A307-A /A153	HEAT#: 5074645 & 10062440

MATERIAL CHEMISTRY

C	MN	P	S	SI	CU	NI	CR	V	MO	SN	AL	CB	N	B	TI
.09	.41	.008	.004	.10	.07	.08	.07	.001	.04	.006	.041	.000	.0065	NA	NA
.09	.48	.008	.012	.09	.09	.05	.06	.001	.02	.008	.028	.001	.008	.0001	.001

PLATING AND/OR PROTECTIVE COATING

HOT DIP GALVANIZED (OZ. PER SQ. FT.)		2.58 Avg.

****THIS PRODUCT WAS MANUFACTURED IN THE UNITED STATES OF AMERICA****

THE MATERIAL USED IN THIS PRODUCT WAS MELTED AND MANUFACTURED IN THE U.S.A

WE HEREBY CERTIFY THAT TO THE BEST OF OUR KNOWLEDGE ALL INFORMATION CONTAINED HEREIN IS CORRECT.

TRINITY HIGHWAY PRODUCTS, LLC.

STATE OF OHIO, COUNTY OF ALLEN
SWORN AND SUBSCRIBED BEFORE ME
THIS 31ST DAY OF AUGUST, 2010

NOTARY PUBLIC

425 E. O 'CONNOR AVENUE LIMA, OH 45801 419-227-1296

Figure A-10. ⅝-in.x1½-in. Guardrail Bolt Material Specifications, Test No. MGSMIN-1

33406

TRINITY HIGHWAY PRODUCTS, LLC.
425 E. O'CONNOR AVENUE
LIMA, OHIO 45801
419-227-1296

MATERIAL CERTIFICATION

CUSTOMER: STOCK	DATE: MARCH 31, 2011
	INVOICE #:
	LOT #: 110318N2
PART NUMBER: 3340G	QUANTITY: 106,000
DESCRIPTION: 5/8" GR NUT	DATE SHIPPED
SPECIFICATIONS: ASTM A563-A/A153	HEAT # 20131470 & 20131460

MATERIAL CHEMISTY

C	MN	P	S	SI	NI	CR	MO	CU	SN	V	AL	N	B	TI	NB
.08	.35	.007	.004	.07	.05	.05	.02	.09	.007	.004	.023	.008	.0001	.001	.001
.09	.36	.008	.004	.05	.04	.06	.01	.09	.006	.004	.025	.006	.0002	.001	.001

PLATING AND/OR PROTECTIVE COATING

HOT DIP GALVANIZING (OZ. PER SQ. FT.)	2.52 AVG.

****THIS PRODUCT WAS MANUFACTURED IN THE UNITED STATES OF AMERICA***

THE MATERIAL USED IN THIS PRODUCT WAS MELTED AND MANUFACTURED IN THE U.S.A.

WE HEREBY CERTIFY THAT TO THE BEST OF OUR KNOWLEDGE ALL INFORMATION CONTAINED HEREIN IS CORRECT.

TRINITY HIGHWAY PRODUCTS, LLC.

STATE OF OHIO, COUNTY OF ALLEN
SWORN AND SUBSCRIBED BEFORE ME
THIS 31ST DAY OF MARCH, 2011

NOTARY PUBLIC

425 E. O'CONNOR AVENUE LIMA, OHIO 45801 419-227-1296

Figure A-11. ⅝-in. (16-mm) Guardrail Nut Material Specifications, Test No. MGSMIN-1

11/04/2009 06:10 402-761-3288 MIDWEST MACHINERY PAGE 02/10

TRINITY HIGHWAY PRODUCTS, LCC.
Plant #55
425 E. O' CONNOR AVENUE
Lima, OH 45801
419-227-1296

MATERIAL CERTIFICATION

CUSTOMER: STOCK	DATE: JULY29, 2009
	INVOICE #
	LOT NUMBER: 090703B
PART NUMBER: 3360G	QUANTITY: 110,765
DESCRIPTION: 5/8"x 1 ¼" GR BOLT	DATE SHIPPED:
SPECIFICATIONS: ASTM A307-A /A153	HEAT#: 5072014

MATERIAL CHEMISTRY

C	MN	P	S	SI	NI	CR	MO	CU	SN	V	AL	N	B	TI	NB
.15	.47	.006	.003	.09	.06	.05	.02	.05	.005	.000	.046	.0063	.000	.000	.000

PLATING AND/OR PROTECTIVE COATING

HOT DIP GALVANIZED (OZ. PER SQ. FT.)		1.25 Avg.

****THIS PRODUCT WAS MANUFACTURED IN THE UNITED STATES OF AMERICA****

THE MATERIAL USED IN THIS PRODUCT WAS MELTED AND MANUFACTURED IN THE U.S.A

WE HEREBY CERTIFY THAT TO THE BEST OF OUR KNOWLEDGE ALL INFORMATION CONTAINED HEREIN IS CORRECT.

TRINITY HIGHWAY PRODUCTS, LLC.

STATE OF OHIO, COUNTY OF ALLEN
SWORN AND SUBSCRIBED BEFORE ME
THIS 29TH DAY OF JULY, 2009

NOTARY PUBLIC

425 E. O 'CONNOR AVENUE LIMA, OH 45801 419-227-1296

Figure A-12. ⅝-in.x1½-in. Guardrail Bolt Material Specifications, Test No. MGSMIN-1

11/04/2009 06:10 402-761-3288 MIDWEST MACHINERY PAGE 06/10

TRINITY HIGHWAY PRODUCTS, LLC.
425 E. O'CONNOR AVENUE
LIMA, OHIO 45801
419-227-1296

MATERIAL CERTIFICATION

CUSTOMER: STOCK	DATE: JULY 27, 2009
	INVOICE #:
	LOT #: 090717N2
PART NUMBER: 3340G	QUANTITY: 62,000
DESCRIPTION: 5/8" GR NUT	DATE SHIPPED
SPECIFICATIONS: ASTM A563-A/A153	HEAT 5072080

MATERIAL CHEMISTY

C	MN	P	S	SI	CU	NI	CR	V	MO	SN	AL	CB	N		
.14	.45	.013	.003	.14	.05	.05	.07	.002	.02	.006	.037	.000	.006		

PLATING AND/OR PROTECTIVE COATING

HOT DIP GALVANIZING (OZ. PER SQ. FT.)	2.81 AVG.

****THIS PRODUCT WAS MANUFACTURED IN THE UNITED STATES OF AMERICA***

THE MATERIAL USED IN THIS PRODUCT WAS MELTED AND MANUFACTURED IN THE U.S.A.

WE HEREBY CERTIFY THAT TO THE BEST OF OUR KNOWLEDGE ALL INFORMATION CONTAINED HEREIN IS CORRECT.

TRINITY HIGHWAY PRODUCTS, LLC.

STATE OF OHIO, COUNTY OF ALLEN
SWORN AND SUBSCRIBED BEFORE ME
THIS 27TH DAY OF JULY, 2009

NOTARY PUBLIC

425 E. O'CONNOR AVENUE LIMA, OHIO 45801 419-227-1296

Figure A-13. ⅝-in. (16-mm) Guardrail Nut Material Specifications, Test No. MGSMIN-1

\

Figure A-14. ⅝-in (16 mm) Diameter Flat Washer Material Specifications, Test No. MGSMIN-1

425 E. O'Connor
Lima, OH

PAGE 44/52

Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 81097

LINCOLN, NE 68501-1097

Sales Order: 1093497
Customer PO: 2030
BOL # 43073
Document # 1

Print Date: 6/30/08
Project: RESALE
Shipped To: NE
Use State: KS

Trinity Highway Products, LLC

Certificate Of Compliance For Trinity Industries, Inc. ** SLOTTED RAIL TERMINAL **

NCHRP Report 350 Compliant

MIDWEST MACHINERY

Pieces	Description
32	12/12'6/S SRT-1
32	12/25'0/SPEC/S SRT-2
32	3/16X12.5X16 CAB ANC BRKT
32	2" X 5 1/2" PIPE (LONG)
64	6'0 TUBE SL/.188X8X6
32	5/8 X 6 X 8 BEARING PLATE
32	12/BUFFER/ROLLED
32	CBL 3/4X6'6/DBL SWG/NOHWD
640	5/8" RD WASHER 1 3/4 OD
1,728	5/8" GR HEX NUT
1,152	5/8"X1.25" GR BOLT
256	5/8"X1.5" HEX BOLT A307
64	5/8"X9.5" HEX BOLT A307

Upon delivery, all materials subject to Trinity Highway Products , LLC Storage Stain Policy No. LG-002.

ALL STEEL USED WAS MELTED AND MANUFACTURED IN USA AND COMPLIES WITH THE BUY AMERICA ACT
ALL GUARDRAIL MEETS AASHTO M-180, ALL STRUCTURAL STEEL MEETS ASTM A36
ALL OTHER GALVANIZED MATERIAL CONFORMS WITH ASTM-123.
BOLTS COMPLY WITH ASTM A-307 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
NUTS COMPLY WITH ASTM A-563 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
3/4" DIA CABLE 6X19 ZINC COATED SWAGED END AISI C-1035 STEEL ANNEALED STUD 1" DIA ASTM 449 AASHTO M30, TYPE II BREAKING STRENGTH – 49100 LB

State of Ohio, County of Allen. Sworn and Subscribed before me this 30th day of June, 2008

Notary Public:
Commission Expires

Trinity Highway Products, LLC
Certified By:

Figure A-15. ⅝-in (16 mm) Diameter Flat Washer Material Specifications, Test No. MGSMIN-1

AMERICAN TIMBER AND STEEL

FORMERLY MIDWESTERN WHOLESALERS, INC.

This is to certify that the materials shipped, as indicated, conform to the State of Nebraska specifications.
Order Number: 89198
Project Number:

QUANTITY	DESCRIPTION	CHARGE NO.	TREATMENT	TREATER
50	6x8-46" DSS SYP S4S BCT Post	38040	CCA	MWT

BCT Posts
10-0282
White
+white tags.

MWT - MIDWEST WOOD TREATING, INC., NORWALK, OH
MWT-OK - MIDWEST WOOD TREATING, INC., CHICKASHA, OK

Made & Treated in the USA. Meets AASHTO Specs M133 & M168.

AMERICAN TIMBER AND STEEL
By Heather L. Seward
Title Sales Assistant
Date April 13, 2010

NOTARIZED
Sworn to and subscribed before me
this 13th day of April 2010.
by Hope Wilhelm

NOTARY PUBLIC STATE OF OHIO
Hope Wilhelm
Resident Huron County
Notary Public, State Of Ohio
My Commission Expires
March 9, 2014

American Timber And Steel Corp 4832 Plank Rd / PO Box 767 Norwalk, OH 44857 Ph: 419.668.1610 Fax: 419.663.1077

"THE TIMBER SPECIALISTS"

Figure A-16. BCT Timber Posts – MGS Height Material Specifications, Test No. MGSMIN-1

Certified Analysis

Trinity Highway Products , LLC
425 E. O'Connor
Lima, OH
Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 81097

LINCOLN, NE 68501-1097
Project: STOCK

Order Number: 1108107
Customer PO: 2132
BOL Number: 48341
Document #: 1
Shipped To: NE
Use State: KS

As of: 5/22/09

MIDWEST MACHINERY

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat #	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
			M-180	A	2	C49037	64,600	88,600	21.2	0.210	0.880	0.010	0.000	0.030	0.080	0.000	0.060	0.010	4
25	736G	5'/TUBE SL/.188"X6"X8"FLA	A-500			Y85912	56,500	72,980	37.0	0.210	0.770	0.009	0.006	0.016	0.010	0.00	0.020	0.001	4
6	742G	6'0 TUBE SL/.188X8X6	A-500			Y85912	56,500	72,980	37.0	0.210	0.770	0.009	0.006	0.016	0.010	0.00	0.020	0.001	4
26	764G	1/4"X24"X24"SOIL PLATE	A-36			120039	46,660	73,630	26.9	0.190	0.520	0.012	0.003	0.020	0.090	0.00	0.040	0.000	4
12	923G	BRONSTAD 98" W/O	M-180	A	2	122209	63,590	82,010	26.6	0.190	0.730	0.015	0.004	0.020	0.110	0.00	0.040	0.000	4
4	927G	10/END SHOE/EXT	M-180	B	2	A814375	59,770	78,641	27.4	0.210	0.750	0.017	0.005	0.030	0.090	0.00	0.030	0.002	4

402-751-3288

Upon delivery, all materials subject to Trinity Highway Products , LLC Storage Stain Policy No. LG-002.

ALL STEEL USED WAS MELTED AND MANUFACTURED IN USA AND COMPLIES WITH THE BUY AMERICA ACT.
ALL GUARDRAIL MEETS AASHTO M-180, ALL STRUCTURAL STEEL MEETS ASTM A36
ALL GALVANIZED MATERIAL CONFORMS WITH ASTM-123, UNLESS OTHERWISE STATED.
BOLTS COMPLY WITH ASTM A-307 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
NUTS COMPLY WITH ASTM A-563 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
3/4" DIA CABLE 6X19 ZINC COATED SWAGED END AISI C-1035 STEEL ANNEALED STUD 1" DIA ASTM 449 AASHTO M30, TYPE II BREAKING STRENGTH -- 49100 LB

State of Ohio, County of Allen. Sworn and subscribed before me this 22nd day of May, 2009
Notary Public:
Commission Expires 11 28 2012

Trinity Highway Products , LLC
Certified By:
Quality Assurance

06/04/2009 15:35

4 of 7

Figure A-17. Long Foundation Tube Section Material Specifications, Test No. MGSMIN-1

MATERIAL TEST REPORT

(ATE: 09/25/07

PAGE: 1

BILL OF LADING: 164358

CUST: STEEL & PIPE SUPPLY - CATOOSA OK
1050 FORT GIBSON ROAD
CATOOSA OK 74015

ATTN: * Test Report Desk

106201 8027185

LEAVIT(JBE COMPANY, LLC

TUBING MANUFACTURED IN USA

LEAVITT
The Tube People

Leavitt Tube Co., LLC
1717 W. 115th St.
Chicago, IL 60643
Phone: 773-239-7700
Phone: 1-800-LEAVITT
Fax: 773-239-1023
www.leavitt-tube.com
QA1002-0003 Rev. 0

ITEM NO.	PIECES	SIZE, GAUGE,LENGTH	QTY. SHIPPED	CUSTOMER P.O.	ORDER NUMBER	CUSTOMER PART NBR	ASTM SPECIFICATION	GRADE
1	7	8.625-322HRB 252	147	4500088611	1015580 1.000		A500-03b	B
2	6	12X2-188HRB 480	240	4500088813	1016034 1.000		A500-03b	B
3 - 4	28	8.625-322HRB 504	1,176	4500091471	1025579 1.000		A500-03b	B
5	9	8X6-188HRB 480	360	4500092386	1029189 1.000		A500-03b	B

ITEM NO.	1	2	3	4	5
COIL NO.	395453	395532	395813	395460	391232
HEAT NO.	722562	722551	722564	722564	A13386
CORRECTED COIL					
CARBON	.210	.210	.210	.210	.220
MANGANESE	.820	.860	.820	.820	.700
PHOSPHORUS	.004	.006	.004	.004	.006
SULFUR	.006	.004	.006	.006	.003
ALUMINUM	.047	.050	.047	.047	.024
SILICON	.020	.030	.020	.020	.030
WELD TESTING	FLATTEN	FLARE	FLATTEN	FLATTEN	FLARE
YIELD STRENGTH (PSI)	47,297			52,000	55,056
TENSILE STRENGTH (PSI)	62,162			70,666	70,787
ELONGATION IN 2" (%)	29.0			31.0	27.0

Item(s)- 1 2 3 4 5 Are
Made and Melted
In The U.S.A.

I HEREBY CERTIFY THAT THE ABOVE IS CORRECT
AS CONTAINED IN THE RECORDS OF THE COMPANY.

Figure A-18. Long Foundation Tube Section Material Specifications, Test No. MGSMIN-1

425 E. O'Connor
Lima, OH

Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 81097

LINCOLN, NE 68501-1097

Sales Order: 1093497
Customer PO: 2030
BOL # 43073
Document # 1

Print Date: 6/30/08
Project: RESALE
Shipped To: NE
Use State: KS

Trinity Highway Products. LLC

Certificate Of Compliance For Trinity Industries, Inc. ** SLOTTED RAIL TERMINAL **

NCHRP Report 350 Compliant

Pieces	Description
64	5/8"X10" GR BOLT A307
192	5/8"X18" GR BOLT A307
32	1" ROUND WASHER F844
64	1" HEX NUT A563
192	WD 6'0 POST 6X8 CRT
192	WD BLK 6X8X14 DR
64	NAIL 16d SRT
64	WD 3'9 POST 5.5X7.5 BAND
32	STRUT & YOKE ASSY
128	SLOT GUARD '98
32	3/8 X 3 X 4 PL WASHER

MGSBR

Ground Strut

090453-8

Upon delivery, all materials subject to Trinity Highway Products , LLC Storage Stain Policy No. LG-002.

ALL STEEL USED WAS MELTED AND MANUFACTURED IN USA AND COMPLIES WITH THE BUY AMERICA ACT
ALL GUARDRAIL MEETS AASHTO M-180, ALL STRUCTURAL STEEL MEETS ASTM A36
ALL OTHER GALVANIZED MATERIAL CONFORMS WITH ASTM-123.
BOLTS COMPLY WITH ASTM A-307 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
NUTS COMPLY WITH ASTM A-563 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
3/4" DIA CABLE 6X19 ZINC COATED SWAGED END AISI C-1035 STEEL ANNEALED STUD 1" DIA ASTM 449 AASHTO M30, TYPE II BREAKING STRENGTH – 49100 LB

State of Ohio, County of Allen. Sworn and Subscribed before me this 30th day of June, 2008

Notary Public:
Commission Expires

Trinity Highway Products, LLC
Certified By:

2 of 4

06/04/2009 16:36 402-761-3288

Figure A-19. Ground Strut Material Specifications, Test No. MGSMIN-1

Certified Analysis

Trinity Highway Products , LLC
550 East Robb Ave.
Lima, OH 45801

Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 703

MILFORD, NE 68405

Project: RESALE

Order Number: 1145215
Customer PO: 2441
BOL Number: 61905
Document #: 1
Shipped To: NE
Use State: KS

As of: 4/15/11

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat #	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
10	206G	T12/6'3/S	M-180	A	2	140734	64,240	82,640	26.4	0.190	0.740	0.015	0.006	0.010	0.110	0.00	0.060	0.000	4
			M-180	A	2	139587	64,220	81,750	28.5	0.190	0.720	0.014	0.003	0.020	0.130	0.000	0.060	0.002	4
			M-180	A	2	139588	63,850	82,080	24.9	0.200	0.730	0.012	0.004	0.020	0.140	0.000	0.050	0.002	4
			M-180	A	2	139589	55,670	74,810	27.7	0.190	0.720	0.012	0.003	0.020	0.130	0.000	0.060	0.002	4
			M-180	A	2	140733	59,000	78,200	28.1	0.190	0.740	0.015	0.006	0.010	0.120	0.000	0.070	0.001	4
55	260G	T12/25/6'3/S	M-180	A	2	139588	63,850	82,080	24.9	0.200	0.730	0.012	0.004	0.020	0.140	0.00	0.050	0.002	4
			M-180	A	2	139206	61,730	78,580	26.0	0.180	0.710	0.012	0.004	0.020	0.140	0.000	0.050	0.001	4
			M-180	A	2	139587	64,220	81,750	28.5	0.190	0.720	0.014	0.003	0.020	0.130	0.000	0.060	0.002	4
			M-180	A	2	140733	59,000	78,200	28.1	0.190	0.740	0.015	0.006	0.010	0.120	0.000	0.070	0.001	4
			M-180	A	2	140734	64,240	82,640	26.4	0.190	0.740	0.015	0.006	0.010	0.110	0.000	0.060	0.000	4
	260G		M-180	A	2	140734	64,240	82,640	26.4	0.190	0.740	0.015	0.006	0.010	0.110	0.00	0.060	0.000	4
			M-180	A	2	139587	64,220	81,750	28.5	0.190	0.720	0.014	0.003	0.020	0.130	0.000	0.060	0.002	4
			M-180	A	2	139588	63,850	82,080	24.9	0.200	0.730	0.012	0.004	0.020	0.140	0.000	0.050	0.002	4
			M-180	A	2	139589	55,670	74,810	27.7	0.190	0.720	0.012	0.003	0.020	0.130	0.000	0.060	0.002	4
			M-180	A	2	140733	59,000	78,200	28.1	0.190	0.740	0.015	0.006	0.010	0.120	0.000	0.070	0.001	4
26	701A	.25X11.75X16 CAB ANC	A-36			V911470	51,460	71,280	27.5	0.120	0.800	0.015	0.030	0.190	0.300	0.00	0.090	0.023	4
	701A		A-36			N3540A	46,200	65,000	31.0	0.120	0.380	0.010	0.019	0.010	0.180	0.00	0.070	0.001	4
24	729G	TS 8X6X3/16X8'-0" SLEEVE	A-500			N4747	63,548	85,106	27.0	0.150	0.610	0.013	0.001	0.040	0.160	0.00	0.160	0.004	4
24	749G	TS 8X6X3/16X6'-0" SLEEVE	A-500			N4747	63,548	85,106	27.0	0.150	0.610	0.013	0.001	0.040	0.160	0.00	0.160	0.004	4
22	782G	5/8"X8"X8" BEAR PL/OF	A-36			18486	49,000	78,000	25.1	0.210	0.860	0.021	0.036	0.250	0.260	0.00	0.170	0.014	4
25	974G	T12/TRANS RAIL/6'3"/3'1.5	M-180	A	2	140735	61,390	80,240	27.1	0.200	0.740	0.014	0.005	0.010	0.120	0.00	0.070	0.001	4

1 of 2

Figure A-20. Anchor Cable Bearing Plate and Bracket Assembly Material Specifications, Test No. MGSMIN-1

Certified Analysis

Trinity Highway Products, LLC
550 East Robb Ave.
Lima, OH 45801
Customer: MIDWEST MACH.& SUPPLY CO.
P. O. BOX 703

MILFORD, NE 68405
Project: RESALE

Order Number: 1145215
Customer PO: 2441
BOL Number: 61905
Document #: 1
Shipped To: NE
Use State: KS

As of: 4/15/11

Qty	Part #	Description	Spec	CL	TY	Heat Code/ Heat #	Yield	TS	Elg	C	Mn	P	S	Si	Cu	Cb	Cr	Vn	ACW
25	980G	T10/END SHOE/SLANT	A-1011-SS			A57723	49,000	64,500	34.8	0.080	0.350	0.018	0.005	0.020	0.090	0.00	0.060	0.001	4

Upon delivery, all materials subject to Trinity Highway Products, LLC Storage Stain Policy No. LG-002.
ALL STEEL USED WAS MELTED AND MANUFACTURED IN USA AND COMPLIES WITH THE BUY AMERICA ACT.
ALL GUARDRAIL MEETS AASHTO M-180, ALL STRUCTURAL STEEL MEETS ASTM A36
ALL COATINGS PROCESSES OF THE STEEL OR IRON ARE PERFORMED IN USA AND COMPLIES WITH THE "BUY AMERICA ACT"
ALL GALVANIZED MATERIAL CONFORMS WITH ASTM-123, UNLESS OTHERWISE STATED.
BOLTS COMPLY WITH ASTM A-307 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
NUTS COMPLY WITH ASTM A-563 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.
WASHERS COMPLY WITH ASTM F-436 SPECIFICATION AND/OR F-844 AND ARE GALVANIZED IN ACCORDANCE WITH ASTM F-2329.
3/4" DIA CABLE 6X19 ZINC COATED SWAGED END AISI C-1035 STEEL ANNEALED STUD 1" DIA ASTM 449 AASHTO M30, TYPE II BREAKING STRENGTH – 49100 LB

State of Ohio, County of Allen. Sworn and subscribed before me this 15th day of April, 2011
Notary Public:
Commission Expires 1/23/2016

STATE OF OHIO ANGELA COUNTS NOTARY PUBLIC ID# 2011NT0014 Commission Expires January 23, 2016 AUGLAIZE COUNTY

Trinity Highway Products, LLC
Certified By:
Quality Assurance

2 of 2

Figure A-21. BCT Anchor Cable Assesmbly Material Specifications, Test No. MGSMIN-1

EXLTUBE

905 ATLANTIC STREET, NORTH KANSAS CITY, MO 64116 1-816-474-5210 TOLL FREE 1-800-892-TUBE

STEEL VENTURES, LLC dba EXLTUBE

CERTIFIED TEST REPORT

Customer:	Size:	Spec No:	Date:
SPS - New Century 401 New Century Parkway New Century KS 66031	02.375	ASTM A500-07, A53E-07	05/22/2008
	Gauge: .154	Grade: A500B,C, A53BNT	Customer Order No: 4500104158
			B/L No: 81162893

SLEEVE MAT
CRT

Heat No	Yield P.S.I.	Tensile P.S.I.	Elongation % 2 Inch
280638	61,500	66,400	23.00

Heat No	C	MN	P	S	SI	CU	NI	CR	MO	V
280638	0.040	0.330	0.010	0.000	0.034	0.098	0.039	0.042	0.015	0.003

We hereby certify that the above material was manufactured in the U.S.A and that all test results shown in this report are correct as contained in the records of our company. All testing and manufacturing is in accordance to A.S.T.M. parameters encompassed within the scope of the specifications denoted in the specification and grade tiles above.

BNT = Grade B not tested - meets tensile properties ONLY.

STEEL VENTURES, LLC dba EXLTUBE

Steve Frerichs
Quality Assurance Manager

104158

Figure A-22. Long BCT Post Sleeve Material Specifications, Test No. MGSMIN-1

Southeastern Bolt & Screw, Inc.
1037 16th Avenue West
Birmingham, AL 35204

Certification Of Compliance

DATE: September 28, 2010

CUSTOMER: Midwest Machinery & Supply
P.O. Box 703
Milford, NE 68405

RE: Purchase Order No. 2351
SBS Shop Order No. 1093439

QTY	DESCRIPTION	SPECIFICATION	HEAT/LOT NO.
150	5/8-11 X 10 Hex Bolt	A307 Grade A	DL10101333405 1077688-1
100	5/8-11 X 12 Hex Bolt	A307 Grade A	DL10101333405 1077688-2
500	5/8-11 X 19 Hex Bolt	A307 Grade A	DL10101333405 1077688-3
150	3/4-10 X 8 Hex Bolt	A307 Grade A	11893310 1077688-4
500	7/8-9 X 14 Hex Bolt	A307 Grade A	DL1010333403 1077688-5
100	7/8-9 X 16 Hex Bolt	A307 Grade A	DL1010333403 1077688-6

Surface coating: A153 Grade C

We certify the materials listed meet or exceed the latest ASTM specification as shown.

Jim Waddell
Quality Assurance Manager

402 761 3288

10/07/2010 08:52 2052634851 ACCOUNTING PAGE 01/10

Figure A-23. ⅝-in. x 10-in. Long Hex Head Bolt Material Specifications, Test No. MGSMIN-1

TRINITY HIGHWAY PRODUCTS, LLC.
425 E. O'CONNOR AVENUE
LIMA, OHIO 45801
419-227-1296

MATERIAL CERTIFICATION

CUSTOMER: STOCK	DATE: SEPTEMBER 29, 2009
	INVOICE #:
	LOT #: 090123B
PART NUMBER: 3380G	QUANTITY: 119,201
DESCRIPTION: 5/8" X 1 ½ HH BOLT	DATE SHIPPED:
SPECIFICATIONS: ASTM A307-A/A153	HEAT #: 7367052, 7366484,7368369

MATERIAL CHEMISTY

C	MN	P	S	SI	CU	NI	CR	MO	AL	V	N	CB	SN	B	TI	NB
.15	.49	.008	.002	.06	.03	.02	.05	.01	.029	.002	.005	.001	.001	.000	.000	.000
.13	.38	.007	.002	.10	.03	.04	.06	.02	.037	.002	.004	.001	.001	.000	.000	.000
.14	.43	.006	.008	.06	.04	.02	.06	.02	.034	.002	.005	.001	.001	.000	.000	.000

PLATING AND/OR PROTECTIVE COATING

HOT DIP GALVANIZING (OZ. PER SQ. FT.)	2.74 AVG.

****THIS PRODUCT WAS MANUFACTURED IN THE UNITED STATES OF AMERICA***

THE MATERIAL USED IN THIS PRODUCT WAS MELTED AND MANUFACTURED IN THE U.S.A.

WE HEREBY CERTIFY THAT TO THE BEST OF OUR KNOWLEDGE ALL INFORMATION CONTAINED HEREIN IS CORRECT.

TRINITY HIGHWAY PRODUCTS, LLC.

STATE OF OHIO, COUNTY OF ALLEN
SWORN AND SUBSCRIBED BEFORE ME
THIS 29TH DAY SEPTEMBER, 2009

Susan J Henkins NOTARY PUBLIC

425 E. O'CONNOR AVENUE LIMA, OHIO 45801 419-227-1296

Figure A-24. ⅝-in. x 1½-in. Long Hex Head Bolt Material Specifications, Test No. MGSMIN-1

Figure A-25. ⅝-in. (16 mm) Hex Nut Material Specifications, Test No. MGSMIN-1

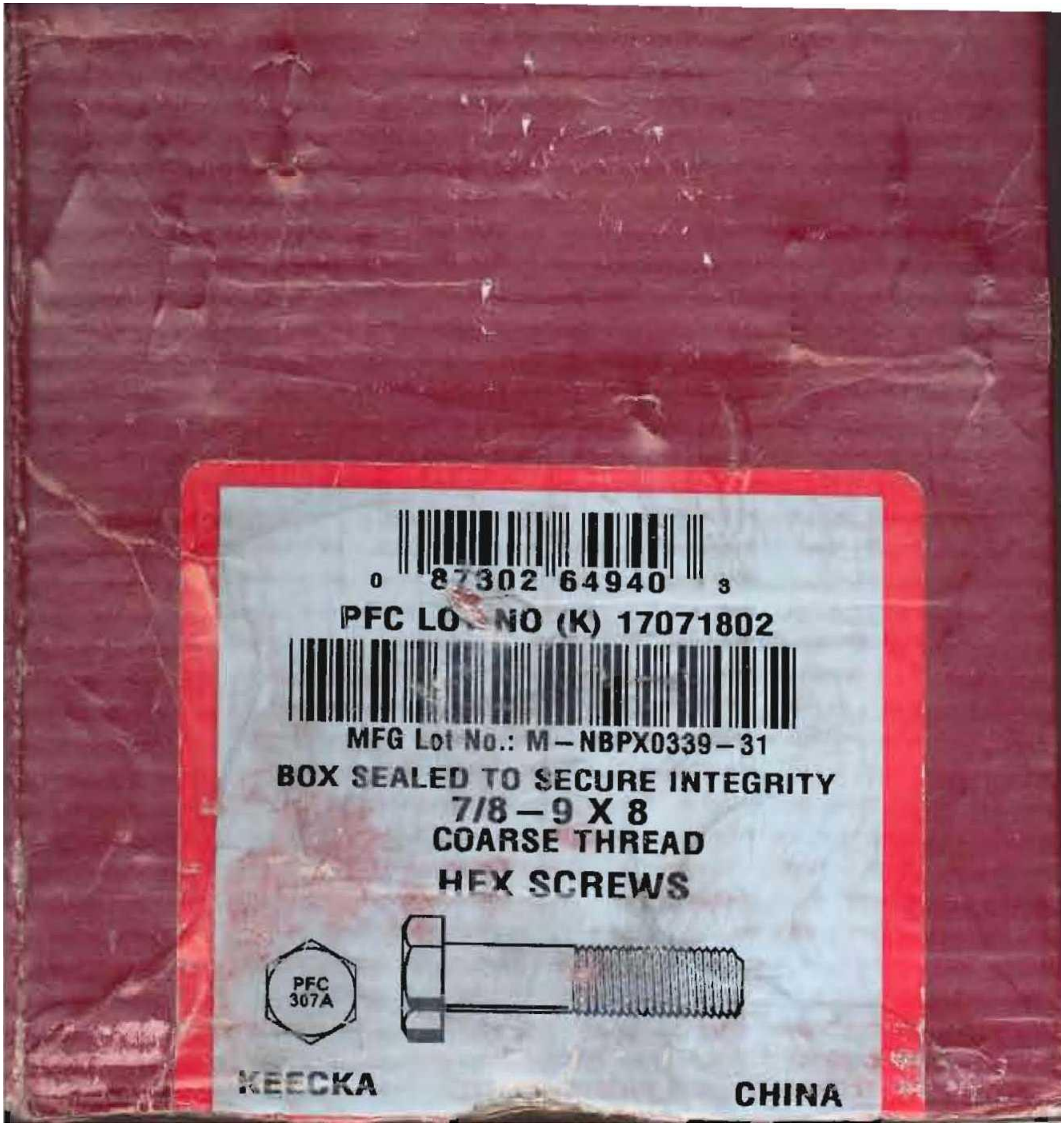


Figure A-26. ⅞-in. x 7½-in. Long Hex Head Bolt Material Specifications, Test No. MGSMIN-1

Figure A-27. ⅞-in. (22 mm) Flat Washer Material Specifications, Test No. MGSMIN-1

Appendix B. Vehicle Center of Gravity Determination

Test: MGSMIN-1 Vehicle: 2270P

Vehicle CG Determination

VEHICLE	Equipment	Weight (lb)	Vert CG (in.)	Vert M (lb-in.)
+	Unbalasted Truck (Curb)	5011	28.243	141525.66
+	Brake receivers/wires	6	54	324
+	Brake Frame	5	26	130
+	Brake Cylinder (Nitrogen)	22	27	594
+	Strobe/Brake Battery	6	31	186
+	Hub	26	15	390
+	CG Plate (EDRs)	7.5	28.5	213.75
-	Battery	-47	40	-1880
-	Oil	-10	17	-170
-	Interior	-62	23	-1426
-	Fuel	-167	17	-2839
-	Coolant	-19	30	-570
-	Washer fluid	0	41	0
BALLAST	Water	170	17	2890
	DTS	17	31	527
	Misc.			0
				139895.41

Estimated Total Weight (lb)	4965.5
Vertical CG Location (in.)	28.17348

wheel base (in.) 140.25

MASH Targets	Targets	Test Inertial	Difference
Test Inertial Weight (lb)	5000 ± 110	4956	-44.0
Long CG (in.)	63 ± 4	62.88	-0.11955
Lat CG (in.)	NA	-0.06848	NA
Vert CG (in.)	28	28.17	0.17348

Note: Long. CG is measured from front axle of test vehicle
Note: Lateral CG measured from centerline - positive to vehicle right (passenger) side

CURB WEIGHT (lb)

	Left	Right
Front	1439	1382
Rear	1100	1090
FRONT	2821 lb	
REAR	2190 lb	
TOTAL	5011 lb	

TEST INERTIAL WEIGHT (lb)
(from scales)

	Left	Right
Front	1381	1353
Rear	1102	1120
FRONT	2734 lb	
REAR	2222 lb	
TOTAL	4956 lb	

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

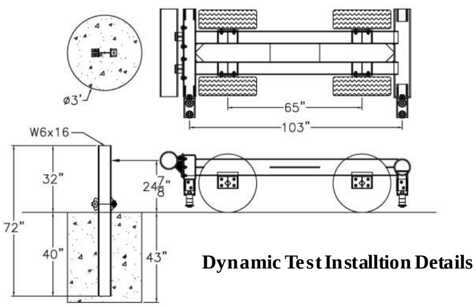
Appendix C. Static Soil Tests

Dynamic Set up

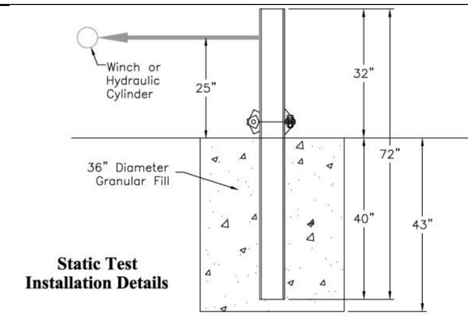
Post-Test Photo of Post

Static Load Test

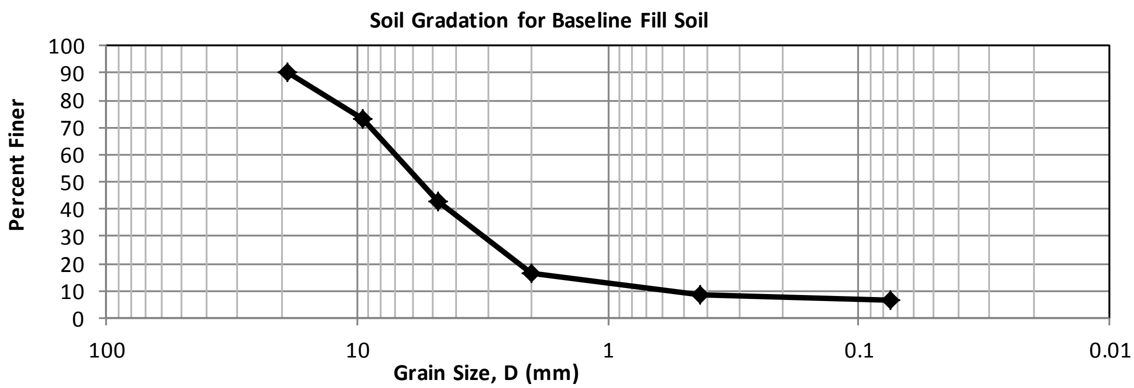
Post-Test Photo of Post

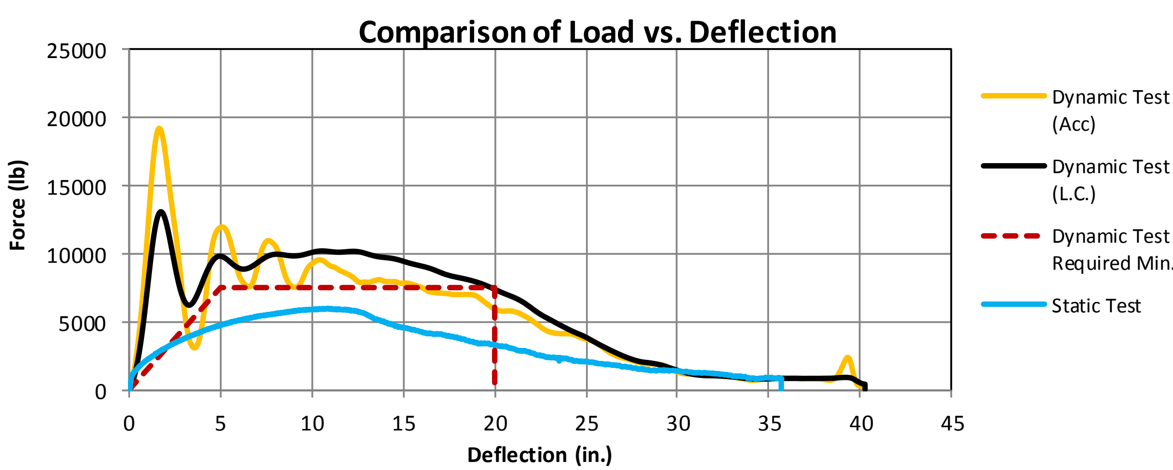


Dynamic Test Installtion Details



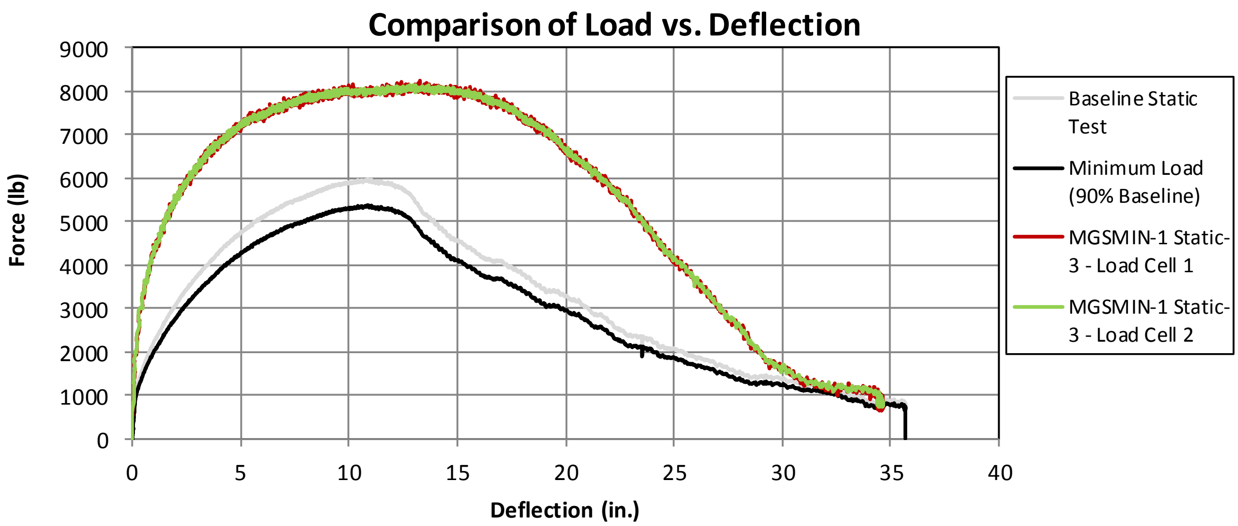
Static Test Installation Details

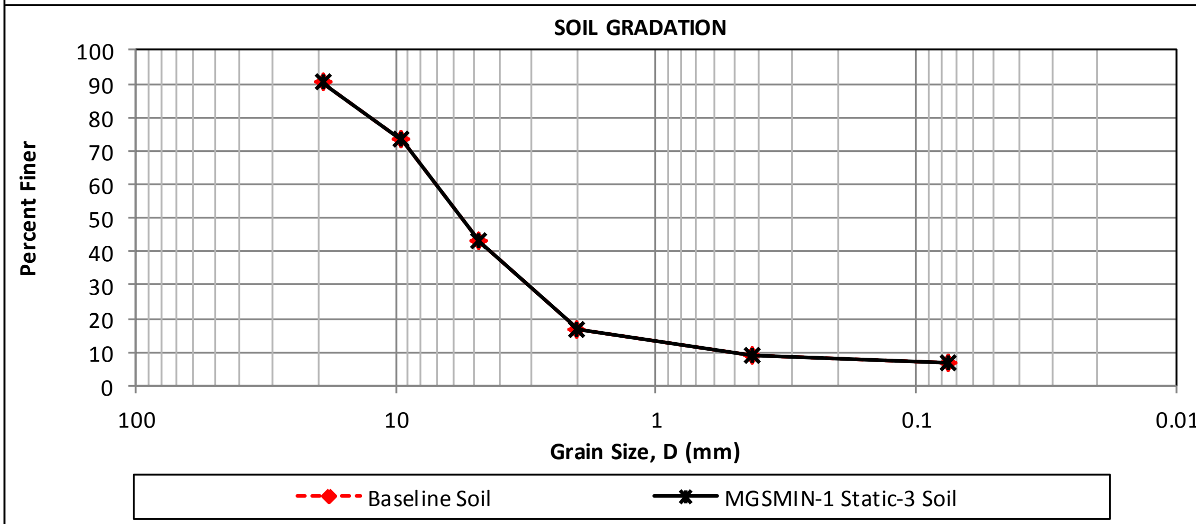




Date...	3/20/2012
Test Facility & Site Location.....................	Midwest Roadside Safety Facility
In situ soil description (ASTM D2487).........	Well Graded Gravel (GW)
Fill material description (ASTM D2487)......	Well Graded Gravel (GW) (see sieve analyses above)
Description of fill placement procedure.....	H.E. -8
Bogie Weight...	1,843 lb
Impact Velocity.....................................	20.02 mph

Figure C-1. Soil Strength, Initial Baseline Tests





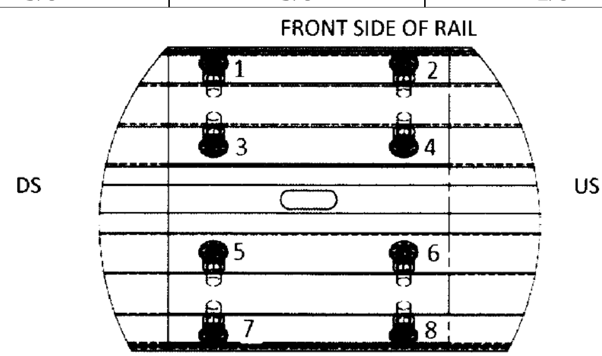
Date..	4/5/2012
Test Facility & Site Location.....................	Midwest Roadside Safety Facility
In situ soil description (ASTM D2487).........	Well Graded Gravel (GW)
Fill material description (ASTM D2487)......	Well Graded Gravel (GW) (see sieve analyses above)
Description of fill placement procedure.....	8-inch lifts tamped with a pneumatic compactor

Figure C-2. Static Soil Test, Test No. MGSMIN-1

Appendix D. Permanent Splice Displacements

Table D-1. Permanent Separation of Splice Connections and Bolt Slippage, Test No. MGSMIN-1

Bolt No.	**Splice No.: 2-3**		**Splice No.: 4-5**		**Splice No.: 5-6**	
	Slippage (in.)		**Slippage (in.)**		**Slippage (in.)**	
	FRONT	**BACK**	**FRONT**	**BACK**	**FRONT**	**BACK**
Rail	5/16	1/4	1/4	1/4	5/16	3/8
1	3/16	0	5/16	1/8	1/4	1/8
2	1/8	1/8	1/4	0	5/16	1/8
3	1/8	0	1/8	1/8	1/4	1/8
4	1/8	1/8	1/8	5/16	7/16	1/4
5	1/4	0	1/4	1/8	1/4	0
6	1/4	1/8	1/4	1/8	5/16	1/8
7	1/4	1/8	1/8	1/8	1/8	1/8
8	1/8	1/4	7/16	7/16	3/8	1/8
Bolt No.	**Splice No.: 7-8**		**Splice No.: 9-10**		**Splice No.: 11-12**	
	Slippage (in.)		**Slippage (in.)**		**Slippage (in.)**	
	FRONT	**BACK**	**FRONT**	**BACK**	**FRONT**	**BACK**
Rail	1/2	1/2	5/16	5/16	1/8	1/16
1	1/4	5/16	1/4	1/8	0	0
2	3/8	1/4	3/16	1/8	0	0
3	5/16	5/8	5/16	1/8	0	0
4	5/16	1/4	5/16	1/4	1/8	1/8
5	1/4	1/4	1/4	0	1/8	0
6	5/16	1/4	5/16	0	0	0
7	1/4	5/16	1/4	1/8	1/4	0
8	5/16	3/8	3/8	1/8	1/4	5/16



Appendix E. Vehicle Deformation Records

VEHICLE PRE/POST CRUSH
FLOORPAN - SET 1

TEST: MGSMIN-1
VEHICLE: 2270P

Note: If impact is on driver side need to enter negative number for Y

POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)
1	27 1/2	-28 1/4	-1 1/2	27 1/2	-28 3/4	-1 1/2	0	- 1/2	0
2	29 1/4	-24 1/2	-2 1/4	29 1/4	-24 1/2	-2	0	0	1/4
3	29 1/4	-16	-3 1/4	29	-16	-3	- 1/4	0	1/4
4	27 1/2	-9 1/4	-1 1/2	27 1/4	-9 1/4	-1 1/4	- 1/4	0	1/4
5	25	-29	-5	25	-29	-5	0	0	0
6	25	-24 3/4	-5 1/4	25	-25	-5 1/4	0	- 1/4	0
7	24 3/4	-17	-5 1/2	24 3/4	-17	-5 1/4	0	0	1/4
8	24	-9	-4 1/2	24	-9	-4 1/4	0	0	1/4
9	21 1/4	-29 1/4	-7 1/2	21 1/4	-29 1/2	-7 1/2	0	- 1/4	0
10	21	-25 1/4	-7 1/4	21	-25	-7 1/4	0	1/4	0
11	21 1/4	-17	-7 1/4	21 1/4	-17 1/4	-7	0	- 1/4	1/4
12	21	-10 1/4	-7	21	-10 1/4	-7	0	0	0
13	15	-28 3/4	-8	15	-29	-8	0	- 1/4	0
14	15	-25 1/2	-7 3/4	15	-25 1/2	-7 3/4	0	0	0
15	14 1/2	-18 1/4	-7 3/4	14 3/4	-24 1/4	-7 3/4	1/4	-6	0
16	14 1/2	-12	-7 1/2	14 1/2	-12	-7 1/2	0	0	0
17	13 1/2	-4 3/4	- 1/4	13 1/4	-5 3/4	- 1/2	- 1/4	-1	- 1/4
18	9 1/4	-28 3/4	-7 3/4	9 1/4	-28 3/4	-7 3/4	0	0	0
19	9 1/2	-23	-7 3/4	9 1/2	-22 3/4	-7 1/2	0	1/4	1/4
20	9 1/2	-17 1/2	-7 1/2	9 1/2	-17 1/4	-7 1/2	0	1/4	0
21	9 1/2	-11 1/2	-7 1/2	9 1/2	-11 1/4	-7 1/2	0	1/4	0
22	8	-7 3/4	-1 1/4	8	-7 3/4	-1 1/2	0	0	- 1/4
23	1/2	-27 1/2	-3 1/2	1/2	-27 1/2	-3 1/2	0	0	0
24	1/4	-23	-3 1/2	1/4	-23	-3 1/2	0	0	0
25	1/4	-17	-3 1/2	1/4	-17	-3 1/2	0	0	0
26	1	-7 1/2	- 3/4	1	-7 1/4	-1	0	1/4	- 1/4
27							0	0	0
28							0	0	0
29							0	0	0
30							0	0	0
31							0	0	0

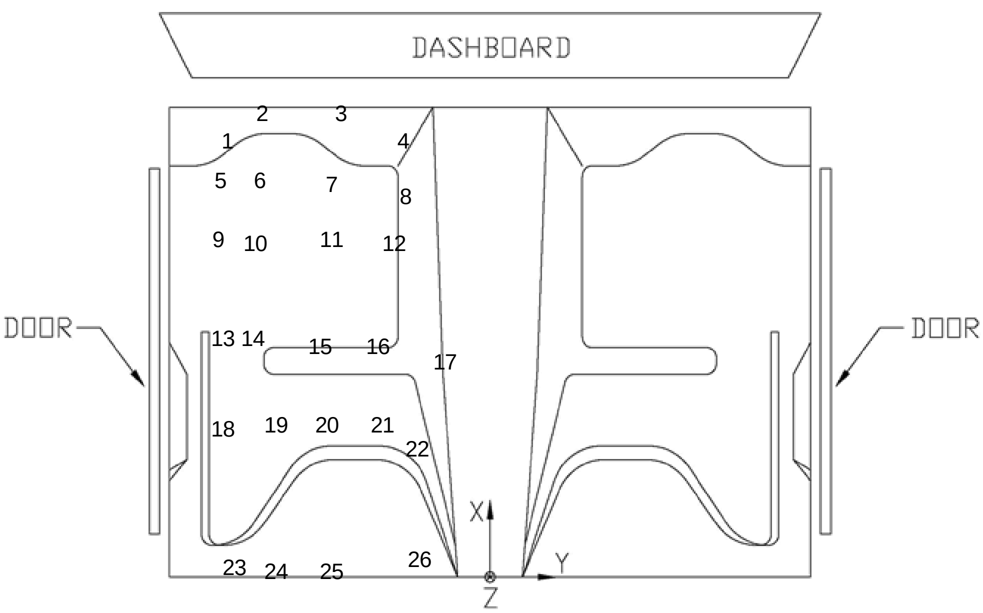


Figure E-1. Floor Pan Deformation Data – Set 1, Test No. MGSMIN-1

VEHICLE PRE/POST CRUSH
FLOORPAN - SET 2

TEST: MGSMIN-1
VEHICLE: 2270P

Note: If impact is on driver side need to enter negative number for Y

POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)
1	50	-24 3/4	- 1/4	49 3/4	-24 1/2	- 1/2	- 1/4	1/4	- 1/4
2	51 3/4	-20 1/4	-1 1/4	51 1/2	-20 1/2	-1 1/4	- 1/4	- 1/4	0
3	51 3/4	-12 1/4	-2 1/2	51 1/2	-12 1/4	-2 1/4	- 1/4	0	1/4
4	49 3/4	-5 1/4	-1 1/4	49 1/2	-5 1/4	-1	- 1/4	0	1/4
5	47 3/4	-25	-4 1/4	47 3/4	-24 3/4	-4	0	1/4	1/4
6	47 3/4	-21	-4 1/2	47 1/2	-20 3/4	-4 1/4	- 1/4	1/4	1/4
7	47 1/2	-13	-4 3/4	47 1/4	-13	-4 3/4	- 1/4	0	0
8	46 1/2	-5 1/4	-4 1/4	46 1/4	-5 1/2	-4 1/4	- 1/4	- 1/4	0
9	44	-25 1/4	-6 1/2	43 3/4	-25 1/2	-6 1/2	- 1/4	- 1/4	0
10	44	-21	-6 1/2	43 3/4	-21 1/4	-6 1/2	- 1/4	- 1/4	0
11	44	-13	-6 3/4	44	-13 1/4	-6 3/4	0	- 1/4	0
12	43 3/4	-5 3/4	-6 3/4	43 3/4	-6 1/4	-6 3/4	0	- 1/2	0
13	37 3/4	-24 3/4	-7	37 3/4	-24 3/4	-7	0	0	0
14	37 1/2	-21 1/2	-7	37 1/2	-21 1/2	-7	0	0	0
15	37 1/4	-14 1/2	-7 1/2	37 1/4	-14 1/4	-7 1/4	0	1/4	1/4
16	37	-7 3/4	-7 1/2	37	-7 3/4	-7 1/2	0	0	0
17	35 3/4	-1 3/4	- 3/4	35 3/4	-1 3/4	- 1/2	0	0	1/4
18	31 1/4	-24 1/2	-7	31 1/4	-24 1/2	-7	0	0	0
19	31 1/4	-18 1/2	-7 1/4	31	-18 1/2	-7 1/4	- 1/4	0	0
20	31 1/2	-13	-7 1/2	31 1/4	-13	-7 1/4	- 1/4	0	1/4
21	31 1/2	-6 3/4	-7 1/2	31 1/2	-6 3/4	-7 1/2	0	0	0
22	30 1/4	-3 3/4	-1 1/2	30 1/4	-3 3/4	-1 1/2	0	0	0
23	23	-23 1/2	-3	23	-23 1/2	-3	0	0	0
24	23	-19	-3 1/4	23	-19 1/4	-3 1/4	0	- 1/4	0
25	23	-13	-3 1/2	23	-13 1/2	-3 1/2	0	- 1/2	0
26	23 1/4	-3 1/4	-1 1/4	23 1/4	-3 1/4	-1 1/4	0	0	0
27							0	0	0
28							0	0	0
29							0	0	0
30							0	0	0
31							0	0	0

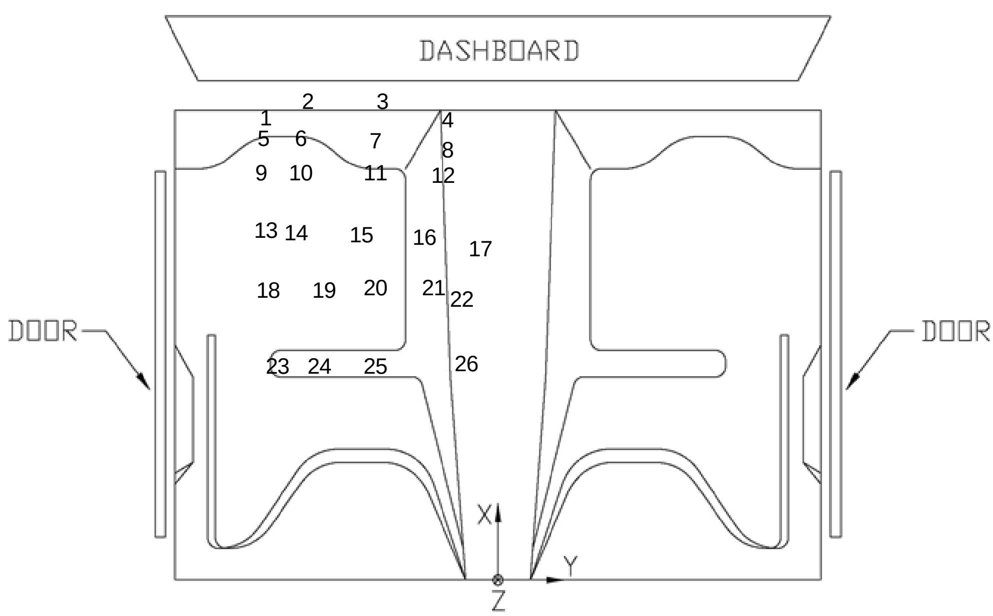


Figure E-2. Floor Pan Deformation Data – Set 2, Test No. MGSMIN-1

VEHICLE PRE/POST CRUSH
INTERIOR CRUSH - SET 1

TEST: MGSMIN-1
VEHICLE: 2270P

Note: If impact is on driver side need to enter negative number for Y

	POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)
DASH	A1	43 1/4	-58 1/2	24 3/4	43 1/4	-58 1/2	24 1/2	0	0	- 1/4
	A2	43 3/4	-43 1/4	26 3/4	44	-43 1/4	26 1/2	1/4	0	- 1/4
	A3	44	-32 1/4	26 1/2	44	-32 1/4	26 1/2	0	0	0
	A4	40	-61 1/2	19 1/2	40	-61 1/4	19 1/2	0	1/4	0
	A5	37 1/2	-44	15 1/4	37 1/2	-44	15	0	0	- 1/4
	A6	35 1/4	-37	12 1/2	35 1/4	-37	12 1/4	0	0	- 1/4
SIDE PANEL	B1	21 1/2	-24 1/2	2	21 1/4	-24 1/2	2	- 1/4	0	0
	B2	24 1/4	-24 3/4	1 3/4	24 1/4	-24 3/4	1 3/4	0	0	0
	B3	21 1/2	-24 1/4	-1 1/2	21 1/2	-24 1/4	-1 1/2	0	0	0
IMPACT SIDE DOOR	C1	8 1/2	-34 1/4	19	8 1/4	-34 1/4	18 3/4	- 1/4	0	- 1/4
	C2	18 3/4	-32 1/2	18 1/4	18 1/2	-32 1/2	18	- 1/4	0	- 1/4
	C3	29	-33 1/4	18 1/4	29	-33	18	0	1/4	- 1/4
	C4	7	-27 1/4	4	6 1/2	-27 1/4	4	- 1/2	0	0
	C5	17 1/2	-26	4 1/4	17 1/4	-26	4 1/4	- 1/4	0	0
	C6	27 1/4	-26 1/2	2 3/4	27	-26 1/2	2 1/2	- 1/4	0	- 1/4
ROOF	D1							0	0	0
	D2							0	0	0
	D3							0	0	0
	D4							0	0	0
	D5							0	0	0
	D6							0	0	0
	D7							0	0	0
	D8							0	0	0
	D9							0	0	0
	D10							0	0	0
	D11							0	0	0
	D12							0	0	0
	D13							0	0	0
	D14							0	0	0
	D15							0	0	0

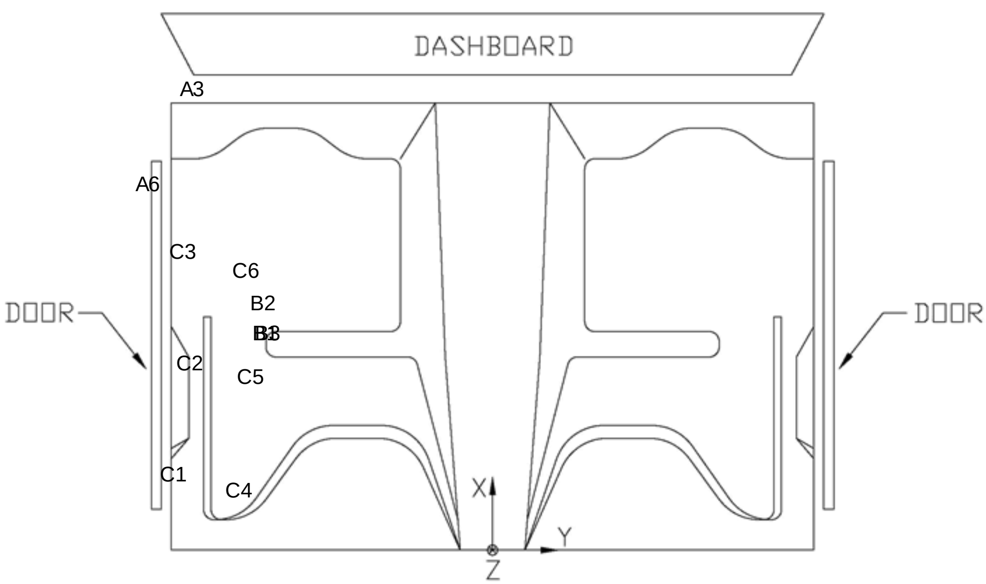


Figure E-3. Occupant Compartment Deformation Data – Set 1, Test No. MGSMIN-1

VEHICLE PRE/POST CRUSH
INTERIOR CRUSH - SET 2

TEST: MGSMIN-1
VEHICLE: 2270P

Note: If impact is on driver side need to enter negative number for Y

	POINT	X (in.)	Y (in.)	Z (in.)	X' (in.)	Y' (in.)	Z' (in.)	ΔX (in.)	ΔY (in.)	ΔZ (in.)
DASH	A1	54 1/4	-58 1/4	25 1/2	54 1/4	-58 1/4	25 1/2	0	0	0
	A2	52 1/2	-42 3/4	26 3/4	52 1/2	-42 3/4	26 3/4	0	0	0
	A3	50 1/4	-32	26	50 1/4	-32	26	0	0	0
	A4	51 3/4	-61 1/4	20 1/4	51 1/2	-61 1/4	20 1/4	- 1/4	0	0
	A5	47 1/2	-44	15 1/4	47 1/2	-44	15 1/4	0	0	0
	A6	42 1/2	-37 3/4	11 3/4	42 1/2	-37 1/2	12	0	1/4	1/4
SIDE PANEL	B1	37 1/4	-24 3/4	3 1/4	37 1/4	-25	3	0	- 1/4	- 1/4
	B2	40 1/2	-25 3/4	2 3/4	40 1/2	-25 3/4	2 3/4	0	0	0
	B3	37 3/4	-24 3/4	- 1/2	37 3/4	-25	- 1/2	0	- 1/4	0
IMPACT SIDE DOOR	C1	11 1/2	-36	19 1/2	11 1/4	-36 1/4	19 1/2	- 1/4	- 1/4	0
	C2	22	-35 3/4	19	21 3/4	-35 3/4	19	- 1/4	0	0
	C3	32 1/4	-35 3/4	19 1/4	32 1/4	-35 1/2	19 1/4	0	1/4	0
	C4	11 1/4	-30 3/4	4 1/2	11	-31	4 1/2	- 1/4	- 1/4	0
	C5	22 1/4	-30 3/4	5 1/4	22	-30 3/4	5 1/4	- 1/4	0	0
	C6	32 1/4	-30 1/4	3 3/4	32	-30 1/4	3 3/4	- 1/4	0	0
ROOF	D1							0	0	0
	D2							0	0	0
	D3							0	0	0
	D4							0	0	0
	D5							0	0	0
	D6							0	0	0
	D7							0	0	0
	D8							0	0	0
	D9							0	0	0
	D10							0	0	0
	D11							0	0	0
	D12							0	0	0
	D13							0	0	0
	D14							0	0	0
	D15							0	0	0

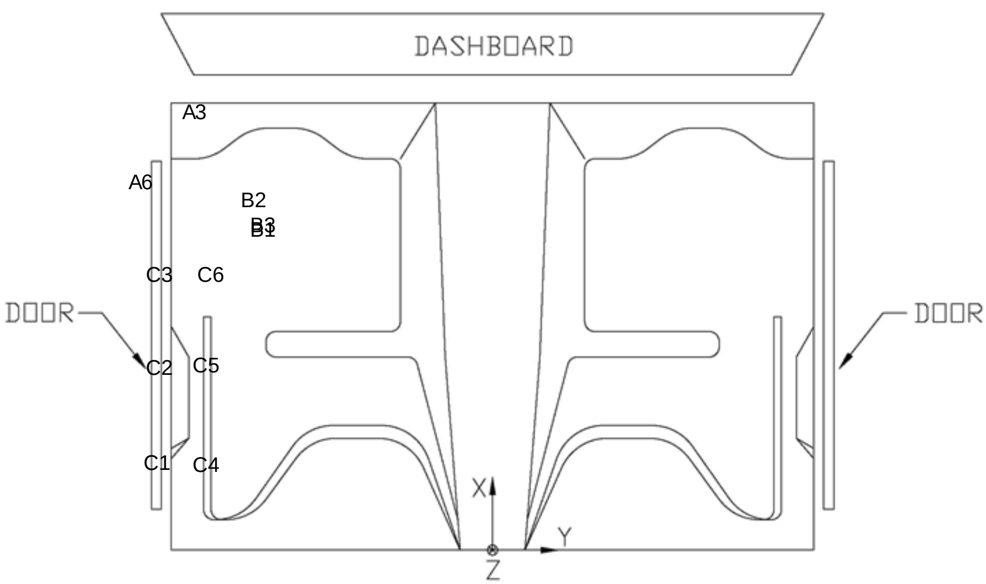
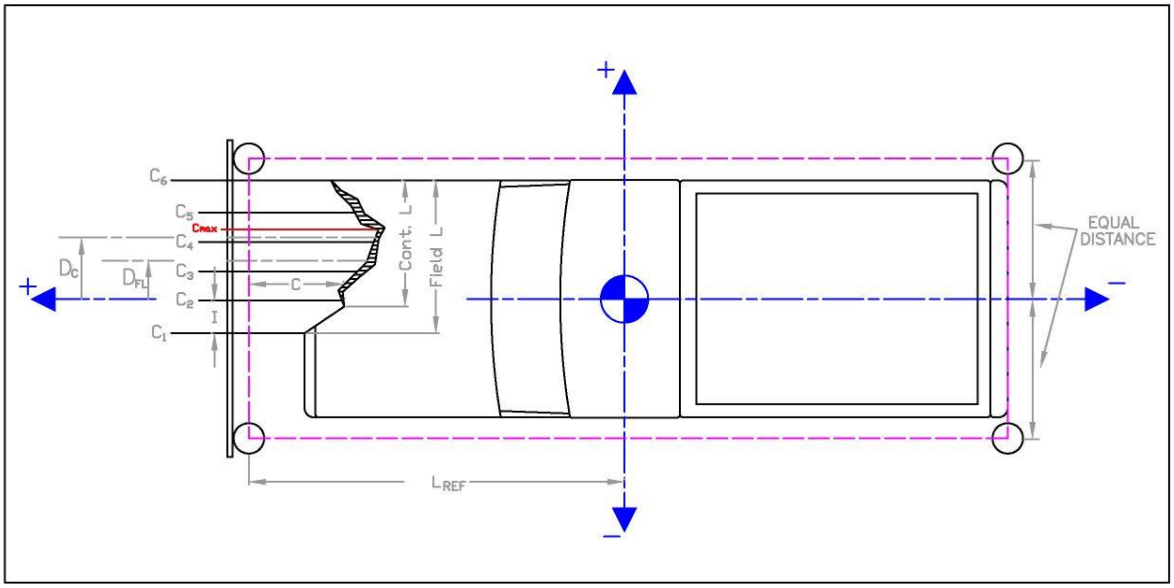


Figure E-4. Occupant Compartment Deformation Data – Set 2, Test No. MGSMIN-1

Date: 7/6/2012 **Test Number:** MGSMIN-1

Make: Dodge Ram **Model:** 2270P **Year:** 2005



	in.	(mm)
Distance from C.G. to reference line - L_{REF}:	110 1/2	(2807)
Width of contact and induced crush - Field L:	26	(660)
Crush measurement spacing interval (L/5) - I:	5.2	(132)
Distance from center of vehicle to center of Field L - D_{FL}:	-26.125	-(664)
Width of Contact Damage:	21	(533)
Distance from center of vehicle to center of contect damage - D_C:	28 5/8	(727)

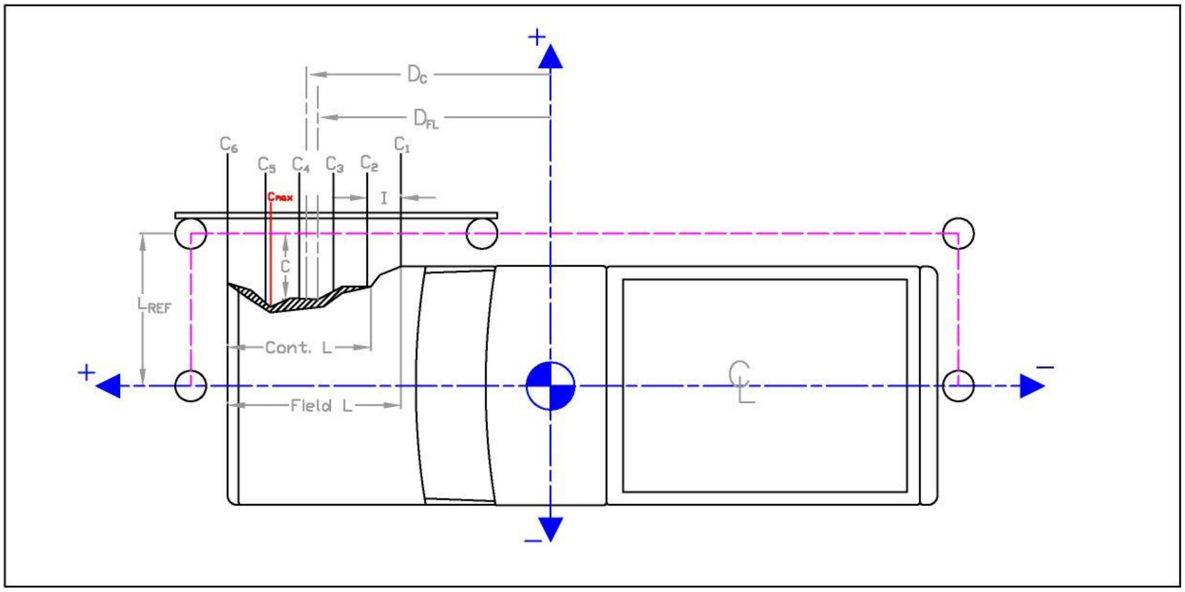
NOTE: Enter "NA" for crush measurement if distance can not be measured (i.e., side of vehicle has been pushed inward)

	Crush Measurement		Lateral Location		Original Profile Measurement		Dist. Between Ref. Lines		Actual	Crush
	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)
C_1	NA	NA	-39 1/8	-(994)	29	(737)	-2 1/8	-(54)	NA	NA
C_2	NA	NA	-34	-(862)	19 1/4	(489)			NA	NA
C_3	25 1/2	(648)	-28 5/7	-(730)	15 4/7	(396)			12	(306)
C_4	16 3/4	(425)	-23 1/2	-(598)	13 5/9	(344)			5 1/3	(135)
C_5	13	(330)	-18 1/3	-(465)	12 2/9	(310)			3	(74)
C_6	10 1/2	(267)	-13 1/8	-(333)	11 1/4	(285)			1 2/5	(35)
C_{MAX}	25 1/2	(648)	-28 5/7	-(729)	15 4/7	(396)			12	(306)

Figure E-5. Exterior Vehicle Crush (NASS) - Front, Test No. MGSMIN-1

Date: 7/6/2012 **Test Number:** MGSMIN-1

Make: Dodge Ram **Model:** 2270P **Year:** 2005



		in.	(mm)
Distance from centerline to reference line - L_{REF}:		45	(1143)
Width of contact and induced crush - Field L:		227 3/4	(5785)
Crush measurement spacing interval (L/5) - I:		45.55	(1157)
Distance from vehicle c.g. to center of Field L - D_{FL}:		-11	-(279)
Width of Contact Damage:		227 3/4	(5785)
Distance from vehicle c.g. to center of contect damage - D_C:		11	(279)

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

	Crush Measurement		Longitudinal Location		Original Profile Measurement		Dist. Between Ref. Lines		Actual	Crush
	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)	in.	(mm)
C_1	NA	NA	-124 7/8	-(3172)	16	(406)	-5	-(127)	NA	NA
C_2	8 1/4	(210)	-79 1/3	-(2015)	10 1/2	(267)			2 3/4	(70)
C_3	6 1/2	(165)	-33 7/9	-(858)	11 5/8	(295)			- 1/8	-(3)
C_4	6 1/4	(159)	11 7/9	(299)	11 1/4	(286)			0	()
C_5	NA	NA	57 1/3	(1456)	10 1/2	(267)			NA	NA
C_6	NA	NA	102 7/8	(2613)	35 1/4	(895)			NA	NA
C_{MAX}	20	(508)	94	(2388)	15 3/4	(400)			9 1/4	(235)

Figure E-6. Exterior Vehicle Crush (NASS) - Side, Test No. MGSMIN-1

Appendix F. Accelerometer and Rate Transducer Data Plots, Test No. MGSMIN-1

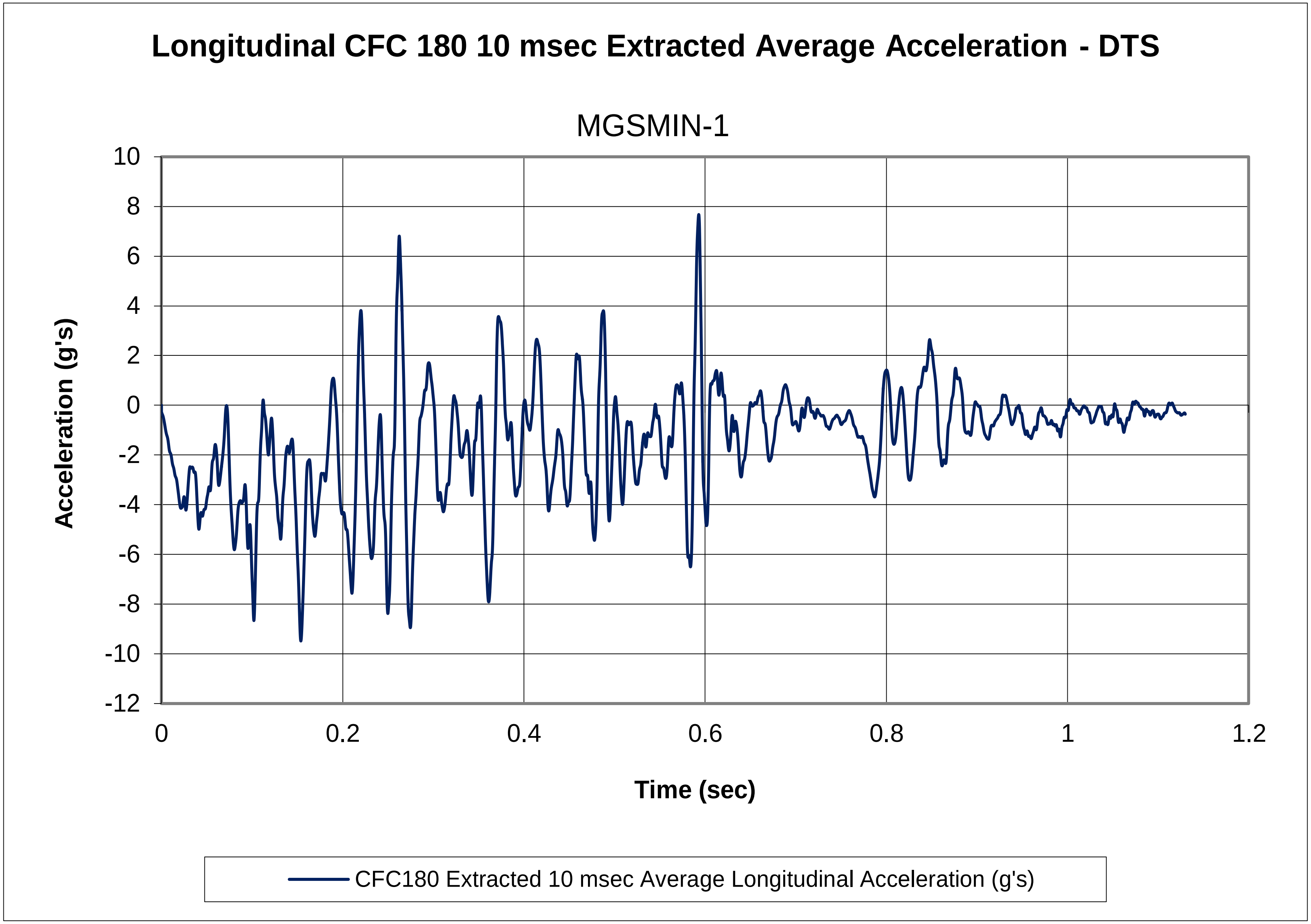


Figure F-1. 10-ms Average Longitudinal Deceleration (DTS), Test No. MGSMIN-1

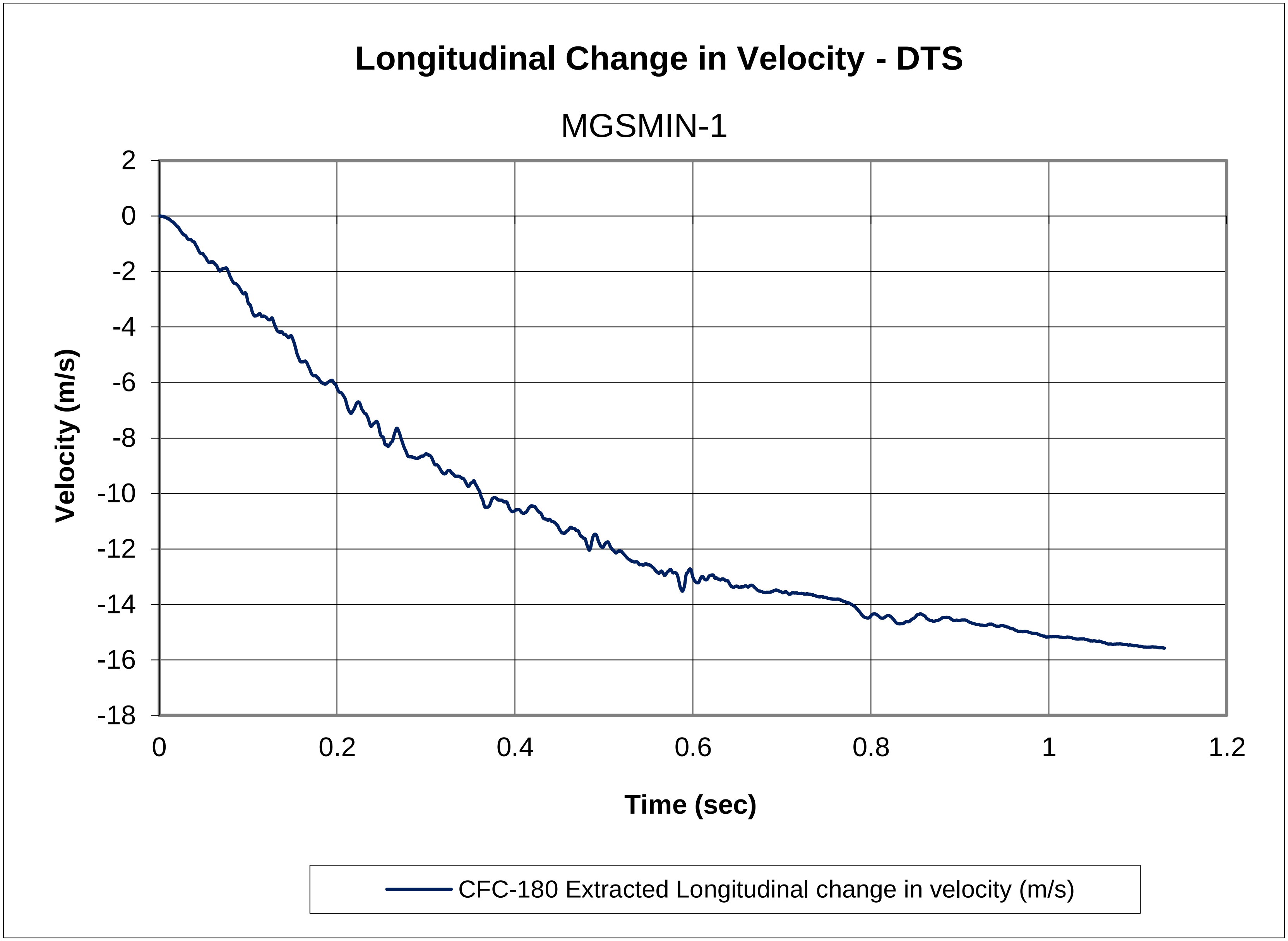


Figure F-2. Longitudinal Change in Velocity (DTS), Test No. MGSMIN-1

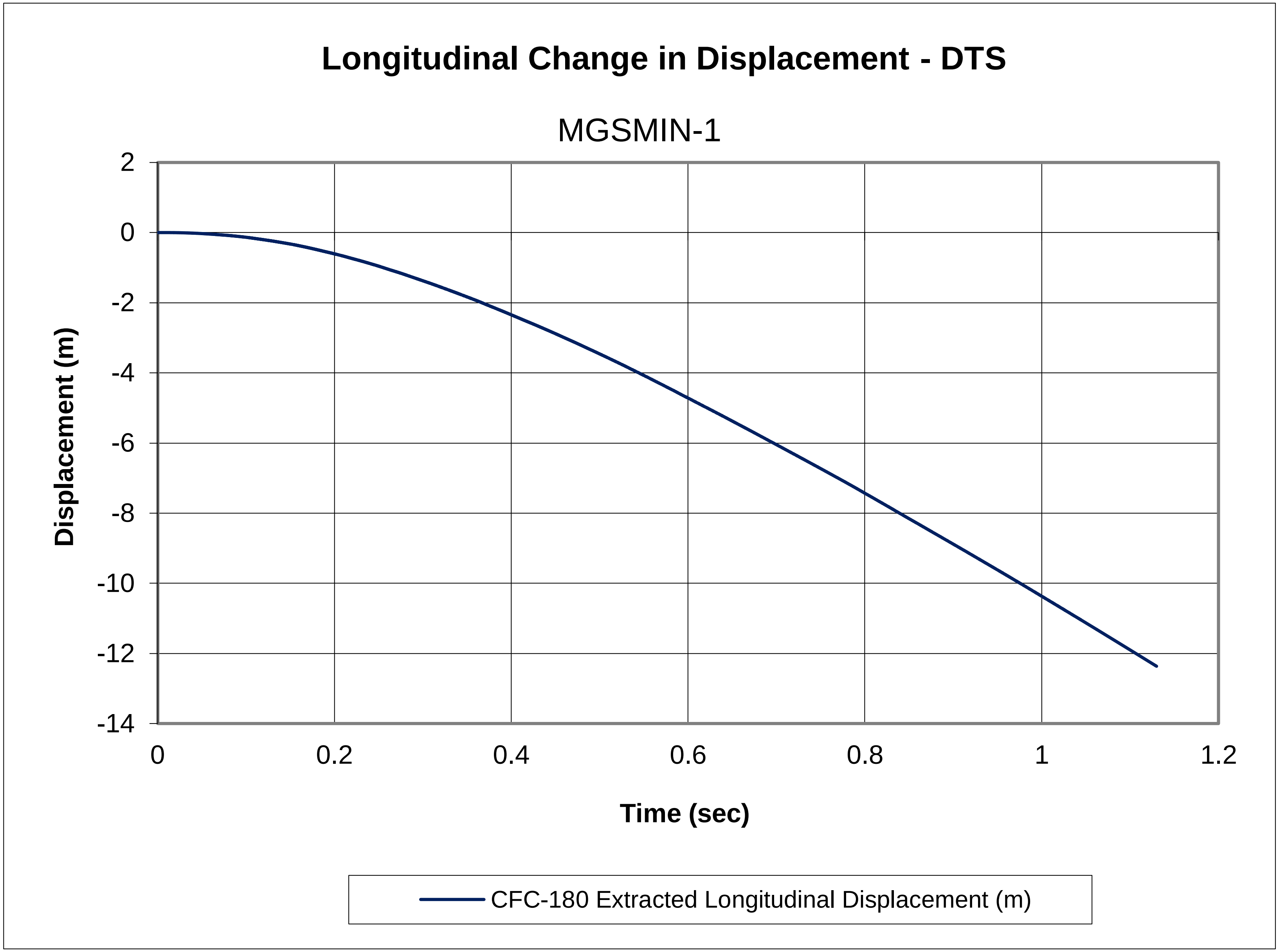


Figure F-3. Longitudinal Occupant Displacement (DTS), Test No. MGSMIN-1

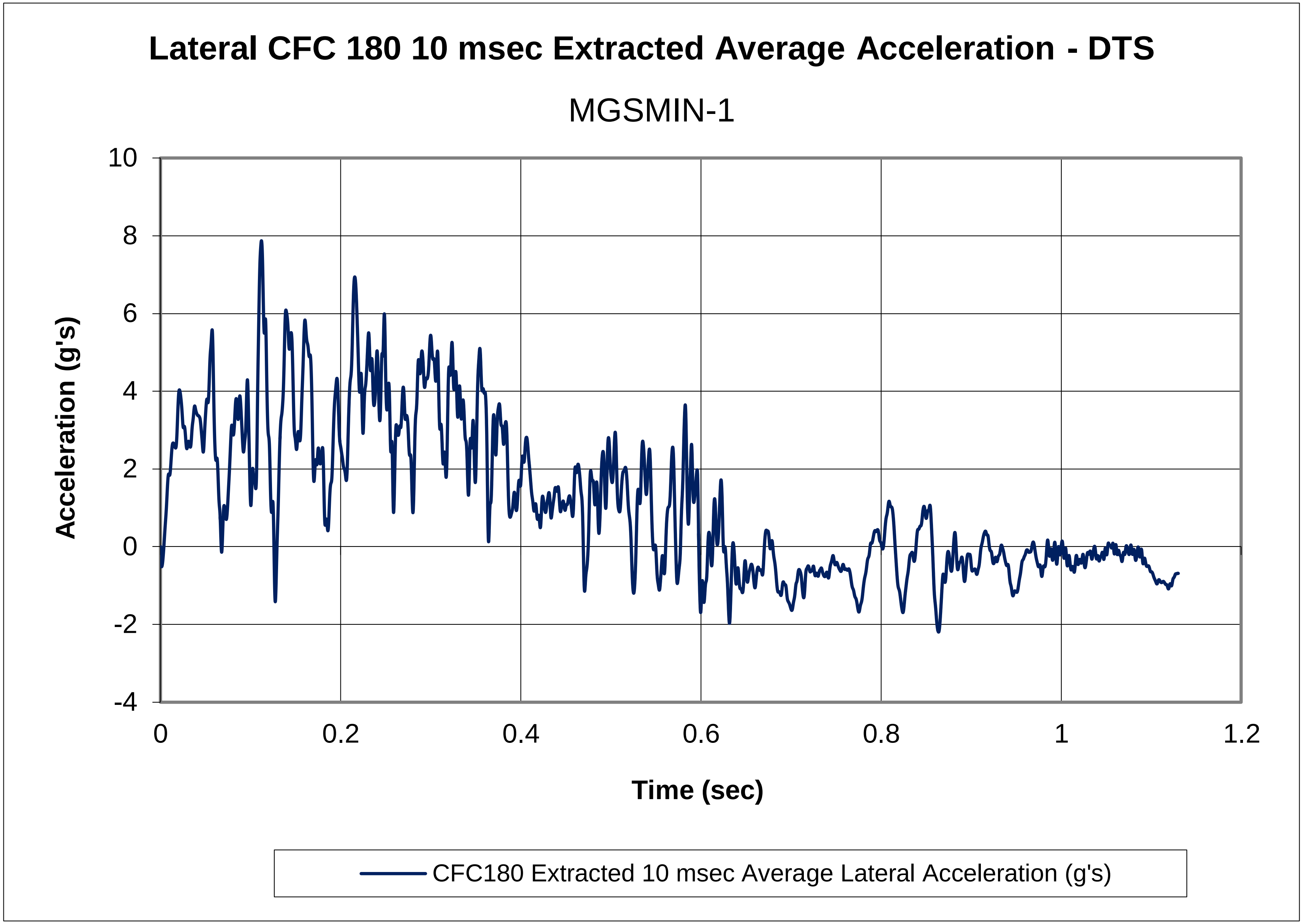


Figure F-4. 10-ms Average Lateral Deceleration (DTS), Test No. MGSMIN-1

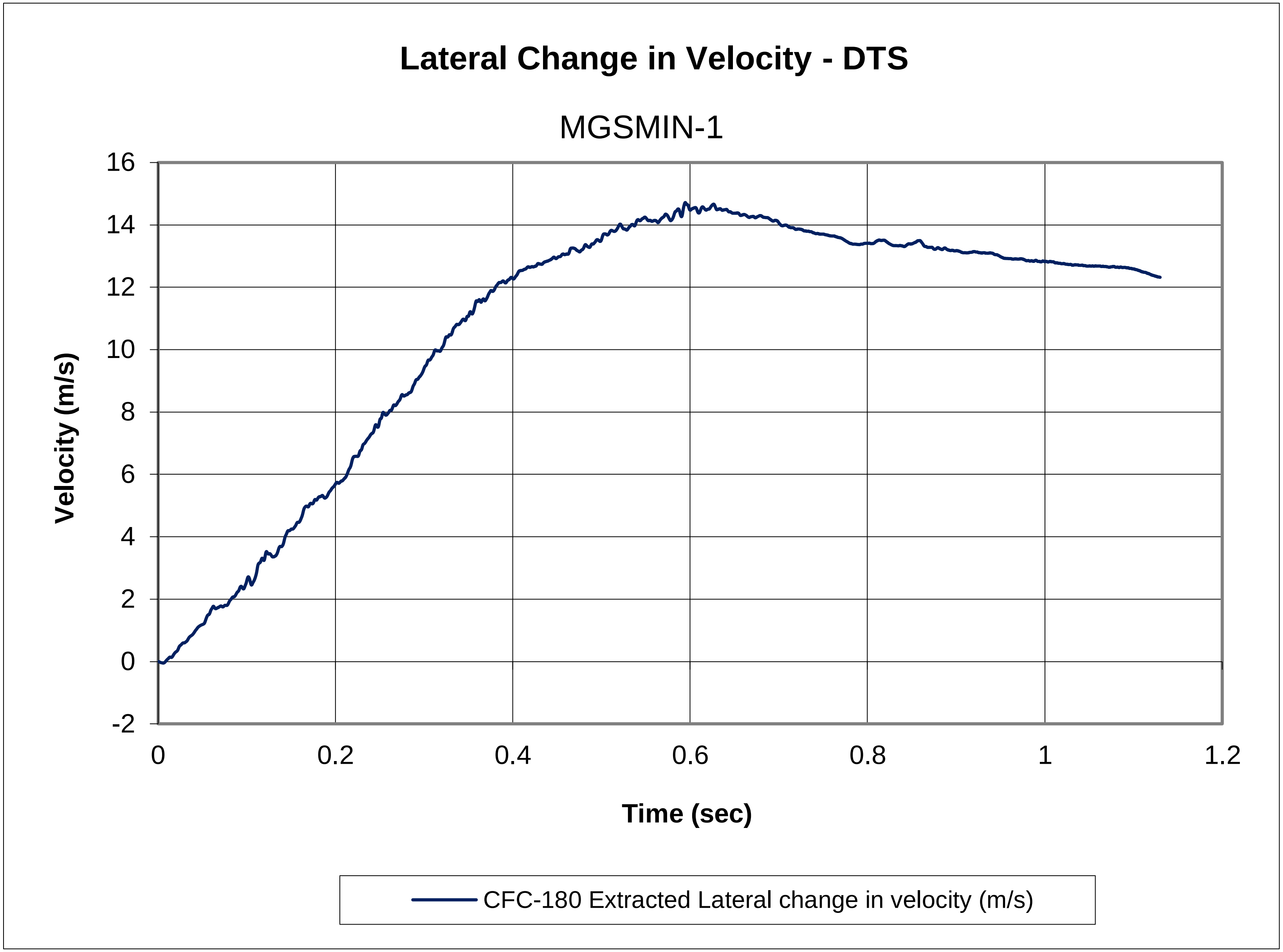


Figure F-5. Lateral Change in Velocity (DTS), Test No. MGSMIN-1

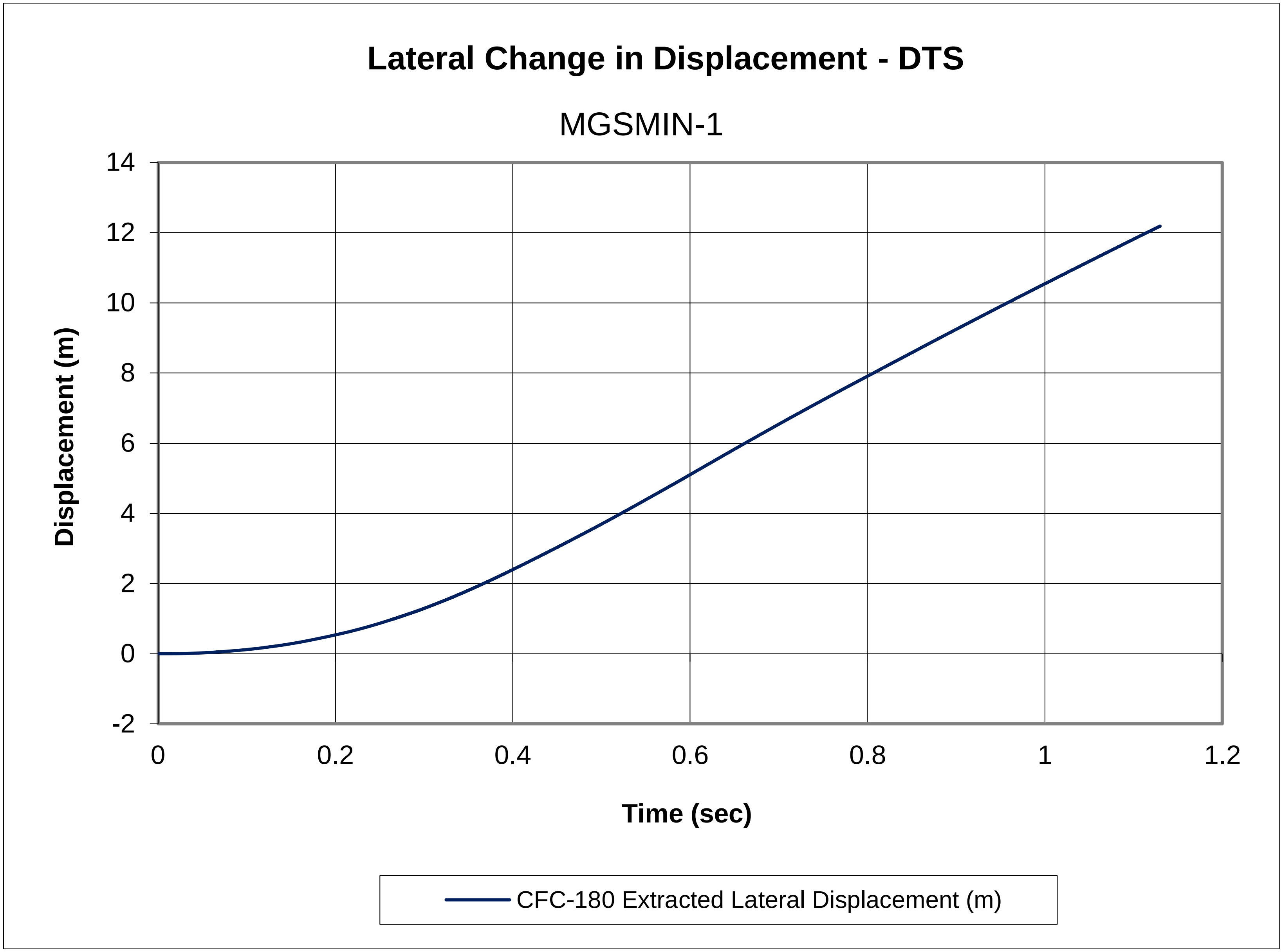


Figure F-6. Lateral Occupant Displacement (DTS), Test No. MGSMIN-1

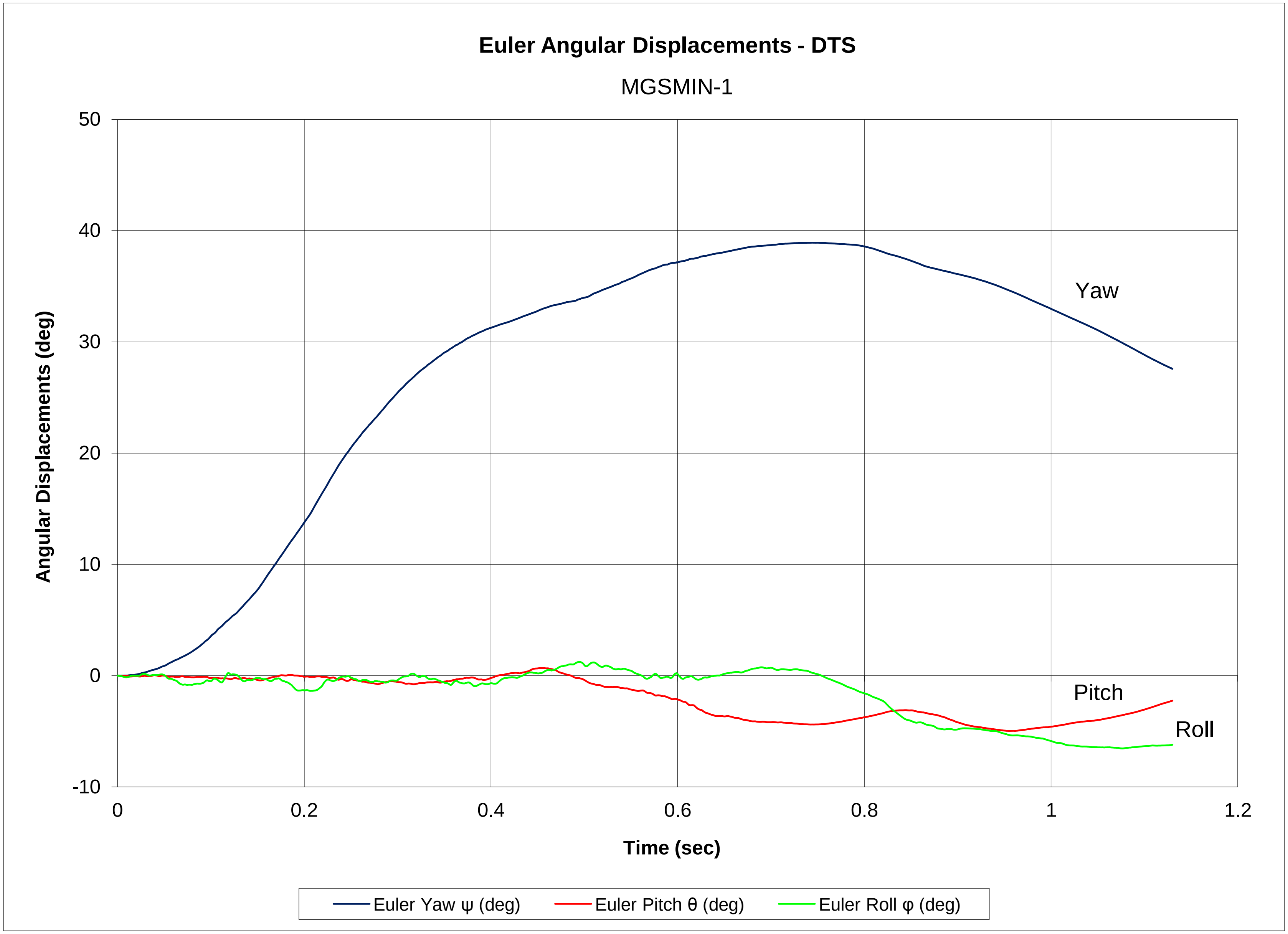


Figure F-7. Vehicle Angular Displacements (DTS), Test No. MGSMIN-1

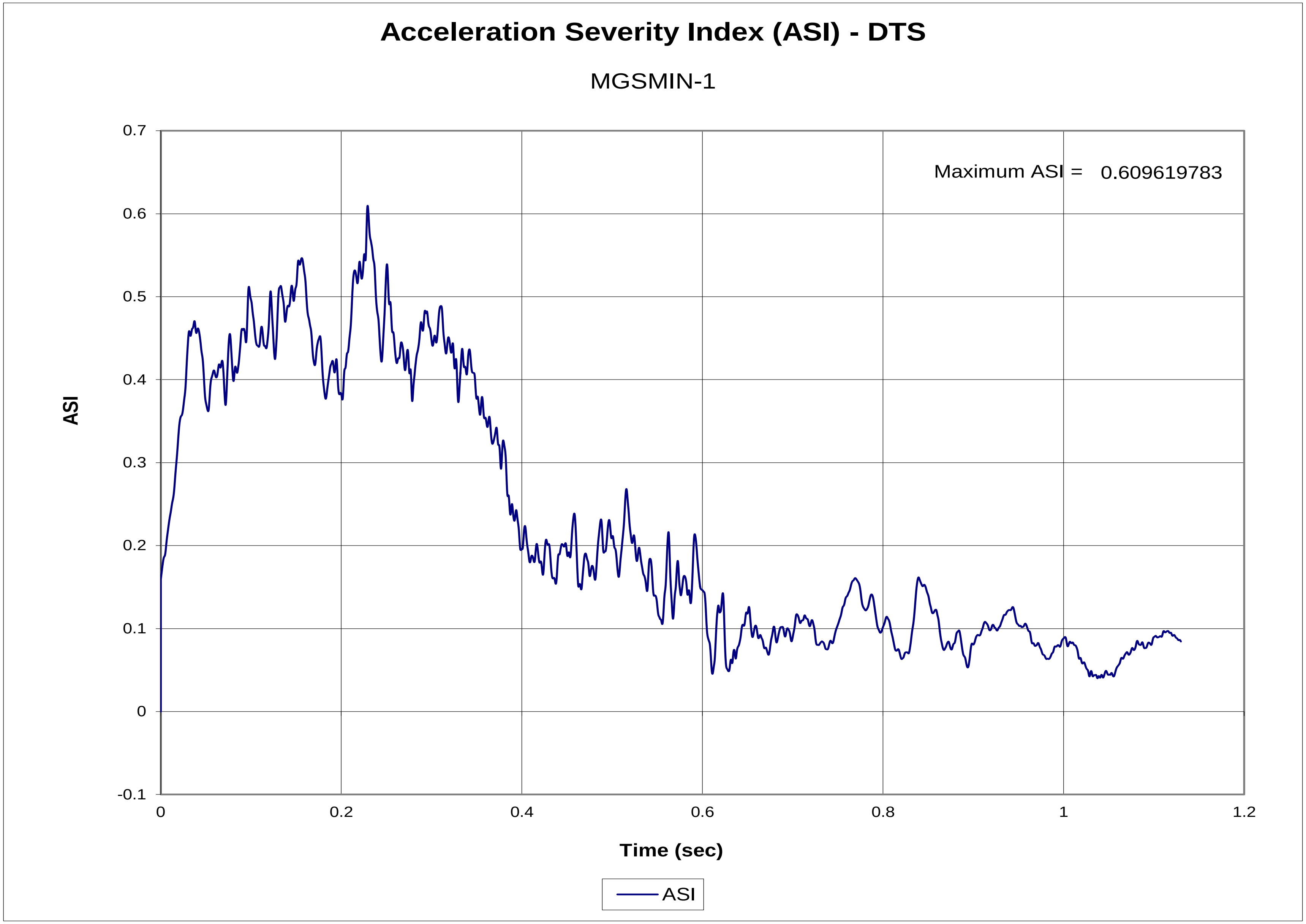


Figure F-8. Acceleration Severity Index (DTS), Test No. MGSMIN-1

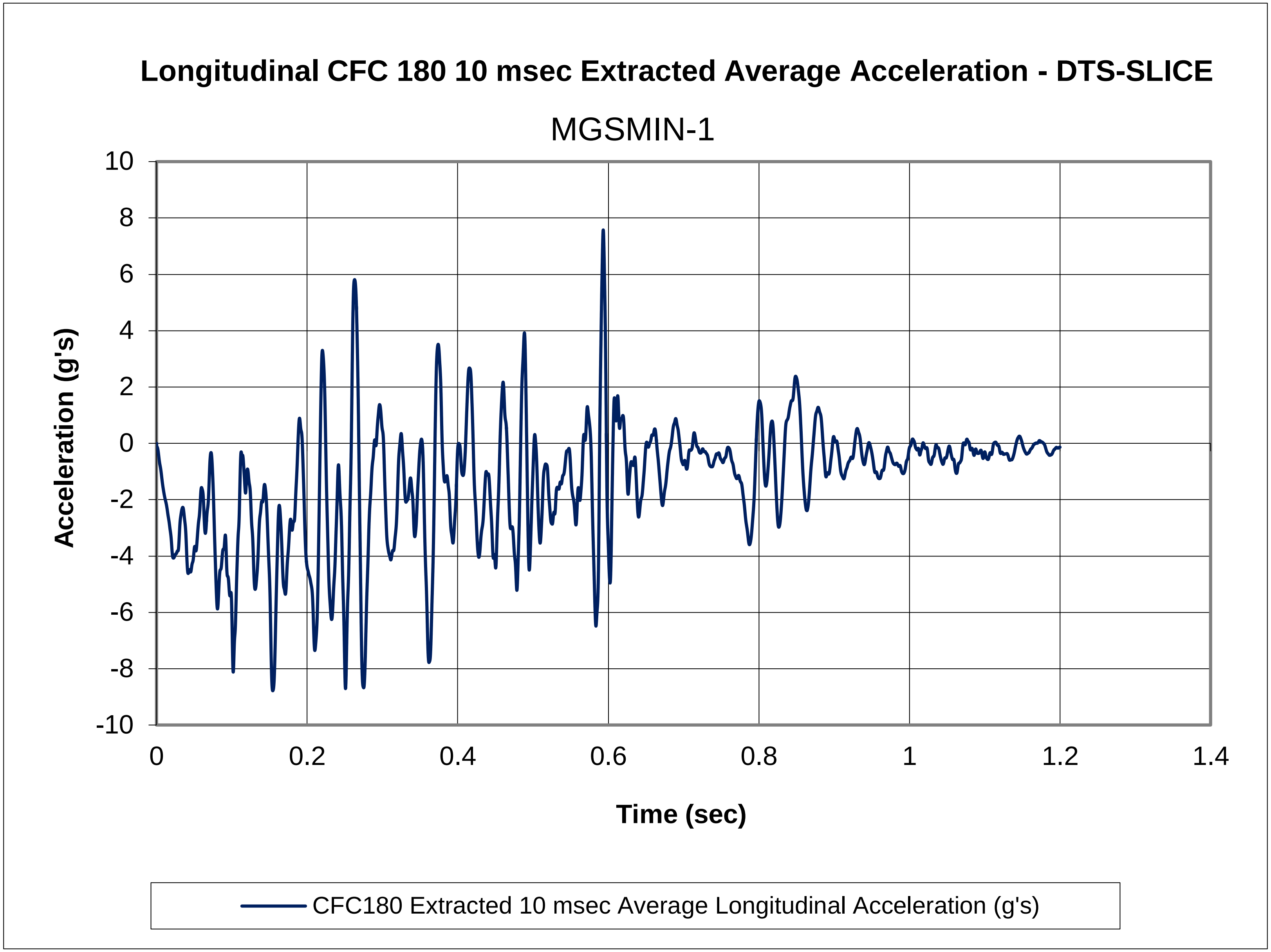


Figure F-9. 10-ms Average Longitudinal Deceleration (DTS-SLICE), Test No. MGSMIN-1

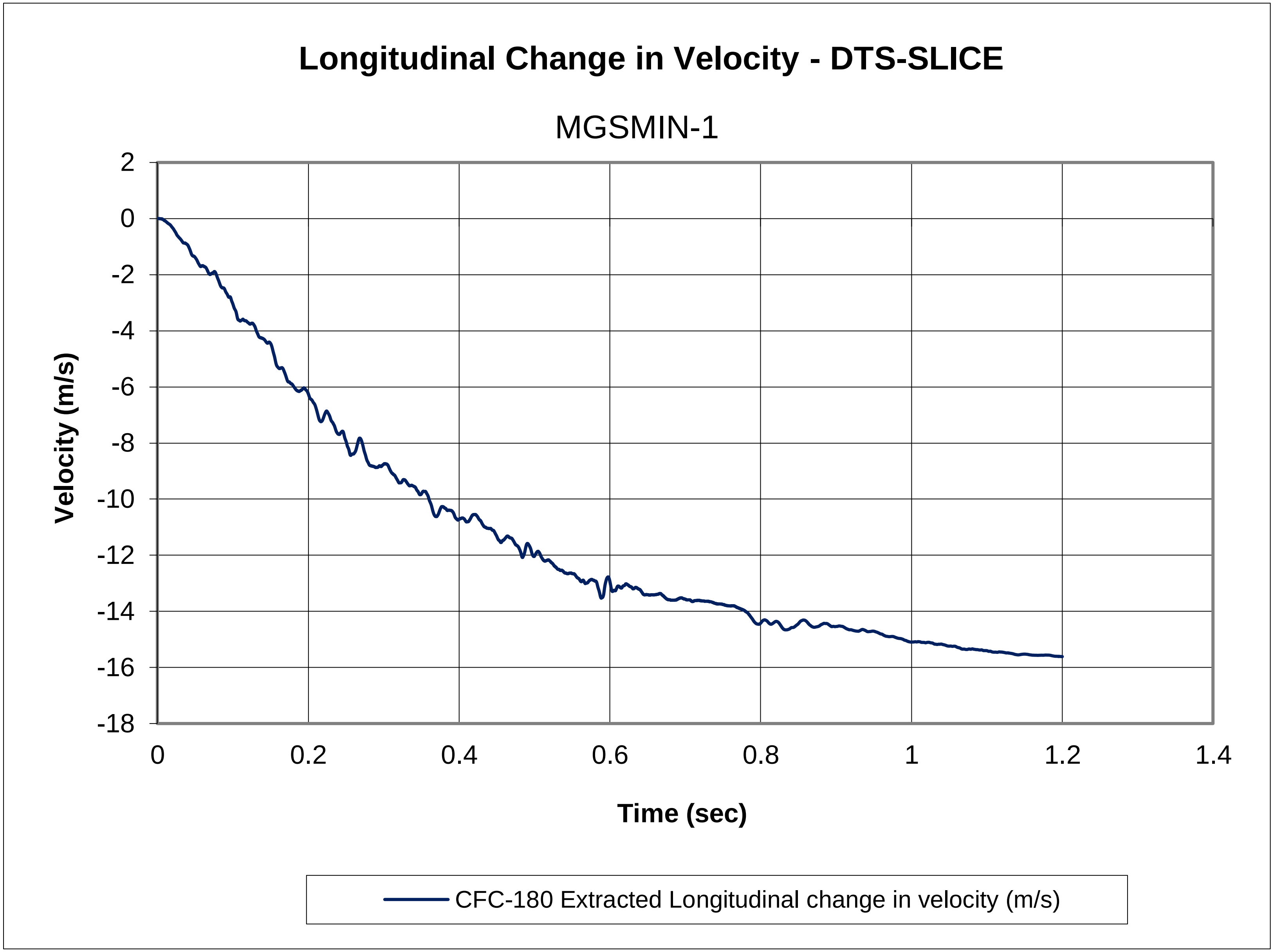


Figure F-10. Longitudinal Change in Velocity (DTS-SLICE), Test No. MGSMIN-1

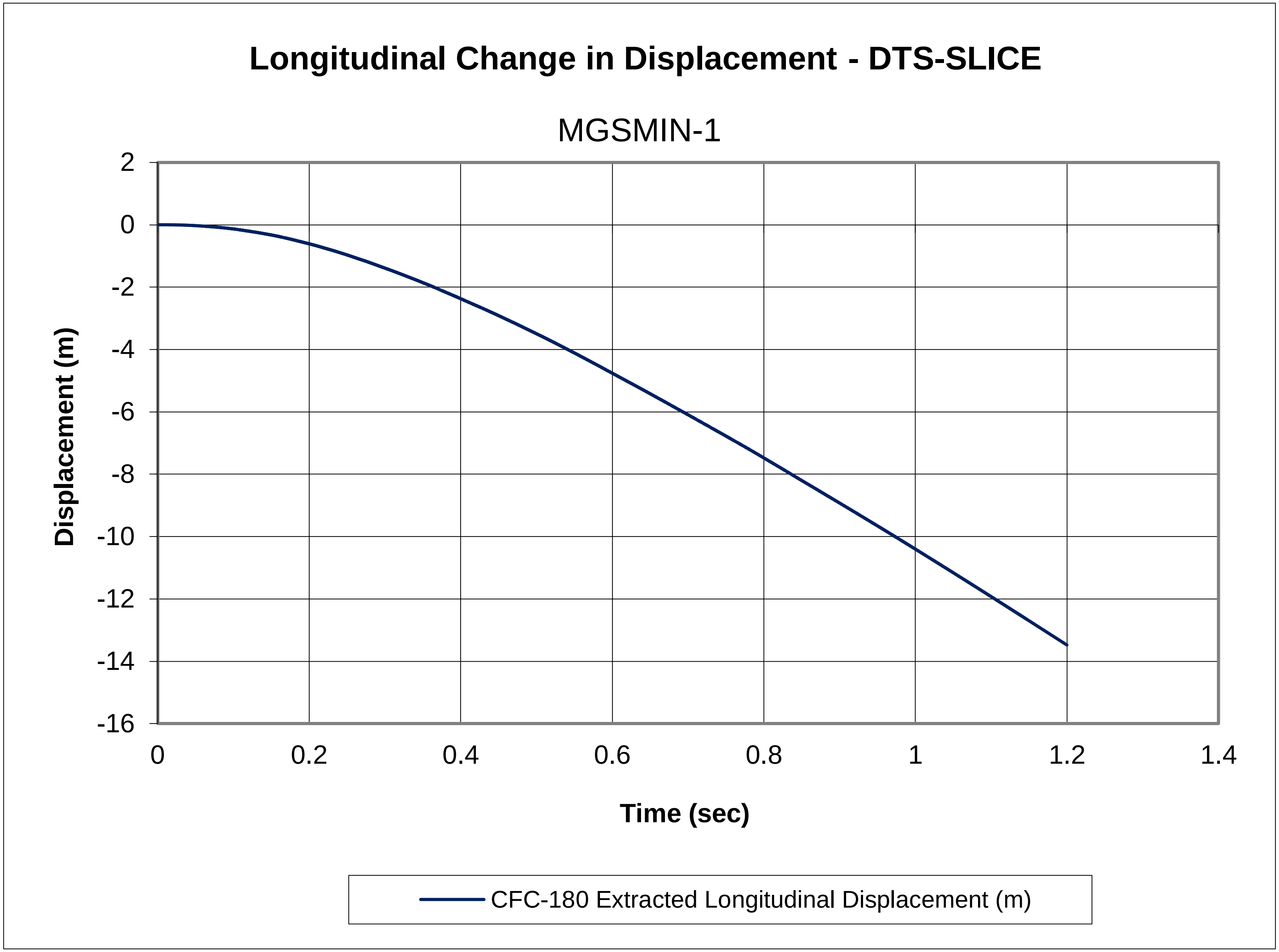


Figure F-11. Longitudinal Occupant Displacement (DTS-SLICE), Test No. MGSMIN-1

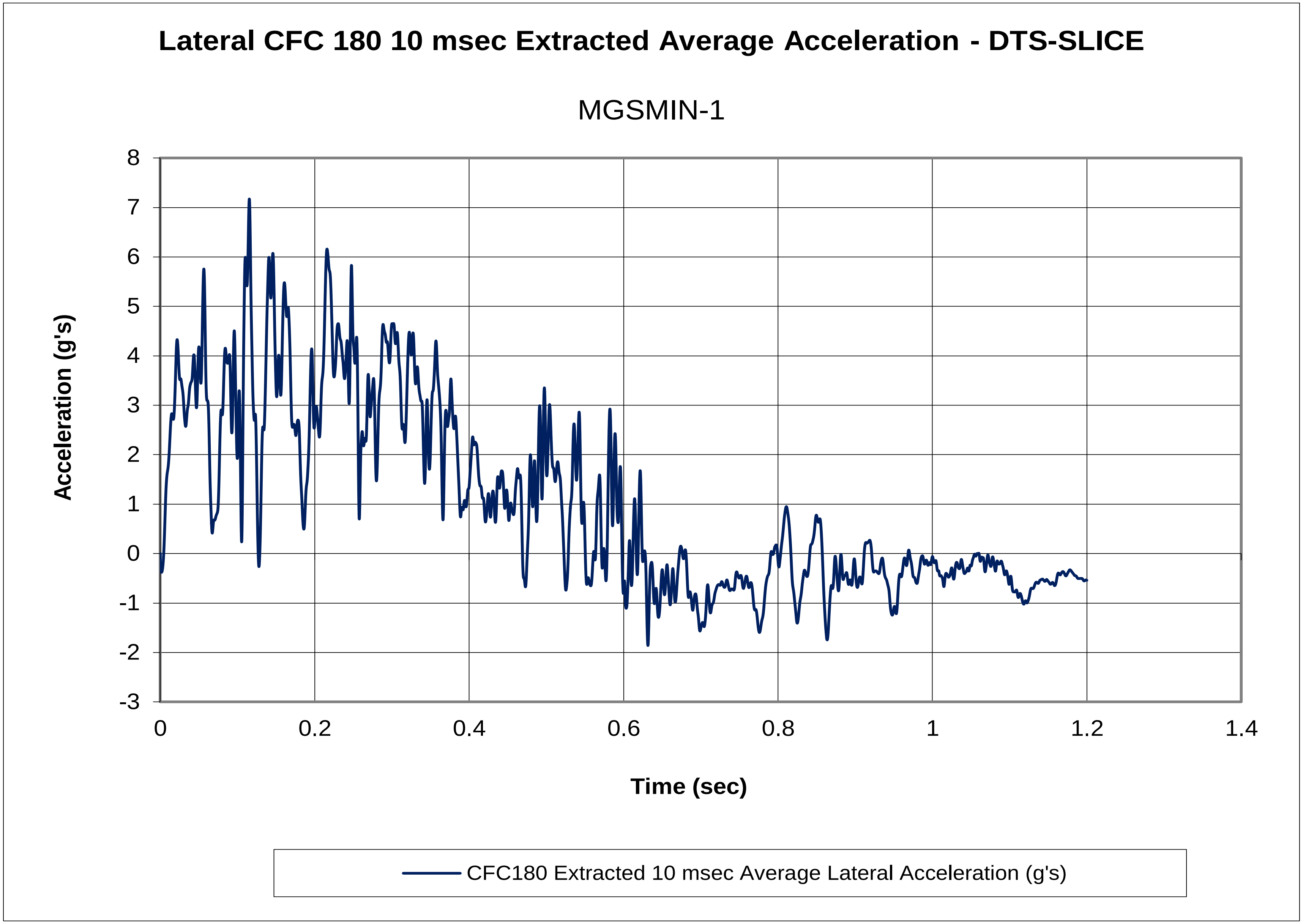


Figure F-12. 10-ms Average Lateral Deceleration (DTS-SLICE), Test No. MGSMIN-1

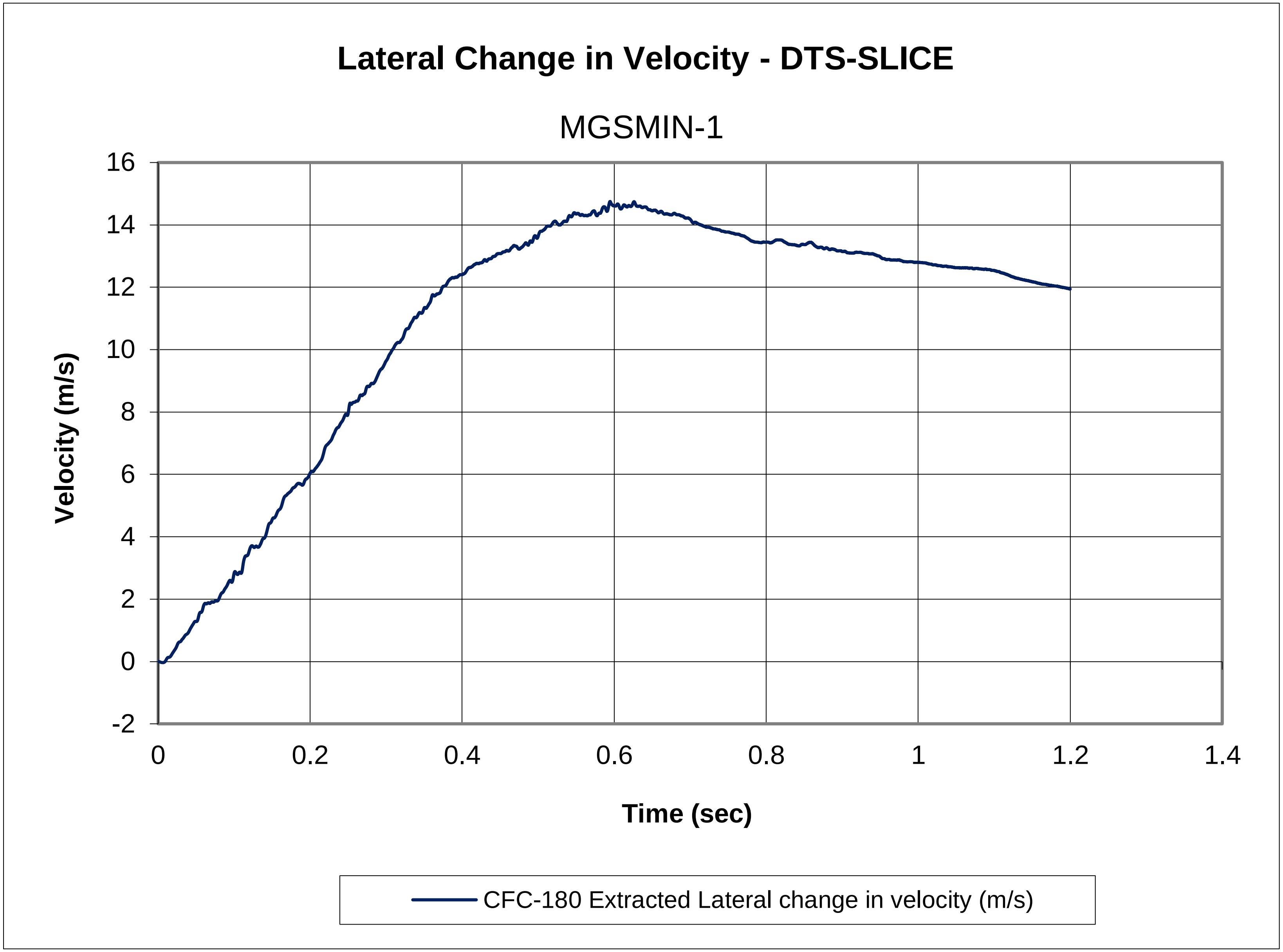


Figure F-13. Lateral Change in Velocity (DTS-SLICE), Test No. MGSMIN-1

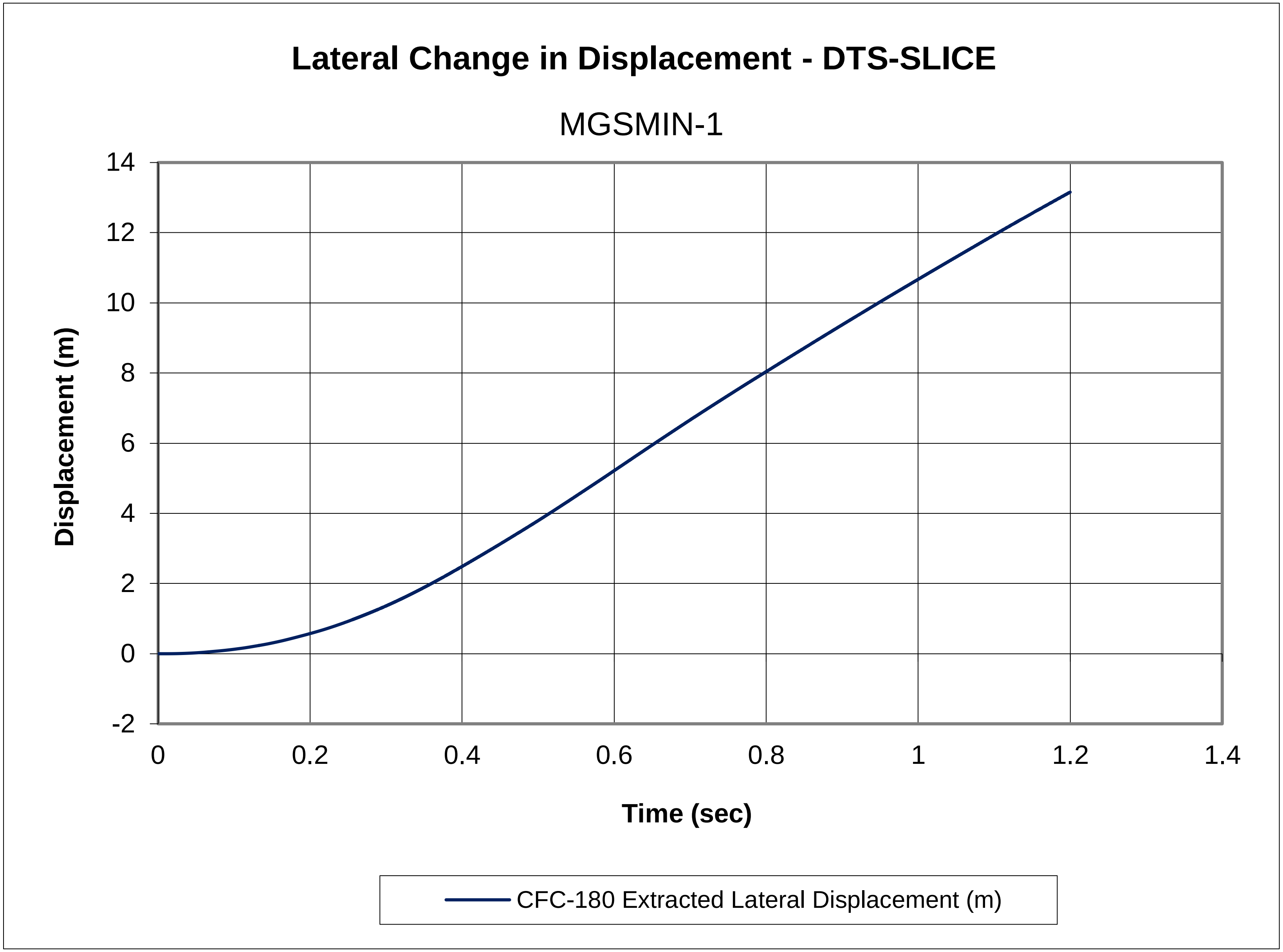


Figure F-14. Lateral Occupant Displacement (DTS-SLICE), Test No. MGSMIN-1

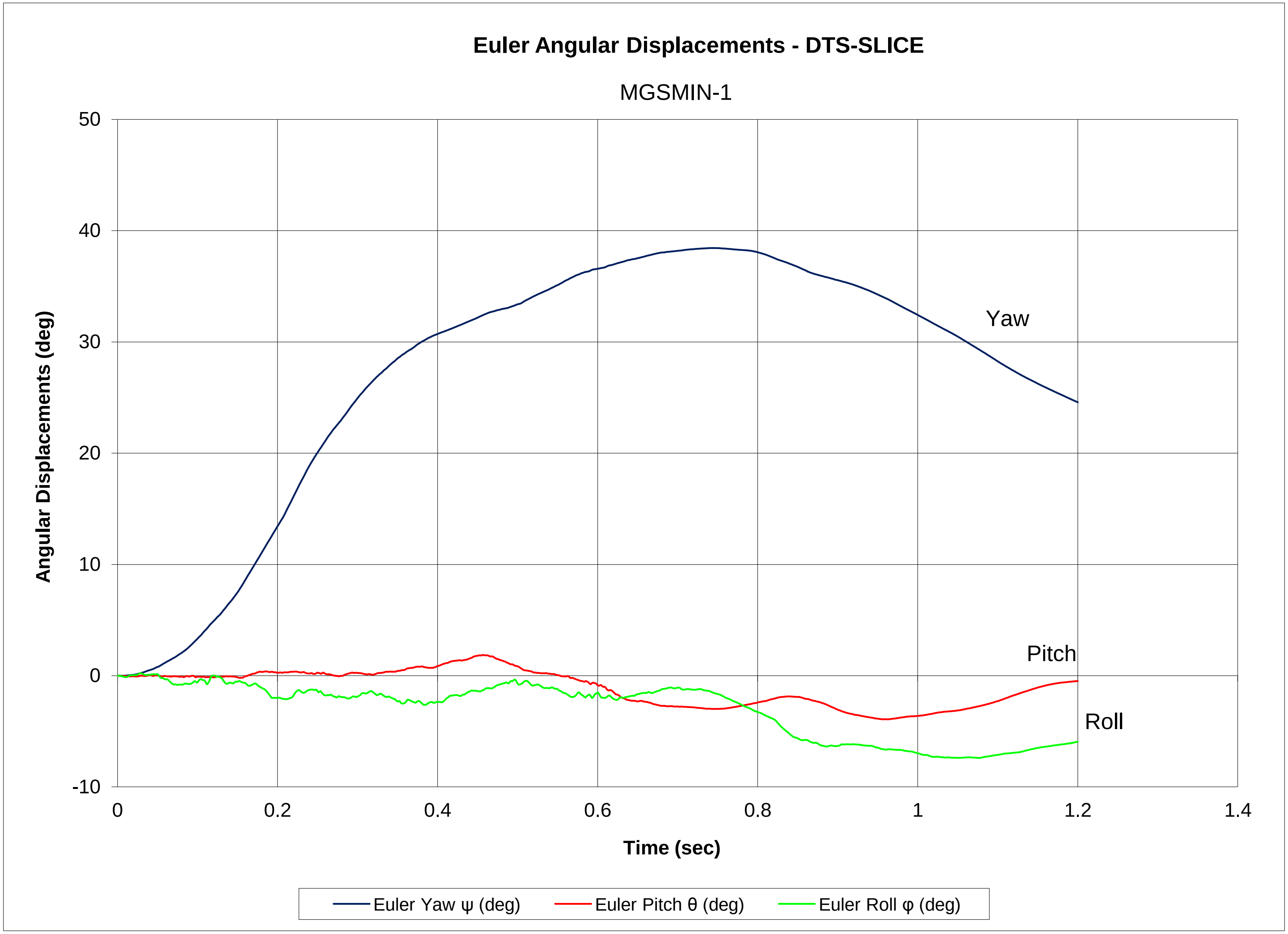


Figure F-15. Vehicle Angular Displacements (DTS-SLICE), Test No. MGSMIN-1

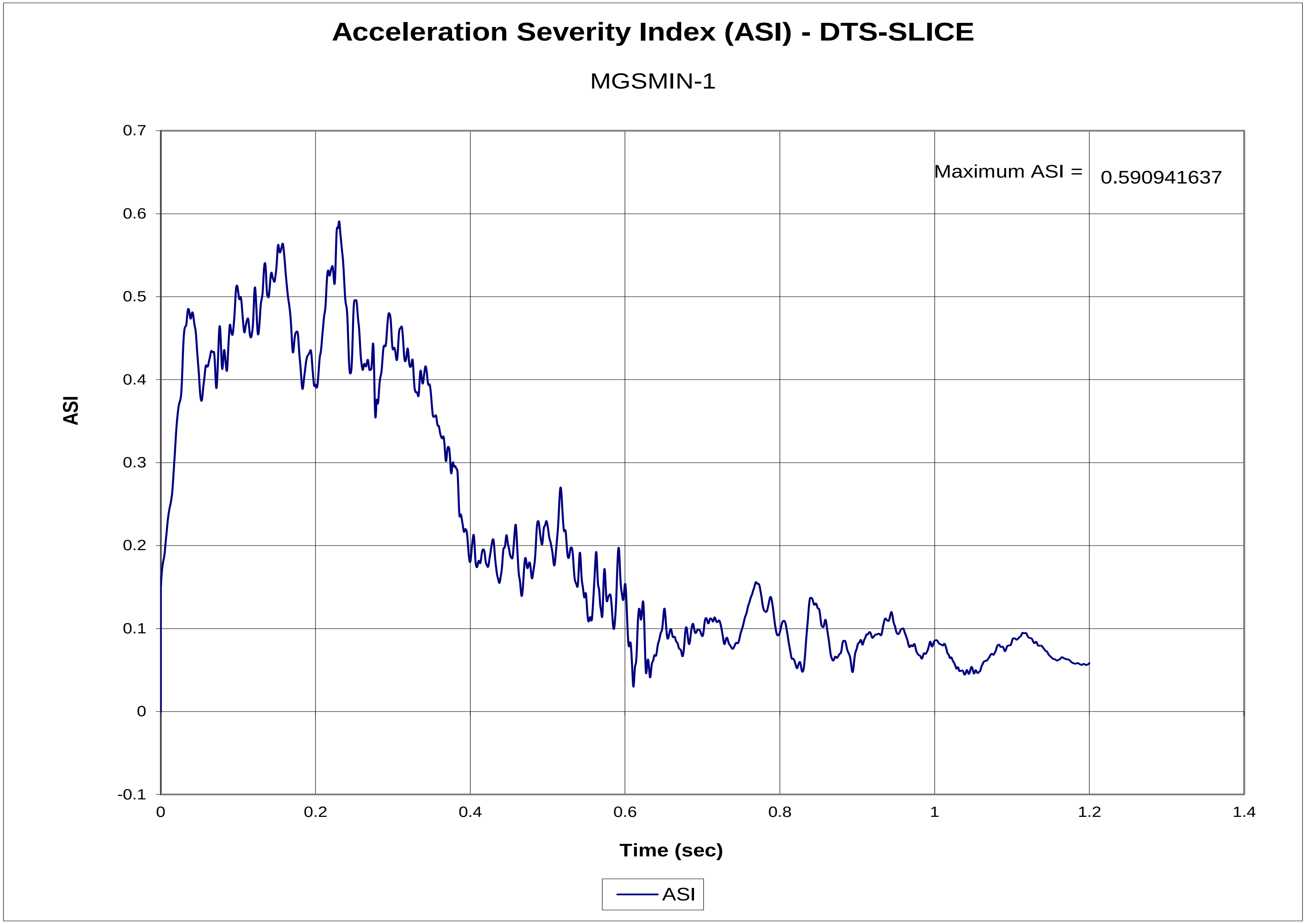


Figure F-16. Acceleration Severity Index (DTS-SLICE), Test No. MGSMIN-1

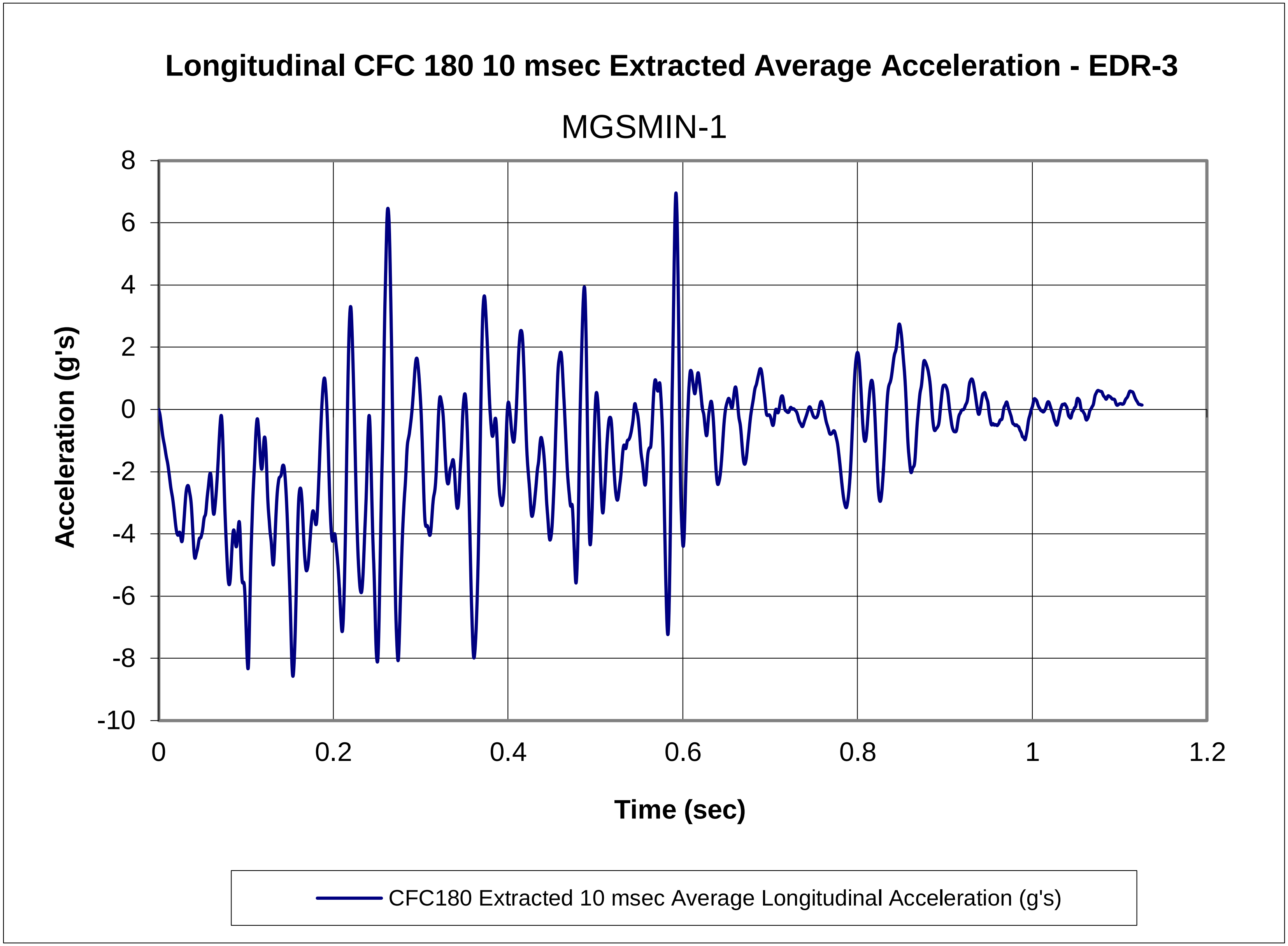


Figure F-17. 10-ms Average Longitudinal Deceleration (EDR-3), Test No. MGSMIN-1

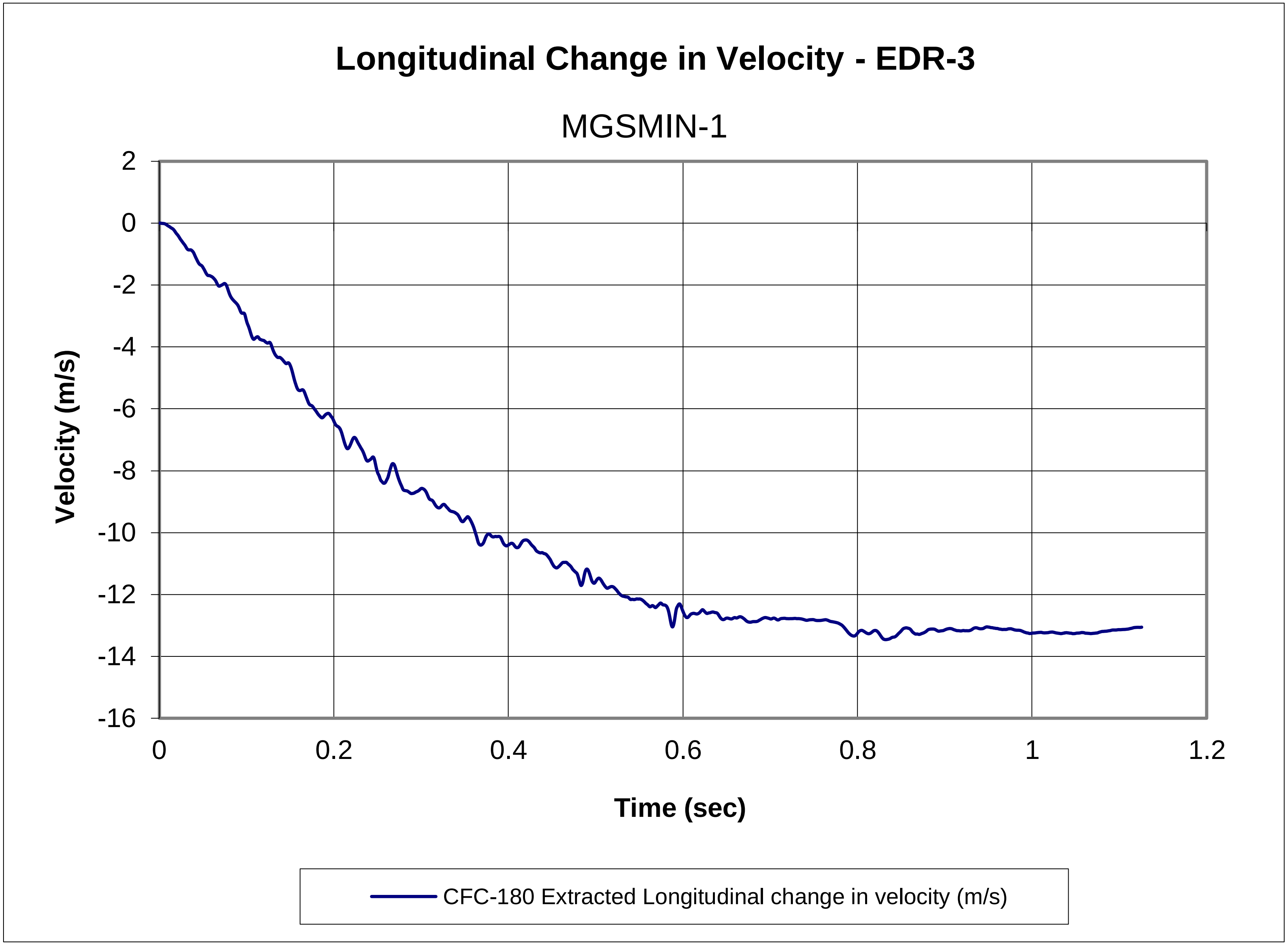


Figure F-18. Longitudinal Change in Velocity (EDR-3), Test No. MGSMIN-1

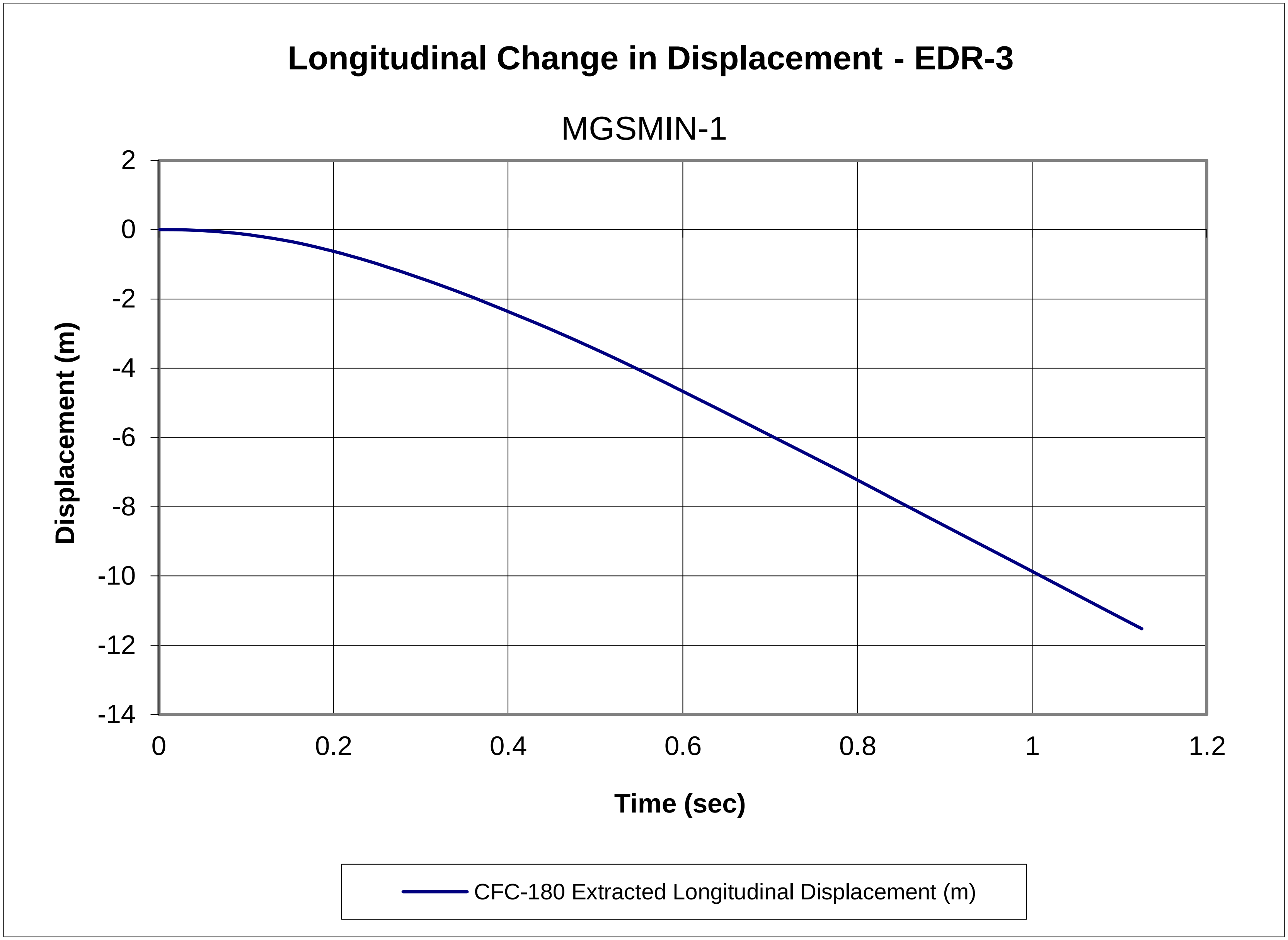


Figure F-19. Longitudinal Occupant Displacement (EDR-3), Test No. MGSMIN-1

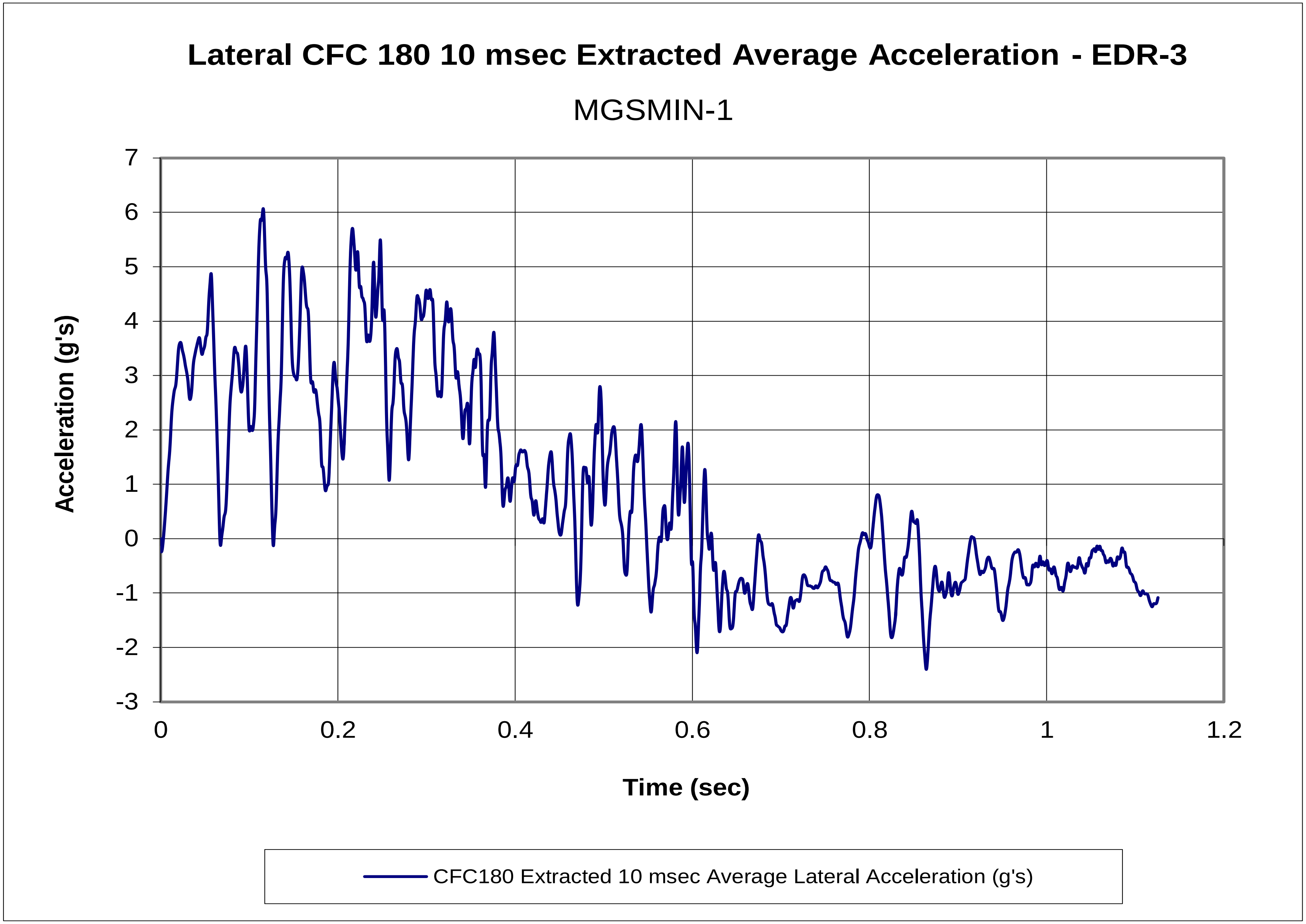


Figure F-20. 10-ms Average Lateral Deceleration (EDR-3), Test No. MGSMIN-1

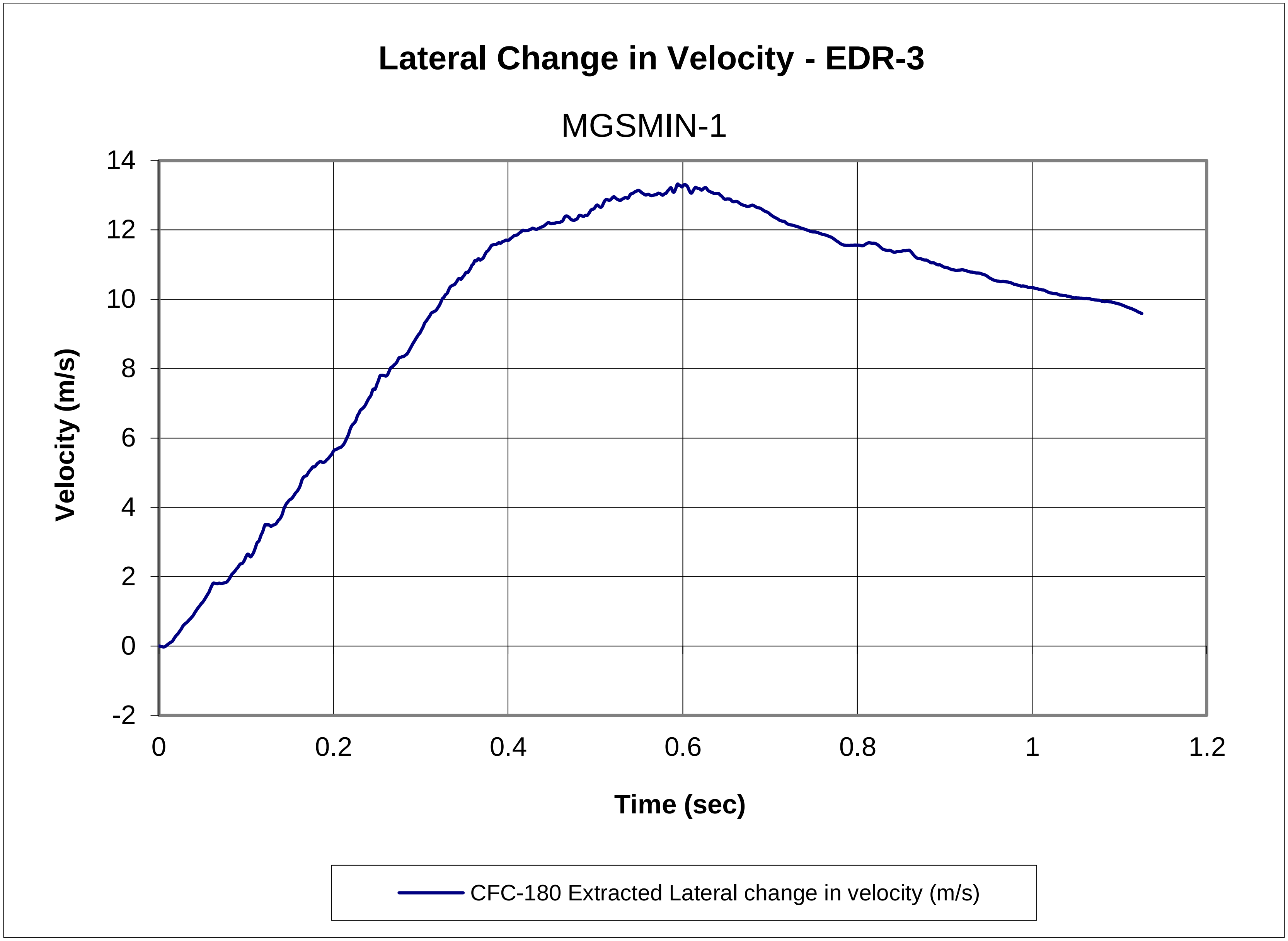


Figure F-21. Lateral Change in Velocity (EDR-3), Test No. MGSMIN-1

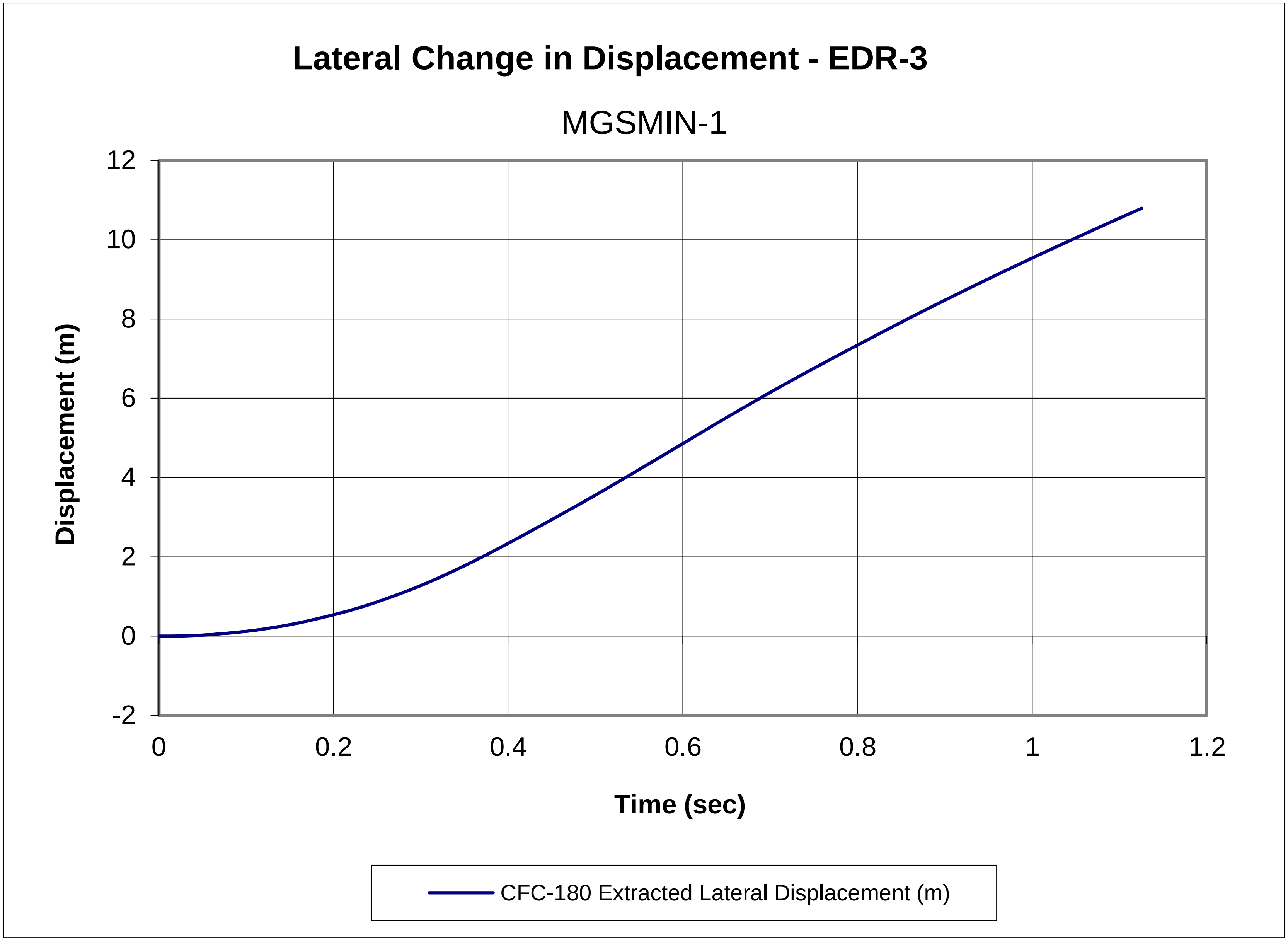


Figure F-22. Lateral Occupant Displacement (EDR-3), Test No. MGSMIN-1

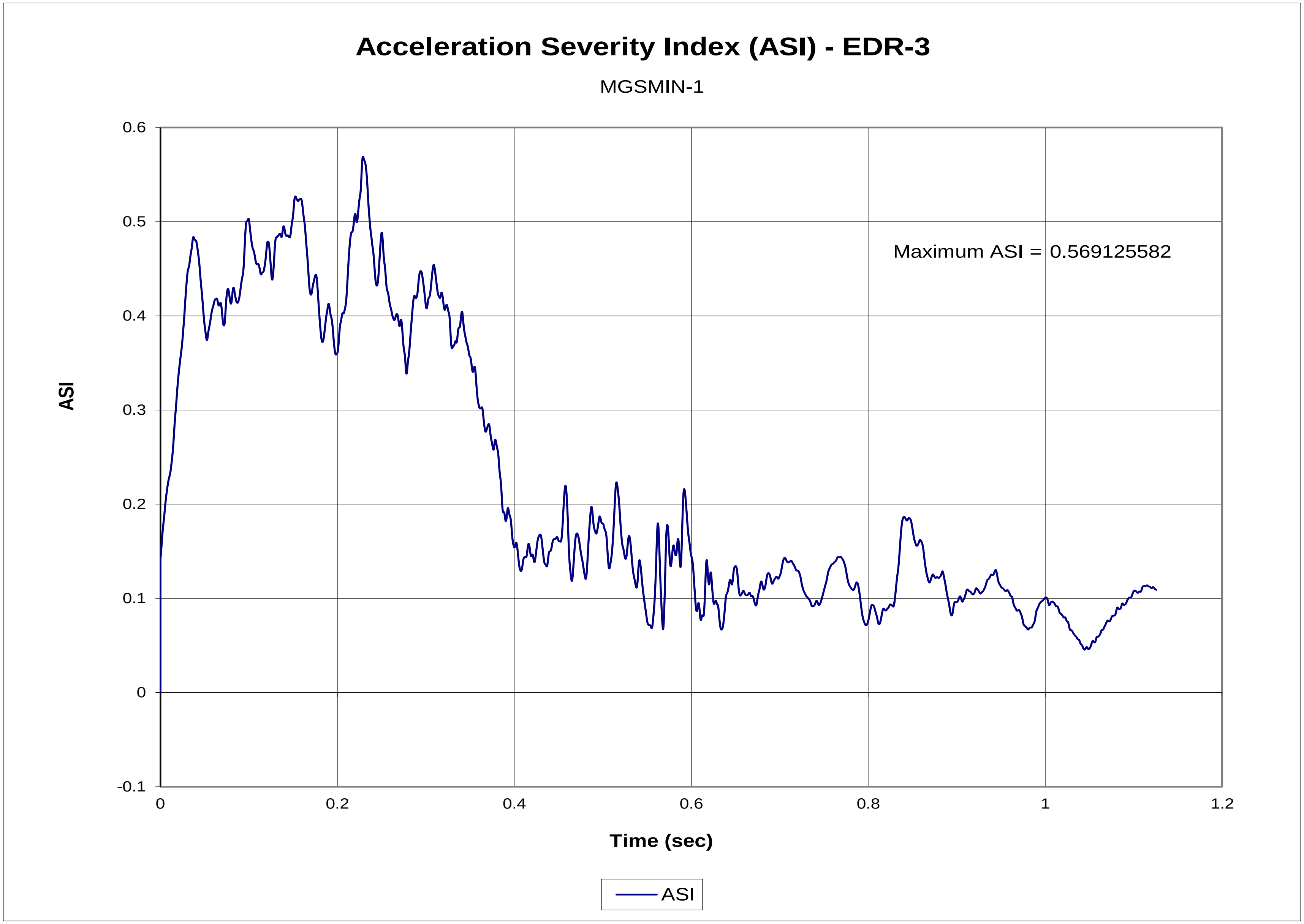


Figure F-23. Acceleration Severity Index (EDR-3), Test No. MGSMIN-1

Appendix G. 175-ft (53.3–m) WIDA-1 BARRIER VII Input Deck (2270P)

```
MGS-175ft-2270P: Standard 31-in.,MASH TL-3, Test No. WIDA-1
  225    2    1    1  253    6    2    0
    0.0001    0.0001     2.000 2500    0       1.0    1
   10   10   10   10   10  500    1
    1       0.0       0.0
  225      2100       0.0
    1  225  223    1     9.375
    1  225      0.35
  225  224  223  222  221  220  219  218  217  216
  215  214  213  212  211  210  209  208  207  206
  205  204  203  202  201  200  199  198  197  196
  195  194  193  192  191  190  189  188  187  186
  185  184  183  182  181  180  179  178  177  176
  175  174  173  172  171  170  169  168  167  166
  165  164  163  162  161  160  159  158  157  156
  155  154  153  152  151  150  149  148  147  146
  145  144  143  142  141  140  139  138  137  136
  135  134  133  132  131  130  129  128  127  126
  125  124  123  122  121  120  119  118  117  116
  115  114  113  112  111  110  109  108  107  106
  105  104  103  102  101  100   99   98   97   96
   95   94   93   92   91   90   89   88   87   86
   85   84   83   82   81   80   79   78   77   76
   75   74   73   72   71   70   69   68   67   66
   65   64   63   62   61   60   59   58   57   56
   55   54   53   52   51   50   49   48   47   46
   45   44   43   42   41   40   39   38   37   36
   35   34   33   32   31   30   29   28   27   26
   25   24   23   22   21   20   19   18   17   16
   15   14   13   12   11   10    9    8    7    6
    5    4    3    2    1
  100    1
    1      2.29      1.99     9.375   30000.0      6.92      99.5      68.5 0.05 12-Gauge W-Beam
  300    3
    1    24.875      0.00       6.0       6.0     100.0     675.0     675.0 0.05 Simulated Strong
Anchor Post
     100.0     100.0      11.0      11.0
    2    24.875      0.00       3.0       3.0     100.0     350.0     350.0 0.05 Second BCT Post
      50.0      50.0       9.0       9.0
    3    24.875       0.0      2.60      3.00      54.0     92.90    165.05 0.05 W6x9 by 6' Long
Emb. 40" in H.E. 8 soil
      15.0      25.0      15.0      15.0
    1    1    2  224    1  101       0.0       0.0       0.0
  225    1               301       0.0       0.0       0.0       0.0       0.0
  226    9               302       0.0       0.0       0.0       0.0       0.0
  227   17       251    8  303       0.0       0.0       0.0       0.0       0.0
  252  217               302       0.0       0.0       0.0       0.0       0.0
  253  225               301       0.0       0.0       0.0       0.0       0.0
    5000.0   58310.0   20    6    4    0    1
    1     0.055      0.12      6.00      17.0
    2     0.057      0.15      7.00      18.0
    3     0.062      0.18     10.00      12.0
    4     0.110      0.35     12.00       6.0
    5      0.35      0.45      6.00       5.0
    6      1.45      1.50     15.00       1.0
    1    102.50    15.875    1      12.0    1    1    0    0
    2    102.50    27.875    1      12.0    1    1    0    0
    3    102.50    39.000    2      12.0    1    1    0    0
    4     88.75    39.000    2      12.0    1    1    0    0
    5     76.75    39.000    2      12.0    1    1    0    0
    6     64.75    39.000    2      12.0    1    1    0    0
    7     52.75    39.000    2      12.0    1    1    0    0
    8     40.75    39.000    2      12.0    1    1    0    0
    9     28.75    39.000    2      12.0    1    1    0    0
   10     16.75    39.000    2      12.0    1    1    0    0
   11    -13.25    39.000    3      12.0    1    1    0    0
   12    -33.25    39.000    3      12.0    1    1    0    0
   13    -53.25    39.000    3      12.0    1    1    0    0
   14    -73.25    39.000    3      12.0    1    1    0    0
   15    -93.25    39.000    3      12.0    1    1    0    0
   16   -125.35    39.000    4      12.0    1    1    0    0
```

```
17   -125.35   -39.000    4      12.0    0    0    0    0
18    102.50   -39.000    1      12.0    0    0    0    0
19     62.40    33.90     5       1.0    1    1    0    0
20    -77.85    33.90     6       1.0    1    1    0    0
 1     62.40    33.90        0.0       608.
 2     62.40   -33.90        0.0       608.
 3    -77.85    33.90        0.0       492.
 4    -77.85   -33.90        0.0       492.
25       0.0       0.0
 3   1725.00       0.0      26.4     62.98       0.0       0.0       1.0
```

Appendix H. Validation for 2270P Pickup Striking a 75-ft MGS

VALIDATION/VERIFICATION REPORT
FOR

A ____________MASH 2270P Pickup Truck_____ ______________________________
(Report 350 or MASH or EN1317 Vehicle Type)

Striking a __ 31-in. tall, 75-ft Midwest Guardrail System_________________
(roadside hardware type and name)

Report Date: __ 10/20/2012 __ ____

Type of Report (check one)

☐ Verification (known numerical solution compared to new numerical solution) or
☒ Validation (full-scale crash test compared to a numerical solution).

General Information	**Known Solution**	**Analysis Solution**
Performing Organization	MwRSF	MwRSF
Test/Run Number:	MGSMIN-1	MGS-75ft-2270P
Vehicle:	2005 Dodge Ram 1500 Quad Cab	2270P Model
Impact Conditions		
Vehicle Mass:	2,228 kg	2,268 kg
Speed:	101.6 km/h	101.4 km/h
Angle:	24.9 deg	25.0 deg
Impact Point:	Downstream post no. 4	Post no. 4

Composite Validation/Verification Score

	List the Report 350/MASH or EN1317 Test Number	3-11
Part I	Did all solution verification criteria in Table A-1 pass?	NA
Part II	Do all the time history evaluation scores from Table A-2 result in a satisfactory comparison (i.e., the comparison passes the criterion)? If all the values in Table A-2 did not pass, did the weighted procedure shown in Table A-3 result in an acceptable comparison. If all the criteria in Table A-2 pass, enter "yes." If all the criteria in Table A-2 did not pass but Table A-3 resulted in a passing score, enter "yes."	Yes
Part III	All the criteria in Table A-4 (Test-PIRT) passed?	Yes
	Are the results of Steps I through III all affirmative (i.e., YES)? If all three steps result in a "YES" answer, the comparison can be considered validated or verified. If one of the steps results in a negative response, the result cannot be considered validated or verified.	Yes

The analysis solution (check one) ☒ is ☐ is NOT verified/validated against the known solution.

PART I: BASIC INFORMATION

These forms may be used for validation or verification of roadside hardware crash tests. If the known solution is a full-scale crash test (i.e., physical experiment) which is being compared to a numerical solution (e.g., LSDYNA analysis) then the procedure is a validation exercise. If the known solution is a numerical solution (e.g., a prior finite element model using a different program or earlier version of the software) then the procedure is a verification exercise. This form can also be used to verify the repeatability of crash tests by comparing two full-scale crash test experiments. Provide the following basic information for the validation/verification comparison:

1. What type of roadside hardware is being evaluated (check one)?
   - ☒ Longitudinal barrier or transition
   - ☐ Terminal or crash cushion
   - ☐ Breakaway support or work zone traffic control device
   - ☐ Truck-mounted attenuator
   - ☐ Other hardware: ______________________________

2. What test guidelines were used to perform the full-scale crash test (check one)?
   - ☐ NCHRP Report No. 350
   - ☒ MASH
   - ☐ EN1317
   - ☐ Other: ______________________________

3. Indicate the test level and number being evaluated (fill in the blank). ___3-11_ __

4. Indicate the vehicle type appropriate for the test level and number indicated in item 3 according to the testing guidelines indicated in item 2.

   NCHRP Report No. 350/MASH

☐ 700C	☐ 820C	☐ 1100C
☐ 2000P	☒ 2270P	
☐ 8000S	☐ 10000S	
☐ 36000V		
☐ 36000T		

   EN1317

☐ Car (900 kg)	☐ Car (1300 kg)	☐ Car (1500 kg)
☐ Rigid HGV (10 ton)	☐ Rigid HGV (16 ton)	
☐ Rigid HGV (30 ton)		
☐ Bus (13 ton)		
☐ Articulated HGV (38 ton)		

PART II: ANALYSIS SOLUTION VERIFICATION

Using the results of the analysis solution, fill in the values for Table A-1. These values are indications of whether the analysis solution produced a numerically stable result and do not necessarily mean that the result is a good comparison to the known solution. The purpose of this table is to ensure that the numerical solution produces results that are numerically stable and conform to the conservation laws (e.g., energy, mass and momentum).

Table H-1. Analysis Solution Verification Table

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	NA*	-
Hourglass Energy of the analysis solution at the end of the run is less than *five percent* of the total *initial energy* at the *beginning* of the run.	NA*	-
Hourglass Energy of the analysis solution at the end of the run is less than *ten percent* of the total *internal energy* at the *end* of the run.	NA*	-
The part/material with the highest amount of hourglass energy at the end of the run is less than ten percent of the total internal energy of the part/material at the end of the run.	NA*	-
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	NA*	-
The part/material with the most mass added had less than 10 percent of its initial mass added.	NA*	-
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	NA*	-
There are no shooting nodes in the solution?	NA*	-
There are no solid elements with negative volumes?	NA*	-

The Analysis Solution (check one) ☐ passes ☐ does NOT pass all the criteria in Table H-1

☐with ☐without exceptions as noted.

*Although BARRIER VII calculates the total energy during a simulation, there is no Hourglass energy calculated during the simulation. Additional masses, shooting nodes and negative volumes are not applicable to BARRIER VII simulations. Therefore, Table H-1 was not considered in this validation analysis.

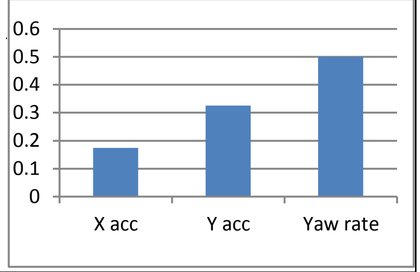
PART III: TIME HISTORY EVALUATION TABLE

Table H-2. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (single channel option)

<table>
<tr><th colspan="10">Evaluation Criteria</th><th colspan="3" rowspan="2">Time interval
[0 sec; 0.82sec]</th></tr>
<tr><td rowspan="10">O</td><td colspan="9">Sprague-Geers Metrics
List all the data channels being compared. Calculate the M and P metrics using RSVVP and enter the results. Values less than or equal to 40 are acceptable.</td></tr>
<tr><td rowspan="3"></td><td colspan="6">RSVVP Curve Preprocessing Options</td><td rowspan="3">M</td><td rowspan="3">P</td><td rowspan="3">Pass?</td></tr>
<tr><td rowspan="2">Filter Option</td><td rowspan="2">Sync. Option</td><td colspan="2">Shift</td><td colspan="2">Drift</td></tr>
<tr><td>True Curve</td><td>Test Curve</td><td>True Curve</td><td>Test Curve</td></tr>
<tr><td>X acceleration</td><td>CFC 60</td><td>Min. Area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>2.4</td><td>26.4</td><td>Yes</td></tr>
<tr><td>Y acceleration</td><td>CFC 60</td><td>Min. Area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>6</td><td>13.2</td><td>Yes</td></tr>
<tr><td>Z acceleration</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Roll rate</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Pitch rate</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td>Yaw rate</td><td>CFC 60</td><td>Min. Area of Residuals</td><td>N</td><td>N</td><td>N</td><td>N</td><td>4.7</td><td>2.4</td><td>Yes</td></tr>
<tr><td rowspan="7">P</td><td colspan="9">ANOVA Metrics
List all the data channels being compared. Calculate the ANOVA metrics using RSVVP and enter the results. Both of the following criteria must be met:
• The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$) and
• The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)</td><td>Mean Residual</td><td>Standard Deviation of Residuals</td><td>Pass?</td></tr>
<tr><td colspan="9">X acceleration/Peak</td><td>-4.35</td><td>27.3</td><td>Yes</td></tr>
<tr><td colspan="9">Y acceleration/Peak</td><td>5.28</td><td>15.94</td><td>Yes</td></tr>
<tr><td colspan="9">Z acceleration/Peak</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="9">Roll rate</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="9">Pitch rate</td><td>-</td><td>-</td><td>-</td></tr>
<tr><td colspan="9">Yaw rate</td><td>2.36</td><td>6.38</td><td>Yes</td></tr>
</table>

The Analysis Solution (check one) ☒ passes ☐ does NOT pass all the criteria in Table H-2.

Table H-3. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (multi-channel option)

Evaluation Criteria (time interval [0 sec; 0.862 sec])		
Channels (Select which were used)		
☒ **X Acceleration**	☒ **Y Acceleration**	☐ **Z Acceleration**
☐ **Roll rate**	☐ **Pitch rate**	☒ **Yaw rate**
Multi-Channel Weights ☒ **Area II method** ☐ **Inertial method**	**X Channel: 0.174088** **Y Channel: 0.325912** **Z Channel: NA** **Yaw Channel: 0.5** **Roll Channel: NA** **Pitch Channel: NA**	

		M	**P**	**Pass?**
O	***Sprague-Geer Metrics*** Values less or equal to 40 are acceptable.	4.8	10.1	Yes
		Mean Residual	**Standard Deviation of Residuals**	**Pass?**
P	***ANOVA Metrics*** Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$) • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)	2.1	13.1	Yes

The Analysis Solution (check one) ☒ passes ☐ does NOT pass <u>all</u> the criteria in Table H-3.

PART IV: PHENOMENA IMPORTANCE RANKING TABLE

Table H-4. Evaluation Criteria Test Applicability Table

<table>
<tr><th>Evaluation Factors</th><th colspan="4">Evaluation Criteria</th><th>Applicable Tests</th></tr>
<tr><td rowspan="3">Structural Adequacy</td><td>A</td><td colspan="3">Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38</td></tr>
<tr><td>B</td><td colspan="3">The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>60, 61, 70, 71, 80, 81</td></tr>
<tr><td>C</td><td colspan="3">Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>30, 31,, 32, 33, 34, 39, 40, 41, 42, 43, 44, 50, 51, 52, 53</td></tr>
<tr><td rowspan="13">Occupant Risk</td><td>D</td><td colspan="3">Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.</td><td>All</td></tr>
<tr><td>E</td><td colspan="3">Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver’s vision or otherwise cause the driver to lose control of the vehicle. (Answer Yes or No)</td><td>70, 71</td></tr>
<tr><td>F</td><td colspan="3">The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.</td><td>All except those listed in criterion G</td></tr>
<tr><td>G</td><td colspan="3">It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>12, 22 (for test level 1 – 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44)</td></tr>
<tr><td rowspan="5">H</td><td colspan="3">Occupant impact velocities should satisfy the following:</td><td rowspan="4">10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 80, 81</td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits (m/s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>9</td><td>12</td></tr>
<tr><td>Longitudinal</td><td>3</td><td>5</td><td>60, 61, 70, 71</td></tr>
<tr><td rowspan="4">I</td><td colspan="3">Occupant ridedown accelerations should satisfy the following:</td><td rowspan="4">10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 60, 61, 70, 71, 80, 81</td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits (g’s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td></tr>
<tr><td rowspan="3">Vehicle Trajectory</td><td>L</td><td colspan="3">The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant ride-down acceleration in the longitudinal direction should not exceed 20 G’s.</td><td>11,21, 35, 37, 38, 39</td></tr>
<tr><td>M</td><td colspan="3">The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38, 39</td></tr>
<tr><td>N</td><td colspan="3">Vehicle trajectory behind the test article is acceptable.</td><td>30, 31, 32, 33, 34, 39, 42, 43, 44, 60, 61, 70, 71, 80, 81</td></tr>
</table>

Table H-5. (a) Roadside Safety Phenomena Importance Ranking Table (Structural Adequacy)

Evaluation Criteria				MGSMIN-1	MGS-75ft-2270P	Difference Relative/ Absolute	Agree?
Structural Adequacy	A	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable. (Answer Yes or No)	Yes	Yes		**Yes**
		A2	Maximum dynamic deflection: - Relative difference is less than 20 percent or - Absolute difference is less than 0.15 m	1.072 m	1.234 m	13.1% 0.162 m	**Yes**
		A3	Length of vehicle-barrier contact: - Relative difference is less than 20 percent or - Absolute difference is less than 2 m	11.3 m	11.4 m	0.87% 0.01 m	**Yes**
		A4	Number of broken or significantly bent posts is less than 20 percent.	5	5	0%	**Yes**
		A5	Did the rail element rupture or tear (Answer Yes or No)	No	No		**Yes**
		A6	Were there failures of connector elements (Answer Yes or No).	No	No		**Yes**
		A7	Was there significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	No	No		**Yes**
		A8	Was there significant snagging between vehicle body components and barrier elements (Answer Yes or No).	No	No		**Yes**

Table H-5. (b) Roadside Safety Phenomena Importance Ranking Table (Occupant Risk)

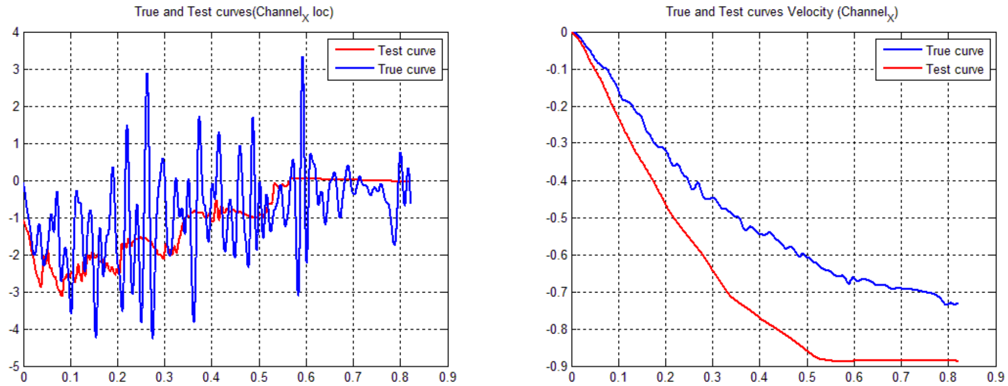
Evaluation Criteria				MGSMIN-1	MGS-75ft-2270P	Difference Relative/ Absolute	Agree?
Occupant Risk	D		Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. (Answer Pass or Fail)	Pass	Pass		Yes
	F	F1	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable. (Answer Pass or Fail)	Pass	Pass		Yes
		F2	Maximum roll of the vehicle: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	-7.4°	*N.M.	NA	**NA**
		F3	Maximum pitch of the vehicle is: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	-5°	*N.M.	NA	**NA**
		F4	Maximum yaw of the vehicle is: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	38.9°	40.4°	3.7% 1.5°	Yes
	L	L1	Occupant impact velocities: - Relative difference is less than 20 percent or - Absolute difference is less than 2 m/s.				
			• Longitudinal OIV (m/s)	-4.41	*N.M.	NA	**NA**
			• Lateral OIV (m/s)	4.47	*N.M.	NA	**NA**
			• THIV (m/s)	6.15	*N.M.	NA	**NA**
		L2	Occupant accelerations: - Relative difference is less than 20 percent or - Absolute difference is less than 4 g’s.				
			• Longitudinal ORA (g’s)	-8.70	*N.M.	NA	**NA**
			• Lateral ORA (g’s)	6.16	*N.M.	NA	**NA**
			• PHD (g’s)	9.62	*N.M.	NA	**NA**
			• ASI	0.59	*N.M.	NA	**NA**

Table H-5. (c) Roadside Safety Phenomena Importance Ranking Table (Vehicle Trajectory)

Evaluation Criteria				MGSMIN-1	MGS-75ft-2270P	Difference Relative/ Absolute	Agree?
Vehicle Trajectory	M	M1	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	NA	-15.4° 61.4%		**No**
		M2	Exit angle at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	NA	-15.4°	NA	**NA**
		M3	Exit velocity at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	NA	62.1 km/h	NA	**NA**
		M4	One or more vehicle tires failed or de-beaded during the collision event (Answer Yes or No).	Yes	*N.M.		**NA**

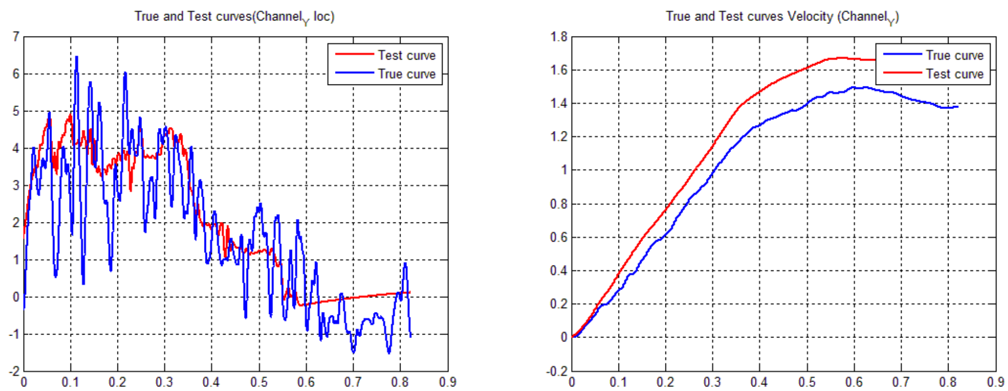
*N.R. - Not Reported *N.M. - Not Modeled

The Analysis Solution (check one) ☐ passes ☒ does NOT pass all the criteria in Table H-5a through Table H-5c ☐with exceptions as noted ☒ without exceptions.



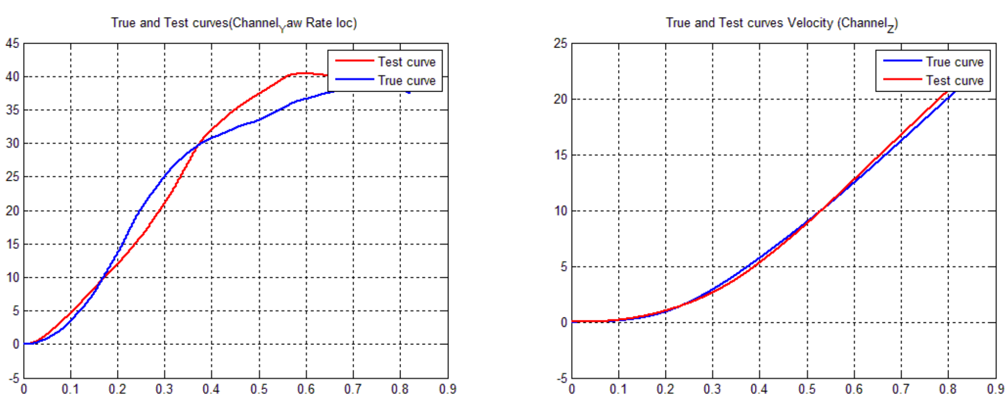
(a) (b)

Figure H-1. X-Channel (a) acceleration-time history data used to compute metrics and (b) integration of acceleration-time history data



(a) (b)

Figure H-2. Y-Channel (a) acceleration-time history data used to compute metrics and (b) integration of acceleration-time history data



(a) (b)

Figure H-3. Yaw Channel (a) angular rate-time history data used to compute metrics and (b) integration of angular rate-time history data

Appendix I. 75-ft (22.9–m) MGS BARRIER VII Input Deck (2270P)

```
MGS-75ft-2270P: Standard 31-in.,MASH TL-3, Test No. MGSMIN-1
   97    2    1    1  109    6    2    0
    0.0001    0.0001     2.000 2500    0       1.0    1
   10   10   10   10   10  500    1
    1       0.0       0.0
   97       900       0.0
    1   97   95    1     9.375
    1   97      0.30
   97   96   95   94   93   92   91   90   89   88
   87   86   85   84   83   82   81   80   79   78
   77   76   75   74   73   72   71   70   69   68
   67   66   65   64   63   62   61   60   59   58
   57   56   55   54   53   52   51   50   49   48
   47   46   45   44   43   42   41   40   39   38
   37   36   35   34   33   32   31   30   29   28
   27   26   25   24   23   22   21   20   19   18
   17   16   15   14   13   12   11   10    9    8
    7    6    5    4    3    2    1
  100    1
    1      2.29      1.99     9.375   30000.0      6.92      99.5      68.5 0.05 12-Gauge W-Beam
  300    3
    1   24.875      0.00       6.0       6.0     100.0     675.0     675.0 0.05 Simulated Strong
Anchor Post
     100.0     100.0      11.0      11.0
    2   24.875      0.00       3.0       3.0     100.0     350.0     350.0 0.05 Second BCT Post
      50.0      50.0       9.0       9.0
    3   24.875       0.0      3.00      2.00      54.0     30.90    180.65 0.05 W6x9 by 6' Long
Emb. 40" in H.E. 8 soil
      15.0      25.0      15.0      15.0
    1    1    2   96    1  101       0.0       0.0       0.0
   97    1                 301       0.0       0.0       0.0       0.0       0.0
   98    9                 302       0.0       0.0       0.0       0.0       0.0
   99   17       107    8  303       0.0       0.0       0.0       0.0       0.0
  108   89                 302       0.0       0.0       0.0       0.0       0.0
  109   97                 301       0.0       0.0       0.0       0.0       0.0
    5000.0   58310.0   20    6    4    0    1
    1     0.055      0.12      6.00      17.0
    2     0.057      0.15      7.00      18.0
    3     0.062      0.18     10.00      12.0
    4     0.110      0.35     12.00       6.0
    5      0.35      0.45      6.00       5.0
    6      1.45      1.50     15.00       1.0
    1    102.50    15.875    1      12.0    1    1    0    0
    2    102.50    27.875    1      12.0    1    1    0    0
    3    102.50    39.000    2      12.0    1    1    0    0
    4     88.75    39.000    2      12.0    1    1    0    0
    5     76.75    39.000    2      12.0    1    1    0    0
    6     64.75    39.000    2      12.0    1    1    0    0
    7     52.75    39.000    2      12.0    1    1    0    0
    8     40.75    39.000    2      12.0    1    1    0    0
    9     28.75    39.000    2      12.0    1    1    0    0
   10     16.75    39.000    2      12.0    1    1    0    0
   11    -13.25    39.000    3      12.0    1    1    0    0
   12    -33.25    39.000    3      12.0    1    1    0    0
   13    -53.25    39.000    3      12.0    1    1    0    0
   14    -73.25    39.000    3      12.0    1    1    0    0
   15    -93.25    39.000    3      12.0    1    1    0    0
   16   -125.35    39.000    4      12.0    1    1    0    0
   17   -125.35   -39.000    4      12.0    0    0    0    0
   18    102.50   -39.000    1      12.0    0    0    0    0
   19     62.40     33.90    5       1.0    1    1    0    0
   20    -77.85     33.90    6       1.0    1    1    0    0
    1     62.40     33.90       0.0      608.
    2     62.40    -33.90       0.0      608.
    3    -77.85     33.90       0.0      492.
    4    -77.85    -33.90       0.0      492.
    1      0.00      0.00
    3   225.000       0.0        25        63       0.0       0.0       1.0
```

Appendix J. 62-ft 6-in. (19.1–m) MGS BARRIER VII Input Deck (2270P)

```
MGS-62.5ft-2270P: Standard 31-in.,MASH TL-3
   81    2    1    1   91    6    2    0
    0.0001    0.0001      2.000 2000    0       1.0    1
   10   10   10   10   10  500    1
    1      0.0        0.0
   81    750.00       0.0
    1   81   79    1      9.375
    1   81       0.30
   81   80   79   78   77   76   75   74   73   72
   71   70   69   68   67   66   65   64   63   62
   61   60   59   58   57   56   55   54   53   52
   51   50   49   48   47   46   45   44   43   42
   41   40   39   38   37   36   35   34   33   32
   31   30   29   28   27   26   25   24   23   22
   21   20   19   18   17   16   15   14   13   12
   11   10    9    8    7    6    5    4    3    2
    1
  100    1
    1      2.29       1.99      9.375   30000.0      6.92      99.5      68.5 0.05 12-Gauge W-Beam
  300    3
    1   24.875       0.00       6.0       6.0     100.0     675.0     675.0 0.05 Simulated Strong
Anchor Post
     100.0     100.0      11.0      11.0
    2   24.875       0.00       3.0       3.0     100.0     350.0    350.00 0.05 Second BCT Post
      50.0      50.0       9.0       9.0
    3   24.875        0.0      3.00      2.00      54.0     30.90    180.65 0.05 W6x9 by 6' Long
      15.0      25.0      15.0      15.0
    1    1    2   80    1  101       0.0       0.0       0.0
   81    1              301       0.0       0.0       0.0       0.0       0.0
   82    9              302       0.0       0.0       0.0       0.0       0.0
   83   17        89    8  303       0.0       0.0       0.0       0.0       0.0
   90   73              302       0.0       0.0       0.0       0.0       0.0
   91   81              301       0.0       0.0       0.0       0.0       0.0
    5000.0   58310.0   20    6    4    0    1
    1     0.055      0.12      6.00      17.0
    2     0.057      0.15      7.00      18.0
    3     0.062      0.18     10.00      12.0
    4     0.110      0.35     12.00       6.0
    5      0.35      0.45      6.00       5.0
    6      1.45      1.50     15.00       1.0
    1    102.50    15.875    1      12.0    1    1    0    0
    2    102.50    27.875    1      12.0    1    1    0    0
    3    102.50    39.000    2      12.0    1    1    0    0
    4     88.75    39.000    2      12.0    1    1    0    0
    5     76.75    39.000    2      12.0    1    1    0    0
    6     64.75    39.000    2      12.0    1    1    0    0
    7     52.75    39.000    2      12.0    1    1    0    0
    8     40.75    39.000    2      12.0    1    1    0    0
    9     28.75    39.000    2      12.0    1    1    0    0
   10     16.75    39.000    2      12.0    1    1    0    0
   11    -13.25    39.000    3      12.0    1    1    0    0
   12    -33.25    39.000    3      12.0    1    1    0    0
   13    -53.25    39.000    3      12.0    1    1    0    0
   14    -73.25    39.000    3      12.0    1    1    0    0
   15    -93.25    39.000    3      12.0    1    1    0    0
   16   -125.35    39.000    4      12.0    1    1    0    0
   17   -125.35   -39.000    4      12.0    0    0    0    0
   18    102.50   -39.000    1      12.0    0    0    0    0
   19     62.40     33.90    5       1.0    1    1    0    0
   20    -77.85     33.90    6       1.0    1    1    0    0
    1     62.40     33.90       0.0      608.
    2     62.40    -33.90       0.0      608.
    3    -77.85     33.90       0.0      492.
    4    -77.85    -33.90       0.0      492.
    1      0.0        0.0
    3    225.00       0.0        25     63.00       0.0       0.0       1.0
```

Appendix K. 50-ft (15.2–m) MGS BARRIER VII Input Deck (2270P)

```
MGS-50ft-2270P: Standard 31-in.,MASH TL-3
   65    2    1    1   73    6    2    0
    0.0001    0.0001     2.000 2000    0       1.0    1
   10   10   10   10   10  500    1
    1      0.0       0.0
   65    600.00      0.0
    1   65   63    1     9.375
    1   65      0.30
   65   64   63   62   61   60   59   58   57   56
   55   54   53   52   51   50   49   48   47   46
   45   44   43   42   41   40   39   38   37   36
   35   34   33   32   31   30   29   28   27   26
   25   24   23   22   21   20   19   18   17   16
   15   14   13   12   11   10    9    8    7    6
    5    4    3    2    1
  100    1
    1      2.29      1.99     9.375   30000.0      6.92      99.5      68.5 0.05 12-Gauge W-Beam
  300    3
    1    24.875      0.00       6.0       6.0     100.0     675.0    675.0  0.05 Simulated Strong
Anchor Post
     100.0     100.0      11.0      11.0
    2    24.875      0.00       3.0       3.0     100.0     350.0    350.0  0.05 Second BCT Post
      50.0      50.0       9.0       9.0
    3    24.875      0.0      3.00      2.60      54.0     30.90    185.65 0.05 W6x9 by 6' Long
      15.0      25.0      15.0      15.0
    1    1    2   64    1  101       0.0       0.0       0.0
   65    1               301       0.0       0.0       0.0       0.0       0.0
   66    9               302       0.0       0.0       0.0       0.0       0.0
   67   17        71    8  303       0.0       0.0       0.0       0.0       0.0
   72   57               302       0.0       0.0       0.0       0.0       0.0
   73   65               301       0.0       0.0       0.0       0.0       0.0
    5000.0   58310.0   20    6    4    0    1
    1     0.055      0.12      6.00      17.0
    2     0.057      0.15      7.00      18.0
    3     0.062      0.18     10.00      12.0
    4     0.110      0.35     12.00       6.0
    5      0.35      0.45      6.00       5.0
    6      1.45      1.50     15.00       1.0
    1    102.50    15.875    1      12.0    1    1    0    0
    2    102.50    27.875    1      12.0    1    1    0    0
    3    102.50    39.000    2      12.0    1    1    0    0
    4     88.75    39.000    2      12.0    1    1    0    0
    5     76.75    39.000    2      12.0    1    1    0    0
    6     64.75    39.000    2      12.0    1    1    0    0
    7     52.75    39.000    2      12.0    1    1    0    0
    8     40.75    39.000    2      12.0    1    1    0    0
    9     28.75    39.000    2      12.0    1    1    0    0
   10     16.75    39.000    2      12.0    1    1    0    0
   11    -13.25    39.000    3      12.0    1    1    0    0
   12    -33.25    39.000    3      12.0    1    1    0    0
   13    -53.25    39.000    3      12.0    1    1    0    0
   14    -73.25    39.000    3      12.0    1    1    0    0
   15    -93.25    39.000    3      12.0    1    1    0    0
   16   -125.35    39.000    4      12.0    1    1    0    0
   17   -125.35   -39.000    4      12.0    0    0    0    0
   18    102.50   -39.000    1      12.0    0    0    0    0
   19     62.40     33.90    5       1.0    1    1    0    0
   20    -77.85     33.90    6       1.0    1    1    0    0
    1     62.40     33.90       0.0      608.
    2     62.40    -33.90       0.0      608.
    3    -77.85     33.90       0.0      492.
    4    -77.85    -33.90       0.0      492.
    1      0.0       0.0
    3    150.00      0.0        25     63.00       0.0       0.0       1.0
```

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