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ALASKA DEPARTMENT OF TRANSPORTATION & PUBLIC FACILITIES

Evaluation of W-Beam Guardrail Terminal Post in Sleeve

Prepared by: Texas A&M Transportation Institute
Texas A&M University System
College Station, TX 77843

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13. ABSTRACT (Maximum 200 words)

States with extreme winter weather are faced with difficulty in maintaining and repairing W-beam guardrail and end terminal posts installed in soil. Due to frozen soil conditions, posts installed directly in soil require more resources and equipment to repair and can delay repair of a damaged guardrail and/or end terminal. In addition, longer duration needed for repair increases the exposure of maintenance workers to oncoming traffic. Some states currently install the steel posts in steel tubes as an alternative to posts installed directly into soil to facilitate repair. This project evaluates the performance of the W-beam guardrail and end terminals with steel posts installed in buried steel sleeves. The researchers performed surrogate bogie vehicle impact tests on posts installed directly in soil and compared their performance to posts installed in buried steel sleeves. On finding similar force-deflection response, the researchers performed a full-scale crash test with posts installed in sleeves. Test 3-35 of American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (*MASH*) was performed with the non-proprietary Downstream Anchor Terminal (DAT) anchoring each end of the test installation.

The 31-inch W-beam guardrail with DAT and steel posts installed in steel sleeves performed acceptably for *MASH* Test 3-35. Results of the test show that W-beam guardrail steel posts installed in buried steel tubes perform similar to the direct embedded posts in guardrail's end terminal region and the length of need.

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METRIC (SI*) CONVERSION FACTORS

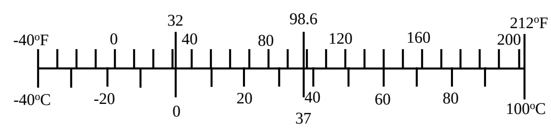
APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4		mm
ft	feet	0.3048		m
yd	yards	0.914		m
mi	Miles (statute)	1.61		km
		AREA		
in^2	square inches	645.2	millimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.4046	hectares	ha
		MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g
lb	Pounds (avdp)	0.454	kilograms	kg
T	Short tons (2000 lb)	0.907	megagrams	mg
		VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL
gal	Gallons (liq)	3.785	liters	liters
ft^3	cubic feet	0.0283	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
Note: Volumes greater than 1000 L shall be shown in m^3				
		TEMPERATURE (exact)		
ºF	Fahrenheit temperature	5/9 (ºF-32)	Celsius temperature	ºC
		ILLUMINATION		
fc	Foot-candles	10.76	lux	lx
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N
psi	pound-force per square inch	6.89	kilopascals	kPa

These factors conform to the requirement of FHWA Order 5190.1A *SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	Miles (statute)	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
km^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.471	acres	ac
		MASS (weight)		
g	grams	0.0353	Ounces (avdp)	oz
kg	kilograms	2.205	Pounds (avdp)	lb
mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	milliliters	0.034	fluid ounces (US)	fl oz
liters	liters	0.264	Gallons (liq)	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
ºC	Celsius temperature	9/5 ºC+32	Fahrenheit temperature	ºF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	pound-force	lbf
kPa	kilopascals	0.145	pound-force per square inch	psi



REPORT AUTHORIZATION

REPORT REVIEWED BY:

DocuSigned by:
Glenn Schroeder
E692F9CB5047487...

Glenn Schroeder, Research Specialist
Drafting & Reporting

DocuSigned by:
Ken Reeves
60D556935596468...

Ken Reeves, Research Specialist
Electronics Instrumentation

DocuSigned by:
Gary Gerke
FBA2101E9F6B4B7...

Gary Gerke, Research Specialist
Construction

DocuSigned by:
Richard Badillo
0F51DA60AB144F9...

Richard Badillo, Research Specialist
Photographic Instrumentation

DocuSigned by:
Scott Dobrovolny
1C613885787C44C...

Scott Dobrovolny, Research Specialist
Mechanical Instrumentation

DocuSigned by:
Wanda L. Menges
B92179622AF24FE...

Wanda L. Menges, Research Specialist
Research Evaluation and Reporting

DocuSigned by:
Bill Griffith
44A122CB271845B...

Bill L. Griffith, Research Specialist
Deputy Quality Manager

DocuSigned by:
Darrell L. Kuhn
D4CC23E85D5B4E7...

Darrell L. Kuhn, P.E., Research Specialist
Quality Manager

DocuSigned by:
Matt Robinson
EAA22BFA5BFD417...

Matthew N. Robinson, Research Specialist
Test Facility Manager & Technical Manager

DocuSigned by:
Nauman Sheikh
662F8286A604403...

Nauman M. Sheikh
Associate Research Engineer

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Chapter 1. INTRODUCTION AND RESEARCH APPROACH

1.1 PROBLEM STATEMENT

States with extreme winter weather are faced with difficulty in maintaining and repairing W-beam guardrail and end terminal posts installed in soil. Due to frozen soil conditions, posts installed directly in soil require more resources and equipment to replace and can delay repair of a damaged guardrail and/or end terminal. Faster replacement can reduce the exposure of maintenance workers to adjacent traffic. In Alaska, for example, many routes are rural two-lane two way traffic without options for detours, which increases risk of work zone accidents for the maintenance crew. Some states currently install the steel posts of the guardrail end terminals in steel tubes as an alternative to posts installed directly into soil to facilitate repair in frozen conditions. There is a need to evaluate and compare the performance of the steel post installed in a steel sleeve to the post installed directly into soil for American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (*MASH*) conditions (*1*).

1.2 OBJECTIVE

The project objective was to evaluate the performance of W-beam guardrail end terminals with steel posts installed in buried steel sleeves for *MASH* compliance. A series of surrogate bogie vehicle impact tests were performed to compare the performance of a post embedded directly in soil to a post installed in a buried steel sleeve. A full-scale *MASH* test was also performed to evaluate the performance of a terminal with posts installed in steel sleeves.

1.3 RESEACH APPROACH AND SCOPE

The work plan for this research included the following tasks.

1.3.1 Task 1: Surrogate Bogie Vehicle Testing

In this task, the TTI research team performed dynamic impact tests on W-beam guardrail steel posts. These tests were performed using a surrogate bogie impact vehicle. A total of four tests were performed, two with posts installed directly in soil and two with posts installed in a buried steel sleeve. The force-deflection response of the posts was recorded from the tests. The research team compared the directly embedded post response and the response of the post installed in steel sleeve.

1.3.2 Task 2: Construction and Crash Testing

In this task, the TTI research team constructed a 31-inch W-beam guardrail installation with a Downstream Anchor Terminal (DAT) on both ends of the installation. The posts adjacent to one of the DATs were installed in buried steel sleeves and *MASH* Test 3-35 was performed for this end terminal.

The researchers chose the DAT because it is a non-proprietary end terminal. Even though it is designed for use on the downstream end of W-beam guardrail that is outside the clear zone for opposing traffic, it was considered to be an appropriate means of evaluating the impact performance of steel posts in steel sleeves for a test at the beginning of guardrail length of need. For the purposes of this research, a fully functional energy absorbing terminal was not deemed necessary to evaluate the performance of the posts installed in steel sleeves versus the directly embedded posts. Almost all W-beam guardrail end terminals anchor the guardrail in the longitudinal direction to enable it to develop tension to contain and redirect impacting vehicles. This constraint is effectively provided by the DAT.

For W-beam guardrail and its end terminals, the weak axis of the post is oriented perpendicular to the traffic direction and the strong axis is oriented parallel to the traffic direction. By installing the steel posts in steel sleeves, the primary change introduced is in the deflection response of the post about its strong axis (i.e. deflection of the post toward the field side). In the weak axis direction (i.e. direction parallel to traffic), the post deforms by laying over at ground level without much movement in soil. Therefore, the introduction of a steel sleeve is not expected to change the force-deflection behavior of the posts about their weak axis. Post deflection about the weak axis is still expected to be controlled by the post bending near ground level without much movement in soil.

For these reasons, the research team considered it sufficient to only perform *MASH* Test 3-35 to evaluate the performance of posts installed in steel sleeves in guardrail end terminals. Other tests for end terminals were considered unnecessary as they pertain primarily to either evaluating the energy absorbing functions of the terminal, where the posts are deformed about the weak axis, or to evaluate the terminal's performance in the reverse direction during which the performance of posts in sleeves would be similar to Test 3-35.

While the specific crash test performed herein was *MASH* Test 3-35 for end terminals, the results of this test are also considered applicable to *MASH* Test 3-11 along the length of need (LON). Both tests have the same impact conditions (2270P vehicle impacting at a speed and angle of 62 mi/h and 25 degrees, respectively) and the difference is only in the impact point. Test 3-35 is considered the more critical of the two tests due to the proximity of the end anchorage and the influence any movement of the end anchorage has on guardrail deflection and pocketing. Therefore, by using a DAT terminal and impacting the guardrail at the location where posts are installed in sleeves, the crash test results are considered acceptable for both Test 3-35 and 3-11 of *MASH*.

MASH also requires performing Test 3-10 with the small passenger car in the guardrail LON. As discussed above, introduction of the steel sleeves is not expected to change the deflection behavior of the posts about its weak axis. Furthermore, the bogie impact testing showed that the force-deflection response of the posts installed in steel sleeves is very similar to directly embedded posts. Due to these reasons, performing *MASH* Test 3-10 was not considered necessary.

This report provides results of above mentioned tasks, details of the 31-inch W-beam guardrail terminal with steel posts in steel sleeves, detailed documentation of the crash test and results, and an assessment of the performance of the 31-inch W-beam guardrail terminal with steel posts in steel sleeves for *MASH* Test 3-35 evaluation criteria.

Chapter 2. FINDINGS

Findings of this research project are summarized below.

- Based on this research, the installation of W-beam guardrail steel posts in buried steel sleeves in end terminals, as tested in this project, is considered MASH compliant.
- Furthermore, the steel posts may also be installed in buried steel sleeves in the length of need of the W-beam guardrail.
- The surrogate bogie vehicle impact tests showed that the W-beam guardrail steel posts installed in buried steel sleeves perform very similar to the directly embedded posts. Details of the surrogate testing are presented in Chapter 3.
- A W-beam guardrail system with a non-proprietary DAT terminal with posts installed in steel sleeves successfully contained and redirected the test vehicle during *MASH* Test 3-35. The guardrail and terminal system passed all applicable *MASH* evaluation criteria for Test 3-35. Test installation details, testing criteria, and test results are presented in Chapters 4 through 8. Other *MASH* tests for guardrail end terminals were not considered necessary for evaluation of the performance of the posts installed in sleeves (see section 1.3.2 for more explanation).
- The results of *MASH* Test 3-35 are also considered applicable to *MASH* Test 3-11, which uses the same impact conditions. Furthermore, due to similar behavior of posts in sleeves with directly embedded posts, as observed in bogie impact testing, performing *MASH* Test 3-10 was not considered necessary (see section 1.3.2 for more explanation).

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Chapter 3. SURROGATE BOGIE VEHICLE TESTING

3.1 INTRODUCTION

The objective of the bogie testing described herein was to compare the impact performance of steel guardrail posts directly embedded in soil to steel guardrail posts inserted into steel sleeves. A total of four tests were performed at two target impact speeds. For each target impact speed, a test was performed with a post directly embedded in soil and a post installed in a steel sleeve. Table 3.1 shows the test matrix.

Table 3.1. Bogie Test Matrix.

Test Number	Target Impact Speed (mph)	Steel Post Type
611011-B1	21	Direct embedded
611011-B2	25	Direct embedded
611011-B3	21	In steel sleeve
611011-B4	25	In steel sleeve

3.2 TEST ARTICLE AND INSTALLATION DETAILS

The steel posts used in the bogie testing were W6x8.5 x 72-inch long Guardrail Posts. Two posts were embedded 40 inches deep in drilled holes, and two posts were inserted into 45-inch long steel sleeves. The posts inserted into the steel sleeves rested on a bolt inserted through the sleeves. The drilled holes into which the posts and sleeves were installed were backfilled with compacted crushed limestone base.

Figures 3.1 and 3.2 present overall information on the direct embedded posts and the posts in steel sleeves.

3.3 SOIL CONDITIONS

The posts were installed in standard soil meeting grading B of AASHTO standard specification M147-65(2004) "Materials for Aggregate and Soil Aggregate Subbase, Base and Surface Courses."

In accordance with Appendix B of *MASH*, soil strength was measured the day of the bogie testing. During installation of the test posts for bogie testing, two W6×16 posts were installed in the immediate vicinity of the test posts utilizing the same fill materials and installation procedures used in the test installation and the standard dynamic test. Table D.1 in Appendix D presents minimum soil strength properties established through the dynamic testing performed in accordance with *MASH* Appendix B.

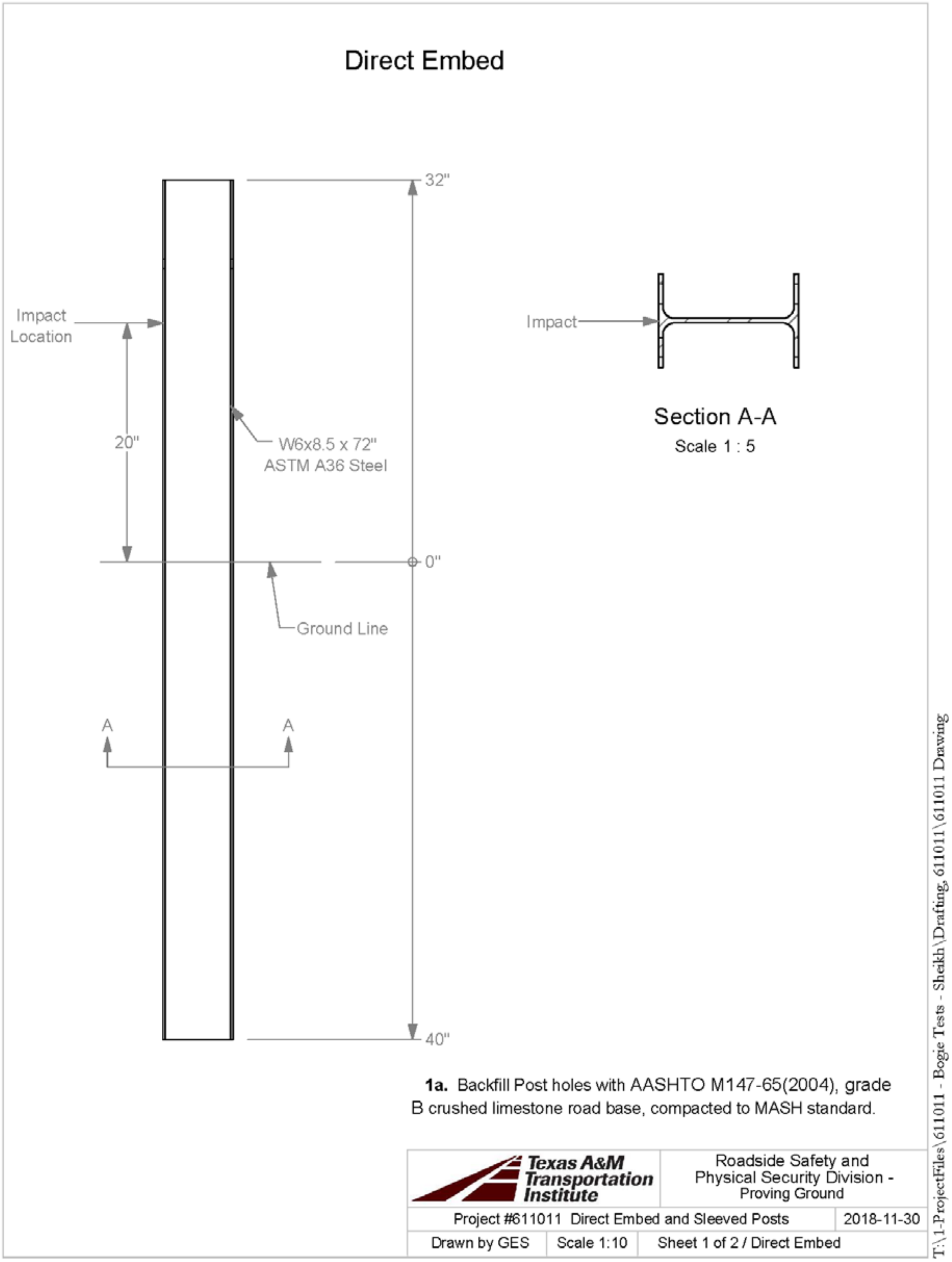

Figure 3.1. Details of Direct Embedded Posts.

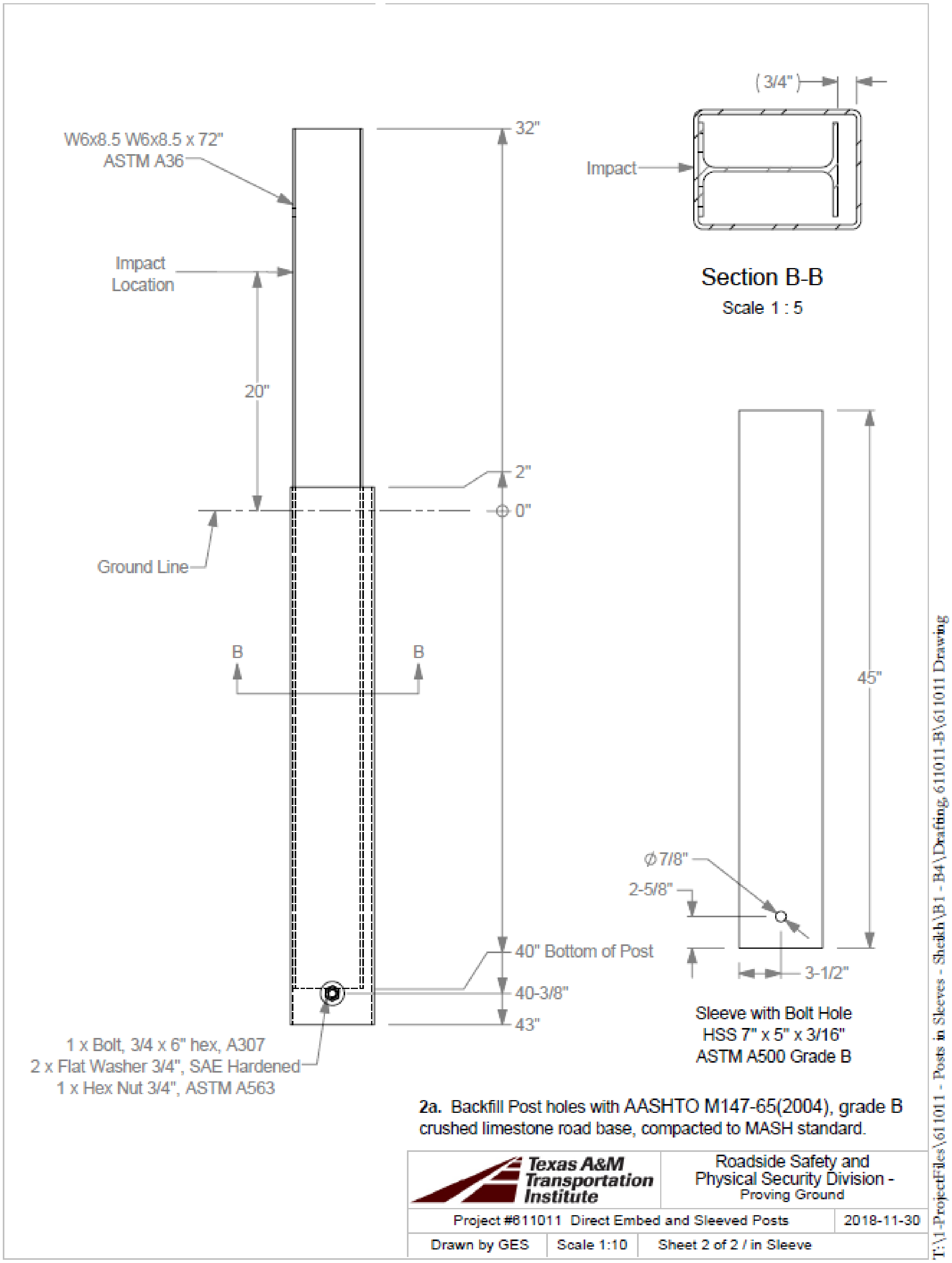

Figure 3.2. Details of Posts in Steel Sleeve.

As determined by the tests summarized in Appendix D, Table D.1, the minimum post loads required for deflections at 5 inches, 10 inches, and 15 inches, measured at a height of 25 inches, are 3940 lb, 5500 lb, and 6540 lb, respectively (90% of static load for the baseline standard installation). On the day of the test, January 29, 2019, loads on the post at deflections of 5 inches, 10 inches, and 15 inches were 7036 lbf, 8293 lbf, and 9210 lbf, respectively. Table D.2 in Appendix D shows the strength of the backfill material in which the posts were installed met minimum *MASH* requirements.

3.4 WEATHER CONDITIONS

The bogie testing was performed January 29, 2019. Weather conditions at the time of testing were as follows: Wind speed: 6-7 mi/h; wind direction: 12-53° (bogie traveling at 360°; temperature: 41-49 ºF; relative humidity: 40-50 percent.

3.5 BOGIE TEST VEHICLE

Figures 3.3 and 3.4 show the bogie test vehicle used for the impact tests. The vehicle's test inertia weight was 1856 lb, and its gross static weight was 1856 lb. Frontal crush of the aluminum honeycomb nose of the bogie simulates the crush of an actual vehicle. The crushable nose configuration is ten stages of cartridges of expendable aluminum honeycomb material of differing densities placed in a sliding nose mechanism. After a test, the honeycomb material is replaced and the bogie is reused. A sketch of the honeycomb configuration used for the pendulum bogie is shown in Appendix A.

The bogie test vehicle was towed into the test installations using a steel cable guidance and reverse tow system. A steel cable for guiding the bogie test vehicle was tensioned along the path, anchored at each end, and threaded through an attachment to the front wheel of the bogie test vehicle. A 1:1 speed ratio between the test and tow vehicle existed with this system. Just prior to impact with the installation, the bogie test vehicle was released and ran unrestrained. The vehicle remained freewheeling (i.e., no steering or braking inputs) until it cleared the immediate area of the test site, after which the brakes were activated, if needed, to bring the bogie test vehicle to a safe and controlled stop.

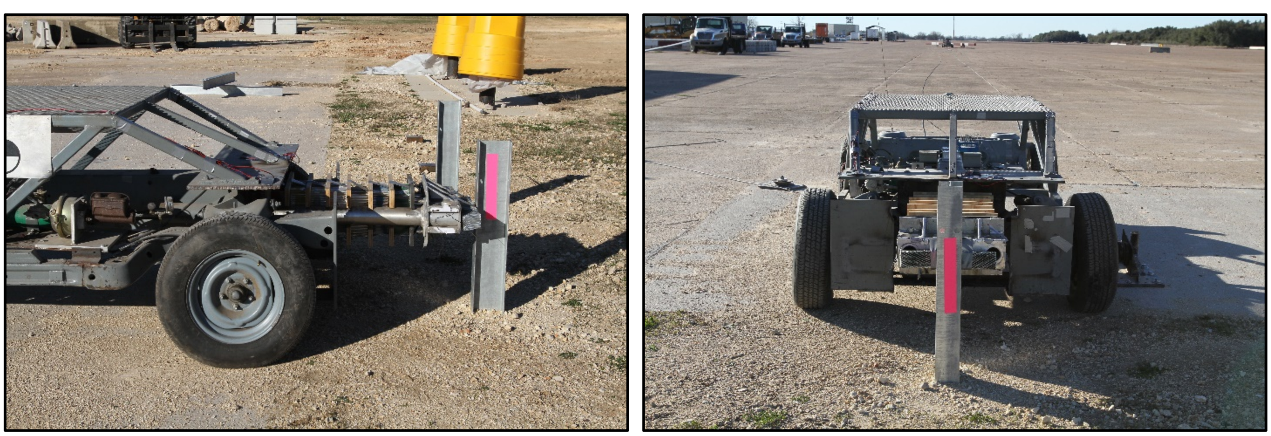

Figure 3.3. Post/Bogie Test Vehicle Geometrics for Test Nos. 611011-B1-B4.

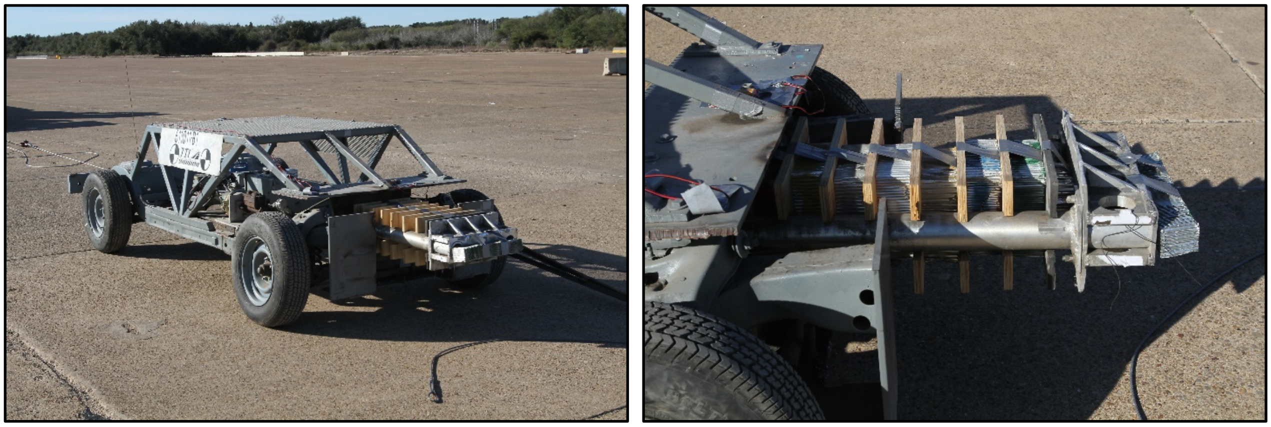

Figure 3.4. Bogie Test Vehicle before Test Nos. 611011-B1-B4.

3.6 DIRECT EMBEDDED POSTS

3.6.1 Bogie Test No. 611011-B1

The bogie impacted the direct embedded post at 90° while traveling at a speed of 20.9 mi/h. The direct embedded post was pushed toward the field side 5.0 inches at grade and was leaning 73° toward the field side. Maximum stroke on the honeycomb nose was 6.5 inches. Figures 3.5 and 3.6 show the post and bogie, respectively, after the test. Acceleration-time, force-time, and force-displacement curves are provided in Figures 3.7 through 3.9, respectively.

Figure 3.5. Direct Embedded Post after Test No. 611011-B1.

Figure 3.6. Bogie Test Vehicle after Test No. 611011-B1.

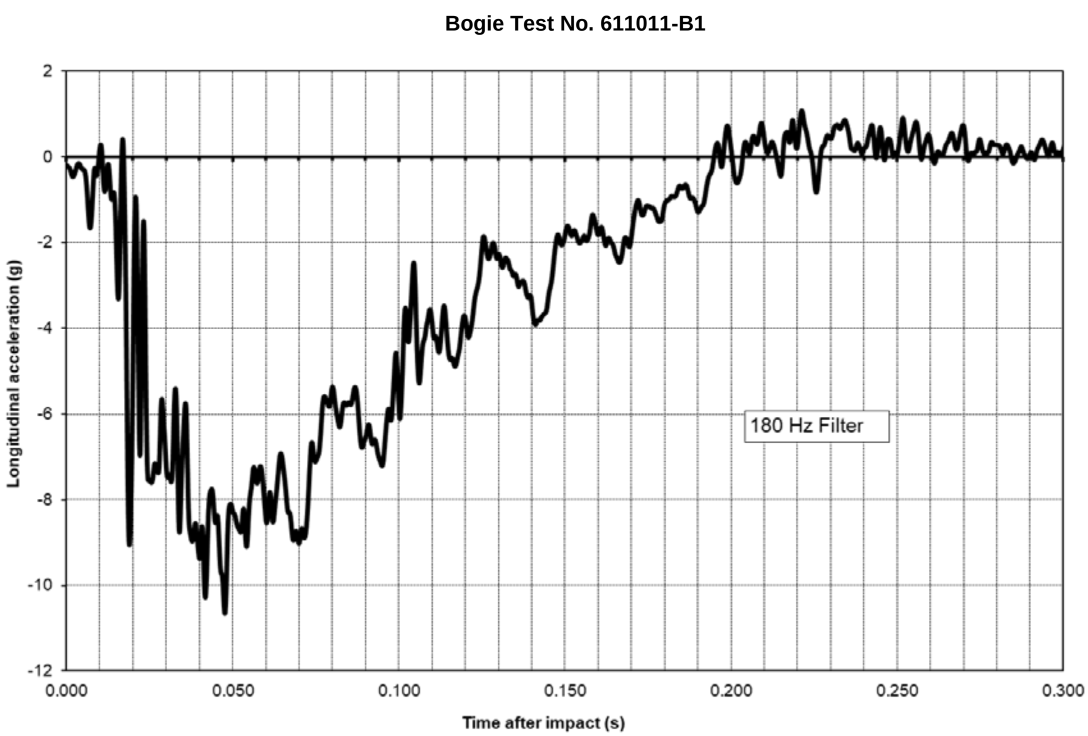

Figure 3.7. Longitudinal Acceleration for Test No. 611011-B1.

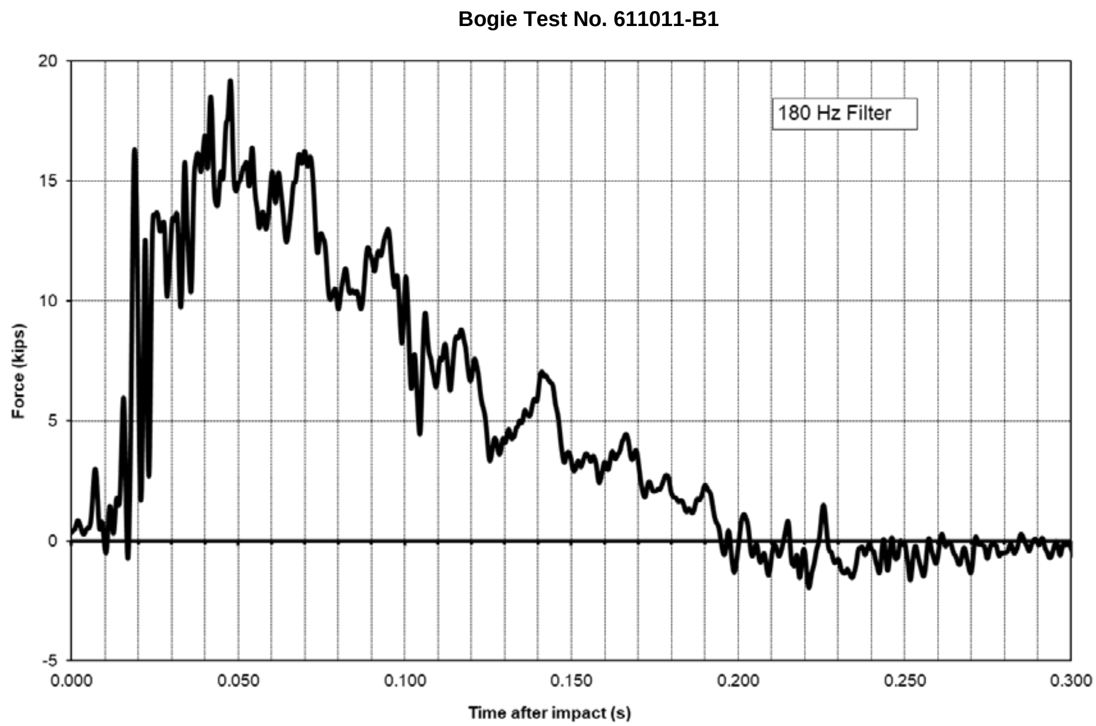

Figure 3.8. Force for Test No. 611011-B1.

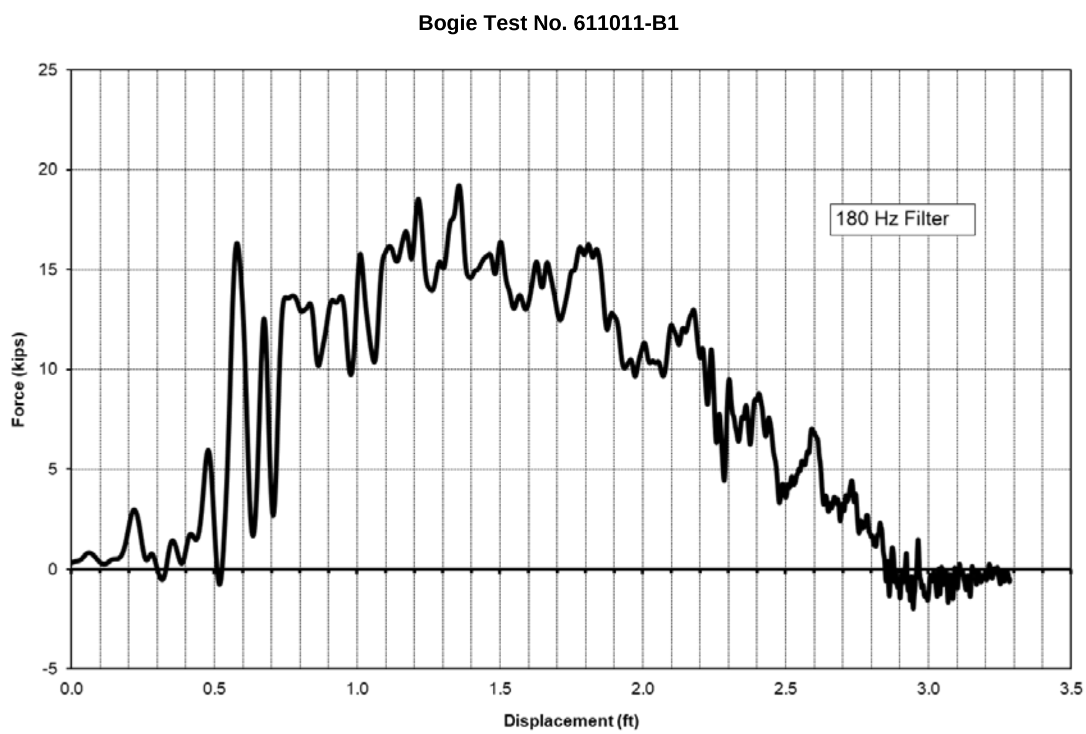

Figure 3.9. Displacement vs Force for Test No. 611011-B1.

3.6.2 Bogie Test No. 611011-B2

The bogie impacted the direct embedded post at 90° while traveling at a speed of 26.0 mi/h. The direct embedded post was pushed toward the field side 12.5 inches at grade and was leaning 59° toward the field side. Maximum stroke on the honeycomb nose was 5.5 inches. Figures 3.10 and 3.11 show the post and bogie, respectively, after the test. Acceleration-time, force-time, and force-displacement curves are provided in Figures 3.12 through 3.14.

Figure 3.10. Direct Embedded Post after Test No. 611011-B2.

Figure 3.11. Bogie Test Vehicle after Test No. 611011-B2.

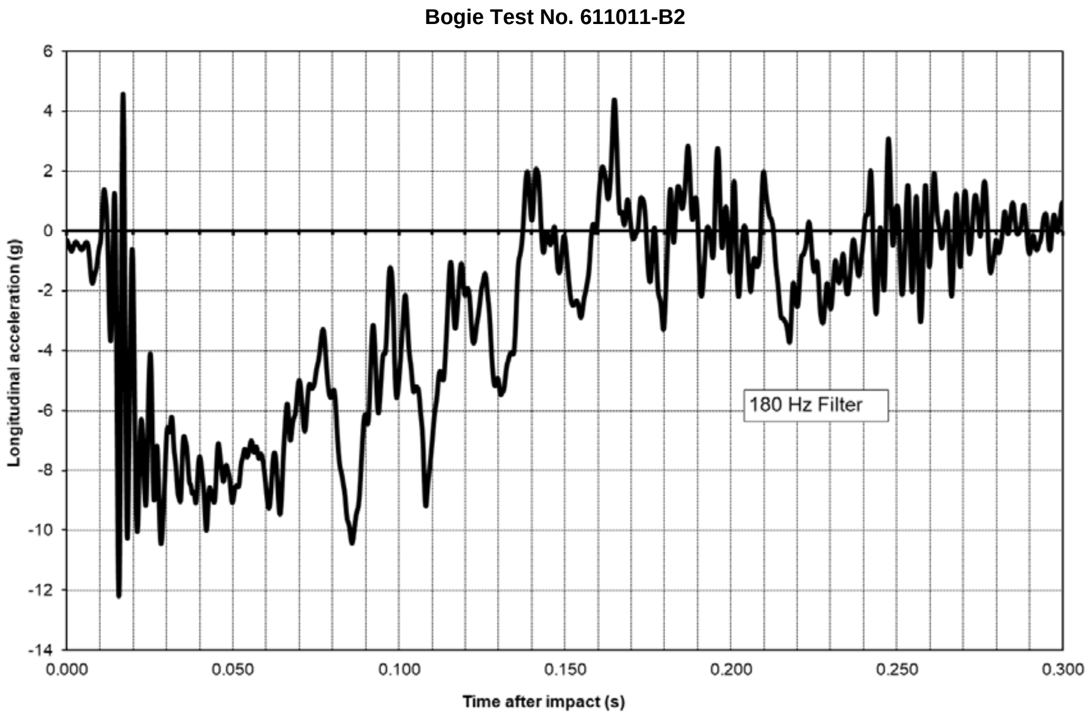

Figure 3.12. Longitudinal Acceleration for Test No. 611011-B2.

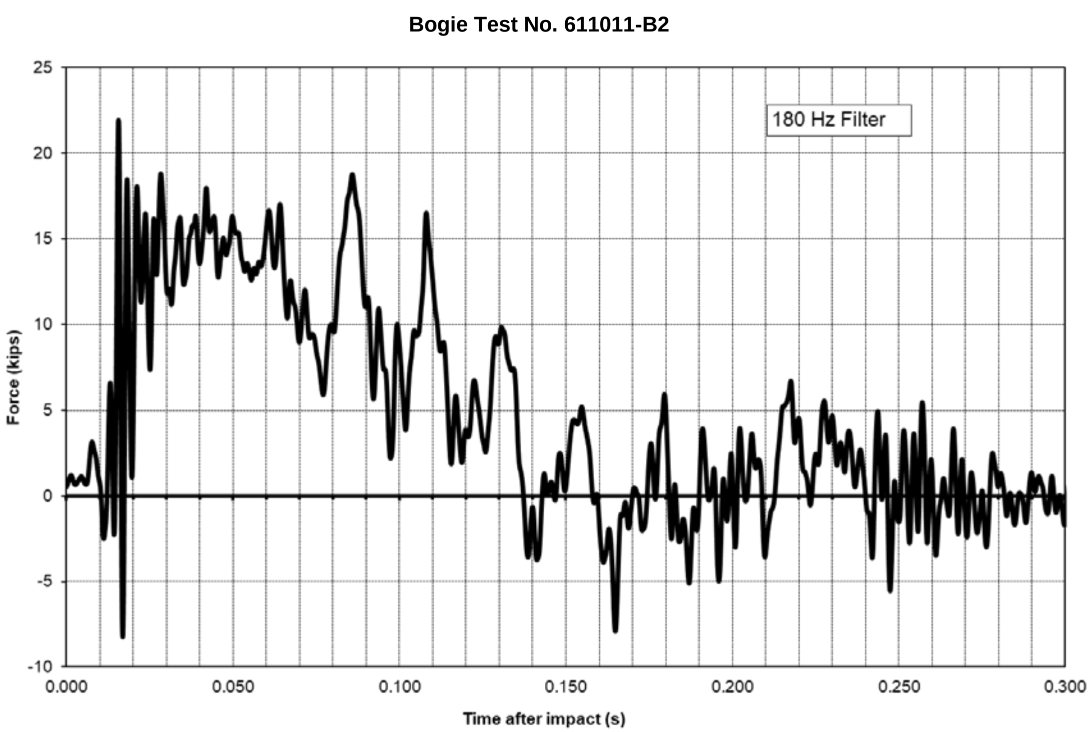

Figure 3.13. Force for Test No. 611011-B2.

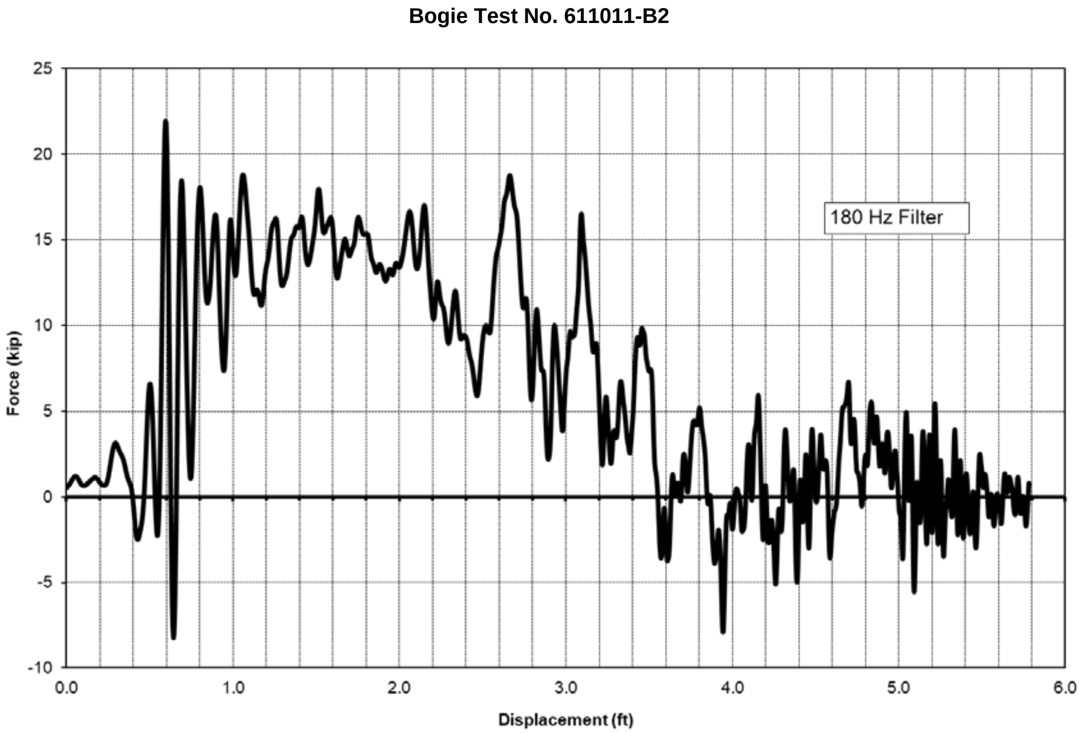

Figure 3.14. Force vs Displacement for Test No. 611011-B2.

3.7 POSTS IN STEEL SLEEVES

3.7.1 Bogie Test No. 611011-B3

The bogie impacted the post installed in a sleeve at 90° while traveling at a speed of 20.9 mi/h. The direct embedded post (and sleeve) was pushed toward the field side 13.0 inches at grade and was leaning 63° toward the field side. Maximum stroke on the honeycomb nose was 5.25 inches. Figures 3.15 and 3.16 show the post and bogie, respectively, after the test. Acceleration-time, force-time, and force-displacement curves are provided in Figures 3.17 through 3.19.

Figure 3.15. Post in Steel Sleeve after Test No. 611011-B3.

Figure 3.16. Bogie Test Vehicle after Test No. 611011-B3.

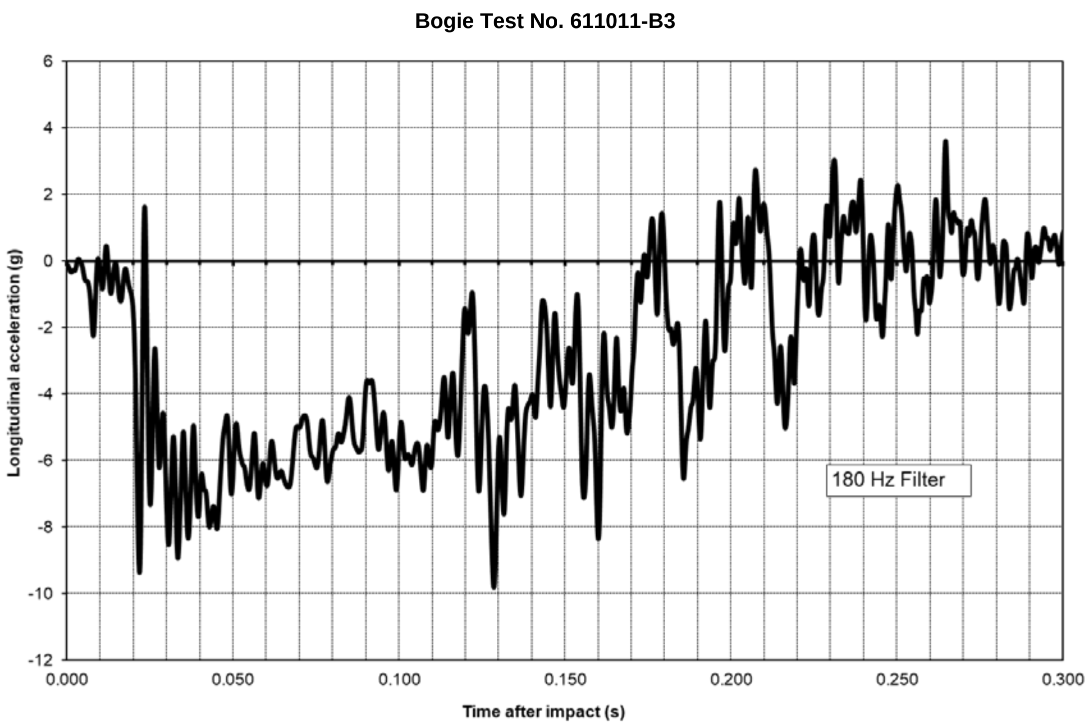

Figure 3.17. Longitudinal Acceleration for Test No. 611011-B3.

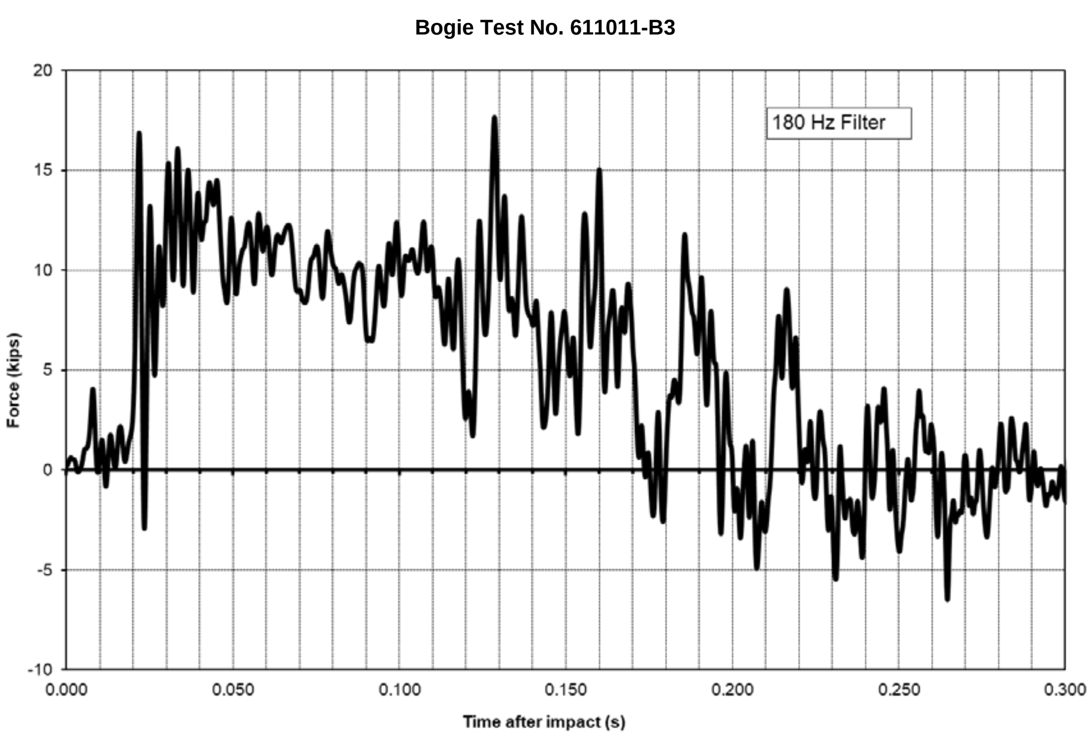

Figure 3.18. Force for Test No. 611011-B3.

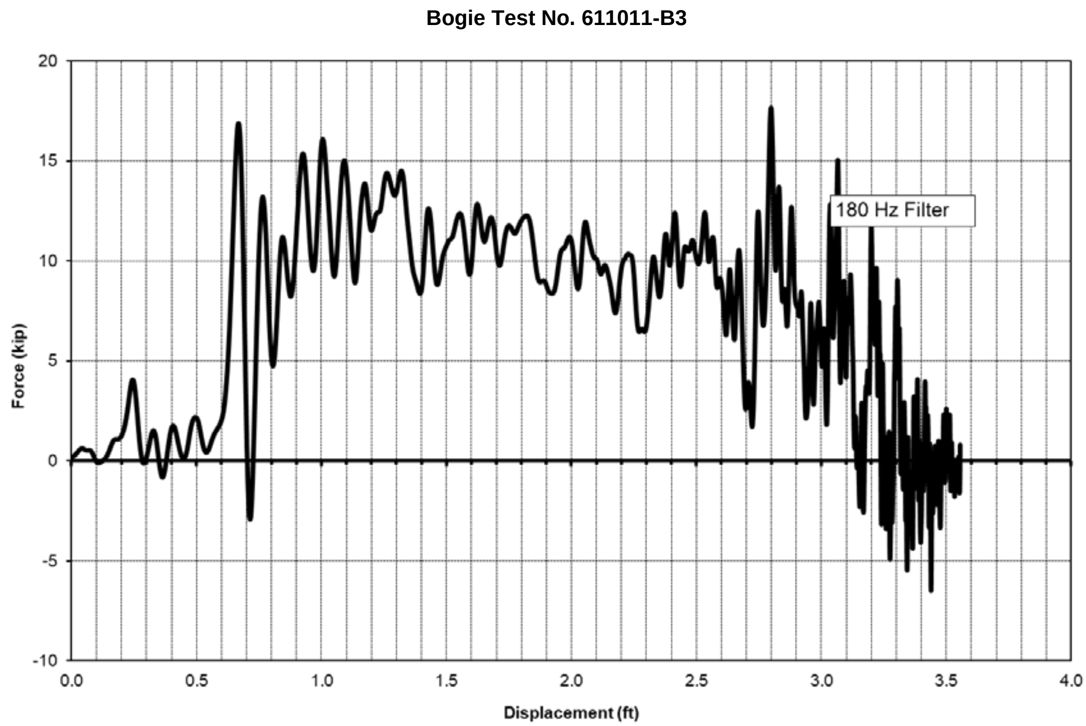

Figure 3.19. Force vs Displacement for Test No. 611011-B3.

3.7.2 Bogie Test No. 611011-B4

The bogie impacted the post installed in a sleeve at 90° while traveling at a speed of 25.1 mi/h. The direct embedded post (and sleeve) was pushed toward the field side 3.0 inches at grade and was leaning 60° toward the field side. Maximum stroke on the honeycomb nose was 6.0 inches. Figures 3.20 and 3.21 show the post and bogie, respectively, after the test. Acceleration-time, force-time, and force-displacement curves are provided in Figures 3.22 through 3.24.

Figure 3.20. Post in Steel Sleeve after Test No. 611011-B4.

Figure 3.21. Bogie Test Vehicle after Test No. 611011-B4.

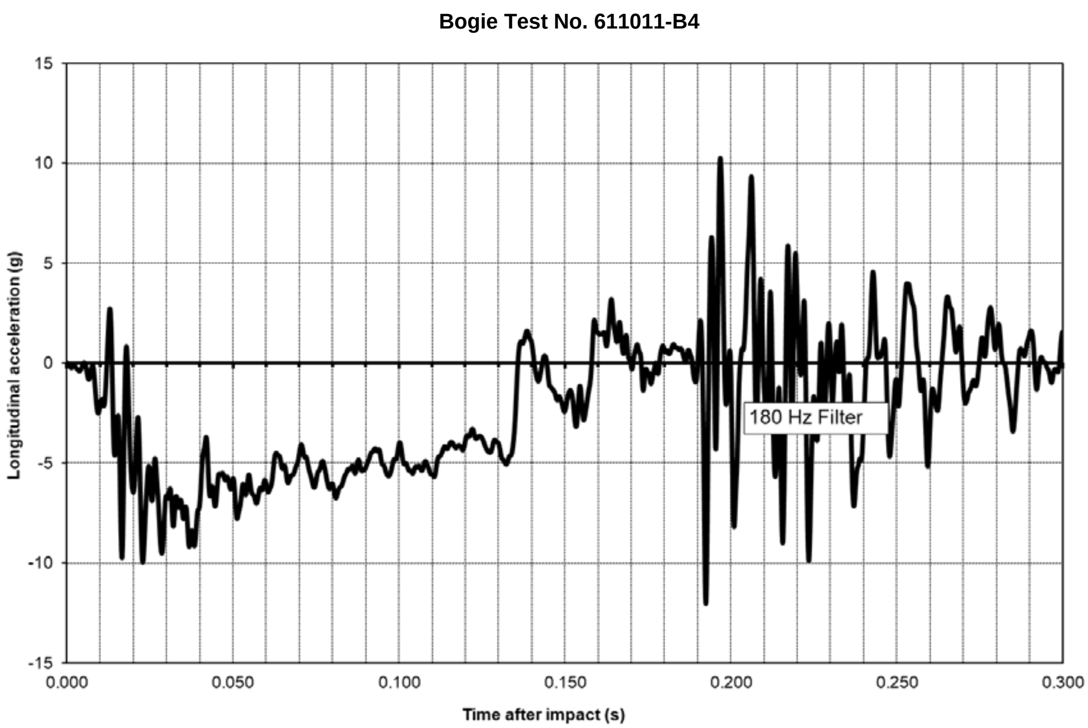

Figure 3.22. Longitudinal Acceleration for Test No. 611011-B4.

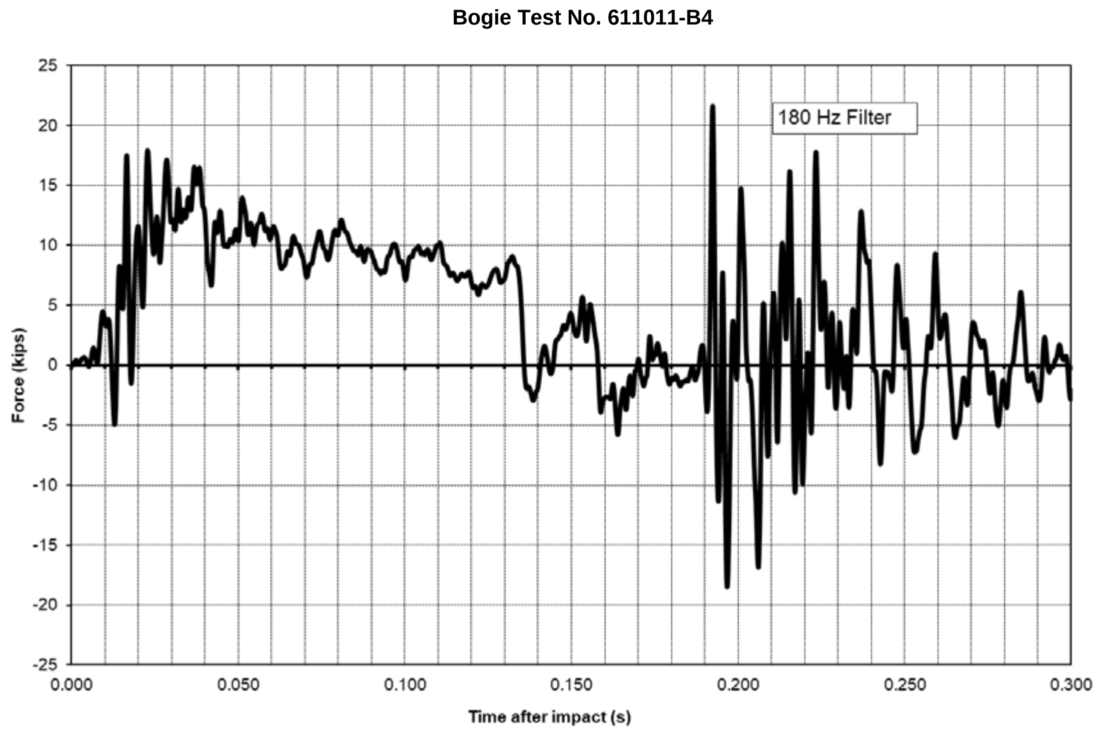

Figure 3.23. Force for Test No. 611011-B4.

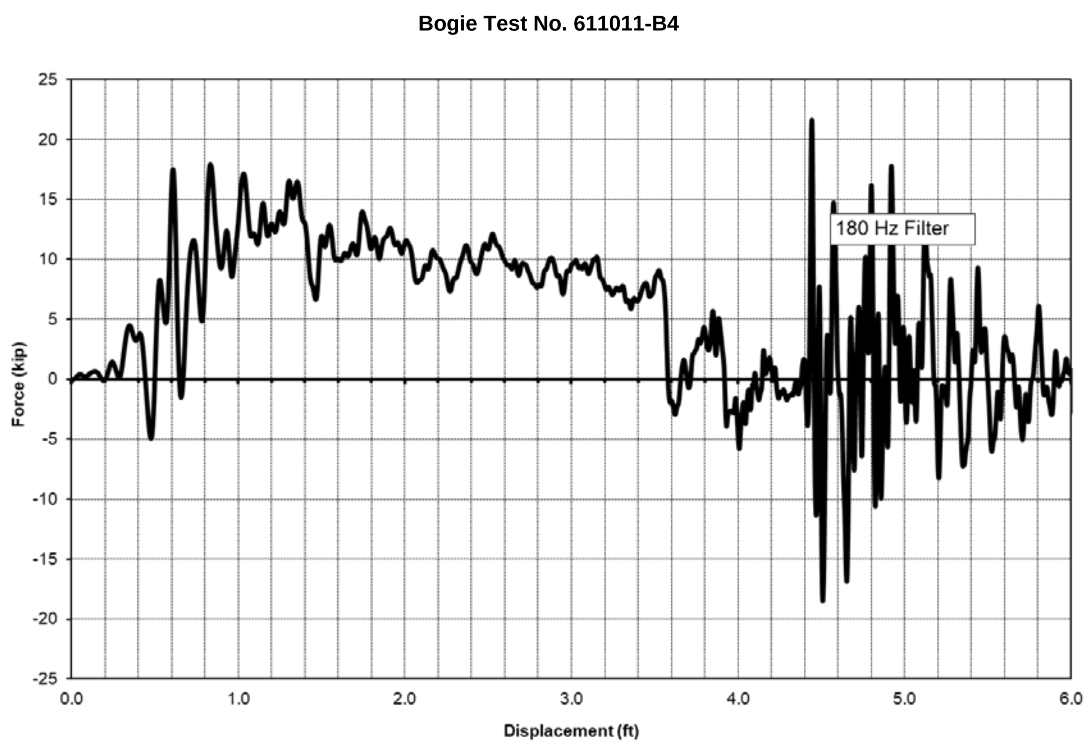

Figure 3.24. Force vs Displacement for Test No. 611011-B4.

3.8 SUMMARY OF RESULTS OF BOGIE TESTING

Comparisons of the force-displacement and energy-time responses of the direct-embedded and in-sleeve posts, for the target impact speeds of 21 mi/h and 25 mi/h, are shown in Figures 3.25 and 3.26, respectively. The response of both post types is very similar for both impact speeds. Due to the similarities in the bogie impact testing, the researchers proceeded with performing *MASH* Test 3-35, details of which are described in the following chapters. Figure 3.27 shows the deformed posts after the bogie testing. Directly embedded posts were more deformed, closer to the ground level, while the posts in sleeves had much less deformation.

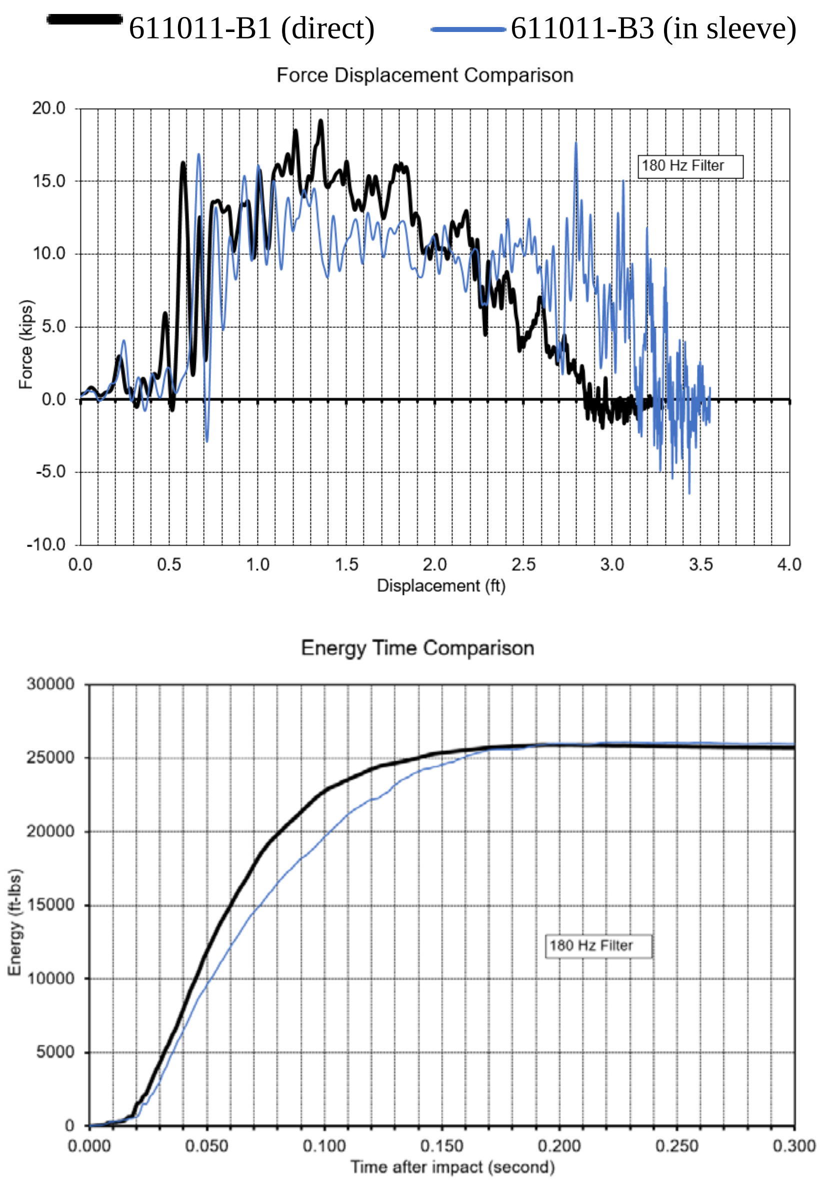

Figure 3.25. Force-Displacement and Energy-Time Comparisons of Posts with 21 mi/h Impact.

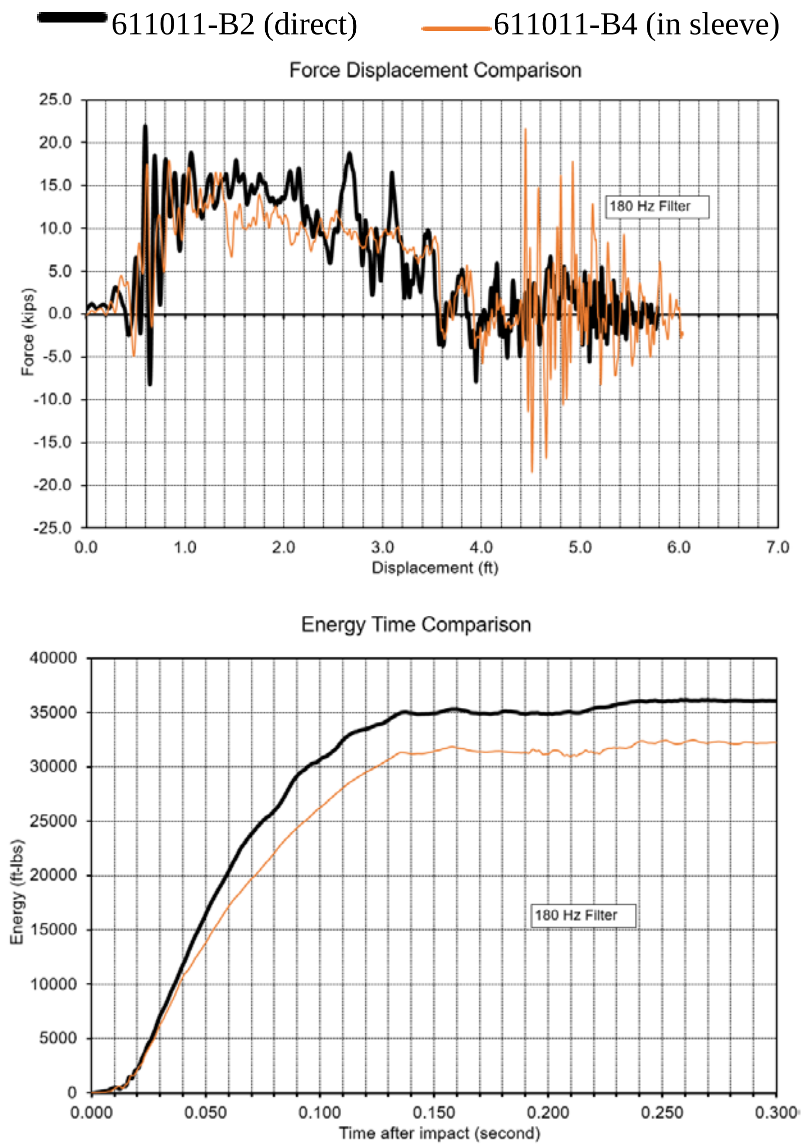

Figure 3.26. Force-Displacement and Energy-Time Comparisons of Posts with 25 mi/h Impact.

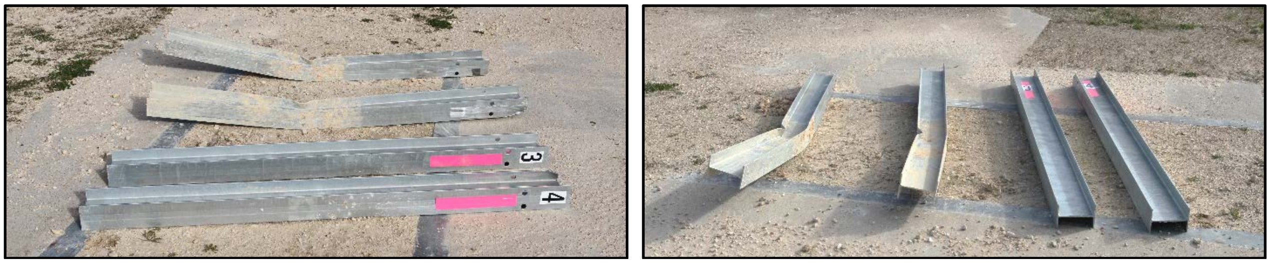

Figure 3.27. Comparison of Posts after Test Nos. 611011-B1-B4.

Chapter 4. SYSTEM DETAILS

4.1 TEST ARTICLE AND INSTALLATION DETAILS

The test installation was 181 ft 3 inches long, and the distance from the ground surface to the top of the W-beam was 31 inches for the entire length of the rail. A Texas Department of Transportation (TxDOT) DAT terminal was installed on each end, and the remaining installation consisted of 12-gauge, 4-space W-beam guardrail supported by W6x8.5 x72-inch guardrail posts spaced at 75 inches. Posts 3 through 11 were inserted into 45-inch long steel tube sleeves, and rested on a bolt inserted through the sleeves near the bottom. The posts and sleeves were installed in compacted crushed limestone base. Rail splices were located midway between the posts.

Timber blockouts were used as spacers between the guardrail and posts. A 10-inch button-head guardrail bolt secured the rail and blockout to each post.

Figure 4.1 presents overall information on the 31-inch W-beam guardrail system and Figure 4.2 provides photographs of the installation. Appendix B provides further details of the test installation.

4.2 MATERIAL SPECIFICATIONS

Appendix C provides material certification documents for the materials used to install/construct the guardrail installation.

4.3 SOIL CONDITIONS

The test installation was installed in standard soil meeting grading B of AASHTO standard specification M147-65(2004) “Materials for Aggregate and Soil Aggregate Subbase, Base and Surface Courses.”

During installation, two W6×16 posts were installed in the immediate vicinity of the guardrail system utilizing the same fill materials and installation procedures used in the test installation. In accordance with Appendix B of *MASH*, soil strength was measured the day of the crash test using the posts installed near the test installation.

The minimum post loads required for deflections at 5 inches, 10 inches, and 15 inches, of the posts, measured at a height of 25 inches, are 3940 lb, 5500 lb, and 6540 lb, respectively (90% of static load for the baseline standard installation). On the day of the test, April 29, 2019, loads on the post installed near the test installation, at deflections of 5 inches, 10 inches, and 15 inches were 6781 lbf, 7056 lbf, and 7263 lbf, respectively. Table D.3 in Appendix D shows the strength of the backfill material, in which the 31-inch guardrail system was installed, met minimum *MASH* requirements.

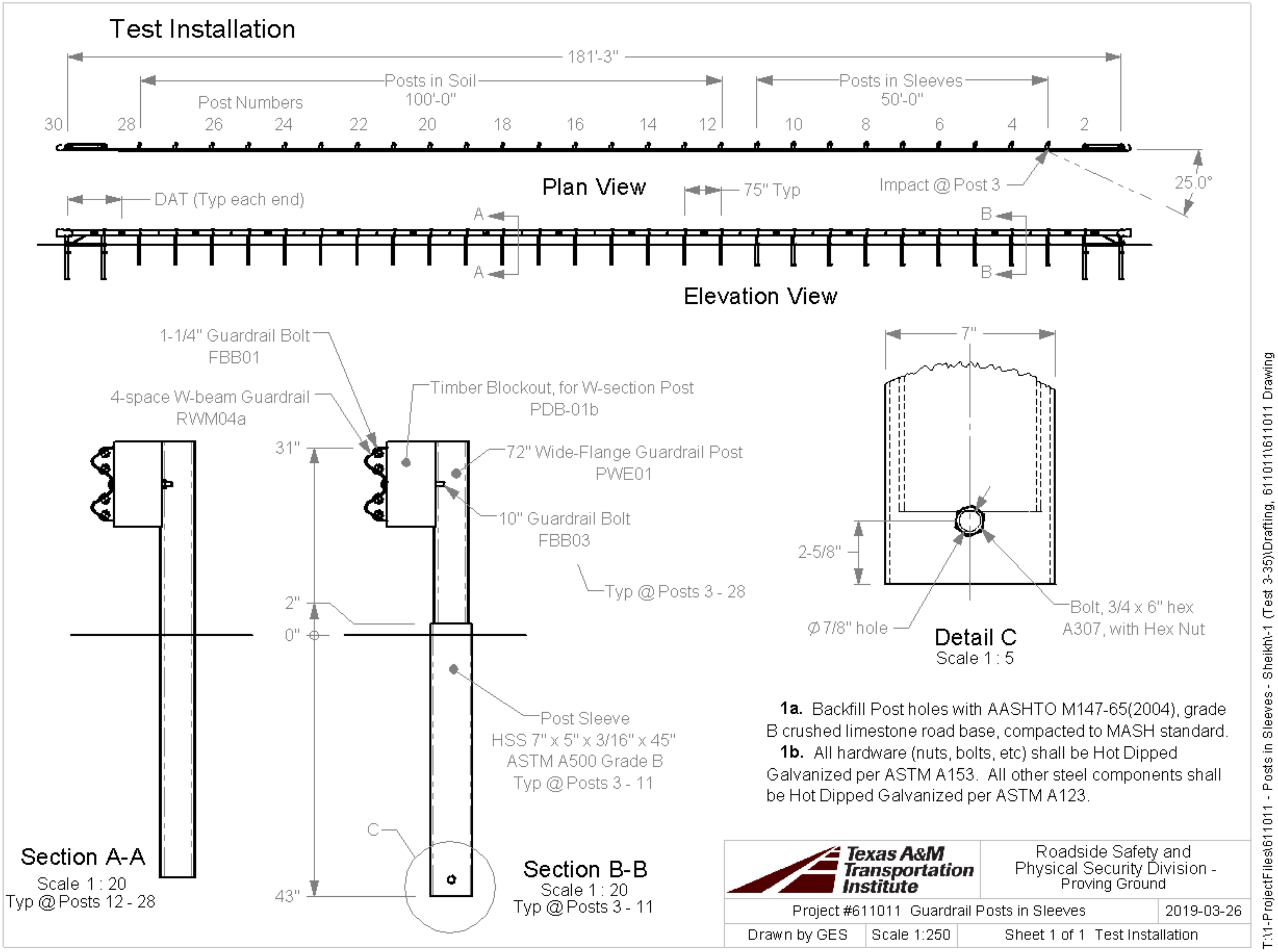

Figure 4.1. Details of 31-inch Guardrail Terminal with Steel Posts in Steel Sleeves.

Figure 4.2. 31-inch Guardrail Terminal with Steel Posts in Steel Sleeves prior to Testing.

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Chapter 5. TEST REQUIREMENTS AND EVALUATION CRITERIA

5.1 CRASH TEST PERFORMED / MATRIX

Table 5.1 shows the test conditions and evaluation criteria for *MASH* TL-3 for terminals and crash cushions. As explained in Section 1.3.2, only *MASH* Test 3-35 was performed to evaluate the performance of the guardrail and the terminal with posts installed in steel sleeves.

Table 5.1. Test Conditions and Evaluation Criteria Specified for *MASH* TL-3 Terminals.

Test Article	Test Designation	Test Vehicle	Impact Conditions		Evaluation Criteria
			Speed	Angle	
Terminals and Redirective Crash Cushions	3-30	1100C	62 mi/h	0°	A, D, F, H, I
	3-31	2270P	62 mi/h	0°	A, D, F, H, I
	3-32	1100C	62 mi/h	5-15°	A, D, F, H, I
	3-33	2270P	62 mi/h	5-15°	A, D, F, H, I
	3-34	1100C	62 mi/h	15°	A, D, F, H, I
	3-35	2270P	62 mi/h	25°	A, D, F, H, I
	3-36	2270P	62 mi/h	25°	A, D, F, H, I
	3-37a	2270P	62 mi/h	25°	A, D, F, H, I
	3-37b	1100C			
	3-38	1500A	62 mi/h	0°	A, D, F, H, I

MASH Test 3-35 was performed on the 31-inch W-beam guardrail terminal with steel posts in steel sleeves. The target impact point for *MASH* Test 3-35 was determined using the information provided in *MASH* Section 2.2.2, Section 2.2.2.2, and Figure 2-3A. The beginning of length of need of the terminal and target impact point was at post 3, and is shown in Figure 5.1.

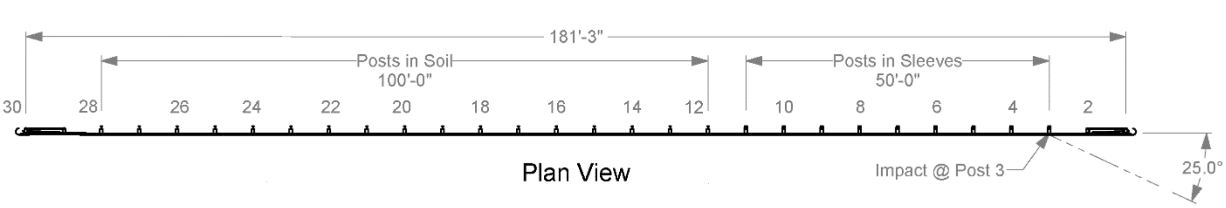

Figure 5.1. Target CIP for *MASH* Test 3-35 on the Terminal.

The crash test and data analysis procedures were in accordance with guidelines presented in *MASH*. Chapter 6 presents brief descriptions of these procedures.

5.2 EVALUATION CRITERIA

The appropriate safety evaluation criteria from Tables 2-3 and 5-1 of *MASH* were used to evaluate the crash test reported herein. The test conditions and evaluation criteria required for *MASH* Test 3-35 for terminals are listed in Table 5.1, and the substance of the evaluation criteria in Table 5.2. An evaluation of the crash test results is presented in detail under the section Assessment of Test Results.

Table 5.2. Evaluation Criteria Required for *MASH* Test 3-35 for Terminals.

Evaluation Factors	Evaluation Criteria
Structural Adequacy	*A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.*
Occupant Risk	*D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone.* *Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.*
	F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.
	H. Occupant impact velocities (OIV) should satisfy the following limits: Preferred value of 30 ft/s, or maximum allowable value of 40 ft/s.
	I. The occupant ridedown accelerations should satisfy the following: Preferred value of 15.0 g, or maximum allowable value of 20.49 g.

Chapter 6. TEST CONDITIONS

6.1 TEST FACILITY

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

The test facilities of the TTI Proving Ground are located on the Texas A&M University System RELLIS Campus, which consists of a 2000-acre complex of research and training facilities situated 10 miles northwest of the flagship campus of Texas A&M University. The site, formerly a United States Army Air Corps base, has large expanses of concrete runways and parking aprons well suited for experimental research and testing in the areas of vehicle performance and handling, vehicle-roadway interaction, durability and efficacy of highway pavements, and evaluation of roadside safety hardware and perimeter protective devices. The site selected for construction and testing of the 31-inch W-beam guardrail system was along the edge of an out-of-service apron. The apron consists of an unreinforced jointed-concrete pavement in 12.5-ft × 15-ft blocks nominally 6 inches deep. The aprons were built in 1942, and the joints have some displacement, but are otherwise flat and level.

6.2 VEHICLE TOW AND GUIDANCE SYSTEM

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

6.3 DATA ACQUISITION SYSTEMS

6.3.1 Vehicle Instrumentation and Data Processing

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

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

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

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

6.3.2 Anthropomorphic Dummy Instrumentation

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

6.3.3 Photographic Instrumentation Data Processing

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

- One overhead with a field of view perpendicular to the ground and directly over the impact point;
- One placed behind the installation at an angle; and
- A third placed to have a field of view parallel to and aligned with the installation at the downstream end.

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

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Chapter 7. *MASH* TEST 3-35 (CRASH TEST NO. 611011-1)

7.1 TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH Test 3-35 involves a 2270P vehicle weighing 5000 lb ±110 lb impacting the beginning of length of need of the terminal at an impact speed of 62 mi/h ±2.5 mi/h and an angle of 25° ±1.5°. The beginning of length of need for *MASH* Test 3-35 on the terminal was selected as post 3.

The 2015 RAM 1500 pickup truck used in the test weighed 5024 lb, and the actual impact speed and angle were 64.0 mi/h and 25.4°, respectively. The actual impact point was 1.5 inches upstream of the centerline of post 3. Minimum target impact severity (IS) was 106 kip-ft, and actual IS was 127 kip-ft.

7.2 WEATHER CONDITIONS

The test was performed on the morning of April 29, 2019. Weather conditions at the time of testing were as follows: wind speed: 9 mi/h; wind direction: 163° (vehicle was traveling at 205°); temperature: 77°F; relative humidity: 82 percent.

7.3 TEST VEHICLE

Figures 7.1 and 7.2 show the 2015 RAM 1500 pickup truck used for the crash test. The vehicle's test inertia weight was 5024 lb, and its gross static weight was 5024 lb. The height to the lower edge of the vehicle bumper was 11.75 inches, and height to the upper edge of the bumper was 27.0 inches. The height to the vehicle's center of gravity was 28.0 inches. Tables E.1 and E.2 in Appendix E1 give additional dimensions and information on the vehicle. The vehicle was directed into the installation using the cable reverse tow and guidance system, and was released to be freewheeling and unrestrained just prior to impact.

Figure 7.1. Terminal/Test Vehicle Geometrics for Test No. 611011-1.

Figure 7.2. Test Vehicle before Test No. 611011-1.

7.4 TEST DESCRIPTION

The test vehicle was traveling at an impact speed of 64.0 mi/h when it contacted the terminal 1.5 inches upstream of the centerline of post 3 at an impact angle of 25.4°. Table 7.1 lists events that occurred during Test No. 611011-1. Figures E.1 and E.2 in Appendix E2 present sequential photographs during the test.

Table 7.1. Events during Test No. 611011-1.

TIME (s)	EVENTS
0.0000	Vehicle contacts terminal
0.0020	Post 3 begins to move toward field side
0.0110	Post 4 begins to move toward field side
0.0210	Post 2 begins to move toward field side
0.0410	Post 5 begins to move toward field side
0.0460	Vehicle begins to redirect.
0.0800	Post 6 begins to move toward field side
0.1180	Post 2 breaks at grade
0.2950	Vehicle is parallel with rail.
0.4690	Vehicle loses contact with barrier while traveling at 32.9 mi/h, exit trajectory of 16.9° with a heading of 9.8° from terminal.

For longitudinal barriers, it is desirable that the vehicle redirects and exits the barrier within the exit box criteria (not less than 32.8 ft downstream from loss of contact for cars and pickups). The test vehicle exited within the exit box criteria defined in *MASH*. After loss of contact with the terminal, the vehicle came to rest 111 ft downstream of the impact and 3 ft toward traffic lanes. Brakes on the vehicle were not applied.

7.5 DAMAGE TO TEST INSTALLATION

Figure 7.3 shows the damage to the guardrail and the DAT terminal. Post 1 was leaning downstream at 85°. Post 2 broke off at grade. Post 3 rotated 95° clockwise and was leaning toward the field side at 85°. Posts 4 through 7 were leaning back at approximately 0-10°, and post 8 was leaning downstream at 53°. The blockouts were missing from posts 4, 5, 7, and 8, and the rail released from posts 1 through 9. Figure 7.4 shows movement of some of the sleeves. Working width* was 54.9 inches, and height of working width was 54.0 inches. Maximum dynamic deflection during the test was 48.5 inches. The maximum permanent deflection was 41.1 inches, located 2 feet downstream of the original post 6 location.

Figure 7.3. Terminal after Test No. 611011-1.

* Working width is defined as the distance between the traffic face of the barrier before impact and the maximum lateral position of any major part of the barrier or the vehicle after impact.

Figure 7.4. Movement of Some of the Sleeves after Test No. 611011-1.

7.6 VEHICLE DAMAGE

Figure 7.5 shows the damage sustained by the vehicle. The front bumper, grill, right front tire and rim, right lower A-arm, right front fender, right front door, right rear exterior bed, and rear bumper were damaged. Maximum exterior crush to the vehicle was 7.0 inches in the side plane at the right front corner at bumper height. No occupant compartment deformation or intrusion was observed. Figure 7.6 shows the interior of the vehicle. Tables E.3 and E.4 in Appendix E1 provide exterior crush and occupant compartment measurements.

Figure 7.5. Test Vehicle after Test No. 611011-1.


Figure 7.6. Front Impact-Side Interior of Test Vehicle after Test No. 611011-1.

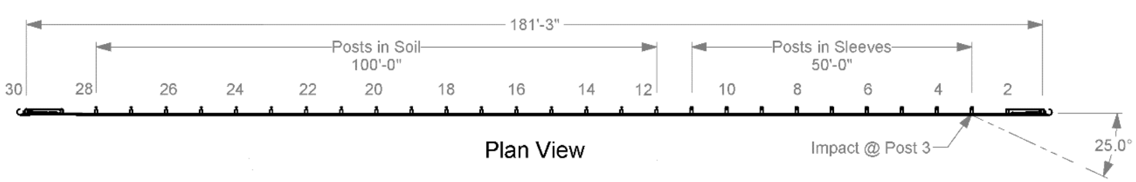
7.7 OCCUPANT RISK FACTORS

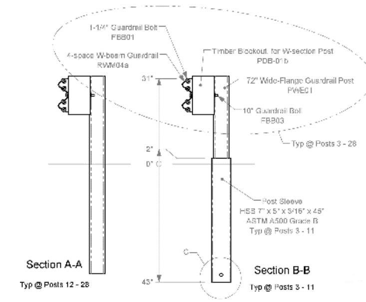
Data from the accelerometer, located at the vehicle center of gravity, were digitized for evaluation of occupant risk and results are shown in Table 7.2. Figure 7.7 summarizes these data and other pertinent information from the test. Figure E.3 in Appendix E3 shows the vehicle angular displacements, and Figures E.4 through E.6 in Appendix E4 show acceleration versus time traces.

Table 7.2. Occupant Risk Factors for Test No. 611011-1.

Occupant Risk Factor	Value	Time
OIV		
Longitudinal	**14.8 ft/s**	0.1561 s on right side of interior
Lateral	**14.4 ft/s**	
Occupant Ridedown Accelerations		
Longitudinal	**7.0 g**	0.2756 - 0.2856 s
Lateral	**5.6 g**	0.2586 - 0.2686 s
THIV	**21.8 km/h** **6.1 m/s**	at 0.1496 s on right side of interior
PHD	**8.2 g**	0.2754 - 0.2854 s
ASI	**0.63**	0.2682 - 0.3182 s
Maximum 50-ms Moving Average		
Longitudinal	**-4.9 g**	0.0853 - 0.1353 s
Lateral	**-4.7 g**	0.2432 - 0.2932 s
Vertical	**1.7 g**	0.5883 - 0.6383 s
Maximum Roll, Pitch, and Yaw Angles		
Roll	**6°**	0.9930 s
Pitch	**7°**	0.6460 s
Yaw	**37°**	0.8597 s

0.000 s	0.200 s	0.400 s	0.600 s





General Information

Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	MASH Test 3-35
TTI Test No.	611011-1
Test Date	2019-04-29

Test Article

Type	Terminal
Name	TxDOT DAT with Posts in Steel Sleeves
Installation Length	181 ft 3 inches
Material or Key Elements	31 inch tall TxDOT DAT with 72-inch long Wide-Flange Guardrail Posts, spaced at 75 inches, inserted into 45-inch long sleeves, resting on a bolt inserted through the sleeves
Soil Type and Condition	AASHTO M147-65(2004), grading B Soil (crushed limestone), Damp/Dry

Test Vehicle

Type/Designation	2270P
Make and Model	2015 RAM 1500 Pickup
Curb	4925 lb
Test Inertial	5024 lb
Dummy	No dummy
Gross Static	5024 lb

Impact Conditions

Speed	64.0 mi/h
Angle	24.5°
Location/Orientation	1.5 inches upstream centerline of post 3
Impact Severity	127 kip-ft

Exit Conditions

Speed	32.9 mi/h
Trajectory/Heading Angle	16.9° / 9.8°

Occupant Risk Values

Longitudinal OIV	14.8 ft/s
Lateral OIV	14.4 ft/s
Longitudinal Ridedown	7.0 g
Lateral Ridedown	5.6 g
THIV	21.8 km/h
PHD	8.2 g
ASI	0.63
Max. 0.050-s Average	
Longitudinal	-4.9 g
Lateral	-4.7 g
Vertical	1.7 g

Post-Impact Trajectory

Stopping Distance	111 ft downstream 3 ft twd traffic lanes

Vehicle Stability

Maximum Yaw Angle	37°
Maximum Pitch Angle	7°
Maximum Roll Angle	6°
Vehicle Snagging	No
Vehicle Pocketing	No

Test Article Deflections

Dynamic	48.5 inches
Permanent	Released from posts
Working Width	54.9 inches
Height of Working Width	54.0 inches

Vehicle Damage

VDS	01RFQ5
CDC	01FREW3
Max. Exterior Deformation	7.0 inches
OCDI	FR0000000
Max. Occupant Compartment Deformation	None

Figure 7.7. Summary of Results for *MASH* Test 3-35 on 31-inch W-Beam Guardrail with DAT Terminal and Steel Posts in Steel Sleeves.

Chapter 8. SUMMARY AND CONCLUSIONS

8.1 ASSESSMENT OF TEST RESULTS

The crash test reported herein was performed in accordance with *MASH* Test 3-35, which involves a 2270P vehicle impacting the 31-inch W-beam guardrail terminal with steel posts in steel sleeves at a target impact speed and impact angle of 62 mi/h and 25°, respectively. An assessment of the test based on the applicable safety evaluation criteria for *MASH* Test 3-35 for terminals is provided in Table 6.1.

8.2 CONCLUSIONS

The 31-inch W-beam guardrail with DAT terminal and steel posts in steel sleeves performed acceptably for *MASH* Test 3-35 for terminals.

Table 8.1. Performance Evaluation Summary for *MASH* Test 3-35 on 31-inch W-Beam Guardrail with DAT Terminal anda Steel Posts in Steel Sleeves.

Test Agency: Texas A&M Transportation Institute | Test No.: 611011-1 | Test Date: 2019-04-29

***MASH* Test 3-35 Evaluation Criteria**	**Test Results**	**Assessment**
<u>Structural Adequacy</u> *A. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.*	The guardrail contained and redirected the 2270P vehicle. The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 48.5 inches.	Pass
<u>Occupant Risk</u> *D. Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians, or personnel in a work zone.*	The W-beam rail element and several blockouts separated from the posts, however, these elements did not penetrate or show potential for penetrating the occupant compartment, or present hazard to others in the area.	Pass
Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E of MASH.	No occupant compartment deformation or intrusion was observed.	
F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.	The 2270P vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 6° and 7°, respectively.	Pass
H. Occupant impact velocities (OIV) should satisfy the following limits: Preferred value of 30 ft/s, or maximum allowable value of 40 ft/s.	Longitudinal OIV was 14.8 ft/s, and lateral OIV was 14.4 ft/s.	Pass
I. The occupant ridedown accelerations should satisfy the following limits: Preferred value of 15.0 g, or maximum allowable value of 20.49 g.	Longitudinal occupant ridedown acceleration was 7.0 g, and lateral occupant ridedown acceleration was 5.6 g.	Pass
<u>Vehicle Trajectory</u> For redirective devices, it is preferable that the vehicle be smoothly redirected and leave the barrier within the “exit box” criteria (not less than 32.8 ft for the 1100C and 2270P vehicles), and should be documented.	The 2270P vehicle exited within the exit box requirements.	Documentation only

Chapter 9. IMPLEMENTATION*

Results of this research project are considered suitable for immediate implementation. The surrogate bogie vehicle impact tests showed that the W-beam guardrail steel posts installed in buried steel sleeves performed very similar to the directly embedded posts. This was also confirmed by a successful *MASH* Test 3-35 performed on a non-proprietary DAT terminal with posts installed in steel sleeves. Other *MASH* tests for guardrail end terminals were not considered necessary for evaluation of the performance of the posts installed in sleeves (see section 1.3.2 for more explanation).

The results of *MASH* Test 3-35 are also considered applicable to *MASH* Test 3-11 due to both tests having the same impact conditions. Furthermore, due to the similar behavior of posts in sleeves compared to directly embedded posts, as observed in bogie impact testing, *MASH* Test 3-10 was not considered necessary (see section 1.3.2 for more explanation).

Based on this research, W-beam guardrail steel posts in end terminals may be installed in buried steel sleeves as tested in this project. Furthermore, the steel posts may also be installed in buried steel sleeves in the length of need of the W-beam guardrail.

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

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REFERENCES

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

2. FHWA Letter of Eligibility, HSST-1/CC-126, https://safety.fhwa.dot.gov/roadway_dept/countermeasures/reduce_crash_severity/barriers/pdf/cc126.pdf, Washington, D.C. June, 2016, Retrieved August, 2019.

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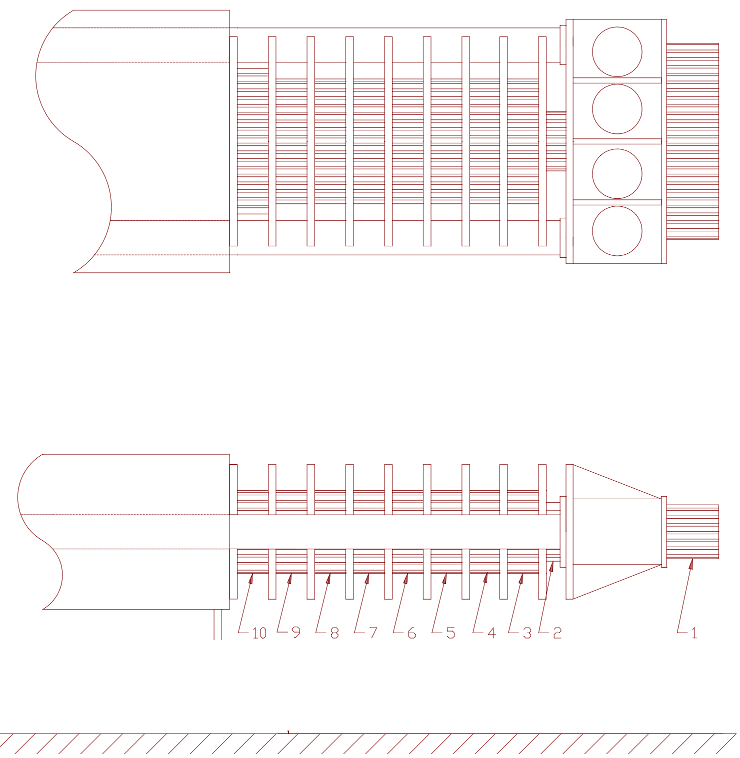
APPENDIX A. BOGIE NOSE DETAILS



Cartridge Number	Size (inches)	Area Effectively Removed by Pre-Crushing (inches^2)	Static Crush Strength (psi)	Total Nominal Crush Force for Each Cartridge (lbf)
1	2.75 × 16 × 3		130	5720
2	4 × 5 × 2		25	500
3	8 × 8 × 3	21	130	5590
4	8 × 8 × 3	15	230	11270
5	8 × 8 × 3	6	230	13340
6	8 × 8 × 3		230	14720
7	8 × 8 × 3	21	400	17200
8	8 × 8 × 3	12	400	20800
9	8 × 8 × 3		400	25600
10	8 × 10 × 3		400	32000

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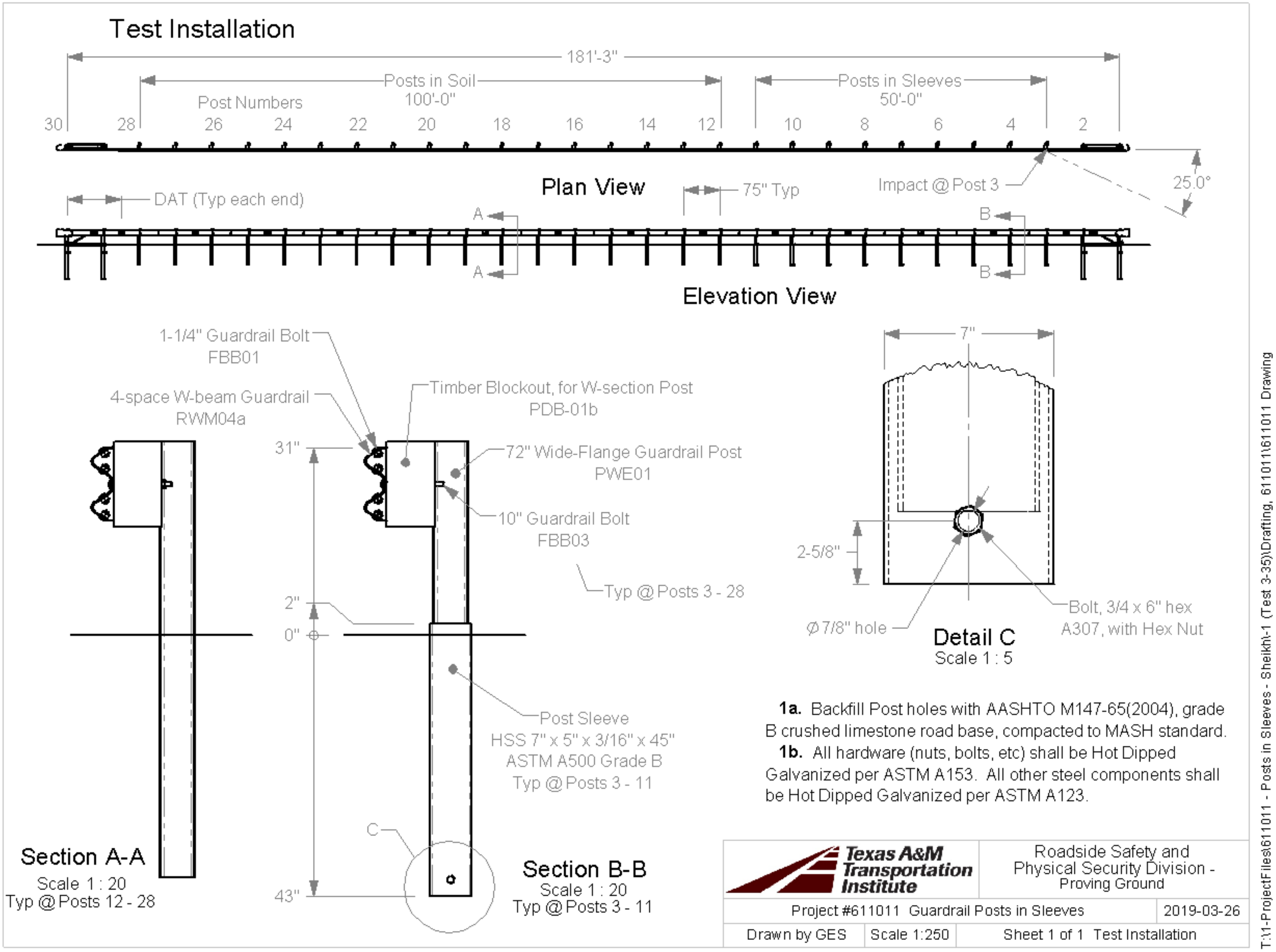
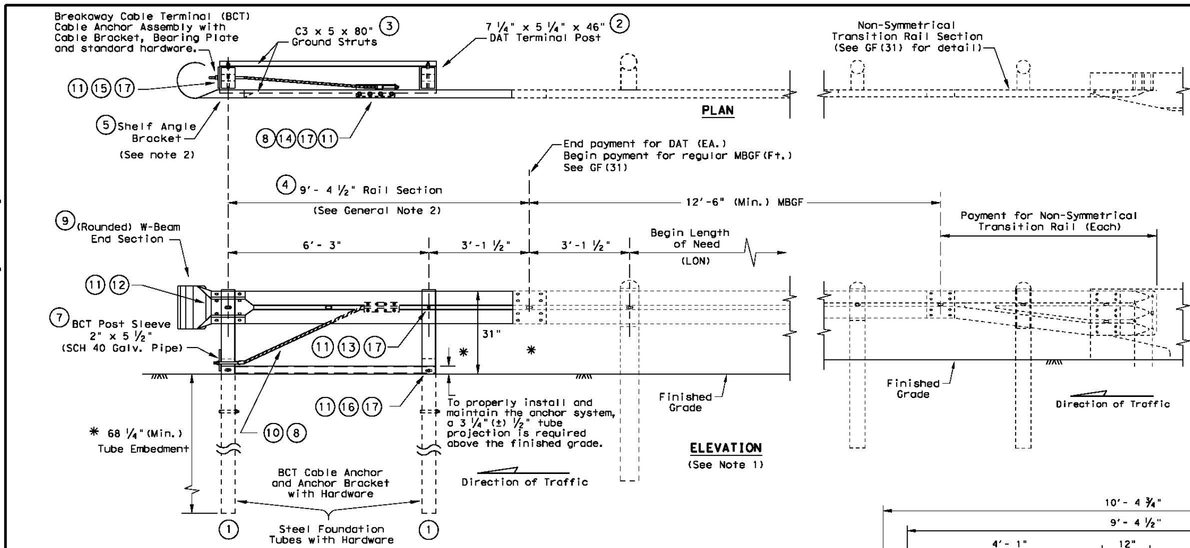
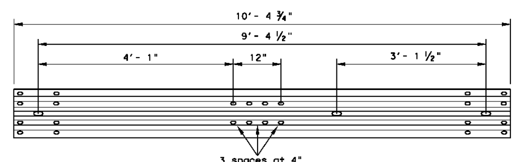
APPENDIX B. DETAILS OF THE INSTALLATION





DOWNSTREAM ANCHOR TERMINAL (DAT)

Only for downstream use, when located outside the horizontal clearance area of opposing traffic.



(4) **TERMINAL RAIL ELEMENT FOR DAT**

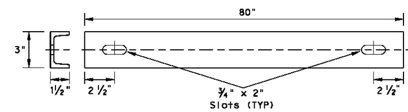
GENERAL NOTES

1. The detail shown is the minimum Length of Need (LON) for a DAT connected to a concrete rail.
2. The rail section at the end post is supported by the Shelf Angle Bracket. The rail element is not attached to the end post.
3. The foundation tubes shall not project more than 3 3/4" above the finished grade.
4. All hardware for DAT shall be ASTM A307 unless otherwise shown.
5. Refer to GF(31) sheet for terminal connection details.

MOW STRIP INSTALLATION

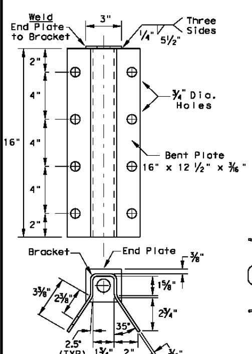
If a mow strip is required with the DAT installation the leave-out area around the steel foundation tubes and the two channel struts may be omitted. This will require a full pour at the foundation tubes.

#	(DAT) PARTS LIST	QTY
1	Steel Foundation Tube	2
2	DAT Terminal Post	2
3	Channel Strut	2
4	Terminal Rail Element	1
5	Shelf Angle Bracket	1
6	BCT Bearing Plate	1
7	BCT Post Sleeve	1
8	Guardrail Anchor Bracket	1
9	(Rounded) W-Beam End Section	1
10	BCT Cable Anchor	1
11	Recessed Nut, Guardrail	20
12	1 1/4" Button Head Bolt	4
13	10" Button Head Bolt	2
14	5/8" x 2" Hex Head Bolt	8
15	5/8" x 8" Hex Head Bolt	4
16	5/8" x 10" Hex Head Bolt	2
17	5/8" Flat Washer	18

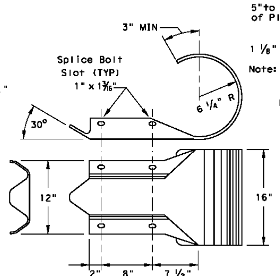


(3) **CHANNEL STRUT**

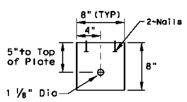
C3 x 5 x 80", Grade A36



(8) **GUARDRAIL ANCHOR BRACKET**

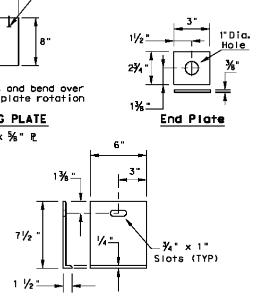


(9) **W-BEAM END SECTION (ROUNDED) (12 GA.)**

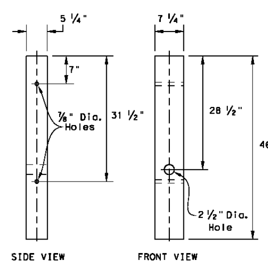


(6) **BEARING PLATE**

8" x 8" x 5/8" PL

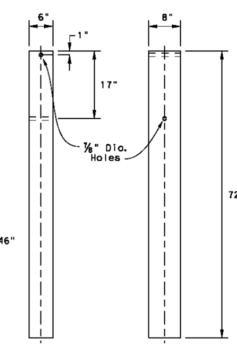


(5) **SHELF ANGLE BRACKET**



(2) **TERMINAL POST**

7 1/4" x 5 1/4" x 46" Wood Post



(1) **STEEL FOUNDATION TUBE**

6" x 8" x 1/8" x 72" Steel Tube

Texas Department of Transportation — Design Division Standard

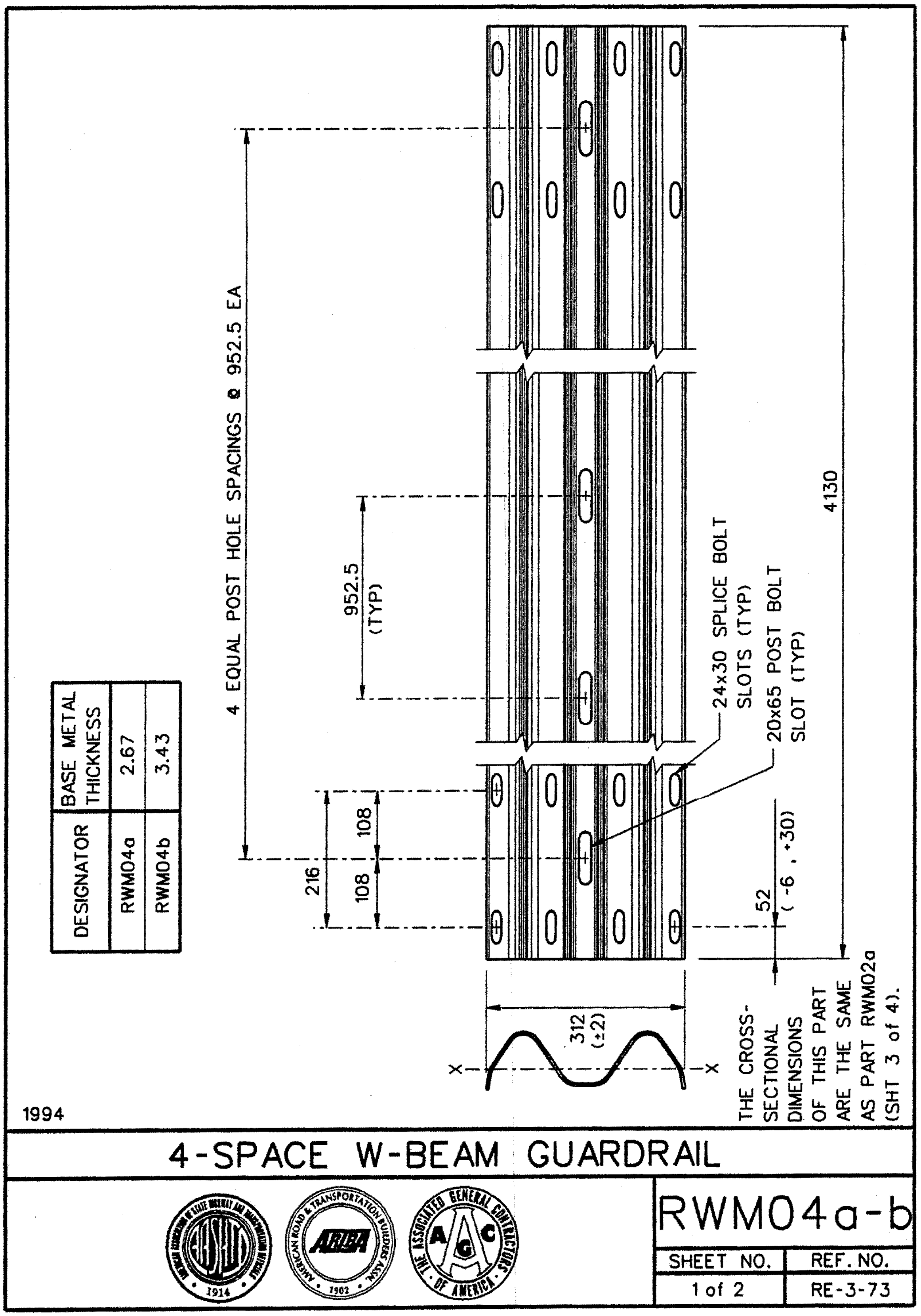
METAL BEAM GUARD FENCE

(Downstream Anchor Terminal)

GF(31)DAT-14

FILE: gf31dt14.dgn	DN: TxDOT	CK: AM	DW: VP	CK: CCL
© TxDOT: December 2011	CONT	SECT	JOB	HIGHWAY
REVISIONS	DIST	COUNTY		SHEET NO.

DATE:
FILE:


4 EQUAL POST HOLE SPACINGS @ 952.5 EA
952.5 (TYP)
4130
24x30 SPLICE BOLT SLOTS (TYP)
20x65 POST BOLT SLOT (TYP)
216
108
108
52 (-6 , +30)
312 (±2)
X
X
DESIGNATOR
BASE METAL THICKNESS
RWM04a
2.67
RWM04b
3.43
THE CROSS-SECTIONAL DIMENSIONS OF THIS PART ARE THE SAME AS PART RWM02a (SHT 3 of 4).
1994
4-SPACE W-BEAM GUARDRAIL
RWM04a-b
SHEET NO.
1 of 2
REF. NO.
RE-3-73

SPECIFICATIONS

Corrugated sheet steel beams shall conform to the current requirements of AASHTO M180. The section shall be manufactured from sheets with a nominal width of 483 mm. Guardrail RWM04a shall conform to AASHTO M180 Class A and RWM04b shall conform to Class B. Corrosion protection may be either Type II (zinc-coated) or Type IV (corrosion resistant steel). Corrosion resistant steel should conform to ASTM A606 for Type IV material and shall not be zinc-coated, painted or otherwise treated. Inertial properties are calculated for the whole cross-section without a reduction for the splice bolt holes.

Designator	Area (10^3 mm^2)	I_x (10^6 mm^4)	I_y (10^6 mm^4)	S_x (10^3 mm^3)	S_y (10^3 mm^3)
RWM04a-b	1.3	1.0	--	23	--

Dimensional tolerances not shown or implied are intended to be those consistent with the proper functioning of the part, including its appearance and accepted manufacturing practices.

INTENDED USE

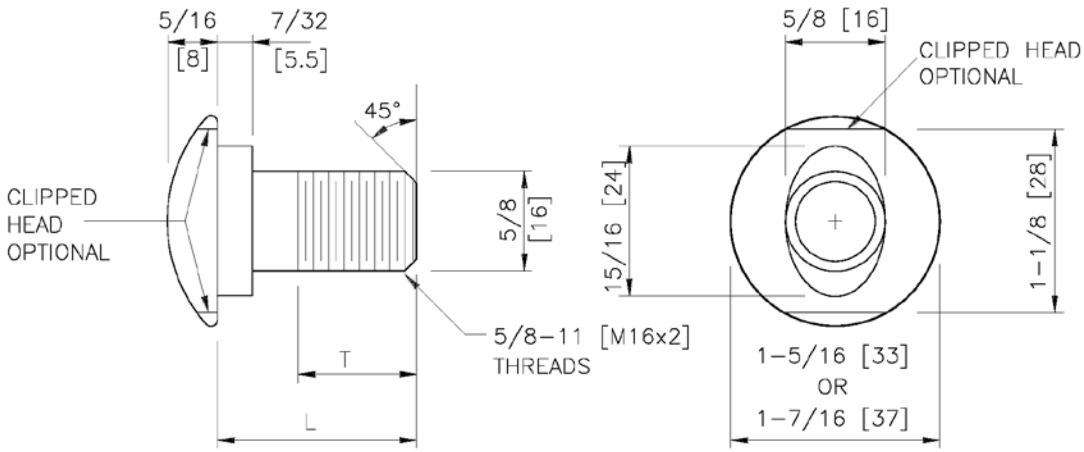
This corrugated sheet steel beam is used as a rail element in transition systems STB02 and STB03 or when a reduced post spacing is desired in the SGR02, SGR04a-b, SGM02, and SGM04a-b.

4-SPACE W-BEAM GUARDRAIL

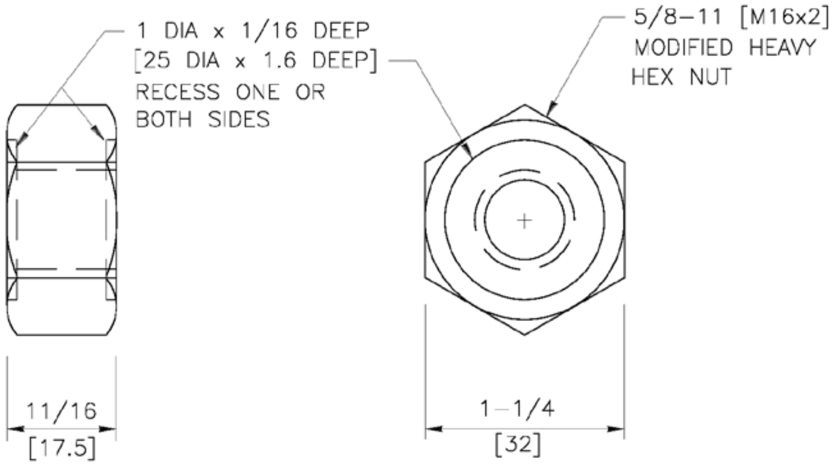
RWM04a-b

SHEET NO.	DATE
2 of 2	04-01-95

NOTES: 1. ALL FILLETS SHALL HAVE A MINIMUM RADIUS OF 1/16 [2].
2. IF THE BOLT EXTENDS MORE THAN 1/4 [6] FROM THE NUT THE BOLT SHOULD BE TRIMMED BACK.



DESIGNATOR	L	T (MIN)
FBB01	1-1/4 [32]	1-1/8 [28]
FBB02	2 [51]	1-3/4 [44]
FBB03	10 [254]	4 [102]
FBB04	18 [457]	4 [102]
FBB05	25 [635]	4 [102]



GUARDRAIL BOLT AND RECESSED NUT

TF13

FBB01-05

SHEET NO.	DATE:
1 of 2	5/2/2018

SPECIFICATIONS

The geometry and material specifications for this oval shoulder button-headed bolt and hex nut are found in AASHTO M 180. The bolt shall have 5/8-11 [M16x2] threads as defined in ANSI B1.1 [ANSI B1.13M] for Class 2A [6g] tolerances. Bolt material shall conform to ASTM A307 Grade A [ASTM F 568M Class 4.6], with a tensile strength of 60 ksi [400 MPa] and yield strength of 36 ksi [240 MPa]. Material for corrosion-resistant bolts shall conform to ASTM A325 Type 3 [ASTM F 568M Class 8.8.3], with tensile strength of 120 ksi [830 MPa] and yield strength of 92 ksi [660 MPa]. This bolt material has corrosion resistance comparable to ASTM A588 steels. Metric zinc-coated bolt heads shall be marked as specified in ASTM F 568 Section 9 with the symbol "4.6."

Nuts shall have ANSI B1.1 Class 2B [ANSI B1.13M Class 6h] 5/8-11 [M16x2] threads. The geometry of the nuts, with the exception of the recess shown in the drawing, shall conform to ANSI B18.2.2 [ANSI B18.2.4.1M Style 1] for zinc-coated hex nuts (shown in drawing) and ANSI B18.2.2 [ANSI B18.2.4.6M] for heavy hex corrosion-resistant nuts (not shown in drawing). Material for zinc-coated nuts shall conform to the requirements of AASHTO M 291 (ASTM A 563) Grade A [AASHTO M 291M (ASTM A 563M) Class 5], and material for corrosion-resistant nuts shall conform to the requirements of AASHTO M 291 (ASTM A 563) Grade C3 [AASHTO M 291M (ASTM A 563M) Class 8S3].

When zinc-coated bolts and nuts are required, the coating shall conform to either AASHTO M 232 (ASTM A 153/A 153M) for Class C or AASHTO M 298 (ASTM B 695) for Class 50. Zinc-coated nuts shall be tapped over-size as specified in AASHTO M 291 (ASTM A 563) [AASHTO M 291M (ASTM A 563M)], except that a diametrical allowance of 0.020 inch [0.510 mm] shall be used instead of 0.016 inches [0.420 mm].

Designator	Stress Area of Threaded Bolt Shank (in^2 [mm^2])	Min. Bolt Tensile Strength (kips [kN])
FBB01-05	0.226 [157.0]	13.6 [62.8]

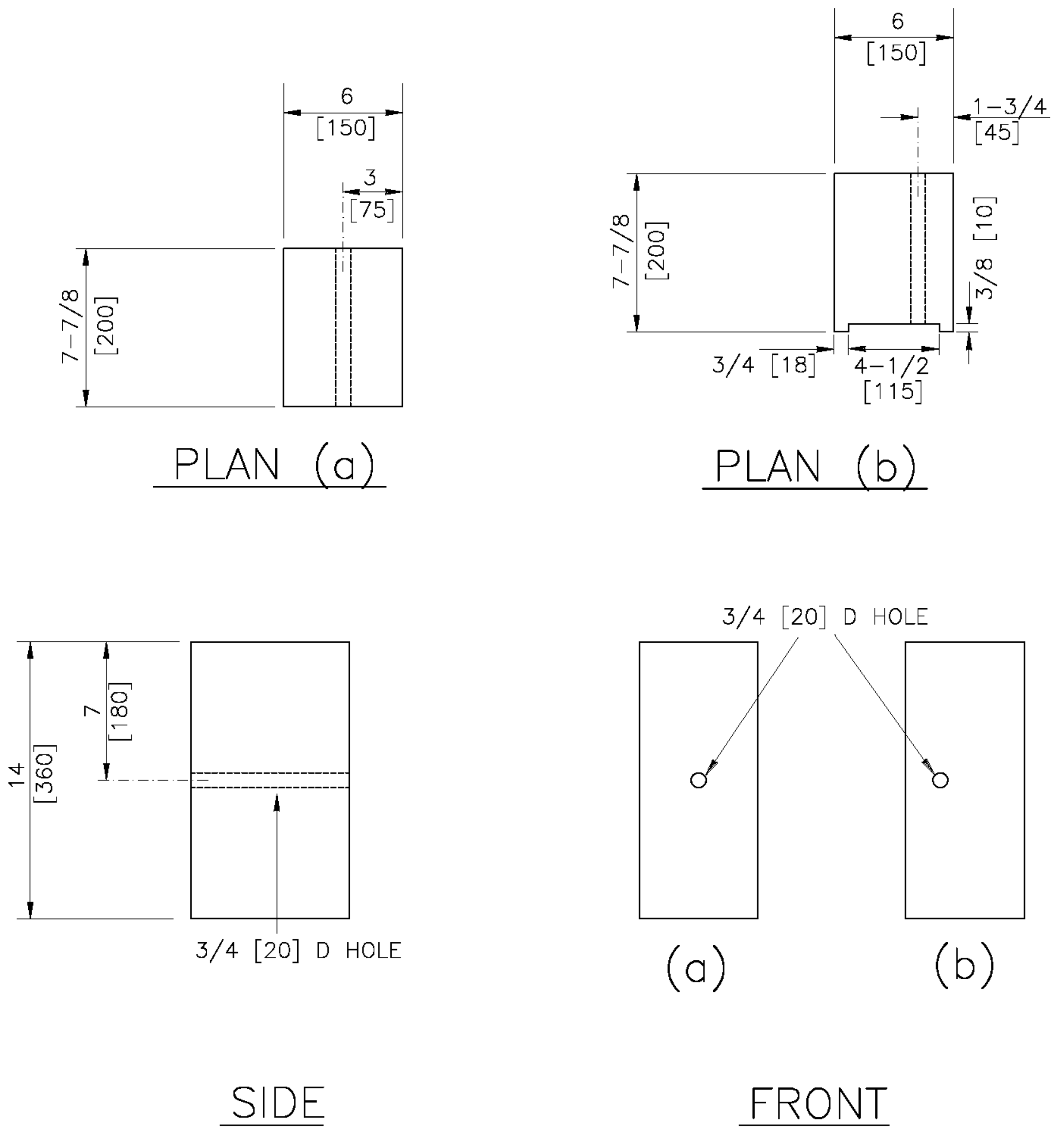
Dimensional tolerances not shown or implied are intended to be those consistent with the proper functioning of the part, including its appearance and accepted manufacturing practices.

INTENDED USE

These bolts and nuts are used in numerous guardrail and median barrier designs.

GUARDRAIL BOLT AND RECESSED NUT

FBB01-05	
SHEET NO.	DATE
2 of 2	5/2/2018



1994

W-BEAM TIMBER BLOCKOUT

PDB01a-b

SHEET NO.	DATE:
1 of 2	6/30/2005

SPECIFICATIONS

Blockouts shall be made of timber with a stress grade of at least 1160 psi [8 MPa]. Grading shall be in accordance with the rules of the West Coast Lumber Inspection Bureau, Southern Pine Inspection Bureau, or other appropriate timber association. Timber for blockouts shall be either rough-sawn (unplaned) or S4S (surfaced four sides) with nominal dimensions indicated. The variation in size of blockouts in the direction parallel to the axis of the bolt holes shall not be more than ± ¼ inch [6 mm]. Only one type of surface finish shall be used for posts and blockouts in any one continuous length of guardrail.

All timber shall receive a preservation treatment in accordance with AASHTO M 133 after all end cuts are made and holes are drilled.

Dimensional tolerances not shown or implied are intended to be those consistent with the proper functioning of the part, including its appearance and accepted manufacturing practices.

INTENDED USE

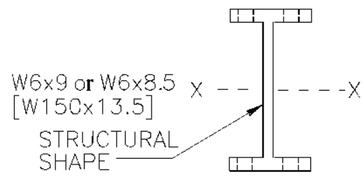
Blockout PDB01a is used with wood post PDE01 or PDE02 in the SGR04b strong-post W-beam guardrail and the SGM04b median barrier. Blockout PDB01b is routed to be used with steel post PWE01 or PWE02 in the SGR04c guardrail and the SGM04a median barrier.

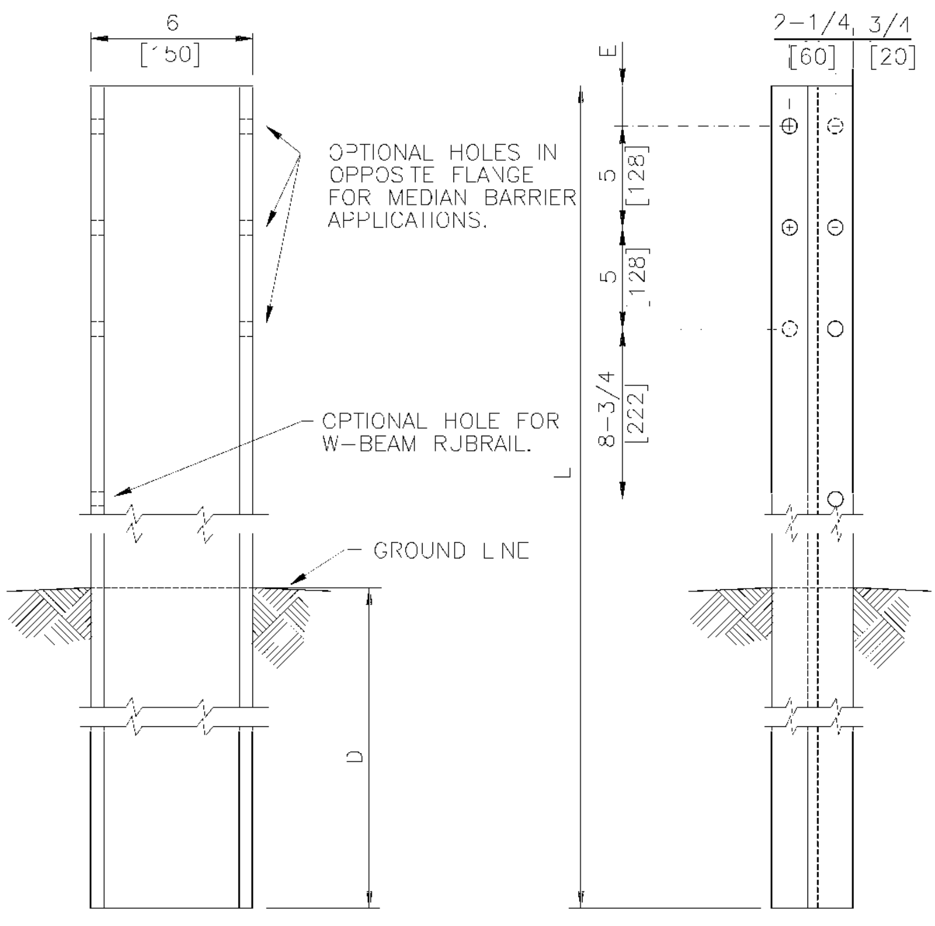
W-BEAM TIMBER BLOCKOUT

PDB01a-b	
SHEET NO.	DATE
2 of 2	7/06/2005

NOTE: ALL HOLES ARE 3/4 [20] D.

DESIGNATOR	I	D	E
PWE01	72 [1830]	43-1/4 [1100]	2 [52]
PWE02	78 [1980]	49-1/4 [1250]	2 [52]
PWE03	78 [1980]	45-3/8 [1153]	5-7/8 [149]
PWE04	81 [2060]	46-1/8 [1173]	5-7/8 [149]





SIDE

FRONT

1994

WIDE-FLANGE GUARDRAIL POST

	PWE01-04	
	SHEET NO.	DATE:
	1 of 2	7/27/2005

SPECIFICATIONS

W-beam and thrie-beam guardrail posts shall be manufactured using AASHTO M 270 / M 270M (ASTM A 709 / A 709M) Grade 36 [250] steel unless corrosion-resistant steel is required, in which case the post shall be manufactured from AASHTO M 270 / M 270M (ASTM A 709 / A 709M) Grade 50W [345W] steel. The dimensions of the cross-section shall conform to a W6x9 [W150x13.5] section as defined in AASHTO M 160 / M 160M (ASTM A 6 / A 6M). [W150x12.6] wide flange posts are an acceptable alternative that is considered equivalent to the [W150x13.5].

After the section is cut and all holes are drilled or punched, the component should be zinc-coated according to AASHTO M 111 (ASTM A 123) unless corrosion-resistant steel is used. When corrosion-resistant steel is used, the portion of the post to be embedded in soil shall be zinc-coated according to AASHTO M 111 (ASTM A 123) and the portion above the soil shall not be zinc-coated, painted or otherwise treated.

Designator	Area in^2 [10^3 mm^2]	I_x in^4 [10^6 mm^4]	I_y in^4 [10^6 mm^4]	S_x in^3 [10^3 mm^3]	S_y in^3 [10^3 mm^3]
PWE01-04	2.63 [1.7]	16.43 [6.84]	2.19 [0.91]	5.57 [91.2]	1.11 [18.2]

Dimensional tolerances not shown or implied are intended to be those consistent with the proper functioning of the part, including its appearance and accepted manufacturing practices.

INTENDED USE

Posts PWE01 and PWE02 are used with the SGR04a and SGR04c guardrails and the SGM04a median barrier. Blockouts like PWB01 (steel) or PDB01 (wood) are attached to each post.

Post PWE03 is used with the SGR09a guardrail and the SGM09a median barrier. Wood or plastic blockouts like the PWB02 are attached to each post with FBB03 bolts and FWC16a washers under the nuts.

Post PWE04 is used with the SGR09b guardrail and the SGM09b median barrier. A modified steel blockout PWB03 is attached to each post with at least two 1.5-inch [40 mm] long FBX16a bolts and nuts.

WIDE-FLANGE GUARDRAIL POST

PWE01-04

SHEET NO.	DATE
2 of 2	7/06/2005

APPENDIX C. SUPPORTING CERTIFICATION DOCUMENTS

Metals 2 Go
254-235-7700

Heat#: 196298* Tag: T24032519

Independence Tube
a Nucor Company

6226 W. 74th St.
Chicago, IL 60638
708-496-0380
Fax: 708-563-1950

https://www.nucortubular.com
https://www.ntpportal.com
Certificate Number: MAR 992722

Sold By:
INDEPENDENCE TUBE CORPORATION
6226 W. 74th St.
Chicago, IL 60638
Tel: 708-496-0380
Fax: 708-563-1950

Purchase Order No: SSW104355
Sales Order No: MAR 366734 - 3
Bill of Lading No: MAR 214528 - 4
Invoice No:

Shipped: 2/27/2019
Invoiced:

611011

CERTIFICATE of ANALYSIS and TESTS

Customer Part No:

TUBING A500 GRADE B(C)
7" X 5" X 3/16" X 40'

* DOMESTIC STEEL M&M *

Certificate No: MAR 992722
Test Date: 2/25/2019

Total Pieces	Total Weight
9	5,231

Bundle Tag	Mill	Heat	Specs	Y/T Ratio	Pieces	Weight
284379	4N	196298	YLD=51770/TEN=62900/ELG=34	0.8231	9	5,231

Mill #: 4N Heat #: 196298 Carbon Eq: 0.3016 Heat Src Origin: MELTED AND MANUFACTURED IN THE USA

C	Mn	P	S	Si	Al	Cu	Cr	Mo	V	Ni	Nb	Cb
0.1900	0.5300	0.0070	0.0030	0.0290	0.0330	0.1080	0.0440	0.0180	0.0040	0.0430	0.0010	0.0010

Sn	N	B	Ti	Sb	O	H
0.0100	0.0050	0.0000	0.0020	0.0020	0.0000	0.0000

LEED Information (based on the most recent LEED information from the producing mill)

Method	Location	Recycled Content	Post Consumer	Post Industrial
EAF	Crawfordsville, IN	74.5%	27.1%	47.4%

Certification:

I certify that the above results are a true and correct copy of records prepared and maintained by Independence Tube Corporation. Sworn this day, 2/25/2019.

WE PROUDLY MANUFACTURE ALL OUR PRODUCTS IN THE USA
NUCOR TUBULAR PRODUCTS ARE MANUFACTURED, TESTED, AND INSPECTED IN ACCORDANCE WITH ASTM STANDARDS.
MATERIAL IDENTIFIED AS A500 GRADE B(C) MEETS BOTH ASTM A500 GRADE B AND A500 GRADE C SPECIFICATIONS.

CURRENT STANDARDS:
A252-10
A500/A500M-18
A513/A513M-15
ASTM A53/A53M-12 | ASME SA-53/SA-53M-13
A847/A847M-14
A1085/A1085M-15

Chris Allen

Chris Allen, ASQ CMQ/OE
Quality Systems Supervisor

Page - 1

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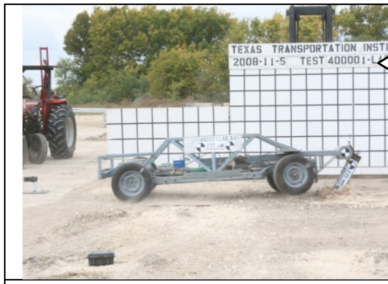
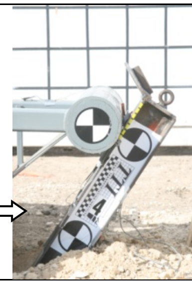
Table D.1. Summary of Strong Soil Test Results for Establishing Installation Procedure.



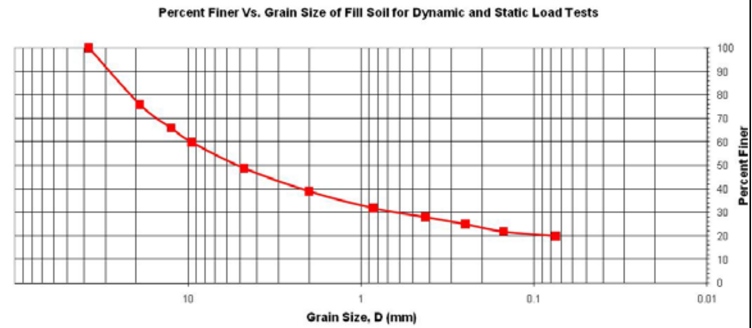
Dynamic Setup

Post-Test Photo of post

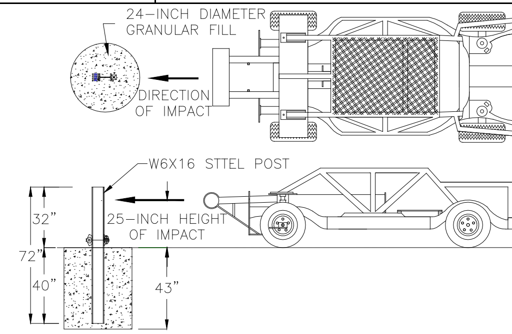


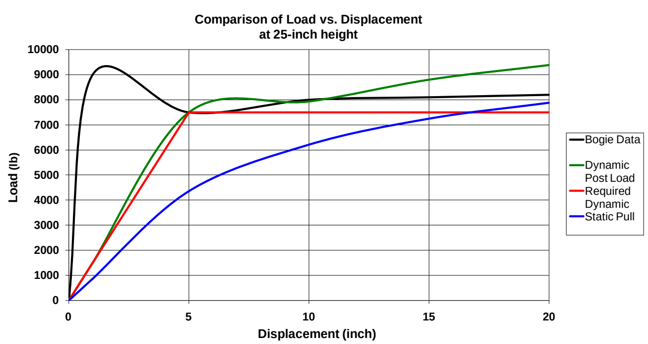
Post-Test Photo

Static Load Test

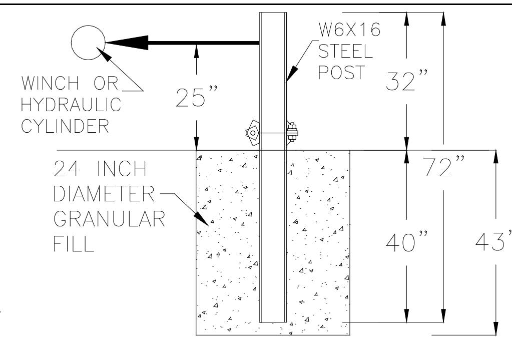


Dynamic Test Installation Details



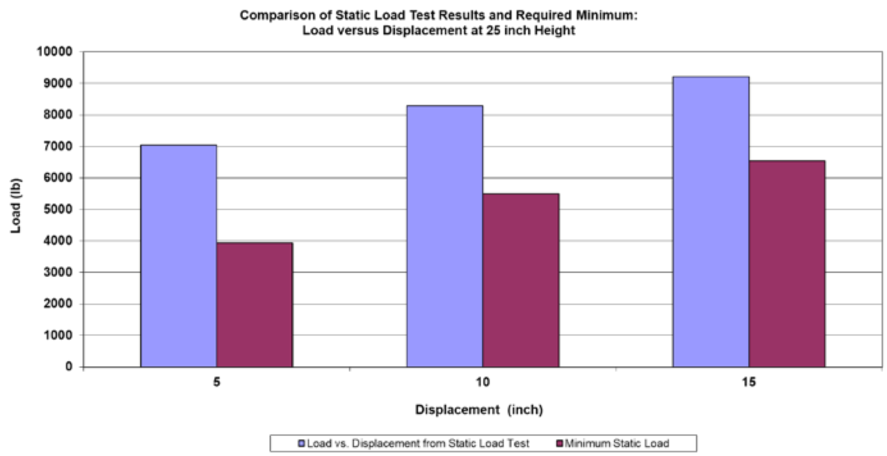


Static Load Test Installation Details

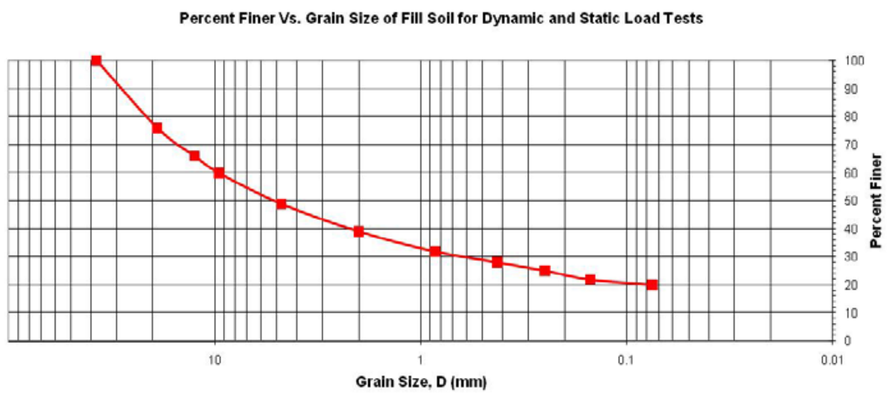


Date	2008-11-05
Test Facility and Site Location	TTI Proving Ground, 3100 SH 47, Bryan, TX 77807
In Situ Soil Description (ASTM D2487)	Sandy gravel with silty fines
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO Grade B Soil-Aggregate (see sieve analysis above)
Description of Fill Placement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

Table D.2. Test Day Static Soil Strength Documentation for Test No. 611011-B1-B4.



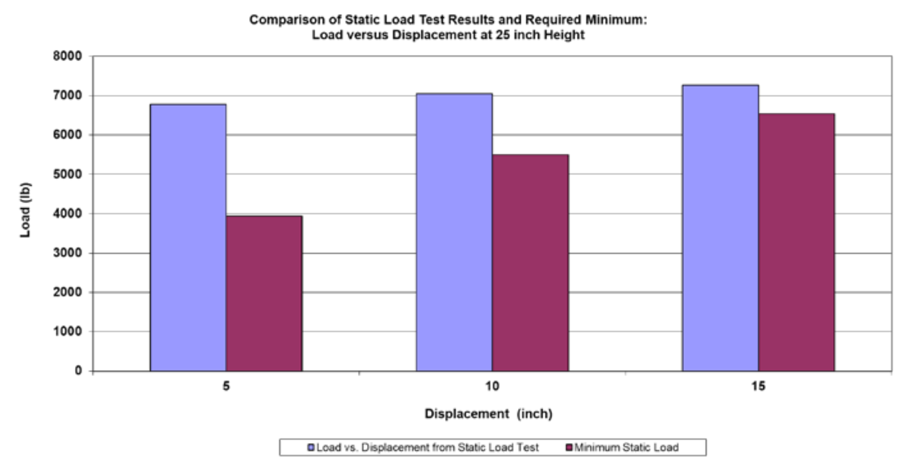
Typical Static Load Setup



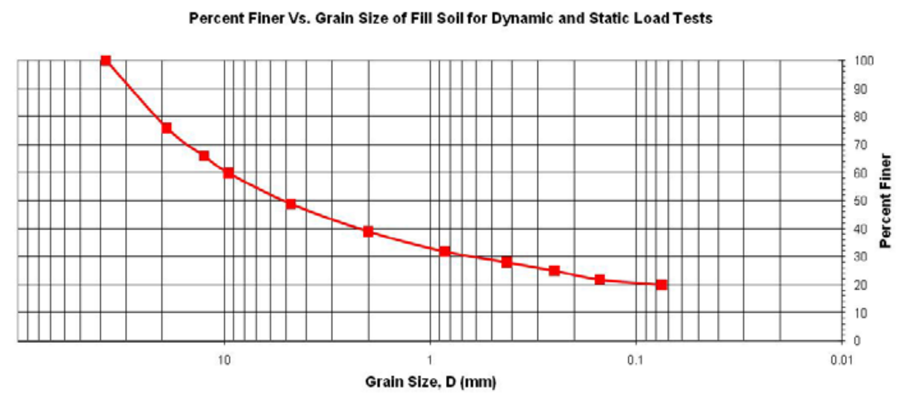
Post-Test Photo of Post

Date	2019-01-29
Test Facility and Site Location	TTI Proving Ground – 3100 SH 47, Bryan, Tx
In Situ Soil Description (ASTM D2487)	Sandy gravel with silty fines
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO Grade B Soil-Aggregate (see sieve analysis)
Description of Fill Placement Procedure	6-inch lifts tamped with a pneumatic compactor

Table D.3. Test Day Static Soil Strength Documentation for Test No. 611011-1.



Typical Static Load Setup



Post-Test Photo of Post

Date	2019-04-29
Test Facility and Site Location	TTI Proving Ground – 3100 SH 47, Bryan, Tx
In Situ Soil Description (ASTM D2487)	Sandy gravel with silty fines
Fill Material Description (ASTM D2487) and sieve analysis	AASHTO Grade B Soil-Aggregate (see sieve analysis)
Description of Fill Placement Procedure	6-inch lifts tamped with a pneumatic compactor

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APPENIDX E. *MASH* TEST 3-35 (CRASH TEST NO. 611011-1)

E1 VEHICLE PROPERTIES AND INFORMATION

Table E.1. Vehicle Properties for Test No. 611011-1.

Date: 2019-04-29 Test No.: 611011-1 VIN No.: 1C6RR6FT8FS624120

Year: 2015 Make: RAM Model: 1500

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

Tread Type: Highway Odometer: 164474

Note any damage to the vehicle prior to test: None

● Denotes accelerometer location.

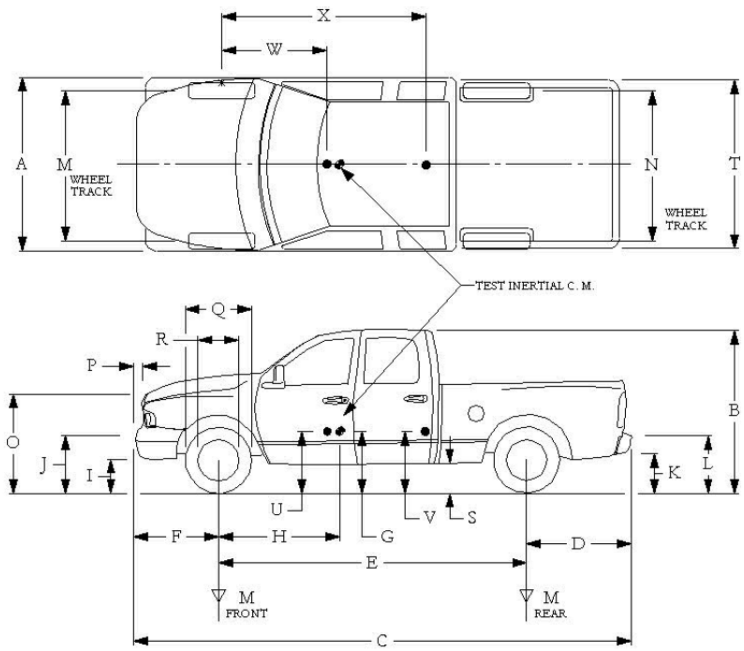
NOTES: None

Engine Type: V-8
Engine CID: 4.7 liter

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

Optional Equipment:
None

Dummy Data:
Type:
Mass: 0 lb
Seat Position:



Geometry: inches

A	78.50	F	40.00	K	20.00	P	3.00	U	27.50
B	74.00	G	28.00	L	30.00	Q	30.50	V	31.25
C	227.50	H	60.35	M	68.50	R	18.00	W	60.35
D	44.00	I	11.75	N	68.00	S	13.00	X	76.50
E	140.50	J	27.00	O	46.00	T	77.00		

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

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

GVWR Ratings:		**Mass:** lb	Curb	Test Inertial	Gross Static
Front	3700	M_{front}	2890	2866	2866
Back	3900	M_{rear}	2035	2158	2158
Total	6700	M_{Total}	4925	5024	5024

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

Mass Distribution:
lb LF: 1413 RF: 1453 LR: 1117 RR: 1041

Table E.2. Measurements of Vehicle Vertical CG for Test No. 611011-1.

Date: 2019-04-29 Test No.: 611011-1 VIN: 1C6RR6FT8FS624120

Year: 2015 Make: RAM Model: 1500

Body Style: Quad Cab Mileage: 164474

Engine: 4.7 liter V-8 Transmission: Automatic

Fuel Level: Empty Ballast: 80 (440 lb max)

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

Measured Vehicle Weights: (lb)							
LF:	1413	RF:	1453		Front Axle:	2866	
LR:	1117	RR:	1041		Rear Axle:	2158	
Left:	2530	Right:	2494		Total:	5024	
						5000 ±110 lb allowed	
Wheel Base:	140.50	inches	Track: F:	68.50	inches R:	68.00	inches
	148 ±12 inches allowed			Track = (F+R)/2 = 67 ±1.5 inches allowed			
Center of Gravity, SAE J874 Suspension Method							
X:	60.35	inches	Rear of Front Axle	(63 ±4 inches allowed)			
Y:	-0.24	inches	Left - Right +	of Vehicle Centerline			
Z:	28.00	inches	Above Ground	(minumum 28.0 inches allowed)			

Hood Height: 46.00 inches
43 ±4 inches allowed

Front Bumper Height: 27.00 inches

Front Overhang: 40.00 inches
39 ±3 inches allowed

Rear Bumper Height: 30.00 inches

Overall Length: 227.50 inches
237 ±13 inches allowed

Table E.3. Exterior Crush Measurements for Test No. 611011-1.

Date:	2019-04-29	Test No.:	611011-1	VIN No.:	1C6RR6FT8FS624120
Year:	2015	Make:	RAM	Model:	1500

VEHICLE CRUSH MEASUREMENT SHEET[1]

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

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

Specific Impact Number	Plane* of C-Measurements	Direct Damage Width** (CDC)	Direct Damage Max*** Crush	Field L**	C_1	C_2	C_3	C_4	C_5	C_6	±D
1	Front plane at bumper	18	6	24	1	3	6	-	-	-	+18
2	Side plane at bumper	18	7	60	1	1.5	2	3	5	7	+77
	Measurements recorded										
	☑ **inches** or ☐ **mm**										

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

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

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

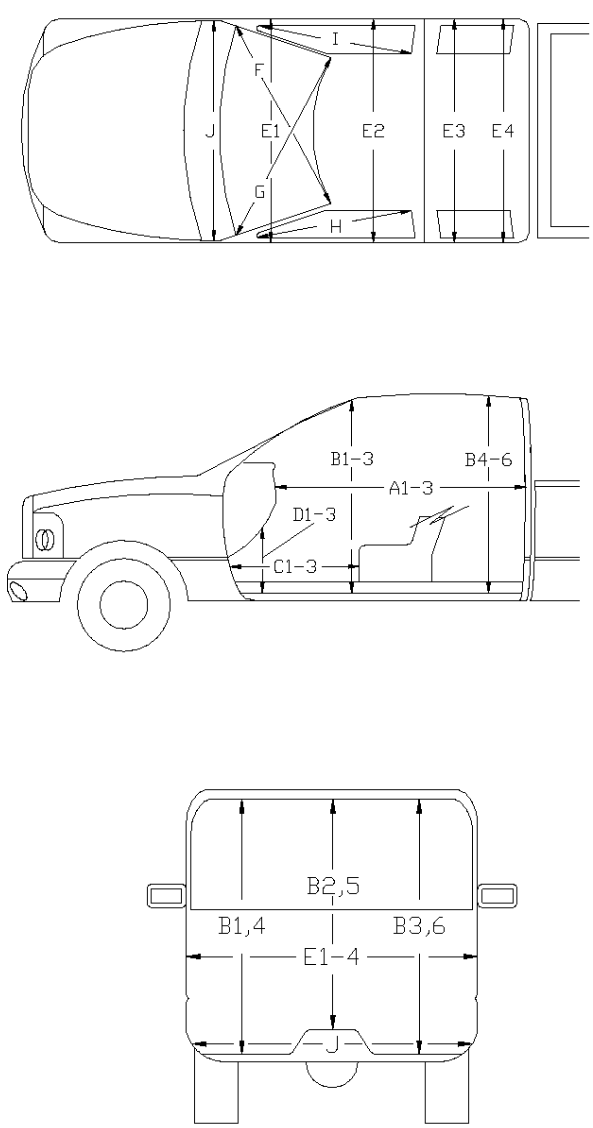
**Measure and document on the vehicle diagram the beginning or end of the direct damage width and field L (e.g., side damage with respect to undamaged axle).

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

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

Table E.4. Occupant Compartment Measurements for Test No. 611011-1.

Date:	2019-04-29	Test No.:	611011-1	VIN No.:	1C6RR6FT8FS624120
Year:	2015	Make:	RAM	Model:	1500



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

OCCUPANT COMPARTMENT DEFORMATION MEASUREMENT

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

E2 SEQUENTIAL PHOTOGRAPHS

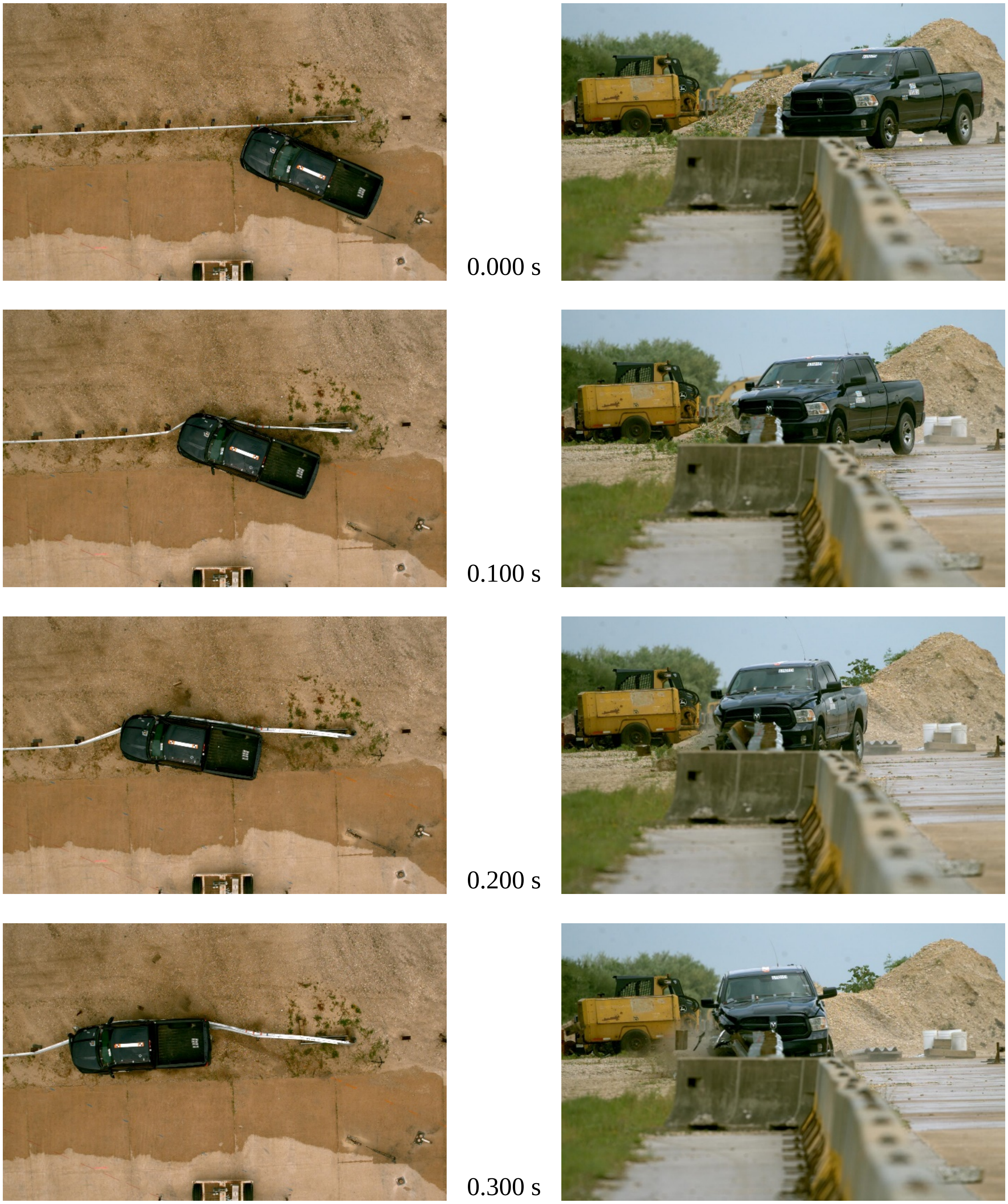
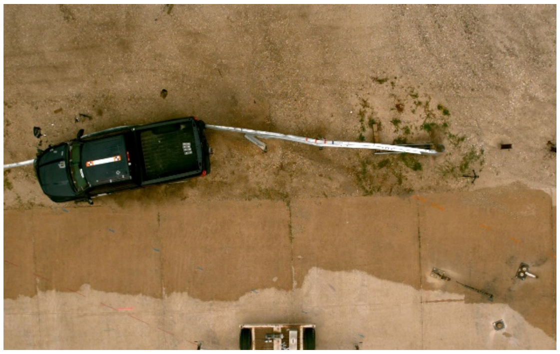
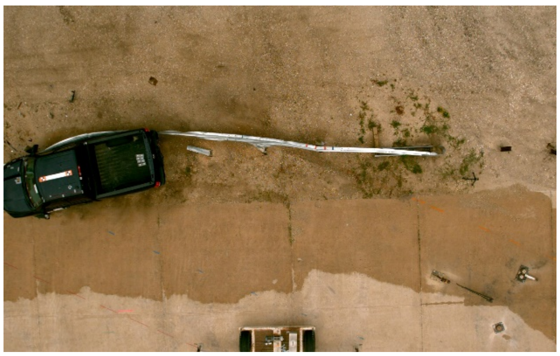


Figure E.1. Sequential Photographs for Test No. 601011-1 (Overhead and Frontal Views).



0.400 s



0.500 s

0.600 s

0.700 s

Figure E.1. Sequential Photographs for Test No. 611011-1 (Overhead and Frontal Views) (Continued).

0.000 s

0.100 s

0.200 s

0.300 s

0.400 s

0.500 s

0.600 s

0.700 s

Figure E.2. Sequential Photographs for Test No. 611011-1 (Rear View).

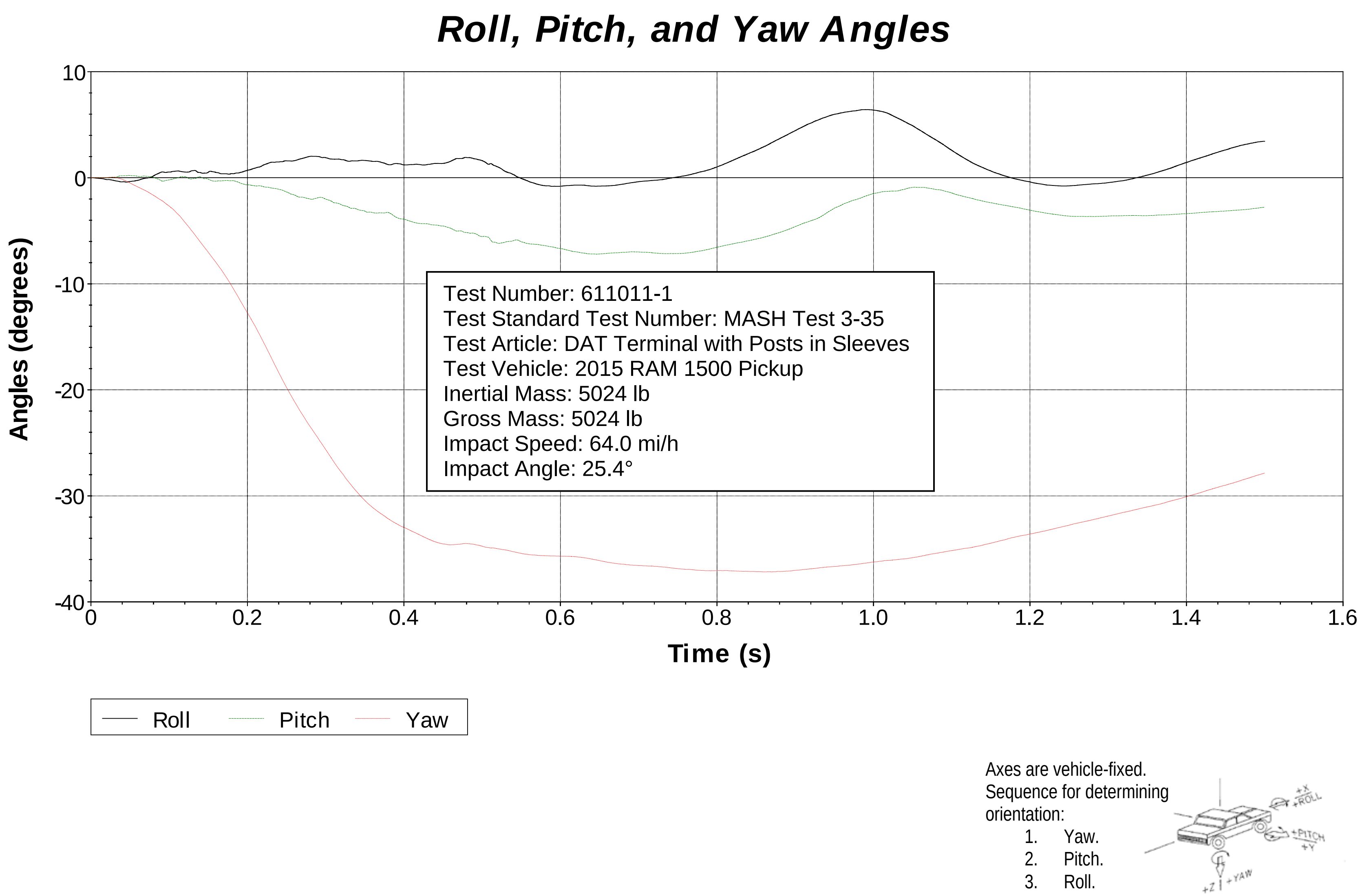


Figure E.3. Vehicle Angular Displacements for Test No. 611011-1.

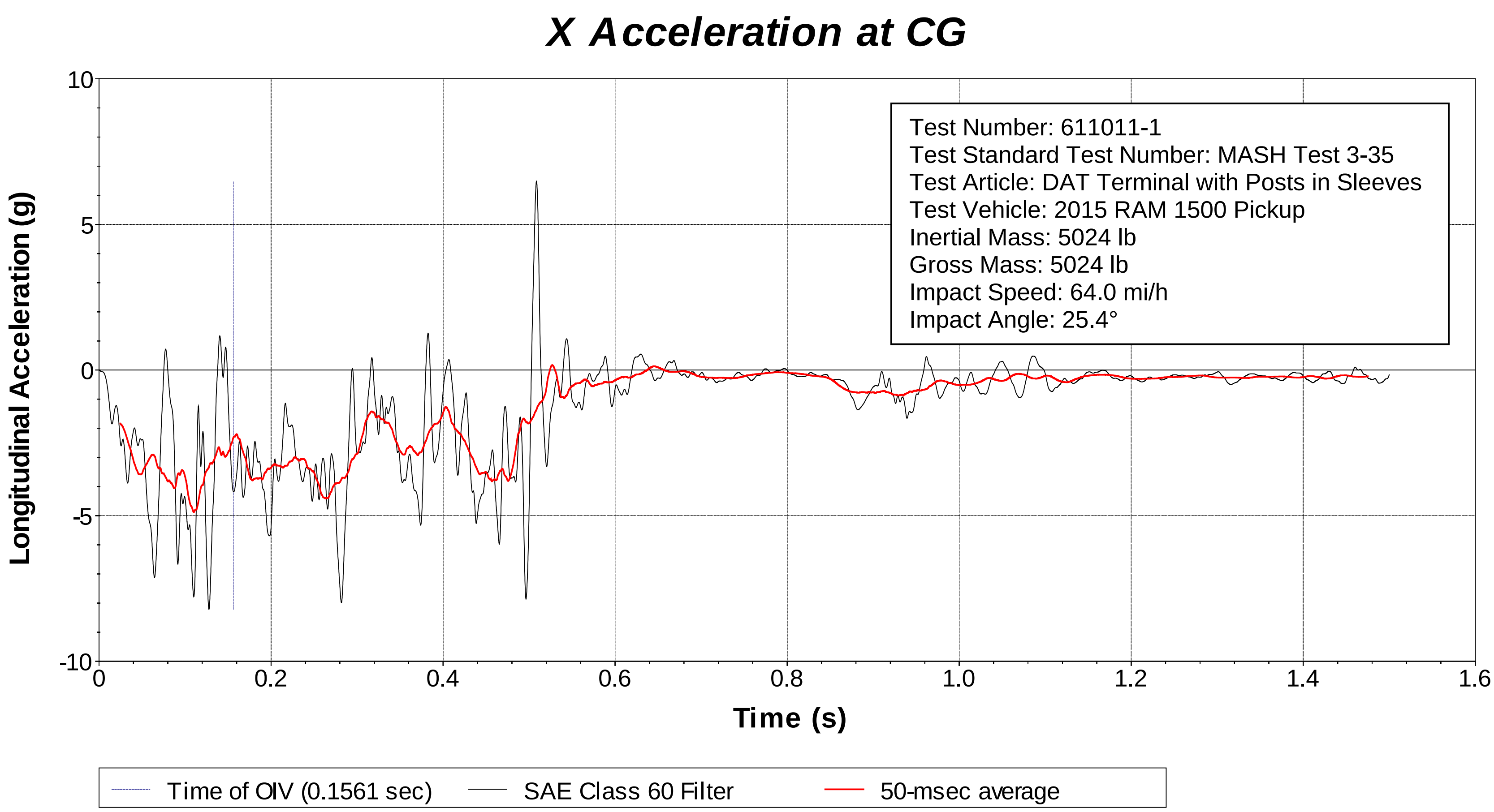


Figure E.4. Vehicle Longitudinal Accelerometer Trace for Test No. 611011-1 (Accelerometer Located at Center of Gravity).

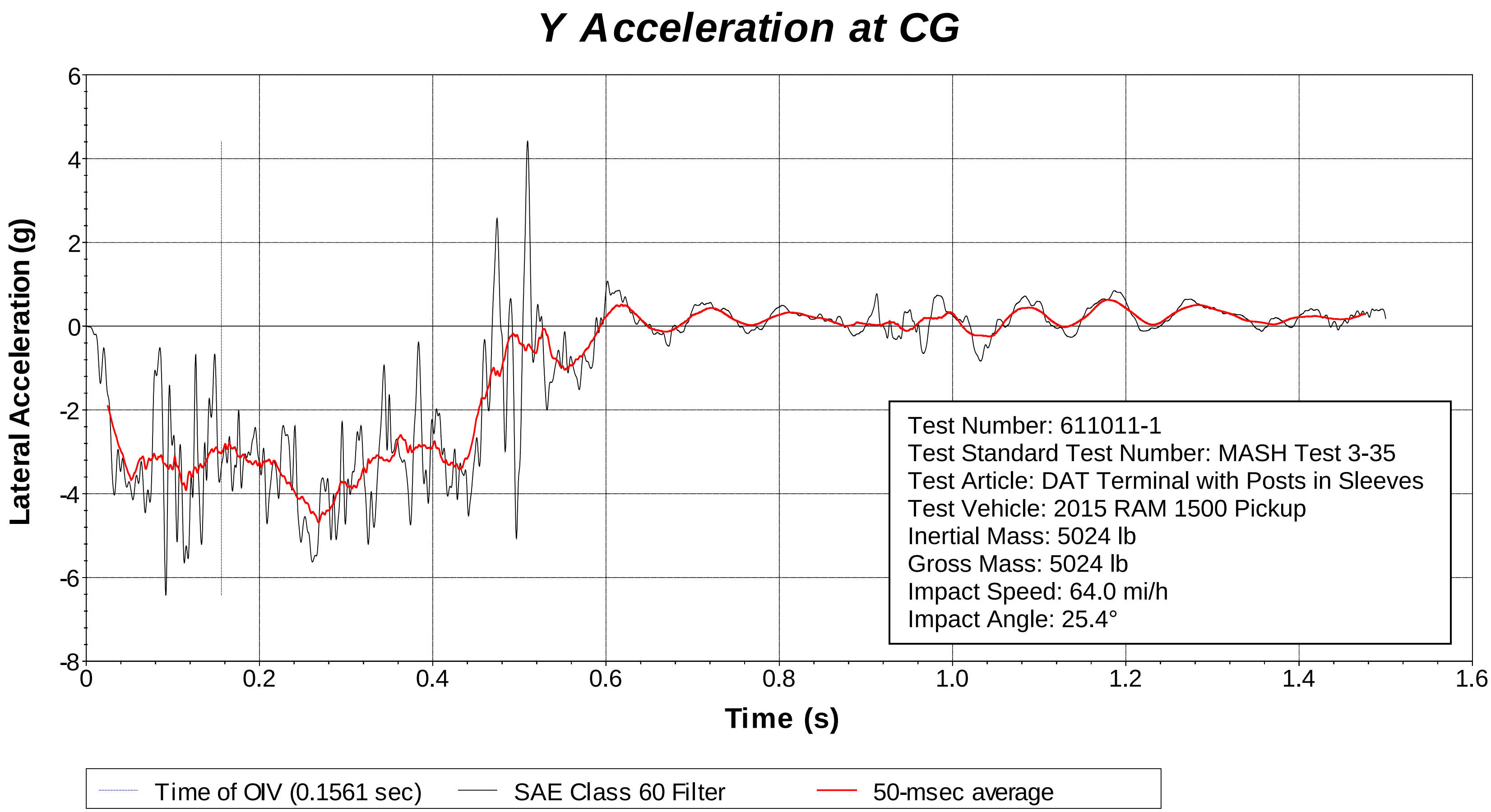


Figure E.5. Vehicle Lateral Accelerometer Trace for Test No. 611011-1 (Accelerometer Located at Center of Gravity).

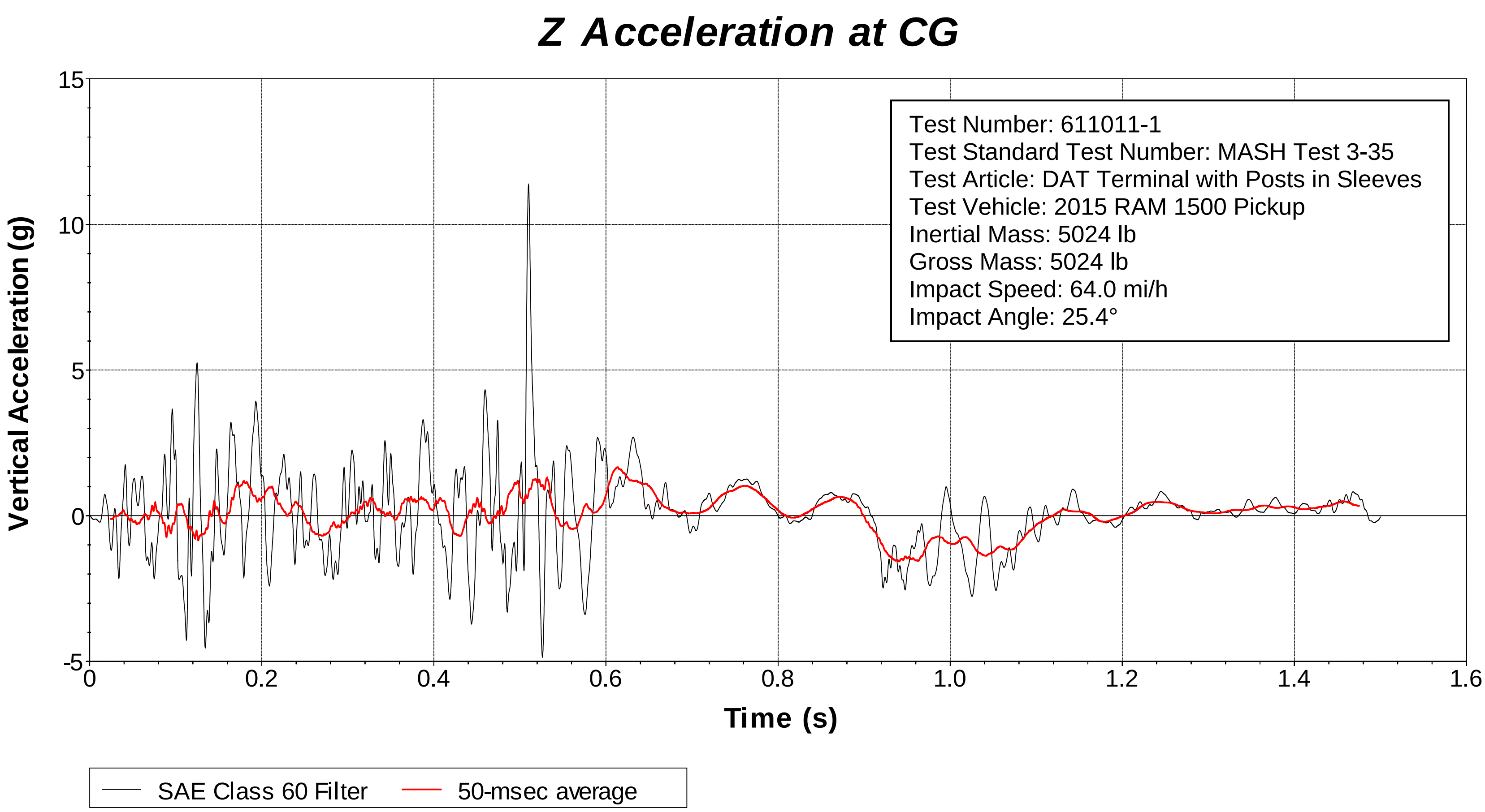


Figure E.6. Vehicle Vertical Accelerometer Trace for Test No. 611011-1 (Accelerometer Located at Center of Gravity).