

MASH TEST 4-12 ON T2P RETROFIT BRIDGE RAIL





Test Report 0-7086-R5

Cooperative Research Program

TEXAS A&M TRANSPORTATION INSTITUTE COLLEGE STATION, TEXAS

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16. Abstract The purpose of the test repo Department of Transportation (TxD guidelines included in the American <i>Manual for Assessing Safety Hardw</i> Test 4-12, which involves a 10000S traveling at a nominal impact speed This report provides details performance assessment of the TxD evaluation criteria. The TxDOT T2P retrofit bri barriers.	rted herein was to a OT) T2P bridge ra a Association of Sta <i>care (MASH)</i> . The of vehicle weighing and angle of 56 mi on the TxDOT T2P OT T2P retrofit br dge rail met the per	assess the performa il according to the ate Highway and Tr crash test was perfo 22,000 lb impacting h and 15 degrees. P retrofit bridge rail idge rail for <i>MASH</i> cformance criteria f	ance of a retrofit rail for the Texas safety-performance evaluation ransportation Officials (AASHTO) ormed in accordance with <i>MASH</i> g the retrofit bridge rail while l, the crash test and results, and the Test 4-12 longitudinal barrier for <i>MASH</i> Test 4-12 for longitudinal
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DISCLAIMER

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

This report is not intended for construction, bidding, or permit purposes. The engineer (researcher) in charge of the project was William F. Williams, P.E., #71898.

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

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	SI* (MODERN M	ETRIC) CONV	ERSION FACTORS	
	APPROXIMA	TE CONVERSIO	NS TO SI UNITS	
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		0
in ²	square inches	645.2	square millimeters	mm²
ft ²	square feet	0.093	square meters	m² 2
ya²	square yards	0.836	square meters	m² b a
ac mi ²	acres	0.405	nectares	na km²
rni-	square miles		square knometers	KIII-
floz	fluid ounces	29.57	milliliters	ml
	allons	3 785	litors	1
ft ³	cubic feet	0.028	cubic meters	m ³
vd ³	cubic vards	0.765	cubic meters	m ³
<i></i>	NOTE: volumes	areater than 1000L	shall be shown in m ³	
		MASS		
oz	ounces	28.35	grams	a
lb	pounds	0.454	kilograms	kg
Т	short tons (2000 lb)	0.907	megagrams (or metric ton")	Mg (or "t")
	TEMP	ERATURE (exac	t degrees)	
°F	Fahrenheit	5(F-32)/9	Celsius	°C
		or (F-32)/1.8		
	FORCE	and PRESSURE	or STRESS	
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
	APPROXIMAT	E CONVERSION	S FROM SI UNITS	
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	teet	ft .
m	meters	1.09	yards	yd
КП	KIIOMELEIS		miles	ITH
mm ²	aguara millimatora		aquara inchas	in ²
m^2	square motors	10 764	square foot	111- f+2
m^2	square meters	1 1 1 9 5	square vards	n vd ²
ha	hectares	2 47	acres	ac
km ²	Square kilometers	0.386	square miles	mi ²
	- 1	VOLUME	- 1	
mL	milliliters	0.034	fluid ounces	oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000lb)	Т
	TEMP	ERATURE (exac	t degrees)	
°C	Celsius	1.8C+32	Fahrenheit	°F
	FORCE	and PRESSURE	or STRESS	
N	newtons	0.225	poundforce	lbf
	kilopascals	0.145	poundforce per square inch	lb/in ²

*SI is the symbol for the International System of Units

Chapter 1. INTRODUCTION

1.1. BACKGROUND

Roadway departure crashes are the most common type of crash in Texas. These crashes represent over 45 percent of all fatal crashes and 34 percent of all serious injury crashes. Texas data show that there were 9,560 fatal and 30,766 serious injury roadway departure crashes from 2010-2016. Roadside safety devices shield motorists from roadside hazards such as non-traversable terrain and fixed objects, thereby reducing injuries and fatalities associated with roadway departure crashes. To improve the safety of the motoring public, there is a need to develop new or improved safety devices that accommodate a variety of site conditions and placement locations, as well as a changing vehicle fleet. To this end, researchers at the Texas A&M Transportation Institute (TTI) have sought to provide the Texas Department of Transportation (TxDOT) with a mechanism to quickly and effectively address high-priority issues related to roadside safety devices. TTI researchers provide results on new and improved safety features that minimize the consequences of vehicles leaving the road and reduce injuries and fatalities associated with roadway departure crashes. The researchers have developed roadside safety devices to meet the 2016 edition of the American Association of State Highway and Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH) roadside safety criteria to address the continuing trend of larger vehicles in the statewide vehicle fleet (1).

1.2. OBJECTIVE

The purpose of the test reported herein was to assess the performance of a retrofit rail for TxDOT's T2P bridge rail according to the safety-performance evaluation guidelines included in *MASH*. The crash test was performed in accordance with *MASH* Test 4-12, which involves a 10000S vehicle weighing 22,000 lb impacting the retrofit bridge rail while traveling at a nominal impact speed and angle of 56 mi/h and 15 degrees.

This report provides details on the TxDOT T2P retrofit bridge rail, the crash test and results, and the performance assessment of the TxDOT T2P retrofit bridge rail for *MASH* Test 4-12 longitudinal barrier evaluation criteria.

Chapter 2. SYSTEM DETAILS

2.1. TEST ARTICLE AND INSTALLATION DETAILS

The test installation was 124 ft long and consisted of three steel rails attached to steel posts, which were mounted on a cantilevered reinforced concrete deck and curb. The deck was 6 inches thick, and the curb was 9 inches tall. The top rail was a hollow structural section (HSS) 4½-inch-diameter section, and the two lower rails were HSS rectangular sections, 2 inches tall and 6 inches wide. Internal rail sleeves measuring 28 inches long were centered at each rail splice. The distance from the top of the deck to the top of each rail was 18 inches, 28 inches, and 42 inches.

The posts were fabricated from ³/₄-inch-thick plates. They were spaced at 96-inch centers, and each was secured to the deck by four ⁷/₈-inch-diameter bolts that were cast in the concrete.

Figure 2.1 presents the overall information on the TxDOT T2P retrofit bridge rail, and Figure 2.2 provides photographs of the installation. Appendix A provides further details on the TxDOT T2P retrofit bridge rail. Drawings were provided by the TTI Proving Ground, and construction was performed Tucker Construction and supervised by TTI Proving Ground personnel.

2.2. DESIGN MODIFICATIONS DURING TEST

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

2.3. MATERIAL SPECIFICATIONS

The specified compressive strength of the concrete used in the deck and curb was 4000 psi. Table 2.1 shows the average compressive strengths of the concrete on the date of the test, July 23, 2021.

Location	Design Strength (psi)	Average Strength (psi)	Age (days)	Detailed Location
Wall and Deck	3600	4713	97	South Half of Wall and Deck
Wall and Deck	3600	5113	97	North Half of Wall and Deck
Curb	4000	4487	38	100% of curb

 Table 2.1. Concrete Strengths.

Appendix B provides material certification documents for the materials used to install/construct the TxDOT T2P retrofit bridge rail.







Figure 2.2. TxDOT T2P Retrofit Bridge Rail prior to Testing.

Chapter 3. TEST REQUIREMENTS AND EVALUATION CRITERIA

3.1. CRASH TEST PERFORMED/MATRIX

Table 3.1 shows the test conditions and evaluation criteria for *MASH* TL-4 for longitudinal barriers. *MASH* Tests 4-10 and 4-11 were not performed for this project since these tests were performed previously on the TxDOT T2P bridge rail. The researchers felt that only *MASH* Test 4-12 (strength test) was necessary for this retrofit bridge rail design.

Test Article	Test	Test	Imp Condi	act tions	Evaluation
	Designation	venicie	Speed	Angle	Criteria
	4-10	1100C	62 mi/h	25°	A, D, F, H, I
Longitudinal Barrier	4-11	2270P	62 mi/h	25°	A, D, F, H, I
Duilio	4-12	10000S	56 mi/h	15°	A, D, G

 Table 3.1. Test Conditions and Evaluation Criteria Specified for MASH TL-4

 Longitudinal Barriers.

The target critical impact point (CIP) for *MASH* Test 4-12 was determined using the information provided in *MASH* Section 2.2.1 and Section 2.3.2. Figure 3.1 shows the target CIP for *MASH* Test 4-12 on the TxDOT T2P retrofit bridge rail.



Figure 3.1. Target CIP for MASH Test 4-12 on TxDOT T2P Retrofit Bridge Rail.

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

3.2. EVALUATION CRITERIA

The appropriate safety evaluation criteria from Tables 2-2 and 5-1 of *MASH* were used to evaluate the crash test reported herein. Table 3.1 lists the test conditions and evaluation criteria required for *MASH* Test 4-12, and Table 3.2 provides detailed information on the evaluation criteria. An evaluation of the crash test results is presented in Chapter 6.

Evaluation Factors	Evaluation Criteria	MASH Test
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.	4-10, 4-11, and 4-12
	 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 	4-10, 4-11, and 4-12
Occupant	 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. 	4-10 and 4-11
Risk	<i>G.</i> It is preferable, although not essential, that the vehicle remain upright during and after the collision.	4-12
	H. Occupant impact velocities (OIV) should satisfy the following limits: Preferred value of 30 ft/s, or maximum allowable value of 40 ft/s.	4-10 and 4-11
	I. The occupant ridedown accelerations should satisfy the following: Preferred value of 15.0 g, or maximum allowable value of 20.49 g.	4-10 and 4-11

 Table 3.2. Evaluation Criteria Required for MASH TL-4 Longitudinal Barriers.

Chapter 4. TEST CONDITIONS

4.1. TEST FACILITY

The full-scale crash test reported herein was performed at the 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, as well as *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 mi 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, highway pavement durability and efficacy, and roadside safety hardware and perimeter protective device evaluation. The site selected for construction and testing of the TxDOT T2P retrofit bridge rail was along the edge of an out-of-service apron. The apron consists of an unreinforced jointed-concrete pavement in 12.5-ft \times 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.

4.2. VEHICLE TOW AND GUIDANCE SYSTEM

The 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 and 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.

4.3. DATA ACQUISITION SYSTEM

4.3.1. Vehicle Instrumentation and Data Processing

The test vehicle was instrumented with a self-contained onboard data acquisition system. The signal conditioning and acquisition system is a multichannel data acquisition system (DAS) 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 ultrasmall, solid-state units designed for crash test service. The data acquisition hardware and software conform to the latest SAE J211, Instrumentation for Impact Test. Each channel 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 up the data inside the unit in case the primary battery cable is severed. Initial contact of a pressure tape switch on the vehicle bumper provides a time zero mark and initiates the recording process. After each test, the data are downloaded from the DAS 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 DAS is returned to the factory annually for complete recalibration and to ensure that all instrumentation used in the vehicle conforms to the 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 DAS receive 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 anytime data are suspect. Acceleration data are measured with an expanded uncertainty of ± 1.7 percent at a confidence factor of 95 percent (k = 2).

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

4.3.2. Anthropomorphic Dummy Instrumentation

MASH does not recommend or require use of a dummy in the 10000S vehicle, and no dummy was placed in the vehicle.

4.3.3. Photographic Instrumentation Data Processing

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

- One placed overhead with a field of view perpendicular to the ground and directly over the impact point.
- One placed upstream from the installation at an angle to have a field of view of the interaction of the rear of the vehicle with the installation.
- A third placed with 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 TxDOT T2P retrofit bridge rail. 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 the test vehicle and the installation before and after the test.

Chapter 5. MASH TEST 4-12 (CRASH TEST NO. 440861-2)

5.1. TEST DESIGNATION AND ACTUAL IMPACT CONDITIONS

MASH Test 4-12 involves a 10000S vehicle weighing 22,000 lb \pm 660 lb impacting the CIP of the longitudinal barrier at an impact speed of 56 mi/h \pm 2.5 mi/h and an angle of 15 degrees \pm 1.5 degrees. The CIP for *MASH* Test 4-12 on the TxDOT T2P retrofit bridge rail was 5 ft \pm 1 ft upstream of the centerline of post 6. Figure 3.1 and Figure 5.1 depict the target impact setup.



Figure 5.1. TxDOT T2P Retrofit Bridge Rail/Test Vehicle Geometrics for Test No. 440861-2.

The 10000S vehicle weighed 22,540 lb, and the actual impact speed and angle were 56.3 mi/h and 14.2 degrees. The actual impact point was 4.4 ft upstream of the centerline of post 6. Minimum target impact severity (IS) was 142 kip-ft, and actual IS was 144 kip-ft.

5.2. WEATHER CONDITIONS

The test was performed on the morning of July 23, 2021. Weather conditions at the time of testing were as follows: wind speed: 8 mi/h; wind direction: 209 degrees (vehicle was traveling at a heading of 335 degrees); temperature: 86°F; relative humidity: 71 percent.

5.3. TEST VEHICLE

Figure 5.2 shows the 2012 Hino 338 single-unit truck (SUT) used for the crash test. The vehicle's test inertia weight was 22,540 lb, and its gross static weight was 22,540 lb. The height to the lower edge of the vehicle bumper was 18.75 inches, and the height to the upper edge of the bumper was 31.50 inches. The height to the center of gravity of the vehicle's ballast was 63.75 inches. Table C.1 in Appendix C.1 gives additional dimensions and information on the vehicle. The vehicle was directed into the installation using a cable reverse tow and guidance system, and was released to be freewheeling and unrestrained just prior to impact.



Figure 5.2. Test Vehicle before Test No. 440861-2.

5.4. TEST DESCRIPTION

Table 5.1 lists events that occurred during Test No. 440861-2. Figures C.1 and C.2 in Appendix C.2 present sequential photographs during the test.

Time (s)	Events
0.000	Vehicle impacts retrofit bridge rail
0.035	Vehicle's front driver-side tire lifts off the pavement
0.050	Vehicle begins to redirect
0.141	Vehicle's right front tire lifts off the pavement
0.245	Vehicle's right rear tire lifts off the pavement
0.264	Vehicle travels parallel with the retrofit bridge rail
0.248	Vehicle's rear bumper contacts the retrofit bridge rail
0.381	Vehicle's left front tire makes contact with the pavement
1.328	Vehicle's right front tire makes contact with the pavement

Table 5.1. Events during Test No. 440861-2.

For longitudinal barriers, it is desirable for the vehicle to redirect and exit the barrier within the exit box criteria (not less than 65.6 ft for heavy vehicles). The test vehicle exited within the exit box criteria defined in *MASH*. Brakes on the vehicle were applied at 2.7 s after impact, and the vehicle subsequently came to rest 241 ft downstream of the point of impact and 12 ft toward the field side of the bridge rail.

5.5. DAMAGE TO TEST INSTALLATION

Figure 5.3 and Figure 5.4 show the damage to the TxDOT T2P retrofit bridge rail, and Table 5.2 shows post lean after the test. There was major cracking of the deck on the traffic side of the curb up to the edge of the field joint, which extended from post 3 to 2 ft downstream from post 10. There was also cracking under the deck from the field joint to 1 ft downstream from post 7, which ran along the anchor bolts, and from the field joint to post 7, there was a crack where the deck and wall intersected. The curb had some spalling and exposed rebar on the traffic and field side at post 6, and the curb downstream of the field joint was 3 inches lower on the field side and 1¼ inches lower on the traffic side than the curb upstream of the joint. The lower

rail was deformed just downstream of impact and was 6 inches lower than its pre-impact height. The existing cracks in the curb were outlined in black, and the cracks that occurred post-impact were outlined in red. Working width* was 64.4 inches, and height of working width was 144.3 inches. Maximum dynamic deflection during the test was 14.9 inches, and maximum permanent deformation was 9.0 inches.

5.6. DAMAGE TO TEST VEHICLE



Figure 5.5 shows the damage sustained by the vehicle. The front bumper, hood, left front tire and rim, left front U-bolts, left rear outer tire and rim, and left rear corner of the cargo box were damaged. No damage to the fuel tank was observed. Maximum exterior crush to the vehicle was 10.0 inches in the front plane at the left front corner at bumper height. No occupant compartment deformation or intrusion was noted. Figure 5.6 shows the interior of the vehicle.

5.7. VEHICLE INSTRUMENTATION

Data from the accelerometers were digitized for informational purposes only and are reported in Figure 5.7. Figure C.3 in Appendix C.3 shows the vehicle angular displacements, and

^{*} Per *MASH*, "The working width is the maximum dynamic lateral position of any major part of the system or vehicle. These measurements are all relative to the pre-impact traffic face of the test article." In other words, working width is the total barrier width plus the maximum dynamic intrusion of any portion of the barrier or test vehicle past the field side edge of the barrier.

Figures C.4 through C.9 in Appendix C.4 show acceleration versus time traces. Figure 5.7 summarizes pertinent information from the test.

Post No.	Lean from Vertical
5	6°
6	11.5°
7	11°
8	4.5°

Table 5.2. Post Lean after Test No. 440861-2.



Figure 5.3. TxDOT T2P Retrofit Bridge Rail after Test No. 440861-2.



Figure 5.4. Field Side of TxDOT T2P Retrofit Bridge Rail after Test No. 440861-2.



Figure 5.5. Test Vehicle after Test No. 440861-2.



Figure 5.6. Interior of Test Vehicle after Test No. 440861-2.



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Chapter 6. SUMMARY AND CONCLUSIONS

6.1. ASSESSMENT OF TEST RESULTS

The crash test reported herein was performed in accordance with *MASH* Test 4-12 on the TxDOT T2P retrofit bridge rail. Table 6.1 provides an assessment of the test based on the applicable safety evaluation criteria for *MASH* TL-4 longitudinal barriers.

6.2. CONCLUSIONS

The TxDOT T2P retrofit bridge rail met the performance criteria for *MASH* Test 4-12 for longitudinal barriers.

	T abit v.t. I utiviliaire lyainauvii duimaly iv	A JUDINAL 12 I LOAVE UN 21-F JOU LAURALI I	IUGO MAIL.
Tes	t Agency: Texas A&M Transportation Institute	Test No.: 440861-2	Fest Date: 2021-07-23
	MASH Test 4-12 Evaluation Criteria	Test Results	Assessment
Str	uctural Adequacy		
А.	Test article should contain and redirect the vehicle or	The TxDOT T2P retrofit bridge rail contained	
	bring the vehicle to a controlled stop; the vehicle	and redirected the 10000S vehicle. The vehicle	
	should not penetrate, underride, or override the	did not penetrate, underride, or override the	Pass
	installation although controlled lateral deflection of	installation. Maximum dynamic deflection	
	the test article is acceptable.	during the test was 14.9 inches.	
Oci	:upant Risk		
D.	Detached elements, fragments, or other debris from	No detached elements, fragments, or other debris	
	the test article should not penetrate or show potential	from the bridge rail were present to penetrate or	
	for penetrating the occupant compartment, or present	show potential for penetrating the occupant	
	an undue hazard to other traffic, pedestrians, or	compartment, or to present undue hazard to	Dass
	personnel in a work zone.	others in the area.	F 455
	Deformations of, or intrusions into, the occupant	No deformation or intrusion of the occupant	
	compartment should not exceed limits set forth in	compartment occurred.	
	Section 5.2.2 and Appendix E of MASH.		
Ŀ.	It is preferable, although not essential, that the vehicle	The 10000S vehicle remained upright during and	
	remain upright during and after collision.	after the collision event. Maximum roll and pitch	Pass
		angles were 42 degrees and 12 degrees.	

Table 6.1. Performance Evaluation Summary for MASH Test 4-12 on TxDOT T2P Retrofit Bridge Rail.

Chapter 7. IMPLEMENTATION*

The TxDOT T2P bridge rail as tested in this project on a 6-inch-thick deck with a single layer of reinforcing steel (#5 bars; 40 ksi or greater) at 12 inches on the centers each way, as shown herein, is recommended for implementation for *MASH* TL-4. This retrofit design is recommended on all existing bridges with deck details that meet or exceed these as-tested conditions.

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

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



APPENDIX A. DETAILS OF TXDOT T2P RETROFIT BRIDGE RAIL



















APPENDIX B. SUPPORTING CERTIFICATION DOCUMENTS

	15 I.
	<u>Certificate of Compliance</u>
CUSTOMER:	СМС
CUSTOMER PO #:	883800
MADDEN BOLT SO#:	
	BOLTS: A193-B7
	FLAT
	WASHER:
	TEMPLATE:
	OTHER:
NOTES:	
Modden Bolt certifies	that the above material is in compliance with the chemical and physic
requirements of the A	STM or AISI specifications.
Thenk you	1
Thank you,	
Authorized Signature:	
Date: June 7, 2021	survy Diggr
13420 Her	npstead HWY ● Houston, TX 77040 ● PH (713) 939-9999 ● FAX (713) 9397200

		Galvanizing, LLC
June 7, 2021 Madden Bolt Corporation 13420 Hempstead Hwy. Houston, TX 77040		
RE: Galvanization Certificat To Whom It May Concern:	e of (ompliance
We certify that our Hot Dip p following order.	oces:	meets the requirements of ASTM A123 Specification on the
CUSTOMER #: CMC		
SALES ORDER #: 122801	PURC	HASE ORDER #: 883800
Approved By:	Rog	er Trejo
13420 Hempstead HW	~•	Houston, TX 77040 ● PH (713) 939-9999 ● FAX (713) 9397200
		WWW.MADDENBOLT.COM

U	PRODUCTS. INC	Vuican Thread 10 Cross Creel Pelham, AL 35 Tel (205) 620- Fax (205) 620-	ed Prode k Trail 124 5100 5150	ucts		JO	B MAT	ERI	AL CE	RTIFIC	ATION
<u> </u>	Job No:	521519			Job Inform	ation		Certil	ied Date:	4/10/17	
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4	Customer:	The Lawless Gr	oup						Ship To:	2200 Alberta Suite 130 Dallas, TX 7	ı 5229
VI	lican Part No:	ATR B7 5/8x12									
Cust	mer Part No:	ATR B7 5/8x12									
C	homes BO Ner	Stock Transfor						Sh	ipped Qtv:	5 containers	
Cus	Comer PO No.	Stock Transier							Line No	47	
	Order No:	322035							2010-110		
	Note:										
					oplicable Spe	cification					
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Heal	Treat		ASME	SA-19	93/SA-193M B7			2013			
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			511	С	ertified Chemi	cal Analy	sis				
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2	2	57	57		57	57	57		57	57	56
.19	J10	J12	J14		J16	J18	J20		J24	J28	J32
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	139	131	23	4D	62	29	28		HRC	
	136	127	19	40	61	30	29		HRC	
	137	128	24	40	62	28	28		HRC	
	139	130	24	40	65	30	20		1000	
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Test No: 422 Description	n Cont		-20	15	7	147	160			
Test No: 422 Description	n Coni		-20	15	1	147				
Test No: 422 Description	n Coni		-20	15	7	147	Mou	helle		4/10/1

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	S 0.048% Si 0.18% Si 0.38% Sr 0.17% Ni 0.12%						
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V 0.000%	•Material is fully killed
Cb 0.004%	* 100% melted and rolled in the USA
Sn 0.012%	• EN10204:2004 3.1 compliant
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Tensile Strength test 1 107.9ksi	of the plant quality manual
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ongation Gage Lgth test 1 8IN	 Warming: This product can expose you to chemicals which are bound to the State of California to cause cancer high defects
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			Bend Test 1	Passed		or of to ww	her reproductive harm. For more information go w. P65Warmings.ca.gov
					-	-	

QTY SIZE	TTI Rail Retro		and the state of the
QTY SIZE		fit - TTI	- J
	DESCRIPTION	BEND	TAG
	GRADE 60		
125 4	5'-6"		
34 4	11' x 10" x 11"	ZBAR	Z1
85 5	7" x 2'-0"	LBAR	L2
248 5	7½" x 11" x 7½"	UBAR	U1
15 5	20'		
51 4	20'		
15 3	20		
	GRADE 40		
126 5	21.9" + 21.10"		11
126 5	2-8 X 3-10	LDAK	
6/ 5	20		

Quality	exas A&M ansportation ostitute y Form	QF 7.3-01 Sam Revised by: B.L. Griffi Approved by: D.L. Ku	Concrete pling	Doc. No. QF 7.3-01 Revision: 7	Revision Date: 2020-0 7- 29 Page: 1 of 1
Project No:	440861-02	Casting Date:	4/16/2021	Mix Design (psi):	4000
Name of Technician Taking Sample	Terr	acon	Name of Technician Breaking Sample	Terr	acon
Signature of Technician Taking Sample	Terr	acon	Signature of Technician Breaking Sample	Terr	acon
Load No.	Truck No.	Ticket No.	Locat	ion (from concrete	e map)
Т1	Tucker	863	South	half of the wall and	d deck
Т2	Tucker	634	North	half of the wall and	d deck
Load No.	Break Date	Cylinder Age	Total Load (lbs)	Break (psi)	Average

TUCKER_concrete

TUCKER_CONSTRUCTION

TICKET # 863

 START
 DATE:
 2021-04-16
 TIME:
 10:34:57

 STOP
 DATE:
 2021-04-16
 TIME:
 11:21:00

MIX DESIGN: B1400 RAW CEMENT COUNTS: 465 RAW CONVEYOR COUNTS: 253806

TOTAL YARDS 10.89

MATERIAL CEMENT SAND STONE WATER ADMIX # 1 ADMIX # 2 ADMIX # 3 DRY COLO

 RATE SETTING
 1

 7.74225LBS/
 5

 4.853882LBS
 1

 5.997994LBS
 2

 24.49684GAL
 2

 0.00Z/MIN
 0

 116.807650Z
 1

 0.00Z/MIN
 0

 0.0LBS/MIN
 0

TOTAL 5634.582 14843.67 20499.96 279.9608 0.00Z 1430.014 0.00Z 0.0LBS

TOTAL SAND MOISTURE: 5.0 TOTAL STONE MOISTURE: 1.0 WATER/CEMENT RATIO: 0.582753 ASTM DATA AVAILABLE UPON REQ Name NOTES:

TUCKER_concrete

979-777-6749 TRUCK_#4 TUCKER_CONSTRUCTION TTI

TICKET # 634

 START
 DATE:
 2021-04-16
 TIME:

 STOP
 DATE:
 2021-04-16
 TIME:

10:59:33 11:49:32

MIX DESIGN: B1400

RAW CEMENT COUNTS: 6147 RAW CONVEYOR COUNTS: 209022 CONVEYOR SPEED: 50 TOTAL YARDS 9.747

MATERIAL RATE SETTING CEMENT 9.343309LBS SAND 5.397386 GA ADJUSTED: STONE 7.101724 GA ADJUSTED: WATER 30.01423GAL ADMIX #1 0.00Z/MIN ADMIX #2 0.00Z/MIN ADMIX #3 0.00Z/MIN TOTAL SAND MOISTURE: 0.0 TOTAL STONE MOISTURE: 0.0

5039.31L 13277.23 18336.62 269.6036 0.00Z

TOTAN

0.00Z

0.00Z

Name NOTES :

CONCRETE COMPRESSIVE STRENGTH TEST REPORT

Report Number: A1171057.0182 Service Date: 04/16/21 **Report Date:** 07/23/21 Revision 1 - Compressive Strength Test Date PO# 440861-02 Task:



College Station, TX 77845-5765 979-846-3767 Reg No: F-3272

Client			Project					
Texas Transportation Attn: Gary Gerke TTI Business Office	Institute		Riverside Campus Riverside Campus Bryan, TX					
3135 TAMU College Station, TX 7	7843-3135		Project Number: A1171057					
Material Informa	tion		Sample Information					
Specified Strength:	4,000 psi @ 2	8 days	Sample Date: Sampled By:	04/16/21 Sample Time: 11 David Carpio				
Supplier: Tucker	Concrete		Accumulative Yards:	10.89 Batch Size (cv): 10.8				
Batch Time: 1034 Truck No.: 1705	Plant: Ticket No.:	Bryan 863	Placement Method: Water Added Before (gal):	Direct Disc 0	charge			
Field Test Data			Water Added After (gal): Sample Location:	0 18' north o	f south end			
Test	Result	Specification	Placement Location:	T2P				
Slump (in): Air Content (%): Concrete Temp. (F):	8 1.9 76	Not specified Not specified 40 - 95						

Laboratory Test Data

Ambient Temp. (F):

Yield (Cu. Yds.):

Plastic Unit Wt. (pcf):

Labo	ratory Tes	st Data			А		Maximum	Compressive		
Set No.	Specimen ID	Avg Diam. (in)	Area (sq in)	Date Received	Date Tested	Test (days)	Load (lbs)	Strength (nsi)	Fracture Tyne	Tested By
			(04)		07/00/01	(,,	122.510	1,720		
1	A	6.00	28.27		0//22/21	97 F	133,510	4,720	1	SUS
1	В	6.00	28.27		07/22/21	97 F	132,630	4,690	4	SLS
1	С	6.00	28.27		07/22/21	97 F	133,860	4,730	1	SLS
1	D					Hold				
Initial	Cure: Outsi	de Plastic Lic	ls	Final C	ure: Field Cu	red				

Comments: F = Field Cured

Note: Reported air content does not include Aggregate Correction Factor (ACF).

40 - 95

Not specified

Samples Made By: Terracon

Services: Obtain samples of fresh concrete at the placement locations (ASTM C 172), perform required field tests and cast, cure, and test compressive strength samples (ASTM C 31, C 39, C 1231). Terracon Rep.: David Carpio Start/Stop: 1015-1245

Reported To: Will

Contractor:

Report Distribution:

(1) Texas Transportation Institute, Gary Gerke (1) Terracon Consultants, Inc., Alex Dunigan, P.E.

66

144.7

(1) Texas Transportation Institute, Bill Griffith

Test Methods: ASTM C 31, ASTM C143, ASTM C231, ASTM C1064

The tests were performed in general accordance with applicable ASTM, AASHTO, or DOT test methods. This report is exclusively for the use of the client indicated above and shall not be reproduced except in full without the written consent of our company. Test results transmitted herein are only applicable to the actual samples tested at the location(s) referenced and are not necessarily indicative of the properties of other apparently similar or identical materials.

CR0001, 11-16-12, Rey 6

Page 1 of 2

CONCRETE COMPRESSIVE STRENGTH TEST REPORT

Report Number: A1171057.0182 Service Date: 04/16/21 **Report Date:** 07/23/21 Revision 1 - Compressive Strength Test Date PO# 440861-02 Task:

75

66

145.5



Client				Project						
Texas Transpo Attn: Gary Ge	ortation Institu erke	te		Riverside Campus Riverside Campus						
3135 TAMU	Office			Bryan, TX						
College Static	on, TX 77843-	3135		Project Number: A1171057						
Material Inf	formation			Sample Information						
Specified Str	ength: 4,000) psi @ 2	28 days	Sample Date: Sampled By:	04/16/21 David Car	Sample Time: pio	1144			
Mix ID:	B1400			Weather Conditions:	Cloudy, lig	ght wind				
Supplier:	Tucker Conc	rete		Accumulative Yards:	9.74	Batch Size (cy):	9.74			
Batch Time:	1059	Plant:	Bryan	Placement Method:	Direct Dis	charge				
Truck No.:	4	Ticket No.:	634	Water Added Before (gal):	0					
	7-4-			Water Added After (gal):	0					
Field lest Data				Sample Location:	57' North of south end					
Test		Result	Specification	Placement Location:	T2P					
Slump (in):		5 3/4	Not specified							
Air Content ((%):	2.4	Not specified							

Laboratory Test Data

Concrete Temp. (F):

Ambient Temp. (F):

Yield (Cu. Yds.):

Plastic Unit Wt. (pcf):

Laboratory Test Data							Maximum	Compressive		
Set No.	Specimen ID	Avg Diam. (in)	Area (sq in)	Date Received	Date Tested	Test (days)	Load (lbs)	Strength (psi)	Fracture Type	Tested By
2	A	6.00	28.27		07/22/21	97 F	137,910	4,880	1	SLS
2	В	6.00	28.27		07/22/21	97 F	156,450	5,530	4	SLS
2	С	6.00	28.27		07/22/21	97 F	139,360	4,930	4	SLS
2	D					Hold				
Initial	Cure: Outsi	de Plastic Lid	ls	Final C	are: Field Cu	red				

Comments: F = Field Cured

Note: Reported air content does not include Aggregate Correction Factor (ACF).

40 - 95 40 - 95

Not specified

Samples Made By: Terracon

Obtain samples of fresh concrete at the placement locations (ASTM C 172), perform required field tests and cast, cure, and Services: test compressive strength samples (ASTM C 31, C 39, C 1231).

Terracon Rep.: David Carpio Reported To: Will

Contractor:

Report Distribution:

(1) Texas Transportation Institute, Gary Gerke (1) Terracon Consultants, Inc., Alex Dunigan, P.E. (1) Texas Transportation Institute, Bill Griffith

Reviewed By:

Start/Stop: 1015-1245

Alexander Dunigan

Project Manager

Test Methods: ASTM C 31, ASTM C143, ASTM C231, ASTM C1064

The tests were performed in general accordance with applicable ASTM, AASHTO, or DOT test methods. This report is exclusively for the use of the client indicated above and shall not be reproduced except in full without the written consent of our company. Test results transmitted herein are only applicable to the actual samples tested at the location(s) referenced and are not necessarily indicative of the properties of other apparently similar or identical materials. Page 2 of 2

CR0001, 11-16-12, Rev.6

	exas A&M ransportation stitute	QF 7.3-01 Sam	Concrete pling	Doc. No. QF 7.3- 01	Revision Date: 2020-0 7- 29
Qualit	y Form	Revised by: B.L. Griffi Approved by: D. L. Ku	th hn	Revision: 7	Page: 1 of 1
Project No:	440861-02	Casting Date:	4/16/2021	Mix Design (psi):	4000
Name of Technician Taking Sample	Terr	acon	Name of Technician Breaking Sample	Terr	acon
Signature of Technician Taking Sample	Terr	acon	Signature of Technician Breaking Sample	Terr	acon
Load No.	Truck No.	Ticket No.	Locat	ion (from concrete	e map)
Т1	Tucker	1094		100% of curb	
Load No.	Break Date	Cylinder Age	Total Load (lbs)	Break (psi)	Average

TUCKER Concrete ⁸⁹³⁰ LACY WELL RD 77845 979 777 6749

Job # TUCKER TTI T2P TICKET # 1094 START DATE: 06/14/2021 TIME: 07:46:26 STOP DATE: 06/14/2021 TIME: 08:33:52

MIX DESIGN B1500	
RAW CEMENT COUNTS	
RAW CONVEYOR COUNTS	6930
	2584

TOTAL YARDS 4.24

MATERIAL	RAT	TE SETTING	TOTAL
CAPTYPE1	4	448.3LBPM	2592.5LBS
LRMSAND		4.6 GATE	5611.5LBS
RGBLND		5.7 GATE	7749.9LBS
WATER		23.5GPM	133.4GAL
SIKA686		0.9GPM	5.1GAL

WATER / CEMENT RATIO 0.43 REQUEST ASTM INFORMATION

NAME_____ NOTES:

CONTINUED FROM 1093

CONCRETE COMPRESSIVE STRENGTH TEST REPORT

Report Number: A1171057.0200 Service Date: 06/14/21 **Report Date:** 07/23/21 Revision 2 - 38-day results PO# 440861-02 Task:



Client		Project						
Texas Transportation Ins	titute	Riverside Campus						
Attn: Gary Gerke		Riverside Campus						
TTI Business Office		Bryan, TX						
3135 TAMU								
College Station, TX 778	43-3135	Project Number: A1171057	,					
Material Informatio	n	Sample Information						
Specified Strength: 4,000 psi @ 28 days		Sample Date:	Sample Time:	0800				
		Sampled By:	ltinghouse					
Mix ID: B1500		Weather Conditions:	Clear, no v	vind				
Supplier: Tucker co	ncrete	Accumulative Yards:	2.0	Batch Size (cy):	4.24			
Batch Time: 0746	Plant: Onsite	Placement Method:	Direct Dise	charge				
Truck No.: VM1801	Ticket No.: From onsit	Water Added Before (gal):	0	-				
		Water Added After (gal):	0					
Field lest Data		Sample Location:	8th section	of edge wall on nor	th side of			
Test	Result Specification		airfield					
Slump (in):	5	Placement Location:	Curb T2P					
Air Content (%):	2.4							

1		h	~		•~		Tee	4 1	Data	
	La	D	О	ra	το	rv	les	τι	Data	

Concrete Temp. (F):

Ambient Temp. (F):

Yield (Cu. Yds.):

Plastic Unit Wt. (pcf):

Laboratory Test Data						Age at	Maximum	Compressive		
Set No.	Specimen ID	Avg Diam. (in)	Area (sq in)	Date Received	Date Tested	Test (days)	Load (lbs)	Strength (nsi)	Fracture Tyne	Tested By
1		()	(39 11)		0.6/1.0/01	(44)0)	(100)	(201)		
1	A	6.01	28.37		06/18/21	4	95,630	3,370	1	SLS
1	В	6.00	28.27		07/22/21	38	125,440	4,440	3	SLS
1	С	6.00	28.27		07/22/21	38	128,520	4,550	3	SLS
1	D	6.00	28.27		07/22/21	38	126,320	4,470	1	SLS
						Aver	age (38 days)	4,480		

Initial Cure: Outside Plastic Lids

Final Cure: Field Cured

Comments: Average compressive strength of 38 day cylinders complies with the specified strength. Note: Reported air content does not include Aggregate Correction Factor (ACF).

Samples Made By: Terracon

Obtain samples of fresh concrete at the placement locations (ASTM C 172), perform required field tests and cast, cure, and Services: test compressive strength samples (ASTM C 31, C 39, C 1231).

Terracon Rep.: Ethan Boultinghouse

Reported To:

Contractor:

Report Distribution:

(1) Texas Transportation Institute, Gary Gerke (1) Terracon Consultants, Inc., Alex Dunigan, P.E. (1) Texas Transportation Institute, Bill Griffith

82

85

145.1

Reviewed By:

Start/Stop: 0645-0900

Alexander Dunigan

Project Manager

Test Methods: ASTM C 31, ASTM C143, ASTM C231, ASTM C1064

The tests were performed in general accordance with applicable ASTM, AASHTO, or DOT test methods. This report is exclusively for the use of the client indicated above and shall not be reproduced except in full without the written consent of our company. Test results transmitted herein are only applicable to the actual samples tested at the location(s) referenced and are not necessarily indicative of the properties of other apparently similar or identical materials. Page 1 of 1

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APPENDIX C. MASH TEST 4-12 (CRASH TEST NO. 440861-2)

C.1. VEHICLE PROPERTIES AND INFORMATION

Table C.1. Vehicle Properties for Test No. 440861-2.



Date:	2021-07	-23	Test No.:	4408	361-2		lo.:	5PVNV8JM5C4S50273			
Year:	2012		Make:	HI	NO	Mode	- :		338		
	WEI (GHTS Ib or Wfm Wrd W]kg) ont axle ear axle TOTAL ange for CURB =	CU	RB 6850 7100 13950 b Allowable Ra	ange for '	TES ⁻	T INERTIAL 8120 14420 22540 2,046 ±660 lb			
E	Ballast: 859	0	(🖌 lb or 🗌 k	(as-need g) (See MA	led) ISH Sec	tion 4.2	2.1.2 for recom	mende	d ballasting)	
Mass D (☑Ib o	r ∐ kg):	LF:	4060	RF : <u>4</u>	060	LR:	741	0	RR:	7010	
Engine Engine	_{Туре:} <u>Т 26</u> Size:	0		-	Acceleror	neter L x ¹	.ocatio	ons (🔽 inche y	es or	☐ mm) z²	
Transm	Transmission Type:										
	Auto or		Manual		Center:	13 <i>′</i>	1.50	0.00)	50.00	
	FWD 🔽 I	RWD	4WD		Rear:	233	3.00	0.0	<u>o</u>	50.00	
Describ	e any damag	e to the	vehicle prior	to test:	None						
Other n attachn Two	n <mark>otes to inclu</mark> nent: concrete b	<mark>ide bal</mark> locks	<mark>last type, di</mark> 30 inches l	<mark>mensions,</mark> nigh x 60	mass, loca	ation, o ide x (c <mark>ente</mark> 30 in	r <mark>of mass, a</mark> ches long	nd m	ethod of	
Cen	tered in mic	dle of	fbed								
63.7	5 inches fro	om gro	ound to cer	nter of blo	ock						
Tied	down with	four 5	/8-inch B7	rod and	four 3/8-in	ich ca	bles				
Perforr	ned by: _ ^{Si}	CD					Da	te:20)21-0	7-23	

Table C.1. Vehicle Properties for Test No. 440861-2 (Continued).

¹ Referenced to the front axle ² Above ground

C.2. SEQUENTIAL PHOTOGRAPHS















Figure C.1. Sequential Photographs for Test No. 440861-2 (Overhead and Frontal Views).

0.100 s



















Figure C.1. Sequential Photographs for Test No. 440861-2 (Overhead and Frontal Views) (Continued).







0.100 s



0.200 s



0.400 s



0.500 s



0.600 s





Figure C.2. Sequential Photographs for Test No. 440861-2 (Rear View).



C.3. VEHICLE ANGULAR DISPLACEMENTS


C.4. VEHICLE ACCELERATIONS

TR No. 0-7086-R5

2021-09-30



TR No. 0-7086-R5







Figure C.7. Vehicle Longitudinal Accelerometer Trace for Test No. 440861-2 (Accelerometer Located at Rear of Vehicle).

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Z Acceleration at Rear of Vehicle

TR No. 0-7086-R5

(Accelerometer Located at Rear of Vehicle).