PERFORMANCE LIMITS FOR 6-IN. (152-MM) HIGH CURBS PLACED IN ADVANCE OF THE MGS USING MASH VEHICLES

PART III: FULL-SCALE CRASH TESTING (TL-2)

Submitted by

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Performance Limits for 6-in. (152-mm) High Curbs Placed in Advance of the MGS Using MASH Vehicles Part III: Full-Scale Crash Testing (TL-2)  

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A full-scale crash test utilizing the Test Level 2 (TL-2) safety performance criteria of the Manual for Assessing Safety Hardware (MASH) was performed on the Midwest Guardrail System (MGS) offset 6 ft (1.8 m) behind a 6-in. (152-mm) high AASHTO Type B curb with a top mounting height of 31 in. (787 mm) relative to the ground [37 in. (940 mm) relative to the roadway]. In the test, the 2270P vehicle was redirected by the guardrail, and all safety performance criteria were met. Thus, the MGS offset 6 ft (1.8 mm) behind a 6-in. (152-mm) high curb with a top mounting height of 31 in. (787 mm) was deemed to be acceptable according to TL-2 of MASH. Based on test results and prior research, preliminary guidelines were developed for use of the MGS when offset behind curbs.
DISCLAIMER STATEMENT

This report was completed with funding from the Federal Highway Administration, U.S. Department of Transportation. The contents of this report reflect the views and opinions of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the state highway departments participating in the Midwest States Regional Pooled Fund Program nor the Federal Highway Administration, U.S. Department of Transportation. This report does not constitute a standard, specification, regulation, product endorsement, or an endorsement of manufacturers.

UNCERTAINTY OF MEASUREMENT STATEMENT

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

The Independent Approving Authority (IAA) for this project was Mr. Scott Rosenbaugh, Research Associate Engineer.
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1 INTRODUCTION

1.1 Problem Statement

Highway design policy typically discourages the use of 6- to 8-in. (152- to 203-mm) vertical curbs on high-speed roadways because of their potential to cause drivers to lose control in a crash [1]. Curbs can also affect the interaction of errant vehicles with roadside barriers by causing vaulting or underride of the barrier. However, the use of curbs is often required because of restricted right-of-way, drainage considerations, access control, and other functions. Often, there is a desire to offset the guardrail from the curb to reduce the propensity for snow plows to gouge and/or damage the W-beam rail sections or to allow for placement of sidewalks between the road and a barrier or other roadside features.

When curbs are required, the offset of the barrier from the curb has been shown to be critical in the performance of the system through modeling and crash testing. Previous work with steel-post, nested W-beam guardrail has shown that a 4-in. (102-mm) high sloped curb with the toe of the curb placed at the front face of the guardrail is capable of meeting National Cooperative Highway Research Program (NCHRP) Report No. 350 safety requirements [2-4]. Further research with standard wood-post W-beam guardrail has shown that a 4-in. (102-mm) high sloped curb with its toe set out 1 in. (25 mm) from the front face of the guardrail is also capable of meeting TL-3 requirements [5].

Investigation of curb-barrier combinations was reported in NCHRP Report No. 537, Recommended Guidelines for Curbs and Curb-Barrier Combinations [6]. This study developed guidelines for the use of curbs and curb-barrier combinations on roadways with operating speeds greater than 37.3 mph (60 km/h). The study recommended that guardrail be installed flush with the face of the sloped curb or offset more than 8.2 ft (2.5 m) behind the curb for operating speeds
in excess of 37.3 mph (60 km/h). In addition, the study recommended that guardrail should not be offset behind sloped curbs for speeds greater than 62.1 mph (100 km/h).

The recent development and testing of the Midwest Guardrail System (MGS) has demonstrated that this system can be used with a 6-in. (152-mm) tall, American Association of State Highway Transportation Officials (AASHTO) Type B curb positioned 6 in. (152 mm) in front of the face of the guardrail element [7-8]. Although this guardrail-to-curb configuration provides increased hydraulic flow for roadway runoff as well as reduced guardrail maintenance arising from snow plowing operations, state departments of transportation (DOTs) often desire to locate roadside curbs farther away from the front face of the guardrail. Thus, a research effort was begun with the goal of determining placement guidelines for the MGS in relation to curbs.

1.2 Background

In 2008, testing was performed with the small car and pickup truck vehicles specified in the Manual for Assessing Safety Hardware (MASH) [9]. The test vehicles impacted a 6-in. (152-mm) high AASHTO Type B curb under Test Level 3 (TL-3) conditions [i.e., 62 mph (100 km/h) and 25 degrees]. The main goal of the tests was to determine the vehicle behavior following the impact, with particular attention focused on the pitch angles and the bumper trajectories of the vehicles [10-11].

By comparing the critical bumper impact point trajectories against the MGS top/bottom corrugation heights, the critical override/underride offset for placing the MGS behind the curb was determined. Results of this analysis created offset guidelines for placement of the MGS with a 6-in. (152-mm) high curb [10-11].

To further investigate the critical offset distance for MGS placement behind an AASHTO Type B curb, finite element analysis was performed. The MGS was offset from a 6-in. (152-mm) high AASTHO Type B curb at various distances and impacted with the 2000P test vehicle.
Based on previous vehicle-curb simulation results and to ensure reliability of the model, the offset distance under investigation was limited to the range of 0.0 ft (0.0 m) to 7.35 ft (2.24 m) behind the curb. Simulation results indicated that the current pickup model (2000P) was fairly accurate in predicting the vehicle trajectory within 7.35 ft (2.24 m) behind the curb. Details of this research effort are documented in prior MwRSF research reports [10-11].

Based on the simulation results, a full-scale crash test was then performed on the MGS with a top mounting height of 37 in. (940 mm) above the roadway, offset 8 ft (2.44 m) behind a 6-in. (152-mm) high AASHTO Type B Curb [12]. In the test, the 2270P vehicle was contained by the guardrail, but it became unstable and rolled over. Analysis of the test revealed that the right-front tire snagged on a post and detached. The right-rear tire of the pickup traversed over the detached tire, causing the rear of the vehicle to pitch upward. The vehicle subsequently became unstable and rolled over. Thus, the MGS offset 8 ft (2.44 mm) behind a 6-in. (152-mm) high curb with a top mounting height of 37 in. (940 mm) relative to the roadway was deemed to be unacceptable according to TL-3 of MASH.

Simulation of this crash test was then performed with the newly released 2270P vehicle model. Simulation results also showed the 2270P rolling over in the same impact scenario as the first crash test.

1.3 Objective

Following the unsuccessful full-scale crash test, the original project was modified based on a survey of the states in the Midwest States Regional Pooled Fund Program. The new objective was to determine a range of distances for which the MGS could be offset behind a 6-in. (152-mm) high AASHTO Type B curb and satisfy the TL-2 safety performance criteria of MASH.
1.4 Scope

The research objective was achieved through the completion of several tasks. First, finite element simulations of the system were performed to determine the critical offset distance of the MGS relative to the curb. This configuration would represent the highest probability of system failure under TL-2 conditions for the range of offsets. Then, a full-scale vehicle crash test was performed on the MGS offset 6 ft (1.83 m) behind a 6-in. (152-mm) high AASHTO Type B curb. The MGS was raised 6 in. (152 mm) resulting in a top mounting height of 37 in. (940 mm) relative to the roadway. The crash test utilized a pickup truck, weighing approximately 5,000 lb (2,268 kg). Target impact conditions for the test were an impact speed of 44 mph (70 km/h) and an impact angle of 25 degrees. Next, the test results were analyzed, evaluated, and documented. Finally, conclusions and recommendations were made that pertain to the safety performance of the MGS and curb system relative to the test performed.
2 BARRIER DESIGN AND ANALYSIS

Researchers concluded that the critical offset distance for the MGS behind the curb was the distance which would provide the most probable conditions for override of the pickup truck test vehicle. It was believed that the worst-case placement for the MGS relative to the curb would be at the location where the front bumper of the truck reached the apex of its trajectory following impact with the curb. The truck would be at its maximum height at this location, and its momentum would not yet be going downward. It was believed an acceptable range for placing the MGS behind the curb could be achieved by testing the worst-case location for the MGS with the pickup truck and using previous knowledge concerning the small car.

Finite element analysis was performed using LS-DYNA to determine the critical offset of the MGS relative to the curb [13]. The vehicle model used for the simulation was the National Crash Analysis Center (NCAC) Silverado V2 model released in March 2009, while the MGS model used in the simulations was developed by MwRSF in previous studies [11].

To determine the critical offset distance for TL-2 conditions, simulations with only the pickup truck and the curb were initially conducted. Results from this study showed the apex of the trajectory of the front bumper occurred at a distance of approximately 6 ft (1.83 m) behind the toe of the curb.

Further simulations were then performed in which the Silverado impacted the MGS at various offsets from the curb. These offsets ranged from 4 ft (1.22 m) to 10 ft (3.05 m) at 1-ft (0.30-m) increments. Results from the 6-ft (1.83-m) and 8-ft (2.44-m) offset simulations, which are shown in Figure 1, clearly indicated that the 6-ft (1.83-m) offset produced the worst-case impact. However, in this scenario, the truck was smoothly redirected by the MGS. Therefore, the system was expected to perform successfully in full-scale crash testing.
Figure 1. 8-ft Offset (Top Vehicle in Each Frame) vs. 6-ft Offset (Bottom Vehicle in Each Frame)
3 DESIGN DETAILS

The barrier system test installation was comprised of 175 ft (53.34 m) of MGS guardrail supported by steel posts and positioned 6 ft (1.83 m) behind a 6-in. (152-mm) tall, AASHTO Type B curb, as shown in Figures 2 through 11. Photographs of the test installation are shown in Figures 12 through 14. Material specifications, mill certifications, and certificates of conformity for the system materials are shown in Appendix A.

The MGS was constructed with twenty-nine guardrail posts. Post nos. 3 through 27 were galvanized ASTM A36 steel W6x8.5 (W152x12.6) sections measuring 72 in. (1,829 mm) long and embedded in 40 in. (1016 mm) of soil, as shown in Figures 3 and 6. Post nos. 1, 2, 28, and 29 were timber posts measuring 5½ in. wide x 7½ in. deep x 46 in. long (140 mm x 190 mm x 1,168 mm) and were placed in 72-in. (1,829-mm) long steel foundation tubes, as shown in Figures 4 and 7. The timber posts and foundation tubes were part of the anchor system designed to replicate the capacity of a tangent guardrail terminal.

Post nos. 1 through 29 were spaced 75 in. (1,905 mm) on center, as shown in Figure 2. The posts were placed in a compacted, coarse, crushed limestone material that met Grading B of AASHTO M147-65 (1990) as described in MASH. For post nos. 3 through 27, 6-in. wide x 12-in. deep x 14¼-in. long (152-mm x 305-mm x 362-mm) wood spacer blockouts were used to block the rail away from the front face of the steel posts, as shown in Figures 3 and 6.

Standard 12-gauge (2.66-mm thick) W-beam rails were placed between post nos. 1 and 29, as shown in Figures 2, 4, and 10. The top mounting height of the W-beam rail was 31 in. (787 mm) above the ground surface with a 24⅜-in. (632-mm) center mounting height, or 37 in. (940 mm) above the roadway surface. Rail splices were placed at midspan locations between guardrail posts, as shown in Figures 2 and 4. All lap splice connections between the rail sections were configured to reduce vehicle snag at the splice during the crash test.
A 6-in. (152-mm) tall, AASHTO Type B curb was placed in front of the MGS. The concrete curb was 73 ft - 6 in. (22.40 m) long, beginning at the midspan between post nos. 8 and 9 to post no. 20, as shown in Figure 2. The toe of the curb was offset 6 ft (1.83 m) in front of the front face of the guardrail. The concrete mix had a minimum 28-day compressive strength of 4,000 psi (27.6 MPa). All steel reinforcement was specified as ASTM A615 Grade 40 rebar and consisted of No. 4 longitudinal and vertical bars, as shown in Figure 3.
Figure 2. Test Installation Layout, Test No. MGSC-6
Figure 3. Post and Curb Details, Test No. MGSC-6

Notes:
1. Curb offset has a tolerance of ±3/4" [44] located between the tangent edge of curb and front face of the guardrail.
2. Asphalt extends entire length of the system.
Figure 4. End Rail and Splice Details, Test No. MGSC-6
Figure 5. Anchor Details, Test No. MGSC-6
Figure 6. Post and Blockout Details, Test No. MGSC-6
Figure 7. BCT Timber Post and Foundation Tube Details, Test No. MGSC-6
Figure 8. BCT Anchor Cable Details, Test No. MGSC-6
Figure 9. Ground Strut and Anchor Bracket Details, Test No. MGSC-6
Figure 10. Rail Section Details, Test No. MGSC-6

Note: (1) Part nos. a3 and a4 can also be 25’ [7620] sections.
<table>
<thead>
<tr>
<th>Item No.</th>
<th>QTY.</th>
<th>Description</th>
<th>Material Specifications</th>
<th>Hardware Guide</th>
</tr>
</thead>
<tbody>
<tr>
<td>a1</td>
<td>25</td>
<td>W6x8.5 [W152x12.6] 72&quot; [1829] long</td>
<td>ASTM A36 Steel</td>
<td>–</td>
</tr>
<tr>
<td>a2</td>
<td>25</td>
<td>6x12x14 1/4&quot; [152x305x38] Blockout</td>
<td>SYP Grade No.1 or better</td>
<td>PDB10a-b</td>
</tr>
<tr>
<td>a3</td>
<td>12</td>
<td>12&quot;-6&quot; [3810] W-Beam MGS Section</td>
<td>12 gauge [2.7] AASHTO M180</td>
<td>RWM04a</td>
</tr>
<tr>
<td>a4</td>
<td>2</td>
<td>12&quot;-8&quot; [3810] W-Beam MGS End Section</td>
<td>12 gauge [2.7] AASHTO M180</td>
<td>RWM14a</td>
</tr>
<tr>
<td>a5</td>
<td>1</td>
<td>6&quot;-3&quot; [1905] W-Beam MGS Section</td>
<td>12 gauge [2.7] AASHTO M180</td>
<td>RWM01a</td>
</tr>
<tr>
<td>a6</td>
<td>4</td>
<td>5/8&quot; [15.8] Dia. x 10&quot; [254] long Guardrail Bolt and Nut</td>
<td>ASTM A307</td>
<td>FBB03</td>
</tr>
<tr>
<td>a8</td>
<td>4</td>
<td>5/8&quot; [15.8] Dia. x 10&quot; [254] long Hex Head Bolt and Nut</td>
<td>ASTM A307</td>
<td>FBB16a</td>
</tr>
<tr>
<td>a9</td>
<td>16</td>
<td>5/8&quot; [15.8] Dia. x 1 1/2&quot; [38] long Hex Head Bolt and Nut</td>
<td>ASTM A307</td>
<td>FBBX16a</td>
</tr>
<tr>
<td>a10</td>
<td>112</td>
<td>5/8&quot; [15.8] Dia. x 1 1/2&quot; [38] long Guardrail Bolt and Nut</td>
<td>ASTM A307</td>
<td>FBB01</td>
</tr>
<tr>
<td>a11</td>
<td>44</td>
<td>5/8&quot; [15.8] Dia. Flat Washer</td>
<td>ASTM F436 Grade 1</td>
<td>FWC16a</td>
</tr>
<tr>
<td>a12</td>
<td>25</td>
<td>180 Double Head Nail</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>b1</td>
<td>4</td>
<td>72&quot; [1829] Foundation Tube</td>
<td>ASTM A500 Gr. B</td>
<td>PTE06</td>
</tr>
<tr>
<td>b2</td>
<td>4</td>
<td>BCT Timber Post</td>
<td>SYP Grade No.1 or better (No knots, 18&quot; [457] above or below ground tension face)</td>
<td>PDF01</td>
</tr>
<tr>
<td>b3</td>
<td>4</td>
<td>7/8&quot; [22.2] Dia. x 7 1/2&quot; [191] long Hex Head Bolt and Nut</td>
<td>ASTM A307</td>
<td>FBBX22a</td>
</tr>
<tr>
<td>b4</td>
<td>8</td>
<td>7/8&quot; [22.2] Dia. Flat Washer</td>
<td>ASTM F436 Grade 1</td>
<td>FWC22a</td>
</tr>
<tr>
<td>b6</td>
<td>2</td>
<td>Strut and Yoke Assembly</td>
<td>ASTM A36 Steel Galvanized</td>
<td>–</td>
</tr>
<tr>
<td>b7</td>
<td>2</td>
<td>Anchor Bracket Assembly</td>
<td>ASTM A36 Steel Galvanized</td>
<td>FPA01</td>
</tr>
<tr>
<td>b8</td>
<td>2</td>
<td>BCT Cable Anchor Assembly</td>
<td>φ3/4&quot; [19] 6x19 IWRC IPS Galvanized Wire Rope</td>
<td>FCA01-02</td>
</tr>
<tr>
<td>b9</td>
<td>2</td>
<td>8&quot;x8&quot;x5/8&quot; [203x203x16] Anchor Bearing Plate</td>
<td>ASTM A36 Steel Galvanized</td>
<td>FBB01</td>
</tr>
<tr>
<td>c1</td>
<td>1</td>
<td>Curb</td>
<td>Concrete (s/g m³) - Min. 4000 psi [27.6 MPa] Comp. Strength</td>
<td>–</td>
</tr>
<tr>
<td>c2</td>
<td>49</td>
<td>#4 Rebar 12&quot; [305] Long</td>
<td>ASTM A615 Grade 40</td>
<td>–</td>
</tr>
<tr>
<td>c3</td>
<td>1</td>
<td>#4 Rebar 73&quot; [22.3 m] Long</td>
<td>ASTM A615 Grade 40</td>
<td>–</td>
</tr>
</tbody>
</table>

Figure 11. Bill of Materials, Test No. MGSC-6
Figure 12. Test Installation Photographs, Test No. MGSC-6
Figure 13. Test Installation Photographs, Test No. MGSC-6
Figure 14. Test Installation Photographs, Test No. MGSC-6
4 TEST REQUIREMENTS AND EVALUATION CRITERIA

4.1 Test Requirements

Longitudinal barriers, such as W-beam guardrails with curbs, must satisfy impact safety standards in order to be accepted by the Federal Highway Administration (FHWA) for use on National Highway System (NHS) new construction projects or as a replacement for existing designs not meeting current safety standards. In recent years, these safety standards have consisted of the guidelines and procedures published in NCHRP Report 350. However, NCHRP Project 22-14(2) generated revised testing procedures and guidelines for use in the evaluation of roadside safety appurtenances and are provided in MASH. According to TL-2 of MASH, longitudinal barrier systems must be subjected to two full-scale vehicle crash tests. The two full-scale crash tests are as follows:

1. Test Designation 2-10 consisting of a 2,425-lb (1,100-kg) passenger car impacting the system at a nominal speed and angle of 44 mph (70 km/h) and 25 degrees, respectively.

2. Test Designation 2-11 consisting of a 5,000-lb (2,268-kg) pickup truck impacting the system at a nominal speed and angle of 44 mph (70 km/h) and 25 degrees, respectively.

The test conditions of TL-2 longitudinal barriers are summarized in Table 1.

Table 1. MASH TL-2 Crash Test Conditions

<table>
<thead>
<tr>
<th>Test Article</th>
<th>Test Designation</th>
<th>Test Vehicle</th>
<th>Impact Conditions</th>
<th>Evaluation Criteria ¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal Barrier</td>
<td>2-10</td>
<td>1100C</td>
<td>Speed</td>
<td>Angle (deg)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>mph</td>
<td>km/h</td>
</tr>
<tr>
<td></td>
<td>2-11</td>
<td>2270P</td>
<td>44</td>
<td>70</td>
</tr>
</tbody>
</table>

¹ Evaluation criteria explained in Table 2.
4.2 Evaluation Criteria

Evaluation criteria for full-scale vehicle crash testing are based on three appraisal areas: (1) structural adequacy; (2) occupant risk; and (3) vehicle trajectory after collision. Criteria for structural adequacy are intended to evaluate the ability of the guardrail to contain and redirect impacting vehicles. Occupant risk evaluates the degree of hazard to occupants in the impacting vehicle. Vehicle trajectory after collision is a measure of the potential for the post-impact trajectory of the vehicle to result in secondary collisions with other vehicles or fixed objects, thereby increasing the risk of injury to the occupant of the impacting vehicle and to other vehicles. These evaluation criteria are summarized in Table 2 and defined in greater detail in MASH. The full-scale vehicle crash test was conducted and reported in accordance with the procedures provided in MASH.

In addition to the standard occupant risk measures, the Post-Impact Head Deceleration (PHD), the Theoretical Head Impact Velocity (THIV), and the Acceleration Severity Index (ASI) were determined and reported on the test summary sheet. Additional discussion on PHD, THIV and ASI is provided in Reference 9.

4.3 Soil Strength Requirements

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

Table 2. MASH Evaluation Criteria for Longitudinal Barrier

<table>
<thead>
<tr>
<th></th>
<th>Structural Adequacy</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.</td>
<td>Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.</td>
</tr>
<tr>
<td></td>
<td>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. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.</td>
</tr>
<tr>
<td></td>
<td>F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Occupant Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>H.</td>
<td>Occupant Impact Velocities (OIV) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:</td>
</tr>
<tr>
<td></td>
<td>Occupant Impact Velocity Limits</td>
</tr>
<tr>
<td></td>
<td>Component</td>
</tr>
<tr>
<td></td>
<td>Longitudinal and Lateral</td>
</tr>
</tbody>
</table>

I. The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:

<table>
<thead>
<tr>
<th></th>
<th>Occupant Ridedown Acceleration Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Component</td>
</tr>
<tr>
<td></td>
<td>Longitudinal and Lateral</td>
</tr>
</tbody>
</table>
5 TEST CONDITIONS

5.1 Test Facility

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

5.2 Vehicle Tow and Guidance System

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

A vehicle guidance system developed by Hinch [14] was used to steer the test vehicle. A guide-flag, attached to the left-front wheel and the guide cable, was sheared off before impact with the barrier system. The ⅜-in. (9.5-mm) diameter guide cable was tensioned to approximately 3,500 lb (15.6 kN) and supported both laterally and vertically every 100 ft (30.48 m) by hinged stanchions. The hinged stanchions stood upright while holding up the guide cable, but as the vehicle was towed down the line, the guide-flag struck and knocked each stanchion to the ground.

5.3 Test Vehicle

For test no. MGSC-6, a 2003 Dodge Ram 1500 Quad Cab pickup truck was used as the test vehicle. The curb, test inertial, and gross static vehicle weights were 5,100 lb (2,313 kg), 4,974 lb (2,256 kg), and 5,144 lb (2,333 kg), respectively. The test vehicle is shown in Figure 15, and vehicle dimensions are shown in Figure 16.
Figure 15. Test Vehicle, Test No. MGSC-6
Date: 11/10/2009  
Test Number: MGSC-6  
Model: 2270P (RAM 1500)  
Make: Dodge  
Vehicle I.D.#: 1D7HA18N738229425  
Tire Size: 265/70 R17  
Year: 2003  
Odometer: 111866  
Tire Inflation Pressure: 35psi  

Vehicle Geometry -- in. (mm)  

<table>
<thead>
<tr>
<th></th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>d</th>
<th>e</th>
<th>f</th>
<th>g</th>
<th>h</th>
<th>i</th>
<th>j</th>
<th>k</th>
<th>l</th>
<th>m</th>
<th>n</th>
<th>o</th>
<th>p</th>
<th>q</th>
<th>r</th>
<th>s</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>78</td>
<td>74</td>
<td>227</td>
<td>47.5</td>
<td>140.25</td>
<td>39.25</td>
<td>28.76</td>
<td>62.91</td>
<td>15</td>
<td>27</td>
<td>20.5</td>
<td>28.75</td>
<td>68</td>
<td>115.5</td>
<td>44</td>
<td>3</td>
<td>32</td>
<td>18.5</td>
<td>15.25</td>
<td>74.5</td>
</tr>
</tbody>
</table>

| Wheel Center Height Front | 15 (381) |  
| Wheel Center Height Rear | 14.75 (375) |  
| Wheel Well Clearance (F) | 35.5 (902) |  
| Wheel Well Clearance (R) | 37.75 (959) |  
| Frame Height (F) | 18 (457) |  
| Frame Height (R) | 25 (635) |  
| Engine Type | Gas V-8 |  
| Engine Size | 4.7L |  
| Transmission Type: | Automatic Manual |  
| FWD | QWD | 4WD |

**Weights (lbs, kg)**  
- Curb  
- Test Inertial  
- Gross Static  

<table>
<thead>
<tr>
<th></th>
<th>W-front</th>
<th>W-rear</th>
<th>W-total</th>
</tr>
</thead>
<tbody>
<tr>
<td>lbs</td>
<td>2838 (1287)</td>
<td>2262 (1026)</td>
<td>5100 (2243)</td>
</tr>
<tr>
<td>kg</td>
<td>1287</td>
<td>1026</td>
<td>2243</td>
</tr>
<tr>
<td>lbs</td>
<td></td>
<td>2735 (1241)</td>
<td>4974 (2256)</td>
</tr>
<tr>
<td>kg</td>
<td></td>
<td>1241</td>
<td>2256</td>
</tr>
<tr>
<td>lbs</td>
<td></td>
<td>2837 (1287)</td>
<td>5144 (2233)</td>
</tr>
<tr>
<td>kg</td>
<td></td>
<td>1287</td>
<td>2233</td>
</tr>
</tbody>
</table>

**GVWR Ratings**  
- Front: 3650  
- Rear: 3900  
- Total: 6650  

**Dummy Data**  
- Type: Hybrid II  
- Mass: 170 lbs  
- Seat Position: Passenger  

Note any damage prior to test: None

Figure 16. Vehicle Dimensions, Test No. MGSC-6
The longitudinal component of the center of gravity (c.g.) was determined using the measured axle weights, while the Suspension Method [15] was used to determine the vertical component of the c.g. for the pickup truck. The latter method is based on the principle that the c.g. of any freely suspended body is in the vertical plane through the point of suspension. The vehicle was suspended successively in three positions, and the respective planes containing the c.g. were established. The intersection of these planes pinpointed the final c.g. location for the test inertial condition. The location of the final c.g. is shown in Figures 16 and 17. Data used to calculate the location of the c.g. and ballast information are shown in Appendix B.

Square, black- and white-checkered targets were placed on the vehicle to aid in the analysis of the high-speed videos, as shown in Figure 17. Round, checkered targets were placed on the center of gravity on the left-side door, the right-side door, and the roof of the vehicle. The remaining targets were located for references so that they could be viewed from the high-speed cameras for video analysis.

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

5.4 Simulated Occupant

For test no. MGSC-6, A Hybrid II 50th Percentile Adult Male Dummy, equipped with clothing and footwear, was placed in the right-front seat of the test vehicle with the seat belt
Figure 17. Target Geometry, Test No. MGSC-6
fastened. The dummy, which had a final weight of 170 lb (77 kg), was represented by model no. 572, serial no. 451, and was manufactured by Android Systems of Carson, California. As recommended by MASH, the dummy was not included in calculating the c.g location.

5.5 Data Acquisition Systems

5.5.1 Accelerometers

Two environmental shock and vibration sensor/recorder systems were used to measure the accelerations in the longitudinal, lateral, and vertical directions. Both of the accelerometers were mounted near the center of gravity of the test vehicle.

One system was a two-arm piezoresistive accelerometer system developed by Endevco of San Juan Capistrano, California. Three accelerometers were used to measure each of the longitudinal, lateral, and vertical accelerations independently at a sample rate of 10,000 Hz. Two additional accelerometers were used to measure the longitudinal and lateral accelerations independently at the same sample rate. The accelerometers were configured and controlled using a system developed and manufactured by Diversified Technical Systems, Inc. (DTS) of Seal Beach, California. More specifically, data was collected using a DTS Sensor Input Module (SIM), Model TDAS3-SIM-16M. The SIM was configured with 16 MB SRAM memory and 8 sensor input channels with 250 kB SRAM/channel. The SIM was mounted on a TDAS3-R4 module rack. The module rack was configured with isolated power/event/communications, 10BaseT Ethernet and RS232 communication, and an internal backup battery. Both the SIM and module rack were crashworthy. The computer software program “DTS TDAS Control” and a customized Microsoft Excel worksheet were used to analyze and plot the accelerometer data.

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

5.5.2 Rate Transducers

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

5.5.3 Pressure Tape Switches

For test no. MGSC-6, five pressure-activated tape switches, spaced at approximately 6.56 ft (2 m) intervals, were used to determine the speed of the vehicle before impact. Each tape switch fired a strobe light which sent an electronic timing signal to the data acquisition system as the right-front tire of the test vehicle passed over it. Test vehicle speed was determined from electronic timing mark data recorded using TestPoint and LabVIEW computer software programs. Strobe lights and high-speed video analysis are used only as a backup in the event that vehicle speed cannot be determined from the electronic data.

5.5.4 High-Speed Photography

Three AOS VITcam high-speed digital video cameras, three AOS X-PRI high-speed digital video cameras, four JVC digital video cameras, and one Canon digital video camera were used to film the crash test. Camera details, camera operating speeds, lens information, and a schematic of the camera locations relative to the system are shown in Figure 18.
The high-speed videos were analyzed using ImageExpress MotionPlus and RedLake MotionScope software programs. Actual camera speed and camera divergence factors were considered in the analysis of the high-speed videos. A Nikon D50 digital still camera was also used to document pre- and post-test conditions for the test.
<table>
<thead>
<tr>
<th>No.</th>
<th>Type</th>
<th>Operating Speed (frames/sec)</th>
<th>Lens</th>
<th>Lens Setting</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>AOS Vitcam CTM</td>
<td>500</td>
<td>Cosmicar 12.5-mm Fixed</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>AOS Vitcam CTM</td>
<td>500</td>
<td>TV Zoom V6x17 17-102 mm 50 mm</td>
<td>50 mm</td>
</tr>
<tr>
<td>4</td>
<td>AOS Vitcam CTM</td>
<td>500</td>
<td>Kowa 8-mm Fixed</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>AOS X-PRI Gigabit</td>
<td>500</td>
<td>Telesar 135-mm Fixed</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>AOS X-PRI Gigabit</td>
<td>500</td>
<td>Sigma 50-mm Fixed</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>AOS X-PRI Gigabit</td>
<td>500</td>
<td>Fujinon 50-mm Fixed</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>JVC – GZ-MC500 (Everio)</td>
<td>29.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>JVC – GZ-MG27u (Everio)</td>
<td>29.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>JVC – GZ-MG27u (Everio)</td>
<td>29.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>JVC – GZ-MG27u (Everio)</td>
<td>29.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Canon ZR90</td>
<td>29.97</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 18. Camera Locations, Speeds, and Lens Settings, Test No. MGSC-6
6 FULL-SCALE CRASH TEST NO. MGSC-6

6.1 Static Soil Test

Before full-scale test no. MGSC-6 was conducted, the strength of the foundation soil was evaluated with a static test, as described in MASH. The static test results, as shown in Appendix C, demonstrated a soil resistance above the baseline test limits. Thus, the soil provided adequate strength, and the barrier system was approved for full-scale testing.

6.2 Test No. MGSC-6

The 5,144-lb (2,333-kg) pickup truck, with a simulated occupant seated in the right-front seat, impacted the curb at a speed of 45.6 mph (73.4 km/h) and at an angle of 25.3 degrees. After mounting the curb, the vehicle impacted the guardrail at an angle of 22.5 degrees. A summary of the test results and sequential photographs are shown in Figure 19. Additional sequential photographs are shown in Figures 20 through 22. Documentary photographs of the crash test are shown in Figures 23 through 25.

6.3 Weather Conditions

Test no. MGSC-6 was conducted on November 10, 2009 at approximately 2:30 pm. The weather conditions as per the National Oceanic and Atmospheric Administration (station 14939/LNK) were reported as shown in Table 3.

Table 3. Weather Conditions, Test No. MGSC-6

<table>
<thead>
<tr>
<th>Condition</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>62° F</td>
</tr>
<tr>
<td>Humidity</td>
<td>46%</td>
</tr>
<tr>
<td>Wind Speed</td>
<td>11 mph</td>
</tr>
<tr>
<td>Wind Direction</td>
<td>120° from True North</td>
</tr>
<tr>
<td>Sky Conditions</td>
<td>Sunny</td>
</tr>
<tr>
<td>Visibility</td>
<td>10 Statute Miles</td>
</tr>
<tr>
<td>Pavement Surface</td>
<td>Dry</td>
</tr>
<tr>
<td>Previous 3-Day Precipitation</td>
<td>0 in.</td>
</tr>
<tr>
<td>Previous 7-Day Precipitation</td>
<td>0 in.</td>
</tr>
</tbody>
</table>
6.4 Test Description

Initial vehicle impact with the guardrail was to occur 14 ft - 11 in. (4.6 m) upstream of the centerline of the splice between post nos. 14 and 15, as shown in Figure 26. The actual point of impact was 15 ft - 2½ in. (4.6 m) upstream of the centerline of the splice between post nos. 14 and 15. A sequential description of the impact events is contained in Table 4. The vehicle came to rest 211 ft - 8 in. (64.5 m) downstream from impact and 87 ft (26.5 m) laterally behind the front face of the guardrail. The vehicle trajectory and final position are shown in Figures 19 and 27, respectively.

Table 4. Sequential Description of Impact Events, Test No. MGSC-6

<table>
<thead>
<tr>
<th>TIME (sec)</th>
<th>EVENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.180</td>
<td>The right-front tire contacted the front face of the mountable curb.</td>
</tr>
<tr>
<td>-0.004</td>
<td>The left-front tire contacted the front face of the mountable curb.</td>
</tr>
<tr>
<td>0.000</td>
<td>The right-front bumper corner impacted the front face of the rail.</td>
</tr>
<tr>
<td>0.036</td>
<td>The rail upstream of impact deflected downstream, and the upstream posts rotated downstream.</td>
</tr>
<tr>
<td>0.064</td>
<td>The vehicle began to redirect.</td>
</tr>
<tr>
<td>0.082</td>
<td>The rail disengaged from post no. 13 due to bolt pullout.</td>
</tr>
<tr>
<td>0.086</td>
<td>The right headlight disengaged from the vehicle.</td>
</tr>
<tr>
<td>0.126</td>
<td>The right-front tire of the vehicle contacted the upstream side of post no. 13.</td>
</tr>
<tr>
<td>0.232</td>
<td>The rail disengaged from post no. 14 due to bolt pullout.</td>
</tr>
<tr>
<td>0.246</td>
<td>The right-front tire contacted the upstream side of post no. 14.</td>
</tr>
<tr>
<td>0.248</td>
<td>The right-front tire disengaged from the vehicle.</td>
</tr>
<tr>
<td>0.258</td>
<td>The right-rear tire contacted the upstream side of post no. 14.</td>
</tr>
<tr>
<td>0.288</td>
<td>The right-rear quarter panel of the vehicle contacted the rail near the impact location.</td>
</tr>
<tr>
<td>0.318</td>
<td>The vehicle was parallel to the system at a speed of 31.6 mph (50.9 km/h).</td>
</tr>
<tr>
<td>0.436</td>
<td>The rail upstream of impact relaxed, and the upstream posts rotated upstream.</td>
</tr>
<tr>
<td>0.582</td>
<td>The right taillight disengaged from the vehicle.</td>
</tr>
<tr>
<td>0.592</td>
<td>The vehicle exited the system at a speed of 30.1 mph (48.4 km/h) and at an angle of 18.7 degrees as the right-rear quarter panel lost contact with the system at the midpoint between post nos. 14 and 15.</td>
</tr>
</tbody>
</table>
6.5 Barrier Damage

Damage to the barrier was moderate, as shown in Figures 28 through 33. Barrier damage consisted of contact marks and deformation of the W-beam rail, deformed guardrail posts, and disengaged post-to-rail connections. The length of vehicle contact along the barrier was approximately 19 ft - 5 in. (5.92 m) which spanned from 2 in. (51 mm) downstream of post no. 12 to 10 in. (254 mm) downstream of post no. 15.

Post nos. 3 through 15 posts showed varying degrees of damage. Post nos. 3 through 11 twisted slightly downstream. Post nos. 12 and 15 rotated slightly backward and sustained minor twisting. Post nos. 13 and 14 sustained large downstream and backward rotations while twisting upstream. Tire marks were found on post no. 13.

Post nos. 13 and 14 were disengaged from the rail due to pullout of the guardrail bolt and deformation of the guardrail slot. A small tear was found in the slot at post no. 13. Gaps of ⅛ in. (3 mm) were present at the splices located between post nos. 2 and 3, 10 and 11, and 12 and 13.

General deformation and flattening of the W-beam rail occurred from post no. 12 to slightly downstream of post no. 15. Contact and tire marks were visible on the guardrail beginning 2 in. (51 mm) downstream of post no. 12 to 10 in. (254 mm) downstream of post no. 15. Slight buckling occurred at post no. 11 and between post nos. 11 and 12. More severe buckling occurred at post nos. 12 and 15.

A 1¼-in. (32-mm) soil gap was present at the upstream edge of post no. 1, and a ½-in. (13-mm) soil gap was present on the downstream edge of post no. 2. A soil gap of ½ in. (13 mm) was present at the downstream edge of post no. 29.

The maximum permanent set rail and post deflections were 14 in. (356 mm) at the midspan between post nos. 13 and 14 and 18 in. (457 mm) at post no. 13, respectively, as measured at the test site. The maximum lateral dynamic rail and post deflections were 24.4 in.
(621 mm) at post no. 13 and 23.6 in. (600 mm) at post no. 13, respectively, as determined from high-speed digital video analysis. The working width of the system was 45.1 in. (1,146 mm), also determined from high-speed video analysis.

6.6 Vehicle Damage

The damage to the vehicle was moderate, as shown in Figures 34 and 35. The maximum occupant compartment deformations are listed in Table 5 along with the deformation limits established in MASH for various areas of the occupant compartment. It should be noted that none of the MASH established deformation limits were violated. Complete occupant compartment and vehicle deformations and the corresponding locations are provided in Appendix D.

Table 5. Maximum Occupant Compartment Deformations by Location

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>MAXIMUM DEFORMATION in. (mm)</th>
<th>MASH ALLOWABLE DEFORMATION in. (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheel Well &amp; Toe Pan</td>
<td>¾ (19)</td>
<td>≤ 9 (229)</td>
</tr>
<tr>
<td>Floor Pan &amp; Transmission Tunnel</td>
<td>¼ (6)</td>
<td>≤ 12 (305)</td>
</tr>
<tr>
<td>Side Front Panel (in Front of A-Pillar)</td>
<td>¼ (6)</td>
<td>≤ 12 (305)</td>
</tr>
<tr>
<td>Side Door (Above Seat)</td>
<td>½ (13)</td>
<td>≤ 9 (229)</td>
</tr>
<tr>
<td>Side Door (Below Seat)</td>
<td>½ (13)</td>
<td>≤ 12 (305)</td>
</tr>
<tr>
<td>Roof</td>
<td>0</td>
<td>≤ 4 (102)</td>
</tr>
<tr>
<td>Windshield</td>
<td>0</td>
<td>≤ 3 (76)</td>
</tr>
</tbody>
</table>

The majority of the damage was concentrated on the right-front corner and right side of the vehicle where the impact occurred. The right side of the front bumper was crushed inward and back. The right-front fender was dented and scraped. The right-front wheel was detached from the vehicle, and the right-front rim was scraped and deformed. The right-front brake lines were cut, and the right-upper control arm was bent inward. The right-side headlight and foglight
were disengaged from the vehicle. Denting and scraping were observed on the entire right side of the vehicle. The right-rear corner of the vehicle and right side of the rear bumper were slightly crushed inward. The right-side taillight was removed. The hood was ajar and slightly crushed inward. Slight deformation to the front of the vehicle frame was observed. The roof and all window glass remained undamaged.

6.7 Occupant Risk

The calculated occupant impact velocities (OIVs) and maximum 0.010-sec occupant ridedown accelerations (ORAs) in both the longitudinal and lateral directions are shown in Table 6. The OIVs and ORAs were within the suggested limits provided in MASH. The calculated THIV, PHD, and ASI values are also shown in Table 6. The results of the occupant risk analysis, as determined from the accelerometer data, are summarized in Figure 19. The recorded data from the accelerometers and the rate transducers are shown graphically in Appendix E.

Table 6. Summary of OIV, ORA, THIV, and PHD Values, Test No. MGSC-6

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Transducer</th>
<th>MASH Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EDR-3</td>
<td>DTS Set 1</td>
</tr>
<tr>
<td>OIV ft/s (m/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal</td>
<td>-11.60 (-3.54)</td>
<td>-13.94 (-4.25)</td>
</tr>
<tr>
<td>Lateral</td>
<td>-13.91 (-4.24)</td>
<td>-13.55 (-4.13)</td>
</tr>
<tr>
<td>ORA g’s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Longitudinal</td>
<td>-10.40</td>
<td>-10.71</td>
</tr>
<tr>
<td>Lateral</td>
<td>-6.60</td>
<td>-7.02</td>
</tr>
<tr>
<td>THIV ft/s (m/s)</td>
<td>NA</td>
<td>18.35 (5.59)</td>
</tr>
<tr>
<td>PHD g’s</td>
<td>NA</td>
<td>11.08</td>
</tr>
<tr>
<td>ASI</td>
<td>0.45</td>
<td>0.49</td>
</tr>
</tbody>
</table>
6.8 Discussion

The analysis of the test results for test no. MGSC-6 showed that the MGS and curb configuration adequately contained and redirected the 2270P vehicle with controlled lateral displacements of the barrier. There were no detached elements nor fragments which showed potential for penetrating the occupant compartment nor presented undue hazard to other traffic. Deformations of, or intrusions into, the occupant compartment that could have caused serious injury did not occur. The test vehicle did not penetrate nor ride over the barrier and remained upright during and after the collision. Vehicle roll, pitch, and yaw angular displacements, as shown in Appendix E, were well below the limit of 75 degrees recommended by MASH. After impact, the vehicle exited the barrier at an angle of 18.7 degrees, and its trajectory did not violate the bounds of the exit box. Therefore, test no. MGSC-6 conducted on the MGS offset 6 ft (1.83 m) behind a 6-in. (152-mm) high AASHTO Type B curb was determined to be acceptable according to the MASH TL-2 safety performance criteria for test designation no. 2-11.
- Test Agency .......................................................... MwRSF
- Test Number .......................................................... MGSC-6
- Date ........................................................................... 11/10/2009
- MASH Test Designation ................................................ 2-11
- Test Article ............ MGS offset 6 ft (1.83 m) behind 6-in. (152-mm) high curb
- Total Length .......................................................... 175 ft (53.3 m)
- Key Component – Midwest Guardrail System
  Length .............................................................................. 175 ft (53.3 m)
  Post Spacing ........................................................... 75 in. (1,905 mm)
- Key Component – AASHTO Type B Curb
  Length .............................................................................. 73 ft - 6 in. (22.40 m)
  Height ................................................................................ 6 in. (152 mm)
- Soil Type ............................................... Grade B of AASHTO M147-65 (1990)
- Vehicle Make /Model .................................... 2003 Dodge Ram 1500 Quad Cab
  Curb .............................................................................. 5,100 lb (2,313 kg)
  Test Inertial ................................................................. 4,974 lb (2,256 kg)
  Gross Static ........................................................ ........... 5,144 lb (2,333 kg)
- Impact Conditions
  Speed ........................................................................... 45.6 mph (73.4 km/h)
  Angle (Curb) ............................................................. 25.3 deg
  Location ...... 15 ft - 2½ in. (4.6 m) US of splice between posts 14 and 15
- Exit Conditions
  Speed ........................................................................... 30.1 mph (48.4 km/h)
  Angle ............................................................................. 18.7 deg
  Exit Box Criterion .......................................................... Pass
- Vehicle Stability .......................................................... Satisfactory
- Vehicle Stopping Distance ................. 211 ft - 8 in. (64.5 m) downstream of impact
  87 ft (26.5 m) laterally behind barrier
- Test Article Damage ................................................. Moderate
- Test Article Deflections
  Permanent Set ........................................................... 18 in. (457 mm)
  Dynamic ................................................................. 24.4 in. (621 mm)
  Working Width .......................................................... 45.1 in. (1,146 mm)
- Maximum Angular Displacements
  Roll ............................................................................. 13.6° < 75°
  Pitch ................................................................. 6.6° < 75°
  Yaw ............................................................................. -41.5°
- Impact Severity ......................................................... 65.3 kip-ft (88.5 kJ) > 52 kip-ft (70.5 kJ)
- Transducer Data

<table>
<thead>
<tr>
<th>Evaluation Criteria</th>
<th>Transducer Data</th>
<th>MASH Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>OIV ft/s (m/s)</td>
<td>Longitudinal</td>
<td>≤ 12.2 (40 kJ)</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>≤ 12.2 (40 kJ)</td>
</tr>
<tr>
<td>ORA g’s</td>
<td>Longitudinal</td>
<td>≤ 20.49</td>
</tr>
<tr>
<td></td>
<td>Lateral</td>
<td>≤ 20.49</td>
</tr>
<tr>
<td>THIV – ft/s (m/s)</td>
<td>NA</td>
<td>18.35 (5.59)</td>
</tr>
<tr>
<td>PHD – g’s</td>
<td>NA</td>
<td>11.08</td>
</tr>
<tr>
<td>ASI</td>
<td>0.45</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Figure 19. Summary of Test Results and Sequential Photographs, Test No. MGSC-6
Figure 20. Additional Sequential Photographs, Test No. MGSC-6
Figure 21. Additional Sequential Photographs, Test No. MGSC-6
Figure 22. Additional Sequential Photographs, Test No. MGSC-6
Figure 23. Documentary Photographs, Test No. MGSC-6
Figure 24. Documentary Photographs, Test No. MGSC-6
Figure 25. Documentary Photographs, Test No. MGSC-6
Figure 26. Impact Location, Test No. MGSC-6
Figure 27. Vehicle Final Position and Trajectory Marks, Test No. MGSC-6
Figure 28. System Damage, Test No. MGSC-6
Figure 29. Post No. 12 Damage, Test No. MGSC-6
Figure 31. Post No. 14 Damage, Test No. MGSC-6
Figure 32. Post No. 15 Damage, Test No. MGSC-6
Figure 33. Anchorage Damage, Test No. MGSC-6
Figure 34. Vehicle Damage, Test No. MGSC-6
Figure 35. Undercarriage Damage, Test No. MGSC-6
DISCUSSION OF FINDINGS

Two items must be considered in determining the lateral placement of a 6-in. (152-mm) high curb relative to the MGS when installed with a 37-in. (940-mm) top rail height relative to the roadway at the toe of the curb.

First, if there is a zero offset (i.e., the rail face is aligned directly over the face of the curb), then a vehicle (2270P or 1100C) would impact the rail with its tires still on the roadway. The vehicle could wedge beneath the raised rail (i.e., the MGS installed at 37 in. (940 mm) relative to the roadway) with potentially severe consequences. This behavior cannot be accurately predicted and would require full-scale crash testing to fully understand the phenomena. For greater lateral offsets between the MGS and the curb, the relationship between the vehicle and the MGS becomes more like the standard 31-in. (787-mm) tall MGS placed over the curb.

Second, it is believed that vehicles cannot become wedged beneath the rail for offsets of at least 4 ft (1.22 m) from the curb, as the curb and ground geometry lower the effective rail height. Note that the small car (1100C), which becomes airborne following impact with the curb, may wedge itself under the rail due to front end suspension compression upon landing on the ground. Based on previous 25-degree angle vehicle-to-curb impact studies performed by MwRSF [10-11] and NCAC [unpublished work], it is believed that the 1100C vehicle bumper will have returned at least to its normal static equilibrium height when the vehicle has reached the 4-ft (1.22-m) lateral offset. Thus, a minimum lateral offset of 4 ft (1.22 m) is recommended for raising the MGS rail height from 31 in. (787 mm) to 37 in. (940 mm) relative to the roadway at the toe of the curb. The 37 in. (940-mm) rail height was determined by combining the heights of the 6-in. (152-mm) curb with that for the 31 in. (787 mm) MGS.
8 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The Midwest Guardrail System was installed 6 ft (1.83 m) behind a 6-in. (152-mm) high, AASHTO Type B curb and was subjected to full-scale crash testing under TL-2 conditions, as defined in MASH. The lateral offset and impact conditions were selected after the system failed to meet the TL-3 criteria with an 8-ft (2.44-m) lateral offset behind the same curb. LS-DYNA simulations demonstrated that a 6-ft (1.83-m) lateral offset produced the greatest propensity for truck override of the barrier at the TL-2 impact conditions.

Full-scale crash testing demonstrated that the MGS with a 37-in. (940-mm) top rail height relative to the roadway is valid for MASH TL-2 for lateral offsets ranging between 4 and 12 ft (1.22 and 3.66 m) behind a 6-in. (152-mm) high, AASHTO Type B curb. Note that no relevant TL-2 crash tests were available for 1100C and/or 2270P vehicles striking a curb without other barriers located behind the curb. Thus, a maximum 12-ft (3.66-m) lateral offset is recommended; since, prior TL-3 curb testing indicated potential vehicle problems beyond a 12-ft (3.66-m) lateral offset. As discussed in References 10 and 11, the Type B curb is considered the worst-case geometry for sloped curbs. Thus, this recommendation is also valid for other sloped curbs with heights of 6 in. (152 mm) or less. For lower-height curbs, the rail height should be reduced in order to maintain the 31-in. (787-mm) top rail height relative to the ground behind the curb.

The full-scale crash testing was conducted with level terrain in front of and behind the curb. However, the research sponsors have indicated that the actual terrain is rarely level in front of and behind the curb. A common roadway slope found in front of curbs consists of a 6 percent slope toward the curb. Typical slopes found behind curbs include a 2 percent slope toward the curb for adjacent sidewalks and a 4 percent slope toward or away from the curb for grass terrain.

The researchers are not concerned with a traveled way sloped downward toward the gutter region found in front of curbs. However, it is the researchers’ opinion that sloped terrain
behind the curb can significantly affect a guardrail system’s redirective capability. In order to address that concern, it is recommended that the top rail height relative to the top of the curb range between 31 and 32 in. (787 and 813 mm), while at the same time the rail height relative to the ground directly below the rail be no higher than 34 inches (864 mm). Thus, the desired lateral offset from the curb as well as the two criteria noted in the previous sentence must be used to determine an acceptable ground slope.

The researchers have no evidence to make any other statements regarding the use of the MGS with 6-in. (152-mm) high curbs under the TL-2 impact conditions. For example, there is no point where the rail height makes the change from 31 in. (787 mm) to 37 in. (940 mm) relative to the roadway because the valid range for the 31-in. (787-mm) rail height relative to the roadway is unknown.

Currently, there are neither plans nor budget to determine any other valid scenarios for MGS placement relative to a curb. It is believed that any such determination would require additional full-scale vehicle crash testing.
Table 7. Summary of Safety Performance Evaluation Results

<table>
<thead>
<tr>
<th>Evaluation Factors</th>
<th>Evaluation Criteria</th>
<th>Test No. MGSC-6</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structural Adequacy</strong></td>
<td>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.</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>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. Deformations of, or intrusions into, the occupant compartment should not exceed limits set forth in Section 5.3 and Appendix E of MASH.</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>F. The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.</td>
<td>S</td>
</tr>
<tr>
<td><strong>Occupant Risk</strong></td>
<td>H. Occupant Impact Velocities (OIV) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Occupant Impact Velocity Limits</td>
</tr>
<tr>
<td></td>
<td>Component</td>
<td>Preferred</td>
</tr>
<tr>
<td></td>
<td>Longitudinal and Lateral</td>
<td>30 ft/s (9.1 m/s)</td>
</tr>
<tr>
<td></td>
<td>I. The Occupant Ridedown Acceleration (ORA) (see Appendix A, Section A5.3 of MASH for calculation procedure) should satisfy the following limits:</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Occupant Ridedown Acceleration Limits</td>
</tr>
<tr>
<td></td>
<td>Component</td>
<td>Preferred</td>
</tr>
<tr>
<td></td>
<td>Longitudinal and Lateral</td>
<td>15.0 g’s</td>
</tr>
</tbody>
</table>

S – Satisfactory  U – Unsatisfactory  NA - Not Applicable
9 REFERENCES


10 APPENDICES
Appendix A. Material Specifications
## Certified Analysis

| Qty | Part # | Description | Spec Cl. | TY | Heat Cod/ Heat # | Yield | TS | Elg  | C | Mn | P | S | Si | Cu | Cr | Vn | ACW |
|-----|--------|-------------|----------|----|-----------------|-------|----|------|---|----|---|---|----|----|----|----|----|-----|
| 750 | 5450G  | 60 POST/DIE/DDR | A-36  | J86489 | 50,565 | 68,130 | 25.1 | 0.090 | 0.930 | 0.010 | 0.040 | 0.290 | 0.00 | 0.160 | 0.003 | 4 |
| 50  | 14620G | 60 POST/8.5/DIE/DDR NB | A-36  | J86489 | 50,565 | 68,130 | 25.1 | 0.090 | 0.930 | 0.010 | 0.040 | 0.290 | 0.00 | 0.160 | 0.003 | 4 |

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

ALL STEEL USED WAS MELTED AND MANUFACTURED IN USA AND COMPLIES WITH THE BUY AMERICA ACT.

ALL GUARDRAIL MEETS AASHTO M-180, ALL STRUCTURAL STEEL MEETS ASTM A36.

ALL GALVANIZED MATERIAL CONFORMS WITH ASTM-123, UNLESS OTHERWISE STATED.

BOLTS COMPLY WITH ASTM A-307 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.

NUTS COMPLY WITH ASTM A-563 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.

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

State of Ohio, County of Allen. Sworn and subscribed before me this 16th day of September, 2009

Notary Public: 

Certified By:

Trinity Highway Products, LLC

Quality Assurance

1 of 1

Figure A-1. W6x8.5 (W152x12.6) Posts Material Specification
Figure A-2. W6x8.5 (W152x12.6) Posts Material Specification (Continued)
Figure A-3. Post Blockouts Certificate of Compliance

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>CHARGE #</th>
<th>DATE</th>
<th>RETENTION</th>
<th>QUANTITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>6x8x14&quot; Blockout (CD)</td>
<td>09-06</td>
<td>1/29/09</td>
<td>0.66</td>
<td>70</td>
</tr>
<tr>
<td>6x8x14&quot; Blockout (CD)</td>
<td>09-67</td>
<td>2/19/09</td>
<td>0.60</td>
<td>70</td>
</tr>
<tr>
<td>6x8x14&quot; OCD Blockout</td>
<td>09-95</td>
<td>3/5/09</td>
<td>0.62</td>
<td>140</td>
</tr>
<tr>
<td>6x8x6&quot; CRT Post</td>
<td>09-94</td>
<td>3/5/09</td>
<td>0.69</td>
<td>70</td>
</tr>
<tr>
<td>6x8x6&quot; Line Post</td>
<td>09-94</td>
<td>3/5/08</td>
<td>0.68</td>
<td>70</td>
</tr>
<tr>
<td>5½x7¾x62½&quot; BCT Post</td>
<td>08-74</td>
<td>1/29/08</td>
<td>0.67</td>
<td>48</td>
</tr>
<tr>
<td>6x8x18&quot; Blockout</td>
<td>09-95</td>
<td>3/5/00</td>
<td>0.62</td>
<td>70</td>
</tr>
<tr>
<td>6x8x18&quot; Blockout</td>
<td>09-95</td>
<td>3/5/09</td>
<td>0.62</td>
<td>70</td>
</tr>
</tbody>
</table>

This certificate applies to material ordered from your order No. 91717. For any inquiries, please retain this document for future reference.

Thank you for your order.

Sincerely,

Karen Storey

Signed before me this 12 day of March 2009.
Figure A-4. Post Blockouts Certificate of Compliance (Continued)
Figure A-5. 12-ft 6-in. (3.81-m) W-Beam Guardrail Material Specification

<table>
<thead>
<tr>
<th>HEAT #</th>
<th>C</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Tensile Yield</th>
<th>Elong</th>
<th>Quantity</th>
<th>Class</th>
<th>Type</th>
</tr>
</thead>
<tbody>
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<td>0.007</td>
<td>0.01</td>
<td>81680</td>
<td>63920</td>
<td>20.76</td>
<td>100</td>
<td>2</td>
</tr>
</tbody>
</table>
Figure A-6. Additional 12-ft 6-in. (3.81-m) W-Beam Guardrail Material Specification
Certified Test Report

NORTH STAR BLUESCOPE STEEL LLC
6767 County Road 9
Delta, Ohio 43515
Telephone: (888) 822-2112

Customer:
Lawson Steel, Inc.
3238 E. 82nd St.
Cleveland, OH 44104
Customer P.O.: D21336
Cust. Ref/Part # n/a

Order Number 171137
Line Item Number 1
Heat Number 111813
Coil Number 842536

Ordered Width (mm/in) 1454.150 / 57.250
Ordered Gauge (mm/in) 2.438 / 0.098
Material Description ASTM A568, 1018 CQ Modified
Production Date/Time Mar 1, 2008 5:41PM

Heat Chemical Analysis (wt%)

| Type | C  | Mn | P  | S  | Si  | Al | Cu | Cr | Ni | Mo | Sn | N   | B  | V  | Nb | Ti | Ca |
|------|----|----|----|----|-----|----|----|----|----|----|----|-----|----|----|----|----|
| Heat | 0.19 | 0.73 | 0.012 | 0.003 | 0.03 | 0.02 | 0.09 | 0.04 | 0.03 | 0.01 | 0.00 | 0.005 | 0.000 | 0.000 | 0.000 | 0.002 | 0.002 |

Mechanical Test Report

Yield Strength: 64,860 psi
Tensile Strength: 83,230 psi
% Elongation in 2 inches: 23.5%

This material has been produced and tested in accordance with the following applicable standards: ASTM E 1560-06, ASTM E 415-88a, ASTM A 751-01, ASTM A 370-09a, JIS Z2201:1998, JIS Z 2441:1998. This report certifies that the above test results are representative of those contained in the records of North Star Bluescope Steel LLC for the material identified in this test report and is intended to comply with the requirements of the material description. North Star Bluescope Steel LLC is not responsible for the inability of this material to meet specific applications. Any modifications to this certificate as provided negate the validity of this test report. All reproductions must have the written approval of North Star Bluescope Steel. This product was manufactured, melt, cast, and hot-rolled (min. 3:1 reduction ratio), entirely within the USA at North Star Bluescope Steel LLC, Delta, Ohio. This material was not exposed to Mercury or any alloy which is liquid at ambient temperature during processing or while in North Star Bluescope Steel LLC possession. Test equipment calibration certificates are available upon request. NIST traceability is established through test equipment calibration certificates which are available upon request. Uncertainty calculations are calculated in accordance with NIST standards and are maintained at a 4:1 ratio in accordance with NIST standards. Uncertainty data is available upon request.

Tim Mitchell
Manager Quality Assurance and Technology

Date issued: Mar 12, 2008 11:00:32
Revision #: 01

Figure A-7. 6-ft 3-in. (1.91-m) W-Beam Guardrail Material Specification
## Certificate of Compliance

We certify that all bolts are made and manufactured in the USA.

**To:** Trinity Industries Inc.  
**Plant #55**  
425 E. O'Connor  
Lima, Ohio  
419-222-7398

**Ship Date:** 11/6/2008  
**Manufacturer:** Mid West Fabricating Co.  
**ASTM:** A367A  
**Galvanizers:** Columbus/Pilot  
**To A-153 Class C**

<table>
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<tr>
<th>QTY</th>
<th>PART NO.</th>
<th>HEAT NO.</th>
<th>LOT NO.</th>
<th>P.O. NO.</th>
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<td>3,524</td>
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<td>2,550</td>
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<td>5/8 X 18-6&quot;</td>
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<td>85157</td>
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<td>5978091</td>
<td>85016</td>
<td>126266BR82</td>
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</table>

**Signature:**  
**D. Smith**  
**TITLE:** Quality Control  
**DATE:** 11/6/2008

---

Figure A-8. ⅝-in. (15.9-mm) x 10-in. (254-mm) Guardrail Bolt/Nut Material Specification
## Figure A-9:

1/2-in. (15.9-mm) Dia. x 14-in. (356-mm) Long Bolt/Nut Material Specification

### Certificate of Compliance

We certify that all bolts are made and manufactured in the USA.

**To:** Trinity Industries Inc.  
Plant #55  
550 East Robb Ave, Lima, Ohio  
419-222-7398

**Ship Date:** 4/13/2009

**Manufacturer:** Mid West Fabricating Co.  
ASTM: A307A

**Galvanizers:** Bristol/Pilot/Columbus  
TO A-153 CLASS C

<table>
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<tr>
<td>5,250</td>
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<td>20060370</td>
<td>95055</td>
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<td>7366618</td>
<td>85199</td>
<td>128266BR114</td>
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</tbody>
</table>

**Signature:** D. Smith  
**Title:** Quality Control  
**Date:** 4/13/2009
Figure A-10. ⅝-in. (15.9-mm) Dia. Bolts, Washers, and Nuts Certificate of Compliance
TRINITY HIGHWAY PRODUCTS, LLC.
Plant #55
425 E. O'CONNOR AVENUE
Lima, OH  45801
419-237-1296

MATERIAL CERTIFICATION

<table>
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<tr>
<th>CUSTOMER: STOCK</th>
<th>DATE: March 10, 2009</th>
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<tbody>
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<td></td>
<td>INVOICE #</td>
</tr>
<tr>
<td></td>
<td>LOT NUMBER: 0611288</td>
</tr>
<tr>
<td>PART NUMBER:  33606</td>
<td>QUANTITY: 102,452</td>
</tr>
<tr>
<td>DESCRIPTION: 5/8&quot; x 1 1/4&quot; GR BOLT</td>
<td>DATE SHIPPED:</td>
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<tr>
<td>SPECIFICATIONS: ASTM A307-A/A193</td>
<td>HEAT: 7366484,7265312</td>
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MATERIAL CHEMISTRY

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<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Si</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>Sn</th>
<th>V</th>
<th>Al</th>
<th>N</th>
<th>B</th>
<th>Ti</th>
<th>Ne</th>
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<td>.02</td>
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<td>.024</td>
<td>.0059</td>
<td>.060</td>
<td>.080</td>
<td>.009</td>
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</table>

PLATING AND/OR PROTECTIVE COATING

HOT DIP GALVANIZED (OZ. PER SQ. FT.) | L35 Avg.

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

THE MATERIAL USED IN THIS PRODUCT WAS MELTED AND MANUFACTURED IN THE USA.

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

STATE OF OHIO, COUNTY OF ALLEN
SWORN AND SUBSCRIBED BEFORE ME
THIS 10TH DAY OF MARCH, 2009

NOTARY PUBLIC

Figure A-11. ⅝-in. (15.9-mm) Guardrail Splice Bolts Material Specification
Figure A-12. ⅝-in. (15.9-mm) Guardrail Splice Nuts Material Specification
Figure A-13. ⅝-in. (15.9-mm) Guardrail Splice Nuts Material Specification (Continued)
Figure A-14. ⅝-in. (15.9-mm) Guardrail Splice Nuts Material Specification (Continued)
Figure A-15. ⅝-in. (15.9-mm) Guardrail Splice Nuts Material Specification (Continued)
The following statements are applicable to the material described on the front of the Test Report:

1. Except as noted, the steel supplied for this order was melted, rolled and processed in the United States, and heat treatments were performed in the United States, unless otherwise noted.

2. Mercury was not used during the manufacture of this product, nor was the steel contaminated with any mercury during processing.

3. Unless directed by the customer, there are no welds in any of the coils produced for this order.

4. The laboratory that generated the analytical or test results can be identified by the following key:

<table>
<thead>
<tr>
<th>Certificate</th>
<th>Lab Code</th>
<th>Laboratory</th>
<th>Address</th>
</tr>
</thead>
<tbody>
<tr>
<td>0358-01</td>
<td>7388</td>
<td>CSRO</td>
<td>1858 Cold Springs Road, Southfield, MI 48075</td>
</tr>
<tr>
<td>0358-02</td>
<td>4171</td>
<td>CSRd/CSRd</td>
<td>3659 Cold Springs Road, Southfield, MI 48075</td>
</tr>
<tr>
<td>0358-03</td>
<td>123853</td>
<td>P4</td>
<td>6185 US Highway 23, Riviera, OH 44067</td>
</tr>
<tr>
<td>0358-04</td>
<td>255946</td>
<td>CSCE</td>
<td>4900 E. 24th St., Cayahoga Heights, OH 44125-1004</td>
</tr>
<tr>
<td>9898-05</td>
<td>126901</td>
<td>CSMP</td>
<td>Charter Steel Detroit, 22800 Shrewsbury Ave., Center Line, MI 48015</td>
</tr>
</tbody>
</table>

5. When run by a Charter Steel laboratory, the following tests were performed according to the latest revision of the specifications listed below, as noted in the Charter Steel Laboratory Quality Manuals:

<table>
<thead>
<tr>
<th>Test</th>
<th>Receiving Laboratory</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry</td>
<td>CSRO, CSRd</td>
<td>ASTM E116, ASTM E518</td>
</tr>
<tr>
<td>X-ray Fluorescence Stainless and Alloy Steel</td>
<td>CSRO, CSRd</td>
<td>ASTM E125, ASTM E126</td>
</tr>
<tr>
<td>Hardness Test</td>
<td>CSRO, CSRd</td>
<td>ASTM A370, ASTM A72, ASTM E112</td>
</tr>
<tr>
<td>Grain Size</td>
<td>CSRO, CSRd</td>
<td>ASTM A370, ASTM A376</td>
</tr>
<tr>
<td>Tensile Test</td>
<td>CSRO, CSRd, P4, CSC, CSYT</td>
<td>ASTM E8, ASTM A370</td>
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<tr>
<td>Microstructure</td>
<td>CSRO, CSRd, P4,</td>
<td>ASTM A202, ASTM A370</td>
</tr>
</tbody>
</table>

Charter Steel has been accredited to perform all of the above tests by the American Association for Laboratory Accreditation (A2LA). These accreditations expire 01/31/09.

All other test results associated with a Charter Steel laboratory that appear on the front of this report, if any, were performed according to documented procedures developed by Charter Steel and are not accredited by A2LA.

6. The test results on the front of this report are the true values measured on the samples taken from the production lot. They do not apply to any other sample.

7. This test report cannot be reproduced or distributed except in full without the written permission of Charter Steel. The primary customer whose name and address appear on the front of this form may reproduce this test report, subject to the following restrictions:
   - It may be distributed only to their customers.
   - Both sides of all pages must be reproduced in full.

8. This certification is given subject to the terms and conditions of sale provided in Charter Steel's acknowledgment (designated by our Sales Order number) to the customer's purchase order. Both Order numbers appear on the front page of this report.

9. Where the customer has provided a specification, the results on the front of this test report conform to that specification unless otherwise noted on this test report.
**Figure A-17. Foundation Tube Material Specification**

<table>
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<tr>
<th>ITEM NO.</th>
<th>PIECES</th>
<th>SIZE, GAUGE, LENGTH</th>
<th>QTY. SHIPPED</th>
<th>CUSTOMER P.O.</th>
<th>ORDER NUMBER</th>
<th>CUSTOMER PART NBR</th>
<th>ASTM SPECIFICATION</th>
<th>GRADE</th>
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<tbody>
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<td>7</td>
<td>8.625-322HRB 252</td>
<td>147</td>
<td>4500088611</td>
<td>1015580</td>
<td>1.000</td>
<td>A500-03b</td>
<td>B</td>
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<tr>
<td>2</td>
<td>6</td>
<td>12X2-188HRB 480</td>
<td>240</td>
<td>4500088813</td>
<td>1016034</td>
<td>1.000</td>
<td>A500-03b</td>
<td>B</td>
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<td>3-4</td>
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<td>8.625-322HRB 504</td>
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<td>1025579</td>
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<tr>
<td>5</td>
<td>9</td>
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<td>4500092386</td>
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<td>1.000</td>
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<table>
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<tr>
<th>ITEM NO.</th>
<th>COIL NO.</th>
<th>HEAT NO.</th>
<th>CORRECTED COIL</th>
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<tbody>
<tr>
<td>1</td>
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<td>722562</td>
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<td>2</td>
<td>395532</td>
<td>722551</td>
<td>.210</td>
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<td>.210</td>
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<td>4</td>
<td>395460</td>
<td>722564</td>
<td>.210</td>
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<td>5</td>
<td>391232</td>
<td>A13386</td>
<td>.220</td>
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<td>PHOSPHORUS</td>
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<tr>
<td>SULFUR</td>
</tr>
<tr>
<td>ALUMINUM</td>
</tr>
<tr>
<td>SILICON</td>
</tr>
<tr>
<td>WELD TESTING</td>
</tr>
<tr>
<td>YIELD STRENGTH (PSI)</td>
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<tr>
<td>TENSILE STRENGTH (PSI)</td>
</tr>
<tr>
<td>ELONGATION IN 2&quot; (%)</td>
</tr>
</tbody>
</table>

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

I HEREBY CERTIFY THAT THE ABOVE IS CORRECT AS CONTAINED IN THE RECORDS OF THE COMPANY.
Figure A-18. BCT Timber Posts Certificate of Compliance

AUGUST 4, 2009

MIDWEST MACHINERY & SUPPLY
PO Box 81097
LINCOLN, NE 68501

THE FOLLOWING MATERIAL DELIVERED ON 8/3/09 ON BILL OF LADING NUMBER 19477 HAS BEEN INSPECTED BEFORE AND AFTER TREATMENT AND IS IN FULL COMPLIANCE WITH APPLICABLE NEBRASKA DEPARTMENT OF ROADS REQUIREMENTS FOR SOUTHERN YELLOW PINE TIMBER GUARDRAIL COMPONENTS, PRESERVATIVE TREATED WITH CHROMATED-COPPER-ARSENATE (CCA-C) TO A MINIMUM RETENTION OF .60 LBS./CU.FT. THE ACCEPTANCE OF EACH PIECE BY COMPANY QUALITY CONTROL IS INDICATED BY A HAMMER BRAND ON THE END OF EACH PIECE.

<table>
<thead>
<tr>
<th>MATERIAL</th>
<th>CHARGE #</th>
<th>DATE</th>
<th>RETENTION</th>
<th>QUANTITY</th>
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<tbody>
<tr>
<td>6x8x14&quot; Blockout (CD)</td>
<td>09-283</td>
<td>7/29/09</td>
<td>0.67</td>
<td>70</td>
</tr>
<tr>
<td>6x8x6&quot; Line Post</td>
<td>09-283</td>
<td>7/29/09</td>
<td>0.67</td>
<td>175</td>
</tr>
<tr>
<td>51/2x71/2x46&quot; TB Bullnose</td>
<td>09-283</td>
<td>7/29/09</td>
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<td>48</td>
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<tr>
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<td>09-283</td>
<td>7/29/09</td>
<td>0.67</td>
<td>100</td>
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<tr>
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<td>09-283</td>
<td>7/29/09</td>
<td>0.67</td>
<td>70</td>
</tr>
</tbody>
</table>

THIS CERTIFICATE APPLIES TO MATERIAL ORDERED FOR YOUR ORDER NO.: 2191

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

THANK YOU FOR YOUR ORDER.

SINCERELY,

Karen Storey

SIGNED BEFORE ME THIS 4 DAY OF AUGUST 2009.

Phone: 706-234-1605
P.O. Box 99, Armuchee, GA 30105
Fax: 706-235-8132
Figure A-19. BCT Timber Posts Certificate of Compliance (Continued)
Figure A-20. BCT Post Sleeves Material Specification
Figure A-21. Strut and Yoke Assembly Certificate of Compliance
# Certified Analysis

Trinity Highway Products, LLC  
2348 N.E. 28th St.  
Ft Worth, TX  

Customer: MIDWEST MACH. & SUPPLY CO.  
P. O. BOX 81997  
LINCOLN, NE 68501-8197  

Project: RESALE  

<table>
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<th>Part#</th>
<th>Description</th>
<th>Spec. Cl.</th>
<th>TV</th>
<th>Base Code/ Sheet #</th>
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<th>TS</th>
<th>Elg.</th>
<th>C</th>
<th>Mo</th>
<th>P</th>
<th>Si</th>
<th>Cu</th>
<th>Cr</th>
<th>Mn</th>
<th>Vn</th>
<th>ACW</th>
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</thead>
<tbody>
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<td>125058</td>
<td>M-180 A</td>
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<td>0.220</td>
<td>0.012</td>
<td>0.018</td>
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<td>0.060</td>
<td>0.065</td>
<td>0.040</td>
<td>4</td>
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<td>20</td>
<td>701A</td>
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<td>A-36</td>
<td>413053</td>
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<td>64,235</td>
<td>80,600</td>
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<td>0.750</td>
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<td>0.020</td>
<td>0.030</td>
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<td>4</td>
</tr>
<tr>
<td>10</td>
<td>792G</td>
<td>60 TUBE 2.1825X05</td>
<td>A-36</td>
<td>489110</td>
<td>74,000</td>
<td>74,000</td>
<td>87,000</td>
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<td>0.670</td>
<td>0.013</td>
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<td>10</td>
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<td>25X30X20 YEAR PLUG</td>
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<td>40</td>
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<td>M-180 A</td>
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<td>54,235</td>
<td>73,500</td>
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<td>0.030</td>
<td>0.060</td>
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</table>

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

ALL STEEL, UP TO 12 FT. LONG, AS RELATLED AND MANUFACTURED IN USA AND COMPLIES WTH THE BUY AMERICA ACT.

ALL GUARDRAIL MEETS AASHTO M-183, ALL STRUCTURAL STEEL MEETS A36.

ALL OTHER GALVANIZED MATERIAL CONFORMS TO ASTM-123.

SOLTS COMPLY WITH ASTM A-307 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.

NUTS COMPLY WITH ASTM A-563 SPECIFICATIONS AND ARE GALVANIZED IN ACCORDANCE WITH ASTM A-153, UNLESS OTHERWISE STATED.

3/8" DIA CABLE G119 ZINC COATED SWAGED AND AISI C-1035 STEEL ANNEALED STUD 1" DIA. ASTM 449 AASHATO K430, TYPE II BREAKING STRENGTH - 49100 LB.

State of Texas, County of Houston, Sworn and subscribed before me this 30th day of June, 2009.

Notary Public:

[Signature]

Certified by:

[Signature]

Figure A-22. Anchor Bracket Material Specification
Figure A-23. BCT Cable Anchor Assembly Certificate of Compliance
Figure A-24. BCT Cable Anchor Assembly Certificate of Compliance (Continued)
Figure A-25. Anchor Bearing Plate Certificate of Compliance
Figure A-26. Concrete Material Specification
Figure A-27. Reinforcing Steel Material Specification
Appendix B. Vehicle Center of Gravity Determination
Figure B-1. Vehicle Mass Distribution, Test No. MGSC-6
Appendix C. Static Soil Tests
Figure C-1. Soil Strength, Initial Calibration Tests
Figure C-2. Static Soil Test, Test No. MGSC-6
Appendix D. Vehicle Deformation Records
Figure D-1. Floor Pan Deformation Data – Set 1, Test No. MGSC-6
**Figure D-2. Floor Pan Deformation Data – Set 2, Test No. MGSC-6**
**Figure D-3. Occupant Compartment Deformation Data – Set 1, Test No. MGSC-6**

<table>
<thead>
<tr>
<th>POINT</th>
<th>X (in.)</th>
<th>Y (in.)</th>
<th>Z (in.)</th>
<th>X' (in.)</th>
<th>Y' (in.)</th>
<th>Z' (in.)</th>
<th>ΔX (in.)</th>
<th>ΔY (in.)</th>
<th>ΔZ (in.)</th>
</tr>
</thead>
<tbody>
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<td>A1</td>
<td>12</td>
<td>1.5</td>
<td>21.5</td>
<td>11.75</td>
<td>1.5</td>
<td>21.75</td>
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<td>21.5</td>
<td>-0.25</td>
<td>0</td>
<td>-0.25</td>
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<td>21</td>
<td>21</td>
<td>12</td>
<td>20.25</td>
<td>21</td>
<td>0</td>
<td>-0.75</td>
<td>0</td>
</tr>
<tr>
<td>A4</td>
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<td>15</td>
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<td>-0.25</td>
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<tr>
<td>B1</td>
<td>23</td>
<td>23.25</td>
<td>0.25</td>
<td>23</td>
<td>23.25</td>
<td>0.5</td>
<td>0</td>
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<tr>
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<tr>
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<tr>
<td>C4</td>
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<tr>
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<td>0</td>
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<tr>
<td>C6</td>
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<td>0</td>
<td>0.25</td>
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</table>

Note: If impact is on driver side need to enter negative number for Y.
Figure D-4. Occupant Compartment Deformation Data – Set 2, Test No. MGSC-6
Figure D-5. Exterior Vehicle Crush (NASS) - Front, Test No. MGSC-6

<table>
<thead>
<tr>
<th>Crush Measurement</th>
<th>Lateral Location</th>
<th>Original Profile Measurement</th>
<th>Dist. Between Ref. Lines</th>
<th>Actual Crush</th>
</tr>
</thead>
<tbody>
<tr>
<td>in. (mm)</td>
<td>in. (mm)</td>
<td>in. (mm)</td>
<td>in. (mm)</td>
<td>in. (mm)</td>
</tr>
<tr>
<td>C1 8.75 (222)</td>
<td>17.5 (445)</td>
<td>12.0313 (306)</td>
<td>-2.655892 (-67)</td>
<td>-0.625385 (-16)</td>
</tr>
<tr>
<td>C2 11 (279)</td>
<td>21.8 (554)</td>
<td>12.9375 (329)</td>
<td></td>
<td>0.718392 (18)</td>
</tr>
<tr>
<td>C3 16 (406)</td>
<td>26.1 (665)</td>
<td>14.5 (368)</td>
<td></td>
<td>4.155892 (16)</td>
</tr>
<tr>
<td>C4 23.5 (607)</td>
<td>30.4 (772)</td>
<td>16.2969 (414)</td>
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<td>9.859017 (250)</td>
</tr>
<tr>
<td>C6 NA #VALUE!</td>
<td>24.7 (681)</td>
<td>19.3375 (506)</td>
<td></td>
<td>#VALUE! #VALUE!</td>
</tr>
<tr>
<td>C5 59 (191)</td>
<td>29 (737)</td>
<td></td>
<td></td>
<td>#VALUE! #VALUE!</td>
</tr>
<tr>
<td>CMAX 28.25 (718)</td>
<td>35 (889)</td>
<td>20.625 (524)</td>
<td></td>
<td>10.28089 (261)</td>
</tr>
</tbody>
</table>
Figure D-6. Exterior Vehicle Crush (NASS) - Side, Test No. MGSC-6
Appendix E. Accelerometer and Rate Transducer Data Plots, Test No. MGSC-6
Figure E-1. 10-ms Average Longitudinal Deceleration (DTS, Set 1), Test No. MGSC-6
Figure E-2. Longitudinal Occupant Impact Velocity (DTS, Set 1), Test No. MGSC-6
Figure E-3. Longitudinal Occupant Displacement (DTS, Set 1), Test No. MGSC-6
Figure E-4. 10-ms Average Lateral Deceleration (DTS, Set 1), Test No. MGSC-6
Figure E-5. Lateral Occupant Impact Velocity (DTS, Set 1), Test No. MGSC-6
Figure E-6. Lateral Occupant Displacement (DTS, Set 1), Test No. MGSC-6
Figure E-7. Vehicle Angular Displacements (DTS), Test No. MGSC-6
Figure E-8. Acceleration Severity Index (DTS Set 1), Test No. MGSC-6
Figure E-9. 10-ms Average Longitudinal Deceleration (DTS, Set 2), Test No. MGSC-6
Figure E-10. Longitudinal Occupant Impact Velocity (DTS, Set 2), Test No. MGSC-6
Figure E-11. Longitudinal Occupant Displacement (DTS, Set 2), Test No. MGSC-6
Figure E-12. 10-ms Average Lateral Deceleration (DTS, Set 2), Test No. MGSC-6
Figure E-13. Lateral Occupant Impact Velocity (DTS, Set 2), Test No. MGSC-6
Figure E-14. Lateral Occupant Displacement (DTS, Set 2), Test No. MGSC-6
Figure E-15. 10-ms Average Longitudinal Deceleration (EDR-3), Test No. MGSC-6
Figure E-16. Longitudinal Occupant Impact Velocity (EDR-3), Test No. MGSC-6
Figure E-17. Longitudinal Occupant Displacement (EDR-3), Test No. MGSC-6
Figure E-18. 10-ms Average Lateral Deceleration (EDR-3), Test No. MGSC-6
Figure E-19. Lateral Occupant Impact Velocity (EDR-3), Test No. MGSC-6
Figure E-20. Lateral Occupant Displacement (EDR-3), Test No. MGSC-6
Figure E-21. Acceleration Severity Index (EDR-3), Test No. MGSC-6
END OF DOCUMENT