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MGS Dynamic Deflections and Working Widths at Lower Speeds

Nicholas A. Weiland

University of Nebraska-Lincoln, nweiland@huskers.unl.edu

Cody S. Stolle

University of Nebraska at Lincoln, cstolle2@unl.edu

John D. Reid

University of Nebraska-Lincoln, jreid@unl.edu

Ronald K. Faller

University of Nebraska - Lincoln, rfaller1@unl.edu

Robert W. Bielenberg

University of Nebraska - Lincoln, rbielenberg2@unl.edu

See next page for additional authors

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Authors

Nicholas A. Weiland, Cody S. Stolle, John D. Reid, Ronald K. Faller, Robert W. Bielenberg, and Karla A. Lechtenberg



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MGS DYNAMIC DEFLECTIONS AND WORKING WIDTHS AT LOWER SPEEDS

Submitted by

Nicholas A. Weiland, M.S.M.E., E.I.T.
Former Graduate Research Assistant

Cody S. Stolle, Ph.D., E.I.T.
Research Assistant Professor

John D. Reid, Ph.D.
Professor

Ronald K. Faller, Ph.D., P.E.
Research Associate Professor
MwRSF Director

Robert W. Bielenberg, M.S.M.E., E.I.T.
Research Associate Engineer

Karla A. Lechtenberg, M.S.M.E., E.I.T.
Research Associate Engineer

MIDWEST ROADSIDE SAFETY FACILITY

Nebraska Transportation Center
University of Nebraska-Lincoln
130 Whittier Research Center
2200 Vine Street
Lincoln, Nebraska 68583-0853
(402) 472-0965

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16. Abstract <p>The Midwest Guardrail System (MGS) has been full-scale crash tested in many configurations, including installations adjacent to slopes, with different types of wood posts, with and without blockouts, for culvert and bridge applications, and at high flare rates. Although the performance of the MGS and the dynamic deflection and working width of the barrier have been examined, little is known about the dynamic deflection and working width of the MGS when impacted at lower speeds. The MGS is a relatively low-cost barrier, and the Test Level 3 (TL-3) version could be installed for TL-2 and TL-1 applications. The barrier is expected to capture or redirect errant vehicles impacting at speeds less than or equal to those used for crash testing according to TL-3 of the <i>Manual for Assessing Safety Hardware</i> (MASH).</p> <p>Accurate dynamic deflections and working widths of the MGS when impacted at lower speeds are critical for the safe placement of guardrail to reduce the likelihood of vehicle impact with a shielded hazard in the Zone of Intrusion (ZOI) for use on level terrain and in combination with curbs. LS-DYNA computer simulation models of a 2007 Chevrolet Silverado impacting both a tangent MGS and MGS in combination with a curb at a 6-ft 3-in. (1.9-m) post spacing (i.e., standard post spacing) were calibrated against previous crash tests. Then, the model was simulated with two lower speeds and at five impact locations with a conservative soil model to determine the maximum dynamic deflection and working width of the system at TL-1 and TL-2 impact conditions of MASH.</p>			
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Undergraduate and Graduate Research Assistants

Illinois Department of Transportation

Priscilla A. Tobias, P.E., State Safety Engineer/Bureau Chief
Tim Sheehan, P.E., Safety Design Engineer
Paul L. Lorton, P.E., Safety Programs Unit Chief

Indiana Department of Transportation

Todd Shields, P.E., Maintenance Field Support Manager

Iowa Department of Transportation

Chris Poole, P.E., Roadside Safety Engineer
Brian Smith, Methods Engineer

Kansas Department of Transportation

Scott King, P.E., Road Design Bureau Chief
Kelly Cool, P.E., Road Design Leader
Thomas Rhoads, P.E., Engineering Associate III, Bureau of Road Design

Minnesota Department of Transportation

Michael Elle, P.E., Design Standards Engineer

Missouri Department of Transportation

Joseph G. Jones, P.E., Engineering Policy Administrator

Nebraska Department of Roads

Phil TenHulzen, P.E., Design Standards Engineer
Jim Knott, P.E., State Roadway Design Engineer
Jodi Gibson, Research Coordinator

New Jersey Department of Transportation

Dave Bizuga, Manager 2, Roadway Design Group 1

Ohio Department of Transportation

Maria E. Ruppe, P.E., Roadway Standards Engineer

South Dakota Department of Transportation

Bernie Clocksin, Lead Project Engineer
David Huft, Research Engineer

Wisconsin Department of Transportation

Jerry Zogg, P.E., Chief Roadway Standards Engineer
Rodney Taylor, P.E., Roadway Design Standards Unit Supervisor
Erik Emerson, P.E., Standards Development Engineer

Wyoming Department of Transportation

William Wilson, P.E., Architectural and Highway Standards Engineer

Federal Highway Administration

John Perry, P.E., Nebraska Division Office
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TABLE OF CONTENTS

TECHNICAL REPORT DOCUMENTATION PAGE	i
DISCLAIMER STATEMENT	ii
ACKNOWLEDGEMENTS	iii
LIST OF FIGURES	vi
LIST OF TABLES	vii
1 INTRODUCTION	1
1.1 Problem Statement	1
1.2 Research Objective	1
1.3 Scope	1
2 LS-DYNA MODEL CALIBRATION	2
2.1 MGS Model	2
2.2 Vehicle Model Comparison	2
2.2.1 Vehicle Stability and Barrier Deflections	3
2.2.2 Velocity Profile	4
3 MGS AT TL-1 AND TL-2 IMPACT CONDITIONS	6
3.1 Qualitative Analysis	6
3.2 Working Width Dependency on Impact Location	6
3.3 Maximum Barrier Deflections and Working Widths	14
3.4 Discussion	16
4 MGS INSTALLED IN COMBINATION WITH CURB	18
4.1 Introduction and Motivation	18
4.2 Comparison and Validation of Simulation Model with Curb	18
4.2.1 Modifications to Level Terrain Baseline Model	19
4.2.2 Description of Test No. NPG-5	20
4.2.3 Comparison of Results, Simulation and Test No. NPG-5	20
4.3 Modifications for Alternative Impact Locations and Speeds	26
4.4 Qualitative Analysis	26
4.5 Working Width Dependency on Impact Location	27
4.6 Discussion	28
5 ALTERNATIVE APPLICATIONS FOR MGS WITH LOWER IMPACT SPEEDS	38
6 CONCLUSIONS AND RECOMMENDATIONS	40
7 REFERENCES	42

LIST OF FIGURES

Figure 1. Computer Simulation Models of 2270P Chevrolet Silverado Pickup Trucks.....	2
Figure 2. Vehicle Behavior Comparison	3
Figure 3. Longitudinal Velocity Profile.....	4
Figure 4. Simulated Tangent MGS System Drawings.....	7
Figure 5. Sequential Images of TL-1 Impact with MGS	9
Figure 6. Sequential Images of TL-2 Impact with MGS	10
Figure 7. Sequential Images of TL-3 Impact with MGS	11
Figure 8. System Deflections Versus Impact Location for Test Level 1 Impacts	12
Figure 9. System Deflections Versus Impact Location for Test Level 2 Impacts	13
Figure 10. System Deflections Versus Impact Location for Test Level 3 Impacts	13
Figure 11. Maximum Working Width and Dynamic Deflections Based on Impact Speed.....	15
Figure 12. Working Width and Dynamic Deflection Based on IS Value.....	15
Figure 13. Model of MGS in Combination with Curb.....	19
Figure 14. Impact Location and MGS Installed in Combination with Curb, Test No. NPG-5	21
Figure 15. Sequential Images, Simulation (2270P) and Test No. NPG-5 (2000P)	22
Figure 16. System Damage, Test No. NPG-5.....	23
Figure 17. Post No. 16 Pulled Out of Ground, Test No. NPG-5	24
Figure 18. Post and Soil Displacement, Test No. NPG-5 (a) Upstream End Anchorage (b) Post No. 12	25
Figure 19. Sequential Images of TL-1 Impact with MGS with Curb	29
Figure 20. Sequential Images of TL-1 Impact with MGS with Curb	30
Figure 21. Sequential Images of TL-2 Impact with MGS with Curb	31
Figure 22. Sequential Images of TL-2 Impact with MGS with Curb	32
Figure 23. Sequential Images of TL-3 Impact with MGS with Curb	33
Figure 24. Sequential Images of TL-3 Impact with MGS with Curb	34
Figure 25. Maximum Working Widths for MGS Installed in Combination with Curbs, by IS Value	36
Figure 26. Maximum Dynamic Deflection for MGS Installed in Combination with Curb, by IS Value	36

LIST OF TABLES

Table 1. Maximum Dynamic Deflections.....	4
Table 2. Test Level 1: Barrier Deflections and Working Widths.....	8
Table 3. Test Level 2: Barrier Deflections and Working Widths.....	8
Table 4. Test Level 3: Barrier Deflections and Working Widths.....	8
Table 5. Barrier Deflection and Working Width Comparison across Test Levels.....	14
Table 6. Summary of Simulation and Test No. NPG-5 Results.....	23
Table 7. Test Level 1: Barrier Deflections and Working Widths.....	35
Table 8. Test Level 2: Barrier Deflections and Working Widths.....	35
Table 9. Test Level 3: Barrier Deflections and Working Widths.....	35
Table 10. Comparison of MGS Deflections at TL-1 Impact Conditions.....	37
Table 11. Comparison of MGS Deflections at TL-2 Impact Conditions.....	37
Table 12. Comparison of MGS Deflections at TL-3 Impact Conditions.....	37
Table 13. Simulated Number of Posts Deflected or Disengaged.....	37
Table 14. Estimated Working Width Envelopes for Non-Blocked MGS.....	38
Table 15. Recommended Working Width Envelopes for Guardrail.....	40

1 INTRODUCTION

1.1 Problem Statement

The Midwest Guardrail System (MGS) has been full-scale crash tested in many configurations, including installations on and adjacent to slopes [1-5], with different types of wood posts [6-12], with and without blockouts [13-22], for culvert and bridge applications [23-28], and in combination with curbs, transitions, and high flare rates [14, 29-34]. Although the performance of the MGS, the dynamic deflection, and working width of the barrier have been examined in great detail at Test Level 3 (TL-3) impact conditions, little is known about the dynamic deflection and working width of the MGS when impacted at lower speeds.

The MGS is a relatively low-cost barrier, and the TL-3 version could be installed for TL-2 and TL-1 applications. However, it can be difficult to provide TL-3 deflection or working width for the MGS in lower speed urban or transitional areas because of bicyclist and pedestrian considerations, limited right of way, traffic control structures, or obstructions which have close proximity to the roadway. The barrier is expected to capture or redirect errant vehicles impacting at speeds less than used for crash testing according to TL-3 of the *Manual for Assessing Safety Hardware* (MASH) [35]. Accurate dynamic deflections and working widths of the MGS when impacted at lower speeds are critical for the safe placement of guardrail to reduce the likelihood of vehicle impact with a shielded hazard in the Zone of Intrusion (ZOI). Also, some modifications to the MGS, such as reduced blockout depth or non-blocked options, may help to reduce working width and dynamic deflections in limited offset installations. These modifications are more desirable at lower speeds, because the likelihood of vehicles snagging on posts decreases as impact speed decreases.

1.2 Research Objective

The research objective was to identify the dynamic deflection and working width of the MGS for TL-3, TL-2, and TL-1 impact conditions on level ground and in combination with 6-in. (152-mm) tall, AASHTO Type B curbs.

1.3 Scope

In order to complete the research objective, several tasks were completed. First, a model of a 175-ft (53.3-m) long MGS impacted by a 2007 Chevrolet Silverado 2270P pickup truck model was simulated in LS-DYNA and calibrated against test no. 2214MG-2 [36]. Next, impacts with the MGS were simulated at 31 mph (50 km/h), 44 mph (70 km/h), and 62 mph (100 km/h) and 25 degrees, in accordance with MASH [35] TL-1, TL-2, and TL-3 test conditions, respectively. The impact locations were varied from the midspan upstream from post no. 12 to the midspan downstream from post no. 12, in increments of 1/4-post spans. Lastly, the maximum dynamic deflections and working widths were identified.

2 LS-DYNA MODEL CALIBRATION

2.1 MGS Model

Computer simulation models of the Midwest Guardrail System (MGS) were successfully calibrated and validated against full-scale crash testing [e.g., 37-38] using the Roadside Safety Verification and Validation Program (RSVVP) [39-40]. The baseline model of the MGS was calibrated with results from test no. 2214MG-2 [36], and consisted of a 2270P pickup truck impacting the MGS installed in standard soil and with standard post spacing. Impact conditions were consistent with MASH TL-3. The simulated impact conditions were based on the actual impact speed and angle determined from test results. The MGS model consisted of calibrated end anchorages [41-42], refined meshes in critical rail locations, and improved vehicle-to-barrier contacts.

2.2 Vehicle Model Comparison

Three revised models of a 2007 Chevrolet Silverado pickup truck model originally developed by the National Crash Analysis Center (NCAC) [43] were used to simulate test no. 2214MG-2. The three Silverado models were the Silverado Version 2 (Silverado-v2), Version 3 (Silverado-v3), and reduced Version 3 (Silverado-v3r), as shown in Figure 1. Each vehicle model was modified with refined meshes of critical components and modified contacts, and each was modified for use in roadside safety impacts.



Figure 1. Computer Simulation Models of 2270P Chevrolet Silverado Pickup Trucks

Each model contains different features and can be well-suited for different applications [43]. In general, the Silverado-v2 pickup truck model is not well-suited for simulations in which steering or accurate representations of lateral wheel forces are critical, although Silverado-v3 and Silverado-v3r versions included the possibility for the wheels to turn when lateral forces were applied to the wheel or tire. The tire model utilized with the Silverado-v2 model was more compliant than the tire models applied to the Silverado-v3 and Silverado-v3r versions of the pickup truck. Model developers indicated that the softer tire more accurately represented tire impacts (including curbs, posts, or rocks) but was also prone to instabilities. As a result, the Silverado-v3 and Silverado-v3r tire models were more numerically stable, in general, than the Silverado-v2 tire model. Both the Silverado-v2 and Silverado-v3 versions of the pickup truck utilized detailed component models with finely-meshed components but tended to be more computationally expensive than the coarser-mesh Silverado-v3r model. Simulation run times and

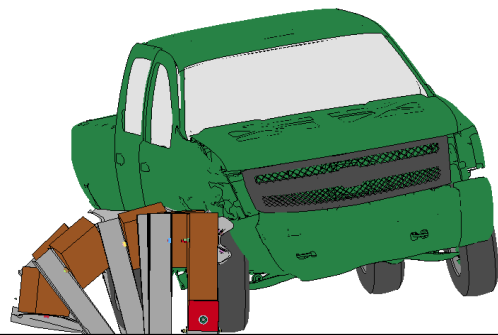
file sizes decreased for the Silverado-v3r model compared to the Silverado-v2 and Silverado-v3 versions, but the coarser mesh tended to be stiffer and less sensitive than the refined meshes.

2.2.1 Vehicle Stability and Barrier Deflections

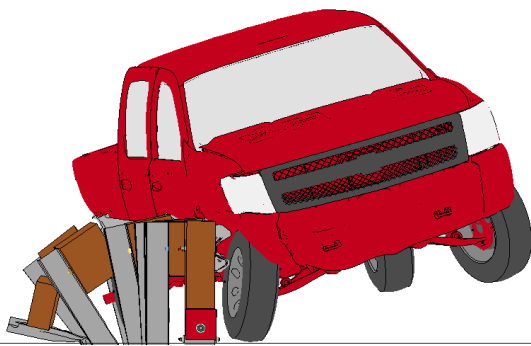
For test no. 2214MG-2, the vehicle was stable during and after redirection, with minimal pitch or roll motion. The simulation models tended to over-predict rotations, as shown in Figure 2. The dynamic deflection of the pickup truck during test no. 2214MG-2 was larger than the simulation models predicted. All three vehicle models were redirected sooner after impact than occurred in the full-scale test, and maximum dynamic deflection of the test was approximately 5 to 6 in. (127 to 152 mm) larger than in the simulations, as shown in Table 1. It appeared that the simulated system was stiffer overall than the as-tested system, resulting in amplified roll and pitch angular rotations and reduced dynamic deflections compared to the physical test. Soil properties of the simulation did not exactly replicate the behavior observed in the full-scale tests. The soil used in the full-scale test was not uniformly compacted and may have contributed to some anomalous behavior. This phenomenon is discussed in detail in Section 4.2.



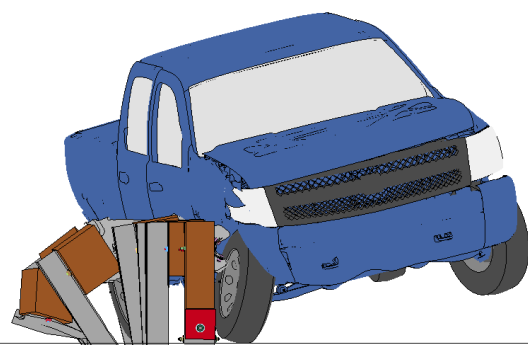
Test No. 2214MG-2



Silverado-v2



Silverado-v3



Silverado-v3r

Figure 2. Vehicle Behavior Comparison

Table 1. Maximum Dynamic Deflections

Test No./ Vehicle Model	Roll	Pitch	Yaw
Full-Scale Crash Test			
2214MG-2	3.0°	1.8°	-43.0°
Simulations			
Silverado-v2	12.9°	5.7°	-43.8°
Silverado-v3	19.5°	6.1°	-40.3°
Silverado-v3r	15.8°	7.7°	-44.3°

2.2.2 Velocity Profile

The changes in longitudinal velocity for the test and simulation are shown in Figure 3. Both test and simulation results were processed using the same procedure. Overall, the Silverado-v3 model was the most similar to the test results through 250 ms after impact, but the Silverado-v2 model correlated better with the test results through 400 ms. The Silverado-v3r model indicated a larger reduction in speed, over a shorter time period, than the other two models. For all vehicle models, the change in longitudinal velocity correlated reasonably well with the test data, but the Silverado-v2 model was determined to be optimized.

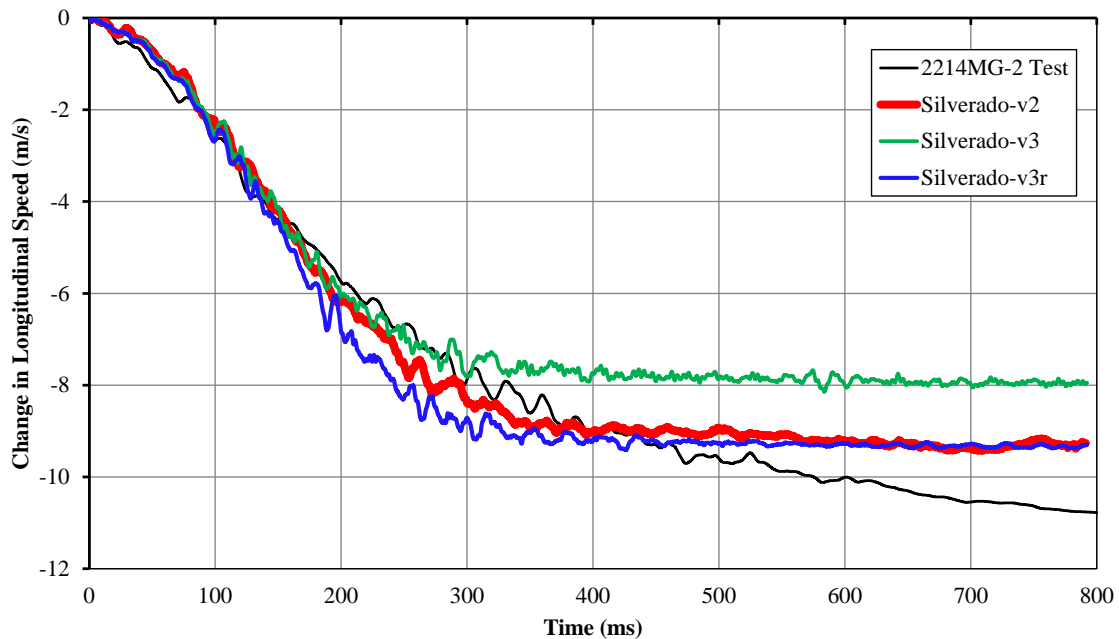


Figure 3. Longitudinal Velocity Profile

The Silverado-v2 model most accurately represented the vehicle behavior and system response observed in test no. 2214MG-2. The Silverado v2 model predicted the lowest pitch and roll angles and highest barrier deflections. The longitudinal velocity profile was best-correlated with the full-scale crash test. The simulation with the Silverado v2 vehicle model passed statistical significance tests according to RSVVP [37-40] and was determined to be an acceptable representation of the test data. Therefore, the Silverado-v2 model was used to investigate the MGS model at the MASH TL-1 and TL-2 impact conditions.

3 MGS AT TL-1 AND TL-2 IMPACT CONDITIONS

The baseline simulation of the Chevrolet Silverado v2 pickup truck impacting a tangent, 175-ft (53.3-m) long MGS in standard soil was modified to simulate impacts at 31 mph (50 km/h) and 44 mph (70 km/h). The lower impact speeds corresponded to impacts with the MGS at TL-1 and TL-2 impact conditions, respectively, and drawings of the system which was simulated are shown in Figure 4. A total of five impacts were simulated for each speed, and impact conditions were varied in ¼-post span increments starting at the midspan between post nos. 11 and 12, respectively, and terminating at the midspan between post nos. 12 and 13.

Soil conditions vary widely from state to state, and even vary widely within a state. It is impossible to predict what the dynamic deflection and working width will be without knowing the type, strength, moisture content, and cohesiveness of the soil in that location. Other complicating factors, such as asphalt overlays or posts embedded in soil tubes or concrete, further affect vehicle-to-barrier impact dynamics. To reduce the probability that impacting vehicles will impact or interact with a shielded feature or hazard, a soil model weaker than the standard MASH soil was selected to generate conservative working width estimates. Stronger soils for real-world systems may result in reduced deflections compared to those shown in this analysis, but if dynamic deflections and working widths must be less than those recommended in this report, stiffer barrier constructions (i.e., half- or quarter-post spacing, or three beam) are preferable to relying on a unsaturated, compacted, MASH strong soil.

3.1 Qualitative Analysis

Sequential images of TL-1, TL-2, and TL-3 impacts with a tangent MGS are shown in Figures 5 through 7. Barrier deflections, barrier exit times and longitudinal exit displacements, vehicle roll and pitch angles, and the number of posts damaged increased with increased impact speed. For all impact conditions, vehicles were smoothly redirected with no instabilities. Vehicle damage was limited for impacts at TL-1 and TL-2 impact conditions, and barrier permanent sets were minimal.

3.2 Working Width Dependency on Impact Location

Maximum dynamic deflection of the system is a measure of the maximum distance any individual component in the system deflected when compared to its undeflected position. Working width is defined as the farthest distance the barrier or vehicle extended laterally during impact, as measured from the original, undeformed front face of the guardrail. Working widths are always greater than or equal to dynamic deflections.

Several impact locations were investigated at each test level to determine how impact location influenced maximum dynamic deflections and working widths, as shown in Tables 2 through 4. These impact locations demonstrated how impacting at and around a post influenced barrier deflections.

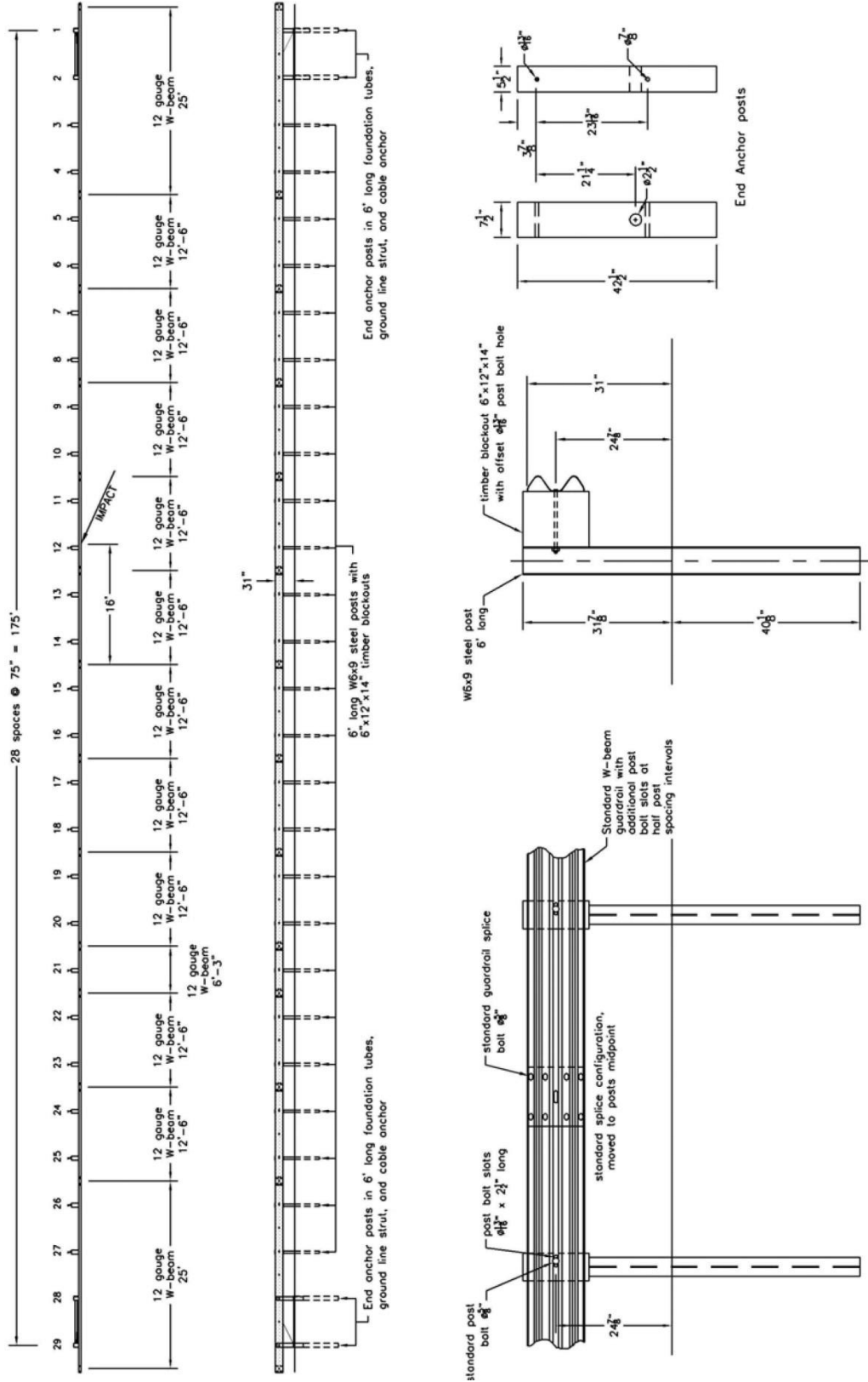


Figure 4. Simulated Tangent MGS System Drawings

Table 2. Test Level 1: Barrier Deflections and Working Widths

Test Level 1 - 31 mph (50 km/h)			
Impact Location	Maximum Dynamic Deflection in. (mm)	Working Width in. (mm)	Max Working Width Component
11½	16.6 (422)	35.3 (896)	Post no. 12
11¾	15.6 (397)	37.0 (940)	Post no. 13
12	15.1 (383)	37.6 (955)	Post no. 13
12¼	15.7 (398)	37.3 (947)	Post no. 13
12½	15.9 (405)	35.2 (895)	Post no. 13

Table 3. Test Level 2: Barrier Deflections and Working Widths

Test Level 2 - 44 mph (70 km/h)			
Impact Location	Maximum Dynamic Deflection in. (mm)	Working Width in. (mm)	Max Working Width Component
11½	24.0 (610)	48.5 (1,232)	Post no. 13
11¾	25.0 (634)	49.3 (1,251)	Post no. 13
12	24.5 (622)	46.5 (1,181)	Post no. 13
12¼	24.4 (619)	47.6 (1,210)	Post no. 14
12½	24.1 (612)	48.3 (1,228)	Post no. 14

Table 4. Test Level 3: Barrier Deflections and Working Widths

Test Level 3 - 62 mph (100 km/h)			
Impact Location	Maximum Dynamic Deflection in. (mm)	Working Width in. (mm)	Max Working Width Component
11½	37.5 (952)	58.1 (1,475)	Post no. 13
11¾	38.0 (964)	60.2 (1,530)	Post no. 14
12	36.6 (930)*	59.6 (1,515)*	Post no. 14
12¼	39.3 (997)	59.3 (1,505)	Post no. 14
12½	37.7 (957)	58.7 (1,491)	Post no. 14

*Simulation terminated at 240 ms

NOTE: Impact location indicates where the barrier was first contacted by the vehicle. Spacings denoted with a ¼, ½, or ¾ post spacing increment refer to fractions of nominal post spacing, equal to 75 in. (1,905 mm). Thus, an impact at 11¾ refers to an impact ¾ of a post span, or 56¼ in. (1,429 mm), downstream from post no. 11.

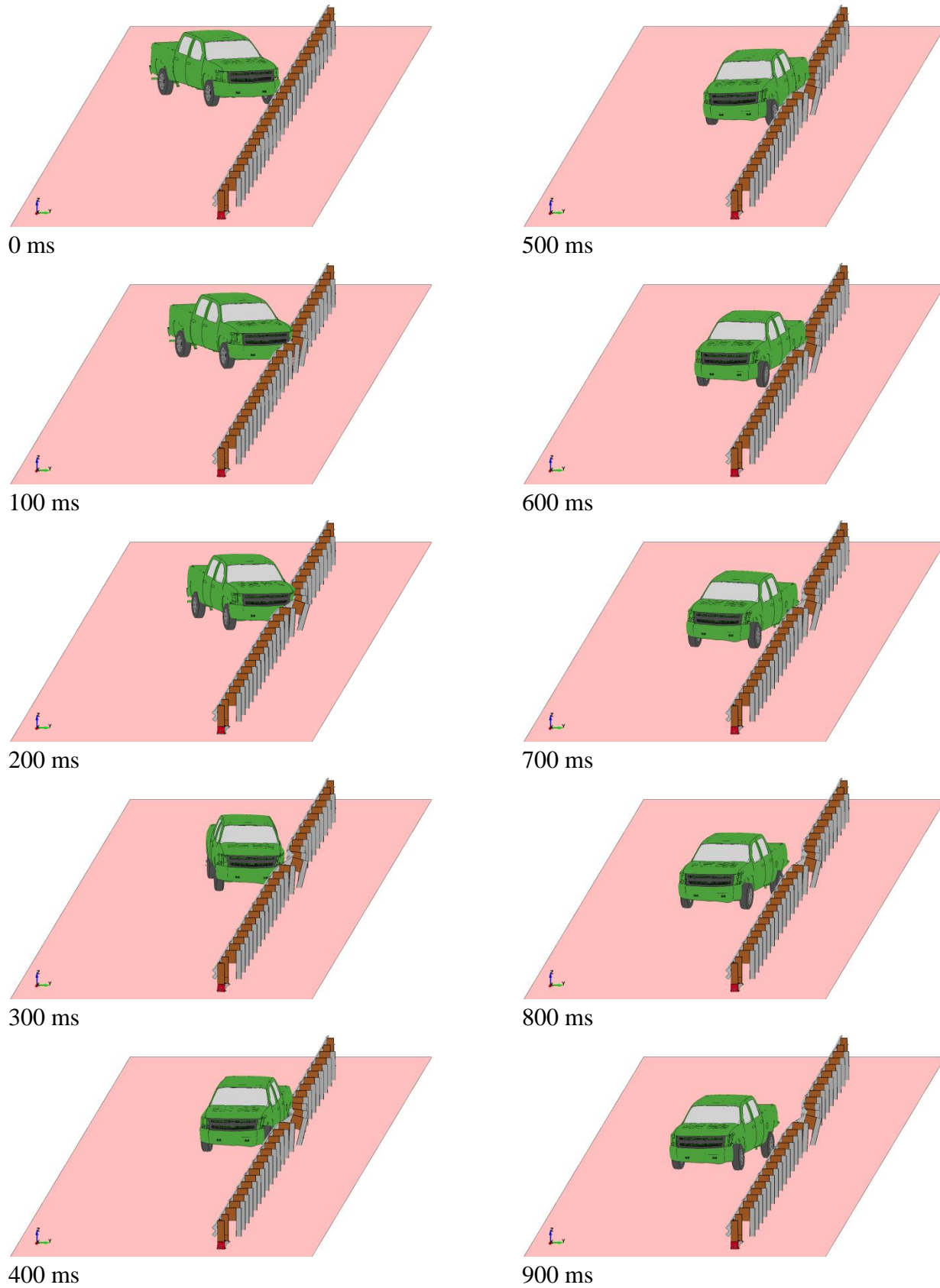


Figure 5. Sequential Images of TL-1 Impact with MGS

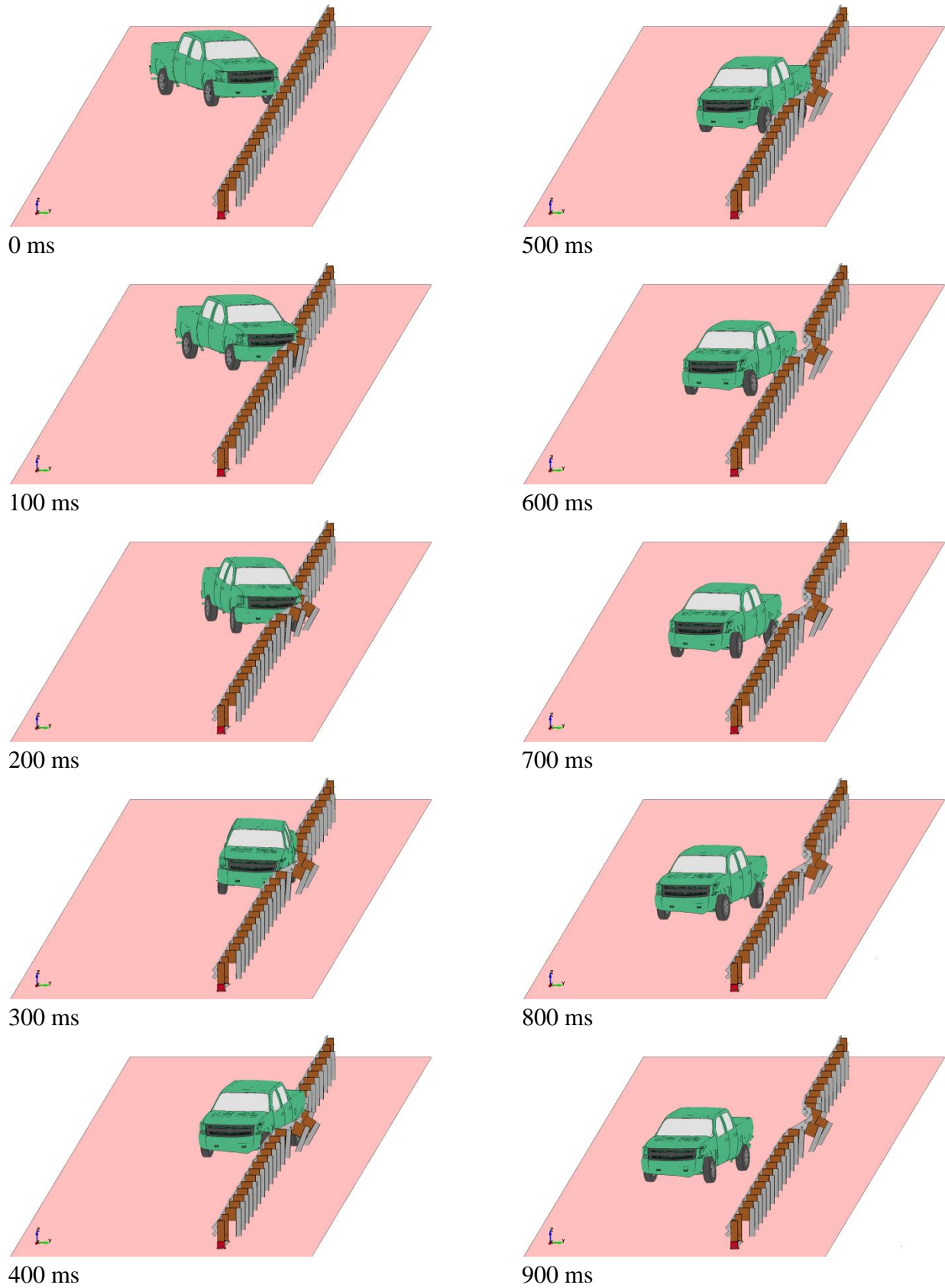


Figure 6. Sequential Images of TL-2 Impact with MGS

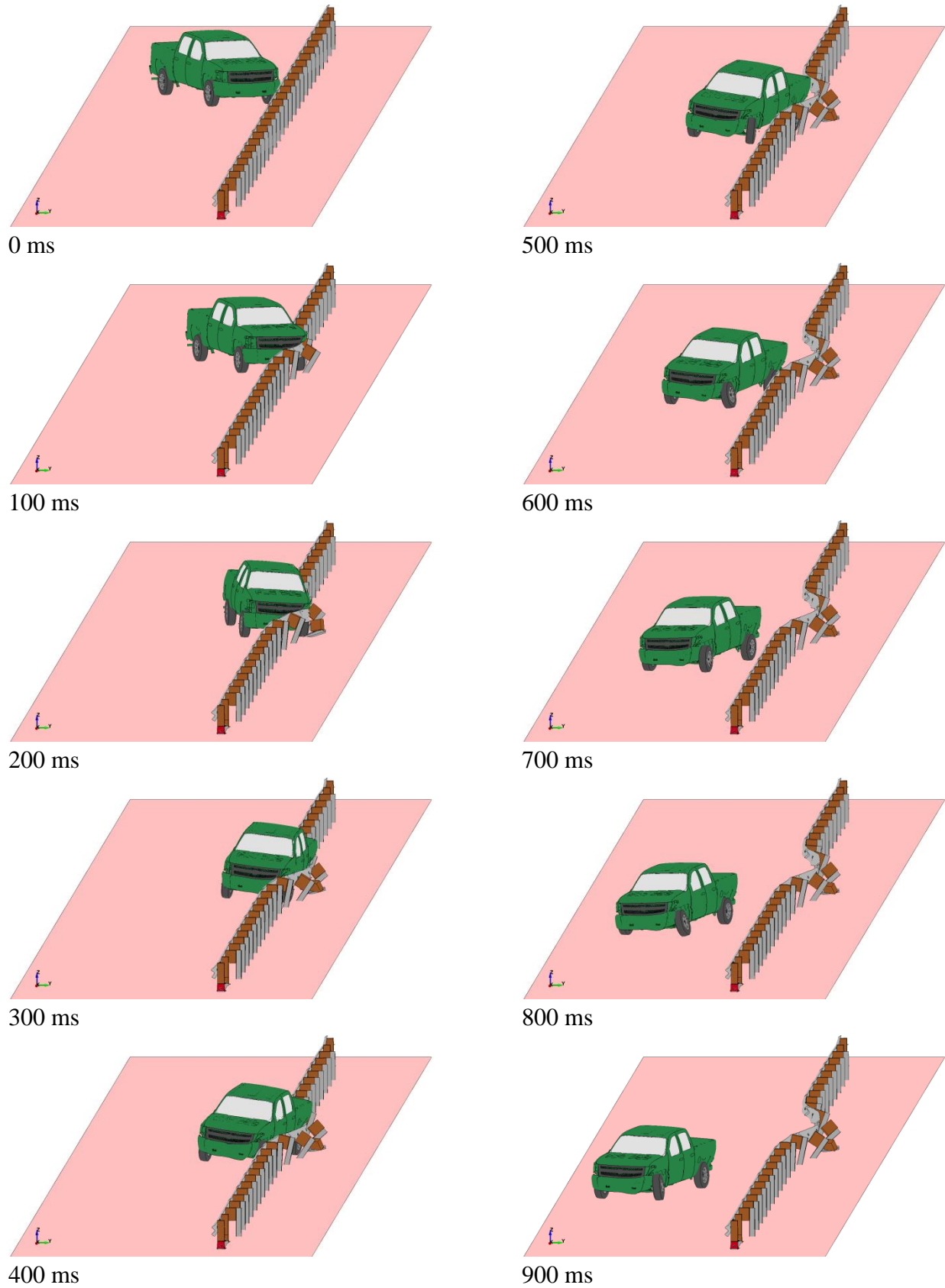


Figure 7. Sequential Images of TL-3 Impact with MGS

Maximum dynamic deflections and working widths were relatively constant regardless of impact location, although fluctuations of up to three inches were observed. The maximum dynamic deflection and working width were never maximized for impacts at posts, as shown in Figures 8 through 10. In general, the vehicle's location within the system at the point of maximum dynamic deflection influenced how far the system was able to deflect. Impacts which occurred at post locations were associated with shorter dynamic deflections and working widths than impacts at the midspans for all speeds. However, the maximum dynamic deflections and working widths occurred at the midspan upstream from post no. 12 for TL-1 impact conditions, ¼-span upstream from post no. 12 for TL-2 impact conditions, and ¼-span downstream from post no. 12 for TL-3 impact conditions.

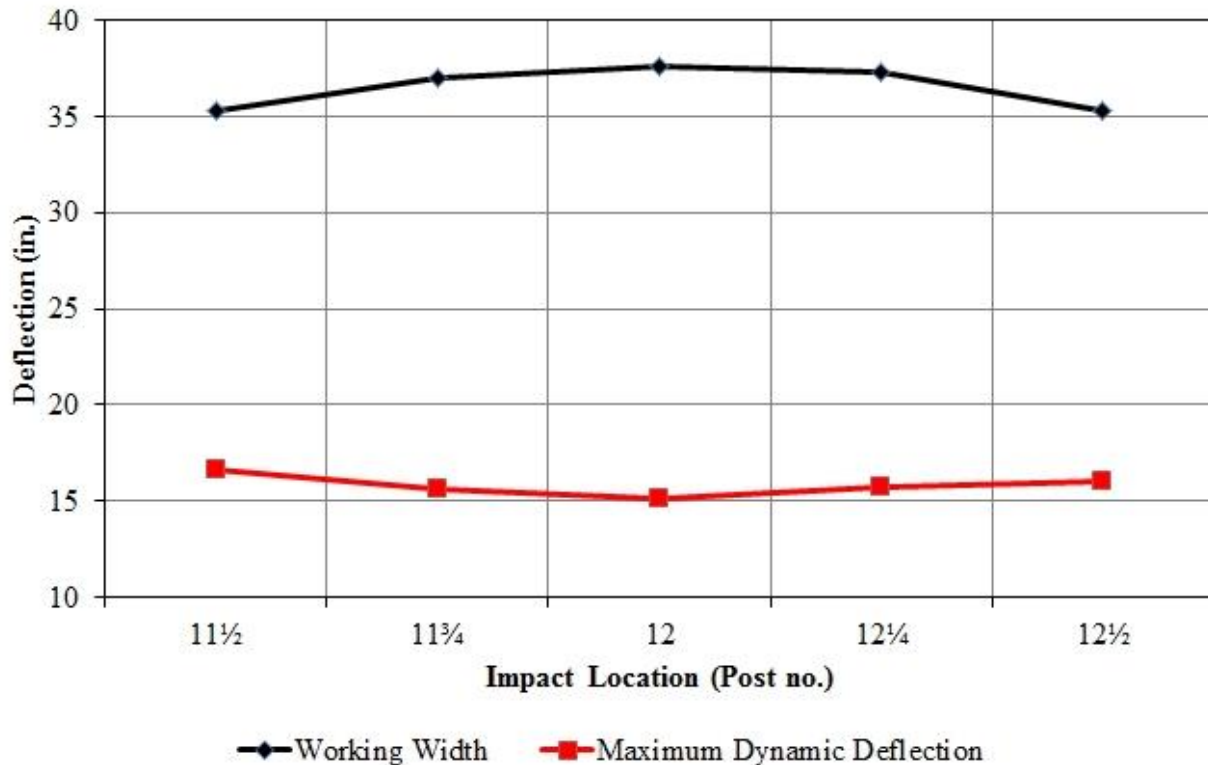


Figure 8. System Deflections Versus Impact Location for Test Level 1 Impacts



Figure 9. System Deflections Versus Impact Location for Test Level 2 Impacts

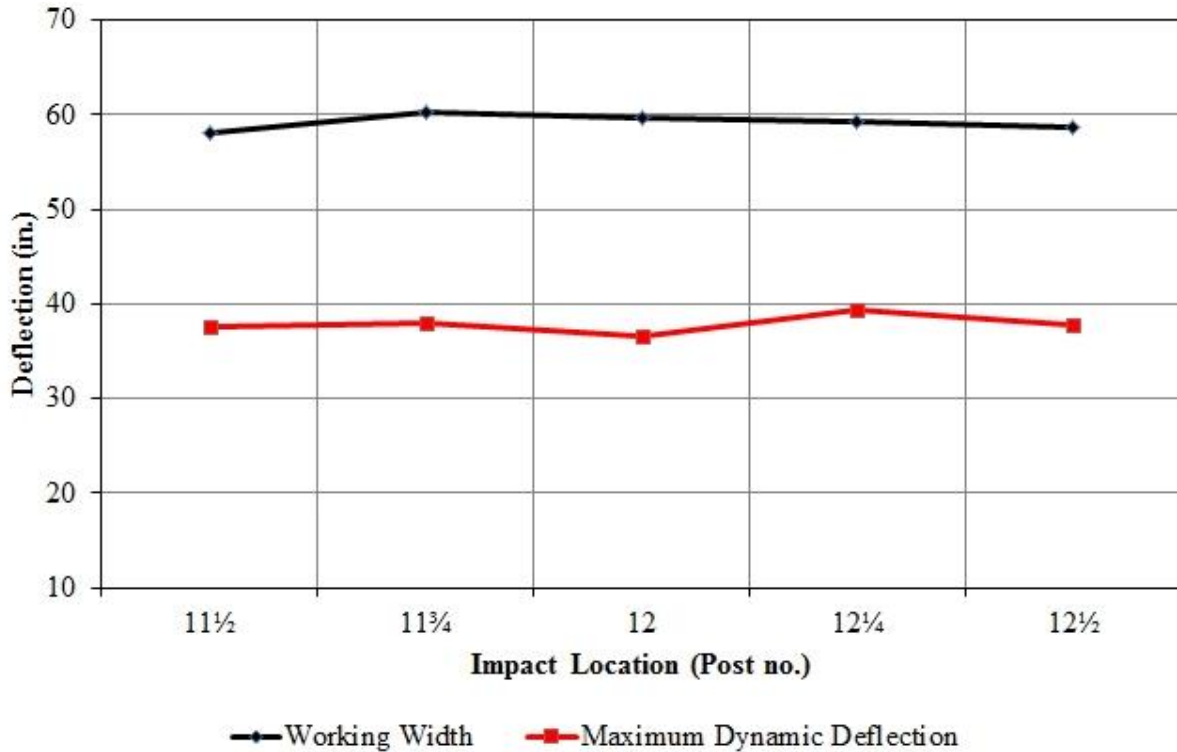


Figure 10. System Deflections Versus Impact Location for Test Level 3 Impacts

3.3 Maximum Barrier Deflections and Working Widths

Maximum barrier deflections and working widths were recorded for each of the three simulations to determine how test levels influenced barrier deflections and working widths, as shown in Table 5. There was a larger increase in barrier deflections between the TL-2 and TL-3 impact conditions, equal to 13.0 in. (330 mm), than between TL-1 and TL-2 impact conditions, equal to 9.3 in. (237 mm). The differences were likely associated with an 18.6 mph (30 km/h) increase in velocity and 104 percent increase in impact energy between the TL-2 and TL-3 impact conditions, in comparison with a 12.4 mph (20 km/h) increase in velocity and 96 percent increase in impact energy between TL-1 and TL-2 impact conditions.

Table 5. Barrier Deflection and Working Width Comparison across Test Levels

Test Level	MASH IS Value kip-in. (kJ)	Maximum Dynamic Deflection in. (mm)	Working Width in. (mm)	Vehicle/System Component
1	28.7 (38.9)	15.6 (397)	37.0 (940)	Post no. 13
2	57.8 (78.4)	25.0 (634)	49.3 (1,251)	Post no. 13
3	114.8 (155.6)	38.0 (964)	60.2 (1,530)	Post no. 14

The working widths increased by 12.2 in. (311 mm) from TL-1 to TL-2 and 11.0 in. (279 mm) from TL-2 to TL-3. At all three test levels, deflected posts were the elements with the greatest working width. At the TL-1 and TL-2 impact conditions, post no. 13 deflected the farthest, whereas at TL-3, post no. 14 deflected the farthest. In addition to working width and dynamic deflection, the contact length, or longitudinal length of barrier in contact with the vehicle, also increased with higher impact speeds. The redirection times also increased corresponding to increased length of barrier engagement. It appears that the correlation between maximum dynamic deflection and working width is approximately linear at an impact angle of 25 degrees, as shown in Figures 11 and 12.

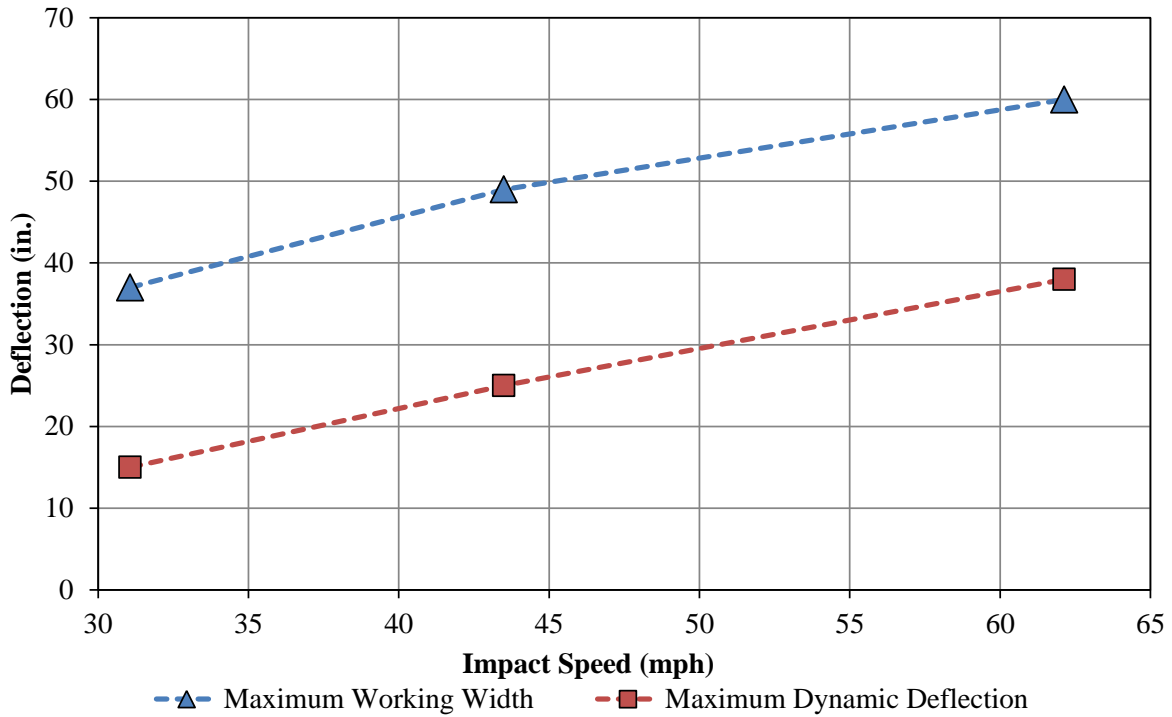


Figure 11. Maximum Working Width and Dynamic Deflections Based on Impact Speed

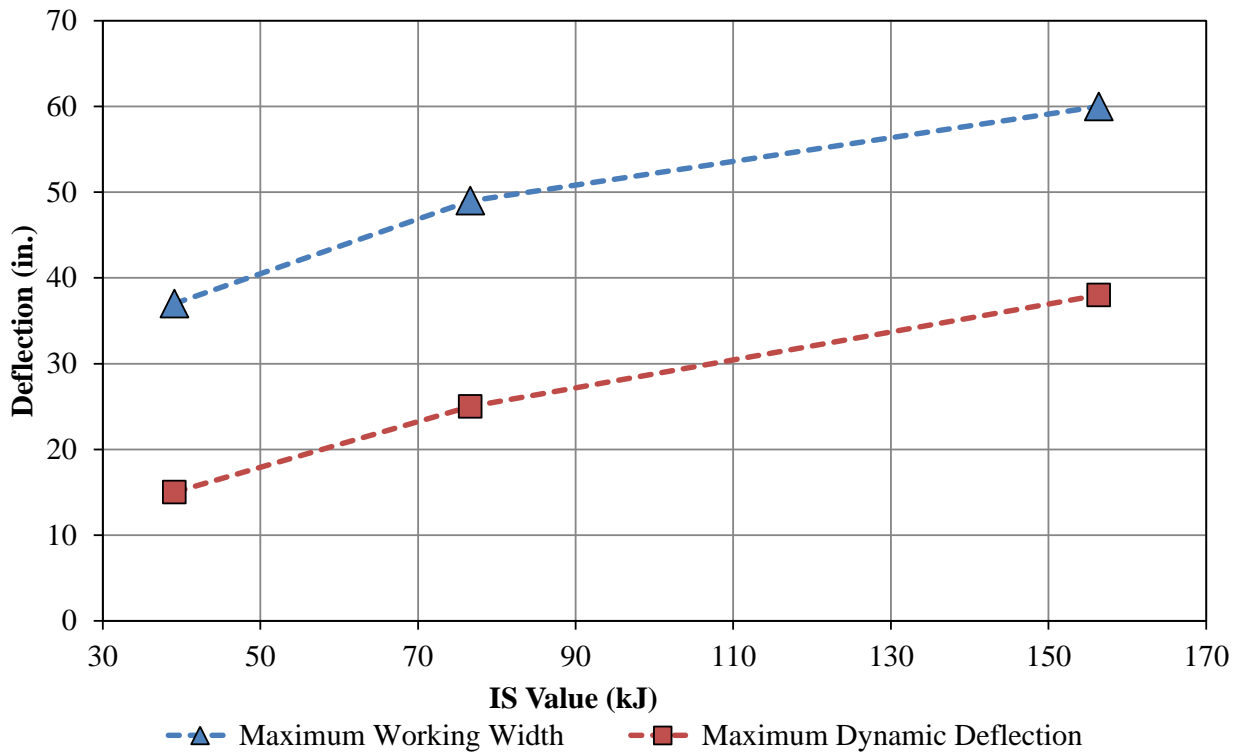


Figure 12. Working Width and Dynamic Deflection Based on IS Value

3.4 Discussion

Maximum dynamic deflections and working widths increased as speed increased. As shown in Tables 2 through 4, there appears to be a 10- to 15-in. (254- to 381-mm) increase in the maximum dynamic deflection and working width for each increase in test level. For TL-1, TL-2, and TL-3 impact speeds, dynamic deflections were generally minimized for impacts at posts. In contrast, impact locations contributing to maximum working widths varied based on impact speed. Nonetheless, all working width and dynamic deflection differences were within 3 in. (76 mm).

For all simulations, the maximum working width corresponded to the top of a post or blockout. Researchers observed that the post-in-soil forces exhibited similar load and deflection characteristics to “weak” or native soils. Thus, the simulated working widths were believed to be conservative. Simulated working widths were associated with post or blockout deflections, whereas full-scale test working widths were more commonly associated with rail or vehicle displacements. However, because the posts tended to rotate further than what was observed in full-scale crash tests, and engaged the rail for a longer period of time, more energy was absorbed by the posts’ soil rotations, and the dynamic deflections of the rail and impacting vehicle were lower than observed in full-scale testing.

Barriers installed in compliance with the conservative estimates of working width from simulations will reduce the likelihood that an impacting vehicle will engage a hazard located behind the guardrail at the design impact condition (i.e., TL-3, TL-2, or TL-1). In contrast, adopting a guardrail placement consistent with the maximum dynamic deflection may permit the use of less expensive shielding systems when hazards are located close to the roadway, such as in urban or suburban areas, or may allow for increased guardrail offsets from the roadway. However, it is possible that some vehicles impacting at the design impact conditions may engage the shielded hazard behind the guardrail. Maintenance records for guardrail repair may provide limited scope of the extent of permanent set experienced, by noting the number of posts deformed or separated from the rail, the number of posts and rail segments replaced, and number of damaged blockouts [44].

It would be desirable to estimate the percentage of crashes in which the vehicle would engage the hazard or statistical likelihood of a design impact engaging a shielded hazard using the maximum dynamic deflection condition. Unfortunately, crash reconstruction databases, such as the one collected in support of the National Cooperative Highway Research Program (NCHRP) Report No. 665 [45], tended to oversample crashes high impact speeds and severities particularly on lower-speed roadways. The Impact Severity Values (IS Values) for impacts consistent with TL-3, TL-2, and TL-1 test conditions were 115.4, 64.9, and 28.8 kip-ft (156.5, 88.0, and 39.0 kJ). According to the NCHRP Report No. 665 crash reconstruction database, these IS values were representative of the 95th, 91st, and 83rd percentile IS values, respectively. The diminishing representation of IS values higher than the design condition may indicate that more vehicles depart the road at elevated IS values on lower design condition roads, but it likely also reflects that the database oversampled higher-speed, higher-severity crashes on roads with lower speed limits in comparison with crashes on higher-speed, higher-service level roads. As a result, a design condition based on the maximum working width provided in this report should result in a minimum of 95, 91, and 83 percent of vehicles impacting in critical locations which will be

satisfactorily redirected with impact conditions consistent with MASH TL-3, TL-2, and TL-1, respectively.

If guardrail offsets from hazards are reduced, there is a possibility that the impacting vehicle will engage or interact with the shielded hazard. However, the statistical likelihood of (1) impact in critical locations with (2) IS values at or above the design condition are small. States must determine if the benefits associated with closer guardrail-to-hazard offset and increased guardrail offset from the road outweigh the potential consequences of a vehicle engaging a hazard while being redirected by the rail.

4 MGS INSTALLED IN COMBINATION WITH CURB

4.1 Introduction and Motivation

In some locations, particularly urban or suburban arterials, collectors, and local roads, guardrail may be installed in combination with a curb or drainage structure. Vehicle instabilities have been observed with some curb-and-guardrail installation configurations [46-47]. The MGS was successfully full-scale crash tested with the face of the guardrail located 6 in. (152 mm) behind the front face of a curb consistent with the AASHTO Type B curb [13-14, 48]. A second configuration consisting of an MGS-to-thrie beam transition with a wedge-shaped curb [29-32] was also successfully full-scale crash tested.

Many of the curb-and-guardrail installations on urban or suburban roads occur in combination with TL-2 or TL-1 design level roadways, which can be characterized by lower posted speed limits, more discrete hazards, and closer hazard proximities to the roadway. In addition, right-of-way in urban and suburban areas may not be as large as for rural highways. Guardrail installed behind curbs can reduce deflections [13-14], which is advantageous for scenarios in which guardrail offsets from hazards and the roadway are limited. Thus, the effects of guardrail and curb combinations were also selected for analysis at lower test level applications according to MASH.

As with guardrail installed on level terrain, it was unlikely that passenger cars, and in particular small cars, would demonstrate increased instability or likelihood of underride, override, rail rupture, occupant compartment deformation, or adverse occupant risk when impacts occurred at lower speeds than at higher speeds. Thus, only pickup trucks were considered during simulations of guardrails installed in combination with curbs.

The baseline simulation of the Chevrolet Silverado v2 pickup truck impacting a tangent, 175-ft (53.3-m) long MGS was modified to simulate impacts with guardrail located 6 in. (152 mm) behind the front face of a 6-in. (152-mm) tall AASHTO Type B curb. Further simulations were conducted at 31 mph (50 km/h) and 44 mph (70 km/h). The lower impact speeds corresponded to impacts with the MGS at TL-1 and TL-2 impact conditions, respectively. A total of five impacts were simulated for each speed, at quarter-post spacing starting at the midspan between post nos. 11 and 12, and terminating at the midspan between post nos. 12 and 13.

4.2 Comparison and Validation of Simulation Model with Curb

The MGS was approved for installation 6 in. (152 mm) behind a curb, based on successful full-scale crash test no. NPG-5 [13-14], which was conducted under the TL-3 test conditions and evaluation criteria found in NCHRP Report No. 350 [51]. The 2000P test vehicle used for that test series was a ¾-ton, Chevrolet C2500 pickup truck. With the adoption of MASH, some systems, including the MGS, were grandfathered as successful systems. Further testing with the MGS with MASH vehicles indicated a high likelihood of successful performance with standard impact conditions [38].

No tests have been conducted on the MGS installed 6 in. (152 mm) behind a curb using the MASH 2270P vehicle. Other tests have been related to the use of guardrail adjacent to curbs, including the MGS installed 8 ft (2.4 m) behind the front face of a curb [46-47] and guardrail

installed 6 in. (152 mm) behind the front face of a 4-in. (102-mm) tall, wedge-shaped curb [49-50]. However, the performance of these systems varied greatly from the MGS installed behind curb in standard configuration. For example, the barrier located 8 ft (2.4 m) behind the front face of a curb was impacted by an airborne vehicle and had standard embedment depth with respect to the ground behind the curb. However, the MGS installed 6 in. (152 mm) behind the front face of the curb had a 6-in. (152-mm) deeper embedment depth to retain a 31-in. (787-mm) tall guardrail top mounting height. In addition, the guardrail installed with wedge-shaped curb was utilized in a transition, and thus had smaller post spacings, larger and stiffer posts, and a different anchorage than the MGS behind curb. Instead, test no. NPG-5 results were evaluated to determine if the performance of the simulated system was reasonable, compared with the as-tested system approved according to the criteria presented in NCHRP Report No. 350.

4.2.1 Modifications to Level Terrain Baseline Model

The model of the MGS located 6 in. (152 mm) behind the face of an AAHSTO Type B curb was identical to the model used in the first phase of this research project, except for two major modifications. First, a 6-in. (152-mm) tall, rigid, AASHTO type B curb was added to the model, and it was located with the front face of the curb 6 in. (152 mm) in front of the front face of the rail. Second, the embedment depth of the posts was increased by 6 in. (152 mm). The composite soil moment was increased proportionately with the square of the ratio of the embedment depths, consistent with previous recommendations by MwRSF [52]. The ratio of soil stiffness relative to level, flat ground was reduced from a nominal number of 1.15 to 1.10, in an attempt to be conservative and overestimate the working width. The simulated test vehicle and impact conditions for the MGS barrier in combination with curb were identical to those used in the level terrain phase of this project: 62.1 mph (100 km/h) and 25 degrees relative to the face of the barrier, with the left side of the vehicle aligned with the upstream edge of post no. 12. The model of the system is shown in Figure 13.

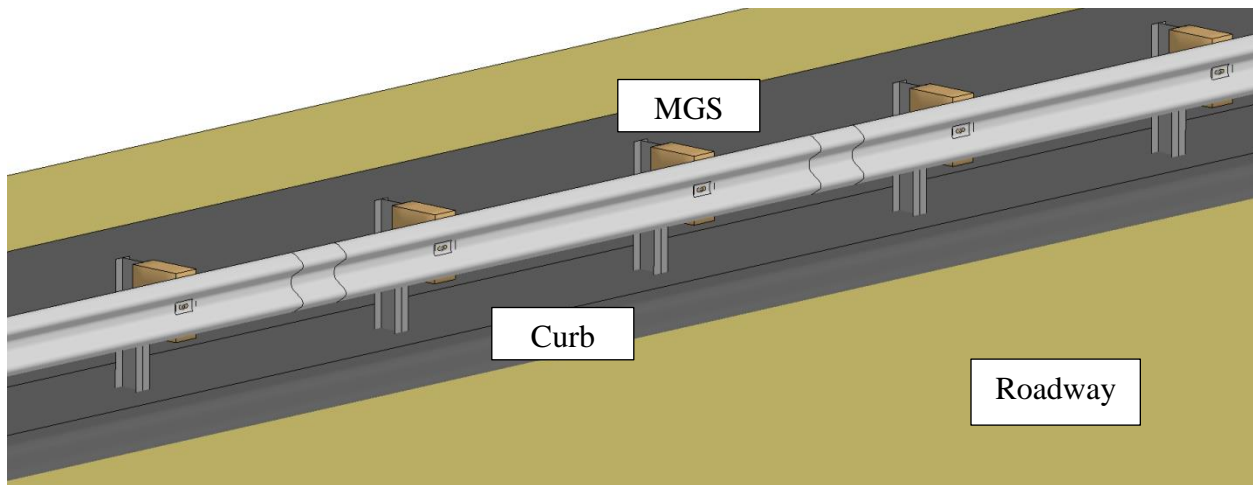


Figure 13. Model of MGS in Combination with Curb

4.2.2 Description of Test No. NPG-5

Test no. NPG-5 consisted of a standard configuration of MGS, with two major modifications. First, a 6-in. (152-mm) tall, AASHTO Type B curb was installed 6 in. (152 mm) from the midpoint of the curb face to the guardrail. Second, soil fill behind the post was made level with the top surface of the curb. The posts were 72 in. (1,829 mm) long and embedded 46 in. (1,168 mm) in soil behind the curb, such that the top guardrail mounting height was 31 in. (787 mm) measured above the roadway. Each W6x9 (W152x13.4) post was installed with a 12-in. (305-mm) deep blockout. The test vehicle, a 1997 Chevrolet C2500, ¾-ton pickup truck weighing 4,389 lb (1,991 kg), impacted the system 3 in. (76 mm) upstream from post no. 12 at 60.1 mph (96.7 km/h) and 24.8 degrees. Impact conditions and system photographs are shown in Figure 14.

4.2.3 Comparison of Results, Simulation and Test No. NPG-5

Results from the simulation of the MGS installed in combination with a 6-in. (152-mm) tall, AASHTO Type B curb and impacted with a 2270P pickup truck model at 62.1 mph (100 km/h) and 25 degrees were compared to results from test no. NPG-5 to determine if the model could be reasonably calibrated based on available test data. Sequential images of the simulation and test are shown in Figure 15, and results are shown in Table 6. Post-test photographs are shown in Figures 16 through 18.

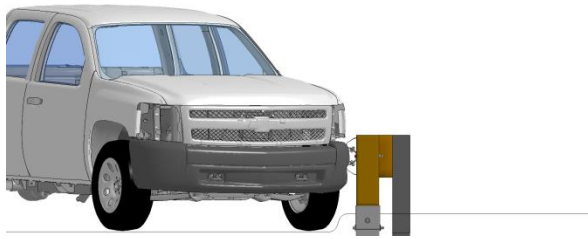
For test no. NPG-5, the 2000P test vehicle impacted the rail and was redirected, with a maximum dynamic deflection of 43.1 in. (1,095 mm), and a maximum working width of 49.6 in. (1,260 mm) measured from the right-front corner of the hood to the undamaged front face of the rail. Posts upstream and downstream from impact experienced significant twisting toward impact, and the end anchorages were permanently displaced approximately 1½ in. (38 mm). During impact, the right-front tire impacted the blockout attached to post no. 16 which deflected longitudinally, and was pulled completely out of the soil and came to rest against post no. 17, as shown in Figure 17.

For the simulation, the maximum dynamic deflection was 33.4 in. (848 mm), and the maximum vehicle protrusion over the rail was 38.8 in. (986 mm). The maximum working width was 48.8 in. (1,240 mm), measured between the deflected back flange of post no. 14 to the undamaged front face of the rail. The working width associated with vehicle protrusion over the rail was less than the working width associated with post deflection. Note that the geometries of the hood and fenders were different for the 2000P test vehicle and 2270P simulation vehicle.

The simulated dynamic deflection was less than what was recorded for test no. NPG-5. However, dynamic deflections and working widths of recent full-scale crash tests involving a 2270P pickup truck impacting an MGS in a non-blocked configuration [18-19], and in combination with a mechanically-stabilized earth (MSE) wall [20-22], both had working widths less than or equal to 45 in. (1,143 mm). Also, the permanent anchorage displacement during a TL-3 MASH test with a 2270P light pickup truck impacting a system that was only 75 ft (22.9 m) long in support of the determination of the minimum effective length of guardrail was ¾ in. (19 mm) [55]. Due to the increased embedment depth of the posts in the MGS installed in combination with a 6-in. (152-mm) tall AASHTO Type B curb, it would be reasonable to expect



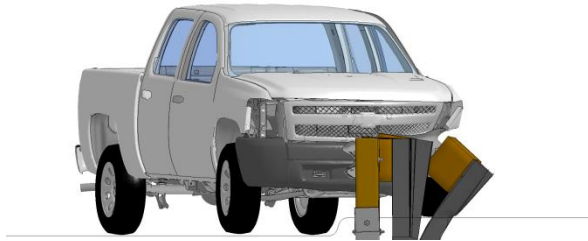
Figure 14. Impact Location and MGS Installed in Combination with Curb, Test No. NPG-5



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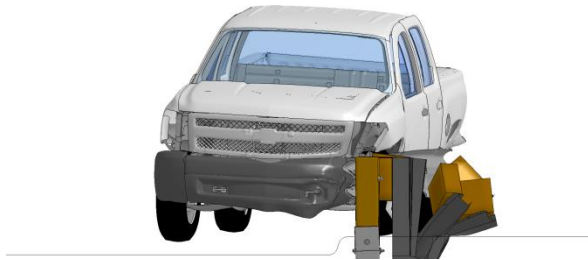
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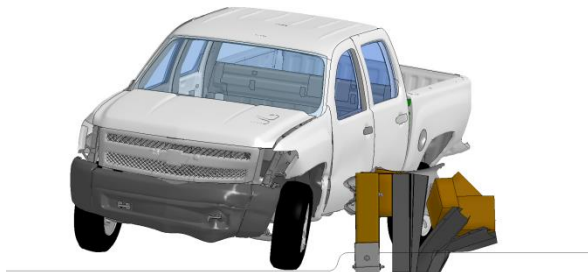
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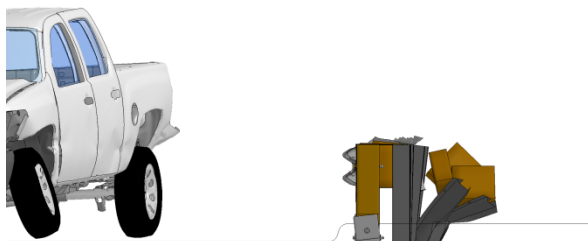
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Figure 15. Sequential Images, Simulation (2270P) and Test No. NPG-5 (2000P)

Table 6. Summary of Simulation and Test No. NPG-5 Results

Comparison	Working Width in. (mm)	Maximum Dynamic Deflection in. (mm)	IS Value kJ	Posts Deflected	Posts Disengaged from Rail	End Anchorage Permanent Set in. (mm)
Simulation	48.8 (1,240)	33.4 (848)	156	6	3	Negligible
Test No. NPG-5*	49.6 (1,260)**	38.4 (975)**	126	7	5	1.5 (38)

*NOTE: The soil foundation for posts and end anchorages used in test no. NPG-5 was determined to have unusually low-strength.

**NOTE: Working width and dynamic deflection obtained from overhead camera view have a uncertainty of 10%.



Figure 16. System Damage, Test No. NPG-5



Figure 17. Post No. 16 Pulled Out of Ground, Test No. NPG-5



(a)



(b)

Figure 18. Post and Soil Displacement, Test No. NPG-5 (a) Upstream End Anchorage
(b) Post No. 12

that the maximum dynamic deflections and working widths would be substantially less than for systems installed on level terrain or on slopes. Because MASH testing has so far resulted in similar, and at times lower, dynamic deflections and working widths than tests conducted in accordance with NCHRP Report No. 350, despite a 13.5 percent increase in energy at impact (i.e., IS value), researchers believe the soil was weaker than often used in full-scale crash testing in this test and a comparison with the 2270P simulation was reasonable.

There is further evidence that soil strengths associated with full-scale crash tests conducted prior to the final acceptance of MASH may have been less stringently controlled than what MASH requires. At times, this led to some unexpected test results. For example, significant vertical and longitudinal displacement of an MGS end anchorage occurred during full-scale crash tests of a long-span system [25-26] and a flared approach guardrail length during test no. FR-4 [33].

Another major difference between the test and simulation consisted of wheel geometry. The vehicle utilized during test no. NPG-5 had a stiffer suspension (i.e., ¾-ton vs. ½-ton in the model) and increased gap between the wheel and fender, which allowed the guardrail to protrude behind the wheel during redirection. As the rail protruded behind the wheel, it lifted the right (impacting) side upward. This rolling moment and the truck's lesser roll moment of inertia compared to the 2270P resulted in a higher roll angle displacement, and the truck remained engaged with the rail for a longer amount of time than the 2270P model. The right-front wheel of the simulated truck was not restricted and rebound occurred more smoothly and quickly.

Although not all events of the test could be replicated, particularly the end anchorage displacement and post removal from the ground, researchers believe that calibration with this weak soil test was both reasonable and conservative. The simulated and full-scale test working widths were nearly identical, despite unusually weak soil for the posts installed behind a curb. Also, the MGS model for level terrain compared well with the testing results, and the modifications to the model to account for increased embedment depth have been previously validated, as discussed. Thus, the simulation results were believed to be conservative, and thus useful for continued use to determine maximum working widths at varying speeds and impact locations.

4.3 Modifications for Alternative Impact Locations and Speeds

The same procedure used during the level-terrain simulation of the MGS at TL-3, TL-2, and TL-1 conditions was used to investigate the working width of the MGS installed with the front face of the guardrail located 6 in. (152 mm) behind the midpoint of the front face of a 6-in. (152-mm) tall AASHTO Type B curb. Impacts were investigated at between ½-post span (midspan) upstream from post no. 12 to ½-post span (midspan) downstream from post no. 12. Three speeds were simulated: 62 mph (100 km/h), 44 mph (70 km/h), and 31 mph (50 km/h).

4.4 Qualitative Analysis

Sequential images of TL-1, TL-2, and TL-3 impacts with the MGS located 6 in. (152 mm) behind the face of a 6-in. (152-mm) tall AASHTO Type B curb are shown in Figures 19 through 24. Barrier deflections, barrier exit times and longitudinal exit displacements, vehicle

roll and pitch angles, and the number of posts damaged increased with increased impact speed. For all impact conditions, vehicles were smoothly redirected with no instabilities. Vehicle damage was limited for impacts at TL-1 and TL-2 impact conditions, and barrier permanent sets were minimal.

4.5 Working Width Dependency on Impact Location

Several impact locations were investigated at each test level to determine how impact location influenced maximum dynamic deflections and working widths, as shown in Tables 7 through 9. Quarter-post impacts occurred at the midspan between post nos. 11 and 12 (at a splice) through the midspan of post nos. 12 and 13 (no splice). These impact locations demonstrated how impacting at and around a post influenced barrier deflections.

Maximum working widths were relatively constant regardless of impact location, although fluctuations of up to 4 in. (102 mm) were observed for TL-2 and TL-1 impact conditions, as shown in Figure 25. Similar to level terrain simulations, the working widths repeated at regular intervals, such that the working width at the midspan between post nos. 12 and 13 was nearly identical to the working width recorded for impacts at the midspan between post nos. 11 and 12. Minor differences were likely related to the distribution of upstream and downstream rail tension as well as the contributions from posts upstream and downstream from impact.

Barrier deflections and working widths were compared for impacts at TL-1, TL-2, and TL-3 conditions and results are summarized in Tables 10 through 12. The impact locations associated with maximum working widths were at the $\frac{1}{4}$ -post span upstream from post no. 12 for TL-3 impact conditions, between post no. 12 and $\frac{1}{4}$ -post span upstream for TL-2 impact conditions, and at post no. 12 for TL-1 impact conditions. As impact speed increased, the location associated with the largest working width gradually moved upstream from post no. 12.

The trend of maximum dynamic deflection was similar for TL-2 and TL-3 impacts, as shown in Figure 26. The maximum dynamic deflections were at least 15 in. (381 mm) less than the maximum working widths. For all impact conditions, the maximum dynamic deflection occurred at approximately the $\frac{1}{4}$ -post span upstream from post no. 12.

The number of posts deflected were compared for tangent, level-terrain MGS and MGS installed in combination with a curb, and results are summarized in Table 13. For purposes of analysis, a post was considered “deflected” if it rotated backward at least 1 in. (25 mm) at the post bolt. Other posts which twisted toward impact were not considered “deflected”. Likewise, posts were considered to be disengaged from the rail if the post bolt was no longer engaged with the inside surface of the rail slot. It was observed that, on average, impacts on level terrain deflected and disengaged more posts than systems installed in combination with curbs, but the effects were more noticeable at lower test levels (i.e., TL-1 and TL-2). Simulations may underpredict the number of posts deflected and disengaged due to the difficulty of obtaining accurate soil models, but the overall reaction of the systems was reasonable. This may be indicative of the severity of an impact when assessed based on energy and system configuration.

4.6 Discussion

MGS maximum dynamic deflections and working widths on level terrain and in combination with curbs were compared and are shown in Tables 10 through 12. The MGS installed in combination with a curb reduced both dynamic deflections and working widths, typically by more than 15%. The reduction in working width was relatively constant for all of the speeds considered, ranging between 16% and 25% based on individual impact location, and between 17% and 19% on average. Conversely, the maximum dynamic deflection reductions ranged broadly for each individual impact location considered, varying from a low of 6% to a high of 30%. On average, the presence of curbs reduced dynamic deflections between 9% and 26%.

The MGS has been full-scale crash tested and approved with full-post spacing, 12-in. (305-mm) deep blockouts and located 6 in. (152 mm) behind the midpoint of the front face of a 6-in. (152-mm) tall AASHTO Type B curb. The guardrail was approved with tolerances for construction such that the guardrail is 6 in. (152 mm) behind the front face of the curb, to 6 in. (152 mm) in front of the front face of the curb. Although guardrail was not modeled in front of or at the front face of the curb, it is believed that placing the guardrail as far behind the curb as is allowable is the most severe configuration [14-17]. Thus, similar application guidelines for placement of the MGS in conjunction with a curb apply for lower service level applications.

The largest variations in working widths based on impact location and speed occurred for impacts at TL-1 impact conditions. For TL-3 impact conditions, reductions in dynamic deflections and working widths were relatively constant based on impact location. For increases in impact speed, the number of posts which the vehicle interacted with increased as well, which distributed the force applied by each post and tended to average out fluctuations in lateral stiffness due to contributions from the posts.

In some urban locations, clear zone may come at a premium expense. It may be cost effective to install guardrail in these locations, but space requirements may be impractical, due to shy line and hazard offsets, particularly for rigid, unmovable hazards. Reducing speed limits to accommodate existing working width recommendations may not be practical in all applications. For these unique and difficult scenarios, typical recommendations for guardrail offsets – maintaining a hazard-free envelope defined by the working width – may be impractical. Special considerations may be required for these situations.

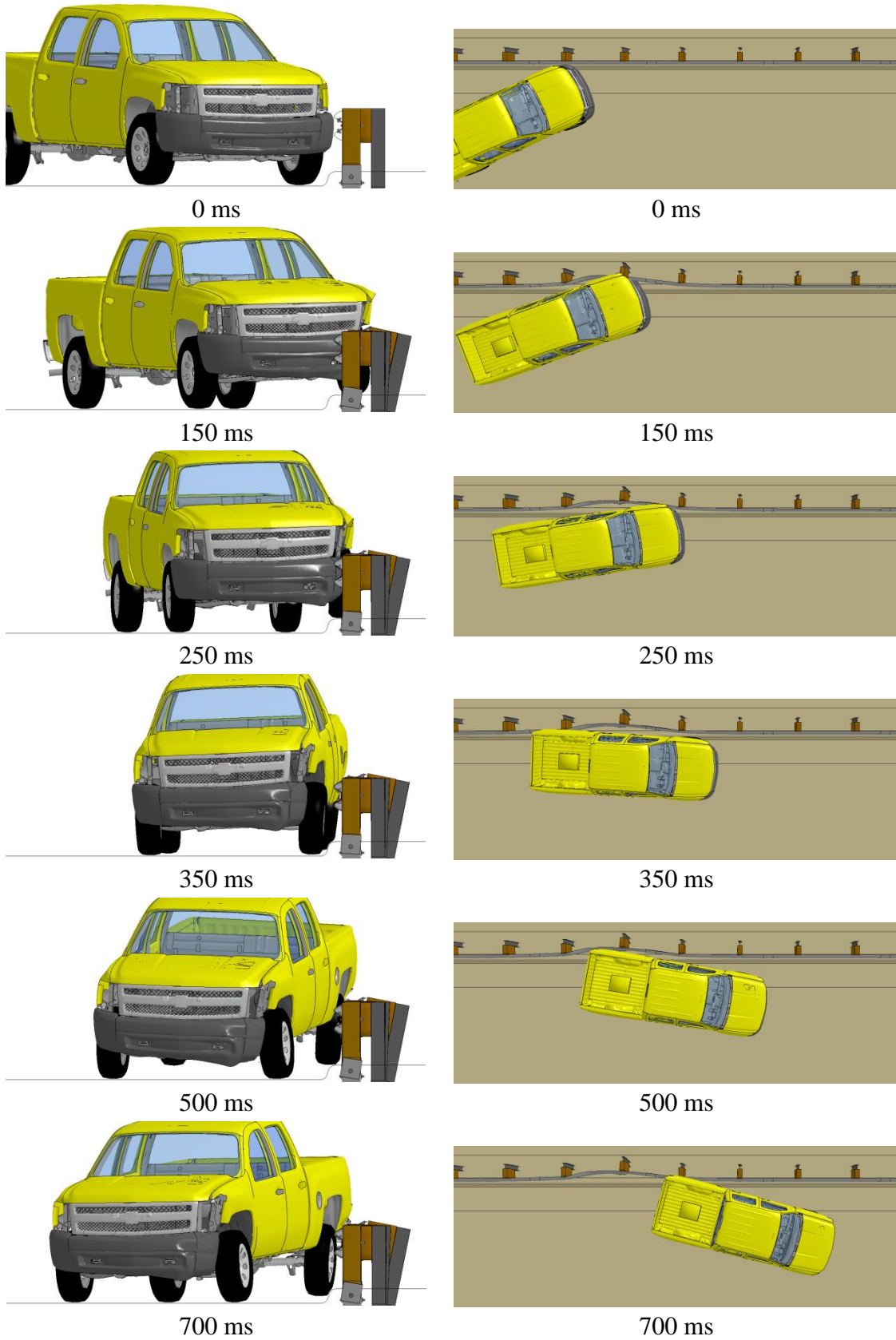
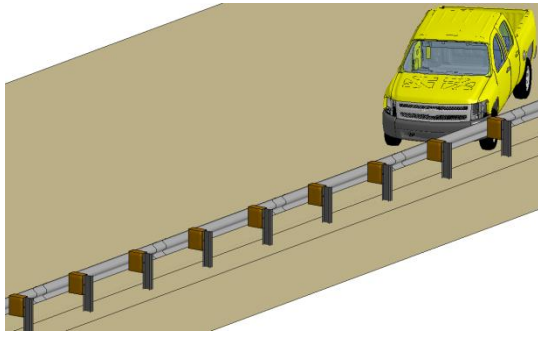
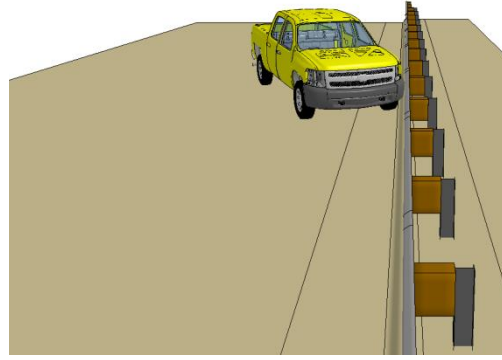


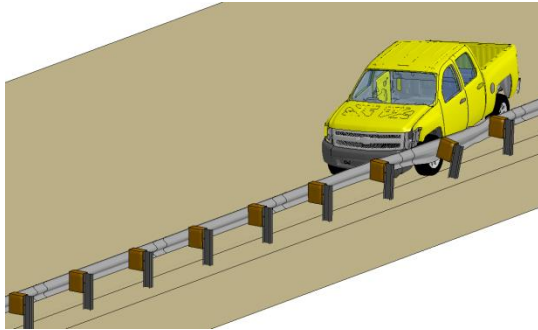
Figure 19. Sequential Images of TL-1 Impact with MGS with Curb



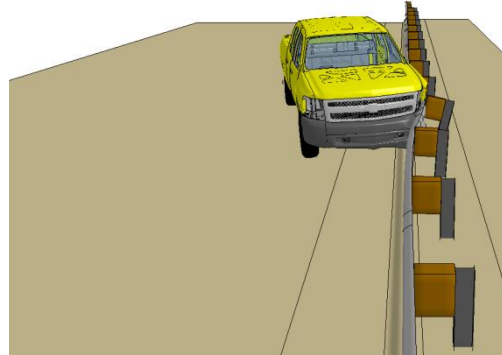
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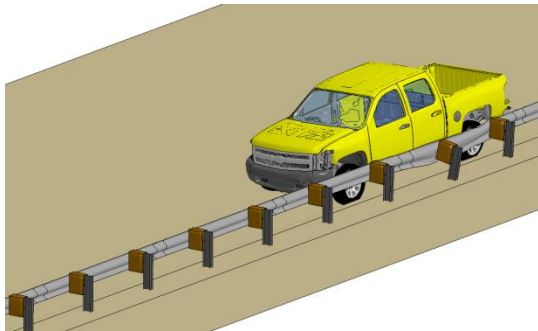
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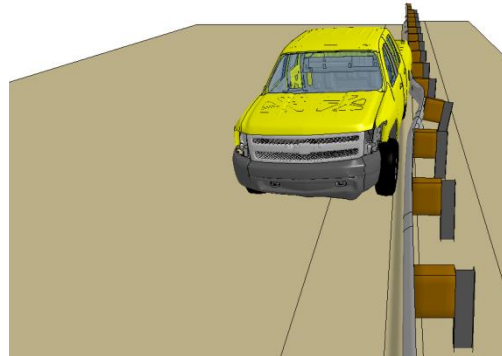
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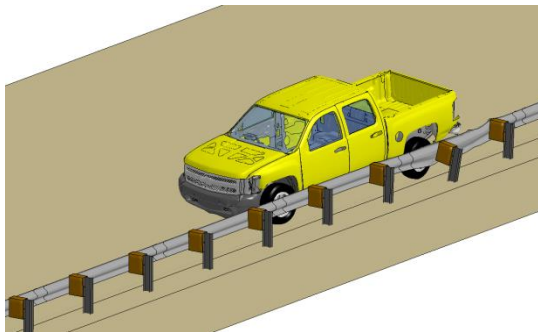
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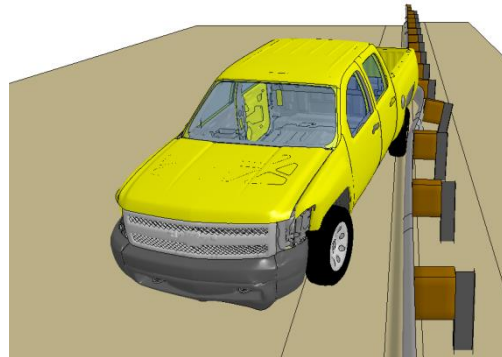
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350 ms



500 ms



500 ms

Figure 20. Sequential Images of TL-1 Impact with MGS with Curb

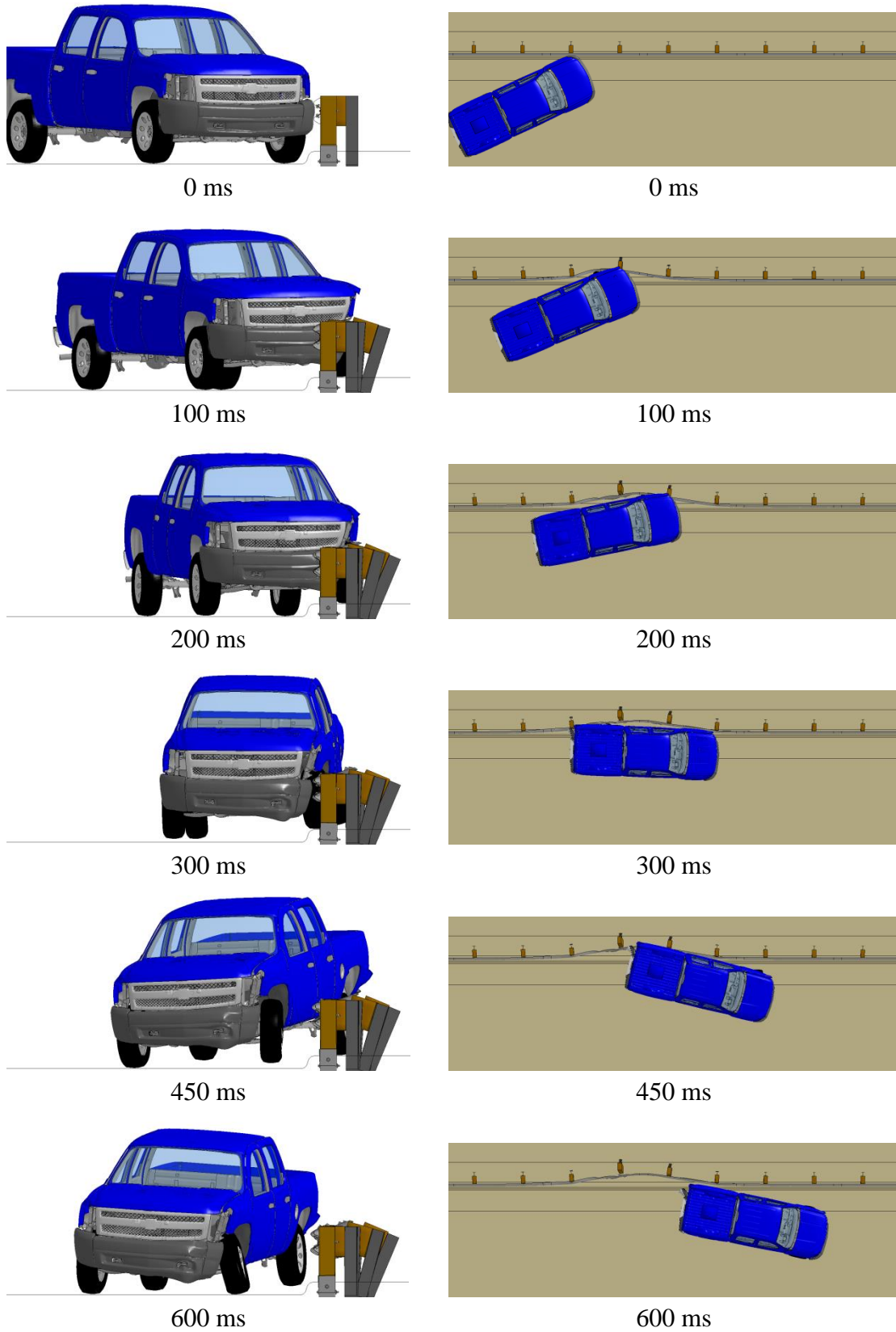


Figure 21. Sequential Images of TL-2 Impact with MGS with Curb

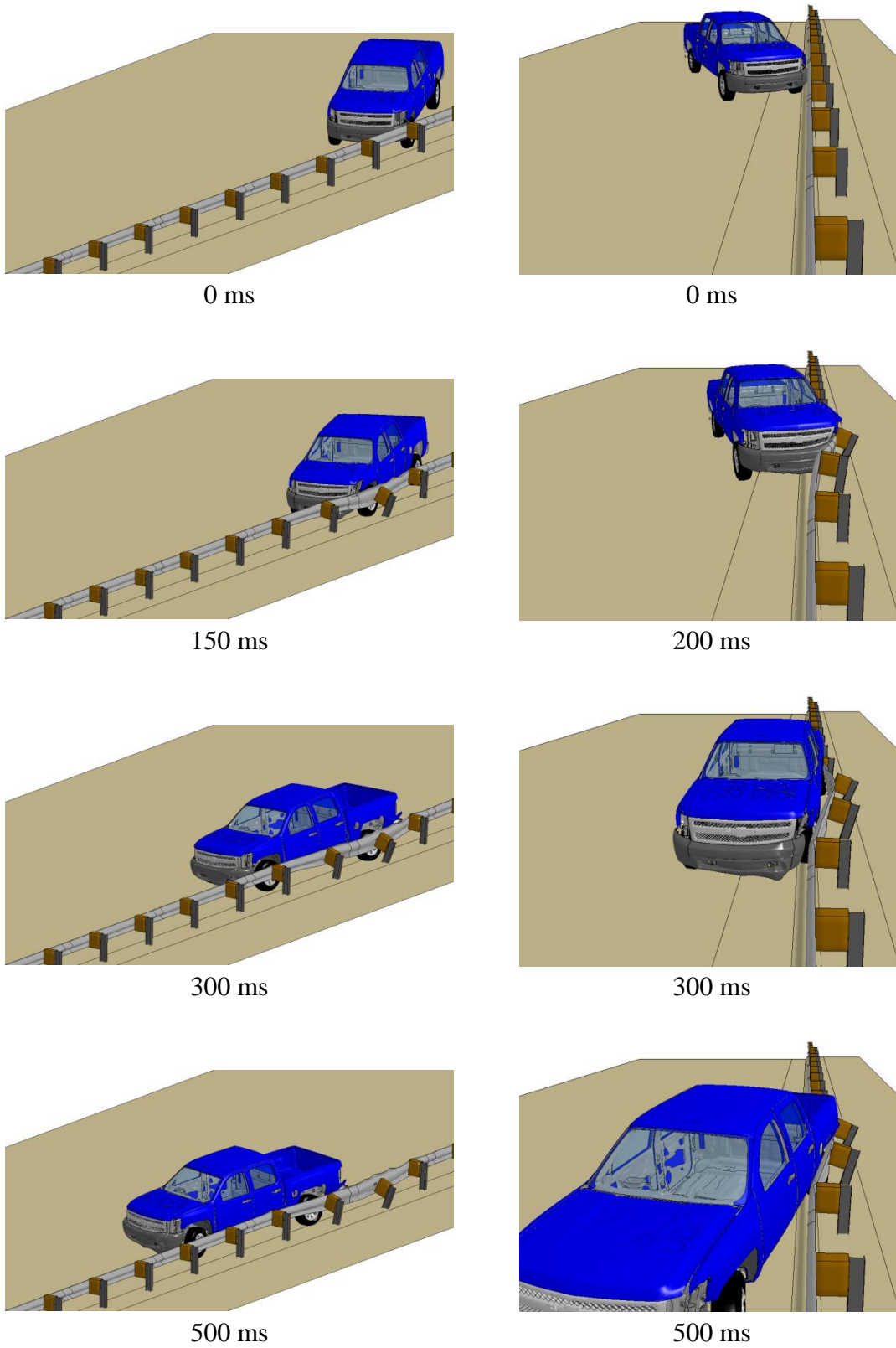


Figure 22. Sequential Images of TL-2 Impact with MGS with Curb

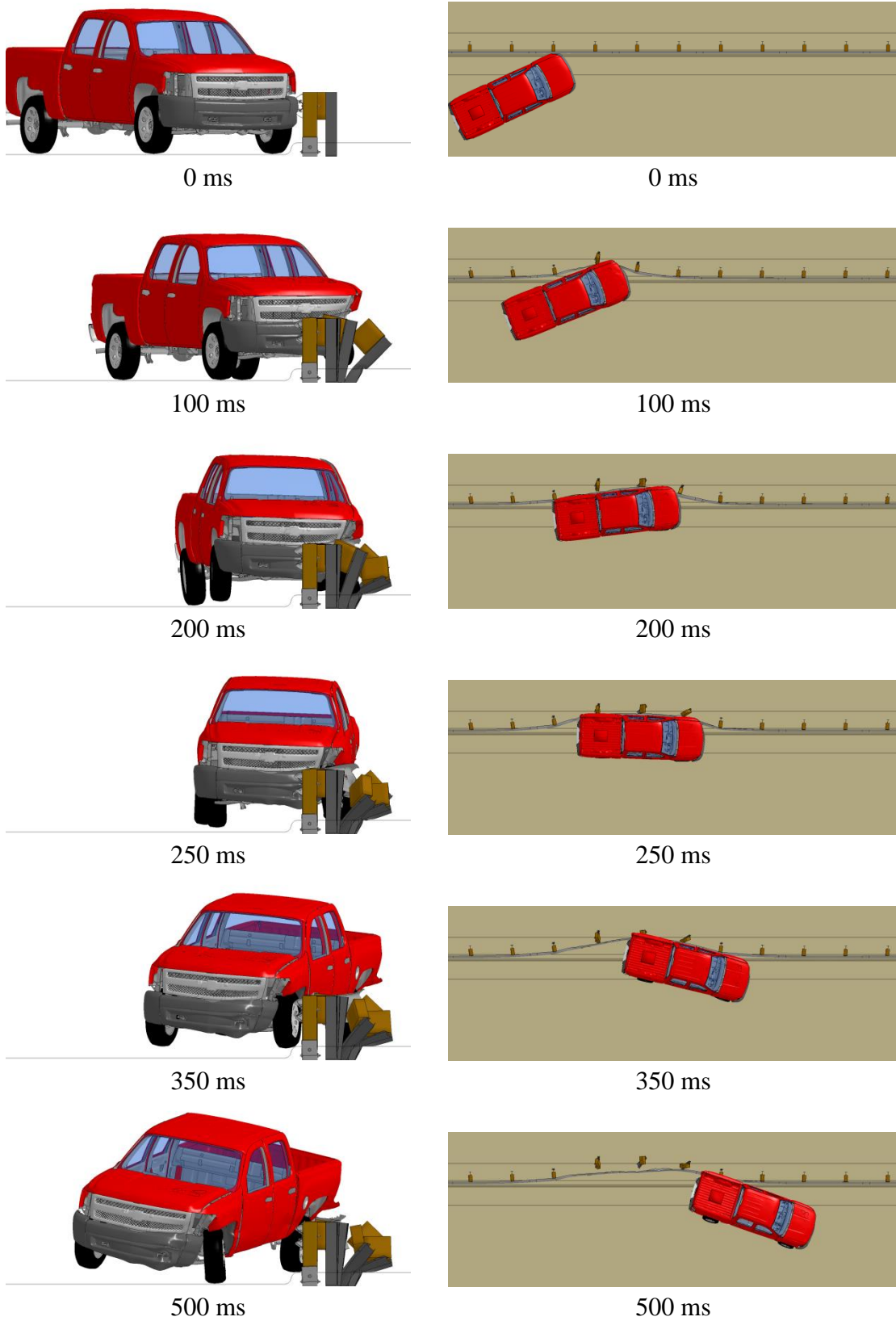


Figure 23. Sequential Images of TL-3 Impact with MGS with Curb

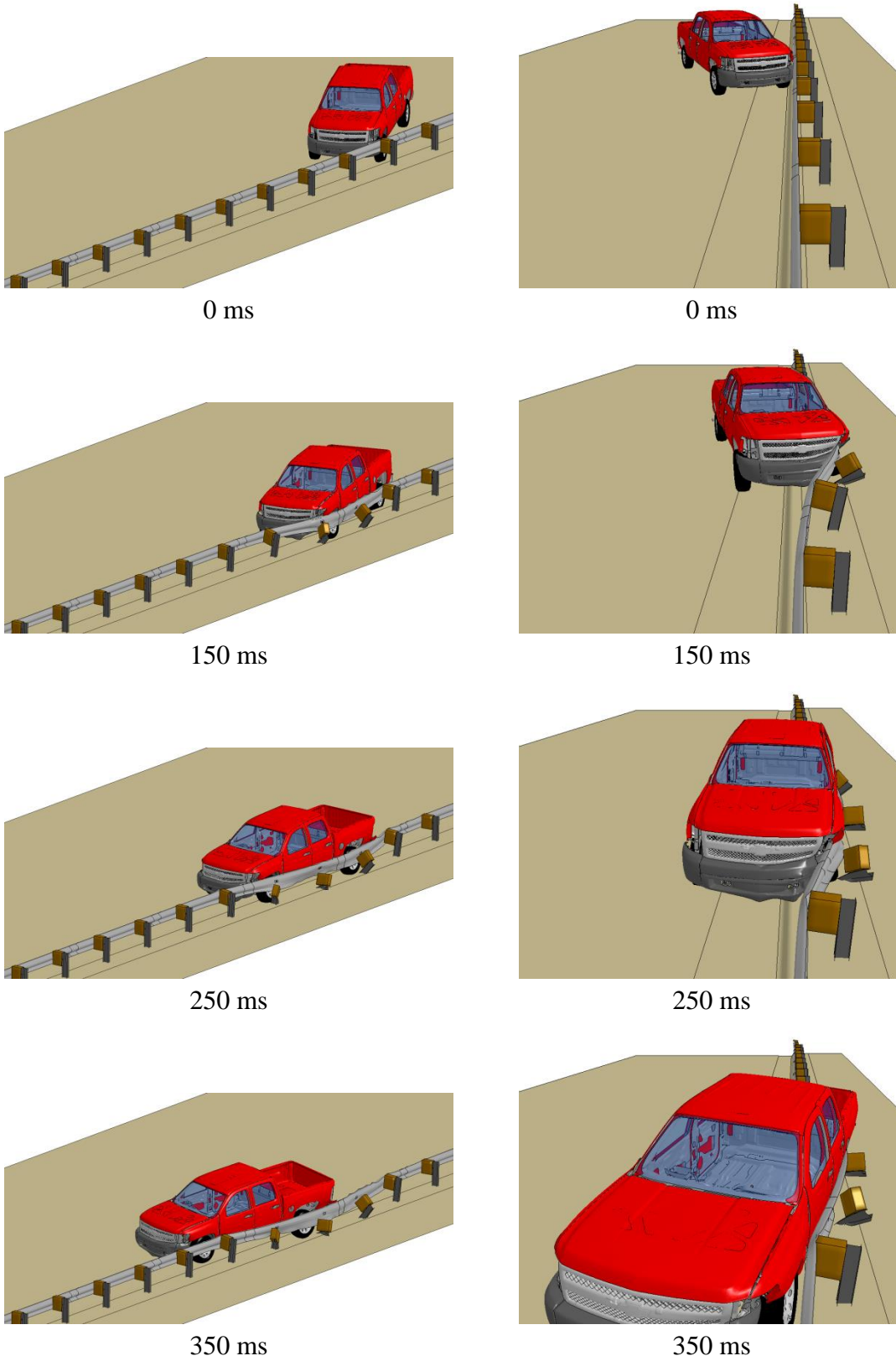


Figure 24. Sequential Images of TL-3 Impact with MGS with Curb

Table 7. Test Level 1: Barrier Deflections and Working Widths

Test Level 1 - 31 mph (50 km/h)			
Post Location	Maximum Dynamic Deflection in. (mm)	Working Width in. (mm)	Max Working Width Location
11½	11.6 (295)	28.4 (722)	Post no. 12
11¾	12.2 (311)	27.6 (701)	Post no. 13
12	12.2 (310)	30.4 (772)	Post no. 13
12¼	12.3 (313)	30.5 (775)	Post no. 13
12½	11.0 (279)	28.3 (720)	Post no. 13

Table 8. Test Level 2: Barrier Deflections and Working Widths

Test Level 2 - 44 mph (70 km/h)			
Post Location	Maximum Dynamic Deflection in. (mm)	Working Width in. (mm)	Max Working Width Location
11½	22.5 (571)	40.7 (1033)	Post no. 13
11¾	22.7 (576)	40.9 (1038)	Post no. 13
12	21.7 (551)	39.9 (1013)	Post no. 13
12¼	20.3 (517)	36.7 (931)	Post no. 14
12½	21.8 (553)	40.0 (1015)	Post no. 14

Table 9. Test Level 3: Barrier Deflections and Working Widths

Test Level 3 - 62 mph (100 km/h)			
Post Location	Maximum Dynamic Deflection in. (mm)	Working Width in. (mm)	Max Working Width Location
11½	33.7 (856)	48.5 (1232)	Post no. 13
11¾	34.4 (873)	49.2 (1250)	Post no. 13
12	33.3 (847)	48.8 (1240)	Post no. 14
12¼	32.6 (829)	48.9 (1243)	Post no. 14
12½	33.2 (844)	48.7 (1238)	Post no. 14

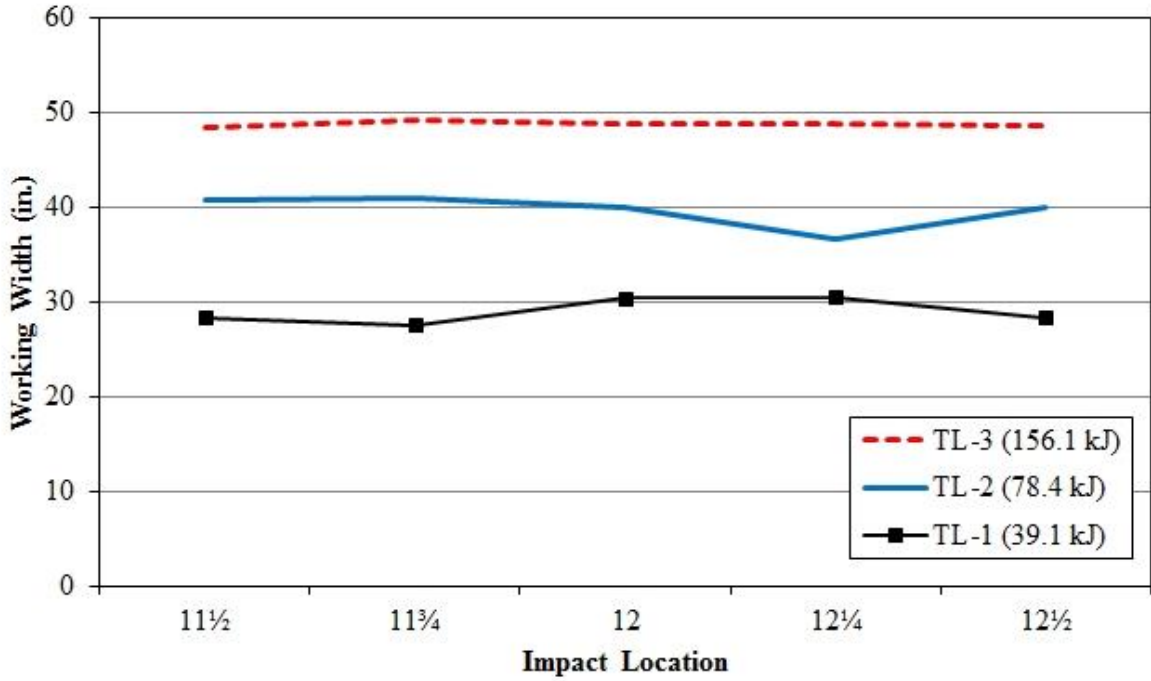


Figure 25. Maximum Working Widths for MGS Installed in Combination with Curbs, by IS Value

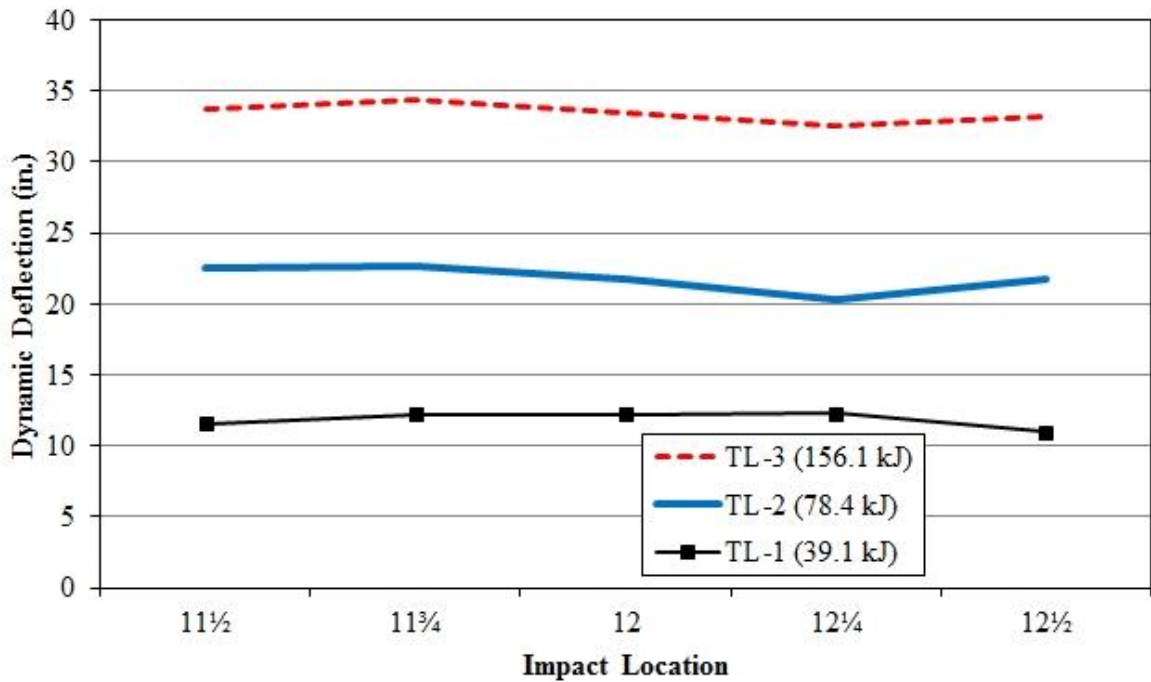


Figure 26. Maximum Dynamic Deflection for MGS Installed in Combination with Curb, by IS Value

Table 10. Comparison of MGS Deflections at TL-1 Impact Conditions

Post Location	TL-1 Dynamic Deflection, in. (mm)			TL-1 Working Width, in. (mm)		
	Level Terrain	With Curb	% Reduction	Level Terrain	With Curb	% Reduction
11½	16.6 (422)	11.6 (295)	30%	35.3 (896)	28.4 (722)	20%
11¾	15.6 (397)	12.2 (311)	22%	37.0 (940)	27.6 (701)	25%
12	15.1 (383)	12.2 (310)	19%	37.6 (955)	30.4 (772)	19%
12¼	15.7 (398)	12.3 (313)	22%	37.3 (947)	30.5 (775)	18%
12½	16.0 (405)	11.0 (279)	31%	35.3 (895)	28.4 (720)	20%
Maximum	16.6 (422)	12.3 (313)	26%	37.6 (955)	30.5 (775)	19%

Table 11. Comparison of MGS Deflections at TL-2 Impact Conditions

Post Location	TL-2 Dynamic Deflection, in. (mm)			TL-2 Working Width, in. (mm)		
	Level Terrain	With Curb	% Reduction	Level Terrain	With Curb	% Reduction
11½	24.0 (610)	22.5 (571)	6%	48.5 (1,232)	40.7 (1033)	16%
11¾	25.0 (634)	22.7 (576)	9%	49.3 (1,251)	40.9 (1038)	17%
12	24.5 (622)	21.7 (551)	11%	46.5 (1,181)	39.9 (1013)	14%
12¼	24.4 (619)	20.3 (517)	17%	47.6 (1,210)	36.7 (931)	23%
12½	24.1 (612)	21.8 (553)	10%	48.3 (1,228)	40.0 (1015)	17%
Maximum	25.0 (634)	22.7 (576)	9%	49.3 (1,251)	40.9 (1038)	17%

Table 12. Comparison of MGS Deflections at TL-3 Impact Conditions

Post Location	TL-3 Dynamic Deflection, in. (mm)			TL-3 Working Width, in. (mm)		
	Level Terrain	With Curb	% Reduction	Level Terrain	With Curb	% Reduction
11½	37.5 (952)	33.7 (856)	10%	58.1 (1,475)	48.5 (1232)	17%
11¾	38.0 (964)	34.4 (873)	9%	60.2 (1,530)	49.2 (1250)	18%
12	36.6 (930)**	33.4 (847)	9%	59.6 (1,515)**	48.8 (1240)	18%
12¼	39.3 (997)	32.6 (829)	17%	59.3 (1,505)	48.9 (1243)	18%
12½	37.7 (957)	33.2 (844)	12%	58.7 (1,491)	48.7 (1238)	17%
Maximum	39.3 (997)	34.4 (873)	12%	60.2 (1,530)	49.2 (1250)	18%

**Simulation terminated at 240ms

Table 13. Simulated Number of Posts Deflected or Disengaged

Impact Condition	IS Value (kJ)	Standard Configuration, Level Terrain		In Combination with Curb	
		Posts Deflected	Posts Disengaged	Posts Deflected	Posts Disengaged
TL-1	38.9	3-4	0 or 1	1	0
TL-2	78.4	5	2	2-3	1-2
TL-3	155.6	6-7	2-3	4-6	2-3

5 ALTERNATIVE APPLICATIONS FOR MGS WITH LOWER IMPACT SPEEDS

Study results were examined to determine what modifications, if any, could increase the versatility of the MGS, particularly for lower-speed roadways. Several modifications were considered for a variety of reasons: reduction or elimination of the blockout, modified post spacing, and varying configurations with curbs.

A non-blocked version of the MGS was successfully tested on level terrain at TL-3 impact conditions [18-19]. Given the successful performance of the system at TL-3 conditions, it is reasonable to assume that the system will also perform acceptably at TL-2 and TL-1 conditions. The working width of the non-blocked MGS recorded during the test was 43.2 in. (1,097 mm). The soil conditions at the time of the test were densely-compacted, coarse crush limestone, strong soil per MASH test requirements.

An attempt was made to estimate the effective working width of a system on level terrain without blockouts, and impacted with impact conditions consistent with MASH TL-1 and TL-2 test criteria. The depth of the posts and rail were added to the maximum dynamic deflection of the guardrail, which was typically the element with the largest dynamic deflection, as shown in Table 14. Note that the approximate depth of the MGS with a standard configuration is 21¼ in. (540 mm), and the depth of the system without blockouts is approximately 9¼ in. (235 mm). This approach led to a working width recommendation for guardrail with TL-3 impact conditions which was 13% higher than observed in the test, as shown in Table 14. Because this estimate was conservative at high-energy impact conditions consistent with TL-3 impacts according to MASH, researchers believed that this method was similarly conservative for lower-severity test levels.

Table 14. Estimated Working Width Envelopes for Non-Blocked MGS

Design Speed mph (km/h)	IS Value kJ	Dynamic Deflection, MGS with Blockouts in. (mm)	Recommended Working Width Non-Block MGS in. (mm)	Working Width Test No. MGSNB-1 Non-Block MGS in. (mm)
31 (50)	38.9	16.6 (422)	25.9 (657)	-
44 (70)	78.4	25.0 (634)	34.3 (869)	-
62 (100)	155.6	39.3 (997)	48.6 (1232)	43.2 (1,097) [18]

At TL-1 impact conditions, the maximum dynamic deflections were typically between 11 and 12 in. (279 and 305 mm) for MGS installed in combination with curbs, and were as high as 16.6 in. (422 mm) without curbs. For these low deflections, it may be reasonable to reduce the depth of the blockout to 4 or 8 in. (102 or 203 mm) to reduce the cost of the barrier and its associated working width. Whereas MGS without blockouts has been installed on level terrain, the non-blocked MGS has not been full-scale crash tested in combination with curbs. Full-scale crash testing is recommended before installing a non-blocked MGS in combination with 4-in. and 6-in. (102-mm and 152-mm) tall AASHTO Type B curbs.

Decreased post spacing has been tested on level terrain for MGS with blockouts. A quarter post-spacing full-scale crash test was successful according to NCHRP Report No. 350 [13-14]. Reducing the post spacing from 6 ft – 3 in. (1.9 m) to 18¾ in. (476 mm) resulted in a 35% reduction in working width, from 57.2 in. (1,453 mm) to 36.7 in. (931 mm). If the trend is approximately linear, a half-post spacing would reduce deflections by approximately 18%. These reductions would be applicable for full 12-in. (305-mm) deep blockouts and would likely be successful with 8-in. (203-mm) deep blockouts as well. Shallower blockouts or non-blocked systems may require further analysis with full-scale crash testing and/or simulation. Also, half- and quarter-post systems have not been tested in combination with curbs to assess structural adequacy and to determine working widths or dynamic deflections.

For some low-speed locations with limited clearance, working widths may be limited to less than recommended based on the MGS installed in combination with curbs. For these situations, it may be desirable to install guardrail in combination with 8-in. (203-mm) or 10-in. (254-mm) tall curbs. These conditions should be considered for future studies involving lower-speed impacts into guardrails with limited lateral clearances.

6 CONCLUSIONS AND RECOMMENDATIONS

The MGS is a relatively low-cost barrier, and the TL-3 version could be installed for TL-2 and TL-1 applications. Although the performance of the MGS, the dynamic deflection, and working width of the barrier have been examined in great detail at TL-3 impact conditions, little is known about the dynamic deflection and working width of the MGS when impacted at lower speeds. Models of the MGS installed on level terrain and in combination with curbs were simulated using the non-linear FEA program LS-DYNA to investigate the dynamic deflections and working widths of these systems at lower speeds and at alternative impact locations.

Impact conditions selected for analysis were consistent with TL-3, TL-2, and TL-1 impact conditions described in MASH. Each simulation utilized a 2270P Chevrolet Silverado quad cab pickup truck model impacting at 25 degrees, at speeds of 62, 44, and 31 mph (100, 75, or 50 km/h). Maximum dynamic deflections of the rail and posts and extension of the pickup truck over the top of the rail were tabulated.

The recommended working width of MGS installed on level terrain and in combination with curbs was determined using simulation results, which generally compared well with TL-3 full-scale test results. For some installations with minimal clearance, working widths were estimated using the maximum dynamic deflection of the rail, and were determined to be conservative. Recommended working widths for systems based on design speeds and configurations are shown in Table 15.

Table 15. Recommended Working Width Envelopes for Guardrail

Design Speed mph (km/h)	Minimum Working Width Envelope by Guardrail Configuration in. (mm)			
	Level Terrain with Blockouts	6 in. (152 mm) Behind Curb with Blockouts	Level Terrain without Blockouts	6 in. (152 mm) Behind Curb without Blockouts
31 (50)	37.6 (955)	30.5 (775)	25.9 (657)	Recommend Testing
44 (70)	49.3 (1,251)	40.9 (1,038)	34.3 (869)	Recommend Testing
62 (100)	60.2 (1,530) (simulation) 60.3 (1,532) ^[11] (full-scale)	49.6 (1,250) (simulation)	48.6 (1232) (simulation) 49.6 (1,260) ^[15] (full-scale)	Recommend Testing

Reduced post spacings are likely to reduce guardrail working widths for TL-3, TL-2, and TL-1 design impact conditions, but were not simulated for this research effort. Previously, full-scale crash tests were conducted with MGS configured with standard and quarter-post spacings, and computer simulation was conducted to estimate working widths for half-post spacing, according to TL-3 impact conditions provided in NCHRP Report No. 350 [13-15]. It was noted that the working width of a half-post system was approximately 10% smaller than the working width of a standard-post spacing system. Likewise, the system with quarter-post spacing working

width was 29% smaller than the standard-post spacing system. It is recommended that state DOTs use these reduction factors to estimate what effect reduced post spacings will have on deflections, for the scenarios provided in Table 15. However, further research is recommended to confirm or modify these estimates.

Further research is necessary for the following MGS configurations: MGS with varying height curbs; MGS without blockouts and in combination with curbs; MGS at varying post spacings and in combinations with curbs; and MGS without blockouts.

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