Midwest Pooled Fund Research Program
Fiscal Years 2018-2021 (Year 29)
TPF-5(193) Supplement #149
NDOT Sponsoring Agency Code RPFP-19-LSDYNA

DEVELOPMENT AND VALIDATION OF A THRIE-BEAM AGT LS-DYNA MODEL

Submitted by

Ryan F. Bickhaus, M.S.M.E.
Former Graduate Research Assistant

Jennifer D. Rasmussen, Ph.D., P.E.
Former Research Associate Professor

John D. Reid, Ph.D.
Professor

MIDWEST ROADSIDE SAFETY FACILITY
Nebraska Transportation Center
University of Nebraska-Lincoln

Main Office
Prem S. Paul Research Center at Whittier School
Room 130, 2200 Vine Street
Lincoln, Nebraska 68583-0853
(402) 472-0965

Outdoor Test Site
4630 N.W. 36th Street
Lincoln, Nebraska 68524

Submitted to

MIDWEST POOLED FUND PROGRAM
Nebraska Department of Transportation
1500 Nebraska Highway 2
Lincoln, Nebraska 68502

MwRSF Research Report No. TRP-03-441-22

May 13, 2022

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. TRP-03-441-22	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Development and Validation of a Thrie-Beam AGT LS-DYNA Model		**5. Report Date** May 13, 2022
		6. Performing Organization Code
7. Author(s) Bickhaus, R.F., Rasmussen, J.D., and Reid, J.D.		**8. Performing Organization Report No.** TRP-03-441-22
9. Performing Organization Name and Address Midwest Roadside Safety Facility (MwRSF) Nebraska Transportation Center University of Nebraska-Lincoln Main Office: Prem S. Paul Research Center at Whittier School Room 130, 2200 Vine Street Lincoln, Nebraska 68583-0853 Outdoor Test Site: 4630 N.W. 36th Street Lincoln, Nebraska 68524		**10. Work Unit No.**
		11. Contract TPF-5(193) Supplement #149
12. Sponsoring Agency Name and Address Midwest Pooled Fund Program Nebraska Department of Transportation 1500 Nebraska Highway 2 Lincoln, Nebraska 68502		**13. Type of Report and Period Covered** Final Report: 2018-2022
		14. Sponsoring Agency Code RPFP-19-LSDYNA

15. Supplementary Notes

Prepared in cooperation with U.S. Department of Transportation, Federal Highway Administration

16. Abstract

The primary purpose of this research effort was to develop a validated LS-DYNA model of a tangent approach guardrail transition (AGT) with standardized concrete buttress. The AGT model was modeled after the test installation in test no. AGTB-2. The simulation results were compared to the data collected during test no. AGTB-2. Throughout the validation process, several changes were made to the model, including part geometries, material properties, and vehicle models, in an effort to more accurately model the physical crash test. Three simulations were evaluated using the procedures for verification and validation (V&V) of computer simulations used for roadside safety applications, outlined in National Cooperative Highway Research Program (NCHRP) Report No. W179, two of which were determined to be validated with exceptions.

The validated AGT model was utilized in the Midwest Pooled Fund Year 29 Flared AGT Phase I research effort to identify the critical flare rates for an AGT installation.

17. Key Words Highway Safety, Crash Test, Roadside Appurtenances, MASH 2016, LS-DYNA, Approach Guardrail Transition, AGT, Computer Simulation		**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service. 5285 Port Royal Road Springfield, VA 22161	
19. Security Classification (of this report) Unclassified	**20. Security Classification (of this page)** Unclassified	**21. No. of Pages** 117	**22. Price**

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

DISCLAIMER STATEMENT

This material is based upon work supported by the Federal Highway Administration, U.S. Department of Transportation and the Midwest Pooled Fund Program under TPF-5(193) Supplement #149. 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 University of Nebraska-Lincoln, state highway departments participating in the Midwest Pooled Fund Program nor the Federal Highway Administration, U.S. Department of Transportation. This report does not constitute a standard, specification, or regulation. Trade or manufacturers' names, which may appear in this report, are cited only because they are considered essential to the objectives of the report. The United States (U.S.) government and the State of Nebraska do not endorse products or manufacturers.

ACKNOWLEDGEMENTS

The authors wish to acknowledge several sources that made a contribution to this project: (1) the Midwest Pooled Fund Program funded by the California Department of Transportation, Florida Department of Transportation, Georgia Department of Transportation, Hawaii Department of Transportation, Illinois Department of Transportation, Indiana Department of Transportation, Iowa Department of Transportation, Kansas Department of Transportation, Kentucky Department of Transportation, Minnesota Department of Transportation, Missouri Department of Transportation, Nebraska Department of Transportation, New Jersey Department of Transportation, North Carolina Department of Transportation, Ohio Department of Transportation, South Carolina Department of Transportation, South Dakota Department of Transportation, Utah Department of Transportation, Virginia Department of Transportation, Wisconsin Department of Transportation, and Wyoming Department of Transportation for sponsoring this project; and (2) the Holland Computing Center (HCC) at the University of Nebraska-Lincoln for the computational resources. Acknowledgement is also given to the following individuals who contributed to the completion of this research project.

Midwest Roadside Safety Facility
R.K. Faller, Ph.D., P.E., Research Professor & MwRSF Director
J.C. Holloway, M.S.C.E., Research Engineer & Assistant Director –Physical Testing Division
K.A. Lechtenberg, M.S.M.E., Research Engineer
R.W. Bielenberg, M.S.M.E., Research Engineer
S.K. Rosenbaugh, M.S.C.E., Research Engineer
C.S. Stolle, Ph.D., Research Assistant Professor
J.S. Steelman, Ph.D., P.E., Associate Professor
M. Pajouh, Ph.D., P.E., Research Assistant Professor
A.T. Russell, B.S.B.A., Testing and Maintenance Technician II
E.W. Krier, B.S., Construction and Testing Technician II
S.M. Tighe, Construction and Testing Technician I
D.S. Charroin, Construction and Testing Technician II
R.M. Novak, Construction and Testing Technician II
T.C. Donahoo, Construction and Testing Technician I
J.T. Jones, Construction and Testing Technician I
E.L. Urbank, B.A., Research Communication Specialist
Z.Z. Jabr, Engineering Technician
J.R. Revell, M.S.C.E., Former Research Communication Assistant
Undergraduate and Graduate Research Assistants

California Department of Transportation
Bob Meline, Chief, Roadside Safety Research Branch
David Whitesel, P.E., Transportation Engineer
John Jewell, P.E., Senior Transportation Engineer, Specialist

Florida Department of Transportation
Derwood C. Sheppard, Jr., P.E., Design Standards Publication Manager, Roadway Design Engineer

Georgia Department of Transportation
Christopher Rudd, P.E., State Design Policy Engineer
Frank Flanders IV, P.E., Assistant State Design Policy Engineer

Hawaii Department of Transportation
James Fu, P.E., State Bridge Engineer
Dean Takiguchi, P.E., Engineer, Bridge Design Section
Kimberly Okamura, Engineer, Bridge Design Section

Illinois Department of Transportation
Filiberto Sotelo, P.E., Engineering Policy Unit Chief
Martha Brown, P.E., Safety Evaluation Unit Chief

Indiana Department of Transportation
Katherine Smutzer, P.E., Standards Engineer
Elizabeth Phillips, P.E., Highway Design Director

Iowa Department of Transportation
Chris Poole, P.E., Roadside Safety Engineer
Daniel Harness, P.E., Transportation Engineer Specialist
Stuart Nielsen, P.E., Transportation Engineer Administrator, Design

Kansas Department of Transportation
Ron Seitz, P.E., Director of Design
Scott King, P.E., Road Design Bureau Chief
Brian Kierath Jr., Engineering Associate III, Bureau of Road Design

Kentucky Department of Transportation
Jason J. Siwula, P.E., Assistant State Highway Engineer
Kevin Martin, P.E., Transportation Engineer Specialist
Gary Newton, Engineering Tech III, Design Standards

Minnesota Department of Transportation
Michael Elle, P.E., Design Standards Engineer
Michelle Moser, P.E., Assistant Design Standards Engineer

Missouri Department of Transportation
Sarah Kleinschmit, P.E., Policy and Innovations Engineer

Nebraska Department of Transportation
Phil TenHulzen, P.E., Design Standards Engineer
Jim Knott, P.E., Construction Engineer
Mick Syslo, P.E., State Roadway Design Engineer
Brandon Varilek, P.E., Materials and Research Engineer & Division Head
Mark Fischer, P.E., PMP, Research Program Manager
Lieska Halsey, Research Project Manager
Angela Andersen, Research Coordinator
David T. Hansen, Internal Research Coordinator
Jodi Gibson, Former Research Coordinator

New Jersey Department of Transportation
Hung Tang, P.E., Principal Engineer, Transportation
Joseph Warren, Assistant Engineer, Transportation

North Carolina Department of Transportation
Neil Mastin, P.E., Manager, Transportation Program Management – Research and Development
D. D. "Bucky" Galloway, P.E., CPM, Field Operations Engineer
Brian Mayhew, P.E., State Traffic Safety Engineer
Joel Howerton, P.E., Plans and Standards Engineer

Ohio Department of Transportation
Don Fisher, P.E., Roadway Standards Engineer

South Carolina Department of Transportation
J. Adam Hixon, P.E., Design Standards Associate
Mark H. Anthony, P.E., Letting Preparation Engineer
Henry Cross, P.E., Design Standards Engineer
Jason Hall, P.E., Engineer

South Dakota Department of Transportation
David Huft, P.E., Research Engineer
Randy Brown, P.E., Standards Engineer

Utah Department of Transportation
Shawn Debenham, Traffic and Safety Specialist
Glenn Blackwelder, Operations Engineer

Virginia Department of Transportation
Charles Patterson, P.E., Standards/Special Design Section Manager
Andrew Zickler, P.E., Complex Bridge Design and ABC Support Program Manager

Wisconsin Department of Transportation
Erik Emerson, P.E., Standards Development Engineer
Rodney Taylor, P.E., Roadway Design Standards Unit Supervisor

Wyoming Department of Transportation
William Wilson, P.E., Architectural and Highway Standards Engineer

Federal Highway Administration
David Mraz, Division Bridge Engineer, Nebraska Division Office

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Objective and Scope

The primary purpose of this research effort was to develop a validated LS-DYNA model of a tangent approach guardrail transition (AGT) with standardized concrete buttress. The AGT model was based on the test installation in test no. AGTB-2 [1]. The simulation results were compared to the data collected during test no. AGTB-2. As part of the validation process, several changes were made to the model, including part geometries, material properties, and vehicle models, in an effort to more accurately model the physical crash test. Three simulations were evaluated using the procedures for verification and validation (V&V) of computer simulations used for roadside safety applications, outlined in National Cooperative Highway Research Program (NCHRP) Report No. W179 [2], and two of the simulations were determined to be validated with exceptions. The validated AGT model was utilized in the Midwest Pooled Fund Year 29 Flared AGT Phase I research effort to identify the critical flare rates for an AGT installation [3].

2 INITIAL BARRIER MODEL

An 81-ft 8¼-in. (24.9-m) long AGT LS-DYNA finite element analysis model was developed and validated against a full-scale crash test previously conducted by the Midwest Roadside Safety Facility (MwRSF) [1]. The physical and modeled tangent AGT installations are shown in Figures 1 and 2, respectively. The model was developed using LS-DYNA Version 10.1 [4]. Several model versions were created during the validation process, with updates to post and guardrail geometries, as well as the soil and post material properties. Each model consisted of several components, including the upstream system anchorage, soil model, guardrail posts, W-beam guardrail, thrie-beam guardrail, and the standardized concrete buttress. The final validated AGT model and material properties are detailed in Chapter 7.

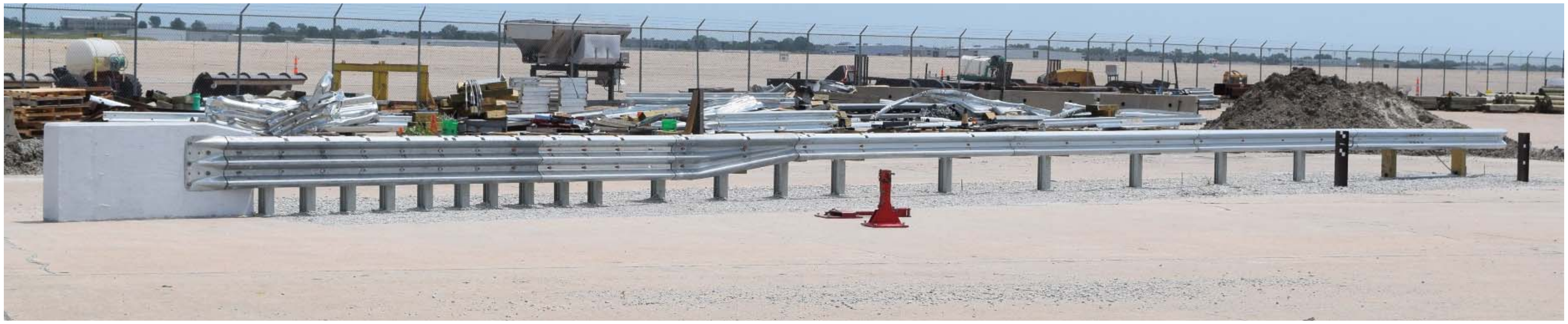


Figure 1. AGTB-2 Guardrail Installation

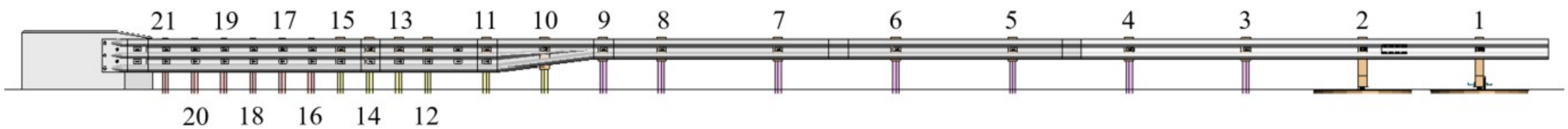


Figure 2. Finite Element Model of AGTB-2 Guardrail Installation

2.1 Upstream Anchorage

The upstream end of the AGT was modeled after the MGS downstream anchorage [5-7]. The anchorage consisted of two timber breakaway cable terminal (BCT) posts embedded in solid Drucker-Prager soil elements, a groundline strut spanning post nos. 1 and 2, a cable anchor bracket attached to the backside of the W-beam rail, a cable anchor spanning from the cable anchor bracket through the groundline hole in post no. 1, and an anchor bearing plate. The calibration of the material parameters for the anchorage components, including the failure of the BCT posts and resistance of the anchorage system, was based on a series of dynamic component tests performed at MwRSF [5]. The upstream anchorage assembly is shown in Figure 3. Each of the anchorage components were composed of multiple systems, including the bolted connections between parts.

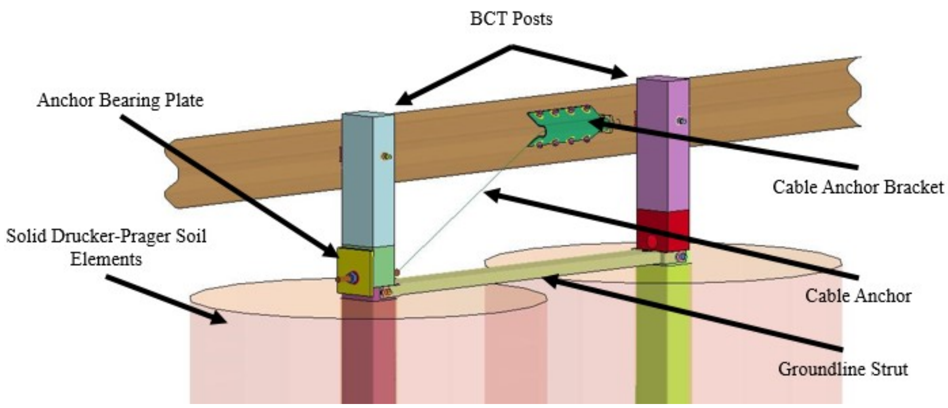


Figure 3. Upstream AGT Anchorage

The timber BCT posts were modeled with type 2 (fully integrated S/R) solid elements given a *MAT_PLASTIC_KINEMATIC material formulation. As shown in Figure 4, the region near the groundline of BCT post nos. 1 and 2 was modeled as a separate part. These regions of the BCT posts near the groundline had a plastic failure strain defined and were modeled with type 3 (fully integrated quadratic 8-node element with nodal rotations) solid elements given a *MAT_ISOTROPIC_ELASTIC_FAILURE material formulation.

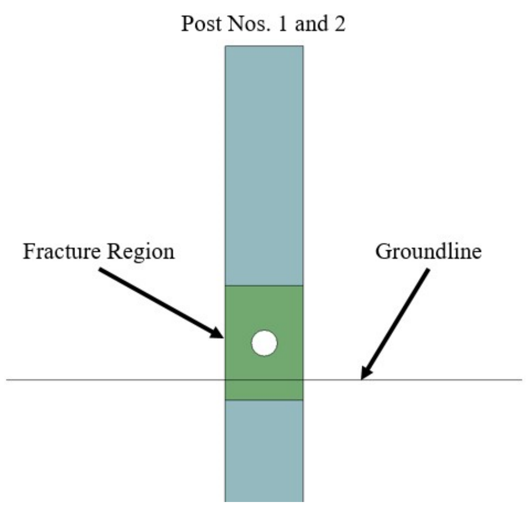


Figure 4. BCT Post Nos. 1 and 2

2.2 Soil Model

The soil for post nos. 3 through 21 was modeled with a rigid soil tube around the base of each post with a pair of soil springs attached to the top of the soil tube in the lateral and longitudinal directions, as shown in Figure 5. The soil tubes were pinned at their center of gravity, which allowed rotation. The soil springs simulated the reaction of the soil on the posts and were used for improved computational efficiency over solid soil elements.

The soil springs were assigned a loading curve that modeled the soil resistance used in full-scale crash tests at MwRSF. To calibrate the soil spring loading curve, dynamic bogie testing on a steel W6x16 pile embedded in *Manual for Assessing Safety Hardware 2016* (MASH 2016) [8] compliant soil was conducted under a previous research study to quantify the soil force-deflection behavior [9]. Note that the modeled soil spring configuration applied load individually to each post, and did not account for the combined soil loading, due to the close proximity of the posts, that occurred in full-scale testing. Post nos. 1 and 2 were embedded into solid Drucker-Prager soil elements, which offered a more accurate representation of soil deformation.

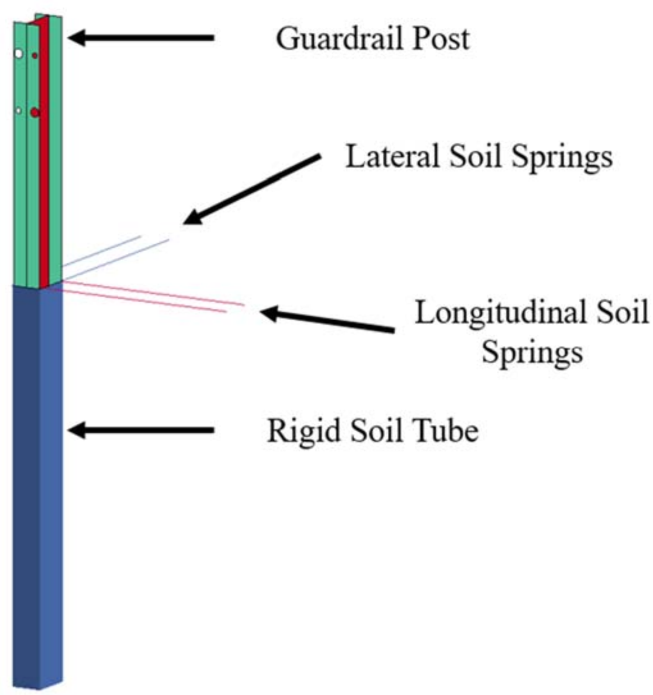


Figure 5. Guardrail Post with Soil Tube and Soil Springs

2.3 Steel Guardrail Posts and Timber Blockouts

Post nos. 3 through 21 were steel guardrail posts, initially modeled as W6x9 posts with a yield stress of 47 ksi (324 MPa). The steel guardrail posts were modeled with type 16 (fully integrated) shell elements given a *MAT_PIECEWISE_LINEAR_PLASTICITY material formulation. As shown in Figure 6, the post spacing was 75 in. (1,905 mm), 37½ in. (953 mm), and 18¾ in. (476 mm) between post nos. 1 through 8, post nos. 8 through 12, and post nos. 12 through 21, respectively.

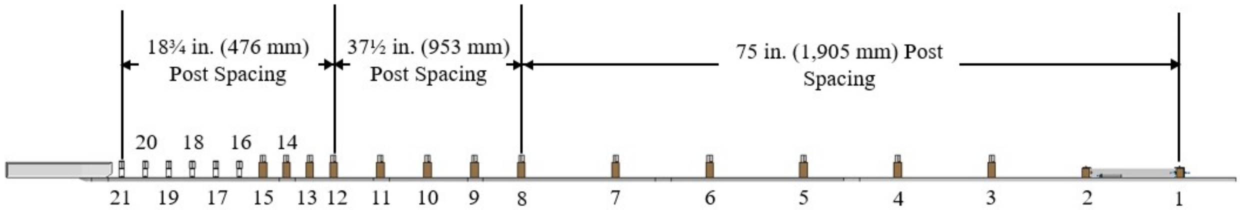


Figure 6. AGT Model Post Spacing

Timber blockouts, with dimensions of 12 in. x 6 in. x 14¼ in. (305 mm x 152 mm x 362 mm) were modeled between the W-beam guardrail and post nos. 3 through 9. Timber blockouts, with dimensions of 12 in. x 6 in. x 19 in. (305 mm x 152 mm x 483 mm) were modeled between the asymmetric W-to-thrie transition section and the thrie-beam guardrail and post nos. 10 through 15. Both sizes of timber blockouts were modeled with type 2 (fully integrated S/R) solid elements and were given a *MAT_ELASTIC material property. As shown in Figure 7, HSS 7-in. x 4-in. x $^{3}/_{16}$–in. x 17 ½-in. tall (178-mm x 102-mm x 5-mm x 445-mm tall) steel blockouts were modeled between the thrie-beam guardrail and post nos. 16 through 21. The steel blockouts were modeled with type 16 (fully integrated) shell elements and given a *MAT_PIECEWISE_LINEAR_PLASTICITY material formulation.

The posts, blockouts, and guardrail were connected via modeled bolted connections. The guardrail bolts and nuts were modeled with type 2 (fully integrated S/R) solid elements and were given a *MAT_RIGID material property. Discrete nonlinear spring elements connected the guardrail bolts and nuts and provided preload in the bolted connection.

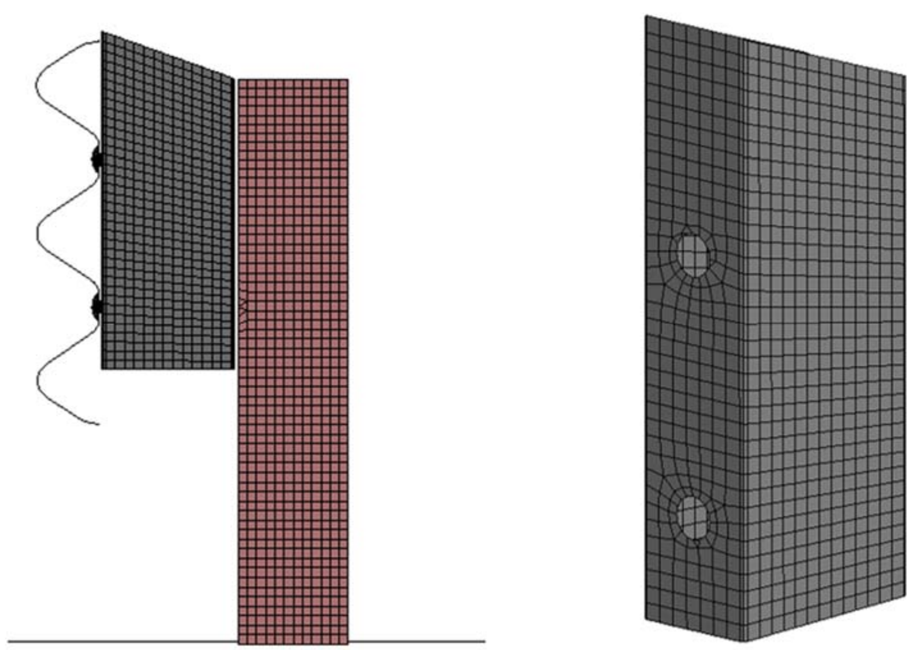


Figure 7. Steel Blockout, Post Nos. 16 Through 21

2.4 Guardrail

The upstream portion of the AGT installation used 12-gauge (2.7-mm) W-beam guardrail with a top rail height of 31 in. (787 mm). The system transitioned from W-beam to standard thrie-beam guardrail with a 10-gauge (3.4-mm) asymmetrical W-to-thrie transition section, which maintained the 31-in. (787-mm) top rail height. A 6-ft 3-in. (1,905-mm) long single section of 12-gauge (2.7-mm) thrie-beam was attached to the downstream end of the asymmetric W-to-thrie transition section. A 12-ft 6-in. (3,810-mm) long section of nested thrie-beam guardrail composed the final guardrail section and was anchored to the standardized concrete buttress located at the downstream end of the installation with a thrie-beam terminal connector.

All guardrail sections were modeled with type 16 (Fully Integrated) shell elements and given a *MAT_PIECEWISE_LINEAR_PLASTICITY material formulation with no failure defined. The approximate element size was 0.37 in. x 0.97 in. (9 mm x 25 mm) with a finer mesh of approximately 0.25 in. (6 mm) around the bolt holes in the guardrail. The initial nested thrie-beam section was modeled with two overlaid 12-gauge (2.7-mm) thrie-beam sections which occupied the same model space and had merged nodes. The bolted splice connections between each section of guardrail were not explicitly modeled. Instead, the splice connections were modeled through overlapped elements. Therefore, the splice connections were not modeled with any tolerances and splice slip could not occur.

The modeled thrie-beam terminal connector anchored the thrie-beam guardrail to the traffic-side face of the standardized concrete buttress. The splice connection between the nested thrie-beam section and terminal connector was modeled identically to the other guardrail splice connections, meaning the splice connection was not modeled with any tolerances and splice slip could not occur. The connection between the terminal connector and the buttress was not expected to fail. Accordingly, the five bolts connecting the terminal connector and buttress were not explicitly modeled. The bolt holes located on the terminal connector were modeled as rigid bodies, as shown in Figure 8, and the *CONSTRAINED_RIGID_BODIES keyword was used to constrain the terminal connector to the face of the concrete buttress.

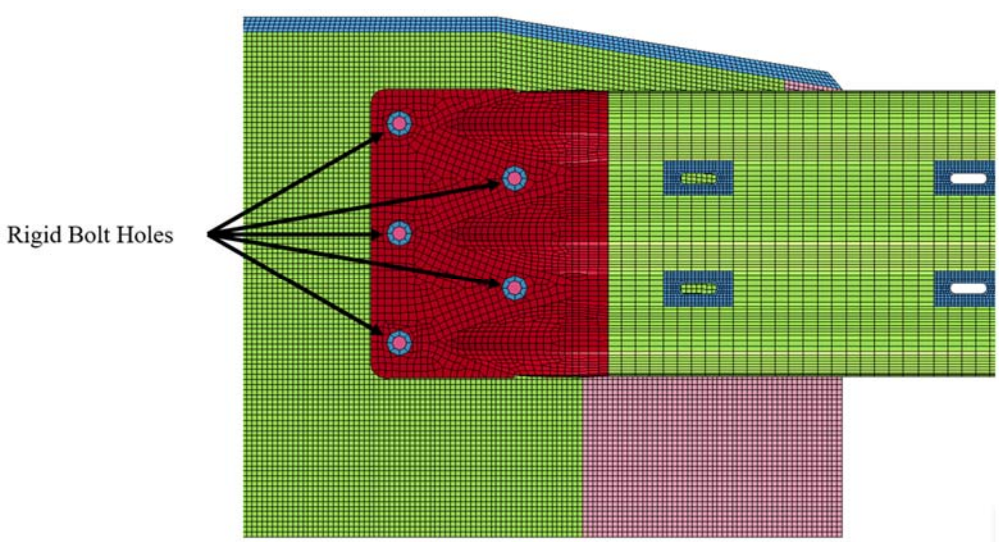


Figure 8. End Terminal Rigid Bolt Hole Connection

2.5 Standardized Concrete Buttress

The standardized concrete buttress was modeled with type 2 (Belytschko-Tsay) shell elements and given a *MAT_RIGID material formulation. The modeled buttress was fully constrained from displacements and rotations in the x, y, and z directions, and therefore, did not experience movement during simulations. The standardized concrete buttress design had an overall height of 36 in. (914 mm) and included an 18-in. long x 4½-in. wide x 14-in. tall (457-mm x 114-mm x 356-mm) chamfer on the upstream, traffic-side corner, which reduced the potential for wheel snag. An additional 3-in. x 4-in. (76-mm x 102-mm) chamfer extended along the remaining height of the upstream, traffic-side corner of the buttress. The buttress also included a 24-in. long x 4-in. tall (610-mm long x 102-mm tall) taper at the upstream top face and all top edges were chamfered by 1 in. (25 mm). The modeled standardized concrete buttress is shown in Figure 9.

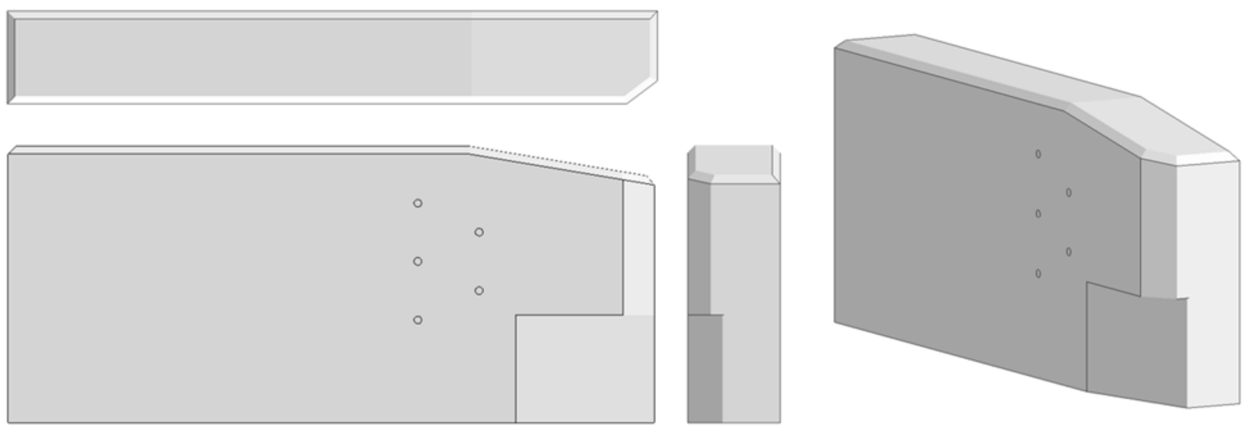


Figure 9. Standardized Concrete Buttress

3 VEHICLE MODELS

The simulation study used two different 2270P pickup truck vehicle models. Initially, the reduced-element 2270P Chevrolet Silverado pickup truck model, originally developed by the National Crash Analysis Center at George Washington University [10], was used to simulate impacts with the modeled AGT installation. During the development of the AGT model, researchers obtained a vehicle model of a 2018 Dodge Ram pickup truck. The Ram vehicle model was originally developed by the Center for Collision Safety and Analysis Team at George Mason University, and was modified by MwRSF personnel for use in roadside safety applications [11]. The 2007 Chevrolet Silverado and 2018 Dodge Ram vehicle models are shown in Figures 10 and 11, respectively.

The Ram vehicle model simulations were better correlated with the full-scale crash test metrics (occupant risk and system behavior) than the Silverado vehicle model simulations. In addition, the Ram model had geometric and structural similarities to the physical test vehicle, a 2010 Ram 1500 crew cab pickup truck. As a result, the Ram vehicle model was utilized in the final simulations of the modeled AGT installation.

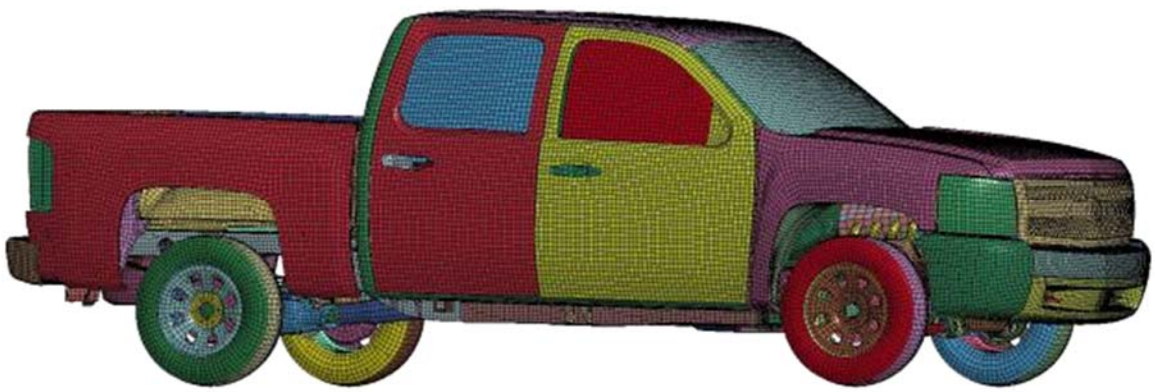


Figure 10. Reduced 2007 Chevrolet Silverado Finite Element Model

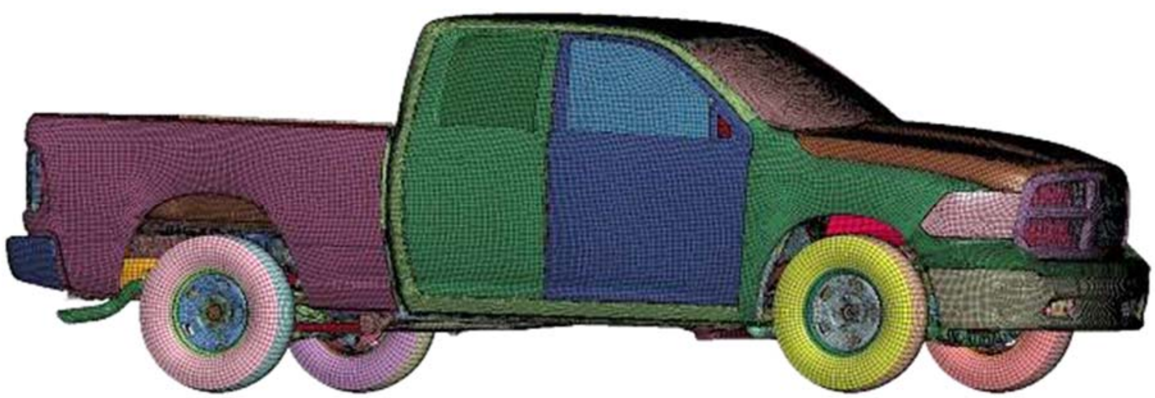


Figure 11. 2018 Dodge Ram Finite Element Model

4 MODEL VALIDATION PROCESS

The modeled AGT system with standardized concrete buttress was validated against the data from full-scale test no. AGTB-2. In test no. AGTB-2 a 4,998-lb (2,267-kg) 2010 Dodge Ram 1500 crew cab pickup truck impacted the AGT system at a speed of 62.7 mph (100.8 km/h) and at an angle of 25.4 degrees. The barrier system successfully contained and redirected the vehicle with a maximum lateral dynamic deflection of 5.4 in. (136 mm) located at post no. 19. Damage to the test installation was minimal, primarily consisting of contact marks and minor guardrail deformation. All occupant risk criteria were met as shown in Table 1, and test no. AGTB-2 was determined to be acceptable according to the MASH Test Level 3 (TL-3) safety performance criteria for test designation no. 3-21 [1].

Table 1. Summary of OIV, ORA, and Angular Displacement Values, Test No. AGTB-2

Evaluation Criteria		AGTB-2	MASH Limits
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	±40 (12.2)
	Lateral	-24.61 (-7.50)	±40 (12.2)
ORA g's	Longitudinal	-7.06	±20.49
	Lateral	-10.40	±20.49
Maximum Angular Displacement deg.	Roll	21.3	±75
	Pitch	-6.3	±75
	Yaw	-39.6	not required

The AGT model was validated using the procedures for V&V of computer simulations used for roadside safety applications outlined in NCHRP Report No. W179 [2]. To validate the AGT model, several parameters were examined, including maximum dynamic deflections, Euler angles, occupant impact velocities (OIVs), occupant ridedown accelerations (ORAs), exit conditions, and vehicle length of contact. The occupant risk factors, including OIV and ORA, were calculated for each simulation utilizing the data from the local accelerometer node at the vehicle's center of gravity and were processed using similar procedures for processing MASH full-scale crash test data.

As part of the validation process, several updates were made to the initial model in an effort to improve the correlation between the full-scale and modeled test results. The updates included changes to component dimensions, soil resistance, vehicle suspension failure, material properties, impact velocity, and vehicle model. The AGT models and results throughout the validation process are summarized in the following sections.

4.1 Initial Model

Simulation no. agt-v3r-v8 of test no. AGTB-2 used the reduced-element, 2270P Chevrolet Silverado pickup truck model. The 5,005-lb (2270-kg) vehicle model impacted the modeled AGT system at a speed of 62.1 mph (100.0 km/h) and at an angle of 25 degrees. Sequential images of the full-scale testing results and LS-DYNA simulation are shown in Figure 12, and a summary of results is shown in Table 2.

In simulation no. agt-v3r-v8, the maximum post dynamic deflection was 1.26 in. (32 mm) higher than the measured maximum post dynamic deflection in test no. AGTB-2. The simulated maximum roll and yaw were higher and the simulated maximum pitch was lower when compared to test no. AGTB-2. The simulated OIV and ORA values in both the longitudinal and lateral directions were higher than the full-scale test, with a maximum difference of 8.23 g's between the simulated and actual values of the longitudinal ORA. The large discrepancies between the simulation and the full-scale test prevented the validation of the model and led to further examination of both the model and the full-scale test.

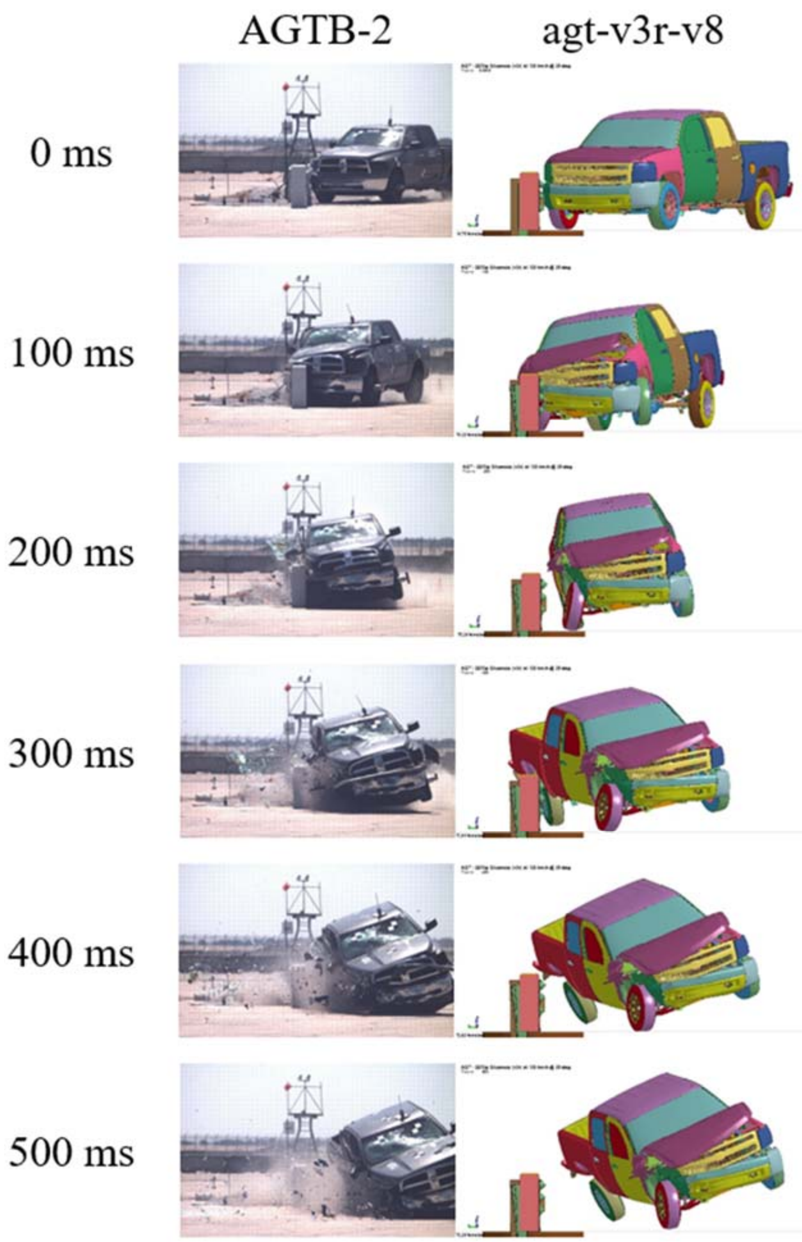


Figure 12. Sequential Images, Test No. AGTB-2 and Simulation No. agt-v3r-v8

Table 2. Summary of Test No. AGTB-2 and Simulation No. agt-v3r-v8

Evaluation Criteria		AGTB-2	agt-v3r-v8
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-28.83 (-8.79)
	Lateral	24.61 (7.50)	25.87 (7.88)
ORA g's	Longitudinal	-7.06	-15.29
	Lateral	10.40	14.70
Maximum Angular Displacement deg.	Roll	21.3	25.6
	Pitch	6.3	5.0
	Yaw	39.6	43.5
Post Max. Dynamic Deflection in. (mm)		5.35 (136)	6.61 (168)
Length of Contact in. (mm)		159 (4,039)	126 (3,200)

During test no. AGTB-2, the right-front suspension failed, which led to the detachment of the right-front wheel shortly after impact. The initial simulation no. agt-v3r-v8 did not account for the detachment of the right-front wheel. It is possible that the wheel detachment could have caused the discrepancies between the full-scale test and simulation no. agt-v3r-v8. As a result, additional simulations were run which simulated the detachment of the right-front wheel on the modeled 2270P Silverado pickup truck.

4.2 Suspension Failure Models

In test no. AGTB-2 the right-front suspension failed which led to the disengagement of the right-front wheel during the impact event. Analysis of the high-speed digital video from the test revealed that the cameras did not capture the failure event. It was not possible to determine the failure sequence of the suspension components, or the precise moment of wheel disengagement. As a result, three different versions of suspension failure were simulated, each with a different time and sequence of component failure. In each of the suspension failure simulations, the model remained unchanged from the initial simulation except for the addition of the suspension component failures to the 2270P Chevrolet Silverado pickup truck model.

To model the suspension failure and detachment of the right front wheel, the upper control arm, lower control arm, and steering arm joints, shown in Figure 13, were separated at a specified time. The naming convention of each of the three suspension failure models describes the sequence and time of suspension component failures. For example, in the model no. agt-v3r-v8—sf-l50-s60-u80, the lower control arm fails at 50 ms, the steering arm fails at 60 ms, and the upper control arm fails at 80ms after the start of the simulation.

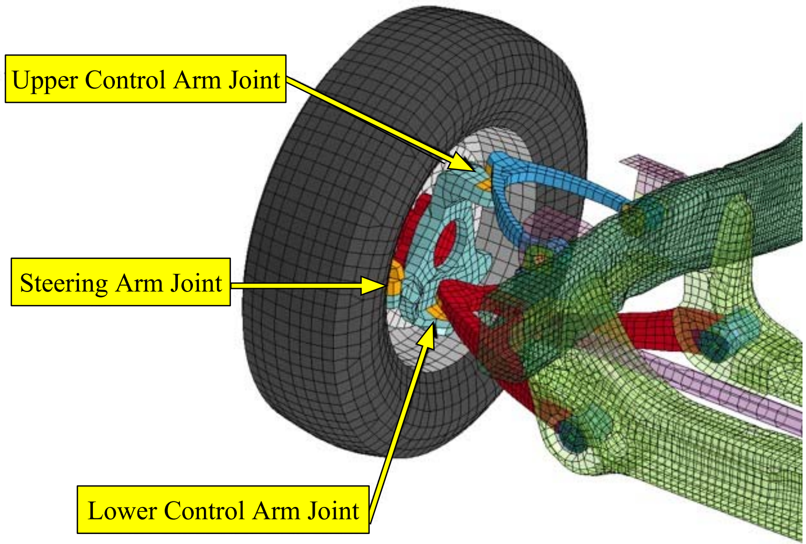


Figure 13. Silverado Vehicle Model Right-Front Suspension Joints

Simulation nos. agt-v3r-v8—sf-l50-s60-u80, agt-v3r-v8—sf-s20-l40-u50, and agt-v3r-v8—sf-s20-u40-l50 used the reduced-element, 2270P Chevrolet Silverado pickup truck model. In all three simulations, the 5,005 lb (2270 kg) vehicle model impacted the modeled AGT system at a speed of 62.1 mph (100.0 km/h) and an angle of 25 degrees. Sequential images of the full-scale testing results and LS-DYNA simulations are shown in Figure 14, and a summary of results is shown in Table 3.

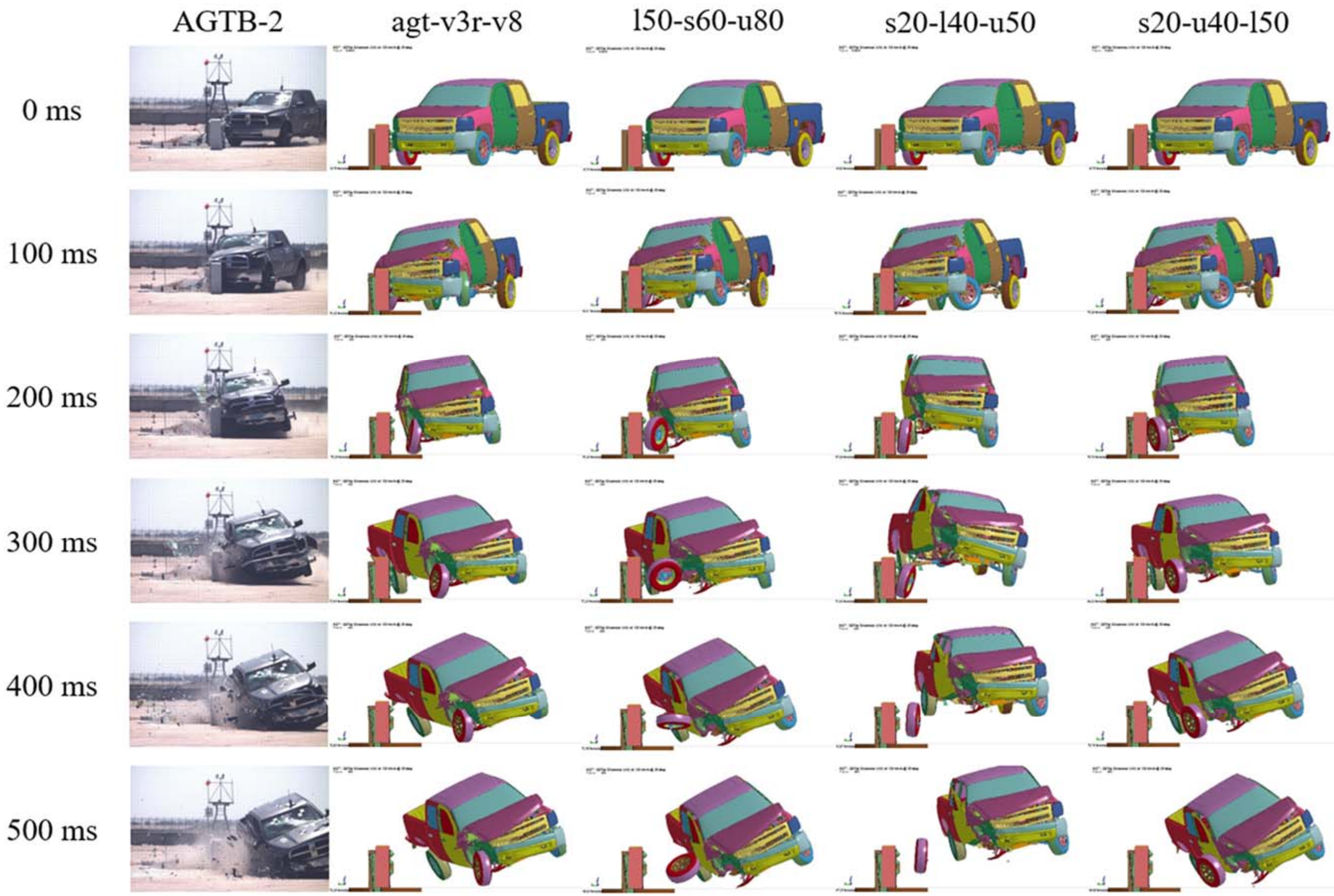


Figure 14. Sequential Images, Test No. AGTB-2, Simulation No. agt-v3r-v8, and Suspension Failure Simulation

Table 3. Summary of Test No. AGTB-2 and Simulation Nos. agt-v3r-v8, agt-v3r-v8—sf-l50-s60-u80, agt-v3r-v8—sf-s20-l40-u50, and agt-v3r-v8—sf-s20-u40-l50

Evaluation Criteria		AGTB-2	agt-v3r-v8	agt-v3r-v8-sf-l50-s60-u80	agt-v3r-v8-sf-s20-l40-u50	agt-v3r-v8-sf-s20-u40-l50
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-28.83 (-8.79)	-26.12 (-7.96)	-26.01 (-7.93)	-25.49 (-7.77)
	Lateral	24.61 (7.50)	25.87 (7.88)	26.07 (7.95)	25.01 (7.62)	24.99 (7.62)
ORA (g's)	Longitudinal	-7.06	-15.29	-13.89	-10.87	-11.22
	Lateral	10.40	14.70	12.82	13.60	12.71
Maximum Angular Displacement (deg.)	Roll	21.3	25.6	28.7	14.7	31.5
	Pitch	6.3	5.0	7.2	-6.5	4.4
	Yaw	39.6	43.5	39.2	38.5	40.2
Post Max. Dynamic Deflection in. (mm)		5.35 (136)	6.61 (168)	5.98 (152)	5.94 (151)	5.79 (147)
Length of Contact in. (mm)		159 (4,039)	126 (3,200)	126 (3,209)	114 (2,892)	123 (3,130)

All three of the suspension failure models over-deflected when compared with full-scale test no. AGTB-2. The dynamic behavior of the vehicle changed significantly when the suspension failure sequences and times were altered. As a result the simulated maximum roll, pitch, and yaw for the three suspension failure models varied. The simulated OIV and ORA values in both the longitudinal and lateral directions were higher than the full-scale test. However, all three suspension failure models exhibited an improved OIV and ORA correlation with full-scale test no. AGTB-2. The suspension failure models reduced the discrepancies between the maximum post dynamic deflections and occupant risk values to more closely match the full-scale test. Despite the improvement, the discrepancies between the suspension failure simulations and the full-scale test remained too large and prevented the validation of the model.

In all four of the previous simulations, the dynamic deflections of both the posts and guardrail were larger than the measured dynamic deflections in full-scale test no. AGTB-2. Due to the greater post and rail deflections, the pocketing angle in all four simulations was larger than the pocketing angle in the full-scale test. A larger pocketing angle would result in larger vehicle decelerations due to greater interaction with the rigid standardized concrete buttress at the downstream end of the system. Further inspection of the modeled guardrail components revealed that the initial models did not accurately represent the guardrail components that were physically tested, likely resulting in larger system deflections.

4.3 Updated Guardrail Dimensions

In model no. agt-v3r-v8 and the subsequent suspension failure models, the thrie-beam terminal connector was modeled with a 12-gauge (2.7-mm) thickness. However, in full-scale test no. AGTB-2 the thrie-beam terminal connector had a 10-gauge (3.4-mm) thickness. To more accurately represent the physically tested system, the modeled thrie-beam terminal connector thickness was increased from 12 gauge (2.7 mm) to 10 gauge (3.4 mm) in all future simulations.

Additionally, in the previous models the section of nested thrie-beam had been modeled by overlaying two 12-gauge (2.7-mm) thrie-beam guardrails, meaning the two thrie-beam guardrails occupied the same space. This matched the two 12-gauge (2.7-mm) thrie-beam sections used in the physical test installation, but did not model the proper rail strength due to the absence of the added thickness and space that occurs between the two rail sections when physically nesting guardrail. Therefore, in the previous simulations, the nested section of thrie-beam guardrail was likely weaker than in the full-scale test.

In an effort to reduce the complexity of modeling two separate thrie-beam guardrail sections yet correctly represent the tested guardrail strength, a single thrie-beam guardrail of increased thickness replaced the nested section of thrie-beam guardrail in future simulations.

Three simulations were run that included the updated guardrail dimensions. Due to the significant difference in dynamic behavior that occurred between the three suspension failure models, all changes were made to the original model, no. agt-v3r-v8, without the addition of the suspension failure. In all three simulations, model no. agt-v3r-v8 was updated to include the 10-gauge (3.4-mm) thrie-beam terminal connector. Simulation no. agt-v3r-v9-10ga-endshoe had no further modifications. In simulation nos. agt-v3r-v10-single-thrie and agt-v3r-v11-single-thrie, the nested thrie-beam section was replaced with a single thrie-beam section with a thickness of 0.14 in. (3.4 mm) and 0.21 in. (5.3 mm), respectively.

Simulation nos. agt-v3r-v9-10ga-endshoe, agt-v3r-v10-single-thrie, and agt-v3r-v11-single-thrie used the reduced-element, 2270P Chevrolet Silverado pickup truck model. The 5,005-lb (2270-kg) vehicle model impacted the modeled AGT system at a speed of 62.1 mph (100.0 km/h) and an angle of 25 degrees in all three simulations. Sequential images of the full scale testing results and LS-DYNA simulations are shown in Figure 15, and a summary of results is shown in Table 4.

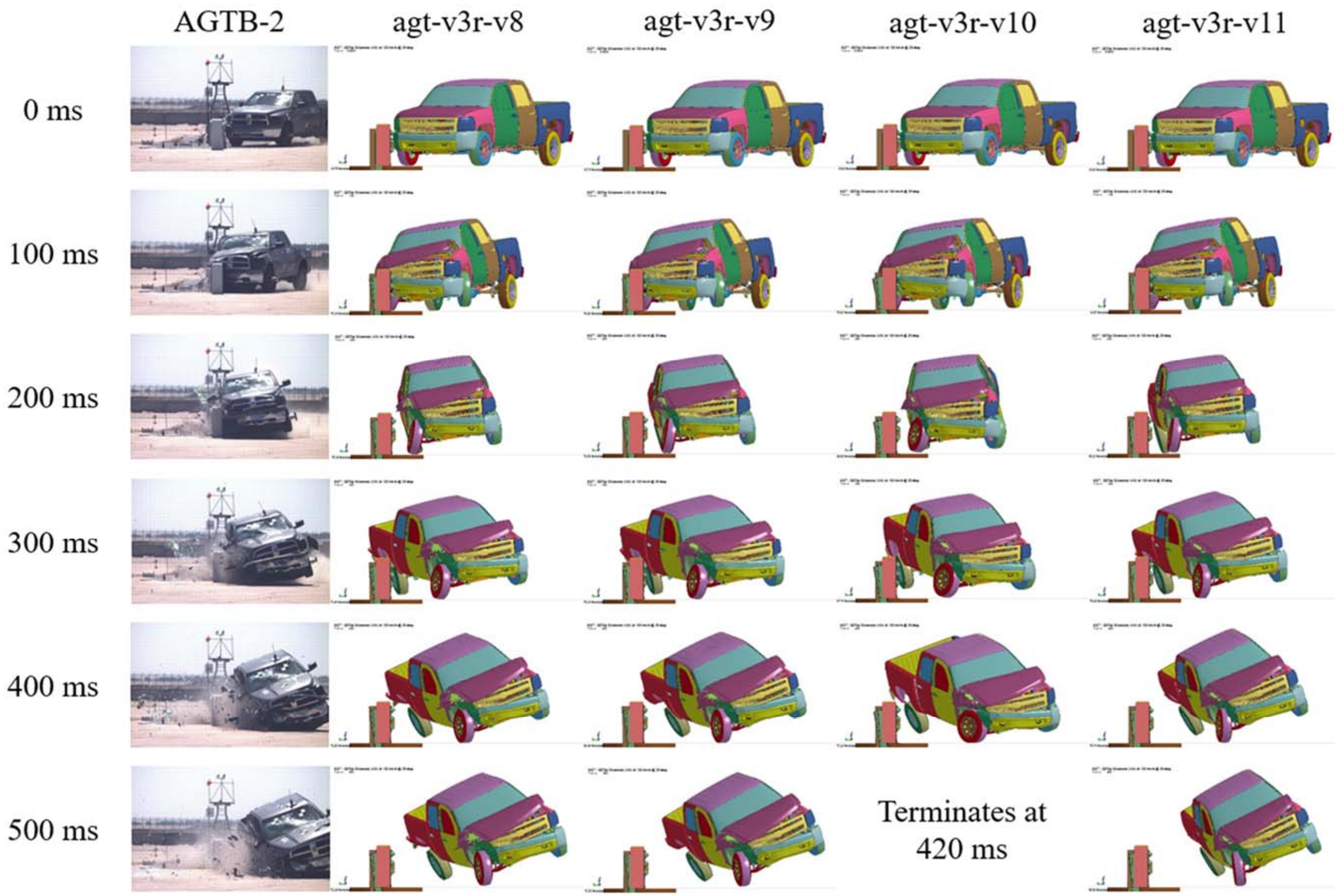


Figure 15. Sequential Images, Test No. AGTB-2, Simulation No. agt-v3r-v8, and Updated Guardrail Dimension Simulation

Table 4. Summary of Test No. AGTB-2 and Simulation Nos. agt-v3r-v8, agt-v3r-v9-10ga-endshoe, agt-v3r-v10-single-thrie, and agt-v3r-v11-single-thrie

Evaluation Criteria		AGTB-2	agt-v3r-v8	agt-v3r-v9-10ga-endshoe	agt-v3r-v10-single-thrie	agt-v3r-v11-single-thrie
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-28.83 (-8.79)	-29.19 (-8.90)	-31.68 (-9.66)	-27.47 (-8.37)
	Lateral	24.61 (7.50)	25.87 (7.88)	25.93 (7.90)	24.17 (7.37)	26.93 (8.21)
ORA g's	Longitudinal	-7.06	-15.29	-13.92	-21.26	-11.61
	Lateral	10.40	14.70	13.96	13.66	13.32
Maximum Angular Displacement deg.	Roll	21.3	25.6	28.3	17.7	28.6
	Pitch	6.3	5.0	5.4	7.8	5.3
	Yaw	39.6	43.5	44.0	47.0	41.1
Post Max. Dynamic Deflection in. (mm)		5.35 (136)	6.61 (168)	6.46 (164)	7.83 (199)	5.83 (148)
Length of Contact in. (mm)		159 (4,039)	126 (3,200)	127 (3,227)	131 (3,315)	128 (3,262)

All three of the updated guardrail dimension simulations over-deflected when compared to the full-scale test. Simulation no. agt-v3r-v11-single-thrie exhibited the best correlation with a peak deflection of 5.83 in. (148 mm). The simulated maximum roll, pitch, and yaw for the three updated rail dimension models varied in agreement with test no. AGTB-2. Simulation no. agt-v3r-v9-10ga-endshoe offered marginal improvements to the maximum post dynamic deflection as well as ORA values, but exhibited greater OIV values in both the lateral and longitudinal directions when compared to the initial simulation no. agt-v3r-v8.

In simulation no. agt-v3r-v10-single-thrie, the maximum post dynamic deflection was higher than the maximum post dynamic deflections in the other simulations and the full-scale test. The larger test installation deflections in simulation no. agt-v3r-v10-single-thrie resulted from the replacement of the overlaid 12-gauge (2.7-mm) thrie-beam sections with a single section of 0.14-in. (3.4-mm) thick thrie-beam. The reduction in guardrail strength resulted in larger deflections and longitudinal ORA and OIV values.

Of the updated guardrail dimension simulations, simulation no. agt-v3r-v11-single-thrie exhibited the most improvement, with the closest maximum post dynamic deflection and lateral and longitudinal ORA values to the full-scale test results. The greater rail and thrie-beam terminal connector thickness reduced the dynamic deflection and pocketing angle of the system, which resulted in lower ORA values. However, the discrepancies between the updated rail dimension simulations and the full-scale test remained significant and prevented the validation of the model.

Despite improvements, the discrepancies between the updated guardrail dimension simulations and the full-scale test persisted and additional updates were made in an effort to further improve the model. Further inspection of the modeled guardrail components revealed that the previous models did not accurately represent the correct embedment depths of the physically tested steel guardrail posts in the transition region.

4.4 Updated Soil Curve Models I

In all of the AGT models, the soil for post nos. 3 through 21 was modeled by encasing each post in a rigid soil tube that is attached to four soil springs (two fixed in the lateral direction and two fixed in the longitudinal direction). The soil forces applied to the guardrail posts can be calibrated to an individual post's dimension and embedment depth by adjusting the loading curve which controls the stiffness of the soil springs.

In full-scale test no. AGTB-2, post nos. 3 through 15 were embedded into the soil at a depth of 40 in. (1,016 mm) and post nos. 16 through 21 were embedded into the soil at a depth of 49 in. (1,245 mm). However, in all previous models of the AGT test installation, soil springs at all posts had been calibrated to simulate the soil resistance at an embedment depth of 40 in. (1,016 mm). Since the posts in the transition region had an actual embedment depth of 49 in. (1,245 mm), the soil model for these posts was too weak. The soil model was adjusted for post nos. 16 through 21 by following the procedures outlined in MASH 2016. This resulted in scaling the soil spring curves for post nos. 16 through 21 by a factor of 1.5 to adjust for the greater embedment depth [8].

Two simulations, nos. agt-v3r-v12-single-thrie and agt-v3r-v13-single-thrie, were run using the updated soil model. The simulations remained identical to those run in simulation nos. agt-v3r-v10-single-thrie and agt-v3r-v11-single-thrie, but added the updated soil model to post nos. 16 through 21. Thus, simulation no. agt-v3r-v12-single-thrie (based on agt-v3r-v10-single-thrie) included the 10-gauge (3.4-mm) thrie-beam terminal connector and 0.14-in. (3.4-mm) thick single thrie-beam guardrail for the nested guardrail section, and simulation no. agt-v3r-v13-single-thrie (based on agt-v3r-v11-single-thrie) included the 10-gauge (3.4-mm) thrie-beam terminal connector and 0.21-in. (5.3-mm) thick single thrie-beam guardrail for the nested guardrail section.

Simulation nos. agt-v3r-v12-single-thrie and agt-v3r-v13-single-thrie used the reduced-element, 2270P Chevrolet Silverado pickup truck model. The 5,005-lb (2270-kg) vehicle model impacted the modeled AGT system at a speed of 62.1 mph (100.0 km/h) and at an angle of 25 degrees in both simulations. Sequential images of the full-scale test and LS-DYNA simulations are shown in Figure 16, and a summary of results is shown in Table 5.

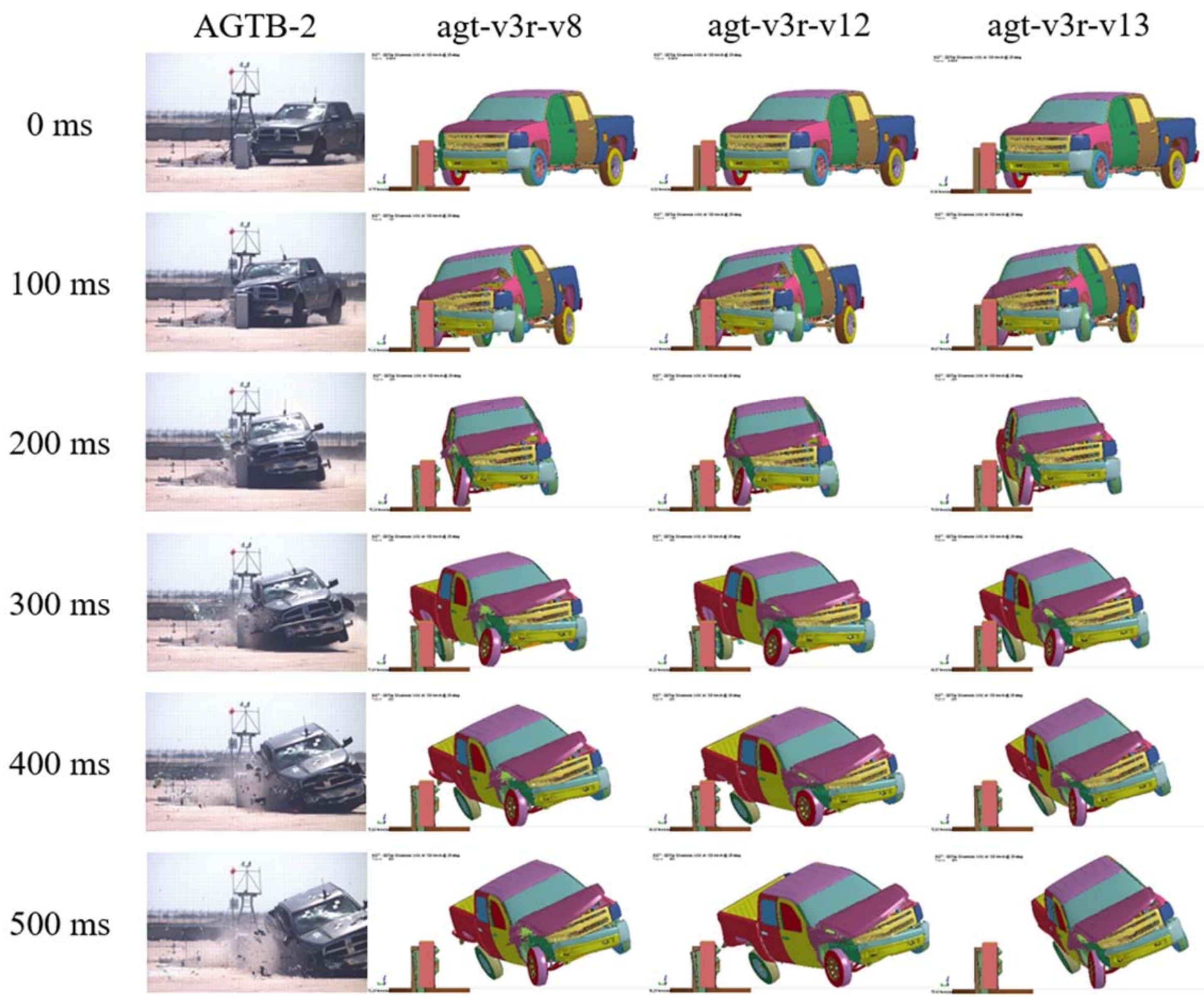


Figure 16.Sequential Images, Test No. AGTB-2, Simulation No. agt-v3r-v8, and Updated Soil Curve I Simulation

Table 5. Summary of Test No. AGTB-2 and Simulation Nos. agt-v3r-v8, agt-v3r-v12-single-thrie, and agt-v3r-v13-single-thrie

Evaluation Criteria		AGTB-2	agt-v3r-v8	agt-v3r-v12-single-thrie	agt-v3r-v13-single-thrie
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-28.83 (-8.79)	-31.21 (-9.51)	-26.95 (-8.21)
	Lateral	24.61 (7.50)	25.87 (7.88)	24.30 (7.41)	26.73 (8.15)
ORA g's	Longitudinal	-7.06	-15.29	-17.43	-10.87
	Lateral	10.40	14.70	15.42	11.82
Maximum Angular Displacement deg.	Roll	21.3	25.6	26.7	29.3
	Pitch	6.3	5.0	5.7	6.4
	Yaw	39.6	43.5	51.3	40.1
Post Max. Dynamic Deflection in. (mm)		5.35 (136)	6.61 (168)	7.99 (203)	5.35 (136)
Length of Contact in. (mm)		159 (4,039)	126 (3,200)	132 (3,341)	128 (3,253)

Simulation no. agt-v3r-v12-single-thrie deflected too much and exhibited much larger OIV and ORA values than the full-scale test and displayed mixed improvement when compared to simulation no. agt-v3r-v10-single-thrie. The single 0.14-in. (3.43-mm) thick thrie-beam guardrail section continued to enable larger barrier deflections and exhibited greater ORA values than the full-scale test.

The maximum post dynamic deflection in simulation no. agt-v3r-v13-single-thrie was equal to the maximum post dynamic deflection in test no. AGTB-2. The simulated maximum pitch and yaw angles for simulation no. agt-v3r-v13-single-thrie closely correlated to the full-scale test values, but the maximum roll angle was 8.04 degrees larger than the full-scale test maximum roll angle value. The simulated OIV and ORA values in simulation no. agt-v3r-v13-single-thrie remained higher than the full-scale test, but showed improvement over the initial simulation no. agt-v3r-v8. Simulation no. agt-v3r-v13-single-thrie also showed improvement in test article deflection, longitudinal and lateral ORA, and longitudinal and lateral OIV when compared to simulation no. agt-v3r-v11-single-thrie, which did not include the soil model updates. Despite improvements, the discrepancies between the updated soil model simulations and the full-scale test persisted and additional updates were made in an effort to further improve the model.

4.5 Updated Soil Curve Models II

Additional updates were made to the modeled soil in an effort to increase the accuracy of the AGT model. The guardrail posts in the full-scale AGT test installation and in the modeled AGT had a width of 6 in. (152 mm). However, in the previous AGT models the longitudinal soil springs modeled a post having a width of approximately 4 in. (102 mm). To resolve the issue, the stiffness of the weak axis soil springs was increased to model a 6-in. post width. In addition, the soil tubes were updated in order to more accurately simulate post rotation.

Component testing has determined that posts embedded in soil rotate about a point located ⅔ of the embedment depth below the ground line [9]. In LS-DYNA, the soil tubes rotate around the center of gravity of the part. Thus, to simulate the proper post rotation, the soil tubes must be the correct length so that the soil tube's center of gravity coincides with the point located at ⅔ of the post embedment depth below the ground line.

The soil springs and soil tubes were updated so that the soil forces were applied 6 in. (152 mm) below the ground line and the posts would rotate at a point ⅔ the embedment depth below the ground line. This was accomplished by translating the springs and soil tubes along the z-axis and adding additional elements to the soil tubes.

Two simulations were run using the updated soil model. Simulation no. agt-v3r-v14-single-thrie used the model from simulation no. agt-v3r-v13-single-thrie, which had a single 0.21-in. (5.3-mm) thick thrie-beam to represent the nested thrie-beam section, and included the updates to the weak axis soil springs and extended the length of the soil tubes. Simulation no. agt-v3r-v15-single-thrie was run with the same model as simulation no. agt-v3r-v14-single-thrie, with the only difference being the impact speed. For simulation no. agt-v3r-v15-single-thrie, the impact speed was increased from 62.1 mph (100.0 km/h) to 62.7 mph (100.8 km/h) to match the impact speed of full-scale test no. AGTB-2.

The reduced-element, 2270P Chevrolet Silverado pickup truck model was utilized during simulation nos. agt-v3r-v14-single-thrie and agt-v3r-v15-single-thrie. The 5,005-lb (2270-kg) vehicle model impacted the modeled AGT system at a speed of 62.1 mph (100.0 km/h) and at an angle of 25 degrees in simulation no. agt-v3r-v14-single-thrie and at a speed of 62.7 mph (100.8 km/h) and at an angle of 25 degrees in simulation no. agt-v3r-v15-single-thrie. Sequential images of the full-scale testing results and LS-DYNA simulations are shown in Figure 17, and a summary of the results is shown in Table 6.

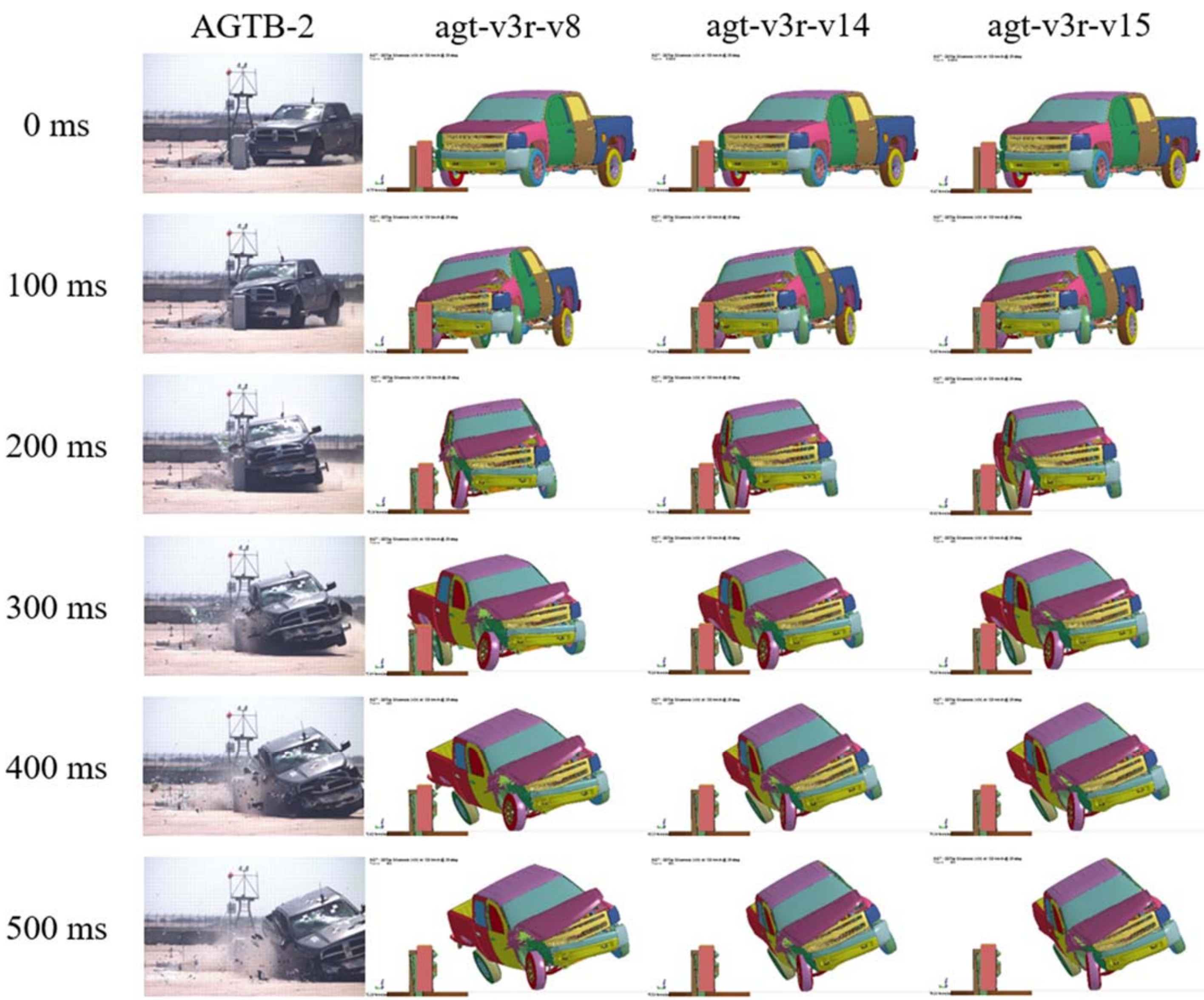


Figure 17. Sequential Images, Test No. AGTB-2, Simulation No. agt-v3r-v8, and Updated Soil Curve II Simulation

Table 6. Summary of Test No. AGTB-2 and Simulation Nos. agt-v3r-v8, agt-v3r-v14-single-thrie, and agt-v3r-v15-single-thrie

Evaluation Criteria		AGTB-2	agt-v3r-v8	agt-v3r-v14-single-thrie	agt-v3r-v15-single-thrie
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-28.83 (-8.79)	-25.68 (-7.83)	-26.34 (-8.03)
	Lateral	24.61 (7.50)	25.87 (7.88)	26.68 (8.13)	26.68 (8.13)
ORA (g's)	Longitudinal	-7.06	-15.29	-8.94	-12.10
	Lateral	10.40	14.70	10.48	11.00
MAX. ANGULAR DISPL. (deg.)	Roll	21.3	25.6	29.6	29.1
	Pitch	6.3	5.0	5.2	6.1
	Yaw	39.6	43.5	38.4	39.4
Post Max. Dynamic Deflection in. (mm)		5.35 (136)	6.61 (168)	4.76 (121)	4.96 (126)
Length of Contact in. (mm)		159 (4,039)	126 (3,200)	118 (2,989)	121 (3,068)

Both simulation no. agt-v3r-v14-single-thrie and simulation no. agt-v3r-v15-single-thrie deflected less than full-scale test no. AGTB-2. The maximum roll angle in both simulation nos. agt-v3r-v14-single-thrie and agt-v3r-v15-single-thrie was significantly higher than the maximum roll of the full-scale test. The maximum pitch and maximum yaw angles were much closer to the values of the full-scale test but did not significantly improve when compared to the values of simulation no. agt-v3r-v13-single-thrie. The OIV and ORA values in simulation nos. agt-v3r-v14-single-thrie and agt-v3r-v15-single-thrie remained higher than the full-scale test values but showed improvement over the initial simulation no. agt-v3r-v8.

Following the conclusion of the analysis for the previous two simulations, simulation no. agt-v3r-v15-single-thrie was identified as the best comparison to the full-scale test, thus far. It was selected to go through the procedures for V&V of computer simulations used for roadside safety applications outlined in NCHRP Report No. W179. The validation is discussed in Section 6.1 and the full V&V comparison is shown in Appendix A. The simulation required exceptions to pass the V&V process and additional updates were made to the model in an effort to further reduce the discrepancies between the model and full-scale test.

4.6 Updated Transition Post Material Properties

In simulation no. agt-v3r-v18-single-thrie, the modeled installation was identical to that of simulation no. agt-v3r-v15-single-thrie, but with two significant changes to the thrie-beam guardrail posts. First, the modeled posts were changed from W6x9 to W6x8.5 to reflect the as-tested post size. Thus, the flange thickness was changed from 0.215 in. (5.46 mm) thick to 0.195 in. (4.95 mm) thick. Second, the yield stress of the transition posts was increased from 47 ksi (324 MPa) to 56 ksi (386 MPa) to match the material certifications for the guardrail posts from the physical test installation.

Simulation no. agt-v3r-v18-single-thrie used the reduced-element, 2270P Chevrolet Silverado pickup truck model. The 5,005-lb (2270-kg) vehicle model impacted the modeled AGT system at a speed of 62.7 mph (100.8 km/h) and at an angle of 25 degrees. Sequential images of the full-scale testing results and LS-DYNA simulations are shown in Figure 18, and a summary of results is shown in Table 7.

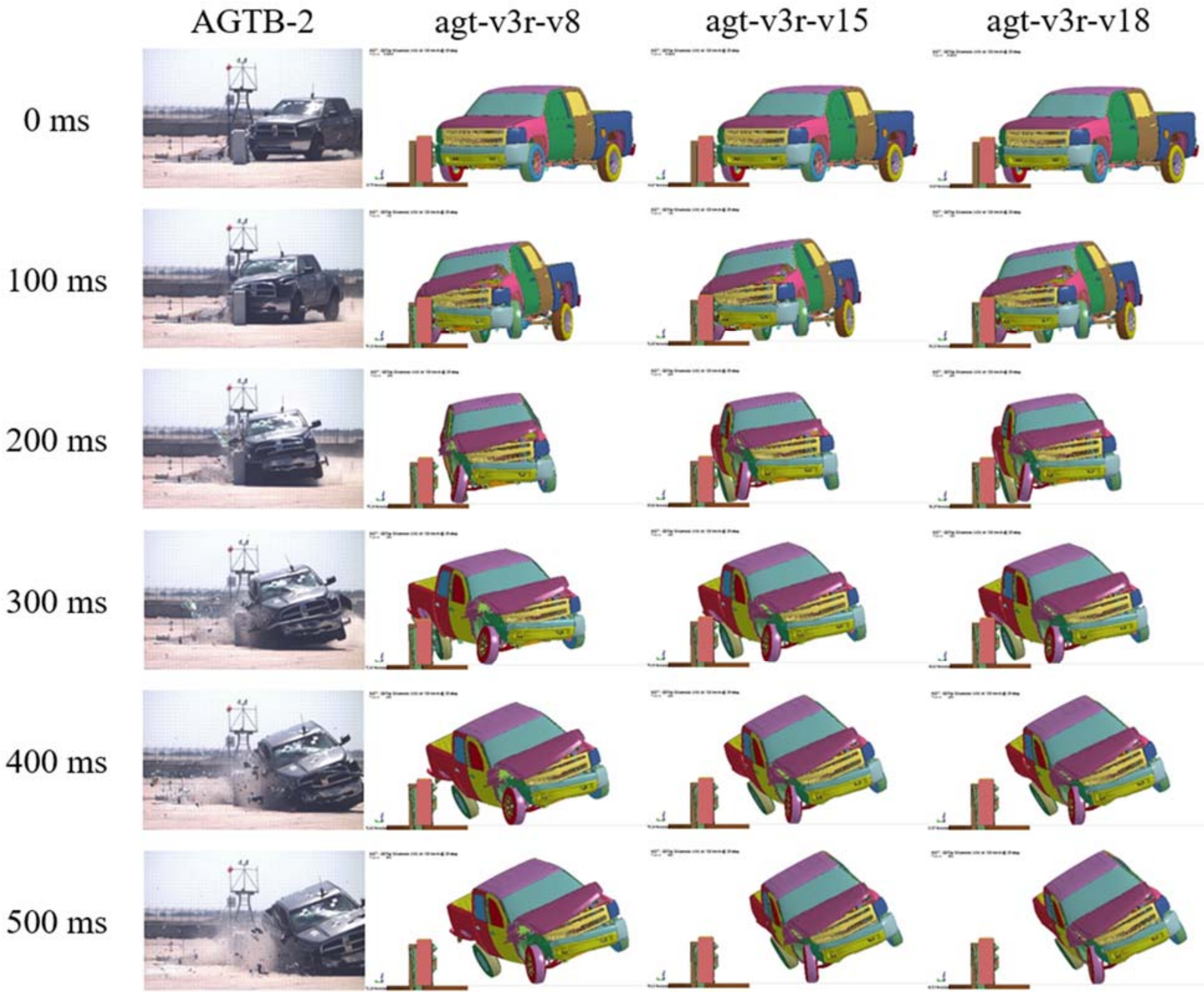


Figure 18. Sequential Images, Test No. AGTB-2, Simulation No. agt-v3r-v8, and Updated Transition Post Simulation

Table 7. Summary of Test No. AGTB-2 and Simulation Nos. agt-v3r-v8, agt-v3r-v15-single-thrie, and agt-v3r-v18-single-thrie.

Evaluation Criteria		AGTB-2	agt-v3r-v8	agt-v3r-v15-single-thrie	agt-v3r-v18-single-thrie
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-28.83 (-8.79)	-26.34 (-8.03)	-27.44 (-8.36)
	Lateral	24.61 (7.50)	25.87 (7.88)	26.68 (8.13)	26.72 (8.14)
ORA g's	Longitudinal	-7.06	-15.29	-12.10	-9.53
	Lateral	10.40	14.70	11.00	12.61
Maximum Angular Displacement deg.	Roll	21.3	25.6	29.1	31.9
	Pitch	6.3	5.0	6.1	6.4
	Yaw	39.6	43.5	39.4	40.2
Post Max. Dynamic Deflection in. (mm)		5.35 (136)	6.61 (168)	4.96 (126)	5.67 (144)
Length of Contact in. (mm)		159 (4,039)	126 (3,200)	121 (3,068)	124 (3,156)

Simulation no. agt-v3r-v18-single-thrie over deflected when compared to the full-scale test but showed minor improvement over simulation nos. agt-v3r-v8 and agt-v3r-v15-single-thrie. Simulation no. agt-v3r-v18-single-thrie also showed improvement over simulation no. agt-v3r-v15-single-thrie in longitudinal ORA. However, simulation no. agt-v3r-v18-single-thrie did not improve the correlation of the lateral ORA and OIV values with the full-scale test when compared to simulation no. agt-v3r-v15-single-thrie. The maximum roll, pitch, and yaw values also did not show significant improvement over simulation no. agt-v3r-v15-single-thrie. However, despite the closer correlation between some of the evaluation parameters of simulation no. agt-v3r-v15-single-thrie and full-scale test no. AGTB-2, simulation no. agt-v3r-v18-single-thrie was identified as the better representation of the full-scale test, as it incorporated all of the model updates included in simulation no. agt-v3r-v15-single-thrie with the addition of the updates to the post dimensions and material properties. Thus, simulation no. agt-v3r-v18-single-thrie provided a more accurate representation of the as-tested full-scale test installation than the previous models.

4.7 Initial Ram Vehicle Model Simulations

Previously, all simulations had used the reduced-element model of the 2007 Chevrolet Silverado. During the development of the AGT model, researchers obtained a vehicle model of a 2018 Dodge Ram pickup truck. The Ram vehicle model was originally developed by the Center for Collision Safety and Analysis Team at George Mason University, and was modified by MwRSF personnel for use in roadside safety applications [11]. It was believed that the Ram vehicle model would provide a much better correlation between the simulations and the full-scale test than the Silverado vehicle model due to improved vehicle geometry and deformation characteristics.

Several simulations were run to update and modify the Ram vehicle model for use with the AGT model. During the process, simulations were run with the Ram vehicle model impacting different modeled test installations, including the modeled AGT installation from simulation no. agt-v3r-v15-single-thrie.

The 2270P Dodge Ram pickup truck model impacted the modeled AGT installation at a speed of 62.1 mph (100.0 km/h) and at an angle of 25 degrees. Both the Ram and Silverado simulations impacted the same impact point on identical, modeled AGT test installations, but the Ram simulation included right-front wheel detachment and had an impact speed approximately 0.6 mph (1 km/h) slower than the Silverado. Results from model no. agt-v3r-v15-single-thrie impacted by the Ram and Silverado vehicle models provided a direct comparison between the behaviors of the two vehicle models. Sequential images of the full-scale test results and LS-DYNA simulations are shown in Figure 19, and a summary of results is shown in Table 8.

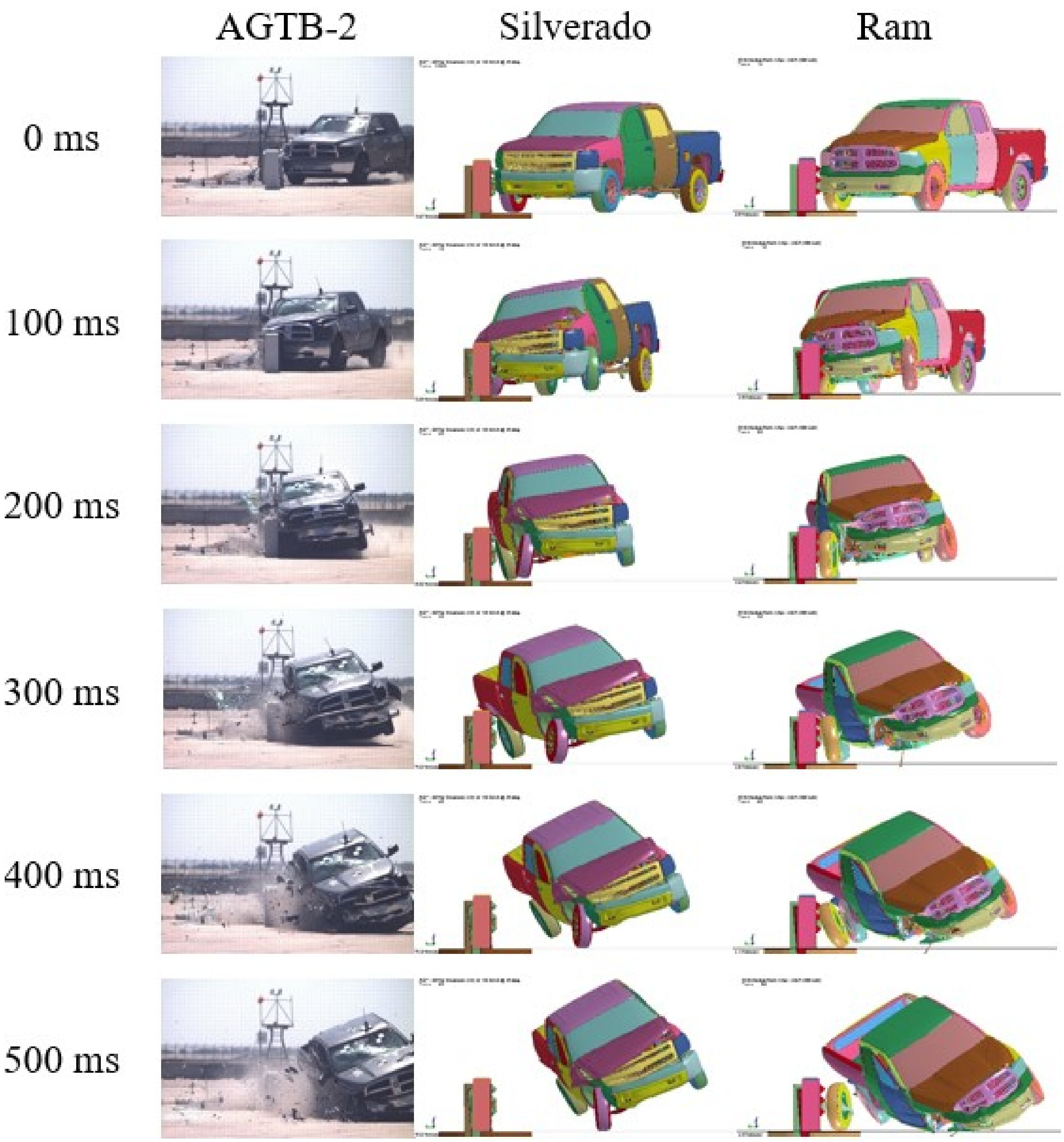


Figure 19. Sequential Images, Test No. AGTB-2, Silverado Simulation, and Ram Simulation

Table 8. Summary of Results for Test No. AGTB-2, Silverado Simulation, and Ram Simulation

Evaluation Criteria		AGTB-2	Silverado	Ram
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-26.34 (-8.03)	-21.22 (-6.47)
	Lateral	24.61 (7.50)	26.68 (8.13)	27.20 (8.29)
ORA g's	Longitudinal	-7.06	-12.10	-6.71
	Lateral	10.40	11.00	8.40
Maximum Angular Displacement deg.	Roll	21.3	29.1	28.6
	Pitch	6.3	6.1	6.2
	Yaw	39.6	39.4	43.9
Post Max. Dynamic Deflection in. (mm)		5.35 (136)	4.96 (126)	4.17 (106)
Length of Contact in. (mm)		159 (4,039)	121 (3,068)	129 (3,280

The Ram vehicle model exhibited improved correlation with the full-scale longitudinal occupant risk values over the Silverado vehicle model, but did not improve the correlation of lateral evaluation parameters. Additionally, the Ram vehicle model under deflected when compared to both the full-scale test and the Silverado simulation.

While the Ram model did not improve over the Silverado in all evaluation parameters, the Ram model did provide an improved correlation in vehicle deformation due to vehicle geometry and deformation characteristics, as shown in Figures 20 through 22.

Figure 20. Right-Front Vehicle Deformation Comparison

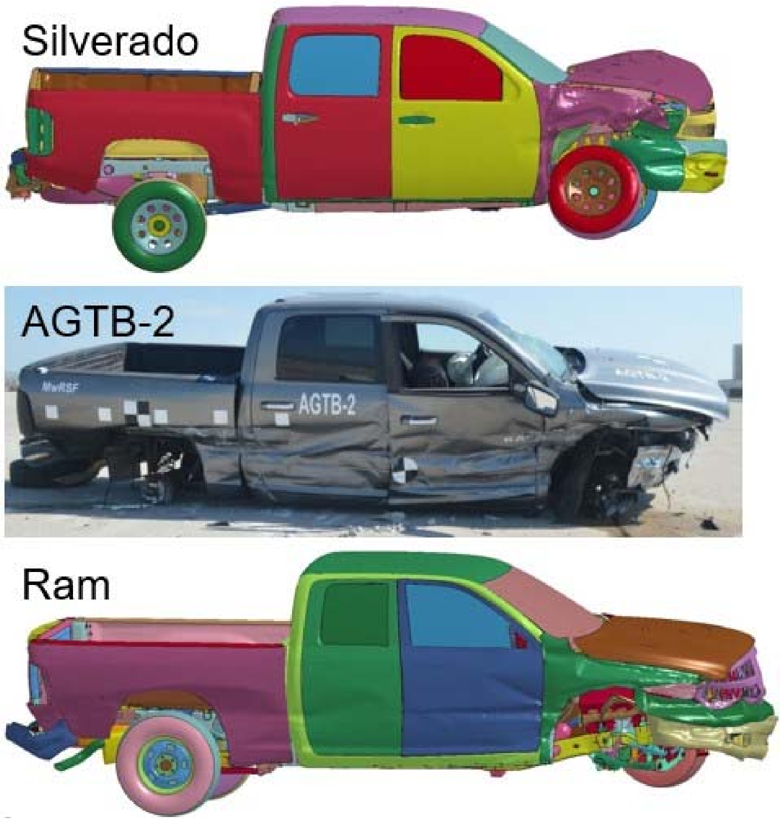


Figure 21. Vehicle Right Side Deformation Comparison

Figure 22. Right-front Suspension Components Comparison

The Ram vehicle model experienced right-side vehicle deformation which was more consistent with the full-scale test than the damage to the Silverado vehicle model. Suspension failure and wheel detachment was included in the Ram simulation, following the method previously discussed in Section 4.2, but was not included in the Silverado simulation. Because the wheel remained attached, the Silverado's right-front suspension may have experienced additional deformation and should not be directly compared to the Ram simulation which modeled the detachment of the right-front wheel. However, when comparing the simulated Ram's right-front suspension to the right-front suspension of the test no. AGTB-2 test vehicle, the post-test deformation and orientation of the suspension components appear very similar to the modeled Ram suspension.

Additionally, although the Silverado vehicle model exhibited a better correlation to some of the full-scale test's peak evaluation parameters, the Ram vehicle model showed a considerably better correlation to the full-scale test's longitudinal and lateral changes in velocity and displacement over time, as shown in Figures 23 and 24.

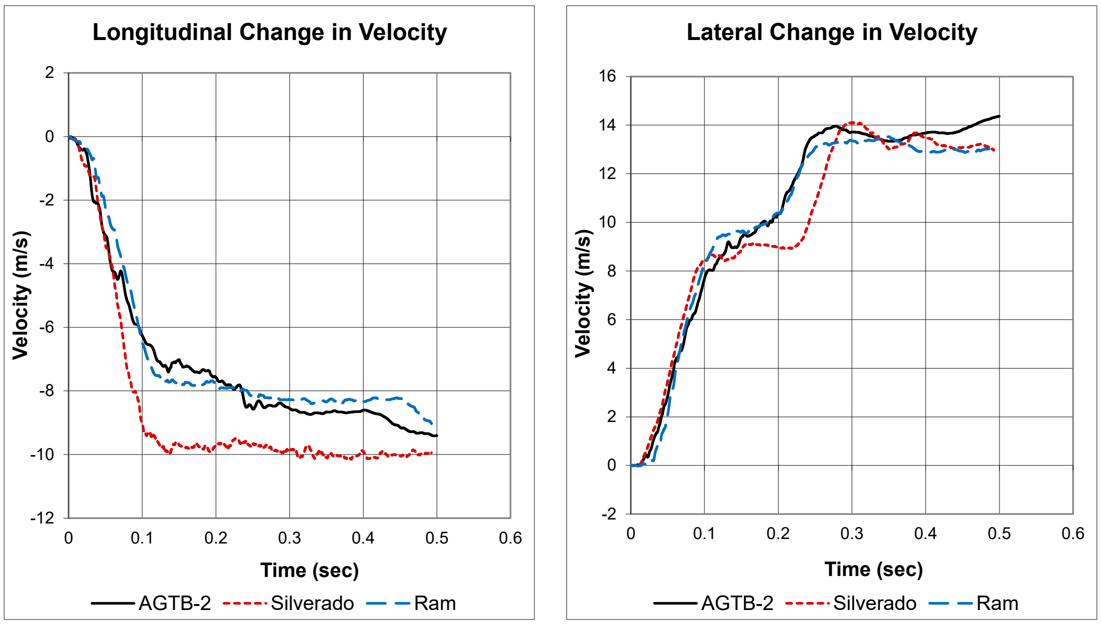


Figure 23. AGTB-2 vs. Silverado vs. Ram Changes in Velocity

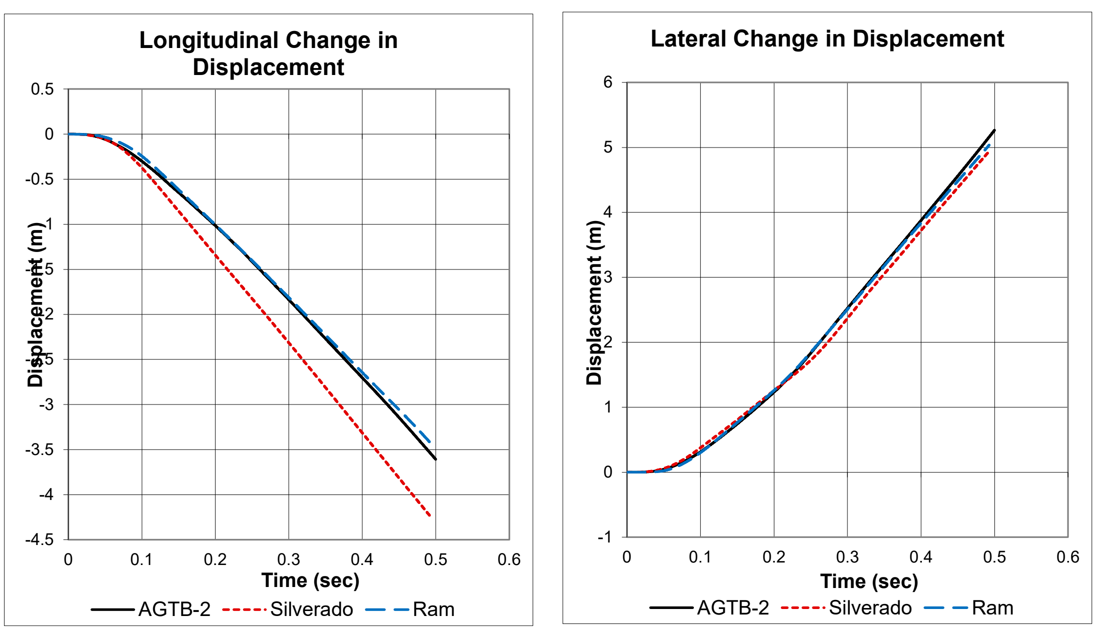


Figure 24. AGTB-2 vs. Silverado vs. Ram Changes in Displacement

In summary, the Ram vehicle model improved the correlation between the simulated and full-scale test vehicle damage and exhibited an improvement over the Silverado vehicle model when comparing the changes in velocity and displacement over time. Therefore, the Ram vehicle model was selected as the primary vehicle model for the V&V of the AGT simulation.

4.8 Ram Vehicle Model with Anthropomorphic Test Device (ATD)

Following the comparison between the Silverado and Ram vehicle models, additional changes were made to the Ram vehicle model to more accurately represent the test vehicle in test no. AGTB-2. The final version of the Ram vehicle model incorporated both right-front suspension failure and an anthropomorphic test device (ATD) located in the right-front passenger seat. The suspension failure was modeled by defining failure times for the upper control arm, lower control arm, and steering arm joints, following the method previously discussed in Section 4.2. The failure times were determined through examination of the joint forces in the model and comparison of the simulation with test no. AGTB-2 crash test footage.

As previously documented, further improvements were made to the modeled AGT installation following the attempted validation of simulation no. agt-v3r-v15-single-thrie, which included updates to the post geometry and material properties. This resulted in simulation no. agt-v3r-v18-single-thrie, which was identified as the best representation of the as-tested full-scale test installation. With the improvements to the Ram vehicle model, it was desired to run a simulation with the updated Ram vehicle model and the most accurate representation of the as-tested full-scale test installation. Thus, simulation no. agt-v18--Ram was conducted which utilized the AGT installation from simulation no. agt-v3r-v18-single-thrie and the updated Dodge Ram vehicle model complete with ATD and suspension failure.

The 5,005-lb (2270-kg) Dodge Ram vehicle model impacted the modeled AGT system at a speed of 62.1 mph (100.0 km/h) and at an angle of 25 degrees. Both the Ram and Silverado simulations impacted the same impact point on identical modeled AGT test installations (v18), but the Ram simulation in this comparison included right-front wheel detachment and had an impact speed approximately 0.6 mph (1 km/h) slower than the Silverado. Sequential images of the full-scale testing results and LS-DYNA simulations are shown in Figure 25, and a summary of results is shown in Table 9.

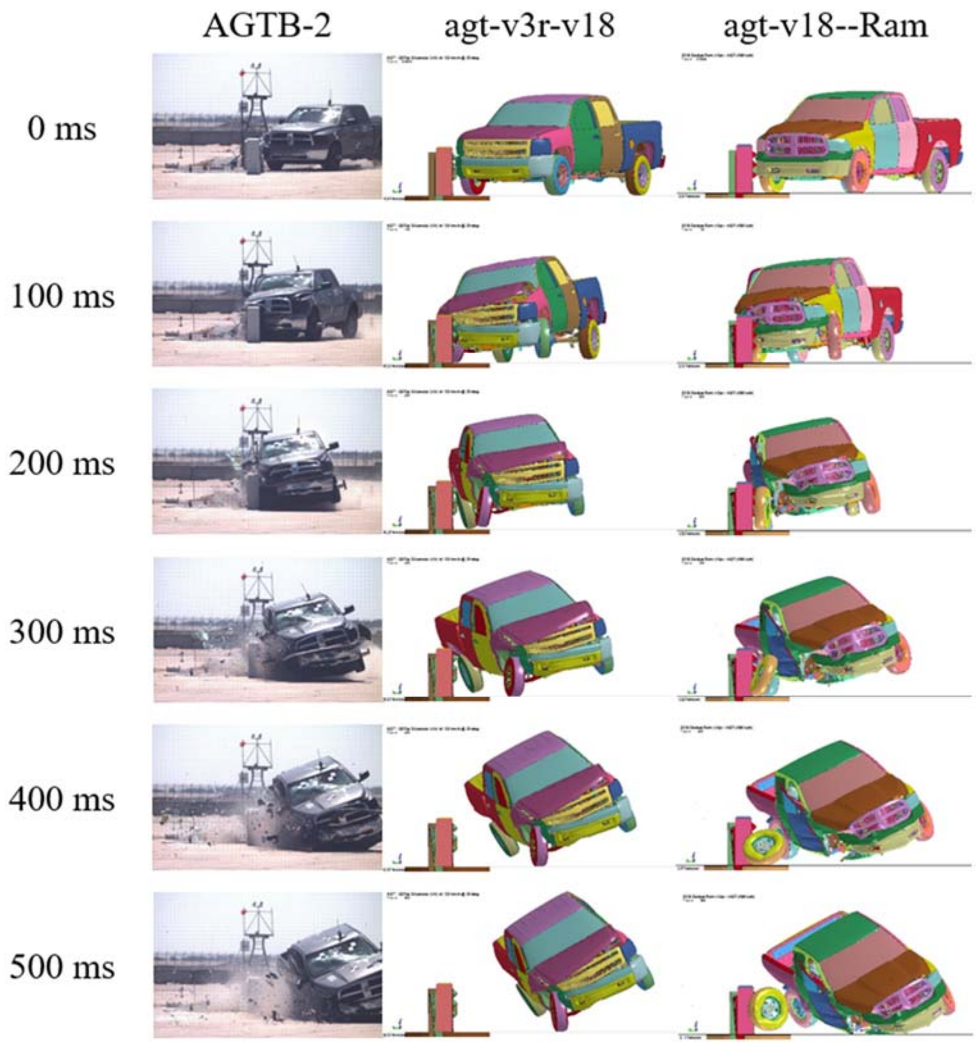


Figure 25. Sequential Images, Test No. AGTB-2, Simulation Nos. agt-v3r-v18 and agt-v18—Ram

Table 9. Summary of Test No. AGTB-2 and Simulation Nos. agt-v3r-v18-single-thrie and agt-v18--Ram

Evaluation Criteria		AGTB-2	agt-v3r-v18-single-thrie (Silverado)	agt-v18--Ram
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-27.44 (-8.36)	-20.96 (-6.39)
	Lateral	24.61 (7.50)	26.72 (8.14)	27.15 (8.28)
ORA g's	Longitudinal	-7.06	-9.53	-6.36
	Lateral	10.40	12.61	8.22
Maximum Angular Displacement deg.	Roll	21.3	31.9	26.5
	Pitch	6.3	6.4	7.2
	Yaw	39.6	40.2	42.7
Post Max. Dynamic Deflection – in. (mm)		5.35 (136)	5.67 (144)	4.53 (115)
Length of Contact – in. (mm)		159 (4,039)	124.26 (3,156)	134.33 (3,412)

Similar to the previous comparison between the Ram and Silverado vehicle models, the Ram vehicle model exhibited an improved correlation with the longitudinal occupant risk values of the full-scale test over the Silverado vehicle model. However, the Ram failed to offer improvement over the Silverado vehicle model's lateral OIV correlation with the full-scale test value. Additionally, the Ram vehicle model deflected less than both the full-scale test and the Silverado simulation. Though the Ram model did not improve over the Silverado in all evaluation parameters, the Ram model resulted in a significant reduction of both longitudinal ORA and OIV values and exhibited improved correlation to the vehicle deformation.

During the simulation, the ATD impacted the door, resulting in outward deformation of the right-front passenger door that closely matched the deformation exhibited in the full-scale crash test. Additionally, during test no. AGTB-2 the head of the ATD impacted the window in the right-front passenger door 112 ms after impact and the window shattered. The simulation accurately exhibited this behavior through the erosion of window elements which began 114 ms after impact. The window element erosion in the simulation began approximately 20 ms prior to the impact of the ATD head, likely due to bending of the glass caused by the outward door deformation. The deformation of the door and the element erosion of right-front passenger door window are shown in Figures 26 and 27, respectively.

Figure 26. Right-Front Door Deformation with ATD, Simulation No. agt-v18--Ram and Test No. AGTB-2

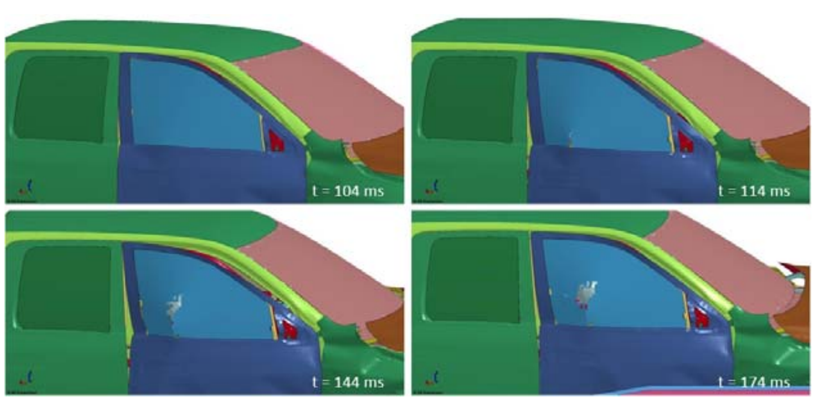


Figure 27. Simulation No. agt-v18--Ram Window Element Erosion

Simulation no. agt-v18--Ram was identified as the best comparison to the full-scale test, thus far, and was selected to go through the procedures for V&V of computer simulations used for roadside safety applications, outlined in NCHRP Report No. W179. The simulation V&V exhibited improved correlation to test no. AGTB-2 when compared to simulation no. agt-v3r-v15-single-thrie and passed the V&V with exceptions. The validation is discussed in Section 6.2 and the full V&V comparison is shown in Appendix B.

4.9 Ram Vehicle Model with Test No. AGTB-2 Impact Velocity

In full-scale test no. AGTB-2, the 2270P vehicle impacted the tangent AGT installation at a speed of 62.7 mph (100.8 km/h). However, in previous simulations with the Ram vehicle model, the vehicle impacted the installation at the target MASH 2016 test level 3 (TL-3) impact speed of 62.1 mph (100.0 km/h). In order to more accurately represent the impact conditions of the full-scale test, an additional simulation was run in which the impact velocity was increased from 62.1 mph (100.0 km/h) to 62.7 mph (100.8 km/h).

In simulation no. agt-v18--Ram-v2, the 5,005-lb (2270-kg) Dodge Ram vehicle model impacted the modeled AGT system at a speed of 62.7 mph (100.8 km/h) and at an angle of 25 degrees. The impact velocity was the only change from simulation no. agt-v18--Ram to simulation no. agt-v18--Ram-v2. Sequential images of the full-scale test results and LS-DYNA simulations are shown in Figure 28, and a summary of the test results is shown in Table 10.

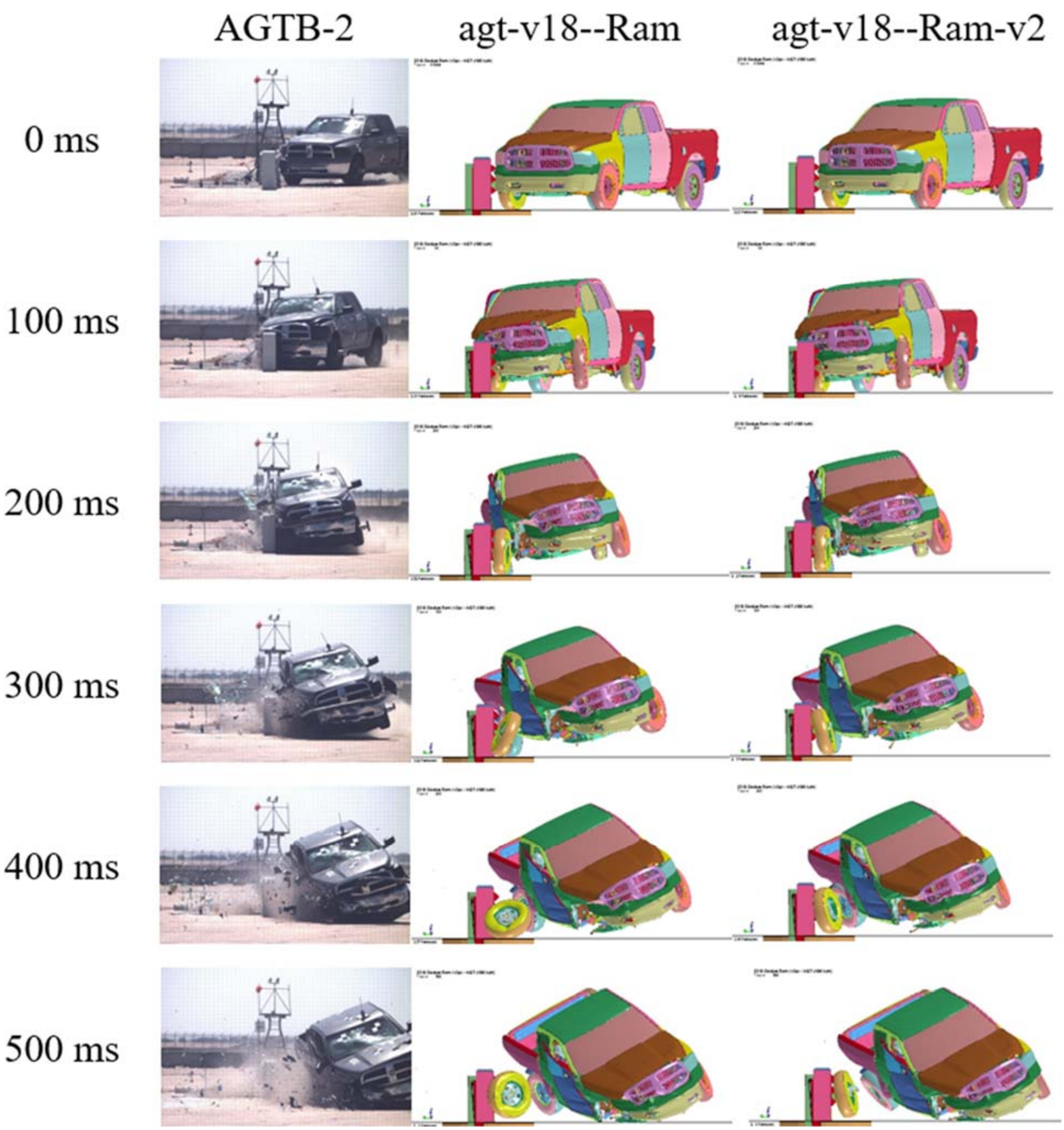


Figure 28. Sequential Images, Test No. AGTB-2 and Simulation Nos. agt-v18--Ram and agt-v18--Ram-v2

Table 10. Summary of Test No. AGTB-2 and Simulation Nos. agt-v18--Ram and agt-v18--Ram-v2

Evaluation Criteria		AGTB-2	agt-v18--Ram	agt-v18--Ram-v2
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-20.96 (-6.39)	-20.84 (-6.35)
	Lateral	24.61 (7.50)	27.15 (8.28)	27.04 (8.24)
ORA g's	Longitudinal	-7.06	-6.36	-7.75
	Lateral	10.40	8.22	8.13
Maximum Angular Displacement deg.	Roll	21.3	26.5	24.8
	Pitch	6.3	7.2	6.3
	Yaw	39.6	42.7	43.2
Post Max. Dynamic Deflection in. (mm)		5.35 (136)	4.53 (115)	4.31 (109)
Length of Contact in. (mm)		159 (4,039)	134.33 (3,412)	124.61 (3,165)

The Ram vehicle model simulation using a 62.7 mph (100.8 km/h) impact velocity resulted in slightly improved correlation with the full-scale test roll, pitch, and OIV values when compared to the previous Ram vehicle model simulation at 62.1 mph (100 km/h). The longitudinal ORA increased by 1.39 g's in simulation no. agt-v18--Ram-v2 and had an approximately equal relative difference with the full-scale test value when compared to the simulated Ram impact at 62.1 mph (100 km/h). However, the post maximum dynamic deflection, length of contact, yaw and lateral ORA values did not improve in correlation with the full-scale test when compared to the Ram vehicle model simulation at 62.1 mph (100 km/h).

Simulation no. agt-v18--Ram-v2 was identified as the most accurate representation of the full-scale test, as it included the most representative AGT model and the updated Ram vehicle model with an impact velocity that matched the full-scale test. It was selected to go through the procedures for V&V of computer simulations used for roadside safety applications, outlined in NCHRP Report No. W179. The simulation passed the V&V process with exceptions. The validation is discussed in Section 6.3 and the full V&V comparison is shown in Appendix C.

5 ROADSIDE SAFETY VERIFICATION AND VALIDATION PROGRAM (RSVVP)

The Roadside Safety Verification and Validation Program (RSVVP) analysis quantitatively compares the similarity between two data sets by computing comparison metrics that offer a mathematical measure of agreement [2]. The RSVVP analysis compared the CFC-60 and CFC-180 filtered data sets from the simulations and the full-scale test for the X, Y, and Z accelerations as well as roll, pitch, and yaw data.

In the simulation no. agt-v3r-v15-single-thrie comparisons, a multi-channel RSVVP analysis was performed on the data sets, which used weighting factors for each channel to compute a single set of composite metrics intended to provide an overall assessment. The CFC-60 and CFC-180 data sets passed the multi-channel RSVVP analysis and were determined to be in agreement with the full-scale test data. A summary of the RSVVP analysis results for the simulation no. agt-v3r-v15-single-thrie CFC-60 and CFC-180 filtered data is included in Tables 11 and 12. Further information regarding the RSVVP analysis is contained in the V&V of simulation no. agt-v3r-v15-single-thrie in Appendix A.

A RSVVP analysis was also performed for simulation nos. agt-v18--Ram and agt-v18--Ram-v2. The CFC-60 and CFC-180 filtered data sets met the RSVVP criteria during the multi-channel RSVVP analysis for both simulations. The RSVVP analysis results for the CFC-60 and CFC-180 filtered data are summarized in Tables 13 and 14 for simulation no. agt-v18--Ram and in Tables 15 and 16 for simulation no. agt-v18--Ram-v2. Further information regarding the RSVVP analyses is located in the V&V of simulation nos. agt-v18--Ram and agt-v18--Ram-v2 in Appendix B and Appendix C, respectively.

The evaluation metrics in the RSVVP analysis provide a measure of the correlation between the data sets. If the evaluation metric is zero then the two data sets are identical. Therefore, the lower the magnitude of the evaluation metric, the better the correlation between the two data sets. While all three simulations successfully met the acceptance criteria for the multi-channel RSVVP analysis, the Ram simulations exhibited an improved correlation to the full-scale test data over simulation no. agt-v3r-v15-single-thrie with the Silverado vehicle model. The magnitudes of the calculated MPC and ANOVA metrics for the Ram simulations were consistently closer to zero than the evaluation metrics calculated for simulation no. agt-v3r-v15-single-thrie, as seen in Tables 11 through 16.

Table 11. Simulation No. agt-v3r-v15-single-thrie RSVVP Analysis Results for CFC-60 Filtered Data

		AGTB-2 vs. Simulation No. agt-v3r-v15-single-thrie (CFC-60)													
		X loc		Y loc		Z loc		Yaw Rate loc		Roll Rate loc		Pitch Rate loc		Multi-Channel	
MPC Metrics	Sprague-Geers Magnitude	20.7	Pass	6.4	Pass	27.1	Pass	20	Pass	0.9	Pass	11	Pass	12.5	Pass
	Sprague-Geers Phase	31.6	Pass	25.7	Pass	48.5	Fail	11.2	Pass	36.2	Pass	47.5	Fail	27	Pass
	Sprague-Geers Comprehensive	37.8	Pass	26.5	Pass	55.6	Fail	22.9	Pass	36.2	Pass	48.8	Fail	31.6	Pass
ANOVA Metrics	Average	-0.48	Pass	1.84	Pass	-2.31	Pass	0.93	Pass	1.24	Pass	0.24	Pass	0.9	Pass
	Standard Deviation	21.61	Pass	26.53	Pass	33.5	Pass	11.37	Pass	7.1	Pass	9.34	Pass	17.3	Pass

Table 12. Simulation No. agt-v3r-v15-single-thrie RSVVP Analysis Results for CFC-180 Filtered Data

		AGTB-2 vs. Simulation No. agt-v3r-v15-single-thrie (CFC-180)													
		X loc		Y loc		Z loc		Yaw Rate loc		Roll Rate loc		Pitch Rate loc		Multi-Channel	
MPC Metrics	Sprague-Geers Magnitude	29.9	Pass	3.1	Pass	1	Pass	20	Pass	0.9	Pass	11	Pass	12.8	Pass
	Sprague-Geers Phase	36	Pass	28.7	Pass	50.4	Fail	11.2	Pass	36.2	Pass	47.5	Fail	28.7	Pass
	Sprague-Geers Comprehensive	46.8	Fail	28.8	Pass	50.4	Fail	22.9	Pass	36.2	Pass	48.8	Fail	33.9	Pass
ANOVA Metrics	Average	-0.43	Pass	1.49	Pass	-1.67	Pass	0.93	Pass	1.24	Pass	0.24	Pass	0.8	Pass
	Standard Deviation	23.44	Pass	25.23	Pass	31.54	Pass	11.37	Pass	7.1	Pass	9.34	Pass	17.2	Pass

Table 13. Simulation No. agt-v18--Ram RSVVP Analysis Results for CFC-60 Filtered Data

		AGTB-2 vs. Simulation No. agt-v18--Ram (CFC-60)													
		X loc		Y loc		Z loc		Yaw Rate loc		Roll Rate loc		Pitch Rate loc		Multi-Channel	
MPC Metrics	Sprague-Geers Magnitude	15.3	Pass	3	Pass	14.4	Pass	17	Pass	5.6	Pass	20.4	Pass	11	Pass
	Sprague-Geers Phase	27.9	Pass	20.7	Pass	56.3	Fail	7.2	Pass	34	Pass	42.7	Fail	23.2	Pass
	Sprague-Geers Comprehensive	31.8	Pass	20.9	Pass	58.1	Fail	18.5	Pass	34.4	Pass	47.3	Fail	27.4	Pass
ANOVA Metrics	Average	1.21	Pass	1.98	Pass	-3.1	Pass	-2.86	Pass	1.01	Pass	-0.31	Pass	0.1	Pass
	Standard Deviation	16.19	Pass	21.25	Pass	40.1	Fail	7.38	Pass	6.56	Pass	10.09	Pass	13.8	Pass

Table 14. Simulation No. agt-v18--Ram RSVVP Analysis Results for CFC-180 Filtered Data

		AGTB-2 vs. Simulation No. agt-v18--Ram (CFC-180)													
		X loc		Y loc		Z loc		Yaw Rate loc		Roll Rate loc		Pitch Rate loc		Multi-Channel	
MPC Metrics	Sprague-Geers Magnitude	13	Pass	1.4	Pass	43.8	Fail	17	Pass	5.6	Pass	20.4	Pass	10.7	Pass
	Sprague-Geers Phase	31.3	Pass	25.6	Pass	55.1	Fail	7.2	Pass	34	Pass	42.7	Fail	25.3	Pass
	Sprague-Geers Comprehensive	33.9	Pass	25.6	Pass	70.4	Fail	18.5	Pass	34.4	Pass	47.3	Fail	29.4	Pass
ANOVA Metrics	Average	1.03	Pass	1.61	Pass	-2.27	Pass	-2.86	Pass	1.01	Pass	-0.31	Pass	0	Pass
	Standard Deviation	16.69	Pass	22.61	Pass	41.71	Fail	7.38	Pass	6.56	Pass	10.09	Pass	14.3	Pass

Table 15. Simulation No. agt-v18--Ram-v2 RSVVP Analysis Results for CFC-60 Filtered Data

		AGTB-2 vs. Simulation No. agt-v18--Ram (CFC-60)													
		X loc		Y loc		Z loc		Yaw Rate loc		Roll Rate loc		Pitch Rate loc		Multi-Channel	
MPC Metrics	Sprague-Geers Magnitude	13.2	Pass	2.3	Pass	1.7	Pass	16	Pass	4.5	Pass	31	Pass	10.6	Pass
	Sprague-Geers Phase	29.9	Pass	20.5	Pass	56.6	Fail	7.2	Pass	34.3	Pass	43.4	Fail	23.7	Pass
	Sprague-Geers Comprehensive	32.7	Pass	20.7	Pass	56.6	Fail	17.5	Pass	34.6	Pass	53.3	Fail	27.7	Pass
ANOVA Metrics	Average	1.02	Pass	2.03	Pass	-3	Pass	-3.36	Pass	0.77	Pass	-0.12	Pass	0	Pass
	Standard Deviation	17.4	Pass	21.05	Pass	42.93	Fail	6.93	Pass	6.69	Pass	10.79	Pass	14	Pass

Table 16. Simulation No. agt-v18--Ram-v2 RSVVP Analysis Results for CFC-180 Filtered Data

		AGTB-2 vs. Simulation No. agt-v18--Ram (CFC-180)													
		X loc		Y loc		Z loc		Yaw Rate loc		Roll Rate loc		Pitch Rate loc		Multi-Channel	
MPC Metrics	Sprague-Geers Magnitude	8.7	Pass	2.1	Pass	54.9	Fail	16	Pass	4.5	Pass	31	Pass	10.7	Pass
	Sprague-Geers Phase	32.9	Pass	25.4	Pass	54.8	Fail	7.2	Pass	34.3	Pass	43.4	Fail	25.6	Pass
	Sprague-Geers Comprehensive	34.1	Pass	25.5	Pass	77.6	Fail	17.5	Pass	34.6	Pass	53.3	Fail	29.8	Pass
ANOVA Metrics	Average	0.88	Pass	1.64	Pass	-2.17	Pass	-3.36	Pass	0.77	Pass	-0.12	Pass	-0.2	Pass
	Standard Deviation	17.78	Pass	22.57	Pass	43.67	Fail	6.93	Pass	6.69	Pass	10.79	Pass	14.5	Pass

6 VERIFICATION AND VALIDATION (V&V)

Three of the modeled AGT installations detailed in the preceding sections were compared to test no. AGTB-2 using the procedures for the V&V of computer simulations used for roadside safety applications, outlined in NCHRP Report No. W179. Simulation no. agt-v3r-v15-single-thrie used the Silverado vehicle model at a speed of 62.7 mph (100.8 km/h), simulation no. agt-v18--Ram used the Ram vehicle model at a speed of 62.1 mph (100 km/h), and simulation no. agt-v18--Ram-v2 used the Ram vehicle model at a speed of 62.7 mph (100.8 km/h).

6.1 Simulation No. agt-v3r-v15-single-thrie V&V

In the first validation of the AGT model, the 2270P Silverado vehicle model impacted the modeled AGT installation 89 in. (2,261 mm) upstream from the concrete buttress at a speed of 62.7 mph (100.8 km/h) and at an angle of 25 degrees. The modeled AGT successfully contained and redirected the Silverado vehicle model with OIVs and ORAs that satisfied the MASH 2016 safety performance criteria, as shown in Table 17. However, when compared to the test no. AGTB-2 crash test data, the Silverado simulation exhibited greater longitudinal and lateral OIVs and ORAs and lower system deflections. Results from the Silverado simulation and full-scale test no. AGTB-2 are summarized in Table 17, and the full V&V of the Silverado simulation is included in Appendix A. A comparison between the Silverado simulation and full-scale test no. AGTB-2 is depicted in Figure 29 at a time state of 100 ms after impact and sequential images are shown in Figure 30.

Table 17. Summary of Crash Test No. AGTB-2 and Simulation No. agt-v3r-v15-single-thrie Results

Evaluation Criteria		AGTB-2	agt-v3r-v15-single-thrie	MASH Limits
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-26.34 (-8.03)	±40
	Lateral	24.61 (7.50)	26.68 (8.13)	±40
ORA g's	Longitudinal	-7.06	-12.10	±20.49
	Lateral	10.40	11.00	±20.49
Maximum Angular Displacement deg.	Roll	21.3	29.1	±75
	Pitch	6.3	6.1	±75
	Yaw	39.6	39.4	not required
Post Max. Dynamic Deflection in. (mm)		5.35 (136)	4.96 (126)	NA
Length of Contact in. (mm)		159 (4,039)	120.79 (3,068)	NA

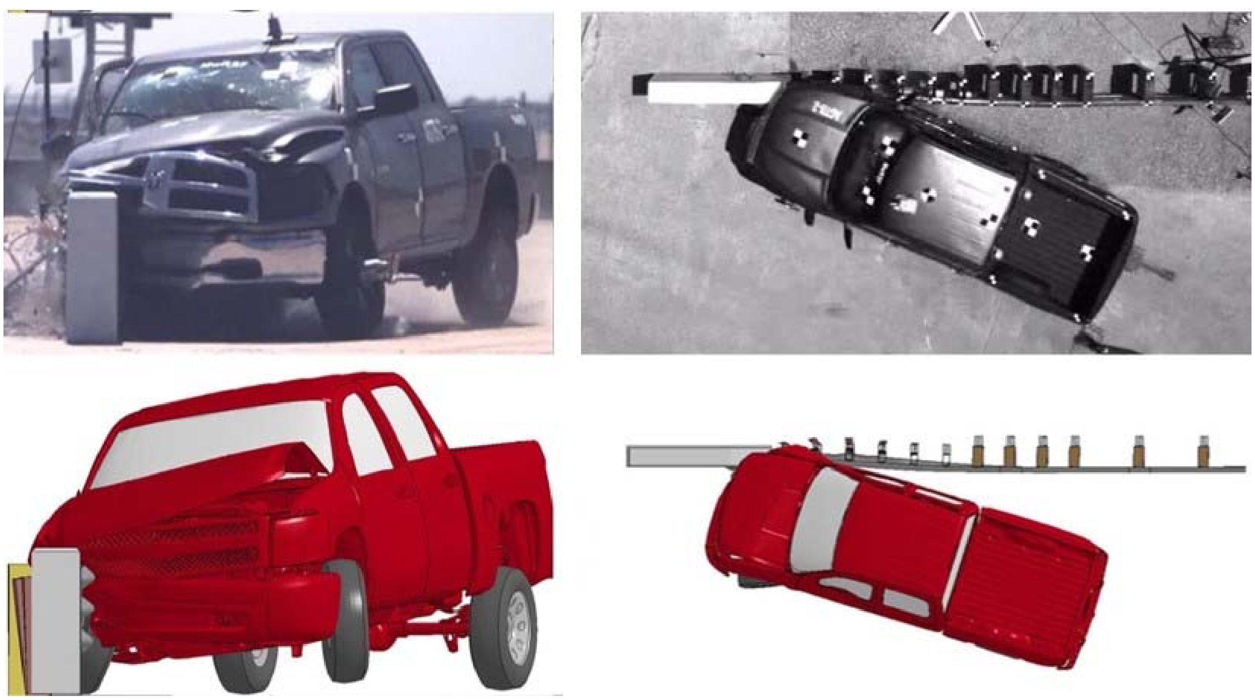


Figure 29. Full-Scale Crash Test No. AGTB-2 (Top) and Simulation No. agt-v3r-v15-single-thrie (Bottom)

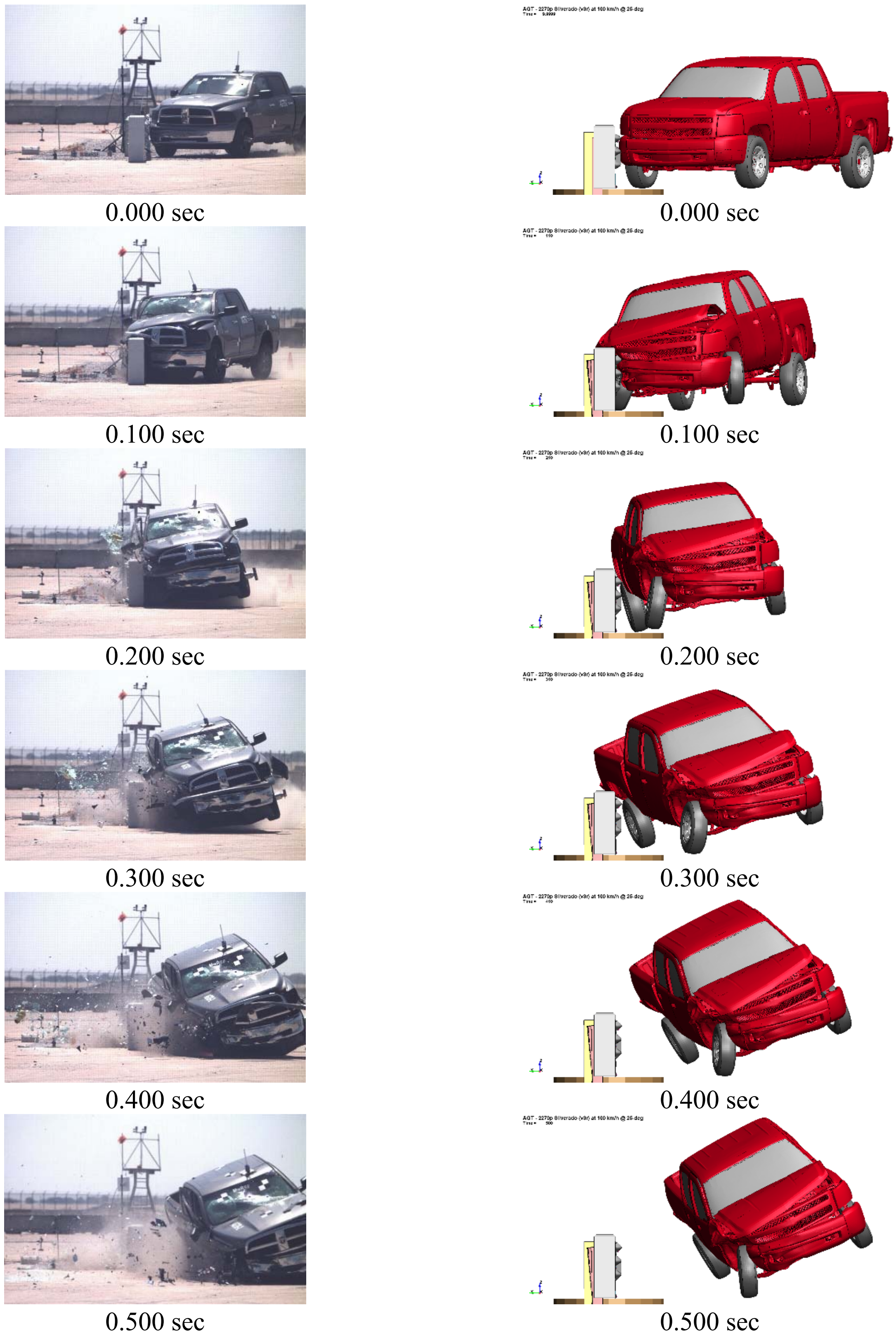


Figure 30. Sequential Images, Test No. AGTB-2 (Left) vs. Simulation No. agt-v3r-v15-single-thrie (Right)

The Silverado simulation would only pass the V&V procedure requirements with exceptions, because the Silverado simulation's longitudinal ORA, vehicle roll, and exit angle exceeded those of the full-scale test. The simulation over predicted the longitudinal ORA by 5.0 g's or 71 percent, which exceeded the V&V relative difference limit of either 4.0 g's or 20 percent. Additionally, the Silverado simulation did not meet the maximum roll or exit angle criteria, as the simulation over predicted the roll by 7.9 degrees (37.0 percent) and the exit angle by 5.0 degrees (55.6 percent), which both exceeded the V&V angular relative difference limit of either 20 percent or 5 degrees.

Finally, the hourglass energy, and added mass requirements outlined in NCHRP Report No. W179 were not satisfied. The hourglass energy at the end of the simulation exceeded the total initial energy at the beginning of the run by more than 5 percent and exceeded the total internal energy at the end of the run by more than 10 percent. The right-front tire exhibited the highest amount of hourglass energy, which exceeded the total internal energy of the tire by more than 10 percent and did not meet the V&V criteria. The added mass of the steel transition blockouts exceeded the initial mass of the part by 20 percent, which did not satisfy the V&V criteria requirement of 10 percent. However, it is important to note that both the hourglass energy and added mass could be resolved at the cost of greater computational run time when compared to the current model.

Thus, the Silverado simulation would not meet the V&V criteria without additional modifications and/or exceptions. The Silverado vehicle model was geometrically different from the tested 2010 Dodge Ram vehicle and was anticipated to diverge from the full-scale test data. However, due to the magnitude of the discrepancies between the Silverado simulation and the full-scale test, the simulation only satisfied the V&V requirements with the noted exceptions.

6.2 Simulation No. agt-v18--Ram V&V

The second validation of the AGT model used the 2270P 2018 Dodge Ram vehicle model and included changes to the AGT model used in the Silverado vehicle simulation. In the Ram simulation, the thrie-beam post sections were changed from W6x9 to W6x8.5 and the yield stress of the transition posts was increased from 47 ksi (324 MPa) to 56 ksi (386 MPa) to match the material certifications for the guardrail posts from test no. AGTB-2. Additionally, the simulated impact with the Ram vehicle model included suspension failure and wheel detachment in an effort to accurately represent test no. AGTB-2.

In the simulation, the 2270P Ram vehicle model impacted the modeled AGT installation 89 in. (2,261 mm) upstream from the concrete buttress at a speed of 62.1 mph (100.0 km/h) and at an angle of 25 degrees. Note that the impact conditions represented ideal MASH 2016 TL-3 conditions that were slightly lower than the full-scale test no. AGTB-2 impact conditions of 62.7 mph (100.9 km/h) and 25.4 degrees.

The modeled AGT successfully contained and redirected the Ram vehicle model with occupant risk values that satisfied the MASH 2016 safety performance criteria. However, when compared to the test no. AGTB-2 crash test data, the Ram simulation exhibited greater longitudinal and lateral OIV values. Additionally, the Ram simulation had lower system deflections and lower longitudinal and lateral ORA values than test no. AGTB-2. Results from the Ram simulation and full-scale test no. AGTB-2 are summarized in Table 18. The full V&V of the simulation no. agt-v18--Ram simulation is included in Appendix B. A comparison between the Ram simulation and full-scale test no. AGTB-2 is depicted in Figure 31 at a time state of 100 ms and sequential images are shown in Figure 32.

Table 18. Summary of Crash Test No. AGTB-2 and Simulation No. agt-v18--Ram Results

Evaluation Criteria		AGTB-2	agt-v18--Ram	MASH Limits
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-20.96 (-6.39)	±40
	Lateral	24.61 (7.50)	27.15 (8.28)	±40
ORA (g's)	Longitudinal	-7.06	-6.36	±20.49
	Lateral	10.40	8.22	±20.49
Maximum Angular Displacement (deg.)	Roll	21.3	26.5	±75
	Pitch	6.3	7.2	±75
	Yaw	39.6	42.7	not required
Post Max. Dynamic Deflection in. (mm)		5.35 (136)	4.53 (115)	NA
Length of Contact in. (mm)		159 (4,039)	134 (3,412)	NA

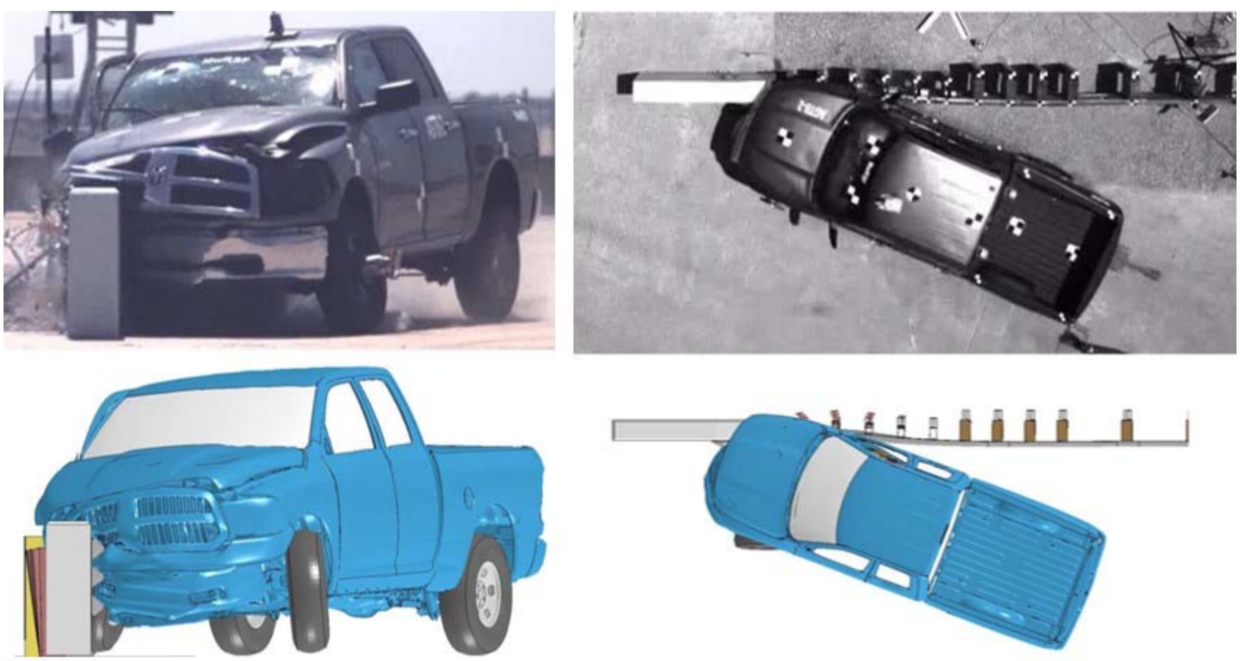


Figure 31. Full-Scale Crash Test No. AGTB-2 (Top) and Simulation No. agt-v18--Ram (Bottom)

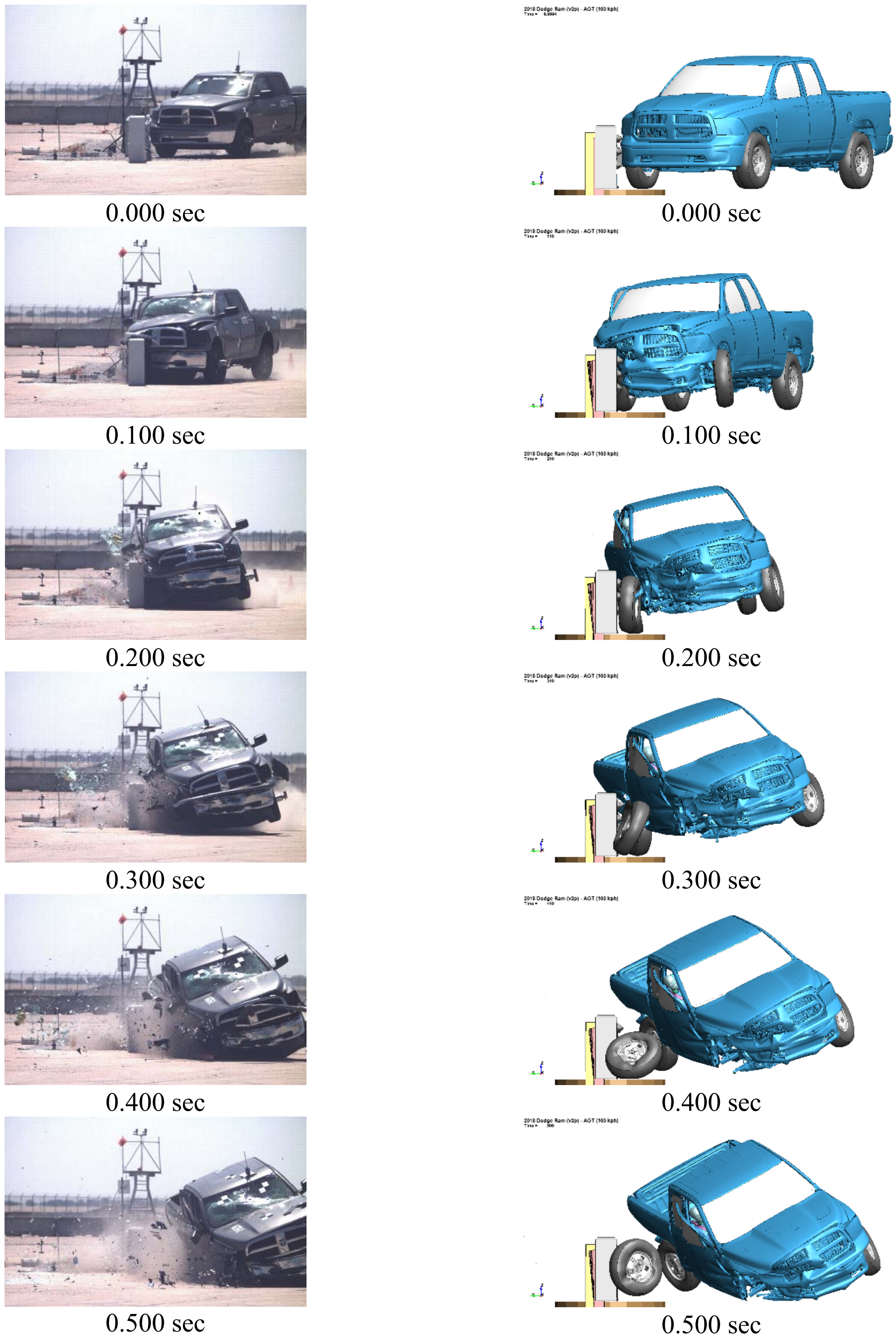


Figure 32. Sequential Images, Test No. AGTB-2 (Left) vs. Simulation No. agt-v18--Ram (Right)

The Ram simulation satisfied the V&V procedure requirements with noted exceptions. The modeled AGT installation exhibited a reduced number of significantly bent posts than the full-scale test, which exceeded the 20 percent difference requirement by V&V. A threshold value of 1 in. (25 mm) was used to classify a post deflection as significant. Seven posts exhibited deflections greater than 1 in. (25 mm) in the full-scale test, compared with five posts in the simulation. The difference between the numbers of deflected posts was likely caused by the behavior of the soil.

The posts were installed at a post spacing of 18¾ in. (476 mm) within the impacted region. In the full-scale test, this close proximity meant the soil resistance was dependent on the loading of the adjacent posts. In the simulation however, the soil for each post was modeled with independent soil springs that did not account for the loading of the surrounding soil. Due to this modeling simplification, the load imparted into the barrier by the impacting vehicle in the simulation resulted in localized deflections and fewer significantly deflected posts than the full-scale test.

The Ram vehicle model also exhibited an exit angle that was 5.1 degrees, or 57 percent, greater than the 9.0 degree exit angle in full-scale test no. AGTB-2, which exceeded the 20 percent or 5 degree limit of the V&V criteria. During the full-scale test, the vehicle's right-front wheel detached and slid under the vehicle, vacating the wheel well. In the simulation, the detached right-front wheel remained in the wheel well while the vehicle was in contact with the installation, likely contributing to the exit angle discrepancy.

Additionally, the simulation did not meet the hourglass energy and added mass requirements outlined in NCHRP Report No. W179. The excessive hourglass energy occurred in the impacting right-front inner rim of the vehicle model and exceeded the total internal energy of the part at the end of the run by more than 10 percent. The part with the most added mass was the set of steel transition blockouts located at post nos. 16 through 21, which had a final mass that exceeded the initial mass of the part by 14 percent and not satisfy the V&V criteria requirement of less than 10 percent. While the hourglass energy and added mass could be resolved, it would result in greater computational run time when compared to the current model. Thus, exceptions were made for the excessive hourglass energy and added mass. The simulated AGT impact with the Ram vehicle model passed the validation criteria with exceptions for deflected posts, exit angle, hourglass energy, and added mass.

6.3 Simulation No. agt-v18--Ram-v2 V&V

In the final validation of the AGT model, the 2270P Ram vehicle model impacted the modeled AGT installation 89 in. (2,261 mm) upstream from the concrete buttress at a speed of 62.7 mph (100.8 km/h) and at an angle of 25 degrees. The modeled AGT successfully contained and redirected the Ram vehicle model with OIVs and ORAs that satisfied the MASH 2016 safety performance criteria, as shown in Table 19. However, when compared to the test no. AGTB-2 crash test data, the Ram simulation exhibited greater longitudinal and lateral OIV values and longitudinal ORA value. Additionally, the Ram simulation had lower system deflections and a lateral ORA value that was lower than test no. AGTB-2.

A summary of the evaluated simulation and full-scale test no. AGTB-2 is contained in Table 19. The full V&V of the simulation no. agt-v18--Ram-v2 simulation is included in Appendix C. A comparison between simulation no. agt-v18--Ram-v2 and full-scale test no. AGTB-2 is depicted in Figure 33 at a time state of 100 ms after impact and sequential images are shown in Figure 34.

Table 19. Summary of Crash Test No. AGTB-2 and Simulation No. agt-v18--Ram-v2 Results

Evaluation Criteria		AGTB-2	agt-v18--Ram-v2	MASH Limits
OIV ft/s (m/s)	Longitudinal	-20.28 (-6.18)	-20.84 (-6.35)	±40
	Lateral	24.61 (7.50)	27.04 (8.24)	±40
ORA g's	Longitudinal	-7.06	-7.75	±20.49
	Lateral	10.40	8.13	±20.49
Maximum Angular Displacement deg.	Roll	21.3	24.8	±75
	Pitch	6.3	6.3	±75
	Yaw	39.6	43.2	not required
Post Max. Dynamic Deflection in. (mm)		5.35 (136)	4.31 (109)	NA
Length of Contact in. (mm)		159 (4,039)	125 (3,165)	NA

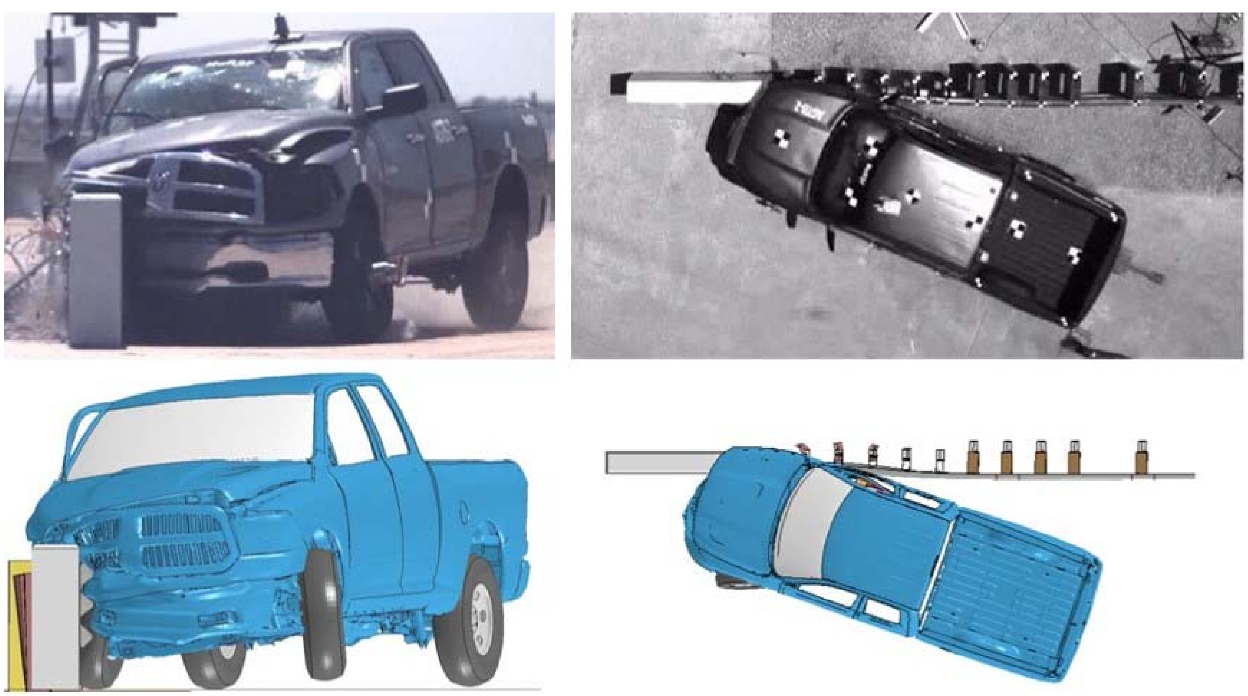
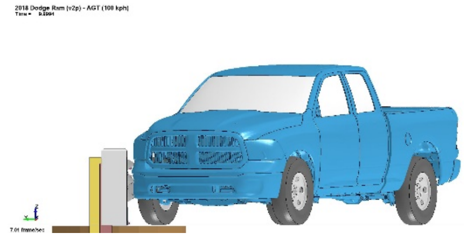


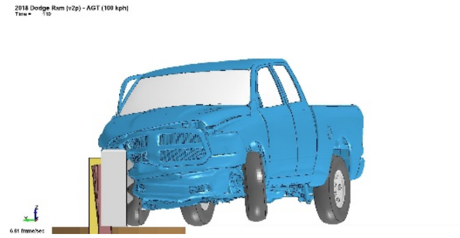
Figure 33. Full-Scale Crash Test No. AGTB-2 (Top) and Simulation No. agt-v18--Ram-v2 (Bottom)

0.000 sec

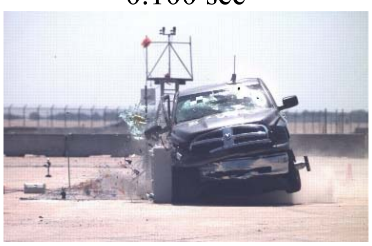


0.000 sec

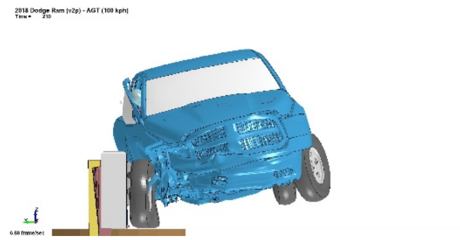
0.100 sec



0.100 sec

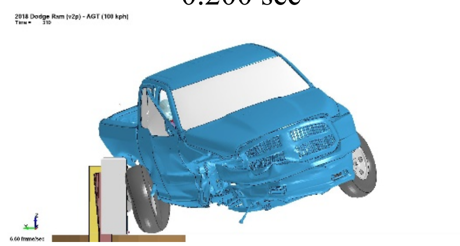


0.200 sec



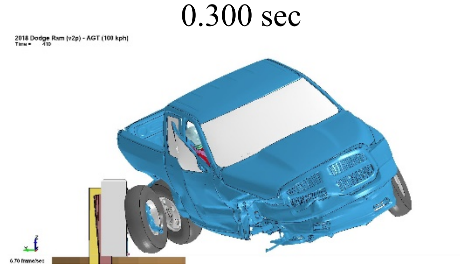
0.200 sec

0.300 sec



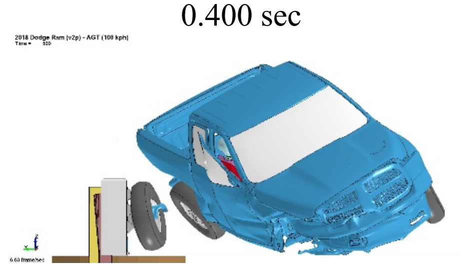
0.300 sec

0.400 sec



0.400 sec

0.500 sec



0.500 sec

Figure 34. Test No. AGTB-2 (Left) vs. Simulation No. agt-v18--Ram-v2 (Right) Sequential Images

The Ram simulation satisfied the V&V procedure requirements with noted exceptions. The modeled AGT installation exhibited a reduced number of significantly bent posts than the known solution. A threshold value of 1 in. (25 mm) was used to classify a post deflection as significant. Seven posts exhibited deflections greater than 1 in. (25 mm) in the full-scale test, compared with five posts in the simulation. This resulted in a relative difference of 29 percent, which exceeded the 20 percent relative difference limit established in the V&V criteria. The difference between the numbers of significantly deflected posts was likely caused by the behavior of the soil.

The posts were installed at a post spacing of 18¾ in. (476 mm) within the impacted region. In the full-scale test, this close proximity meant the soil resistance was dependent on the loading of the adjacent posts. In the simulation however, the soil for each post was modeled with independent soil springs that did not account for the loading of the surrounding soil. Due to this modeling simplification, the load imparted into the barrier by the impacting vehicle in the simulation resulted in localized deflections and fewer significantly deflected posts than the full-scale test.

The Ram vehicle model also exhibited an exit angle that was 5.1 degrees, or 57 percent, greater than the 9.0 degree exit angle in full-scale test no. AGTB-2, which exceeded the 20 percent or 5-degree limit of the V&V criteria. During the full-scale test, the vehicle's right-front wheel detached and slid under the vehicle, creating a partial void in the wheel well. In the simulation, the detached right-front wheel remained in the wheel well while the vehicle was in contact with the installation, likely contributing to the exit angle discrepancy.

Additionally, the simulation did not meet the hourglass energy and added mass requirements outlined in NCHRP Report No. W179. The excessive hourglass energy occurred in the impacting right-front inner rim of the vehicle model and exceeded the total internal energy of the part at the end of the run by more than 10 percent. The part with the most added mass was the set of steel transition blockouts located at post nos. 16 through 21, which had a final mass that exceeded the initial mass of the part by 14 percent and did not satisfy the V&V criteria requirement of less than 10 percent. While the hourglass energy and added mass could be resolved, it would result in greater computational run time when compared to the current model. Thus, exceptions were made for the excessive hourglass energy and added mass. The simulated AGT impact with the Ram vehicle model passed the validation criteria with exceptions for deflected posts, exit angle, hourglass energy, and added mass.

7 SUMMARY OF FINAL MODEL

A model of an AGT was developed and validated against a full-scale crash test previously conducted by MwRSF [1]. The 81-ft 8¼-in. (24.9-m) long modeled AGT installation was composed of 21 guardrail posts, W-beam guardrail, a W-to-thrie transition section, thrie-beam guardrail, a thrie-beam terminal connector, and the standardized concrete buttress. The physical and modeled AGT installations are shown in Figures 35 through 38. A summary of the final, validated AGT model parts and LS-DYNA parameters is included in Tables 20 through 22.

Post nos. 3 through 21 were steel W6x8.5 guardrail posts, which had a yield stress of 56 ksi (386 MPa), and post nos. 1 and 2 were timber breakaway cable terminal (BCT) posts that formed the upstream anchorage. The post spacing was 75 in. (1,905 mm), 37½ in. (953 mm), and 18¾ in. (476 mm) between post nos. 1 through 8, post nos. 8 through 12, and post nos. 12 through 21, respectively. Post nos. 3 through 15 were embedded at a depth of 40 in. (1,016 mm) and post nos. 16 through 21 were embedded at a depth of 49 in. (1,245 mm) below the ground line.

Post nos. 1 and 2 were embedded into solid Drucker-Prager soil elements, which offered a more accurate representation of soil deformation. The soil resistance for post nos. 3 through 21 was simulated by attaching lateral and longitudinal springs to soil tubes that encased the posts below the ground line. The soil springs simulated the reaction of the soil on the posts and were used for the computational efficiency over solid soil elements. The soil tubes were pinned at their center of gravity and the length of the tube length was adjusted to account for each of the embedment depths and ensure proper post rotation.

The upstream portion of the AGT installation used 12-gauge (2.7-mm) W-beam guardrail with a top rail height of 31 in. (787 mm). The system transitioned from W-beam guardrail to standard 12-gauge (2.7-mm) thrie-beam guardrail with an asymmetrical 10-gauge (3.4-mm) W-to-thrie transition section, which maintained the 31-in. (787-mm) top rail height. A 6-ft 3-in. (1,905-mm) long single section of 12-gauge (2.7-mm) thrie-beam was attached to the downstream end of the asymmetric W-to-thrie transition section. The nested section of thrie-beam guardrail, which spanned from post nos. 14 to 21, was modeled with a single 0.21-in. (5.3-mm) thick thrie-beam section, which was equivalent to twice the thickness of a single 12-gauge (2.7-mm) guardrail section. The nested thrie-beam section was anchored to the standardized concrete buttress at the downstream end of the installation with a 10-gauge (3.4-mm) thrie-beam terminal connector.

The standardized concrete buttress had a vertical traffic-side face and a 36-in. (914-mm) total height. The buttress geometry included an 18-in. long x 4½-in. wide x 14-in. tall (457-mm x 114-mm x 356-mm) chamfer on the upstream, traffic-side corner to reduce the potential for wheel snag. An additional 3-in. x 4-in. (76-mm x 102-mm) chamfer extended along the remaining height of the upstream, traffic-side corner of the buttress. The buttress also included a 24-in. long x 4-in. tall (610-mm long x 102-mm tall) taper at the upstream top face and all top edges were chamfered by 1 in. (25 mm).

The validated AGT with standardized buttress LS-DYNA model, developed herein, can be used in numerous AGT research projects. The model can be utilized to evaluate AGT installations as well as modifications to AGT components and configurations. This model was developed and validated based on the installation and performance of test no. AGTB-2. Thus, changes may be made to the model to provide a better comparison in future research projects.

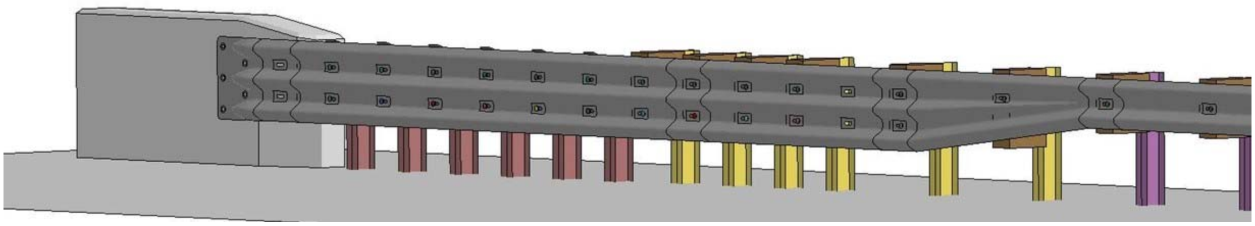


Figure 35. Front View of Test No. AGTB-2 AGT (Top) and Modeled AGT (Bottom)

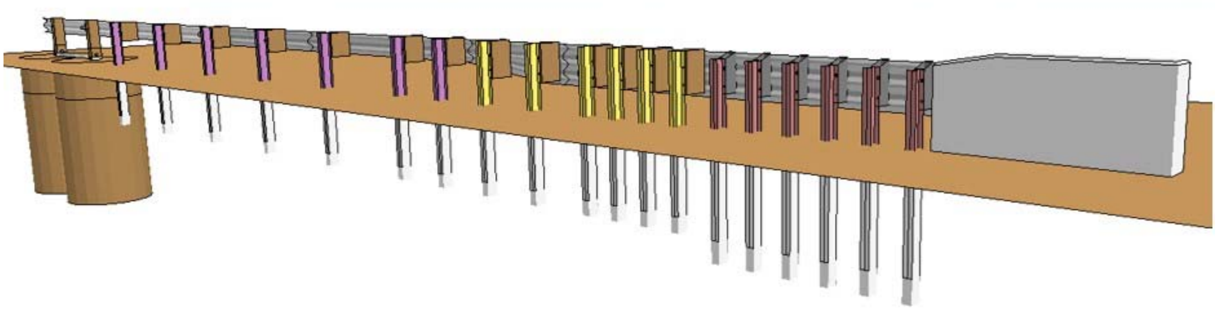


Figure 36. Back View of Test No. AGTB-2 AGT (Top) and Modeled AGT (Bottom)

Figure 37. Front Close-up View of Test No. AGTB-2 AGT (Top) and Modeled AGT (Bottom)

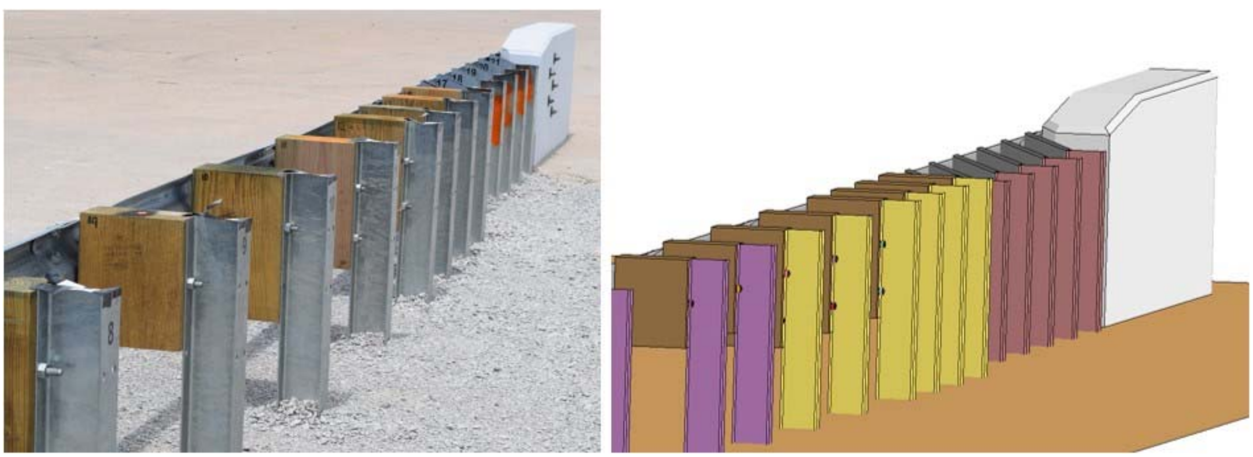


Figure 38. Back Downstream View of Test No. AGTB-2 AGT (Left) and Modeled AGT (Right)

Table 20. Summary of AGT Model Parts and LS-DYNA Parameters

Part Number	Part Name	Element Type (*SECTION)	Element Formulation	Thickness	Material Type	Material Formulation (*MAT)
4700	post-1	Solid	Fully Integrated S/R (2)	-	Wood	Plastic Kinematic
4708	post-1-hole	Solid	Fully Integrated Quadratic 8 Node Element (3)	-	-	Isotropic Elastic Failure
4701	p1-bolt-head-nulls	Shell	Belytschko-Tsay (2)	1	-	Null
4702	p1-bolt-solids	Solid	Constant Stress (1)	-	Steel	Rigid
4703	p1-washer	Solid	Constant Stress (1)	-	Steel	Rigid
4704	p1-tube	Shell	Belytschko-Tsay (2)	2.38125	Steel?	Rigid
4705	p1-tube-bolt	Solid	Constant Stress (1)	-	Steel	Rigid
4706	p1-tube-washers	Solid	Constant Stress (1)	-	Steel	Rigid
4707	p1-tube-yoke-holes	Shell	Belytschko-Tsay (2)	2.38125	-	Rigid
4710	post-2	Solid	Fully Integrated S/R (2)	-	Wood	Plastic Kinematic
4718	post-2-hole	Solid	Fully Integrated Quadratic 8 Node Element (3)	-	-	Isotropic Elastic Failure
4711	p2-bolt-head-nulls	Shell	Belytschko-Tsay (2)	1	-	Null
4712	p2-bolt-solids	Solid	Constant Stress (1)	-	Steel	Rigid
4713	p2-washer	Solid	Constant Stress (1)	-	Steel	Rigid
4714	p2-tube	Shell	Belytschko-Tsay (2)	2.38125	Steel?	Rigid
4715	p2-tube-bolt	Solid	Constant Stress (1)	-	Steel	Rigid
4716	p2-tube-washers	Solid	Constant Stress (1)	-	Steel	Rigid
4717	p2-tube-yoke-holes	Shell	Belytschko-Tsay (2)	2.38125	-	Rigid
4721	ac_bearing-plate	Solid	Constant Stress (1)	-	Steel	Rigid
4722	ac-swage-fitting-and-stud-1	Solid	Constant Stress (1)	-	Steel	Rigid
4723	ac-washer-1	Solid	Constant Stress (1)	-	Steel	Rigid
4724	ac-nut-1	Solid	Constant Stress (1)	-	Steel	Rigid
4725	ac-post-sleeve-1	Solid	Constant Stress (1)	-	Steel	Rigid
4726	ac-end-plate	Solid	Constant Stress (1)	-	Steel	Rigid
4727	ac-swage-fitting-and-stud-2	Solid	Constant Stress (1)	-	Steel	Rigid
4728	ac-washer-2	Solid	Constant Stress (1)	-	Steel	Rigid
4729	ac-nut-2	Solid	Constant Stress (1)	-	Steel	Rigid
4730	anchor-bracket	Solid	Constant Stress (1)	-	Steel	Rigid
4731	ab-washers-nut-side	Solid	Constant Stress (1)	-	Steel	Rigid
4732	ab-washers-head-side	Solid	Constant Stress (1)	-	Steel	Rigid
4733	ab-bolts	Solid	Constant Stress (1)	-	Steel	Rigid
4740	ground-line-strut	Shell	Belytschko-Tsay (2)	5	Steel	Piecewise Linear Plasticity
4720	anchor-cable	Beam	Hughes-Liu (1)	-	6x19 .75 in. Wire Rope	Piecewise Linear Plasticity
4761	soil-top	Solid	-	-	Soil	Drucker Prager
4762	soil-bottom	Solid	-	-	Soil	Drucker Prager
4763	soil-nulls	Shell	Belytschko-Tsay (2)	1	-	Null

Table 21. Summary of AGT Model Parts and LS-DYNA Parameters, Cont.

Part Number	Part Name	Element Type (*SECTION)	Element Formulation	Thickness	Material Type	Material Formulation (*MAT)
4764	soil-crate	Shell	Belytschko-Tsay (2)	1	-	Rigid
1001	buttress--front	Shell	Belytschko-Tsay (2)	2	Concrete	Rigid
1002	buttress-side	Shell	Belytschko-Tsay (2)	2	Concrete	Rigid
1003	buttress-top	Shell	Belytschko-Tsay (2)	2	Concrete	Rigid
1004	buttress-back	Shell	Belytschko-Tsay (2)	2	Concrete	Rigid
4100	post-bolt-springs-w	Discrete	DRO=Translational Spring/Damper (0)	-	Steel?	Spring Nonlinear Elastic
4101	post-bolt-springs-thrie	Discrete	DRO=Translational Spring/Damper (0)	-	Steel?	Spring Nonlinear Elastic
4102	post-bolt-springs-tran	Discrete	DRO=Translational Spring/Damper (0)	-	Steel?	Spring Nonlinear Elastic
4203-4221	bolt-p3 - bolt-p21	Solid	Fully Integrated S/R (2)	-	Steel	Rigid
4303-4321	nut-p3 - nut-p21	Solid	Fully Integrated S/R (2)	-	Steel	Rigid
4151	post-bolt-springs-thrie-b	Discrete	DRO=Translational Spring/Damper (0)	-	Steel?	Spring Nonlinear Elastic
4152	post-bolt-springs-tran-b	Discrete	DRO=Translational Spring/Damper (0)	-	Steel?	Spring Nonlinear Elastic
4261-4271	bolt-p11b - bolt-p21b	Solid	Fully Integrated S/R (2)	-	Steel	Rigid
4361-4371	nut-p11b - nut-p21b	Solid	Fully Integrated S/R (2)	-	Steel	Rigid
4001	posts-w-flange	Shell	Fully Integrated Shell Element (16)	4.953	Steel (A36)	Piecewise Linear Plasticity
4002	posts-w-web	Shell	Fully Integrated Shell Element (16)	4.318	Steel (A36)	Piecewise Linear Plasticity
4003	posts-w-blockouts	Solid	Fully Integrated S/R (2)	-	Wood	Elastic
4011	posts-thrie-flange	Shell	Fully Integrated Shell Element (16)	4.953	Steel (A36)	Piecewise Linear Plasticity
4012	posts-thrie-web	Shell	Fully Integrated Shell Element (16)	4.318	Steel (A36)	Piecewise Linear Plasticity
4013	posts-thrie-blockouts	Solid	Fully Integrated S/R (2)	-	Wood	Elastic
4021	posts-tran-flange	Shell	Fully Integrated Shell Element (16)	4.953	Steel (A36)	Piecewise Linear Plasticity
4022	posts-tran-web	Shell	Fully Integrated Shell Element (16)	4.318	Steel (A36)	Piecewise Linear Plasticity
4400	soil-parallel-w	Discrete	DRO=Translational Spring/Damper (0)	-	Equivalent Soil	Spring General Nonlinear
4401	soil-perpendic-w	Discrete	DRO=Translational Spring/Damper (0)	-	Equivalent Soil	Spring General Nonlinear
4402	soil-parallel-thrie	Discrete	DRO=Translational Spring/Damper (0)	-	Equivalent Soil	Spring General Nonlinear
4403	soil-perpendic-thrie	Discrete	DRO=Translational Spring/Damper (0)	-	Equivalent Soil	Spring General Nonlinear
4404	soil-parallel-tran	Discrete	DRO=Translational Spring/Damper (0)	-	Equivalent Soil	Spring General Nonlinear
4405	soil-perpendic-tran	Discrete	DRO=Translational Spring/Damper (0)	-	Equivalent Soil	Spring General Nonlinear
4410	soil-masses-w	Shell	Belytschko-Tsay (2)	0.5	-	Rigid
4412	soil-masses-thrie	Shell	Belytschko-Tsay (2)	0.5	-	Rigid
4414	soil-masses-tran	Shell	Belytschko-Tsay (2)	0.5	-	Rigid
4503-4521	tube-3 - tube-21	Shell	Belytschko-Tsay (2)	0.5	-	Rigid
4023	tran-blockouts-steel	Shell	Fully Integrated Shell Element (16)	4.7625	Steel	Piecewise Linear Plasticity
4040-4051	bo-hole-p16-rr-upr - bo-hole-p21-rr-lwr	Shell	Fully Integrated Shell Element (16)	4.7625	-	Rigid
4060-4071	bo-hole-p16-frt-upr - bo-hole-p21-frt-lwr	Shell	Fully Integrated Shell Element (16)	4.7625	-	Rigid
2001	wbeam-1-25ft	Shell	Fully Integrated Shell Element (16)	2.67	Steel	Piecewise Linear Plasticity
2002	wbeam-1-holes	Shell	Fully Integrated Shell Element (16)	2.67	-	Piecewise Linear Plasticity
2003	wbeam-1-holes-ab-rigid	Shell	Fully Integrated Shell Element (16)	2.67	-	Rigid
2004	wbeam-1-holes-nulls	Shell	Fully Integrated Shell Element (16)	2.67	-	Null

Table 22. Summary of AGT Model Parts and LS-DYNA Parameters, Cont.

Part Number	Part Name	Element Type (*SECTION)	Element Formulation	Thickness	Material Type	Material Formulation (*MAT)
2005	wbeam-2-12.5ft	Shell	Fully Integrated Shell Element (16)	2.67	Steel	Piecewise Linear Plasticity
2006	wbeam-3-12.5ft	Shell	Fully Integrated Shell Element (16)	2.67	Steel	Piecewise Linear Plasticity
2007	wbeam-mid-holes	Shell	Fully Integrated Shell Element (16)	2.67	-	Piecewise Linear Plasticity
2011	w2t-rail	Shell	Fully Integrated Shell Element (16)	3.43	Steel	Piecewise Linear Plasticity
2012	w2t-rail-holes	Shell	Fully Integrated Shell Element (16)	3.43	-	Piecewise Linear Plasticity
2015	thrie-1	Shell	Fully Integrated Shell Element (16)	2.67	Steel	Piecewise Linear Plasticity
2016	thrie-1-holes	Shell	Fully Integrated Shell Element (16)	2.67	-	Piecewise Linear Plasticity
2017	thrie-2	Shell	Fully Integrated Shell Element (16)	5.34	Steel	Piecewise Linear Plasticity
2018	thrie-2-holes	Shell	Fully Integrated Shell Element (16)	5.34	-	Piecewise Linear Plasticity
2021	thrie-end-shoe	Shell	Fully Integrated Shell Element (16)	3.43	Steel	Piecewise Linear Plasticity
2022	thrie-end-shoe-holes	Shell	Fully Integrated Shell Element (16)	3.43	-	Rigid

8 REFERENCES

1. Rosenbaugh, S.K., Faller, R.K., Asselin, N., and Hartwell, J.A., *Development of a Standardized Buttress for Approach Guardrail Transitions,* Report No. TRP-03-369-20, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, November 10, 2020.

2. Ray, M.H., Plaxico, C.A., and Anghileri, M., *Procedures for Verification and Validation of Computer Simulations Used for Roadside Safety Applications,* NCHRP Web-Only Report No. 179, NCHRP Project No. 22-24, March 2010.

3. Bickhaus, R.F., Rasmussen, J.D., Bielenberg, R.W., Rosenbaugh, S.K., Faller, R.K., and Reid, J.D., *Evaluation of Flare Rates for Approach Guardrail Transitions – Phase I,* Report No. TRP-03-439-20, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, Draft Report.

4. *LS-DYNA Keyword User's Manual, Volume 1 R10.1* Livermore Software Technology Company (LSTC), Livermore, California, 2017.

5. Mongiardini, M., Faller, R.K., Reid, J.D., Sicking, D.L., Stolle, C.S., and Lechtenberg, K.A., *Downstream Anchoring Requirements for the Midwest Guardrail System*, Report No. TRP-03-279-13, Midwest Roadside Safety Facility, University of Nebraska-Lincoln, Lincoln, Nebraska, October 28, 2013.

6. Mongiardini, M., Faller, R.K., Reid, J.D., and Sicking, D.L., *Dynamic Evaluation and Implementation Guidelines for a Non-Proprietary W-Beam Guardrail Trailing-End Terminal*, Paper No. 13-5277, Transportation Research Record No. 2377, Journal of the Transportation Research Board, TRB AFB20 Committee on Roadside Safety Design, Transportation Research Board, Washington D.C., January 2013, pages 61-73.

7. Stolle, C.S., Reid, J.D., Faller, R.K., and Mongiardini, M., *Dynamic Strength of a Modified W-Beam BCT Trailing-End Termination*, Paper No. IJCR 886R1, Manuscript ID 1009308, International Journal of Crashworthiness, Taylor & Francis, Vol. 20, Issue 3, Published online February 23, 2015, pages 301-315.

8. *Manual for Assessing Safety Hardware (MASH), Second Edition*, American Association of State Highway and Transportation Officials (AASHTO), Washington, D.C., 2016.

9. Pajouh, M.A., Schmidt, J.D., Bielenberg, R.W., Reid, J.D., and Faller, R.K., *Simplified Soil-Pile Interaction Modeling under Impact Loading,* Geotechnical Earthquake Engineering and Soil Dynamics V GSP 292, ASCE, 2018, pages 269-280.

10. *Vehicle Modeling,* National Crash Analysis Center, George Washington University, Washington, D.C. Retrieved from: http://www.ncac.gwu.edu/research/reports.html, August 20, 2014.

11. Dhafer, M., *Update on New MASH Pickup Truck Model,* Center for Collision Safety and Analysis, TRB 98th Annual Meeting (2019) Roadside Safety Design Computational Mechanics Subcommittee, AFB20(1), Washington, D.C., January 14, 2019, Obtained on February 12, 2019.Polivka, K.A., Eller, C.M., Faller, R.K., Sicking, D.S., Rohde, J.R., Reid, J.D.,

9 APPENDICES

Appendix A. V&V of Simulation No. agt-v3r-v15-single-thrie

A MASH 2270P Pickup Truck
(Report 350 or MASH08 or EN1317 Vehicle Type)

Striking a 31-in. tall Approach Guardrail Transition
(roadside hardware type and name)

Report Date: ______

Type of Report (check one)

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

General Information	Known Solution	Analysis Solution
Performing Organization	MwRSF	MwRSF
Test/Run Number:	AGTB-2	agt-v3r-v15-single-thrie
Vehicle:	2010 Dodge Ram 1500 Quad Cab	2007 Chevrolet Silverado
Reference:		
Impact Conditions		
Vehicle Mass:	2267 kg	2270 kg
Speed:	100.8 km/h	100.8 km/h
Angle:	25.4	25.0
Impact Point:	152 mm US CL P17	152 mm US CL P17

Composite Validation/Verification Score

	List the Report 350/MASH08 or EN1317 Test Number
Part I	Did all solution verification criteria in Table E-1 pass?
Part II	Do all the time history evaluation scores from Table E-2 result in a satisfactory comparison (i.e., the comparison passes the criterion)? If all the values in Table E-2 did not pass, did the weighted procedure shown in Table E-3 result in an acceptable comparison. If all the criteria in Table E-2 pass, enter "yes." If all the criteria in Table E-2 did not pass but Table E-3 resulted in a passing score, enter "yes."
Part III	All the criteria in Table E-4 (Test-PIRT) passed?
	Are the results of Steps I through III all affirmative (i.e., YES)? If all three steps result in a "YES" answer, the comparison can be considered validated or verified. If one of the steps results in a negative response, the result cannot be considered validated or verified.

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

PART I: BASIC INFORMATION

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

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

2. What test guidelines were used to perform the full-scale crash test (check one)?
   ☐ NCHRP Report 350
   ☐ MASH08
   ☐ EN1317
   ☒ Other: _____MASH 2016______________________________

3. Indicate the test level and number being evaluated (fill in the blank). ________3-21__________

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

NCHRP Report 350/MASH08

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

EN1317

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

PART II: ANALYSIS SOLUTION VERIFICATION

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

Table E-1. Analysis Solution Verification Table

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	1.2%	**Yes**
Hourglass Energy of the analysis solution at the end of the run is less than *five percent* of the total *initial energy* at the *beginning* of the run.	11.36%	**No**
Hourglass Energy of the analysis solution at the end of the run is less than *ten percent* of the total *internal energy* at the *end* of the run.	54.69%	**No**
The part/material with the highest amount of hourglass energy at the end of the run is less than ten percent of the total internal energy of the part/material at the end of the run. (Part id=2000682, hg=40200, internal energy at end of run=302)	13,311%	**No**
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	0.07%	**Yes**
The part/material with the most mass added had less than 10 percent of its initial mass added. (Part id=4023: tran-blockouts-steel, Initial Mass=48.285 kg, Mass Added=9.64 kg)	19.96%	**No**
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	0.19%	**Yes**
There are no shooting nodes in the solution?	No	**Yes**
There are no solid elements with negative volumes?	No	**Yes**

If all the analysis solution verification criteria are scored as passing, the analysis solution can be verified or validated against the known solution. If any criterion in Table E-1 does not pass one of the verification criterion listed in Table E-1, the analysis solution cannot be used to verify or validate the known solution. If there are exceptions that the analyst thinks are relevant these should be footnoted in the table and explained below the table.

The Analysis Solution (check one) ☐ passes ☒ does NOT pass <u>all</u> the criteria in Table E1-1

☐with ☐without exceptions as noted.

PART III: TIME HISTORY EVALUATION TABLE

Using the RSVVP computer program ('Single channel' option), compute the Sprague-Geers MPC metrics and ANOVA metrics using time-history data from the known and analysis solutions for a time period starting at the beginning of the contact and ending at the loss of contact. Both the Sprague-Geers and ANOVA metrics must be calculated based on the original units the data was collected in (e.g., if accelerations were measured in the experiment with accelerometers then the comparison should be between accelerations. If rate gyros were used in the experiment, the comparison should be between rotation rates). If all six data channels are not available for both the known and analysis solutions, enter "N/A" in the column corresponding to the missing data. Enter the values obtained from the RSVVP program in Table E-2 and indicate if the comparison was acceptable or not by entering a "yes" or "no" in the "Agree?" column. Attach a graph of each channel for which the metrics have been compared at the end of the report.

Enter the filter, synchronization method and shift/drift options used in RSVVP to perform the comparison so that it is clear to the reviewer what options were used. Normally, SAE J211 filter class 180 is used to compare vehicle kinematics in full-scale crash tests. Either synchronization option in RSVVP is acceptable and both should result in a similar start point. The shift and drift options should generally only be used for the experimental curve since shift and drift are characteristics of sensors. For example, the zero point for an accelerometer sometimes "drifts" as the accelerometer sits out in the open environment of the crash test pad whereas there is no sensor to "drift" or "shift" in a numerical solution.

In order for the analysis solution to be considered in agreement with the known solution (i.e., verified or validated), all the criteria scored in Table E-2 must pass. If all the channels in Table E-2 do not pass, fill out Table E-3, the multi-channel weighted procedure.

If one or more channels do not satisfy the criteria in Table E-2, the multi-channel weighting option may be used. Using the RSVVP computer program ('Multiple channel' option), compute the Sprague-Geers MPC metrics and ANOVA metrics using all the time histories data from the known and analysis solutions for a time period starting at the beginning of the contact and ending at the loss of contact. If all six data channels are not available for both the known and analysis solutions, enter "N/A" in the column corresponding to the missing data.

For some types of roadside hardware impacts, some of the channels are not as important as others. An example might be a breakaway sign support test where the lateral (i.e., Y) and vertical (i.e., Z) accelerations are insignificant to the dynamics of the crash event. The weighting procedure provides a way to weight the most important channels more highly than less important channels. The procedure used is based on the area under the curve, therefore, the weighing scheme will weight channels with large areas more highly than those with smaller areas. In general, using the "Area (II)" method is acceptable although if the complete inertial properties of the vehicle are available the "inertial" method may be used. Enter the values obtained from the RSVVP program in Table E-3 and indicate if the comparison was acceptable or not by entering a "yes" or "no" in the "Agree?" column.

In order for the analysis solution to be considered in agreement with the known solution (i.e., verified or validated), all the criteria scored in Table E-3 must pass.

Table E-2. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (single channel option – CFC-60)

	Evaluation Criteria							Time interval [_0 sec; 0.5 sec_]		
O	***Sprague-Geers Metrics*** List all the data channels being compared. Calculate the M and P metrics using RSVVP and enter the results. Values less than or equal to 40 are acceptable.									
		RSVVP Curve Preprocessing Options						**M**	**P**	**Pass?**
		Filter Option	**Sync. Option**	**Shift**		**Drift**				
				True Curve	**Test Curve**	**True Curve**	**Test Curve**			
	X acceleration	CFC 60	N	N	N	N	N	20.7	31.6	**Yes**
	Y acceleration	CFC 60	N	N	N	N	N	6.4	25.7	**Yes**
	Z acceleration	CFC 60	N	N	N	N	N	27.1	48.5	**No**
	Roll rate	CFC 60	N	N	N	N	N	0.9	36.2	**Yes**
	Pitch rate	CFC 60	N	N	N	N	N	11	47.5	**No**
	Yaw rate	CFC 60	N	N	N	N	N	20	11.2	**Yes**
P	***ANOVA Metrics*** List all the data channels being compared. Calculate the ANOVA metrics using RSVVP and enter the results. Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$) and • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)							**Mean Residual**	**Standard Deviation of Residuals**	**Pass?**
	X acceleration/Peak							-0.48	21.61	**Yes**
	Y acceleration/Peak							1.84	26.53	**Yes**
	Z acceleration/Peak							-2.31	33.5	**Yes**
	Roll rate							1.24	7.1	**Yes**
	Pitch rate							0.24	9.34	**Yes**
	Yaw rate							0.93	11.37	**Yes**

The Analysis Solution (check one) ☐ passes ☒ does NOT pass all the criteria in Table E-2 (single-channel time history comparison). If the Analysis Solution does NOT pass, perform the analysis in Table E-3 (multi-channel time history comparison).

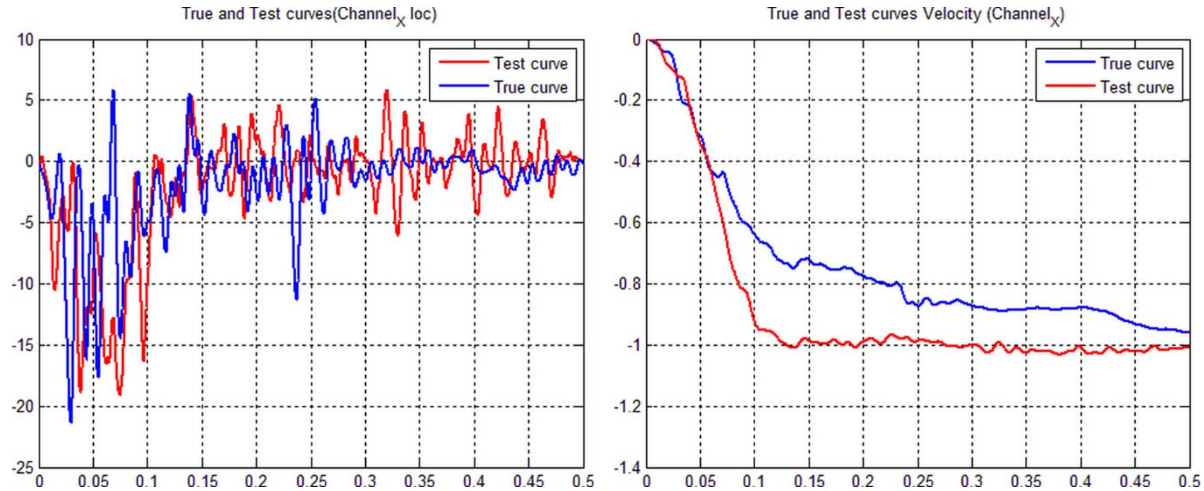


Figure 1. X-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

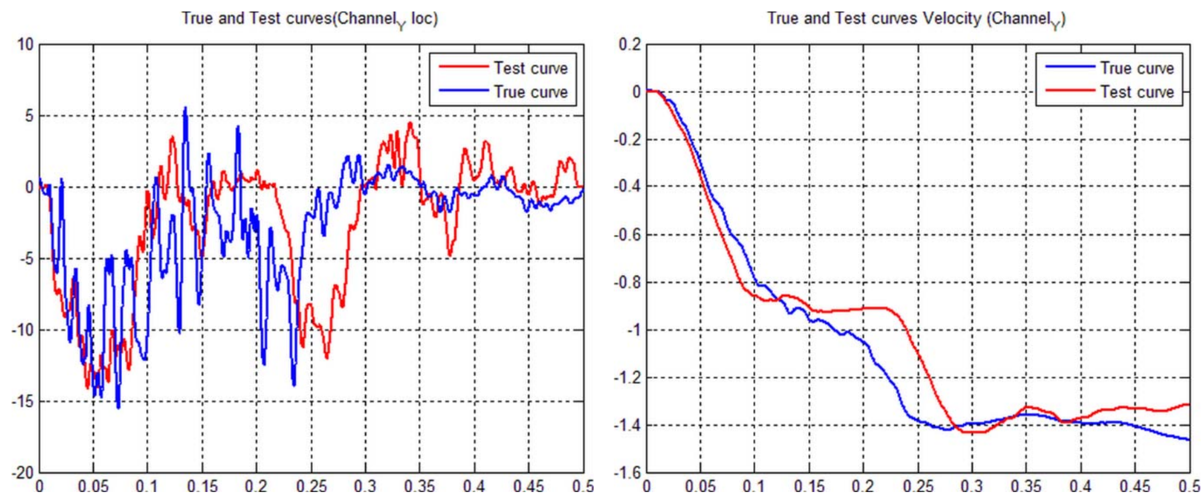


Figure 2. Y-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

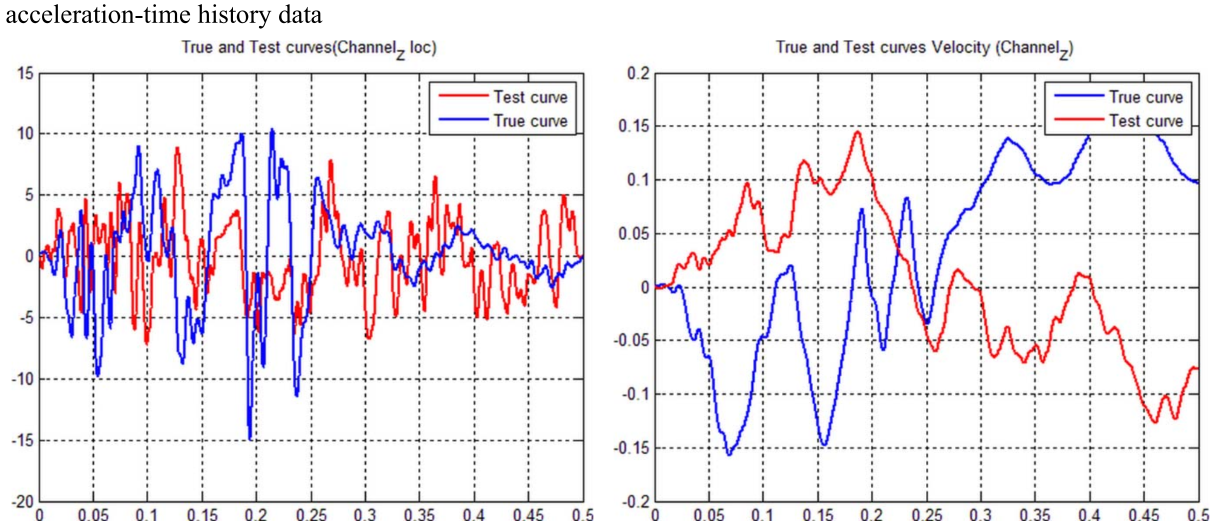


Figure3. Z-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

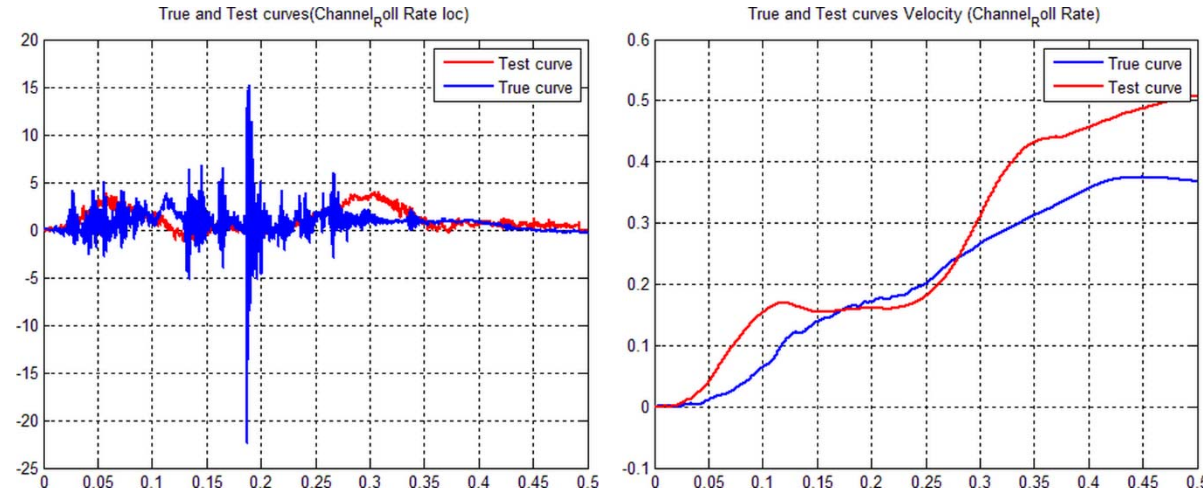


Figure 4. Roll Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

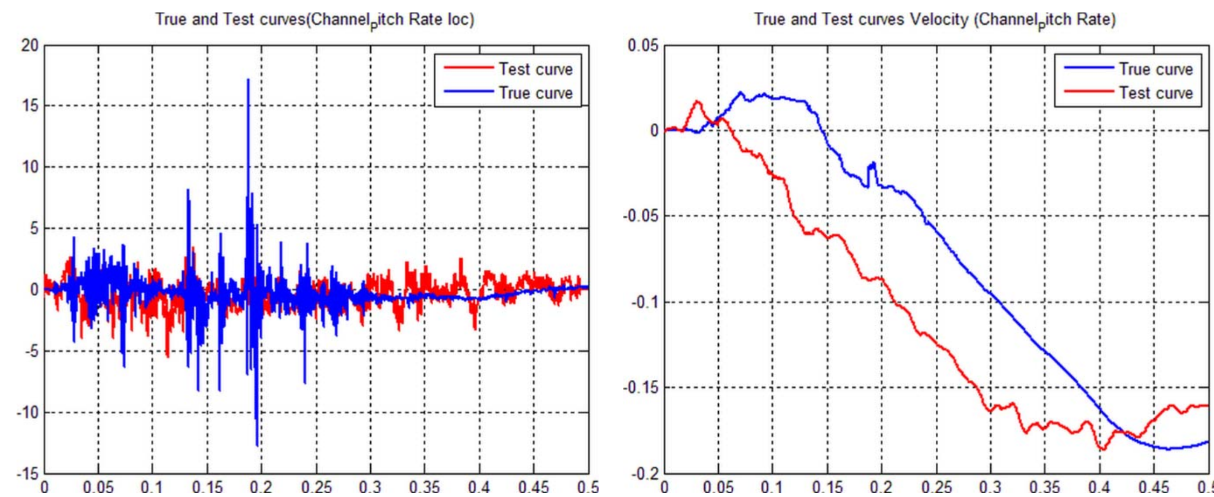


Figure 5. Pitch Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

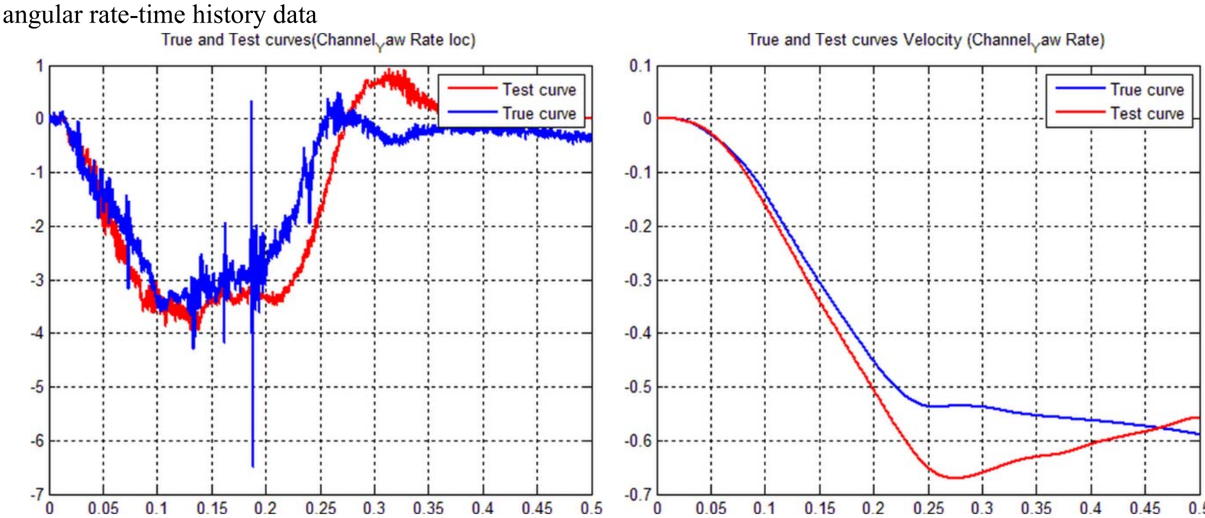
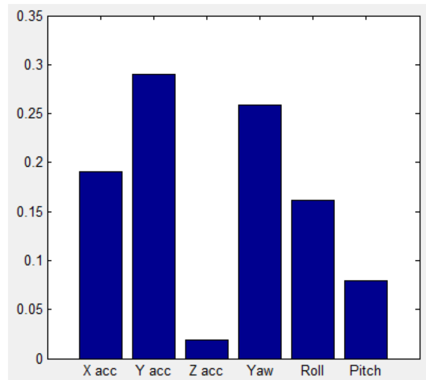


Figure 6. Yaw Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

Table E-3. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (multi-channel option – CFC-60)

Evaluation Criteria (time interval [_0 sec; 0.5 sec_])					
Channels (Select which were used)					
☒ **X Acceleration**		☒ **Y Acceleration**	☒ **Z Acceleration**		
☒ **Roll rate**		☒ **Pitch rate**	☒ **Yaw rate**		
Multi-Channel Weights ☒ **Area II method** ☐ **Inertial method**		**X Channel:** **Y Channel:** **Z Channel:** **Yaw Channel:** **Roll Channel:** **Pitch Channel:**			
O	***Sprague-Geer Metrics*** Values less or equal to 40 are acceptable.		**M** 12.5	**P** 27	**Pass?** **Yes**
P	***ANOVA Metrics*** Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$) • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)		**Mean Residual** 0.9	**Standard Deviation of Residuals** 17.3	**Pass?** **Yes**

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

Table E-2. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (single channel option – CFC-180)

Evaluation Criteria										
O	***Sprague-Geers Metrics*** List all the data channels being compared. Calculate the M and P metrics using RSVVP and enter the results. Values less than or equal to 40 are acceptable.							**Time interval [_0 sec; 0.5 sec_]**		
		RSVVP Curve Preprocessing Options						**M**	**P**	**Pass?**
		Filter Option	**Sync. Option**	**Shift**		**Drift**				
				True Curve	**Test Curve**	**True Curve**	**Test Curve**			
	X acceleration	CFC 180	N	N	N	N	N	29.9	36	**Yes**
	Y acceleration	CFC 180	N	N	N	N	N	3.1	28.7	**Yes**
	Z acceleration	CFC 180	N	N	N	N	N	1	50.4	**No**
	Roll rate	CFC 180	N	N	N	N	N	0.9	36.2	**Yes**
	Pitch rate	CFC 180	N	N	N	N	N	11	47.5	**No**
	Yaw rate	CFC 180	N	N	N	N	N	20	11.2	**Yes**
P	***ANOVA Metrics*** List all the data channels being compared. Calculate the ANOVA metrics using RSVVP and enter the results. Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\overline{e} \leq 0.05 \cdot a_{Peak}$) and • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)							**Mean Residual**	**Standard Deviation of Residuals**	**Pass?**
	X acceleration/Peak							-0.43	23.44	**Yes**
	Y acceleration/Peak							1.49	25.23	**Yes**
	Z acceleration/Peak							-1.67	31.54	**Yes**
	Roll rate							1.24	7.1	**Yes**
	Pitch rate							0.24	9.34	**Yes**
	Yaw rate							0.93	11.37	**Yes**

The Analysis Solution (check one) ☐ passes ☒ does NOT pass all the criteria in Table E-2 (single-channel time history comparison). If the Analysis Solution does NOT pass, perform the analysis in Table E-3 (multi-channel time history comparison).

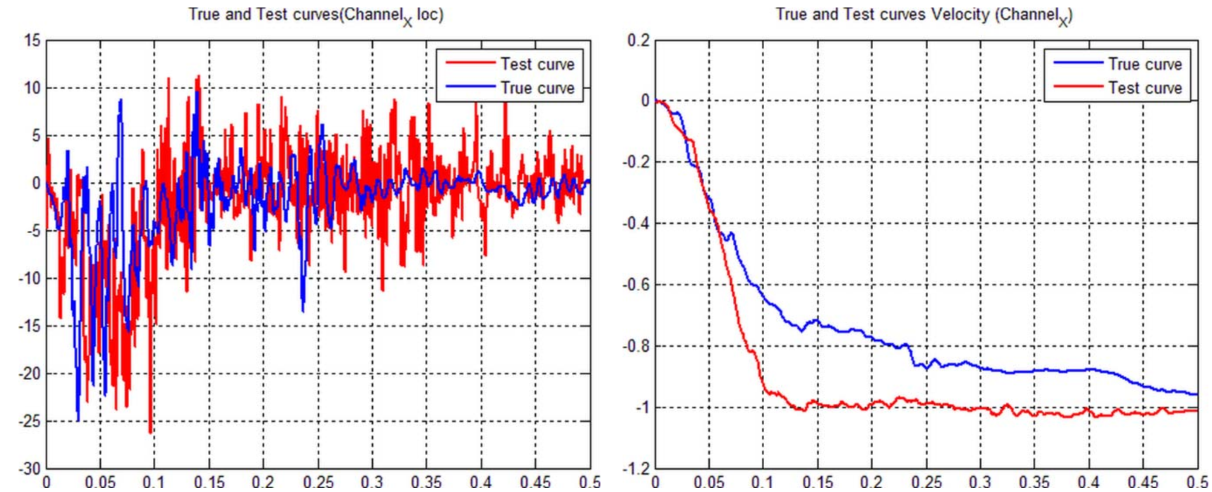


Figure 7. X-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

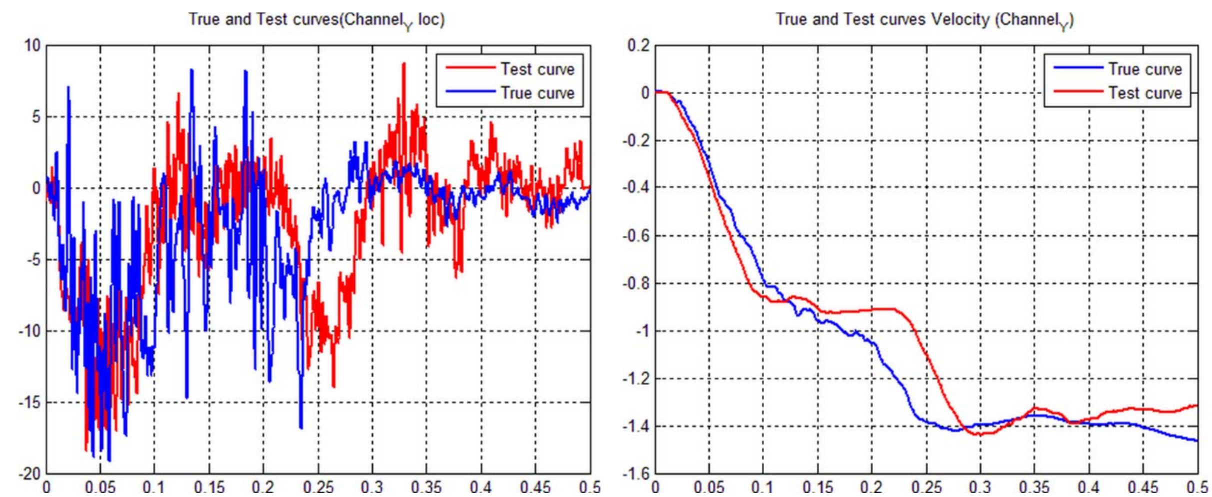


Figure 8. Y-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

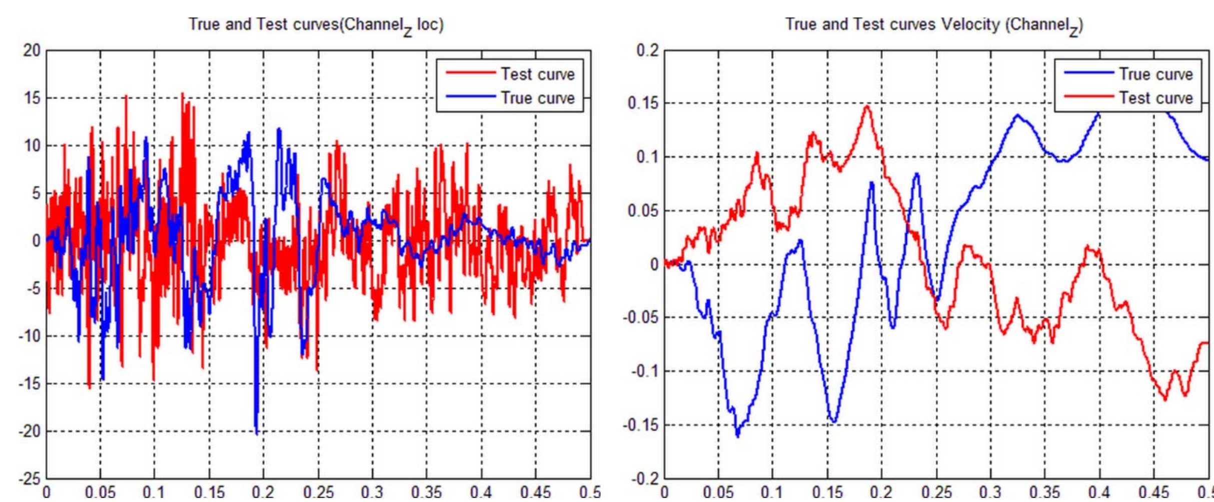


Figure 9. Z-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

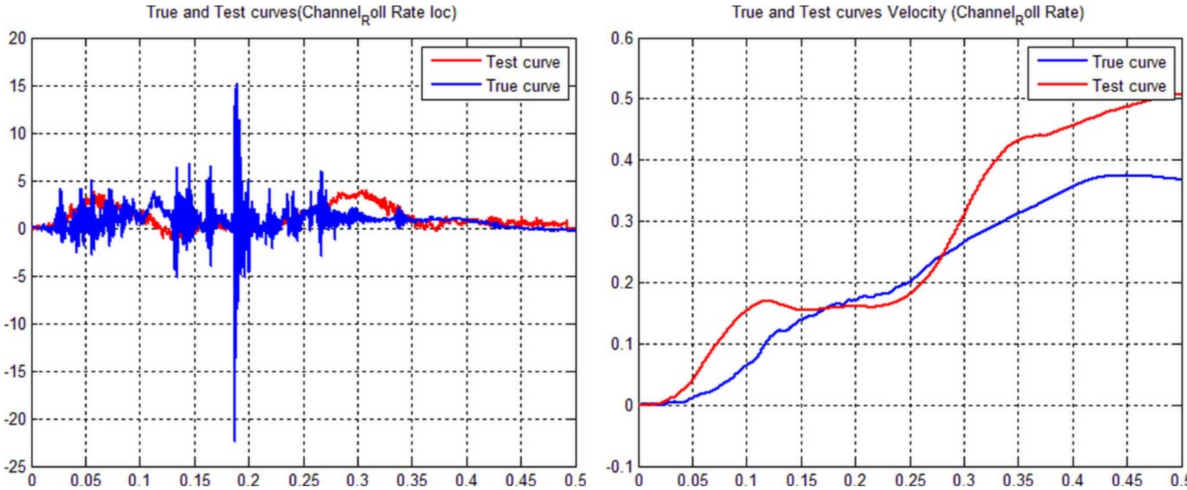


Figure 10. Roll Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

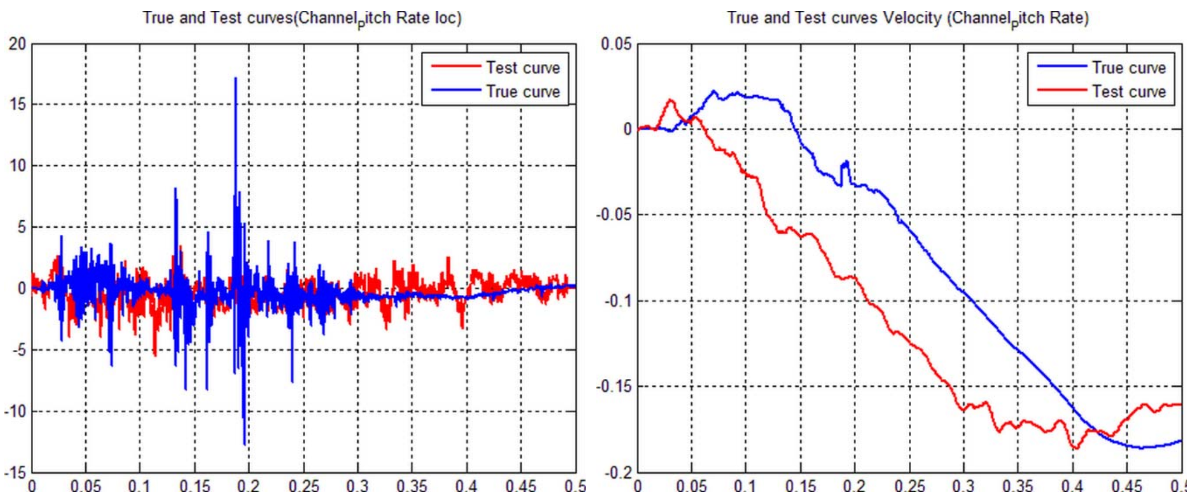


Figure 11. Pitch Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

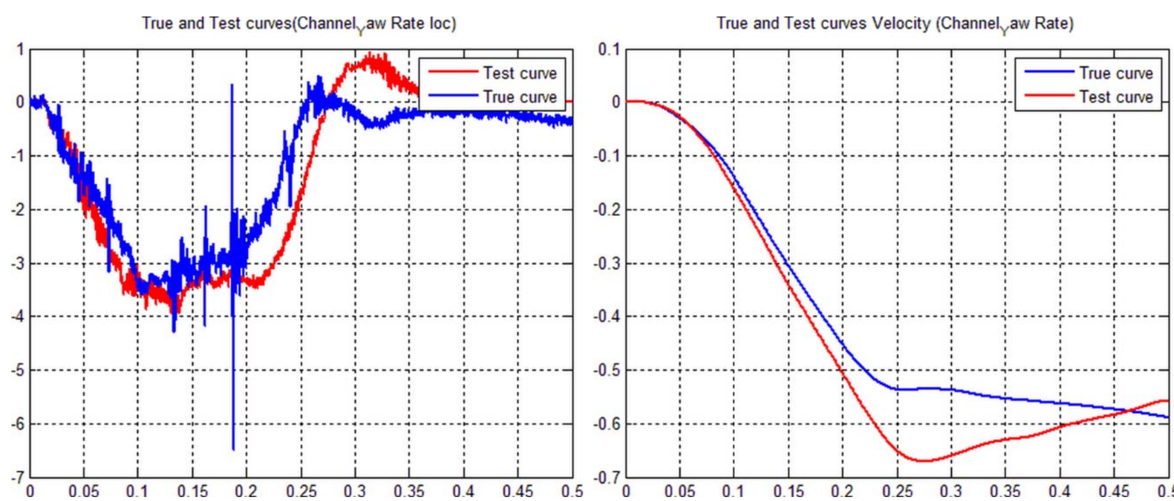
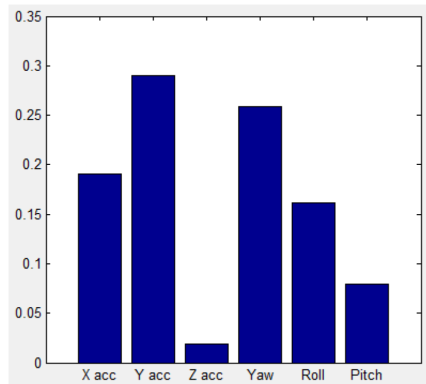


Figure 12. Yaw Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

Table E-3. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (multi-channel option – CFC-180)

Evaluation Criteria (time interval [_0 sec; 0.5 sec_])		
Channels (Select which were used)		
☒ **X Acceleration**	☒ **Y Acceleration**	☒ **Z Acceleration**
☒ **Roll rate**	☒ **Pitch rate**	☒ **Yaw rate**
Multi-Channel Weights ☒ **Area II method** ☐ **Inertial method**	**X Channel:** **Y Channel:** **Z Channel:** **Yaw Channel:** **Roll Channel:** **Pitch Channel:**	

O	***Sprague-Geer Metrics*** Values less or equal to 40 are acceptable.	**M**	**P**	**Pass?**
		12.8	28.7	**Yes**
P	***ANOVA Metrics*** Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration $(\bar{e} \leq 0.05 \cdot a_{Peak})$ • The standard deviation of the residuals must be less than 35 percent of the peak acceleration $(\sigma \leq 0.35 \cdot a_{Peak})$	**Mean Residual**	**Standard Deviation of Residuals**	**Pass?**
		0.8	17.2	**Yes**

The Analysis Solution (check one) ☒ passes ☐ does NOT pass all the criteria in Table E-3.

PART IV: PHENOMENA IMPORTANCE RANKING TABLE

Table E-4 is similar to the evaluation tables in Report 350 and MASH. For the Report 350 or MASH test number identified in Part I (e.g., test 3-10, 5-12, etc.), circle all the evaluation criteria applicable to that test in Table E-4. The tests that apply to each criterion are listed in the far right column without the test level designator. For example, if a Report 350 test 3-11 is being compared (i.e., a pickup truck striking a barrier at 25 degrees and 100 km/hr), circle all the criteria in the second column where the number “11” appears in the far right column. Some of the Report 350 evaluation criteria have been removed (i.e., J and K) since they are not generally useful in assessing the comparison between the known and analysis solutions.

Table E-4. Evaluation Criteria Test Applicability Table

<table>
<tr><th>Evaluation Factors</th><th colspan="2">Evaluation Criteria</th><th>Applicable Tests</th></tr>
<tr><td rowspan="2">Structural Adequacy</td><td>A</td><td>Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38</td></tr>
<tr><td>B</td><td>The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>60, 61, 70, 71, 80, 81</td></tr>
<tr><td></td><td>C</td><td>Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>30, 31,, 32, 33, 34, 39, 40, 41, 42, 43, 44, 50, 51, 52, 53</td></tr>
<tr><td rowspan="7">Occupant Risk</td><td>D</td><td>Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.</td><td>All</td></tr>
<tr><td>E</td><td>Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver's vision or otherwise cause the driver to lose control of the vehicle. (Answer Yes or No)</td><td>70, 71</td></tr>
<tr><td>F</td><td>The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.</td><td>All except those listed in criterion G</td></tr>
<tr><td>G</td><td>It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>12, 22 (for test level 1 – 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44)</td></tr>
<tr><td rowspan="2">H</td><td>Occupant impact velocities should satisfy the following:<table><tr><th colspan="3">Occupant Impact Velocity Limits (m/s)</th></tr><tr><th>Component</th><th>Preferred</th><th>Maximum</th></tr><tr><td>Longitudinal and Lateral</td><td>9</td><td>12</td></tr></table></td><td>10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 80, 81</td></tr>
<tr><td><table><tr><td>Longitudinal</td><td>3</td><td>5</td></tr></table></td><td>60, 61, 70, 71</td></tr>
<tr><td>I</td><td>Occupant ridedown accelerations should satisfy the following:<table><tr><th colspan="3">Occupant Ridedown Acceleration Limits (g's)</th></tr><tr><th>Component</th><th>Preferred</th><th>Maximum</th></tr><tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td></tr></table></td><td>10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 60, 61, 70, 71, 80, 81</td></tr>
<tr><td rowspan="3">Vehicle Trajectory</td><td>L</td><td>The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant ride-down acceleration in the longitudinal direction should not exceed 20 G's.</td><td>11,21, 35, 37, 38, 39</td></tr>
<tr><td>M</td><td>The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38, 39</td></tr>
<tr><td>N</td><td>Vehicle trajectory behind the test article is acceptable.</td><td>30, 31, 32, 33, 34, 39, 42, 43, 44, 60, 61, 70, 71, 80, 81</td></tr>
</table>

Complete Table E-5 according to the results of the known solution (e.g., crash test) and the numerical solution (e.g., simulation). Consistent with Report 350 and MASH, Task E-5 has three parts: the structural adequacy phenomena listed in Table E-5a, the occupant risk phenomena listed in Table E-5b and the vehicle trajectory criteria listed in Table E-5c. If the result of the analysis solution agrees with the known solution, mark the “agree” column “yes.” For example, if the vehicle in both the known and analysis solutions rolls over and, therefore, fails criterion F1, the known and the analysis columns for criterion F1 would be evaluated as “no.” Even though both failed the criteria, they agree with each other so the “agree” column is marked as “yes.” Any criterion that is not applicable to the test being evaluated (i.e., not circled in Table E-4) should be indicated by entering “NA” in the “agree?” column for that row.

Many of the Report 350 evaluation criteria have been subdivided into more specific phenomenon. For example, criterion A is divided into eight sub-criteria, A1 through A8, that provide more specific and quantifiable phenomena for evaluation. Some of the values are simple yes or no questions while other request numerical values. For the numerical phenomena, the analyst should enter the value for the known and analysis result and then calculate the relative difference. Relative difference is always the absolute value of the difference of the known and analysis solutions divided by the known solution. Enter the value in the “relative difference” column. If the relative difference is less than 20 percent, enter “yes” in the “agree?” column.

Sometimes, when the values are very small, the relative difference might be large while the absolute difference is very small. For example, the longitudinal occupant ride down acceleration (i.e., criterion L2) in a test might be 3 g’s and in the corresponding analysis might be 4 g’s. The relative difference is 33 percent but the absolute difference is only 1 g and the result for both is well below the 20 g limit. Clearly, the analysis solution in this case is a good match to the experiment and the relative difference is large only because the values are small. The absolute difference, therefore, should also be entered into the “Difference” column in Table E-5.

The experimental and analysis result can be considered to agree as long as either the relative difference or the absolute difference is less than the acceptance limit listed in the criterion. Generally, relative differences of less than 20 percent are acceptable and the absolute difference limits were generally chosen to represent 20 percent of the acceptance limit in Report 350 or MASH. For example, Report 350 limits occupant ride-down accelerations to those less than 20 g’s so 20 percent of 20 g’s is 4 g’s. As shown for criterion L2 in Table E-5, the relative acceptance limit is 20 percent and the absolute acceptance limit is 4 g’s.

If a numerical model was not created to represent the phenomenon, a value of “NM” (i.e., not modeled) should be entered in the appropriate column of Table E-5. If the known solution for that phenomenon number is “no” then a “NM” value in the “test result” column can be considered to agree. For example, if the material model for the rail element did not include the possibility of failure, “NM” should be entered for phenomenon number T in Table E-5. If the known solution does not indicate rail rupture or failure (i.e., phenomenon T = “no”), then the known and analysis solutions agree and a “yes” can be entered in the “agree?” column. On the other hand, if the known solution shows that a rail rupture did occur resulting in a phenomenon T entry of “yes” for the known solution, the known and analysis solutions do not agree and “no” should be entered in the “agree?” column. Analysts should seriously consider refining their model to incorporate any phenomena that appears in the known solution and is shown in Table E-5.

All the criteria identified in Table E-4 are expected to agree but if one does not and, in the opinion of the analyst, is not considered important to the overall evaluation for this particular comparison, then a footnote should be provided with a justification for why this particular criteria can be ignored for this particular comparison.

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

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Structural Adequacy	A	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable. (Answer Yes or No)	Yes	Yes		**Yes**
		A2	Maximum dynamic deflection: - Relative difference is less than 20 percent or - Absolute difference is less than 0.15 m	0.136 m	0.126 m	7.35% 0.01 m	**Yes**
		A3	Length of vehicle-barrier contact: - Relative difference is less than 20 percent or - Absolute difference is less than 2 m	4.04 m	3.07 m	24.01% 0.97 m	**Yes**
		A4	Number of broken or significantly bent posts is less than 20 percent. (Posts that deflected greater than 1 in.)	7	6	14.29% 1 post	**Yes**
		A5	Did the rail element rupture or tear (Answer Yes or No)	No	No		**Yes**
		A6	Were there failures of connector elements (Answer Yes or No).	No	No		**Yes**
		A7	Was there significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	No	No		**Yes**
		A8	Was there significant snagging between vehicle body components and barrier elements (Answer Yes or No).	Yes	Yes		**Yes**

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

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Occupant Risk	D		Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. (Answer Yes or No)	Yes	Yes		**Yes**
	F	F1	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable. (Answer Yes or No)	Yes	Yes		**Yes**
		F2	Maximum roll of the vehicle: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	21.25°	29.11°	37.0% 7.86°	**No**
		F3	Maximum pitch of the vehicle is: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	6.30°	6.12°	2.9% 0.18°	**Yes**
		F4	Maximum yaw of the vehicle is: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	39.58°	39.38°	0.5% 0.20°	**Yes**
	L	L1	Occupant impact velocities: - Relative difference is less than 20 percent or - Absolute difference is less than 2 m/s.				
			• Longitudinal OIV (m/s)	-6.18	-8.03	29.9% 1.85 m/s	**Yes**
			• Lateral OIV (m/s)	7.50	8.13	8.4% 0.63 m/s	**Yes**
			• THIV (m/s)	9.43 m/s	NA	-	**NA**
		L2	Occupant accelerations: - Relative difference is less than 20 percent or - Absolute difference is less than 4 g's.				
			• Longitudinal ORA	-7.06 g	-12.10 g	71.4% 5.04 g	**No**
			• Lateral ORA	10.40 g	11.00 g	5.8% 0.60 g	**Yes**
			• PHD	12.53 g	NA	-	**NA**
			• ASI	1.37	NA	-	**NA**

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

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Vehicle Trajectory	M	M1	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	Yes	Yes		**Yes**
		M2	Exit angle at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	8.99°	13.99°	55.6% 5.0°	**No**
		M3	Exit velocity at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	69.98 km/h	64.92 km/h	7.2% 5.06 km/h	**Yes**
		M4	One or more vehicle tires failed or de-beaded during the collision event (Answer Yes or No).	Yes	NM		**No**

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

Appendix B. V&V of Simulation No. agt-v18--Ram

A **MASH 2270P Pickup Truck**
(Report 350 or MASH08 or EN1317 Vehicle Type)

Striking a **31-in. tall Approach Guardrail Transition**
(roadside hardware type and name)

Report Date: **11/21/2019**

Type of Report (check one)

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

General Information	**Known Solution**	**Analysis Solution**
Performing Organization	MwRSF	MwRSF
Test/Run Number:	AGTB-2	agt-v18--Ram
Vehicle:	2010 Dodge Ram 1500 Quad Cab	2018 Dodge Ram
Reference:		
Impact Conditions		
Vehicle Mass:	2267 kg	2270 kg
Speed:	100.8 km/h	100.0 km/h
Angle:	25.4 degrees	25 degrees
Impact Point:	152 mm US CL P17	153 mm US CL P17

Composite Validation/Verification Score

	List the Report 350/MASH08 or EN1317 Test Number
Part I	Did all solution verification criteria in Table E-1 pass?
Part II	Do all the time history evaluation scores from Table E-2 result in a satisfactory comparison (i.e., the comparison passes the criterion)? If all the values in Table E-2 did not pass, did the weighted procedure shown in Table E-3 result in an acceptable comparison. If all the criteria in Table E-2 pass, enter “yes.” If all the criteria in Table E-2 did not pass but Table E-3 resulted in a passing score, enter “yes.”
Part III	All the criteria in Table E-4 (Test-PIRT) passed?
	Are the results of Steps I through III all affirmative (i.e., YES)? If all three steps result in a “YES” answer, the comparison can be considered validated or verified. If one of the steps results in a negative response, the result cannot be considered validated or verified.

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

PART I: BASIC INFORMATION

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

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

6. What test guidelines were used to perform the full-scale crash test (check one)?
   ☐ NCHRP Report 350
   ☐ MASH08
   ☐ EN1317
   ☒ Other: ___________MASH 2016____________________

7. Indicate the test level and number being evaluated (fill in the blank). _____3-21_____

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

NCHRP Report 350/MASH08

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

EN1317

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

PART II: ANALYSIS SOLUTION VERIFICATION

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

Table E-1. Analysis Solution Verification Table

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	0.42%	**Yes**
Hourglass Energy of the analysis solution at the end of the run is less than *five percent* of the total *initial energy* at the *beginning* of the run.	2.23%	**Yes**
Hourglass Energy of the analysis solution at the end of the run is less than *ten percent* of the total *internal energy* at the *end* of the run.	9.33%	**Yes**
The part/material with the highest amount of hourglass energy at the end of the run is less than ten percent of the total internal energy of the part/material at the end of the run. (Part id=32000440, hg=11600, Internal energy at end of run=3270)	28.19%*	**No**
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	0.05%	**Yes**
The part/material with the most mass added had less than 10 percent of its initial mass added. (Part id=40004023, Added mass=6.88, Initial mass=48.29)	14.25%**	**No**
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	0.09%	**Yes**
There are no shooting nodes in the solution?	No	**Yes**
There are no solid elements with negative volumes?	No	**Yes**

*Largest hourglass energy part is vehicle's outer right-front rim, resolvable with increased computation
**Steel transition blockouts have most added mass, resolvable with increased computation

If all the analysis solution verification criteria are scored as passing, the analysis solution can be verified or validated against the known solution. If any criterion in Table E-1 does not pass one of the verification criterion listed in Table E-1, the analysis solution cannot be used to verify or validate the known solution. If there are exceptions that the analyst things are relevant these should be footnoted in the table and explained below the table.

The Analysis Solution (check one) ☒ passes ☐ does NOT pass <u>all</u> the criteria in Table E1-1
☒with ☐without exceptions as noted.

PART III: TIME HISTORY EVALUATION TABLE

Using the RSVVP computer program ('Single channel' option), compute the Sprague-Geers MPC metrics and ANOVA metrics using time-history data from the known and analysis solutions for a time period starting at the beginning of the contact and ending at the loss of contact. Both the Sprague-Geers and ANOVA metrics must be calculated based on the original units the data was collected in (e.g., if accelerations were measured in the experiment with accelerometers then the comparison should be between accelerations. If rate gyros were used in the experiment, the comparison should be between rotation rates). If all six data channels are not available for both the known and analysis solutions, enter "N/A" in the column corresponding to the missing data. Enter the values obtained from the RSVVP program in Table E-2 and indicate if the comparison was acceptable or not by entering a "yes" or "no" in the "Agree?" column. Attach a graph of each channel for which the metrics have been compared at the end of the report.

Enter the filter, synchronization method and shift/drift options used in RSVVP to perform the comparison so that it is clear to the reviewer what options were used. Normally, SAE J211 filter class 180 is used to compare vehicle kinematics in full-scale crash tests. Either synchronization option in RSVVP is acceptable and both should result in a similar start point. The shift and drift options should generally only be used for the experimental curve since shift and drift are characteristics of sensors. For example, the zero point for an accelerometer sometimes "drifts" as the accelerometer sits out in the open environment of the crash test pad whereas there is no sensor to "drift" or "shift" in a numerical solution.

In order for the analysis solution to be considered in agreement with the known solution (i.e., verified or validated), <u>all</u> the criteria scored in Table E-2 must pass. If all the channels in Table E-2 do not pass, fill out Table E-3, the multi-channel weighted procedure.

If one or more channels do not satisfy the criteria in Table E-2, the multi-channel weighting option may be used. Using the RSVVP computer program ('Multiple channel' option), compute the Sprague-Geers MPC metrics and ANOVA metrics using all the time histories data from the known and analysis solutions for a time period starting at the beginning of the contact and ending at the loss of contact. If all six data channels are not available for both the known and analysis solutions, enter "N/A" in the column corresponding to the missing data.

For some types of roadside hardware impacts, some of the channels are not as important as others. An example might be a breakaway sign support test where the lateral (i.e., Y) and vertical (i.e., Z) accelerations are insignificant to the dynamics of the crash event. The weighting procedure provides a way to weight the most important channels more highly than less important channels. The procedure used is based on the area under the curve, therefore, the weighing scheme will weight channels with large areas more highly than those with smaller areas. In general, using the "Area (II)" method is acceptable although if the complete inertial properties of the vehicle are available the "inertial" method may be used. Enter the values obtained from the RSVVP program in Table E-3 and indicate if the comparison was acceptable or not by entering a "yes" or "no" in the "Agree?" column.

In order for the analysis solution to be considered in agreement with the known solution (i.e., verified or validated), <u>all</u> the criteria scored in Table E-3 must pass.

Table E-2. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (single channel option – CFC60)

	Evaluation Criteria	Time interval [0.0 sec; 0.49 sec]
O	***Sprague-Geers Metrics*** List all the data channels being compared. Calculate the M and P metrics using RSVVP and enter the results. Values less than or equal to 40 are acceptable.	

	RSVVP Curve Preprocessing Options						M	P	Pass?
	Filter Option	Sync. Option	Shift		Drift				
			True Curve	Test Curve	True Curve	Test Curve			
X acceleration	CFC60	N	N	N	N	N	15.3	27.9	Yes
Y acceleration	CFC60	N	N	N	N	N	3.0	20.7	Yes
Z acceleration	CFC60	N	N	N	N	N	14.4	56.3	No
Roll rate	CFC60	N	N	N	N	N	5.6	34.0	Yes
Pitch rate	CFC60	N	N	N	N	N	20.4	42.7	No
Yaw rate	CFC60	N	N	N	N	N	17.0	7.2	Yes

P	***ANOVA Metrics*** List all the data channels being compared. Calculate the ANOVA metrics using RSVVP and enter the results. Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$) and • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)	Mean Residual	Standard Deviation of Residuals	Pass?
	X acceleration/Peak	1.21	16.19	Yes
	Y acceleration/Peak	1.98	21.25	Yes
	Z acceleration/Peak	-3.10	40.10	No
	Roll rate	1.01	6.56	Yes
	Pitch rate	-0.31	10.09	Yes
	Yaw rate	-2.86	7.38	Yes

The Analysis Solution (check one) ☐ passes ☒ does NOT pass all the criteria in Table E-2 (single-channel time history comparison). If the Analysis Solution does NOT pass, perform the analysis in Table E-3 (multi-channel time history comparison).

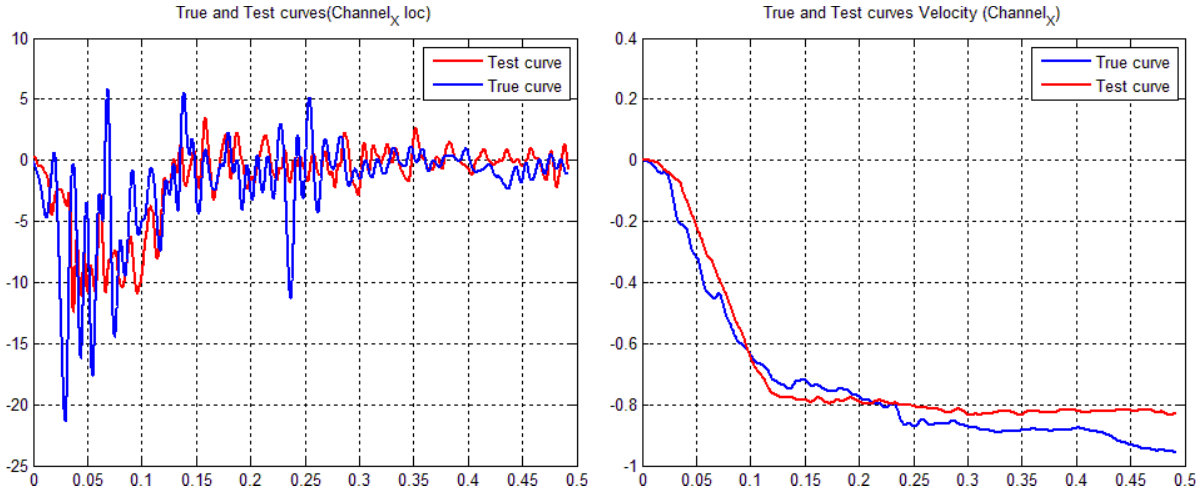


Figure 1. X-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

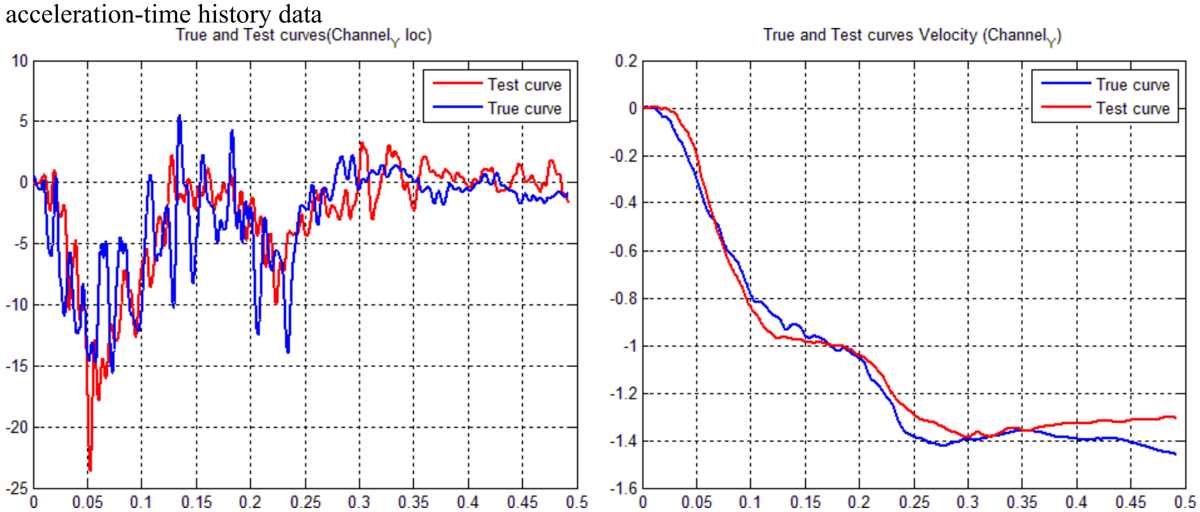


Figure 2. Y-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

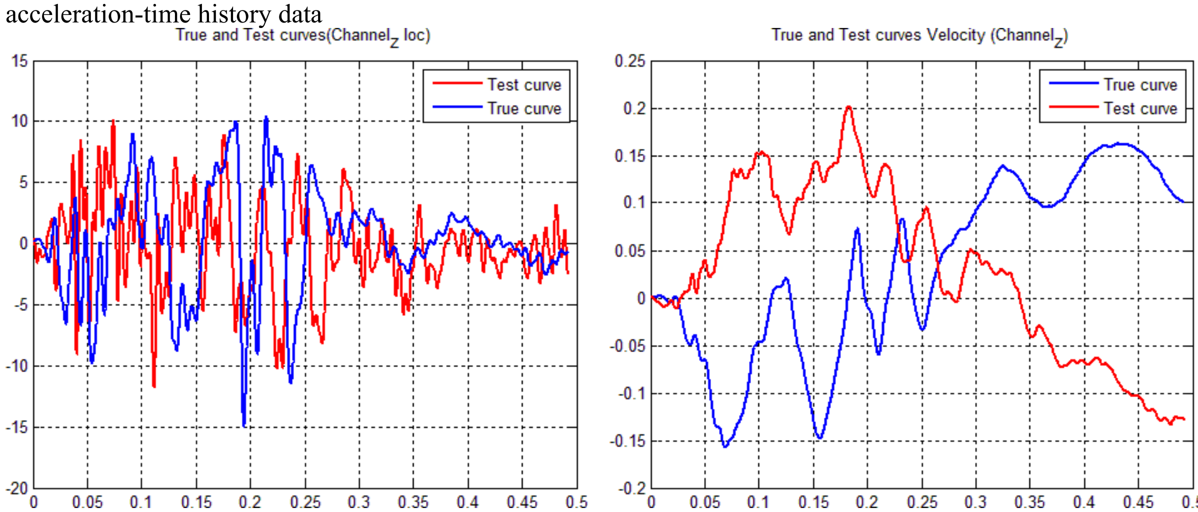


Figure 3. Z-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

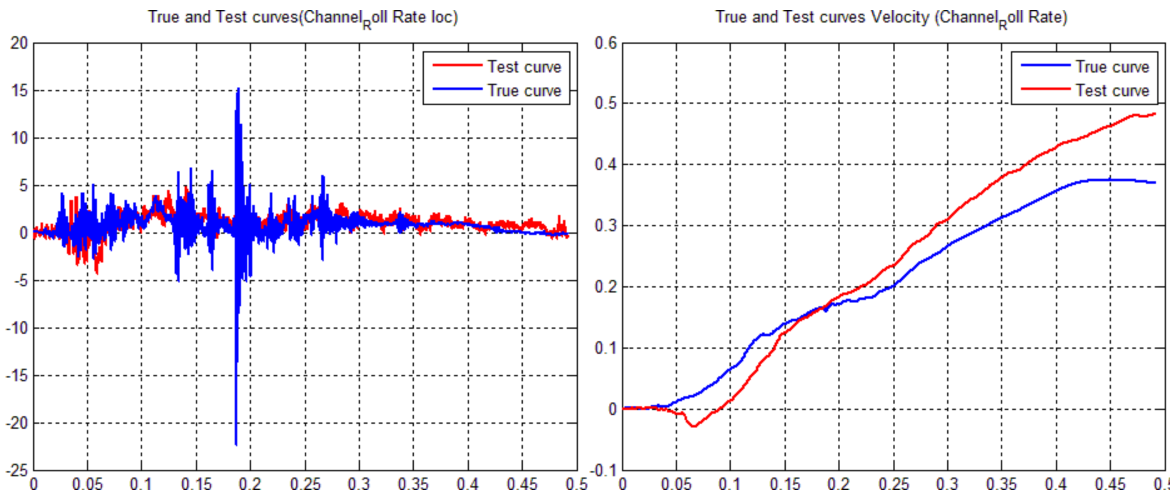


Figure 4. Roll Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

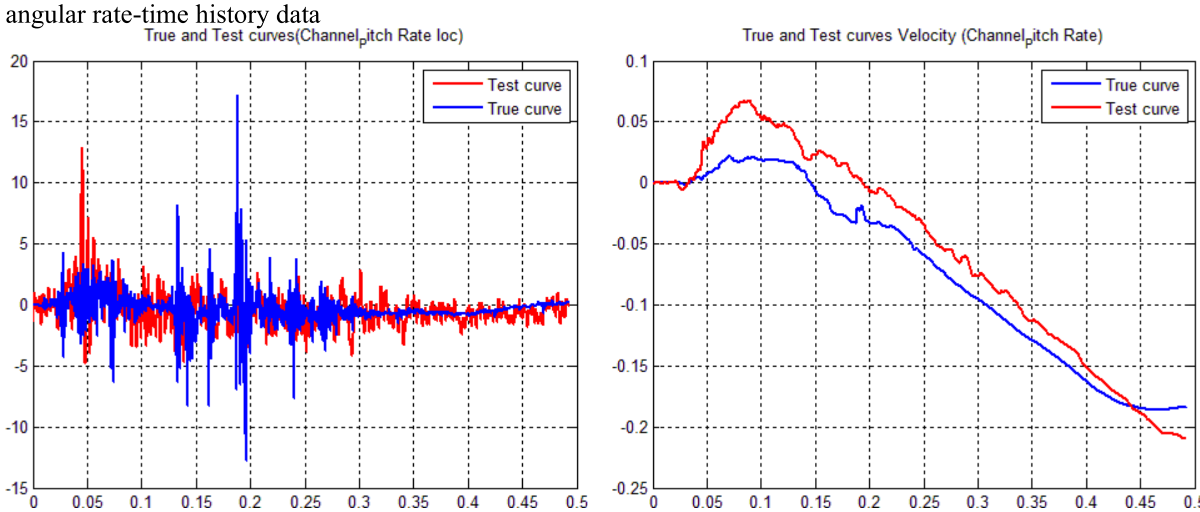


Figure 5. Pitch Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

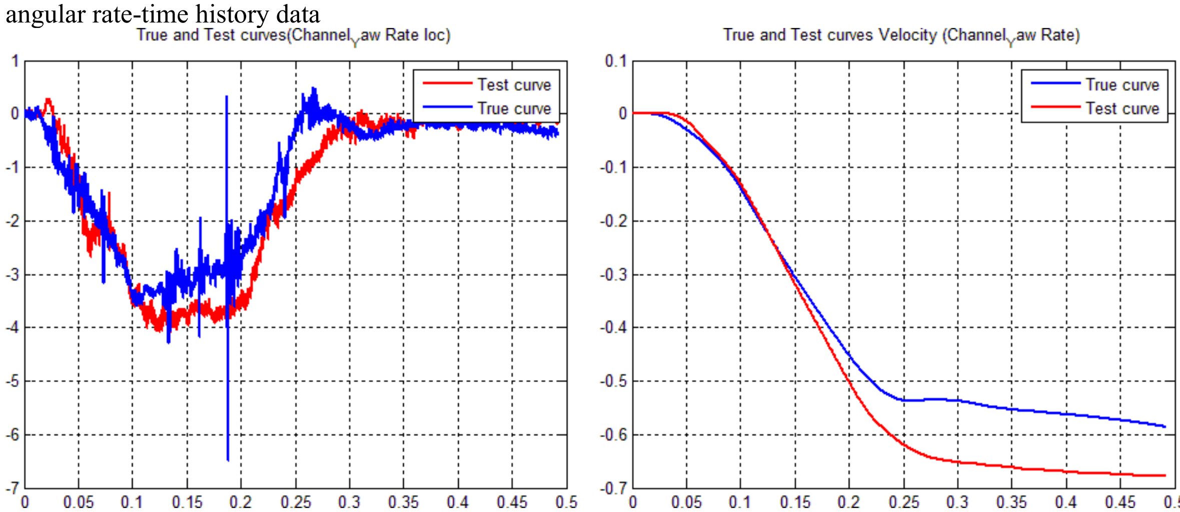
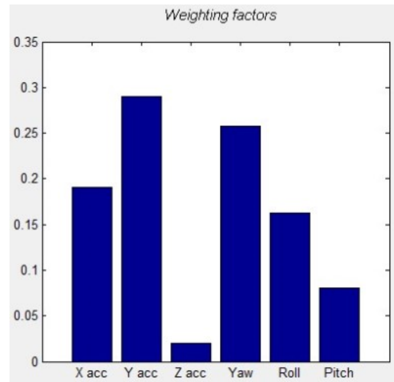


Figure 6. Yaw Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

Table E-3. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (multi-channel option CFC60)

Evaluation Criteria (time interval [0.0 sec; 0.49 sec])		
Channels (Select which were used)		
☒ **X Acceleration**	☒ **Y Acceleration**	☒ **Z Acceleration**
☒ **Roll rate**	☒ **Pitch rate**	☒ **Yaw rate**
Multi-Channel Weights ☒ **Area II method** ☐ **Inertial method**	**X Channel:** **Y Channel:** **Z Channel:** **Yaw Channel:** **Roll Channel:** ___ **Pitch Channel:**	

		M	P	Pass?
O	***Sprague-Geer Metrics*** Values less or equal to 40 are acceptable.	11	23.2	**Yes**

		Mean Residual	**Standard Deviation of Residuals**	**Pass?**
P	***ANOVA Metrics*** Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$) • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)	0.1	13.8	**Yes**

The Analysis Solution (check one) ☒ passes ☐ does NOT pass all the criteria in Table E-3.

Table E-2. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (single channel option – CFC180)

Evaluation Criteria										
O	***Sprague-Geers Metrics*** List all the data channels being compared. Calculate the M and P metrics using RSVVP and enter the results. Values less than or equal to 40 are acceptable.							**Time interval [0.0 sec; 0.49 sec]**		
		RSVVP Curve Preprocessing Options						**M**	**P**	**Pass?**
		Filter Option	**Sync. Option**	**Shift**		**Drift**				
				True Curve	**Test Curve**	**True Curve**	**Test Curve**			
	X acceleration	CFC180	N	N	N	N	N	13.0	31.3	Yes
	Y acceleration	CFC180	N	N	N	N	N	1.4	25.6	Yes
	Z acceleration	CFC180	N	N	N	N	N	43.8	55.1	No
	Roll rate	CFC180	N	N	N	N	N	5.6	34.0	Yes
	Pitch rate	CFC180	N	N	N	N	N	20.4	42.7	No
	Yaw rate	CFC180	N	N	N	N	N	17.0	7.2	Yes
P	***ANOVA Metrics*** List all the data channels being compared. Calculate the ANOVA metrics using RSVVP and enter the results. Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$) and • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)							**Mean Residual**	**Standard Deviation of Residuals**	**Pass?**
	X acceleration/Peak							1.03	16.69	Yes
	Y acceleration/Peak							1.61	22.61	Yes
	Z acceleration/Peak							-2.27	41.71	No
	Roll rate							1.01	6.56	Yes
	Pitch rate							-0.31	10.09	Yes
	Yaw rate							-2.86	7.38	Yes

The Analysis Solution (check one) ☐ passes ☒ does NOT pass all the criteria in Table E-2 (single-channel time history comparison). If the Analysis Solution does NOT pass, perform the analysis in Table E-3 (multi-channel time history comparison).

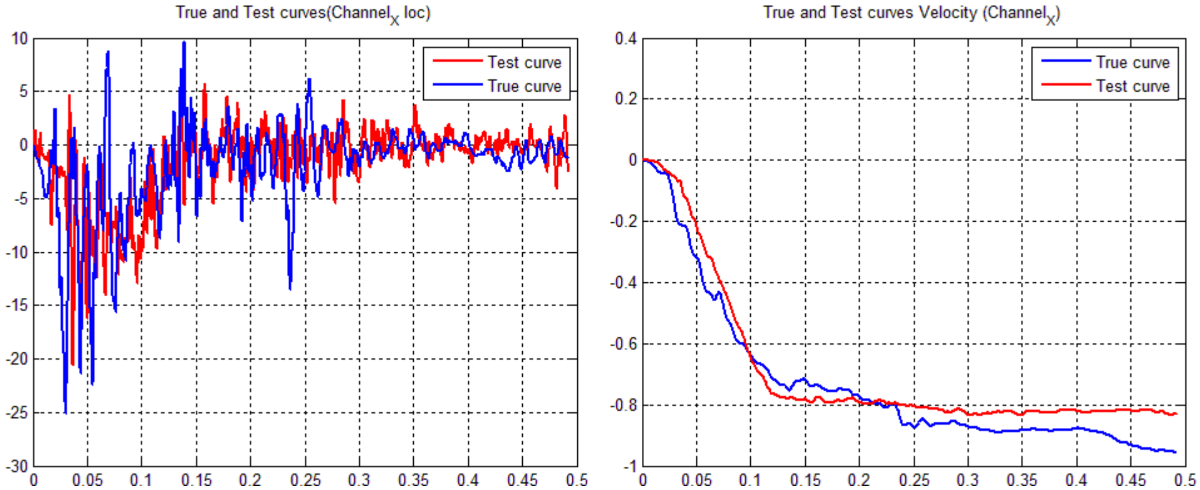


Figure 7. X-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

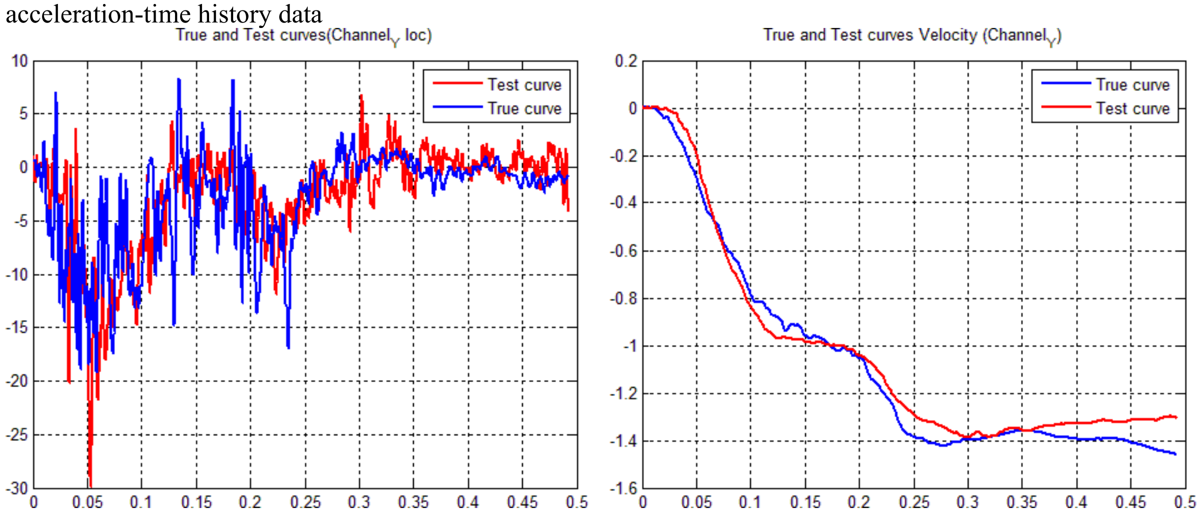


Figure 8. Y-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

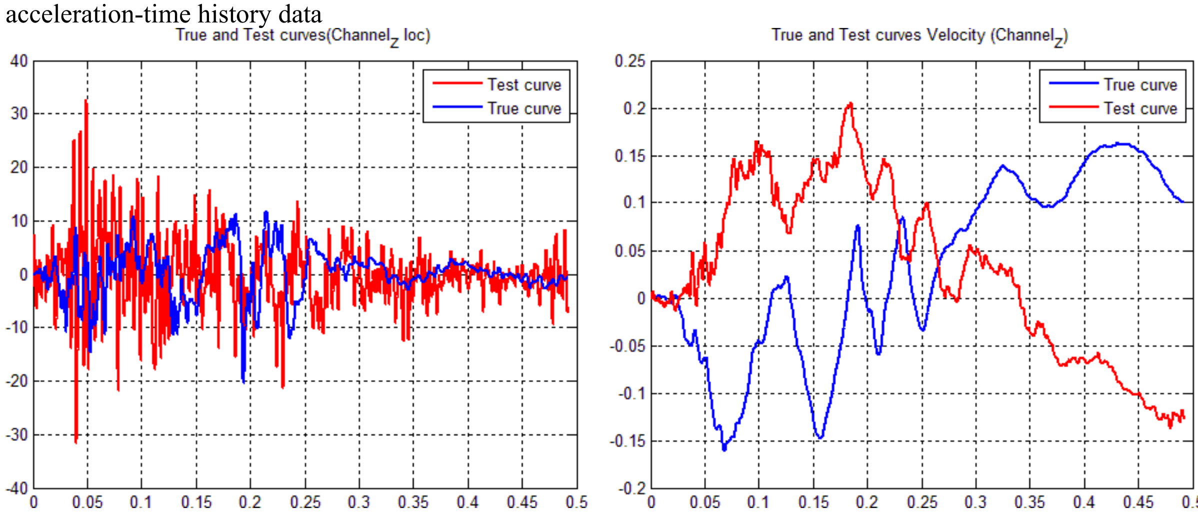


Figure 9. Z-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

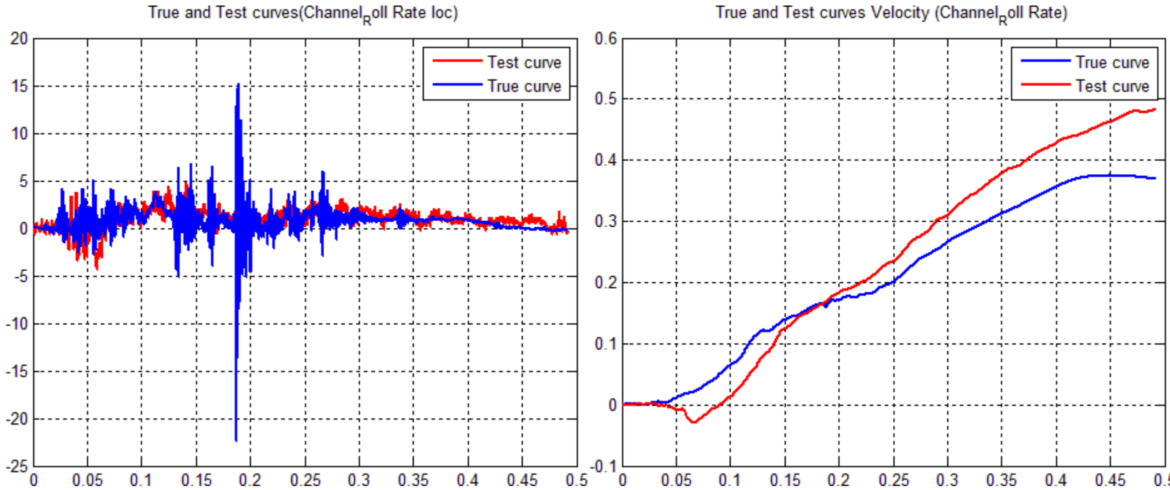


Figure 10. Roll Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

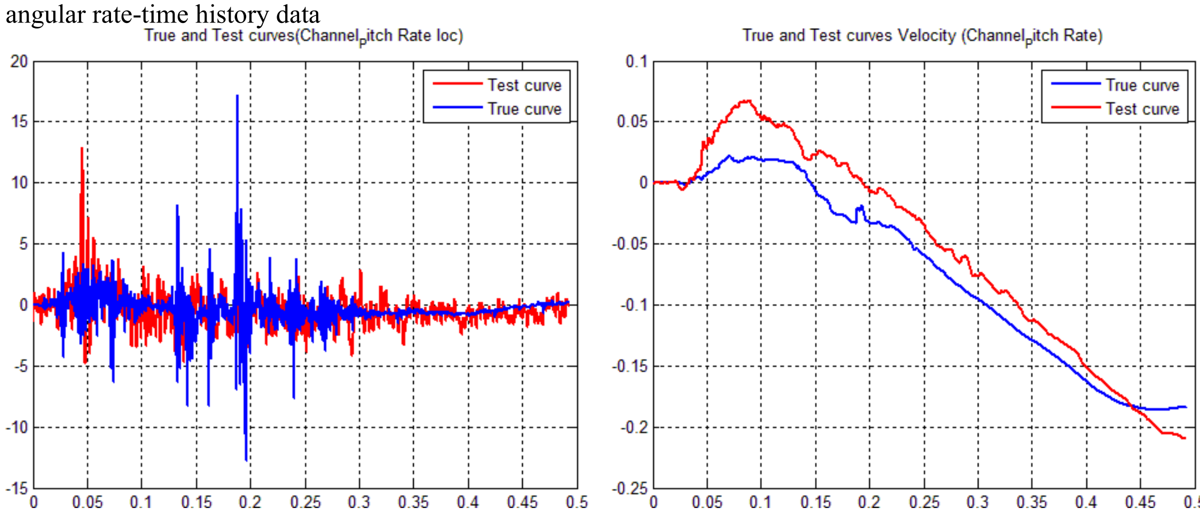


Figure 11. Pitch Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

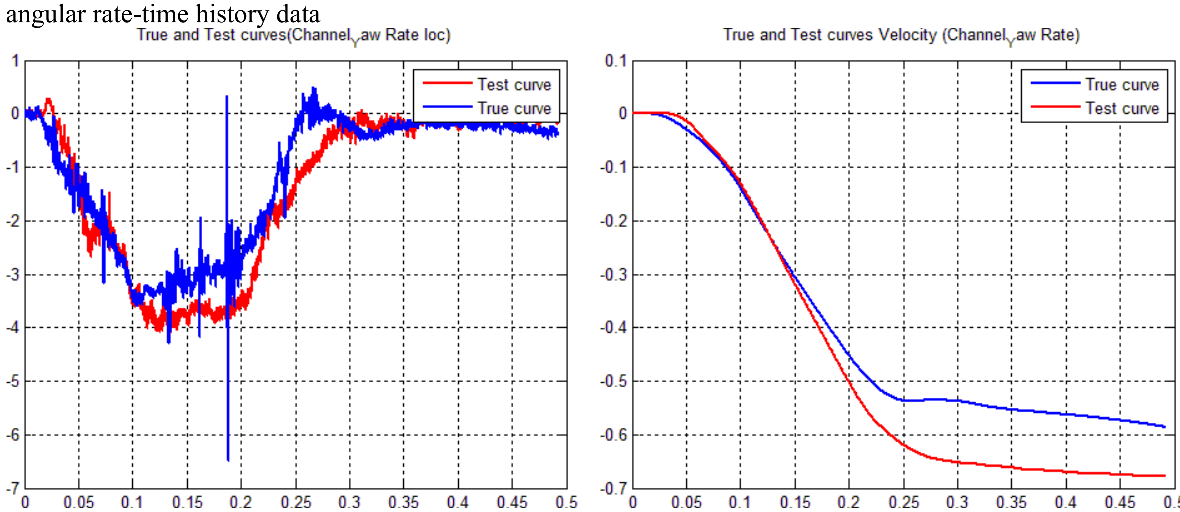
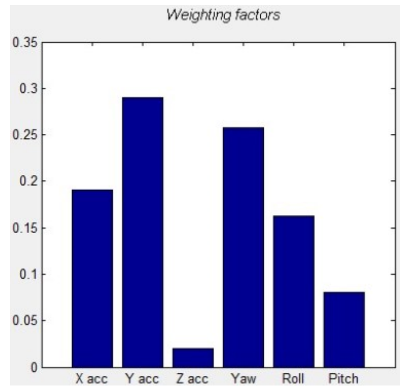


Figure 12. Yaw Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

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

<table>
<tr><th colspan="6">Evaluation Criteria (time interval [0.0 sec; 0.49 sec])</th></tr>
<tr><td colspan="6">Channels (Select which were used)</td></tr>
<tr><td colspan="2">☒ X Acceleration</td><td colspan="2">☒ Y Acceleration</td><td colspan="2">☒ Z Acceleration</td></tr>
<tr><td colspan="2">☒ Roll rate</td><td colspan="2">☒ Pitch rate</td><td colspan="2">☒ Yaw rate</td></tr>
<tr><td colspan="2">Multi-Channel Weights
☒ Area II method
☐ Inertial method</td><td colspan="2">X Channel:
Y Channel:
Z Channel:
Yaw Channel:
Roll Channel: ___
Pitch Channel:</td><td colspan="2">
</td></tr>
<tr><td rowspan="2">O</td><td rowspan="2">Sprague-Geer Metrics
Values less or equal to 40 are acceptable.</td><td>M</td><td>P</td><td colspan="2">Pass?</td></tr>
<tr><td>10.7</td><td>25.3</td><td colspan="2">Yes</td></tr>
<tr><td rowspan="2">P</td><td rowspan="2">ANOVA Metrics
Both of the following criteria must be met:
• The mean residual error must be less than five percent of the peak acceleration
($\bar{e} \leq 0.05 \cdot a_{Peak}$)
• The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)</td><td>Mean Residual</td><td>Standard Deviation of Residuals</td><td colspan="2">Pass?</td></tr>
<tr><td>0.0</td><td>14.3</td><td colspan="2">Yes</td></tr>
</table>

The Analysis Solution (check one) ☒ passes ☐ does NOT pass all the criteria in Table E-3.

PART IV: PHENOMENA IMPORTANCE RANKING TABLE

Table E-4 is similar to the evaluation tables in Report 350 and MASH. For the Report 350 or MASH test number identified in Part I (e.g., test 3-10, 5-12, etc.), circle all the evaluation criteria applicable to that test in Table E-4. The tests that apply to each criterion are listed in the far right column without the test level designator. For example, if a Report 350 test 3-11 is being compared (i.e., a pickup truck striking a barrier at 25 degrees and 100 km/hr), circle all the criteria in the second column where the number "11" appears in the far right column. Some of the Report 350 evaluation criteria have been removed (i.e., J and K) since they are not generally useful in assessing the comparison between the known and analysis solutions.

Table E-4. Evaluation Criteria Test Applicability Table

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

Complete Table E-5 according to the results of the known solution (e.g., crash test) and the numerical solution (e.g., simulation). Consistent with Report 350 and MASH, Task E-5 has three parts: the structural adequacy phenomena listed in Table E-5a, the occupant risk phenomena listed in Table E-5b and the vehicle trajectory criteria listed in Table E-5c. If the result of the analysis solution agrees with the known solution, mark the "agree" column "yes." For example, if the vehicle in both the known and analysis solutions rolls over and, therefore, fails criterion F1, the known and the analysis columns for criterion F1 would be evaluated as "no." Even though both failed the criteria, they agree with each other so the "agree" column is marked as "yes." Any criterion that is not applicable to the test being evaluated (i.e., not circled in Table E-4) should be indicated by entering "NA" in the "agree?" column for that row.

Many of the Report 350 evaluation criteria have been subdivided into more specific phenomenon. For example, criterion A is divided into eight sub-criteria, A1 through A8, that provide more specific and quantifiable phenomena for evaluation. Some of the values are simple yes or no questions while other request numerical values. For the numerical phenomena, the analyst should enter the value for the known and analysis result and then calculate the relative difference. Relative difference is always the absolute value of the difference of the known and analysis solutions divided by the known solution. Enter the value in the "relative difference" column. If the relative difference is less than 20 percent, enter "yes" in the "agree?" column.

Sometimes, when the values are very small, the relative difference might be large while the absolute difference is very small. For example, the longitudinal occupant ride down acceleration (i.e., criterion L2) in a test might be 3 g's and in the corresponding analysis might be 4 g's. The relative difference is 33 percent but the absolute difference is only 1 g and the result for both is well below the 20 g limit. Clearly, the analysis solution in this case is a good match to the experiment and the relative difference is large only because the values are small. The absolute difference, therefore, should also be entered into the "Difference" column in Table E-5.

The experimental and analysis result can be considered to agree as long as either the relative difference or the absolute difference is less than the acceptance limit listed in the criterion. Generally, relative differences of less than 20 percent are acceptable and the absolute difference limits were generally chosen to represent 20 percent of the acceptance limit in Report 350 or MASH. For example, Report 350 limits occupant ride-down accelerations to those less than 20 g's so 20 percent of 20 g's is 4 g's. As shown for criterion L2 in Table E-5, the relative acceptance limit is 20 percent and the absolute acceptance limit is 4 g's.

If a numerical model was not created to represent the phenomenon, a value of "NM" (i.e., not modeled) should be entered in the appropriate column of Table E-5. If the known solution for that phenomenon number is "no" then a "NM" value in the "test result" column can be considered to agree. For example, if the material model for the rail element did not include the possibility of failure, "NM" should be entered for phenomenon number T in Table E-5. If the known solution does not indicate rail rupture or failure (i.e., phenomenon T = "no"), then the known and analysis solutions agree and a "yes" can be entered in the "agree?" column. On the other hand, if the known solution shows that a rail rupture did occur resulting in a phenomenon T entry of "yes" for the known solution, the known and analysis solutions do not agree and "no" should be entered in the "agree?" column. Analysts should seriously consider refining their model to incorporate any phenomena that appears in the known solution and is shown in Table E-5.

All the criteria identified in Table E-4 are expected to agree but if one does not and, in the opinion of the analyst, is not considered important to the overall evaluation for this particular comparison, then a footnote should be provided with a justification for why this particular criteria can be ignored for this particular comparison.

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

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Structural Adequacy	A	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable. (Answer Yes or No)	Yes	Yes		**Yes**
		A2	Maximum dynamic deflection: - Relative difference is less than 20 percent or - Absolute difference is less than 0.15 m	0.136 m	0.115 m	15.44% 0.02 m	**Yes**
		A3	Length of vehicle-barrier contact: - Relative difference is less than 20 percent or - Absolute difference is less than 2 m	4.04 m	3.41 m	15.59% 0.63 m	**Yes**
		A4	Number of broken or significantly bent posts is less than 20 percent. (Posts with deflections > 1 in. (25.4 mm)	7	5	28.57% 2 posts	**No***
		A5	Did the rail element rupture or tear (Answer Yes or No)	No	No		**Yes**
		A6	Were there failures of connector elements (Answer Yes or No).	No	No		**Yes**
		A7	Was there significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	No	No		**Yes**
		A8	Was there significant snagging between vehicle body components and barrier elements (Answer Yes or No).	No	No		**Yes**

* Soil strength is dependent on post spacing in full-scale test and acts independently in simulation.

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

			Evaluation Criteria	Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Occupant Risk	D		Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. (Answer Yes or No)	Yes	Yes		**Yes**
	F	F1	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable. (Answer Yes or No)	Yes	Yes		**Yes**
		F2	Maximum roll of the vehicle (t=350ms): - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	17.51	20.31	15.99% 2.8 deg.	**Yes**
		F3	Maximum pitch of the vehicle is (t=350ms): - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	3.67	2.48	32.43% 1.19 deg.	**Yes**
		F4	Maximum yaw of the vehicle is (t=350ms): - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	33.12	39.59	19.54% 6.47 deg.	**Yes**
	L	L1	Occupant impact velocities: - Relative difference is less than 20 percent or - Absolute difference is less than 2 m/s.				
			• Longitudinal OIV (m/s)	-6.18	-6.39	3.40% 0.21 m/s	**Yes**
			• Lateral OIV (m/s)	7.50	8.28	10.40% 0.78 m/s	**Yes**
			• THIV (m/s)	9.43 m/s	NA	-	NA
		L2	Occupant accelerations: - Relative difference is less than 20 percent or - Absolute difference is less than 4 g's.				
			• Longitudinal ORA	-7.06	-6.36	9.92% 0.70 g's	**Yes**
			• Lateral ORA	10.40	8.22	20.96% 2.18 g's	**Yes**
			• PHD	12.53	NA	-	NA
			• ASI	1.37	NA	-	NA

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

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Vehicle Trajectory	M	M1	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	Yes	Yes		**Yes**
		M2	Exit angle at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	8.99	14.13	57.17% 5.14 deg.	**No***
		M3	Exit velocity at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	69.98	70.97	1.41% 0.99 km/h	**Yes**
		M4	One or more vehicle tires failed or de-beaded during the collision event (Answer Yes or No).	Yes	Yes		**Yes**

* In the simulation, the detached tire remained in the wheel well and did not exit under the vehicle as in the full-scale test resulting in an exit angle discrepancy.

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

Appendix C. V&V of Simulation No. agt-v18--Ram-v2

A **MASH 2270P Pickup Truck**
(Report 350 or MASH08 or EN1317 Vehicle Type)

Striking a **31-in. tall Approach Guardrail Transition**
(roadside hardware type and name)

Report Date: **6/16/2020**

Type of Report (check one)

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

General Information	**Known Solution**	**Analysis Solution**
Performing Organization	MwRSF	MwRSF
Test/Run Number:	AGTB-2	agt-v18--Ram-v2
Vehicle:	2010 Dodge Ram 1500 Quad Cab	2018 Dodge Ram
Reference:		
Impact Conditions		
Vehicle Mass:	2267 kg	2270 kg
Speed:	100.8 km/h	100.8 km/h
Angle:	25.4 degrees	25 degrees
Impact Point:	152 mm US CL P17	153 mm US CL P17

Composite Validation/Verification Score

	List the Report 350/MASH08 or EN1317 Test Number
Part I	Did all solution verification criteria in Table E-1 pass?
Part II	Do all the time history evaluation scores from Table E-2 result in a satisfactory comparison (i.e., the comparison passes the criterion)? If all the values in Table E-2 did not pass, did the weighted procedure shown in Table E-3 result in an acceptable comparison. If all the criteria in Table E-2 pass, enter “yes.” If all the criteria in Table E-2 did not pass but Table E-3 resulted in a passing score, enter “yes.”
Part III	All the criteria in Table E-4 (Test-PIRT) passed?
	Are the results of Steps I through III all affirmative (i.e., YES)? If all three steps result in a “YES” answer, the comparison can be considered validated or verified. If one of the steps results in a negative response, the result cannot be considered validated or verified.

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

PART I: BASIC INFORMATION

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

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

10. What test guidelines were used to perform the full-scale crash test (check one)?
    - ☐ NCHRP Report 350
    - ☐ MASH08
    - ☐ EN1317
    - ☒ Other: ___________MASH 2016____________________

11. Indicate the test level and number being evaluated (fill in the blank). ________3-21___________

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

NCHRP Report 350/MASH08

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

EN1317

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

PART II: ANALYSIS SOLUTION VERIFICATION

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

Table E-1. Analysis Solution Verification Table

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	0.42%	**Yes**
Hourglass Energy of the analysis solution at the end of the run is less than *five percent* of the total *initial energy* at the *beginning* of the run.	2.36%	**Yes**
Hourglass Energy of the analysis solution at the end of the run is less than *ten percent* of the total *internal energy* at the *end* of the run.	9.70%	**Yes**
The part/material with the highest amount of hourglass energy at the end of the run is less than ten percent of the total internal energy of the part/material at the end of the run. (Part id=32000440, hg=3,480, Internal energy at end of run=12,700)	27.40%*	**No**
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	0.05%	**Yes**
The part/material with the most mass added had less than 10 percent of its initial mass added. (Part id=40004023, Added mass=6.88, Initial mass=48.29)	14.25%**	**No**
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	0.09%	**Yes**
There are no shooting nodes in the solution?	No	**Yes**
There are no solid elements with negative volumes?	No	**Yes**

*Largest hourglass energy part is vehicle's outer right-front rim, resolvable with increased computation
**Steel transition blockouts have most added mass, resolvable with increased computation

If all the analysis solution verification criteria are scored as passing, the analysis solution can be verified or validated against the known solution. If any criterion in Table E-1 does not pass one of the verification criterion listed in Table E-1, the analysis solution cannot be used to verify or validate the known solution. If there are exceptions that the analyst things are relevant these should be footnoted in the table and explained below the table.

The Analysis Solution (check one) ☒ passes ☐ does NOT pass <u>all</u> the criteria in Table E1-1

☒with ☐without exceptions as noted.

PART III: TIME HISTORY EVALUATION TABLE

Using the RSVVP computer program ('Single channel' option), compute the Sprague-Geers MPC metrics and ANOVA metrics using time-history data from the known and analysis solutions for a time period starting at the beginning of the contact and ending at the loss of contact. Both the Sprague-Geers and ANOVA metrics must be calculated based on the original units the data was collected in (e.g., if accelerations were measured in the experiment with accelerometers then the comparison should be between accelerations. If rate gyros were used in the experiment, the comparison should be between rotation rates). If all six data channels are not available for both the known and analysis solutions, enter "N/A" in the column corresponding to the missing data. Enter the values obtained from the RSVVP program in Table E-2 and indicate if the comparison was acceptable or not by entering a "yes" or "no" in the "Agree?" column. Attach a graph of each channel for which the metrics have been compared at the end of the report.

Enter the filter, synchronization method and shift/drift options used in RSVVP to perform the comparison so that it is clear to the reviewer what options were used. Normally, SAE J211 filter class 180 is used to compare vehicle kinematics in full-scale crash tests. Either synchronization option in RSVVP is acceptable and both should result in a similar start point. The shift and drift options should generally only be used for the experimental curve since shift and drift are characteristics of sensors. For example, the zero point for an accelerometer sometimes "drifts" as the accelerometer sits out in the open environment of the crash test pad whereas there is no sensor to "drift" or "shift" in a numerical solution.

In order for the analysis solution to be considered in agreement with the known solution (i.e., verified or validated), all the criteria scored in Table E-2 must pass. If all the channels in Table E-2 do not pass, fill out Table E-3, the multi-channel weighted procedure.

If one or more channels do not satisfy the criteria in Table E-2, the multi-channel weighting option may be used. Using the RSVVP computer program ('Multiple channel' option), compute the Sprague-Geers MPC metrics and ANOVA metrics using all the time histories data from the known and analysis solutions for a time period starting at the beginning of the contact and ending at the loss of contact. If all six data channels are not available for both the known and analysis solutions, enter "N/A" in the column corresponding to the missing data.

For some types of roadside hardware impacts, some of the channels are not as important as others. An example might be a breakaway sign support test where the lateral (i.e., Y) and vertical (i.e., Z) accelerations are insignificant to the dynamics of the crash event. The weighting procedure provides a way to weight the most important channels more highly than less important channels. The procedure used is based on the area under the curve, therefore, the weighing scheme will weight channels with large areas more highly than those with smaller areas. In general, using the "Area (II)" method is acceptable although if the complete inertial properties of the vehicle are available the "inertial" method may be used. Enter the values obtained from the RSVVP program in Table E-3 and indicate if the comparison was acceptable or not by entering a "yes" or "no" in the "Agree?" column.

In order for the analysis solution to be considered in agreement with the known solution (i.e., verified or validated), all the criteria scored in Table E-3 must pass.

Table E-2. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (single channel option – CFC60)

	Evaluation Criteria									
O	***Sprague-Geers Metrics*** List all the data channels being compared. Calculate the M and P metrics using RSVVP and enter the results. Values less than or equal to 40 are acceptable.							**Time interval [0.0 sec; 0.49 sec]**		
		RSVVP Curve Preprocessing Options						**M**	**P**	**Pass?**
		Filter Option	**Sync. Option**	**Shift**		**Drift**				
				True Curve	**Test Curve**	**True Curve**	**Test Curve**			
	X acceleration	CFC60	N	N	N	N	N	13.2	29.9	Yes
	Y acceleration	CFC60	N	N	N	N	N	2.3	20.5	Yes
	Z acceleration	CFC60	N	N	N	N	N	1.7	56.6	No
	Roll rate	CFC60	N	N	N	N	N	4.5	34.3	Yes
	Pitch rate	CFC60	N	N	N	N	N	31.0	43.4	No
	Yaw rate	CFC60	N	N	N	N	N	16.0	7.2	Yes
P	***ANOVA Metrics*** List all the data channels being compared. Calculate the ANOVA metrics using RSVVP and enter the results. Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\overline{e} \leq 0.05 \cdot a_{Peak}$) and • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)							**Mean Residual**	**Standard Deviation of Residuals**	**Pass?**
	X acceleration/Peak							1.02	17.40	Yes
	Y acceleration/Peak							2.03	21.05	Yes
	Z acceleration/Peak							-3.00	42.93	No
	Roll rate							0.77	6.69	Yes
	Pitch rate							-0.12	10.79	Yes
	Yaw rate							-3.36	6.93	Yes

The Analysis Solution (check one) ☐ passes ☒ does NOT pass all the criteria in Table E-2 (single-channel time history comparison). If the Analysis Solution does NOT pass, perform the analysis in Table E-3 (multi-channel time history comparison).

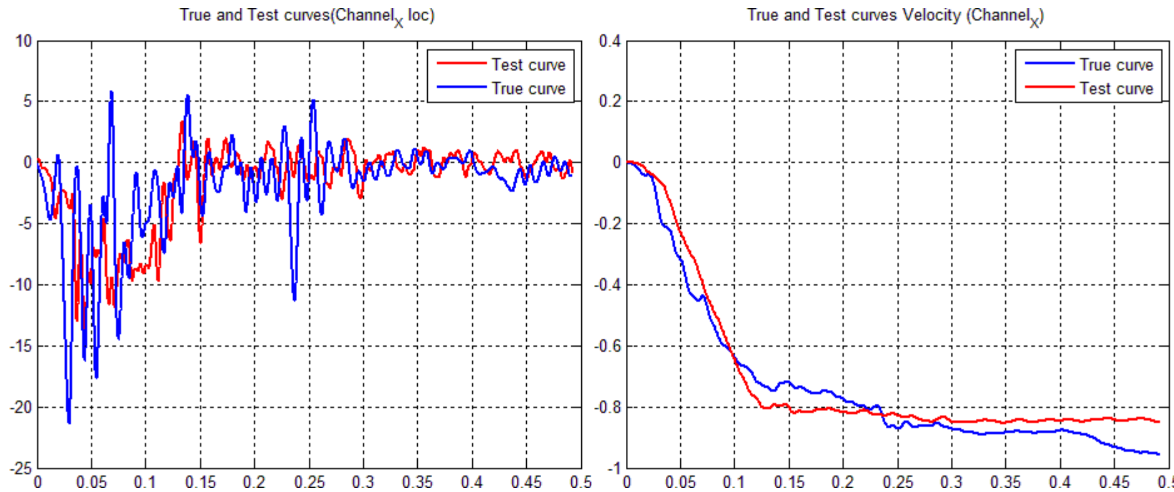


Figure 1. X-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

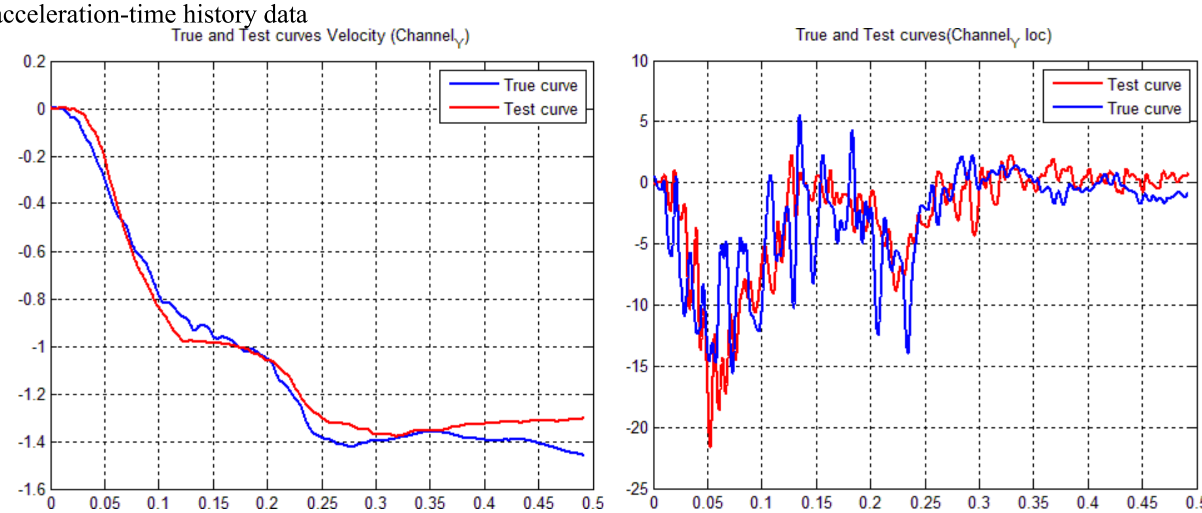


Figure 2. Y-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

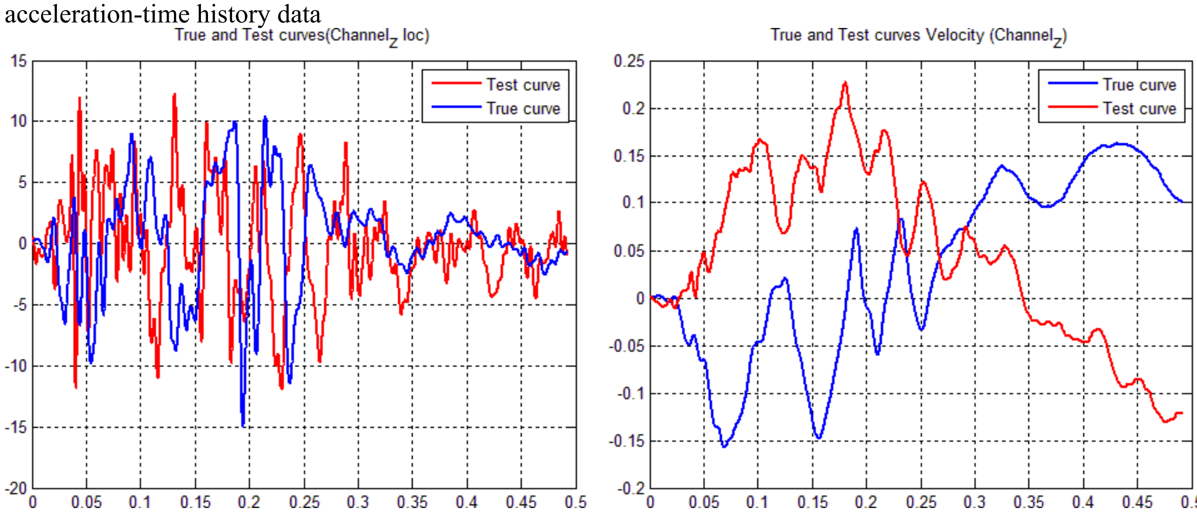


Figure 3. Z-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

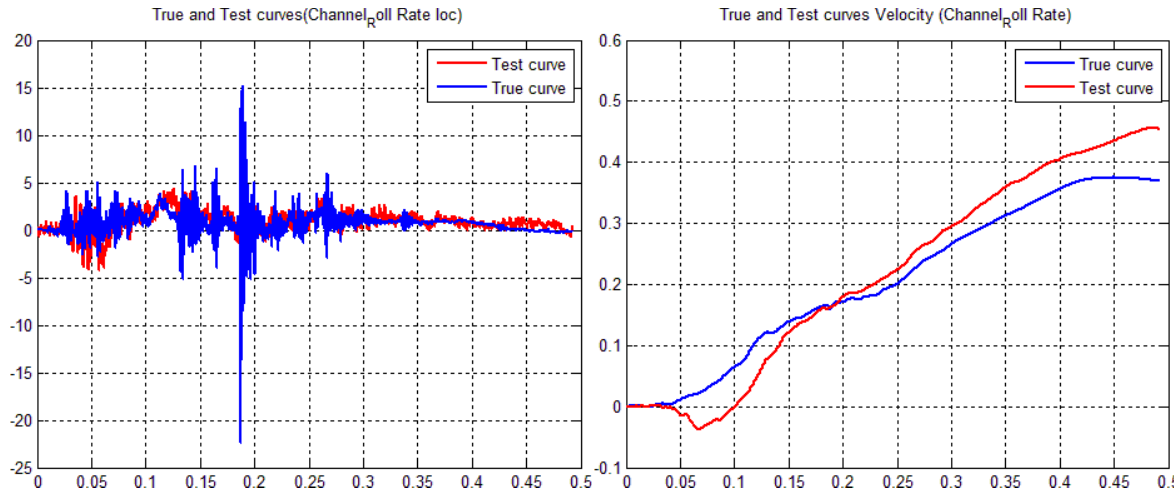


Figure 4. Roll Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

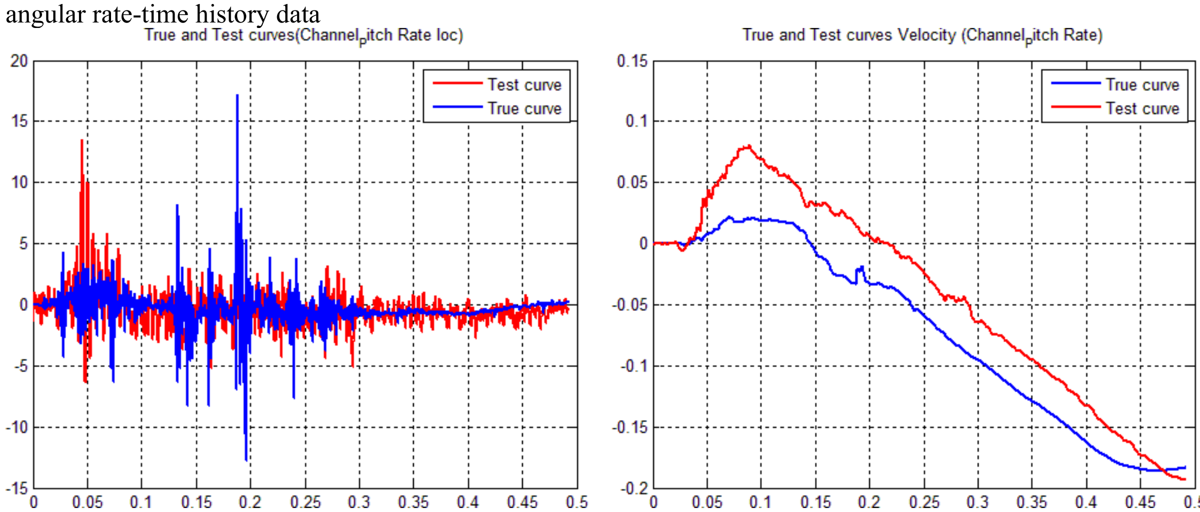


Figure 5. Pitch Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

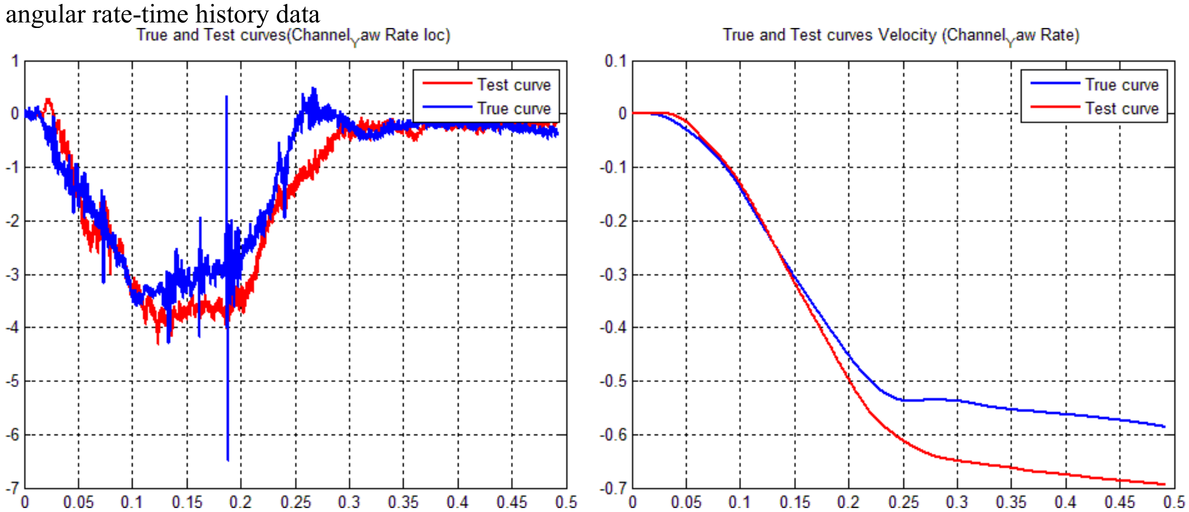
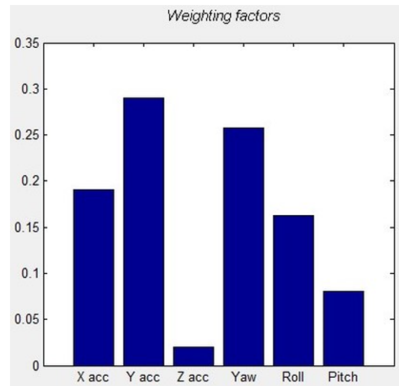


Figure 6. Yaw Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

Table E-3. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (multi-channel option CFC60)

<table>
<tr><th colspan="5">Evaluation Criteria (time interval [0.0 sec; 0.49 sec])</th></tr>
<tr><td colspan="5">Channels (Select which were used)</td></tr>
<tr><td colspan="2">☒ X Acceleration</td><td>☒ Y Acceleration</td><td colspan="2">☒ Z Acceleration</td></tr>
<tr><td colspan="2">☒ Roll rate</td><td>☒ Pitch rate</td><td colspan="2">☒ Yaw rate</td></tr>
<tr><td colspan="2">Multi-Channel Weights
☒ Area II method
☐ Inertial method</td><td>X Channel:
Y Channel:
Z Channel:
Yaw Channel:
Roll Channel: ___
Pitch Channel:</td><td colspan="2">
</td></tr>
<tr><td rowspan="2">O</td><td rowspan="2">Sprague-Geer Metrics
Values less or equal to 40 are acceptable.</td><td>M</td><td>P</td><td>Pass?</td></tr>
<tr><td>10.6</td><td>23.7</td><td>Yes</td></tr>
<tr><td rowspan="2">P</td><td rowspan="2">ANOVA Metrics
Both of the following criteria must be met:
• The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$)
• The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)</td><td>Mean Residual</td><td>Standard Deviation of Residuals</td><td>Pass?</td></tr>
<tr><td>0.0</td><td>14.0</td><td>Yes</td></tr>
</table>

The Analysis Solution (check one) ☒ passes ☐ does NOT pass all the criteria in Table E-3.

Table E-2. Roadside Safety Validation Metrics Rating Table – Time History Comparisons (single channel option – CFC180)

Evaluation Criteria										
O	***Sprague-Geers Metrics*** List all the data channels being compared. Calculate the M and P metrics using RSVVP and enter the results. Values less than or equal to 40 are acceptable.							**Time interval [0.0 sec; 0.49 sec]**		
		RSVVP Curve Preprocessing Options						**M**	**P**	**Pass?**
		Filter Option	**Sync. Option**	**Shift**		**Drift**				
				True Curve	**Test Curve**	**True Curve**	**Test Curve**			
	X acceleration	CFC180	N	N	N	N	N	8.7	32.9	Yes
	Y acceleration	CFC180	N	N	N	N	N	2.1	25.4	Yes
	Z acceleration	CFC180	N	N	N	N	N	54.9	54.8	No
	Roll rate	CFC180	N	N	N	N	N	4.5	34.3	Yes
	Pitch rate	CFC180	N	N	N	N	N	31.0	43.4	No
	Yaw rate	CFC180	N	N	N	N	N	16.0	7.2	Yes
P	***ANOVA Metrics*** List all the data channels being compared. Calculate the ANOVA metrics using RSVVP and enter the results. Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \le 0.05 \cdot a_{Peak}$) and • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \le 0.35 \cdot a_{Peak}$)							**Mean Residual**	**Standard Deviation of Residuals**	**Pass?**
	X acceleration/Peak							0.88	17.78	Yes
	Y acceleration/Peak							1.64	22.57	Yes
	Z acceleration/Peak							-2.17	43.67	No
	Roll rate							0.77	6.69	Yes
	Pitch rate							-0.12	10.79	Yes
	Yaw rate							-3.36	6.93	Yes

The Analysis Solution (check one) ☐ passes ☒ does NOT pass all the criteria in Table E-2 (single-channel time history comparison). If the Analysis Solution does NOT pass, perform the analysis in Table E-3 (multi-channel time history comparison).

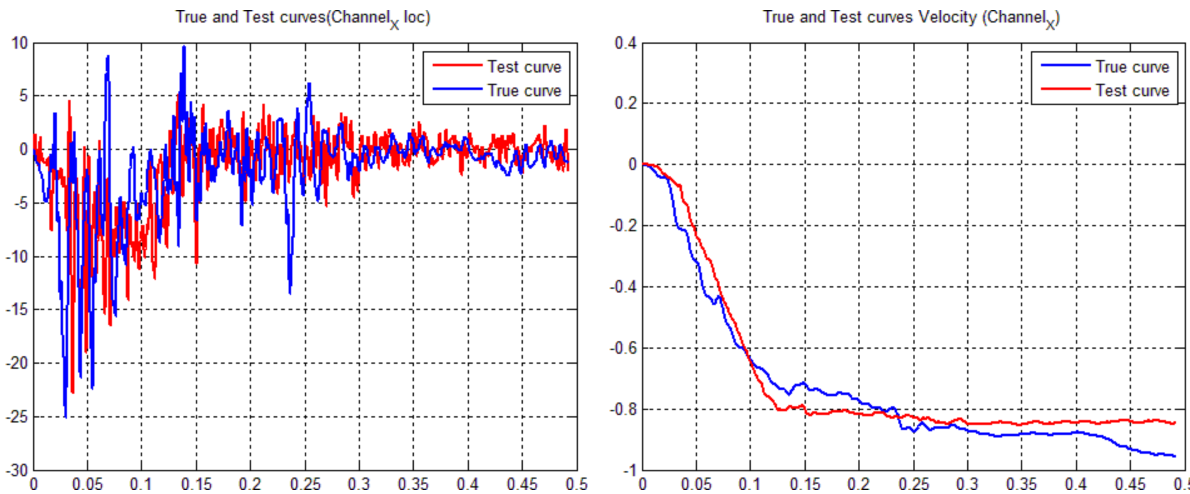


Figure 7. X-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

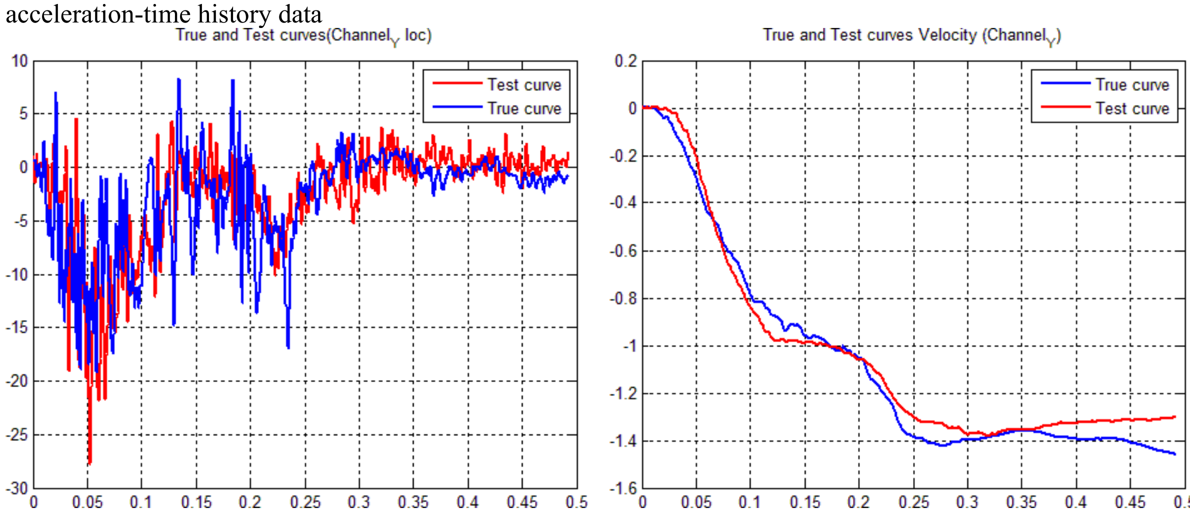


Figure 8. Y-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

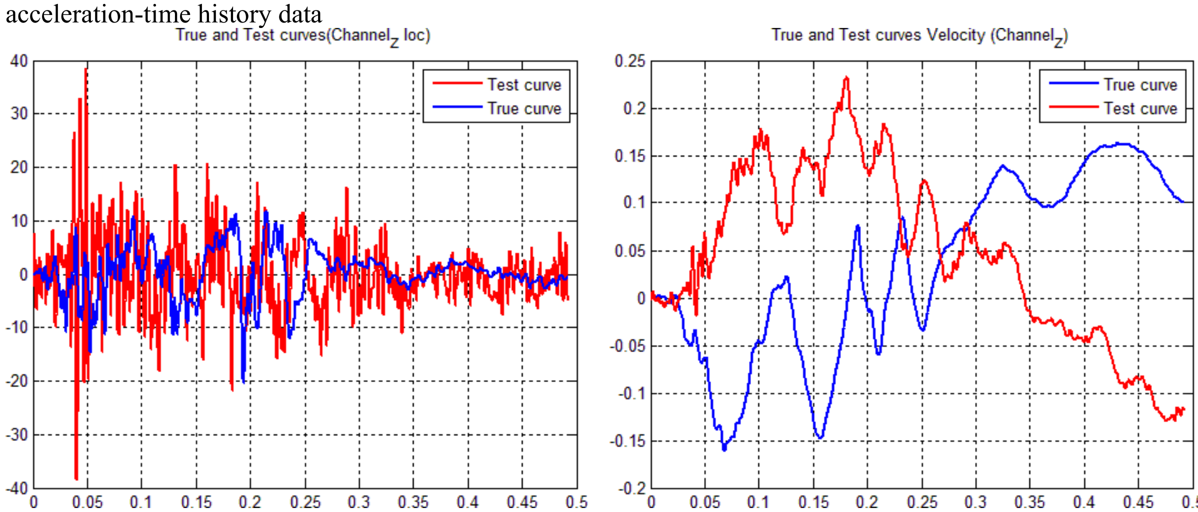


Figure 9. Z-Channel (left) acceleration-time history data used to compute metrics, and (right) integration of acceleration-time history data

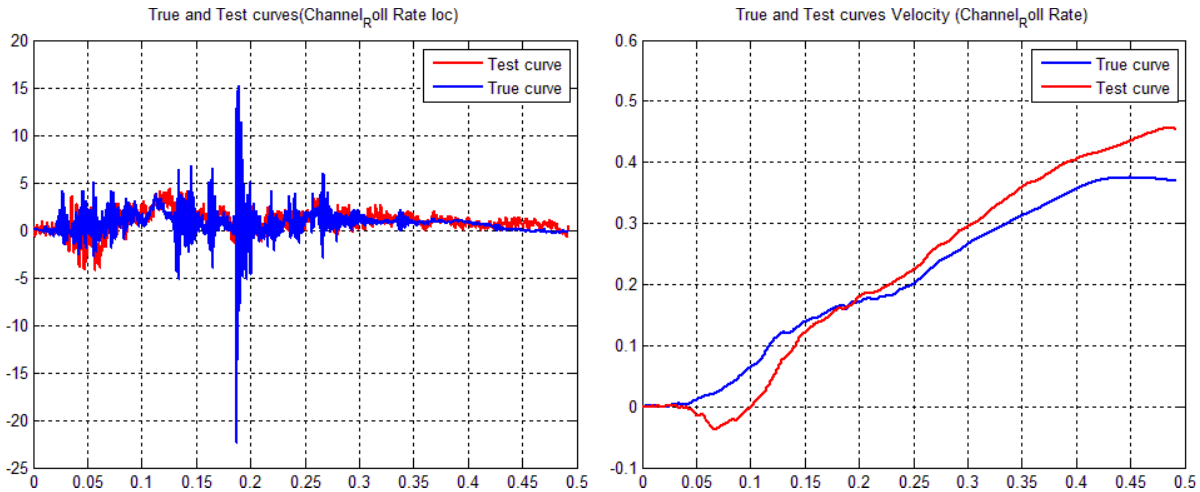


Figure 10. Roll Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

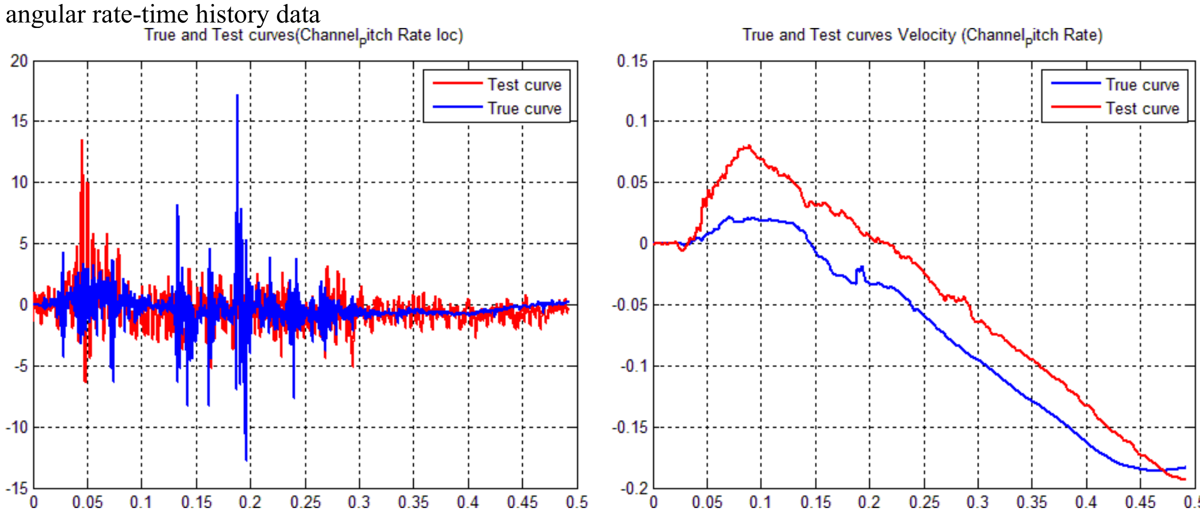


Figure 11. Pitch Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

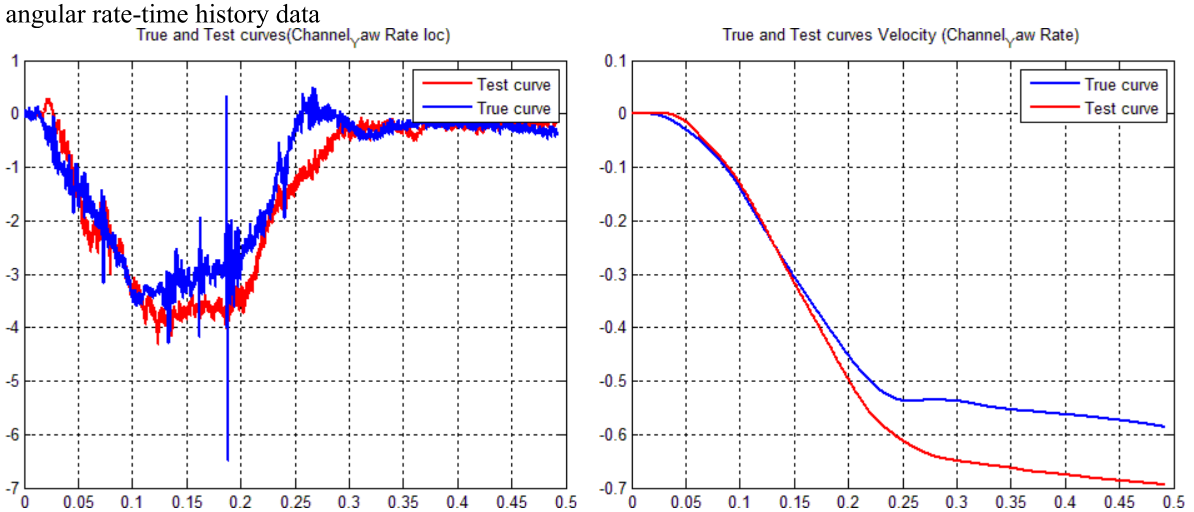
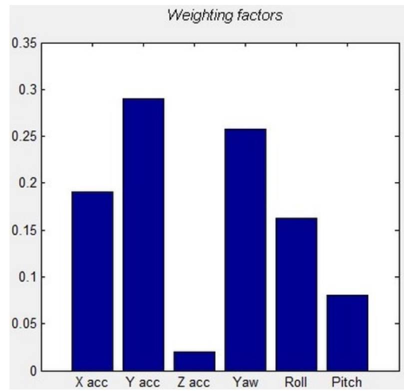


Figure 12. Yaw Channel (left) angular rate-time history data used to compute metrics, and (right) integration of angular rate-time history data

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

Evaluation Criteria (time interval [0.0 sec; 0.49 sec])		
Channels (Select which were used)		
☒ **X Acceleration**	☒ **Y Acceleration**	☒ **Z Acceleration**
☒ **Roll rate**	☒ **Pitch rate**	☒ **Yaw rate**
Multi-Channel Weights ☒ **Area II method** ☐ **Inertial method**	**X Channel:** **Y Channel:** **Z Channel:** **Yaw Channel:** **Roll Channel:** ___ **Pitch Channel:**	

O	***Sprague-Geer Metrics*** Values less or equal to 40 are acceptable.	**M**	**P**	**Pass?**
		10.7	25.6	**Yes**
P	***ANOVA Metrics*** Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \leq 0.05 \cdot a_{Peak}$) • The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \leq 0.35 \cdot a_{Peak}$)	**Mean Residual**	**Standard Deviation of Residuals**	Pass?
		-0.2	14.5	**Yes**

The Analysis Solution (check one) ☒ passes ☐ does NOT pass all the criteria in Table E-3.

PART IV: PHENOMENA IMPORTANCE RANKING TABLE

Table E-4 is similar to the evaluation tables in Report 350 and MASH. For the Report 350 or MASH test number identified in Part I (e.g., test 3-10, 5-12, etc.), circle all the evaluation criteria applicable to that test in Table E-4. The tests that apply to each criterion are listed in the far right column without the test level designator. For example, if a Report 350 test 3-11 is being compared (i.e., a pickup truck striking a barrier at 25 degrees and 100 km/hr), circle all the criteria in the second column where the number "11" appears in the far right column. Some of the Report 350 evaluation criteria have been removed (i.e., J and K) since they are not generally useful in assessing the comparison between the known and analysis solutions.

Table E-4. Evaluation Criteria Test Applicability Table

<table>
<tr><th>Evaluation Factors</th><th colspan="4">Evaluation Criteria</th><th>Applicable Tests</th></tr>
<tr><td rowspan="2">Structural Adequacy</td><td>A</td><td colspan="3">Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38</td></tr>
<tr><td>B</td><td colspan="3">The test article should readily activate in a predictable manner by breaking away, fracturing or yielding.</td><td>60, 61, 70, 71, 80, 81</td></tr>
<tr><td></td><td>C</td><td colspan="3">Acceptable test article performance may be by redirection, controlled penetration or controlled stopping of the vehicle.</td><td>30, 31,, 32, 33, 34, 39, 40, 41, 42, 43, 44, 50, 51, 52, 53</td></tr>
<tr><td rowspan="13">Occupant Risk</td><td>D</td><td colspan="3">Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone.</td><td>All</td></tr>
<tr><td>E</td><td colspan="3">Detached elements, fragments or other debris from the test article, or vehicular damage should not block the driver’s vision or otherwise cause the driver to lose control of the vehicle. (Answer Yes or No)</td><td>70, 71</td></tr>
<tr><td>F</td><td colspan="3">The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable.</td><td>All except those listed in criterion G</td></tr>
<tr><td>G</td><td colspan="3">It is preferable, although not essential, that the vehicle remain upright during and after collision.</td><td>12, 22 (for test level 1 – 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44)</td></tr>
<tr><td rowspan="5">H</td><td colspan="3">Occupant impact velocities should satisfy the following:</td><td rowspan="4">10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 80, 81</td></tr>
<tr><td colspan="3">Occupant Impact Velocity Limits (m/s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>9</td><td>12</td></tr>
<tr><td>Longitudinal</td><td>3</td><td>5</td><td>60, 61, 70, 71</td></tr>
<tr><td rowspan="4">I</td><td colspan="3">Occupant ridedown accelerations should satisfy the following:</td><td rowspan="4">10, 20, 30,31, 32, 33, 34, 36, 40, 41, 42, 43, 50, 51, 52, 53, 60, 61, 70, 71, 80, 81</td></tr>
<tr><td colspan="3">Occupant Ridedown Acceleration Limits (g’s)</td></tr>
<tr><td>Component</td><td>Preferred</td><td>Maximum</td></tr>
<tr><td>Longitudinal and Lateral</td><td>15</td><td>20</td></tr>
<tr><td rowspan="3">Vehicle Trajectory</td><td>L</td><td colspan="3">The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant ride-down acceleration in the longitudinal direction should not exceed 20 G’s.</td><td>11,21, 35, 37, 38, 39</td></tr>
<tr><td>M</td><td colspan="3">The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.</td><td>10, 11, 12, 20, 21, 22, 35, 36, 37, 38, 39</td></tr>
<tr><td>N</td><td colspan="3">Vehicle trajectory behind the test article is acceptable.</td><td>30, 31, 32, 33, 34, 39, 42, 43, 44, 60, 61, 70, 71, 80, 81</td></tr>
</table>

Complete Table E-5 according to the results of the known solution (e.g., crash test) and the numerical solution (e.g., simulation). Consistent with Report 350 and MASH, Task E-5 has three parts: the structural adequacy phenomena listed in Table E-5a, the occupant risk phenomena listed in Table E-5b and the vehicle trajectory criteria listed in Table E-5c. If the result of the analysis solution agrees with the known solution, mark the "agree" column "yes." For example, if the vehicle in both the known and analysis solutions rolls over and, therefore, fails criterion F1, the known and the analysis columns for criterion F1 would be evaluated as "no." Even though both failed the criteria, they agree with each other so the "agree" column is marked as "yes." Any criterion that is not applicable to the test being evaluated (i.e., not circled in Table E-4) should be indicated by entering "NA" in the "agree?" column for that row.

Many of the Report 350 evaluation criteria have been subdivided into more specific phenomenon. For example, criterion A is divided into eight sub-criteria, A1 through A8, that provide more specific and quantifiable phenomena for evaluation. Some of the values are simple yes or no questions while other request numerical values. For the numerical phenomena, the analyst should enter the value for the known and analysis result and then calculate the relative difference. Relative difference is always the absolute value of the difference of the known and analysis solutions divided by the known solution. Enter the value in the "relative difference" column. If the relative difference is less than 20 percent, enter "yes" in the "agree?" column.

Sometimes, when the values are very small, the relative difference might be large while the absolute difference is very small. For example, the longitudinal occupant ride down acceleration (i.e., criterion L2) in a test might be 3 g's and in the corresponding analysis might be 4 g's. The relative difference is 33 percent but the absolute difference is only 1 g and the result for both is well below the 20 g limit. Clearly, the analysis solution in this case is a good match to the experiment and the relative difference is large only because the values are small. The absolute difference, therefore, should also be entered into the "Difference" column in Table E-5.

The experimental and analysis result can be considered to agree as long as either the relative difference or the absolute difference is less than the acceptance limit listed in the criterion. Generally, relative differences of less than 20 percent are acceptable and the absolute difference limits were generally chosen to represent 20 percent of the acceptance limit in Report 350 or MASH. For example, Report 350 limits occupant ride-down accelerations to those less than 20 g's so 20 percent of 20 g's is 4 g's. As shown for criterion L2 in Table E-5, the relative acceptance limit is 20 percent and the absolute acceptance limit is 4 g's.

If a numerical model was not created to represent the phenomenon, a value of "NM" (i.e., not modeled) should be entered in the appropriate column of Table E-5. If the known solution for that phenomenon number is "no" then a "NM" value in the "test result" column can be considered to agree. For example, if the material model for the rail element did not include the possibility of failure, "NM" should be entered for phenomenon number T in Table E-5. If the known solution does not indicate rail rupture or failure (i.e., phenomenon T = "no"), then the known and analysis solutions agree and a "yes" can be entered in the "agree?" column. On the other hand, if the known solution shows that a rail rupture did occur resulting in a phenomenon T entry of "yes" for the known solution, the known and analysis solutions do not agree and "no" should be entered in the "agree?" column. Analysts should seriously consider refining their model to incorporate any phenomena that appears in the known solution and is shown in Table E-5.

All the criteria identified in Table E-4 are expected to agree but if one does not and, in the opinion of the analyst, is not considered important to the overall evaluation for this particular comparison, then a footnote should be provided with a justification for why this particular criteria can be ignored for this particular comparison.

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

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Structural Adequacy	A	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable. (Answer Yes or No)	Yes	Yes		**Yes**
		A2	Maximum dynamic deflection: - Relative difference is less than 20 percent or - Absolute difference is less than 0.15 m	0.136 m	0.109 m	19.85% 0.03 m	**Yes**
		A3	Length of vehicle-barrier contact: - Relative difference is less than 20 percent or - Absolute difference is less than 2 m	4.04 m	3.17 m	21.53% 0.87 m	**Yes**
		A4	Number of broken or significantly bent posts is less than 20 percent. (Posts with deflections > 1 in. (25.4 mm)	7	5	28.57% 2 posts	**No***
		A5	Did the rail element rupture or tear (Answer Yes or No)	No	No		**Yes**
		A6	Were there failures of connector elements (Answer Yes or No).	No	No		**Yes**
		A7	Was there significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	No	No		**Yes**
		A8	Was there significant snagging between vehicle body components and barrier elements (Answer Yes or No).	No	No		**Yes**

* Soil strength is dependent on post spacing in full-scale test and acts independently in simulation.

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

			Evaluation Criteria	Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Occupant Risk	D		Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. (Answer Yes or No)	Yes	Yes		**Yes**
	F	F1	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable. (Answer Yes or No)	Yes	Yes		**Yes**
		F2	Maximum roll of the vehicle (t=350ms): - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	17.51	18.97	8.34% 1.46 deg.	**Yes**
		F3	Maximum pitch of the vehicle is (t=350ms): - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	3.67	1.76	52.04% 1.91 deg.	**Yes**
		F4	Maximum yaw of the vehicle is (t=350ms): - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	33.12	39.44	19.08% 6.32 deg.	**Yes**
	L	L1	Occupant impact velocities: - Relative difference is less than 20 percent or - Absolute difference is less than 2 m/s.				
			• Longitudinal OIV (m/s)	-6.18	-6.35	2.75% 0.17 m/s	**Yes**
			• Lateral OIV (m/s)	7.50	8.24	9.87% 0.74 m/s	**Yes**
			• THIV (m/s)	9.43 m/s	NA	-	NA
		L2	Occupant accelerations: - Relative difference is less than 20 percent or - Absolute difference is less than 4 g's.				
			• Longitudinal ORA	-7.06	-7.75	9.77% 0.69 g's	**Yes**
			• Lateral ORA	10.40	8.13	21.83% 2.27 g's	**Yes**
			• PHD	12.53	NA	-	NA
			• ASI	1.37	NA	-	NA

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

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Vehicle Trajectory	M	M1	The exit angle from the test article preferable should be less than 60 percent of test impact angle, measured at the time of vehicle loss of contact with test device.	Yes	Yes		**Yes**
		M2	Exit angle at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	8.99	14.07	56.51% 5.08 deg.	**No***
		M3	Exit velocity at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	69.98	71.01	1.47% 1.03 km/h	**Yes**
		M4	One or more vehicle tires failed or de-beaded during the collision event (Answer Yes or No).	Yes	Yes		**Yes**

* In the simulation, the detached tire remained in the wheel well and did not exit under the vehicle as in the full-scale test resulting in an exit angle discrepancy.

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

END OF DOCUMENT