Final Report

MASH TL4 Evaluation of MassDOT's Curb-Mounted and Sidewalk-Mounted S3-TL4 Steel Bridge Railing Using Finite Element Analysis

Prepared for: **Gill Engineering and the Massachusetts Department of Transportation**

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16. Abstract

The crash performance of an existing 42-inch tall steel 3-tube bridge railing (S3-TL4) design was evaluated for the Massachusetts Department of Transportation (MassDOT). The evaluation was performed using finite element analysis (FEA) using impact conditions and evaluation procedures set forth in the AASHTO Manual for Assessing Safety Hardware (MASH) for Test Level 4 (TL4). Two design options for the bridge rail were evaluated: 1) a curb-mounted option in which the bridge rail was mounted onto the top of an 8-inch tall reinforced curb that was integral to the bridge deck, and 2) a sidewalk-mounted option in which the bridge rail was mounted onto the top of a 5-ft wide sidewalk with an 8-inch curb face. The overall results indicated that the S3-TL4 design would meet MASH TL-4 conditions.

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CHAPTER 1 – INTRODUCTION

The purpose of this project was to evaluate the crash performance of an existing steel bridge rail design (i.e., S3-TL4) for the Massachusetts Department of Transportation (MassDOT). Test installation photos of the sidewalk-mounted and curb-mounted S3-TL4 bridge rail are shown in Figure 1. The evaluation was performed using finite element analysis (FEA) under evaluation procedures set forth in the AASHTO *Manual for Assessing Safety Hardware (MASH)* for Test Level 4 (TL4).

(a) (b)

Figure 1. Test installation phots of the (a) sidewalk-mounted and (b) curb-mounted S3-TL4 bridge rail.

This system was previously full-scale crash tested at the Texas Transportation Institute (TTI) under *NCHRP Report 350* (i.e., predecessor to *MASH*) for Test Level 4, in which the system met all required structural and safety criteria. [*Ross93; Buth99*] There have been no changes to the system's design, but it was of interest to MassDOT to determine if the system meets the strength and safety criteria of the current crash testing standards of *MASH*, which involve higher impact severities for each of the required test cases.

Objectives and Scope

The objective of this project was to evaluate the crash performance of the MassDOT S3-TL4 bridge rail design using finite element analysis (FEA). Crash simulations were performed using the non-linear, dynamic, explicit finite element analysis software LS-DYNA. [*LSDYNA15*] The finite element analysis (FEA) model of the bridge rail system previously developed in Phase I for evaluation of the transition design, was adopted for this study. The FEA model was updated to include: extended system length, detailed splice connections, verification of concrete model, and subsequent validation of overall model based on comparison to full-scale Report 350 tests (as available).

The impact conditions and assessment procedures conformed to the specifications in *MASH* for TL-4, which included evaluations of structural capacity, risk of occupant injury and vehicle stability during impact and redirection. Two design options for the bridge rail were evaluated: 1) a curb-mounted option in which the bridge rail was mounted onto the top of an 8-inch tall reinforced curb that is integral to the bridge deck, and 2) a sidewalk-mounted option in which the bridge rail was mounted onto the top of a 5-ft wide sidewalk with an 8-inch curb face.

CHAPTER 2 – RESEARCH APPROACH AND EVALUATION CRITERIA

The basic approach for the study was to:

1. Develop a finite element model of the existing S3-TL4 bridge rail (see Chapter 5),
2. Validate the model using the procedures outlined in NCHRP Web Document 179 by comparing the model results to existing full-scale crash tests on the system (see Chapter 6),
3. Update model to include MASH vehicle types and impact conditions and again use FEA to simulate MASH TL4 tests and evaluate the system's performance (see Chapter 7).

As previously mentioned, the finite element analysis (FEA) model of the S3-TL4 bridge rail system, which was developed in Phase I for evaluation of the transition design, was adopted and updated for this study. Since the scope of work relied heavily upon FEA, it was therefore necessary to validate the model to gain confidence in the model's results. The validation procedures of NCHRP Web-Document 179 (W179) were used to assess the fidelity of the model. [*Ray10*] The W179 validation procedures have three steps:

1. Solution verification: Indicates whether the analysis solution produced numerically stable results (ensures that basic physical laws are upheld in the model).
2. Time-history evaluation: Quantitative measure of the level of agreement of time-history data (e.g., x, y, z accelerations and roll, pitch, and yaw rates) between the analysis and test.
3. Phenomena Importance Ranking Table (PIRT): A table that documents the types of phenomena that a numerical model is intended to replicate and verifies that the model produces results consistent with its intended use.

The available full-scale test data for the validation task included tests performed by Buth et. al according to NCHRP *Report 350* and included: [*Buth99*]

- Test 404251-1 (R350 Test 4-10): small car test on sidewalk-mounted system
- Test 404251-2 (R350 Test 4-11): pickup test on sidewalk-mounted system
- Test 404251-3 (R350 Test 4-12): 8000-kg single unit truck (SUT) test on sidewalk-mounted system
- Test 404251-5 (R350 Test 4-11): pickup test on curb-mounted system
- Test 404251-6 (R350 Test 4-12): 8000-kg SUT test on curb-mounted system.

Once the FEA model was validated, it was then used to simulate the required impact conditions specified in *MASH* for Test Level 4 to again evaluate crash performance of the system regarding structural capacity, occupant risk measures and vehicle stability during impact and redirection according to the recommended procedures and criteria contained in *MASH*. The required test conditions specified in *MASH* for test level 4 evaluation of longitudinal barrier include:

- MASH Test 4-10 – the 1100C vehicle (2,225-lb sedan) impacting the barrier at the critical impact point at a nominal speed and angle of 62.0 mph and 25 degrees, respectively.
- MASH Test 4-11 – the 2270P vehicle (5,000-lb ½-ton quad-cab pickup) impacting the barrier at the critical impact point at a nominal speed and angle of 62.0 mph and 25 degrees, respectively.
- MASH Test 4-12 – the 10000S vehicle (22,046-lb single unit truck) impacting the barrier at the critical impact point at a nominal speed and angle of 56.0 mph and 15 degrees, respectively.

Table 1 shows a summary of the evaluation criteria required for test levels 1 through 4 (taken directly from *MASH*) with the specific criteria for TL-4 barrier denoted by a red box. Table 2 shows the specific limitations for each criterion and identifies the applicable tests.

Table 1. (MASH Table 2-2A) Recommended test matrices for longitudinal barriers. [AASHTO16]

Test Level	Barrier Section[c]	Test No.	Vehic.	Impact Speed,[a] mph (km/h)	Impact Angle,[a] θ, deg.	Im-pact Point	Acceptable IS Range,[a] kip-ft (kJ)	Evaluation Criteria[b]
1	Length-of-Need	1-10 1-11	1100C 2270P	31 (50.0) 31 (50.0)	25 25	(c) (c)	≥13 (17.4) ≥27 (36.0)	A,D,F,H,I A,D,F,H,I
	Transition	1-20[d] 1-21	1100C 2270P	31 (50.0) 31 (50.0)	25 25	(c) (c)	≥13 (17.4) ≥27 (36.0)	A,D,F,H,I A,D,F,H,I
2	Length-of-Need	2-10 2-11	1100C 2270P	44 (70.0) 44 (70.0)	25 25	(c) (c)	≥25 (34.2) ≥52 (70.5)	A,D,F,H,I A,D,F,H,I
	Transition	2-20[d] 2-21	1100C 2270P	44 (70.0) 44 (70.0)	25 25	(c) (c)	≥25 (34.2) ≥52 (70.5)	A,D,F,H,I A,D,F,H,I
3	Length-of-Need	3-10 3-11	1100C 2270P	62 (100.0) 62 (100.0)	25 25	(c) (c)	≥51 (69.7) ≥106 (144)	A,D,F,H,I A,D,F,H,I
	Transition	3-20[d] 3-21	1100C 2270P	62 (100.0) 62 (100.0)	25 25	(c) (c)	≥51 (69.7) ≥106 (144)	A,D,F,H,I A,D,F,H,I
4	Length-of-Need	4-10 4-11 4-12	1100C 2270P 10000S	62 (100.0) 62 (100.0) 56 (90.0)	25 25 15	(c) (c) (c)	≥51 (69.7) ≥106 (144) ≥142 (193)	A,D,F,H,I A,D,F,H,I A,D,G
	Transition	4-20[d] 4-21 4-22	1100C 2270P 10000S	62 (100.0) 62 (100.0) 56 (90.0)	25 25 15	(c) (c) (c)	≥51 (69.7) ≥106 (144) ≥142 (193)	A,D,F,H,I A,D,F,H,I A,D,G

Table 2. (MASH Table 5-1A and 5-1B) Safety evaluation guidelines for structural adequacy and occupant risk. *[AASHTO16]*

Evaluation Factors	Evaluation Criteria	Test 4-10	Test 4-11	Test 4-12
Structural Adequacy	. Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Y	Y	Y
Occupant Risk	. Detached elements, fragments or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present an undue hazard to other traffic, pedestrians or personnel in a work zone. Deformations of, or intrusions into, occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Y	Y	Y
	. The vehicle should remain upright during and after the collision. The maximum roll and pitch angles are not to exceed 75 degrees.	Y	Y	N
	. It is preferable, although not essential, that the vehicle remain upright during and after collision.	N	N	Y
	. The longitudinal and lateral occupant impact velocity (OIV) shall not exceed 40 ft/s (12.2 m/s), with a preferred limit of 30 ft/s (9.1 m/s)	Y	Y	N
	. The longitudinal and lateral occupant ridedown acceleration (ORA) shall not exceed 20.49 G, with a preferred limit of 15.0 G.	Y	Y	N

Accelerometers were included at the center of gravity for each of the vehicle models. For the 1100C vehicle (e.g., passenger car) and the 2270V vehicle (e.g., pickup), the center of gravity was located between the front seat occupants. For the 10000S vehicle (e.g., single unit truck) the center of gravity was located inside the cargo box, typically just in front of the ballast. Thus, for the single unit truck (SUT) an additional accelerometer was included inside the cabin of the truck model for use in computing occupant risk metrics.

The acceleration-time histories and angular rate-time histories were collected from the cabin accelerometers during the impact event and were used to evaluate occupant risk metrics according to the procedures outlined in *MASH*. The acceleration data from the analyses were collected at a frequency of 50,000 Hz and were filtered using the SAE Class 180 filter prior to input into the Test Risk Assessment Program (TRAP). [*TTI98*] The TRAP program calculates standardized occupant risk factors from vehicle crash data in accordance with *MASH* guidelines and the European Committee for Standardization (EN1317). TRAP computes important evaluation parameters including the occupant impact velocities (OIV), ridedown accelerations (ORA), 50 millisecond running average acceleration, and maximum roll, pitch and yaw. Also computed in TRAP are the EN1317 occupant risk metrics which include the Theoretical Head Impact Velocity (THIV), the Post Impact Head Deceleration (PHD) and the Acceleration Severity Index (ASI). The details of these calculations are provided in *MASH*. [*AASHTO16*]

The evaluation of occupant risk metrics is not required for Test 4-12; however, they are included herein for completeness.

With regards to occupant risk, *MASH* lists certain limitations for passenger compartment intrusion. Specifically, it states:

"*A clear distinction should be made between: (a) penetration, in which a component of the test article actually penetrates into the occupant compartment; and (b) intrusion or deformation, in which the occupant compartment is deformed and reduced in size, but no actual penetration is observed. No penetration by any element of the test article into the occupant compartment is allowed. As for deformation or intrusion, the extent of deformation varies by area of the vehicle damaged and should be limited as follows:"*

- *"Roof ≤ 4.0 in. (102 mm).*
- *Windshield – no tear of plastic liner and maximum deformation of 3 in. (76 mm).*
- *Window – no shattering of a side window resulting from direct contact with a structural member of the test article, except for special considerations pertaining to tall, continuous barrier elements discussed below (Note: evaluation of this criteria requires the side windows to be in the up position for testing). In cases where side windows are laminated, the guidelines for windshields will apply.*
- *A- and B- pillars – no complete severing of support member and maximum resultant deformation of 5 in. (127 mm). Lateral deformation should be limited to 3 in. (76 mm).*
- *Wheel/foot well and toe pan areas ≤ 9 in. (229 mm).*
- *Side front panel (forward of A-pillar) ≤ 12 in. (305 mm).*
- *Front side door area (above seat) ≤ 9 in. (229 mm).*
- *Front side door area (below seat) ≤ 12 in. (305 mm).*
- *Floor pan and transmission tunnel areas ≤ 12 in. (305 mm)."* [*AASHTO16*]

Post-impact vehicle behavior, although not required by *MASH*, was examined for completeness of the evaluations. *MASH* uses the concept of the "exit box" which was adopted directly from CEN standards. It is defined by the initial traffic face of the barrier and a line parallel to the initial traffic face of the barrier at a lateral distance "A" plus the width of the vehicle plus 16 percent of the length of the vehicle, starting at the final intersection (break) of the wheel track with the initial traffic face of the barrier for a longitudinal distance of "B". All wheel tracks of the vehicle should not cross the parallel line within the distance B. [*AASHTO16*] A graphical representation of the exit box is shown in Figure 2.

Distance for Exit Box Criterion

Vehicle Type	A ft (m)	B ft (m)
Car/Pickup	$7.2 + V_W + 0.16V_L$ $(2.2 + V_W + 0.16V_L)$	32.8 (10.0)
Other Vehicles	$14.4 + V_W + 0.16V_L$ $(4.4 + V_W + 0.16V_L)$	65.6 (20.0)

V_W = Vehicle Width
V_L = Vehicle Length

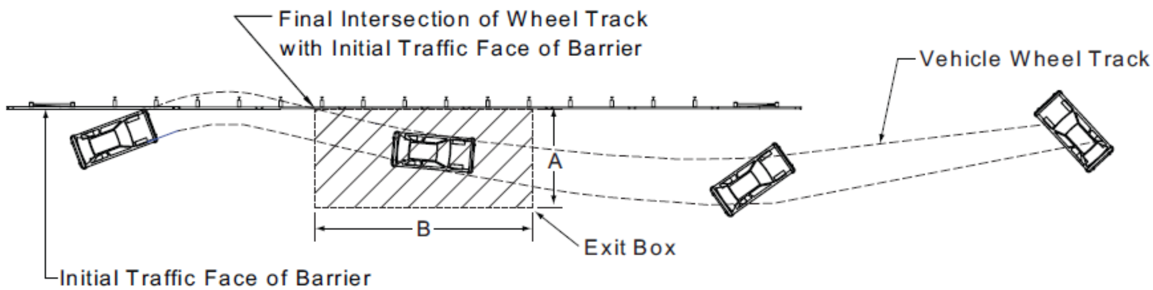


Figure 2. *MASH* exit box. [*AASHTO16*]

The exit box values were calculated based on the dimensions of the finite element analysis vehicle models that are further described in Chapter 4 – FEA Vehicle Models. Table 3 shows the vehicle widths and lengths and resulting exit box dimensions for the small car, pickup truck, and SUT.

Table 3. Exit box dimensions for *MASH* tests for small car, pickup, and SUT

Test	V_w (ft)	V_L (ft)	A (ft)	B (ft)
4-10	5.5	14.1	15	32.8
4-11	6.02	16.8	15.86	32.8
4-12	8.01	28.15	26.95	65.6

The details of the finite element model development are presented in Chapter 5 – FEA Model Development and the results of the evaluations are presented in Chapters 6, and 7.

CHAPTER 3 – DESCRIPTION OF DESIGN

An elevation drawing of the S3-TL4 bridge rail is shown in Figure 3. Profile drawings are shown in Figures 4 and 5 for the sidewalk-mounted system and the curb-mounted system, respectively. The bridge rail consists of three tubular rails, including two HSS 5x5x1/4 inch for the two lower rails and a 5x4x1/4 inch for the upper rail. The height to the center of the lower rail is 15 inches; the height to the center of the middle rail is 28 inches; and the height to the center of the top rail is 39.5 inches. The overall height to the top of the bridge rail is 42-1/8 inches. The height is measured from the roadway surface for the curb-mounted design and is measured from the top of the sidewalk for the sidewalk-mounted design (see Appendix A for details).

The rails are supported by W6x25 posts spaced at 6.5 feet on centers (maximum). The tube rails are fastened to the post flange using two 7/8-inch diameter round-head bolts with washers, lock washers, and nuts, as shown in Figure 6. A 15/16" x 2-3/16" vertical slot is cut in the post for the connection. A 1.25-inch thick steel base plate is welded to the bottom of each post, and the base plate is fastened to the top of the curb or sidewalk using five (5) 1-inch diameter ASTM F1554 Grade 105 anchor bolts that are 12-inch long, as shown in Figure 7. Three (3) bolts are positioned on the front side of the posts and two (2) bolts positioned just in front of the back flange of the posts, as shown in Figure 1(b) and in Figure 7. A 5/8" x 10" x12" anchor plate is attached at the bottom of the anchor bolts to secure the anchors and prevent pullout during impact.

To reduce the chance of a vehicle extending over the top rail and contacting the post, the top of the post is ¾ inch lower than the top surface of the top rail tube and is cut at an angle sloping downward toward the back of the post. The slope starts on the top of the post at 2 inches from the face of the front flange and continues to the back edge of the post to a vertical distance of 7.5 inches lower than the top of the post.

The splice connection of adjoining tube rails consists of a 28-inch long splice-tube inserted 14 inches (measured from the centerline of the splice gap) into both the upstream- and downstream end of the rails. The splice-tube is fabricated from 3/8" thick steel plate with ¼-inch continuous welds at the edge joints. The splice-tube is also welded to the end of one of the main rail tubes; while the opposite end of the splice-tube slides freely inside the adjoining main rail tube, as shown in Figure 8. A ½-inch gap between the adjoining main-rail sections was included at the splice according to design (i.e., @ 50°F). The complete drawing details for the S3-TL4 bridge rail are provided in Appendix A.

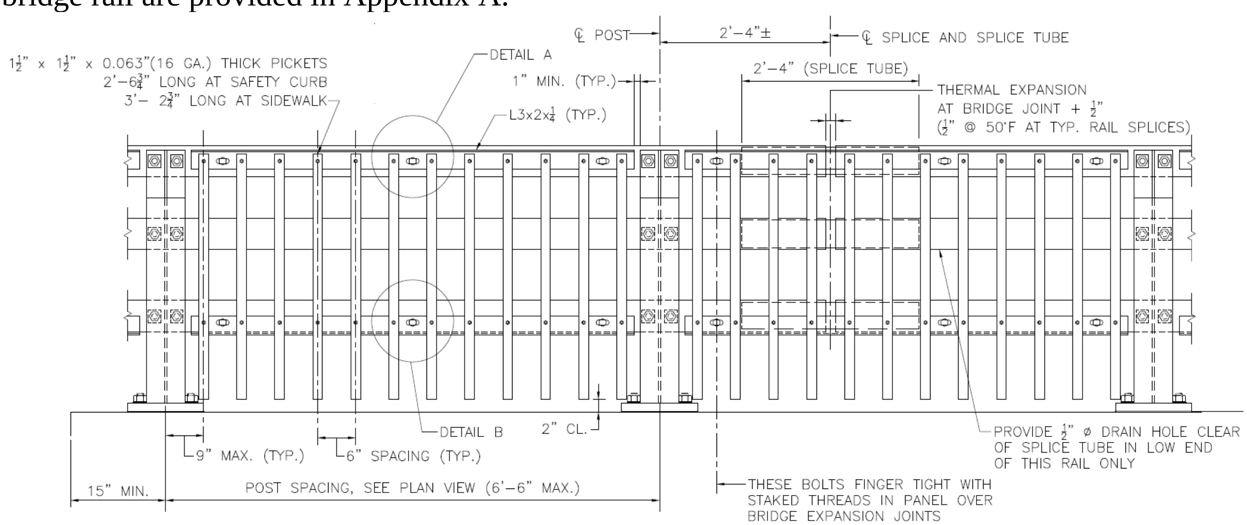


Figure 3. Elevation drawing for S3-TL4 bridge rail.

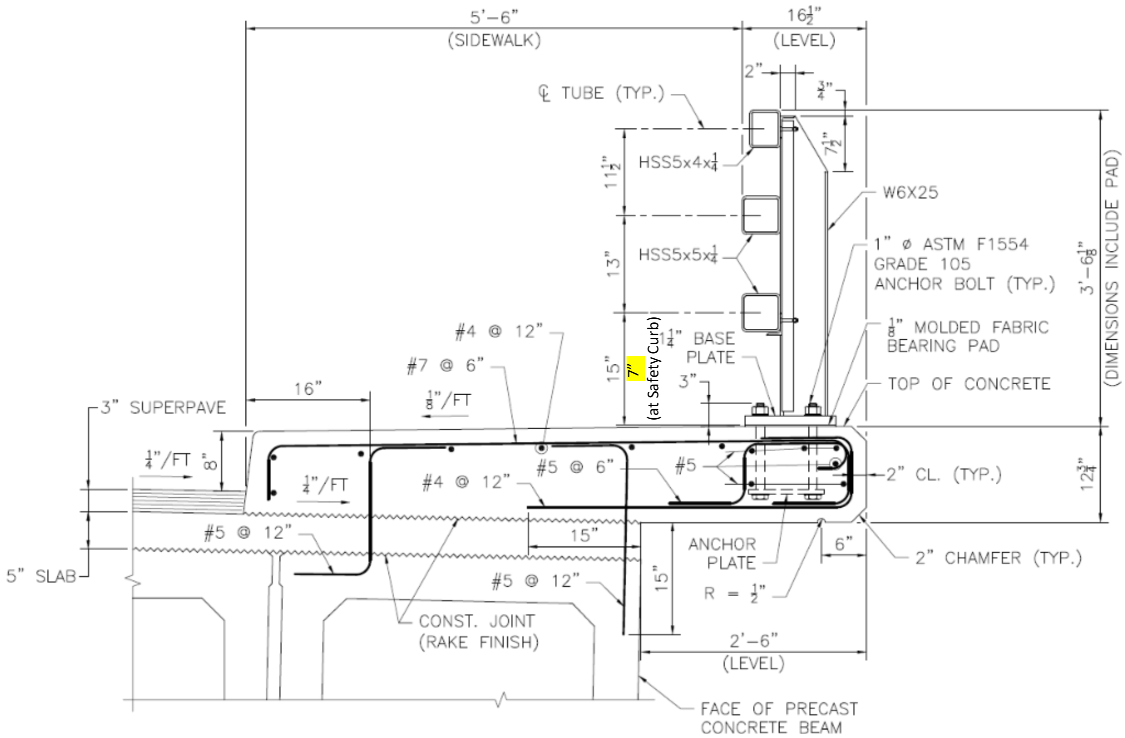


Figure 4. Profile drawing of the S3-TL4 bridge rail for sidewalk-mounted system.

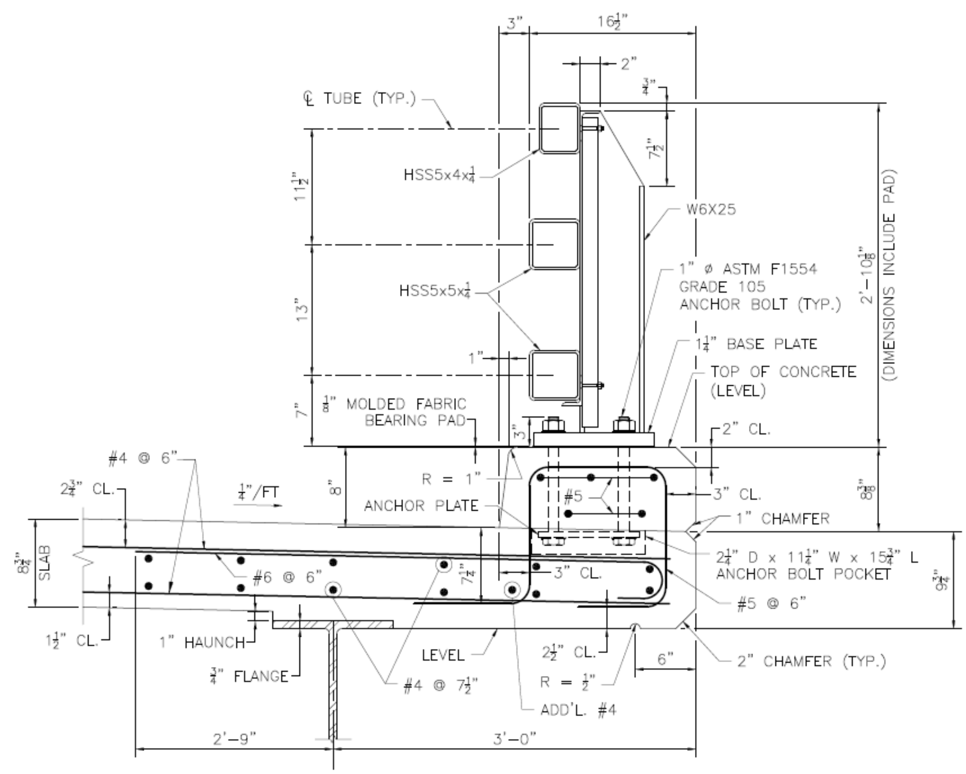


Figure 5. Profile drawing of the S3-TL4 bridge rail for curb-mounted system.

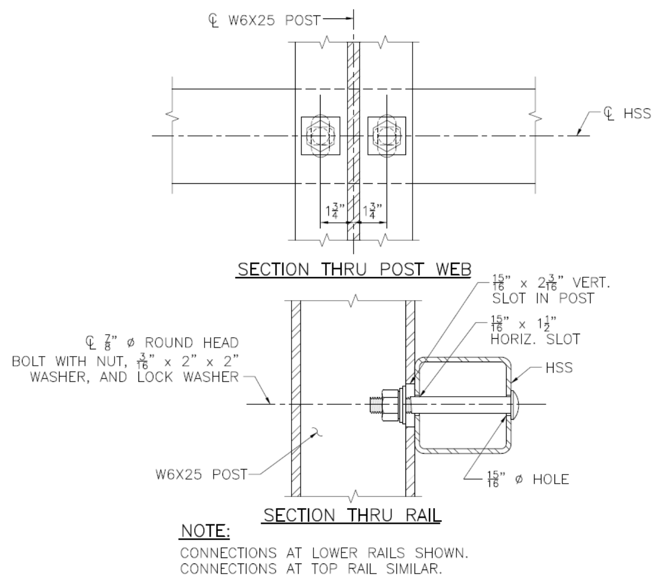


Figure 6. Typical rail to post connections for the S3-TL4 bridge rail.

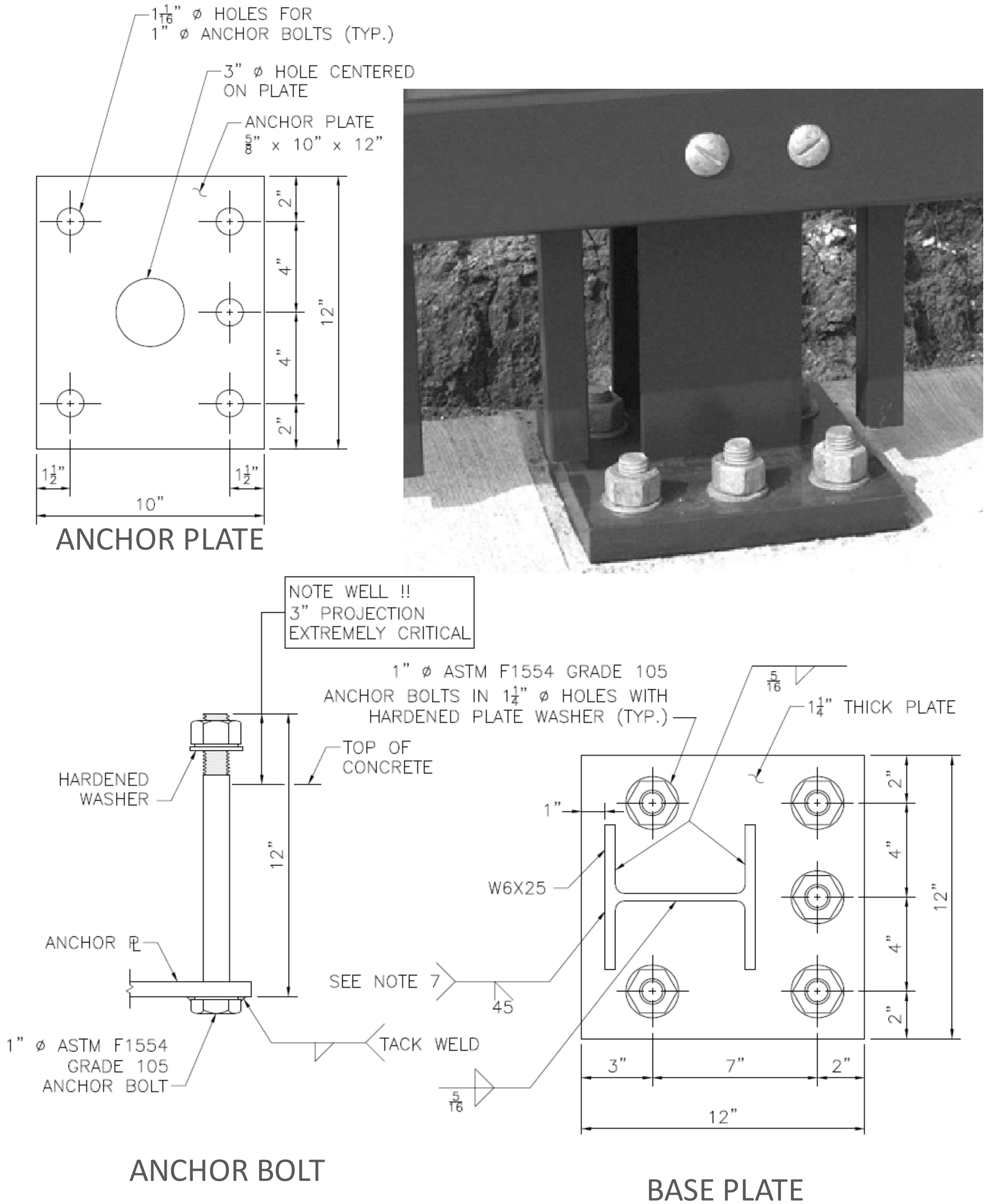


Figure 7. Anchor assembly for the S3-TL4 bridge rail posts.

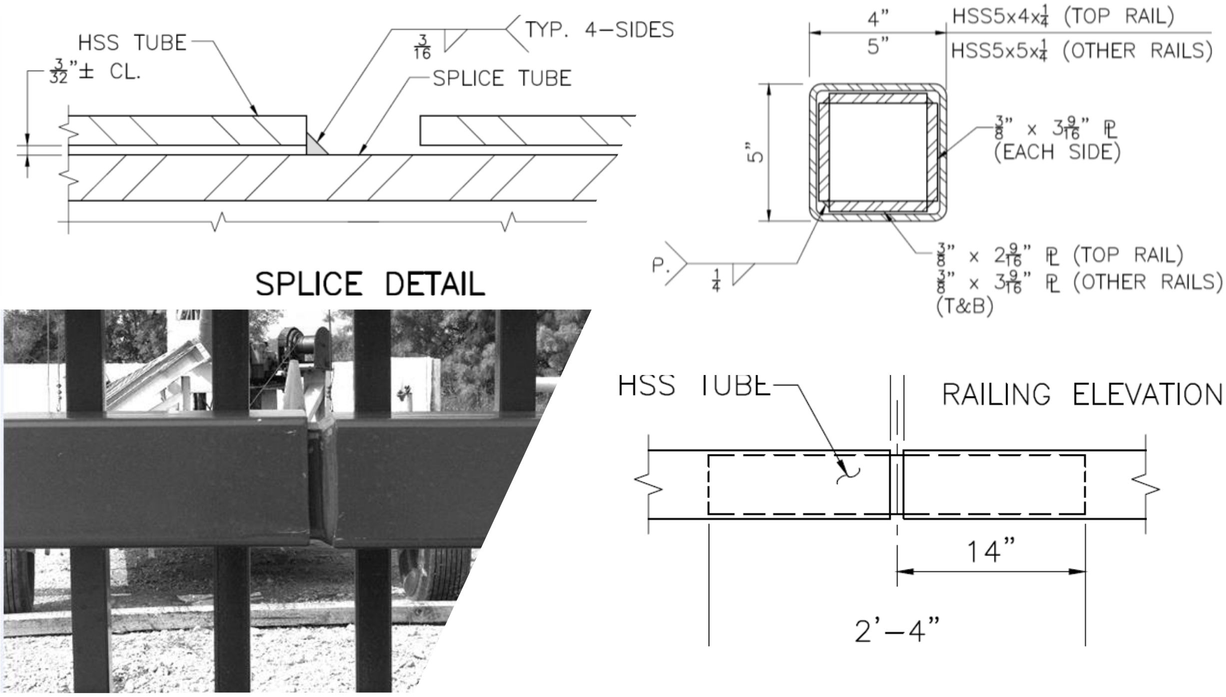


Figure 8. Splice assembly for the S3-TL4 bridge rail.

CHAPTER 4 – FEA VEHICLE MODELS

The vehicle models used in the crash performance evaluations include:

- NCHRP Report 350 crash simulation cases:
    - F800 version 181114 ballasted to 8,000 kg (i.e., 8000S vehicle)
    - Modified F800 with raised cargo bed (version 181114-3).
- MASH crash simulation cases:
    - YarisC version 1L (i.e., 1100C vehicle)
    - SilveradoC_v3a (i.e., 2270P vehicle)
    - F800 version 181114 ballasted to 10,000 kg (i.e., 10,000S vehicle)
    - Modified F800 with raised cargo bed (version 181114-3).

The models for the 1100C and 2270P vehicles used for the *MASH* analysis cases were the YarisC_v1L model (based on a 2010 Toyota Yaris) and the SilveradoC_v3a model (based on a 2007 quad-cab Chevy Silverado). These vehicles closely represent the two test vehicles specified in *MASH*. [*AASHTO16*] The vehicle models were developed through the process of reverse engineering by the members of George Mason University (GMU) and were initially validated based on NCAP frontal wall impact tests through comparison with NHTSA test data. [*Marzougui08*] The models also include validated suspension and steering subsystems. [*Marzougui10*] The Silverado model has been continually improved by GMU as well as the user community since its development and has been used successfully in several studies involving crash analysis with roadside safety hardware. The Yaris model has not been used as much as the Silverado but is expected to provide reasonable results. Validation PIRTs for these models were provided by George Mason University and are included with this report as Appendix D and Appendix E.

Additional modifications were made to the 2270P model for this study, which included changing the material characterization for some of the parts that were previously modeled as "rigid" (e.g., wheel rims and various suspension components) to an appropriate steel material (characterized as *Mat_24 in LS-DYNA) corresponding to the specific part. Based on preliminary results of the vehicle traversing the 8-inch tall curb and sidewalk, further modifications were incorporated for the tire model based on the work by Orengo et al. and Reid et al. [*Orengo03; Reid06*].

The baseline model for the 8000S and the 10000S single unit truck vehicle was developed at the National Crash Analysis Center (NCAC) in Ashburn, Virginia. This model was further modified by various researchers over the years to improve its fidelity in analysis of impact conditions corresponding to NCHRP Report 350 Test 4-12. [*Miele05*; *Mohan07; Plaxico13*] Additional modifications to the baseline model made in this study included remeshing of several parts in the crush zone of the vehicle and changing the element type to the fully integrated shell element (i.e., type 16 in LS-DYNA). The model of the ballast was calibrated to the mass inertial properties of the test vehicle specifications (e.g., 8000S and 10000S as appropriate). In particular, the ballast type was modeled based on a recent test vehicle used by the Texas Transportation Institute (TTI) in full-scale test number 607451-1. [*Williams17*] The ballast included two rigid blocks with dimensions 60 inches wide x 30 inches long x 30 inches tall, positioned one behind the other, and the ballasts were fastened to the truck frame rail using a series of cables. The positioning of the ballast model inside the cargo box for the 8000S and the 10000S vehicle models was determined based on the reported centers of gravity of the vehicles used in the R350 test series which are being used for model validation (i.e., Test 404251-3 (8000S) and Test 404251-6 (8000S)), and a recent MASH Test 4-12 test performed at TTI using a 10000S vehicle. [*Buth99; Williams17*]

Additional modifications to the SUT model included replacing the cargo box on the baseline model with a more detailed model which included better geometric and material fidelity, as shown in Figure 9. Based on visual inspection of several single unit truck boxes, it was decided that the basic structure for the cargo box model would be adopted from an existing semitrailer model and subsequently modified to match the external dimensions of the existing baseline model. An overview of the various components that were included in the model, as well as their corresponding dimensions and material assignments can be found in [*Plaxico19*]. Further details regarding the development of this box structure can be found in the literature. [*Plaxico09; Miele10*]

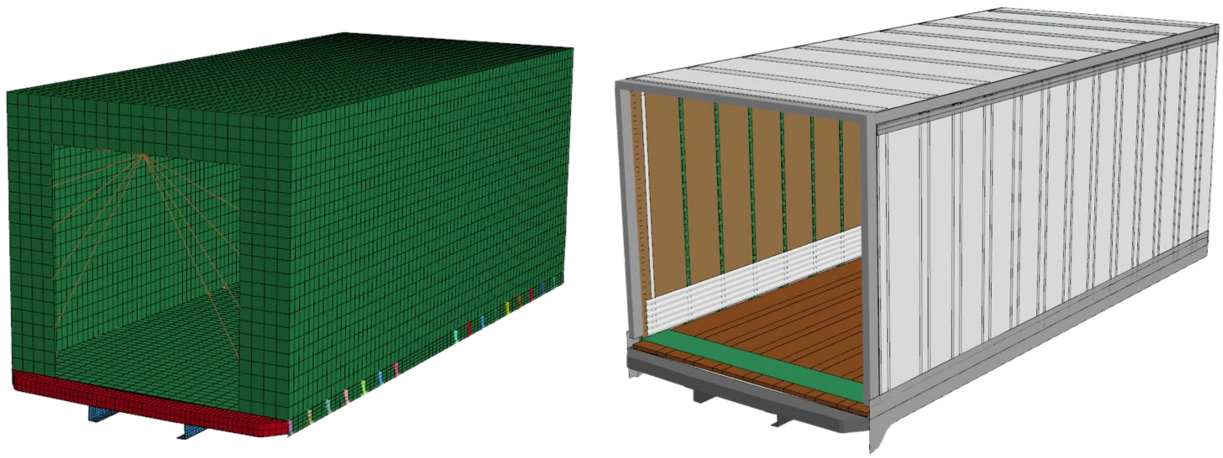


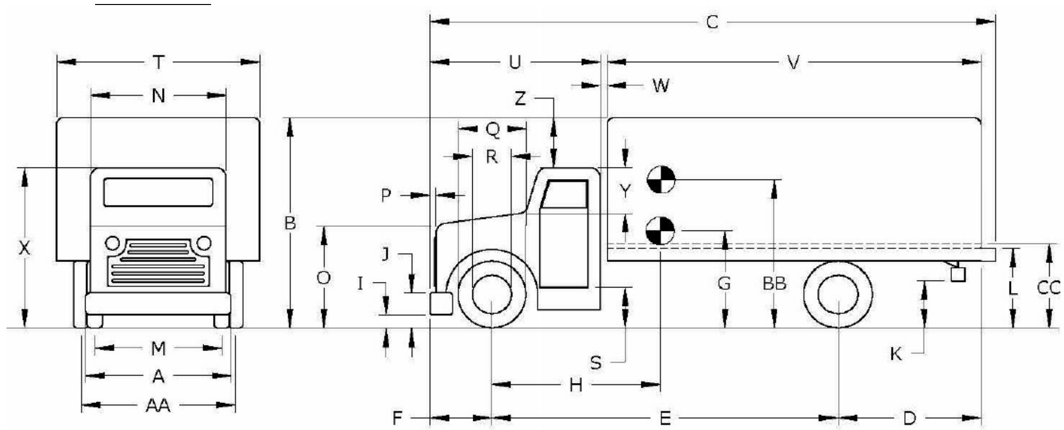
Figure 9. Images of the FEA model for the baseline and detailed cargo-box models (rear door not shown to facilitate viewing inside of cargo box).

A comparison of the physical and inertial properties of the 8000S vehicle models with those of previous full-scale test vehicles on the S3-TL4 system is provided in Figures 10 and 11 for tests 404251-3 and 404251-6, respectively. The most notable difference between the model and the test vehicle was related to the height of the cargo-bed which was very close to the height of the bridge rail. Although the difference was only 5 percent, slight differences in this metric will determine if the cargo-box impacts directly against the rail or passes over the top of the rail. Note that in both cases, the cargo-bed of the test vehicle was approximately 2.5 inches taller than that of the FEA model. Also, regarding the test vehicle in Test 404251-6, the curb weight on the front axle of the FEA model was 12.4 percent greater than the test vehicle, and the corresponding ballast mass was therefore 15.2 percent less for the model. All other measurements were within 10 percent of the corresponding test vehicles measurements and are expected to have minimal effects on the impact response.

A comparison of the physical and inertial properties of the MASH vehicle models with those of recent full-scale test vehicles (i.e., Test 607451-3, Test 607451-2 and Test 607451-1) is provided in Figure 12, Figure 13 and Figure 14, respectively. [*Williams17*] The most notable difference for the 1100C vehicle was that the center of gravity (c.g.) was set approximately 7 inches farther back in the model compared to the test vehicle, which resulted in a 19 percent difference. For the 2270P vehicle model, except for the *bumper extension* and the *wheel-well clearance*, all other measurements were within 4 percent of those measured on the test vehicle. The longitudinal and vertical c.g. of the 2270P model was within 1.5 percent and 4 percent, respectively, compared to the test vehicle. The accelerometer for both the 1100C and the 2270P models were positioned at the c.g. of the vehicle. For the 10000S vehicle model, the differences in several of the dimensions were greater than 10 percent compared to the test vehicle; however, those particular properties were considered to have minimal effect on the applied loading to the barrier and the resulting dynamic response of the vehicle during impact.

VEHICLE PROPERTIES AND INFORMATION

Date:	6/19/1998	Test No.:	404251-3	Vin No.:	C17DD9V157484
Year:	1979	Make:	Chevrolet	Model:	C 70
Odometer:	52792	Tire Size Front:	11R22.5	Tire Size Rear:	11R22.5



Vehicle Geometry (in)

		Test	Model	% Error			Test	Model	% Error
A	Front Bumper Width:	-	93.11	-	P	Bumper Extension:	4.33	-	-
B	Overall Height:	137.01	133.35	-2.7	Q	Front Tire Width:	41.73	37.40	-10.4
C	Overall Length:	-	337.60	-	R	Front Wheel Width:	24.02	23.54	-2.0
D	Rear Overhang:	87.01	89.96	3.4	S	Bottom Door Height:	-	36.93	-
E	Wheel Base:	205.91	208.15	1.1	T	Overall Width:	87.40	96.10	10.0
F	Front Overhang:	30.51	33.07	8.4	U	Cab Length:	-	108.66	-
G	C.G. Height:	47.70	48.94	2.6	V	Box Length:	-	226.34	-
H	C.G. Horz. Dist.	121.95	122.50	0.5	W	Gap Width:	-	3.19	-
I	Front Bumper Bottom:	21.65	22.46	3.7	X	Overall front Height:	-	87.95	-
J	Front Bumper Top:	34.25	34.61	1.0	Y	Roof-Hood Dist.	-	18.82	-
K	Rear Bumper Bottom:	-	19.84	-	Z	Roof-Box Height Diff.	-	43.39	-
L	Rear frame Top:	-	-	-	AA	Rear Track Width	72.05	72.72	0.9
M	Front Track Width:	77.56	80.51	3.8	BB	Ballast Center of Mass	-	64.76	-
N	Roof width:	-	57.80	-	CC	Cargo Bed Height:	50.00	49.72	-0.6
O	Hood Height:	63.78	64.22	0.7					

Accelerometer Locations (inches) - measured from front axle and ground		X	Y	Z
	Front	-	-	-
	Center	-	-	-

Weights (lb)

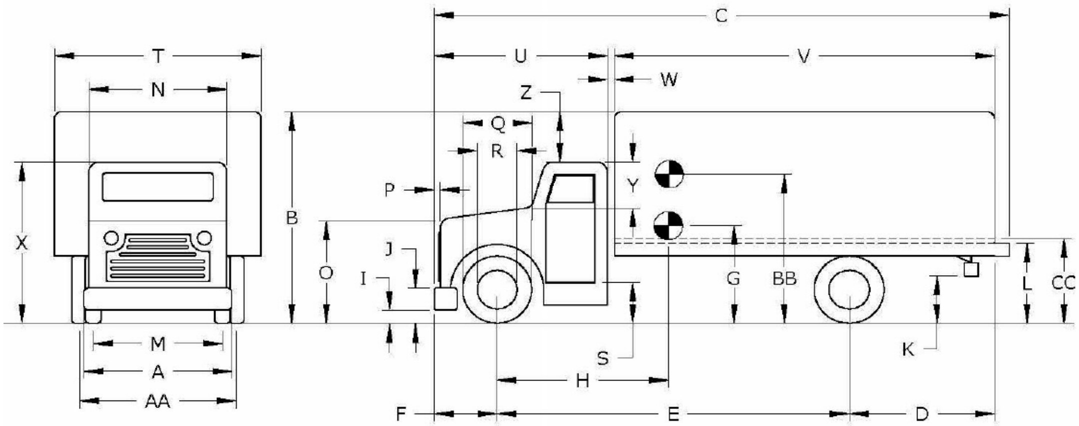
	Curb		
	Test	Model	% Error
$W_{front\ axle}$	5,639	5,520	-2.1
$W_{rear\ axle}$	6,841	6,812	-0.4
W_{total}	12,480	12,333	-1.2

	Test Inertial		
	Test	Model	% Error
$W_{front\ axle}$	7,191	7,260	1.0
$W_{rear\ axle}$	10,445	10,392	-0.5
W_{total}	17,637	17,652	0.1
Ballast	5,157	5,320	3.2

Figure 10. Vehicle property sheet for the 8000S vehicle model (V181114-3) compared with a full-scale Test 404251-3 (i.e., validation case).

VEHICLE PROPERTIES AND INFORMATION

Date:	7/22/1999	Test No.:	404251-6	Vin No.:	1GDJ7D1B5HV514329
Year:	1987	Make:	GMC	Model:	7000
Odometer:	142826	Tire Size Front:	11R22.5	Tire Size Rear:	11R22.5



Vehicle Geometry (in)

		Test	Model	% Error			Test	Model	% Error
A	Front Bumper Width:	-	93.11	-	P	Bumper Extension:	3.94	0	-100.00
B	Overall Height:	140.16	132.60	-5.4	Q	Front Tire Width:	41.34	37.40	-9.5
C	Overall Length:	-	337.60	-	R	Front Wheel Width:	23.23	23.54	1.4
D	Rear Overhang:	85.04	89.96	5.8	S	Bottom Door Height:	-	36.93	-
E	Wheel Base:	205.00	208.15	1.5	T	Overall Width:	88.58	96.10	8.5
F	Front Overhang:	31.10	33.07	6.3	U	Cab Length:	-	108.66	-
G	C.G. Height:	48.58	48.46	-0.2	V	Box Length:	-	226.34	-
H	C.G. Horz. Dist.	122.23	122.54	0.3	W	Gap Width:	-	3.19	-
I	Front Bumper Bottom:	21.65	22.46	3.7	X	Overall front Height:	-	87.95	-
J	Front Bumper Top:	33.46	34.61	3.4	Y	Roof-Hood Dist.	-	18.82	-
K	Rear Bumper Bottom:	28.94	19.84	-	Z	Roof-Box Height Diff.	-	43.39	-
L	Rear frame Top:	-	46.42	-	AA	Rear Track Width	72.44	72.72	0.4
M	Front Track Width:	75.98	80.51	6.0	BB	Ballast Center of Mass	-	63.78	-
N	Roof width:	-	57.80	-	CC	Cargo Bed Height:	48.82	48.70	-0.2
O	Hood Height:	63.78	64.22	0.7					

Accelerometer Locations (inches) - measured from front axle and ground		X	Y	Z
	Front	-	-	-
	Center	-	-	-

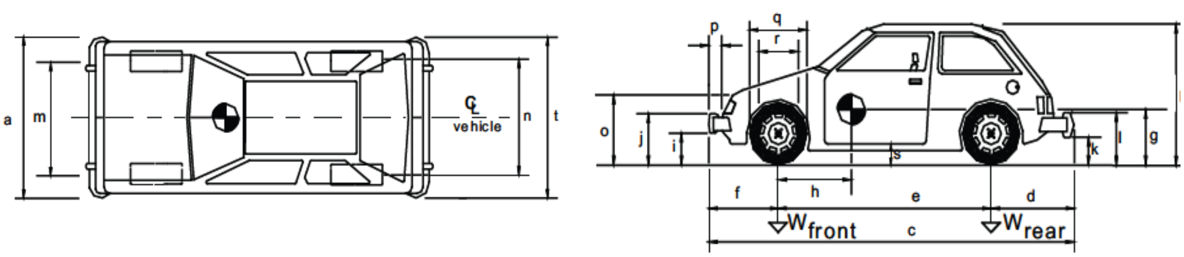
Weights (lb)

	Curb				Test Inertial		
	Test	Model	% Error		Test	Model	% Error
$W_{front\ axle}$	4,910	5,520	12.4	$W_{front\ axle}$	7,121	7,260	2.0
$W_{rear\ axle}$	6,451	6,812	5.6	$W_{rear\ axle}$	10,516	10,392	-1.2
W_{total}	11,360	12,333	8.6	W_{total}	17,637	17,652	0.1
				Ballast	6,276	5,320	-15.2

Figure 11. Vehicle property sheet for the 8000S vehicle model (V181114) compared with a full-scale Test 404251-6 (i.e., validation case).

VEHICLE PROPERTIES AND INFORMATION

Date:	12/21/2016	Test No.:	607451-3	Vin No.:	KNADHA33A6692034
Year:	2010	Make:	Kia	Model:	Rio
Odometer:	140035	Tire Size:	35/65R14	Tire Inflation Pressure:	32 psi



Vehicle Geometry (inches)

		Test	Model	% Error
a	Front Bumper Width:	66.38	64.528	-2.79
b	Overall Height:	58	57.717	-0.49
c	Overall Length:	165.75	169.13	2.04
d	Rear Overhang:	34	37.087	9.08
e	Wheel Base:	98.75	99.961	1.23
f	Front Overhang:	33	32.126	-2.65
g	C.G. Height:		21.732	
h	C.G. Horz. Dist.	35.28	42.008	19.07
i	Front Bumper Bottom:	8	7.9134	-1.08
j	Front Bumper Top:	21	21.417	1.99
k	Rear Bumper Bottom:	11.5	13.74	19.48
l	Rear Bumper Top:	25	25.197	0.79
m	Front Track Width:	57.75	58.622	1.51
n	Rear Track Width:	57.7	57.638	-0.11
o	Hood Height:	28.25	31.732	12.33

		Test	Model	% Error
p	Bumper Extension:	4.12	3.661417	-11.13
q	Front Tire Width:	22.5	23.50394	4.46
r	Front Wheel Width:	15.8	16.14173	2.16
s	Bottom Door Height:	8	11.88976	48.62
t	Rear Bumper Width:	66.2	63.70079	-3.78
	Wheel Center Height:	11	11.92913	8.45
	Engine Type:	4 cylinder		
	Engine Size:	1.6 liter		

	X	Y	Z
Accelerometer Location (inches) - measured from front axle and ground	35.25		15.62

Weights (lbs)

	Curb			Test Inertial		
	Test	Model	% Error	Test	Model	% Error
$W_{front\ axle}$	1597	-	-	1561	1504.542	-3.62
$W_{rear\ axle}$	921	-	-	868	1090.59	25.64
W_{total}	2518	-	-	2429	2595.132	6.84

GVWR Ratings (lbs)	Test	Model	% Error
Front	1718	-	-
Rear	1874	-	-

Dummy Data

Type

Mass (lbs)

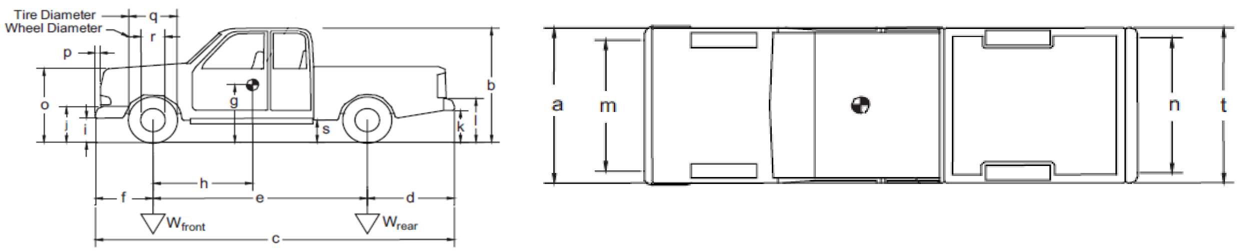
Seat Position

Other Notes:

Figure 12. Vehicle property sheet for the 1100C vehicle model compared with a recent test vehicle from Test 607451-3.

VEHICLE PROPERTIES AND INFORMATION

Date:	12/20/2016	Test No.:	607451-2	Vin No.:	1D7RB1GP9BS673991
Year:	2011	Make:	Dodge	Model:	1500
Odometer:	262075	Tire Size Front:	265/70R17	Tire Size Rear:	265/70R17



Vehicle Geometry (inches)

		Test	Model	% Error			Test	Model	% Error
a	Front Bumper Width:	78.5	79.843	1.71	p	Bumper Extension:	3	2.4015748	-19.95
b	Overall Height:	75	75.354	0.47	q	Front Tire Width:	30.5	30.393701	-0.35
c	Overall Length:	227.5	229.8	1.01	r	Front Wheel Width:	18	18.425197	2.36
d	Rear Overhang:	47	46.929	-0.15	s	Bottom of Body Height:	13	12.874016	-0.97
e	Wheel Base:	140.5	143.5	2.14	t	Overall Width:	77	79.488189	3.23
f	Front Overhang:	40	39.567	-1.08		Wheel Center Height Front:	14.75	15.275591	3.56
g	C.G. Height:	29.25	28.819	-1.47		Wheel Center Height Back:	14.75	15.275591	3.56
h	C.G. Horz. Dist.	62.39	60.039	-3.77		Wheel Well Clearance (F):	6	7.7952756	29.92
i	Front Bumper Bottom:	12	12.402	3.35		Wheel Well Clearance (R):	9.25	9.6456693	4.28
j	Front Bumper Top:	27	26.614	-1.43		Frame Height (F):	17	17.562992	3.31
k	Rear Bumper Bottom:	20.25	20.748	2.46		Frame Height (R):	25.5	25.984252	1.90
l	Rear frame Top:	29.5	30.236	2.50		Engine Type:			
m	Front Track Width:	68.5	69.488	1.44		Engine Size:			
n	Rear Track Width:	68	66.142	-2.73					
o	Hood Height:	46.5	47.087	1.26			X	Y	Z
						Accelerometer Location (inches) - measured from front axle and ground			

Weights (lbs)

	Curb				Test Inertial		
	Test	Model	% Error		Test	Model	% Error
$W_{front\ axle}$	2828	0	-100.00	$W_{front\ axle}$	2800	3051.4978	8.98
$W_{rear\ axle}$	2108	0	-100.00	$W_{rear\ axle}$	2237	1949.7269	-12.84
W_{total}	4936	0	-100.00	W_{total}	5037	5001.2115	-0.71

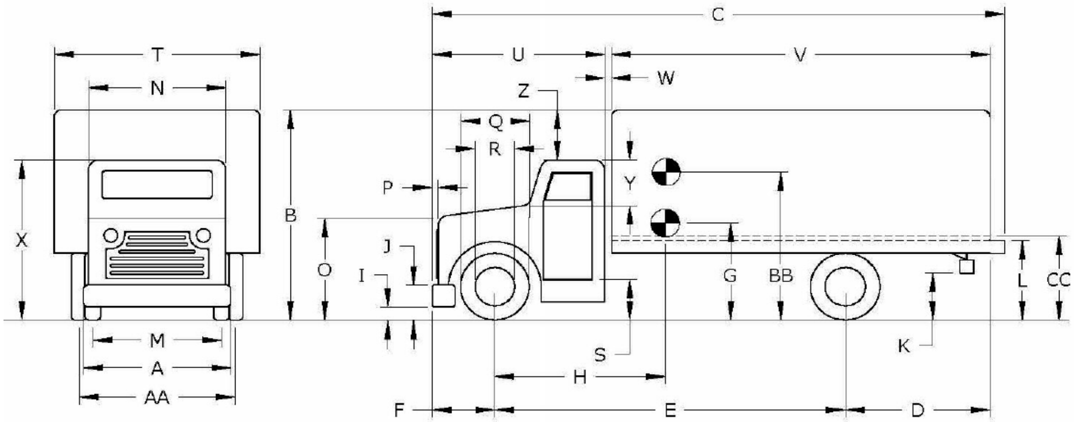
GVWR Ratings (lbs)		Test	Model	% Error
	Front	3700	0	-100.00
	Rear	3900	0	-100.00
Dummy Data	**Type**	50th Percentile Male		
	Mass (lbs)	165	0	-100.00
	Seat Positio	Driver		

Other Notes:

Figure 13. Vehicle property sheet for the 2270P vehicle model compared with a recent test vehicle from Test 607451-2.

VEHICLE PROPERTIES AND INFORMATION

Date:	12/16/2016	Test No.:	607451-1	Vin No.:	1HMPAFN86h206312
Year:	2006	Make:	International	Model:	4200
Odometer:	275640	Tire Size Front:		Tire Size Rear:	



Vehicle Geometry (in)

		Test	Model	% Error			Test	Model	% Error
A	Front Bumper Width:	95.00	93.11	-2.0	P	Bumper Extension:	1.00	0	-100.00
B	Overall Height:	132.00	131.46	-0.4	Q	Front Tire Width:	39.00	37.40	-4.1
C	Overall Length:	329.75	337.60	2.4	R	Front Wheel Width:	23.50	23.54	0.2
D	Rear Overhang:	89.00	89.96	1.1	S	Bottom Door Height:	37.00	38.50	4.1
E	Wheel Base:	204.75	208.15	1.7	T	Overall Width:	96.00	96.10	0.1
F	Front Overhang:	36.00	33.07	-8.1	U	Cab Length:	106.00	101.65	-4.1
G	C.G. Height:	-	50.44	-	V	Box Length:	227.00	226.34	-0.3
H	C.G. Horz. Dist.	133.28	133.47	0.1	W	Gap Width:	1.00	3.19	218.9
I	Front Bumper Bottom:	19.00	20.94	10.2	X	Overall front Height:	98.50	87.95	-10.7
J	Front Bumper Top:	34.00	32.64	-4.0	Y	Roof-Hood Dist.	30.00	18.82	-37.3
K	Rear Bumper Bottom:	-	18.66	-	Z	Roof-Box Height Diff.	36.00	43.39	20.5
L	Rear frame Top:	37.00	41.65	12.6	AA	Rear Track Width	73.00	72.72	-0.4
M	Front Track Width:	80.00	80.51	0.6	BB	Ballast Center of Mass	61.90	62.52	1.0
N	Roof width:	71.00	57.80	-18.6	CC	Cargo Bed Height:	49.25	48.70	-1.1
O	Hood Height:	59.00	62.87	6.6					

Accelerometer Locations (inches) - measured from front axle and ground		X	Y	Z
	Front	133.2	0	50
	Center	223.2	0	50

Weights (lb)

	Curb				Test Inertial		
	Test	**Model**	**% Error**		**Test**	**Model**	**% Error**
$W_{front\ axle}$	6,090	6,811	11.8	$W_{front\ axle}$	7,690	7,915	2.9
$W_{rear\ axle}$	6,090	5,521	-9.4	$W_{rear\ axle}$	14,340	14,146	-1.4
W_{total}	12,180	12,332	1.2	W_{total}	22,030	22,061	0.1

+165lb for dummy not included in TIM

	Test	Model	% Error
Ballast	10,282	9,729	-5.4

Figure 14. Vehicle property sheet for the baseline 10000S vehicle model compared with a recent test vehicle from Test 607451-1.

CHAPTER 5 – FEA MODEL DEVELOPMENT

A detailed finite element model of the S3-TL4 bridge rail was developed, as shown in Figure 15, based on construction drawings provided by MassDOT, which are provided in Appendix A of this report. Refer to Chapter 3 for more detailed description of the design. The FEA model includes 78 feet of the bridge rail. Details of the model regarding material characterization and element formulations used for the various components are presented in the following sections of this chapter. The basic components of the bridge rail model include:

- Twelve (12) W6x25 posts,
- Twelve (12) 12"x12"x1.25" base plate (i.e., one at each post),
- Twelve (12) 12"x10"x5/8" anchor plate (i.e., one at each post)
- Sixty (60) anchor bolts (i.e. five (5) at each base plate connecting the base plate to the curb/sidewalk),
- Six (6) HSS 5x5x0.25 tube rails that are 28.9 feet long (each) and hardware,
- Three (3) HSS 4x5x0.25 tube rails that are 28.9 feet long (each) and hardware,
- Nine (9) splice tube weldments, 28 inches long (each) made from 3/8-inch thick steel plate, and
- Concrete curb/sidewalk and bridge deck.

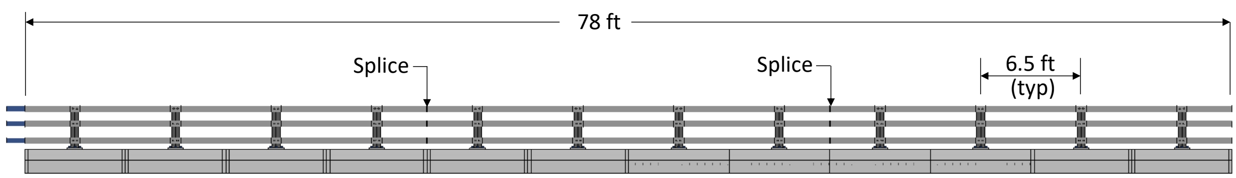


Figure 15. Finite element analysis model of the MassDOT S3-TL4 bridge rail.

The model includes twelve posts spaced at 6.5 feet (typical) on centers; and three sections of tube railing at 25'-11.5" each, including two splice connections with a ½-inch splice gap between adjoining rails. The geometry of these components was modeled according to the drawings included in Appendix A.

A representative section of the FEA model for the bridge rail is shown in Figures 16 through 18. The profile views in Figure 18 provide specific dimensions of the model for both the curb-mounted case and the sidewalk-mounted case. Additional details of the FEA model for each of the bridge rail components are provided in the following sections.

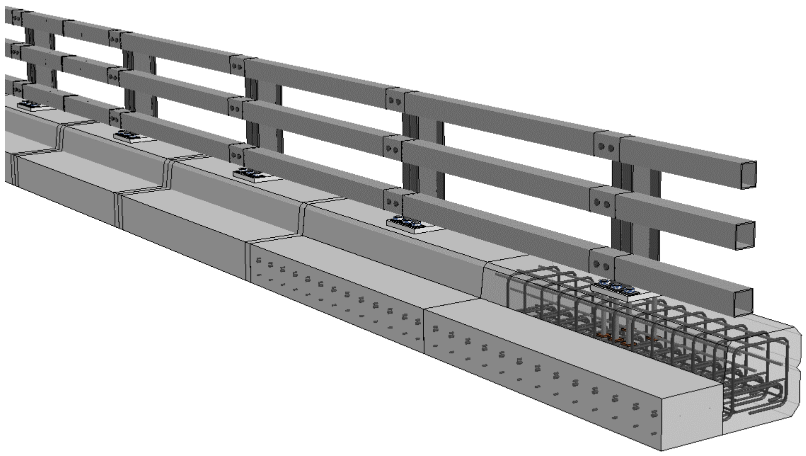


Figure 16. FEA model for the MassDOT S3-TL4 bridge rail.

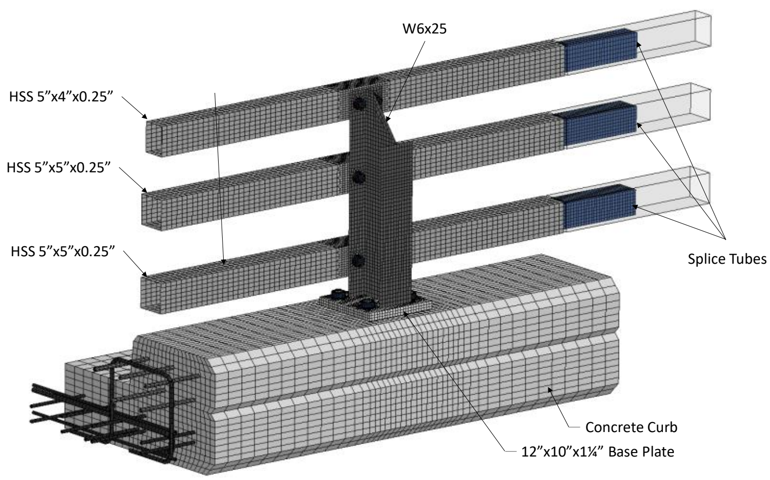


Figure 17. Representative section of the FEA model of the bridge rail (curb-mounted option shown).

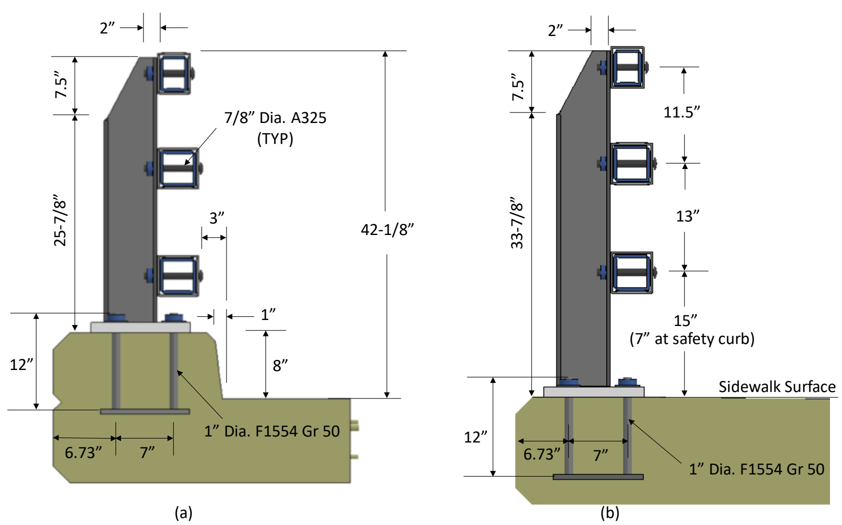


Figure 18. Representative section of the FEA model of the bridge rail from a profile view for the (a) curb-mounted option and the (b) sidewalk-mounted option.

Posts

The geometry of the posts was modeled according to the detailed drawings in Appendix A and included six (6) vertically slotted mounting holes in the flanges with dimensions 15/16" x 2-3/16". The FEA model of the post is shown in Figure 19. The material for the post model conformed to ASTM A709 Grade 50 steel. The post was modeled with thin-shell Belytschko-Tsay elements (Type 2 in LS-DYNA) with five (5) integration points through the thickness. The flange and web were meshed with a nominal element size of 0.6" x 0.5". The elements around the edge of the mounting holes were meshed with nominal element size of 0.36 inches.

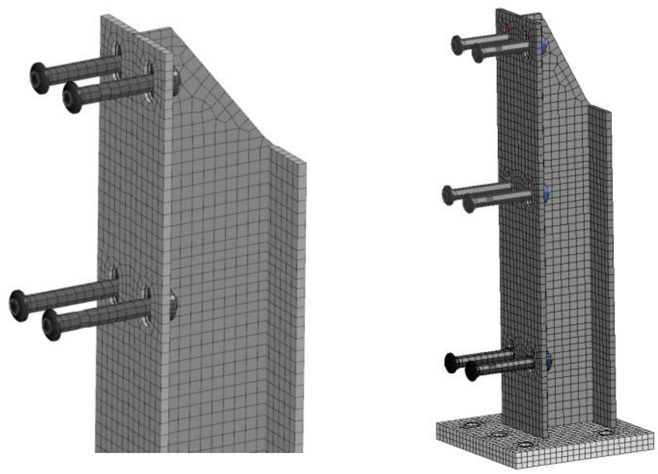


Figure 19. FEA Model of bridge rail post.

Tubular Rails and Mounting Bolts

The tubular rail sections were modeled according to the dimensional specifications for HSS 5" x 4" x 0.25" (top rail) and HSS 5" x 5" x 0.25" (middle and lower rails). The FEA model of the rail connection point is shown in Figure 20. The material for all tube railing conformed to ASTM A500 Grade C. The tube rails were modeled with Type 2 element with five (5) integration points through the thickness. The nominal element size for the mesh is 0.67" x 1" for the span of rail between the posts and 0.33" x 0.48" for the section of rail in contact with the posts. The mounting holes in the rail were slotted horizontally with dimensions 15/16" x 1.5". The mesh around the slotted holes were meshed with a nominal element length of 0.25 inches.

The 7/8-inch diameter button head mounting bolts were modeled with Hughes-Liu beam elements (Type 1 in LS-DYNA) with properties corresponding to ASTM A325. [*Rumpf62*] The head of the bolts, as well as the nuts and washers were modeled with rigid material properties, since the effects of deformation of these components were expected to be negligible compared to the effects of bolt deformations. The bolts were given a pre-strain condition to tighten the railing onto the post.

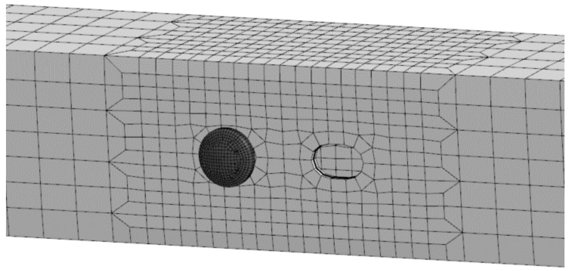


Figure 20. FE mesh of the middle tube-rail and bolt (one bolt removed to facilitate viewing slotted mounting hole).

The splice connection of the adjoining tube rails included a 28-inch long tubular sleeve inserted 13.75 inches into the upstream and downstream ends of the main rails (see Appendix A for dimension details). The welded connection of the splice-tube to the main rail was modeled using spotweld constraints in LSDYNA. The other end of the splice tube does not include any fasteners, thereby allowing the splice tube to slide freely inside the adjoining rail section. A ½-inch gap between the adjoining main-rail sections was included at the splice according to design. The modeled splice connection is shown in Figure 21. The splice tubes were modeled with the same material properties and mesh details as the main rail tubes.

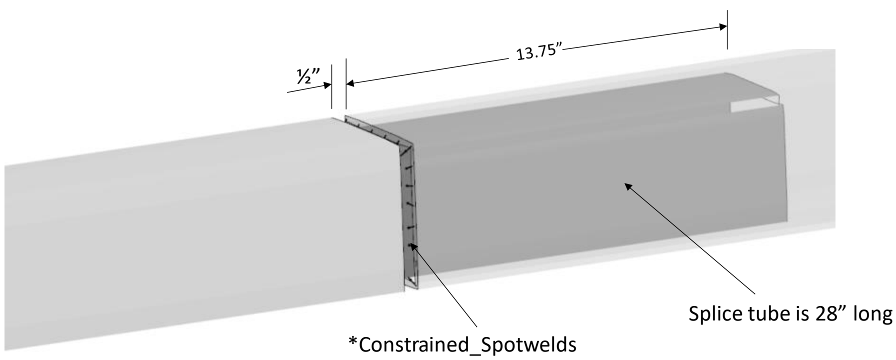


Figure 21. Model of rail splice with rail-tube shown transparent.

Base Plate and Anchor Bolts

The base plate was modeled with dimensions 12” x 12” x 1.25” and with material properties conforming to ASTM A709 Grade 50. The part was meshed with Type 2 (selective reduced 2x2 in-plane integration) thick shell elements. The welded connection of the post to the base plated was modeled using continuous *Constrained_spotwelds around the perimeter of the base of the post. The 1-inch diameter anchor bolts were modeled with Type 1 beam elements in LS-DYNA. The material for the anchor bolts conformed to ASTM F1554 Grade 105, which has a minimum yield strength of 105 ksi, ultimate strength of 125 ksi, and 15 percent elongation. The nuts and washers were modeled as rigid. The anchor bolts extended into the rigid deck, as illustrated in Figure 18 and Figure 22. The bolts were anchored inside the deck using the *Constrained_Beam_in_Solid option in LS-DYNA. Null beams were added to the anchor plate and which were also constrained to the curb/deck using *Constrained_Beam-in-Solid.

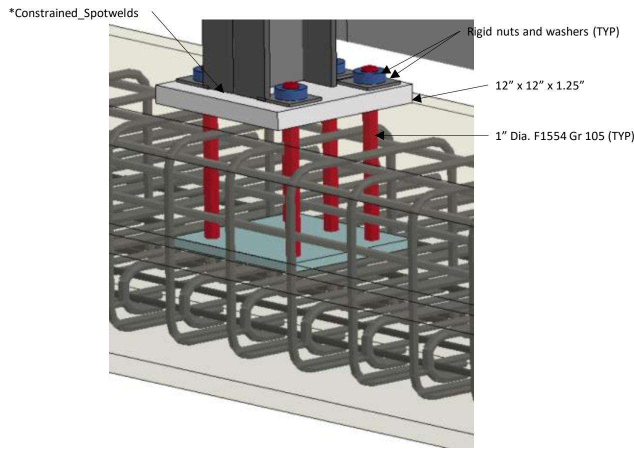


Figure 22. Transparent view of concrete showing model of base plate and anchor bolts.

Concrete Curb, Sidewalk and Deck

The materials for the curb, sidewalk and deck components were modeled using *Mat_RHT in LS-DYNA, with default material properties based on an unconfined compressive strength of 4,000 psi. The concrete was modeled with Type 1 brick elements in LS-DYNA with nominal element size of 1" x 1" x 1" at the post locations and with the element side length then gradually increasing to approximately 2.5 inches at maximum distance from the post, as illustrated in Figures 23 and 24 for the sidewalk-mounted system. Images of the curb-mounted system model are shown in Figures 25 and 26.

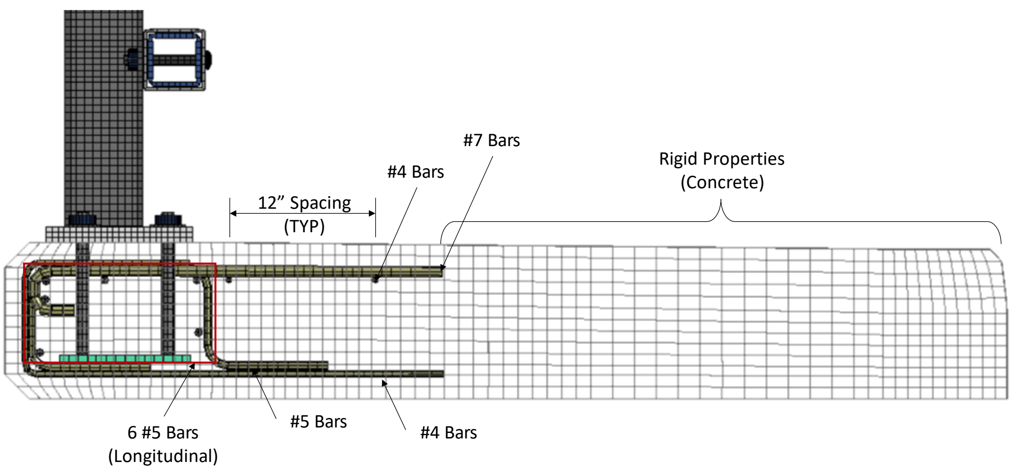


Figure 23. Profile view of sidewalk model.

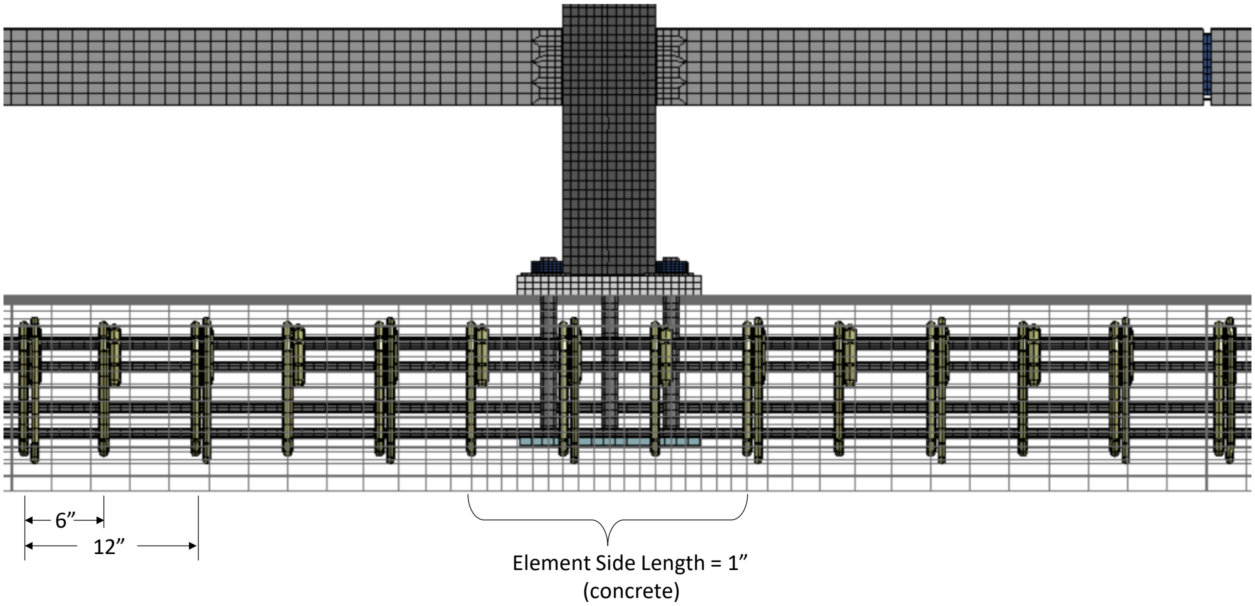


Figure 24. Plan view of sidewalk model (from back of bridge rail).

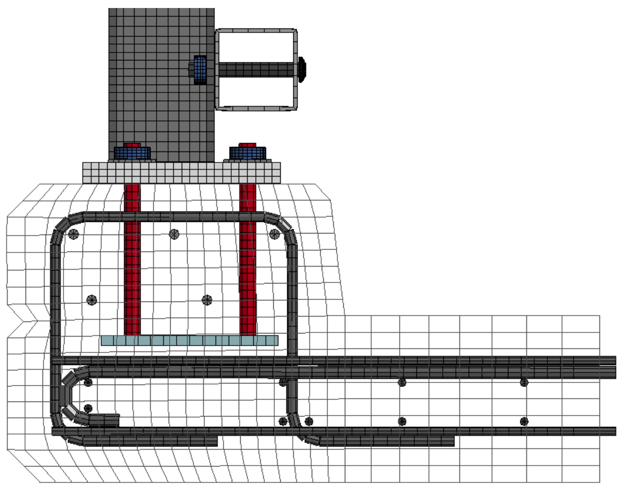


Figure 25. Profile view of curb-mounted model.

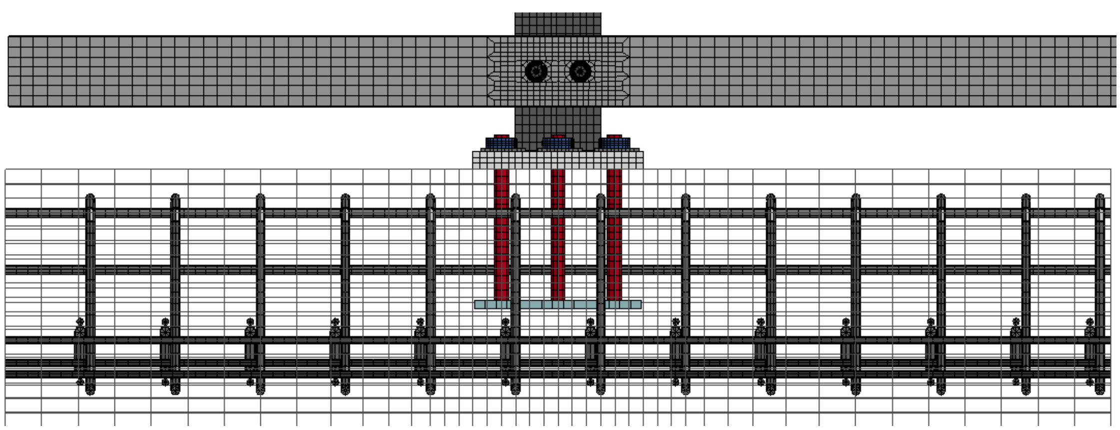


Figure 26. Plan view of curb-mounted model (traffic-side view).

The longitudinal reinforcement (relative to the bridge rail) at the top of the sidewalk/curb near the anchor bolts was modeled with six #5 bars. All other longitudinal steel (relative to the bridge rail) was modeled with #4 bars. The longitudinal steel running lateral to the bridge rail was modeled with #6 bars at the top of the sidewalk and with #5 bars in the bridge deck. The stirrups were modeled with #5 bars with 6-inch spacing. Refer to Appendix A for additional details regarding location of the reinforcing steel.

All reinforcing bars were modeled with Type 1 beam elements with a nominal element length of 1 inch. The material properties for the reinforcing steel conformed to ASTM A615 Grade 60 steel with properties measured at Turner Fairbanks Highway Research Center. [*TFHRC15*] The stress-strain characterization is shown in Figure 27.

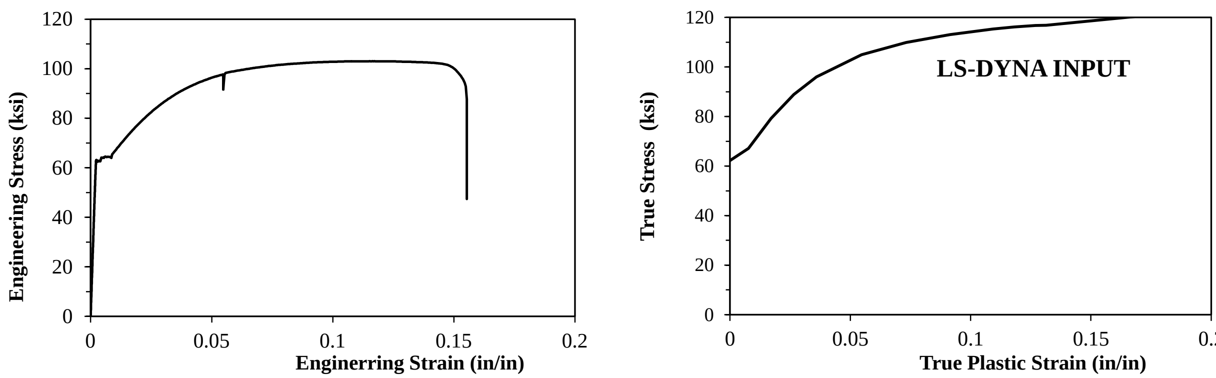


Figure 27. Stress vs. strain curve for ASTM A615 Grade 60 steel.

The interaction of the reinforcing steel within the concrete curb/deck was modeled using the *Constrained_Beam_in_Solid option in LS-DYNA. Unfortunately, slip of the anchor bolts in the concrete cannot be simulated with this method unless the concrete fails around the rebar; however, it is apparent from the drawings that the anchor blots cannot physically "slip" unless they break from the anchor plate which is buried deep inside the sidewalk/deck.

Materials

All steel materials were modeled in LS-DYNA using material model *Mat_Piecewise_Linear_Plasticity. The Young's modulus was set to 29,000 ksi and Poisson's ratio was set to 0.33. The piecewise-linear stress-strain characterization for each component varied depending on steel type and grade.

All steel posts and base plates were modeled as ASTM A572 Grade 50 steel (e.g., same as AASHTO M270 Grade 50); the material characterization was based on stress-strain curves from tensile tests conducted at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia in an earlier study performed by Roadsafe. The yield strength for the material in these tests were 51 ksi, which was just over the minimum yield strength for the material. Researchers at MwRSF also performed material strength tests for this material via coupons cut from bridge rail posts which resulted in yield strength values of approximately 60 ksi (e.g., 20% stronger). A comparison of the stress-strain curves for the TFHRC and MwRSF tests are shown in Figure 28. It is assumed that these two cases represent a lower and upper bound for the material. Since both strengths are possible for posts installed in the field and in full-scale test installations, both material strengths will be used in this study. The weaker strength post will assess maximum post plasticity. The stronger material will assess greater loading on the anchor and concrete. The lower bound strength will be used for evaluations of Tests 4-10 and 4-11; whereas, both strength values will be used for evaluations of Test 4-12.

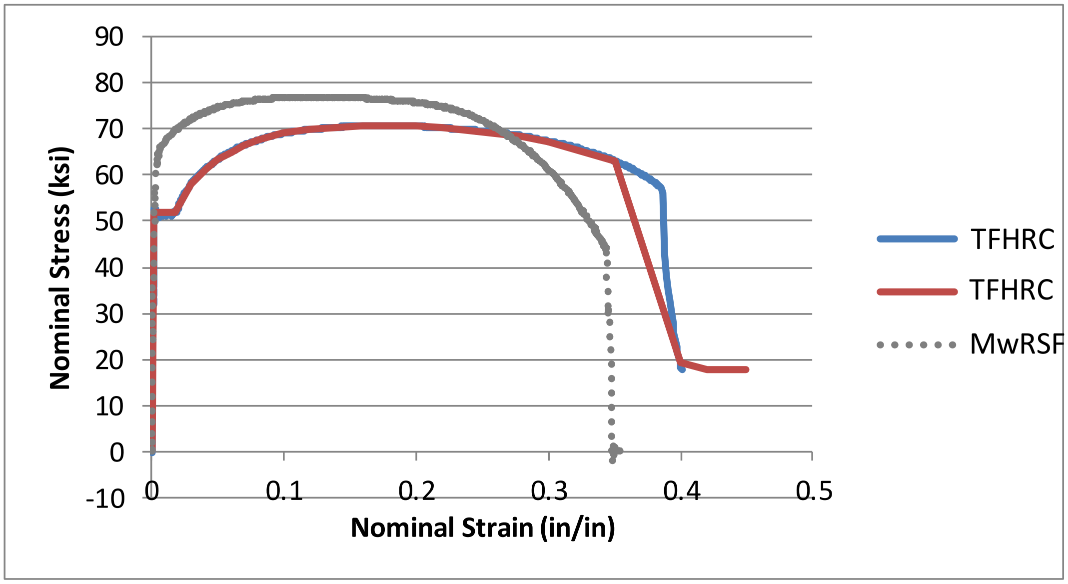


Figure 28. Stress-strain curves for A572-50 steel from coupons cut from steel bridge rail posts.

The material for all tube rails were modeled as ASTM A500 Grade C, with minimum yield and tensile strength of 50 ksi and 62 ksi, respectively.

All 7/8-inch diameter round head bolts were modeled as ASTM A325 with yield strength of 92 ksi and ultimate strength of 120 ksi (nominal stress). The 1-inch diameter anchor bolts were modeled as ASTM F1554 Grade 105 with yield strength 105 ksi and ultimate strength 125 ksi.

The material for the sidewalk, curb and deck was modeled as deformable or rigid depending on location. Outside the impact region, the materials for the sidewalk, curb and deck components were modeled with rigid properties. Inside the impact region, the constitutive properties for the sidewalk, curb and bridge deck were modeled using *Mat_RHT in LS-DYNA with default material properties based on an unconfined compressive strength of 4,000 psi. This material model in LS-DYNA was selected based on the results of a recent study performed by the research team in which the material model was validated against pendulum impact tests on reinforced concrete columns where the columns were subjected to lateral impact forces. [*Ray18a; Ray18b*]

CHAPTER 6 – MODEL VALIDATION

The FEA model of the S3-TL4 bridge rail developed in Chapter 5 was used to simulate TTI Test 404251-6 (curb-mounted system) and Test 404251-3 (sidewalk-mounted system) with impact conditions consistent with the full-scale tests. There are a few differences between the tested design and the current design (e.g., described in Chapters 3 and 5) regarding the concrete material, curb/deck dimension, anchor bolt type and anchor bolt size. For the simulation of the tests, the model developed in Chapter 5 was modified to include:

- Concrete material: Modeled with reported unconfined compressive strength of 5,655 psi (based on average compressive strength at 31 days). [*Buth99, pg12*]
- Anchor bolts: 1-1/8" diameter A449 (as tested).
- The tested curb/deck system was taller than the current design (21.65 inches vs. 18.125 inches); however, the design detail corresponding to the current design modeled in Chapter 5 was used for the validation analysis.

The results of the validation cases are provided in the following sections.

Curb-Mounted S3-TL4 Bridge Rail

Test 404251-6 was conducted by the Texas Transportation Institute (TTI) in College Station, Texas on July 22, 1999 [*Buth99*] and involved a 1987 GMC 7000 single unit truck impacting the bridge rail under NCHRP Report 350 Test 4-12 impact conditions. The gross static mass of the test vehicle was 17,363 lbs (8,000 kg). The test installation was 75.5 feet long with no end-anchorage for the test article. Because of the damage to the system in a previous test, this test was performed with the vehicle impacting from the opposite end of the barrier and in the opposite direction. The test vehicle struck the bridge railing at 49.15 mph (79.1 km/hr) and impact angle of 15.3 degrees. The initial point of contact was 4.6 ft (1.4 m) upstream of Post 5 and 16.2 inches upstream of the rail splice between Posts 4 and 5.

The vehicle model used in analysis was the 8000S single unit truck model described in Chapter 4. The analysis was performed using LS-DYNA version mpp_s_R8.1.1 revision number 119543. The analysis was conducted with a time-step of 1.0 microsecond for a time period of 1.0 seconds. A comparison of the vehicle properties for the model and the test vehicle is shown in Figure 11. Except for the front bumper extension and the height of the rear bumper, all other vehicle geometry properties were with 10 percent of the test vehicle. The curb weight of the model was also 8.6 percent heavier than the test vehicle, which resulted in the ballast model being 15.2 percent lighter than the ballast for the test vehicle. The center of gravity of the final ballasted SUT model, however, was essentially identical to that of the test vehicle.

The following is a commentary describing the timing and occurrence of various events during the simulated impact with comparison to the full-scale test; this information is also tabulated in Table 4

Table 4. The vehicle model impacted the bridge rail at 4.59 feet upstream of Post 4, traveling at a speed of 49.15 mph and at an angle of 15.3 degrees. The front bumper contacted the middle rail and the front fender contacted the upper rail. At 0.015 seconds the front impact side tire contacted the curb and the lower rail simultaneously, and Posts 4 and 5 began to deflect. At 0.02 seconds the front impact-side tire lifted off the ground. at 0.025 seconds the front tire contacted the middle rail; and the lower rail began to deflect downward. At 0.12 seconds the opposite-side front tire lifted of the ground (occurred at 0.158 sec in test). At 0.155 seconds the front lower edge of the cargo box contacted the top-side of the top rail (occurred at same time for test). At 0.24 seconds the opposite-side rear tires lifted off the ground (occurred at 0.278 sec in test). At 0.28 seconds the rear tandem tires impacted against the curb and the lower two rails (occurred at 0.264 sec in test). At 0.3 seconds the truck cab was parallel to the rail traveling at 44.6 mph (occurred at 0.265 sec traveling at 44.2 mph in test); also, at this time, the top railing reached maximum dynamic deflection of 2.9 inches. At 0.49 seconds the vehicle separated from rail at a speed and angle of 43.37 mph and 1.5 degrees, respectively (event occurred at 0.496 sec at 43.06 mph and 2 degrees in test); however, the lower edge of the cargo-box continued to extend over-top of and behind the face of the top rail (event occurred in both the test and FEA). At 0.88 seconds the cargo-box recontacted the top-side of the top rail; at 0.91 seconds the rear opposite-side tires recontacted the ground (these events were not included in the test report, but the test video showed that the tires were still lifted at the termination of the video at 0.76 sec). At 0.995 seconds the front of edge of the cargo box slid off the end of the top rail of the bridge railing traveling at 41.94 mph and the vehicle was steering behind the rail at an angle of 6.2 degrees (event not included in test report). The analysis was terminated manually at 1.0 seconds, at which time:

- The roll angle of the cargo box was 2.7 degrees away from the barrier and stable (5.3 degrees in test).
- The roll angle of the truck cabin was 0.5 degrees away from barrier and increasing.
- The pitch angle of the cargo box was 1.4 degrees with rear pitching up and stable (6.3 degrees in test).
- The pitch angle of the truck cabin was -3.0 degrees and stable.
- The yaw angle was 6.18 degrees toward the barrier (3.6 degrees in test), and
- The forward velocity of the vehicle was 42.0 mph (40.5 mph in test).

Table 4. Summary of phenomenological events for full-scale Test 404251-6 [*Buth99*] and FEA simulation.

Event	Test 404251-6	FE Analysis
Redirection began	0.044 sec	
Opposite-side front tire lost contact with ground	0.158 sec	0.120 sec
Front of cargo box contacted upper rail	≈ 0.155 sec	0.155 sec
Opposite-side rear tires lost contact with ground	0.278 sec	0.240 sec
Rear tandem tires impact curb	≈ 0.264 sec	0.28 sec
Cab was parallel to bridge railing	0.265 sec	0.30 sec
Vehicle speed at parallel	44.2 mph	44.6 mph
Maximum dynamic deflection of system	-	2.9 in (0.3 sec)
Vehicle separates from rail	0.496 sec	0.490 sec
Speed at separation	43.1 mph	43.4 mph
Angle at separation	2.0 deg (box) -0.1 deg (cab)	1.5 deg (box) 0.9 (cab)
Total contact length at separation	(1) 15.1 ft	(2) 16.4 ft
Cargo bed recontacts top of rail	-	0.880 sec
Opposite rear tire recontacts ground	(3) -	0.91 sec
Front of cargo box slides off end of bridge railing	-	0.995 sec
Speed at final separation	-	41.94 mph
Angle at final separation	-	6.2 deg (toward railing)

≈ estimated from test video time-history plots
- value not reported and could not be discerned from test videos
(1) reported and appears to correspond to contact length on face of rail based on test video
(2) corresponds to contact on face of rail in FEA
(3) Wheel set had not re-contacted the ground at the time of termination of the test video at 0.760 seconds.

Damage to Bridge Rail

Damage to the bridge rail is shown in Figure 29. The concrete at Posts 4 and 5 was reported to have sustained hairline cracks from the bolts during the full-scale test, which radiated out on the top of the curb. This did not occur in the FEA simulation. In the FEA the concrete curb at Posts 4 and 5 did experience notable strains, but not of a magnitude that would indicate probability of cracks. The maximum permanent deflection of the bridge rail was 0.18 inches in the test and was 1.65 inches in FEA. It is expected that this was due to differences in material properties for the post. The actual yield for post material is often 10-20 percent higher than the specified minimum for the material. In this case, however, the post was modeled with yield equal to the specified minimum of 50 ksi. Figure 29 shows contours of plastic strain for the post and rail at Post 4, which sustained the highest degree of damage in the FEA. It is evident from the contour plot that the web buckled at the top of the post and that there was moderate plastic strain in the flanges at the bottom of the post at the welded connection to the base plate.

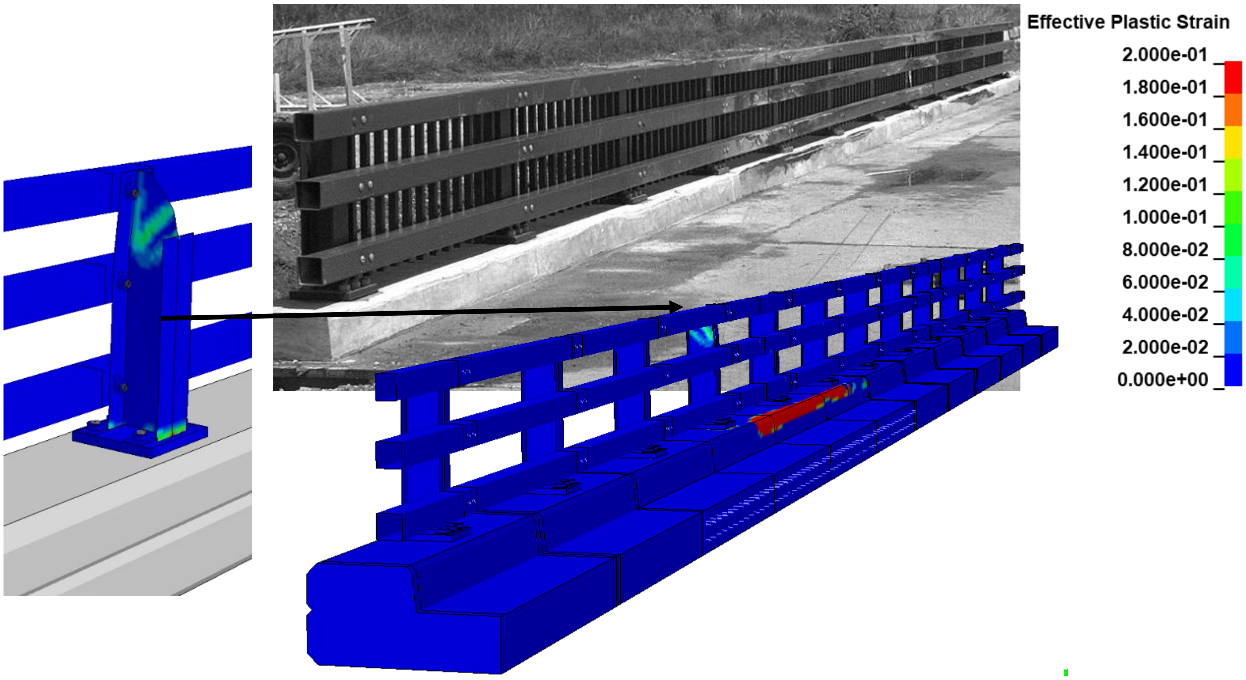


Figure 29. Comparing overall deformation of system for FEA and Test 404251-6.

Qualitative Validation

Sequential Views

Figure 30, Figure 31 and Figure 32 show sequential snapshots of the impact event from an overhead viewpoint, a downstream viewpoint, and from an oblique (downstream and behind the barrier) viewpoint, respectively. The model appears to simulate the basic kinematic behavior of the SUT and adequately captures the basic phenomenological events that occur during impact.

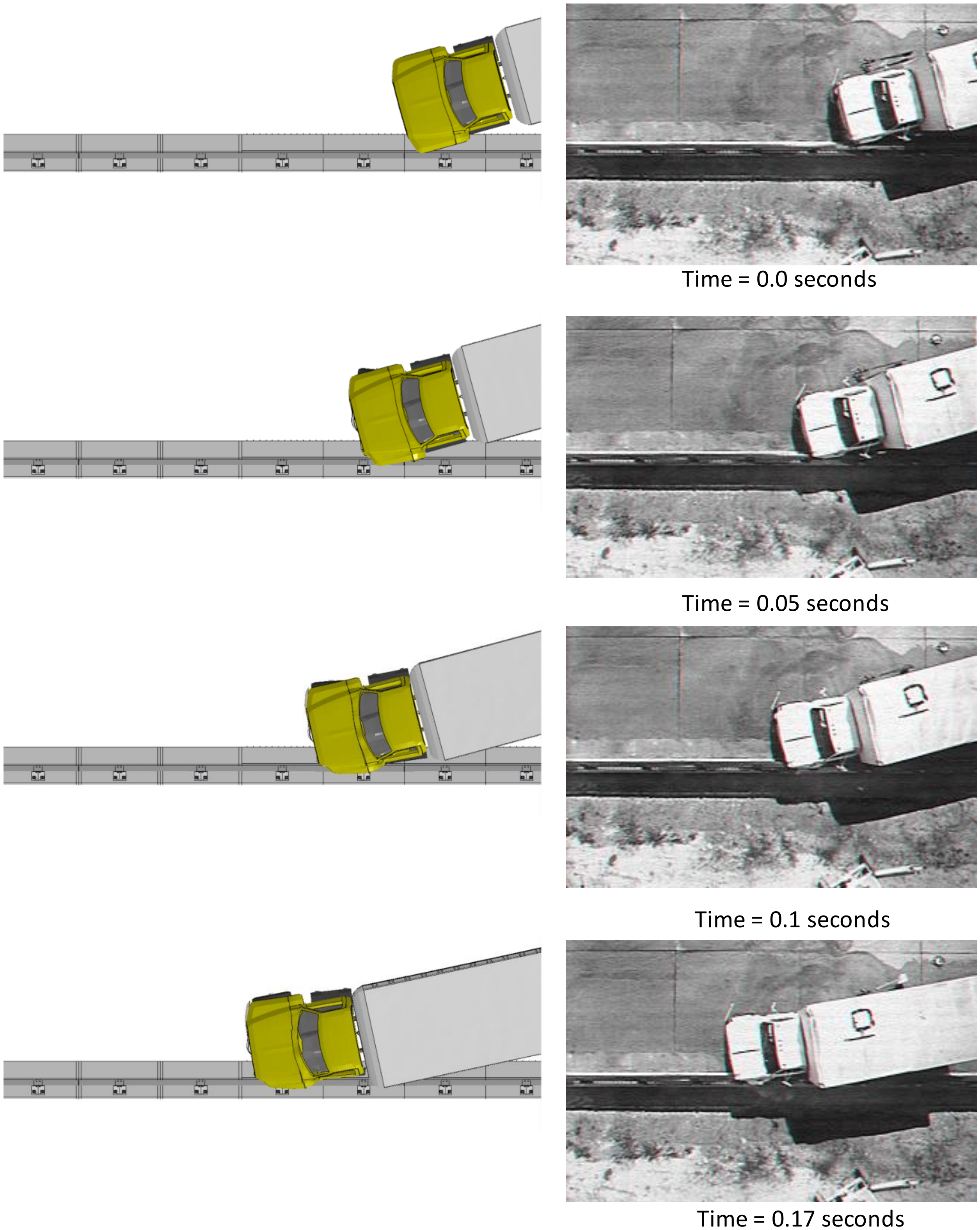
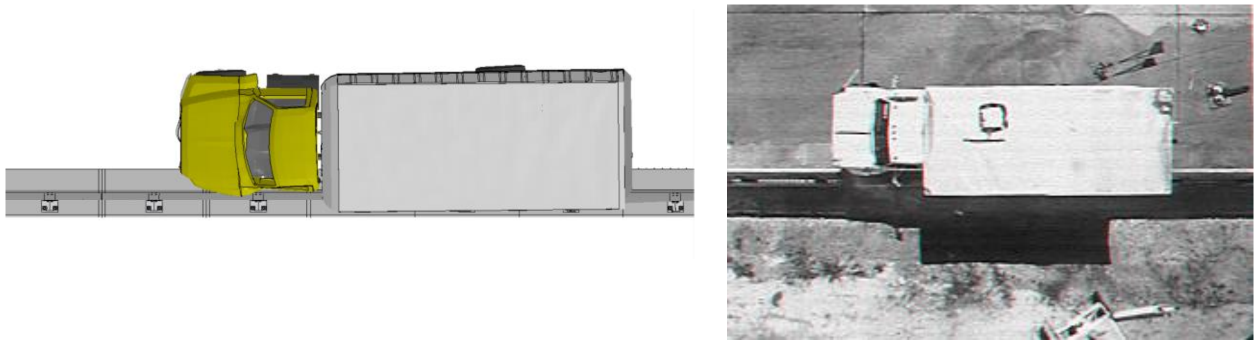
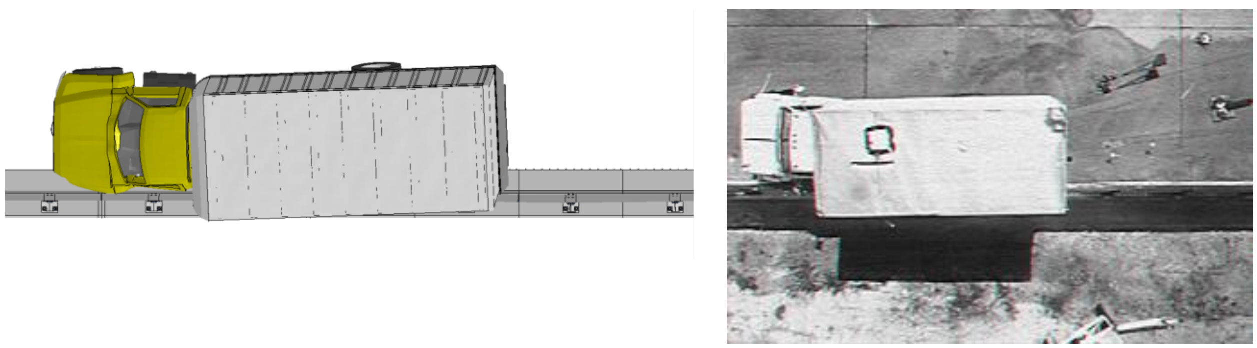


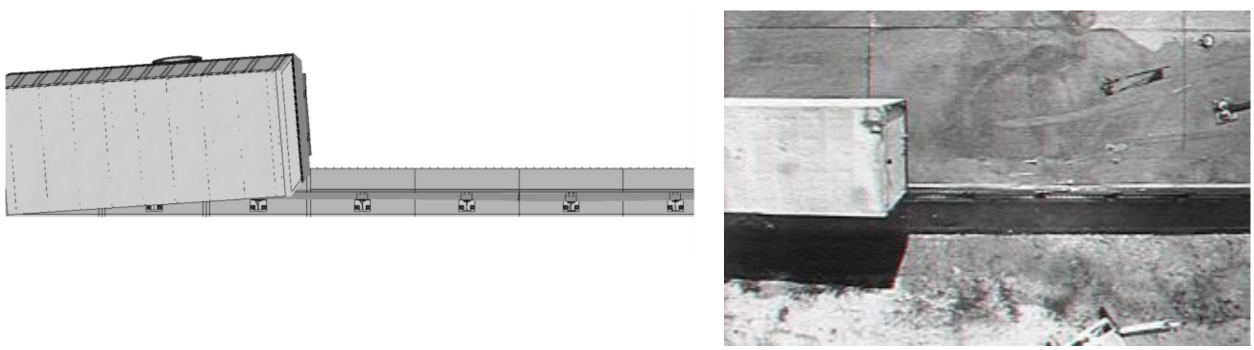
Figure 30. Sequential views from FEA and Test 404251-6 from an overhead view point.



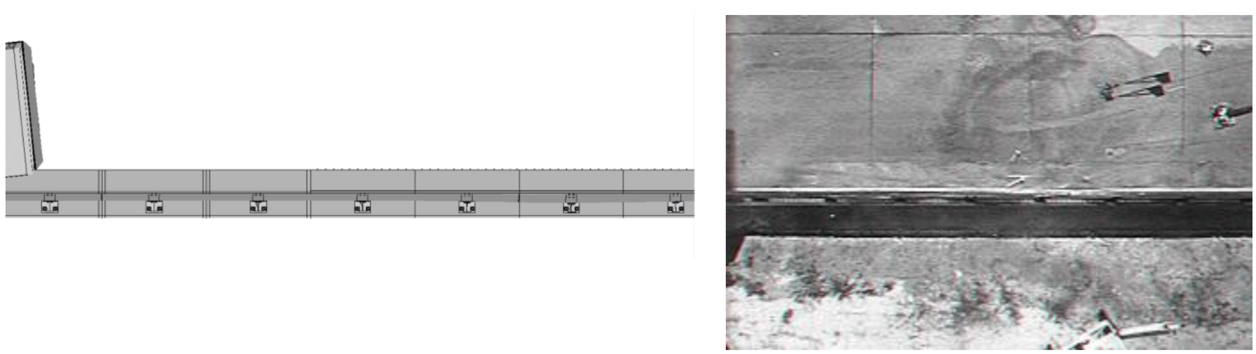
Time = 0.30 seconds



Time = 0.42 seconds



Time = 0.615 seconds



Time = 0.885 seconds

Figure 30. [Continued] Sequential views from FEA and Test 404251-6 from an overhead view point.

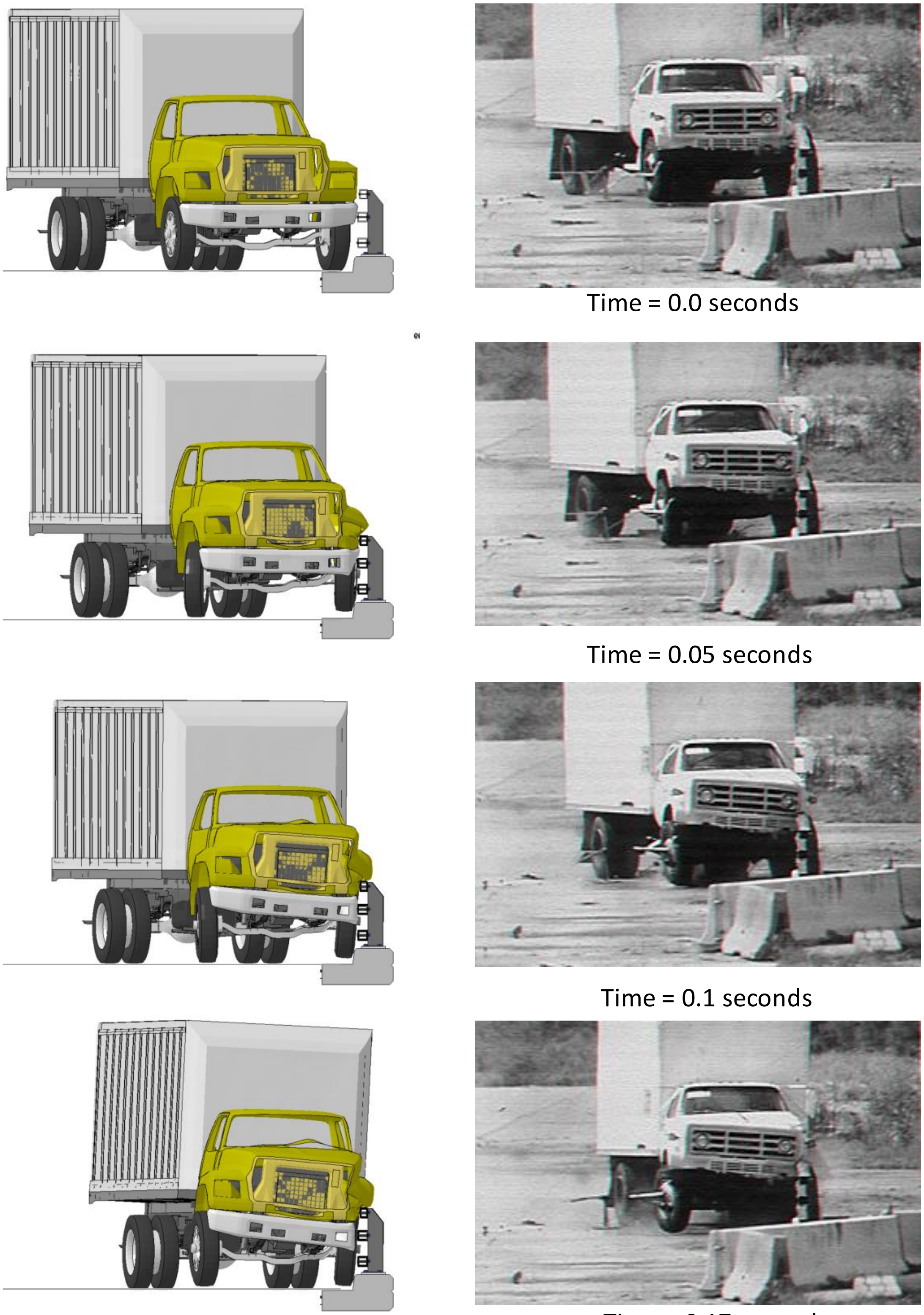


Figure 31. Sequential views from FEA and Test 404251-6 from a downstream view point.

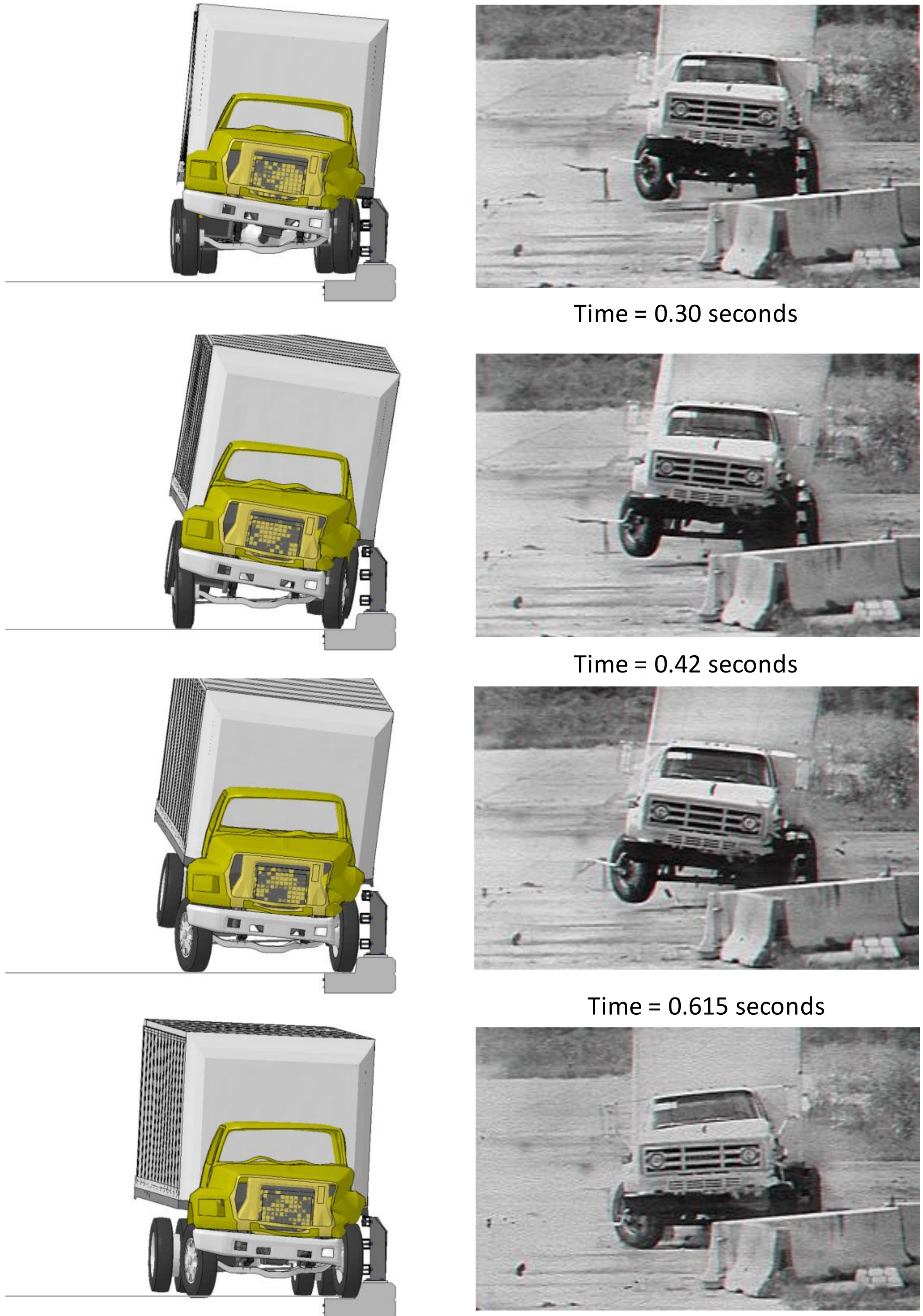


Figure 31. [Continued] Sequential views from FEA and Test 404251-6 from a downstream view point.

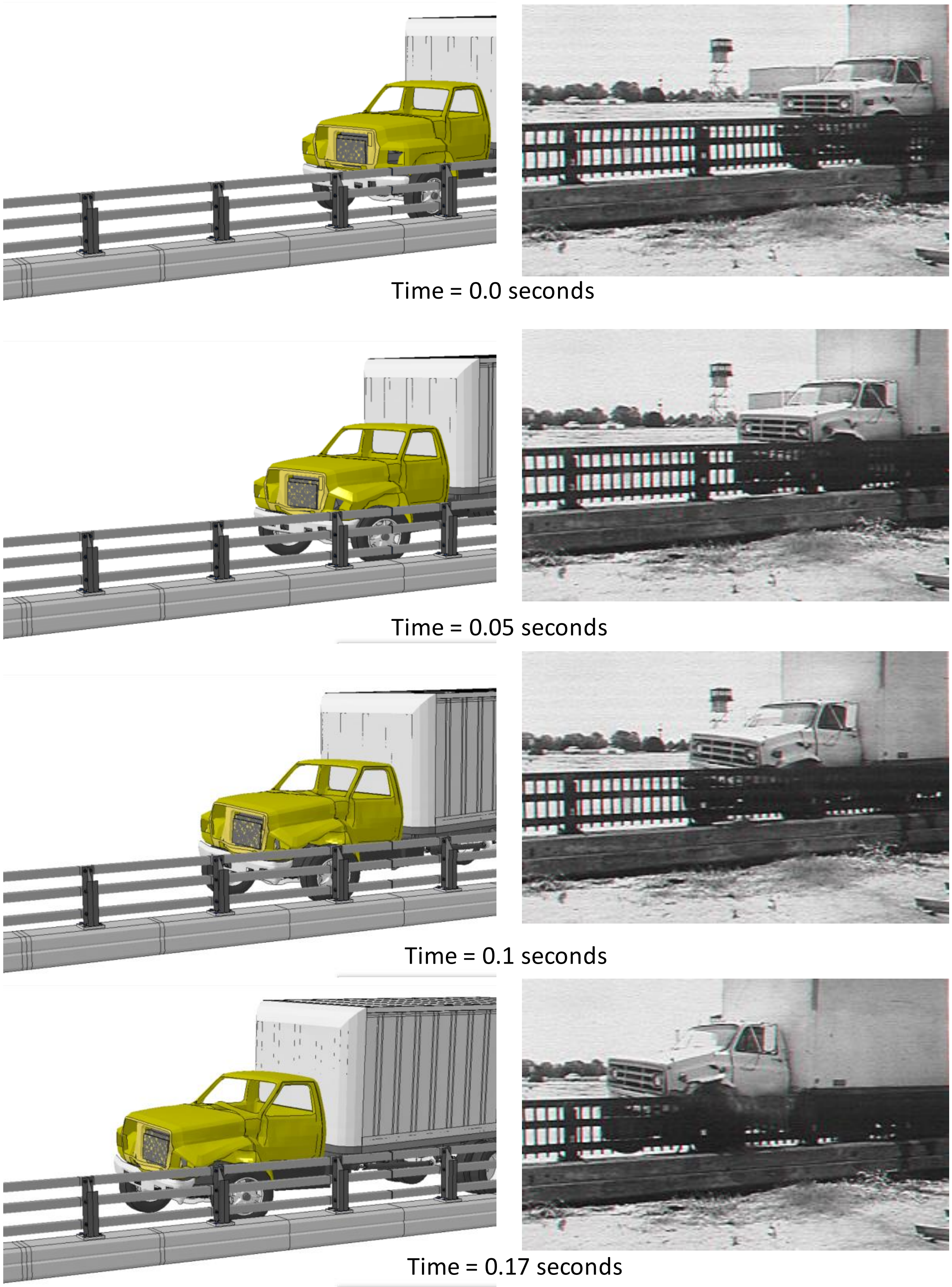


Figure 32. Sequential views from FEA and Test 404251-6 from a viewpoint behind rail.

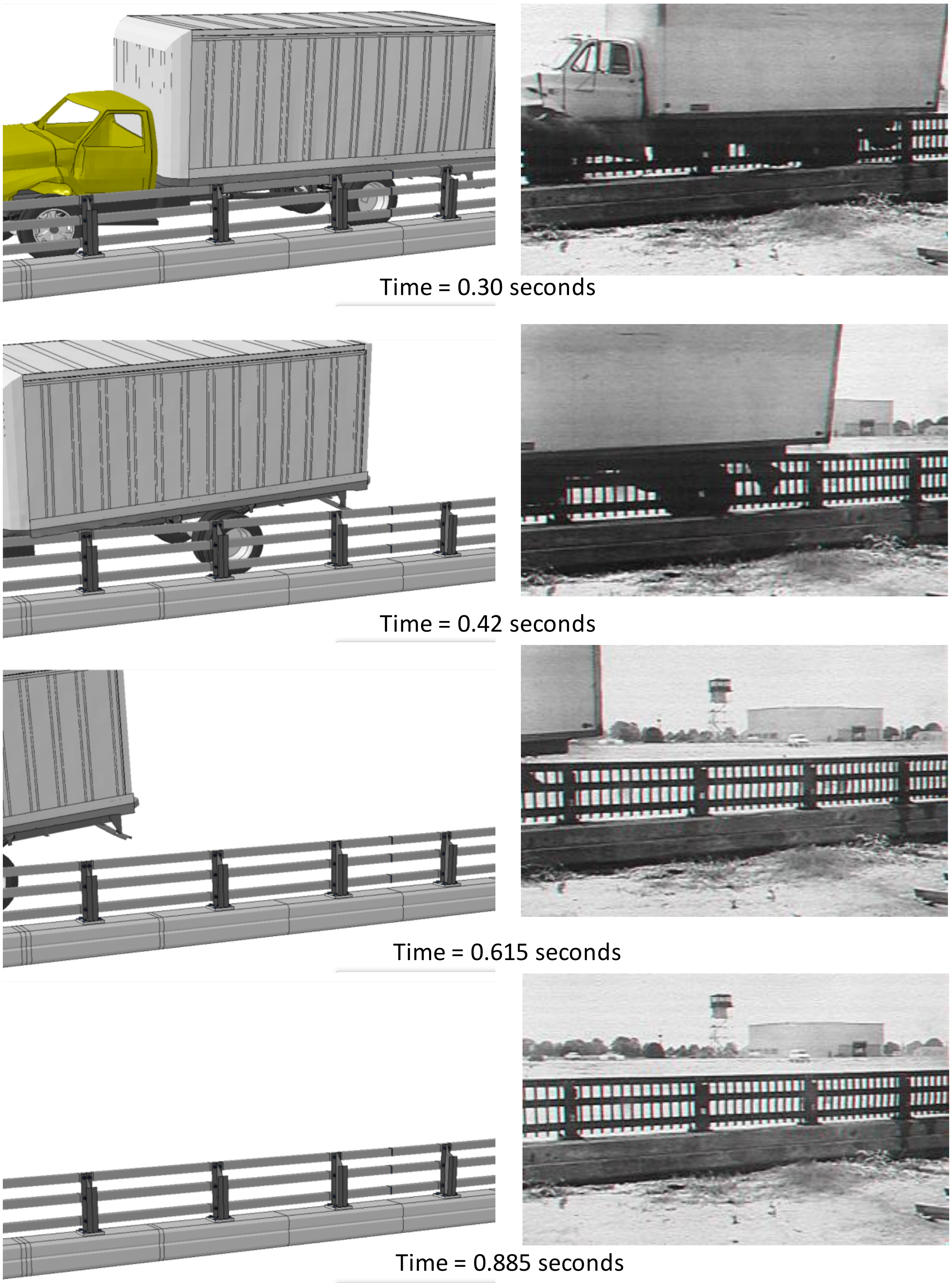


Figure 32. [Continued] Sequential views from FEA and Test 404251-6 from a viewpoint behind rail.

Occupant Risk Measures

Acceleration-time histories and angular rate-time histories were collected at two locations: 1) inside the cargo box near the center of gravity of the vehicle and 2) inside the cabin behind the seat, as illustrated in Figure 33 (compare to G and H in Figure 11). The time-history data was collected from the accelerometers in a local reference coordinate system that was fixed to the vehicle with the x-direction coincident with the forward direction of the vehicle, the local y-direction was oriented toward the right side of the vehicle and the local z-direction was oriented downward. The data was collected at a frequency of 50 kHz. Since the vehicle model struck the bridge rail from the opposite direction than the test vehicle, the "sign" for the data values collected for several of the channels was reversed for direct comparison with the test data (e.g., y-acceleration, roll-rate, and yaw-rate channels). For the assessment of occupant risk metrics, the acceleration data was taken from the c.g. location, and the angular rate data was taken from the cabin location (e.g., consistent with the full-scale test).

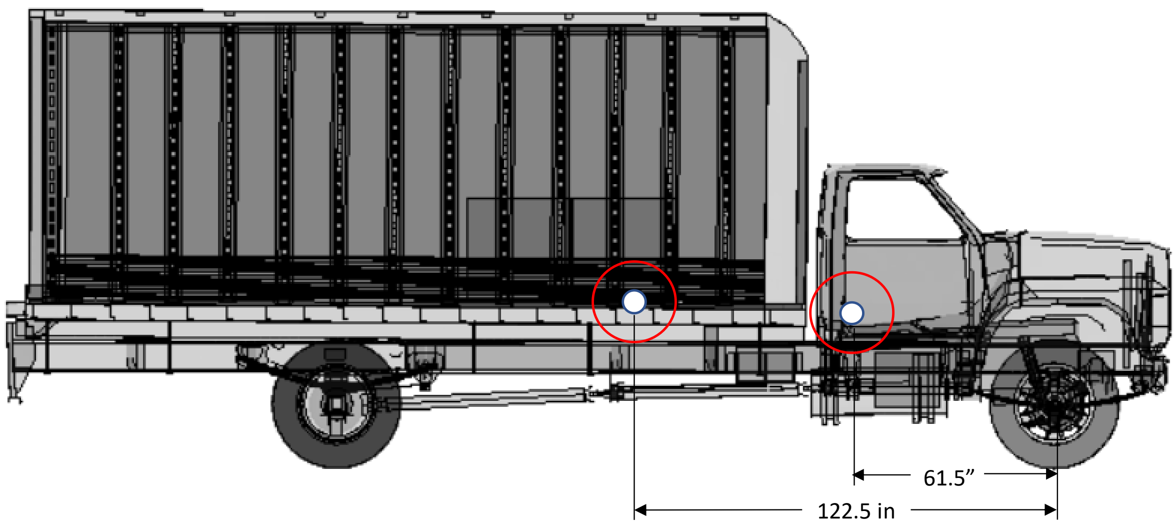


Figure 33. Location of accelerometer in FE model.

The analysis results obtained from TRAP for the full-scale test and the FE analysis are shown in Table 5 and Figure 34. The acceleration data used in the TRAP program was pre-filtered using the BW Class 180 filter. The table shows the two occupant risk factors recommended by R350: 1) the lateral and longitudinal components of Occupant Impact Velocity (OIV), and 2) the maximum lateral and longitudinal component of resultant vehicle acceleration averaged over a 10-millisecond interval after occupant impact, called the Occupant Ridedown Acceleration (ORA). Also provided in the table are the CEN risk factors including the Theoretical Head Impact Velocity (THIV), the Post Impact Head Deceleration (PHD) and the Acceleration Severity Index (ASI). The table also includes comparison of the 50-millisecond moving average of the accelerations.

The occupant risk metrics for both the full-scale test and the simulation are in good agreement. The occupant impact velocity in the longitudinal direction was predicted from the simulation to be 5.25 ft/s (0.3 ft/s higher than the test OIV of 5.58 ft/s) at 0.2225 seconds. In the transverse direction, the occupant impact velocity predicted in the simulation was 11.8 ft/s (0.66 ft/s higher than the test OIV of 11.2 ft/s). The highest 0.010-second occupant ridedown acceleration in the longitudinal direction was 4.4 g (2.1 g higher than test ORA of 2.3 g) between 0.3060 and 0.3160 seconds. In the transverse direction, the highest 0.010-second occupant ridedown acceleration was 7.3 g (3.9 percent or 0.8 g lower than test ORA of 7.6) between 0.2955 and 0.3053 seconds. The THIV, PHD and ASI predicted from the simulation were 13.1 ft/s (5.3 percent higher), 8.5 g's (10.4 percent higher), and 0.43 (18.9 percent lower), respectively. The maximum 50-millisecond moving average accelerations in the x-, y-, and z-directions were 1.4 g (same as test), 3.5 g (1.1 g higher), and 1.8 g (0.4 g lower), respectively. The maximum yaw, roll and pitch angles were 15.7 degrees (0.7 degrees lower), -8.3 degrees (same as test) and -6.0 degrees (12.4 degrees less), respectively. It is possible that there was "drift" in the pitch-rate channel; the sequential views (see Figure 29) show the pitch comparison to be much closer. For example, at 0.615 seconds both the test and the FEA vehicle have a negative pitch (i.e., rear pitching upwards), while the time-history plot shows the test vehicle to have zero pitch at that time.

Except for the pitch angle, the results of the FEA were well within the recommended limits of Report W179 for each of the comparison metrics. That is, the difference in OIV was less than 20 percent or 6.6 ft/s; the difference in maximum ORA was less than 20 percent or 4 g; and the difference in angular displacement was less than 20 percent or 5 degrees.

Table 5. Occupant risk measured computed using TRAP software for the FEA and test data for R350 Test 4-12.

Occupant Risk Factors		MASH Test 3-11		Error		W179 Criteria	
		Test 404251-6	FEA				
		(0 - 1.0 seconds)	(0 - 1.0 seconds)	%	Absolute	Criteria	Pass
Occupant Impact Velocity (ft/s)	x-direction	5.58	5.25	5.9%	-0.33	<20% or < 6.6 f/s	Y
	y-direction	-11.15	-11.81	5.9%	-0.66	<20% or < 6.6 f/s	Y
	at time	at 0.2115 seconds on left side of interior	at 0.2225 seconds on left side of interior				
THIV (m/s)		12.5 at 0.2115 seconds on left side of interior	13.1 at 0.2164 seconds on left side of interior	5.3%	0.66	<20% or < 6.6 f/s	Y
Ridedown Acceleration (g's)	x-direction	-2.3 (0.2775 - 0.2875 seconds)	-4.4 (0.3060 - 0.3160 seconds)	91.3%	-2.10	<20% or < 4G	Y
	y-direction	7.6 (0.2730 - 0.2830 seconds)	7.3 (0.2953 - 0.3053 seconds)	3.9%	-0.30	<20% or < 4G	Y
PHD (g's)		7.7 (0.2730 - 0.2830 seconds)	8.5 (0.2955 - 0.3055 seconds)	10.4%	0.80	<20% or < 4G	Y
ASI		0.53 (0.0945 - 0.1445 seconds)	0.43 (0.2970 - 0.3470 seconds)	18.9%	-0.10	<20% or < 0.2	Y
Max 50-ms moving avg. acc. (g's)	x-direction	-1.4 (0.0795 - 0.1295 seconds)	-1.4 (0.2661 - 0.3161 seconds)	0.0%	0.00	<20% or < 4G	Y
	y-direction	4.6 (0.0940 - 0.1440 seconds)	3.5 (0.2969 - 0.3469 seconds)	23.9%	-1.10	<20% or < 4G	Y
	z-direction	2.2 (0.3450 - 0.3950 seconds)	1.8 (0.2855 - 0.3355 seconds)	18.2%	-0.40	<20% or < 4G	Y
Maximum Angular Disp. (deg)	Yaw	16.4 (0.7440 seconds)	15.7 (0.3326 seconds)	4.3%	-0.70	<20% or < 5 deg	Y
	Roll	-8.3 (0.5400 seconds)	-8.3 (0.4323 seconds)	0.0%	0.00	<20% or < 5 deg	Y
	Pitch	6.4 (0.9755 seconds)	-6.0 (0.5764 seconds)	193.8%	-12.40	<20% or < 5 deg	Y

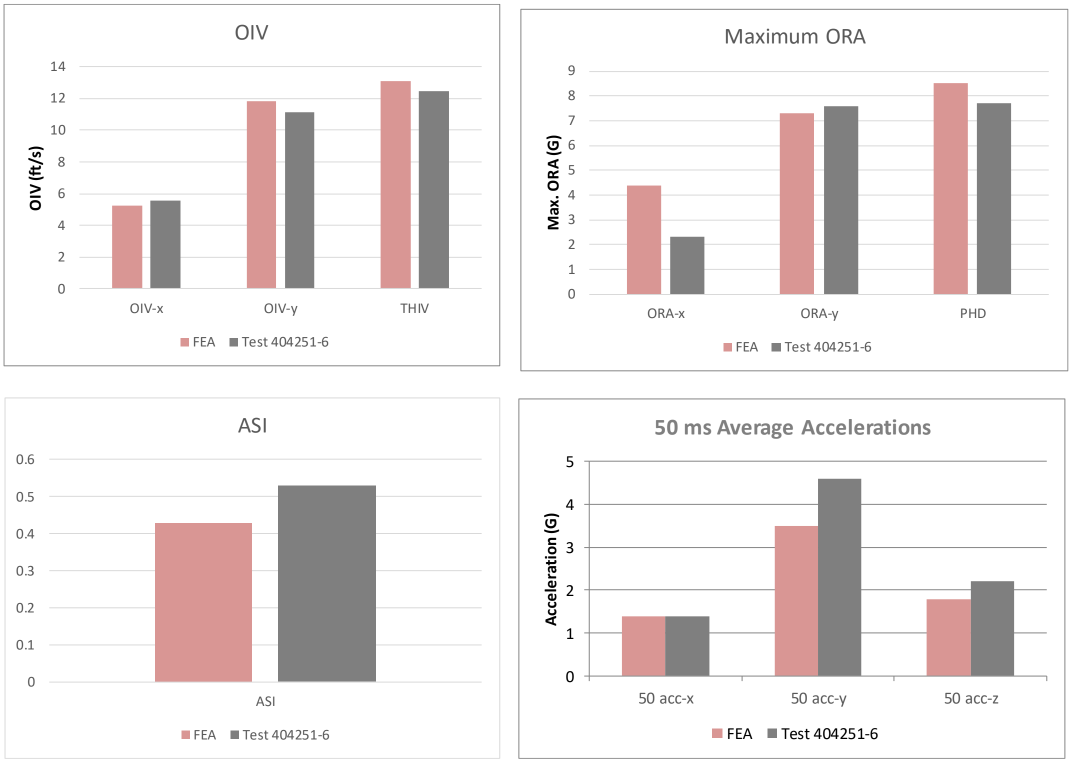


Figure 34. Graphical comparison of FEA vs. Test for key occupant risk metrics.

Time-History Data Comparison

Figure 35, Figure 36, and Figure 37 show a comparison of the 10-millisecond moving average and the 50-millisecond moving average acceleration-time history at the c.g. of the vehicle (i.e., on the cargo box) for the longitudinal, transverse and vertical channels, respectively. Figure 38, Figure 39 and Figure 40 show comparisons of the angular rates and angular displacements (i.e., yaw, roll, and pitch) measured from the cabin location in the test and FE analysis. Values for the quantitative evaluation metrics are also shown on the time-history plots. These quantities are discussed in more detail in the Quantitative Evaluation section of this Chapter and are shown with these plots only for reference. The values in red font indicate poor correlation between test and analysis results, while the values in black font indicate good correlation. Figure 41 shows a comparison of the vehicle's velocity-time history.

There was a very significant positive spike in y-acceleration at 0.13 seconds, immediately followed by a significant negative spike at 0.15 seconds, at approximately the time the lower-front corner of the cargo box strikes the top rail. After review of the test video, it is not clear what caused the spike, since there is no noticeable change in motion of the cargo box, and the impulse resulting from the two spikes essentially cancel each other. It may be possible that something (e.g., debris) inside the cargo box directly struck the accelerometer – but that is only an assumption.

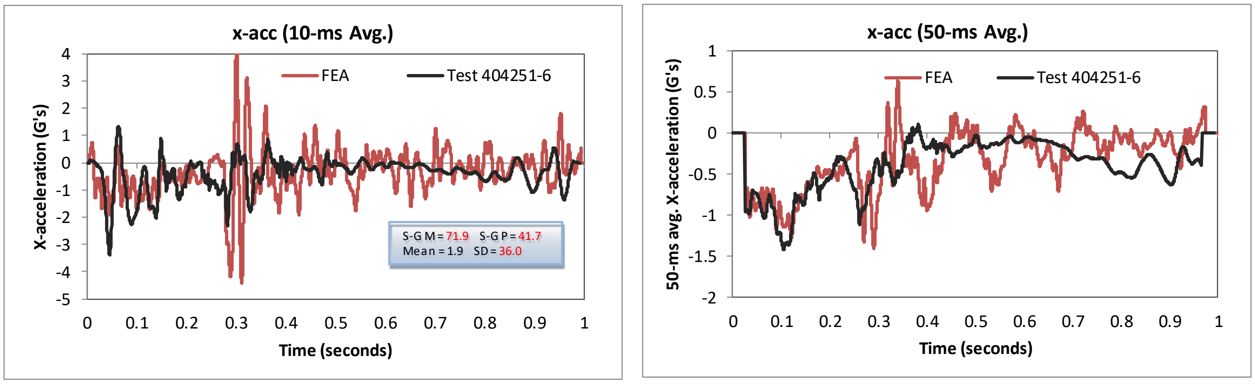


Figure 35. Longitudinal acceleration-time history plot from accelerometer at c.g. for full-scale Test 404251-6 and FEA (10-ms and 50-ms moving averages).

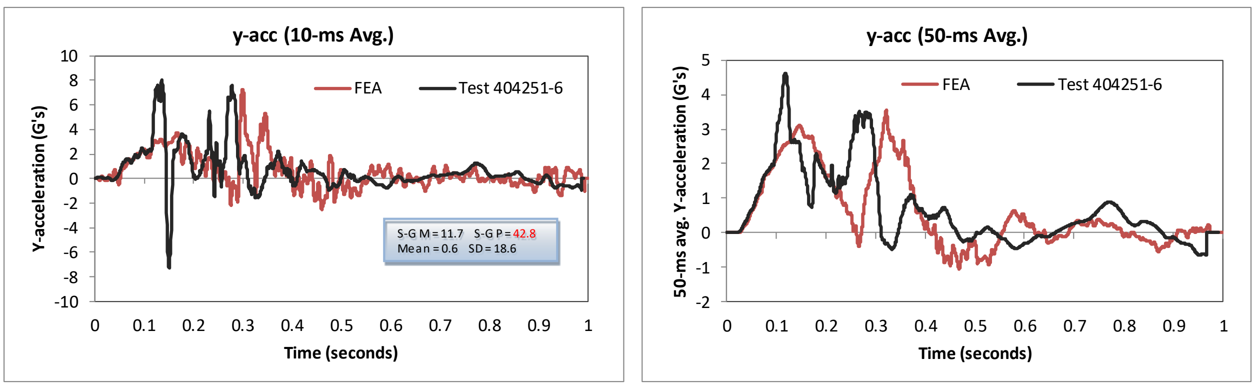


Figure 36. Lateral acceleration-time history plot from accelerometer at c.g. for full-scale Test 404251-6 and FEA (10-ms and 50-ms moving averages).

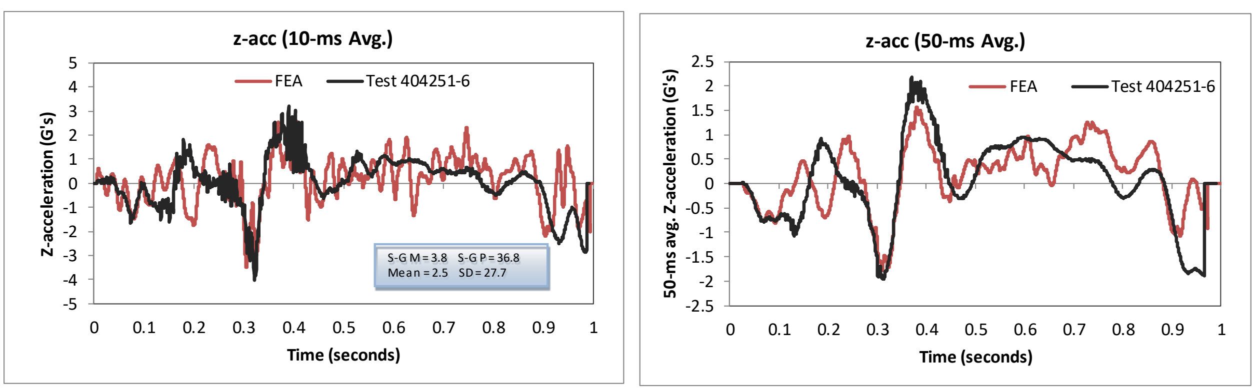


Figure 37. Vertical acceleration-time history plot from accelerometer at c.g. for full-scale Test 404251-6 and FEA (10-ms and 50-ms moving averages).

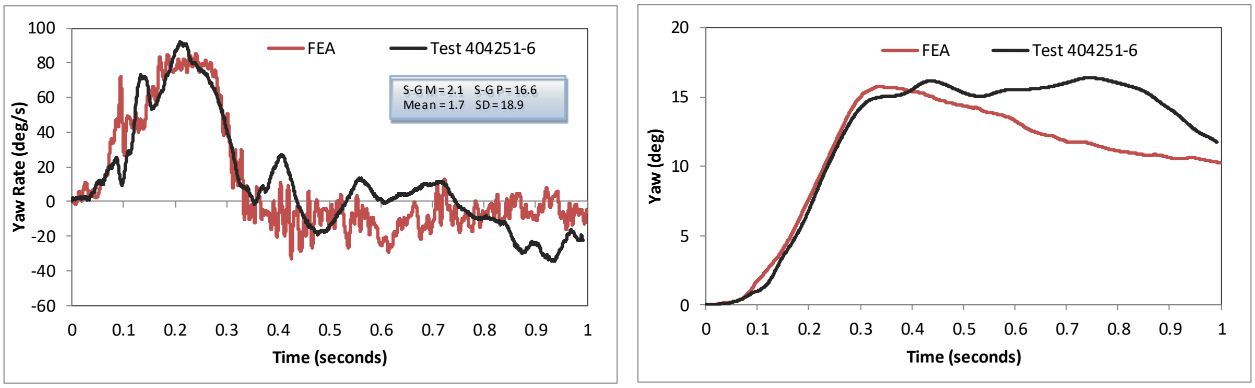


Figure 38. Yaw-time history plot from accelerometer inside cabin for full-scale test 404251-6 and FEA (angular rate and displacement).

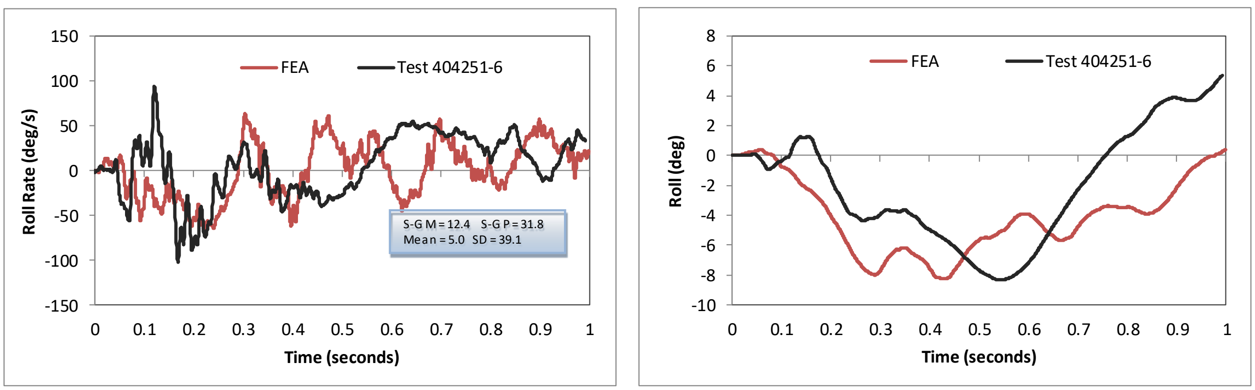


Figure 39. Roll-time history plot from accelerometer inside cabin for full-scale test 404251-6 and FEA (angular rate and displacement).

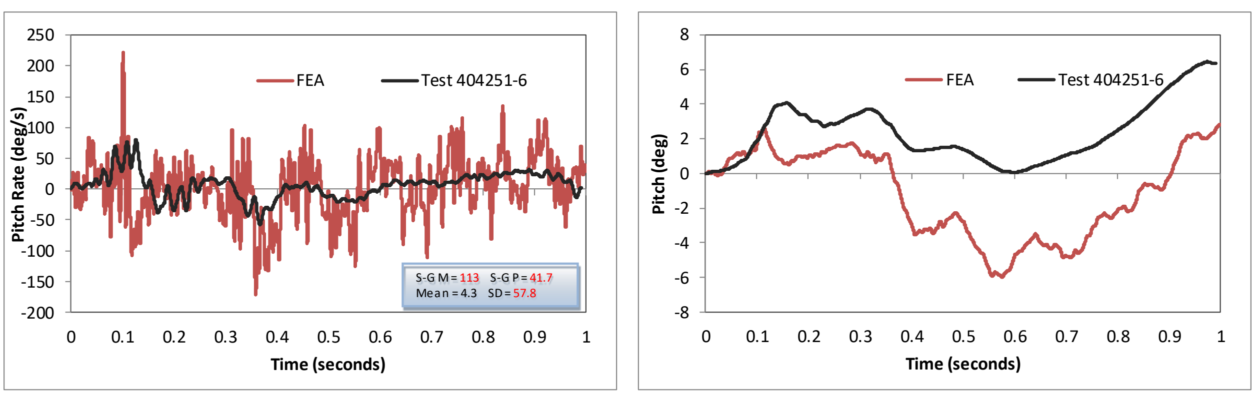


Figure 40. Pitch-time history plot from accelerometer inside cabin for full-scale test 404251-6 and FEA (angular rate and displacement).

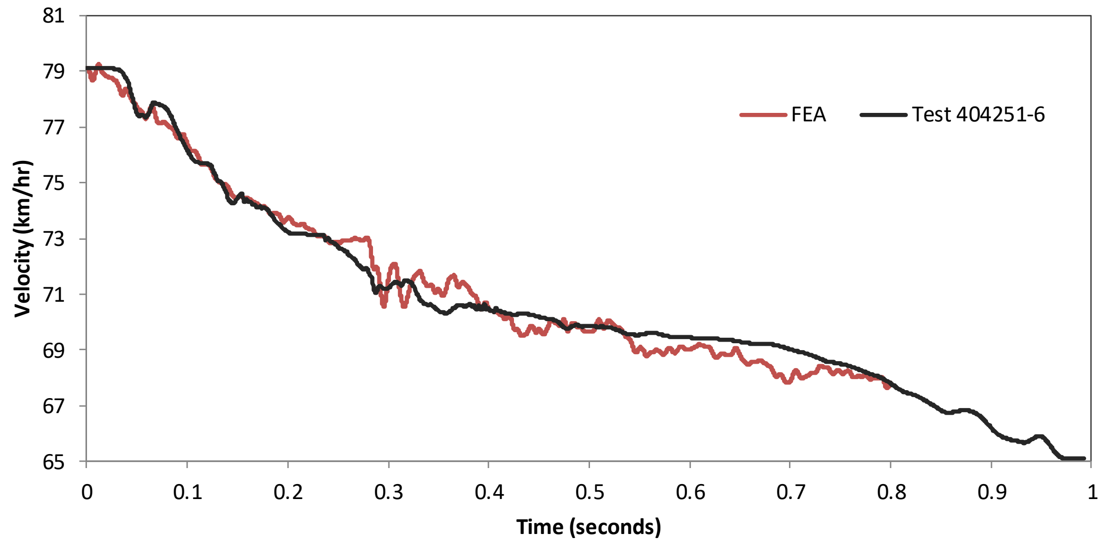


Figure 41. Velocity-time history plot from accelerometer at c.g. for full-scale test 404251-6 and FEA.

Quantitative Validation

The quantitative evaluation was based on comparison of acceleration-time histories and angular rate-time histories computed in the analysis to those measured in full-scale crash test 404251-6 using the procedures specified in Report W179. [*Ray10*] A summary of the quantitative comparison results are provided here. Additional comparison data can be found in Appendix B.

Solution Verification

Table 6 shows a summary of the global verification assessment based on criteria recommended in Report W179. Figure 42 shows a plot of the global energy-time histories from the analysis. All the solution verification parameters were satisfied. The concrete did not fail during the simulation of Test 404251-6and the energies remained balanced throughout the impact event.

Table 6. 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.	4%	**Y**
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.	0%	**Y**
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.	0%	**Y**
The part/material with the highest amount of hourglass energy at the end of the run is less than twenty percent of the total internal energy of the part/material at the end of the run.	12%	**Y**
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	0%	**Y**
The part/material with the most mass added had less than 10 percent of its initial mass added.	0%	**Y**
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	0%	**Y**
There are no shooting nodes in the solution?	Y	**Y**
There are no solid elements with negative volumes?	Y	**Y**

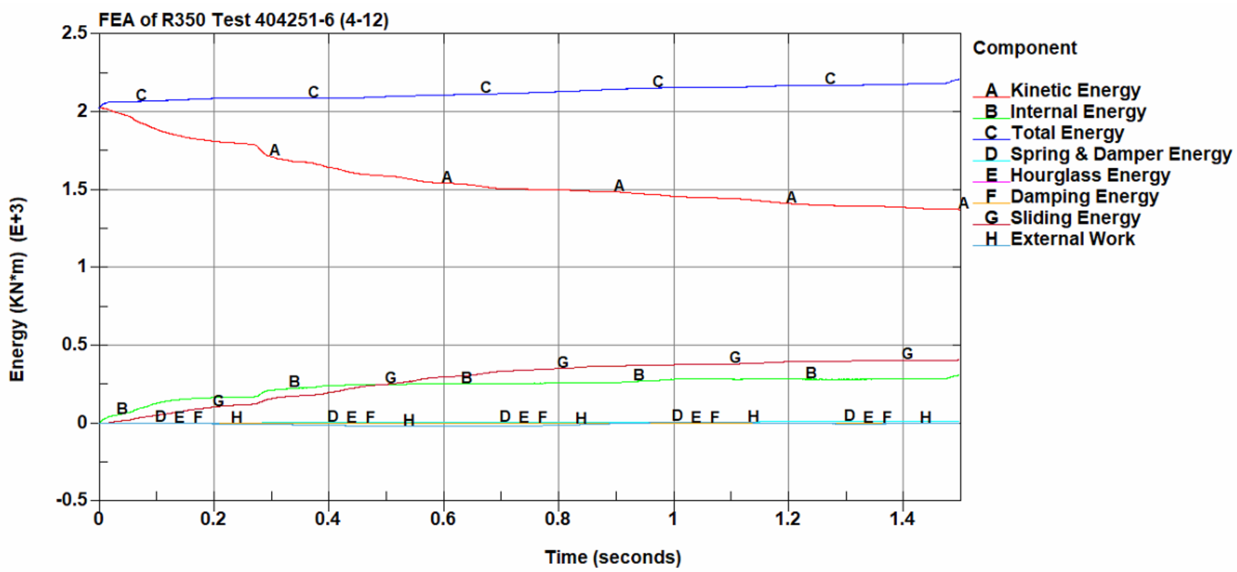


Figure 42. Plot of global energy-time histories from the analysis.

Time-History Validation

The data from the three acceleration channels located at the center of gravity of the vehicle and the angular rate data (i.e., roll, pitch and yaw) which was collected from inside the cabin were input into the RSVVP software to calculate quantitative differences between the FEA and test results. The data was filtered in RSVVP using a CFC Class 60 filter. The synchronization options in RSVVP were not used for the physical test data since both the test and analysis data started at the time of impact with the barrier. The default metrics evaluation options in RSVVP were used, which included the Sprague & Geers and the ANOVA metrics. The curves were evaluated over 1.0 seconds of the impact event, corresponding to the limits of the test data.

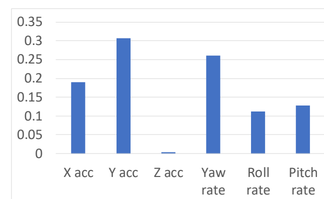
The results from RSVVP are shown in Table 7. Based on the validation metrics, a comparison of the individual components of acceleration indicated that the simulation was in good agreement for the z-acceleration, and yaw-rate; while the y-acceleration and roll-rate were in borderline agreement with respect to the Sprague-Geers metrics and good agreement with respect to the ANOVA. The pitch-rate showed mixed agreement, and the x-acceleration showed poor correlation. Since the metrics computed for the individual data channels did not all satisfy the acceptance criteria, the multi-channel option in RSVVP was used to calculate the weighted Sprague-Geer and ANOVA metrics for the six channels of data.

Table 7. Roadside safety validation metrics rating table – time history comparison (single-channel option).

<table>
<tr><th colspan="10">Evaluation Criteria</th><th colspan="3" rowspan="2">Time interval
[0.00 – 1.0 sec]</th></tr>
<tr><td rowspan="9"></td><td colspan="9">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.</td></tr>
<tr><td rowspan="3"></td><td colspan="8">RSVVP Curve Preprocessing Options</td><td rowspan="3">M</td><td rowspan="3">P</td><td rowspan="3">Pass?</td></tr>
<tr><td rowspan="2">Filter Option</td><td rowspan="2">Sync. Option</td><td colspan="2">Shift</td><td colspan="2">Drift</td></tr>
<tr><td>True Curve</td><td>Test Curve</td><td>True Curve</td><td>Test Curve</td></tr>
<tr><td>X acceleration</td><td>CFC 60</td><td>none</td><td>none</td><td>none</td><td>none</td><td>none</td><td>71.9</td><td>41.7</td><td>N</td></tr>
<tr><td>Y acceleration</td><td>CFC 60</td><td>none</td><td>none</td><td>none</td><td>none</td><td>none</td><td>11.7</td><td>42.8</td><td>≈Y</td></tr>
<tr><td>Z acceleration</td><td>CFC 60</td><td>none</td><td>none</td><td>none</td><td>none</td><td>none</td><td>3.8</td><td>36.8</td><td>Y</td></tr>
<tr><td>Yaw rate</td><td>CFC 60</td><td>none</td><td>none</td><td>none</td><td>none</td><td>none</td><td>2.1</td><td>16.6</td><td>Y</td></tr>
<tr><td>Roll rate</td><td>CFC 60</td><td>none</td><td>none</td><td>none</td><td>none</td><td>none</td><td>12.4</td><td>41.4</td><td>≈Y</td></tr>
<tr><td></td><td>Pitch rate</td><td>CFC 60</td><td>none</td><td>none</td><td>none</td><td>none</td><td>none</td><td>113</td><td>41.7</td><td>N</td></tr>
<tr><td rowspan="7">P</td><td colspan="9">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 ($\sigma \leq 0.35 \cdot a_{Peak}$)</td><td>Mean Reidual (%)</td><td>Standard Deviation of Residuals</td><td>Pass?</td></tr>
<tr><td colspan="9">X acceleration/Peak</td><td>1.9</td><td>36.0</td><td>Y</td></tr>
<tr><td colspan="9">Y acceleration/Peak</td><td>.56</td><td>18.6</td><td>Y</td></tr>
<tr><td colspan="9">Z acceleration/Peak</td><td>2.5</td><td>27.7</td><td>Y</td></tr>
<tr><td colspan="9">Yaw rate</td><td>1.7</td><td>18.9</td><td>Y</td></tr>
<tr><td colspan="9">Roll rate</td><td>5.0</td><td>39.1</td><td>N</td></tr>
<tr><td colspan="9">Pitch rate</td><td>4.3</td><td>57.8</td><td>N</td></tr>
</table>

Table 8 shows the results from RSVVP for the multi-channel option. The resulting weights computed for each channel are shown in both tabular form and graphical form in the tables. The results indicate that the x- and y-acceleration and the yaw rate have significant influence over the kinematics of the impact event; while the roll and pitch rate have notable influence. The z-acceleration did not have significant influence on the vehicle's impulse response. The weighted metrics computed in RSVVP in the multi-channel mode all satisfy the acceptance criteria; therefore, the time history comparison can be considered acceptable.

Table 8. Roadside safety validation metrics rating table – (multi-channel option).

Evaluation Criteria (time interval [0.0 – 1.0 seconds])		
Channels (Select which were used)		
☒ **X Acceleration**	☒ **Y Acceleration**	☒ **Z Acceleration**
☒ **Roll rate**	☒ **Pitch rate**	☒ **Yaw rate**
Multi-Channel Weights **- Area II method -**	**X Channel: 0.190** **Y Channel: 0.306** **Z Channel: 0.004** **Yaw Channel: 0.260** **Roll Channel: 0.113** **Pitch Channel: 0.127**	

		M	P	Pass?
	Sprague-Geer Metrics Values less or equal to 40 are acceptable.	33.6	35.4	**Y**
	ANOVA Metrics Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \le 0.05 \cdot a_{Peak}$) • 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** 1.4	**Standard Deviation of Residuals** 29.3	Pass? **Y**

PIRT – Crash Specific Phenomena

Table 9 contains the Report 350 crash test criteria. Those that apply to Test 4-12 are marked in red. These include criteria A, D, G, K and M. Table 10 through Table 12 contain an expanded list of these same criteria including additional specific phenomena that were measured in the test and that could be directly compared to the numerical solution. Table 10 contains a comparison of phenomena related to structural adequacy, Table 11 contains a comparison of phenomena related to occupant risk, and Table 12 contains a comparison of phenomena related to vehicle trajectory. Some of this information has already been presented but is repeated here for convenience. Comparisons for all the applicable crash specific phenomena between the FEA and test were within the allowable limits of Report W179.

Table 9. Report 350 crash test criteria with the applicable test numbers.

<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="12">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="4">Vehicle Trajectory</td><td>K</td><td colspan="3">After collision it is preferable that the vehicle’s trajectory not intrude into adjacent traffic lanes.</td><td>All</td></tr>
<tr><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>

Table 10. Roadside safety phenomena importance ranking table (structural adequacy).

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Structural Adequacy	A	1	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)	Y	Y		Y
		2	Maximum permanent deflection: - Relative difference is less than 20 percent or - Absolute difference is less than 6 inches	0.18 in	1.65 in	20% 0.4 in	Y
		3	Length of vehicle-barrier contact (at initial separation): - Relative difference is less than 20 percent or - Absolute difference is less than 6.6 ft	15.1 ft	16.4 ft	8.6 % 1.3 ft	Y
		4	Number of broken or significantly bent posts is less than 20 percent.	0	0		Y
		5	Did the rail element rupture or tear (Answer Yes or No)	No	No		Y
		6	Concrete curb/deck failure	*No	No		Y
		7	Was there significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	N	N		Y
		8	Was there significant snagging between vehicle body components and barrier elements (Answer Yes or No).	N	N		Y

** Cracks at base of post*

Table 11. 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)	N	N		Y
	F	1	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable. (Answer Yes or No)	Y	Y		Y
		2	Maximum roll of the vehicle through 1.0 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	-8.3 deg	-8.3 deg	0 % 0.0 deg	Y
		3	Maximum pitch of the vehicle through 1.0 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	*6.0 deg	**5.1 deg	7.0 % 0.9 deg	Y
		4	Maximum yaw of the vehicle through 0.446 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	16.4 deg	15.7 deg	4.2 % 0.7 deg	Y
	G	1	Did the vehicle remain upright during and after collision	Y	Y		Y
	L	1	Occupant impact velocities: - Relative difference is less than 20 percent or - Absolute difference is less than 6.6 ft/s.				
			• Longitudinal OIV (ft/s)	5.6	5.2	7% 0.4 ft/s	Y
			• Lateral OIV (ft/s)	-11.2	-11.8	5% 0.6 ft/s	Y
			• THIV (ft/s)	12.5	13.1	5% 0.6 ft/s	Y
		2	Occupant accelerations: - Relative difference is less than 20 percent or - Absolute difference is less than 4 g's.				
			• Longitudinal ORA	-2.3	-4.4	8.7 % 0.2 g	Y
			• Lateral ORA	7.6	7.4	3 % 0.2 g	Y
			• PHD	7.7	8.5	10 % 0.8 g	Y
			• ASI	0.53	0.43	19 % 0.1	Y

* *Possible "drift" in the pitch-rate channel; the sequential views (Figure 32) show the pitch comparison to be much closer.*

*** Taken at time=1.0 second coincident with the time of maximum pitch in the test.*

Table 12. Roadside safety phenomena importance ranking table (vehicle trajectory).

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Vehicle Trajectory	K	1	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.	13% cargo box	9.8% cargo box		Y
	M	2	Exit angle at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	2.0 deg cargo box	1.5 deg cargo box	25% 0.5 deg	Y
		3	Exit velocity at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 6.2 mph.	43.4 mph	43.1 mph	0.7 % 0.3 mph	Y

Sidewalk-Mounted S3-TL4 Bridge Rail

Test 404251-3 was conducted by the Texas Transportation Institute (TTI) in College Station, Texas on June 19, 1998 [*Buth99*] and involved a 1979 Chevrolet C70 single unit truck impacting the bridge rail under NCHRP Report 350 Test 4-12 impact conditions. The gross static mass of the test vehicle was 17,363 lbs (8,000 kg). The test installation was 75.5 feet long with no end-anchorage for the test article. The test vehicle struck the bridge railing at 49.46 mph (79.6 km/hr) and impact angle of 14.9 degrees. The initial point of contact was 7.15 ft (2.18 m) downstream from the end of the sidewalk.

The vehicle model used in analysis was the 8000S single unit truck model described in Chapter 4. The analysis was performed using LS-DYNA version mpp_s_R8.0.0 revision number 95309. The analysis was conducted with a time-step of 1.0 microsecond for a time period of 1.5 seconds. A comparison of the vehicle properties for the model and the test vehicle is shown in Figure 10. Except for the front bumper extension, all other vehicle geometry properties were within 10 percent of the test vehicle. The curb weight of the model was 1.2 percent lighter than the test vehicle, which resulted in the ballast model being 3.16 percent heavier than the ballast for the test vehicle. The horizontal center of gravity of the final ballasted SUT model, however, was less than 0.5 percent error compared to the test vehicle.

The following is a commentary describing the timing and occurrence of various events during the simulated impact with comparison to the full-scale test; this information is also tabulated in Table 13. The front-left tire of the vehicle model impacted the curb face of the sidewalk traveling at a speed of 49.46 mph and at an angle of 14.9 degrees. At 0.040 seconds the front wheels turned to the right (toward the bridge rail) and then straightened (0.03 seconds in test). By 0.1 seconds the front-right wheel reached the top of the sidewalk (0.064 seconds in test). At 0.23 seconds the rear right wheel contacted the curb-face of the sidewalk (0.211 seconds in test). The front-right corner of the bumper contacted the center rail element of the bridge rail at 0.28 seconds (0.281 seconds in test). The speed of the vehicle was 48.6 mph, and the impact angle was 15.2 degrees (48.4 mph and 16.0 degrees in test). The front-right quarter panel also contacted the upper rail element at this time (0.291 seconds in test) and the front-right tire contacted the lower element at 0.285 seconds (0.294 seconds in test). The lower front right corner of the box reached the top of the top rail element at 0.46 seconds (0.434 seconds in test). At 0.56 seconds the rear-right tire contacted the lower and middle rail elements (0.590 seconds in test) and the vehicle was traveling parallel with the rail at a speed of 45.5 mph (44.9 mph in test). The box of the vehicle continued to ride on top of the rail element and lost contact at 1.4 feet upstream of post 9 (between post 9 and 10 in test). The speed of the vehicle at 1.0 seconds was 43.0 mph (44.1 mph in test). The analysis was terminated manually at 1.5 seconds, at which time:

- The roll angle of the cargo box was 16.3 degrees away from the barrier and becoming stable (not reported in test).
- The roll angle of the truck cabin was 15.5 degrees away from barrier and decreasing.
- The pitch angle of the cargo box was 1.03 degrees with rear pitching up and stable (not reported in test).
- The pitch angle of the truck cabin was 2.1 degrees with front pitching upwards and stable.
- The yaw angle was 9.2 degrees toward the barrier (not reported in test), and
- The forward velocity of the vehicle was 42.0 mph (not reported in test).

Table 13. Summary of phenomenological events for full-scale Test 404251-3 and FEA simulation [*Buth99*].

Event	Test 404251-3	FE Analysis
Front wheels turned right then straightened	0.03 sec	0.04 sec
Front-right wheel impacted top of sidewalk	0.064 sec	0.10 sec
Rear-right wheel contact curb	0.21 sec	0.23 sec
Bumper impacted center rail	0.28 sec	0.28 sec
Vehicle speed at time of impact with barrier	48.4 mph	48.6 mph
Impact angle at initial contact with barrier	16 deg	15.2 deg
Lower corner of box impacts top rail	0.434 sec	0.46 sec
Rear-right wheel impacts railing	0.59 sec	0.56 sec
Vehicle parallel with railing	0.59 sec	0.56 sec
Speed at parallel	44.9 mph	45.5 mph
Speed at final separation	44.1 mph	43.0 mph
Angle at final separation	5 deg (toward railing)	2.5 deg (toward railing)

Damage to Bridge Rail

Damage to the bridge rail is shown in Figure 43. The concrete sidewalk at Post 6 was reported to have sustained hairline cracks radiating from the front bolts during the full-scale test. This did not occur in the FEA simulation. The maximum dynamic lateral deflection of the bridge rail model was 1.56 inches (not reported in test). The maximum permanent deflection of the bridge rail model was 1.04 inches (0.4 inches in the test). As mentioned in the previous section, it is expected that this was due to differences in material properties for the post. The actual yield for post material is often 10-20 percent higher than the specified minimum for the material; however, the post in this case was modeled with yield equal to the specified minimum of 50 ksi. The image on the left in Figure 43 shows contours of plastic strain for the post and rail at the critical Post from the FEA. The plastic strains were isolated to the base of the post at the welded connection to the base plate. Also, the lower rail element was pushed down 0.71 inches (18 mm) during interaction with the tire in the FEA, compared to a vertical deflection of 0.59 inches (15 mm) in the test.

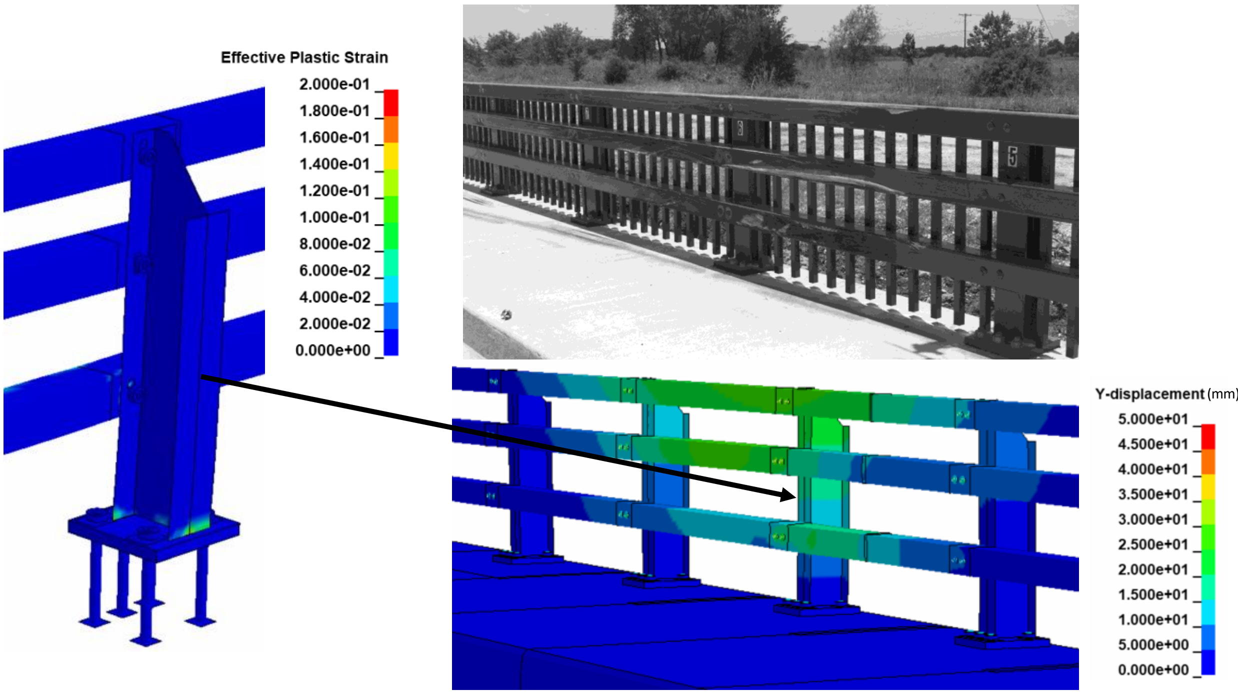


Figure 43. Comparing overall deformation of system for FEA and Test 404251-3.

Qualitative Validation

Sequential Views

Figure 44, Figure 45, and Figure 46 show sequential snapshots of the impact event from an overhead viewpoint, a downstream viewpoint, and an overhead viewpoint, respectively. The model appears to simulate the basic kinematic behavior of the SUT and adequately captures the basic phenomenological events that occur during impact.

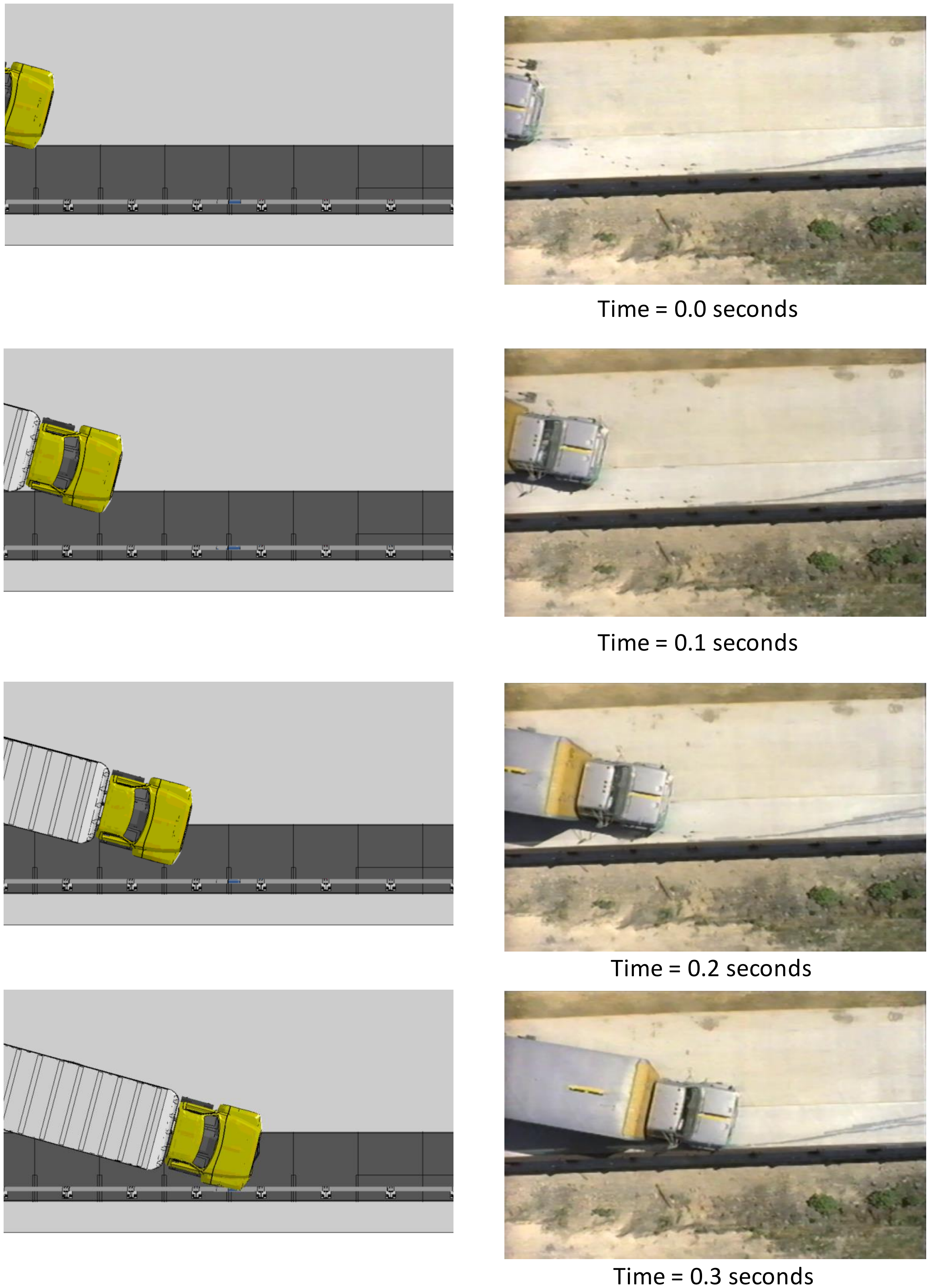
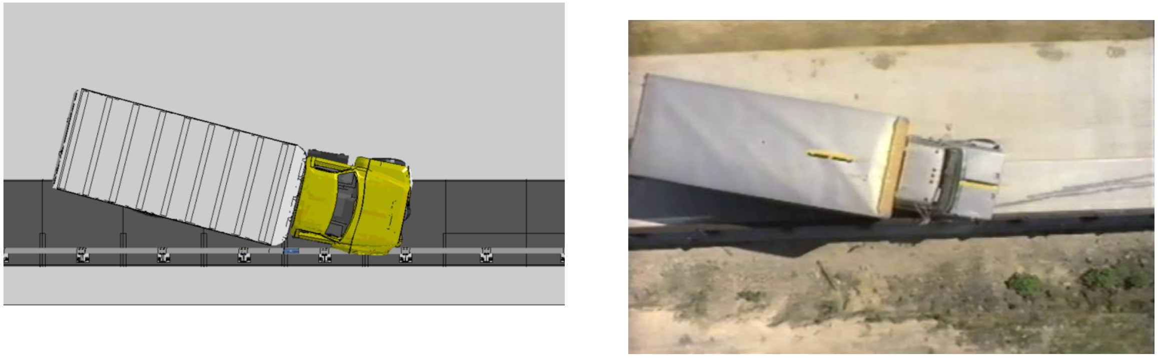
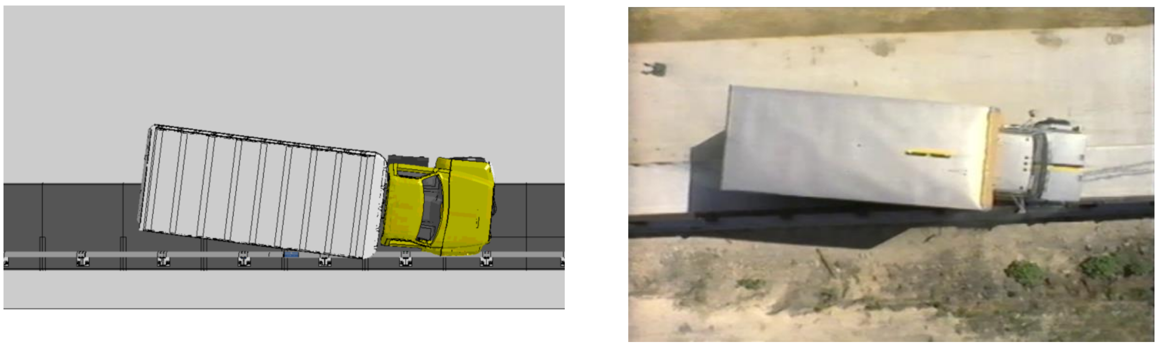


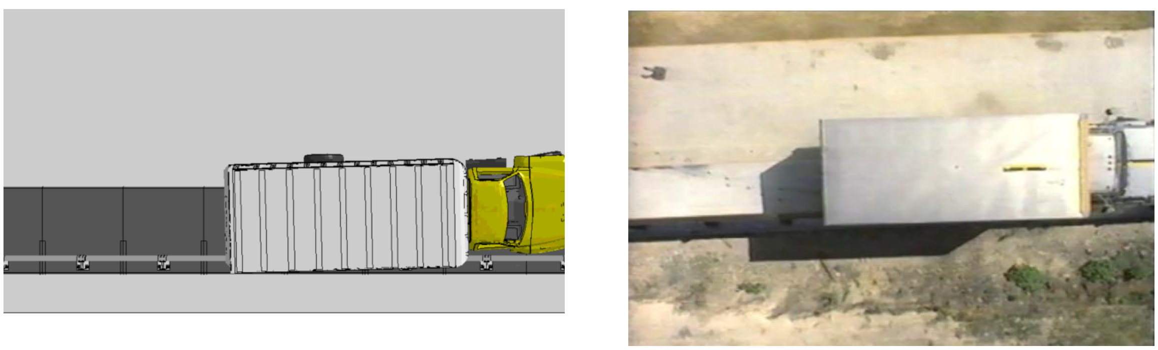
Figure 44. Sequential views from FEA and Test 404251-3 from an overhead view point.



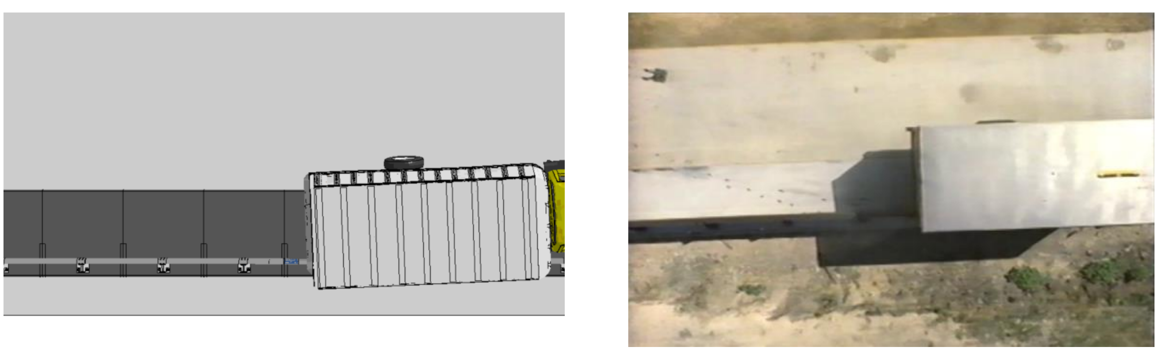
Time = 0.4 seconds



Time = 0.5 seconds

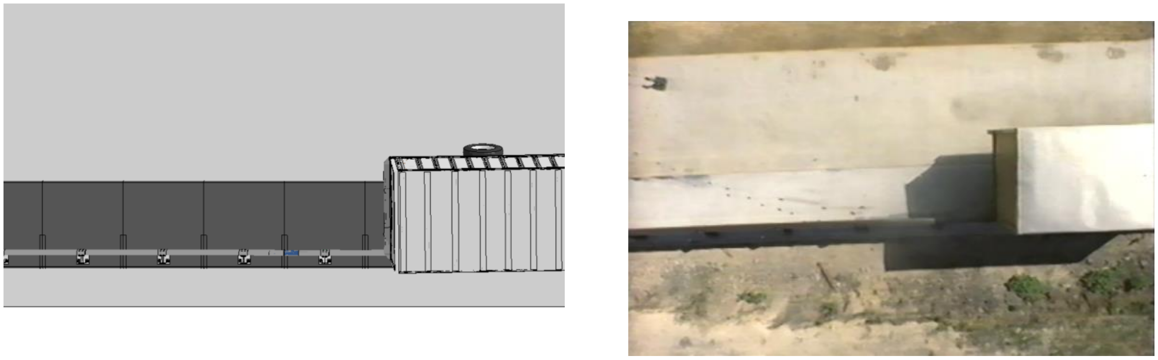


Time = 0.6 seconds

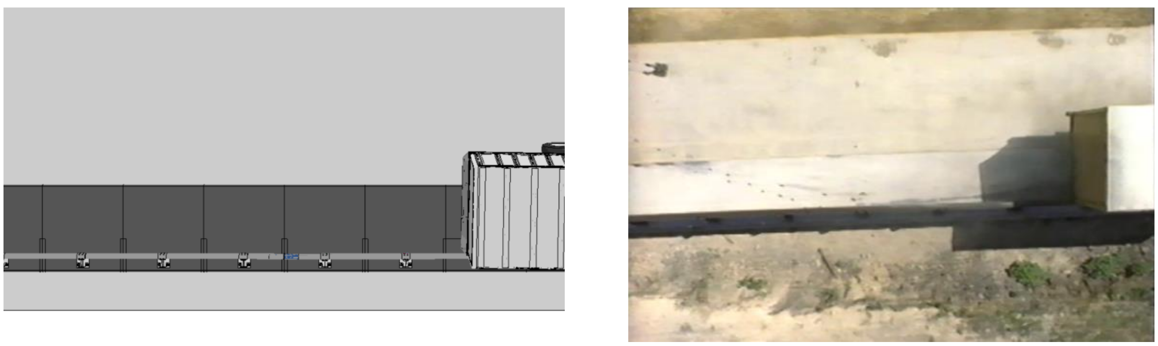


Time = 0.7 seconds

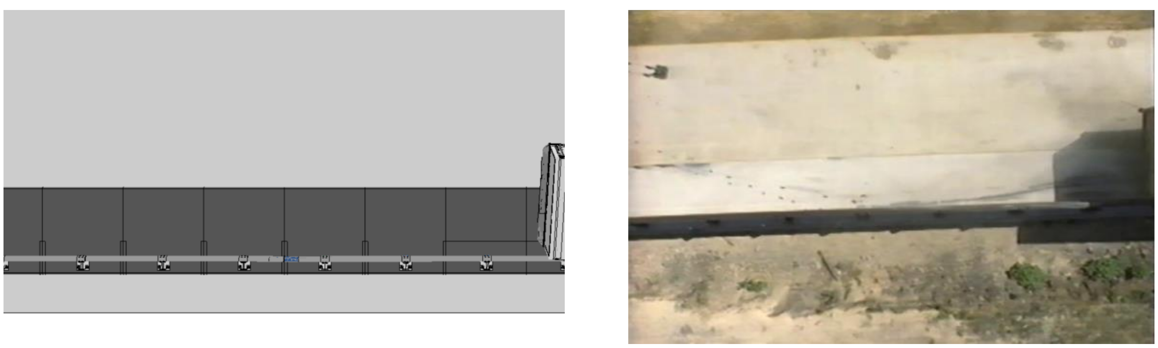
Figure 44. [Continued] Sequential views from FEA and Test 404251-3 from an overhead view point.



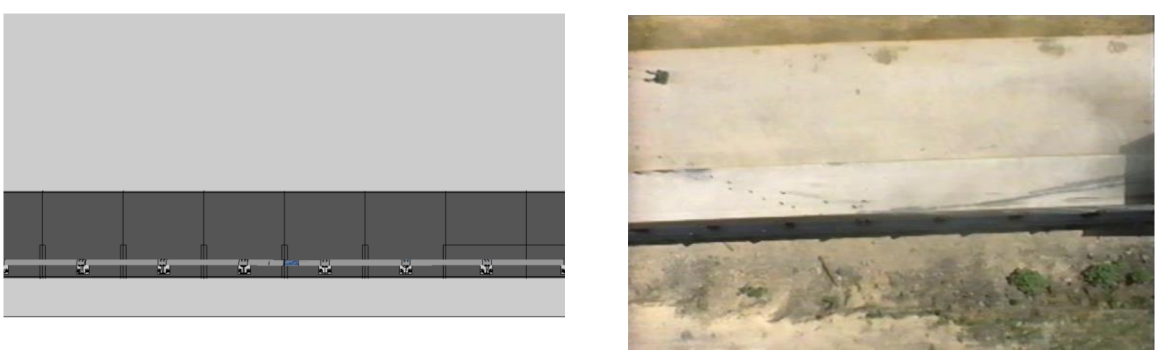
Time = 0.8 seconds



Time = 0.9 seconds



Time = 1.0 seconds



Time = 1.1 seconds

Figure 44. [Continued] Sequential views from FEA and Test 404251-3 from an overhead view point.

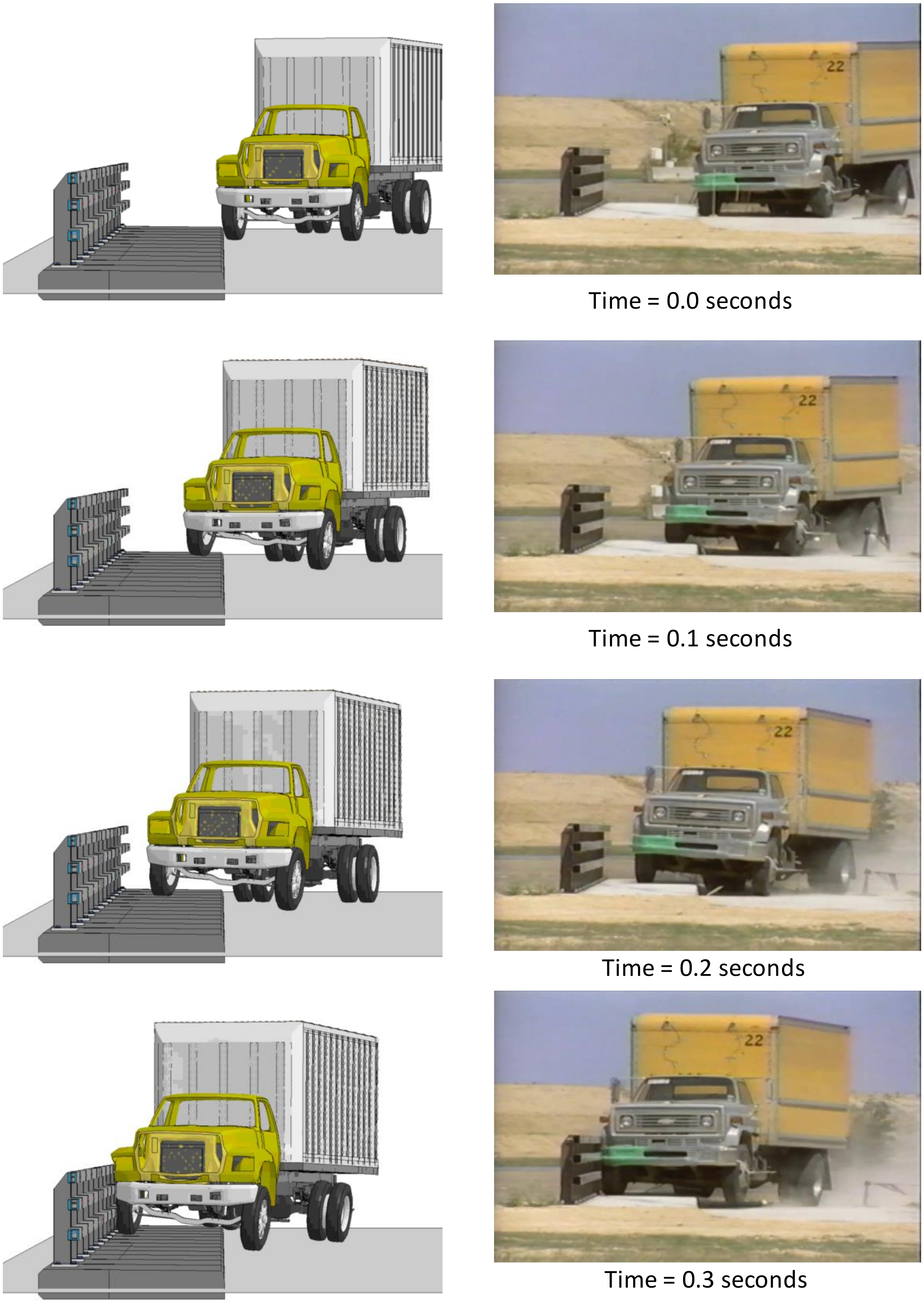
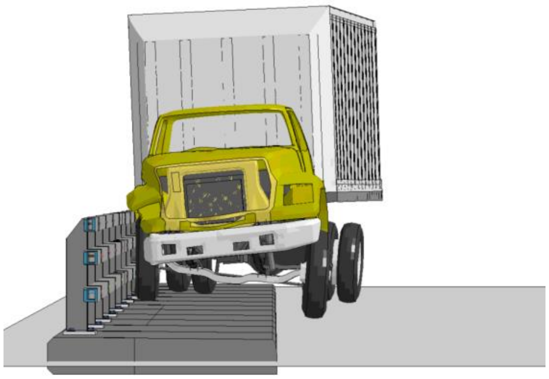


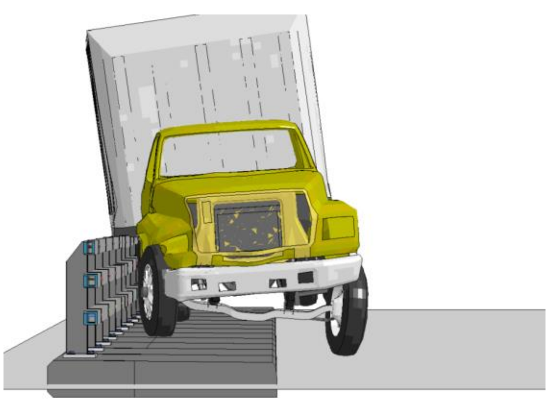
Figure 45. Sequential views from FEA and Test 404251-3 from a downstream view point.

Time = 0.4 seconds



Time = 0.5 seconds

Time = 0.6 seconds



Time = 0.7 seconds

Figure 45. [Continued] Sequential views from FEA and Test 404251-3 from a downstream view point.

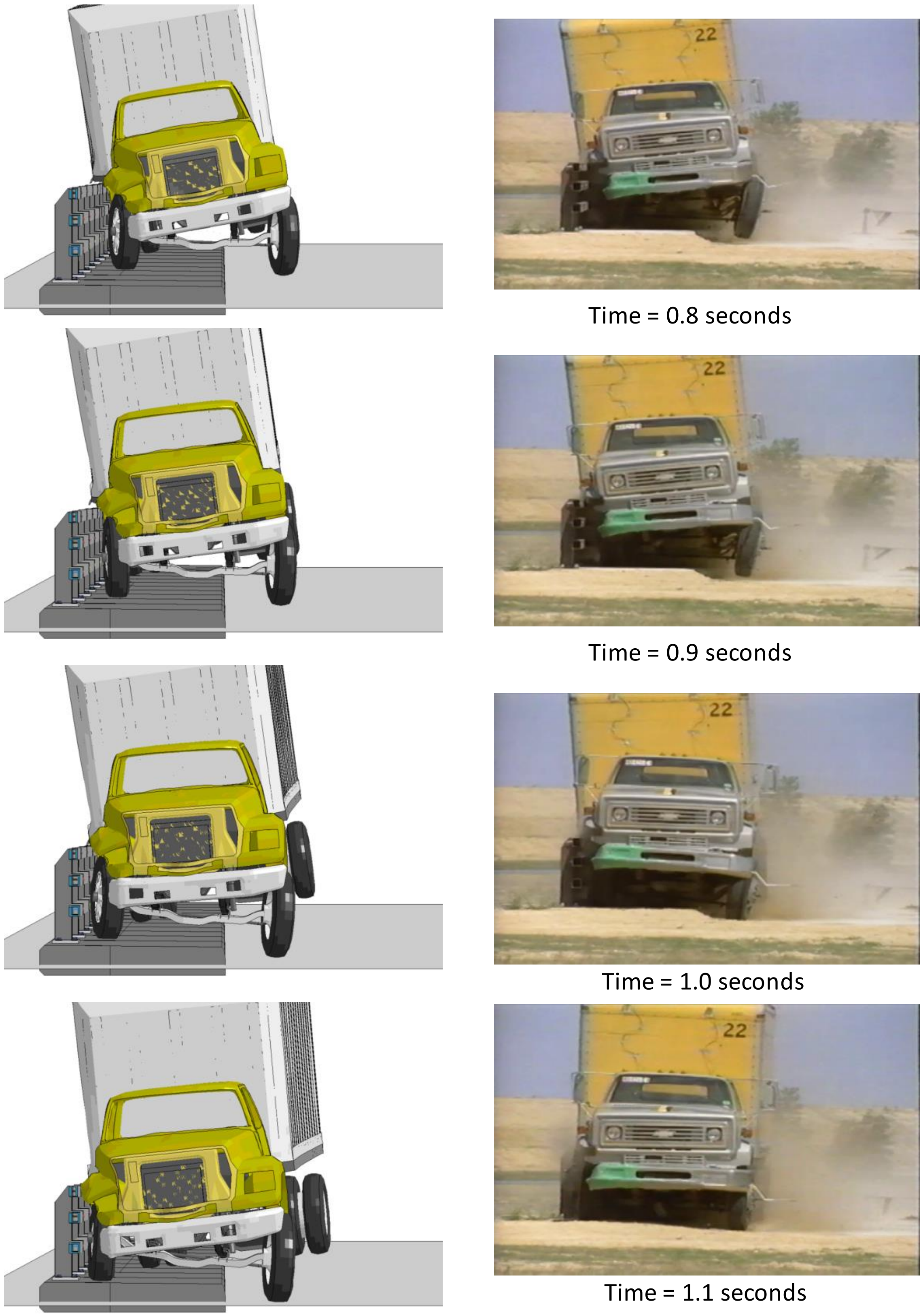


Figure 45. [Continued] Sequential views from FEA and Test 404251-3 from a downstream view point.

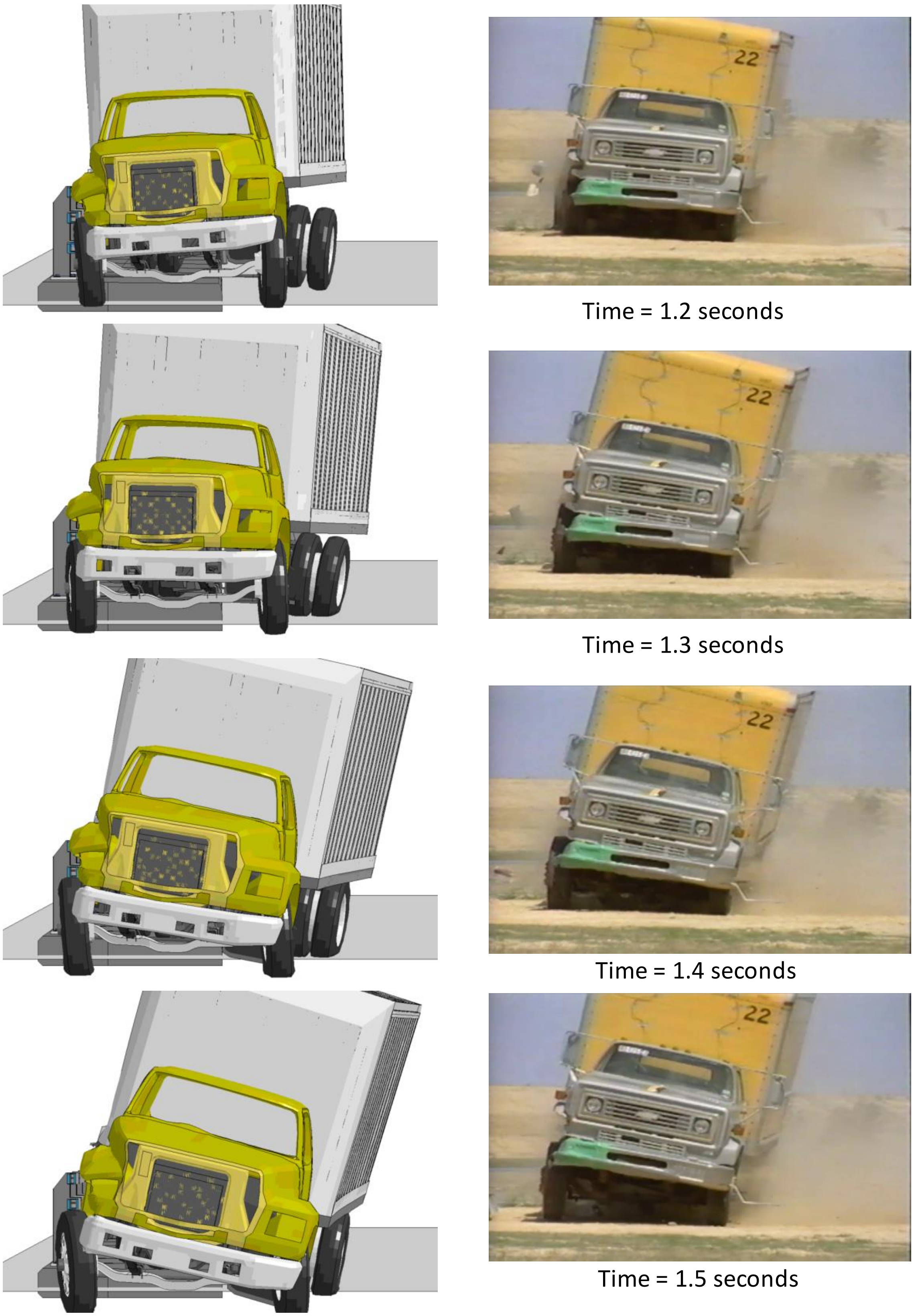


Figure 45. [Continued] Sequential views from FEA and Test 404251-3 from a downstream view point.

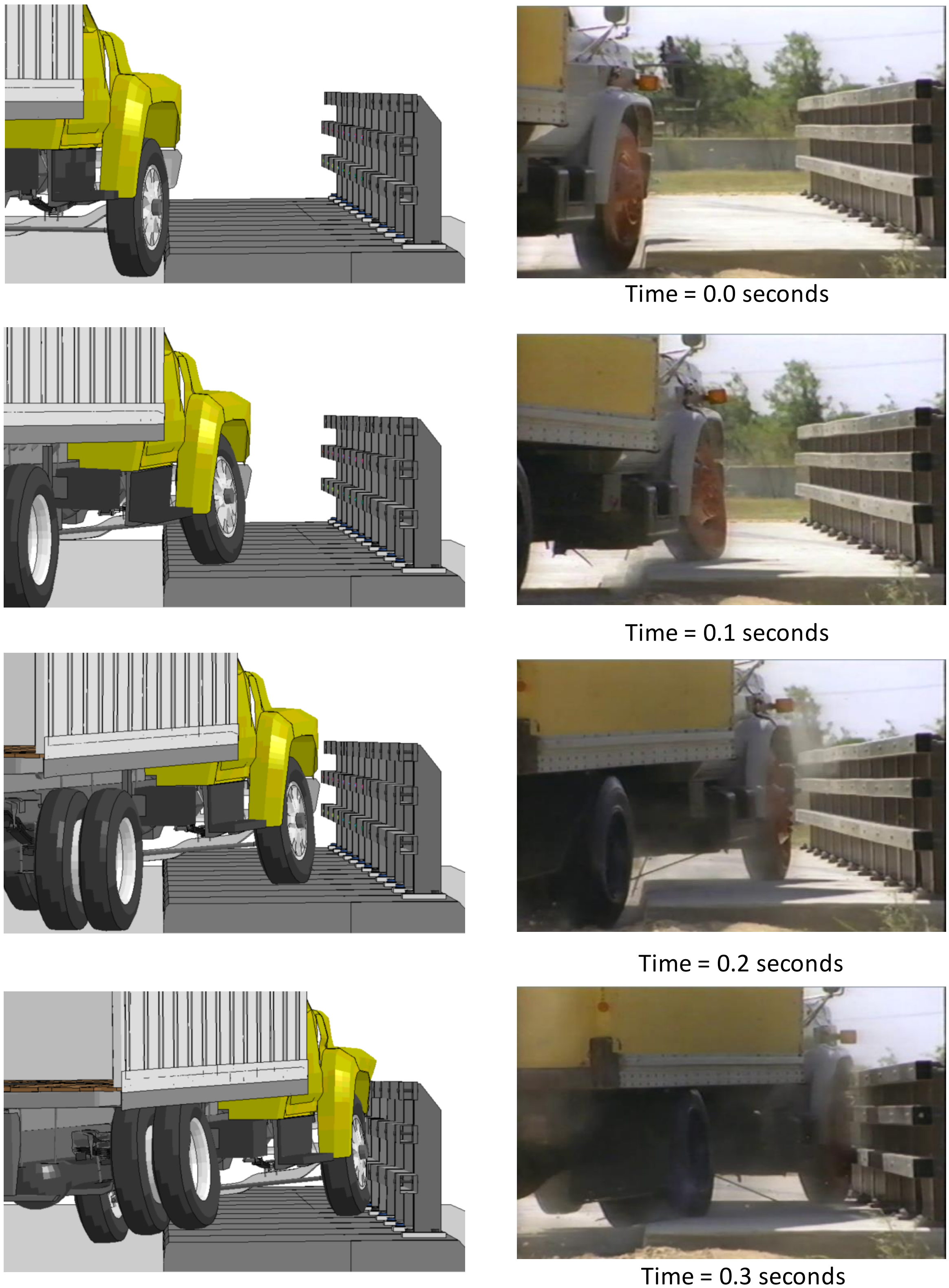


Figure 46. Sequential views from FEA and Test 404251-3 from an upstream view point.

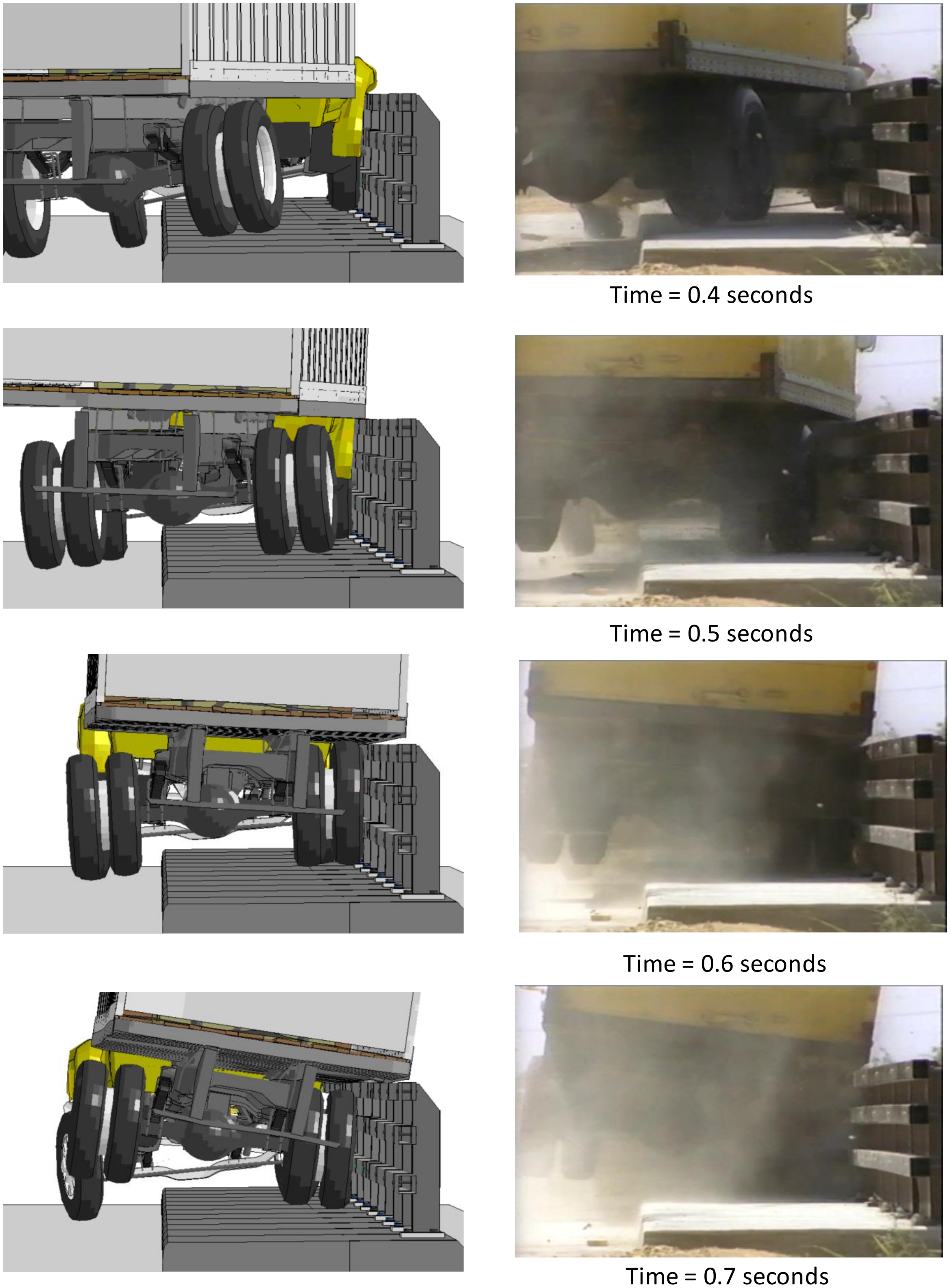
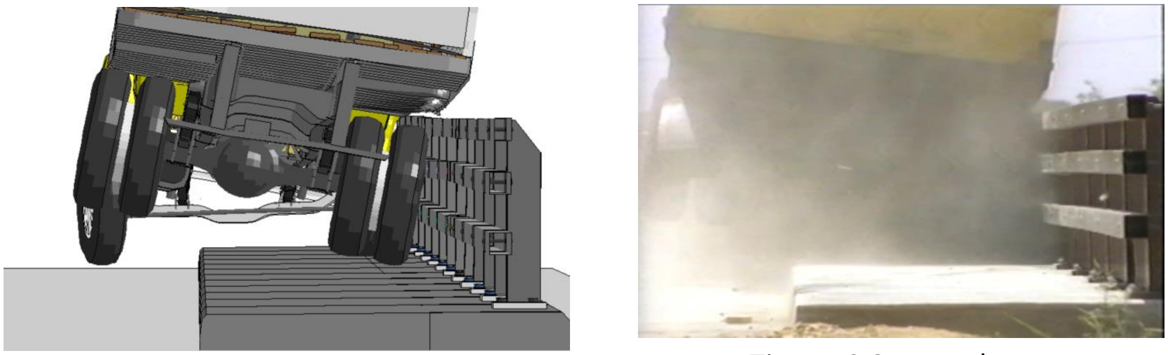
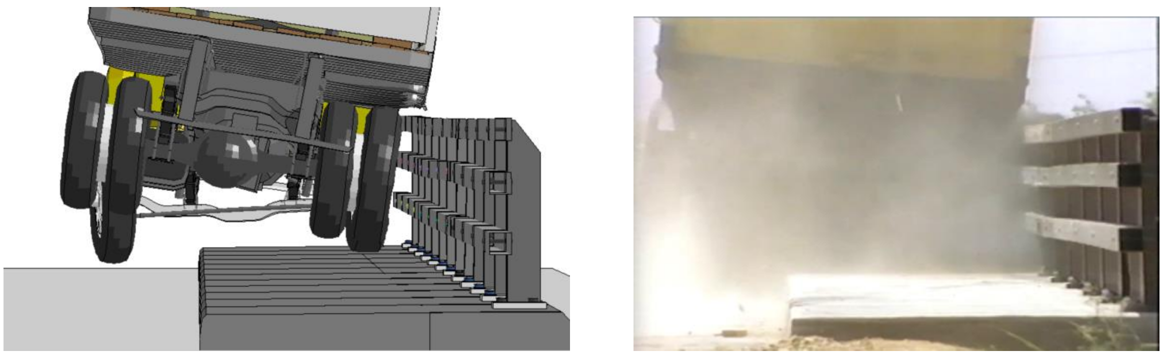


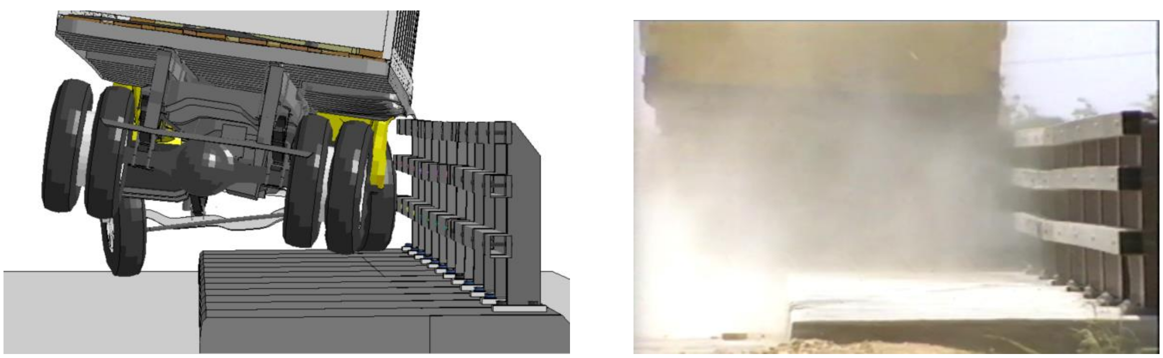
Figure 46. [Continued] Sequential views from FEA and Test 404251-3 from an upstream viewpoint.



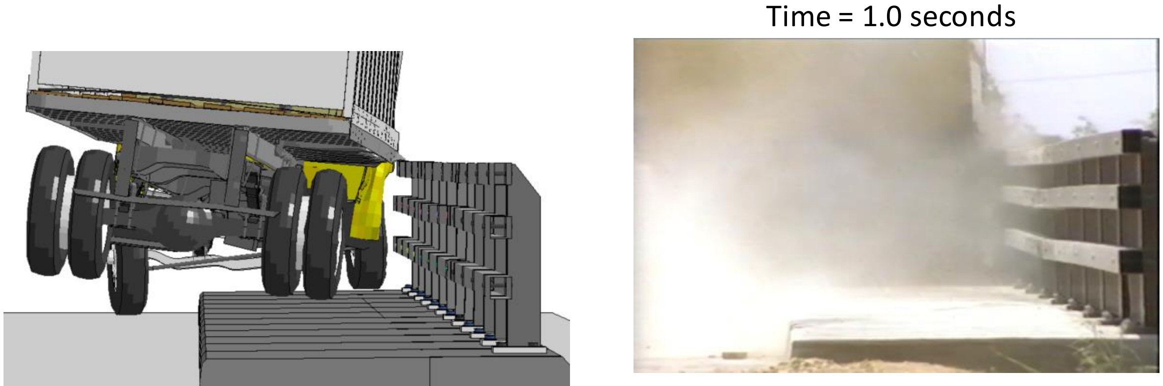
Time = 0.8 seconds



Time = 0.9 seconds



Time = 1.0 seconds



Time = 1.1 seconds

Figure 46. [Continued] Sequential views from FEA and Test 404251-3 from an upstream viewpoint.

Occupant Risk Measures

Acceleration-time histories and angular rate-time histories were collected at two locations: 1) inside the cargo box near the center of gravity of the vehicle and 2) inside the cabin behind the seat, as illustrated in Figure 33. The time-history data was collected from the accelerometers in a local reference coordinate system that was fixed to the vehicle with the x-direction coincident with the forward direction of the vehicle, the local y-direction was oriented toward the right side of the vehicle and the local z-direction was oriented downward. The data was collected at a frequency of 50 kHz. For the assessment of occupant risk metrics, the acceleration data was taken from the c.g. location, and the angular rate data was taken from the cabin location (e.g., consistent with the full-scale test).

The analysis results obtained from TRAP for the full-scale test and the FE analysis are shown in Table 14 and Figure 47. The acceleration data used in the TRAP program was pre-filtered using the BW Class 180 filter. The table shows the two occupant risk factors recommended by R350: 1) the lateral and longitudinal components of Occupant Impact Velocity (OIV), and 2) the maximum lateral and longitudinal component of resultant vehicle acceleration averaged over 10-millisecond interval after occupant impact, called the Occupant Ridedown Acceleration (ORA). Also provided in the table are the CEN risk factors including the Theoretical Head Impact Velocity (THIV), the Post Impact Head Deceleration (PHD) and the Acceleration Severity Index (ASI). The table also includes comparison of the 50-millisecond moving average of the accelerations.

The occupant risk metrics are in good agreement for all metrics except the yaw and roll displacements. The occupant impact velocity in the longitudinal direction was predicted from the simulation to be 5.6 ft/s (1.3 ft/s higher than the test OIV of 4.3 ft/s) at 0.4655 seconds. In the transverse direction, the occupant impact velocity predicted in the simulation was 10.8 ft/s (2.3 ft/s higher than the test OIV of 8.5 ft/s). The highest 0.010-second occupant ridedown acceleration in the longitudinal direction was 3.8 g (3.0 g higher than test ORA of 1.8 g) between 0.6572 and 0.6672 seconds. In the transverse direction, the highest 0.010-second occupant ridedown acceleration was 5.9 g (3.7 g lower than test ORA of 9.6) between 0.6092 and 0.6192 seconds. The THIV, PHD and ASI predicted from the simulation were 12.5 ft/s (3.0 ft/s higher), 5.9 g's (3.8 g lower), and 0.35 (0.17 lower), respectively. The maximum 50-millisecond moving average accelerations in the x-, y-, and z-directions were 1.7 g (0.2 g higher), 3.0 g (1.4 g lower), and 1.2 g (0.8 g lower), respectively. The maximum yaw, roll and pitch angles were -18.5 degrees (5.7 degrees higher), 9.9 degrees (5.3 degrees higher) and 2.7 degrees (0.9 degree lower), respectively.

Except for the yaw and roll angle, the results of the FEA were within the recommended limits of Report W179 for each of the comparison metrics. That is, the difference in OIV was less than 20 percent or 6.6 ft/s; the difference in maximum ORA was less than 20 percent or 4 g; and the difference in angular displacement was less than 20 percent or 5 degrees. However, from the sequential views of Figure 45, the peak roll angle at 0.8 seconds appears very similar between FEA and test.

Table 14. Occupant risk measured computed using TRAP software for the FEA and test data for R350 Test 4-12.

Occupant Risk Factors		MASH Test 3-11: Test 404251-3 (0 - 1.0 seconds)	MASH Test 3-11: FEA (0 - 1.0 seconds)	Error: %	Error: Absolute	W179 Criteria: Criteria	W179 Criteria: Pass
Occupant Impact Velocity (ft/s)	x-direction	4.3	5.6	30.8%	1.3	<20% or < 6.6 f/s	Y
	y-direction	8.5	10.8	26.9%	2.3	<20% or < 6.6 f/s	Y
	at time	at 0.4291 seconds on right side of interior	at 0.4655 seconds on right side of interior				
THIV (ft/s)		9.5 at 0.4291 seconds on right side of interior	12.5 at 0.4591 seconds on right side of interior	31.0%	3.0	<20% or < 6.6 f/s	Y
Ridedown Acceleration (g's)	x-direction	-1.8 (0.6955 - 0.7055 seconds)	-3.8 (0.6572 - 0.6672 seconds)	111.1%	2	<20% or < 4G	Y
	y-direction	-9.6 (0.5974 - 0.6074 seconds)	-5.9 (0.6092 - 0.6192 seconds)	38.5%	3.7	<20% or < 4G	Y
PHD (g's)		9.7 (0.5974 - 0.6074 seconds)	5.9 (0.6090 - 0.6190 seconds)	39.2%	3.8	<20% or < 4G	Y
ASI		0.52 (0.5782 - 0.6282 seconds)	0.35 (0.3782 - 0.4282 seconds)	32.7%	0.17	<20% or < 0.2	Y
Max 50-ms moving avg. acc. (g's)	x-direction	-1.5 (0.3101 - 0.3601 seconds)	-1.7 (0.6257 - 0.6757 seconds)	13.3%	0.2	<20% or < 4G	Y
	y-direction	-4.4 (0.5767 - 0.6267 seconds)	-3 (0.3787 - 0.4287 seconds)	31.8%	1.4	<20% or < 4G	Y
	z-direction	-2 (0.2497 - 0.2997 seconds)	-1.2 (0.2700 - 0.3200 seconds)	40.0%	0.8	<20% or < 4G	Y
Maximum Angular Disp. (deg)	Yaw	-12.8 (0.6850 seconds)	-18.5 (0.7058 seconds)	44.5%	5.7	<20% or < 5 deg	N
	Roll	4.6 (0.8368 seconds)	9.9 (0.8291 seconds)	115.2%	5.3	<20% or < 5 deg	N
	Pitch	3.6 (0.2834 seconds)	2.7 (0.7003 seconds)	25.2%	0.90641	<20% or < 5 deg	Y

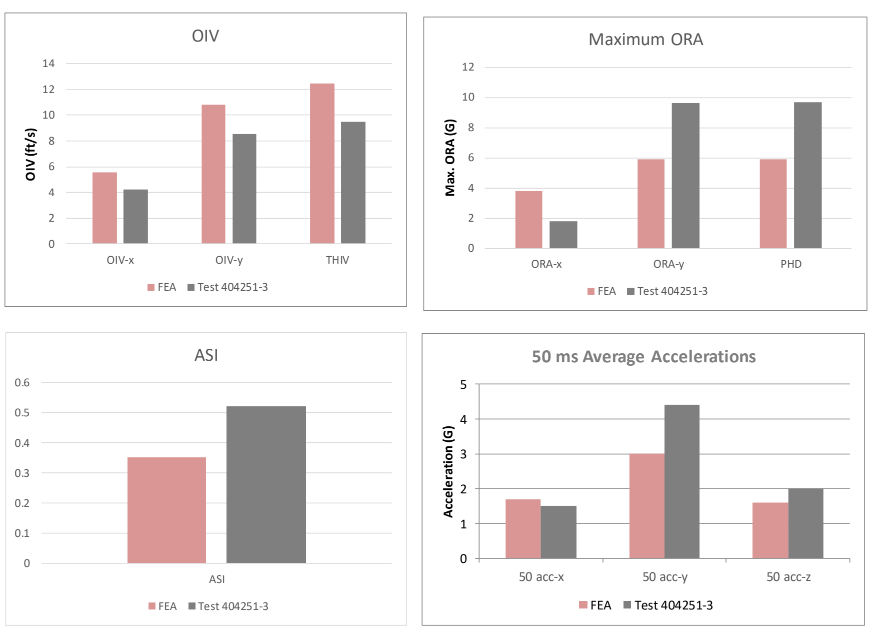


Figure 47. Graphical comparison of FEA vs. Test for key occupant risk metrics.

Time-History Data Comparison

Figure 48, Figure 49 and Figure 50 show a comparison of the 10-millisecond moving average and the 50-millisecond moving average acceleration-time history at the c.g. of the vehicle (i.e., on the cargo box) for the longitudinal, transverse and vertical channels, respectively. Figure 51, Figure 52 and Figure 53 show comparisons of the angular rates and angular displacements (i.e., yaw, roll, and pitch) measured from the cabin location in the test and FE analysis. Values for the quantitative evaluation metrics are also shown on the time-history plots. These quantities are discussed in more detail in the Quantitative Evaluation Section of this Chapter and are shown with these plots only for reference. The values in red font indicate poor correlation between test and analysis results, while the values in black font indicate good correlation. Figure 54 shows a comparison of the vehicle's velocity-time history.

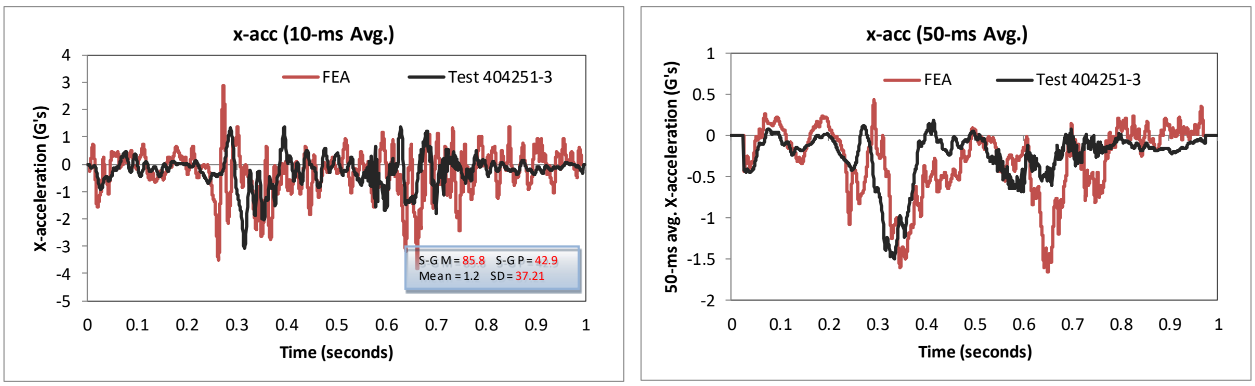


Figure 48. Longitudinal acceleration-time history plot from accelerometer at c.g. for full-scale Test 404251-3 and FEA (10-ms and 50-ms moving averages).

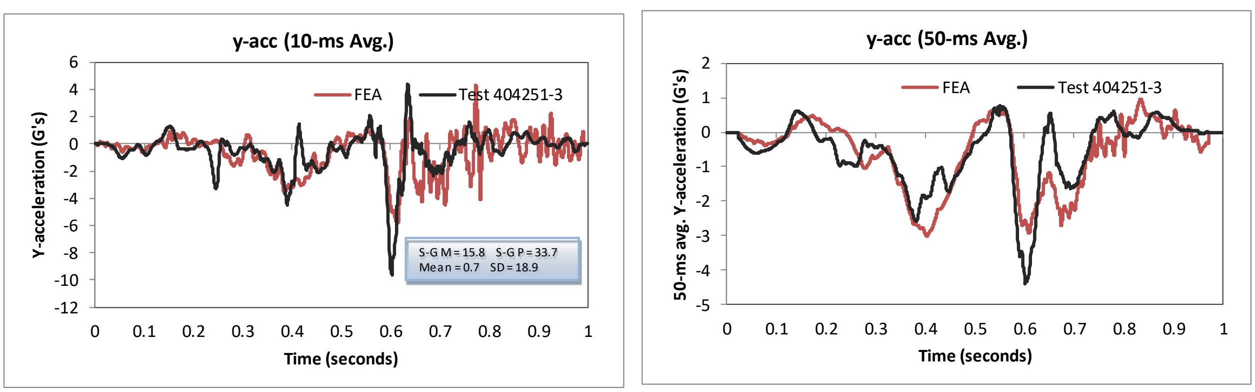


Figure 49. Lateral acceleration-time history plot from accelerometer at c.g. for full-scale Test 404251-3 and FEA (10-ms and 50-ms moving averages).

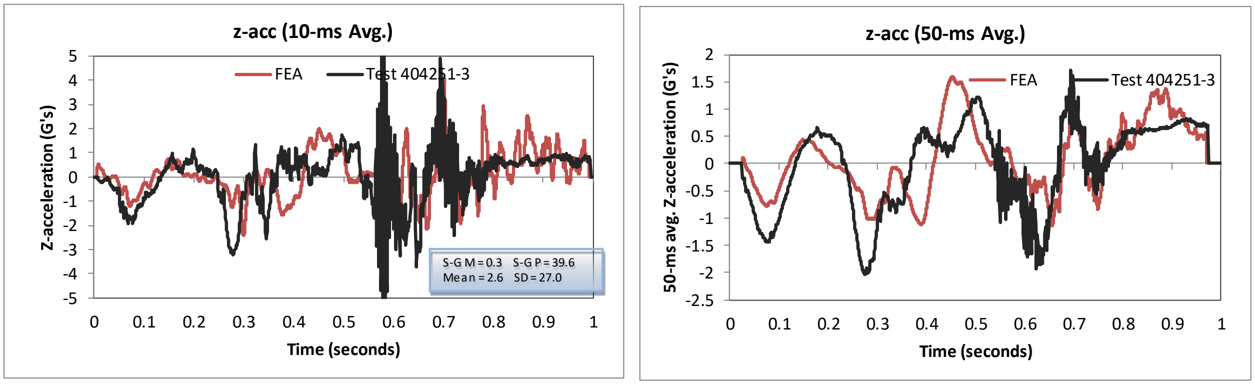


Figure 50. Vertical acceleration-time history plot from accelerometer at c.g. for full-scale Test 404251-3 and FEA (10-ms and 50-ms moving averages).

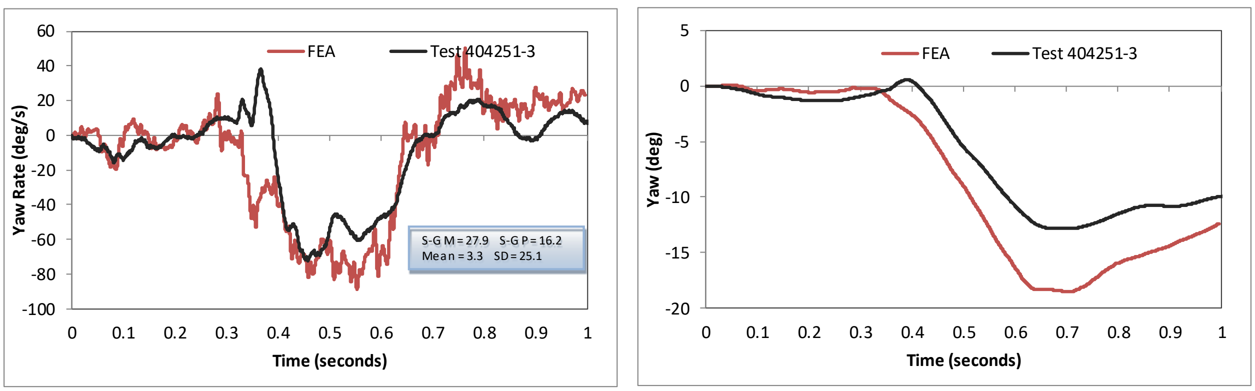


Figure 51. Yaw-time history plot from accelerometer inside cabin for full-scale test 404251-3 and FEA (angular rate and displacement).

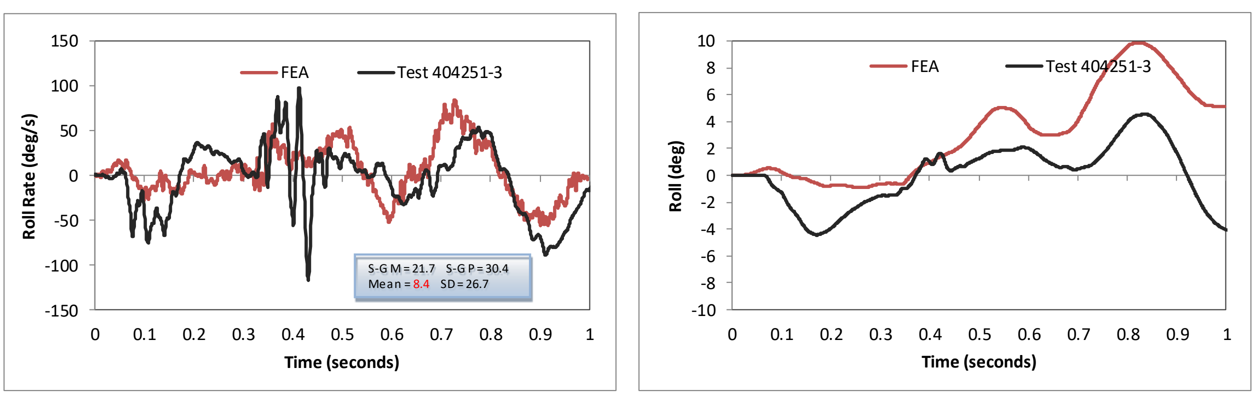


Figure 52. Roll-time history plot from accelerometer inside cabin for full-scale test 404251-3 and FEA (angular rate and displacement).

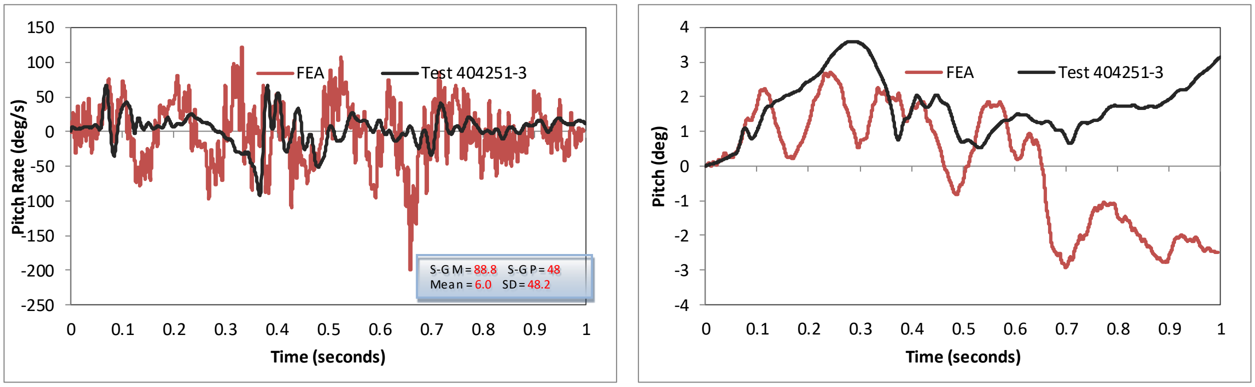


Figure 53. Pitch-time history plot from accelerometer inside cabin for full-scale test 404251-3 and FEA (angular rate and displacement).

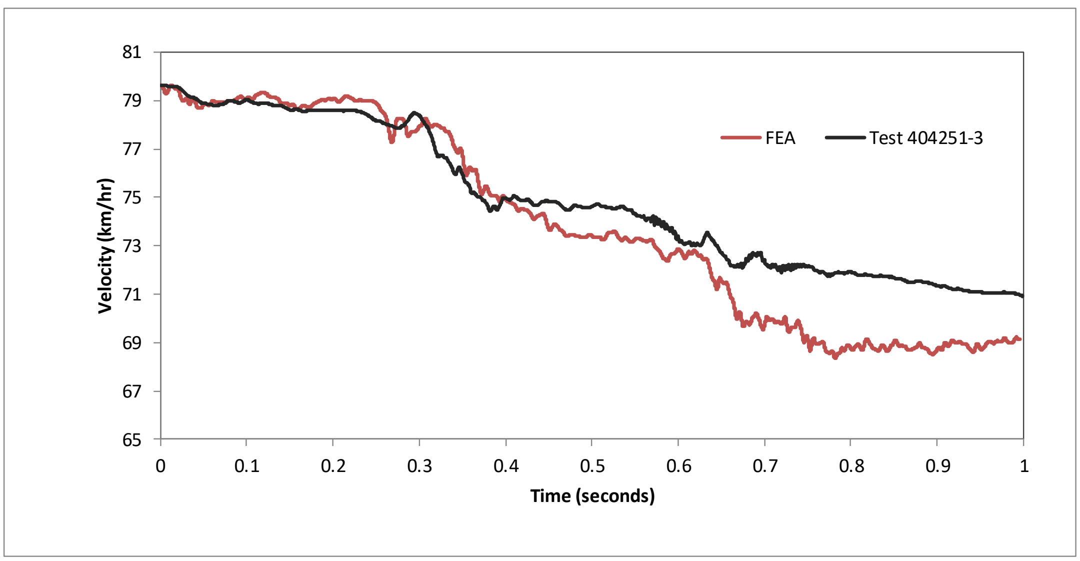


Figure 54. Velocity-time history plot from accelerometer at c.g. for full-scale test 404251-3 and FEA.

Quantitative Validation

The quantitative evaluation was based on comparison of acceleration-time histories and angular rate-time histories computed in the analysis to those measured in full-scale crash test 404251-3 using the procedures specified in Report W179. [*Ray10*] A summary of the quantitative comparison results are provided here. Additional comparison data can be found in Appendix C.

Solution Verification

Table 15 shows a summary of the global verification assessment based on criteria recommended in Report W179. Figure 55 shows a plot of the global energy-time histories from the analysis. All the solution verification parameters were satisfied. The concrete did not fail during the simulation of Test 404251-3 and the energies remained balanced throughout the impact event.

Table 15. 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.	3%	**Y**
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.	0.01%	**Y**
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.	0.06%	**Y**
The part/material with the highest amount of hourglass energy at the end of the run is less than twenty percent of the total internal energy of the part/material at the end of the run.	17%	**Y**
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	0%	**Y**
The part/material with the most mass added had less than 10 percent of its initial mass added.	5.7%	**Y**
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	0%	**Y**
There are no shooting nodes in the solution?	Y	**Y**
There are no solid elements with negative volumes?	Y	**Y**

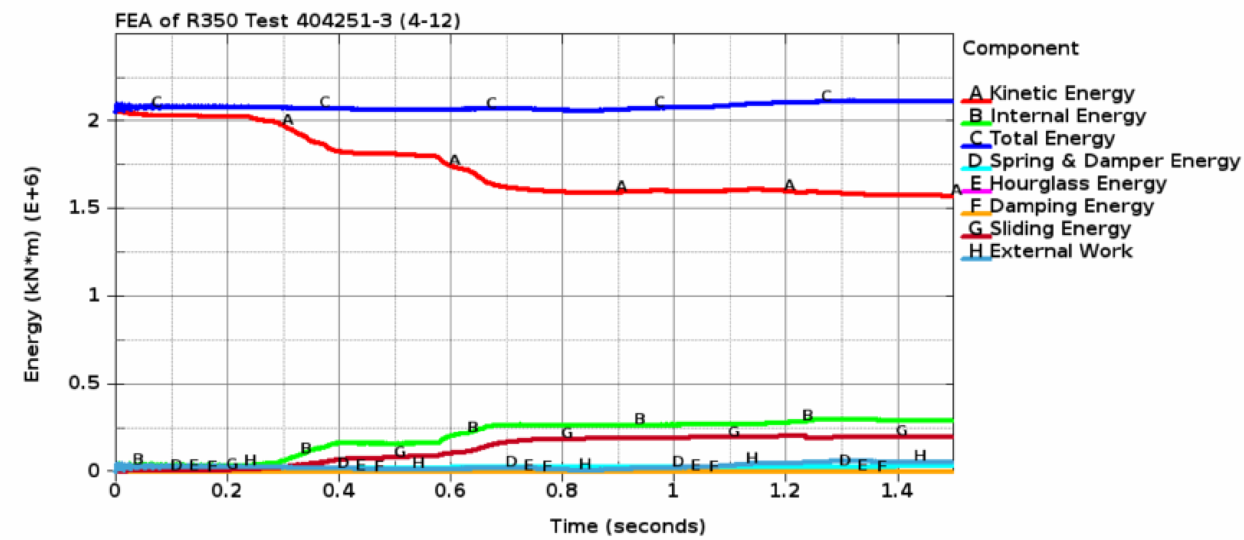


Figure 55. Plot of global energy-time histories from the analysis.

Time-History Validation

The data from the three acceleration channels located at the center of gravity of the vehicle and the angular rate data (i.e., roll, pitch and yaw) which was collected from inside the cabin were input into the RSVVP software to calculate quantitative differences between the FEA and test results. The data was filtered in RSVVP using a CFC Class 60 filter. The synchronization options in RSVVP were not used for the physical test data since both the test and analysis data started at the time of impact with the barrier. The default metrics evaluation options in RSVVP were used, which included the Sprague & Geers and the ANOVA metrics. The curves were evaluated over 1.0 seconds of the impact event, corresponding to the limits of the test data.

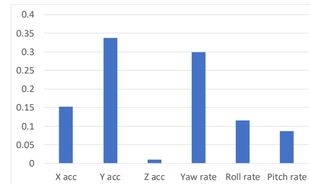
The results from RSVVP are shown in Table 16. Based on the validation metrics, a comparison of the individual components of acceleration indicated that the simulation was in good agreement for the y-acceleration, z-acceleration, and yaw-rate; while the roll-rate was in good agreement with respect to the Sprague-Geers metrics and in borderline agreement with respect to the ANOVA. The x-acceleration and pitch-rate showed relatively poor correlation. Since the metrics computed for the individual data channels did not all satisfy the acceptance criteria, the multi-channel option in RSVVP was used to calculate the weighted Sprague-Geer and ANOVA metrics for the six channels of data.

Table 17 shows the results from RSVVP for the multi-channel option. The resulting weights computed for each channel are shown in both tabular form and graphical form in the tables. The results indicate that the x- and y-acceleration and the yaw rate have significant influence over the kinematics of the impact event; while the roll- and pitch rate have notable influence. The z-acceleration did not have significant influence on the vehicle's impulse response. The weighted metrics computed in RSVVP in the multi-channel mode all satisfy the acceptance criteria; therefore, the time history comparison can be considered acceptable.

Table 16. Roadside safety validation metrics rating table – time history comparison (single-channel option).

	Evaluation Criteria							Time interval [0.00 – 1.0 sec]		
	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	none	none	none	none	none	85.8	42.9	N
	Y acceleration	CFC 60	none	none	none	none	none	15.8	33.7	Y
	Z acceleration	CFC 60	none	none	none	none	none	0.3	39.6	Y
	Yaw rate	CFC 60	none	none	none	none	none	27.9	16.2	Y
	Roll rate	CFC 60	none	none	none	none	none	21.7	30.4	Y
	Pitch rate	CFC 60	none	none	none	none	none	88.8	48	N
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							1.2	37.21	N
	Y acceleration/Peak							0.72	18.9	Y
	Z acceleration/Peak							2.6	27.0	Y
	Yaw rate							3.29	25.1	Y
	Roll rate							8.4	26.7	N
	Pitch rate							6.0	48.2	N

Table 17. Roadside safety validation metrics rating table – (multi-channel option).

Evaluation Criteria (time interval [0.0 – 1.0 seconds])			
Channels (Select which were used)			
☒ **X Acceleration**	☒ **Y Acceleration**	☒ **Z Acceleration**	
☒ **Roll rate**	☒ **Pitch rate**	☒ **Yaw rate**	
Multi-Channel Weights **- Area II method -**	**X Channel: 0.152** **Y Channel: 0.338** **Z Channel: 0.010** **Yaw Channel: 0.299** **Roll Channel: 0.115** **Pitch Channel: 0.086**		
Sprague-Geer Metrics Values less or equal to 40 are acceptable.	**M**	**P**	**Pass?**
	36.9	30.8	**Y**
ANOVA Metrics Both of the following criteria must be met: • The mean residual error must be less than five percent of the peak acceleration ($\bar{e} \le 0.05 \cdot a_{Peak}$) • 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?
	0.9	27.1	**Y**

PIRT – Crash Specific Phenomena

Table 18 contains the Report 350 crash test criteria. Those that apply to Test 4-12 are marked in red. These include criteria A, D, G, K and M. Tables 19 - 21 contain an expanded list of these same criteria including additional specific phenomena that were measured in the test and that could be directly compared to the numerical solution. Table 19 contains a comparison of phenomena related to structural adequacy, Table 20 contains a comparison of phenomena related to occupant risk, and Table 21 contains a comparison of phenomena related to vehicle trajectory. Some of this information has already been presented but is repeated here for convenience. Comparisons for all the applicable crash specific phenomena between the FEA and test were within the allowable limits of Report W179, except where noted.

Table 18. Report 350 crash test criteria with the applicable test numbers.

<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="4">Vehicle Trajectory</td><td>K</td><td>After collision it is preferable that the vehicle’s trajectory not intrude into adjacent traffic lanes.</td><td>All</td></tr>
<tr><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>

Table 19. Roadside safety phenomena importance ranking table (structural adequacy).

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Structural Adequacy	A	1	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)	Y	Y		Y
		2	Maximum permanent deflection: - Relative difference is less than 20 percent or - Absolute difference is less than 6 inches	0.4 in	1.02 in	155% 0.62 in	Y
		3	Length of vehicle-barrier contact (at initial separation): - Relative difference is less than 20 percent or - Absolute difference is less than 6.6 ft	28.2 ft	26.6 ft	5.8 % 1.6 ft	Y
		4	Number of broken or significantly bent posts is less than 20 percent.	0	0		Y
		5	Did the rail element rupture or tear (Answer Yes or No)	No	No		Y
		6	Concrete curb/deck failure	*No	No		Y
		7	Was there significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	N	N		Y
		8	Was there significant snagging between vehicle body components and barrier elements (Answer Yes or No).	N	N		Y

** Cracks at base of post*

Table 20. 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)	N	N		Y
	F	1	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable. (Answer Yes or No)	Y	Y		Y
		2	Maximum roll of the vehicle through 1.0 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	4.6 deg	9.9 deg	115 % 5.3 deg	Y
		3	Maximum pitch of the vehicle through 1.0 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	3.6 deg	2.7 deg	25 % 0.9 deg	Y
		4	Maximum yaw of the vehicle through 0.446 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	12.8 deg	18.5 deg	44 % 5.7 deg	N
	G	1	Did the vehicle remain upright during and after collision	Y	Y		Y
	L	1	Occupant impact velocities: - Relative difference is less than 20 percent or - Absolute difference is less than 6.6 ft/s.				
			• Longitudinal OIV (ft/s)	4.3	5.6	31% 1.3 ft/s	Y
			• Lateral OIV (ft/s)	8.5	10.8	27 % 2.3 ft/s	Y
			• THIV (ft/s)	9.5	12.5	31% 3 ft/s	Y
		2	Occupant accelerations: - Relative difference is less than 20 percent or - Absolute difference is less than 4 g's.				
			• Longitudinal ORA	-1.8	-3.8	111 % 2 g	Y
			• Lateral ORA	-9.6	-5.9	38.5 % 3.7 g	Y
			• PHD	9.7	5.9	39.2 % 3.8 g	Y
			• ASI	0.52	0.35	32.7 % 0.2	Y

* *The maximum yaw of the vehicle model occurred while the bed of the truck was still engaged with the barrier. The yaw angle matched much closer to the test by the time the vehicle exited the system (see following table). This error is not considered to be critical for model accuracy.*

Table 21. Roadside safety phenomena importance ranking table (vehicle trajectory).

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Vehicle Trajectory	K	1	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.	*33% cargo box	*16.8% cargo box		Y
		2	Exit angle at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	*5.0 deg cargo box	*2.5 deg cargo box	50% 2.5 deg	Y
	M	3	Exit velocity at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 6.2 mph.	*44.1 mph	*43.0 mph	1.0 % 1.1 mph	Y

** When the front of vehicle passes end of barrier*

Results Summary

The baseline finite element model of the S3-TL4 bridge rail was used to simulate two full-scale crash tests on the bridge rail. The tests corresponded to R350 Test 4-12 on the curb-mounted and sidewalk-mounted bridge rail systems. The results of the analysis were compared to the full-scale tests to validate the fidelity of the model. The validation included both qualitative and quantitative elements. Qualitative assessments included comparing sequential snapshots of the test and simulation to verify vehicle kinematic response, as well as, the sequence and timing of key phenomenological events. The quantitative assessment was performed according to the procedures specified in NCHRP Web Report 179. These procedures included: (1) verifying that the analysis solution was stable and obeying basic laws of physics, (2) point-by-point comparison of the acceleration and angular-rate time-history data form the FEA and test (collected from accelerometers and rate gyros placed on-board the vehicle) using the RSVVP software, and (3) comparison of crash-specific phenomena from the event related to structural adequacy, occupant risk and vehicle trajectory.

In general, the results of the analyses demonstrated that the finite element model replicated the basic phenomenological behavior of the system for both cases under Report 350 Test 4-12 impact conditions. There was good agreement between the tests and the simulations with respect to event timing, overall kinematics of the vehicle, barrier damage, and deflections. Quantitative comparison of the time-history data indicated that the finite element model sufficiently replicated the results of the baseline crash tests. Thus, the model is considered valid for use in assessing the effects of incremental modifications to the bridge rail system. Table 22 provides a summary of key validation metrics for the evaluation of the model for the curb-mounted system, and Table 23 provides a summary of key validation metrics for the evaluation of the model for the sidewalk-mounted system.

Table 22. Summary of validation metrics for the model in simulation of Test 404251-6 (SUT test).

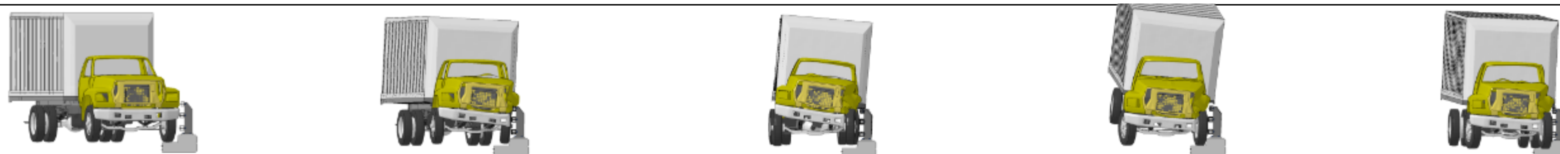
Summary of FEA vs. Test Validation Metrics

System Type:	Bridge Rail	Comparison:	Crash tested original design to FEA of original design	
Device Name:/Variant:	MassDOT S3-TL4 Curb-Mounted	Submissions Type:		Non-Significant -- Effect is Uncertain
Testing Criterion:	Report 350			Non-Significant -- Effect is Positive
Test Level:	TL4			Non-Significant -- Effect is Inconsequential
FHWA Letter:			X	Baseline Validation of Crash Test to FEA Analysis.

Crash Test

Time = 0.0 sec | 0.17 sec | 0.3 sec | 0.62 sec | 0.89sec

FEA Analysis



Baseline Crash Test		
Test Number:	TTI 404251-6	
Vehicle:	1987 GMC 7000 SUT	
Vehicle Mass:	17,636 lbs	
Impact Speed:	49.2 mph	
Impact Location:	4.9 ft upstream of Post 5	
Tested Hardware:	Original Design	
FEA Hardware:	Original Design	
W-179 Table E-1: Verification Evaluation Summary		
Total Energy:	12%	Pass
Hourglass Energy:	0%	Pass
Mass Added:	0%	Pass
Shooting Nodes:	no	Pass
Negative Volumes:	no	Pass

W-179 Table E-5: Roadside PIRTS

Structural Adequacy	**Test**	**FEA**	**Occupant Risk (cont.)**	**Test**	**FEA**
A1 - Acceptable perf.?	yes	yes	H2 – Long. OIV	5.6 ft/s	5.3 ft/s
A2 – Permanent Deflection:	0.18 in	1.65 in	H3 – Lat. OIV	11.2 ft/s	11.8 ft/s
A3 – Contact Length	15.1 ft	16.4 ft	I2 – Long. ORA	2.3 g	4.4 g
A4 - Component Failure	no	no	I3 – Lat. ORA	7.6 g	7.3 g
A5 – Barrier Rupture?	no	no	**Vehicle Trajectory**		
A7 – Wheel Snagging?	no	no	K – Intruded into travel lanes?	no	no
A8 – Vehicle Snagging?	no	no	N – Travel behind barrier?	no	no
Occupant Risk	**Test**	**FEA**	**W-179 Table E-3 (Multi-Channel Method)**		
D – Detached elements?	no	no	Sprague-Geer Magnitude < 40	33.6	Pass
F2 – Max. Vehicle Roll	8.3	8.3	Sprague-Geer Phase < 40	35.4	Pass
F3 – Max. Vehicle Pitch	6.4	-6	ANOVA Mean	1%	Pass
F4 – Max. Vehicle Yaw	16.4	15.7	ANOVA Standard Deviation	29.3	Pass

Table 23. Summary of validation metrics for the model in simulation of Test 404251-3 (SUT test).

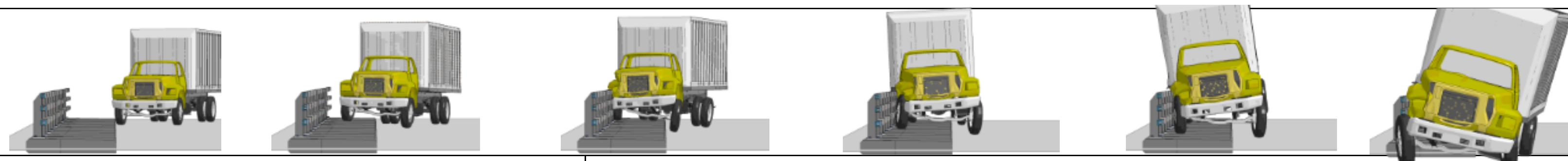
Summary of FEA vs. Test Validation Metrics

System Type:	Bridge Rail	Comparison:	Crash tested original design to FEA of original design	
Device Name:/Variant:	MADOT S3-TL4 Sidewalk-Mounted	Submissions Type:		Non-Significant -- Effect is Uncertain
Testing Criterion:	Report 350			Non-Significant -- Effect is Positive
Test Level:	TL4			Non-Significant -- Effect is Inconsequential
FHWA Letter:			X	Baseline Validation of Crash Test to FEA Analysis.

Crash Test

Time = 0.0 sec | 0.2 sec | 0.4 sec | 0.6 sec | 0.9 sec | 1.5 sec

FEA Analysis



Baseline Crash Test	
Test Number:	TTI 404251-3
Vehicle:	1979 Chevrolet C70 SUT
Vehicle Mass:	17,636 lbs
Impact Speed:	49.5 mph
Impact Location:	3.74 ft upstream of Post 5
Tested Hardware:	Original Design
FEA Hardware:	Original Design

W-179 Table E-1: Verification Evaluation Summary		
Total Energy:	3%	Pass
Hourglass Energy:	0%	Pass
Mass Added:	0%	Pass
Shooting Nodes:	no	Pass
Negative Volumes:	no	Pass

W-179 Table E-5: Roadside PIRTS

Structural Adequacy	**Test**	**FEA**	**Occupant Risk (cont.)**	**Test**	**FEA**
A1 - Acceptable perf.?	yes	yes	H2 – Long. OIV	4.3 ft/s	5.6 ft/s
A2 – Permanent Deflection:	0.4 in	1.02 in	H3 – Lat. OIV	8.5 ft/s	10.8 ft/s
A3 – Contact Length	28.2 ft	26.6 ft	I2 – Long. ORA	1.8 g	3.8 g
A4 - Component Failure	no	no	I3 – Lat. ORA	9.6 g	5.9 g
A5 – Barrier Rupture?	no	no	**Vehicle Trajectory**		
A7 – Wheel Snagging?	no	no	K – Intruded into travel lanes?	no	no
A8 – Vehicle Snagging?	no	no	N – Travel behind barrier?	no	no
Occupant Risk	**Test**	**FEA**	**W-179 Table E-3 (Multi-Channel Method)**		
D – Detached elements?	no	no	Sprague-Geer Magnitude < 40	36.9	Pass
F2 – Max. Vehicle Roll	4.6	9.9	Sprague-Geer Phase < 40	30.8	Pass
F3 – Max. Vehicle Pitch	3.6	2.7	ANOVA Mean	1%	Pass
F4 – Max. Vehicle Yaw	12.8	18.5	ANOVA Standard Deviation	27.1	Pass

CHAPTER 7 – EVALUATION OF THE S3-TL4 UNDER *MASH* TL4 CONDITIONS

FEA was used to evaluate the crash performance of the S3-TL4 bridge rail based on structural adequacy, vehicle stability during and after redirection, and occupant risk factors using criteria specified in *MASH* for Test Level 4. Three impact conditions were evaluated:

- Simulation of Test 4-10 included the 1100C Yaris model ballasted to 2,595 lb (1177 kg) impacting the barrier at 62.2 mph and 25 degrees. The critical impact point was selected as 3.6 feet (1.1 m) upstream of a bridge rail post.
- Simulation of Test 4-11 included the 2270P Chevrolet Silverado model ballasted to 5,001lb (2,269 kg) impacting the railing at 62.2 mph and 25 degrees. The critical impact point was selected as 4.3 feet (1.3 m) upstream of a bridge rail post.
- Simulation of Test 4-12 included the 10000S model ballasted to 22,198 lb (10,068 kg) impacting at 56 mph and 15 degrees. The impact point was set to 5.0 feet (1.52 m) upstream of a bridge rail post.

The following sections of this report present the results of the analyses for the bridge rail system. The analysis in all cases was performed using LS-DYNA version mpp_s_R9.1.0 revision number 113698. The analysis was conducted with a time-step of 1.0 microsecond for a time period of 1.0 second for Tests 4-10 and 4-11, and for a time period of 1.5 seconds for Test 4-12.

Test 4-10

The critical impact condition for Test 4-10 was selected based the *MASH* recommended CIP for rigid barrier tests (see Table 2-7 of *MASH*). [*AASHTO16*] The target impact point was 3.6 feet upstream of a bridge rail post which was consistent with the recommended CIP in *MASH* (refer to Figure 56 which includes reproductions of *MASH* Table 2-7 and Figure 2-1) and was selected to maximize potential for snagging at the post. [*AASHTO16*] The following sections provide a summary of the results and include a commentary describing the timing and occurrence of various events during the simulated impact, time-history data evaluation, occupant risk assessments, and damages sustained by both the barrier and vehicle.

TABLE 2-7. Critical Impact Point for Rigid Barrier Tests with 1100C and 2270P Vehicles

Test Designation[a]	*x* Distance,[b] ft (m)
1-10, 2-10	3.3 (1.0)
3-10, 4-10, 5-10, 6-10	3.6 (1.1)
1-11, 2-11	2.6 (0.8)
3-11, 4-11, 5-11, 6-11	4.3 (1.3)

a See Table 2-2A for test details.
b See Figure 2-1 for illustration of x distance.

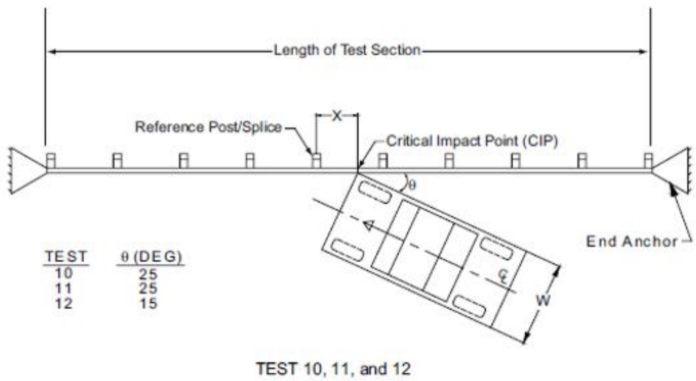


Figure 56. Table 2-7 and Figure 2-1 from *MASH* showing critical impact point for longitudinal barriers regarding passenger vehicles tests. [*AASHTO16*]

Summary of Key Phenomenological Events

Curb-Mounted

The 2,595-lb car model struck the barrier at a speed of 62 mph and at an angle of 25 degrees per *MASH* Test 4-10 specifications, as illustrated in Figure 57. The sequential views of the impact event are shown in Appendix F in Figures F-1 through F-3 from an overhead viewpoint, downstream and upstream viewpoint, and oblique viewpoint, respectively. At time equal to 0.005 seconds the front bumper of the car contacted the lower railing at 3.6 feet upstream from Post 5. Before 0.01 seconds, the front-right tire struck the curb and the front-right fender contacted the middle railing. At 0.015 seconds the front-right tire began to steer slightly away from the barrier. At 0.019 seconds the front impact-side tire continued to steer away from the barrier and sustained damage to the wheel rim, and the front impact-side fender of the vehicle was significantly crushed. At 0.025 seconds the impact-side front wheel was parallel to the barrier. At 0.035 seconds the front impact-side corner of the vehicle was passing Post 5 and the post began to deflect back. At 0.045 seconds the hood of the vehicle passed between the middle and top rail and contacted the post but did not result in any significant damage to the hood's hinges; also, at this time the rear section of the fender and the lower front corner of the A-pillar contacted the top rail. At 0.055 seconds the barrier reached a maximum dynamic deflection of 0.87 inches on the top rail at the splice connection upstream of Post 5. At 0.0741 seconds the lower front corner of the A-pillar was still engaged with the top railing and was at Post 5; the Occupant impact velocity occurred at this time on the right side of the interior at 23.6 ft/s in the longitudinal direction and 30.8 ft/s in the lateral direction. At 0.135 seconds the front of the vehicle lost contact with the barrier. At 0.16 seconds the rear of the vehicle contacted the middle rail and the rear-right tire contacted the curb. At 0.17 seconds the rear tire was noticeably deformed, and the top of the tire contacted the lower railing, and the rear of the vehicle began to pitch upward slightly. At 0.18 seconds the rear fender of the vehicle contacted the top railing at Post 5. At 0.1912 seconds maximum lateral ORA occurred with magnitude 13.5 G. At 0.245 seconds the vehicle separated from the barrier at an exit speed and angle of 43.9 mph and 8.8 degrees. At approximately 0.315 seconds, the maximum ORA in the longitudinal direction occurred at 4.7 G. At 0.332 seconds the vehicle reached a maximum roll angle of 7.5 degrees (toward barrier). At 0.34 seconds the vehicle reached a maximum pitch of 6.6 degrees (rear pitching upward). The vehicle remained stable throughout post-impact trajectory. The analysis ended at 1.0 seconds, at which time:

- The roll, pitch, and yaw of the vehicle were, respectively, 2.16 degrees (away from barrier), 3.5 degrees (rear pitching up), and 14.1 degrees (10.9 degrees relative to and toward barrier).
- The forward velocity of the vehicle was 40.6 mph (65.3 km/h).

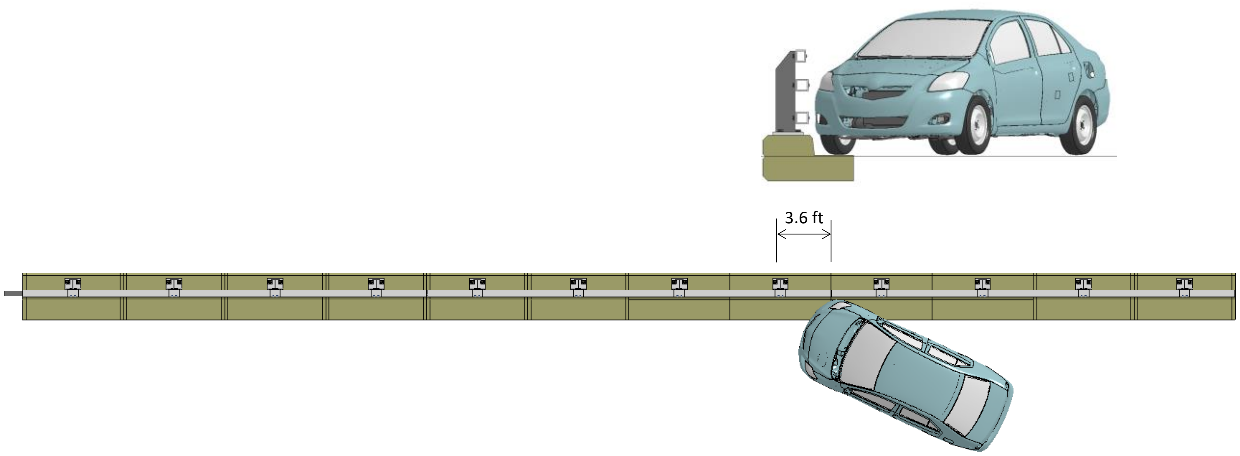


Figure 57. Impact point for Test 4-10 on the curb-mounted S3-TL4.

Sidewalk-Mounted

The results for this case, which involves the small car impacting and mounting the 8-inch tall sidewalk, resulted in higher than expected vertical trajectory of the vehicle. It is assumed that the increased trajectory is caused by the tire model, which does not allow for deflection and does not include any detail of the tire structure. This resulted in excessive rebound of the tire after compression and impact at a higher point of the barrier than expected. Although the research team is aware of this issue, the following commentary provides the results just as they were provided from the analysis, with the assumption that they are likely a worse-case event given the higher impact point on the barrier.

The 2,595-lb car model struck the sidewalk at a speed of 62 mph and at an angle of 25 degrees per *MASH* Test 4-10 specifications. The initial starting point for the vehicle was approximately 14.3 ft upstream of the target critical post at Post 5, as illustrated in Figure 58. The sequential views of the impact event are shown in Appendix G in Figures G-1 through G-3 from an overhead viewpoint, downstream and upstream viewpoint, and isometric viewpoint, respectively. At 0.005 seconds, the front-right tire compressed at the point of contact with the curb, and at 0.01 seconds the wheel rim was noticeably deformed from the impact. At 0.03 seconds the tire had fully mounted the sidewalk and the vehicle began to roll away from the barrier. The tire was, at this time, compressed fully flat. The ability of the tire to deflate was not incorporated into the model; therefore, the tire immediately began to rebound from the top of the sidewalk and lift the front of the vehicle. The rear-right tire began to lift off the ground at 0.06 seconds. At 0.065 seconds the front-right tire rebounded off the sidewalk. At 0.095 seconds, the rear-right tire contacted the curb and was fully mounted onto the sidewalk at 0.115 seconds. Also, at this time, the front-left tire impacted against the curb face of the sidewalk. At 0.125, the front-left rim was significantly deformed at the point of contact with the curb; also, at this time, the rear-right tire rebounded off the sidewalk. At 0.14 seconds the lower edge of the front bumper contacted the lower railing of the barrier. At 0.145 seconds the upper part of the bumper contacted the middle railing at 3 ft upstream of Post 5 traveling at 59.7 mph and 25 degrees; also, at this time the front-left tire was fully mounted on the sidewalk. At 0.16 seconds the hood of the car contacted the lower edge of the top rail, and at 0.165 seconds Post 5 began to deflect. At 0.175 seconds the vehicle's right fender was fully engaged with the top railing and the front-right tire was steered parallel to the barrier; also, at this time the rear-left tire began to lift of the roadway. At 0.18 seconds the faring on the front bumper contacted Post 5 but did not result in any noticeable snag potential; also, at this time the vehicle reached maximum longitudinal and lateral accelerations of 14.2 g and 24.9g, respectively. At 0.1925 seconds the occupant contacted the right-side interior of the vehicle with OIV's in the longitudinal and lateral directions of 30.18 ft/s and 32.48 ft/s, respectively. At 0.2 seconds the occupant contacted the right-side interior of the vehicle with OIV's in the longitudinal and lateral directions of 20 ft/s and 29.9 ft/s, respectively; also, at this time the vehicle reached its maximum roll angle of 11 degrees away from the barrier, and the barrier reached the maximum dynamic deflection of 1.22 inches at Post 5. At 0.22 seconds the vehicle reached a peak pitch angle of 5.5 degrees (front pitching upward). At 0.355 seconds the maximum ORA in the lateral direction occurred with magnitude 13.1 G. At 0.255 seconds the front of the car lost contact with the barrier as the rear of the vehicle continued to yaw toward the barrier. At 0.3 seconds the vehicle was parallel to the barrier. At 0.31 seconds the rear-left tire began to pass over the sidewalk curb with minimal or no contact. At 0.325 seconds the rear fender of the car contacted the middle rail just downstream of Post 5. At 0.335 seconds the rear-right tire contacted the lower railing and began to compress both into the rail and down toward the sidewalk. At 0.35 seconds the tire was compressed almost flat and began to rebound. At 0.345 seconds the rear of the car contacted the upper railing. At 0.4 seconds the vehicle lost contact with the barrier traveling at 44.7 mph with an exit angle of 10.75 degrees (43 percent of the impact angle). At 0.465 seconds the front-right tire recontacted the sidewalk. At 0.54 seconds the vehicle reached maximum roll angle of 15.4 degrees toward the barrier. At 0.81 seconds the vehicle reached maximum pitch angle of 7.1 degrees (rear pitching upward). The vehicle remained stable throughout post-impact trajectory. The analysis ended at 1.0 seconds, at which time:

- The roll, pitch, and yaw of the vehicle were, respectively, 0.81 degrees, 0.47 degrees, and 44 degrees (24.6 degrees relative to and away from barrier).
- The forward velocity of the vehicle was 41.7 mph (67.1 km/h).

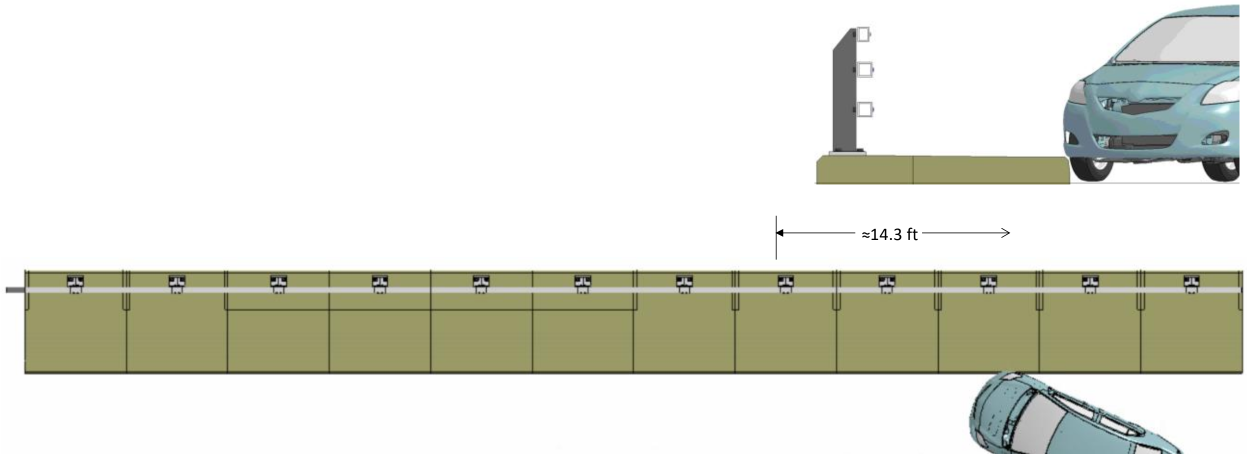


Figure 58. Initial starting position for Test 4-10 on the sidewalk-mounted S3-TL4.

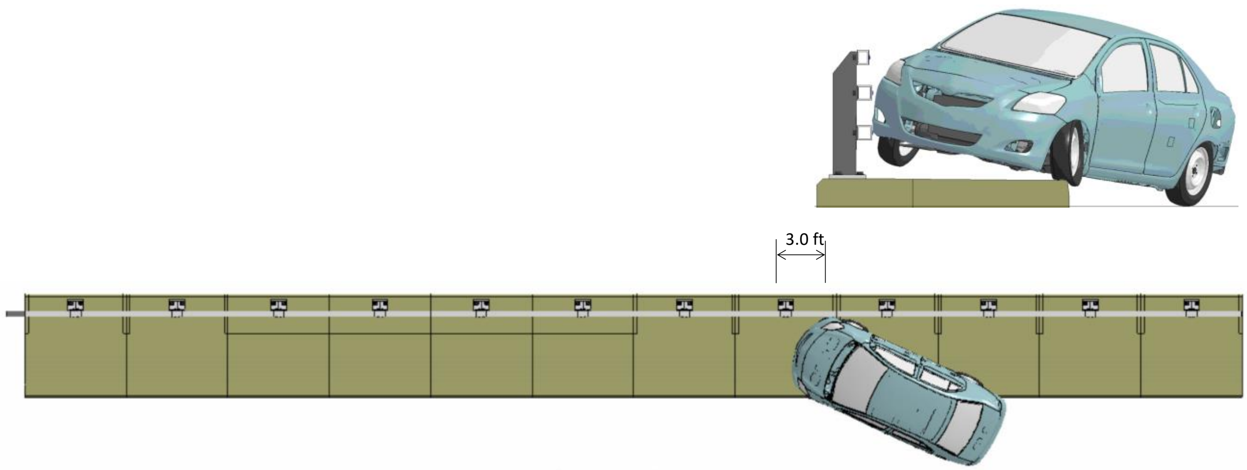


Figure 59. Impact point with bridge rail for Test 4-10 on the sidewalk-mounted S3-TL4.

Time History Data Evaluation

Figures 60 through 62 show the longitudinal, transverse, and vertical acceleration-time histories, respectively, computed from the center of gravity of the vehicle; Figures 63 through 65 show the comparison of the angular rates and angular displacements (i.e., roll, pitch and yaw) at the center of gravity of the vehicle.

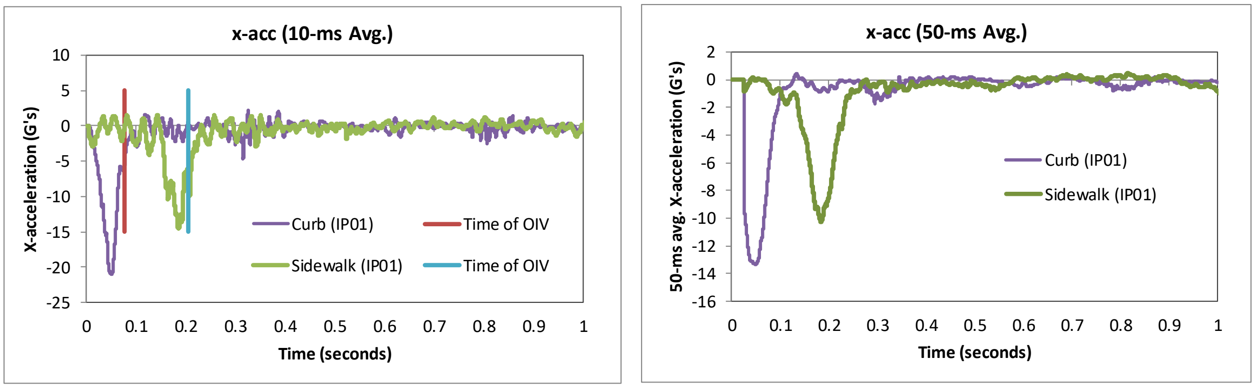


Figure 60. 10- and 50-millisecond average X-acceleration from FEA of Test 4-10 on the curb-mounted and sidewalk-mounted bridge rail.

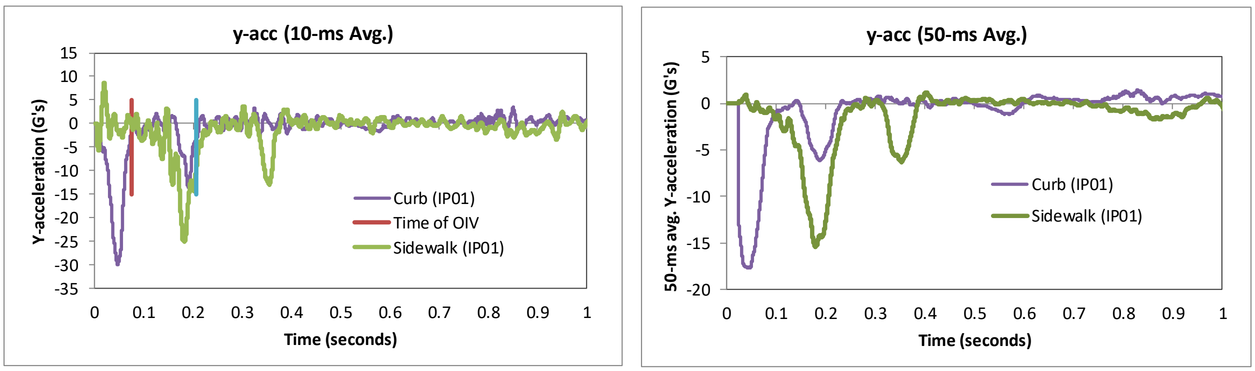


Figure 61. 10- and 50-millisecond average Y-acceleration from FEA of Test 4-10 on the curb-mounted and sidewalk-mounted bridge rail.

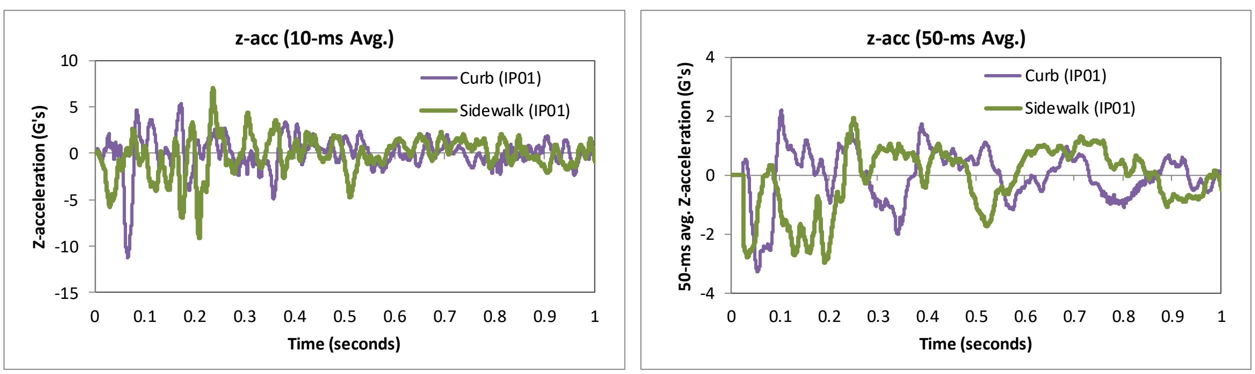


Figure 62. 10- and 50-millisecond average Z-acceleration from FEA of Test 4-10 on the curb-mounted and sidewalk-mounted bridge rail.

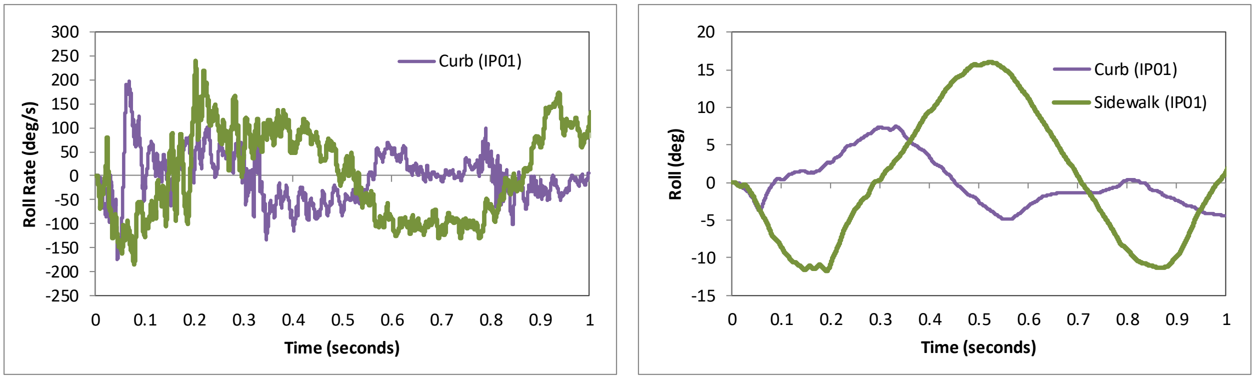


Figure 63. Roll rate and roll angle time-history from FEA of Test 4-10 on the curb-mounted and sidewalk-mounted bridge rail.

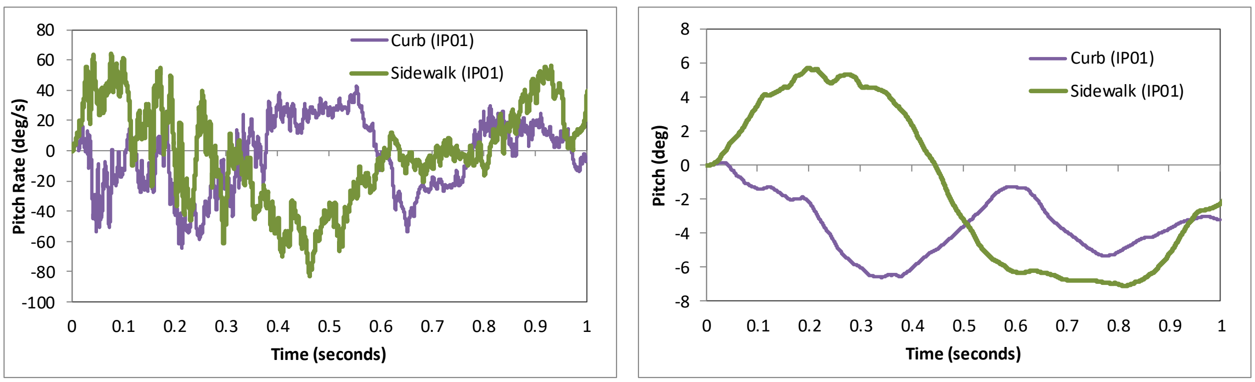


Figure 64. Pitch rate and pitch angle time-history from FEA of Test 4-10 on the curb-mounted and sidewalk-mounted bridge rail.

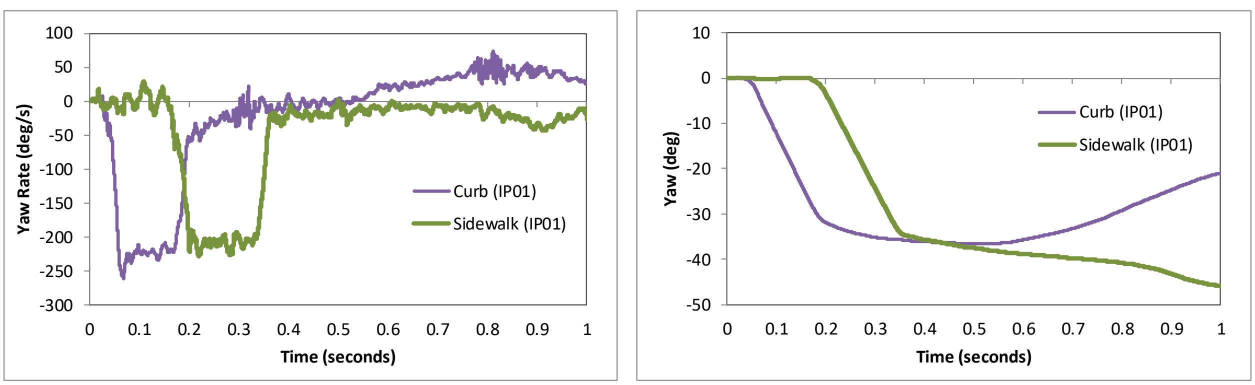


Figure 65. Yaw rate and yaw angle time-history from FEA of Test 4-10 on the curb-mounted and sidewalk-mounted bridge rail.

Occupant Risk Measures

The acceleration-time histories and angular rate-time histories collected at the center of gravity of the vehicle were used to evaluate occupant risk metrics according to the procedures outlined in *MASH*. Table 24 shows the results for the occupant risk calculations. The results indicate that the occupant risk factors meet safety criteria specified in *MASH*.

Curb-Mounted System

The occupant impact velocities in the longitudinal and transverse directions for the curb-mounted system were 23.6 ft/s and 30.8 ft/s, respectively, which were within the critical limits specified in *MASH*. The highest 0.010-second occupant ridedown acceleration in the longitudinal and transverse directions were 4.7 g and 13.5 g, respectively, which were within preferred limits specified in *MASH*. The maximum 50-ms moving average acceleration values in the longitudinal and transverse directions were 13.4 g and 17.7 g, respectively. The maximum roll and pitch angles of the vehicle were 7.5 degrees and 6.6 degrees, respectively, which were well below critical limits in *MASH*.

Sidewalk-Mounted System

The occupant impact velocities in the longitudinal and transverse directions for the sidewalk-mounted system were 20.0 ft/s and 29.9 ft/s, respectively, which were within the preferred limits specified in *MASH*. The highest 0.010-second occupant ridedown acceleration in the longitudinal and transverse directions were 5.9 g and 13.1 g, respectively, which were within preferred limits specified in *MASH*. The maximum 50-ms moving average acceleration values in the longitudinal and transverse directions were 10.3 g and 15.4 g, respectively. The maximum roll and pitch angles of the vehicle were 16.1 degrees and 7.1 degrees, respectively, which were well below critical limits in *MASH*.

Table 24. Summary of *MASH* occupant risk metrics for Test 4-10 on the S3-TL4 Bridge Rail.

Occupant Risk Factors		MASH T4-10	
		Curb (IP01)	Sidewalk (IP01)
Occupant Impact Velocity (ft/s)	x-direction	23.6	20.0
	y-direction	30.8	29.9
	at time	at 0.0741 seconds on right side of interior	at 0.2039 seconds on right side of interior
THIV (ft/s)		38.4 at 0.0741 seconds on right side of interior	35.4 at 0.2039 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-4.7 (0.3103 - 0.3203 seconds)	-5.9 (0.2055 - 0.2155 seconds)
	y-direction	-13.5 (0.1862 - 0.1962 seconds)	-13.1 (0.3502 - 0.3602 seconds)
PHD (g's)		13.6 (0.1864 - 0.1964 seconds)	13.1 (0.3502 - 0.3602 seconds)
ASI		2.27 (0.0242 - 0.0742 seconds)	1.91 (0.1574 - 0.2074 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-13.4 (0.0236 - 0.0736 seconds)	-10.3 (0.1590 - 0.2090 seconds)
	y-direction	-17.7 (0.0198 - 0.0698 seconds)	-15.4 (0.1548 - 0.2048 seconds)
	z-direction	-3.3 (0.0288 - 0.0788 seconds)	-3.1 (1.0310 - 1.0810 seconds)
Maximum Angular Disp. (deg)	Roll	7.5 (0.3320 seconds)	16.1 (0.5228 seconds)
	Pitch	-6.6 (0.3416 seconds)	-7.1 (0.8127 seconds)
	Yaw	-36.5 (0.5290 seconds)	-46.3 (1.0492 seconds)

MASH Criteria

Occupant Impact Velocity: > 30 ft/s (preferred); < 40 ft/s (limit) ✓

Ridedown Acceleration: < 15 G (preferred) ✓; < 20.49 G (limit)

Roll and Pitch: < 75 deg ✓

Occupant Compartment Intrusion

Curb-Mounted

The maximum deformation of the occupant compartment for impact on the curb-mounted bridge rail was 2.8 inches at the lower right-front corner of the wheel well. Figure 66 shows a view of the vehicle interior after the impact, with several components removed to facilitate viewing. The maximum deformation was less than the critical limit of 9 inches specified in *MASH* for this area of the occupant compartment.

Sidewalk-Mounted

The maximum deformation of the occupant compartment for impact on the sidewalk-mounted bridge rail was 2.0 inches at the lower right-front corner of the wheel well, which was also well below the critical limit of 9 inches.

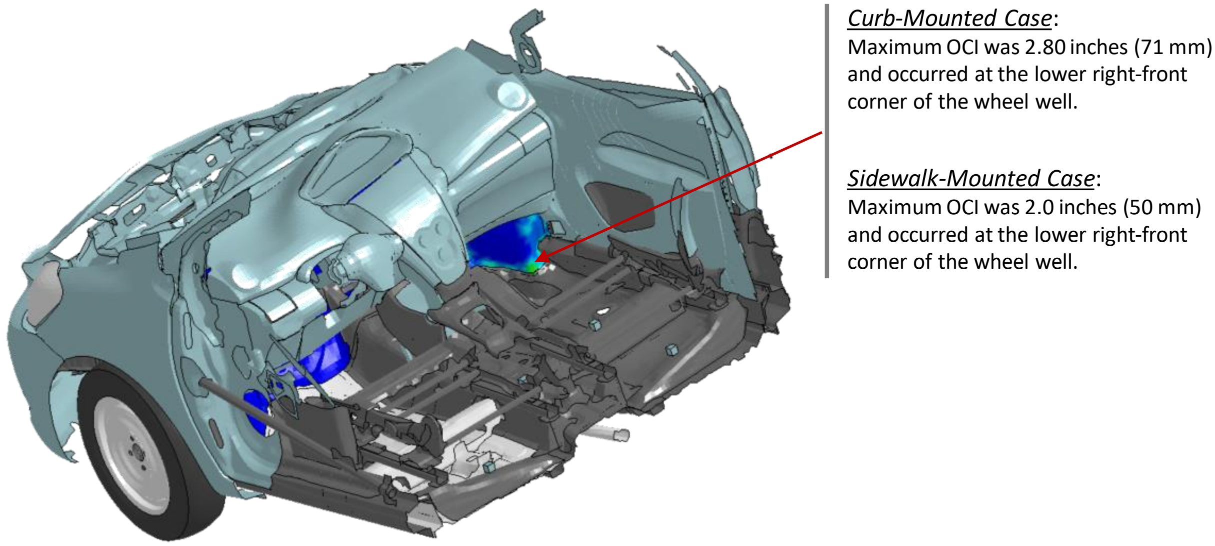


Figure 66. Occupant compartment deformation resulting from Test 4-10 on both bridge rail systems.

Damages to the Barrier System

The damages to the barrier were minimal. Figure 67 shows images of the barrier at the time of maximum dynamic deflection with a contour plot of lateral displacement on the rail elements. The dynamic deflection for the curb-mounted system was 0.83 inches and occurred on the top rail at the splice connection. The maximum dynamic deflection for the sidewalk-mounted system was 1.22 inches and occurred on the top rail at the critical post. Figure 68 shows contour plots of the maximum permanent deflection for both barrier tests. The maximum permanent deflection for the curb-mounted and sidewalk-mounted systems was 0.47 inches and 0.72 inches, respectively. The plastic deformation of the posts was minimal as well, as illustrated in Figure 69.

The deformation was slightly higher for the sidewalk-mounted case due to the vertical trajectory of the car after crossing the curb. The magnitude of the trajectory may have been over-estimated in the model as a result of the simplified tire model which appears to be somewhat stiffer than actual tires and does not include the ability to debead, deflate or rupture.

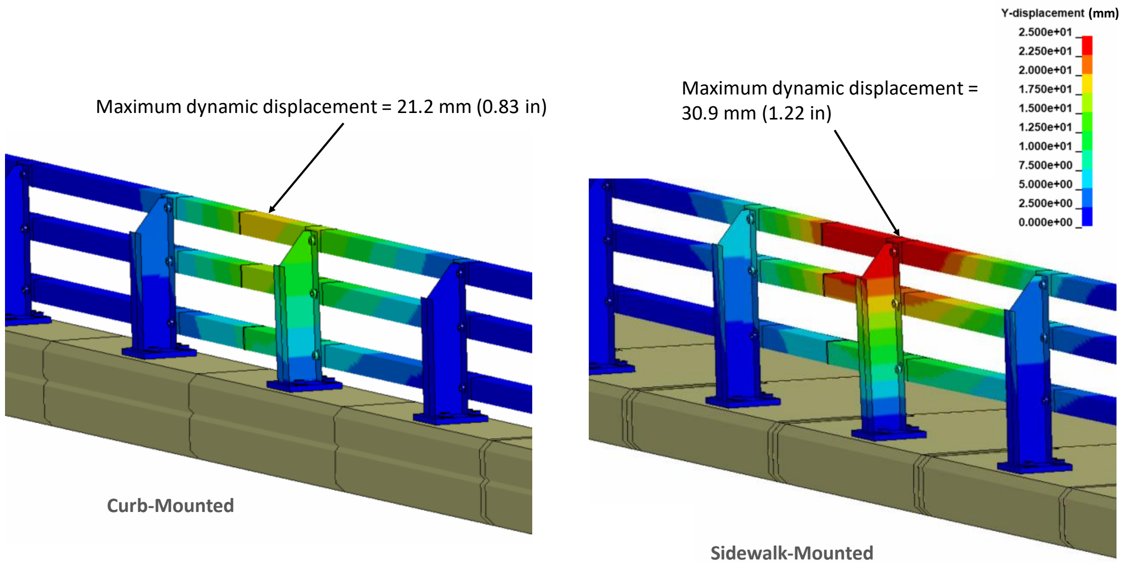


Figure 67. Contour plot of lateral displacement for the bridge rail from Test 4-10 at the time of maximum dynamic deflection for the curb-mounted and sidewalk-mounted systems.

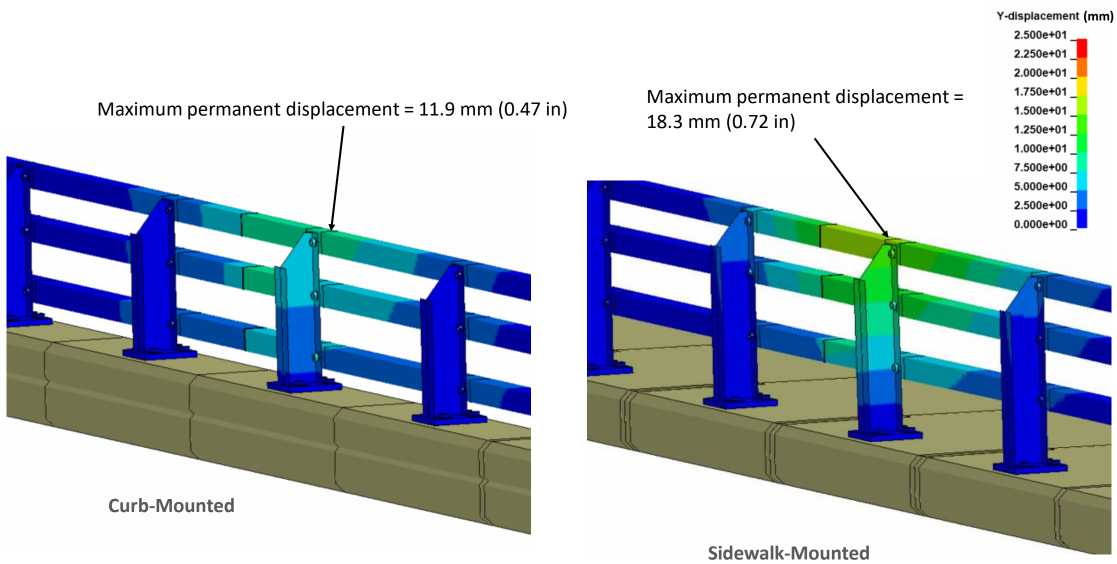


Figure 68. Contour plot of maximum permanent deflection for the bridge rail from Test 4-10 for the curb-mounted and sidewalk-mounted systems.

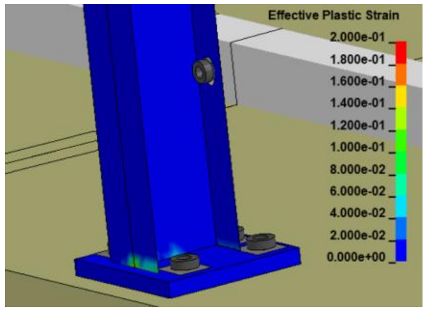


Figure 69. Contours of effective plastic strains on the critical post for Test 4-10 on the sidewalk-mounted system.

Damages to Vehicle

Figure 70 show contour plots of effective plastic strain for the vehicle, which were used to identify areas of the vehicle that suffered damage during the simulated impact event. The most severe damages were to the front bumper, the front fender, the front impact-side suspension, the rear portion of the vehicle body on the impact side, and both front and rear impact-side wheels.

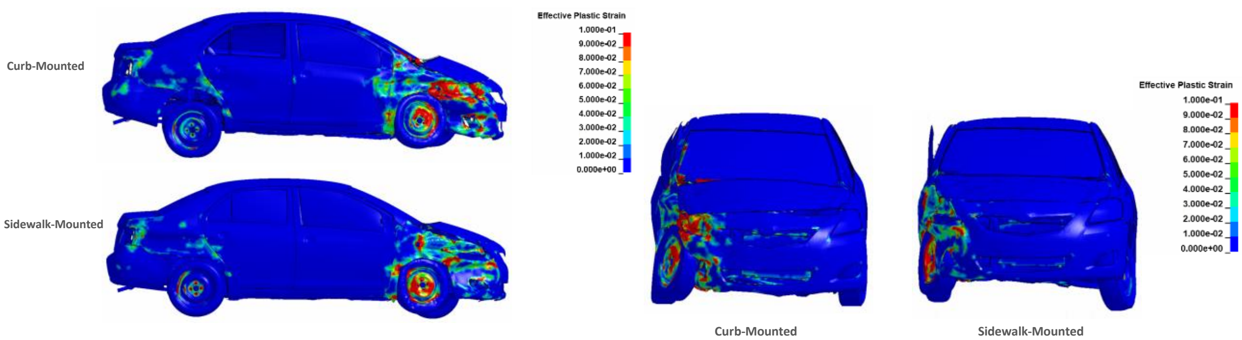


Figure 70. Damages to vehicle in Test 4-10 analysis of curb-mounted and sidewalk-mounted bridge rail (right side and front views).

Exit Box

Figures 71 and 72 show the exit box for Test 4-10 on the curb-mounted and sidewalk-mounted bridge rail systems, respectively. Although the exit box analysis is not required in *MASH*, it was included here for completeness. The vehicle was smoothly redirected and its path was well within the exit box criteria of *MASH*.

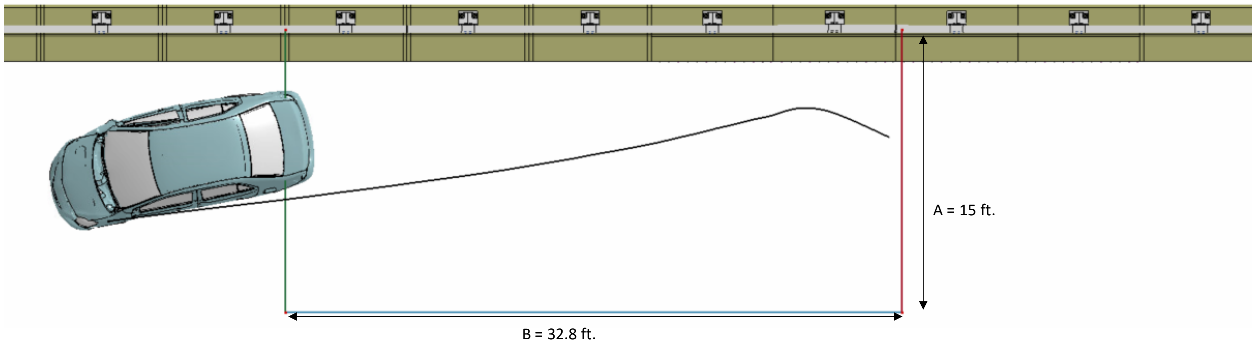


Figure 71. Exit box for Test 4-10 for curb-mounted.

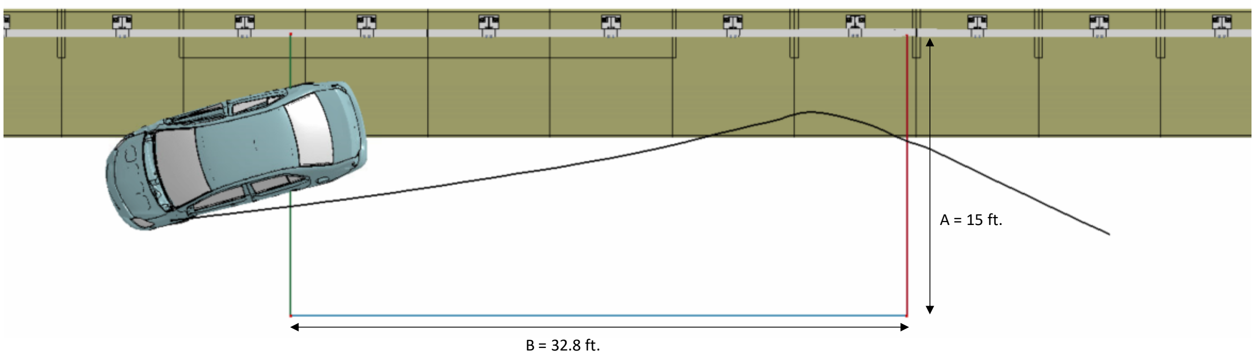


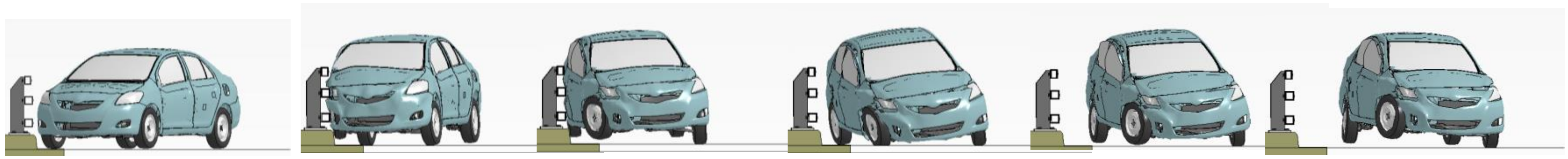
Figure 72. Exit box for Test 4-10 for sidewalk-mounted system.

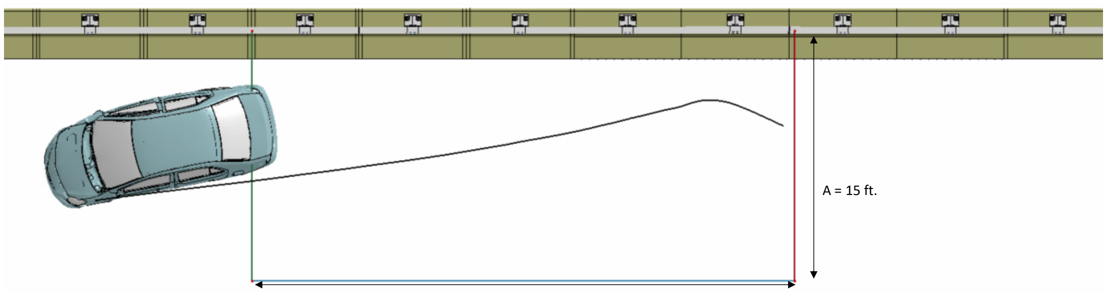
Results Summary

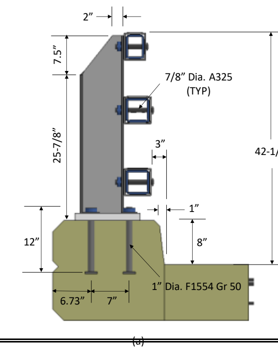
A summary of the *MASH* Test 4-10 results on the curb-mounted and sidewalk-mounted S3-TL4 bridge rail is shown in Table 25 and Figures 73 and 74. The barrier successfully contained and redirected the small car with minimal damage to the bridge rail and no damages to curb or sidewalk. There were no detached elements from the barrier that showed potential for penetrating into the occupant compartment or presenting undue hazard to other traffic. The vehicle remained upright and did not experience excessive roll or pitch angle displacements. The OIV and maximum ORA values were within critical limits specified in *MASH*. Based on the results of this analysis, the barrier is expected to meet all structural and occupant risk criteria in *MASH* for Test 4-10 impact conditions.

Table 25. Summary of *MASH* Test 4-10 results on the curb-mounted bridge rail.

Evaluation Factors		Evaluation Criteria	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass
	F	The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.	Pass
	H	The longitudinal and lateral occupant impact velocity (OIV) shall not exceed 40 ft/s (12.2 m/s), with a preferred limit of 30 ft/s (9.1 m/s)	Pass
	I	The longitudinal and lateral occupant ridedown acceleration (ORA) shall not exceed 20.49 G, with a preferred limit of 15.0 G	Pass







General Information
- Analysis Agency ………… Roadsafe LLC
- Test Standard Test No. ………… MASH Test 4-10
- Analysis No. ………… MADOT_S3TL4_Curb_T410
- Analysis Date ………… 12/24/2018

Test Article
- Type ………… S3-TL4 bridge rail
- Name ………… MassDOT Curb-Mounted
- Installation Length ………… 78 feet
- Material or Key Elements …………

Soil Type and Condition ………… N.A.

Analysis Vehicle
- Type / Designation ………… 1100C
- FEA Model name ………… 510_YarisC_V1l_R180228
- Mass ………… 2,595 lb

Impact Conditions
- Speed ………… 62 mph
- Angle ………… 25 degrees
- Location ………… 3.6 feet upstream of Post 5

Impact Severity ………… 59.5 kip-ft

Exit Conditions
- Speed ………… 43.9 mph
- Angle ………… 8.8 degrees
- Time ………… 0.245 seconds

Occupant Risk Values
- Longitudinal OIV ………… 23.6 ft/s
- Lateral OIV ………… 30.8 ft/s
- Longitudinal ORA ………… 4.7 g
- Lateral ORA ………… 13.5 g
- THIV ………… 38.4 ft/s
- PHD ………… 13.6 g
- ASI ………… 2.27

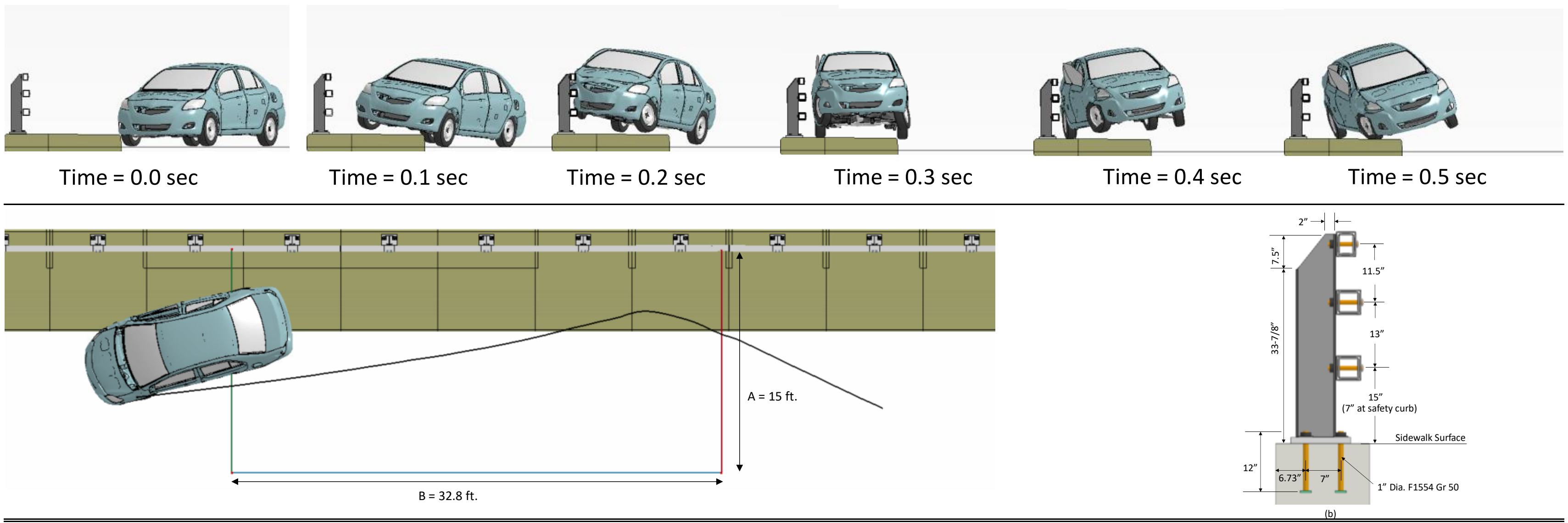
Max50-millisecond Avg. (G)
- Longitudinal ………… 13.4 g
- Lateral ………… 17.7 g
- Vertical ………… 3.3 g

Test Article Deflections (in)
- Dynamic ………… 0.83 inches
- Permanent ………… 0.47 inches
- Working Width ………… N.A.

Max. OCI ………… 2.8 inches

Vehicle Stability
- Roll ………… 7.5 degees
- Pitch ………… 6.6 degrees
- Yaw ………… 36.5 degrees

Figure 73. Summary results for *MASH* Test 4-10 on the curb-mounted bridge rail system.



General Information	
Analysis Agency	Roadsafe LLC
Test Standard Test No.	MASH Test 4-10
Analysis No.	MADOT_S3TL4_SW_T410
Analysis Date	12/25/2018
Test Article	
Type	S3-TL4 bridge rail
Name	MassDOT Sidewalk-Mounted
Installation Length	78 feet
Material or Key Elements	
Soil Type and Condition	N.A.
Analysis Vehicle	
Type / Designation	1100C
FEA Model name	510_YarisC_V1l_R180228
Mass	2,595 lb

Impact Conditions	
Speed	62 mph
Angle	25 degrees
Location	3.0 feet upstream of Post 5
Impact Severity	59.5 kip-ft
Exit Conditions	
Speed	44.7 mph
Angle	10.75 degrees
Time	0.405 seconds
Occupant Risk Values	
Longitudinal OIV	20.0 ft/s
Lateral OIV	29.9 ft/s
Longitudinal ORA	5.9 g
Lateral ORA	13.1 g
THIV	35.4 ft/s
PHD	13.1 g
ASI	1.91

Max50-millisecond Avg. (G)	
Longitudinal	13.1 g
Lateral	15.4 g
Vertical	3.1 g
Test Article Deflections (in)	
Dynamic	1.22 inches
Permanent	0.72 inches
Working Width	N.A.
Max. OCI	2.0 inches
Vehicle Stability	
Roll	16.1 degees
Pitch	7.21 degrees
Yaw	46.3 degrees

Figure 74. Summary results for *MASH* Test 4-10 on the sidewalk-mounted bridge rail system.

MASH Test 4-11

The critical impact condition for MASH Test 4-11 was selected based the *MASH* recommended CIP for rigid barrier tests. The target impact point was 4.3 feet upstream of a bridge rail post which was consistent with the recommended CIP in *MASH* (refer to Figure 56) and was selected to maximize potential for snagging at the post. [*AASHTO16*] The following sections provide a summary of the results and include a commentary describing the timing and occurrence of various events during the simulated impact, time-history data evaluation, occupant risk assessments, and damages sustained by both the barrier and vehicle.

Summary of Key Phenomenological Events

Curb-Mounted

The 5,001-lb pickup struck the barrier at 4.3 feet upstream of the Post 5 at a speed of 62 mph and at an angle of 25 degrees, as illustrated in Figure 75. The sequential views of the impact event are shown in Appendix H in Figures H-1 through H-3 from an overhead viewpoint, downstream and upstream viewpoint, and isometric viewpoint, respectively. At time equal zero seconds the front bumper of the pickup contacted the middle railing of the barrier. At 0.005 seconds the bumper contacted the lower railing. At 0.01 seconds the fender of the vehicle contacted the top railing and the tire contacted both the lower railing and the curb. At 0.0836 seconds the occupant contacted the right side of the interior resulting in an OIV of 17.1 ft/s in the longitudinal direction and 28.2 ft/s in the lateral direction. At 0.091 seconds the maximum ORA in the longitudinal direction occurred with magnitude 4.3 G. At 0.015 seconds the barrier began to deflect, and the front-right tire began to steer away from the barrier while also beginning to mount the curb. At 0.03 seconds the deformation of the tire was sufficient to debead the tire; however, tire deflation was not included in the model. At 0.035 seconds the tire was steered parallel to the barrier and was fully mounted onto the curb; the ball-joint of the lower control arm for the wheel also failed at this time. At 0.055 seconds the front-right fender of the pickup was significantly crushed, and the hood of the vehicle was over top of the barrier and extended 10.5 inches behind the face of the barrier. At 0.06 seconds the front-right tire was at Post 5, and Post 5 reached a peak deflection of 1.35 inches; also, at this time the front bumper contacted the front flange of Post 5 but did not result in a noticeable snag, and the front-right door of the vehicle began to deflect as it contacted the middle railing. At 0.15 seconds the vehicle briefly lost contact with the barrier. At 00.165 seconds the rear bed of the pickup contacted the top and middle railings at the splice connection upstream of Post 5. At 0.17 seconds the rear-right tire contacted the curb and immediately after contacted both the middle and lower railings. At 0.185 seconds the barrier reached maximum dynamic deflection of 1.73 inches at the downstream side of the splice. At 0.1929 seconds the maximum lateral ORA occurred with magnitude of 17.6 G; however, based on previous experience with the vehicle model the lateral ORA is typically overestimated. At 0.32 seconds the vehicle separated from the barrier at an exit speed and angle of 47.9 mph and 5.7 degrees, respectively. At 0.32 seconds the vehicle experienced maximum roll angle of 9.7 degrees with the vehicle rolling toward the barrier. At 0.39 seconds the vehicle reached maximum pitch angle of 6.2 degrees with the rear of the vehicle pitching upward. The vehicle remained stable throughout post-impact trajectory. The analysis ended at 1.0 seconds, at which time:

- The roll, pitch, and yaw of the vehicle were, respectively, 6.1 degrees (toward barrier), 3.1 degrees (rear pitching up), and 21 degrees (4 degrees relative to and toward barrier).
- The forward velocity of the vehicle was 39.6 mph (63.7 km/h).

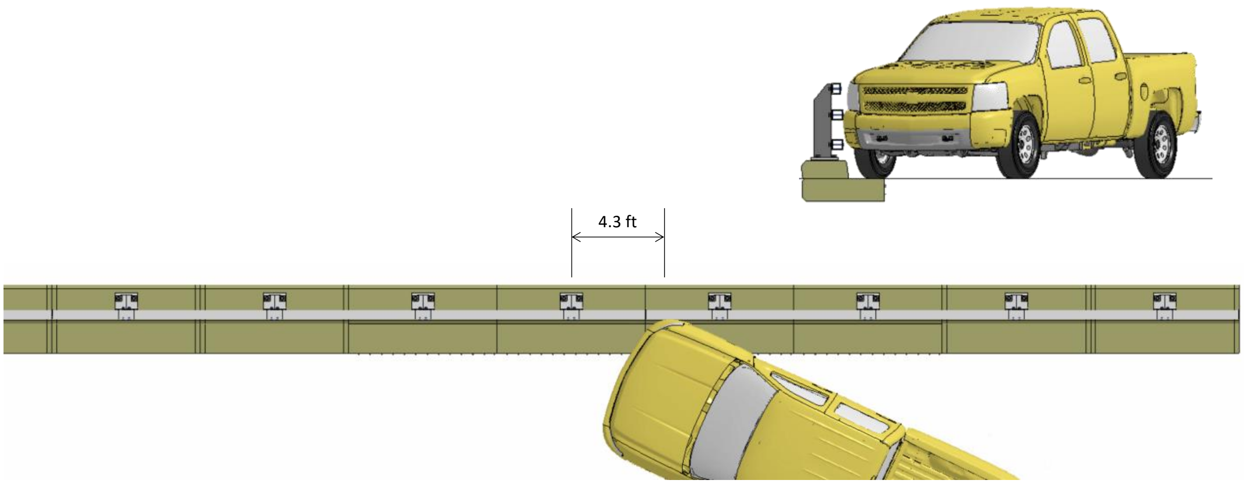


Figure 75. Impact point for Test 4-11 on the curb-mounted S3-TL4.

Sidewalk-Mounted

The 5,001-lb pickup struck the sidewalk at a speed of 62 mph and at an angle of 25 degrees. The initial starting point for the vehicle was approximately 14.7 ft upstream of the target critical post at Post 5, as illustrated in Figure 76. The sequential views of the impact event are shown in Appendix I in Figures I-1 through I-3 from an overhead viewpoint, downstream and upstream viewpoint, and isometric viewpoint, respectively. At 0.005 seconds, the front-right tire compressed at the point of contact with the curb, and at 0.015 seconds the deformation of the tire was sufficient to debead the tire; however, deflation of the tire was not included for this analysis case. At 0.025 seconds the tire had fully mounted the sidewalk and the vehicle began to roll away from the barrier. The tire rebounded slightly from the sidewalk at 0.035 seconds but then recontacted the sidewalk at 0.060 seconds and remained in contact until impact with the barrier. The front bumper of the vehicle impacted the two lower rails of the bridge rail at 0.135 seconds at 4.0 feet upstream of Post 5 at a speed of 61.2 mph and impact angle of 24.7 degrees, as illustrated in Figure 77. At 0.14 seconds the front-right tire contacted the lower railing of the bridge rail; also, at this time, both the rear-right tire and the front-left tire contacted the curb of the sidewalk. At 0.145 seconds the front fender of the vehicle impacted the top railing, and the barrier began to deflect. At 0.15 seconds the wheel rim of the front-right tire rim contacted the lower railing and the tire began to steer away from the barrier. At 0.16 seconds the rear-right tire was fully mounted onto the sidewalk; also, at this time the front-right tire was parallel to the barrier, and the lower wheel joint on the front-right tire failed. At 0.17 seconds the front-left tire was fully mounted onto the sidewalk. The rear-right tire debeaded, but deflation was not included in the analysis. The front-right tire only partially debeaded during the curb traversal. At 0.17 seconds the front bumper of the vehicle passed between the lower two bridge railings and contacted the post; but with no potential for snagging. At 0.175 seconds the rear-right tire lifted off the sidewalk. At 0.18 seconds the front-left tire lifted off the sidewalk. At 0.2106 seconds, the theoretical occupant in the vehicle struck the right side of the interior with a longitudinal and lateral velocity of 17.1 ft/s and 24.9 ft/s, respectively. At 0.22 seconds the rear-right tire lifted off the roadway. At 0.23 seconds the maximum longitudinal acceleration occurred with magnitude 5.6 G. At 0.305 seconds the rear of the vehicle contacted the middle and upper railings, and immediately afterward the rear-right tire contacted the middle and lower railings. At 0.33 seconds the barrier reached maximum dynamic deflection of 2.83 inches just upstream of Post 5 at the splice connection. At 0.337 seconds the maximum lateral ORA occurred with magnitude 18.3 G. As mentioned previously, it is expected that the model over-estimated this value. At 0.4 seconds the vehicle separated from the barrier at traveling at a speed of 47.3 mph and exit angle of 5.7 degrees. At 0.505 seconds the vehicle reached maximum pitch angle of 5.8 degrees with the rear of the vehicle pitching upward. At 0.71 seconds the front-left tire recontacted the roadway, and at 0.725 seconds the rear-left tire recontacted the roadway. At 0.8 seconds the vehicle experienced maximum roll angle of 11.1 degrees with the vehicle rolling toward the barrier. At 0.87 seconds the front-right tire dropped off the sidewalk and recontacted the roadway at 0.93 seconds. The vehicle remained stable throughout post-impact trajectory. The analysis ended at 1.2 seconds, at which time:

- The vehicle had exited the sidewalk.
- The roll, pitch, and yaw of the vehicle were 1.6 degrees (toward the barrier), 4.5 degrees (rear pitching up), and 38.37 degrees (13.4 degrees relative to and away from the barrier)), respectively.
- The forward velocity of the vehicle was 40.1 mph (64.5 km/h).

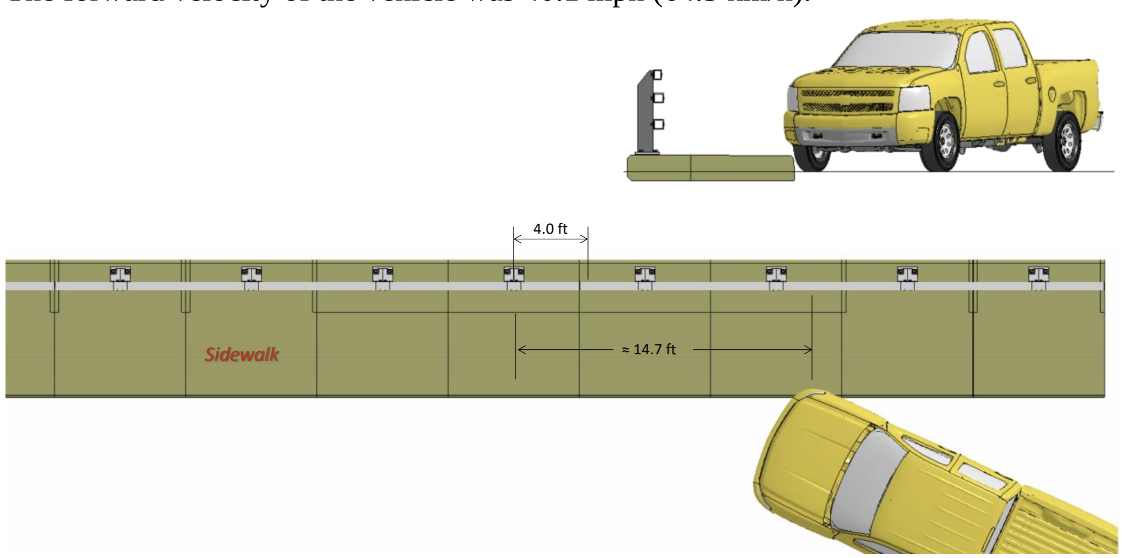


Figure 76. Initial starting position for Test 4-11 on the sidewalk-mounted S3-TL4.

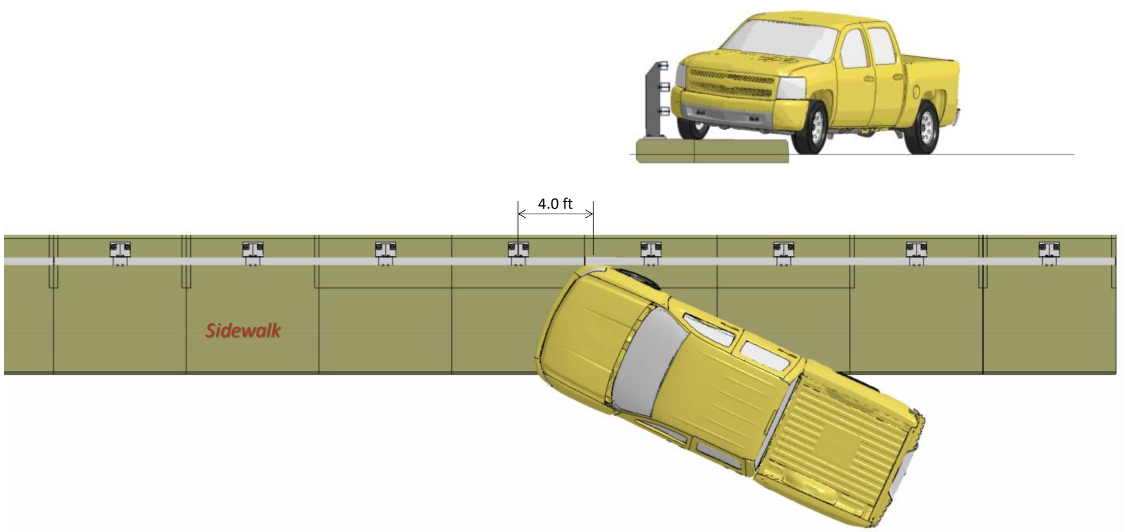


Figure 77. Impact point with bridge rail for Test 4-11 on the sidewalk-mounted S3-TL4.

Time History Data Evaluation

Figures 78 through 80 show the longitudinal, transverse, and vertical acceleration-time histories, respectively, computed from the center of gravity of the vehicle; Figures 81 through 83 show the comparison of the angular rates and angular displacement about the x-, y-, and z-axis at the center of gravity of the vehicle.

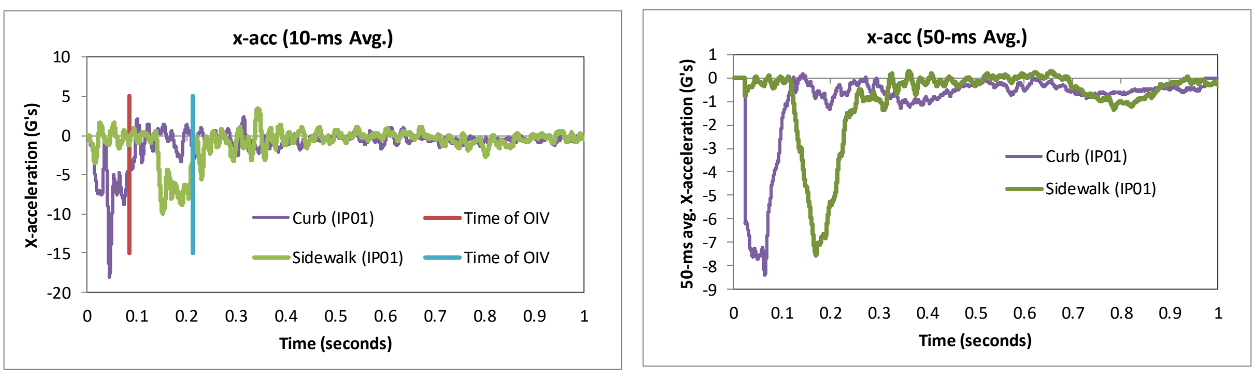


Figure 78. 10- and 50-millisecond average X-acceleration from FEA of Test 4-11 on the curb-mounted and sidewalk-mounted bridge rail.

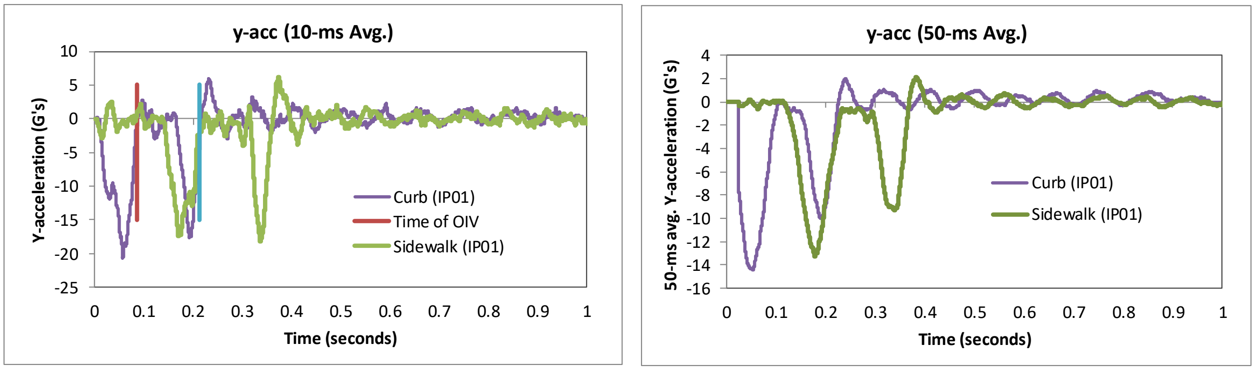


Figure 79. 10- and 50-millisecond average Y-acceleration from FEA of Test 4-11 on the curb-mounted and sidewalk-mounted bridge rail.

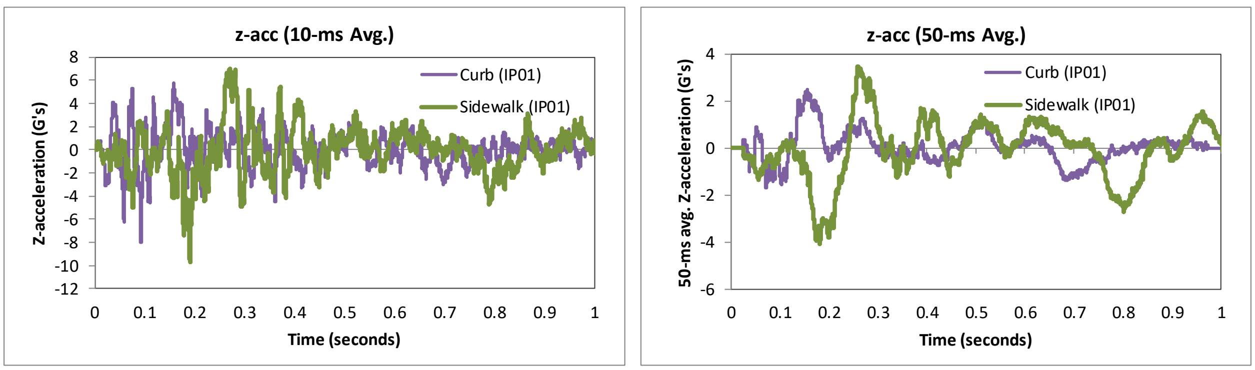


Figure 80. 10- and 50-millisecond average Z-acceleration from FEA of Test 4-11 on the curb-mounted and sidewalk-mounted bridge rail.

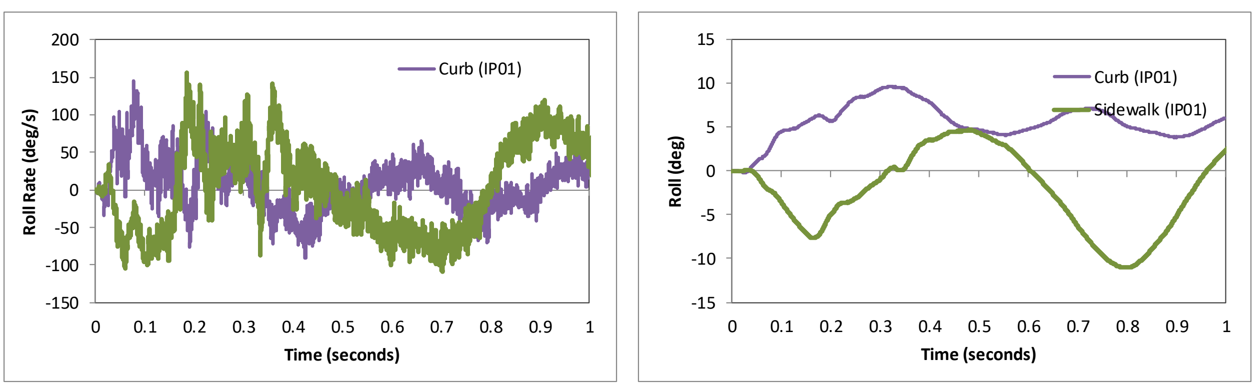


Figure 81. Roll rate and roll angle time-history from FEA of Test 4-11 on the curb-mounted and sidewalk-mounted bridge rail.

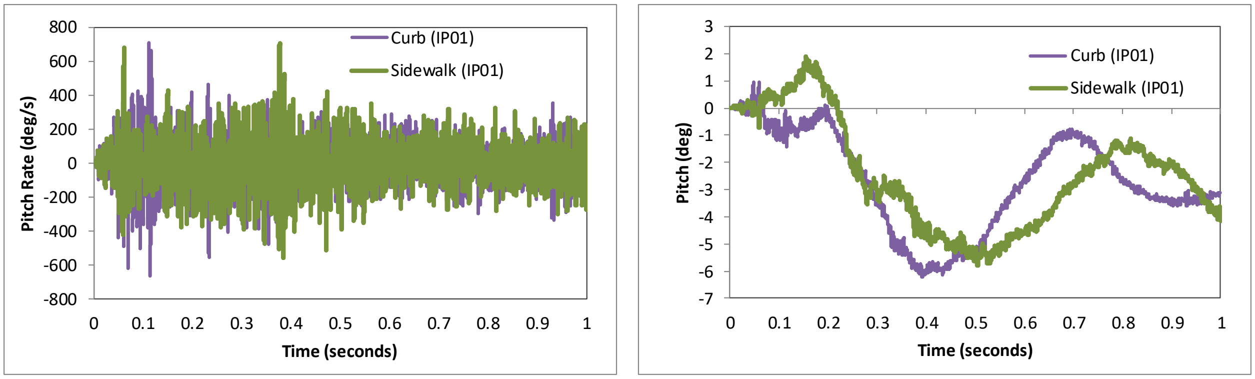


Figure 82. Pitch rate and pitch angle time-history from FEA of Test 4-11 on the curb-mounted and sidewalk-mounted bridge rail.

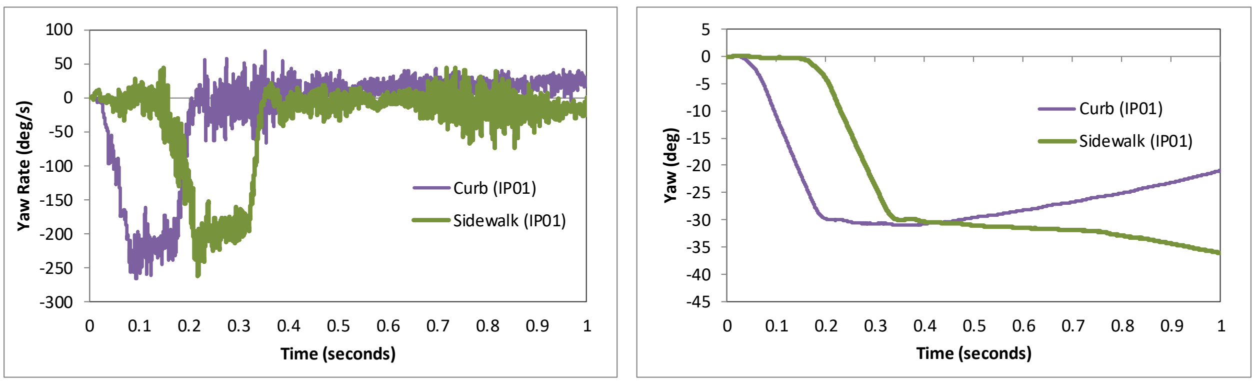


Figure 83. Yaw rate and yaw angle time-history from FEA of Test 4-11 on the curb-mounted and sidewalk-mounted bridge rail.

Occupant Risk Measures

The acceleration-time histories and angular rate-time histories collected at the center of gravity of the vehicle were used to evaluate occupant risk metrics according to the procedures outlined in *MASH*. Table 26 shows the results for the occupant risk calculations. The results indicate that the occupant risk factors met safety criteria specified in *MASH*.

Curb-Mounted System

The occupant impact velocities in the longitudinal and transverse directions for the curb-mounted system were 17.1 ft/s and 28.2 ft/s, respectively, which were within the recommended limits specified in *MASH*. The highest 0.010-second occupant ridedown acceleration in the longitudinal and transverse directions were 4.3 g and 17.6 g, respectively, which were within critical limits specified in *MASH*. The maximum 50-ms moving average acceleration values in the longitudinal and transverse directions were 8.4 g and 14.4 g, respectively. The maximum roll and pitch angles of the vehicle were 9.7 degrees and 6.2 degrees, respectively, which were well below critical limits in *MASH*. From previous results of the 2270P vehicle model impacting rigid barrier, it was determined that the maximum lateral ridedown acceleration is often over-estimated by the model (see Appendix E pg. E-5).

Sidewalk-Mounted System

The occupant impact velocities in the longitudinal and transverse directions for the sidewalk-mounted system were 17.1 ft/s and 24.9 ft/s, respectively, which were within the preferred limits specified in *MASH*. The highest 0.010-second occupant ridedown acceleration in the longitudinal and transverse directions were 5.6 g and 18.3 g, respectively, which were within critical limits specified in *MASH*. The maximum 50-ms moving average acceleration values in the longitudinal and transverse directions were 7.6 g and 13.2 g, respectively. The maximum roll and pitch angles of the vehicle were 11.1 degrees and 5.8 degrees, respectively, which were well below critical limits in *MASH*.

Table 26. Summary of occupant risk metrics for Test 4-11 on the S3-TL4 Bridge Rail.

Occupant Risk Factors		MASH T4-11	
		Curb (IP01)	Sidewalk (IP01)
Occupant Impact Velocity (ft/s)	x-direction	17.1	17.1
	y-direction	28.2	24.9
	at time	at 0.0836 seconds on right side of interior	at 0.2106 seconds on right side of interior
THIV (ft/s)		33.1 at 0.0836 seconds on right side of interior	30.8 at 0.2106 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-4.3 (0.0860 - 0.0960 seconds)	-5.6 (0.2254 - 0.2354 seconds)
	y-direction	-17.6 (0.1879 - 0.1979 seconds)	-18.3 (0.3321 - 0.3421 seconds)
PHD (g's)		17.6 (0.1878 - 0.1978 seconds)	18.3 (0.3321 - 0.3421 seconds)
ASI		1.72 (0.0255 - 0.0755 seconds)	1.62 (0.1537 - 0.2037 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-8.4 (0.0406 - 0.0906 seconds)	-7.6 (0.1460 - 0.1960 seconds)
	y-direction	-14.4 (0.0285 - 0.0785 seconds)	-13.2 (0.1540 - 0.2040 seconds)
	z-direction	2.5 (0.1312 - 0.1812 seconds)	-4.1 (0.1571 - 0.2071 seconds)
Maximum Angular Disp. (deg)	Roll	9.7 (0.3174 seconds)	-11.1 (0.7999 seconds)
	Pitch	-6.2 (0.3916 seconds)	-5.8 (0.5048 seconds)
	Yaw	-31 (0.3710 seconds)	-38.4 (1.1991 seconds)

MASH Criteria

Occupant Impact Velocity: < 30 ft/s (preferred) ✓; < 40 ft/s (limit)

Ridedown Acceleration: > 15 G (preferred); < 20.49 G (limit) ✓

Maximum Angular Disp. (Roll, Pitch): < 75 deg ✓

Occupant Compartment Intrusion

Curb-Mounted

The maximum deformation of the occupant compartment for impact on the curb-mounted bridge rail was approximately 2.6 inches at the lower right-front corner of the toe-pan at the wheel well. Figure 84 shows a view of the vehicle interior after the impact, with several components removed to facilitate viewing. The maximum deformation was less than the critical limit of 9 inches specified in *MASH* for this area of the occupant compartment.

Sidewalk-Mounted

The maximum deformation of the occupant compartment for impact on the sidewalk-mounted bridge rail was approximately 1.5 inches at the lower right-front corner of the toe-pan at the wheel well, which was also well below the critical limit of 9 inches.

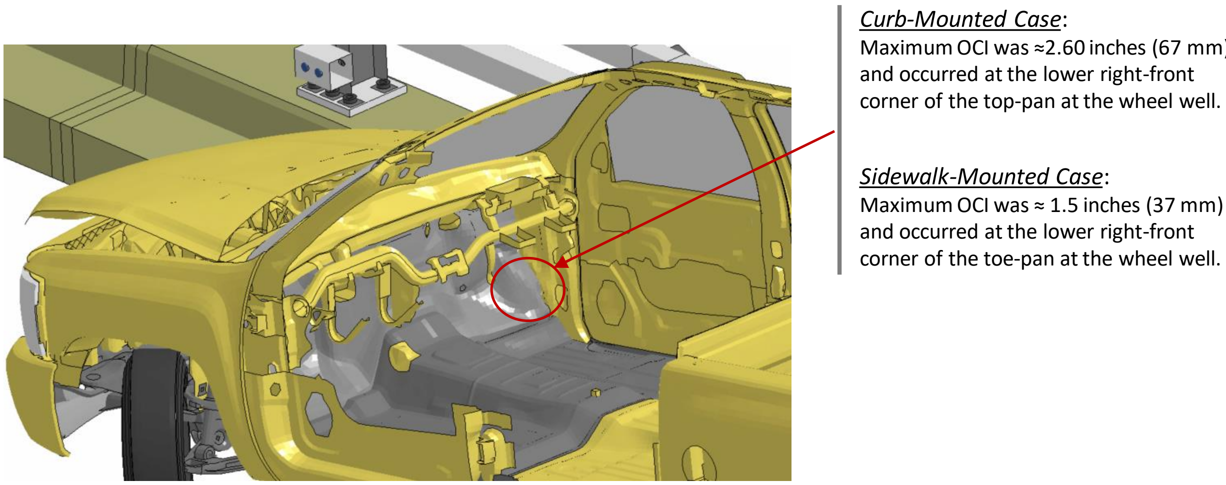


Figure 84. Occupant compartment deformation resulting from Test 4-11 on the bridge rail system.

Damages to the Barrier System

The damages to the barrier were moderate. Figure 85 shows images of the barrier at the time of maximum deflection with a contour plot of lateral displacement on the rail elements. The dynamic deflection for the curb-mounted system was 1.73 inches and occurred on the top rail at the splice connection. The maximum dynamic deflection for the sidewalk-mounted system was 2.83 inches and occurred on the top rail between the splice and the critical post. Figure 86 shows contour plots of the maximum permanent deflection for both barrier tests. The maximum permanent deflection for the curb-mounted and sidewalk-mounted systems was 1.0 inch and 1.31 inches, respectively. The deformation was slightly higher for the sidewalk-mounted case due to the increased moment arm resulting from the longer post in the sidewalk-mounted case (refer to Figures 4 and 5). The plastic deformation of the posts was minimal as well, as illustrated in Figure 87.

There were no damages to the concrete in either case, as illustrated in Figure 88, which shows contours of 1st principal strain with contours cut off at strains of 0.1. In an earlier project conducted by the research team, the concrete material model used in the current study was validated against full-scale tests involving a rigid pendulum impacting into fixed-fixed steel reinforced concrete columns.[*Ray18a*, *Ray18b*] The results of that study indicated that values of 1st Principle strain of 0.07 to 0.08 (yellow contours) indicated initial crack openings in the concrete when correlated to the column impact tests and that strains values of 0.08 to 0.1 (orange/red contours) corresponded to significant crack openings.

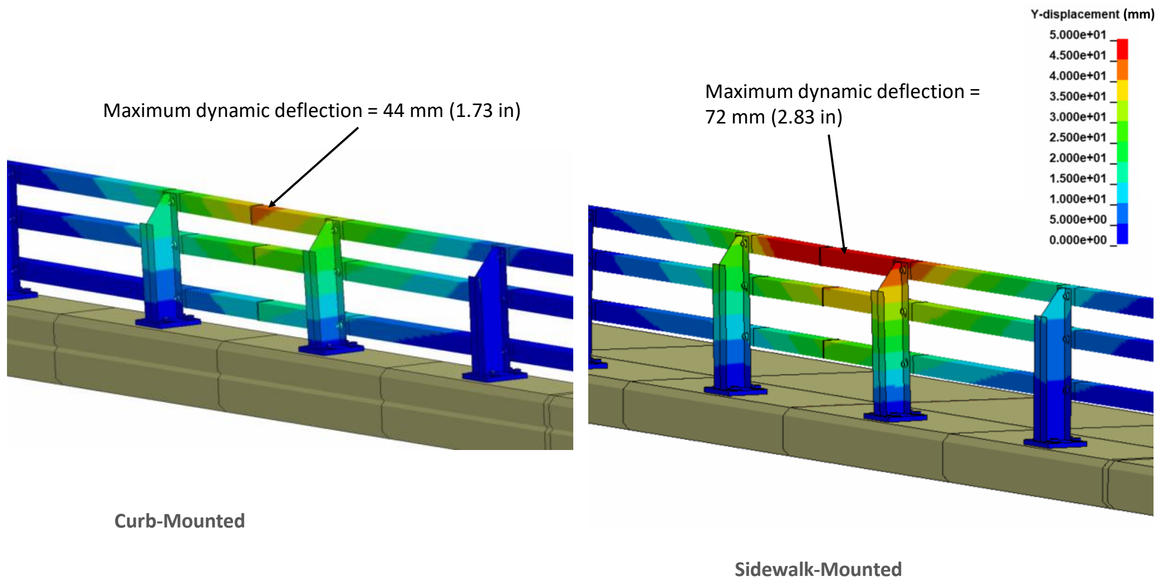


Figure 85. Contour plot of lateral displacement for the bridge rail from Test 4-11 at the time of maximum dynamic deflection for the curb-mounted and sidewalk-mounted systems.

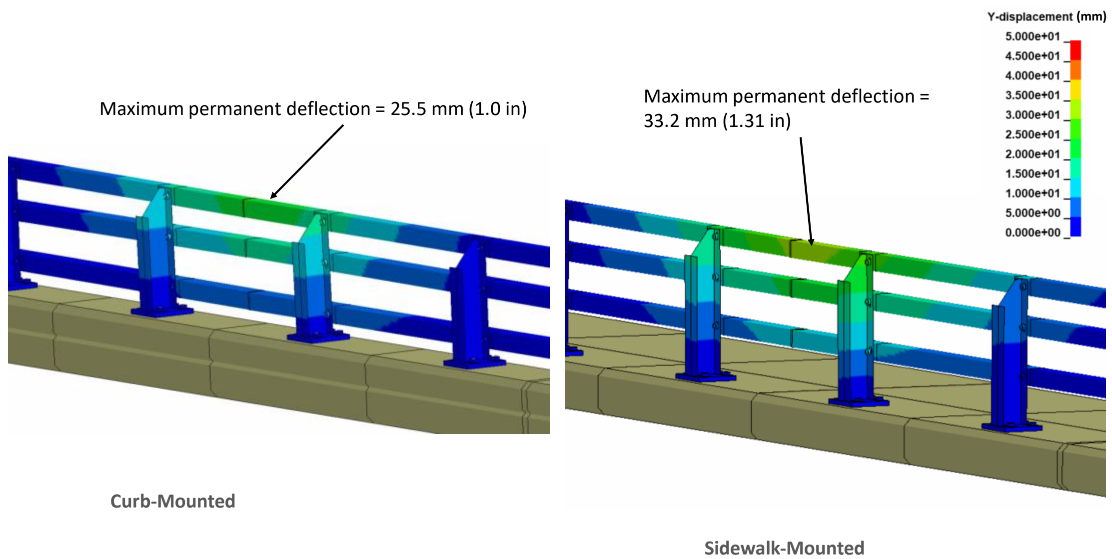


Figure 86. Contour plot of maximum permanent deflection for the bridge rail from Test 4-11 for the curb-mounted and sidewalk-mounted systems.

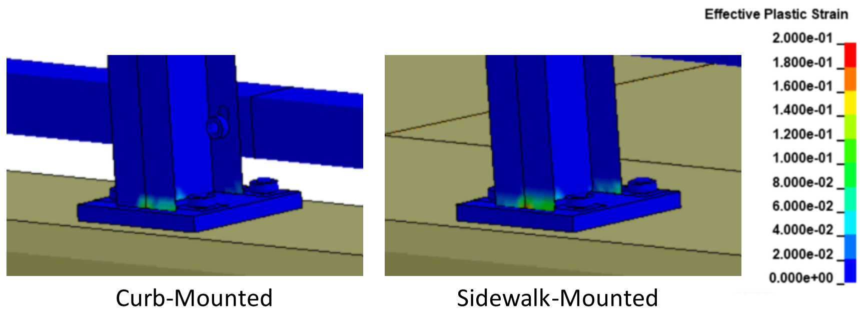


Figure 87. Contours of effective plastic strains on the critical post for Test 4-11 on the curb-mounted and sidewalk-mounted systems.

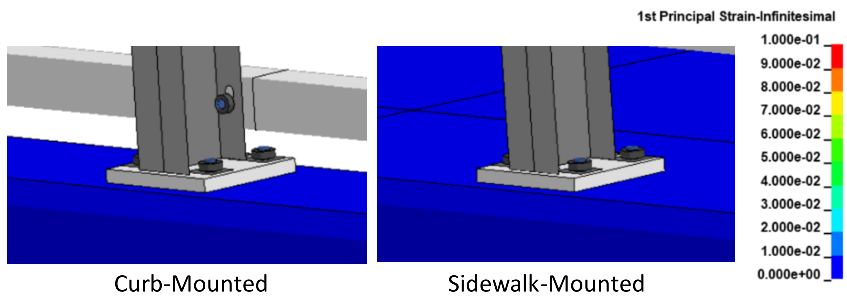


Figure 88. Contours of 1st principal strain for concrete at the critical post for Test 4-11 on the curb-mounted and sidewalk-mounted systems.

Damages to Vehicle

Figure 89 show contour plots of effective plastic strain for the vehicle, which were used to identify areas of the vehicle that suffered damage during the simulated impact event. The most severe damages were to the front bumper, the front fender, the front impact-side suspension, the rear portion of the vehicle body on the impact side, and both front and rear impact-side wheels. For the sidewalk-mounted case, there was a "node snag" between the passenger door and the rail that was caused by an error in the contact algorithm that allowed a non-physical penetration of the two components.

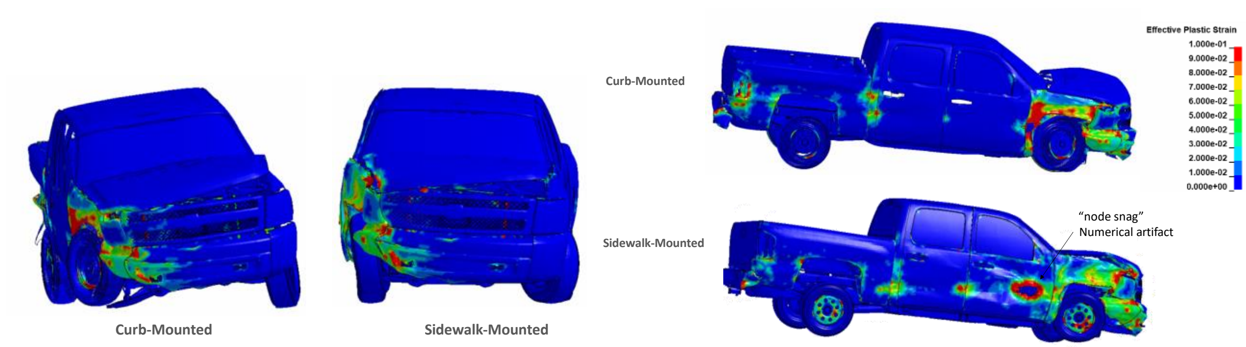


Figure 89. Damages to vehicle in Test 4-11 analysis of curb-mounted bridge rail (front and right-side views).

Exit Box

Figures 90 and 91 shows the exit box for Test 4-11 on the curb-mounted and sidewalk-mounted bridge rail systems, respectively. Although the exit box analysis is not required in *MASH*, it was included here for completeness. The vehicle was smoothly redirected and its path was well within the exit box criteria of *MASH*.

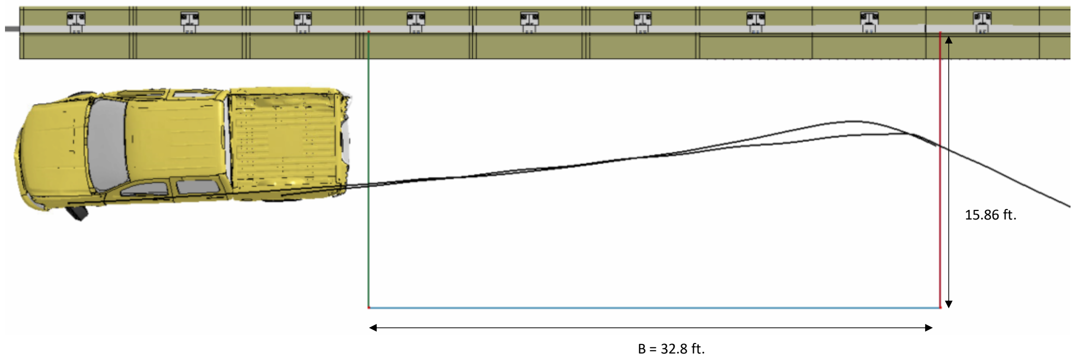


Figure 90. Exit box for Test 4-11 for curb-mounted.

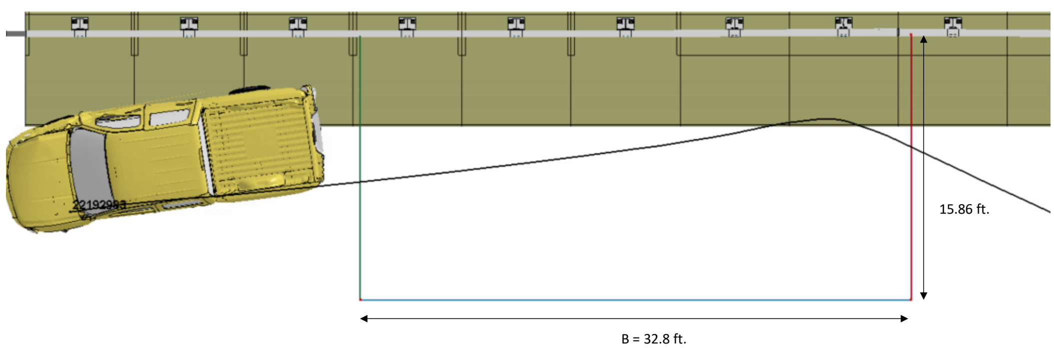


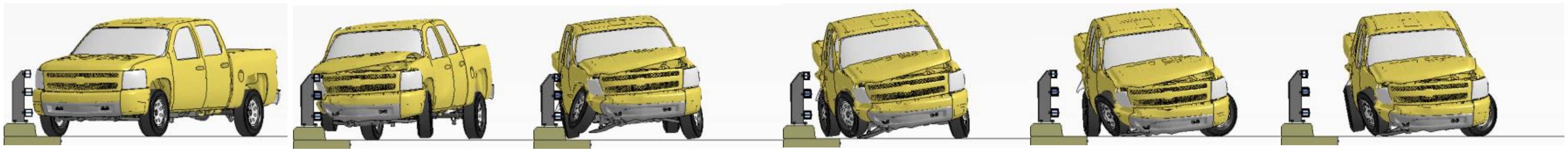
Figure 91. Exit box for Test 4-11 for sidewalk-mounted system.

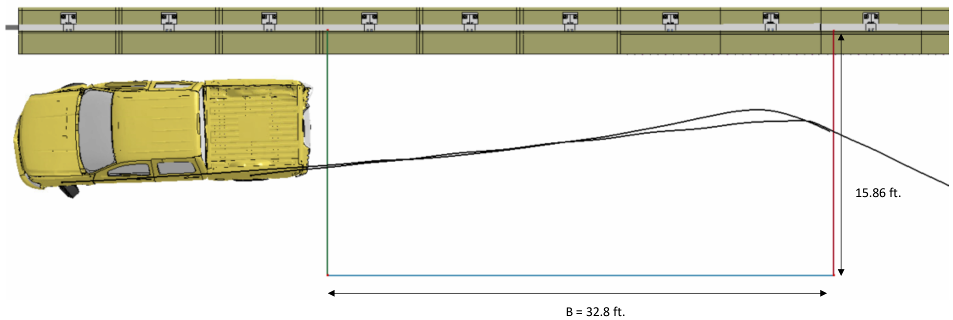
Results Summary

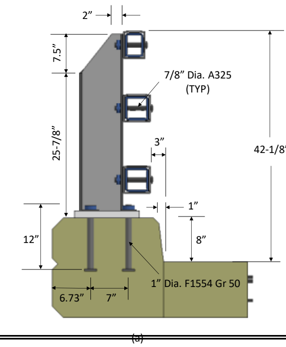
A summary of the *MASH* Test 4-11 results on the curb-mounted and sidewalk-mounted S3-TL4 bridge rail is shown in Table 27 and Figures 92 and 93. The barrier successfully contained and redirected the pickup with moderate damage to the bridge rail and no damages to curb or sidewalk. There were no detached elements from the barrier that showed potential for penetrating into the occupant compartment or presenting undue hazard to other traffic. The vehicle remained upright and did not experience excessive roll or pitch angle displacements. The OIV and maximum ORA values were within critical limits specified in *MASH*. Based on the results of this analysis, the barrier is expected to meet all structural and occupant risk criteria in *MASH* for Test 4-11 impact conditions.

Table 27. Summary of *MASH* Test 4-11 results on the curb-mounted bridge rail.

Evaluation Factors		Evaluation Criteria	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass
	F	The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.	Pass
	H	The longitudinal and lateral occupant impact velocity (OIV) shall not exceed 40 ft/s (12.2 m/s), with a preferred limit of 30 ft/s (9.1 m/s)	Pass
	I	The longitudinal and lateral occupant ridedown acceleration (ORA) shall not exceed 20.49 G, with a preferred limit of 15.0 G	Pass







General Information

Analysis Agency	Roadsafe LLC
Test Standard Test No.	MASH Test 4-11
Analysis No.	MADOT_S3TL4_Curb_T411
Analysis Date	12/23/2018

Test Article

Type	S3-TL4 bridge rail
Name	MassDOT Curb-Mounted
Installation Length	78 feet
Material or Key Elements	

Soil Type and Condition ....…...... N.A.

Analysis Vehicle

Type / Designation	2270P
FEA Model name	SilveradoC_V3a_V180201_TireRS_35psi
Mass	5,001 lb

Impact Conditions

Speed	62 mph
Angle	25 degrees
Location	4.3 feet upstream of Post 5

Impact Severity .... 114.7 kip-ft

Exit Conditions

Speed	47.9 mph
Angle	5.7 degrees
Time	0.32 seconds

Occupant Risk Values

Longitudinal OIV	17.1 ft/s
Lateral OIV	28.2 ft/s
Longitudinal ORA	4.3 g
Lateral ORA	17.6 g
THIV	33.1 ft/s
PHD	17.6 g
ASI	1.72

Max50-millisecond Avg. (G)

Longitudinal	8.4 g
Lateral	14.4 g
Vertical	2.5 g

Test Article Deflections (in)

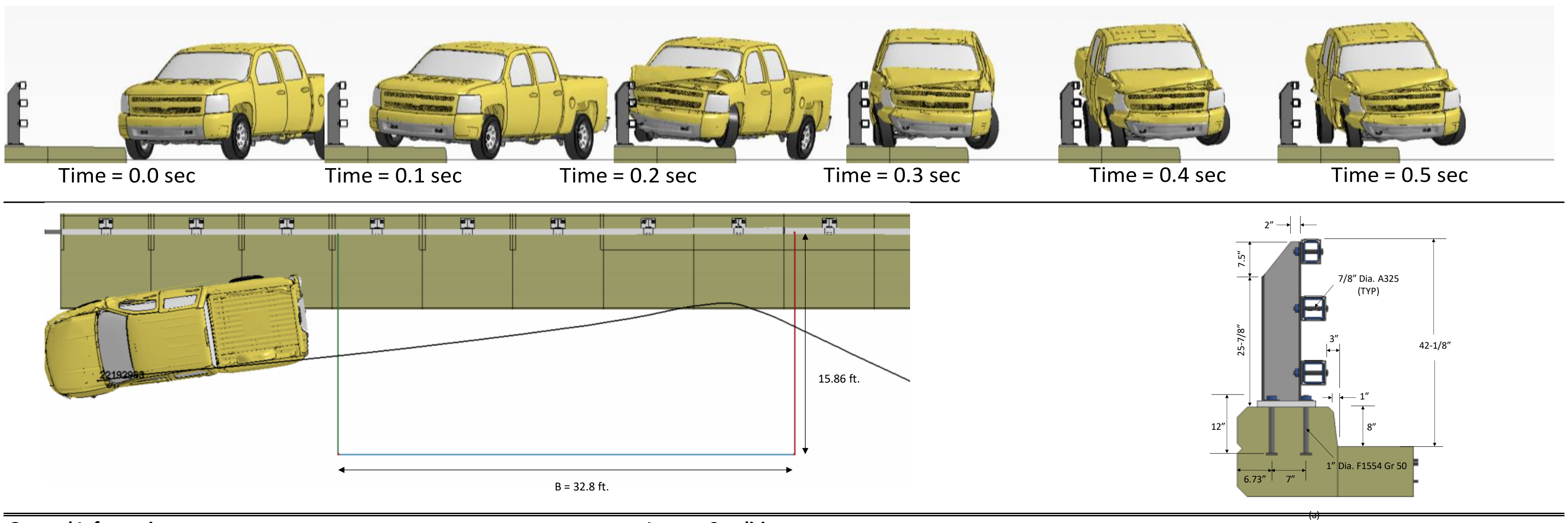
Dynamic	1.73 inches
Permanent	1.0 inch
Working Width	N.A.

Max. OCI .... 2.6 inches

Vehicle Stability

Roll	9.7 degees
Pitch	6.2 degrees
Yaw	31 degrees

Figure 92. Summary results for *MASH* Test 4-11 on the curb-mounted bridge rail system.



General Information

Analysis Agency	Roadsafe LLC
Test Standard Test No.	MASH Test 4-11
Analysis No.	MADOT_S3TL4_Siewalk_T411
Analysis Date	1/11/2019

Test Article

Type	S3-TL4 bridge rail
Name	MassDOT Sidewalk-Mounted
Installation Length	78 feet
Material or Key Elements	

Soil Type and Condition .... N.A.

Analysis Vehicle

Type / Designation	2270P
FEA Model name	SilveradoC_V3a_V180201_TireRS_35psi
Mass	5,001 lb

Impact Conditions

Speed	62 mph
Angle	25 degrees
Location	4.0 feet upstream of Post 5

Impact Severity .... 114.7 kip-ft

Exit Conditions

Speed	47.3 mph
Angle	5.7 degrees
Time	0.47 seconds

Occupant Risk Values

Longitudinal OIV	17.1 ft/s
Lateral OIV	24.9 ft/s
Longitudinal ORA	5.6 g
Lateral ORA	18.3 g
THIV	30.8 ft/s
PHD	18.3 g
ASI	1.62

Max50-millisecond Avg. (G)

Longitudinal	7.6 g
Lateral	13.2 g
Vertical	4.1 g

Test Article Deflections (in)

Dynamic	2.83 inches
Permanent	1.31 inch
Working Width	N.A.

Max. OCI .... 1.5 inches

Vehicle Stability

Roll	11.1 degees
Pitch	5.8 degrees
Yaw	38.4 degrees

Figure 93. Summary results for *MASH* Test 4-11 on the sidewalk-mounted bridge rail system.

MASH Test 4-12 for Curb-Mounted Bridge Rail

The critical impact point for MASH Test 4-12 was selected based the *MASH* recommended CIP for rigid barrier tests. The target impact point was 5.0 feet upstream of a bridge rail post, as illustrated in Figure 94, which was consistent with the recommended CIP in *MASH* (refer to Table 28) and was selected to maximize loading on a post. [*AASHTO16*]

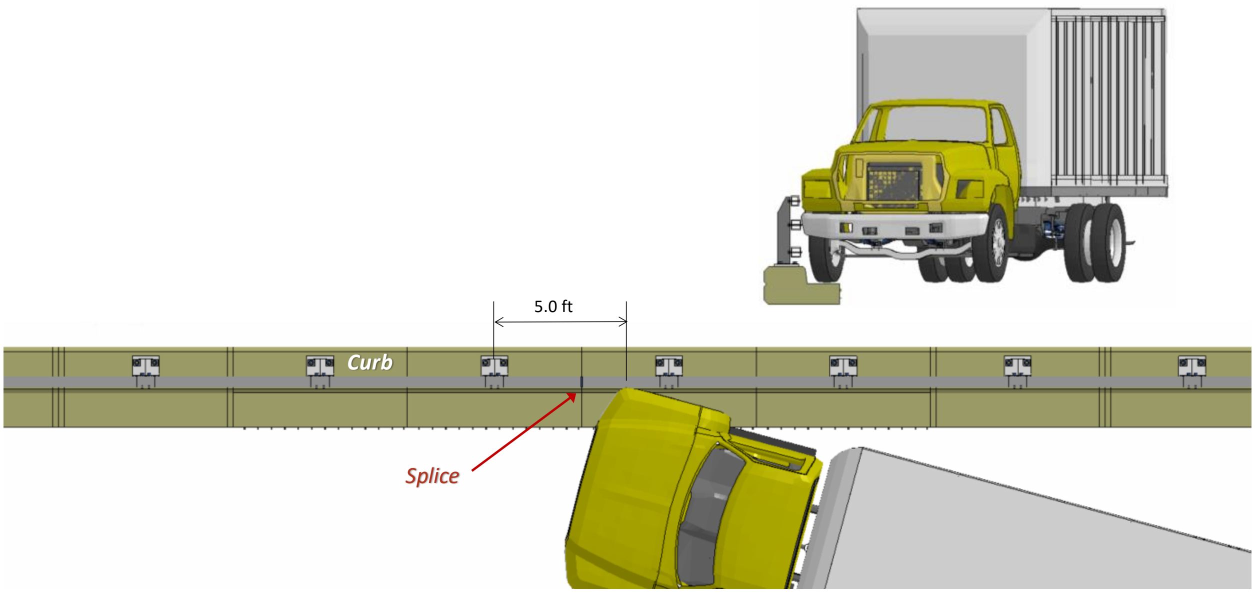


Figure 94. Impact point for Test 4-12 on the curb-mounted S3-TL4.

Table 28. Table 2-8 from *MASH* showing critical impact point for heavy vehicles for evaluation of longitudinal barriers. [*AASHTO16*]

TABLE 2-8. Critical Impact Point for Heavy Vehicle Tests

Test Designation[a]	*x* Distance,[b] ft (m)
4-12	5.0 (1.5)
5-12	–1.0 (–0.3)
6-12	2.0 (0.6)

a See Table 2-2 for test descriptions.

b See Figure 2-1 for illustration of x distance.

Comparisons of the physical and inertial properties of the SUT vehicle model with those of recent test vehicles, showed that the cargo-bed height for the FEA model was 47.5 inches measured from the ground to the top of the cargo-bed floor. This height was consistent with Ford 800 test vehicles (which was the basis for the model) but was lower than most other test vehicles. For example, test 420020-9b involved a 1991 International 4700 with 48-inch bed height [*Sheikh11*]; Test 404251-6 involved a Chevrolet C 70 with 50-inch cargo bed height [*Buth99*]; Test 490026-4-3 involved an International 4200 with 50-inch cargo-bed height [*Williams17b*]; Test 607451-1 involved an International 4200 with 49.25-inch cargo-bed height [*Williams17a*]. When the top of the bridge rail is at approximately the same height as the bed of the cargo-box, then slight differences in the bed height will determine if the cargo-box impacts directly against the rail or passes over the top of the rail. Two different versions of the SUT vehicle model were used for evaluation of Test 4-12: one with cargo-bed height of 47.5 inches (lower bound) and another with cargo-bed height of 50 inches (upper bound), as illustrated in Figure 95.

When evaluating barrier performance under the higher impact severity of Test 4-12, it may be necessary to use a range of strength properties for the post, since the material strength has been shown to vary as much as 20% (refer to the *Materials* section of Chapter 5). The lower bound strength will assess maximum deformation due to post plasticity, while the upper bound strength will assess greater loading on the anchors and concrete.

For the Test 4-12 evaluations, three (3) analysis cases were performed on the curb-mounted system:

- Case 1: Vehicle bed height = 47.5 inches and post yield strength = 51 ksi (lower bound)
- Case 2: Vehicle bed height = 50 inches and post yield strength = 51 ksi (lower bound)
- Case 3: Vehicle bed height =47.5 inches and post yield strength = 60 ksi (upper bound)

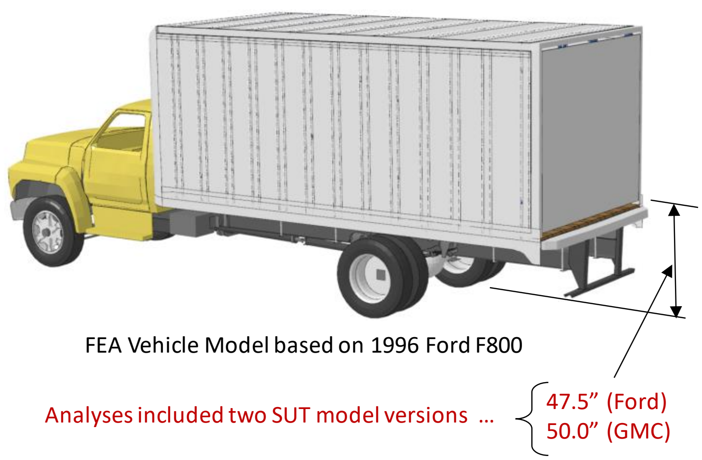


Figure 95. Two versions of the SUT model were used with cargo-bed heights of 47.5” and 50”.

The following sections provide a summary of the results and include a commentary describing the timing and occurrence of various events during the simulated impact, time-history data evaluation, occupant risk assessments, and damages sustained by both the barrier and vehicle. The commentary for Case 3 was not included since the vehicle response in that case was very similar to Case 1.

Summary of Key Phenomenological Events

Case 1 (Case 3 is similar)

The 22,198-lb single unit truck struck the barrier at 5.0 feet upstream of Post 5 at a speed of 56 mph and at an angle of 15 degrees, as illustrated in Figure 94. The sequential views of the Case 1 impact event are shown in Appendix J in Figures J-1 through J-3 from an overhead viewpoint, downstream and upstream viewpoint, and an oblique viewpoint, respectively. The sequential views of the Case 3 impact event are shown in Appendix L in Figures L-1 through L-3 from an overhead viewpoint, downstream and upstream viewpoint, and an oblique viewpoint, respectively. At time equal zero seconds the front bumper contacted the middle railing of the barrier and the front-right fender contacted the upper railing. At 0.01 seconds the front-right tire contacted the curb and immediately afterward contacted the middle and lower railings; also, at this time the railing began to deflect. At 0.025 seconds the front-right tire began to steer away from the barrier and began to mount the curb. At 0.05 seconds the front-right tire had fully mounted the curb, and at 0.06 seconds the tire was parallel to the barrier. At 0.075 seconds one of the u-bolts connecting the front axle to the front-right suspension failed, but the second u-bolt did not fail, and the axle remained attached. At 0.09 seconds the front-right tire was centered at Post 5. At 0.13 seconds the lower front-right corner of the cargo-box contacted the top railing at the splice connection located upstream of Post 5; only the lower 1-inch of the cargo-box contacted the railing, but the stiffness of the box resulted in notable lateral deflection of the barrier. Also, at this time the front-left tire lifted off the ground. At 0.235 seconds the rear tandems of the vehicle contacted the curb, and the rear of the cargo-box impacted against the top railing; the roll angle of the vehicle at this time was 7.9 degrees toward the barrier. At 0.24 seconds the vehicle was parallel to the barrier. At 0.245 seconds the rear-right tandem wheels contacted the middle and lower railings; also, at this time the deflection of the railing began to increase. At 0.267 seconds the maximum loading on the barrier occurred with magnitude of 146 kips (25 millisecond moving average). At 0.28 seconds the maximum dynamic deflection of the barrier was 5 inches and occurred from Post 4 to Post 5 (e.g., essentially uniform deflection over the span); also, at this time the rear-left tandem wheel set lifted off the ground as the vehicle continued to roll toward the barrier. At 0.39 seconds the vehicle lost contact with the barrier traveling at an exit speed and angle of 49 mph and 2.6 degrees. At 0.62 seconds the cargo-box reached maximum pitch angle of 5.5 degrees (rear pitching upward); at 0.637 seconds the cabin reached maximum pitch angle of 6.5 degrees (rear pitching up). At 0.677 seconds the cargo-box experienced maximum roll angle of 25.8 degrees (cargo-box rolling toward the barrier); at 0.886 seconds the cabin of the vehicle reached a maximum roll angle of 22.9 degrees (toward the barrier). At 0.98 seconds the rear-left tandem wheel set recontacted the ground, and at 1.06 seconds the front-left tire recontacted the ground. The vehicle remained upright and relatively stable throughout post-impact trajectory. The analysis ended at 1.5 seconds, at which time:

- The roll, pitch, and yaw of the truck cabin were, respectively, 6.3 degrees (toward barrier), 2.3 degrees (rear pitching up), and 31 degrees (16 degrees relative to and away from barrier).
- The roll, pitch, and yaw of the cargo-box were, respectively, 6.4 degrees (toward barrier), 2.5 degrees (rear pitching up), and 34 degrees (19 degrees relative to and away from barrier).
- The forward velocity of the vehicle was 49.5 mph (79.7 km/h).

Case 2

The 22,198-lb single unit truck struck the barrier at 4.8 feet upstream of Post 5 at a speed of 56 mph and at an angle of 15 degrees, as illustrated in Figure 94. The sequential views of the impact event are shown in Appendix K in Figures K-1 through K-3 from an overhead viewpoint, downstream and upstream viewpoint, and isometric viewpoint, respectively. At time equal zero seconds the front bumper contacted the middle railing of the barrier and the front-right fender contacted the upper railing. At 0.01 seconds the front-right tire contacted the curb and immediately afterward contacted the middle and lower railings; also, at this time the railing began to deflect. At 0.025 seconds the front-right tire began to steer away from the barrier and to mount the curb. At 0.05 seconds the front-right tire had fully mounted the curb, and at 0.06 seconds the tire was parallel to the barrier. At 0.09 seconds the front-right tire was centered at Post 5. At 0.08 seconds one of the u-bolts connecting the front axle to the front-right suspension failed, but the second u-bolt did not fail, and the axle remained attached. At 0.13 seconds the lower front-right corner of the cargo-box passed over the top of the barrier without contact. Also, at this time the front-left tire lifted off the ground. At 0.2 seconds the rear-left tandem wheel set lifted off the ground. At 0.215 seconds the lower edge of the cargo-box contacted the top of the barrier. At 0.24 seconds the rear tandems of the vehicle contacted the curb, and the rear of the cargo-box impacted against the top railing; the roll angle of the vehicle at this time was 8.0 degrees toward the barrier. At 0.245 seconds the rear tandem wheels contacted the middle and lower railings; also, at this time the deflection of the railing began to increase, and the rear-right tandem wheel-set lifted off the ground as the rear of the vehicle began to pitch upward. At 0.275 seconds the maximum dynamic deflection of the barrier was 4.5 inches and occurred at the splice connection. At 0.295 seconds the vehicle was parallel to the barrier. At 0.39 seconds the front-right tire recontacted the roadway; the cargo-box was still riding along the top of the barrier, and the vehicle continued to roll toward and over top the barrier. At 0.43 seconds the cabin reached maximum roll angle of 16.8 degrees (toward the barrier); at 0.53 seconds the cargo-box reached maximum roll angle of 20.1 degrees. At 0.58 seconds the front-left tire recontacted the roadway. At 0.64 seconds the cargo-box experienced maximum pitch angle of 9.4 degrees (rear pitching upward); at 0.725 seconds the cabin reached maximum pitch angle of 8.6 degrees. At 0.88 seconds the vehicle lost contact with the barrier traveling at an exit speed and angle of 48 mph and 4.1 degrees toward the roadside. At 0.99 seconds the rear-right tandem wheel-set recontacted the roadway. At 1.05 seconds the rear-left tandem wheel-set recontacted the roadway. The vehicle remained upright and moderately stable throughout post-impact trajectory. The analysis ended at 1.5 seconds, at which time:

- The roll, pitch, and yaw of the truck cabin were, respectively, 1.0 degrees (away from barrier), 2.0 degrees (rear pitching up), and 14 degrees (1 degree relative to and toward the barrier).
- The roll, pitch, and yaw of the cargo-box were, respectively, 4.0 degrees (away from barrier), 2.8 degrees (rear pitching up), and 13.8 degrees (1.2 degree relative to and toward the barrier).
- The forward velocity of the vehicle was 48.8 mph (78.6 km/h).

Time History Data Evaluation

Acceleration-time histories and angular rate-time histories were collected at two locations on the vehicle: (1) on the cargo box at the center of gravity of the vehicle, and (2) a point inside the cabin of the truck, as shown in Figure 96. The acceleration and angular rate data used for the occupant risk measures came from the cabin location. The time-history data was collected from the accelerometers in a local reference coordinate system that was fixed to the vehicle with the x-direction coincident with the forward direction of the vehicle, the local y-direction was oriented toward the right side of the vehicle and the local z-direction was oriented downward. The data was collected at a frequency of 50 kHz.

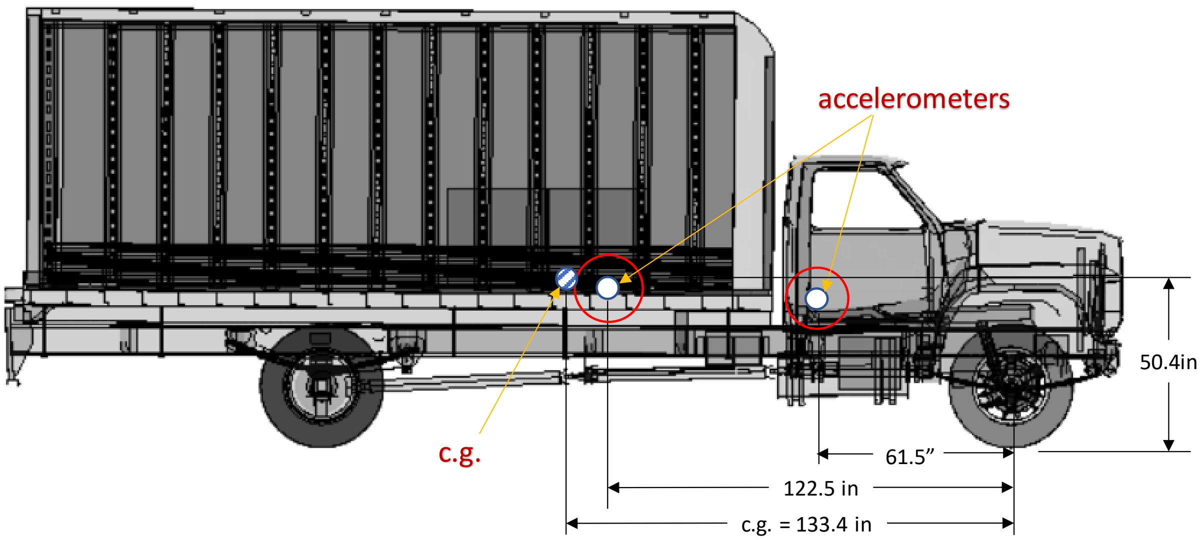


Figure 96. Location of accelerometers and c.g. in FEA model of 10000S vehicle.

Figures 97 through 99 show the longitudinal, transverse, and vertical acceleration-time histories, respectively, computed from near the center of gravity of the vehicle which falls inside the cargo-box near the front of the ballast.

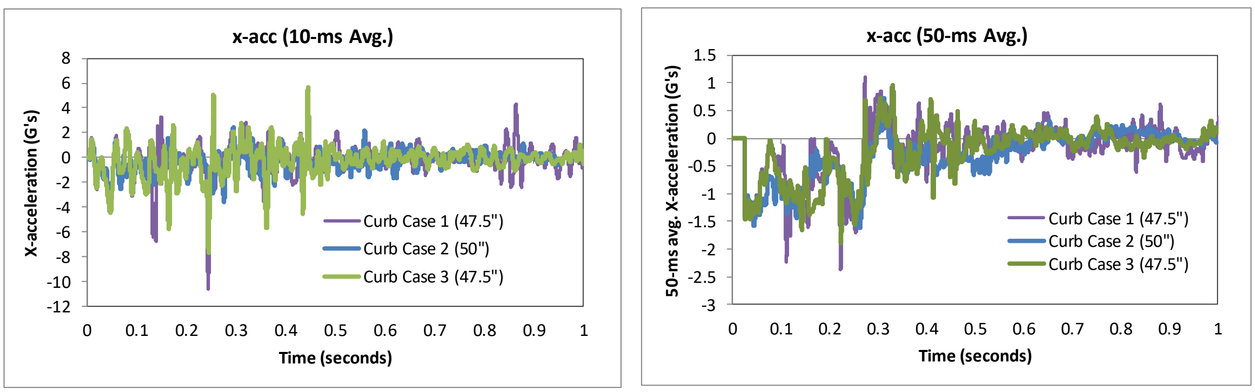


Figure 97. 10- and 50-millisecond average X-acceleration from FEA of Test 4-12 on the curb-mounted bridge rail (c.g. accelerometer).

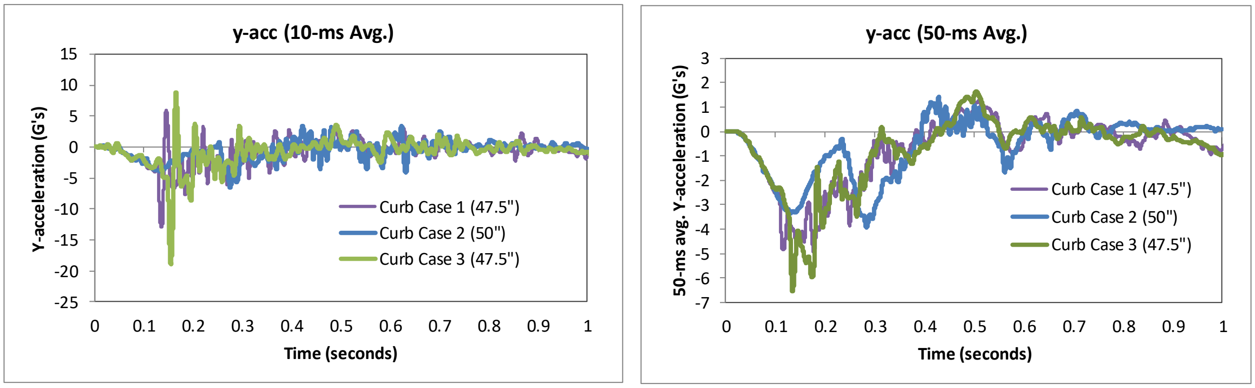


Figure 98. 10- and 50-millisecond average Y-acceleration from FEA of Test 4-12 on the curb-mounted bridge rail (c.g. accelerometer).

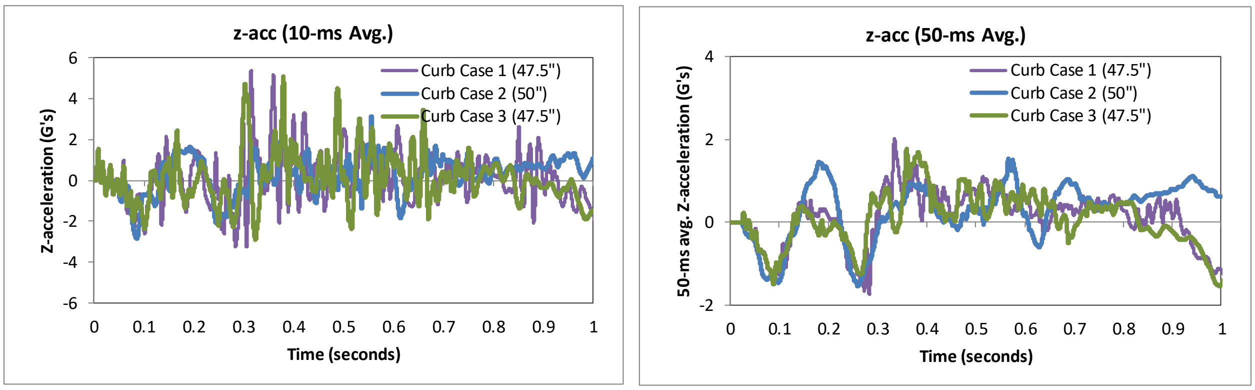


Figure 99. 10- and 50-millisecond average Z-acceleration from FEA of Test 4-12 on the curb-mounted bridge rail (c.g. accelerometer).

Figures 100 through 102 show the longitudinal, transverse, and vertical acceleration-time histories, respectively, computed from the inside the cabin of the vehicle; Figures 103 through 105 show the comparison of the angular rates and angular displacements about the x-, y-, and z-axis from the cabin location. These data are used for calculating the occupant risk metrics. MASH does not require that occupant risk be evaluated; however, they are reported herein (see following section) for completeness.

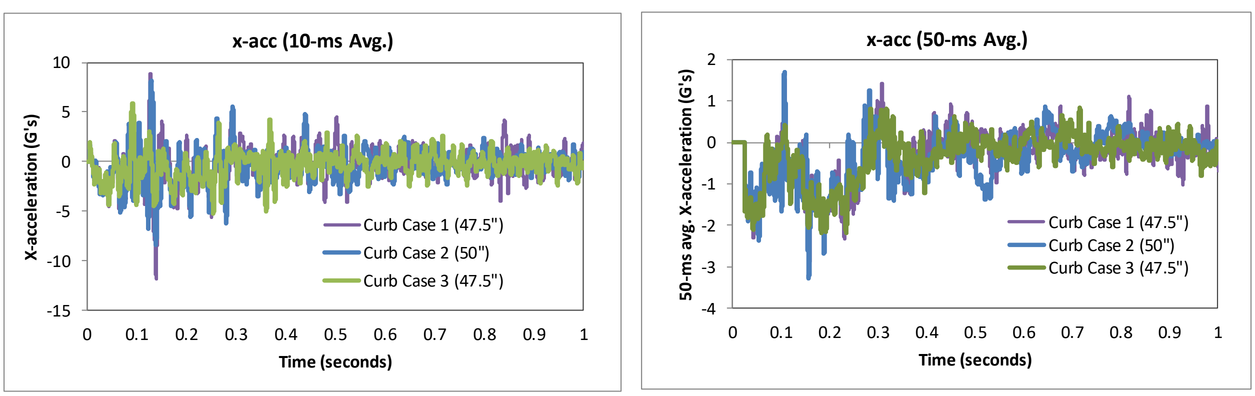


Figure 100. 10- and 50-millisecond average X-acceleration from FEA of Test 4-12 on the curb-mounted bridge rail (cabin accelerometer).

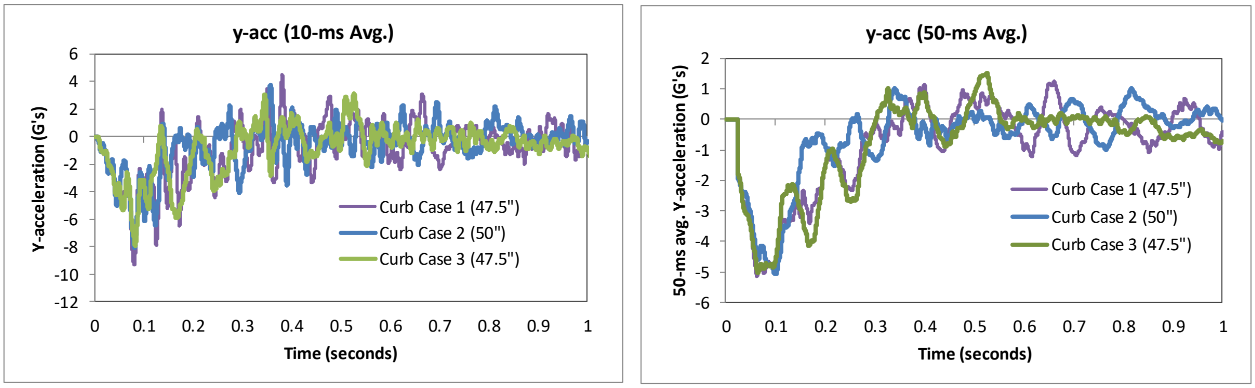


Figure 101. 10- and 50-millisecond average Y-acceleration from FEA of Test 4-12 on the curb-mounted bridge rail (cabin accelerometer).

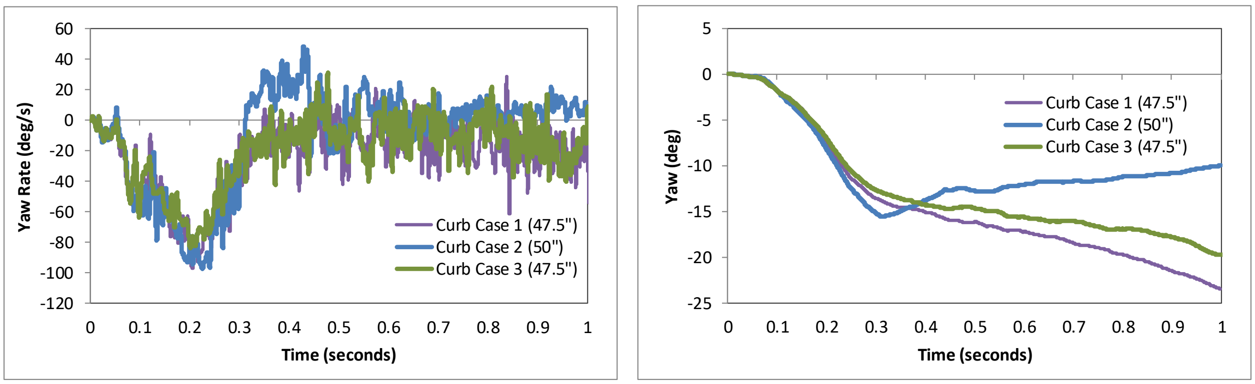


Figure 102. 10- and 50-millisecond average Z-acceleration from FEA of Test 4-12 on the curb-mounted bridge rail (cabin accelerometer).

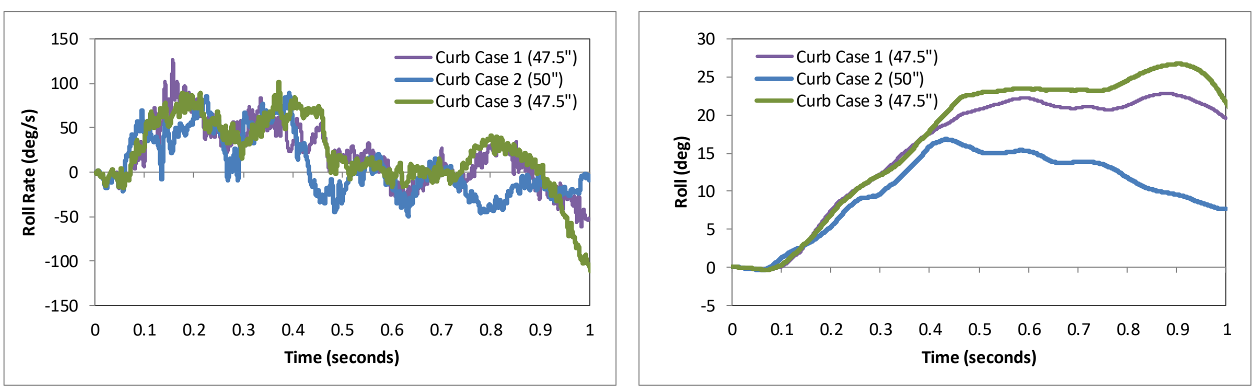


Figure 103. Roll rate and roll angle time-history from FEA of Test 4-12 on the curb-mounted bridge rail (cabin accelerometer).

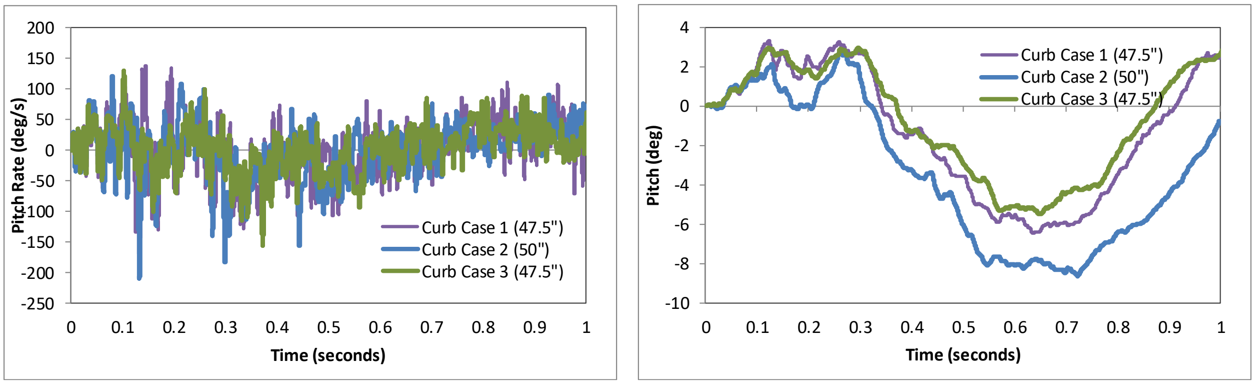


Figure 104. Pitch rate and pitch angle time-history from FEA of Test 4-12 on the curb-mounted bridge rail (cabin accelerometer).

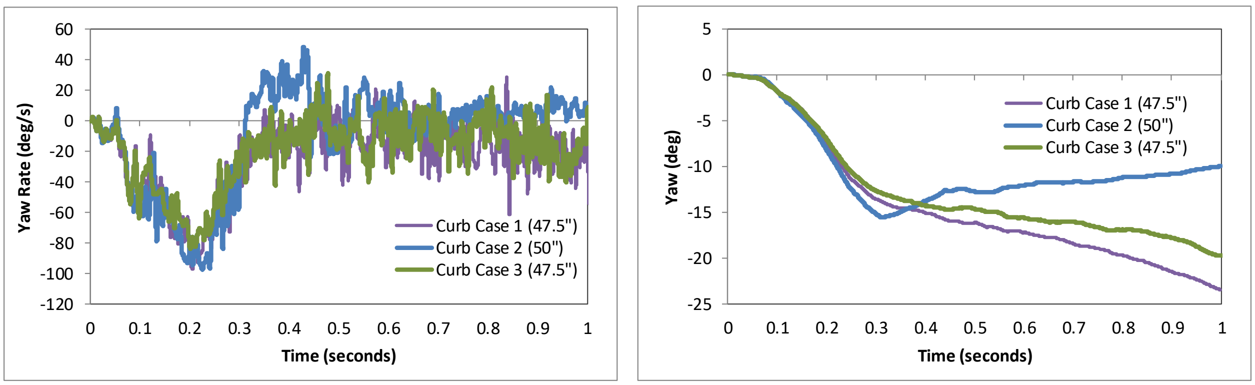


Figure 105. Yaw rate and yaw angle time-history from FEA of Test 4-12 on the curb-mounted bridge rail (cabin accelerometer).

Occupant Risk Measures

The acceleration-time histories and angular rate-time histories collected from inside the truck cabin were used to evaluate occupant risk metrics according to the procedures outlined in *MASH*. Table 29. Summary of occupant risk metrics for Test 4-12 on the S3-TL4 Bridge Rail. shows the results for the occupant risk calculations. The results indicate that the occupant risk factors met safety criteria specified in *MASH*.

Case 1

The occupant impact velocities in the longitudinal and transverse directions for Case 1 were 5.2 ft/s and 15.4 ft/s, respectively. The highest 0.010-second occupant ridedown acceleration in the longitudinal and transverse directions were 5.7 g and 6.5 g, respectively. The maximum 50-ms moving average acceleration values in the longitudinal and transverse directions were 2.9 g and 5.1 g, respectively. The maximum roll and pitch angles of the vehicle were 22.9 degrees and 6.5 degrees, respectively. All metrics were within recommended limits specified in *MASH.*

Case 2

The occupant impact velocities in the longitudinal and transverse directions for Case 2 were 5.2 ft/s and 15.4 ft/s, respectively. The highest 0.010-second occupant ridedown acceleration in the longitudinal and transverse directions were 6.2 g and 4.1 g, respectively. The maximum 50-ms moving average acceleration values in the longitudinal and transverse directions were 3.3 g and 5.1 g, respectively. The maximum roll and pitch angles of the vehicle were 16.8 degrees and 8.6 degrees, respectively. All metrics were within recommended limits specified in *MASH.*

Case 3

The occupant impact velocities in the longitudinal and transverse directions for Case 3 were 4.3 ft/s and 14.1 ft/s, respectively. The highest 0.010-second occupant ridedown acceleration in the longitudinal and transverse directions were 5.3 g and 5.9 g, respectively. The maximum 50-ms moving average acceleration values in the longitudinal and transverse directions were 2.2 g and 5.0 g, respectively. The maximum roll and pitch angles of the vehicle were 26.8 degrees and 5.5 degrees, respectively. All metrics were within recommended limits specified in *MASH.*

Table 29. Summary of occupant risk metrics for Test 4-12 on the S3-TL4 Bridge Rail.

Occupant Risk Factors		MASH T4-12 (Cabin Accelerometers)			MASH Criteria
		Curb Case 1 (47.5")	Curb Case 2 (50")	Curb Case 3 (47.5")	
Occupant Impact Velocity (ft/s)	x-direction	**5.2**	**5.2**	**4.3**	< 30 ft/s (preferred) ✓ < 40 ft/s (limit)
	y-direction	**15.4**	**15.4**	**14.1**	
	at time	at 0.1439 seconds on right side of interior	at 0.1469 seconds on right side of interior	at 0.1452 seconds on right side of interior	
THIV (ft/s)		16.1 at 0.1439 seconds on right side of interior	16.1 at 0.1469 seconds on right side of interior	14.8 at 0.1452 seconds on right side of interior	
Ridedown Acceleration (g's)	x-direction	**-5.7** (0.2456 - 0.2556 seconds)	**-6.2** (0.2751 - 0.2851 seconds)	**-5.3** (0.2493 - 0.2593 seconds)	< 15 G (preferred) ✓ < 20.49 G (limit)
	y-direction	**-6.5** (0.1673 - 0.1773 seconds)	**-4.1** (0.2886 - 0.2986 seconds)	**-5.9** (0.1619 - 0.1719 seconds)	
PHD (g's)		7.7 (0.1681 - 0.1781 seconds)	6.9 (0.2882 - 0.2982 seconds)	6.6 (0.1643 - 0.1743 seconds)	
ASI		0.61 (0.0380 - 0.0880 seconds)	0.6 (0.0770 - 0.1270 seconds)	0.6 (0.0397 - 0.0897 seconds)	
Max 50-ms moving avg. acc. (g's)	x-direction	-2.9 (0.1342 - 0.1842 seconds)	-3.3 (0.1330 - 0.1830 seconds)	-2.2 (0.1589 - 0.2089 seconds)	
	y-direction	-5.1 (0.0376 - 0.0876 seconds)	-5.1 (0.0733 - 0.1233 seconds)	-5 (0.0395 - 0.0895 seconds)	
	z-direction	-2.7 (1.1660 - 1.2160 seconds)	-2.2 (0.0546 - 0.1046 seconds)	-2.1 (0.0525 - 0.1025 seconds)	
Maximum Angular Disp. (deg)	Roll	**22.9** (0.8855 seconds)	**16.8** (0.4334 seconds)	**26.8** (0.9067 seconds)	< 75 deg ✓
	Pitch	**-6.5** (0.6366 seconds)	**-8.6** (0.7225 seconds)	**-5.5** (0.6495 seconds)	
	Yaw	**-31.1** (1.4987 seconds)	**-15.6** (0.3124 seconds)	**-28.2** (1.4987 secon	

Occupant Compartment Intrusion

The maximum deformation of the occupant compartment for impact on the curb-mounted bridge rail was less than 1 inch for Case 1 and Case 3; and was approximately 1 inch for Case 2. The maximum deformation occurred at the lower right-front corner of the toe-pan and the wheel well in all cases. Figure 106 shows a view of the vehicle interior after the impact, with several components removed to facilitate viewing. The maximum deformation was less than the critical limit of 9 inches specified in *MASH* for this area of the occupant compartment.

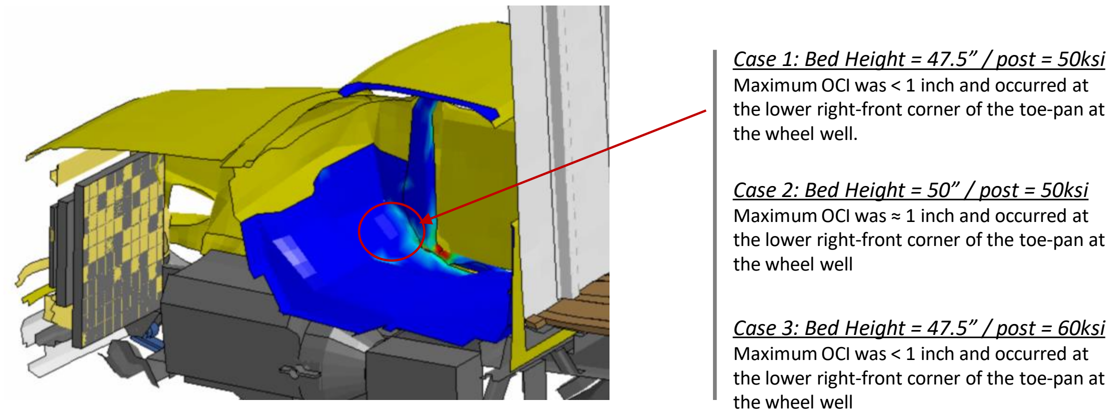


Figure 106. Occupant compartment deformation resulting from Test 4-12 on the curb-mounted bridge rail system.

Damages to the Barrier System

Figure 107 shows images of the barrier at the time of maximum deflection with a contour plot of lateral displacement on the rail elements. The maximum dynamic deflections for Cases 1, 2 and 3 were 5.0 inches, 4.5 inches and 4.4 inches, respectively, and occurred on the top rail near Post 4 when the rear of the cargo-box impacted the railing. Figure 108 shows contour plots of the maximum permanent deflection for all three barrier tests. The maximum permanent deflections for the three cases were 3.55 inches, 3.0 inches and 2.67 inches, respectively. The deformation was slightly higher for Case 1 (e.g., lower bed height) compared to Case 2 (higher bed height) due to additional contact loads from the front of the cargo-box in Case 1. In case 2 the front of the cargo-box contacted the top rail, then proceeded to slide over top of the rail, reducing impact forces. Case 3 resulted in lower deflections than Case 1 due to the additional strength of the posts.

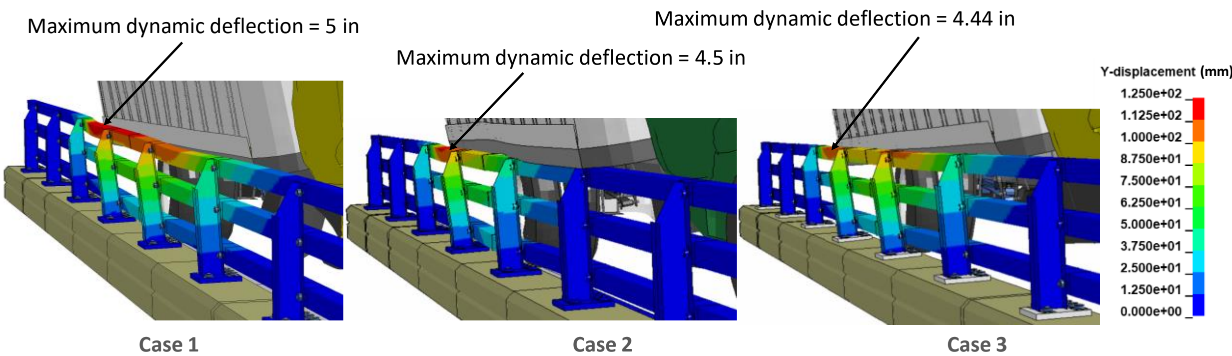


Figure 107. Contour plot of lateral displacement for the bridge rail from Test 4-12 at the time of maximum dynamic deflection for the curb-mounted system.

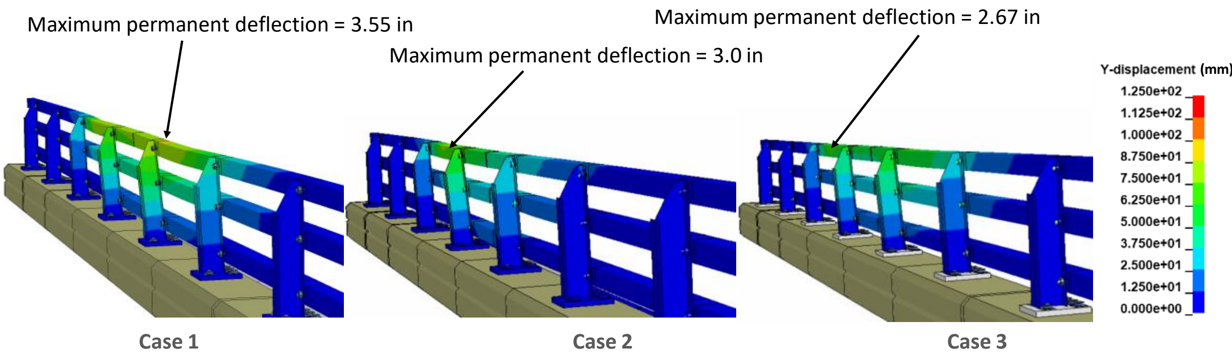


Figure 108. Contour plot of permanent deflection for the bridge rail from Test 4-12 for the curb-mounted system.

Figure 109 shows contours of true effective plastic strains on the bridge rail post and base plate for the three analysis cases. The plastic deformation of the posts was considerable and resulted in buckling of the back flange near the welded connection to the base plate. Cases 1 and 2 resulted in true plastic strain values approaching 0.2, which corresponds to a nominal strain of approximately 0.22. The maximum true plastic strain for Case 3 was approximately 0.16. These values are overlaid onto the nominal stress-strain curves for the material in Figure 110. In each case the strains at the point of the flange-web junction to the base plate at the back of the post were just beyond the point necking for the material, although the strains elsewhere along the flange and base plate were much less. The forces on the welds were not collected during the analysis, but they may be of concern for each of the cases.

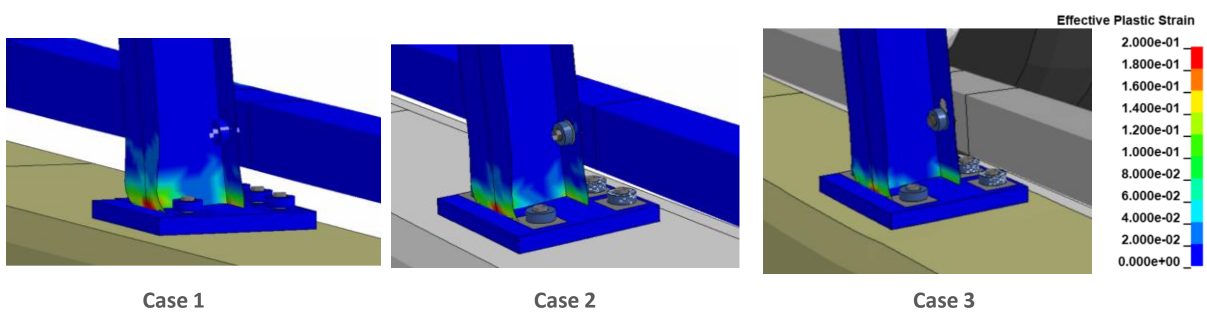


Figure 109. Contours of effective plastic strains on the critical post for Test 4-12 on the curb-mounted system.

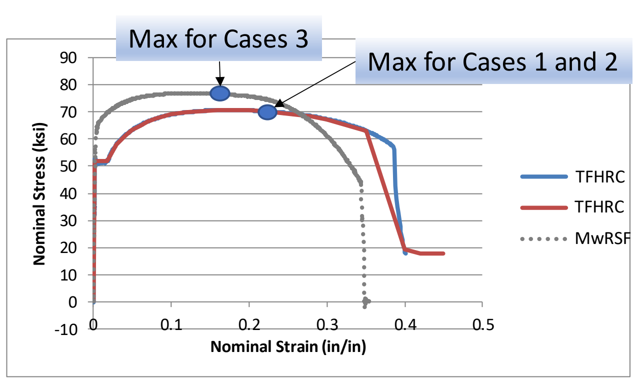


Figure 110. Maximum strain results in relation to material stress-strain curve.

Figure 111 shows contours of 1st principal strain with contours cut off at strains of 0.1. Recall that strains greater than 0.08 for the concrete indicate significant crack openings in the concrete.[*Ray18a*] The damages to the concrete for Cases 1 and 2 were negligible but were relatively high for Case 3. The maximum strain for Case 3 was 0.07 which indicates there is potential for cracks in the concrete; however, strain values were below critical values that would indicate concrete failure.

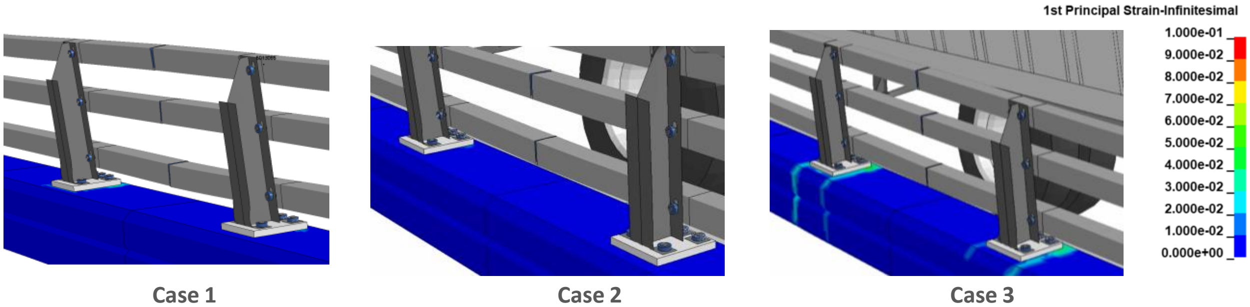


Figure 111. Contours of 1st principal strains for concrete at the critical post for Test 4-12 on the curb-mounted system.

Peak Forces on Barrier

The impact force between the vehicle and the barrier was computed to determine the peak loading on the barrier which could then be compared to the design strength of the bridge rail. The lateral force-time history results are shown in Figure 112 for the 25-millisecond moving average force and the force data filtered with cutoff frequency of 60 Hz. The maximum impact force occurred when the rear tandem wheel set impacted against the bridge rail. The maximum 25-ms moving average force was 146 kips. The lateral strength of the bridge rail should be greater than 145 kips to prevent failure for this impact case.

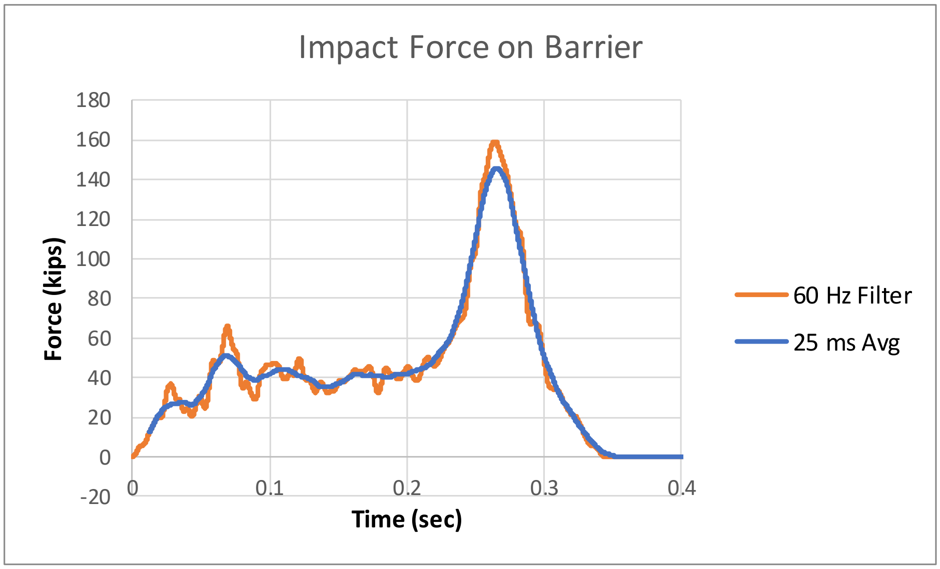


Figure 112. Lateral force-time history between vehicle and barrier for curb-mounted bridge rail.

Damages to Vehicle

Figure 113 shows contour plots of effective plastic strain for the vehicle, which were used to identify areas of the vehicle that suffered damage during the simulated impact event. The most severe damages were to the front bumper, the front fender, the front impact-side suspension, the front axle, the front impact-side corner of the cargo box, the cargo-box floor beams, and the cargo box main rail.

Figure 113. Damages to vehicle in Test 4-12 analysis of curb-mounted bridge rail for Cases 1 and 2.

Exit Box

Figures 114 and 115 show the exit box for Test 4-12 on the curb-mounted bridge rail system for Cases 1 and 2, respectively. The vehicle trajectory for Case 3 was essentially identical to Case 1 and is therefore not shown. Although the exit box analysis is not required in *MASH*, it was included here for completeness. The vehicle was smoothly redirected and its path was well within the exit box criteria of *MASH*.

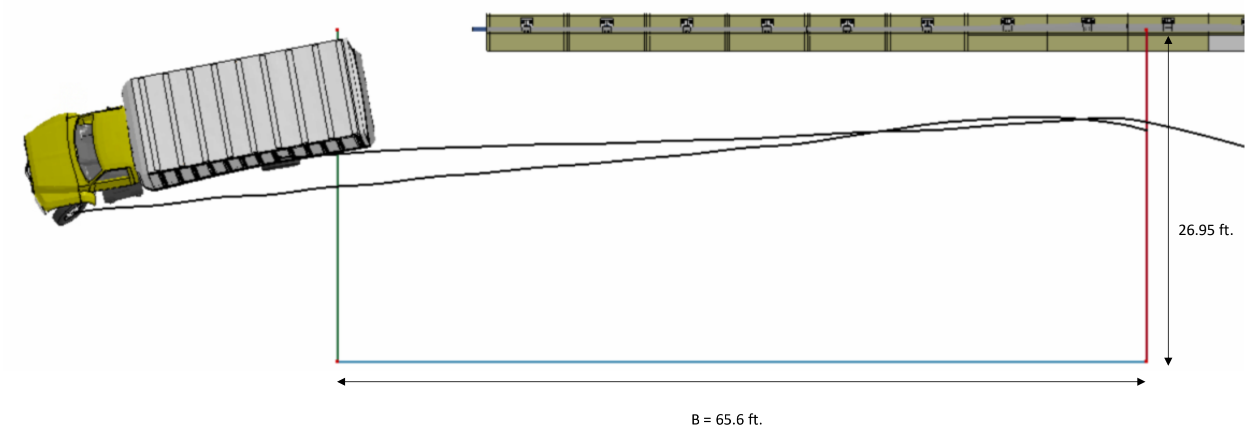


Figure 114. Exit box for Test 4-12 for Case 1 on the curb-mounted system.

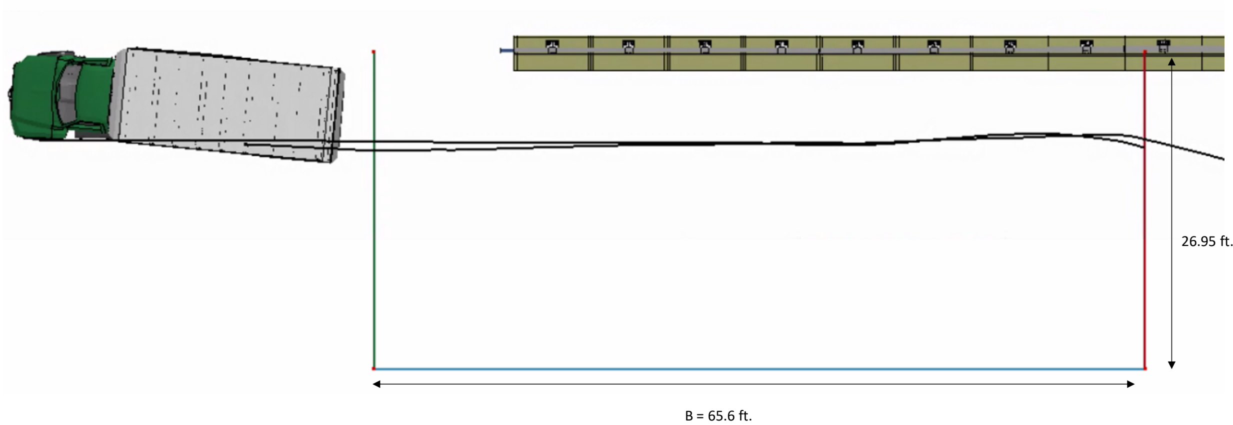


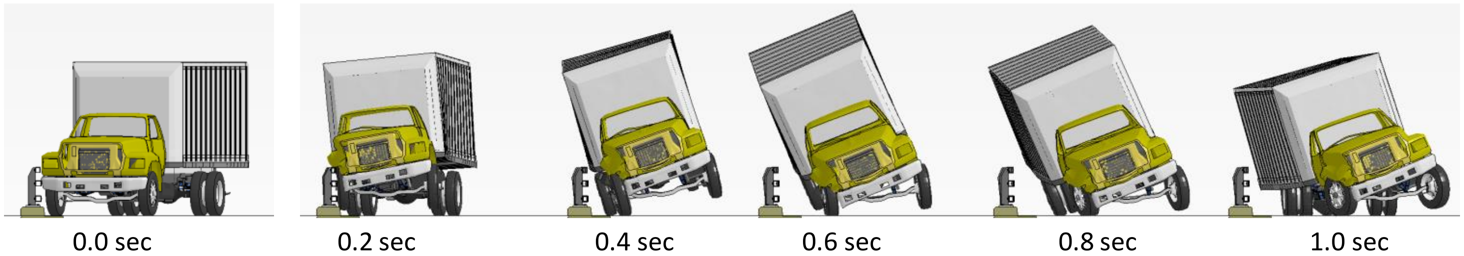
Figure 115. Exit box for Test 4-12 for Case 2 on the curb-mounted system.

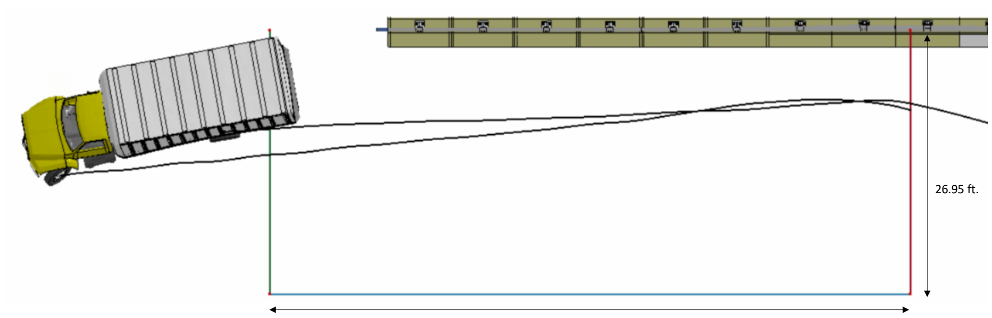
Results Summary

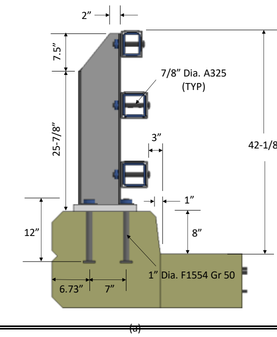
A summary of the *MASH* Test 4-12 results on the curb-mounted S3-TL4 bridge rail is shown in Table 30 and Figures 116 through 118. The barrier successfully contained and redirected the 10000S vehicle (single unit truck) with moderate damage to the bridge rail with possibility of cracks in the concrete curb for Case 3. It is not expected that these damages would extend to the bridge deck. There were no detached elements from the barrier that showed potential for penetrating into the occupant compartment or presenting undue hazard to other traffic. The vehicle remained upright and did not experience excessive roll or pitch angle displacements. Based on the results of this analysis, the barrier is expected to meet all structural and occupant risk criteria in *MASH* for Test 4-12 impact conditions.

Table 30. Summary of *MASH* Test 4-12 results on the curb-mounted bridge rail.

Evaluation Factors		Evaluation Criteria	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass
	G	It is preferable, although not essential, that the vehicle remain upright during and after collision.	Pass







General Information

Analysis Agency	Roadsafe LLC
Test Standard Test No.	MASH Test 4-12
Analysis No.	MADOT_S3TL4_Curb_T412_Case1
Analysis Date	2/27/2019

Test Article

Type	S3-TL4 bridge rail
Name	MassDOT Curb-Mounted
Installation Length	78 feet
Material or Key Elements	

Soil Type and Condition .... N.A.

Analysis Vehicle

Type / Designation	10000S
FEA Model name	F800_No-Box_181114_UboltF0p17 502_TruckBox_181114
Mass	22,198 lb

Impact Conditions

Speed	56 mph
Angle	15 degrees
Location	5.0 feet upstream of Post 5

Impact Severity .... 155.6 kip-ft

Exit Conditions

Speed	49.0 mph
Angle	2.6 degrees
Time	0.39 seconds

Occupant Risk Values

Longitudinal OIV	5.2 ft/s
Lateral OIV	15.4 ft/s
Longitudinal ORA	5.7 g
Lateral ORA	6.5 g
THIV	16.1 ft/s
PHD	7.7 g
ASI	0.61

Max50-millisecond Avg. (G)

Longitudinal	2.9 g
Lateral	5.1 g
Vertical	2.7 g

Test Article Deflections (in)

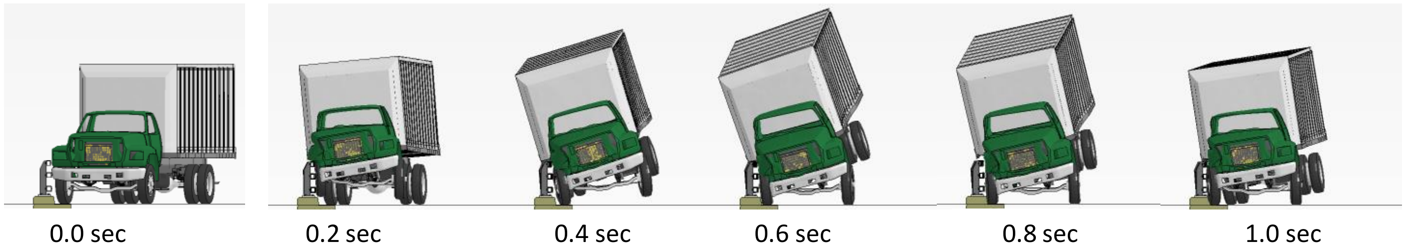
Dynamic	5.0 inches
Permanent	3.55 inch
Working Width	21 inches

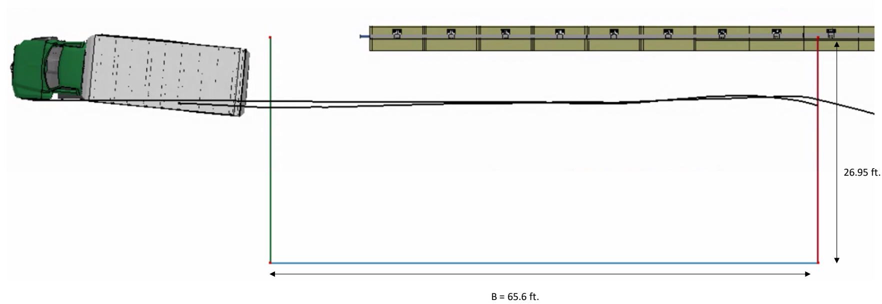
Max. OCI .... <1 inch

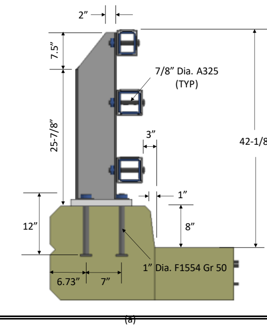
Vehicle Stability

Roll	25.8 degees
Pitch	5.5 degrees
Yaw	34.1 degrees

Figure 116. Summary results for *MASH* Test 4-12 on the curb-mounted bridge rail system for Case 1.





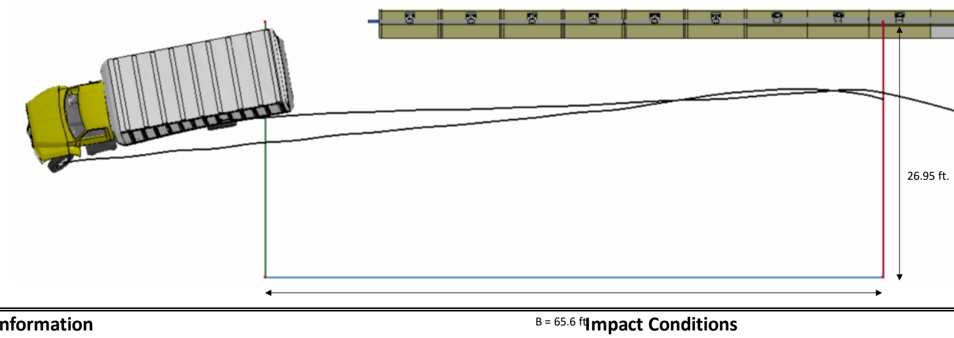


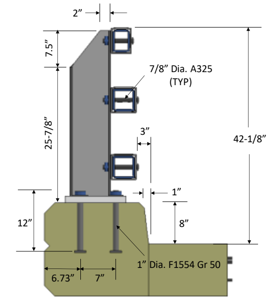
General Information	
Analysis Agency	Roadsafe LLC
Test Standard Test No.	MASH Test 4-12
Analysis No.	MADOT_S3TL4_Curb_T412_Case2
Analysis Date	3/5/2019
Test Article	
Type	S3-TL4 bridge rail
Name	MassDOT Curb-Mounted
Installation Length	78 feet
Material or Key Elements	
Soil Type and Condition	N.A.
Analysis Vehicle	
Type / Designation	10000S
FEA Model name	F800_No-Box_181114_UboltF0p17 502_TruckBox_181114 503_nodes3 (50" bed)
Mass	22,198 lb

Impact Conditions	
Speed	56 mph
Angle	15 degrees
Location	5.0 feet upstream of Post 5
Impact Severity	155.6 kip-ft
Exit Conditions	
Speed	48.0 mph
Angle	-4.1 degrees (toward barrier)
Time	0.88 seconds
Occupant Risk Values	
Longitudinal OIV	5.2 ft/s
Lateral OIV	15.4 ft/s
Longitudinal ORA	6.2 g
Lateral ORA	4.1 g
THIV	16.1 ft/s
PHD	6.9 g
ASI	0.6

Max50-millisecond Avg. (G)	
Longitudinal	3.3 g
Lateral	5.1 g
Vertical	2.2 g
Test Article Deflections (in)	
Dynamic	4.5 inches
Permanent	3.0 inch
Working Width	40 inches
Max. OCI	<1 inch
Vehicle Stability	
Roll	25.8 degees
Pitch	5.5 degrees
Yaw	34.1 degrees

Figure 117. Summary results for *MASH* Test 4-12 on the curb-mounted bridge rail system for Case 2.





General Information

Analysis Agency	Roadsafe LLC
Test Standard Test No.	MASH Test 4-12
Analysis No.	MADOT_S3TL4_Curb_T412_Case3
Analysis Date	2/27/2019
Test Article	
Type	S3-TL4 bridge rail
Name	MassDOT Curb-Mounted
Installation Length	78 feet
Material or Key Elements	60 ksi Post Material
Soil Type and Condition	N.A.
Analysis Vehicle	
Type / Designation	10000S
FEA Model name	F800_No-Box_181114_UboltF0p17 502_TruckBox_181114
Mass	22,198 lb

Impact Conditions

Speed	56 mph
Angle	15 degrees
Location	5.0 feet upstream of Post 5
Impact Severity	155.6 kip-ft
Exit Conditions	
Speed	49.0 mph
Angle	2.6 degrees
Time	0.39 seconds
Occupant Risk Values	
Longitudinal OIV	4.3 ft/s
Lateral OIV	14.1 ft/s
Longitudinal ORA	5.3 g
Lateral ORA	5.9 g
THIV	14.8 ft/s
PHD	6.6 g
ASI	0.6

Max50-millisecond Avg. (G)

Longitudinal	2.2 g
Lateral	5.0 g
Vertical	2.1 g
Test Article Deflections (in)	
Dynamic	4.4 inches
Permanent	2.67 inch
Working Width	21 inches
Max. OCI	<1 inch
Vehicle Stability	
Roll	26.8 degees
Pitch	5.5 degrees
Yaw	28.2 degrees

Figure 118. Summary results for *MASH* Test 4-12 on the curb-mounted bridge rail system for Case 3.

MASH Test 4-12 for Sidewalk-Mounted Bridge Rail

The critical impact point for this case was consistent with that of the curb-mounted bridge rail case, with target impact point of 5.0 feet upstream of a bridge rail post to maximize potential for snagging at the post.

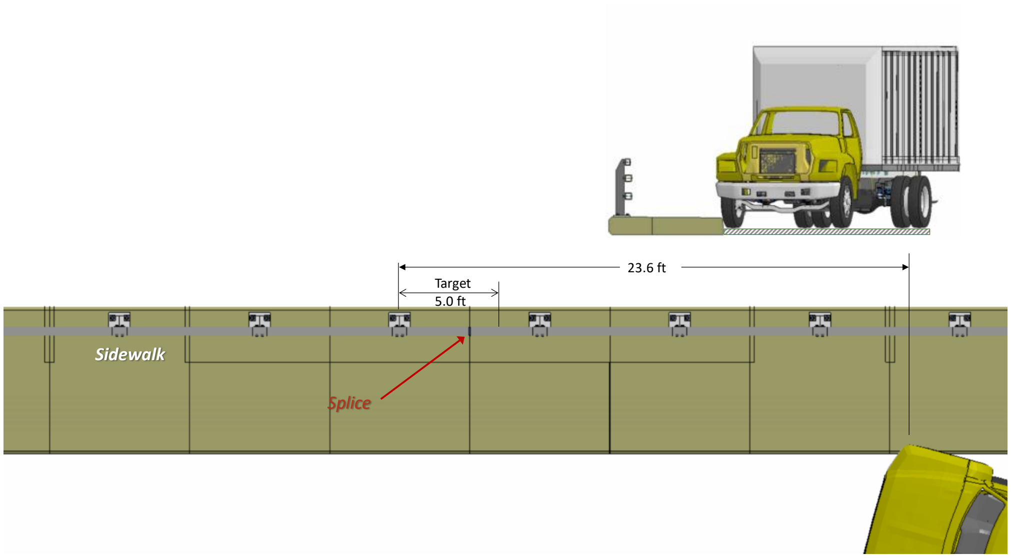


Figure 119. Initial starting position for Test 4-12 on the sidewalk-mounted S3-TL4.

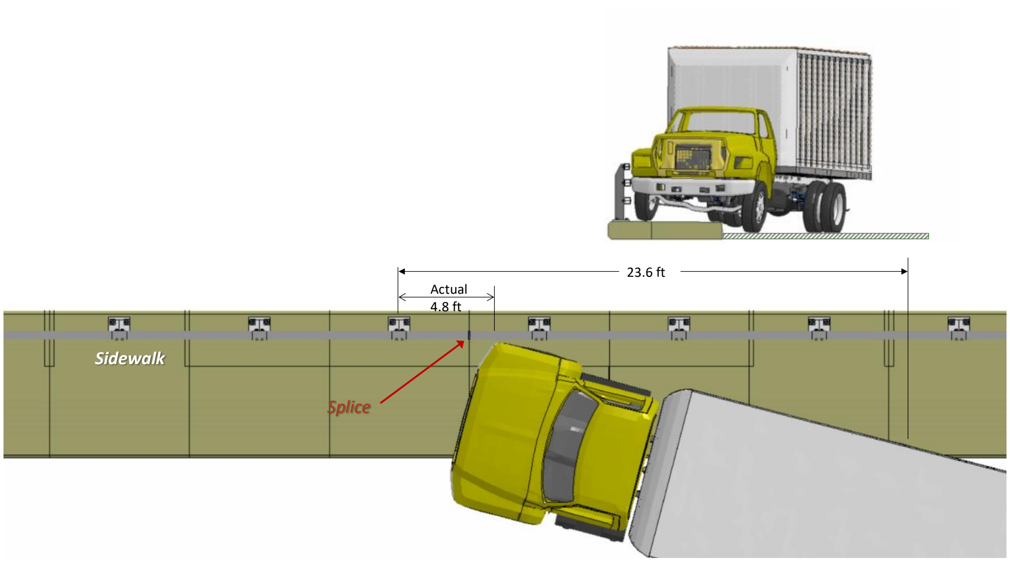


Figure 120. Impact point with bridge rail for Test 4-12 on the sidewalk-mounted S3-TL4.

For the sidewalk-mounted system, two (2) analysis cases were performed for Test 4-12:

- Case 1: Vehicle bed height = 47.5 inches and post yield strength = 51 ksi (lower bound)
- Case 2: Vehicle bed height = 50 inches and post yield strength = 51 ksi (lower bound)

The following sections provide a summary of the results and include a commentary describing the timing and occurrence of various events during the simulated impact, time-history data evaluation, occupant risk assessments, and damages sustained by both the barrier and vehicle.

Summary of Key Phenomenological Events

Case 1

The 22,198-lb single unit truck struck the curb-face of the sidewalk at 23.6 feet upstream of Post 5 at a speed of 56 mph and at an angle of 15 degrees, as illustrated in Figure 119. The sequential views of the impact event are shown in Appendix M in Figures M-1 through M-3 from an overhead viewpoint, downstream and upstream viewpoint, and isometric viewpoint, respectively.

At 0.01 seconds, the front-right tire compressed at the point of contact with the curb, and at 0.04 seconds the tire had fully mounted the sidewalk and the vehicle began to roll away from the barrier. The tire model for the SUT is relatively stiff and immediately rebounded of the surface of the sidewalk. At 0.09 seconds the front-right tire recontacted the sidewalk as the vehicle was yawing slightly counter-clockwise away from the barrier. At 0.205 seconds the rear-right tandem wheel-set contacted the curb-face of the sidewalk. At 0.245 seconds the front bumper impacted against the middle railing of the bridge rail at approximately 4.8 feet upstream of Post 5 at a speed of 53.4 mph and impact angle of 14.86 degrees, as illustrated in Figure 120. Also, at this time the rear-right tire was fully mounted onto the sidewalk. At 0.25 seconds the front fender impacted against the top railing of the bridge rail, and the front-left tire impacted against the lower railing. At 0.26 seconds the front-right tire contacted the middle railing, and the tire began to steer away from the barrier; also, at this time the barrier began to noticeably deflect. At 0.29 seconds the front-right tire was parallel to the bridge rail. At 0.315 seconds the one of the u-bolts connecting the front axle to the front-right suspension failed, but the second u-bolt held, and the front axle remained connected to the suspension. At 0.33 seconds the front-right tire was centered on Post 5, and the post was deflected back approximately 1.8 inches. At 0.345 seconds the front-left tire contacted the curb-face of the sidewalk but did not mount the curb. At 0.375 seconds both front-left tire and the rear-left tandem wheel set lifted off the ground simultaneously, as the cargo box continued to roll toward the barrier. At 0.38 seconds the lower-front corner of the cargo-box contacted the side of the top railing, and the rear-left tandem tire recontacted the ground. At the 0.45 seconds the rear-left tires again lifted off the ground. At 0.485 seconds the rear-right tandem wheel-set contacted the lower and middle railings of the barrier. At 0.5 seconds the rear of the cargo-box impacted forcefully against the top railing near Post 4, and the rear-right tandem wheel-set lifted off the sidewalk. The maximum force on the barrier occurred at 0.52 seconds with a magnitude of 130 kips. At 0.525 seconds the vehicle was parallel to the barrier, and the front of the truck began to separate from the barrier, while the cargo box remained in contact. At 0.54 seconds the barrier reached maximum deflection of 6.3 inches on the top railing at the splice connection. At 0.58 seconds the front-right tire recontacted the sidewalk. At 0.605 seconds the rear-left tandem wheel-set recontacted the sidewalk, but again lifted off at 0.65 seconds. The vehicle separated from the barrier at 0.67 seconds traveling at 48.7 mph and 2.9 degrees (away from the barrier), as the vehicle continued to roll toward the barrier. At 0.705 seconds the front-left tire recontacted the roadway as the rear of the vehicle continued to pitch upward. At 0.80 seconds the vehicle cabin reached maximum pitch angle of 6.4 degrees (rear pitching up); at 0.82 seconds the cargo-box reached maximum pitch angle of 5.8 degrees (rear pitching up). At 0.84 seconds the rear-right tandem wheel-set recontacted the sidewalk. At 1.03 seconds the cargo-box reached a maximum roll angle of 17.7 degrees; at 1.153 seconds the vehicle cabin reached a maximum roll angle of 17.1 degrees. At 1.2 seconds the rear-right tires reached the end of the sidewalk and dropped off. At 1.225 seconds the rear-left tandem wheel-set recontacted the roadway. At 1.25 seconds the front-left tire recontacted the roadway. The analysis was terminated at 1.5 seconds, at which time:

- The roll, pitch, and yaw angles for the truck cabin were 12.9 degrees (toward the barrier and increasing), 5.24 degrees (rear pitching upward and stable), and 28.5 degrees (13.2 degrees relative to and away from the barrier), respectively.
- The roll, pitch, and yaw angles for the cargo box were 10.9 degrees (toward the barrier and stable), 0.2 degrees (stable), and 29.0 degrees (14 degrees relative to the barrier), respectively.
- The forward velocity was 49.2 mph (79.1 km/hr).

Case 2

The results for Case 2 were very similar to Case 1. The 22,198-lb single unit truck struck the curb-face of the sidewalk at 523.6 feet upstream of Post 5 at a speed of 56 mph and at an angle of 15 degrees, as illustrated in Figure 119. The sequential views of the impact event are shown in Appendix N in Figures N-1 through N-3 from an overhead viewpoint, downstream and upstream viewpoint, and isometric viewpoint, respectively.

At 0.01 seconds, the front-right tire compressed at the point of contact with the curb, and at 0.04 seconds the tire had fully mounted the sidewalk and the vehicle began to roll away from the barrier. The tire model for the SUT is relatively stiff and immediately rebounded of the surface of the sidewalk. At 0.09 seconds the front-right tire recontacted the sidewalk as the vehicle was yawing slightly counter-clockwise away from the barrier. At 0.205 seconds the rear-right tandem wheel-set contacted the curb-face of the sidewalk. At 0.245 seconds the front bumper impacted against the middle railing of the bridge rail at approximately 4.8 feet upstream of Post 5 at a speed of 55.7 mph and impact angle of 14.92 degrees. Also, at this time the rear-right tire was fully mounted onto the sidewalk. At 0.25 seconds the front fender impacted against the top railing of the bridge rail, and the front-left tire impacted against the lower railing. At 0.26 seconds the front-right tire contacted the middle railing, and the tire began to steer away from the barrier; also, at this time the barrier began to noticeably deflect. At 0.29 seconds the front-right tire was parallel to the bridge rail. At 0.315 seconds the one of the u-bolts connecting the front axle to the front-right suspension failed, but the second u-bolt held, and the front axle remained connected to the suspension. At 0.33 seconds the front-right tire was centered on Post 5, and the post was deflected back approximately 1.5 inches. At 0.37 seconds the rear-left tandem wheel set lifted off the ground, as the cargo box continued to roll toward the barrier. At 0.375 seconds the lower-front corner of the cargo-box contacted the side of the top railing. At 0.45 seconds the front-right tire recontacted the sidewalk. At 0.495 seconds the rear-right tandem wheel-set contacted the lower and middle railings of the barrier. At 0.505 seconds the rear of the cargo-box impacted forcefully against the top railing near Post 4, and the rear-right tandem wheel-set lifted off the sidewalk. At 0.53 seconds the vehicle was parallel to the barrier, and the front of the truck began to separate from the barrier, while the cargo box remained in contact. At

0.54 seconds the barrier reached maximum deflection of 6.2 inches on the top railing at the splice connection. At 0.595 seconds the rear-left tandem wheel-set recontacted the sidewalk, but again lifted off at 0.645 seconds. The vehicle separated from the barrier at 0.66 seconds traveling at 48.5 mph and 2.0 degrees (away from the barrier), as the vehicle continued to roll toward the barrier. At 0.665 seconds the front-left tire lifted off the roadway, as the vehicle continued to roll toward the barrier. At 0.73 seconds the vehicle cabin reached maximum pitch angle of 7.1 degrees (rear pitching up). At 0.735 seconds the rear-right tandem wheel-set recontacted the sidewalk. At 0.79 seconds the cargo-box reached maximum pitch angle of 5.4 degrees (rear pitching up). At 0.98 seconds the front tire of the vehicle reached the end of the sidewalk and dropped off. At 1.0 seconds the cabin reached a maximum roll angle of 21.3 degrees; at 1.02 seconds the cargo-box reached a maximum roll angle of 23.9 degrees. At 1.19 seconds the rear tires reached the end of the sidewalk and dropped off. At 1.275 seconds the front-left tire recontacted the roadway. At 1.45 seconds the rear-left tandem wheel-set recontacted the roadway. The analysis was terminated at 1.5 seconds, at which time:

- The roll, pitch, and yaw angles for the truck cabin were 15.9 degrees (toward the barrier and stable), 2.1 degrees (rear pitching upward and stable), and 34.6 degrees (19.6 degrees relative to and away from the barrier), respectively.
- The roll, pitch, and yaw angles for the cargo box were 14.6 degrees (toward the barrier and increasing), 1.4 degrees (stable), and 35 degrees (20 degrees relative to the barrier), respectively.
- The forward velocity was 47.8 mph (76.9 km/hr).

Time History Data Evaluation

Acceleration-time histories and angular rate-time histories were collected at two locations on the vehicle: (1) on the cargo box at the center of gravity of the vehicle, and (2) a point inside the cabin of the truck, as shown in Figure 96. The acceleration and angular rate data used for the occupant risk measures came from the cabin location. The data was collected at a frequency of 50 kHz. Figures 121 through 123 show the longitudinal, transverse, and vertical acceleration-time histories, respectively, computed from the center of gravity of the vehicle which falls inside the cargo-box near the front of the ballast.

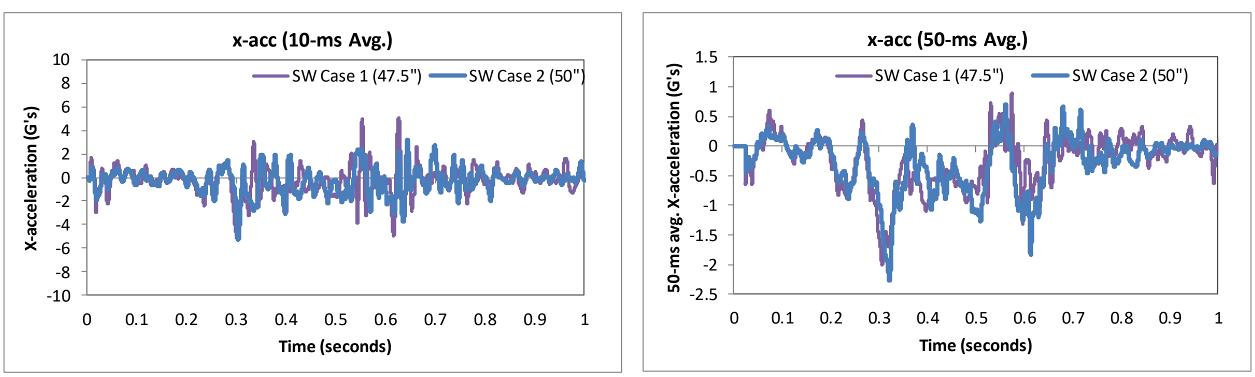


Figure 121. 10- and 50-millisecond average X-acceleration from FEA of Test 4-12 on the sidewalk-mounted bridge rail (c.g. accelerometer).

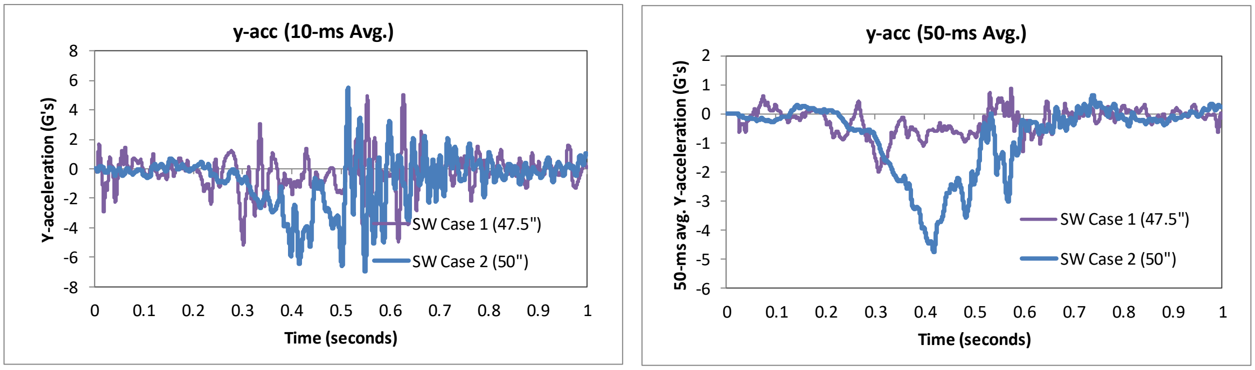


Figure 122. 10- and 50-millisecond average Y-acceleration from FEA of Test 4-12 on the sidewalk-mounted bridge rail (c.g. accelerometer).

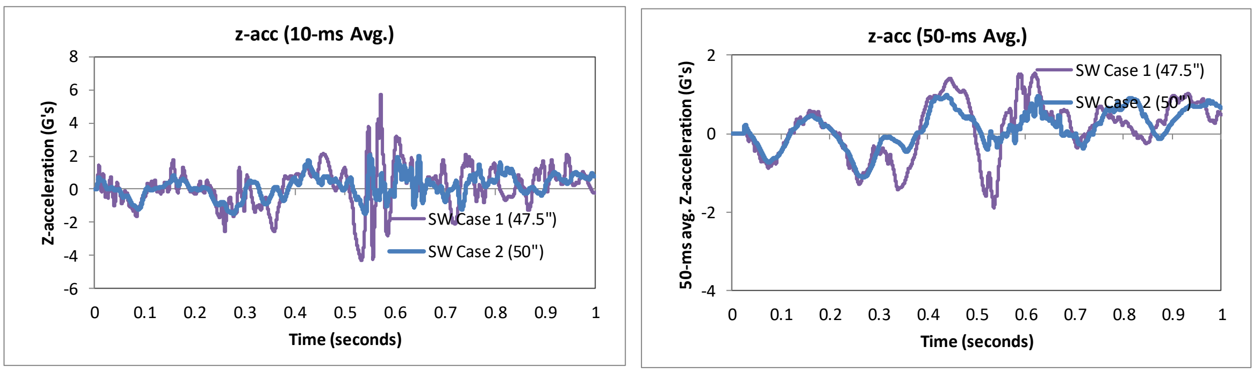


Figure 123. 10- and 50-millisecond average Z-acceleration from FEA of Test 4-12 on the sidewalk-mounted bridge rail (c.g. accelerometer).

Figures 124 through 126 show the longitudinal, transverse, and vertical acceleration-time histories, respectively, computed from the inside the cabin of the vehicle; Figures 127 through 129 show the comparison of the angular rates and angular displacement about the x-, y-, and z-axis from the cabin location. These data are used for calculating the occupant risk metrics. Although not required, the occupant risk metrics are reported here for completeness.

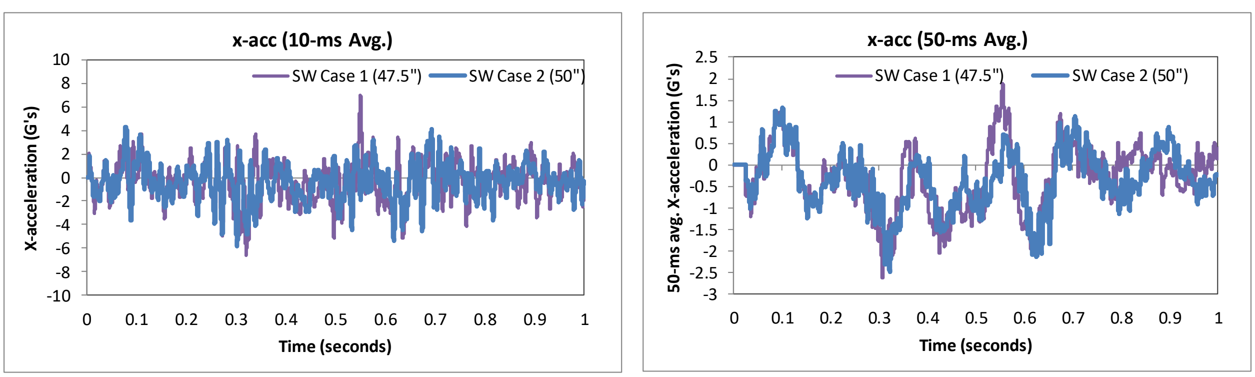


Figure 124. 10- and 50-millisecond average X-acceleration from FEA of Test 4-12 on the sidewalk-mounted bridge rail (cabin accelerometer).

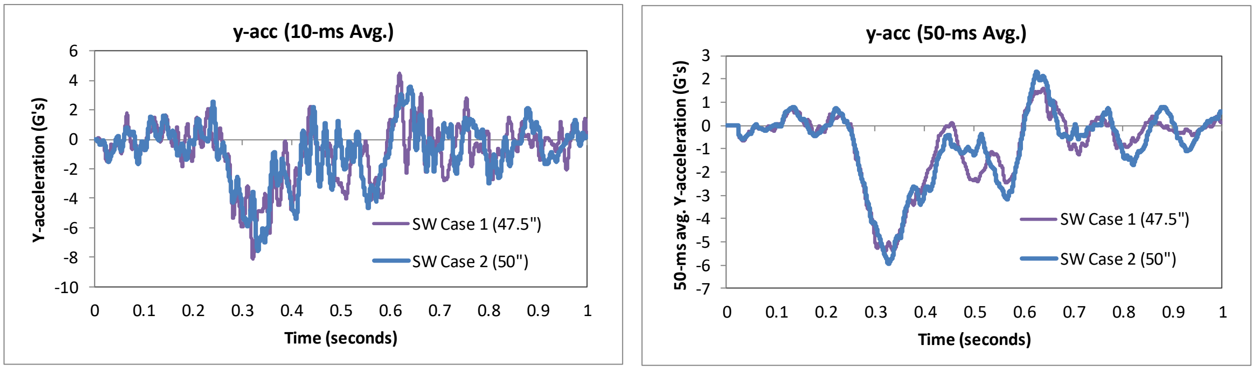


Figure 125. 10- and 50-millisecond average Y-acceleration from FEA of Test 4-12 on the sidewalk-mounted bridge rail (cabin accelerometer).

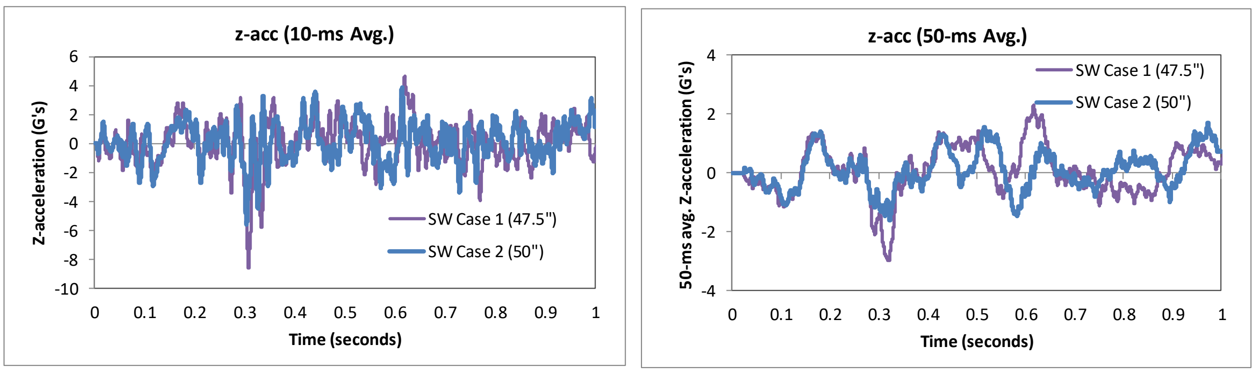


Figure 126. 10- and 50-millisecond average Z-acceleration from FEA of Test 4-12 on the sidewalk-mounted bridge rail (cabin accelerometer).

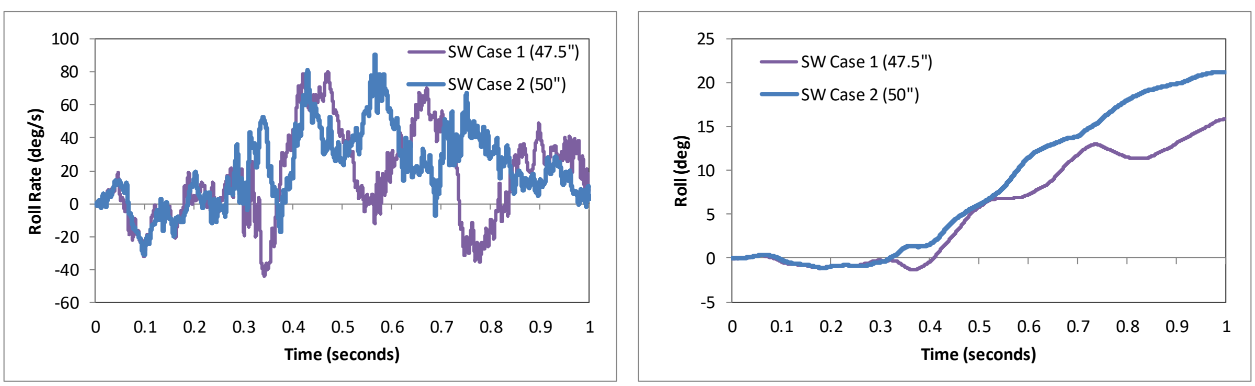


Figure 127. Roll rate and roll angle time-history from FEA of Test 4-12 on the sidewalk-mounted bridge rail (cabin accelerometer).

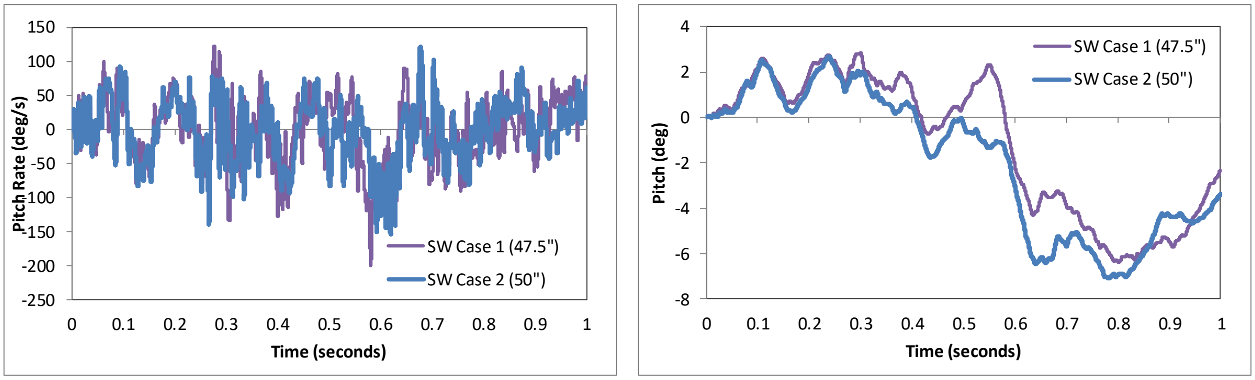


Figure 128. Pitch rate and pitch angle time-history from FEA of Test 4-12 on the sidewalk-mounted bridge rail (cabin accelerometer).

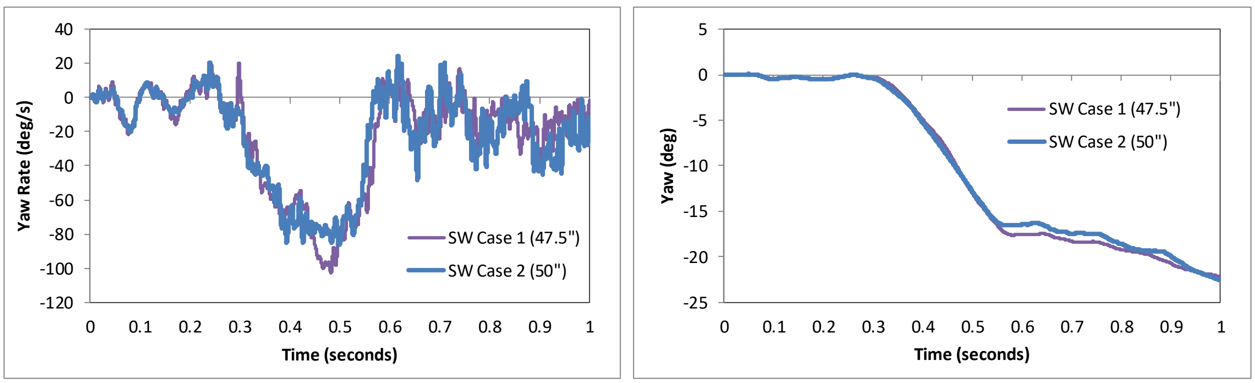


Figure 129. Yaw rate and yaw angle time-history from FEA of Test 4-12 on the sidewalk-mounted bridge rail (cabin accelerometer).

Occupant Risk Measures

The acceleration-time histories and angular rate-time histories collected from inside the truck cabin were used to evaluate occupant risk metrics according to the procedures outlined in *MASH*. The results are shown in Table 31, which indicate that the occupant risk factors met safety criteria specified in *MASH*. [*AASHTO16*]

Case 1

The occupant impact velocities in the longitudinal and transverse directions for Case 1 were 4.3 ft/s and 16.4 ft/s, respectively. The highest 0.010-second occupant ridedown acceleration in the longitudinal and transverse directions were 7.0 g and 4.8 g, respectively. The maximum 50-ms moving average acceleration values in the longitudinal and transverse directions were 2.6 g and 5.4 g, respectively. The maximum roll and pitch angles of the vehicle were 17.1 degrees and 6.4 degrees, respectively. All metrics were within recommended limits specified in *MASH. [AASHTO16]*

Case 2

The occupant impact velocities in the longitudinal and transverse directions for Case 2 were 4.9 ft/s and 15.4 ft/s, respectively. The highest 0.010-second occupant ridedown acceleration in the longitudinal and transverse directions were 5.4 g and 5.4 g, respectively. The maximum 50-ms moving average acceleration values in the longitudinal and transverse directions were 2.5 g and 6.0 g, respectively. The maximum roll and pitch angles of the vehicle were 21.3 degrees and 7.1 degrees, respectively. All metrics were within recommended limits specified in *MASH. [AASHTO16]*

Table 31. Summary of occupant risk metrics for Test 4-12 on the sidewalk-mounted S3-TL4 Bridge Rail.

Occupant Risk Factors		MASH T4-12 (Cabin Accelerometers)	
		SW Case 1 (47.5")	SW Case 2 (50")
Occupant Impact Velocity (ft/s)	x-direction	**4.3**	**4.9**
	y-direction	**16.4**	**15.4**
	at time	at 0.3775 seconds on right side of interior	at 0.3788 seconds on right side of interior
THIV (ft/s)		17.1 at 0.3775 seconds on right side of interior	16.4 at 0.3788 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	**7** (0.5452 - 0.5552 seconds)	**-5.4** (0.6122 - 0.6222 seconds)
	y-direction	**-4.8** (0.3945 - 0.4045 seconds)	**-5.4** (0.4042 - 0.4142 seconds)
PHD (g's)		7 (0.5452 - 0.5552 seconds)	5.8 (0.6122 - 0.6222 seconds)
ASI		0.68 (0.2932 - 0.3432 seconds)	0.69 (0.2992 - 0.3492 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-2.6 (0.2830 - 0.3330 seconds)	-2.5 (0.2978 - 0.3478 seconds)
	y-direction	-5.4 (0.2950 - 0.3450 seconds)	-6 (0.3017 - 0.3517 seconds)
	z-direction	-3 (0.2946 - 0.3446 seconds)	1.7 (0.9476 - 0.9976 seconds)
Maximum Angular Disp. (deg)	Roll	**17.1** (1.1528 seconds)	**21.3** (1.0007 seconds)
	Pitch	**-6.4** (0.8021 seconds)	**-7.1** (0.7832 seconds)
	Yaw	**-28.5** (1.4966 second	**-34.6** (1.4987 seconds)

MASH Criteria

Occupant Impact Velocity: < 30 ft/s (preferred) ✓
< 40 ft/s (limit)

Ridedown Acceleration: < 15 G (preferred) ✓
< 20.49 G (limit)

Roll and Pitch: < 75 deg ✓

Occupant Compartment Intrusion

The maximum deformation of the occupant compartment for impact on the sidewalk-mounted bridge rail was approximately 2 inches for Case 1 and was approximately 1 inch for Case 2. The maximum deformation occurred at the lower right-front corner of the toe-pan at the wheel well for both cases. Figure 130 shows a view of the vehicle interior after the impact, with several components removed to facilitate viewing. The maximum deformation was less than the critical limit of 9 inches specified in *MASH* for this area of the occupant compartment. [*AASHTO16*]

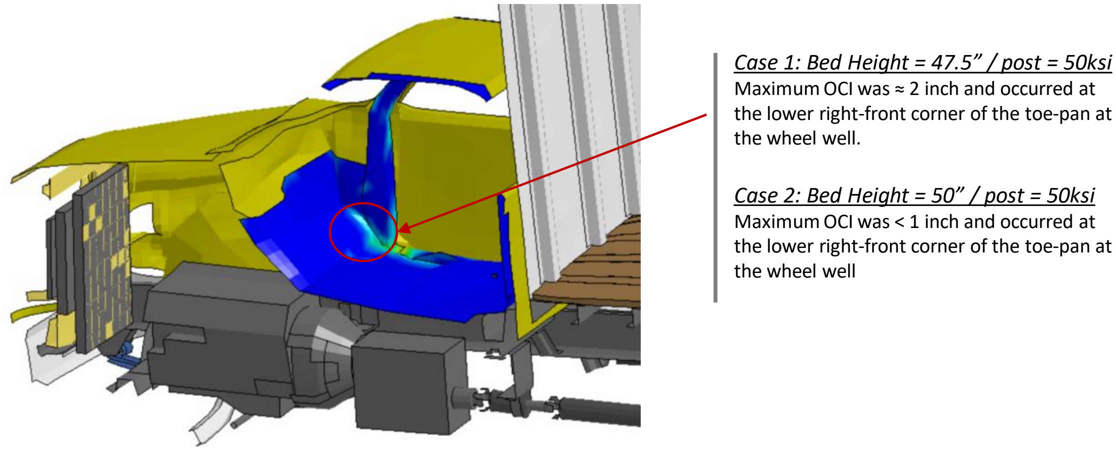


Figure 130. Occupant compartment deformation resulting from Test 4-12 on the sidewalk-mounted bridge rail system.

Damages to the Barrier System

Figure 131 shows images of the barrier at the time of maximum deflection with a contour plot of lateral displacement on the rail elements. The vehicle bed height had minimal influence on barrier loads and vehicle attitude for the sidewalk-mounted case. In both Case 1 and Case 2, the front of the cargo-box bed and the rear of the bed impacted the side of the top railing, resulting in maximum dynamic deflections of 6.3 inches and 6.3 inches, respectively. Figure 132 shows contour plots of the maximum permanent deflection for both barrier tests. The maximum permanent deflections for the two cases were 4.9 inches and 4.8 inches, respectively.

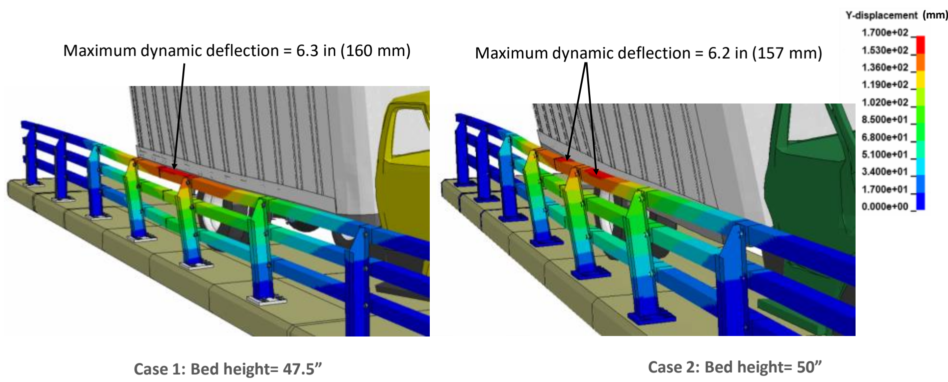


Figure 131. Contour plot of lateral displacement for the bridge rail from Test 4-12 at the time of maximum dynamic deflection for the sidewalk-mounted system.

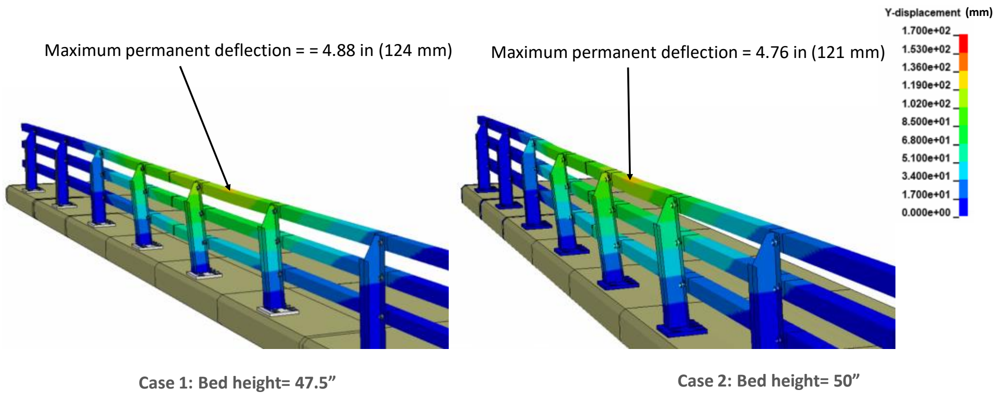


Figure 132. Contour plot of permanent deflection for the bridge rail from Test 4-12 for the sidewalk-mounted system.

Figure 133 shows contour plots of true effective plastic strains on the bridge rail post and base plate for the two analysis cases. The plastic deformation of the posts was considerable and resulted in buckling of the back flange near the welded connection to the base plate. Similar to the curb-mounted system, Cases 1 and 2 resulted in true plastic strain values approaching 0.2, which corresponds to a nominal strain of approximately 0.22. The strains at the point of the flange-web junction to the base plate at the back of the post were just beyond the point necking for the material (refer to the stress-strain curve for the material in Figure 110), although the strains elsewhere along the flange and base plate were much less. The forces on the welds were not collected during the analysis, but they may also be of concern.

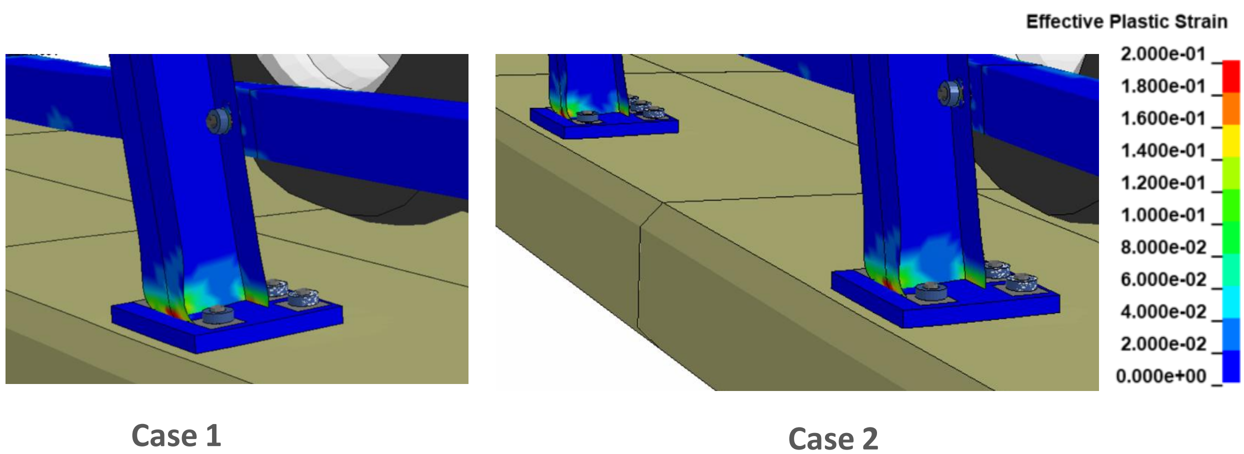
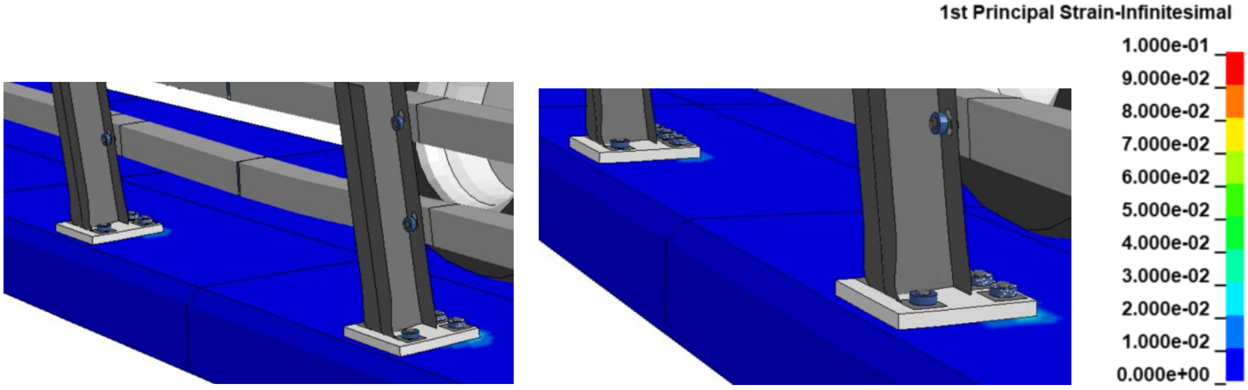


Figure 133. Contours of effective plastic strains on the critical post for Test 4-12 on the sidewalk-mounted system.

Figure 134 shows contours of 1st principal strain with contours cut off at strains of 0.1. The damages to the concrete for Cases 1 and 2 were relatively low with values of approximately 0.02, which indicate a low probability for concrete cracks.[*Ray18a*]

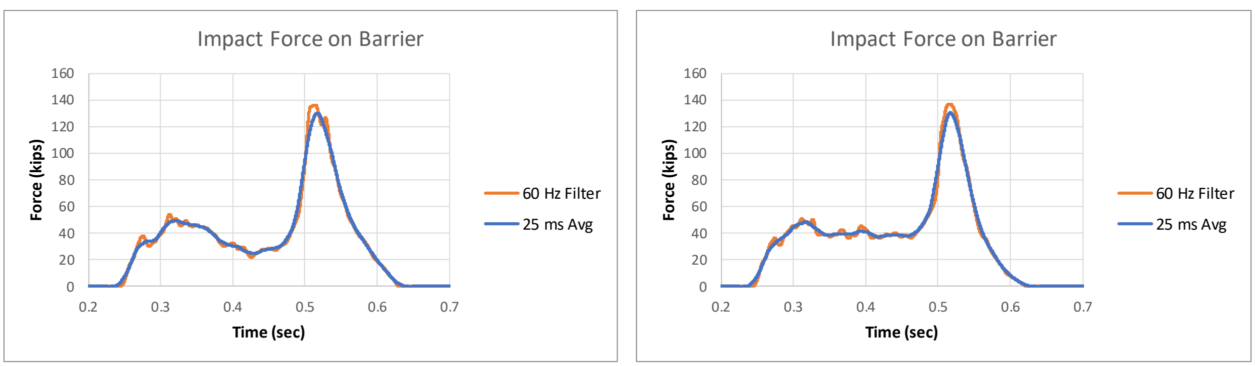


Case 1 Case 2

Figure 134. Contours of 1st principal strains for concrete at the critical post for Test 4-12 on the sidewalk-mounted system.

Peak Forces on Barrier

The impact force between the vehicle and the barrier was computed to determine the peak loading on the barrier which could then be compared to the design strength of the bridge rail. The lateral force-time history results are shown in Figure 135 for the 25-millisecond moving average force and the force data filtered with cutoff frequency of 60 Hz. The maximum impact force occurred when the rear tandem wheel set impacted against the bridge rail. For both tests, the maximum 25-ms moving average force was 130 kips. The lateral strength of the bridge rail should be greater than 130 kips to prevent failure for this impact case.



Case 1 Case 2

Figure 135. Lateral force-time history between vehicle and barrier for sidewalk-mounted bridge rail to AGT case.

Damages to Vehicle

Figure 136 shows contour plots of effective plastic strain for the vehicle, which were used to identify areas of the vehicle that suffered damage during the simulated impact event. The most severe damages were to the front bumper, the front fender, the front impact-side suspension, the front axle, the front impact-side corner of the cargo box, the cargo-box floor beams, and the cargo-box main rail.

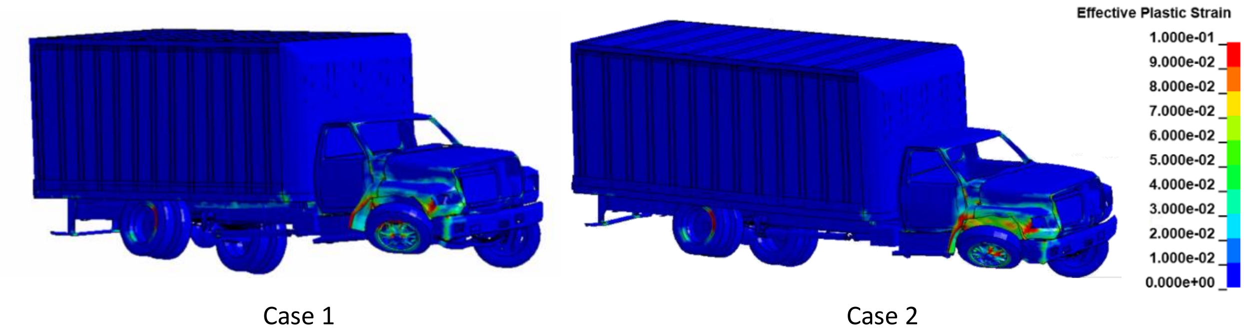


Figure 136. Damages to vehicle in Test 4-12 analysis of sidewalk-mounted bridge rail for Cases 1 and 2.

Exit Box

Figures 137 and 138 show the exit box for Test 4-12 on the sidewalk-mounted bridge rail system for Cases 1 and 2, respectively. Although not required in *MASH*, the exit box was included here for completeness. The vehicle was smoothly redirected and its path was well within the exit box criteria of *MASH*. [*AASHTO16*]

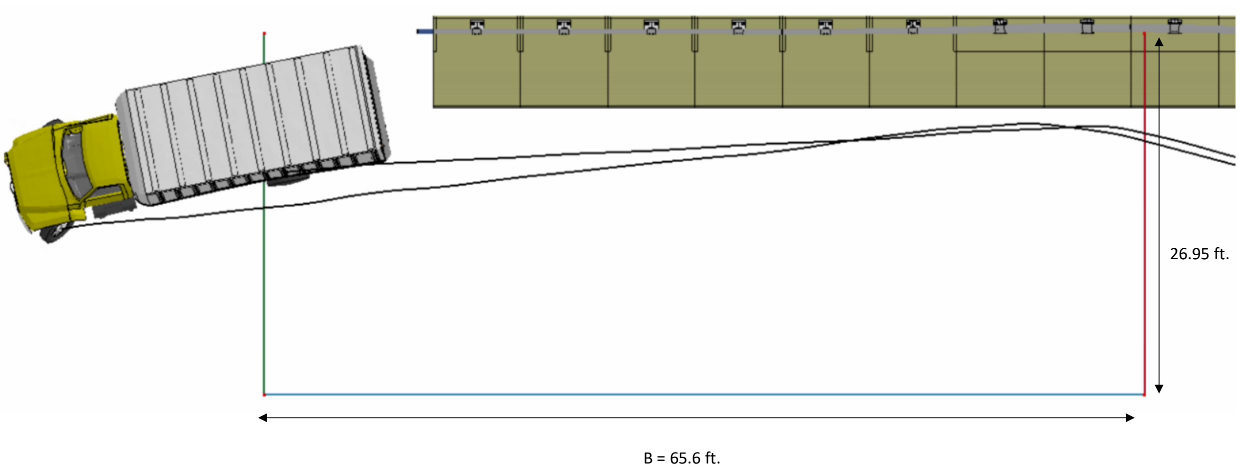


Figure 137. Exit box for Test 4-12 for Case 1 on the sidewalk-mounted system.

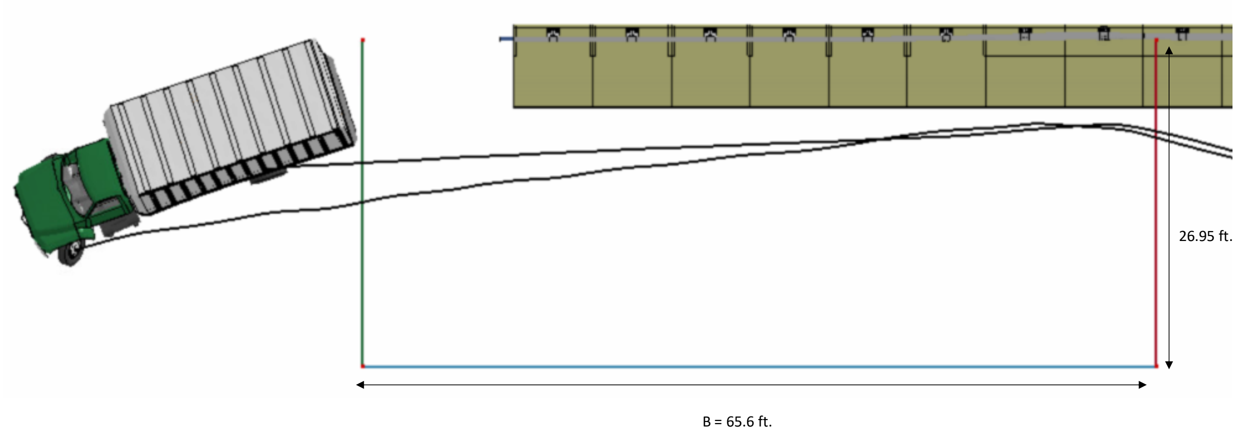


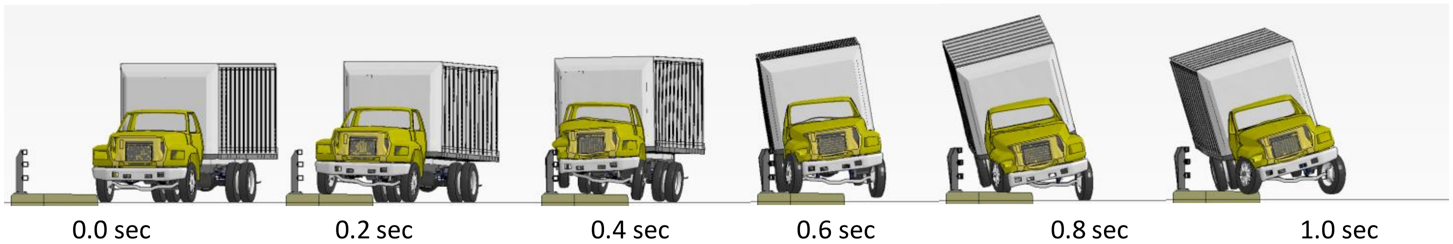
Figure 138. Exit box for Test 4-12 for Case 2 on the sidewalk-mounted system.

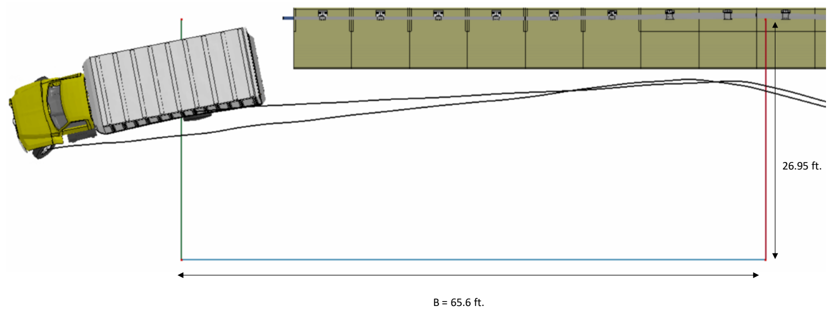
Results Summary

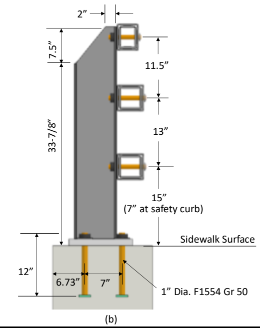
A summary of the *MASH* Test 4-12 results on the sidewalk-mounted S3-TL4 bridge rail is shown in Table 32 and Figures 139 and 140. The barrier successfully contained and redirected the 10000S vehicle (single unit truck) with moderate damage to the bridge rail with low probability of cracks in the concrete curb. Any probable damages to the curb are not expected to extend to the bridge deck. There were no detached elements from the barrier that showed potential for penetrating into the occupant compartment or presenting undue hazard to other traffic. The vehicle remained upright and did not experience excessive roll or pitch angle displacements. The vehicle's cargo-bed height had minimal influence on the barrier loads and vehicle post trajectory. In both analysis cases, the front of the cargo-box bed and the rear of the bed impacted the side of the top railing, resulting in maximum dynamic deflections of approximately 6.25 inches and maximum permanent deflection of approximately 4.9 inches. In both analysis cases, the bridge rail posts experienced buckling near the base. Based on the results of this analysis, the barrier is expected to meet all structural and occupant risk criteria in *MASH* for Test 4-12 impact conditions. [*AASHTO16*]

Table 32. Summary of *MASH* Test 4-12 results on the sidewalk-mounted bridge rail.

Evaluation Factors		Evaluation Criteria	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass
	G	It is preferable, although not essential, that the vehicle remain upright during and after collision.	Pass





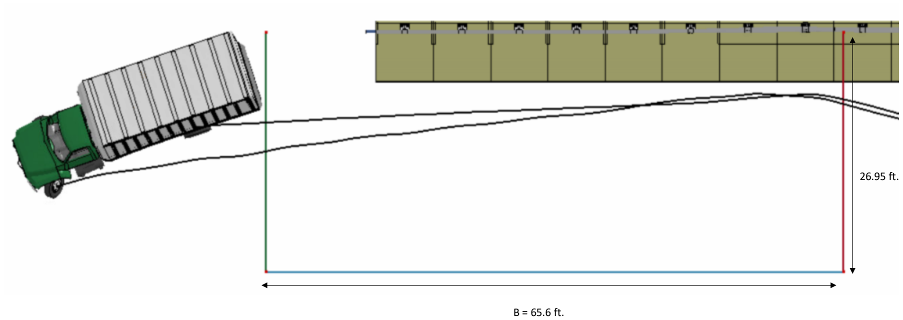


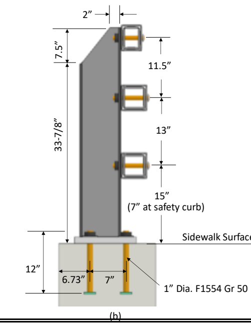
General Information	
Analysis Agency	Roadsafe LLC
Test Standard Test No.	MASH Test 4-12
Analysis No.	MADOT_S3TL4_SW_T412_Case1
Analysis Date	3/2/2019
Test Article	
Type	S3-TL4 bridge rail
Name	MassDOT Sidewalk-Mounted
Installation Length	78 feet
Material or Key Elements	
Soil Type and Condition	N.A.
Analysis Vehicle	
Type / Designation	10000S
FEA Model name	F800_No-Box_181114_UboltF0p17 502_TruckBox_181114
Mass	22,198 lb

Impact Conditions	
Speed	56 mph
Angle	15 degrees
Location	5.0 feet upstream of Post 5
Impact Severity	155.6 kip-ft
Exit Conditions	
Speed	48.7 mph
Angle	2.9 degrees
Time	0.67 seconds
Occupant Risk Values	
Longitudinal OIV	4.3 ft/s
Lateral OIV	16.4 ft/s
Longitudinal ORA	7.0 g
Lateral ORA	4.8 g
THIV	17.1 ft/s
PHD	7.0 g
ASI	0.68

Max50-millisecond Avg. (G)	
Longitudinal	2.6 g
Lateral	5.4 g
Vertical	3.0 g
Test Article Deflections (in)	
Dynamic	6.3 inches
Permanent	4.9 inch
Working Width	22.3 inches
Max. OCI	≈2 inches
Vehicle Stability	
Roll	17.1 degees
Pitch	6.4 degrees
Yaw	28.5 degrees

Figure 139. Summary results for *MASH* Test 4-12 on the sidewalk-mounted bridge rail system for Case 1.





General Information

Analysis Agency	Roadsafe LLC
Test Standard Test No.	MASH Test 4-12
Analysis No.	MADOT_S3TL4_SW_T412_Case2
Analysis Date	3/8/2019

Test Article

Type	S3-TL4 bridge rail
Name	MassDOT Sidewalk-Mounted
Installation Length	78 feet
Material or Key Elements	

Soil Type and Condition .... N.A.

Analysis Vehicle

Type / Designation	10000S
FEA Model name	F800_No-Box_181114_UboltF0p17 502_TruckBox_181114 503_nodes3 (50" bed)
Mass	22,198 lb

Impact Conditions

Speed	56 mph
Angle	15 degrees
Location	5.0 feet upstream of Post 5

Impact Severity .... 155.6 kip-ft

Exit Conditions

Speed	48.5 mph
Angle	2.0 degrees
Time	0.66 seconds

Occupant Risk Values

Longitudinal OIV	4.9 ft/s
Lateral OIV	15.4 ft/s
Longitudinal ORA	5.4 g
Lateral ORA	5.4 g
THIV	16.4 ft/s
PHD	5.8 g
ASI	0.69

Max50-millisecond Avg. (G)

Longitudinal	2.5 g
Lateral	6.0 g
Vertical	1.7 g

Test Article Deflections (in)

Dynamic	6.2 inches
Permanent	4.8 inch
Working Width	27.4 inches

Max. OCI .... <1 inch

Vehicle Stability

Roll	21.3 degees
Pitch	7.1 degrees
Yaw	34.6 degrees

Figure 140. Summary results for *MASH* Test 4-12 on the sidewalk-mounted bridge rail system for Case 2.

SUMMARY AND CONCLUSIONS

The objective of this project was to evaluate the crash performance of the MassDOT S3-TL4 bridge rail design using finite element analysis (FEA). The impact conditions and assessment procedures conformed to the specifications in *MASH* for TL-4, which included evaluations of structural capacity, risk of occupant injury and vehicle stability during impact and redirection. Two design options for the bridge rail were evaluated: 1) a curb-mounted option in which the bridge rail was mounted onto the top of an 8-inch tall reinforced curb integral to the bridge deck, and 2) a sidewalk-mounted option in which the bridge rail was mounted onto the top of a 5-ft wide sidewalk with an 8-inch curb face. The overall results of the evaluation indicated that the S3-TL4 design is MASH TL4 compliant.

A detailed finite element analysis model of the S3-TL4 bridge rail was developed and validated based on comparison of model results of two full-scale crash tests on the bridge rail, Tests 404251-3 and 404251-6. The tests corresponded to NCHRP Report 350 Test 4-12 on the sidewalk-mounted and curb-mounted bridge rail systems, respectively. The validation was performed according to the procedures outlined in NCHRP Web-Document 179, which indicated that the model accurately replicated the response of both the vehicle and barrier for both cases under Report 350 Test 4-12 impact conditions.

The validated model of the S3-TL4 bridge rail was then used to evaluate the crash performance of the curb-mounted and sidewalk-mounted systems for MASH TL4 impact conditions. Nine (9) analysis cases were performed and included:

- Curb-Mounted S3-TL4:
  1) Test 4-10: 1100C vehicle ballasted to 2,595 lb (1177 kg) impacting the barrier at 62.2 mph and 25 degrees.
  2) Test 4-11: 2270P ballasted to 5,001lb (2,269 kg) impacting the railing at 62.2 mph and 25 degrees.
  3) Test 4-12 Case 1: 10000S model ballasted to 22,198 lb (10,068 kg) with top-of-bed height = 47.5 inches impacting at 56 mph and 15 degrees; lower-bound post strength of 51 ksi.
  4) Test 4-12 Case 2: 10000S model ballasted to 22,198 lb (10,068 kg) with top-of-bed height = 50 inches impacting at 56 mph and 15 degrees; lower-bound post strength of 51 ksi.
  5) Test 4-12 Case 3: 10000S model ballasted to 22,198 lb (10,068 kg) with top-of-bed height = 47.5 inches impacting at 56 mph and 15 degrees; upper-bound post strength of 60 ksi.
- Sidewalk-Mounted S3-TL4:
  6) Test 4-10: 1100C vehicle ballasted to 2,595 lb (1177 kg) impacting the barrier at 62.2 mph and 25 degrees.
  7) Test 4-11: 2270P ballasted to 5,001lb (2,269 kg) impacting the railing at 62.2 mph and 25 degrees.

8) Test 4-12 Case 1: 10000S model ballasted to 22,198 lb (10,068 kg) with top-of-bed height = 47.5 inches impacting at 56 mph and 15 degrees; lower-bound post strength of 51 ksi.
9) Test 4-12 Case 2: 10000S model ballasted to 22,198 lb (10,068 kg) with top-of-bed height = 50 inches impacting at 56 mph and 15 degrees; lower-bound post strength of 51 ksi.

The damage to the bridge rail for the small car and pickup were moderate with the sidewalk-mounted system being the worse-case with maximum lateral deflection of 2.83 inches. There was no evident concrete damage for these cases. The damages to the barrier for the single unit truck test were more substantial with up to 6.3 inches dynamic deflection for the sidewalk case. The damage to the concrete was isolated to the front anchor bolts, with some possibility of cracking around the front anchor bolts for the stronger post case. The higher strength post, which is probably more typical for field installations, increases the loading on the concrete anchor bolts and welds. From cursory LRFD calculations, based on MASH TL4 design loads for tall barriers and neglecting concrete reinforcement, the pryout shear-cone strength of the concrete at the front anchor bolts governed the strength of the system (calculations not shown). Increasing the concrete strength to 5 ksi would likely result in pull-out strength matching plastic strength of post. The impact severity for most field impact cases will be less than those of MASH Test 4-12; however, the analyses indicated that the system would contain the vehicle for those high severity cases, although subsequent repairs for the posts and rails may be required post impact.

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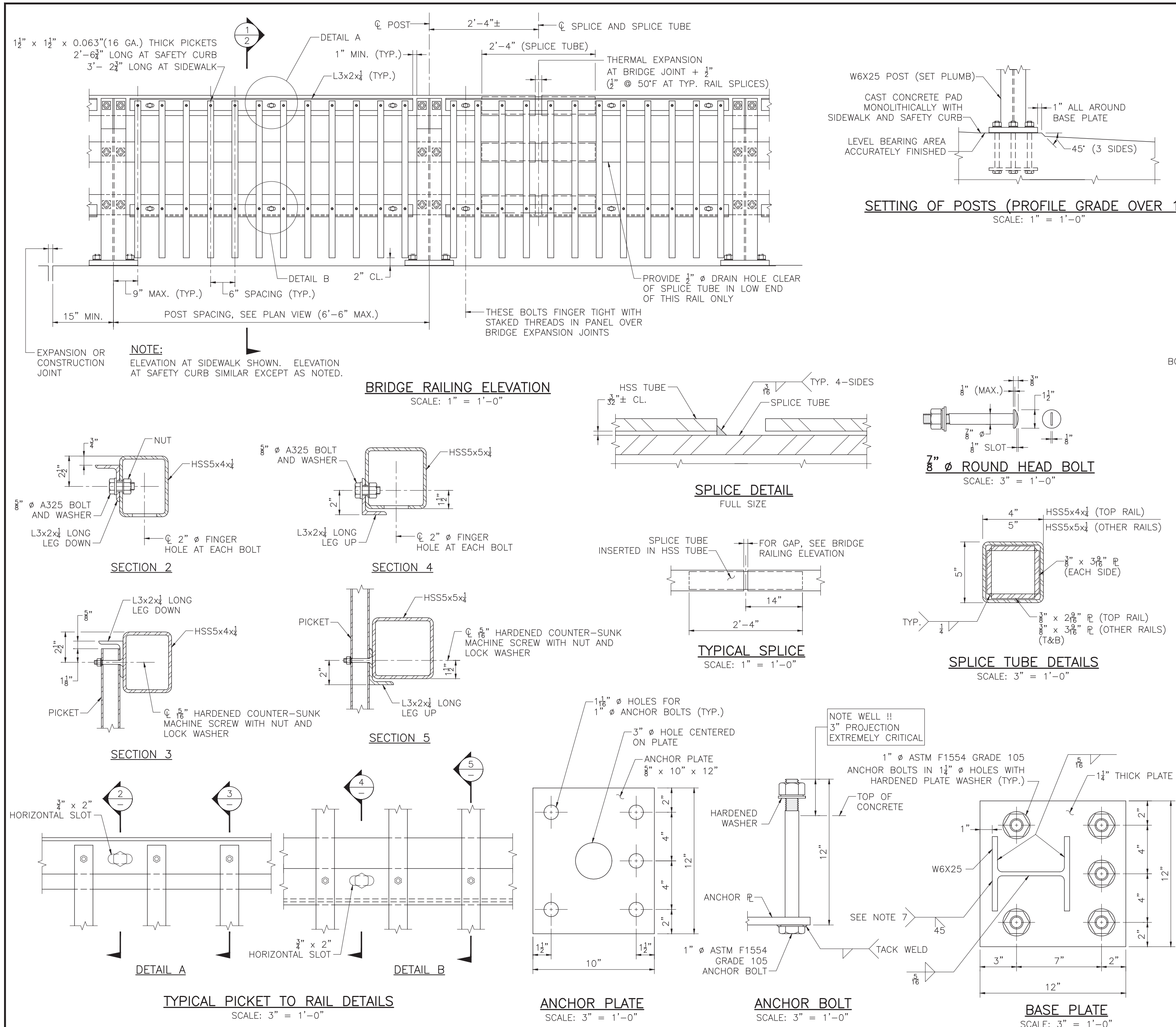
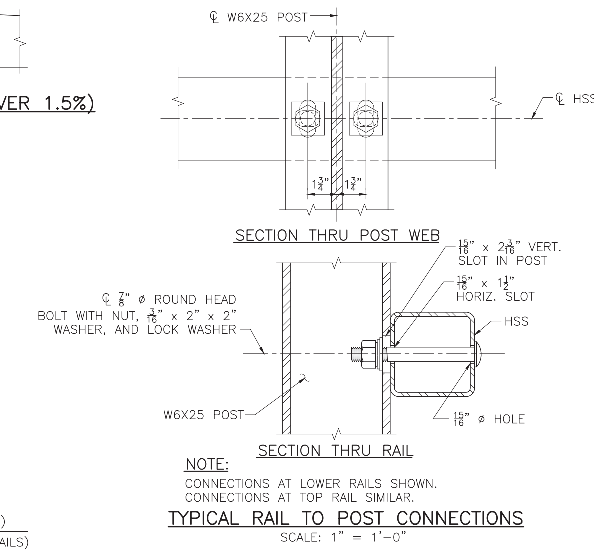
Appendix A

Detail Drawings for the MassDOT S3-TL4 Bridge Rail





RAILING NOTES:

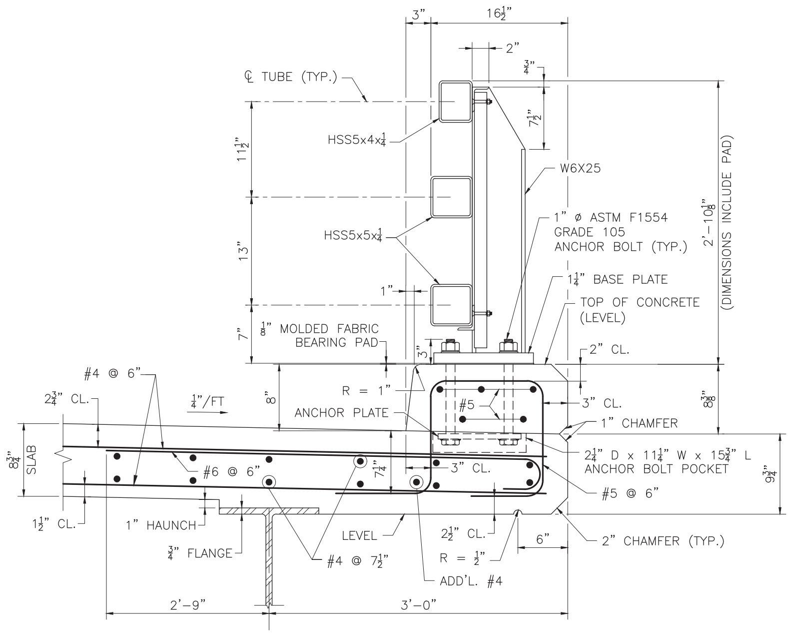
1. RAIL POST AND BASE PLATES SHALL CONFORM TO THE REQUIREMENTS OF AASHTO M 270 GRADE 50. HOLLOW RAILING STRUCTURAL TUBING (HSS) SHALL CONFORM TO THE REQUIREMENTS OF ASTM A 500 WITH A CERTIFIED Fy = 50 KSI MINIMUM. THE MINIMUM HORIZONTAL BENDING RADII OF THE HSS TUBING SHALL BE 8 FEET. PICKET CARRIER ANGLES, ANCHOR PLATES, AND SPLICE TUBE PLATES SHALL CONFORM TO THE REQUIREMENTS OF AASHTO M 270 GRADE 36. PICKET TUBING SHALL CONFORM TO ASTM A 513 WITH Fy = 36 KSI MIN. OR A 500 GRADE B.
2. ALL STEEL (EXCEPT THE ⅝" ANCHOR PLATE AND FASTENERS) SHALL BE GALVANIZED AND PAINTED DARK BRONZE (FEDERAL STD. 595B COLOR NO. 10045). ANCHOR PLATE SHALL BE GALVANIZED ONLY. HEADS OF ⅞" ø ROUND HEAD BOLTS SHALL BE PAINTED TO MATCH RAIL.
3. ANCHOR BOLTS SHALL BE SET WITH TEMPLATES. THE NUT SECURING THE POST BASE PLATE TO THE CONCRETE SHALL BE TIGHTENED TO A SNUG FIT AND GIVEN AN ADDITIONAL 1/8 TURN AFTER STEEL IS IN PLACE.
4. RAILS SHALL BE CONTINUOUS OVER A MINIMUM OF FOUR (4) POSTS WITHOUT SPLICES WHERE POSSIBLE. RAILS SHALL BE SPLICED IN THE PANELS OVER EXPANSION JOINT.
5. ENDS OF TUBE SECTIONS SHALL BE SAWED. GRIND SMOOTH EXPOSED EDGES. ALL CUT ENDS SHALL BE TRUE AND SMOOTH.
6. ALL POSTS TO BE PLUMB WHEN PROFILE GRADE EXCEEDS 1.5%. FOR PROFILE GRADES LESS THAN 1.5%, POSTS SHALL BE SET PERPENDICULAR TO GRADE.
7. POST FLANGE WELD DOES NOT REQUIRE MAGNETIC PARTICLE TESTING. WELD SHALL BE BACK-GOUGED ON BACK SIDE EXCEPT AT WEB. WELD IS THE SAME ON BOTH FLANGES.
8. ⅞" ø ROUND HEAD BOLTS SHALL CONFORM TO THE CHEMICAL AND PHYSICAL REQUIREMENTS OF ASTM A325.

MASSDOT S3-MTL4 BRIDGE RAILING

SHEET 1 OF 2 SHEETS

MASSDOT S3-MTL4 BRIDGE RAILING.DWG 30-May-2017

Xxxxxx Structural Submittal (Sf) DD-Month-YYYY

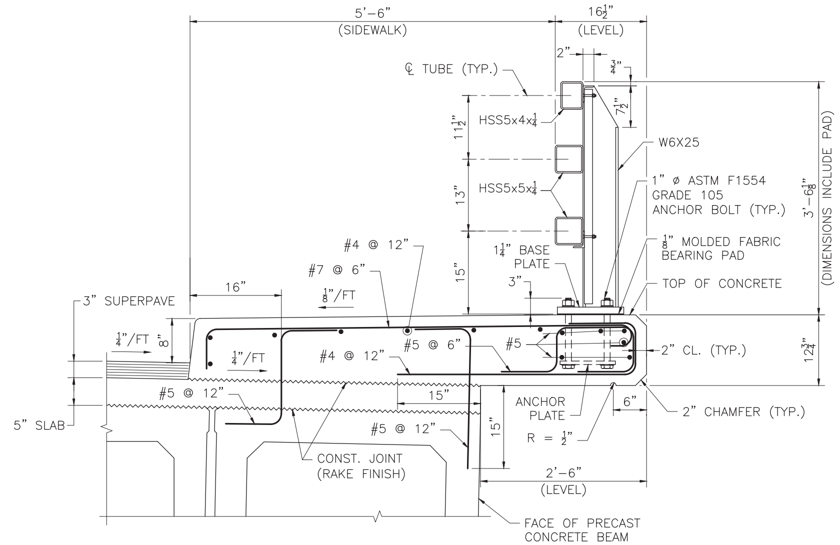


NOTES:

1. ALL CONCRETE SHALL BE 4000 PSI HP CONCRETE.
2. ALL REINFORCEMENT SHALL BE COATED.

SECTION 1 – SECTION THRU SAFETY CURB

SCALE: 1½" = 1'-0"

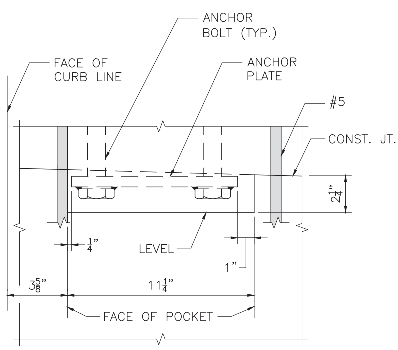


NOTES:

1. SIDEWALK AND DECK SLAB CONCRETE SHALL BE 4000 PSI HP CONCRETE.
2. ALL REINFORCEMENT SHALL BE COATED.

SECTION 1 – SECTION THRU SIDEWALK

SCALE: 1" = 1'-0"



NOTE:

PROVIDE 15¾" LONG, 11¼" WIDE, 2¼" DEEP POCKET IN THE DECK SLAB AT THE LOCATION OF EACH RAIL POST AT SAFETY CURB ONLY.

ANCHOR BOLT POCKET

SCALE: 3" = 1'-0"

MASSDOT S3–MTL4 BRIDGE RAILING

MASSDOT S3-MTL4 BRIDGE RAILING.DWG 30-May-2017

Xxxxxx Structural Submittal (Sn) DD-Month-YYYY

Appendix B

Validation Forms for Curb-Mounted S3-TL4 Model

Comparison to Test 404251-6

NCHRP Report 350 Test 4-12

FEA VALIDATION/VERIFICATION REPORT FORMS

Report 350 Test 4-12______________ (Report 350 or MASH08 or EN1317 Vehicle Type)

Impact of the

MassDOT Curb-Mounded S3-TL4___ (Roadside hardware type and name)

Report Date: _12/30/2018_________

Type of Report (check one)

- ☐ Verification (known numerical solution compared to new numerical solution).
- ☒ Validation (physical test compared to a numerical solution).
- ☐ Extrapolation (validated numerical solution compared to modified numerical solution).

General Information	**Known Solution**	**Analysis Solution**
Performing Organization	TTI	Roadsafe LLC
Analyst/Engineer	**C.E. Buth**	Chuck Plaxico
Test/Run Number:	404251-6	T4-12_curb-baseline_181102
Vehicle:	1987 GMC 7000	F800 Version 181114-3
Reference:	Test 4-12	Test 4-12
Impact Conditions		
Vehicle Mass:	17,637-lb	17,662-lb
Speed:	49.15 mph	49.15 mph
Angle:	15.3 degrees	15.3 degrees
Impact Point:		

Composite Validation/Verification Score

	List the Report 350/MASH08 or EN1317 Test Number: ____4-12______	Pass?
Part I	Did all solution verification criteria in Table B-1 pass?	Y
Part II	Do all the time history evaluation scores from Table B-2 result in a satisfactory comparison (i.e., the comparison passes the criterion)? If all the values in Table B-2 did not pass, did the weighted procedure shown in Table B-3 result in an accepTable Bomparison. If all the criteria in Table B-2 pass, enter “yes.” If all the criteria in Table B-2 did not pass but Table B-3 resulted in a passing score, enter “yes.”	Y
Part III	All the criteria in Table B-4 (Test-PIRT) passed? Not Required for Component Tests	Y
	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.	Y

The analysis solution (check one):

- ☒ Is verified/validated against the known solution.
- ☐ Is NOT verified/validated against the known solution.

PART I: BASIC INFORMATION

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

2. What test guidelines were used to perform the full-scale crash test (check one)?
   - [x] NCHRP Report 350
   - [ ] MASH08
   - [ ] EN1317
   - [ ] Other: ____________________

3. Indicate the test level and number being evaluated (fill in the blank): ______4-12____________

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
- [ ] 8000S
- [x] 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

Table B-1. Analysis Solution Verification Table.

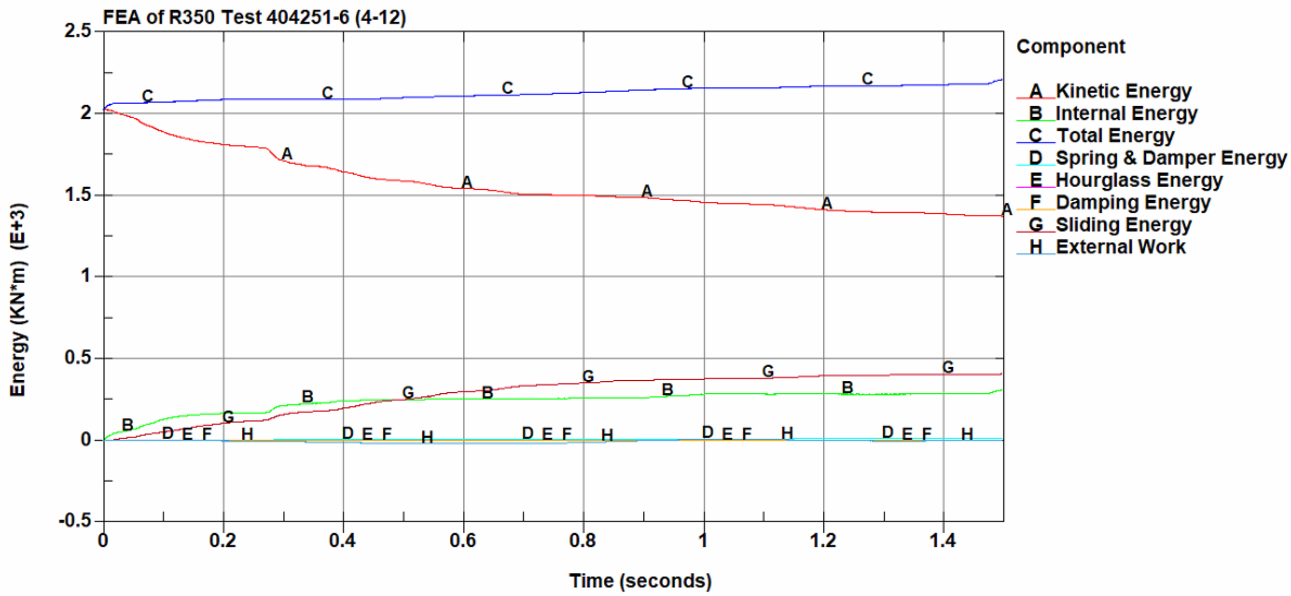
Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	4	Y
Hourglass Energy of the analysis solution at the end of the run is less than *five percent* of the total *initial energy* at the *beginning* of the run.	0	Y
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.	0	Y
The part/material with the highest amount of hourglass energy at the end of the run is less than twenty percent of the total internal energy of the part/material at the end of the run.	12	Y
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	0	Y
The part/material with the most mass added had less than 10 percent of its initial mass added.	0	Y
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	0	Y
There are no shooting nodes in the solution?	Y	Y
There are no solid elements with negative volumes?	Y	Y
Exception Notes:		

☒ Analysis solution passes <u>all</u> the criteria in Table B-1 ☒ without exceptions.

☐ with exceptions as noted in Table B-1.

☐ Analysis solution does NOT pass <u>all</u> the criteria in Table B-1.

☐ Table B-1 is not applicable because ____________________



FEA of R350 Test 404251-6 (4-12)
Energy (KN*m) (E+3)
Time (seconds)
2.5
2
1.5
1
0.5
0
-0.5
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Component
A Kinetic Energy
B Internal Energy
C Total Energy
D Spring & Damper Energy
E Hourglass Energy
F Damping Energy
G Sliding Energy
H External Work

PART III: HISTORY EVALUTION TABLES

Table B-2. Roadside Safety Validation Metrics Rating Table (single channel option).

<table>
<tr><th colspan="10">Evaluation Criteria</th><th colspan="3" rowspan="2">Time interval
[0.45 seconds]</th></tr>
<tr><td rowspan="9">O</td><td colspan="9">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.</td></tr>
<tr><td rowspan="3">Channel</td><td colspan="6">RSVVP Curve Preprocessing Options</td><td rowspan="3">M</td><td rowspan="3">P</td><td rowspan="3">Pass?</td></tr>
<tr><td rowspan="2">Filter Option</td><td rowspan="2">Sync. Option</td><td colspan="2">Shift</td><td colspan="2">Drift</td></tr>
<tr><td>True Curve</td><td>Test Curve</td><td>True Curve</td><td>Test Curve</td></tr>
<tr><td>x-acceleration</td><td>SAE 60</td><td>Y</td><td>none</td><td>None</td><td>none</td><td>None</td><td>71.9</td><td>41.7</td><td>N</td></tr>
<tr><td>y-acceleration</td><td>SAE 60</td><td>Y</td><td>None</td><td>None</td><td>None</td><td>None</td><td>11.7</td><td>42.8</td><td>≈Y</td></tr>
<tr><td>z-acceleration</td><td>SAE 60</td><td>Y</td><td>None</td><td>None</td><td>None</td><td>None</td><td>3.8</td><td>36.8</td><td>Y</td></tr>
<tr><td>Yaw-rate</td><td>SAE 60</td><td>Y</td><td>None</td><td>none</td><td>None</td><td>none</td><td>2.1</td><td>16.6</td><td>Y</td></tr>
<tr><td>Roll-rate</td><td>SAE 60</td><td>Y</td><td>None</td><td>none</td><td>None</td><td>none</td><td>12.4</td><td>41.4</td><td>≈Y</td></tr>
<tr><td></td><td>Pitch-rate</td><td>SAE 60</td><td>Y</td><td>None</td><td>none</td><td>None</td><td>none</td><td>113</td><td>41.7</td><td>N</td></tr>
<tr><td rowspan="7">P</td><td colspan="7">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 ($\sigma \le 0.35 \cdot a_{Peak}$).</td><td>Mean Residual</td><td>Standard Deviation of Residuals</td><td>Pass?</td></tr>
<tr><td colspan="7">x-acceleration</td><td>1.9</td><td>36</td><td>≈Y</td></tr>
<tr><td colspan="7">y-acceleration</td><td>0.56</td><td>18.6</td><td>Y</td></tr>
<tr><td colspan="7">z-acceleration</td><td>2.5</td><td>27.7</td><td>Y</td></tr>
<tr><td colspan="7">Yaw-rate</td><td>1.7</td><td>18.9</td><td>Y</td></tr>
<tr><td colspan="7">Roll-rate</td><td>5.0</td><td>39.1</td><td>N</td></tr>
<tr><td colspan="7">Pitch-rate</td><td>4.3</td><td>57.8</td><td>N</td></tr>
<tr><td colspan="11">Exception Notes:</td></tr>
</table>

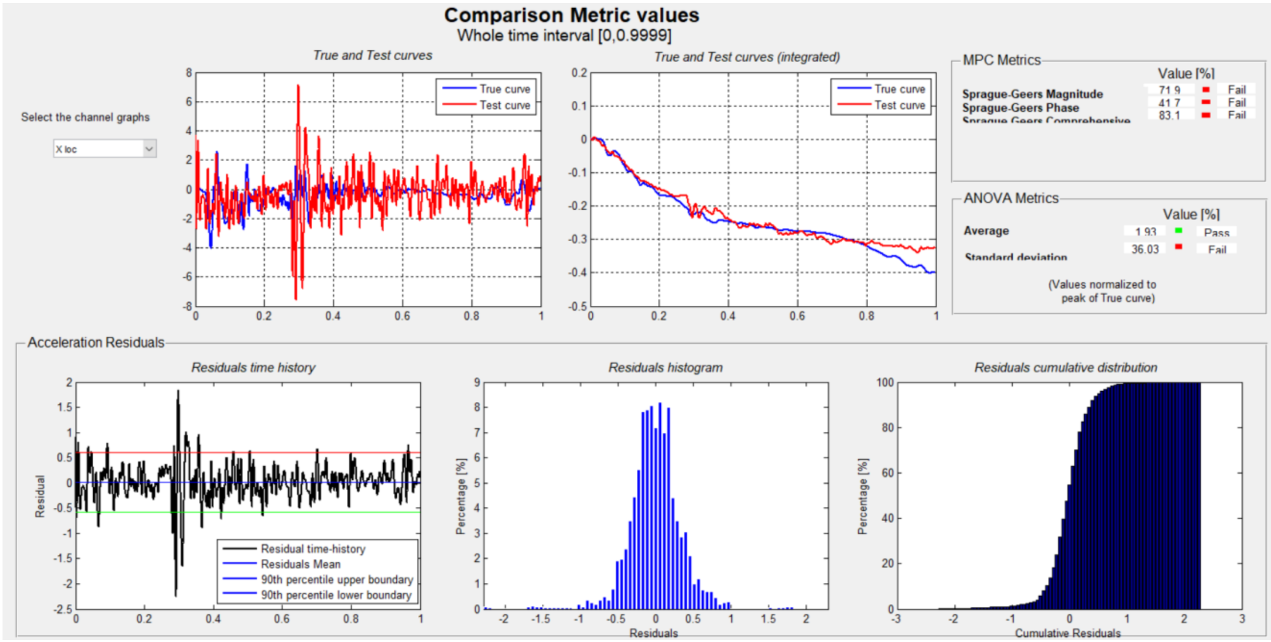
☐ Analysis solution passes all the criteria in Table B-2 ☐ without exceptions.

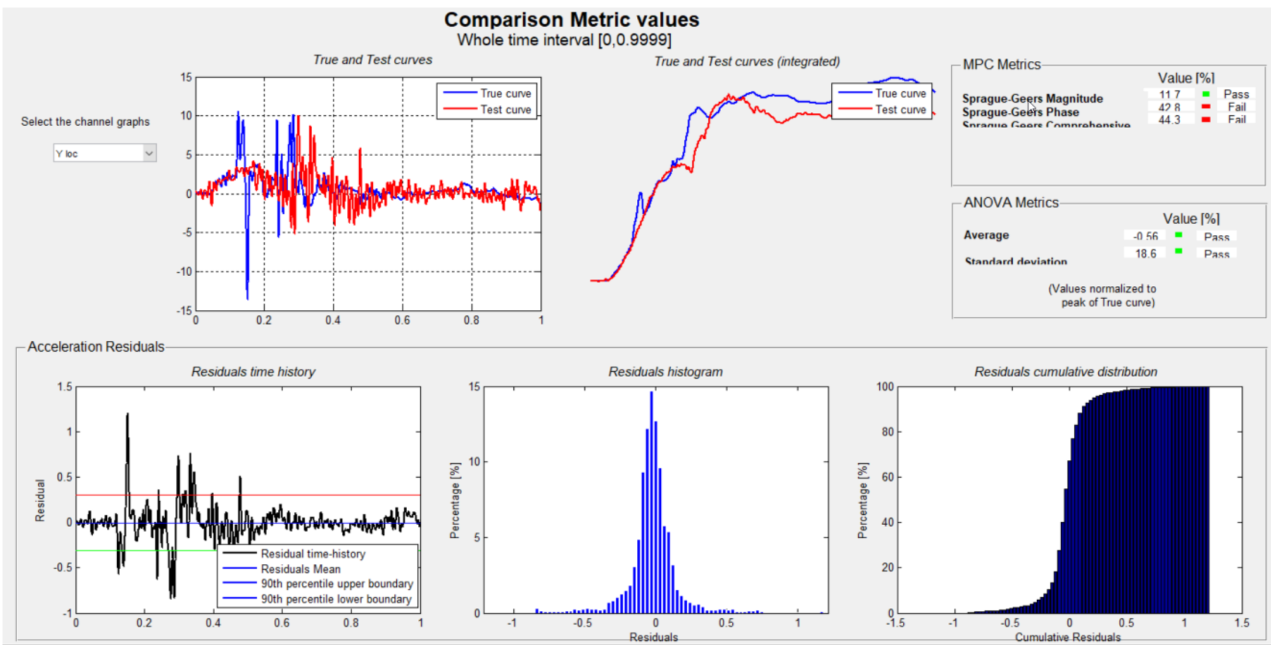
☐ with exceptions as noted in Table B-2.

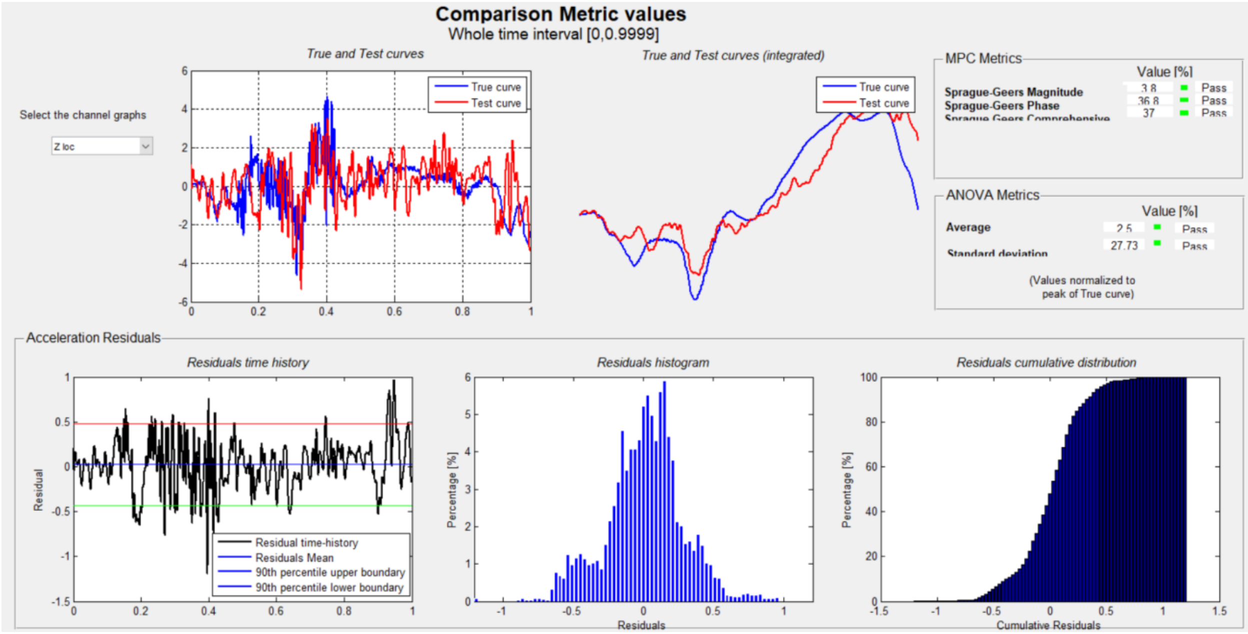
☒ Analysis solution does NOT pass all the criteria in Table B-2.

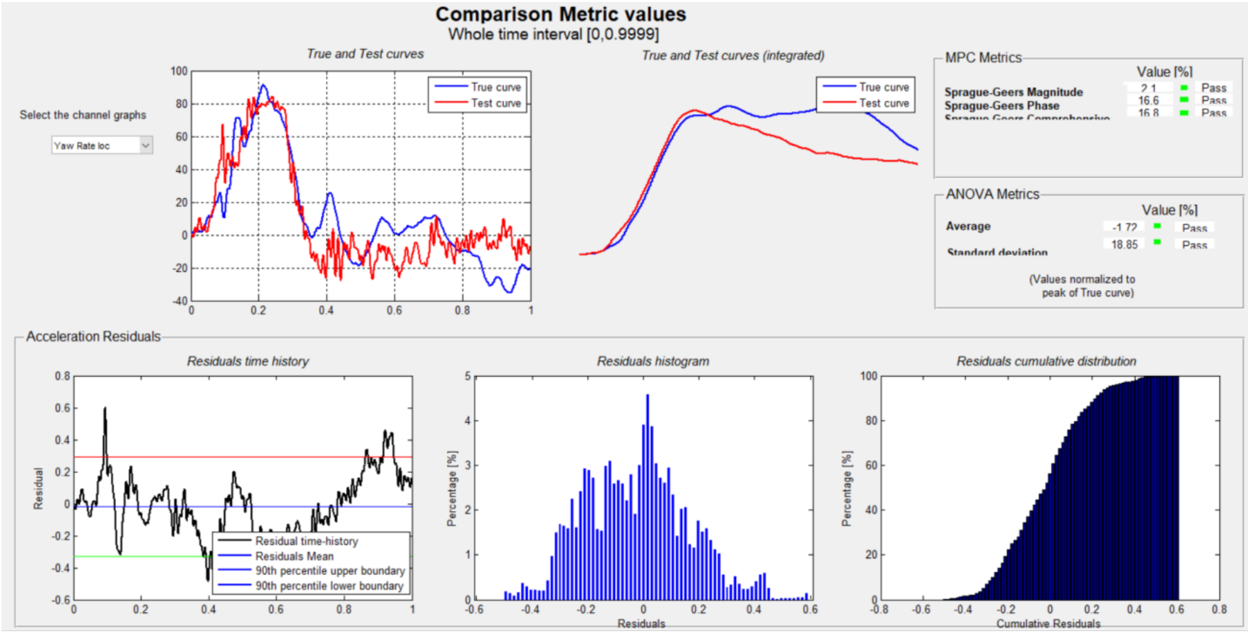
☐ Table B-2 is not applicable because ______________________________

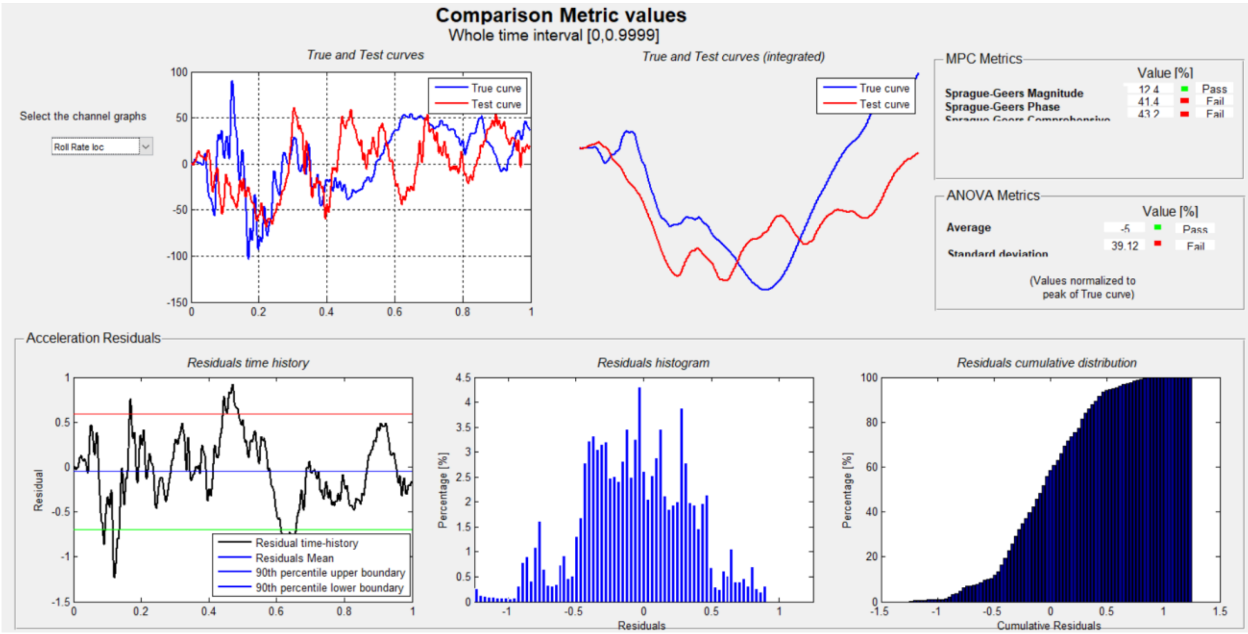
☒ RSVVP Single-Channel Comparison Metric Values Screens for each channel are attached on the following pages.


Comparison Metric values
Whole time interval [0,0.9999]
Select the channel graphs
X loc
True and Test curves
True and Test curves (integrated)
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude 71.9 Fail
Sprague-Geers Phase 41.7 Fail
Sprague-Geers Comprehensive 83.1 Fail
ANOVA Metrics
Value [%]
Average 1.93 Pass
Standard deviation 36.03 Fail
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Cumulative Residuals


Comparison Metric values
Whole time interval [0,0.9999]
Select the channel graphs
Y loc
True and Test curves
True and Test curves (integrated)
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude 11.7 Pass
Sprague-Geers Phase 42.8 Fail
Sprague-Geers Comprehensive 44.3 Fail
ANOVA Metrics
Value [%]
Average -0.56 Pass
Standard deviation 18.6 Pass
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Cumulative Residuals


Comparison Metric values
Whole time interval [0,0.9999]
True and Test curves
True and Test curves (integrated)
Select the channel graphs
Z loc
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude 3.8 Pass
Sprague-Geers Phase 36.8 Pass
37 Pass
ANOVA Metrics
Value [%]
Average 2.5 Pass
27.73 Pass
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residual
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Cumulative Residuals


Comparison Metric values
Whole time interval [0,0.9999]
True and Test curves
True and Test curves (integrated)
Select the channel graphs
Yaw Rate loc
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude 2.1 Pass
Sprague-Geers Phase 16.6 Pass
16.8 Pass
ANOVA Metrics
Value [%]
Average -1.72 Pass
18.85 Pass
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residual
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Cumulative Residuals


Comparison Metric values
Whole time interval [0,0.9999]
Select the channel graphs
Roll Rate loc
True and Test curves
True curve
Test curve
True and Test curves (integrated)
MPC Metrics
Value [%]
Sprague-Geers Magnitude 12.4 Pass
Sprague-Geers Phase 41.4 Fail
43.2 Fail
ANOVA Metrics
Value [%]
Average -5 Pass
Standard deviation 39.12 Fail
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Cumulative Residuals

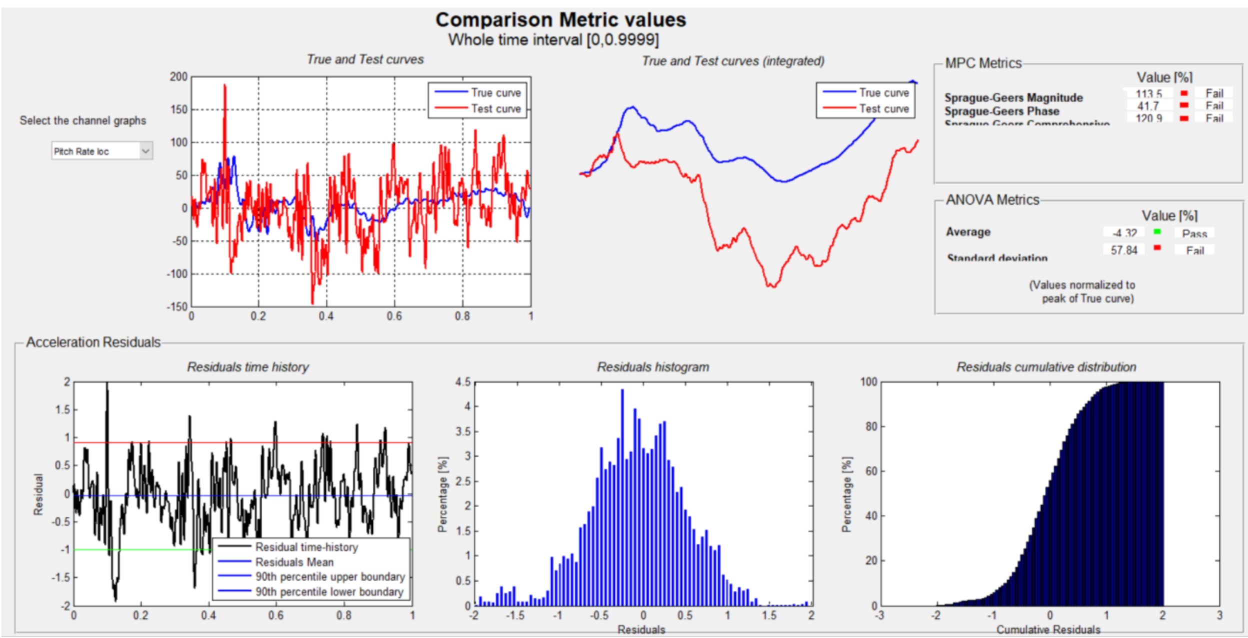
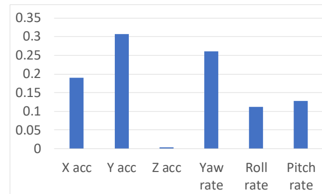

Comparison Metric values
Whole time interval [0,0.9999]
Select the channel graphs
Pitch Rate loc
True and Test curves
True curve
Test curve
True and Test curves (integrated)
MPC Metrics
Value [%]
Sprague-Geers Magnitude 113.5 Fail
Sprague-Geers Phase 41.7 Fail
120.9 Fail
ANOVA Metrics
Value [%]
Average -4.32 Pass
Standard deviation 57.84 Fail
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Cumulative Residuals

Table B-3. Roadside Safety Validation Metrics Rating Table (multi-channel option).

Evaluation Criteria (time interval [0.0 – 1.0 seconds])					
Channels (Select which were used)					
☒ **X Acceleration**		☒ **Y Acceleration**	☒ **Z Acceleration**		
☒ **Roll rate**		☒ **Pitch rate**	☒ **Yaw rate**		
Multi-Channel Weights - **Area II method** -		**X Channel: 0.190** **Y Channel: 0.306** **Z Channel: 0.004** **Yaw Channel: 0.260** **Roll Channel: 0.113** **Pitch Channel: 0.127**	 		
O	***Sprague-Geer Metrics*** Values less or equal to 40 are acceptable.		**M**	**P**	**Pass?**
			33.6	35.4	**Y**
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?
			1.4	29.3	**Y**

☐ Analysis solution passes <u>all</u> the criteria in Table B-3 ☒ without exceptions

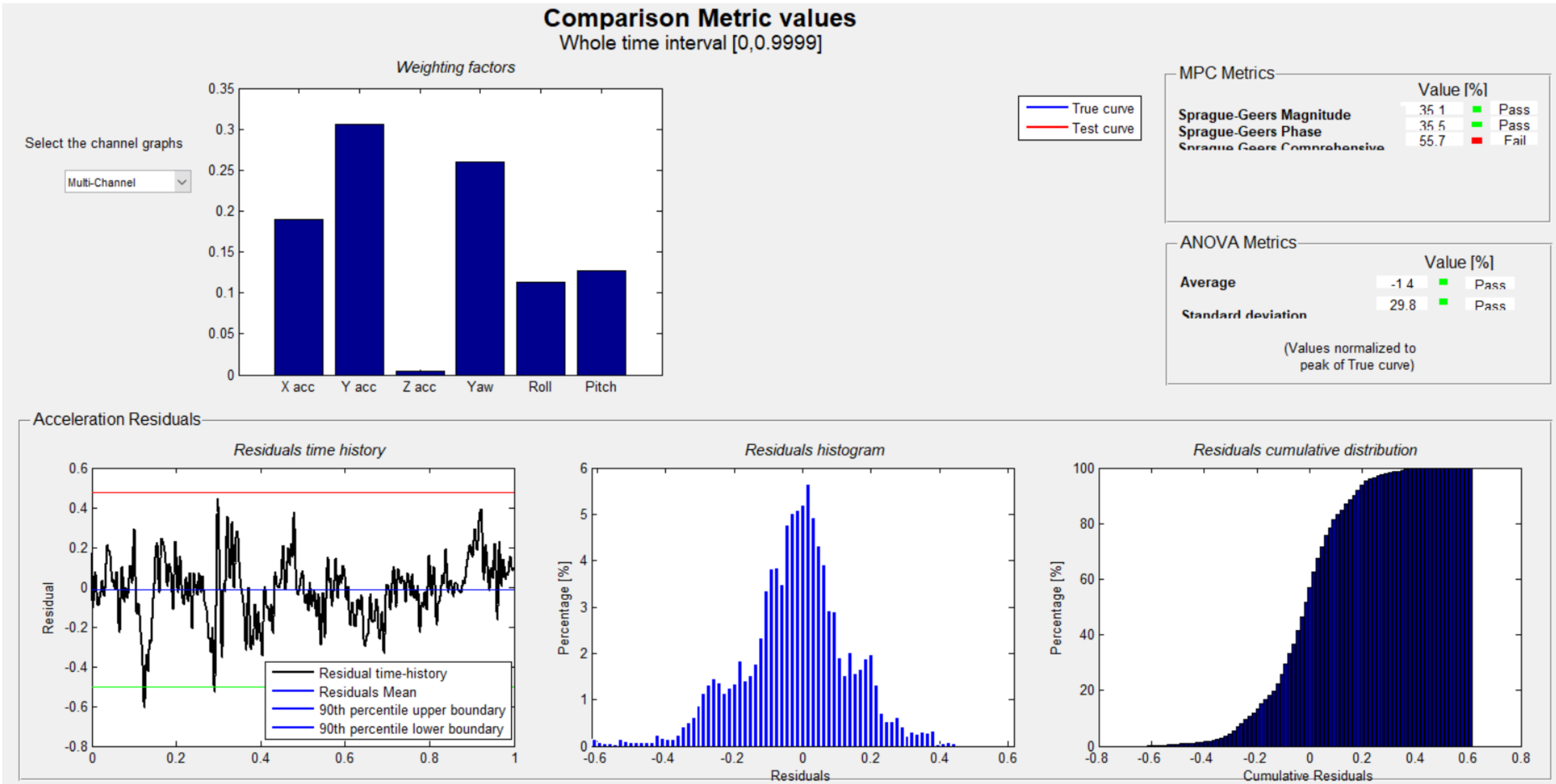
☐ with exceptions as noted in Table B-3.

☐ Analysis solution does NOT pass <u>all</u> the criteria in Table B-3.

☐ Table B-3 does not contain sufficient information for assessment.

☐ Table B-3 is not applicable because criteria were satisfied in Table B-2.

☒ RSVVP Multi-Channel Comparison Metric Values Screen is attached on the following page.



Comparison Metric values
Whole time interval [0,0.9999]
Weighting factors
Select the channel graphs
Multi-Channel
X acc
Y acc
Z acc
Yaw
Roll
Pitch
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude
Sprague-Geers Phase
35.1
35.5
55.7
Pass
Pass
Fail
ANOVA Metrics
Value [%]
Average
-1.4
Pass
29.8
Pass
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Percentage [%]
Cumulative Residuals

PART IV: PHENOMENAA IMPORTANCE RANKING TABLES

Table B-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="4">Vehicle Trajectory</td><td>K</td><td>After collision it is preferable that the vehicle’s trajectory not intrude into adjacent traffic lanes.</td><td>All</td></tr>
<tr><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>

Table B-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)	Y	Y		Y
		A2	Maximum permanent deflection: - Relative difference is less than 20 percent or - Absolute difference is less than 6 inches	0.18 in	1.65 in	20% 0.4 in	Y
		A3	Length of vehicle-barrier contact (at initial separation): - Relative difference is less than 20 percent or - Absolute difference is less than 6.6 ft	15.1 ft	16.4 ft	8.6 % 1.3 ft	Y
		A4	Number of broken or significantly bent posts is less than 20 percent.	0	0		Y
		A5	Did the rail element rupture or tear (Answer Yes or No)	No	No		Y
		A6	Concrete curb/deck failure	*No	No		Y
		A7	Was there significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	N	N		Y
		A8	Was there significant snagging between vehicle body components and barrier elements (Answer Yes or No).	N	N		Y

Note: Additional phenomena can be added to the tables in deemed appropriate by the analyst.

Table B-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)	N	N		Y
	F	F1	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable. (Answer Yes or No)	Y	Y		Y
		F2	Maximum roll of the vehicle through 1.0 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	-8.3 deg	-8.3 deg	0 % 0.0 deg	Y
		F3	Maximum pitch of the vehicle through 1.0 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	*6.0 deg	**5.1 deg	7.0 % 0.9 deg	Y
		F4	Maximum yaw of the vehicle through 0.446 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	16.4 deg	15.7 deg	4.2 % 0.7 deg	Y
	G	1	Did the vehicle remain upright during and after collision	Y	Y		Y
	L	L1	Occupant impact velocities: - Relative difference is less than 20 percent or - Absolute difference is less than 6.6 ft/s.				
			• Longitudinal OIV (ft/s)	5.6	5.2	7% 0.4 ft/s	Y
			• Lateral OIV (ft/s)	-11.2	-11.8	5% 0.6 ft/s	Y
			• THIV (ft/s)	12.5	13.1	5% 0.6 ft/s	Y
		L2	Occupant accelerations: - Relative difference is less than 20 percent or - Absolute difference is less than 4 g's.				
			• Longitudinal ORA	-2.3	-4.4	8.7 % 0.2 g	Y
			• Lateral ORA	7.6	7.4	3 % 0.2 g	Y
			• PHD	7.7	8.5	10 % 0.8 g	Y
			• ASI	0.53	0.43	19 % 0.1	Y

* *Possible "drift" in the pitch-rate channel; the sequential views (**Error! Reference source not found.**) show the pitch comparison to be much closer.*

*** Taken at time=1.0 second coincident with the time of maximum pitch in the test.*

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

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Vehicle Trajectory	K	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.	13% cargo box	9.8% cargo box		Y
		M2	Exit angle at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	2.0 deg cargo box	1.5 deg cargo box	25% 0.5 deg	Y
	M	M3	Exit velocity at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 6.2 mph.	43.4 mph	43.1 mph	0.7 % 0.3 mph	Y

Note: Additional phenomena can be added to the tables in deemed appropriate by the analyst.

☒ Analysis solution passes all the criteria in Tables E-5(a) through E-5(c)

☒ without exceptions.

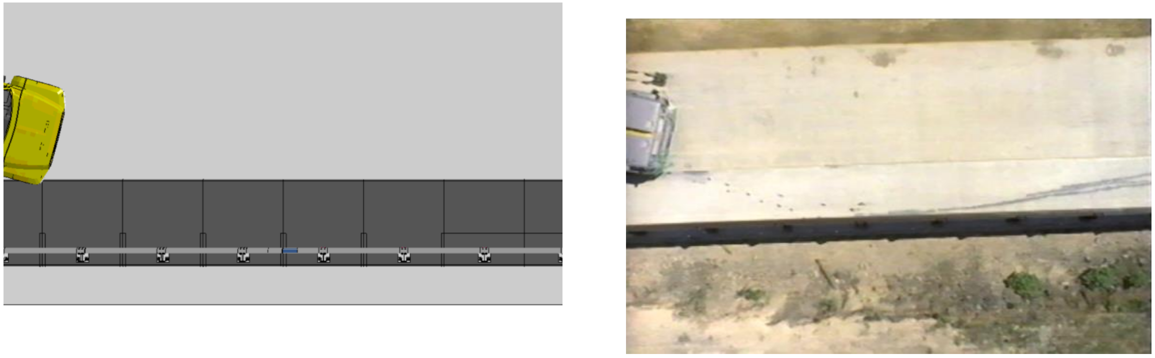
☐ with exceptions as noted in Tables E-5(a) through E-5(c).

☐ Does NOT pass all the criteria in Tables E-5(a) through 5(c).

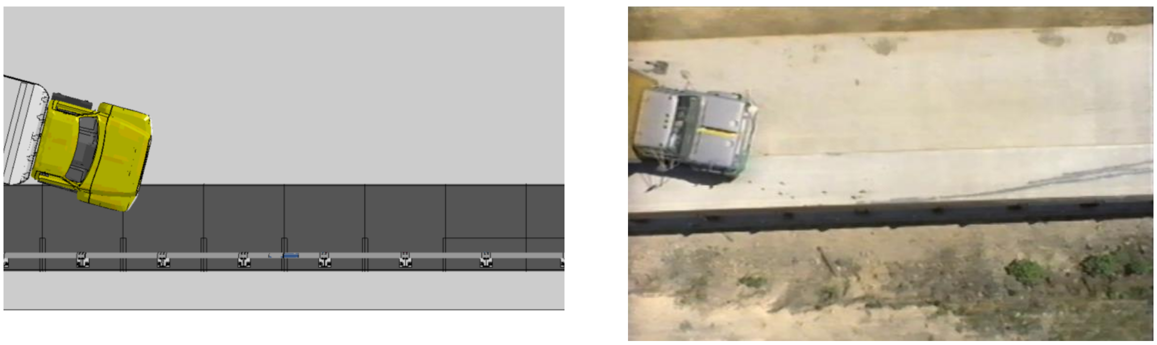
☐ Tables E-5(a) through E-5(c) does not contain sufficient information for assessment.

☐ Tables E-5(a) through E-5(c) are not applicable because ___________________________________

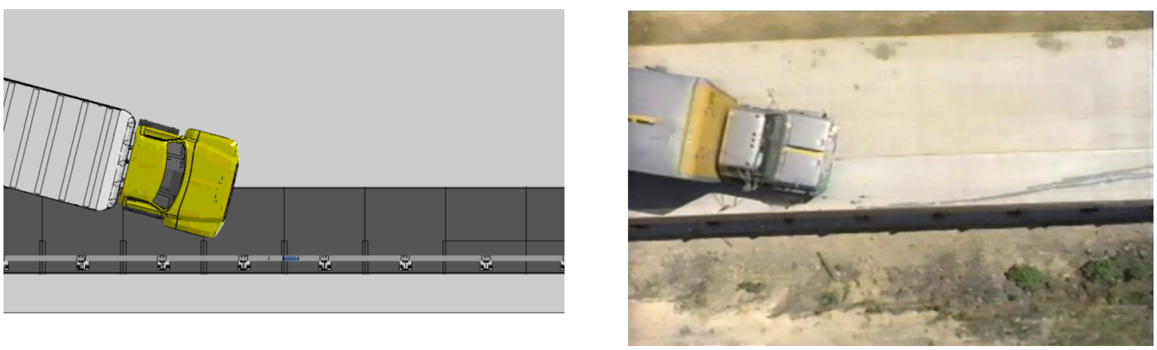
☒ Synchronized side-by-side views of the known and analysis solutions are attached on the following pages.



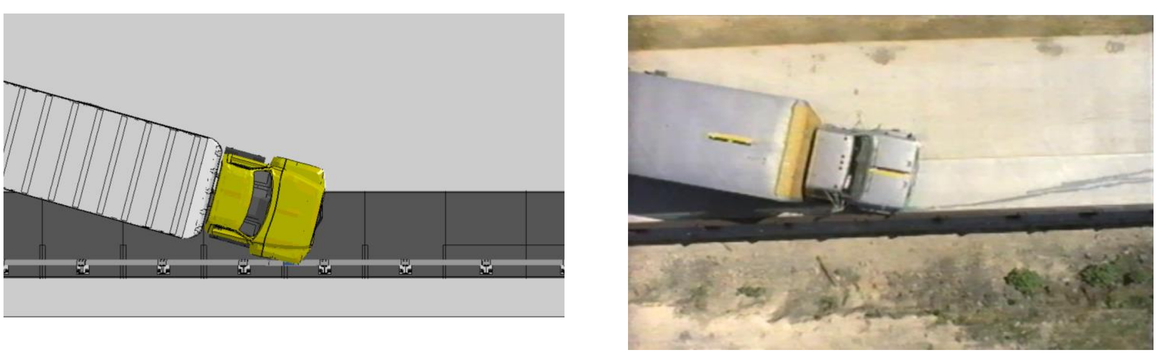
Time = 0.0 seconds



Time = 0.1 seconds

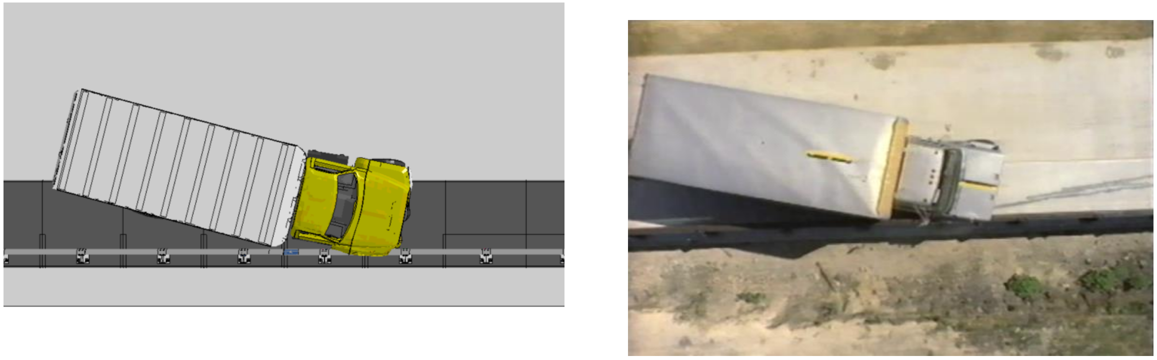


Time = 0.2 seconds

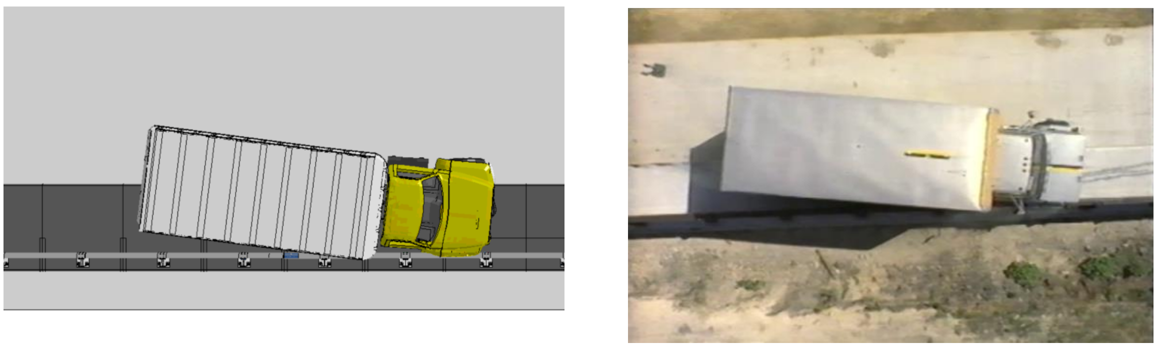


Time = 0.3 seconds

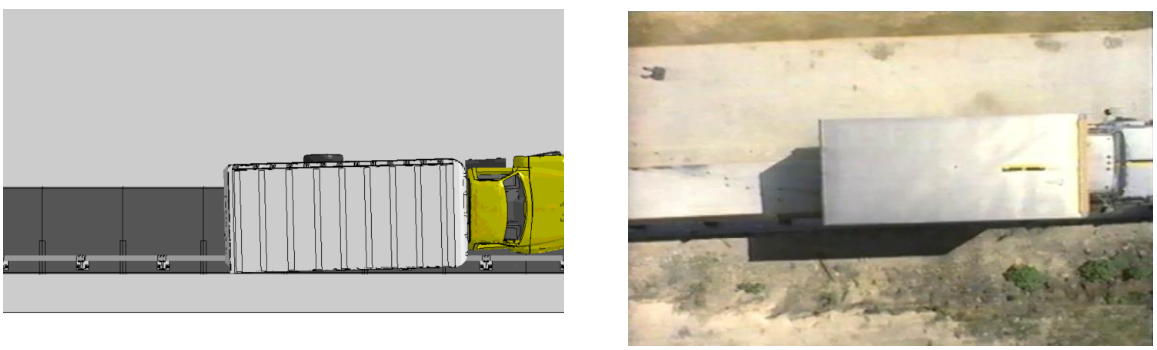
Figure 1. Sequential views from FEA and Test 404251-3 from an overhead view point.



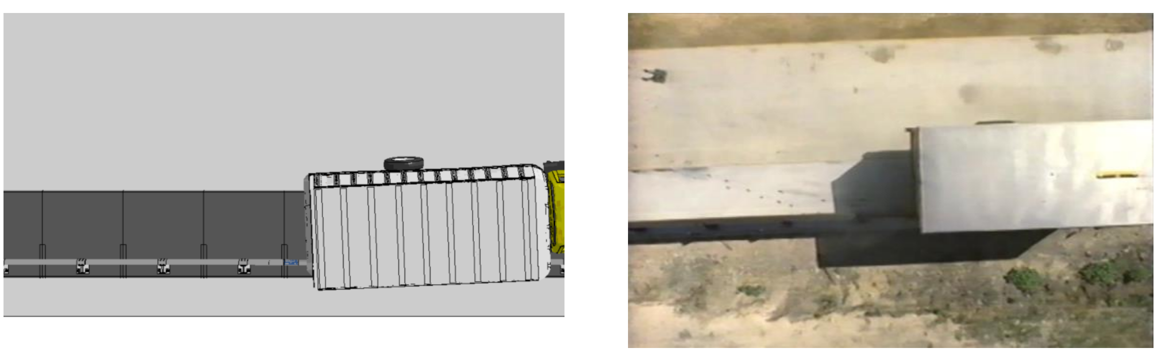
Time = 0.4 seconds



Time = 0.5 seconds

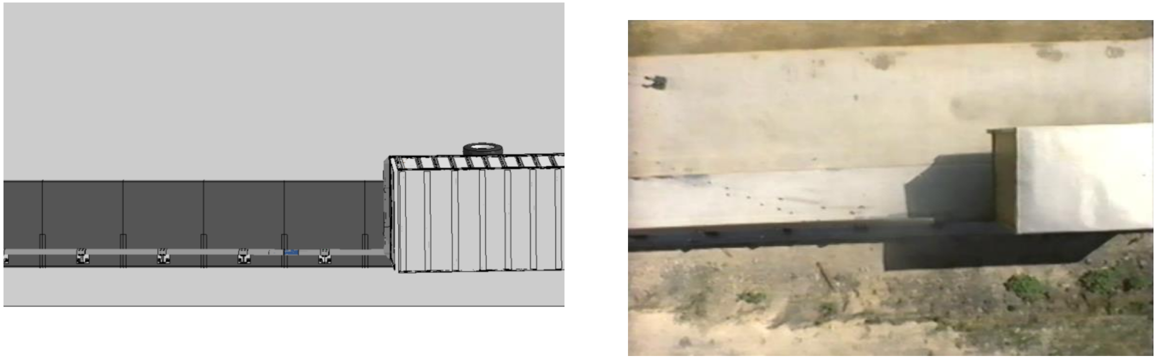


Time = 0.6 seconds

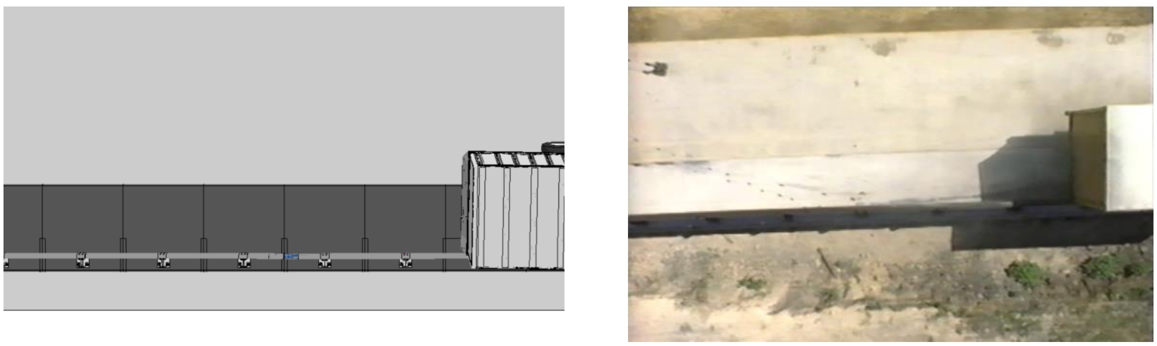


Time = 0.7 seconds

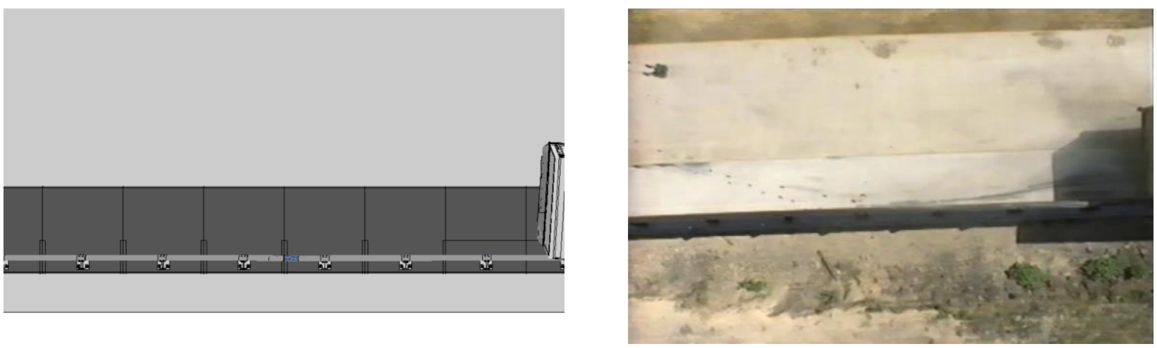
Figure 1. [Continued] Sequential views from FEA and Test 404251-3 from an overhead view point.



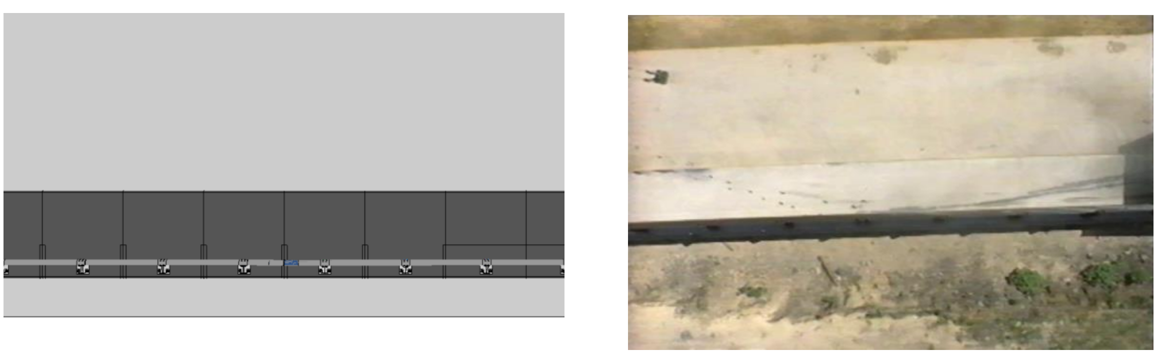
Time = 0.8 seconds



Time = 0.9 seconds



Time = 1.0 seconds



Time = 1.1 seconds

Figure 1. [Continued] Sequential views from FEA and Test 404251-3 from an overhead view point.

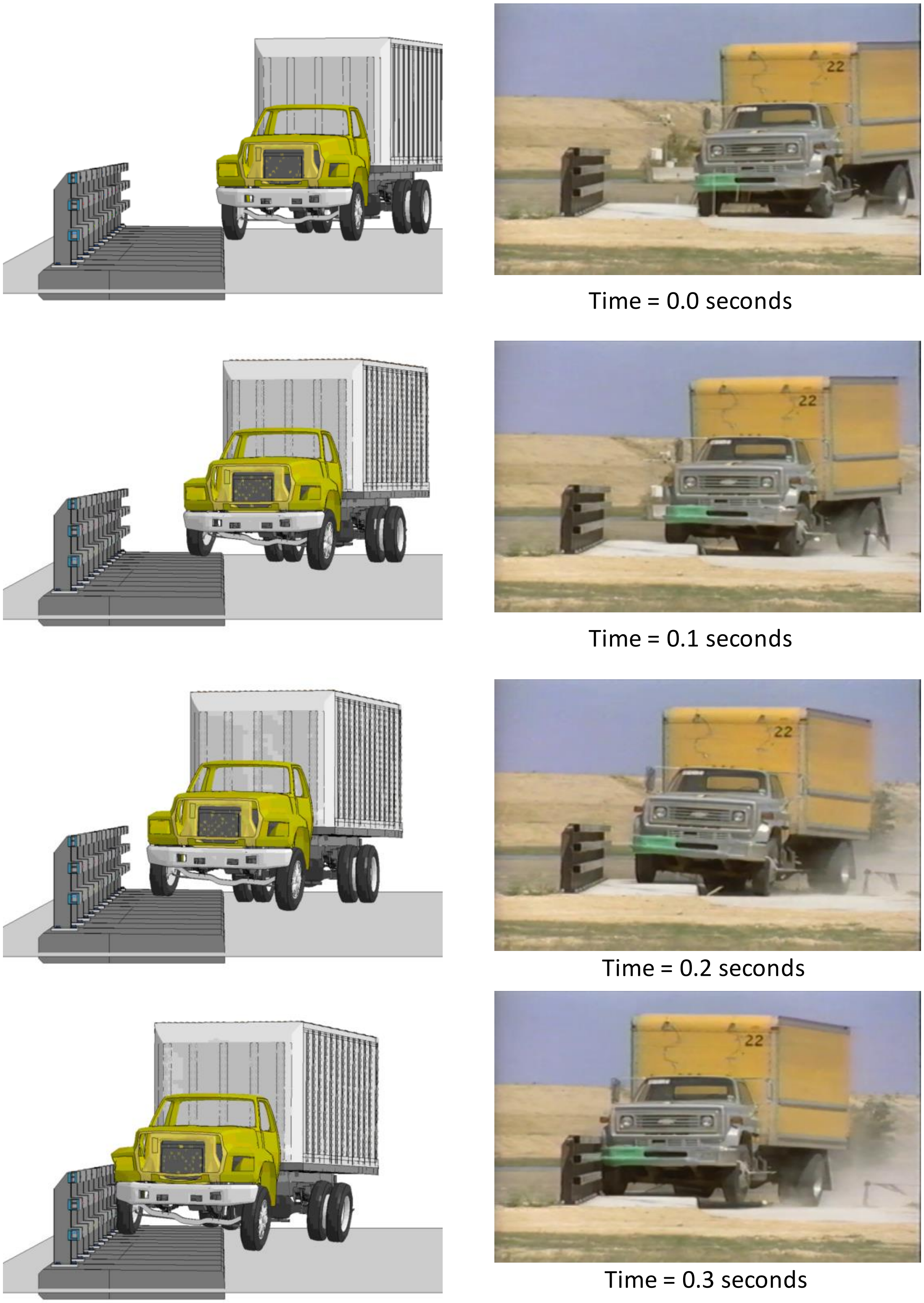
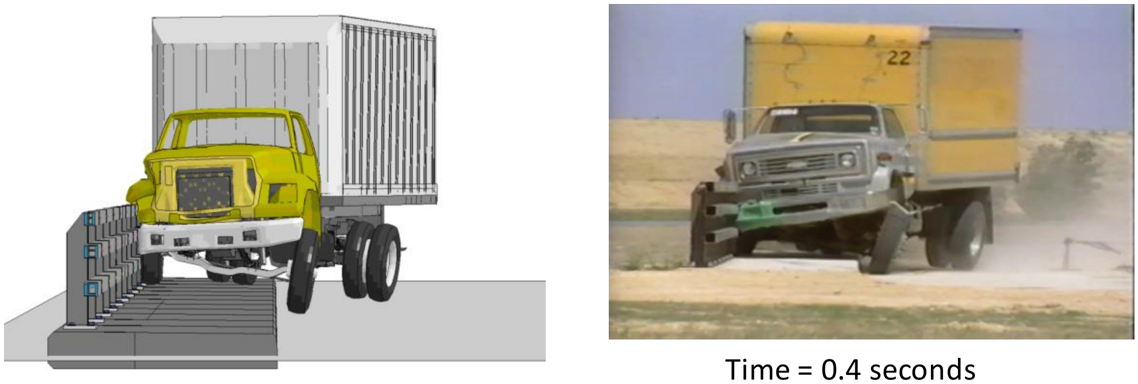


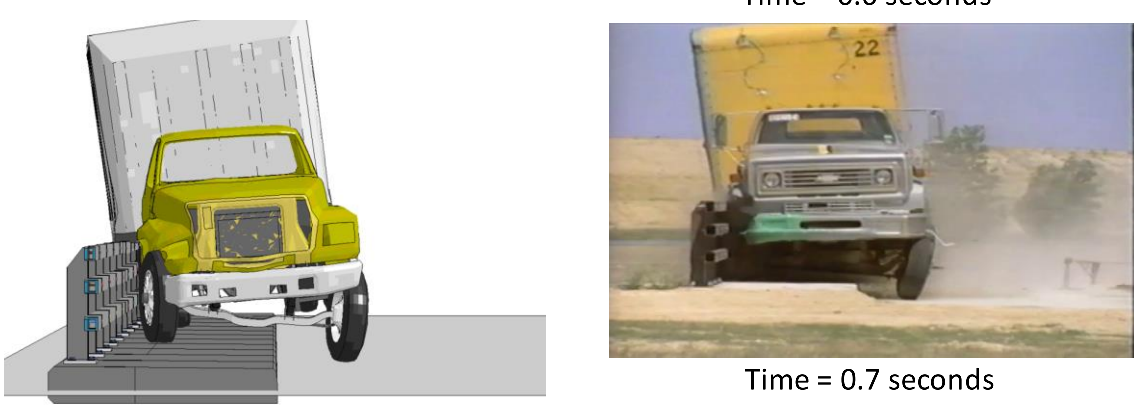
Figure 2. Sequential views from FEA and Test 404251-3 from a downstream view point.



Time = 0.4 seconds

Time = 0.5 seconds

Time = 0.6 seconds



Time = 0.7 seconds

Figure 2. [Continued] Sequential views from FEA and Test 404251-3 from a downstream view point.

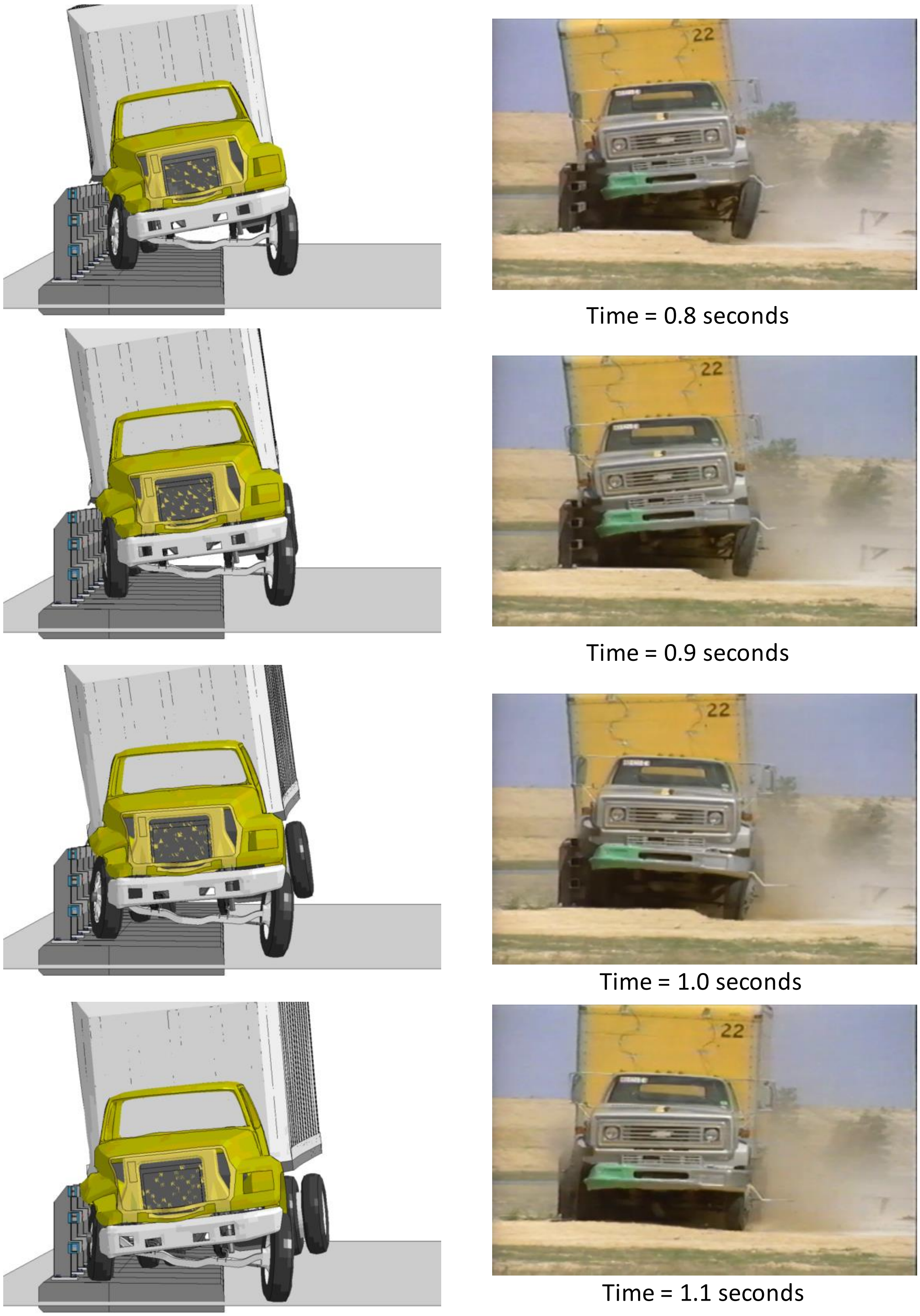
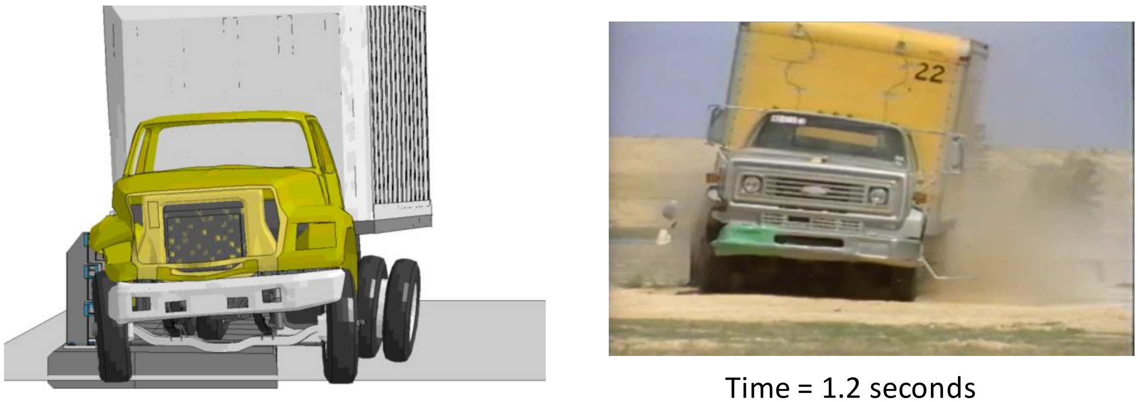
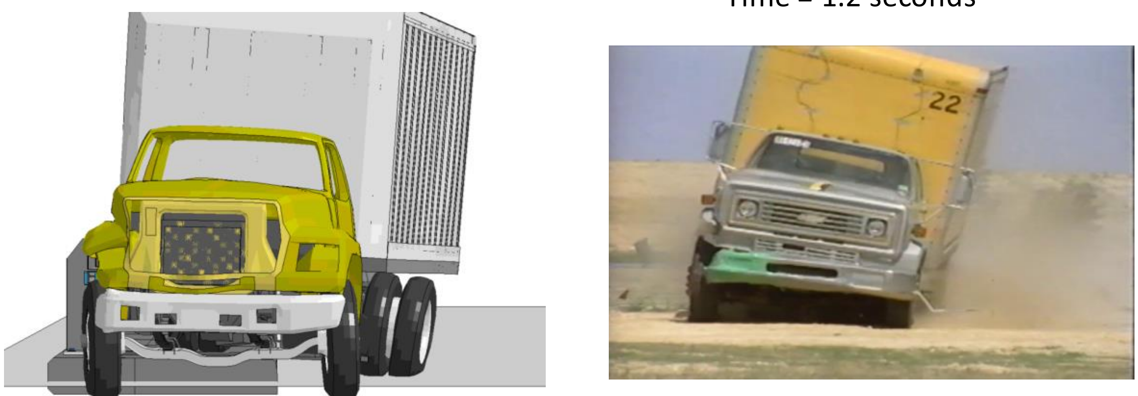


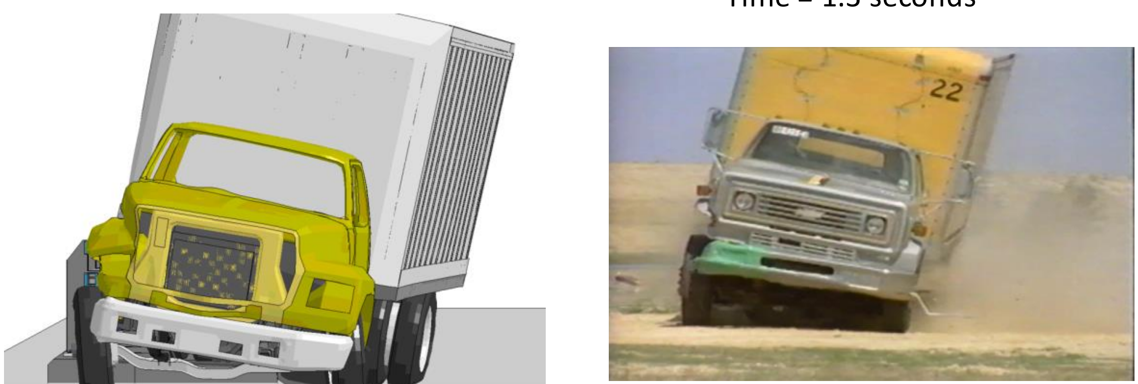
Figure 2. [Continued] Sequential views from FEA and Test 404251-3 from a downstream view point.



Time = 1.2 seconds



Time = 1.3 seconds



Time = 1.4 seconds

Time = 1.5 seconds

Figure 2. [Continued] Sequential views from FEA and Test 404251-3 from a downstream view point.

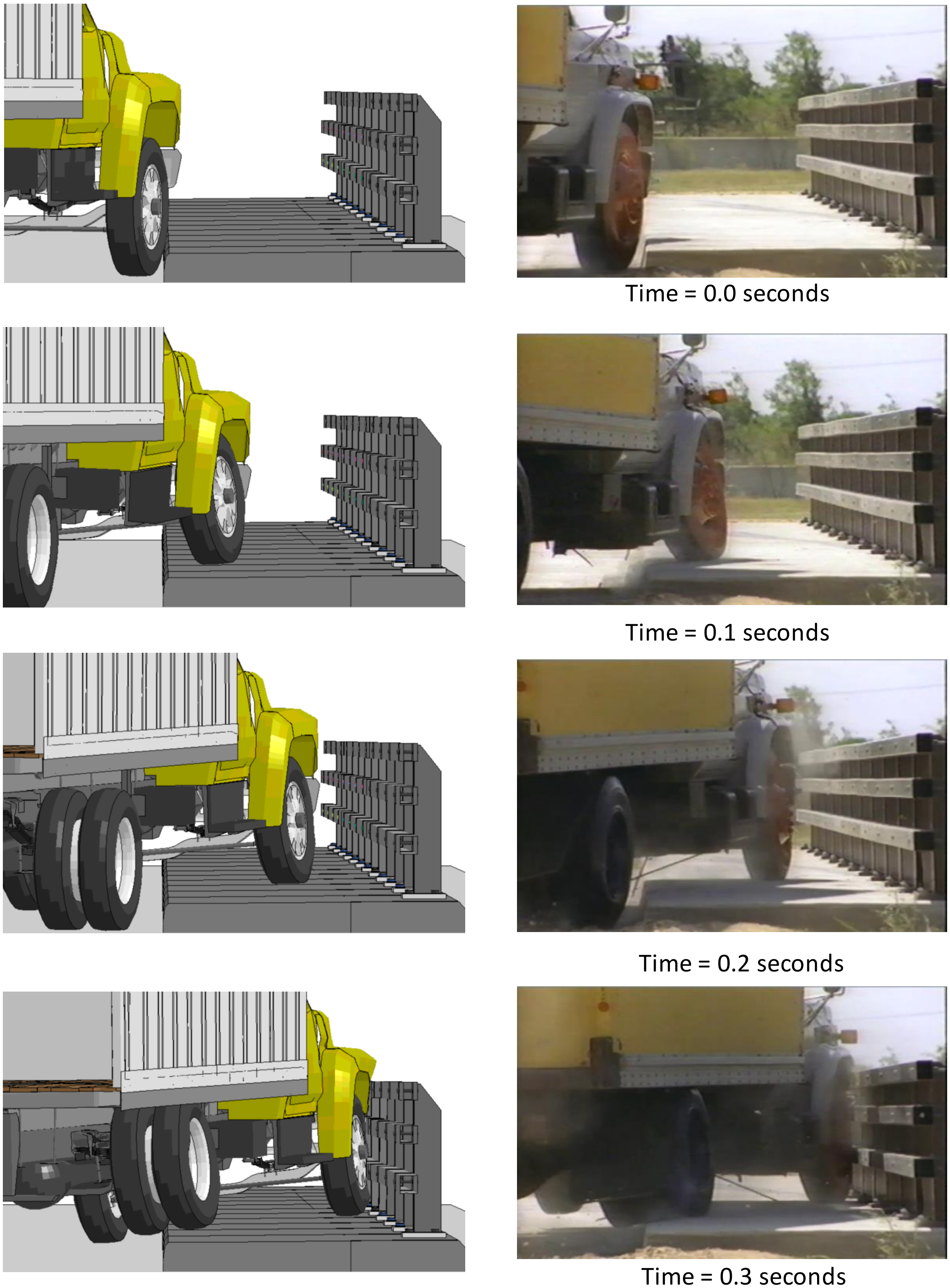
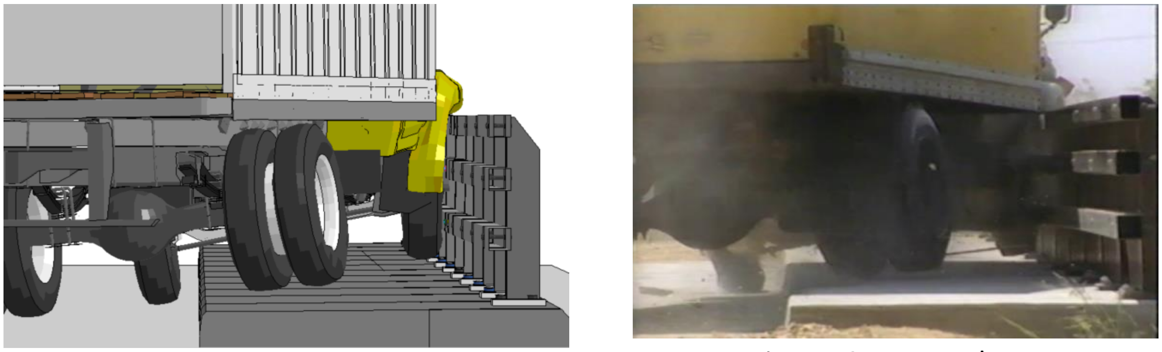
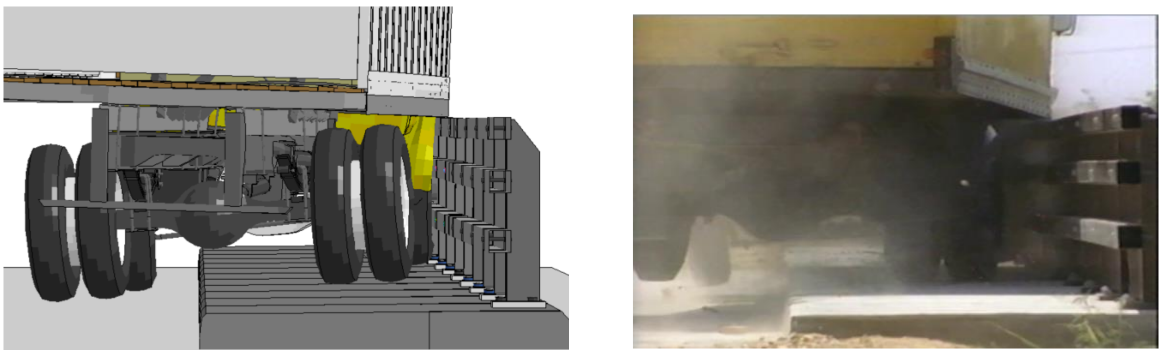


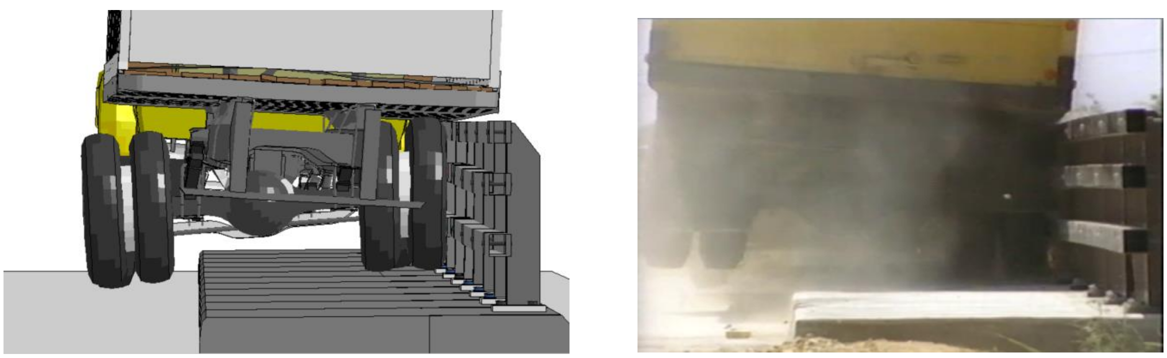
Figure 3. Sequential views from FEA and Test 404251-3 from an upstream view point.



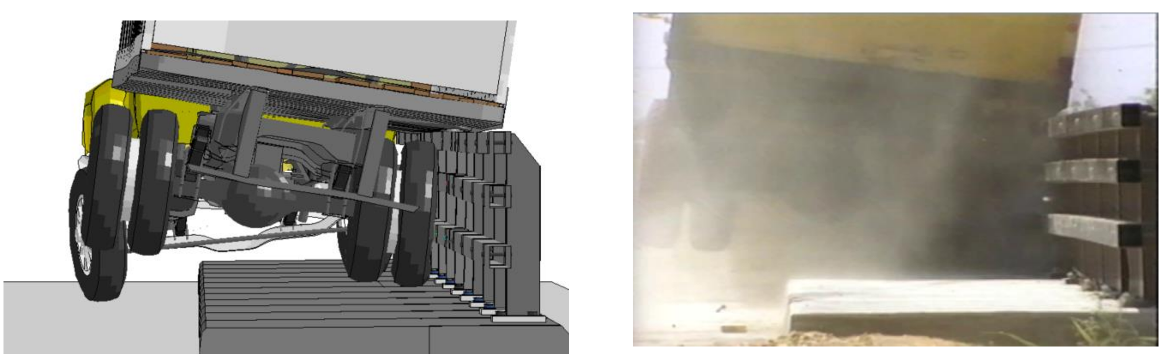
Time = 0.4 seconds



Time = 0.5 seconds

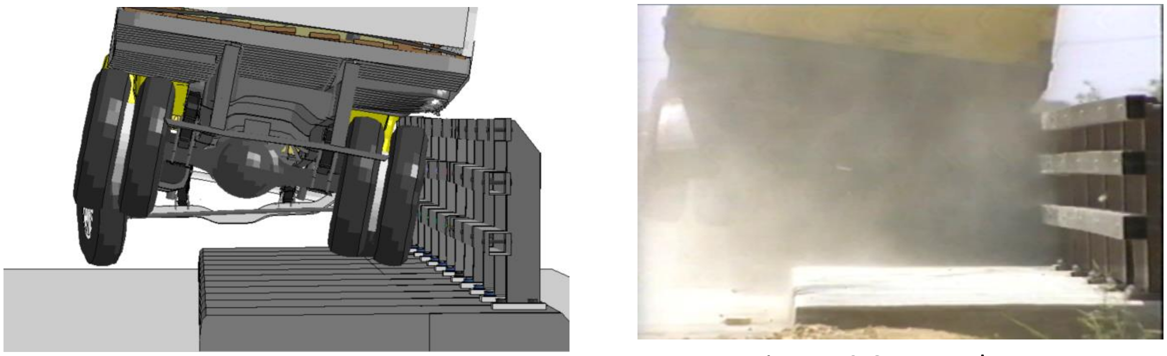


Time = 0.6 seconds

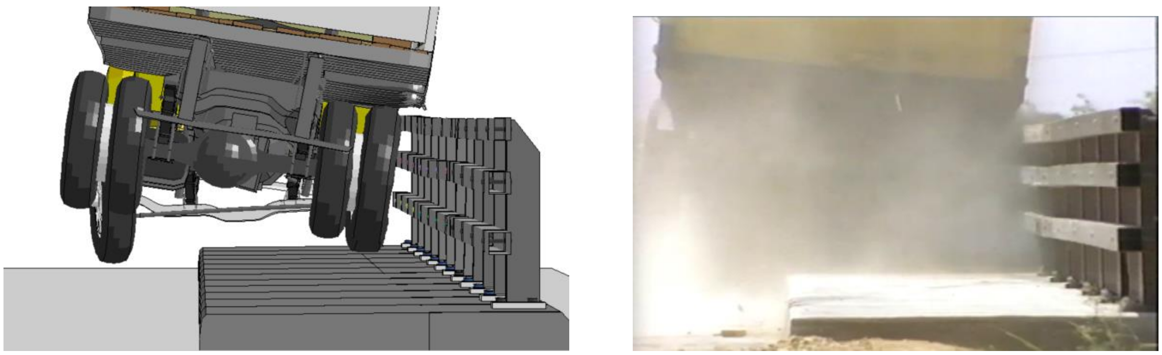


Time = 0.7 seconds

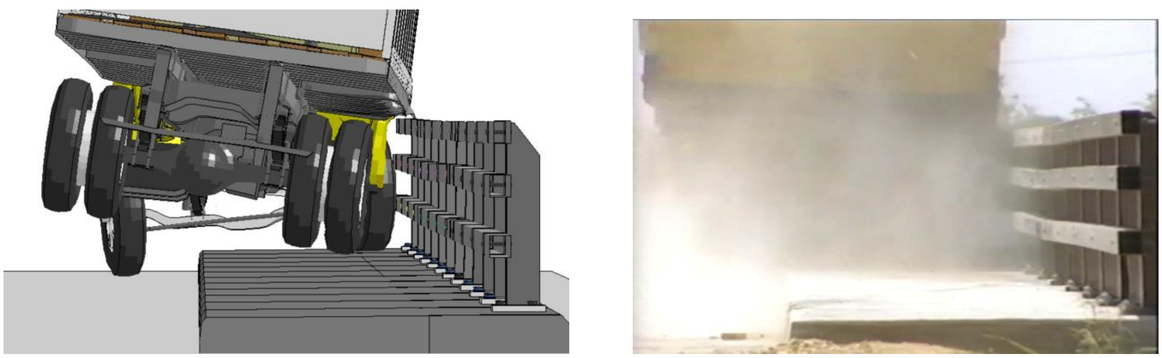
Figure 3. [Continued] Sequential views from FEA and Test 404251-3 from an upstream viewpoint.



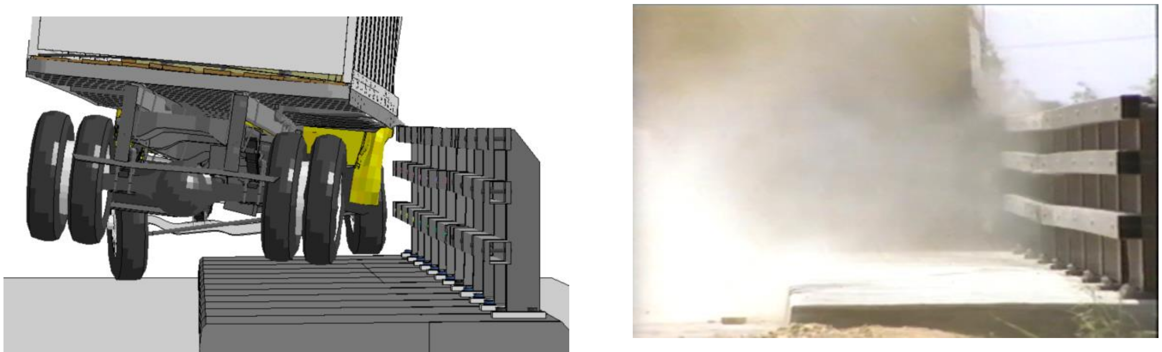
Time = 0.8 seconds



Time = 0.9 seconds



Time = 1.0 seconds



Time = 1.1 seconds

Figure 3. [Continued] Sequential views from FEA and Test 404251-3 from an upstream viewpoint.

Appendix C

Validation Forms for Sidewalk-Mounted S3-TL4 Model

Comparison to Test 404251-3

NCHRP Report 350 Test 4-12

FEA VALIDATION/VERIFICATION REPORT FORMS

Report 350 Test 4-12_____________ (Report 350 or MASH08 or EN1317 Vehicle Type)

Impact of the

MassDOT Sidewalk-Mounded S3-TL4 (Roadside hardware type and name)

Report Date: _12/30/2018________

Type of Report (check one)

- ☐ Verification (known numerical solution compared to new numerical solution).
- ☒ Validation (physical test compared to a numerical solution).
- ☐ Extrapolation (validated numerical solution compared to modified numerical solution).

General Information	**Known Solution**	**Analysis Solution**
Performing Organization	TTI	Roadsafe LLC
Analyst/Engineer	**C.E. Buth**	Chuck Plaxico
Test/Run Number:	404251-3	T4-12_sw-baseline_181119
Vehicle:	1979 Chevrolet C70	F800 Version 181114
Reference:	Test 4-12	Test 4-12
Impact Conditions		
Vehicle Mass:	17,637-lb	17,652-lb
Speed:	49.5 mph	49.5 mph
Angle:	14.9 degrees	14.9 degrees
Impact Point:		

Composite Validation/Verification Score

	List the Report 350/MASH08 or EN1317 Test Number: ____4-12______	Pass?
Part I	Did all solution verification criteria in Table C-1 pass?	Y
Part II	Do all the time history evaluation scores from Table C-2 result in a satisfactory comparison (i.e., the comparison passes the criterion)? If all the values in Table C-2 did not pass, did the weighted procedure shown in Table C-3 result in an acceptable comparison. If all the criteria in Table C-2 pass, enter "yes." If all the criteria in Table C-2 did not pass but Table C-3 resulted in a passing score, enter "yes."	Y
Part III	All the criteria in Table C-4 (Test-PIRT) passed? Not Required for Component Tests	Y
	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.	Y

The analysis solution (check one):

- ☒ Is verified/validated against the known solution.
- ☐ Is NOT verified/validated against the known solution.

PART I: BASIC INFORMATION

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 or component: ____

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

3. Indicate the test level and number being evaluated (fill in the blank): _______4-12____________

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.

<u>NCHRP Report 350/MASH08</u>

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

<u>EN1317</u>

☐ 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

Table C-1. Analysis Solution Verification Table.

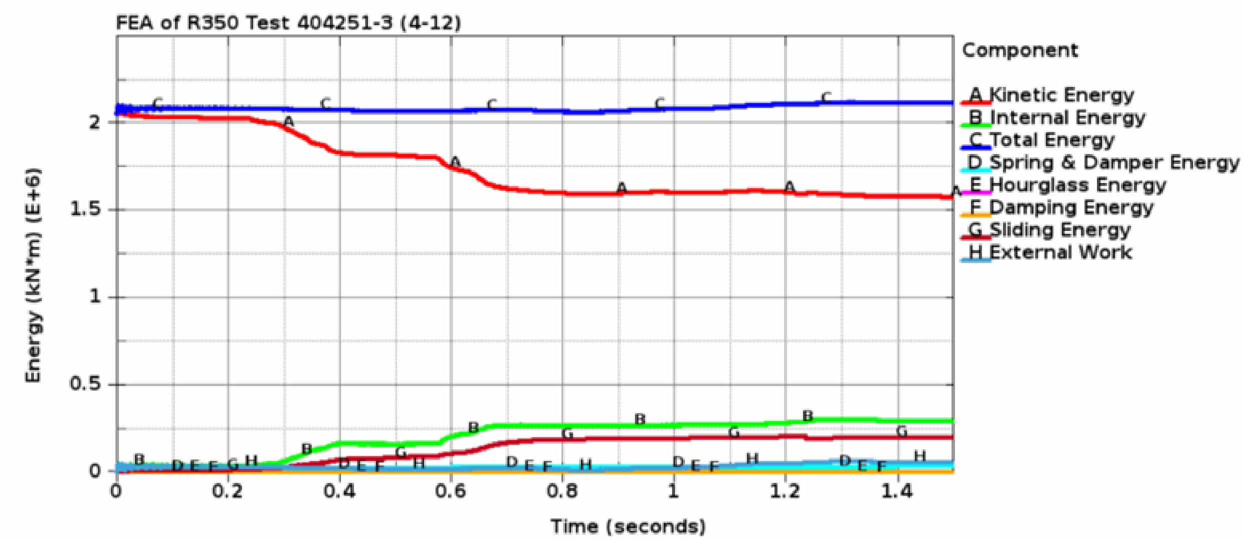
Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	3	Y
Hourglass Energy of the analysis solution at the end of the run is less than *five percent* of the total *initial energy* at the *beginning* of the run.	0.01	Y
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.	0.06	Y
The part/material with the highest amount of hourglass energy at the end of the run is less than twenty percent of the total internal energy of the part/material at the end of the run.	17	Y
Mass added to the total model is less than five percent of the total model mass at the beginning of the run.	0	Y
The part/material with the most mass added had less than 10 percent of its initial mass added.	5.7	Y
The moving parts/materials in the model have less than five percent of mass added to the initial moving mass of the model.	0	Y
There are no shooting nodes in the solution?	Y	Y
There are no solid elements with negative volumes?	Y	Y
Exception Notes:		

☒ Analysis solution passes <u>all</u> the criteria in Table C-1 ☒ without exceptions.

☐ with exceptions as noted in Table C-1.

☐ Analysis solution does NOT pass <u>all</u> the criteria in Table C-1.

☐ Table C-1 is not applicable because ______________________________



FEA of R350 Test 404251-3 (4-12)
Energy (kN*m) (E+6)
Time (seconds)
Component
A Kinetic Energy
B Internal Energy
C Total Energy
D Spring & Damper Energy
E Hourglass Energy
F Damping Energy
G Sliding Energy
H External Work

PART III: HISTORY EVALUTION TABLES

Table C-2. Roadside Safety Validation Metrics Rating Table (single channel option).

	Evaluation Criteria								Time interval [0.45 seconds]		
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.										
	Channel	**RSVVP Curve Preprocessing Options**							**M**	**P**	**Pass?**
		Filter Option	**Sync. Option**	**Shift**		**Drift**					
				True Curve	**Test Curve**	**True Curve**	**Test Curve**				
	x-acceleration	SAE 60	Y	none	None	none	None		85.8	42.9	N
	y-acceleration	SAE 60	Y	None	None	None	None		15.8	33.7	Y
	z-acceleration	SAE 60	Y	None	None	None	None		0.3	39.6	Y
	Yaw-rate	SAE 60	Y	None	none	None	none		27.9	16.2	Y
	Roll-rate	SAE 60	Y	None	none	None	none		21.7	30.4	Y
	Pitch-rate	SAE 60	Y	None	none	None	none		88.8	48	N
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								1.2	37.21	N
	y-acceleration								0.72	18.9	Y
	z-acceleration								2.6	27.0	Y
	Yaw-rate								3.29	25.1	Y
	Roll-rate								8.4	26.7	N
	Pitch-rate								6.0	48.2	N
Exception Notes:											

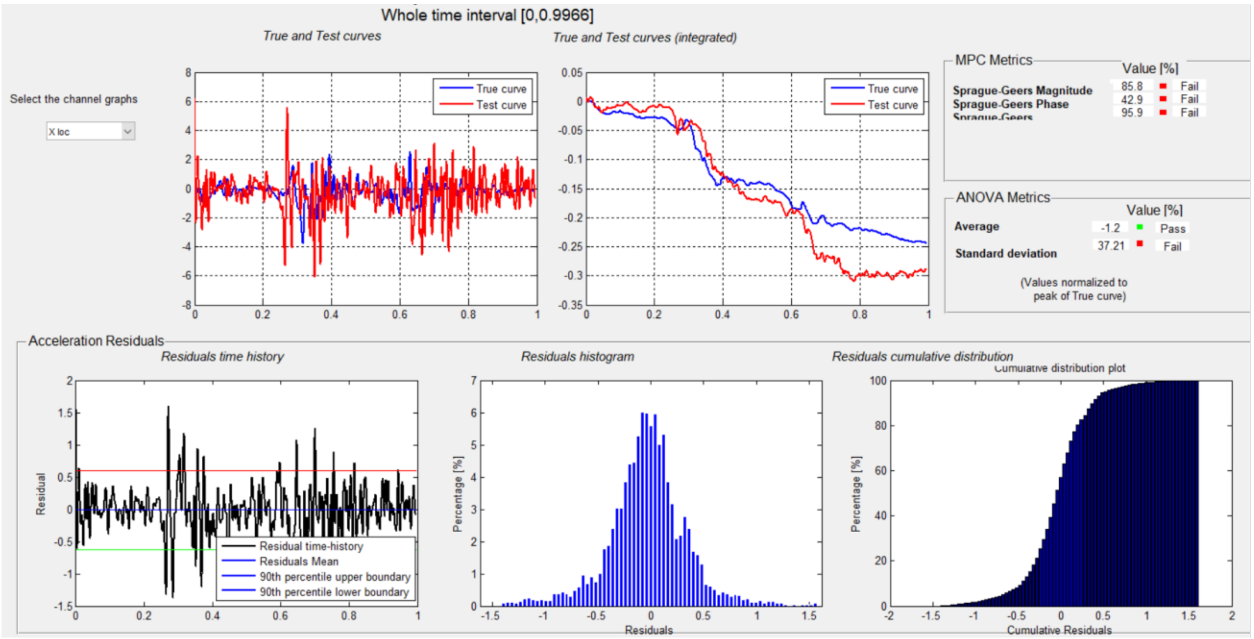
☐ Analysis solution passes <u>all</u> the criteria in Table C-2 ☐ without exceptions.

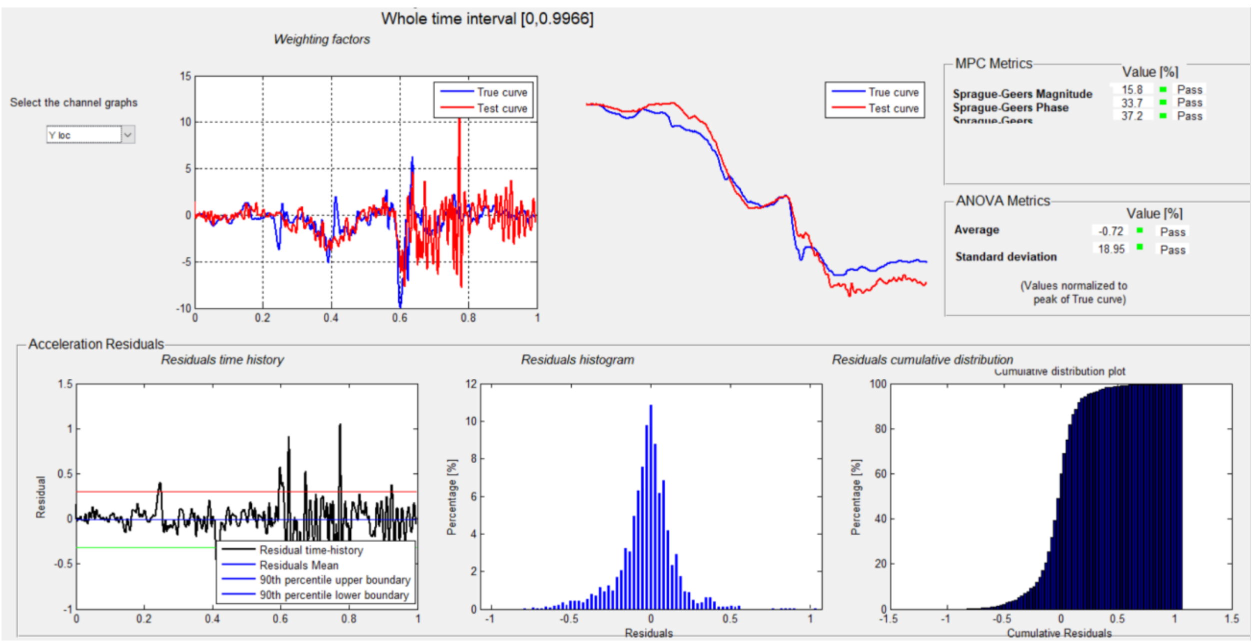
☐ with exceptions as noted in Table C-2.

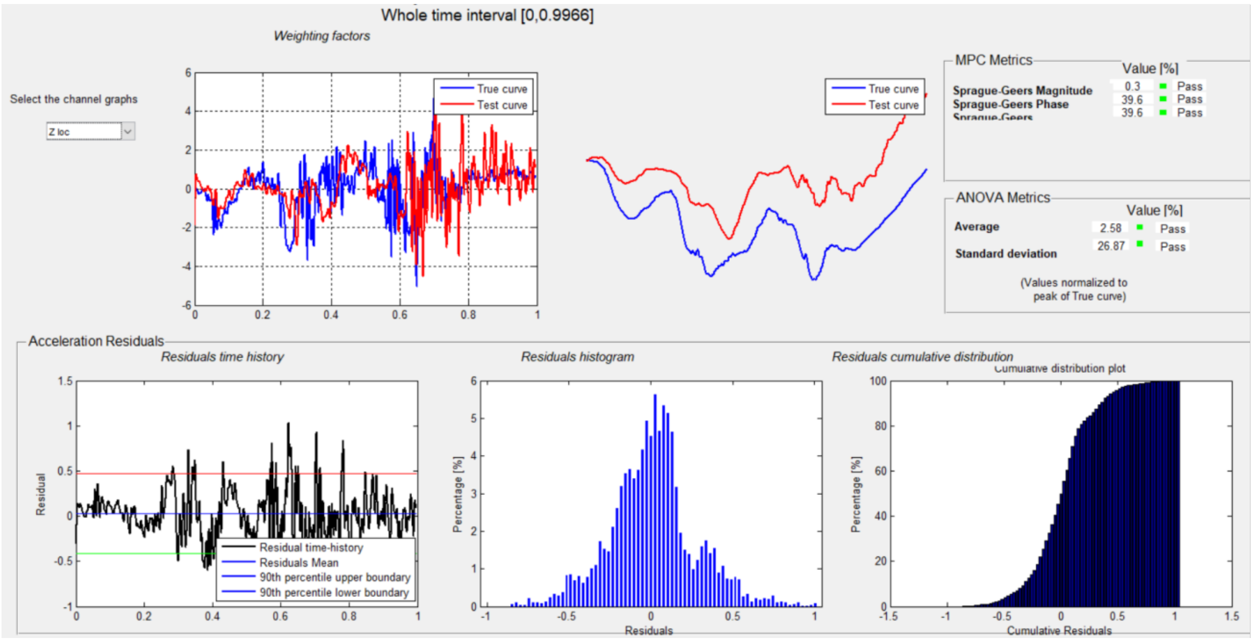
☒ Analysis solution does NOT pass <u>all</u> the criteria in Table C-2.

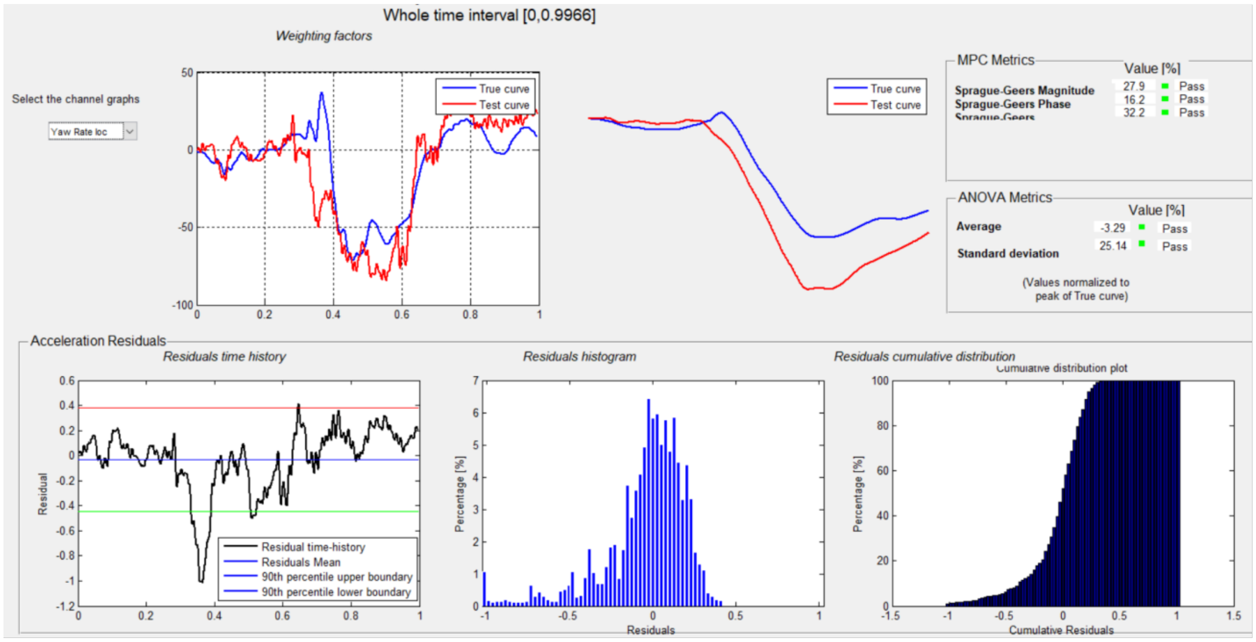
☐ Table C-2 is not applicable because ________________________________

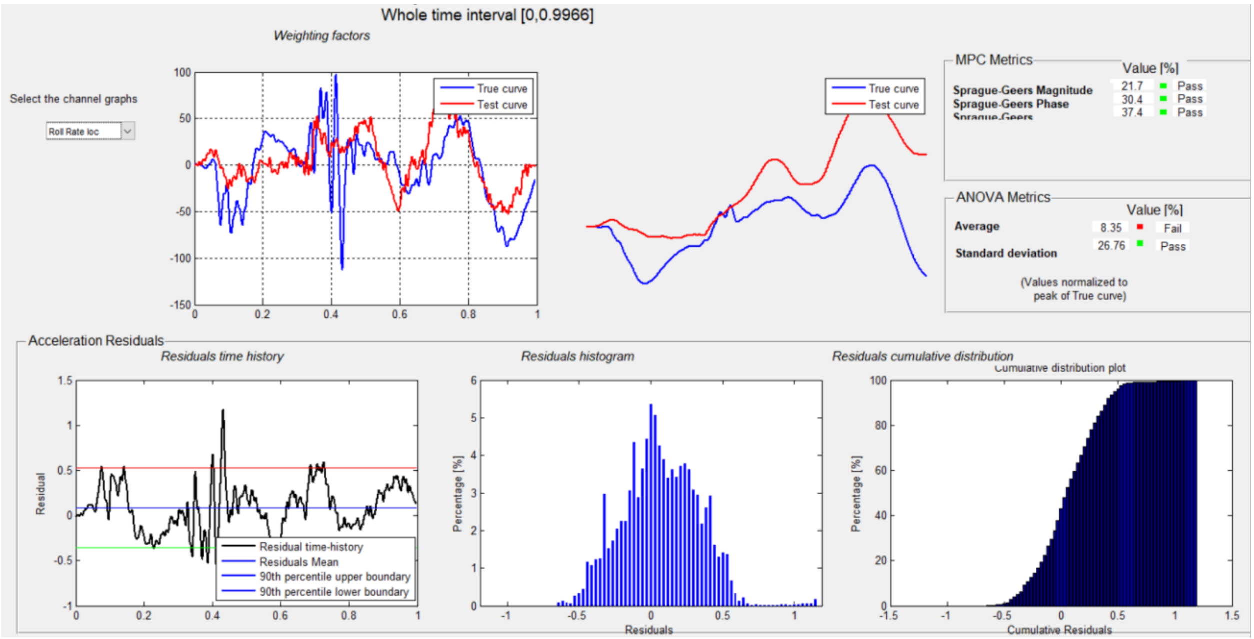
☒ RSVVP Single-Channel Comparison Metric Values Screens for each channel are attached on the following pages.


Whole time interval [0,0.9966]
True and Test curves
True and Test curves (integrated)
Select the channel graphs
X loc
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude 85.8 Fail
Sprague-Geers Phase 42.9 Fail
Sprague-Geers 95.9 Fail
ANOVA Metrics
Value [%]
Average -1.2 Pass
Standard deviation 37.21 Fail
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residuals histogram
Residuals cumulative distribution
Cumulative distribution plot
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Percentage [%]
Residuals
Cumulative Residuals


Whole time interval [0,0.9966]
Weighting factors
Select the channel graphs
Y loc
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude 15.8 Pass
Sprague-Geers Phase 33.7 Pass
Sprague-Geers 37.2 Pass
ANOVA Metrics
Value [%]
Average -0.72 Pass
Standard deviation 18.95 Pass
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residuals histogram
Residuals cumulative distribution
Cumulative distribution plot
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Percentage [%]
Residuals
Cumulative Residuals


Whole time interval [0,0.9966]
Weighting factors
Select the channel graphs
Z loc
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude 0.3 Pass
Sprague-Geers Phase 39.6 Pass
Sprague-Geers 39.6 Pass
ANOVA Metrics
Value [%]
Average 2.58 Pass
Standard deviation 26.87 Pass
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Cumulative distribution plot
Percentage [%]
Cumulative Residuals


Whole time interval [0,0.9966]
Weighting factors
Select the channel graphs
Yaw Rate loc
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude 27.9 Pass
Sprague-Geers Phase 16.2 Pass
Sprague-Geers 32.2 Pass
ANOVA Metrics
Value [%]
Average -3.29 Pass
Standard deviation 25.14 Pass
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Cumulative distribution plot
Percentage [%]
Cumulative Residuals


Whole time interval [0,0.9966]
Weighting factors
Select the channel graphs
Roll Rate loc
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude 21.7 Pass
Sprague-Geers Phase 30.4 Pass
Sprague-Geers 37.4 Pass
ANOVA Metrics
Value [%]
Average 8.35 Fail
Standard deviation 26.76 Pass
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Cumulative distribution plot
Cumulative Residuals

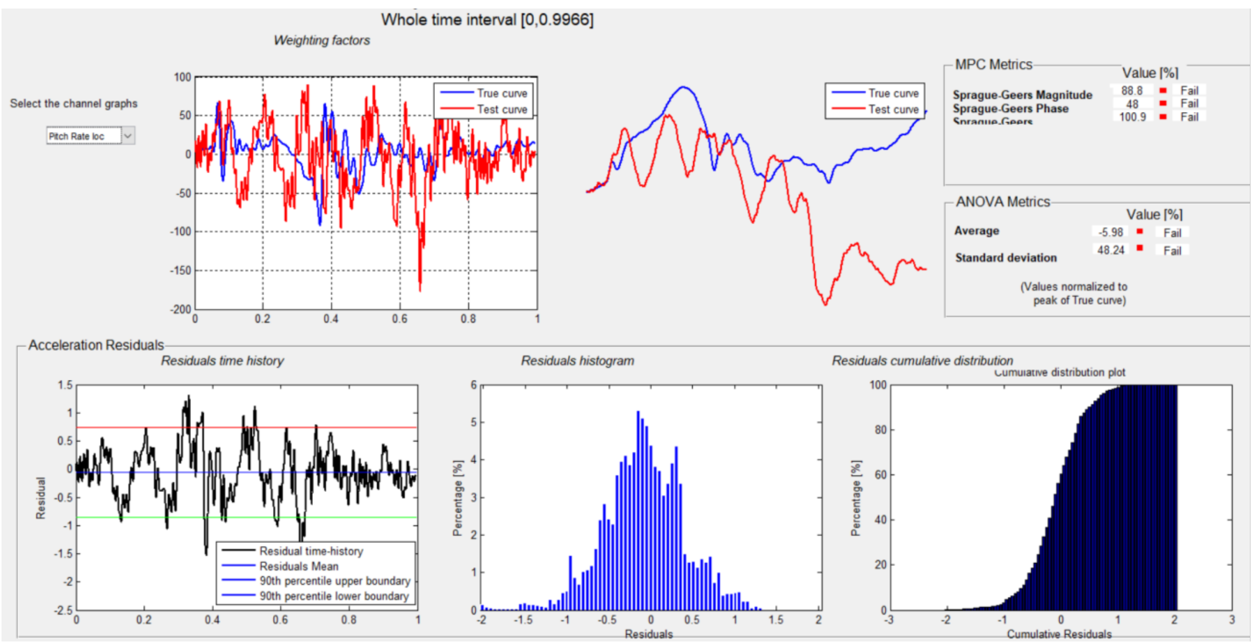
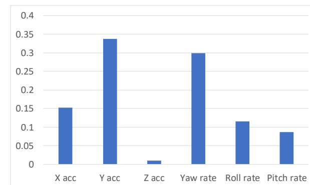

Whole time interval [0,0.9966]
Weighting factors
Select the channel graphs
Pitch Rate loc
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude 88.8 Fail
Sprague-Geers Phase 48 Fail
Sprague-Geers 100.9 Fail
ANOVA Metrics
Value [%]
Average -5.98 Fail
Standard deviation 48.24 Fail
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Cumulative distribution plot
Cumulative Residuals

Table C-3. Roadside Safety Validation Metrics Rating Table (multi-channel option).

<table>
<tr><th colspan="6">Evaluation Criteria (time interval [0.0 – 1.0 seconds])</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 -</td><td colspan="2">X Channel: 0.152
Y Channel: 0.338
Z Channel: 0.010
Yaw Channel: 0.299
Roll Channel: 0.115
Pitch Channel: 0.086</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>36.9</td><td>30.8</td><td colspan="2">Y</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 ($\bar{e} \le 0.05 \cdot a_{Peak}$)
The standard deviation of the residuals must be less than 35 percent of the peak acceleration ($\sigma \le 0.35 \cdot a_{Peak}$)</td><td>Mean Residual</td><td>Standard Deviation of Residuals</td><td colspan="2">Pass?</td></tr>
<tr><td>0.9</td><td>27.1</td><td colspan="2">Y</td></tr>
</table>

☐ Analysis solution passes <u>all</u> the criteria in Table C-3 ☒ without exceptions

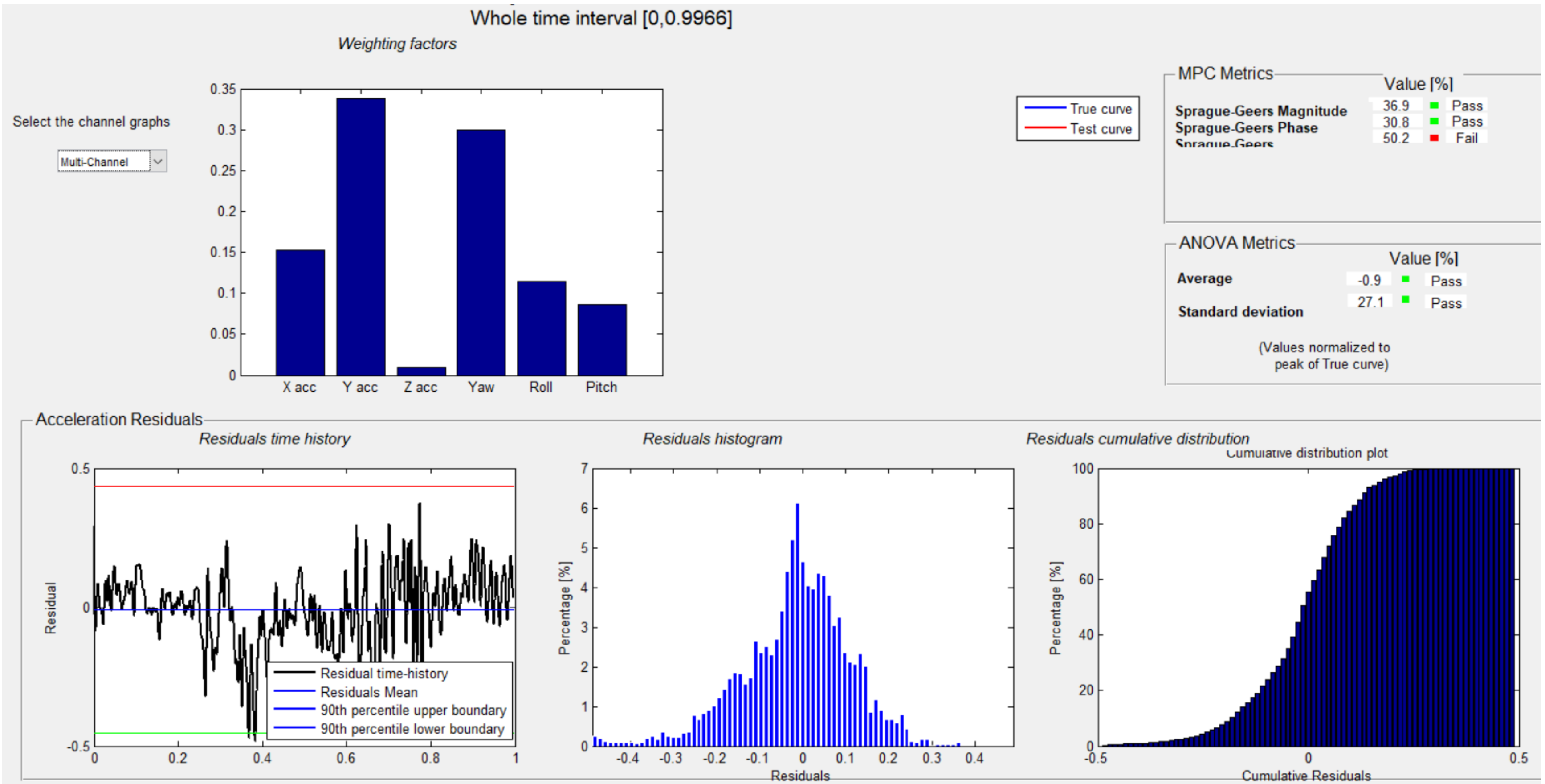
☐ with exceptions as noted in Table C-3.

☐ Analysis solution does NOT pass <u>all</u> the criteria in Table C-3.

☐ Table C-3 does not contain sufficient information for assessment.

☐ Table C-3 is not applicable because criteria were satisfied in Table C-2.

☒ RSVVP Multi-Channel Comparison Metric Values Screen is attached on the following page.



Whole time interval [0,0.9966]
Weighting factors
Select the channel graphs
Multi-Channel
X acc
Y acc
Z acc
Yaw
Roll
Pitch
True curve
Test curve
MPC Metrics
Value [%]
Sprague-Geers Magnitude
Sprague-Geers Phase
36.9
Pass
30.8
Pass
50.2
Fail
ANOVA Metrics
Value [%]
Average
-0.9
Pass
Standard deviation
27.1
Pass
(Values normalized to peak of True curve)
Acceleration Residuals
Residuals time history
Residual
Residual time-history
Residuals Mean
90th percentile upper boundary
90th percentile lower boundary
Residuals histogram
Percentage [%]
Residuals
Residuals cumulative distribution
Percentage [%]
Cumulative Residuals

PART IV: PHENOMENAA IMPORTANCE RANKING TABLES

Table C-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 rowspan="2">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><tr><td>Longitudinal</td><td>3</td><td>5</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>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="4">Vehicle Trajectory</td><td>K</td><td>After collision it is preferable that the vehicle's trajectory not intrude into adjacent traffic lanes.</td><td>All</td></tr>
<tr><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>

Table C-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)	Y	Y		Y
		A2	Maximum permanent deflection: - Relative difference is less than 20 percent or - Absolute difference is less than 6 inches	0.4 in	1.02 in	155% 0.62 in	Y
		A3	Length of vehicle-barrier contact (at initial separation): - Relative difference is less than 20 percent or - Absolute difference is less than 6.6 ft	28.2 ft	26.6 ft	5.8 % 1.6 ft	Y
		A4	Number of broken or significantly bent posts is less than 20 percent.	0	0		Y
		A5	Did the rail element rupture or tear (Answer Yes or No)	No	No		Y
		A6	Concrete curb/deck failure	*No	No		Y
		A7	Was there significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	N	N		Y
		A8	Was there significant snagging between vehicle body components and barrier elements (Answer Yes or No).	N	N		Y

Note: Additional phenomena can be added to the tables in deemed appropriate by the analyst.

Table C-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)	N	N		Y
	F	F1	The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are acceptable. (Answer Yes or No)	Y	Y		Y
		F2	Maximum roll of the vehicle through 1.0 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	4.6 deg	9.9 deg	115 % 5.3 deg	Y
		F3	Maximum pitch of the vehicle through 1.0 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	3.6 deg	2.7 deg	25 % 0.9 deg	Y
		F4	Maximum yaw of the vehicle through 0.446 seconds: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	12.8 deg	18.5 deg	44 % 5.7 deg	N
	G	1	Did the vehicle remain upright during and after collision	Y	Y		Y
	L	L1	Occupant impact velocities: - Relative difference is less than 20 percent or - Absolute difference is less than 6.6 ft/s.				
			• Longitudinal OIV (ft/s)	4.3	5.6	31% 1.3 ft/s	Y
			• Lateral OIV (ft/s)	8.5	10.8	27 % 2.3 ft/s	Y
			• THIV (ft/s)	9.5	12.5	31% 3 ft/s	Y
		L2	Occupant accelerations: - Relative difference is less than 20 percent or - Absolute difference is less than 4 g's.				
			• Longitudinal ORA	-1.8	-3.8	111 % 2 g	Y
			• Lateral ORA	-9.6	-5.9	38.5 % 3.7 g	Y
			• PHD	9.7	5.9	39.2 % 3.8 g	Y
			• ASI	0.52	0.35	32.7 % 0.2	Y

** Possible "drift" in the pitch-rate channel; the sequential views (**Error! Reference source not found.**) show the pitch comparison to be much closer.*

*** Taken at time=1.0 second coincident with the time of maximum pitch in the test.*

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

Evaluation Criteria				Known Result	Analysis Result	Difference Relative/ Absolute	Agree?
Vehicle Trajectory	K	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.	*33% cargo box	*16.8% cargo box		Y
		M2	Exit angle at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 5 degrees.	*5.0 deg cargo box	*2.5 deg cargo box	50% 2.5 deg	Y
	M	M3	Exit velocity at loss of contact: - Relative difference is less than 20 percent or - Absolute difference is less than 6.2 mph.	*44.1 mph	*43.0 mph	1.0 % 1.1 mph	Y

Note: Additional phenomena can be added to the tables in deemed appropriate by the analyst.

☒ Analysis solution passes all the criteria in Tables E-5(a) through E-5(c)

☒ without exceptions.

☐ with exceptions as noted in Tables E-5(a) through E-5(c).

☐ Does NOT pass all the criteria in Tables E-5(a) through 5(c).

☐ Tables E-5(a) through E-5(c) does not contain sufficient information for assessment.

☐ Tables E-5(a) through E-5(c) are not applicable because ___________________________________

☒ Synchronized side-by-side views of the known and analysis solutions are attached on the following pages.

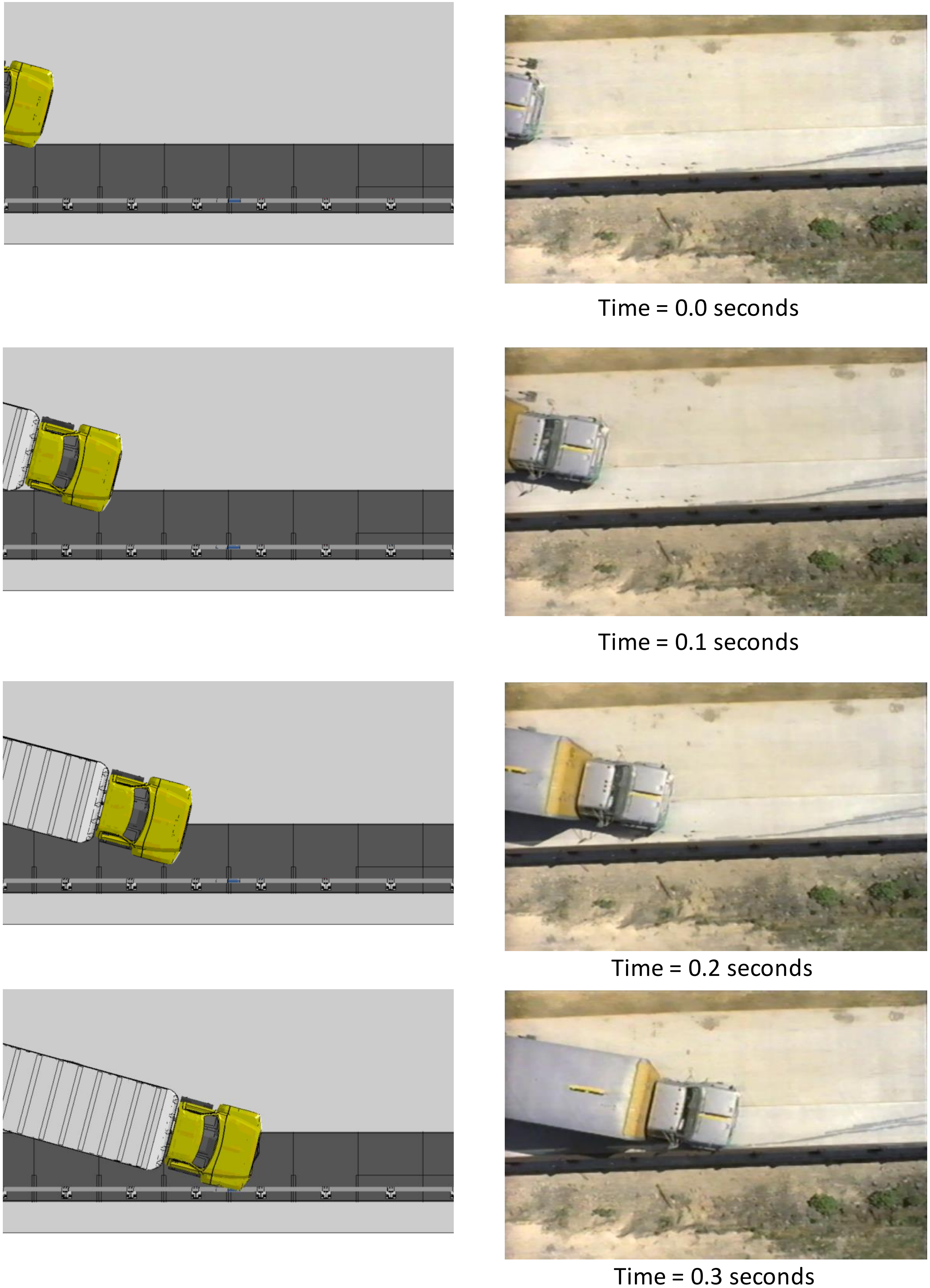
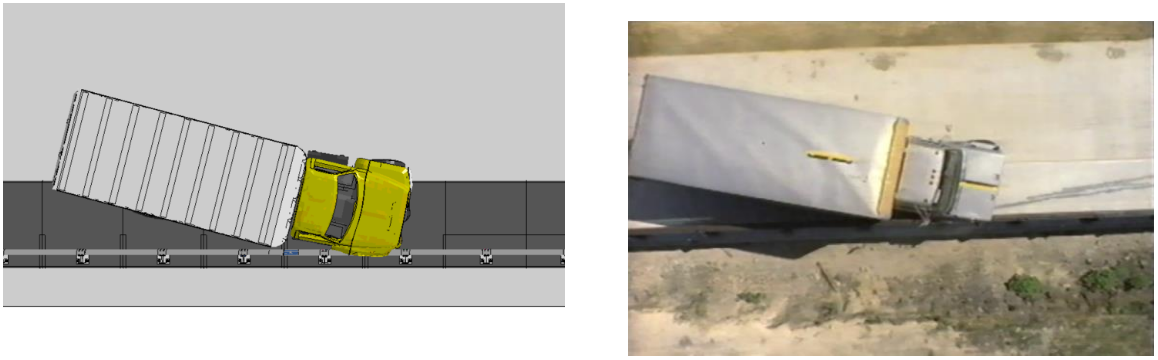
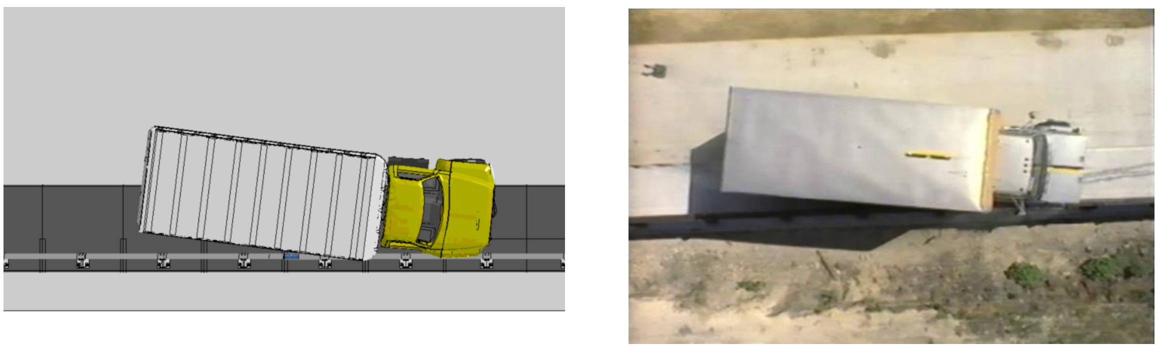


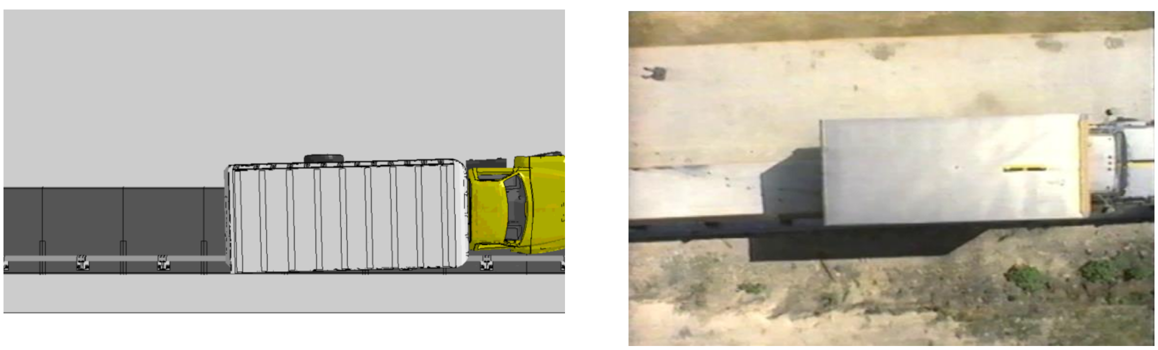
Figure 1. Sequential views from FEA and Test 404251-3 from an overhead view point.



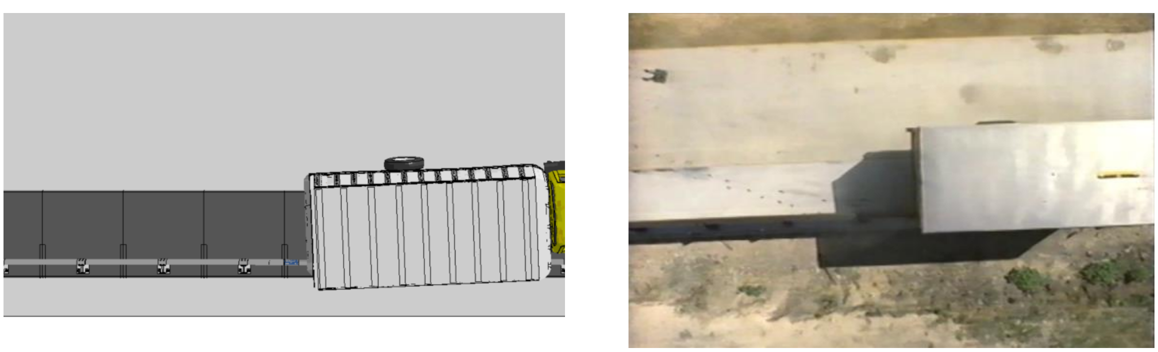
Time = 0.4 seconds



Time = 0.5 seconds

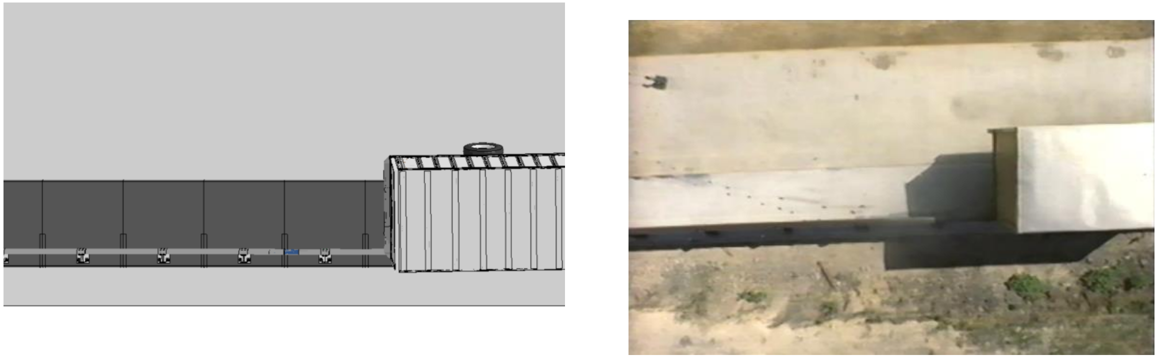


Time = 0.6 seconds

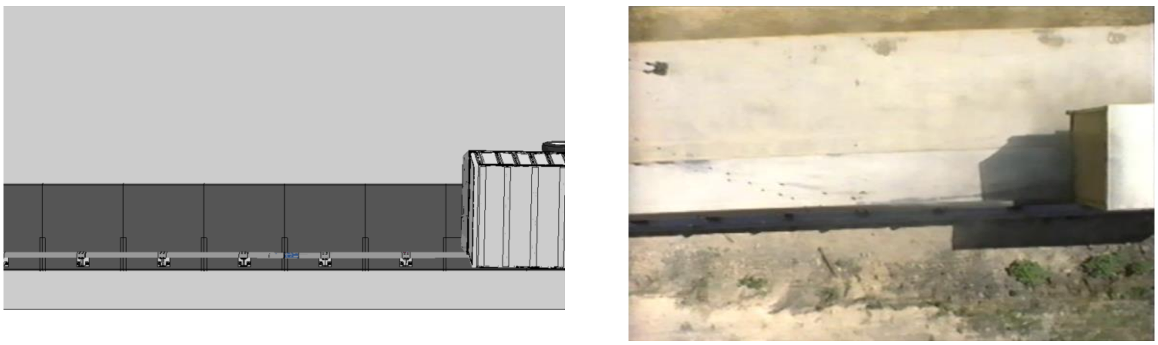


Time = 0.7 seconds

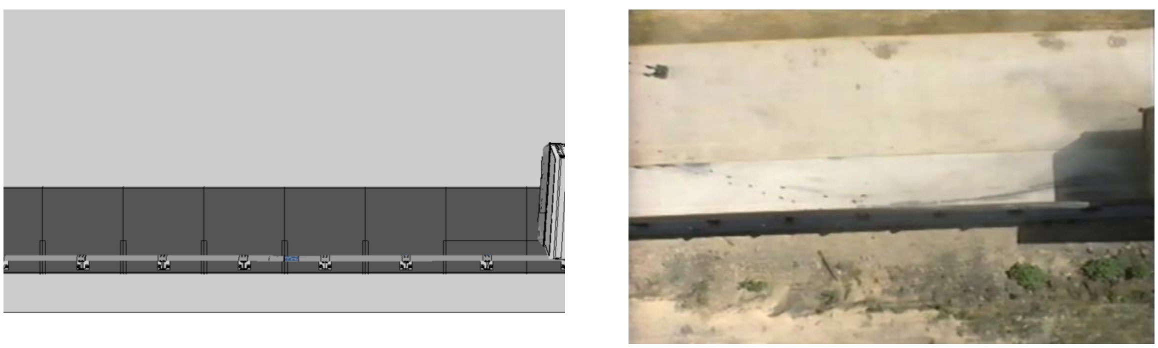
Figure 1. [Continued] Sequential views from FEA and Test 404251-3 from an overhead view point.



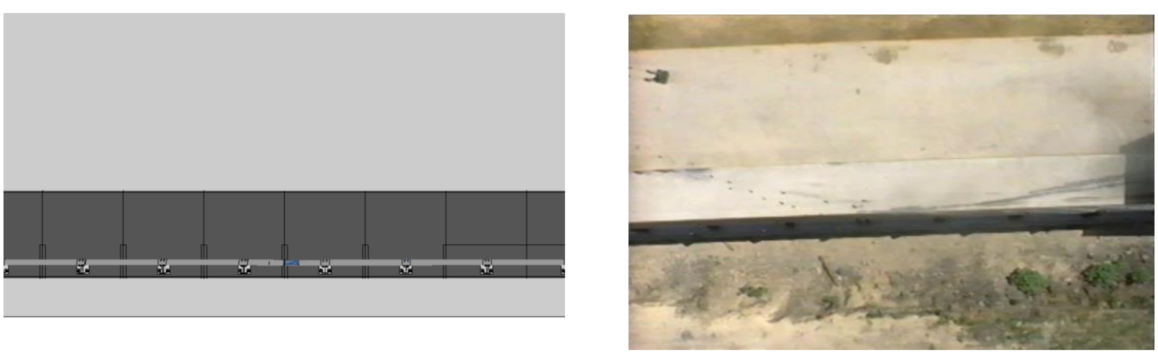
Time = 0.8 seconds



Time = 0.9 seconds

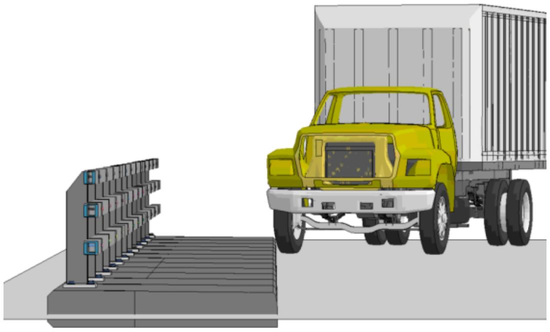


Time = 1.0 seconds



Time = 1.1 seconds

Figure 1. [Continued] Sequential views from FEA and Test 404251-3 from an overhead view point.



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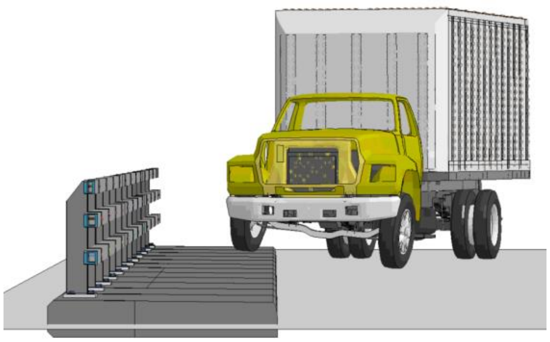


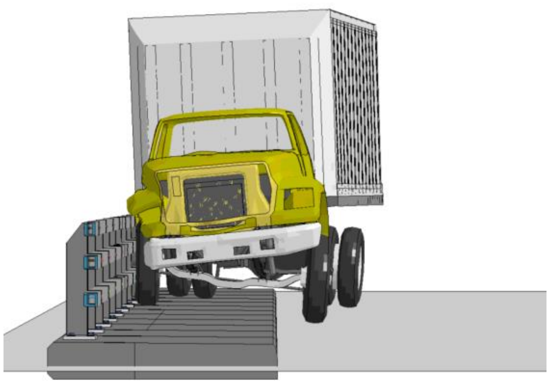
Time = 0.1 seconds

Time = 0.2 seconds

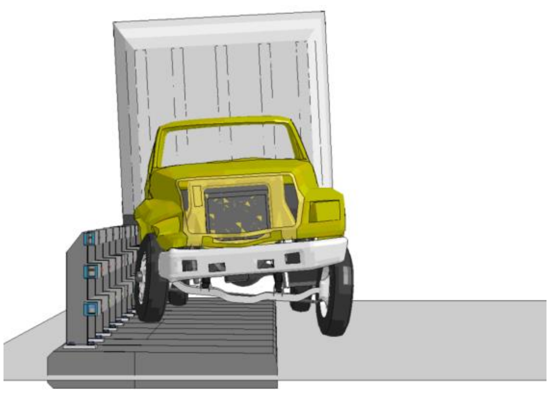
Time = 0.3 seconds

Figure 2. Sequential views from FEA and Test 404251-3 from a downstream view point.

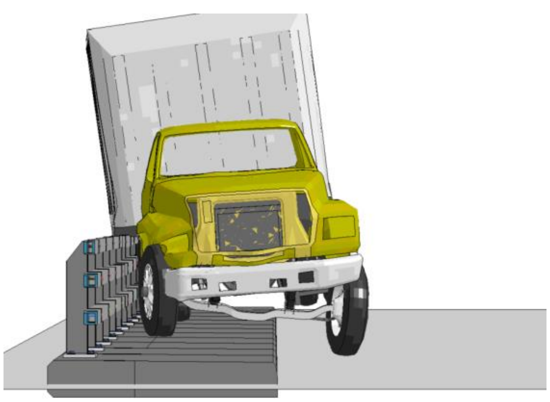
Time = 0.4 seconds



Time = 0.5 seconds

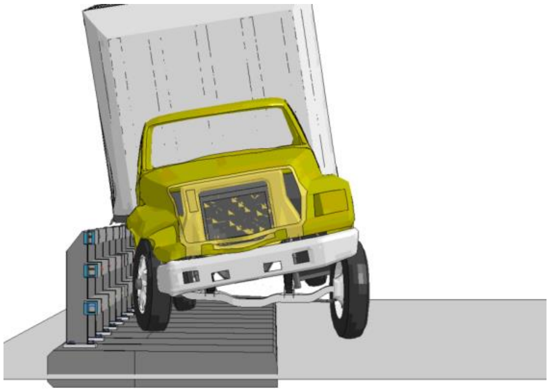


Time = 0.6 seconds

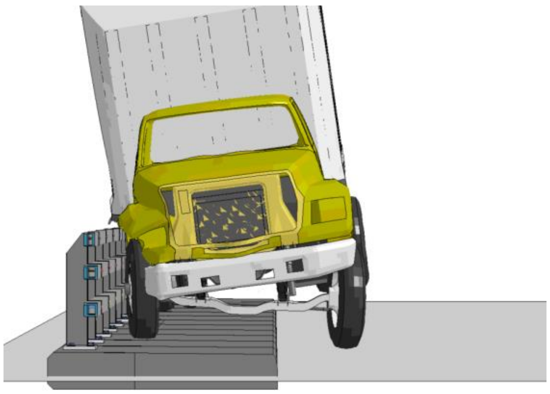


Time = 0.7 seconds

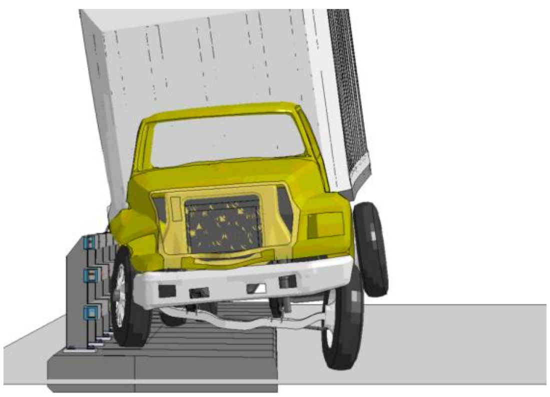
Figure 2. [Continued] Sequential views from FEA and Test 404251-3 from a downstream view point.



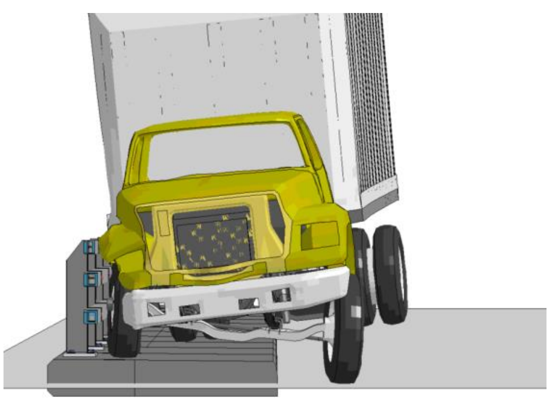
Time = 0.8 seconds



Time = 0.9 seconds

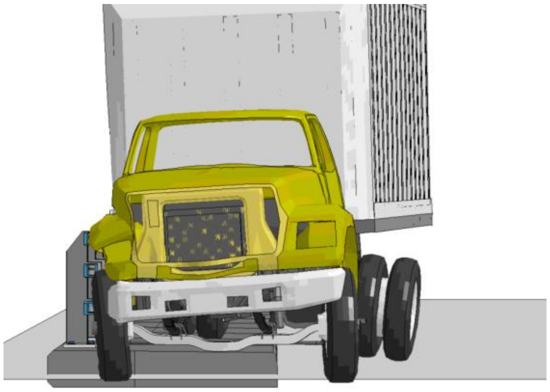


Time = 1.0 seconds

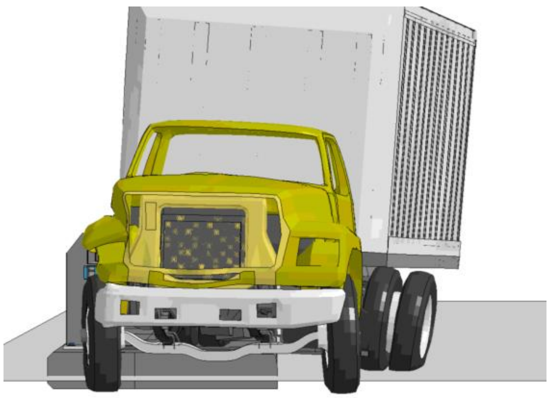


Time = 1.1 seconds

Figure 2. [Continued] Sequential views from FEA and Test 404251-3 from a downstream view point.

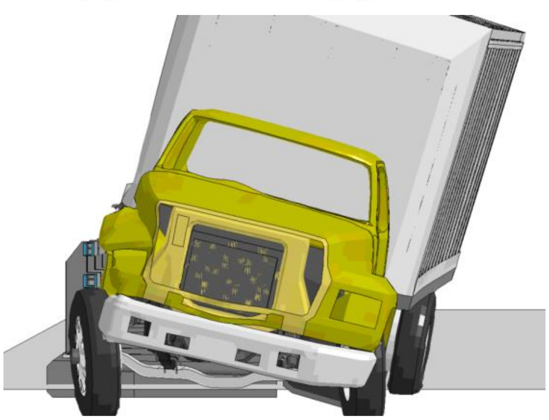


Time = 1.2 seconds



Time = 1.3 seconds

Time = 1.4 seconds



Time = 1.5 seconds

Figure 2. [Continued] Sequential views from FEA and Test 404251-3 from a downstream view point.

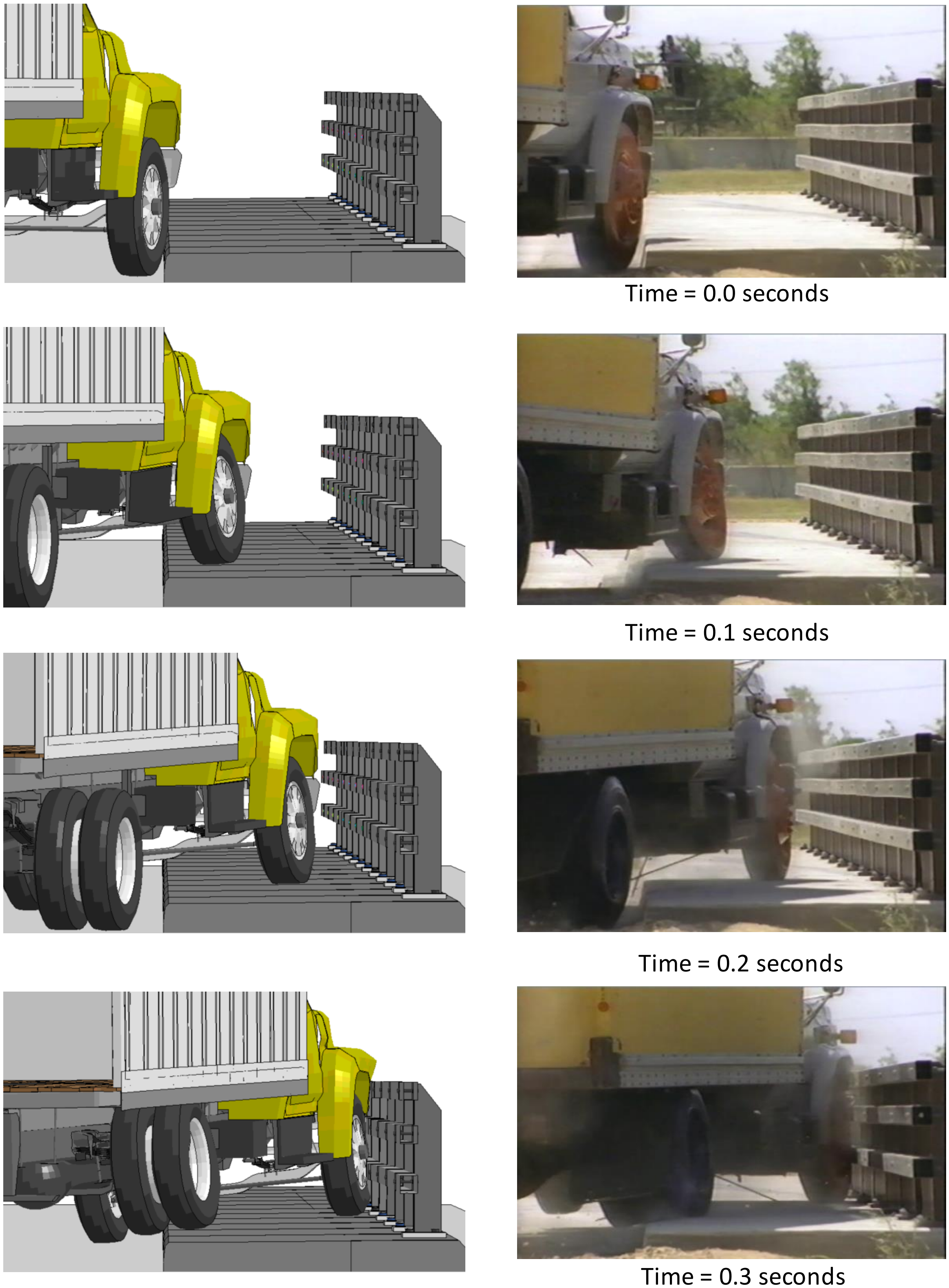
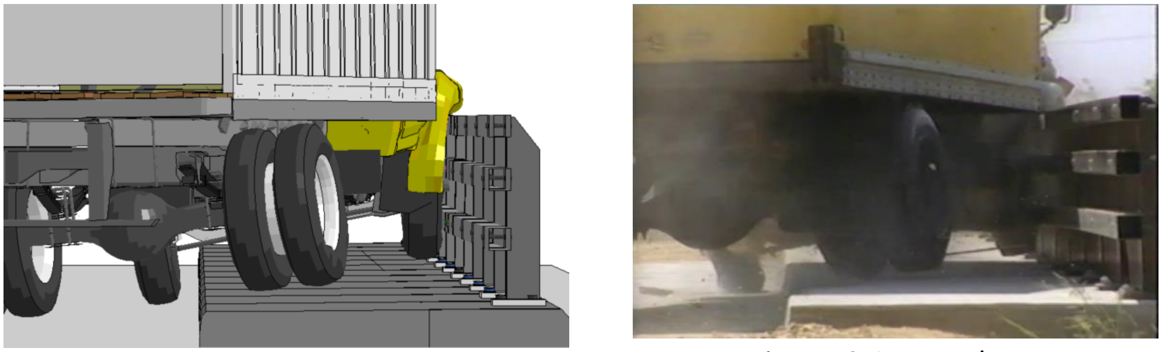
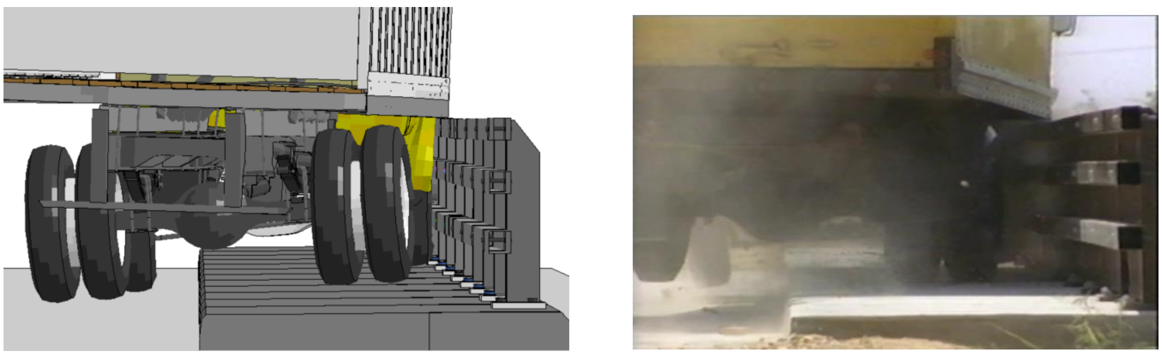


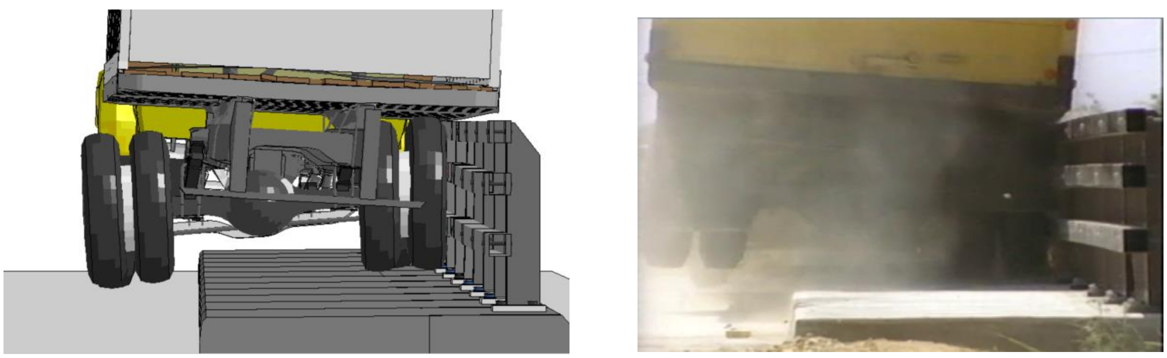
Figure 3. Sequential views from FEA and Test 404251-3 from an upstream view point.



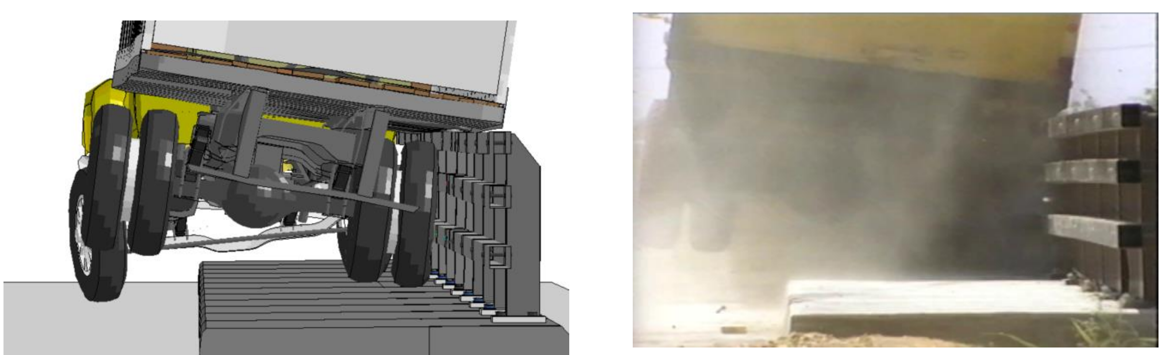
Time = 0.4 seconds



Time = 0.5 seconds

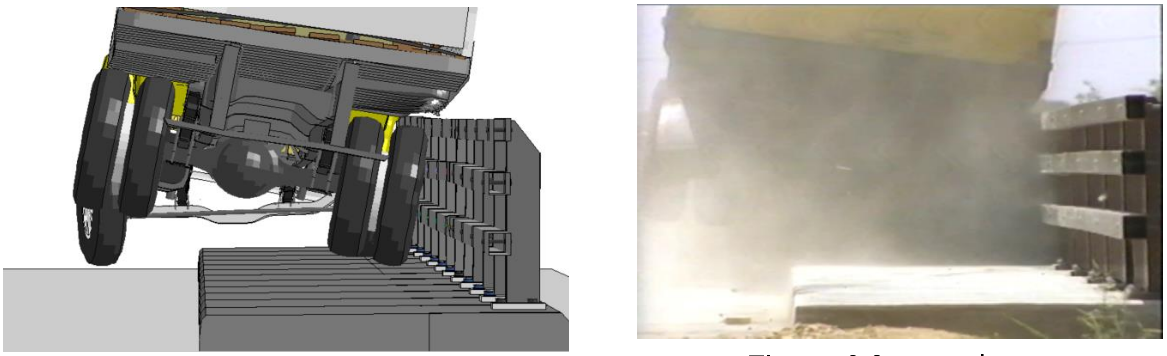


Time = 0.6 seconds

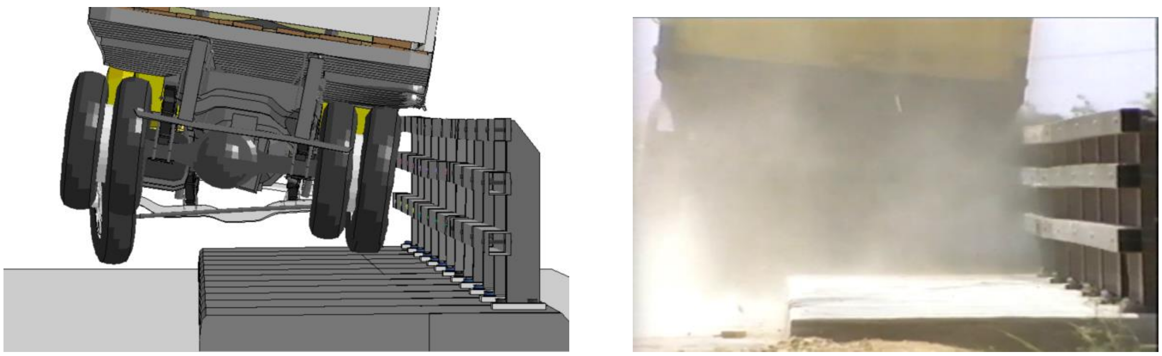


Time = 0.7 seconds

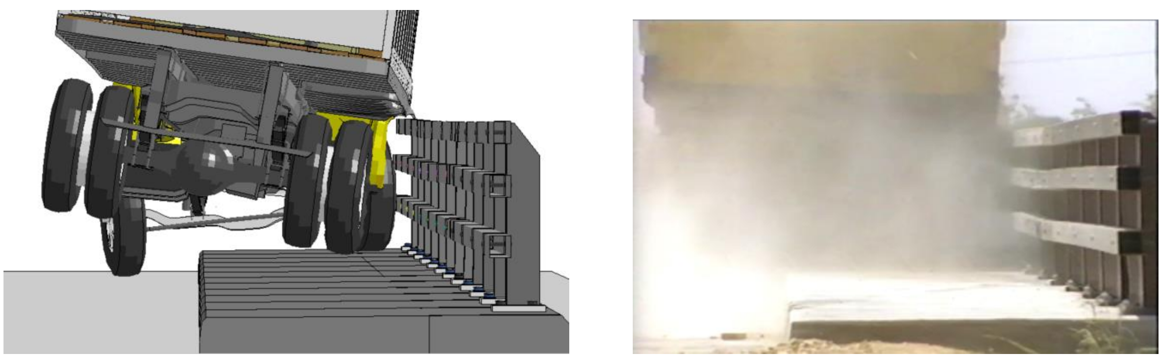
Figure 3. [Continued] Sequential views from FEA and Test 404251-3 from an upstream viewpoint.



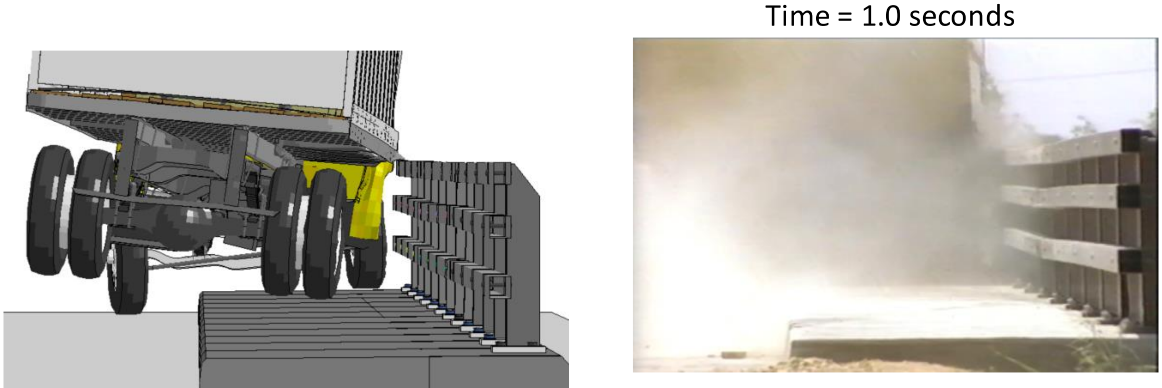
Time = 0.8 seconds



Time = 0.9 seconds



Time = 1.0 seconds



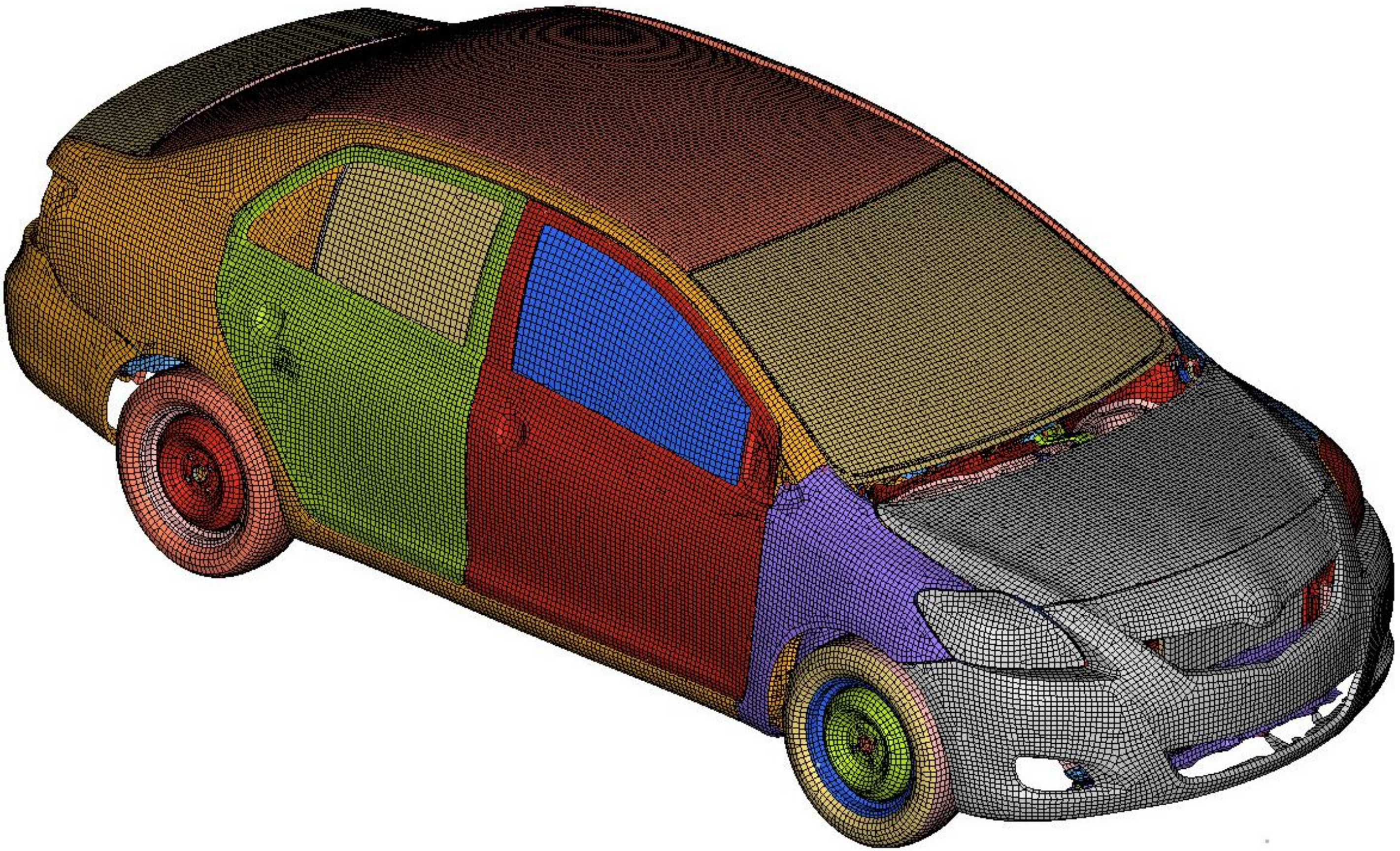
Time = 1.1 seconds

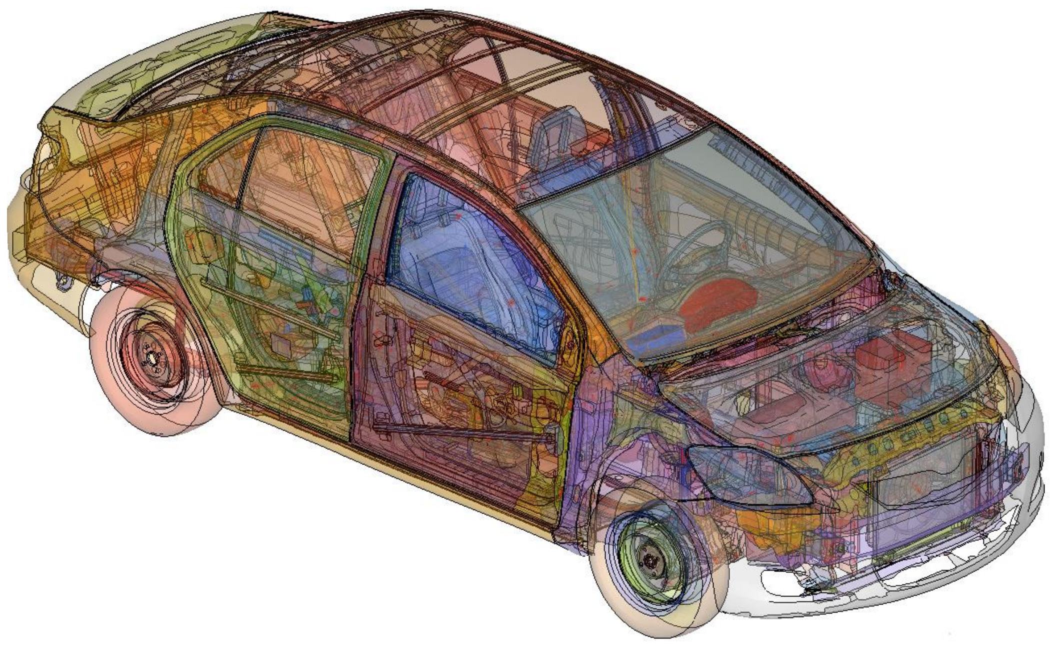
Figure 3. [Continued] Sequential views from FEA and Test 404251-3 from an upstream viewpoint.

Appendix D

Validation Forms for Yaris (1100C) Vehicle Model

Model Information

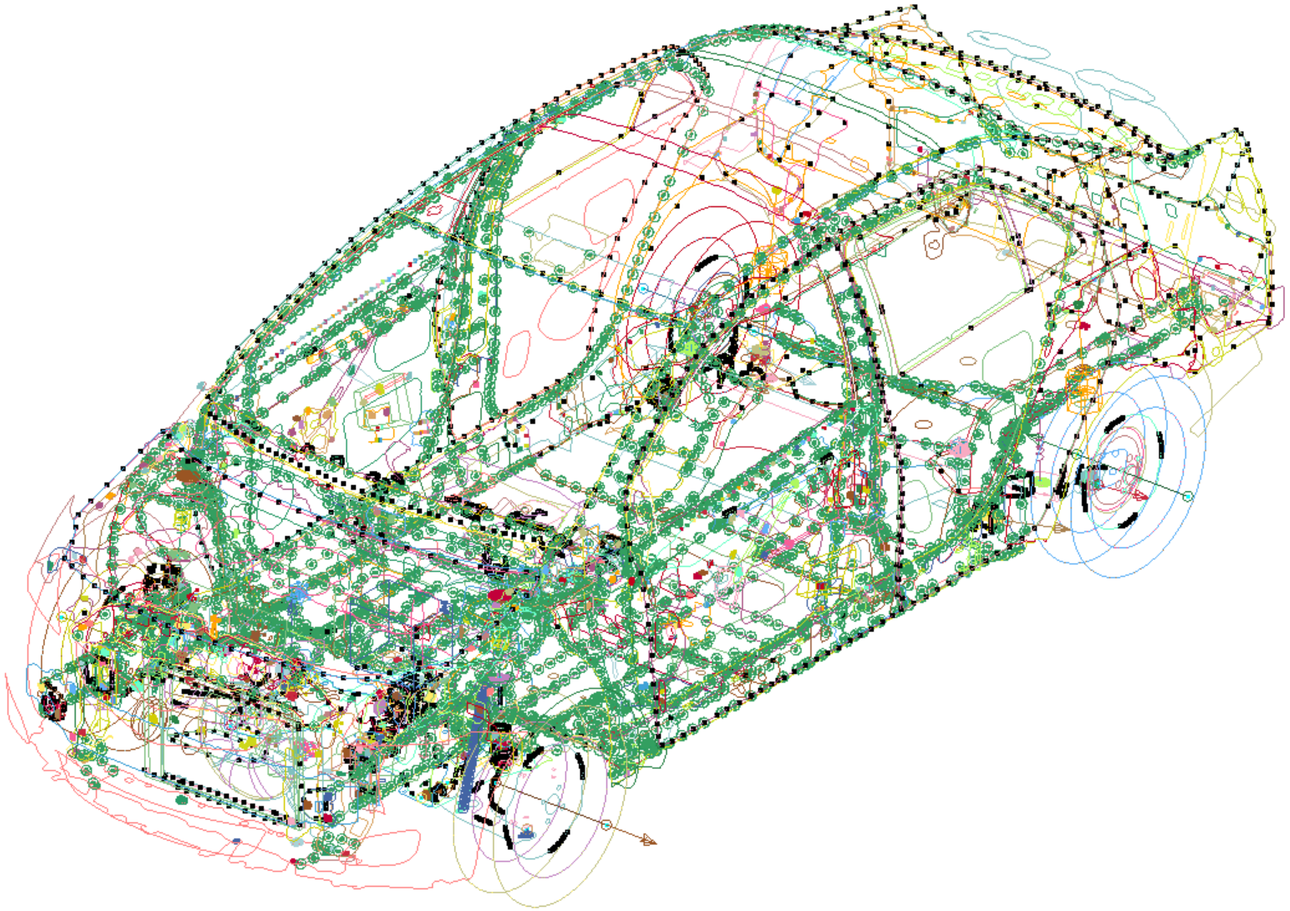




Number of parts	**919**
Number of nodes	**393165**
Number of solid elements	**15234**
Number of shell elements	**358457**
Number of beam elements	**4685**
Number of constrained joints	**19**

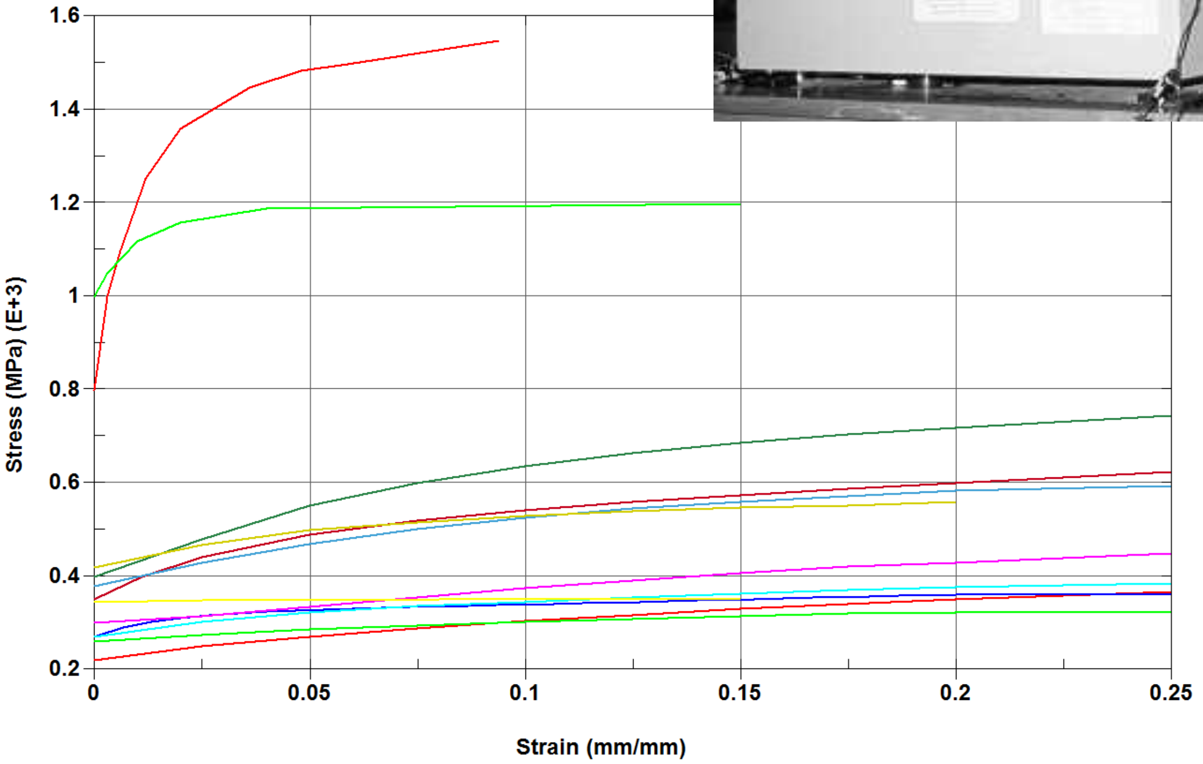
Connections

BEAM CONNECTIONS	4685
NODAL_RIGID_BODY	759
EXTRA_NODES_SET	20
JOINTS	44
RIGID_BODIES	2
SPOTWELD	2828



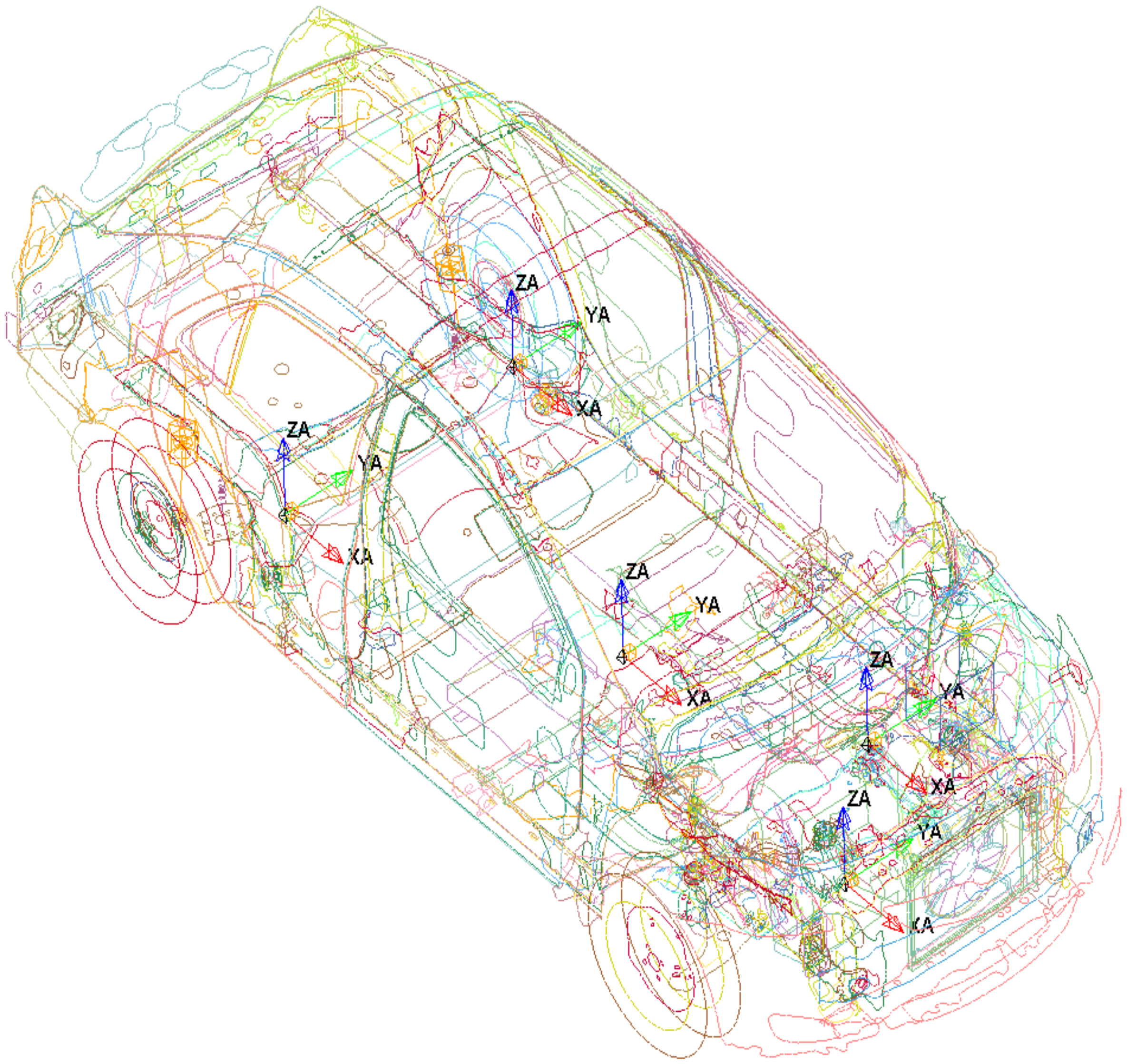
Material Testing

- Specimens were cut from actual components
- 160 tensile tests
- Data converted
- 12 different materials generated based on test data
- Parts grouped into

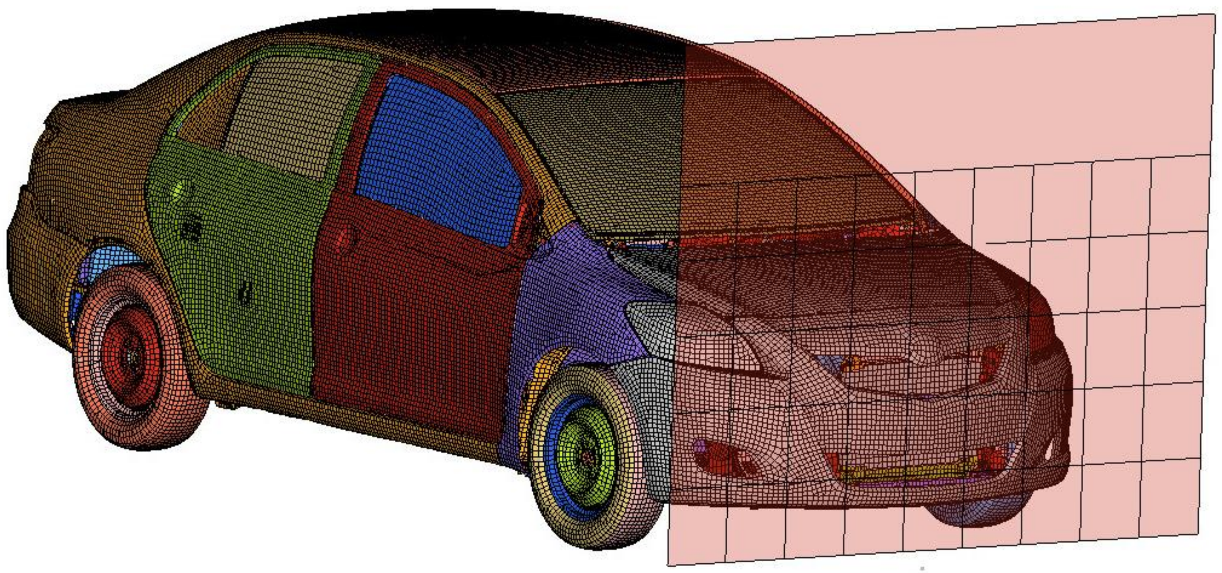


Accelerometers

- Left Rear Seat (Node 4000390)
- Right Rear Seat (Node 4000398)
- Engine Top (Node 4000414)
- Engine Bottom (Node 4000422)
- Vehicle C.G. (Node 4000406)



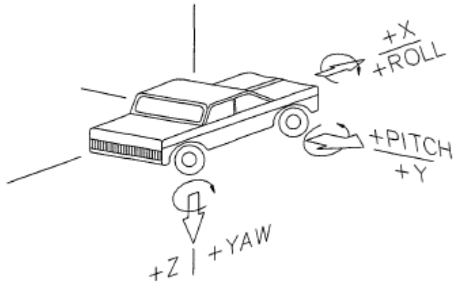
Simulation Benchmark



LS-DYNA	
Platform	Linux RHEL 5.4
Version	mpp s R6.1.2
Revision	85139
Precision	Single precision (I4R4)
Time to simulate 200 ms	1 hour 32 min.
Number of processors	16

Inertia Comparisons

	Actual Vehicle	*FE Model*
Weight, kg	1078	1101
Pitch inertia, kg-m^2	1498	1545
Yaw inertia, kg-m^2	1647	1718
Roll inertia, kg-m^2	388	396
Vehicle CG X, mm	1022	1025
Vehicle CG Y, mm	-8.3	-3.0
Vehicle CG Z, mm	558	557



Full-Scale Crash Tests

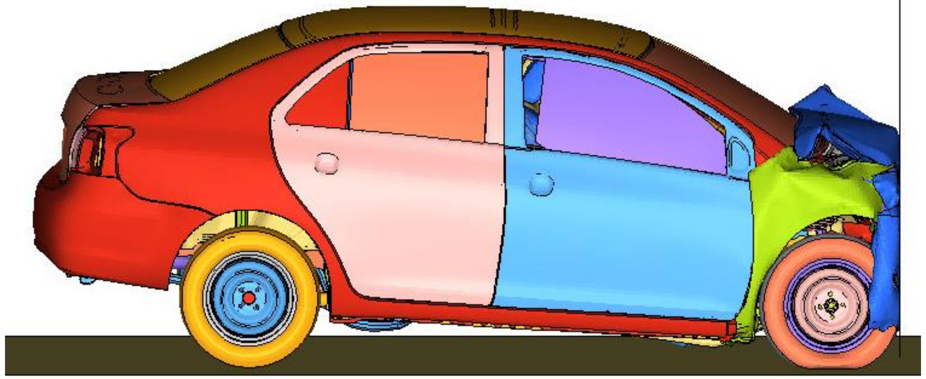
- Toyota Yaris (2006-2010)

Test Type	Test Number
Frontal Full Wall	NHTSA 5677 (56.3 km/hr), 6221 (56.2 km/hr), 6059 (39.8 km/hr), 6060 (39.8 km/hr), 6069 (39.8 km/hr)
Frontal Offset	IIHS CEF0610 (64.7 km/hr)
Side Impact NHTSA	NHTSA 5679 (62.1 km/hr), 6220 (62.3 km/hr), 6558 (61.9 km/h), 6585 (61.8 km/hr)
Side Impact IIHS	IIHS CES50638 (50.2 km/hr), CES0639 (50.0 km/hr)
Rigid Pole Test	NHTSA 7145 (7 deg, 56 km/hr)
Vehicle to Vehicle	NHTSA 7371 (15 deg, 112.7 km/hr, 50 % overlap), 7293 (7 deg, 112.7 km/hr, No frame overlap),
Roof Strength	IIHS SWR0920
Speed Bump	FOIL10002 (8 tests: varied speed bump configurations)
Sloped Terrain	FOIL 10003 (6 tests: 6H:1V slopes, 25 deg - 8, 16, and 24 km/hr)

Yaris – Frontal Full Wall – 56 km/hr

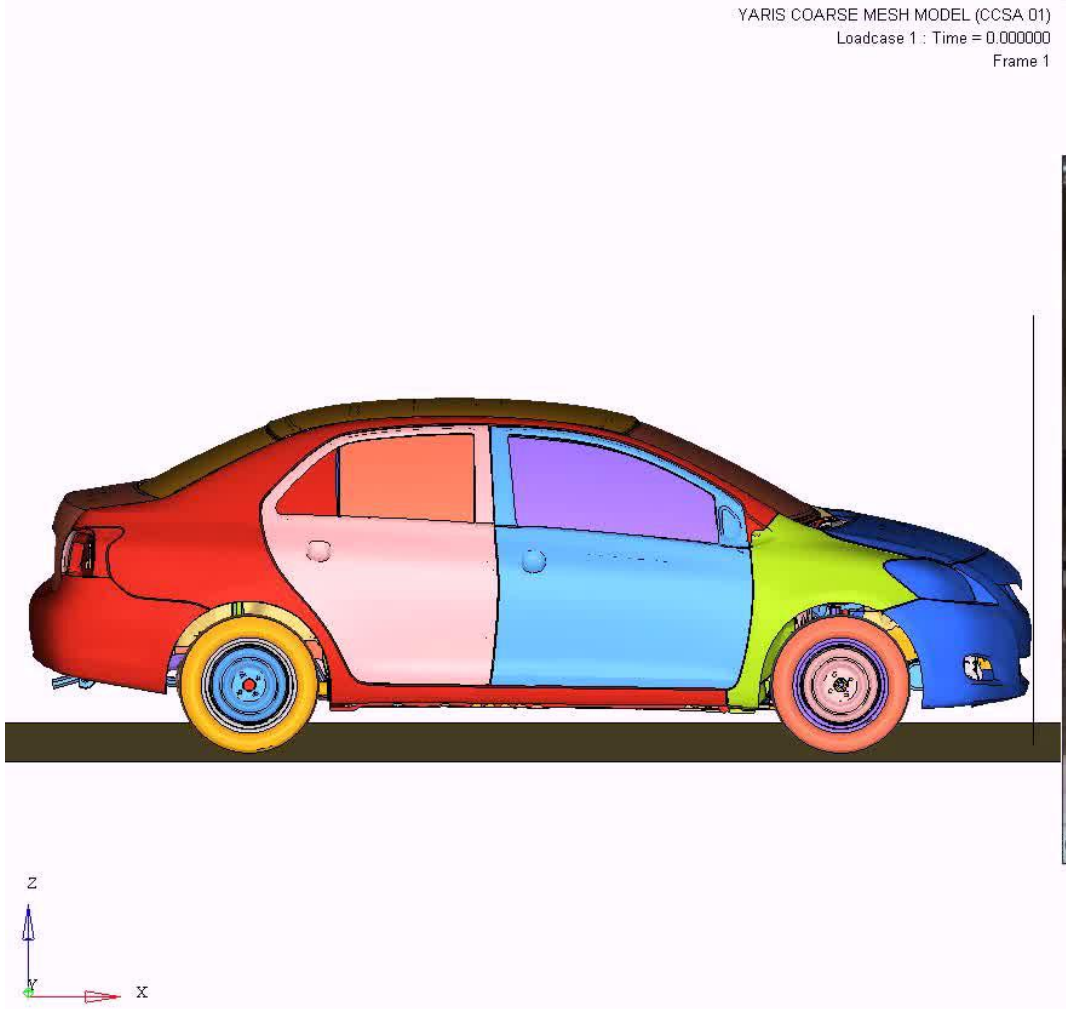
- Two Full-scale Crash Tests @ 56 km/hr:
  - NHTSA 5677 (56.3 km/hr) – 2007 Sedan
  - NHTSA 6221 (56.2 km/hr) – 2008 Hatch Back

Yaris – Frontal Full Wall – 56 km/hr

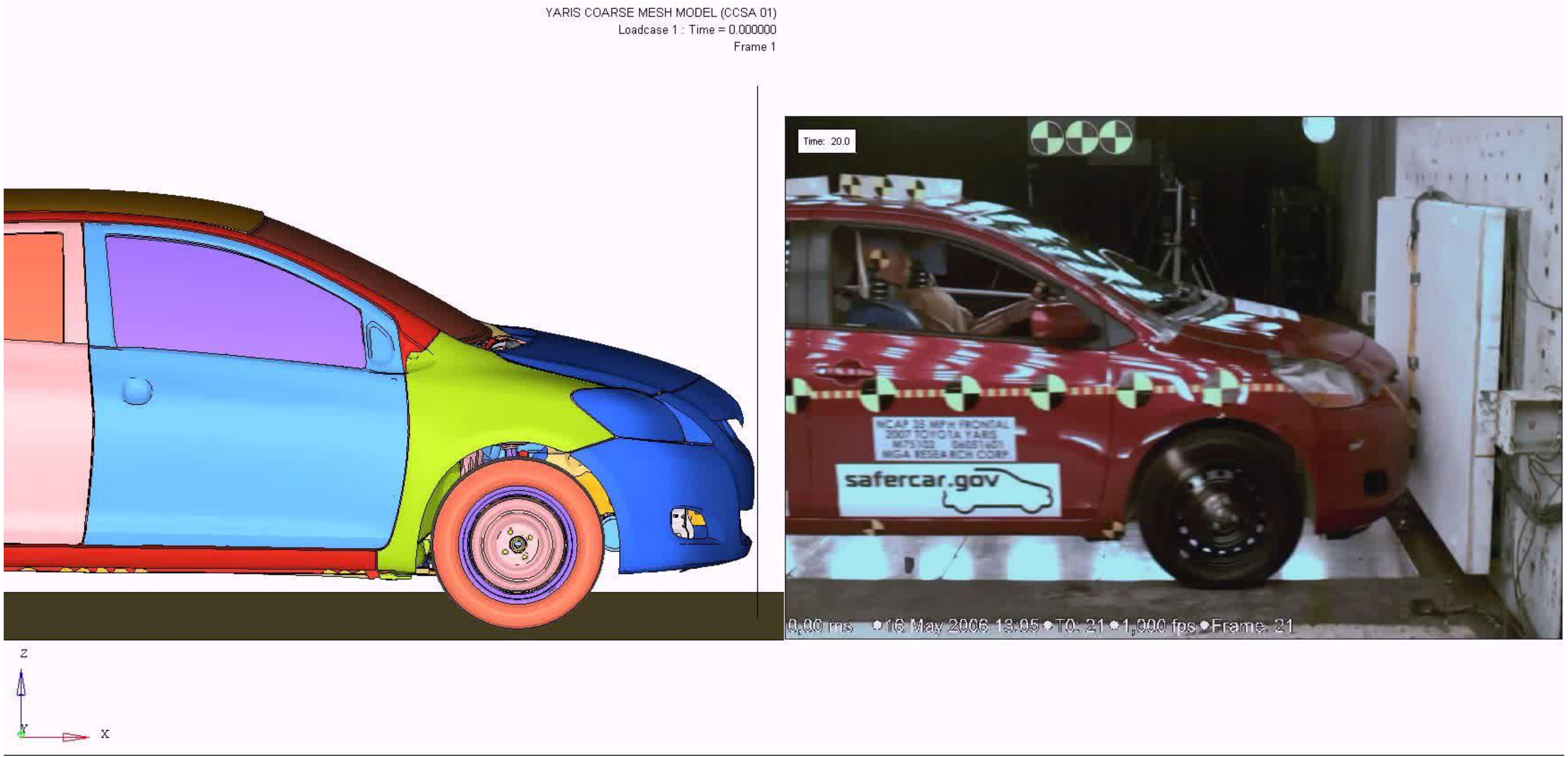


	FE Model	Test 5677	Test 6221
Weight (kg)	1263	1271	1245
Engine Type	1.5L V4	1.5L V4	1.5L V4
Tire size	P185/60R15	P185/60R15	P185/60R15
Attitude (mm) (As delivered)	F – 668	F – 673	F – 675
	R – 673	R – 680	R – 673
Wheelbase (mm)	2538	2551	2463
CG (mm) Rear of front wheel C/L	1035	999	976
Body Style	4 Door Sedan	4 Door Sedan	3 Door Liftback

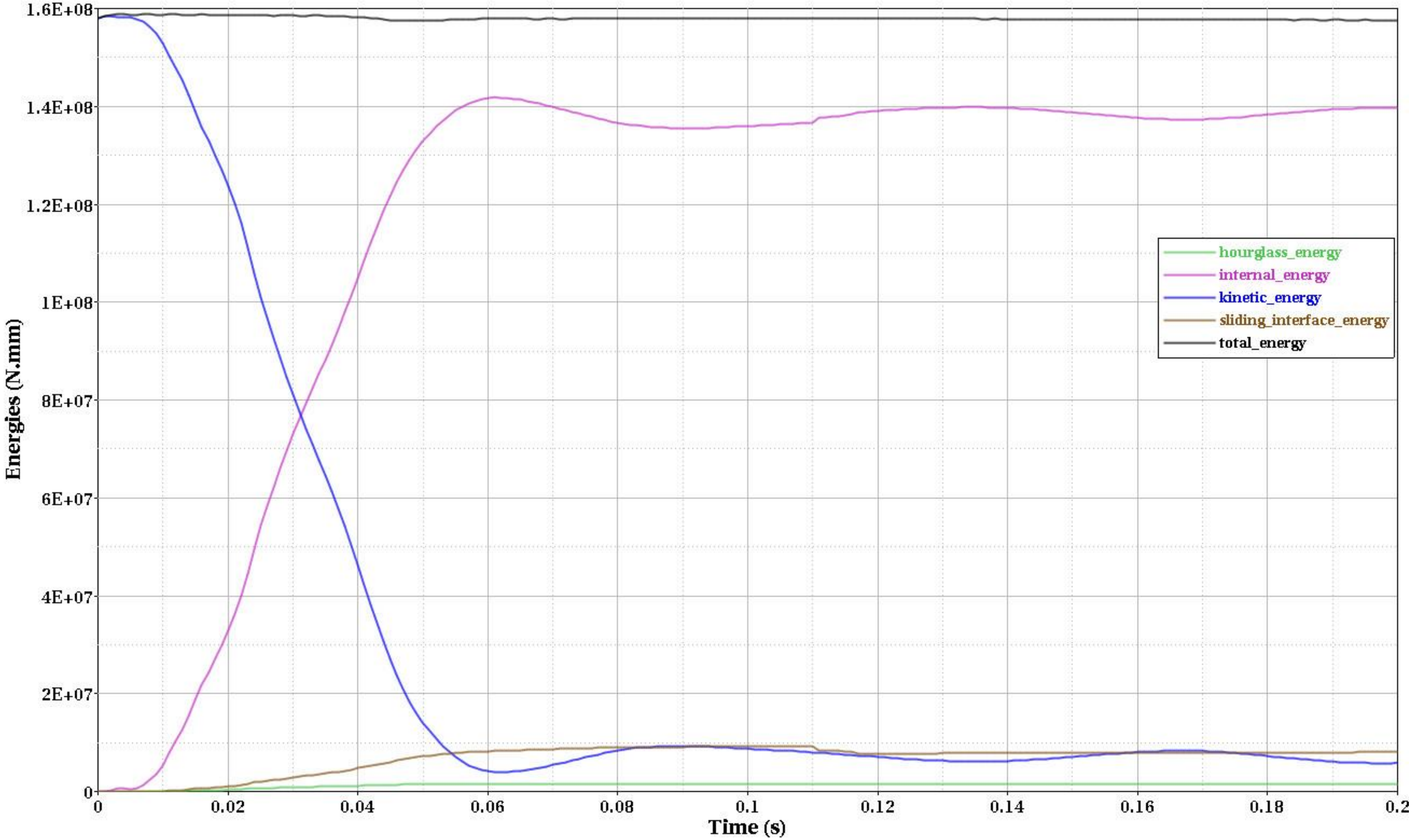
Yaris – Frontal Full Wall – 56 km/h - Video



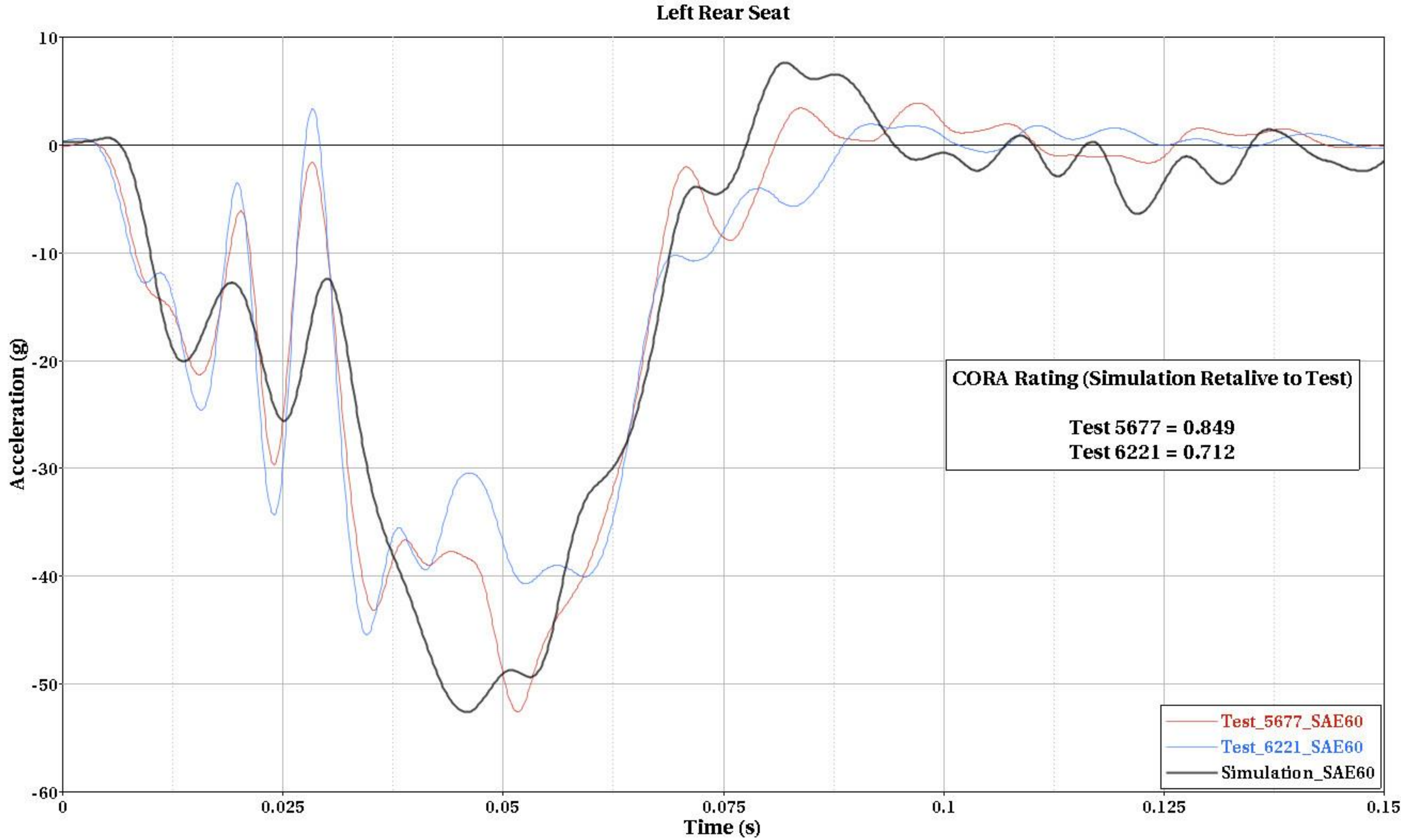
Yaris – Frontal Full Wall – 56 km/h - Video



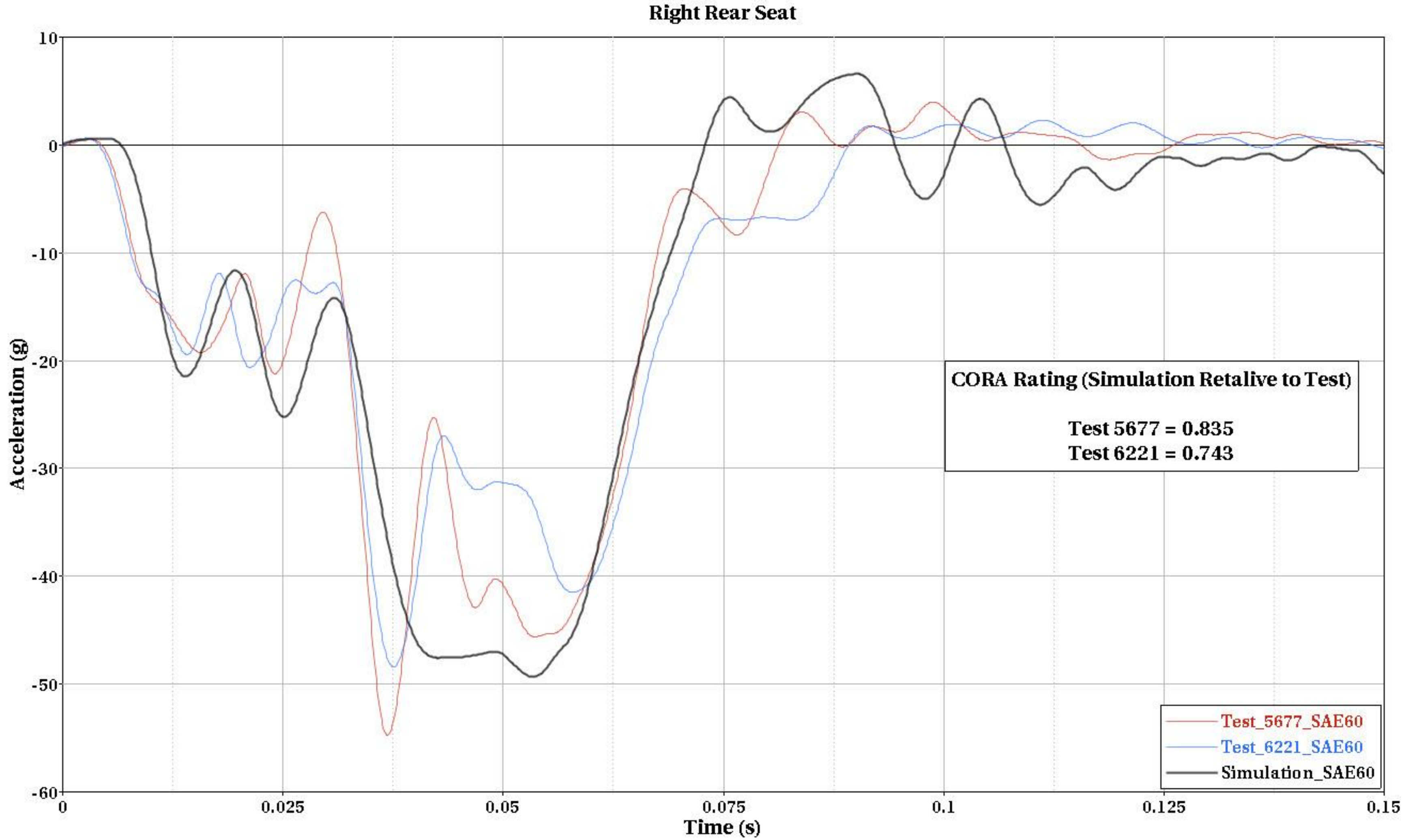
Yaris – Frontal Full Wall – 56 km/hr - Energy Summary



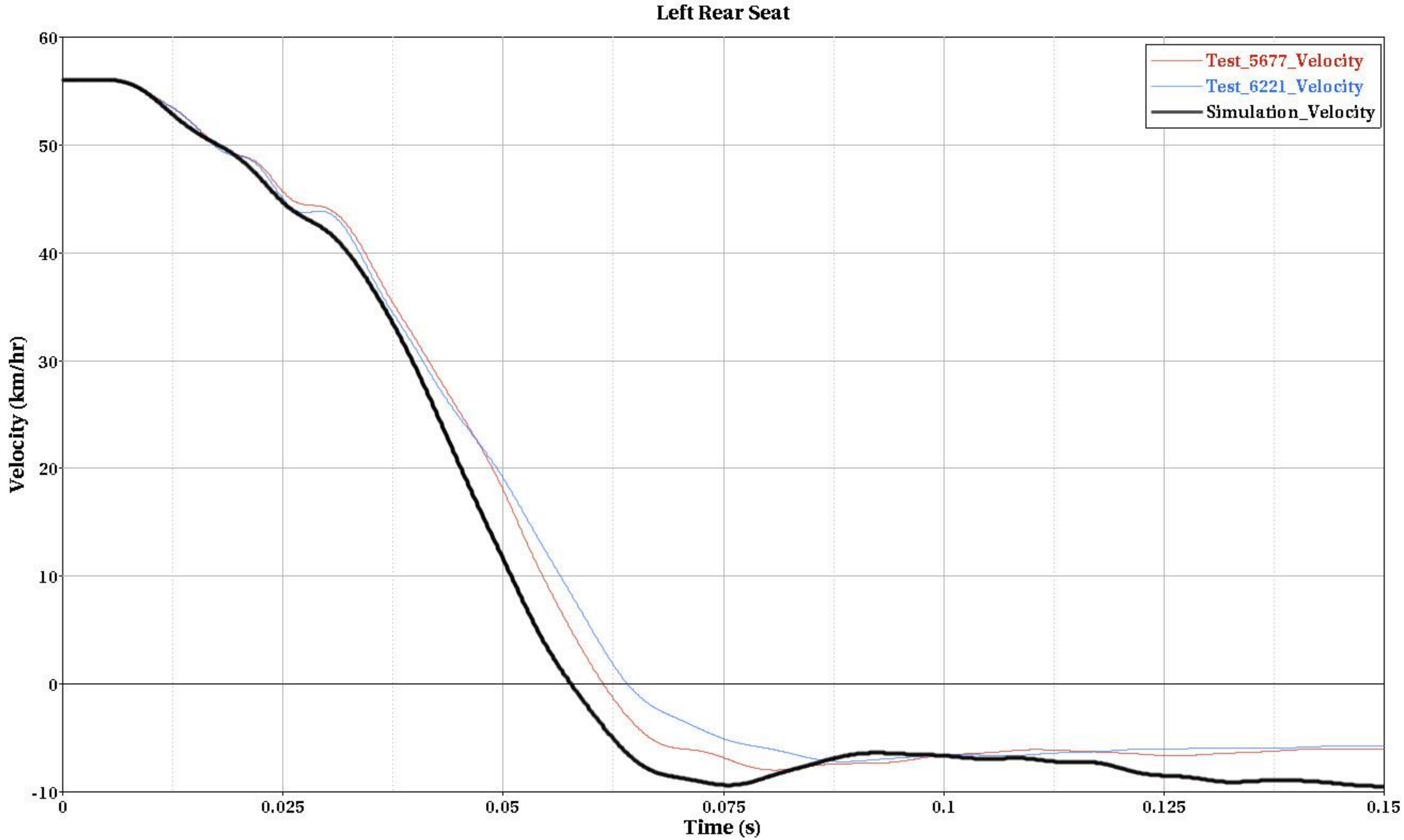
Yaris – Frontal Full Wall – 56 km/hr - Acceleration



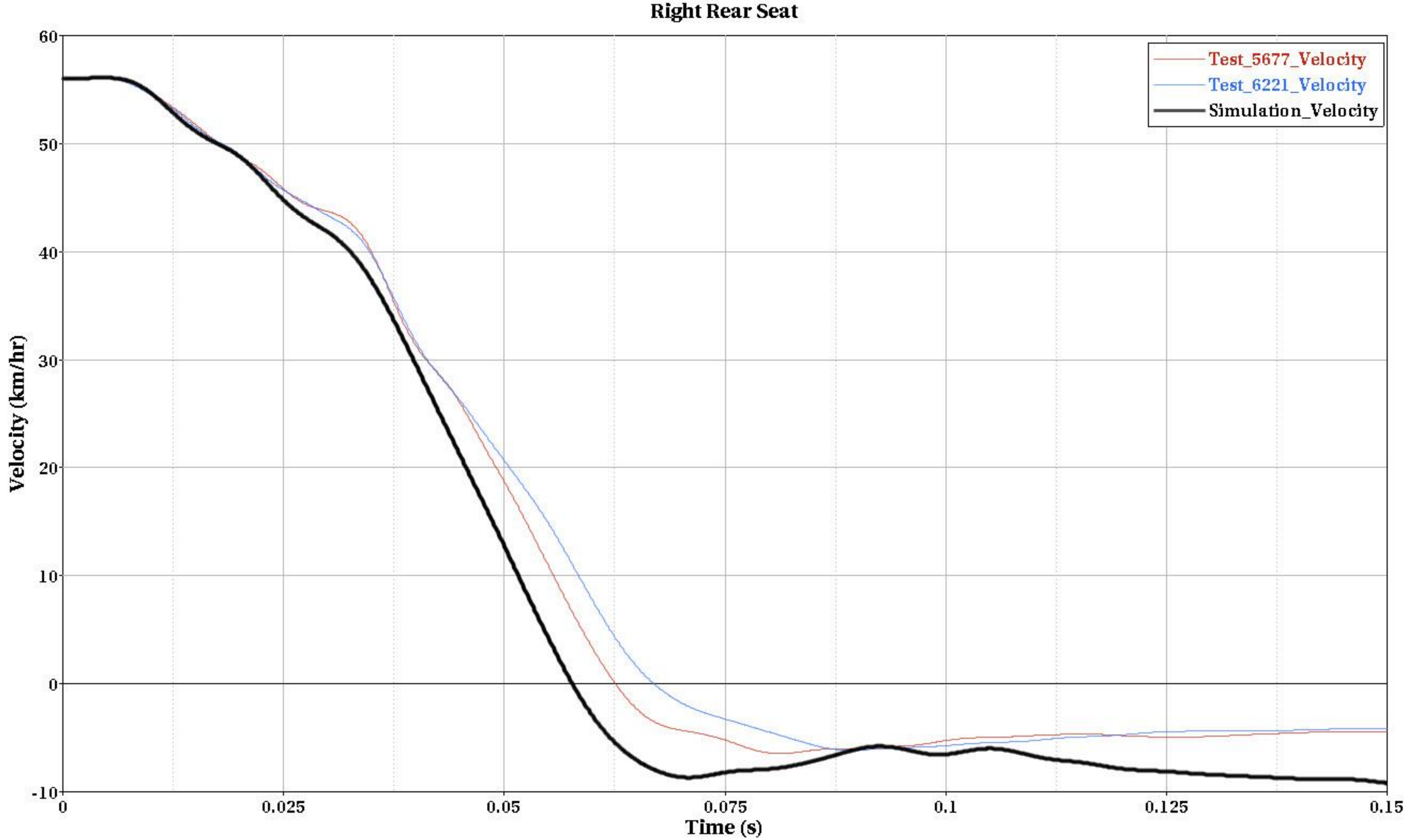
Yaris – Frontal Full Wall – 56 km/hr - Acceleration



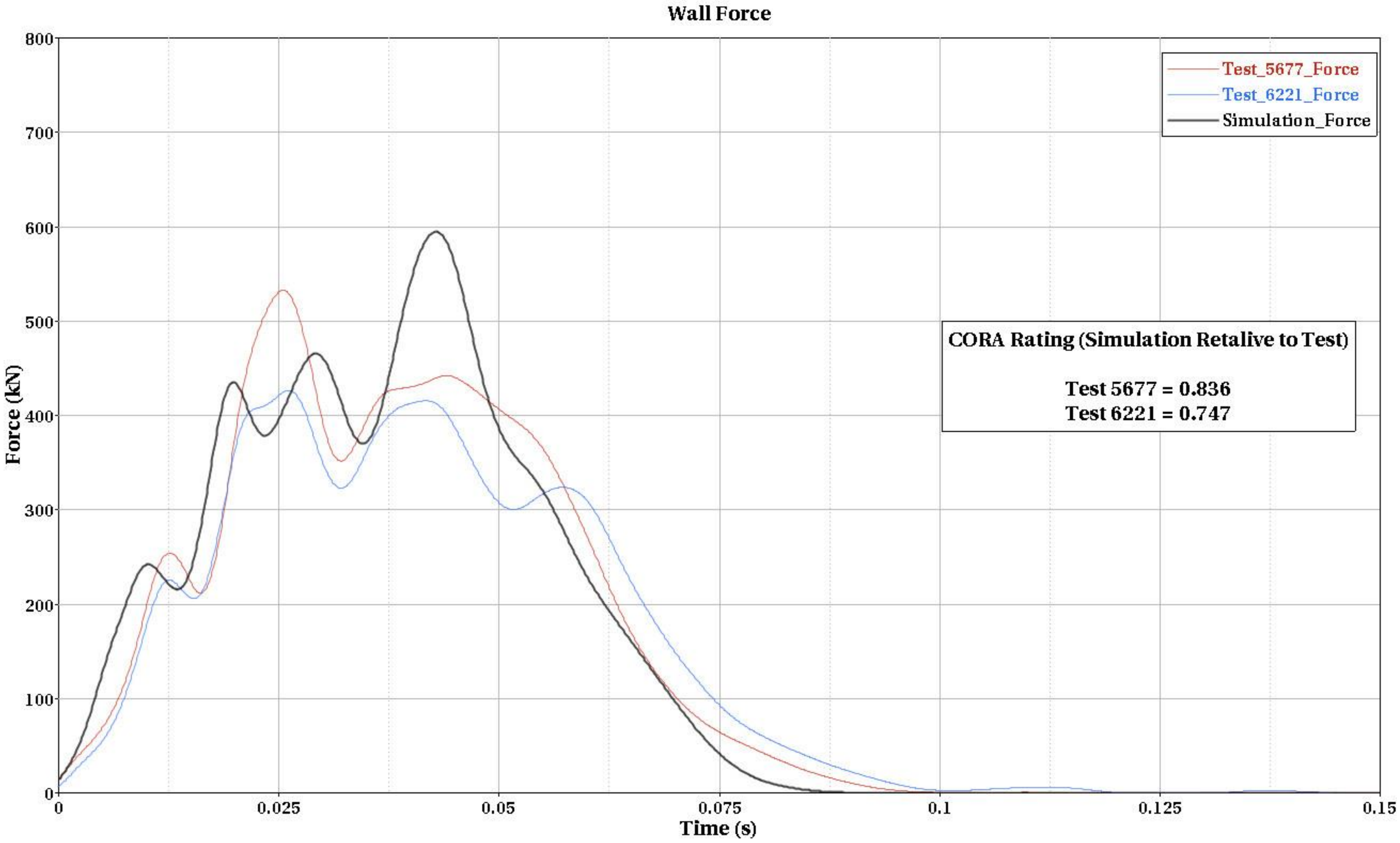
Yaris – Frontal Full Wall – 56 km/hr - Velocity



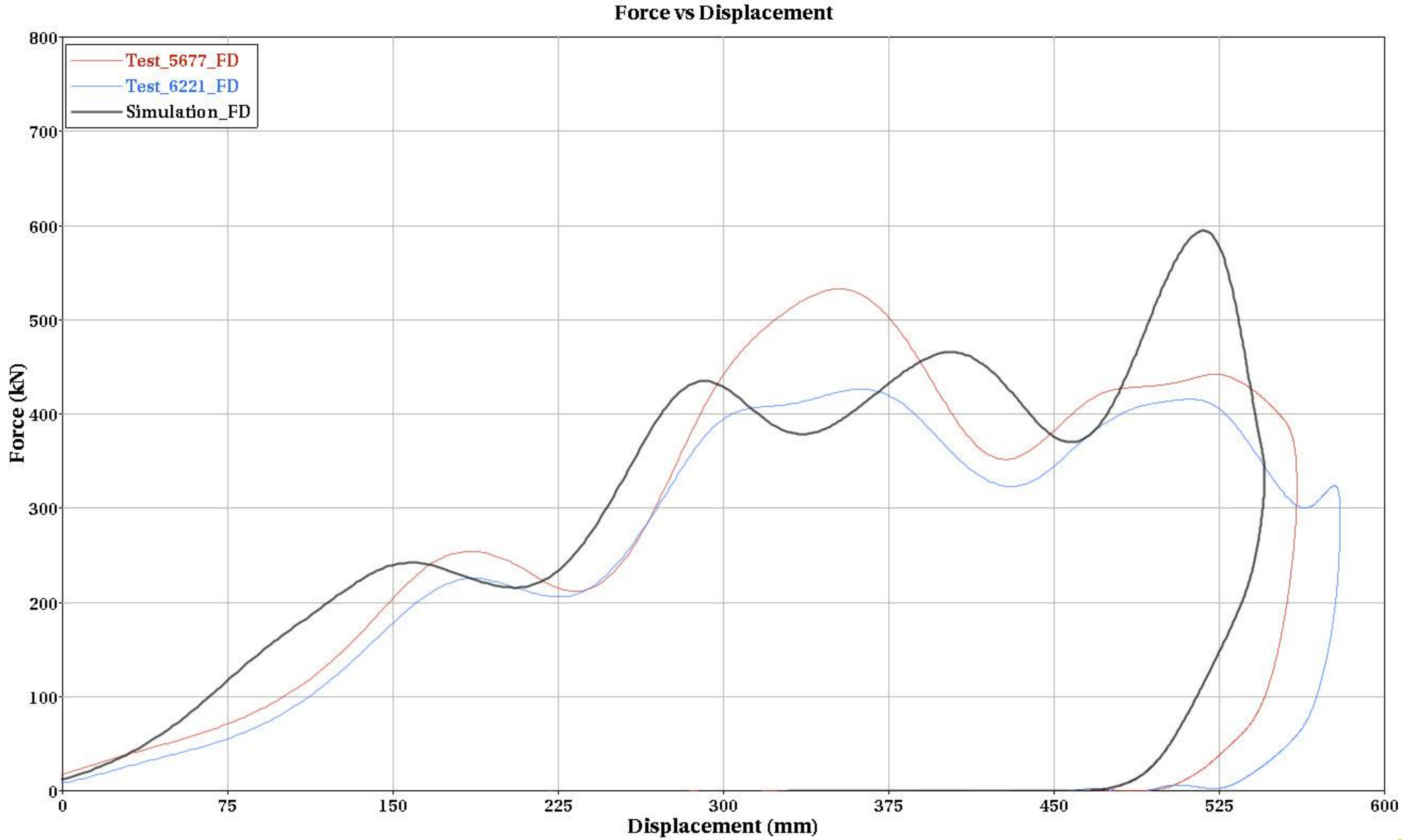
Yaris – Frontal Full Wall – 56 km/hr - Velocity



Yaris – Frontal Full Wall – 56 km/hr – Wall Force

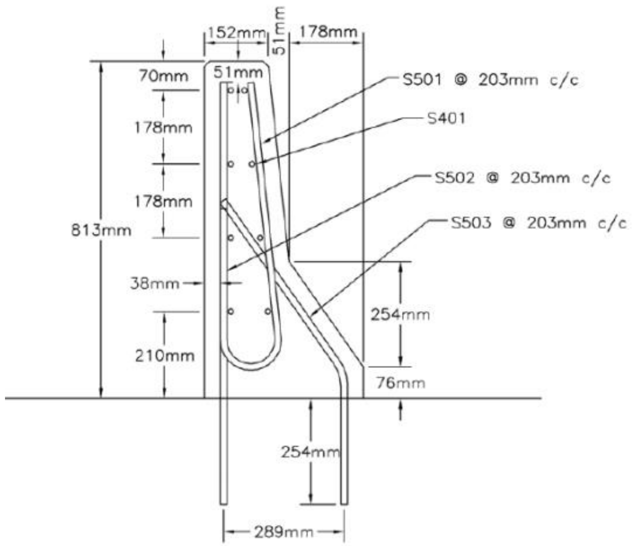


Yaris – Frontal Full Wall – 56 km/hr – Wall Force

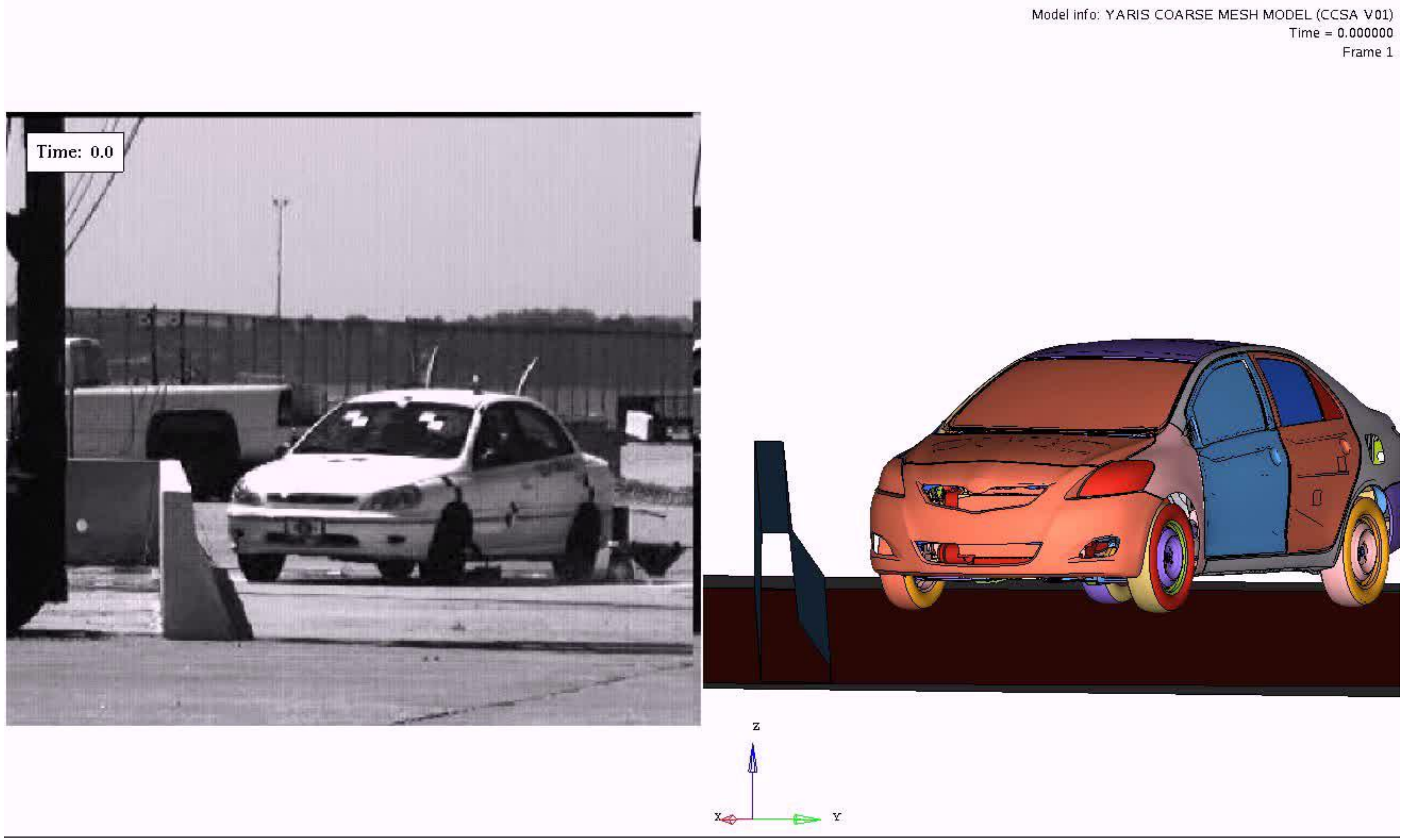


Yaris / NJ CMB

- MwRSF Test 2214NJ-1
- Impact Condition
  - 62.6 mi/hr
  - 26.1 deg
- Vehicle
  - 2002 Kia Rio

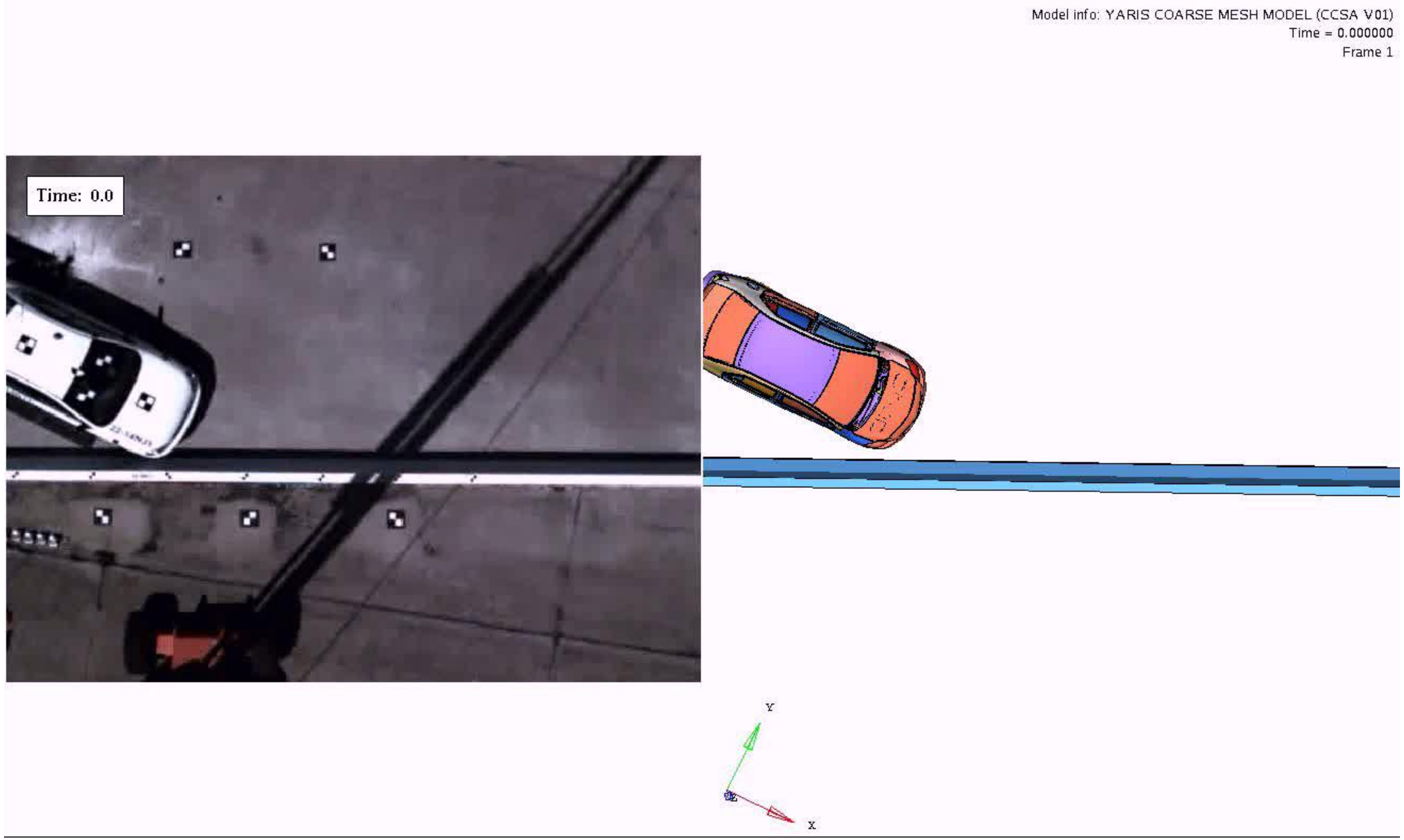


Yaris / NJ CMB - Video

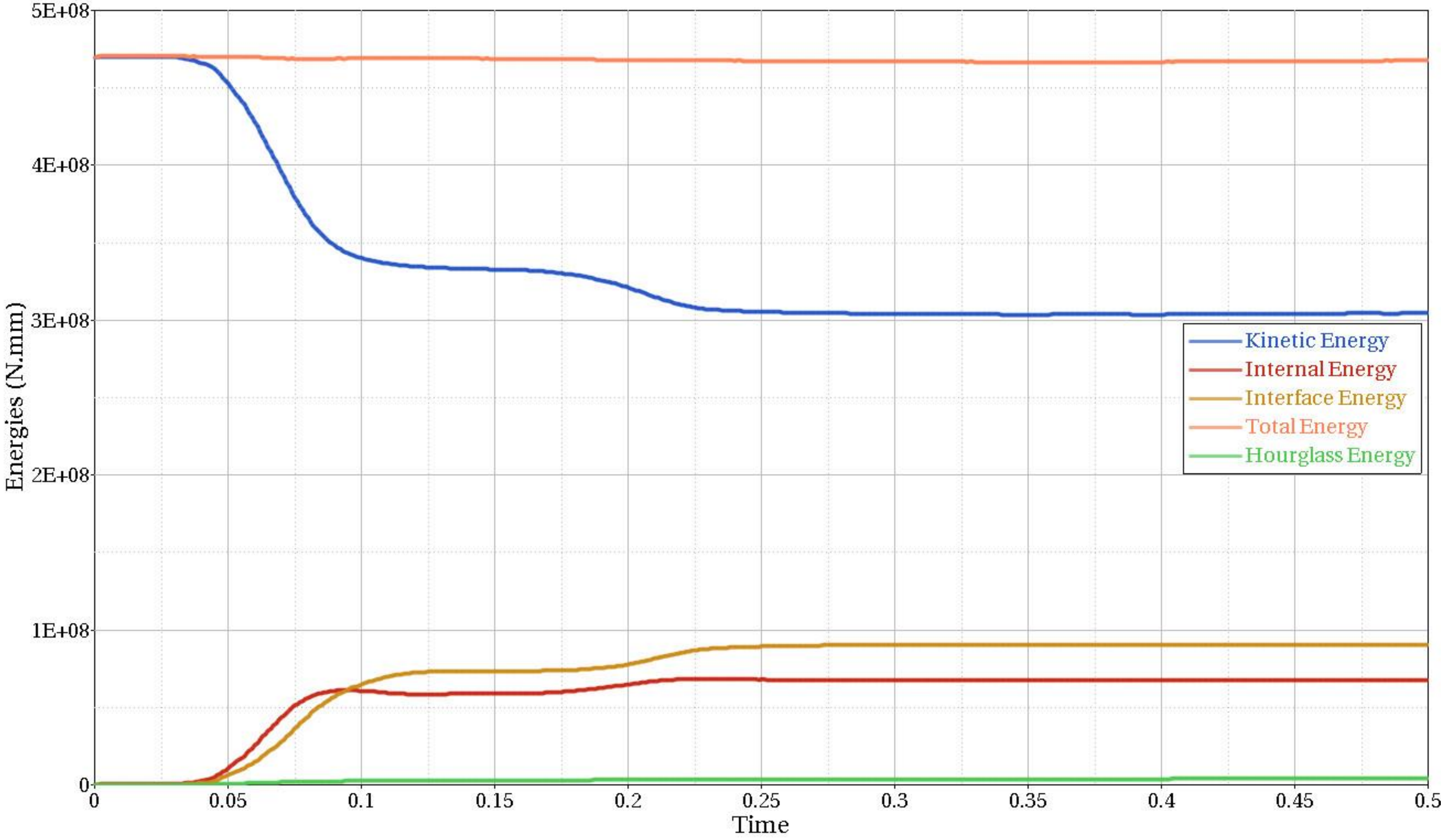


Yaris / NJ CMB - Video

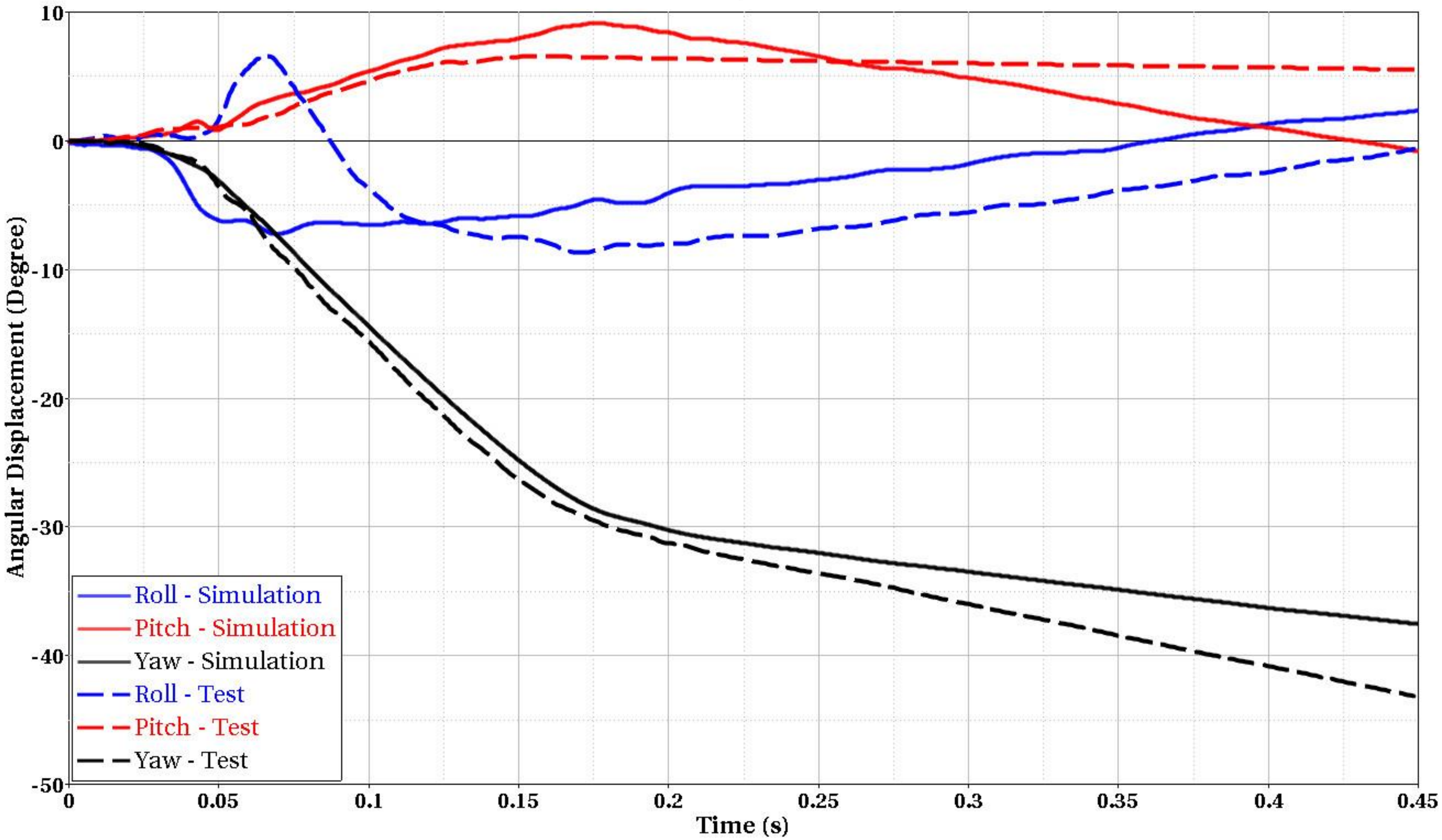
Yaris / NJ CMB - Video



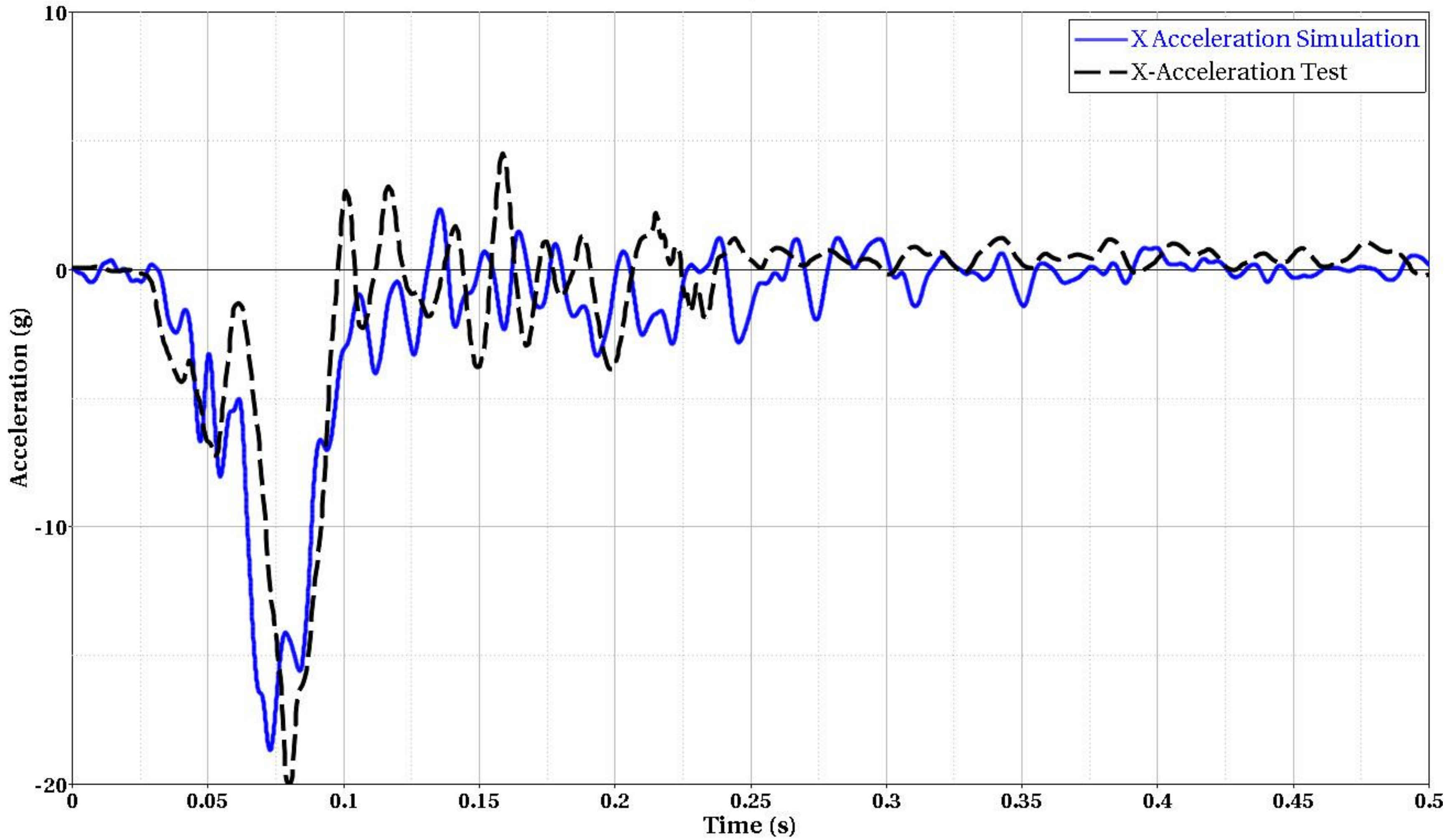
Yaris / NJ CMB - Energy Summary



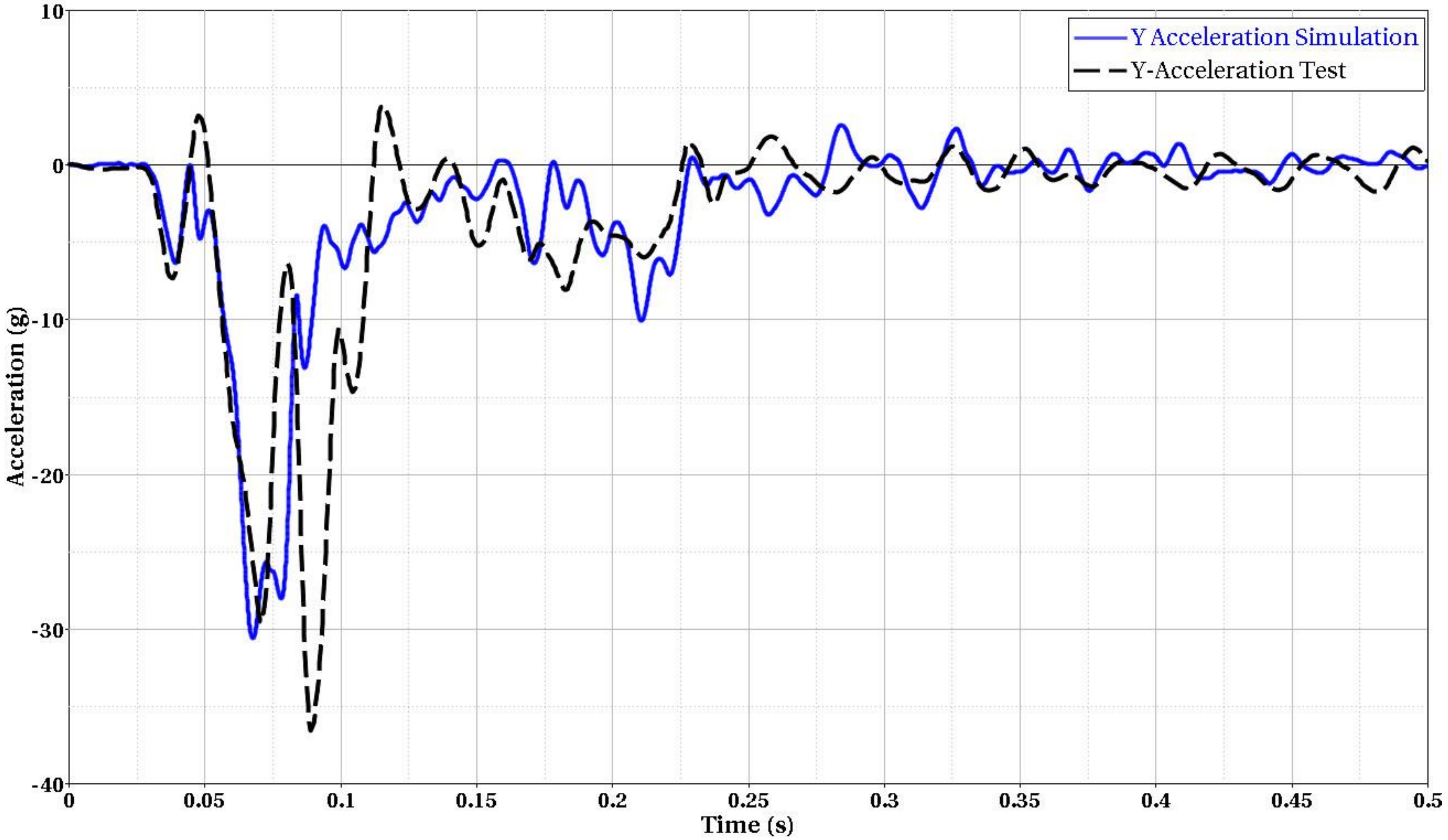
Yaris / NJ CMB - Roll, Pitch, and Yaw



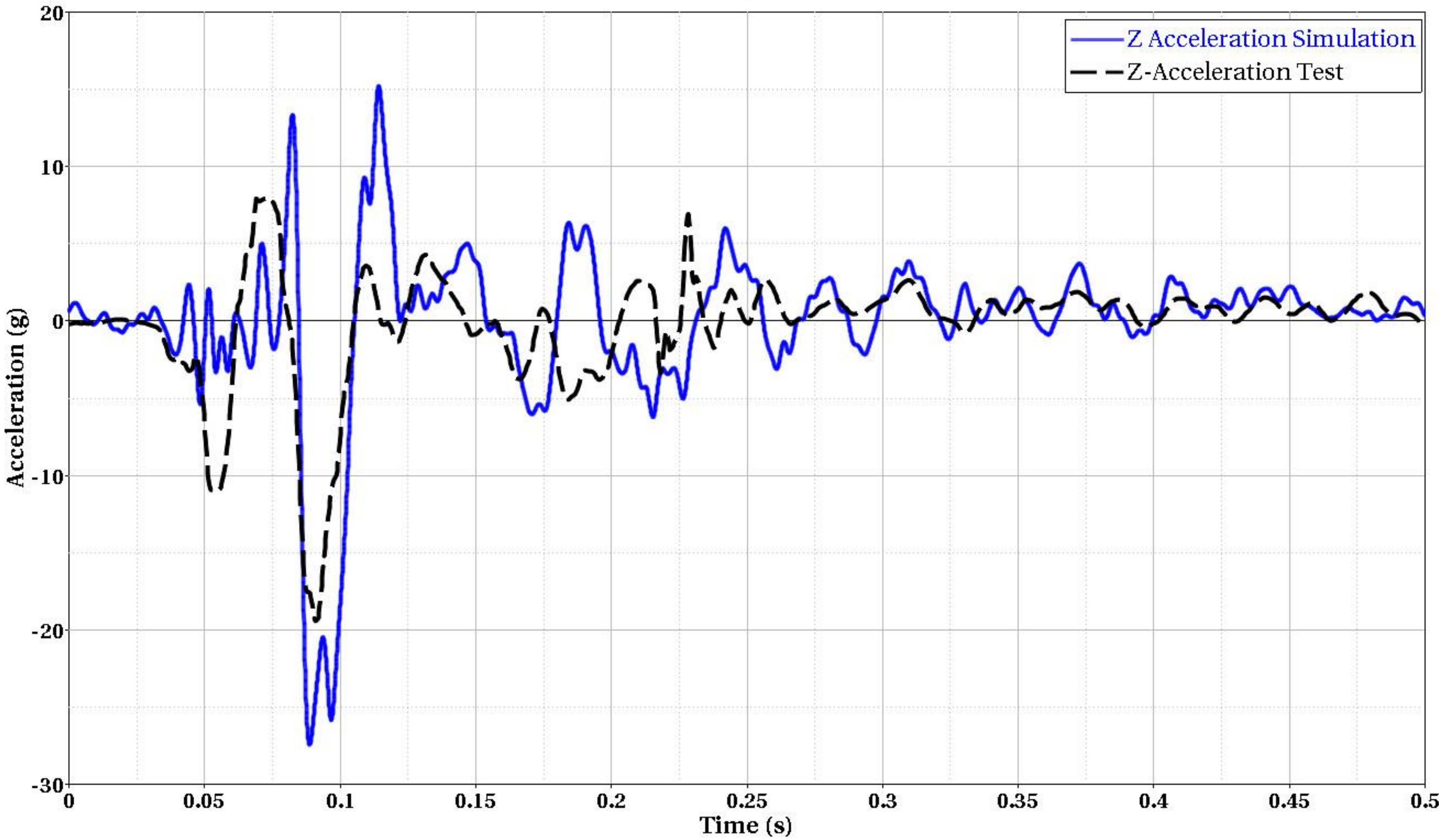
Yaris / NJ CMB – X - Acceleration



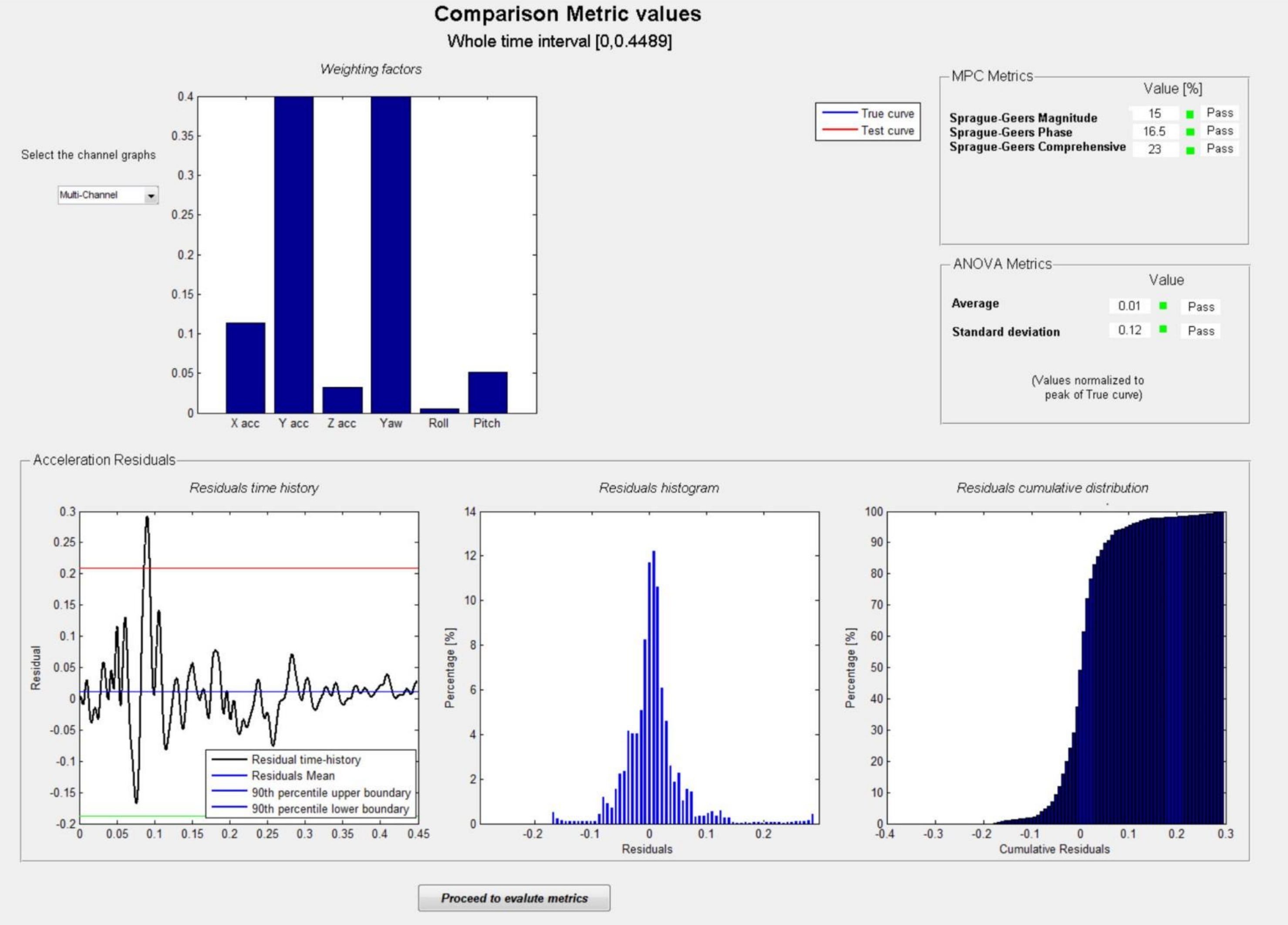
Yaris / NJ CMB – Y - Acceleration



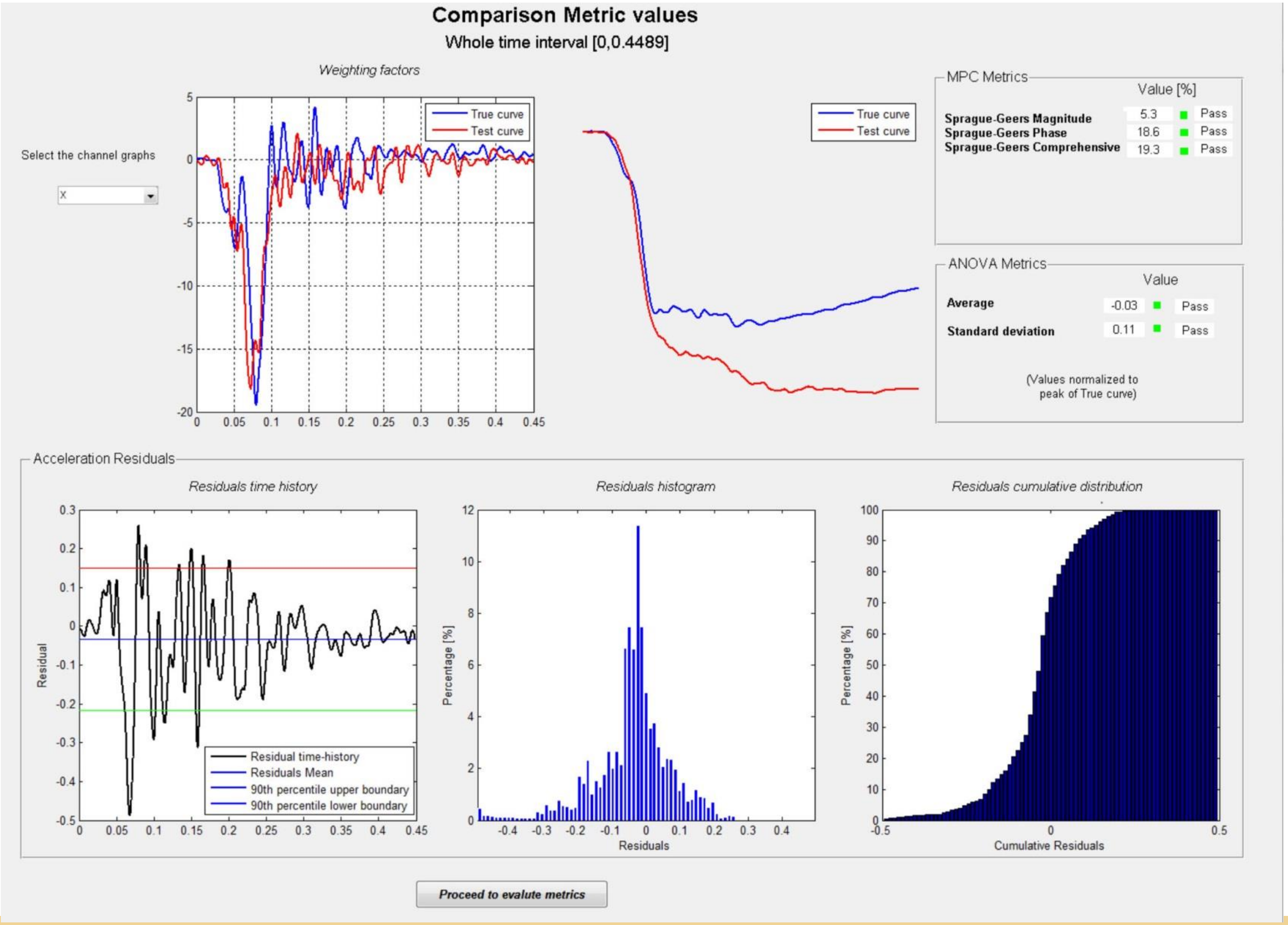
Yaris / NJ CMB – Z - Acceleration



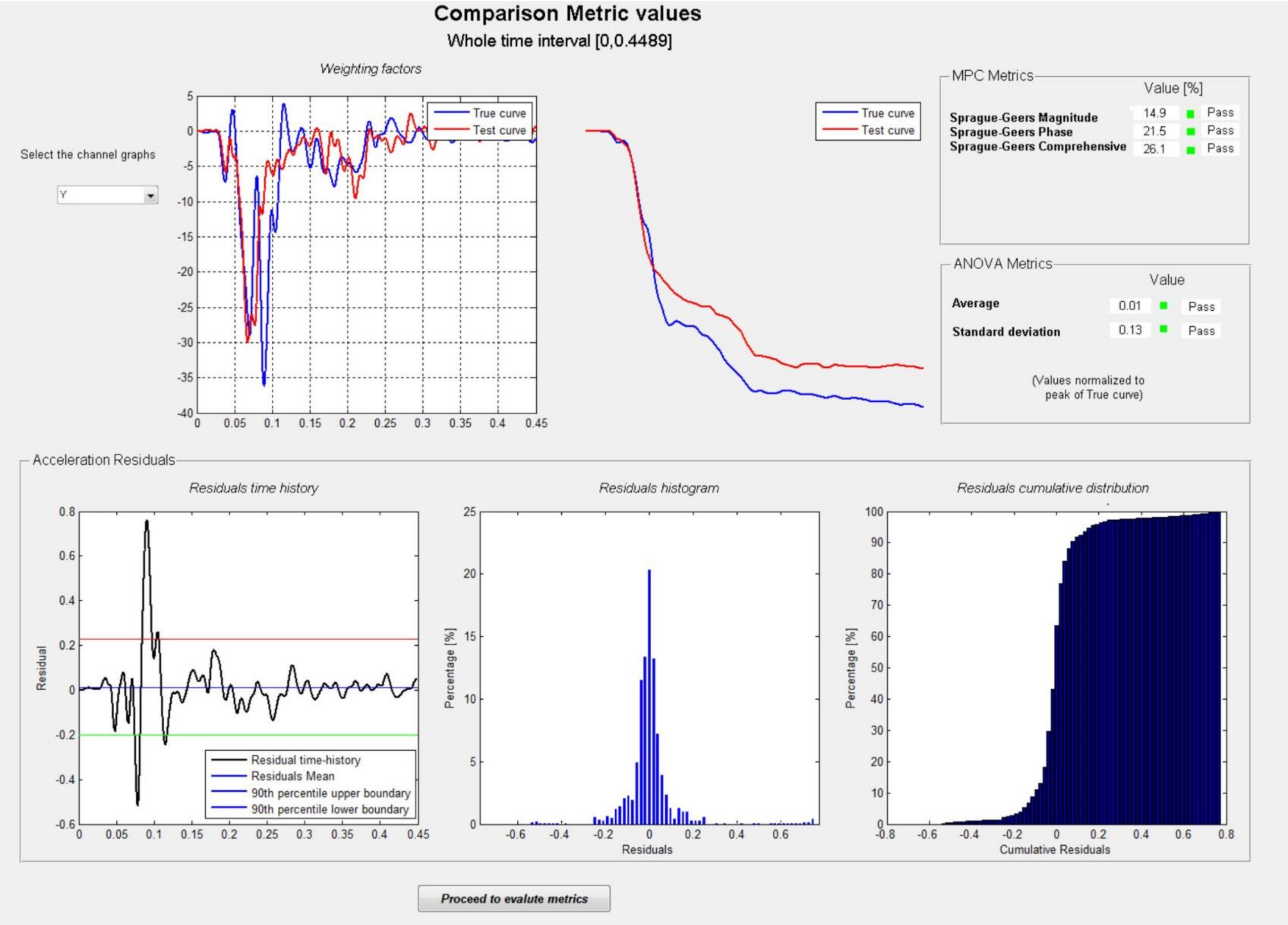
Yaris / NJ CMB – RSVVP Comparison Metrics



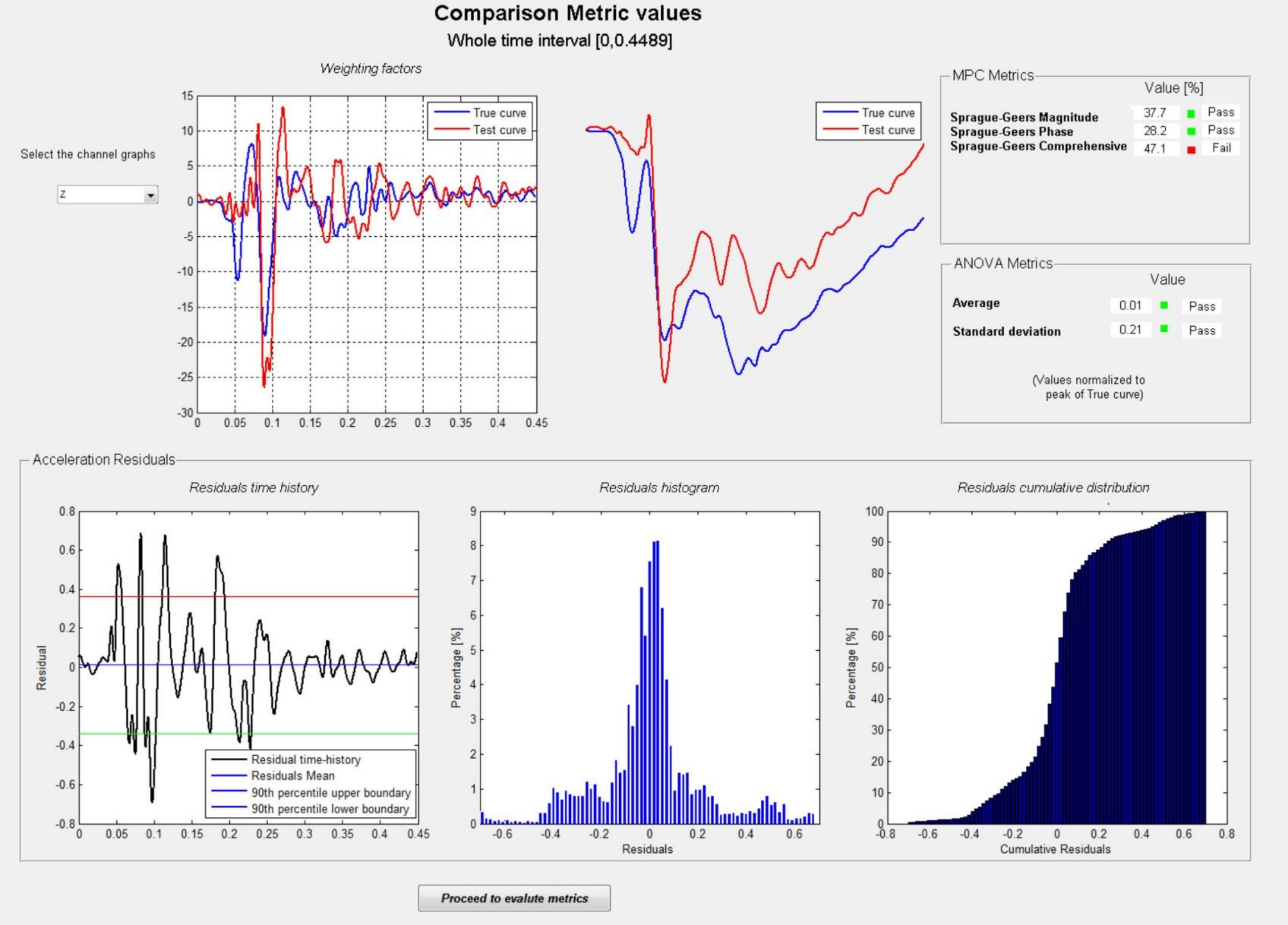
Yaris / NJ CMB – RSVVP Evaluation – X - Acceleration



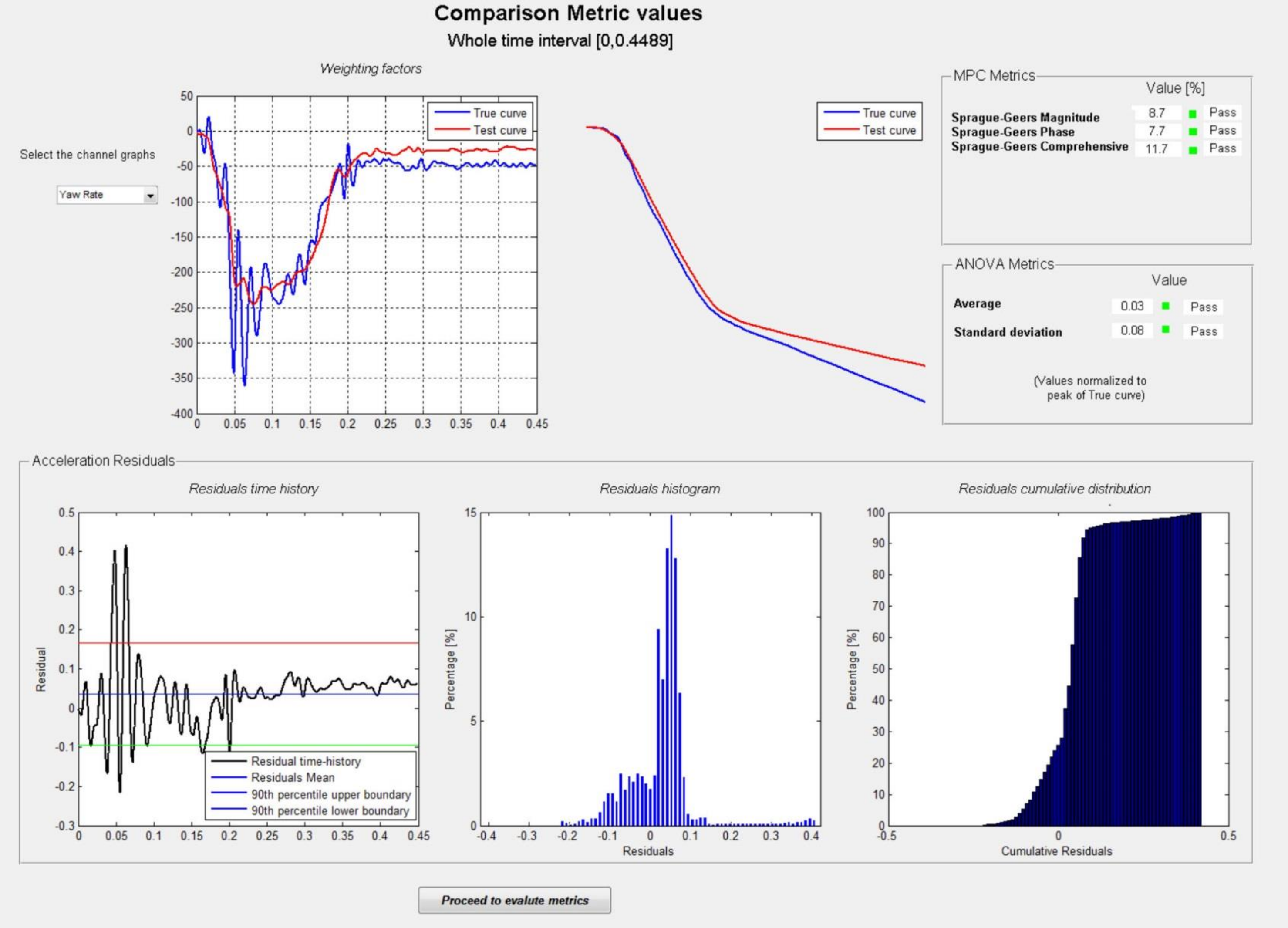
Yaris / NJ CMB – RSVVP Evaluation – Y - Acceleration



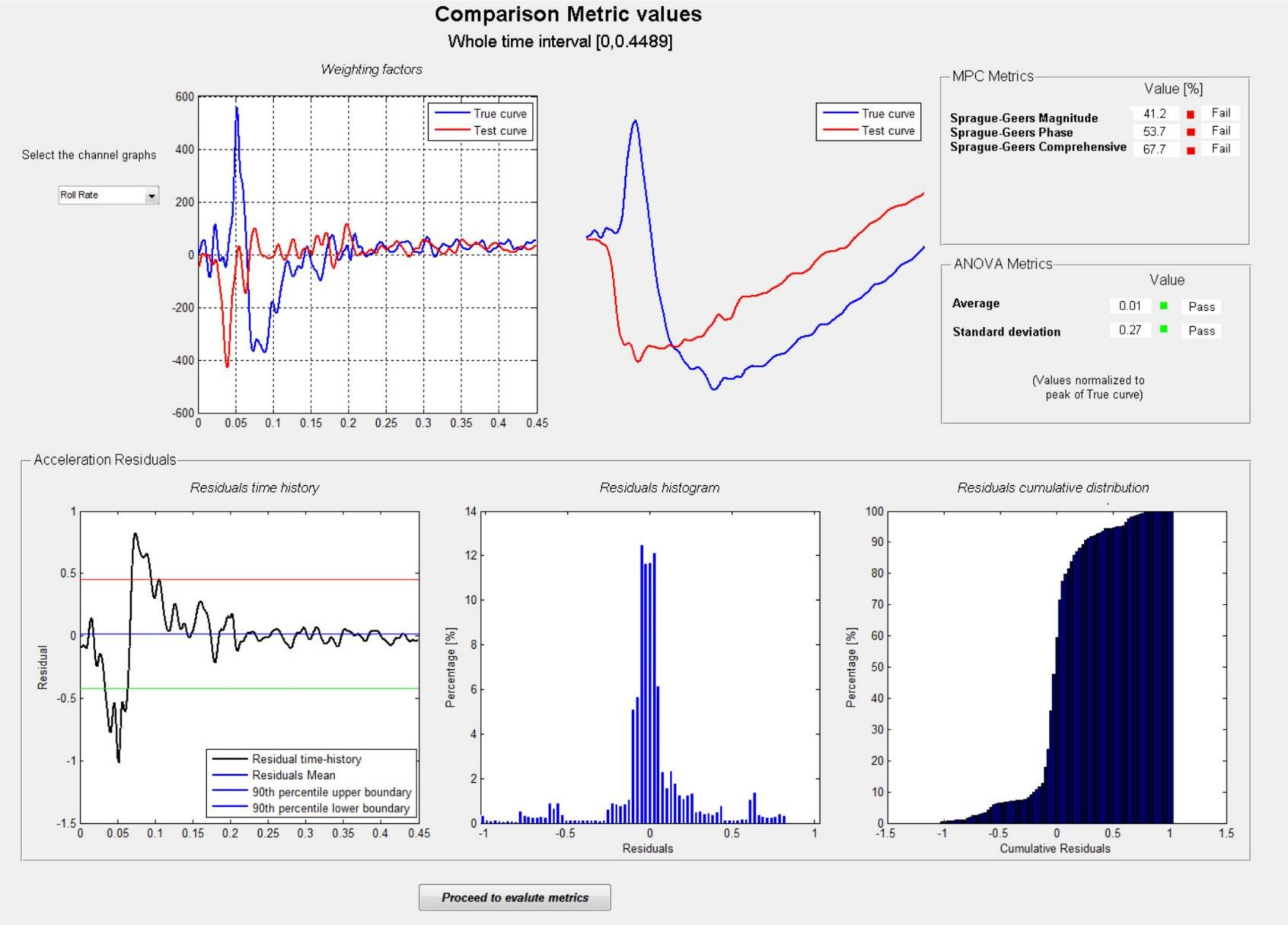
Yaris / NJ CMB – RSVVP Evaluation – Z - Acceleration



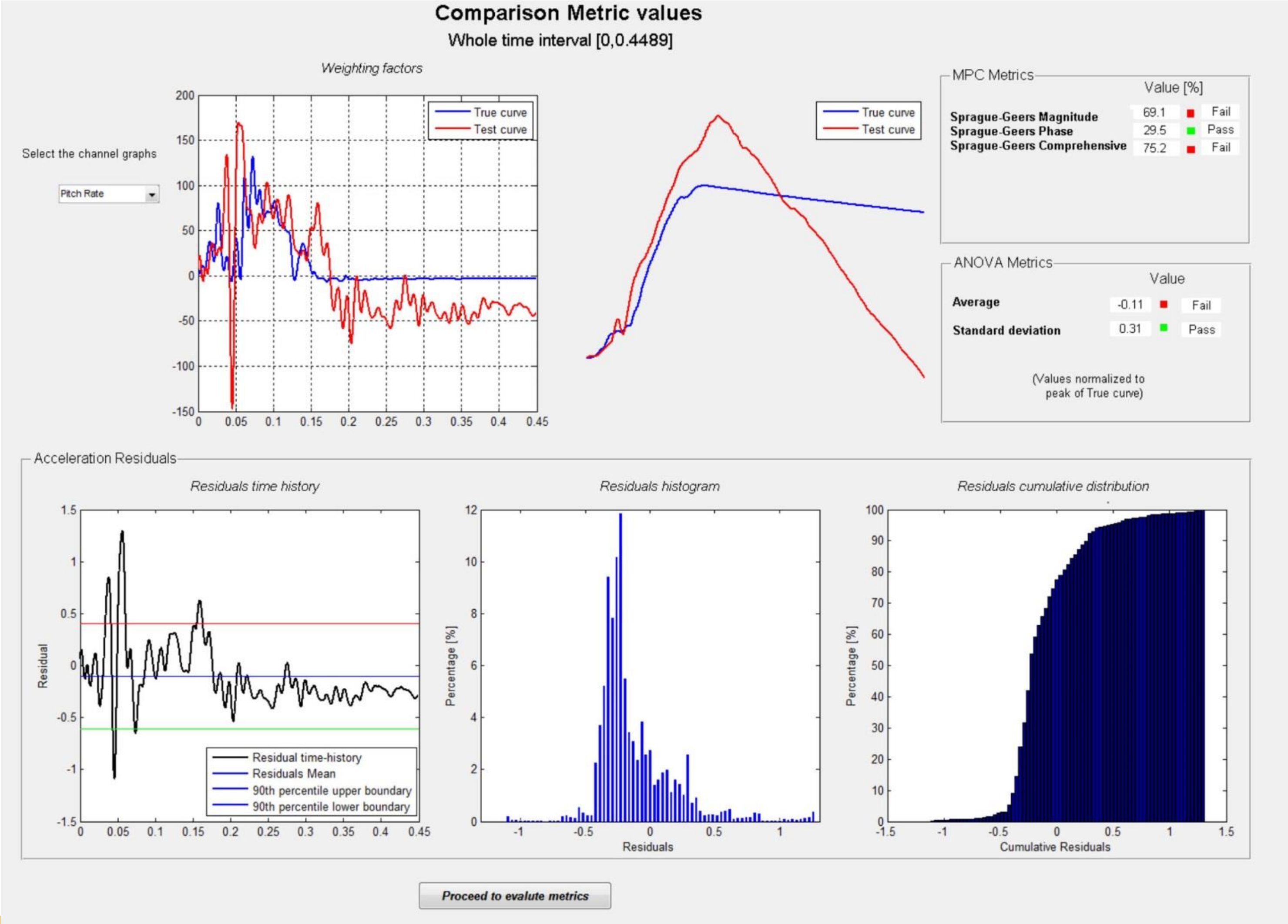
Yaris / NJ CMB – RSVVP Evaluation – Yaw Rate



Yaris / NJ CMB – RSVVP Evaluation – Roll Rate



Yaris / NJ CMB – RSVVP Evaluation – Pitch Rate



Summary

- Model verified in 56 km/hr and 40 km/hr full frontal impacts (NHTSA tests 5677, 6221, and 6069)
- Model verified in 64 km/hr frontal offset impact (IIHS test CEF0610)
- Model verified in NHTSA and IIHS side impacts (NHTSA tests 5679, 6220, 6558, 6585 and IIHS tests CES50638 CES0639)
- Model Validated in NJ shape concrete barrier impact (MwRSF Test 2214NJ-1, Kia Rio vehicle)

Appendix E

Validation Forms for Silverado (2270P) Vehicle Model

Validation Reports

- **Appendix E-1: NJ Concrete Barrier Impact with 2270P Vehicle**
- **Appendix E-2: G4(1S) Barrier Impact with 2270P Vehicle**
- **Appendix E-3: MGS Barrier Impact with 2270P Vehicle**

Each of the Reports Includes:

- **Table 1A – V&V Summary Table**
- **Table 1B – V&V Analysis Solution Verification Summary Table & RSVVP Results**
- **Figure 1 – Energy Balance Diagram**
- **Figure 2A – RSVVP Multi-Channel Comparison**
- **Figure 2B – RSVVP Longitudinal Acceleration Comparison**
- **Figure 2C – RSVVP Lateral Acceleration Comparison**
- **Figure 2D – RSVVP Vertical Acceleration Comparison**
- **Figure 2E – RSVVP Roll Angle Comparison**
- **Figure 2F – RSVVP Pitch Angle Comparison**
- **Figure 2G– RSVVP Yaw Angle Comparison**
- **Figure 3 – Comparison of Changes in Vehicle Velocities**
- **Figure 4 – Comparison of Changes in Vehicle Angles**
- **Table 1C – V&V PIRTs Summary Table**
- **Figure 5 – Full-Scale Test Summary**
- **Figure 6 – Sequential Comparisons (Front, rear, and top views)**
- **Table 1D – V&V Overall Summary Table**

Appendix E-1: New Jersey Concrete Barrier Impact with 2270P Vehicle

CCSA VALIDATION/VERIFICATION REPORT

Project: **CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections**
Comparison Case: **2270P Vehicle with New Jersey Safety Shape Barrier**
Impact Description: **25 degree impact into barrier at 100 km/h (62 mph)**
Governing Criteria: **MASH TL-3**
Report Date: **February 2013**

Table A – Information Sources:

General Information	Known Solution	Analysis Solution
Performing Organization	TTI	CCSA-GWU
Test/Run Number	RF476460-1-4	
Vehicle	2007 Chevrolet Silverado	CCSA - 2007 Silverado Model
Vehicle Mass (lb/kg)	5049 / 2290	5005 / 2270
Impact Speed (mph/kph)	62.6 / 100.75	62.6 / 100.75
Impact Angle (degrees)	25.2	25.2

Table B - Evaluation Parameters Summary:

Category	Subset	Values
Evaluation Method	MASH (V1, 2009)	
Hardware Type	Longitudinal	
Test Number	3-11	
Test Vehicle Required	2270P	
Criterion to be Applied	**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.
	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.
		F - The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are
		H - 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.
		I - Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.
	Vehicle Trajectory	For redirective devices the vehicle shall exit within the prescribed box.

Project: CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections
Comparison Case: 2270P Vehicle with New Jersey Safety Shape Barrier

Table C – Analysis Solution Verification Summary

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%	YES
Hourglass Energy of the analysis solution at the end of the run is less than 5 % of the total initial energy at the beginning of the run	<1%	YES
The part/material with the highest amount of hourglass energy at any time during the run is less than 5 % of the total initial energy at the beginning of the run.	<1%	YES
Mass added to the total model is less than 5 % the total model mass at the start of the run.	<1%	YES
The part/material with the most mass added had less than 10 % of its initial mass added.	<1%	YES
The moving parts/materials in the model have less than 5 % of mass added to the initial moving mass of the model.	<1%	YES
There are no shooting nodes in the solution?	NA	YES
There are no solid elements with negative volumes?	NA	YES

Table D - RSVVP Results

	Single Channel Time History Comparison Results	Time interval [0 sec - 0.5 sec]		
O	***Sprauge-Geer Metrics***	**M**	**P**	**Pass?**
	X acceleration	52.9	35.6	NO
	Y acceleration	3.2	16.2	YES
	Z acceleration	71.7	45.3	NO
	Yaw rate	13.4	9.5	YES
	Roll rate	16.8	24.4	YES
	Pitch rate	35.4	39.9	YES
P	***ANOVA Metrics***	**Mean**	**SD**	**Pass?**
	X acceleration/Peak	1.32	29.37	YES
	Y acceleration/Peak	0.84	12.15	YES
	Z acceleration/Peak	0.66	44.94	NO
	Yaw rate	0.2	14.87	YES
	Roll rate	0.21	17.28	YES
	Pitch rate	10.86	53.95	NO

Multi-Channel Weighting Factors		Time interval [0 sec; 0.5 sec]
Multi-Channel Weighting Method Peaks Area I Area II Inertial	**X Channel**	0.142263141
	Y Channel	0.312496147
	Z Channel	0.045240712
	Yaw Channel	0.19476326
	Roll Channel	0.200826808
	Pitch Channel	0.104409933

Sprauge-Geer Metrics		**M**	**P**	**Pass?**
	All Channels (weighted)	21.4	23.1	YES
ANOVA Metrics		**Mean**	**SD**	**Pass?**
	All Channels (weighted)	1.5	22	YES

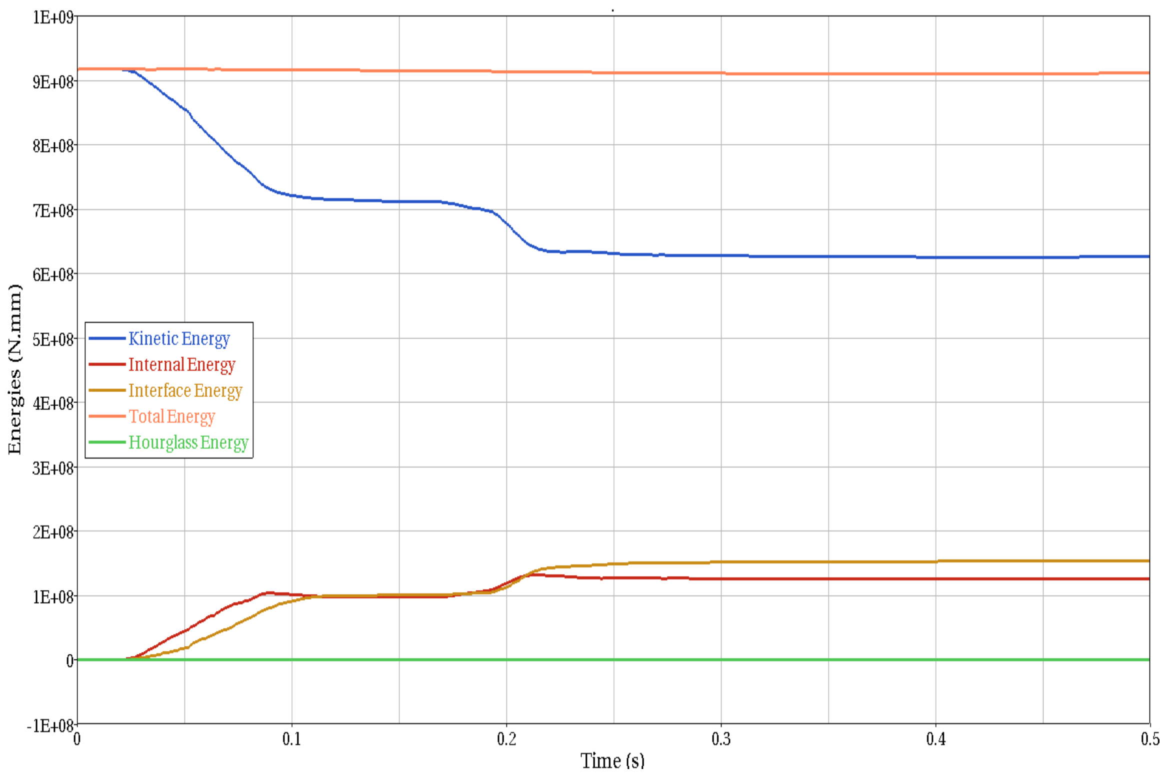


Figure 1: Simulations Energies

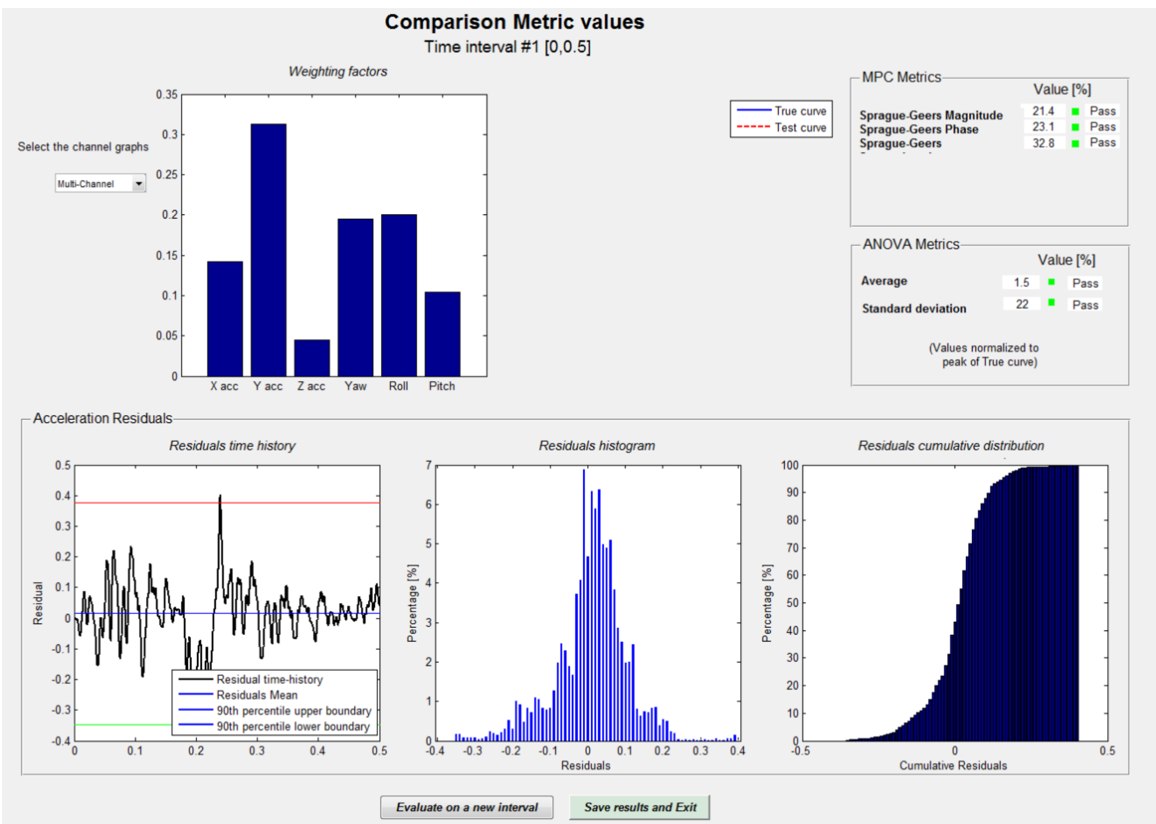


Figure 2a: RSVVP Results – All Channels

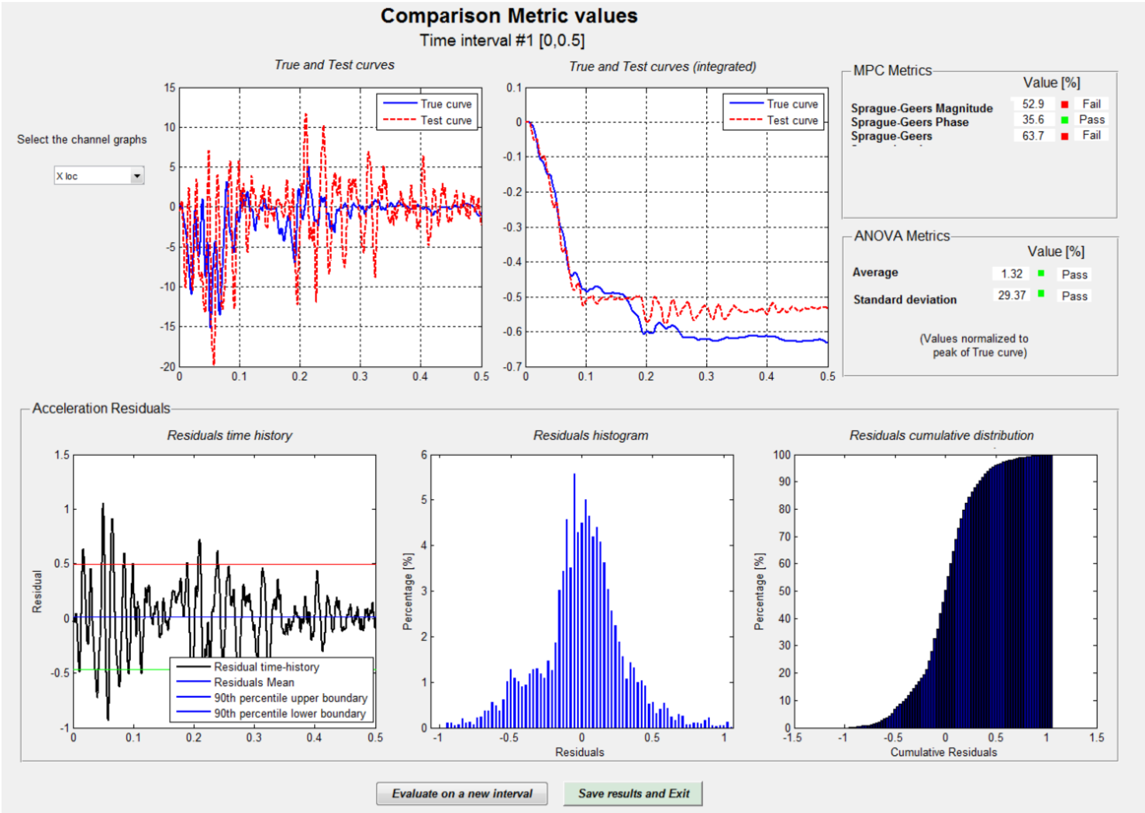


Figure 2b: RSVVP Results – Longitudinal Acceleration

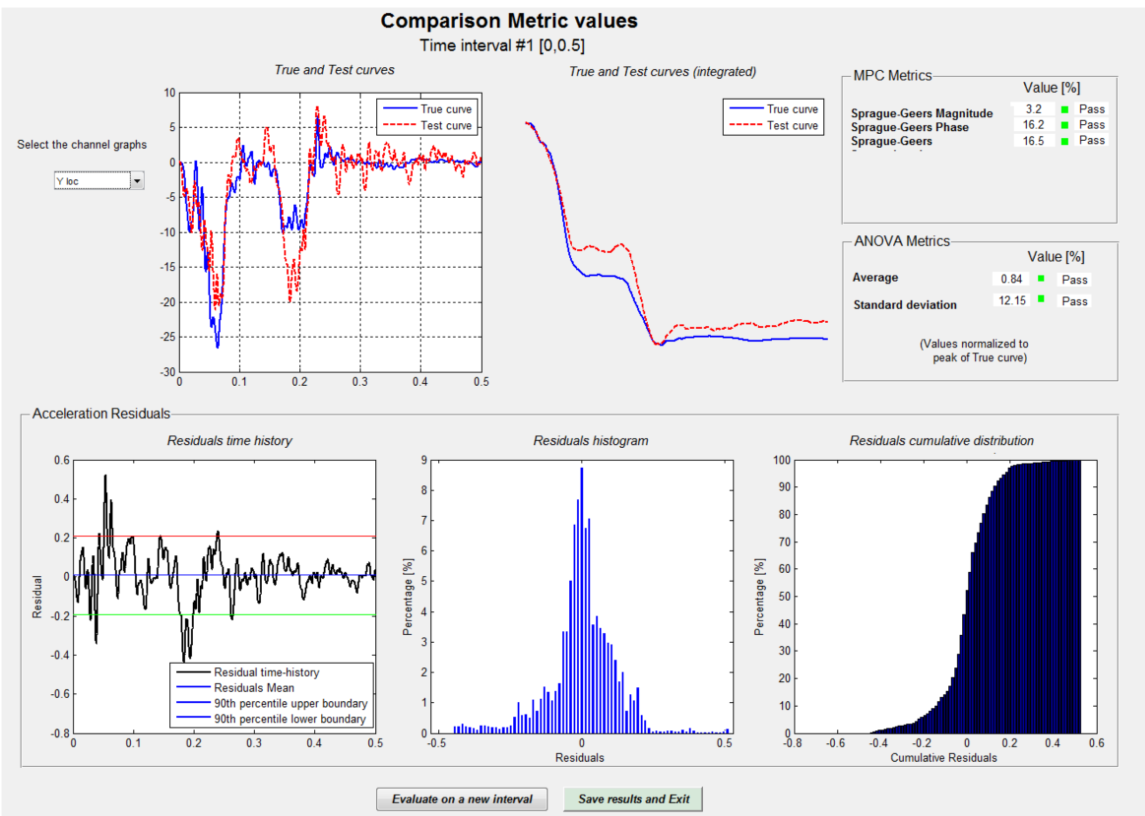


Figure 2c: RSVVP Results – Lateral Acceleration

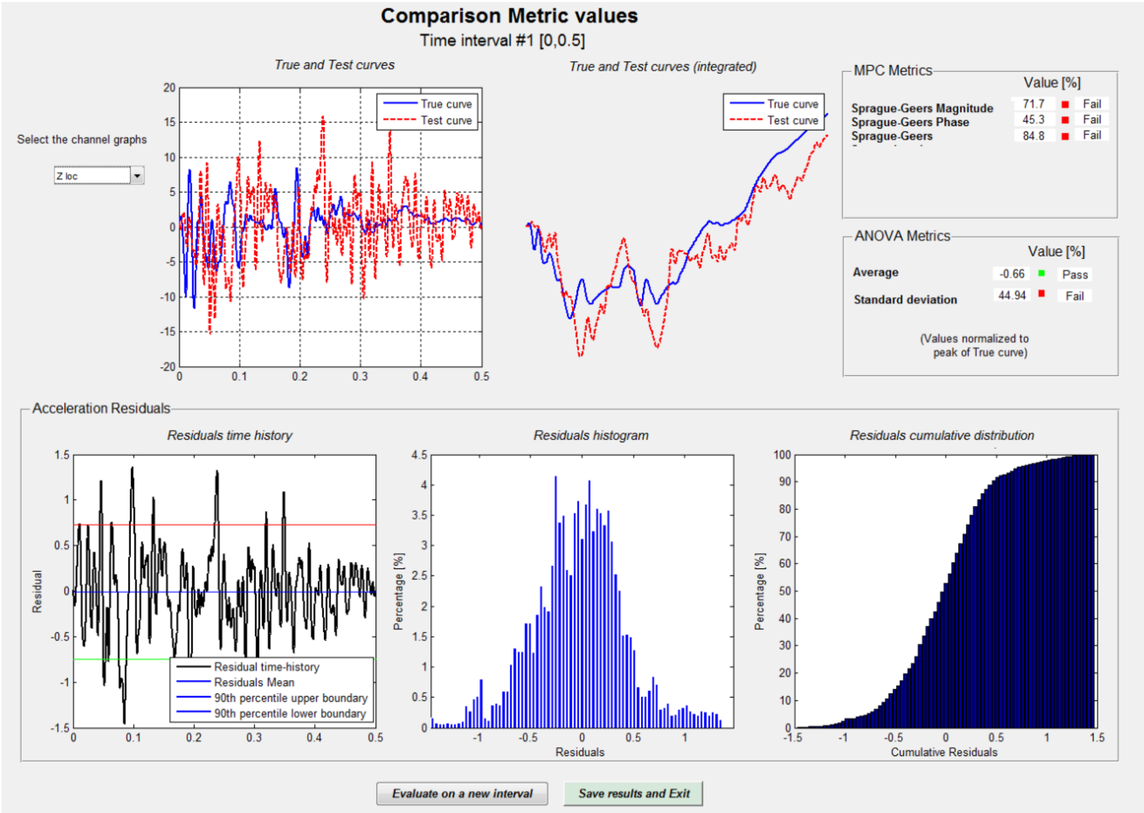


Figure 2d: RSVVP Results – Vertical Acceleration

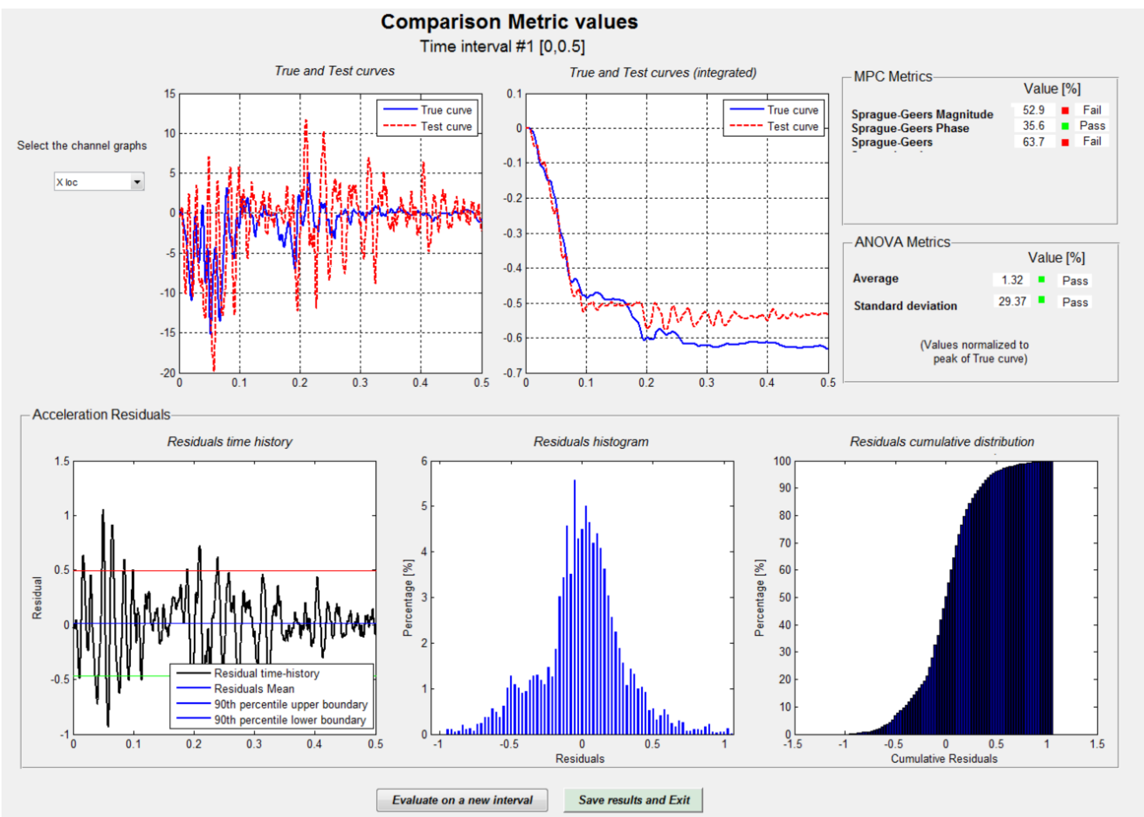


Figure 2e: RSVVP Results – Roll Angle

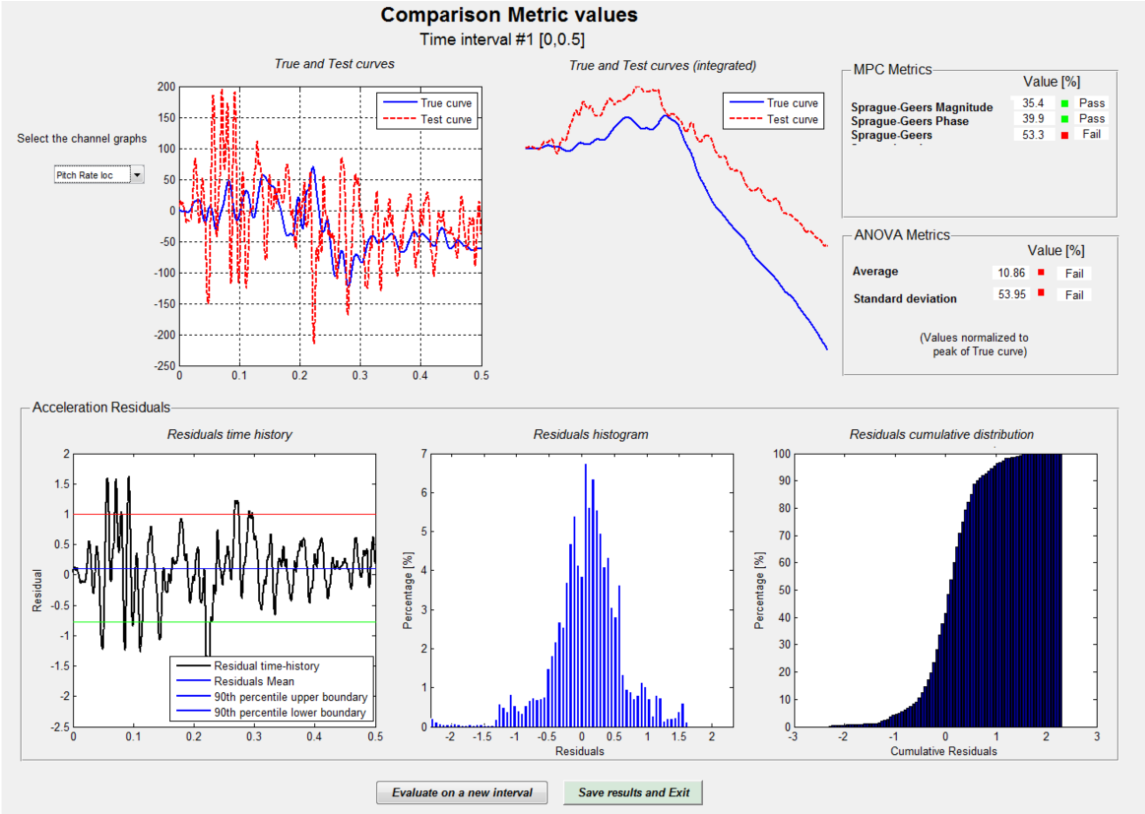


Figure 2f: RSVVP Results – Pitch Angle

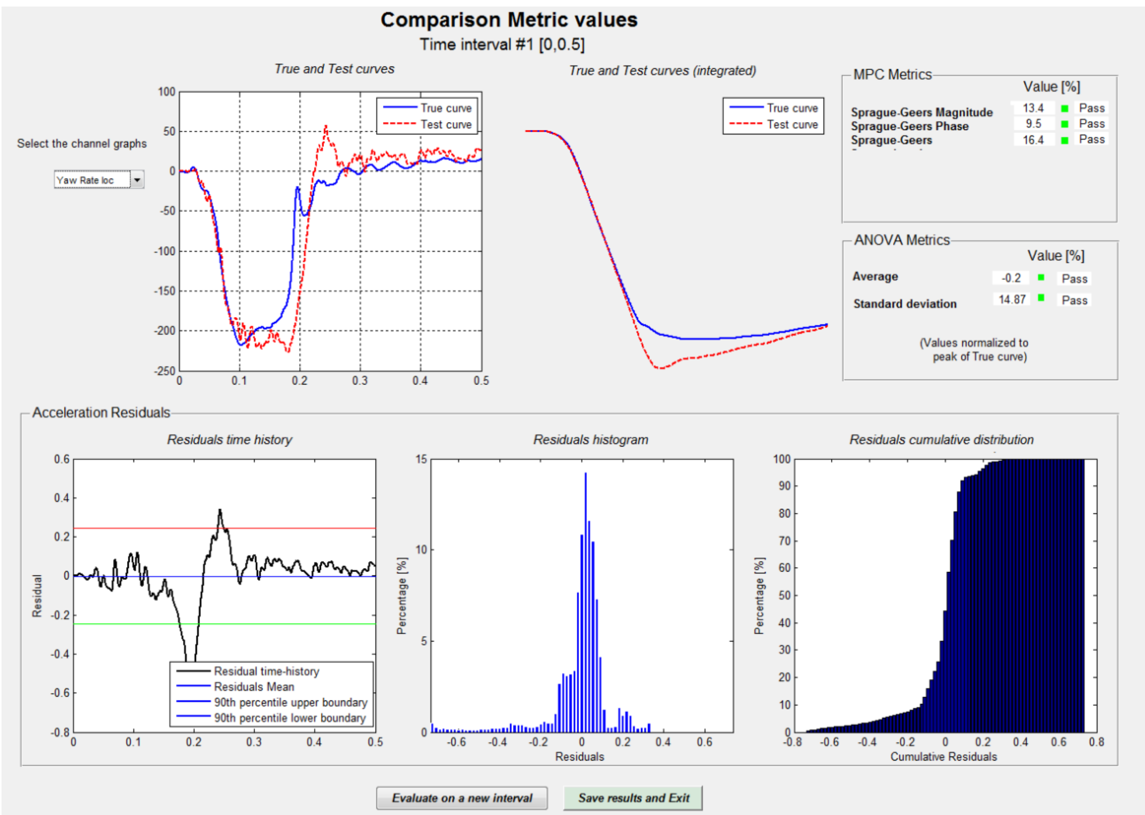


Figure 2g: RSVVP Results – Yaw Angle

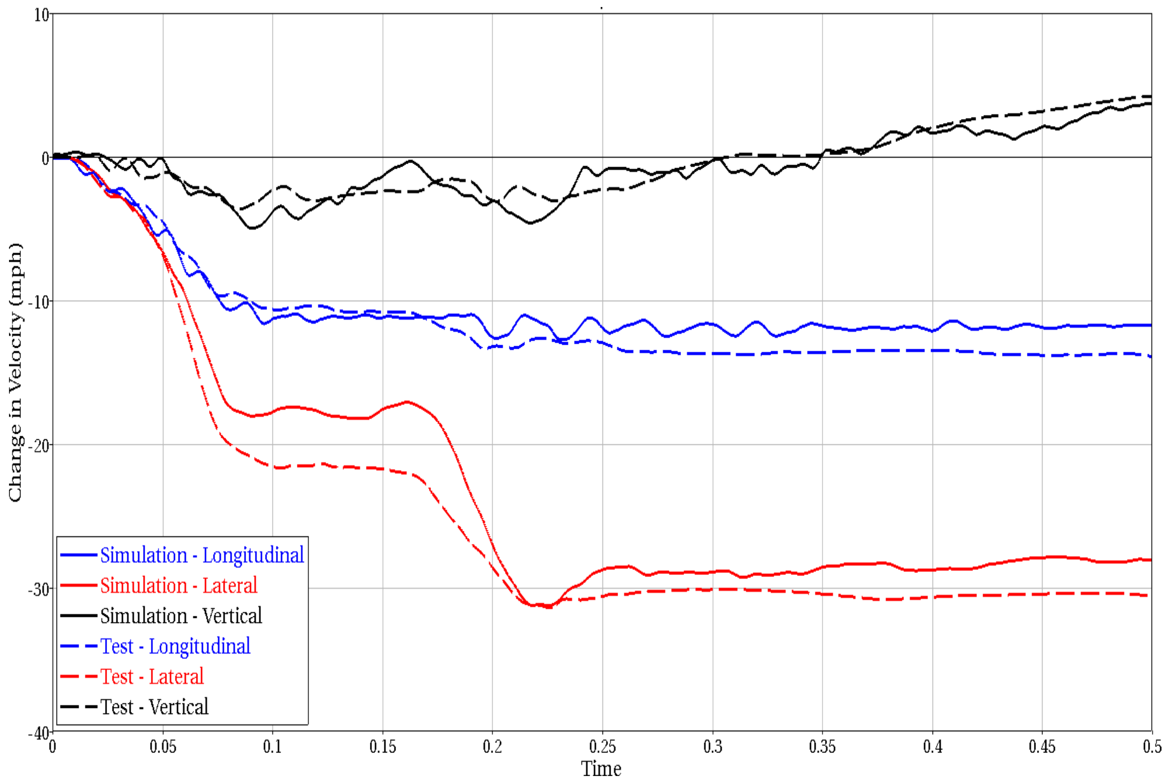


Figure 3: Change in Vehicle Velocities

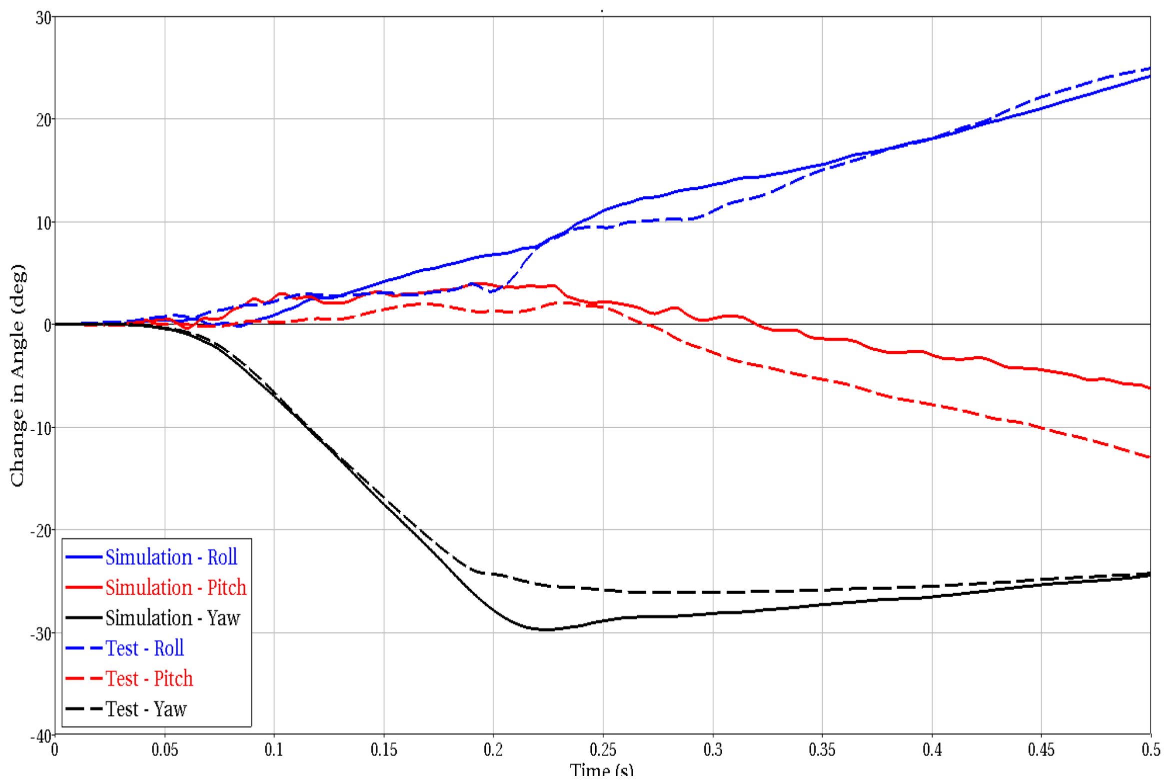
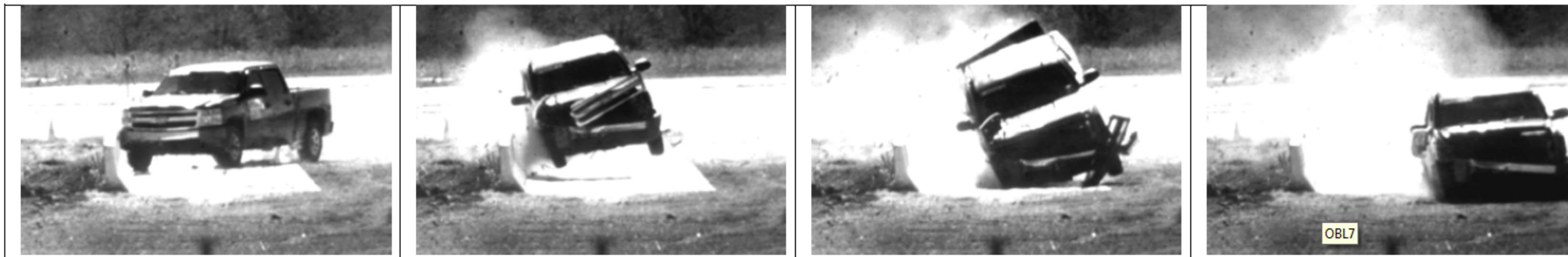


Figure 4: Change in Vehicle Angles

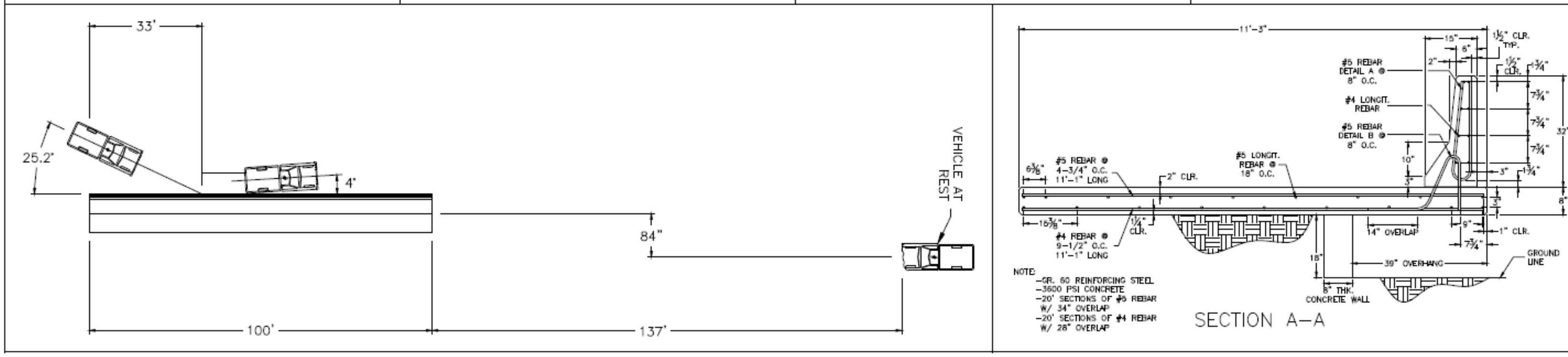
Project: CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections
Comparison Case: 2270P Vehicle with New Jersey Safety Shape Barrier

Table E - Roadside Safety Phenomena Importance Ranking Table (MASH Evaluation)

Evaluation Criteria				Known Result	Analysis Result	Relative Diff. (%)	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.	Yes	Yes		YES
		A2	The relative difference in the maximum dynamic deflection is less than 20 percent.	0.0 m	0.0 m	0%	YES
		A3	The relative difference in the time of vehicle-barrier contact is less than 20 percent.	0.238 s	0.214 s	10%	YES
		A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	Yes	Yes		YES
		A5	Barrier did not fail (Answer Yes or No).	Yes	Yes		YES
		A6	There were no failures of connector elements (Answer Yes or No).	Yes	Yes		YES
		A7	There was no significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	Yes	Yes		YES
		A8	There was no significant snagging between vehicle body components and barrier elements (Answer Yes or No).	Yes	Yes		YES
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. The maximum pitch & roll angles are not to exceed 75 degrees.	Yes	Yes		YES
		F2	Maximum vehicle roll – relative difference is less than 20% or absolute difference is less than 5 degrees.	25 (.5s)	24 (.5s)	4% 1 deg	YES
		F3	Maximum vehicle pitch – relative difference is less than 20% or absolute difference is less than 5 deg.	12 (.5s)	7 (.5s)	41% 5 deg	YES
		F4	Maximum vehicle yaw – relative difference is less than 20% or absolute difference is less than 5 deg.	30 (.5s)	26 (.5s)	13% 4 deg	YES
	H	H1	Longitudinal & lateral occupant impact velocities (OIV) should fall below the preferred value of 30 ft/s (9.1 m/s), or at least below the maximum allowed value of 40 ft/s (12.2 m/s)	Yes	Yes		YES
		H2	Longitudinal OIV (m/s) - Relative difference is less than 20%t or absolute difference is less than 2 m/s	4.3	4.7	9% 0.4 m/s	YES
		H3	Lateral OIV (m/s - Relative difference is less than 20% or absolute difference is less than 2 m/s	9.2	7.9	14% 1.3 m/s	YES
	I	I1	Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.	Yes	Yes		YES
		I2	Longitudinal ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	5.6	7.6	35% 2 g	YES
		I3	Lateral ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	9.6	12.9	34% 3 g	YES
Vehicle Trajectory			The vehicle rebounded within the exit box. (Answer Yes or No)	Yes	Yes		YES



0.000 s | 0.231 s | 0.462 s | 0.693 s



General Information
- Test Agency........................ Texas Transportation Institute
- Test No. RF476460-1-4
- Date 2009-01-30

Test Article
- Type........................ Concrete Barrier
- Name .... 32-inch New Jersey Safety Shape Barrier
- Installation Length .... 100 ft-1 in
- Material or Key Elements .... Concrete

Soil Type and Condition....... Concrete Deck, Dry

Test Vehicle
- Type/Designation................ 2270P
- Make and Model .... 2007 Chevrolet Silverado Pickup
- Mass
  - Curb........................ 5000 lb
  - Test Inertial..................... 5049 lb
  - Gross Static..................... 5049 lb

Impact Conditions
- Speed .... 62.6 mi/h
- Angle .... 25.2 degrees

Exit Conditions
- Speed .... 52.6 mi/h
- Angle .... 4.0 degrees

Occupant Risk Values
- Impact Velocity
  - Longitudinal .... 14.1 ft/s
  - Lateral .... 30.2 ft/s
- Ridedown Accelerations
  - Longitudinal .... -5.6 G
  - Lateral .... -9.6 G
- THIV .... 36.0 km/h
- PHD .... 10.2 G
- Max. 0.050-s Average
  - Longitudinal .... -6.8 G
  - Lateral .... -15.7 G
  - Vertical .... -3.2 G

Post-Impact Trajectory
- Stopping Distance .... 204 ft

Vehicle Stability
- Maximum Yaw Angle.................... -29 degrees
- Maximum Pitch Angle.................. -16 degrees
- Maximum Roll Angle.................... 29 degrees
- Vehicle Snagging........................ No
- Vehicle Pocketing........................ No

Test Article Deflections
- Dynamic........................ 0
- Permanent 0
- Working Width 0

Vehicle Damage
- VDS 01RFQ5
- CDC........................ 01RFEW4
- Max. Exterior Vehicle Crush (inches)........... 14.0 inches
- Max. Occupant Compartment Deformation (inches).............. 2.0 inches

Figure 5: Full-Scale Test Summary

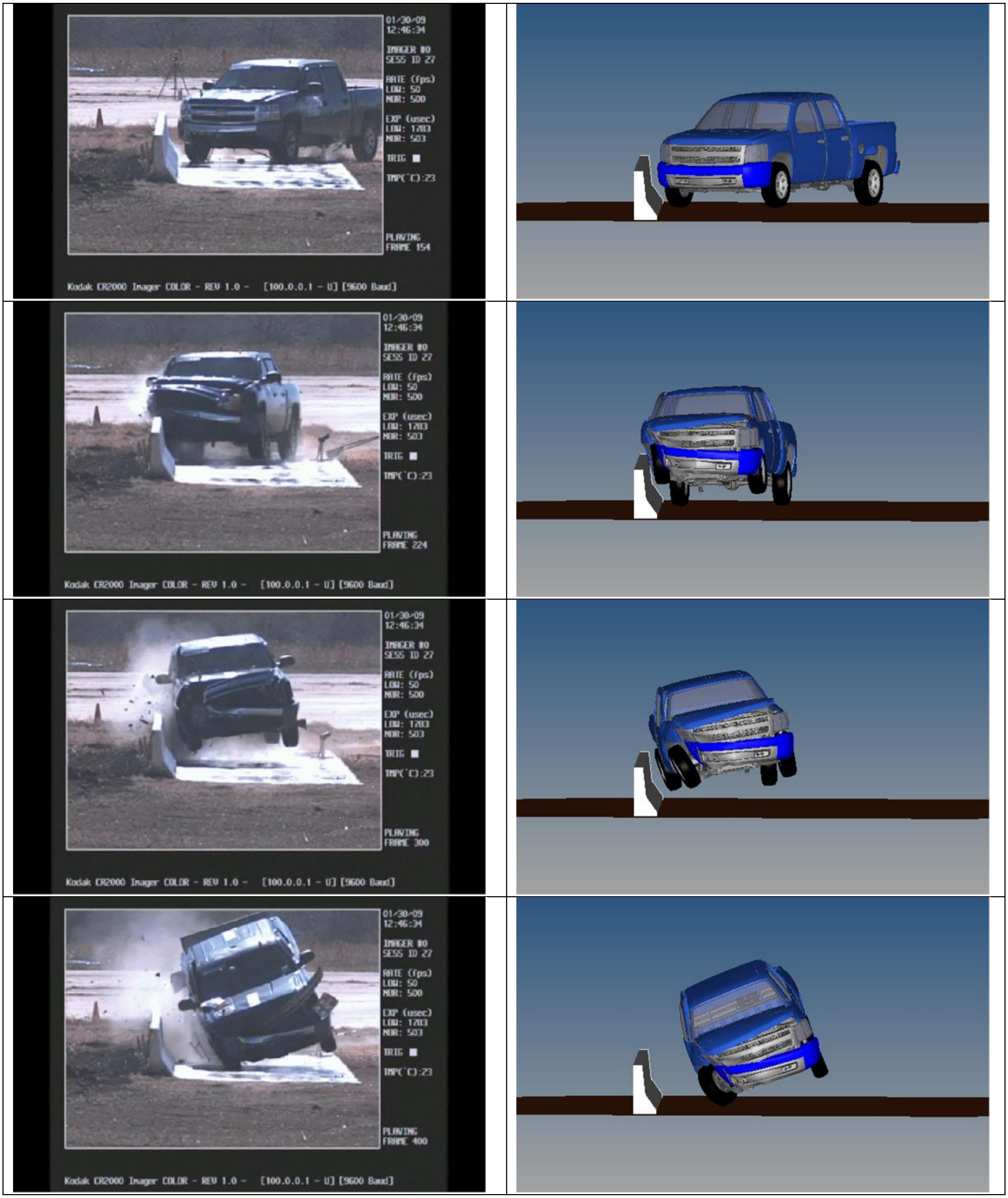


Figure 6a: Sequential Comparisons – Front View

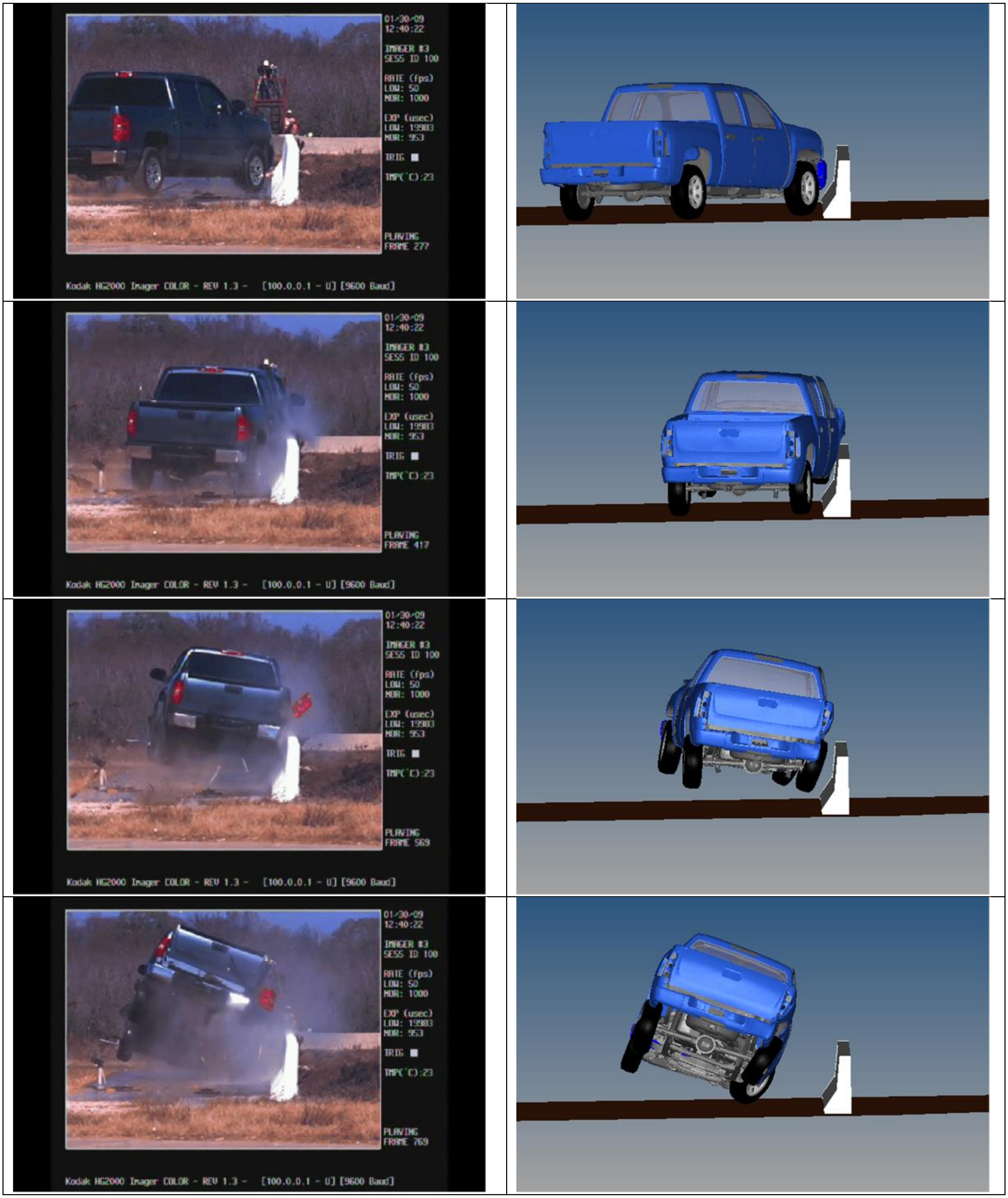


Figure 6b: Sequential Comparisons – Rear View

Figure 6c: Sequential Comparisons – Top View

Project: CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections
Comparison Case: 2270P Vehicle with New Jersey Safety Shape Barrier

Table F - Composite Verification and Validation Summary:

List the Report MASH08 Test Number		
Table C – Analysis Solution Verification s	Did all solution verification criteria in table pass?	YES
Table D - RSVVP Results	Do all the time history evaluation scores from the single channel factors result in a satisfactory comparison (i.e., the comparison passes the criterion)?	NO
	If all the values for Single Channel comparison did not pass, did the weighted procedure result in an acceptable	YES
Table E - Roadside Safety Phenomena Importance Ranking Table	Did all the critical criteria in the PIRT Table pass? Note: Tire deflation was observed in the test but not in the simulation. This due to the fact that tire deflation in not incorporated in the model. This is considered not to have a critical effect on the outcome of the test	YES
Overall	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.	YES

NOTES:
(none)

Appendix F-2: G4(1S) Barrier Impact with 2270P Vehicle

CCSA VALIDATION/VERIFICATION REPORT

Project: CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections
Comparison Case: 2270P (Pickup Truck) with G41S Barrier
Impact Description: 25.8 degree impact into barrier at 100.4 km/h (62.4 mph)
Governing Criteria: MASH TL-3
Report Date: March 2013

Table A – Information Sources:

General Information	Known Solution	Analysis Solution
Performing Organization	MwRSF	CCSA-GWU
Test/Run Number	2214WB-2	RR130422b
Vehicle	Dodge Ram 1500 Quad Cab	Silverado C
Vehicle Mass (lb/kg)	5000 / 2268	4918 / 2231
Impact Speed (mph/kph)	62.4 / 100.4	62.4 / 100.4
Impact Angle (degrees)	25.8	25.8

Table B - Evaluation Parameters Summary:

Category	Subset	Values
Evaluation Method	MASH (V1, 2009)	
Hardware Type	Longitudinal	
Test Number	3-11	
Test Vehicle	2270C	
Criterion to be Applied	**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.
	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.
		F - The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are
		H - 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.
		I - Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.
	Vehicle Trajectory	For redirective devices the vehicle shall exit within the prescribed box.

Project: CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections
Comparison Case: 2270P (Pickup Truck) with G41S Barrier

Table C – Analysis Solution Verification Summary

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%	YES
Hourglass Energy of the analysis solution at the end of the run is less than 5 % of the total initial energy at the beginning of the run	< 1%	YES
The part/material with the highest amount of hourglass energy at any time during the run is less than 5 % of the total initial energy at the beginning of the run.	< 1%	YES
Mass added to the total model is less than 5 % the total model mass at the start of the run.	< 1%	YES
The part/material with the most mass added had less than 10 % of its initial mass added.	< 1%	YES
The moving parts/materials in the model have less than 5 % of mass added to the initial moving mass of the model.	< 1%	YES
There are no shooting nodes in the solution?	NA	YES
There are no solid elements with negative volumes?	NA	YES

Table D - RSVVP Results

Single Channel Time History Comparison Results		Time interval [0 sec - 0.89		
O	***Sprauge-Geer Metrics***	**M**	**P**	**Pass?**
	X acceleration	75	38.3	NO
	Y acceleration	29.9	32.6	YES
	Z acceleration	168.7	45.3	NO
	Yaw rate	14.1	12.7	YES
	Roll rate (test data not available)			
	Pitch rate (test data not available)			
P	***ANOVA Metrics***	**Mean**	**SD**	**Pass?**
	X acceleration/Peak	-1.79	41.87	NO
	Y acceleration/Peak	1.54	31.86	YES
	Z acceleration/Peak	0.16	73.73	NO
	Yaw rate	-.32	18.97	YES
	Roll rate (test data not available)			
	Pitch rate (test data not available)			

Multi-Channel Weighting Factors		Time interval [0 sec; 0.89
Multi-Channel Weighting Method **Peaks Area I** **Area II Inertial**	**X Channel**	0.22878683
	Y Channel	0.225135792
	Z Channel	0.046077378
	Yaw Channel	0.5
	Roll Channel	(test data not available)
	Pitch Channel	(test data not available)

Sprauge-Geer Metrics		**M**	**P**	**Pass?**
	All Channels (weighted)	36.7	24.6	YES
ANOVA Metrics		**Mean**	**SD**	**Pass?**
	All Channels (weighted)	-.02	29.6	YES

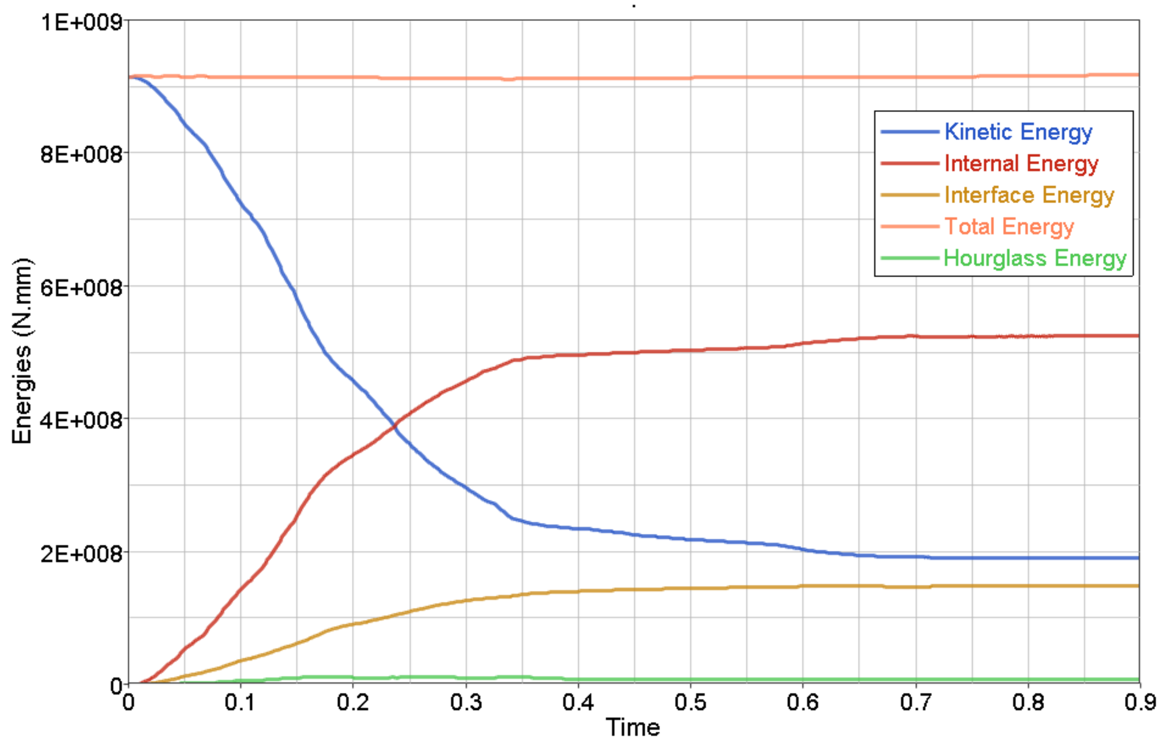


Figure 1: Simulations Energies

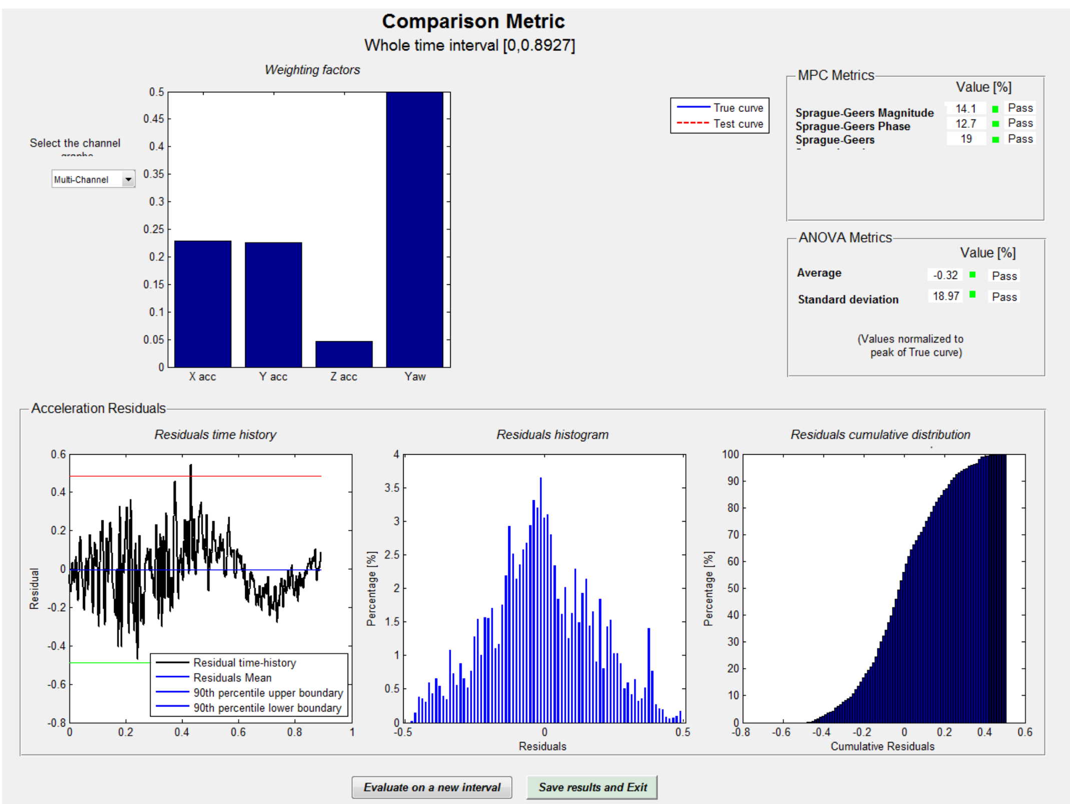


Figure 2a: RSVVP Results – All Channels

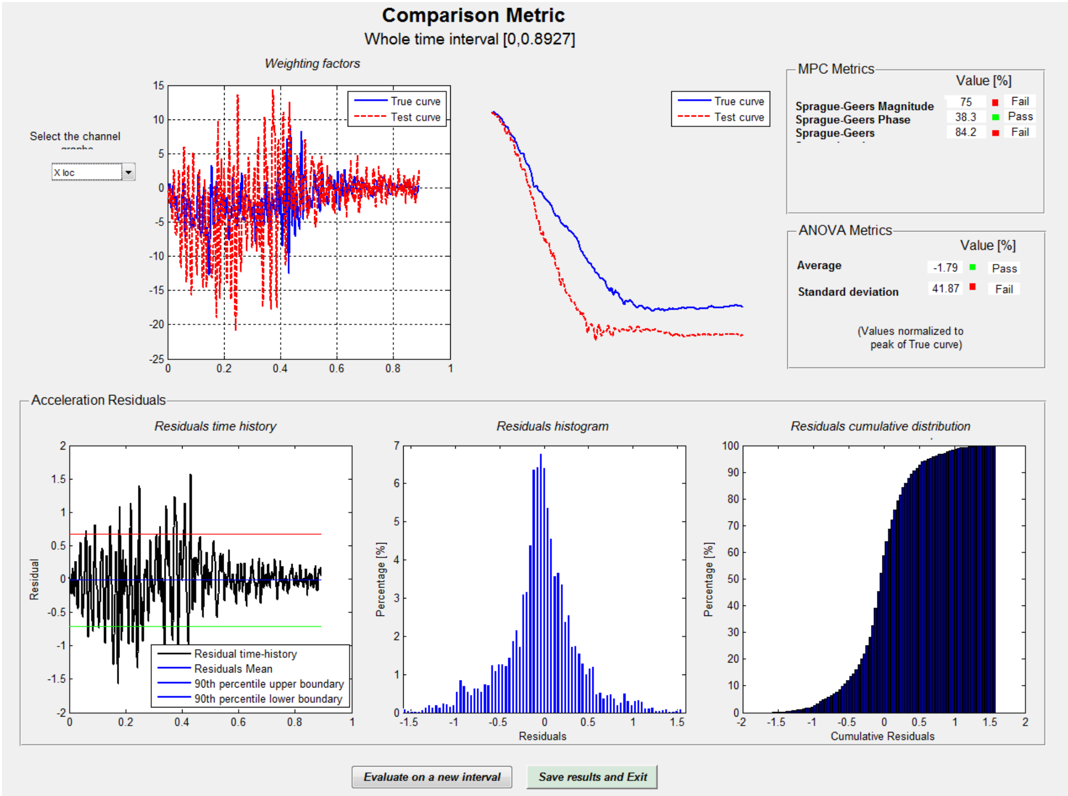


Figure 2b: RSVVP Results – Longitudinal Acceleration

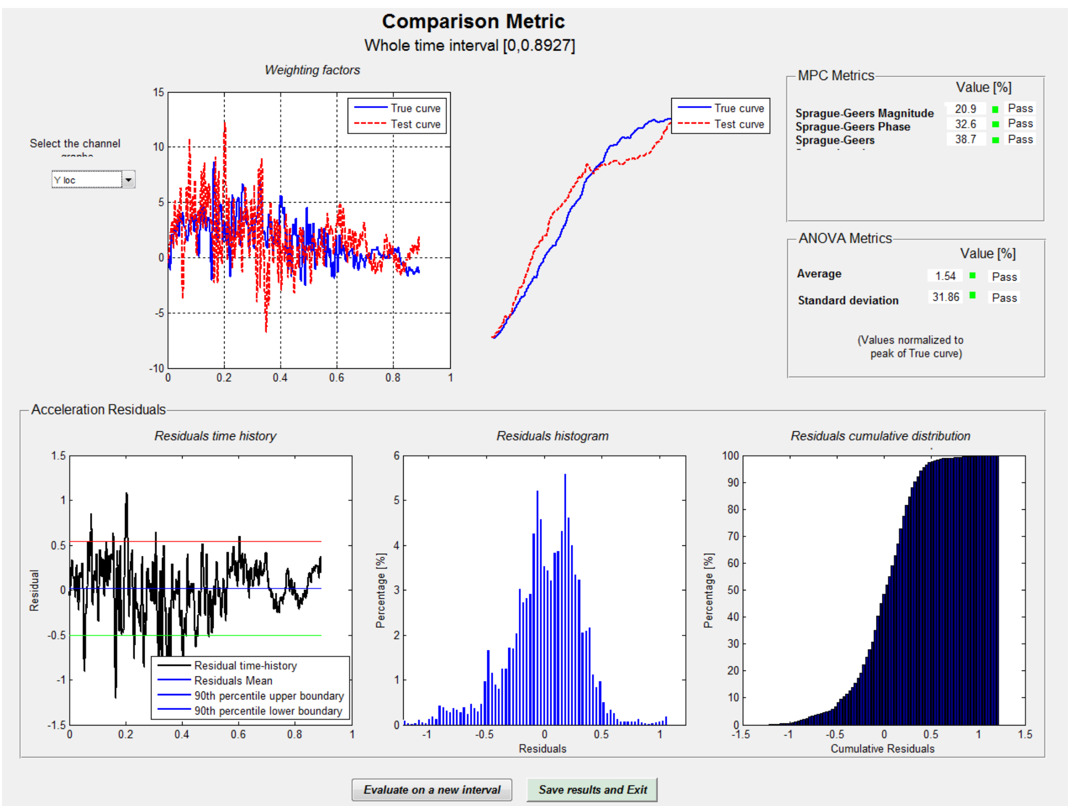


Figure 2c: RSVVP Results – Lateral Acceleration

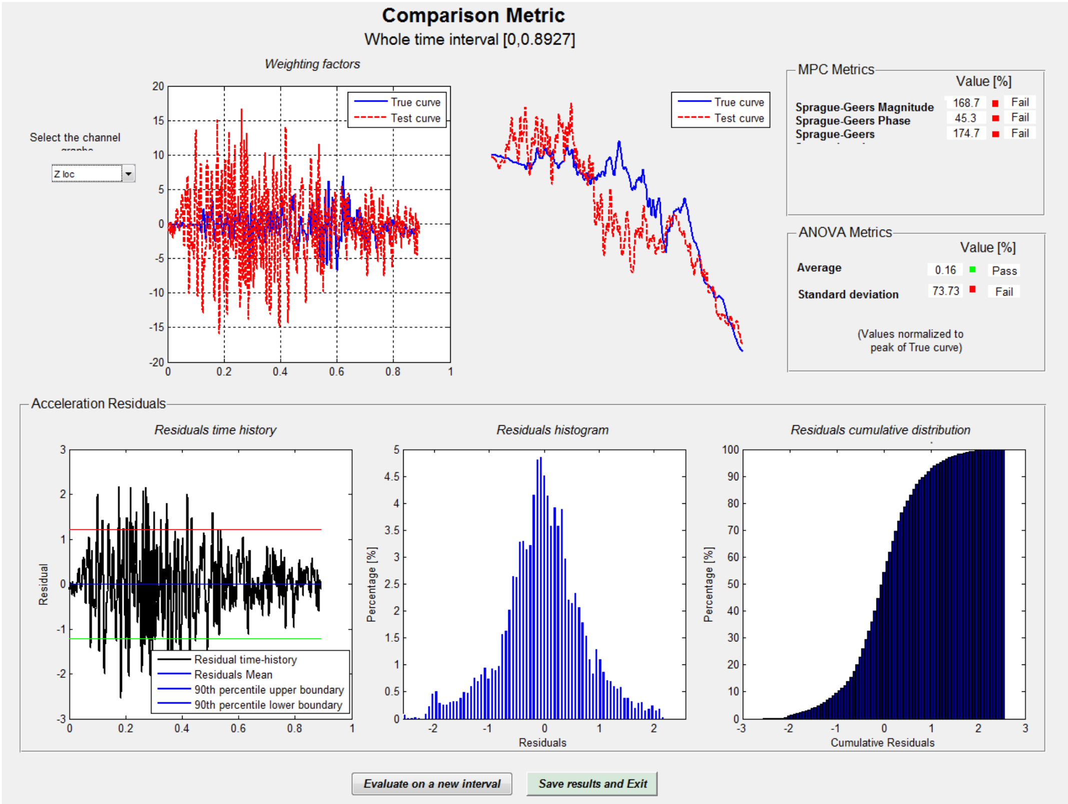


Figure 2d: RSVVP Results – Vertical Acceleration

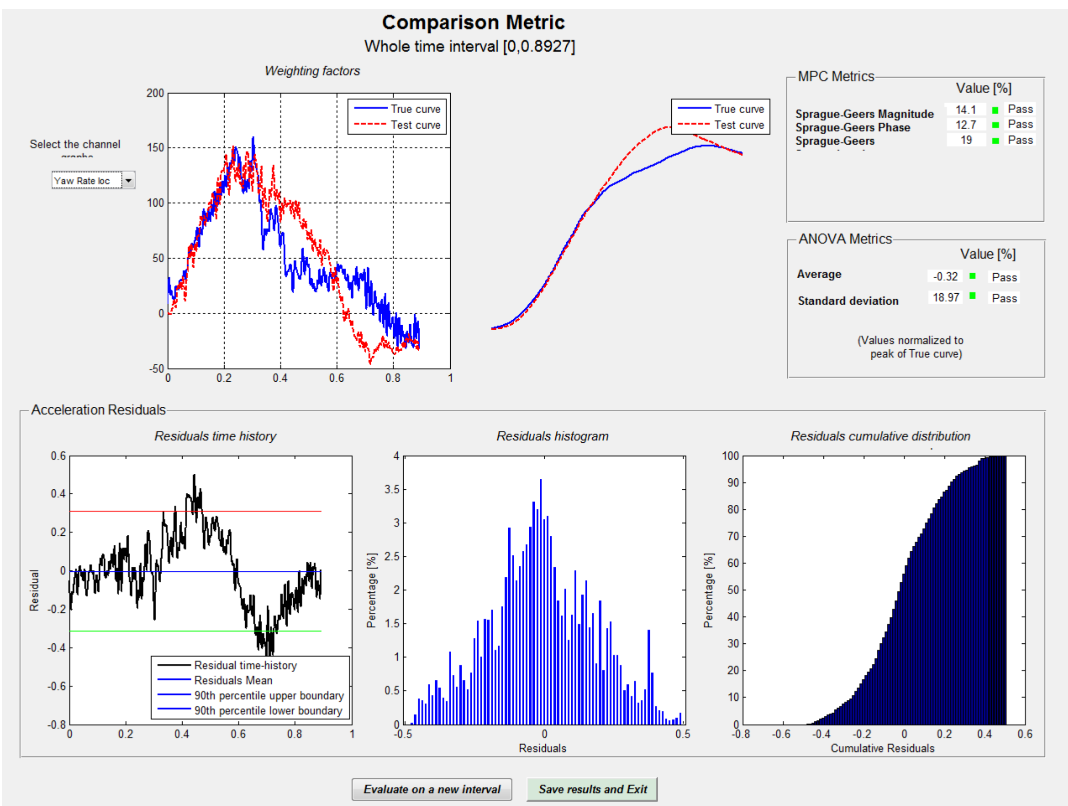


Figure 2e: RSVVP Results – Yaw Angle

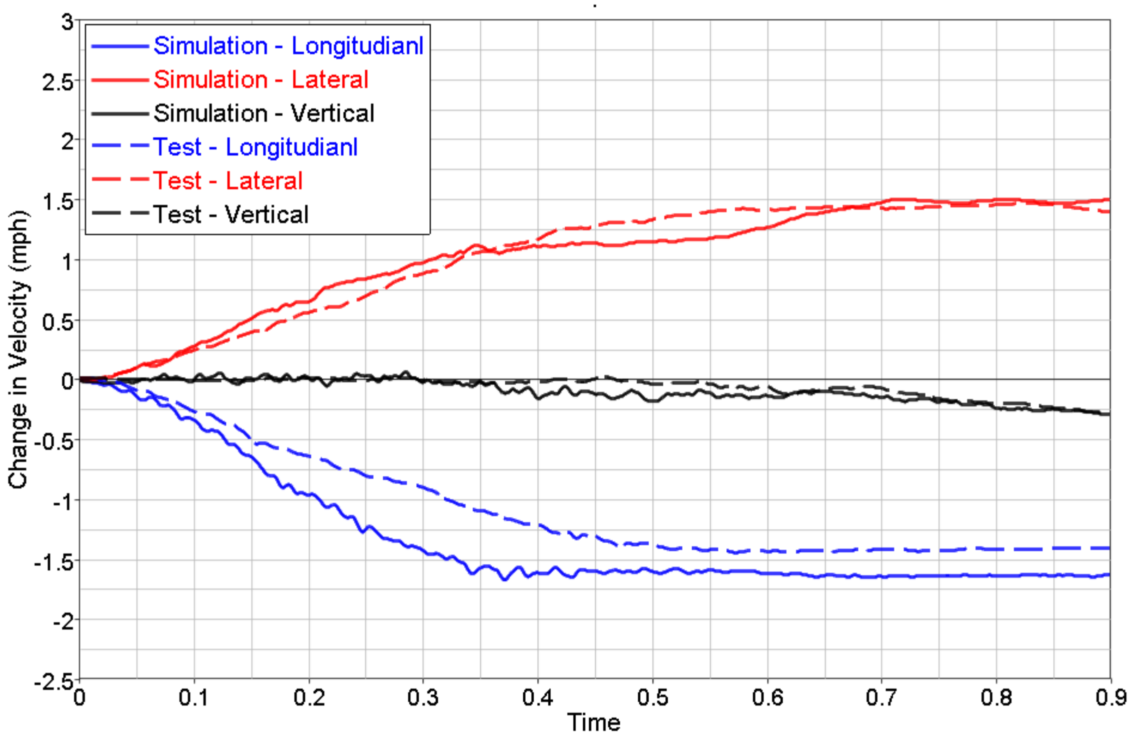


Figure 3: Change in Vehicle Velocities

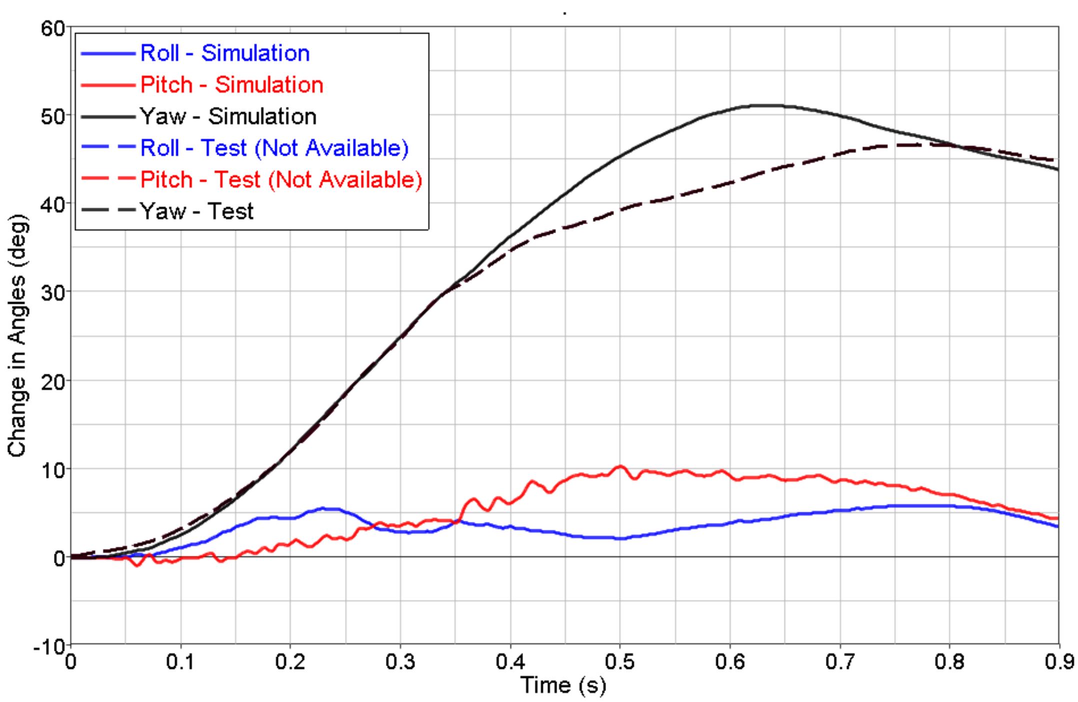
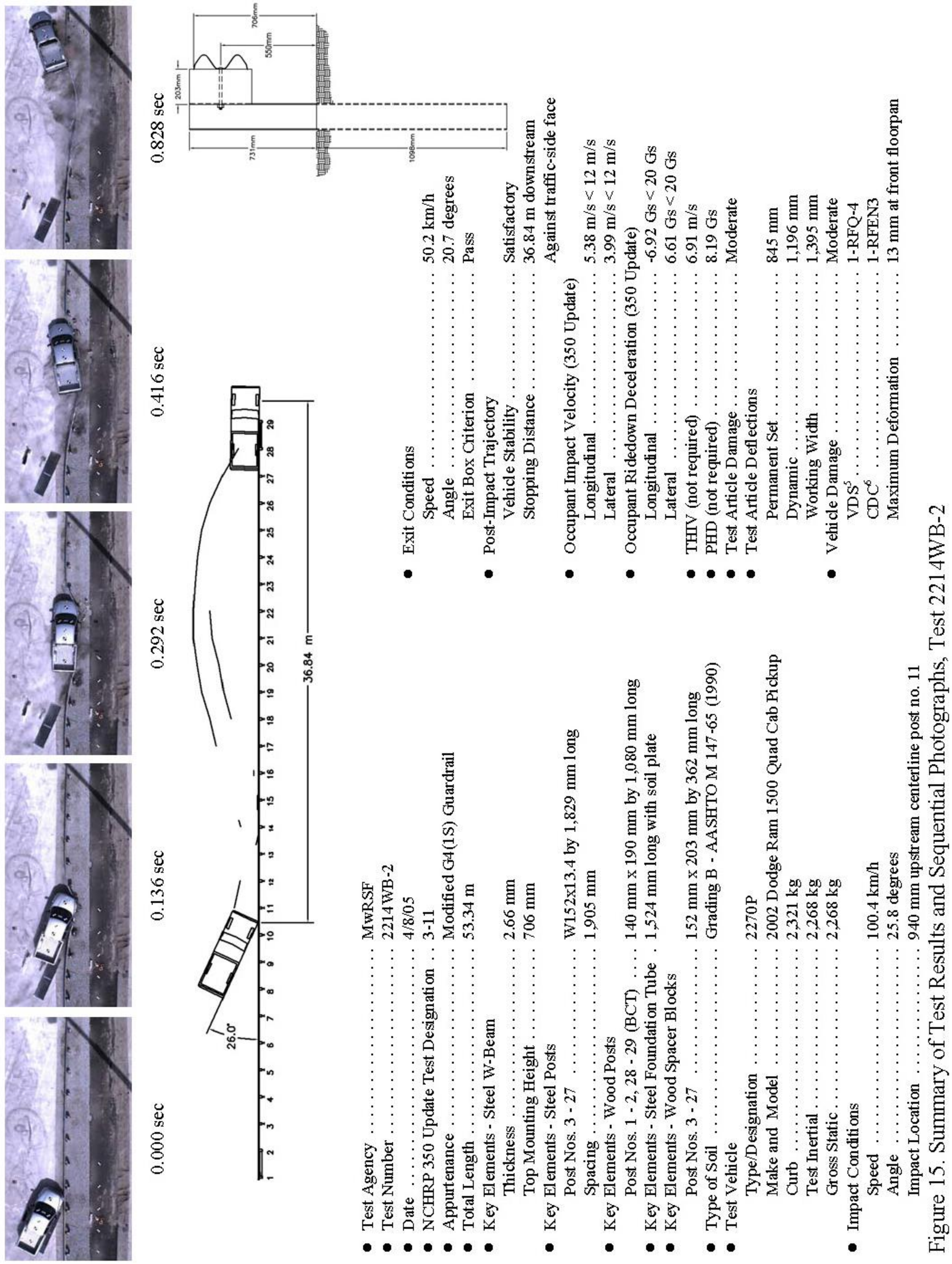


Figure 4: Change in Vehicle Angle

Project: CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections
Comparison Case: 2270P (Pickup Truck) with G41S Barrier

Table E - Roadside Safety Phenomena Importance Ranking Table (MASH Evaluation)

			Evaluation Criteria	Known Result	Analysis Result	Relative Diff. (%)	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.	Yes	Yes		YES
		A2	The relative difference in the maximum dynamic deflection is less than 20 percent.	1.196 m	0.980 m	18.0 %	YES
		A3	The relative difference in the time of vehicle-barrier contact is less than 20 percent.	0.84 s	0.72 s	7.1 %	YES
		A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	3	3		YES
		A5	Barrier did not fail (Answer Yes or No).	Yes	Yes		YES
		A6	There were no failures of connector elements (Answer Yes or No).	Yes	Yes		YES
		A7	There was no significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	Yes	Yes		YES
		A8	There was no significant snagging between vehicle body components and barrier elements (Answer Yes or No).	Yes	Yes		YES
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. The maximum pitch & roll angles are not to exceed 75 degrees.	Yes	Yes		YES
		F2	Maximum vehicle roll – relative difference is less than 20% or absolute difference is less than 5 degrees.	NA	NA	NA	
		F3	Maximum vehicle pitch – relative difference is less than 20% or absolute difference is less than 5 deg.	NA	NA	NA	
		F4	Maximum vehicle yaw – relative difference is less than 20% or absolute difference is less than 5 deg.	51 (.62s)	47 (.78s)	7.8% 4 deg	YES
	H	H1	Longitudinal & lateral occupant impact velocities (OIV) should fall below the preferred value of 30 ft/s (9.1 m/s), or at least below the maximum allowed value of 40 ft/s (12.2 m/s)	Yes	Yes		YES
		H2	Longitudinal OIV (m/s) - Relative difference is less than 20%t or absolute difference is less than 2 m/s	5.38	6.1	13.4% 0.72 m/s	YES
		H3	Lateral OIV (m/s) - Relative difference is less than 20% or absolute difference is less than 2 m/s	3.99	5.0	25.3% 1.01 m/s	YES
	I	I1	Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.	Yes	Yes		YES
		I2	Longitudinal ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	6.92	10.72	54.9% 3.8 g	YES
		I3	Lateral ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	6.61	9.86	49.2% 3.25 g	YES
Vehicle Trajectory			The vehicle rebounded within the exit box. (Answer Yes or No)	Yes	Yes		YES



- Test Agency: MwRSF
- Test Number: 2214WB-2
- Date: 4/8/05
- NCHRP 350 Update Test Designation: 3-11
- Appurtenance: Modified G4(1S) Guardrail
- Total Length: 53.34 m
- Key Elements - Steel W-Beam
  - Thickness: 2.66 mm
  - Top Mounting Height: 706 mm
- Key Elements - Steel Posts
  - Post Nos. 3 - 27: W152x13.4 by 1,829 mm long
  - Spacing: 1,905 mm
- Key Elements - Wood Posts
  - Post Nos. 1 - 2, 28 - 29 (BCT): 140 mm x 190 mm by 1,080 mm long
- Key Elements - Steel Foundation Tube: 1,524 mm long with soil plate
- Key Elements - Wood Spacer Blocks
  - Post Nos. 3 - 27: 152 mm x 203 mm by 362 mm long
- Type of Soil: Grading B - AASHTO M 147-65 (1990)
- Test Vehicle
  - Type/Designation: 2270P
  - Make and Model: 2002 Dodge Ram 1500 Quad Cab Pickup
  - Curb: 2,321 kg
  - Test Inertial: 2,268 kg
  - Gross Static: 2,268 kg
- Impact Conditions
  - Speed: 100.4 km/h
  - Angle: 25.8 degrees
  - Impact Location: 940 mm upstream centerline post no. 11
- Exit Conditions
  - Speed: 50.2 km/h
  - Angle: 20.7 degrees
  - Exit Box Criterion: Pass
- Post-Impact Trajectory
  - Vehicle Stability: Satisfactory
  - Stopping Distance: 36.84 m downstream
    Against traffic-side face
- Occupant Impact Velocity (350 Update)
  - Longitudinal: 5.38 m/s < 12 m/s
  - Lateral: 3.99 m/s < 12 m/s
- Occupant Ridedown Deceleration (350 Update)
  - Longitudinal: -6.92 Gs < 20 Gs
  - Lateral: 6.61 Gs < 20 Gs
- THIV (not required): 6.91 m/s
- PHD (not required): 8.19 Gs
- Test Article Damage: Moderate
- Test Article Deflections
  - Permanent Set: 845 mm
  - Dynamic: 1,196 mm
  - Working Width: 1,395 mm
- Vehicle Damage: Moderate
  - VDS[5]: 1-RFQ-4
  - CDC[6]: 1-RFEN3
  - Maximum Deformation: 13 mm at front floorpan

Figure 15. Summary of Test Results and Sequential Photographs, Test 2214WB-2

Figure 5: Full-Scale Test Summary

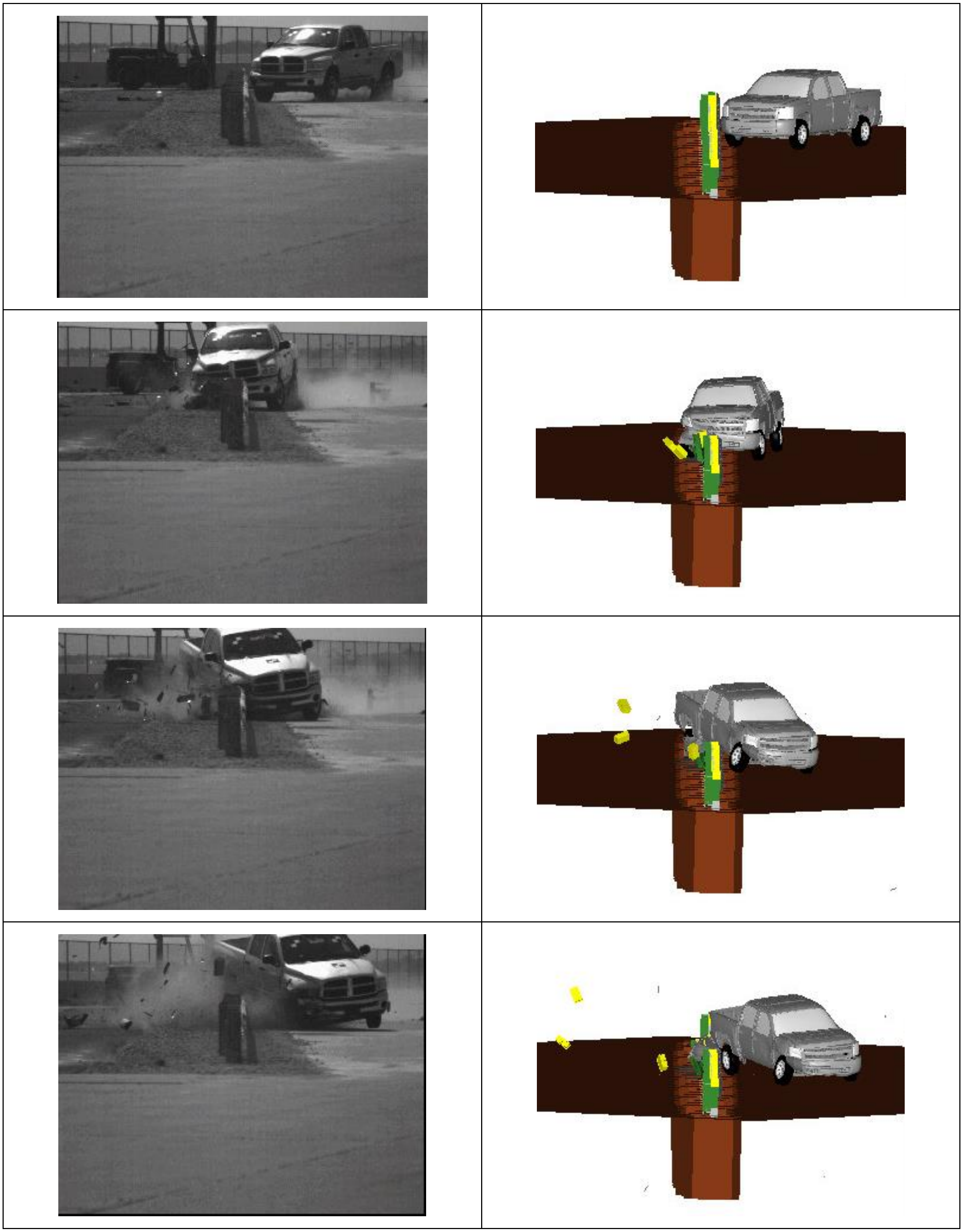


Figure 6a: Sequential Comparisons – Front View

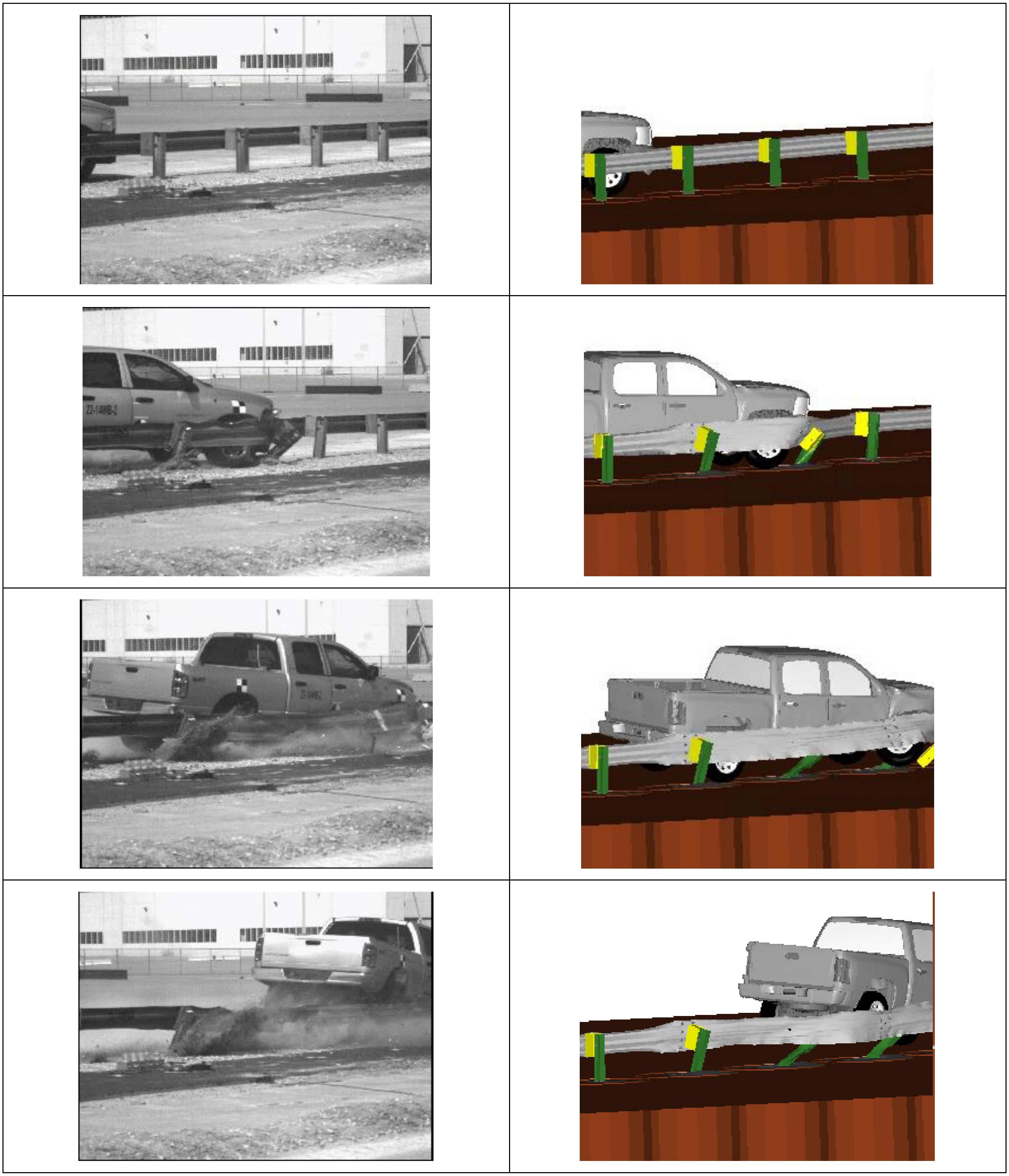


Figure 6b: Sequential Comparisons – Rear View

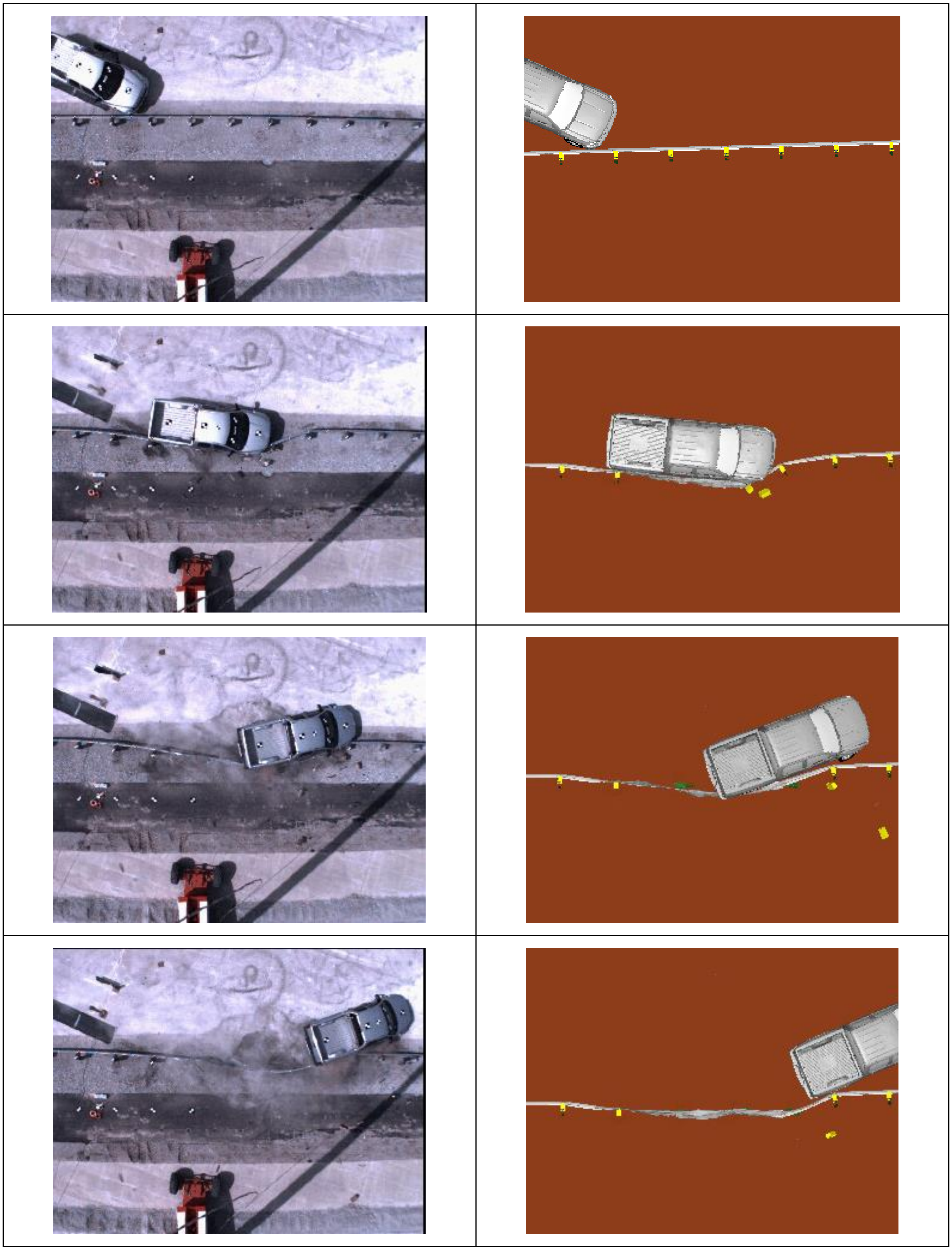


Figure 6c: Sequential Comparisons – Top View

Project: CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections
Comparison Case: 2270P (Pickup Truck) with G41S Barrier

Table F - Composite Verification and Validation Summary:

List the Report MASH08 Test Number		
Table C – Analysis Solution Verification s	Did all solution verification criteria in table pass?	YES
Table D - RSVVP Results	Do all the time history evaluation scores from the single channel factors result in a satisfactory comparison (i.e., the comparison passes the criterion)?	NO
	If all the values for Single Channel comparison did not pass, did the weighted procedure result in an acceptable	YES
Table E - Roadside Safety Phenomena Importance Ranking Table	Did all the critical criteria in the PIRT Table pass? Note: Tire deflation was observed in the test but not in the simulation. This due to the fact that tire deflation in not incorporated in the model. This is considered not to have a critical effect on the outcome of the test	YES
Overall	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	YES

NOTES:
(none)

Appendix F-3: MGS Barrier Impact with 2270P Vehicle

CCSA VALIDATION/VERIFICATION REPORT

Project: CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections
Comparison Case: 2270P (Pickup Truck) with MGS Barrier
Impact Description: 25.5 degree impact into barrier at 101.1 km/h (62.82 mph)
Governing Criteria: MASH TL-3
Report Date: March 2013

Table A – Information Sources:

General Information	Known Solution	Analysis Solution
Performing Organization	MwRSF	CCSA-GWU
Test/Run Number	TRP-03-171-06	s130411a
Vehicle	Dodge Ram 1500 Quad Cab	Silverado C
Vehicle Mass (lb/kg)	5000 / 2268	4918 / 2231
Impact Speed (mph/kph)	62.82 / 101.1	62.82 / 101.1
Impact Angle (degrees)	25.5	25.5

Table B - Evaluation Parameters Summary:

Category	Subset	Values
Evaluation Method	MASH (V1, 2009)	
Hardware Type	Longitudinal	
Test Number	3-11	
Test Vehicle	2270C	
Criterion to be Applied	**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.
	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.
		F - The vehicle should remain upright during and after the collision although moderate roll, pitching and yawing are
		H - 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.
		I - Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.
	Vehicle Trajectory	For redirective devices the vehicle shall exit within the prescribed box.

Project: CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections
Comparison Case: 2270P (Pickup Truck) with MGS Barr

Table C – Analysis Solution Verification Summary

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.	1.07%	YES
Hourglass Energy of the analysis solution at the end of the run is less than 5 % of the total initial energy at the beginning of the run	< 1%	YES
The part/material with the highest amount of hourglass energy at any time during the run is less than 5 % of the total initial energy at the beginning of the run.	< 1%	YES
Mass added to the total model is less than 5 % the total model mass at the start of the run.	< 1%	YES
The part/material with the most mass added had less than 10 % of its initial mass added.	< 1%	YES
The moving parts/materials in the model have less than 5 % of mass added to the initial moving mass of the model.	< 1%	YES
There are no shooting nodes in the solution?	NA	YES
There are no solid elements with negative volumes?	NA	YES

Table D - RSVVP Results

Single Channel Time History Comparison Results		Time interval [0 sec - 0.67		
O	*Sprauge-Geer Metrics*	**M**	**P**	**Pass?**
	X acceleration	45	40	NO
	Y acceleration	13.2	27.6	YES
	Z acceleration	146.8	45.4	NO
	Yaw rate	13.4	11.7	NO
	Roll rate	9.6	52.7	NO
	Pitch rate	251.3	48	YES
P	*ANOVA Metrics*	**Mean**	**SD**	**Pass?**
	X acceleration/Peak	-1.92	39.08	NO
	Y acceleration/Peak	5.81	35.92	NO
	Z acceleration/Peak	1.09	65.76	NO
	Yaw rate	0.79	20.97	NO
	Roll rate	10.04	51.73	NO
	Pitch rate	1.45	119.09	YES

Multi-Channel Weighting Factors		Time interval [0 sec; 0.67
Multi-Channel Weighting Method Peaks Area I Area II Inertial	**X Channel**	0.206777873
	Y Channel	0.275396472
	Z Channel	0.017825655
	Yaw Channel	0.441018937
	Roll Channel	0.032383125
	Pitch Channel	0.026597937

Sprauge-Geer Metrics	**M**	**P**	**Pass?**
All Channels (weighted)	28.5	24.8	YES
ANOVA Metrics	**Mean**	**SD**	**Pass?**
All Channels (weighted)	1.9	33.2	YES

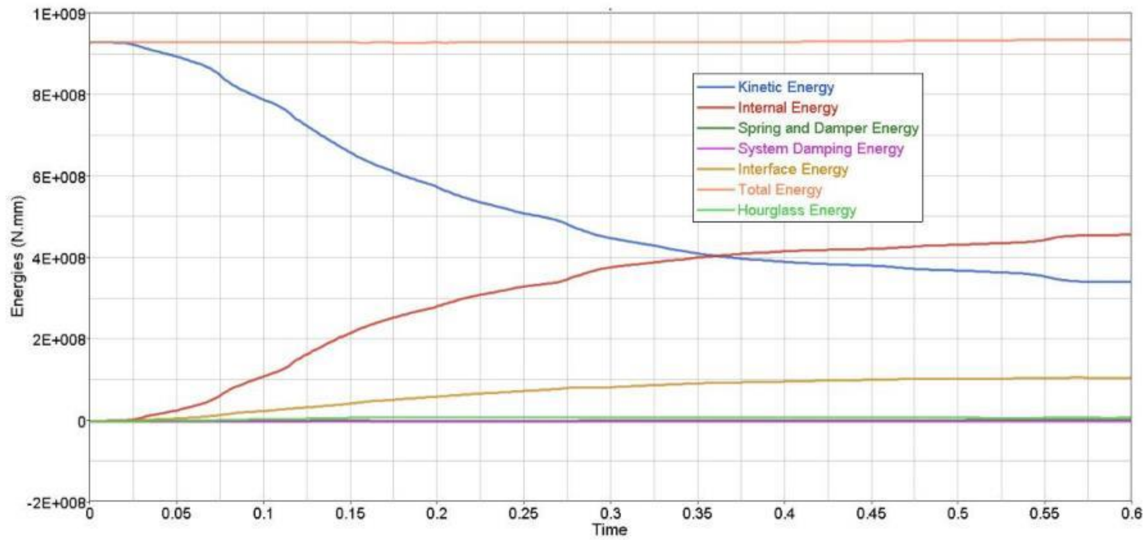


Figure 1: Simulations Energies

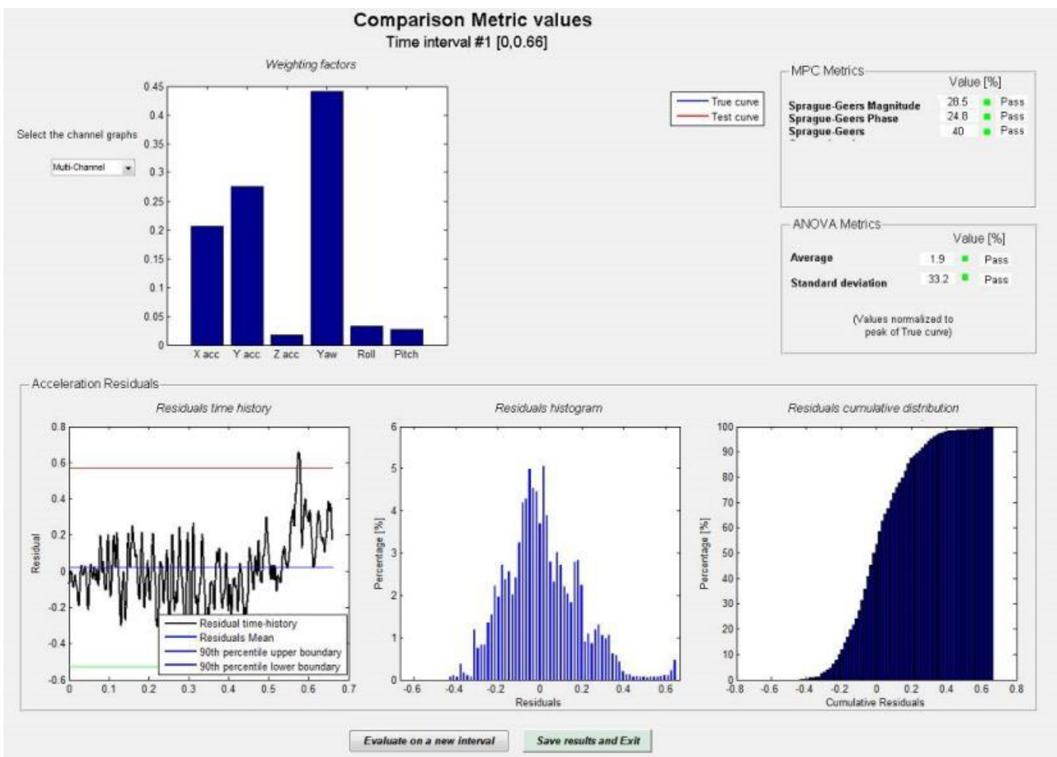


Figure 2a: RSVVP Results – All Channels

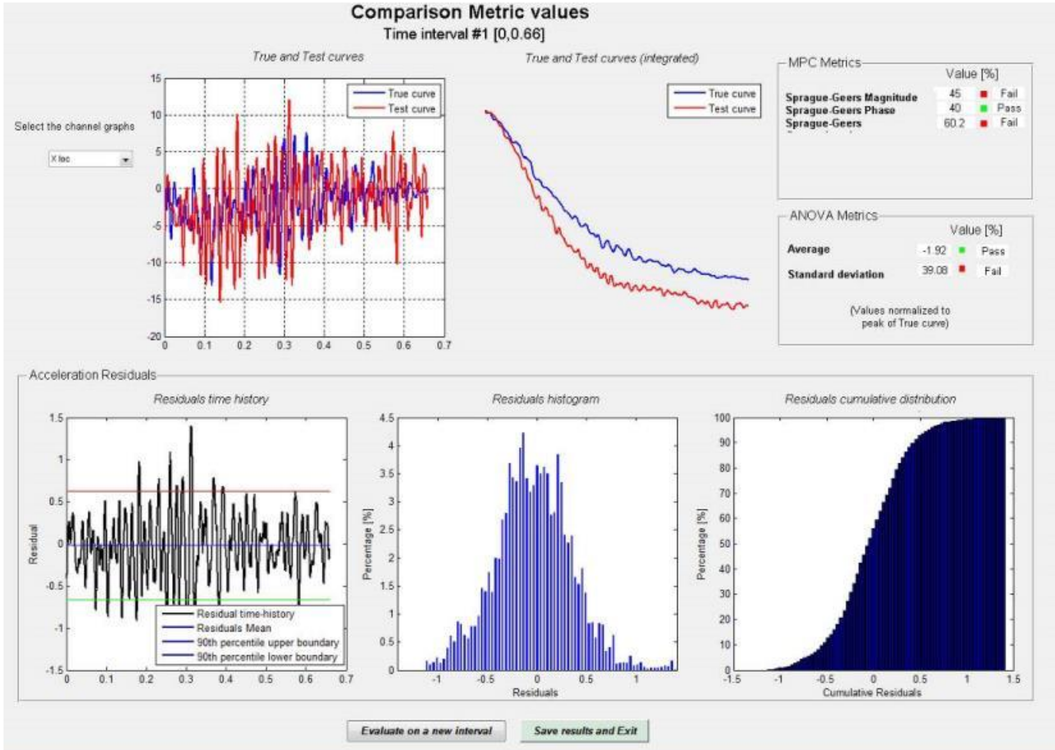


Figure 2b: RSVVP Results – Longitudinal Acceleration

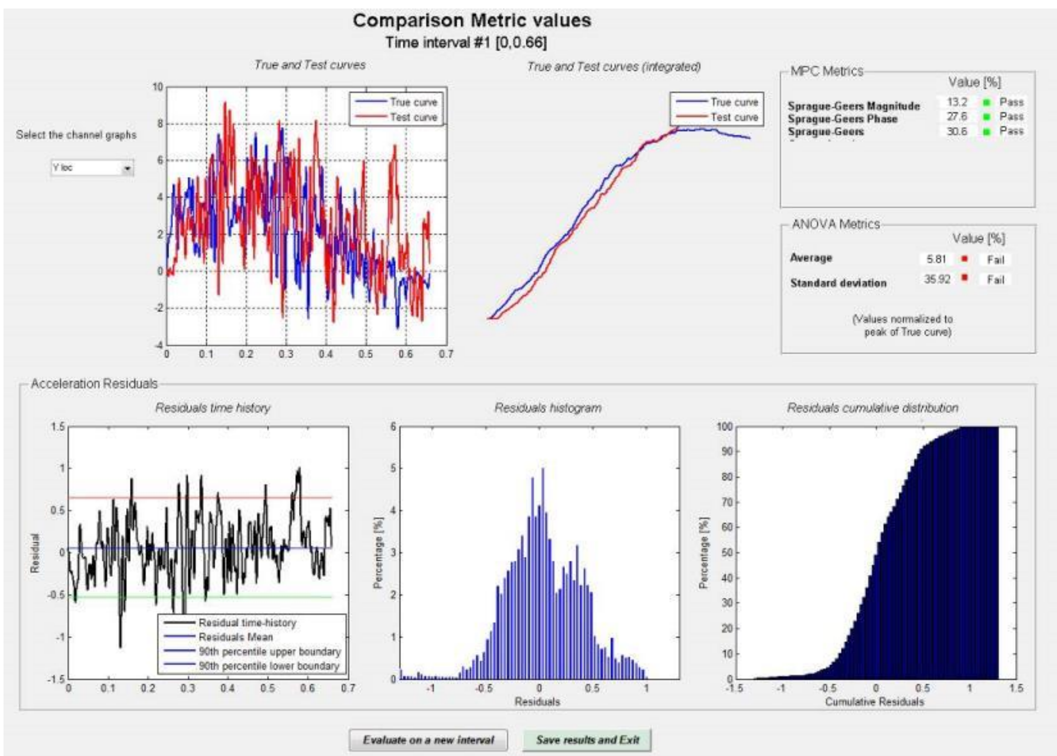


Figure 2c: RSVVP Results – Lateral Acceleration

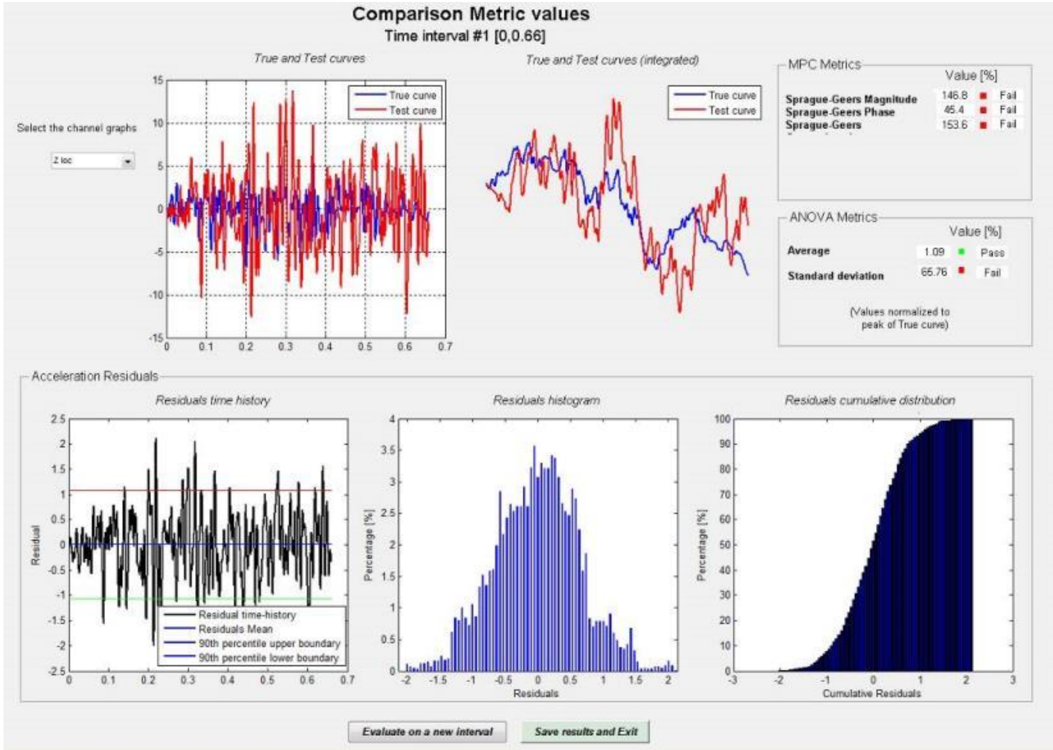


Figure 2d: RSVVP Results – Vertical Acceleration

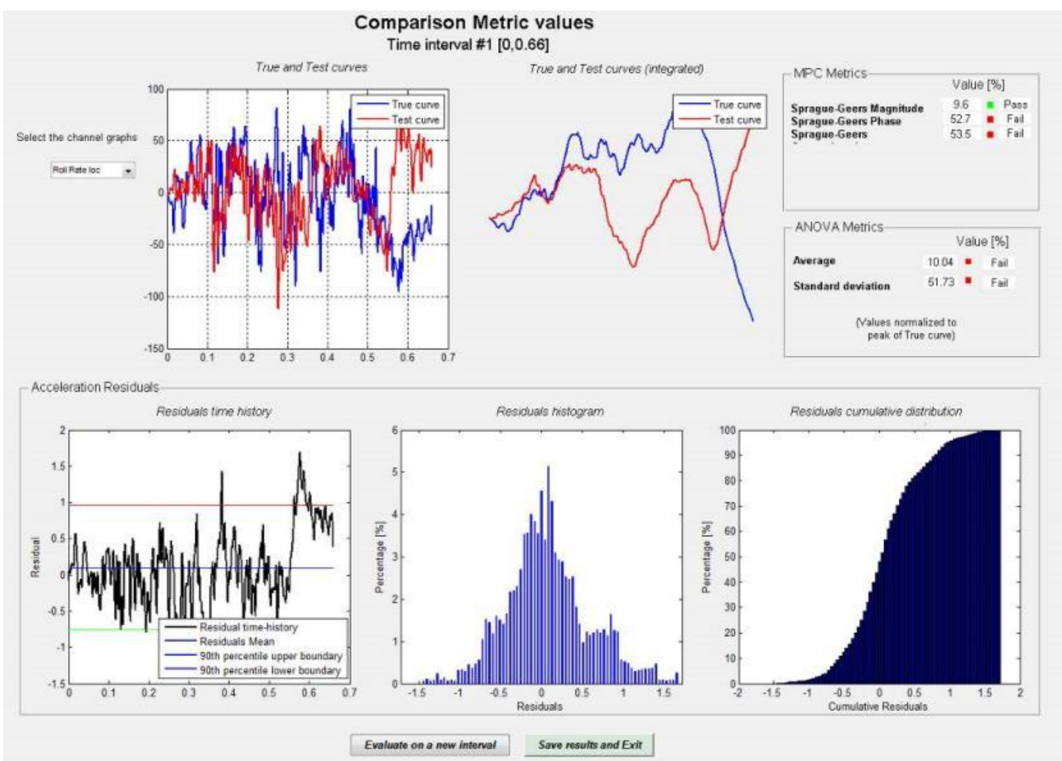


Figure 2e: RSVVP Results – Roll Angle

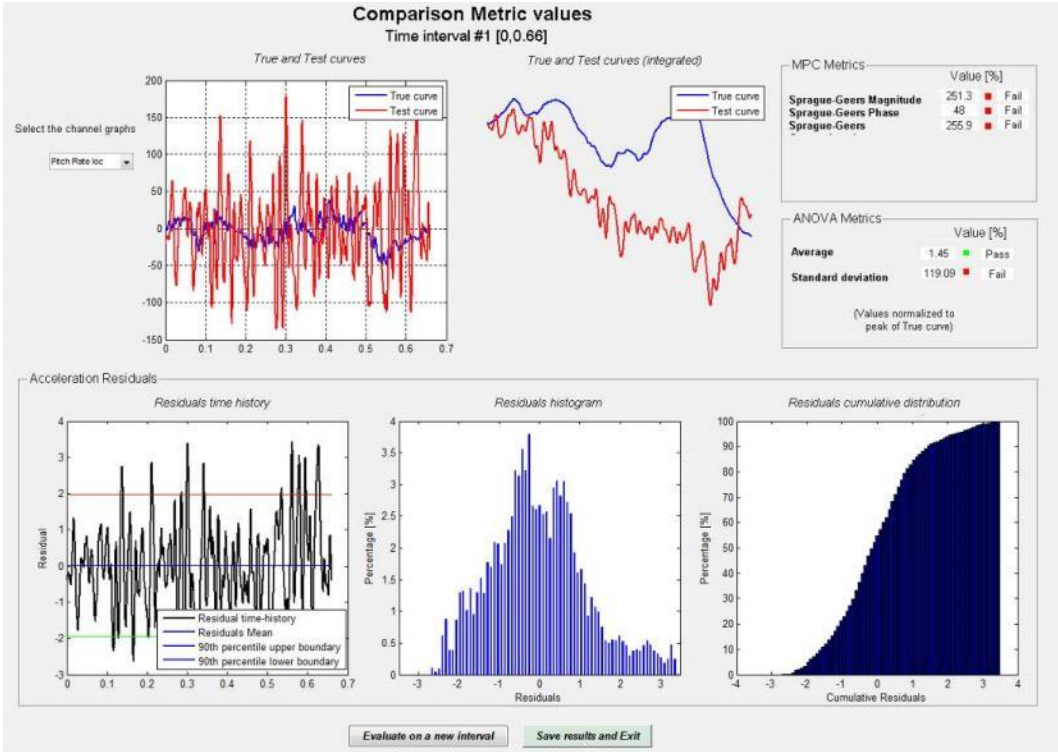


Figure 2f: RSVVP Results – Pitch Angle

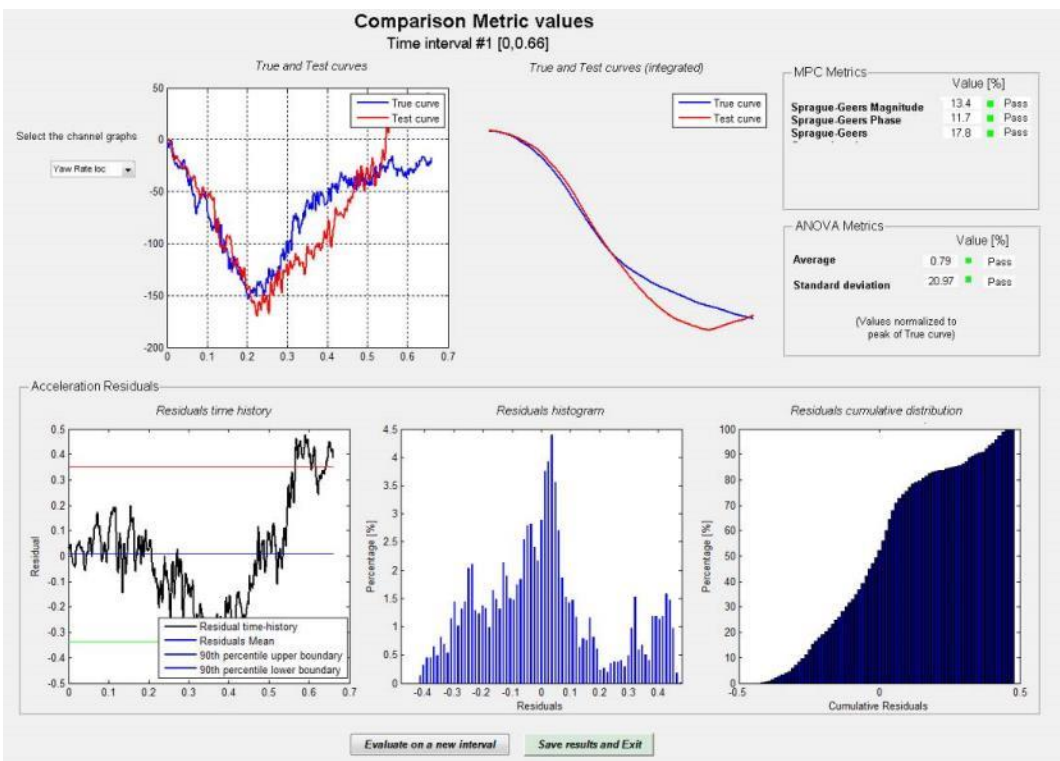


Figure 2g: RSVVP Results – Yaw Angle

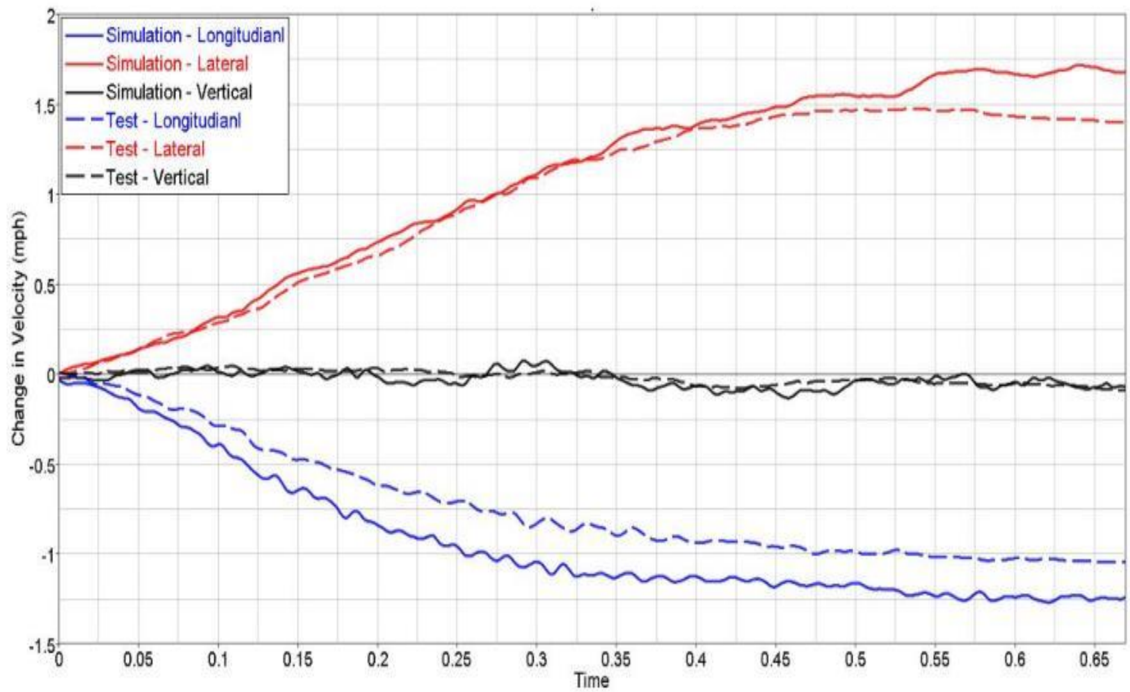


Figure 3: Change in Vehicle Velocities

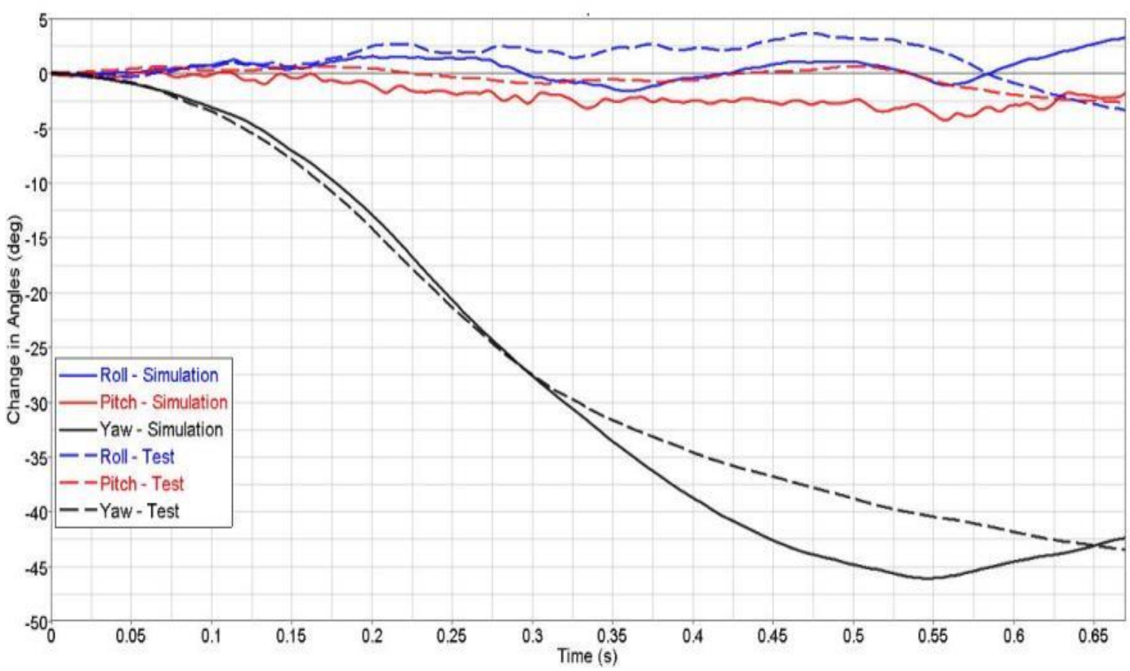


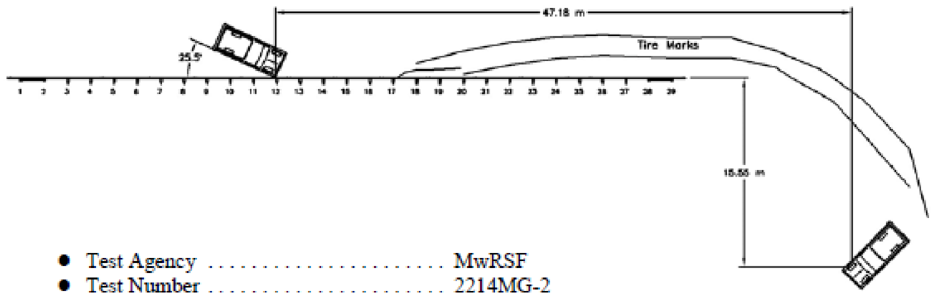
Figure 4: Change in Vehicle Angle

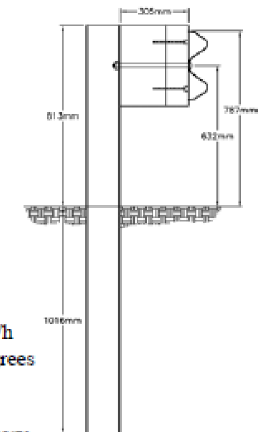
CCSA VALIDATION/VERIFICATION REPORT

Project: CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections
Comparison Case: 2270P (Pickup Truck) with MGS Barrier

Table E - Roadside Safety Phenomena Importance Ranking Table (MASH Evaluation)

Evaluation Criteria				Known Result	Analysis Result	Relative Diff. (%)	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.	Yes	Yes		YES
		A2	The relative difference in the maximum dynamic deflection is less than 20 percent.	1.11 m	1.03 m	7%	YES
		A3	The relative difference in the time of vehicle-barrier contact is less than 20 percent.	0.72 s	0.63 s	12%	
		A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	3	3		YES
		A5	Barrier did not fail (Answer Yes or No).	Yes	Yes		YES
		A6	There were no failures of connector elements (Answer Yes or No).	Yes	Yes		YES
		A7	There was no significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	Yes	Yes		YES
		A8	There was no significant snagging between vehicle body components and barrier elements (Answer Yes or No).	Yes	Yes		YES
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. The maximum pitch & roll angles are not to exceed 75 degrees.	Yes	Yes		YES
		F2	Maximum vehicle roll – relative difference is less than 20% or absolute difference is less than 5 degrees.	3.58 (.68s)	3.49 (.68s)	3% 0.09 deg	YES
		F3	Maximum vehicle pitch – relative difference is less than 20% or absolute difference is less than 5 deg.	2.86 (.68s)	4.17 (.68s)	31.4% 1.31 deg	YES
		F4	Maximum vehicle yaw – relative difference is less than 20% or absolute difference is less than 5 deg.	43.74 (.68s)	46.01 (.68s)	4.9% 2.27 deg	YES
	H	H1	Longitudinal & lateral occupant impact velocities (OIV) should fall below the preferred value of 30 ft/s (9.1 m/s), or at least below the maximum allowed value of 40 ft/s (12.2 m/s)	Yes	Yes		YES
		H2	Longitudinal OIV (m/s) - Relative difference is less than 20%t or absolute difference is less than 2 m/s	4.67	5.59	16.4% 0.92 m/s	YES
		H3	Lateral OIV (m/s) - Relative difference is less than 20% or absolute difference is less than 2 m/s	4.76	5.09	6.5% 0.33 m/s	YES
	I	I1	Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.	Yes	Yes		YES
		I2	Longitudinal ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	8.23	12.10	31.9% 3.87 g	YES
		I3	Lateral ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	6.93	9.68	28.4% 2.75 g	YES
Vehicle Trajectory			The vehicle rebounded within the exit box. (Answer Yes or No)	Yes	Yes		YES





- Test Agency .... MwRSF
- Test Number 2214MG-2
- Date 10/6/04
- NCHRP 350 Update Test Designation .. 3-11
- Appurtenance .... Midwest Guardrail System
- Total Length .... 55.25 m
- Key Elements - Steel W-Beam
  - Thickness .... 2.66 mm
  - Top Mounting Height .... 787 mm
- Key Elements - Steel Posts
  - Post Nos. 3 - 27 .... W152x13.4 by 1,829 mm long
  - Spacing .... 1,905 mm
- Key Elements - Wood Posts
  - Post Nos. 1 - 2, 28 - 29 (BCT) .... 140 mm x 190 mm by 1,080 mm long
- Key Elements - Steel Foundation Tube . 1,829 mm long
- Key Elements - Wood Spacer Blocks
  - Post Nos. 3 - 27 .... 152 mm x 305 mm by 362 mm long
- Type of Soil .... Grading B - AASHTO M 147-65 (1990)
- Test Vehicle
  - Type/Designation 2270P
  - Make and Model .... 2002 Dodge Ram 1500 Quad Cab Pickup
  - Curb .... 2,292 kg
  - Test Inertial .... 2,268 kg
  - Gross Static .... 2,268 kg
- Impact Conditions
  - Speed .... 101.1 km/h
  - Angle .... 25.5 degrees
  - Impact Location .... 5.25 m upstream splice between posts 14 & 15
- Exit Conditions
  - Speed .... 63.7 km/h
  - Angle .... 13.5 degrees
  - Exit Box Criterion .... Pass
- Post-Impact Trajectory
  - Vehicle Stability .... Satisfactory
  - Stopping Distance .... 47.18 m downstream
15.56 m laterally behind
- Occupant Impact Velocity (350 Update)
  - Longitudinal .... 4.67 m/s < 12 m/s
  - Lateral .... 4.76 m/s < 12 m/s
- Occupant Ridedown Deceleration (350 Update)
  - Longitudinal .... 8.23 Gs < 20 Gs
  - Lateral .... 6.93 Gs < 20 Gs
- THIV (not required) .... 6.91 m/s
- PHD (not required) .... 10.76 Gs
- Test Article Damage .... Moderate
- Test Article Deflections
  - Permanent Set .... 803 mm
  - Dynamic .... 1,114 mm
  - Working Width .... 1,234 mm
- Vehicle Damage .... Moderate
  - VDS[5] 1-RFQ-4
  - CDC[6] 1-RYEN2
  - Maximum Deformation .... 19 mm at right-center floorpan

Figure 14. Summary of Test Results and Sequential Photographs, Test 2214MG-2

30

Figure 5: Full-Scale Test Summary

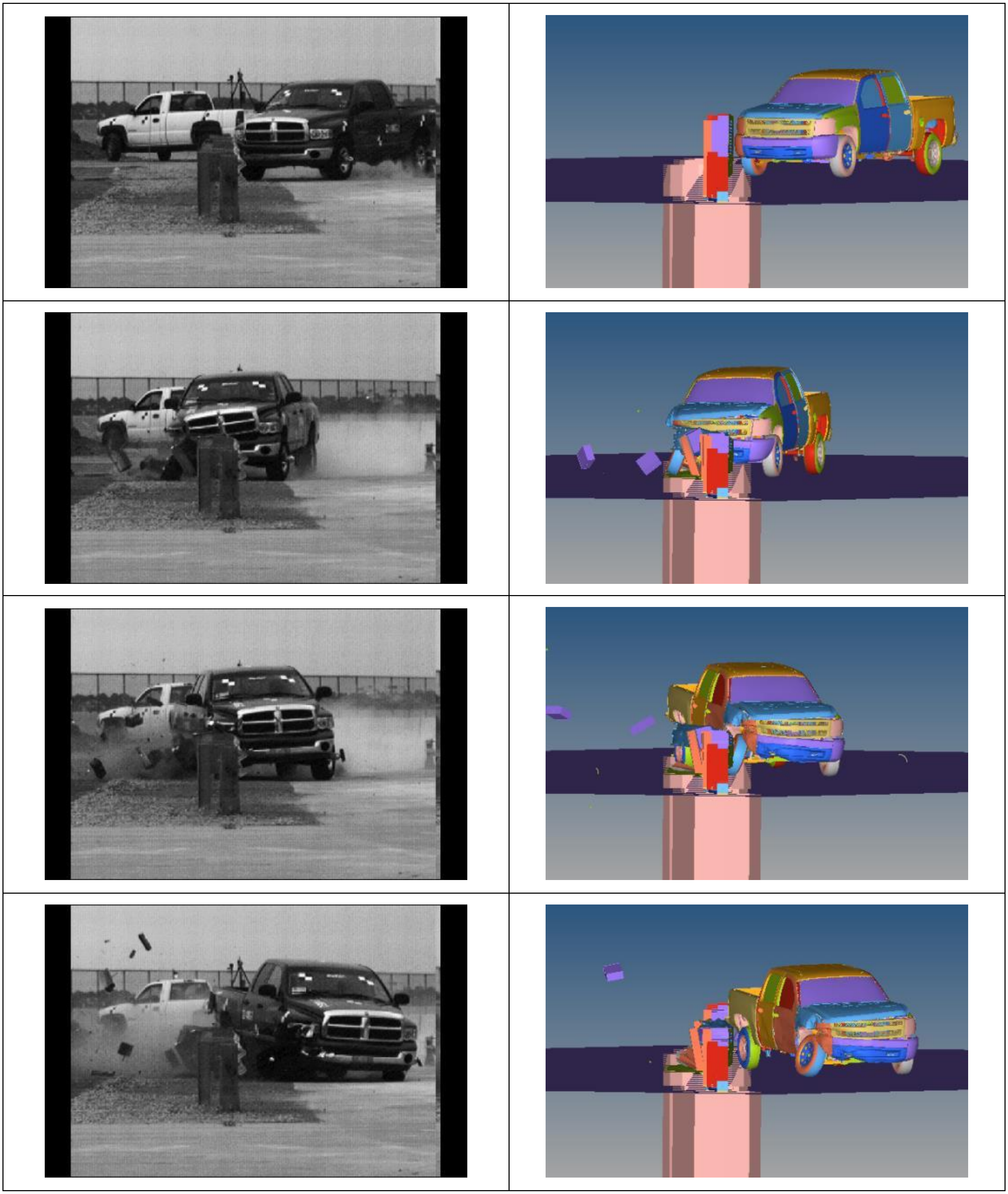


Figure 6a: Sequential Comparisons – Front View

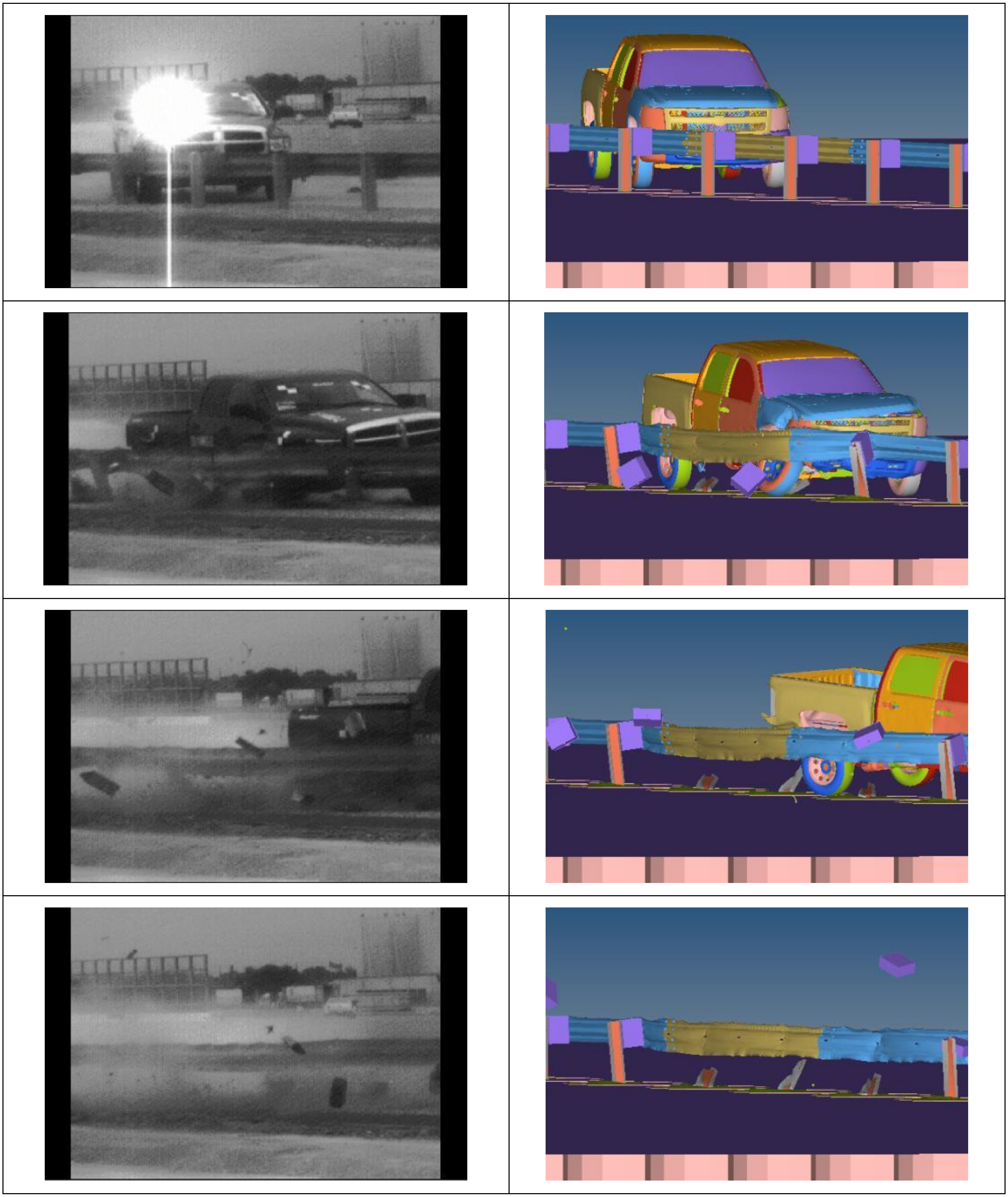


Figure 6b: Sequential Comparisons – Rear View

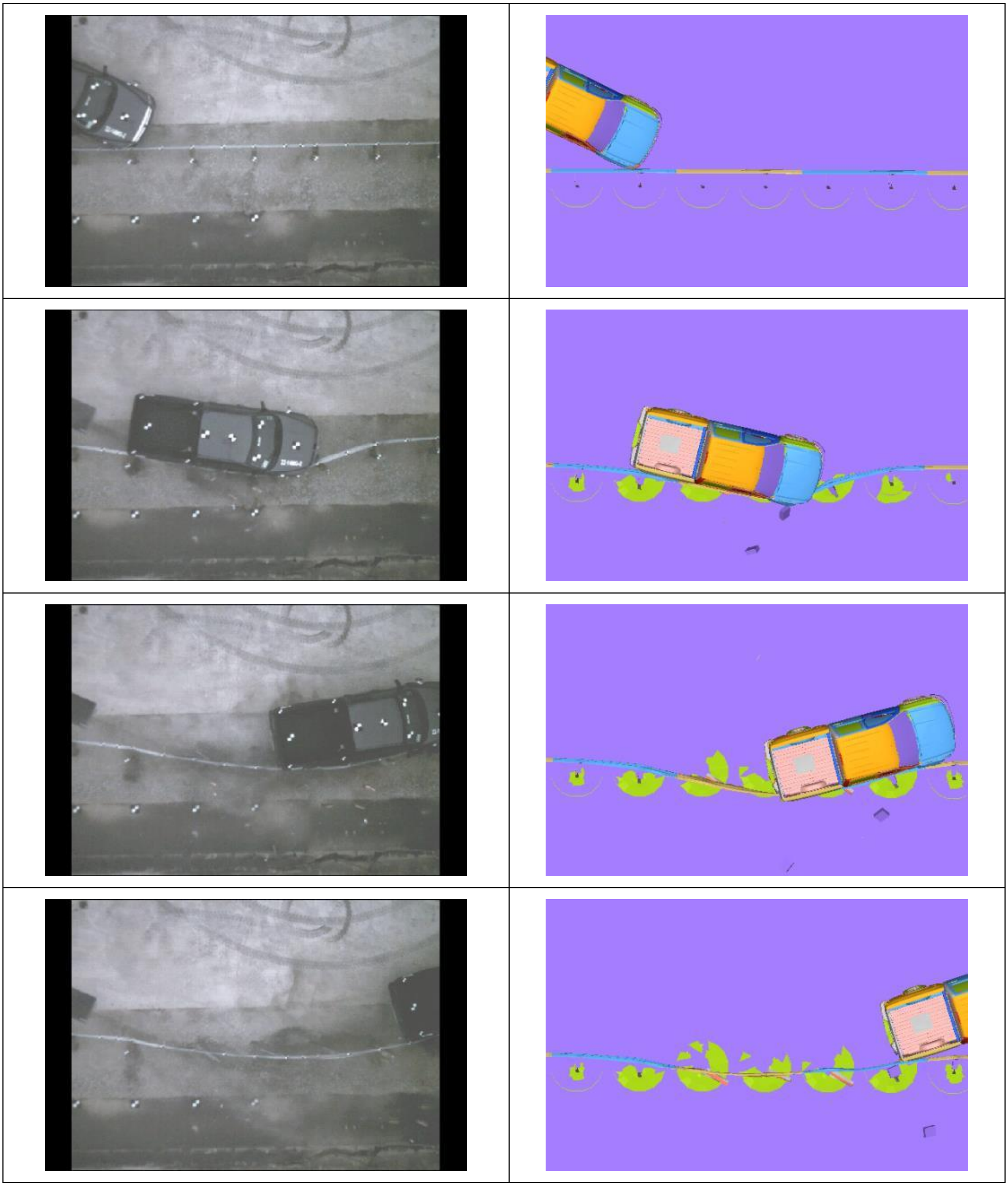


Figure 6c: Sequential Comparisons – Top View

Project: CCSA Longitudinal Barriers on Curved, Superelevated Roadway Sections

Comparison Case: 2270P (Pickup Truck) with MGS Barrier

Table F - Composite Verification and Validation Summary:

List the Report MASH08 Test Number		
Table C – Analysis Solution Verification Summary	Did all solution verification criteria in table pass?	**YES**
Table D - RSVVP Results	Do all the time history evaluation scores from the single channel factors result in a satisfactory comparison (i.e., the comparison passes the criterion)?	**NO**
	If all the values for Single Channel comparison did not pass, did the weighted procedure result in an acceptable comparison.	**YES**
Table E - Roadside Safety Phenomena Importance Ranking Table	Did all the critical criteria in the PIRT Table pass? Note: Tire deflation was observed in the test but not in the simulation. This due to the fact that tire deflation in not incorporated in the model. This is considered not to have a critical effect on the outcome of the test	**YES**
Overall	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.	**YES**

NOTES:

(none)

Appendix F

Sequential Views for MASH Test 4-10 for

Curb-Mounted S3-TL4 Bridge Rail

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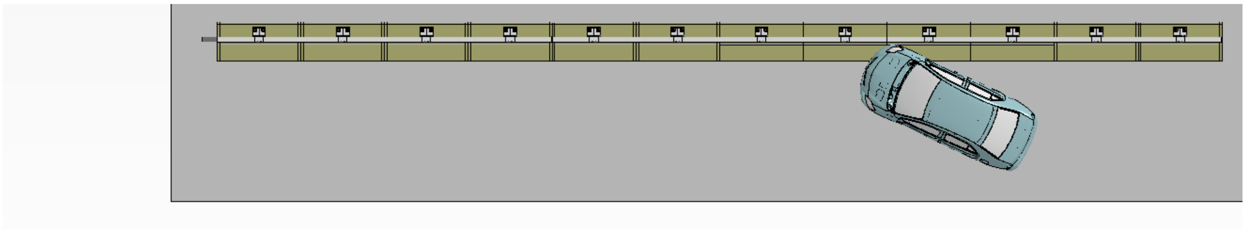

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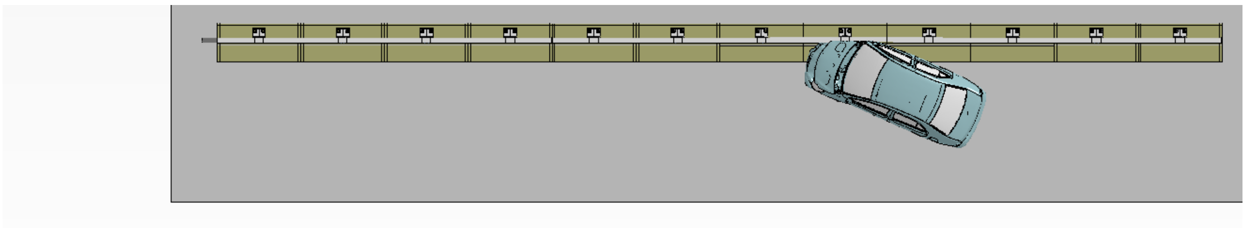

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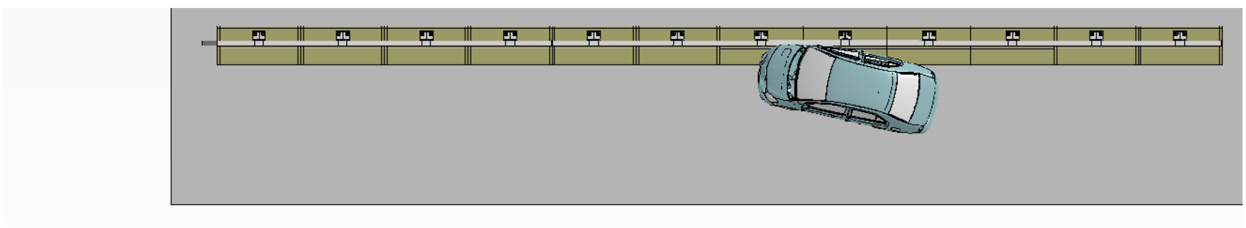

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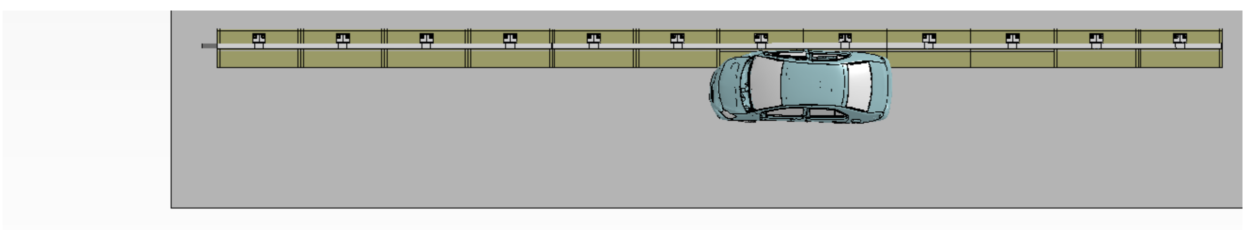

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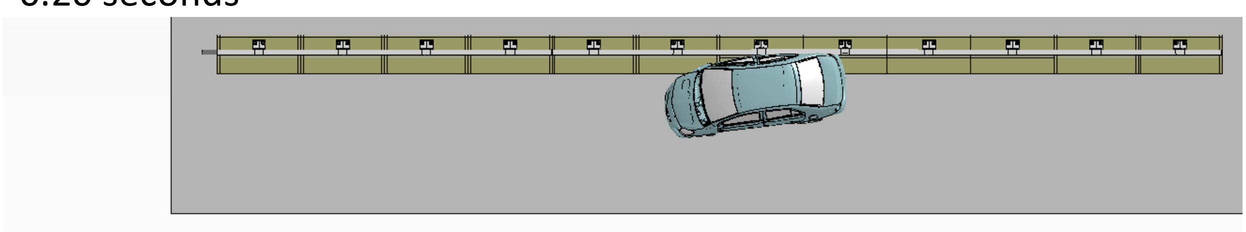

Figure F-1. Sequential views from analysis of MASH Test 4-10 for curb-mounted S3-TL4 from an overhead viewpoint.

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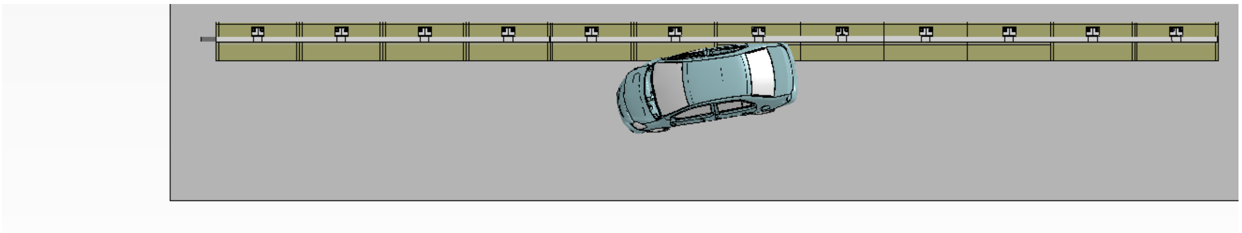

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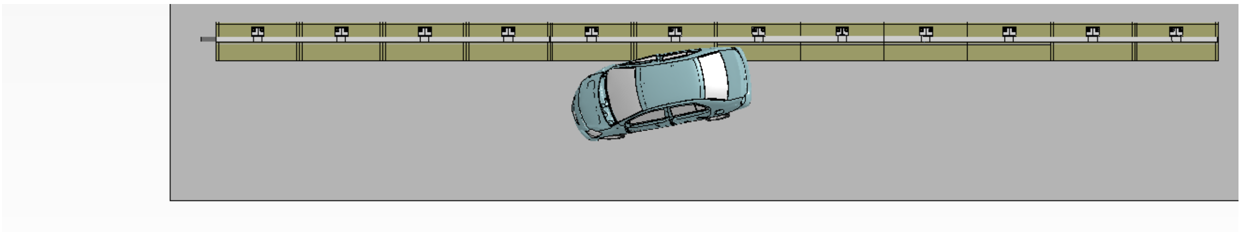

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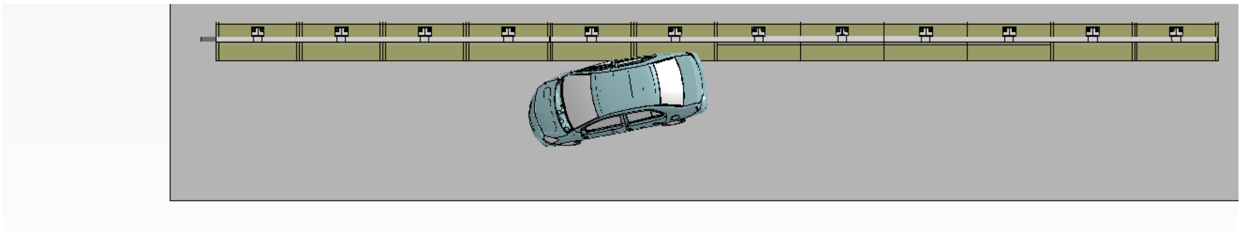

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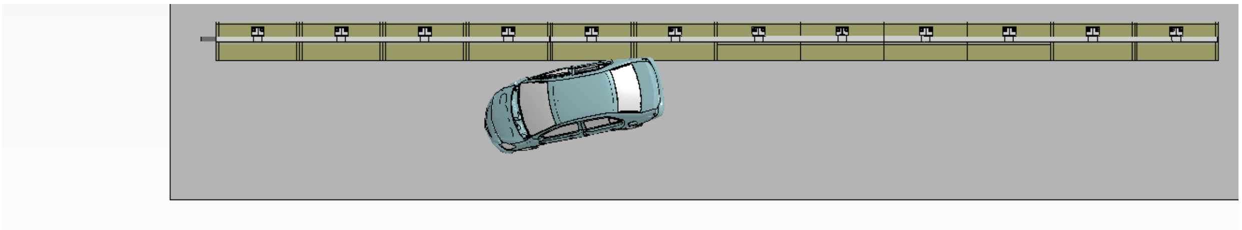

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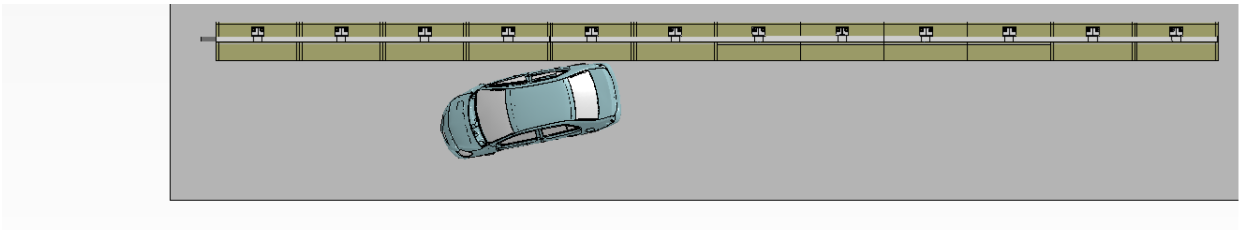

Figure F-1. [Continued] Sequential views from analysis of MASH Test 4-10 for curb-mounted S3-TL4 from an overhead viewpoint.

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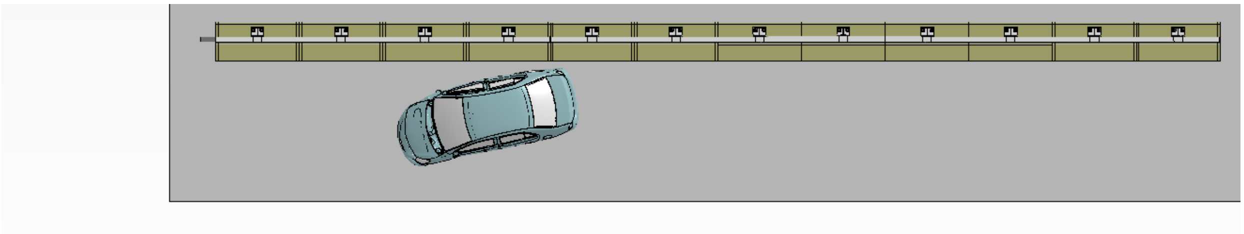

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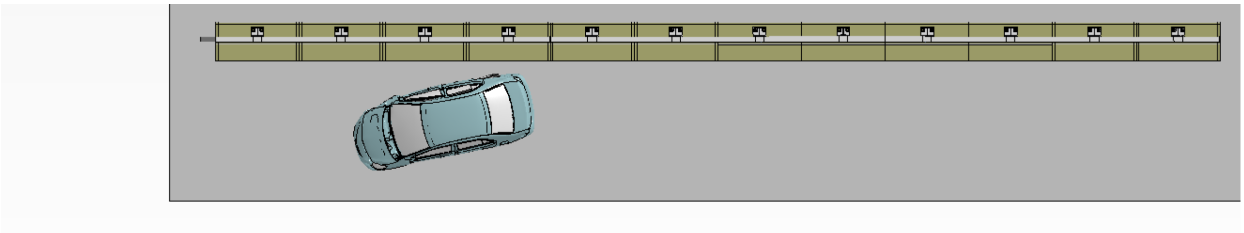

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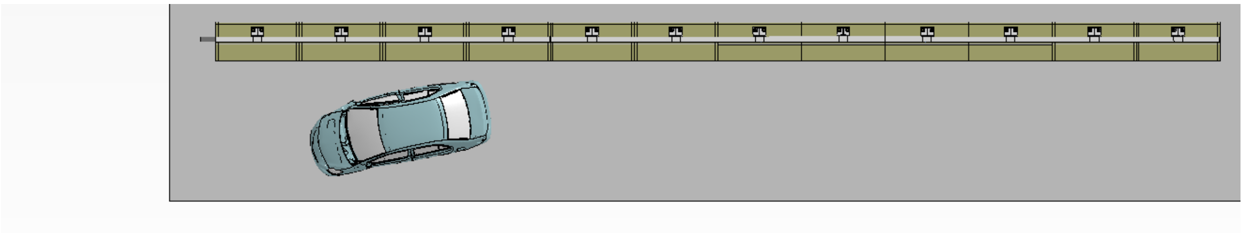

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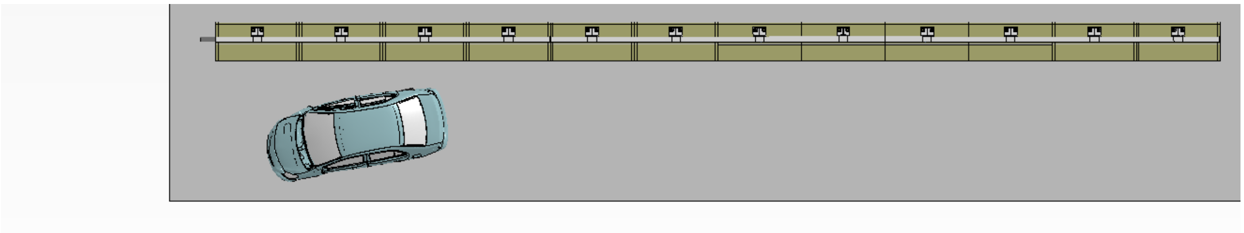

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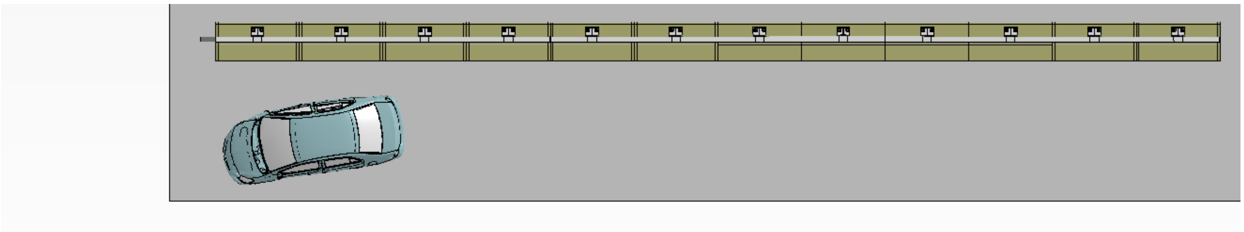

Figure F-1. [Continued] Sequential views from analysis of MASH Test 4-10 for curb-mounted S3-TL4 from an overhead viewpoint.

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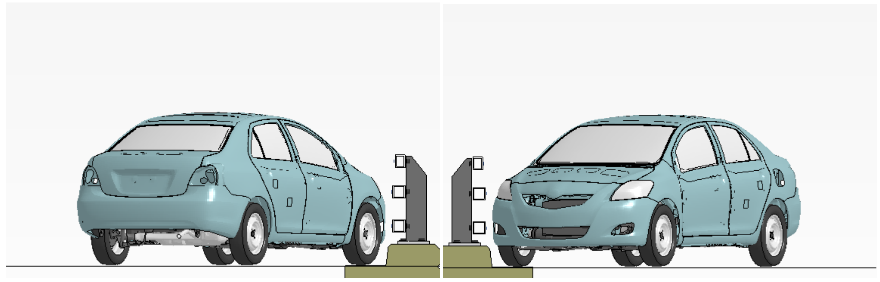

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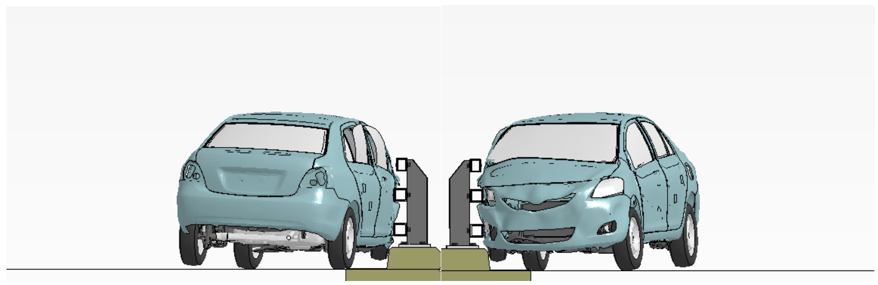

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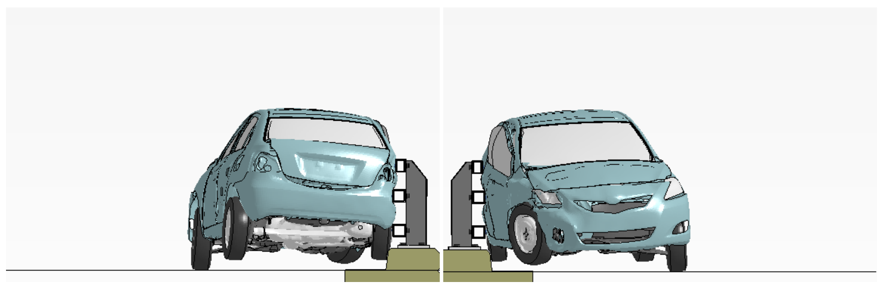

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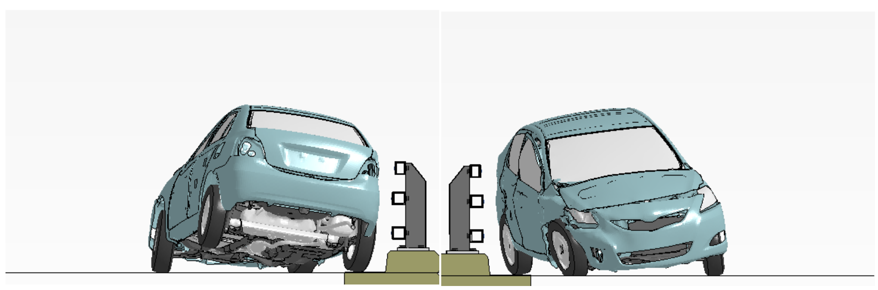

Figure F-2. Sequential views from analysis of MASH Test 4-10 for curb-mounted S3-TL4 from upstream and downstream viewpoints.

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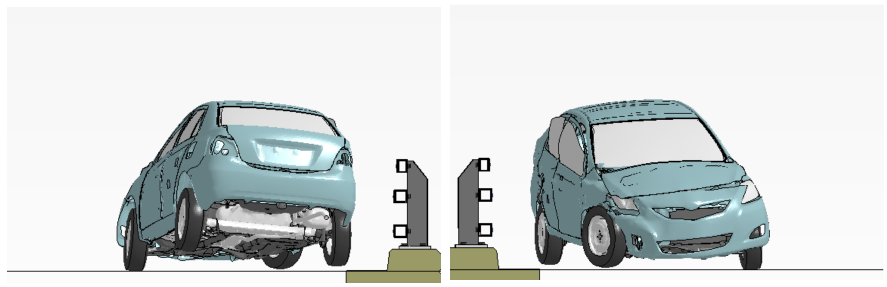

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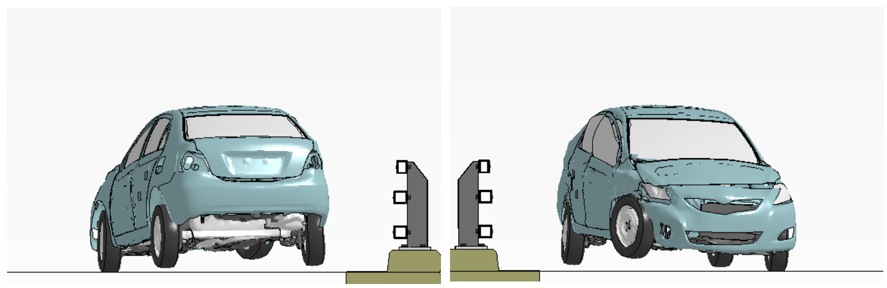

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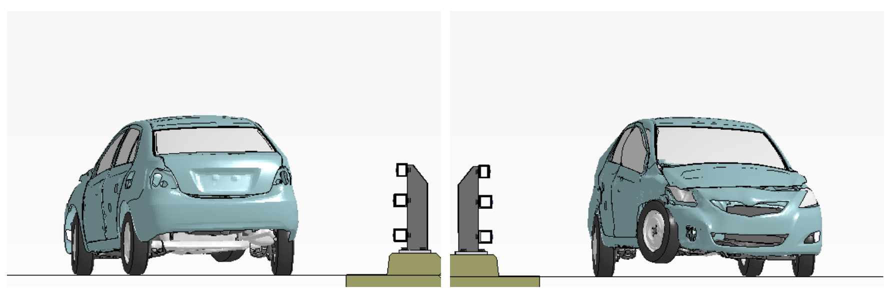

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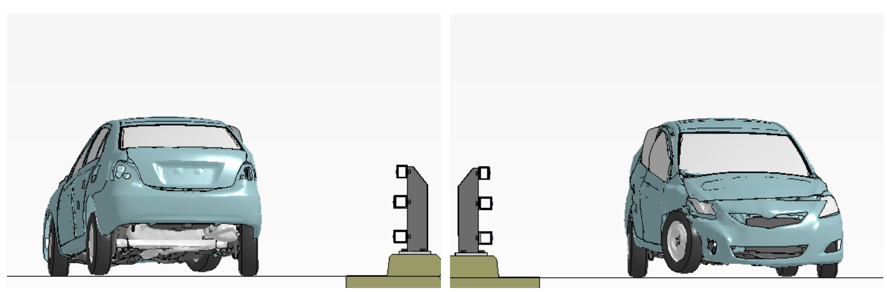

Figure F-2. [Continued] Sequential views from analysis of MASH Test 4-10 for curb-mounted S3-TL4 from upstream and downstream viewpoints.

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0.90 seconds

1.00 seconds

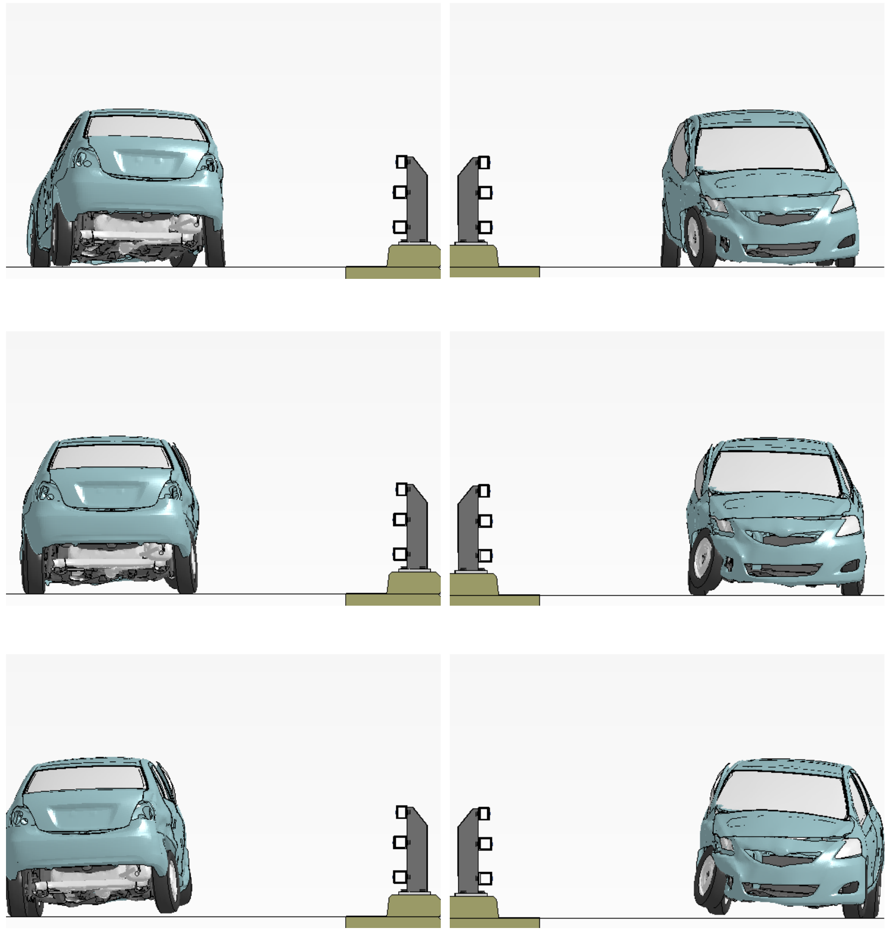

Figure F-2. [Continued] Sequential views from analysis of MASH Test 4-10 for curb-mounted S3-TL4 from upstream and downstream viewpoints.

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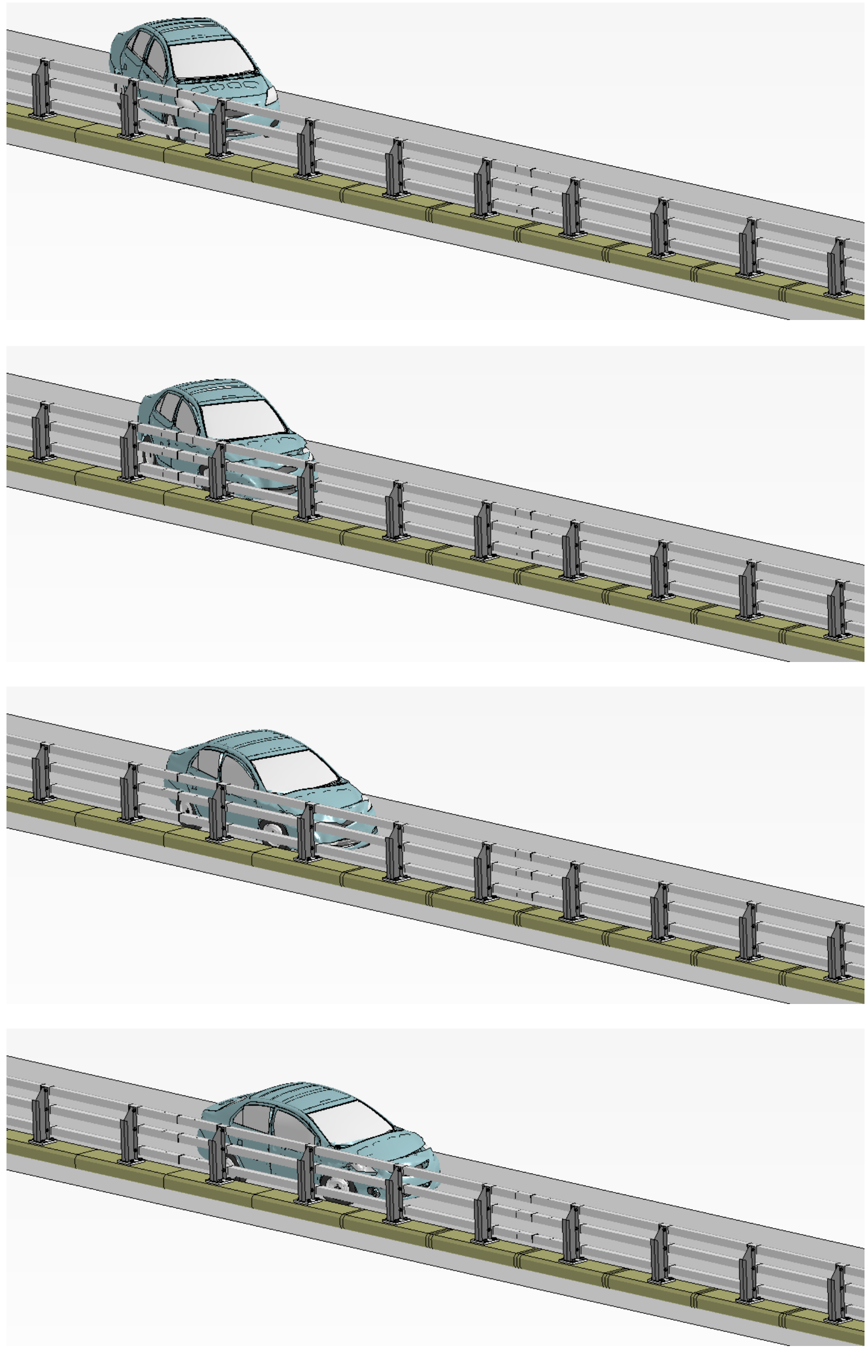

Figure F-3. Sequential views from analysis of MASH Test 4-10 for curb-mounted S3-TL4 from an oblique viewpoint.

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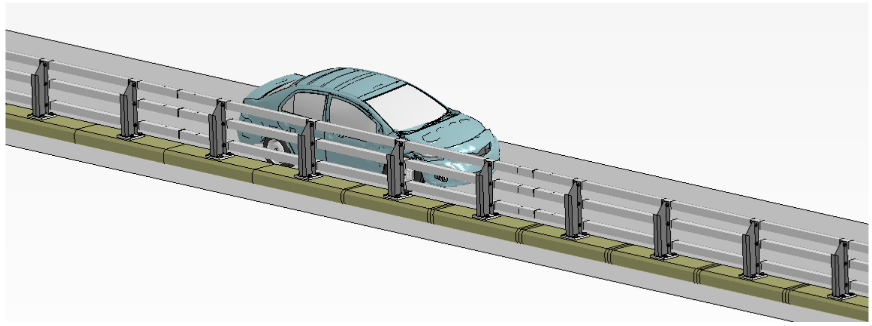

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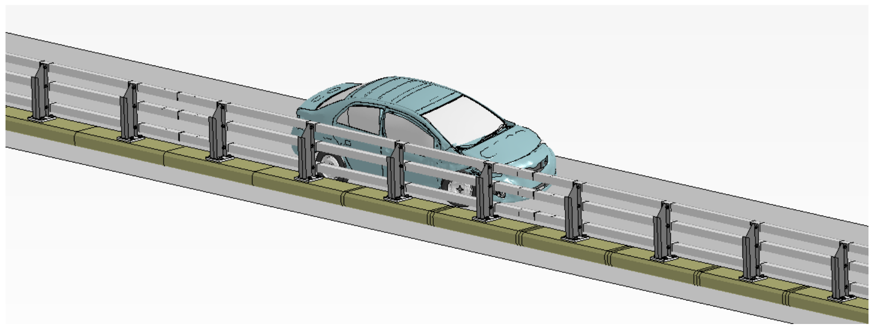

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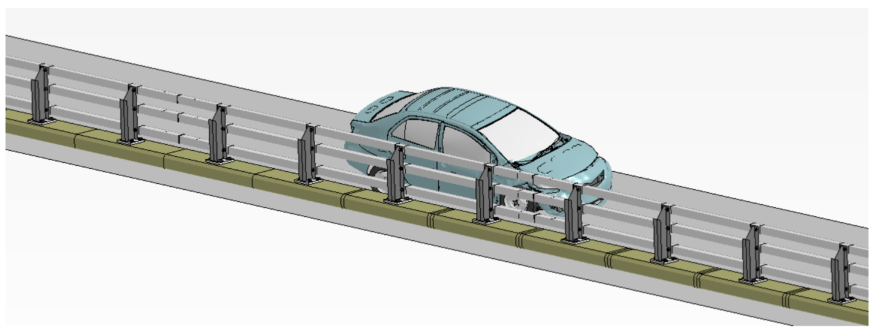

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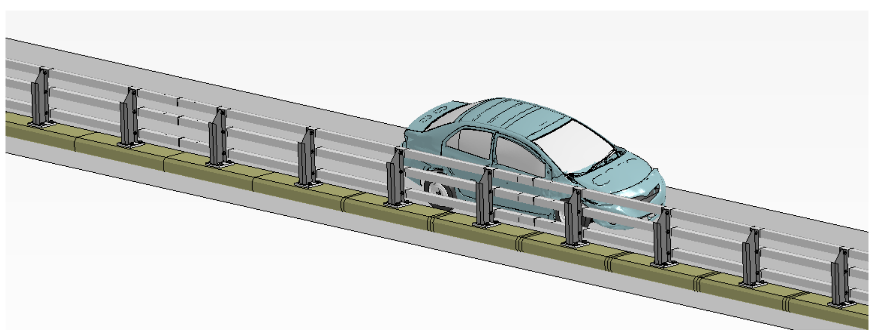

Figure F-3. [Continued] Sequential views from analysis of MASH Test 4-10 for curb-mounted S3-TL4 from an oblique viewpoint.

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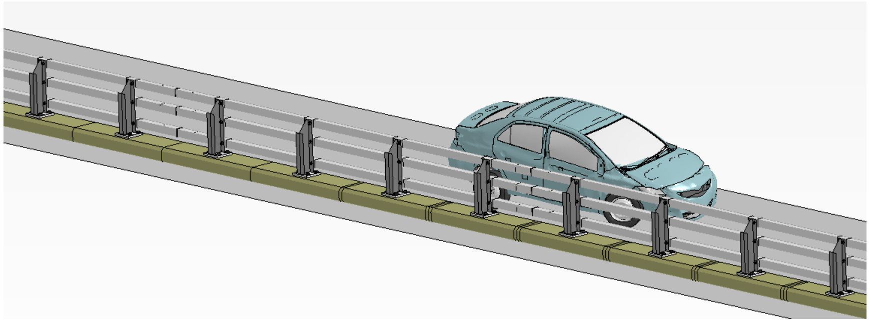

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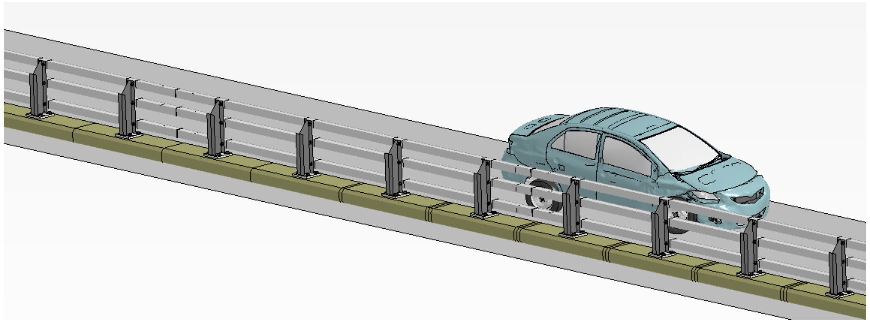

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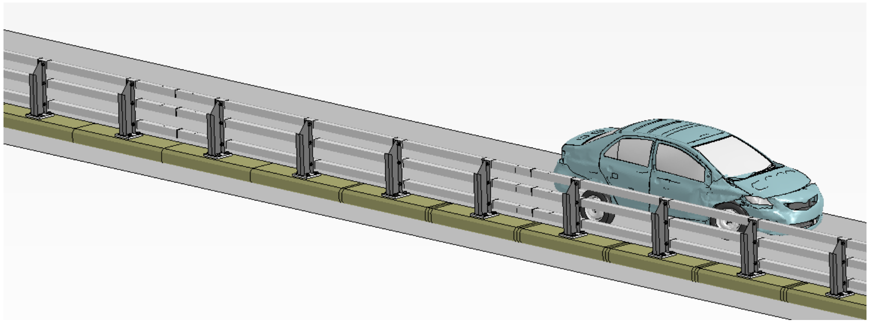

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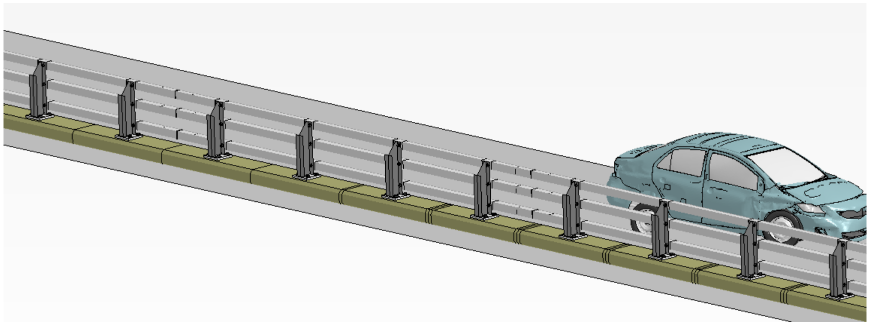


Figure F-3. [Continued] Sequential views from analysis of MASH Test 4-10 for curb-mounted S3-TL4 from an oblique viewpoint.

Appendix G

Sequential Views for MASH Test 4-10 for

Sidewalk-Mounted S3-TL4 Bridge Rail

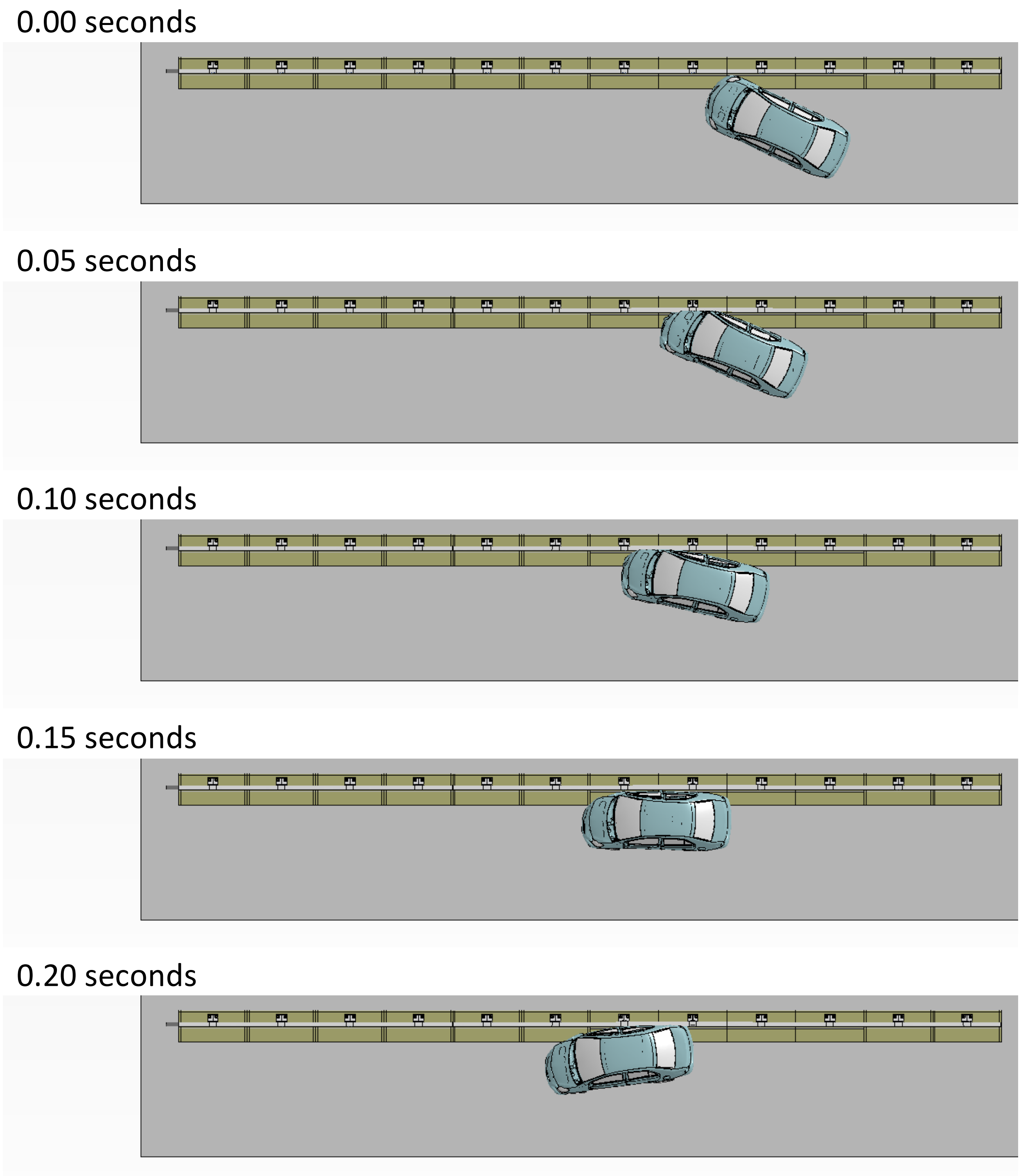
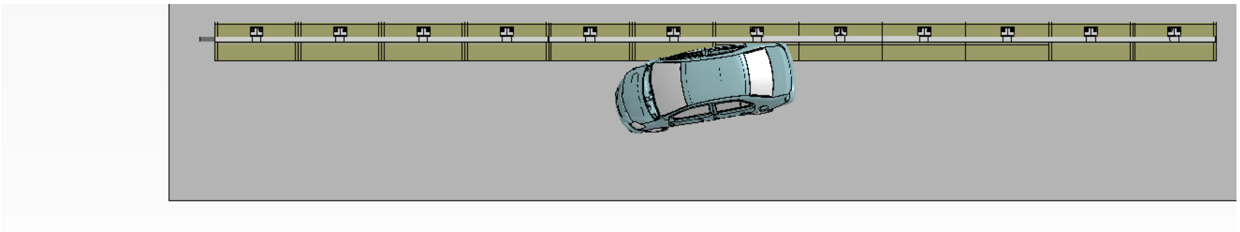


Figure G-1. Sequential views from analysis of MASH Test 4-10 for sidewalk-mounted S3-TL4 from an overhead viewpoint.

0.25 seconds



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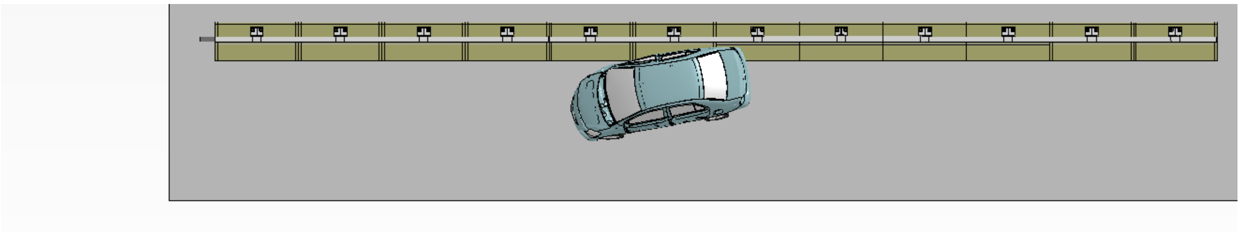

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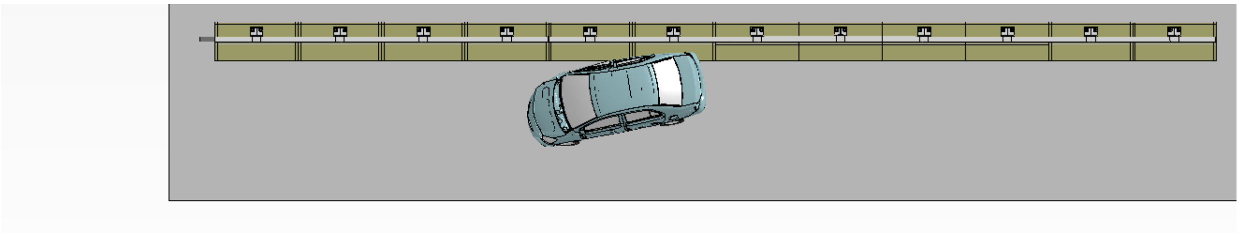

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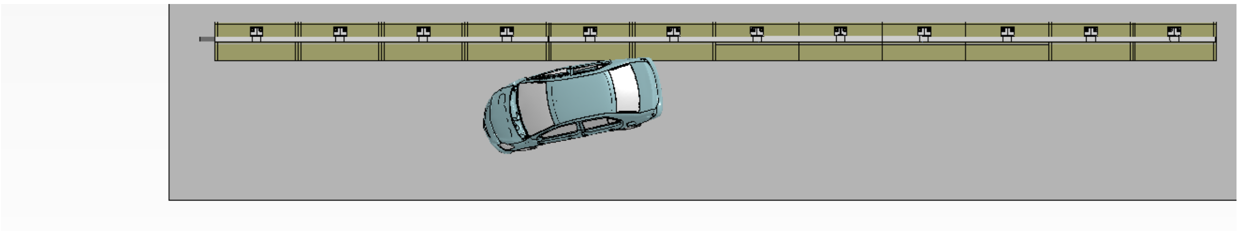

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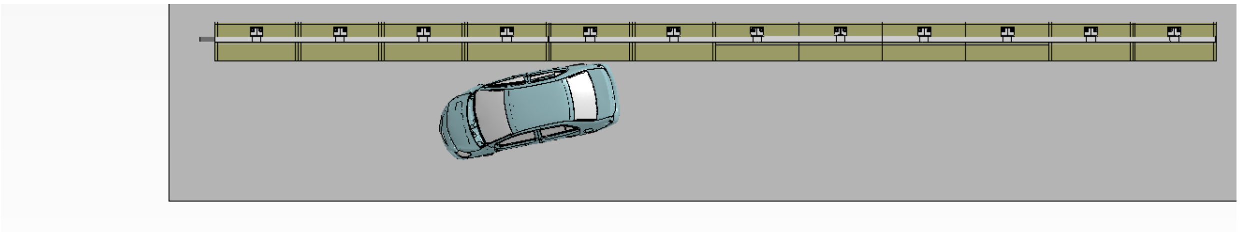
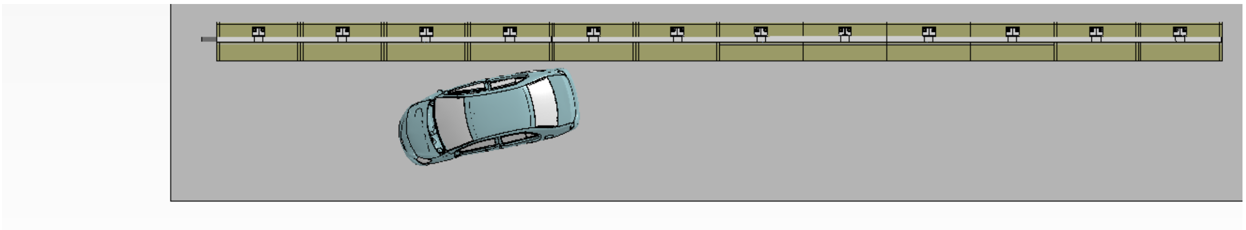


Figure G-1. [Continued] Sequential views from analysis of MASH Test 4-10 for sidewalk-mounted S3-TL4 from an overhead viewpoint.

0.50 seconds



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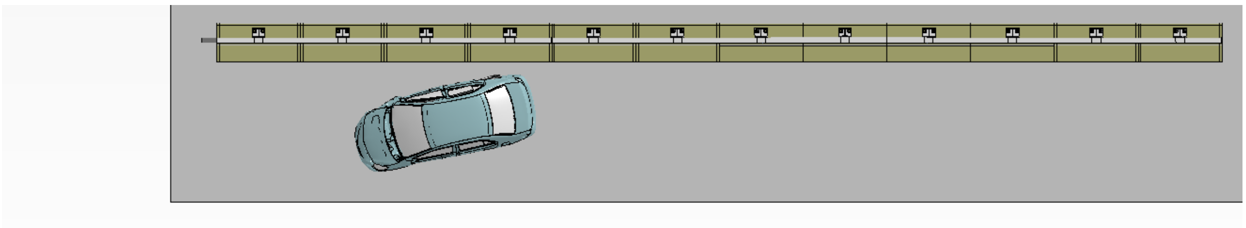

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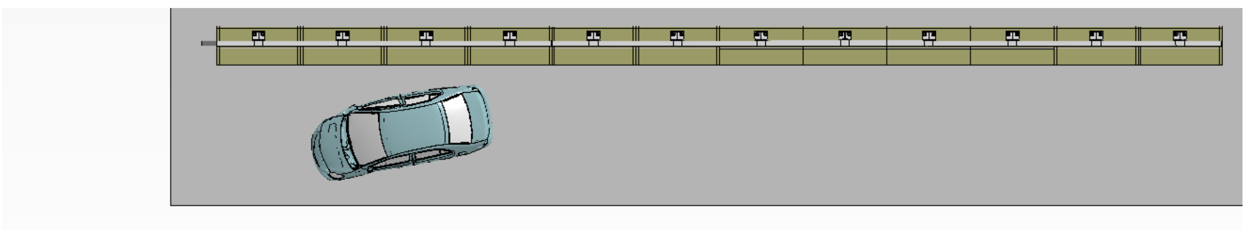

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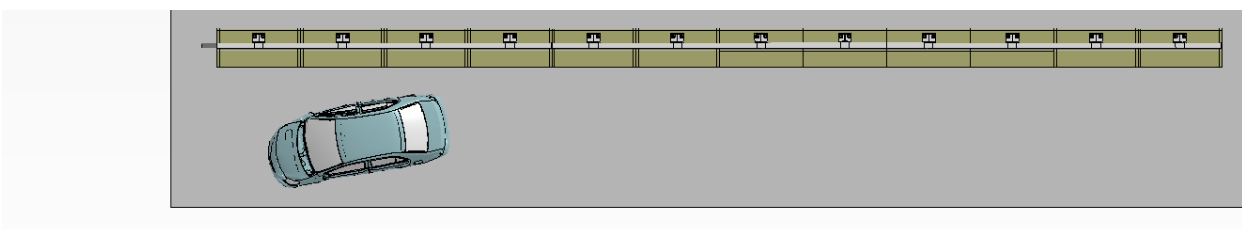

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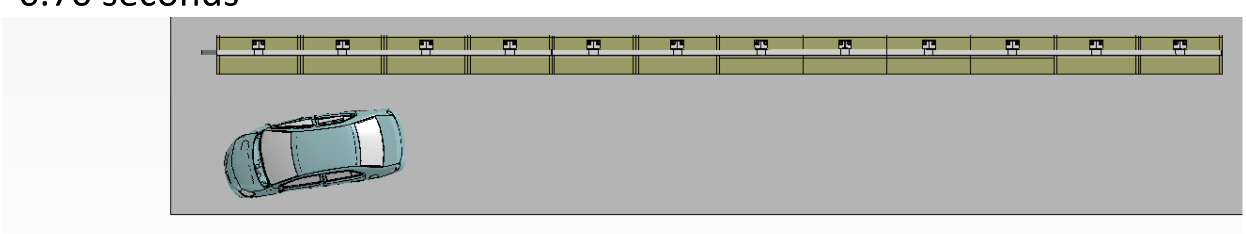
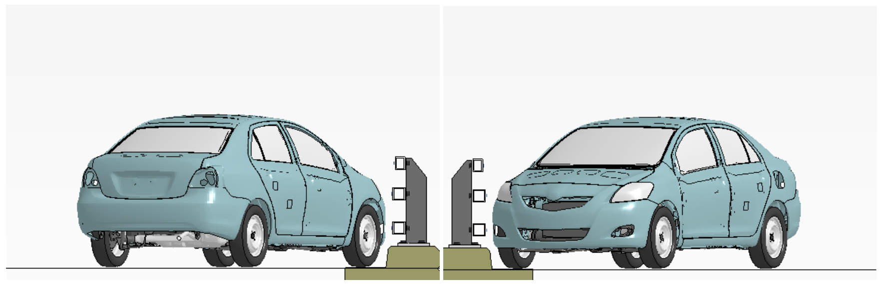


Figure G-1. [Continued] Sequential views from analysis of MASH Test 4-10 for sidewalk-mounted S3-TL4 from an overhead viewpoint.

0.00 seconds



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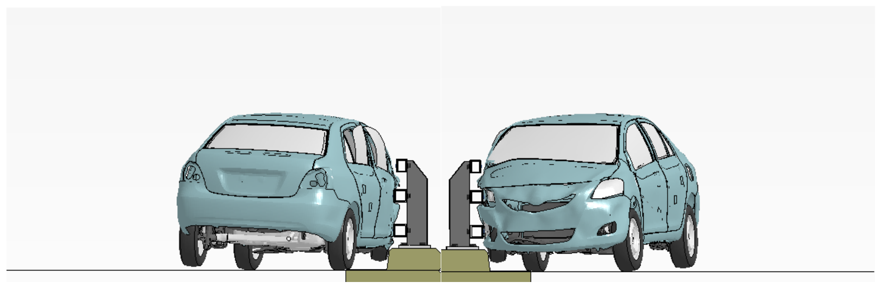

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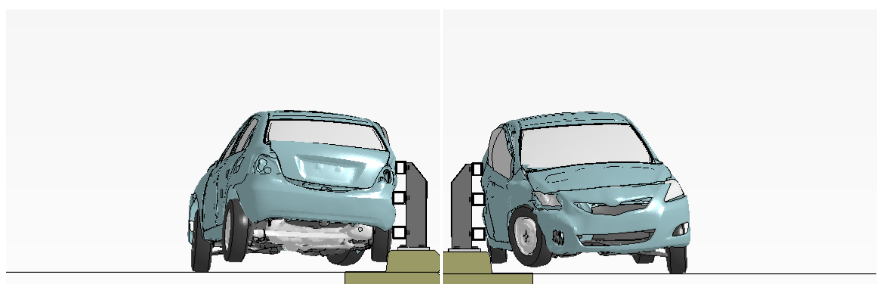

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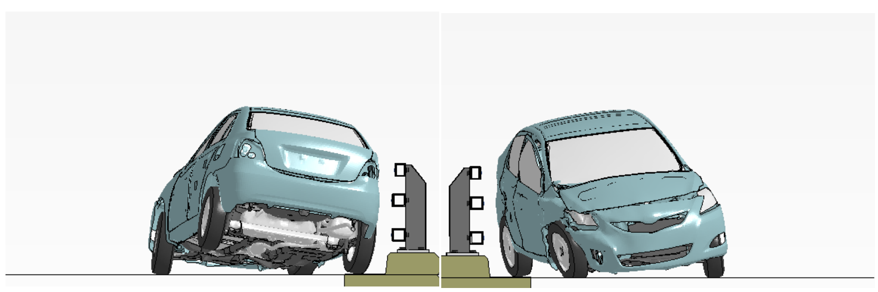
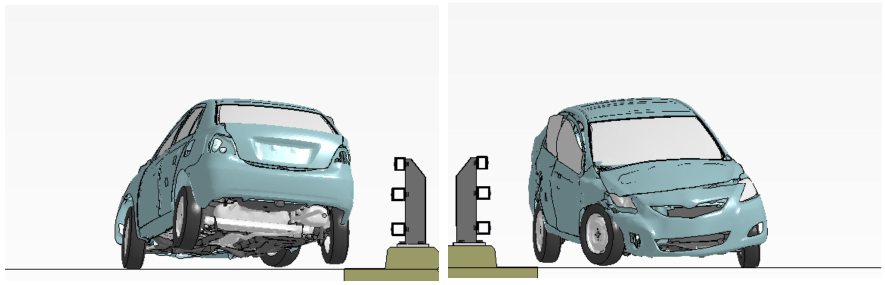


Figure G-2. Sequential views from analysis of MASH Test 4-10 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints.

0.40 seconds



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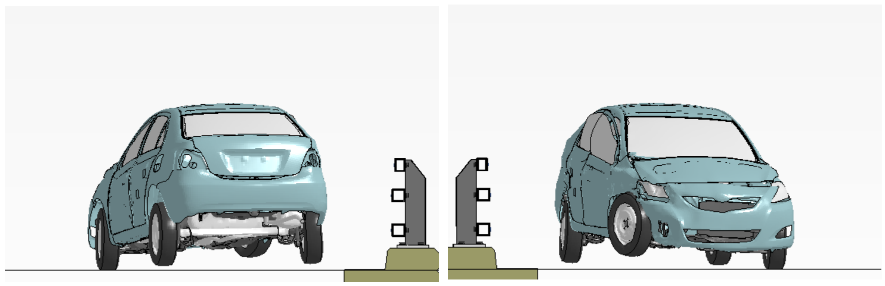

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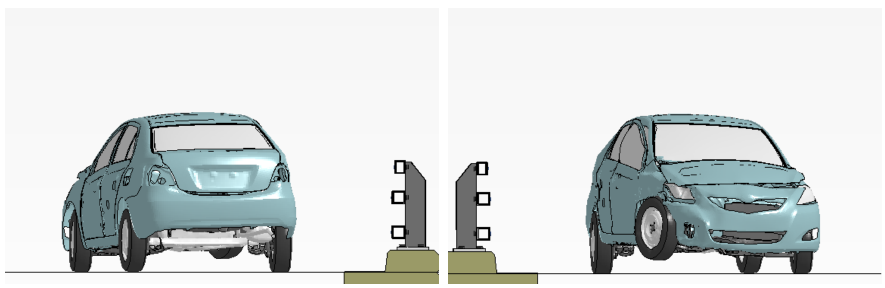

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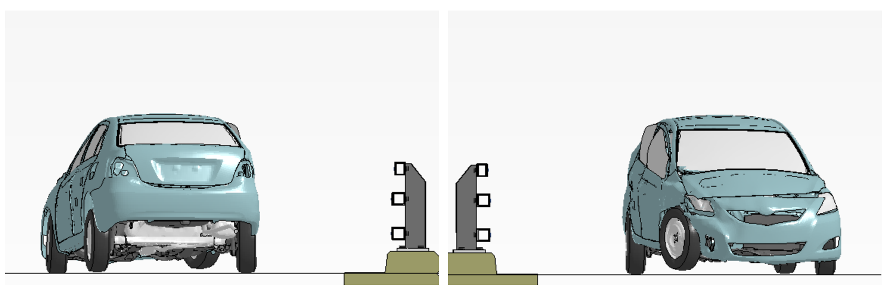
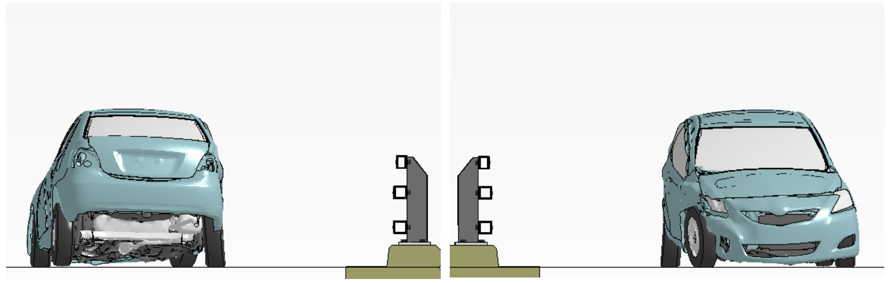


Figure G-2. [Continued] Sequential views from analysis of MASH Test 4-10 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints.

0.80 seconds



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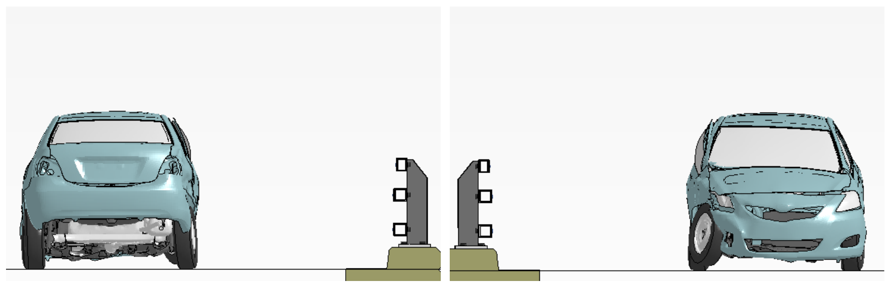

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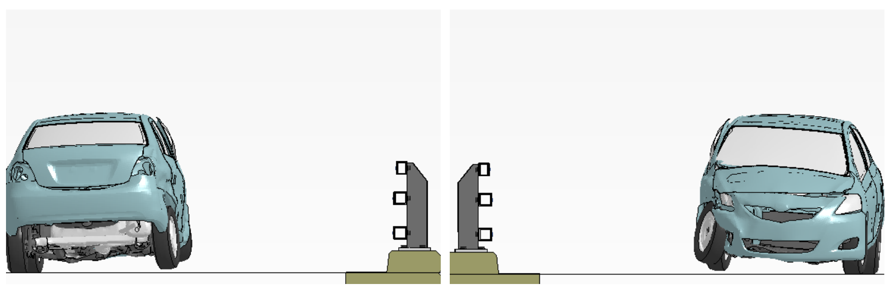
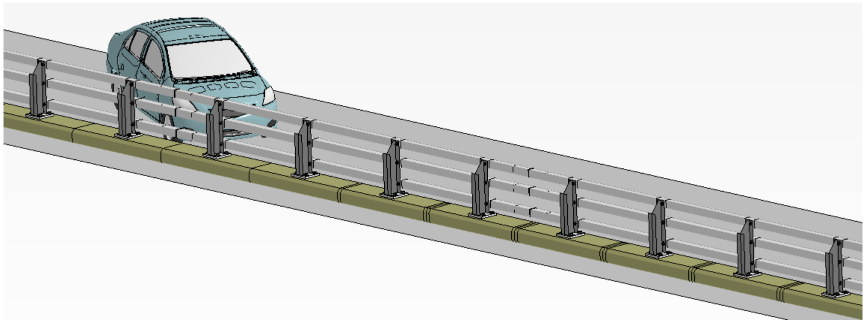


Figure G-2. [Continued] Sequential views from analysis of MASH Test 4-10 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints.

0.00 seconds



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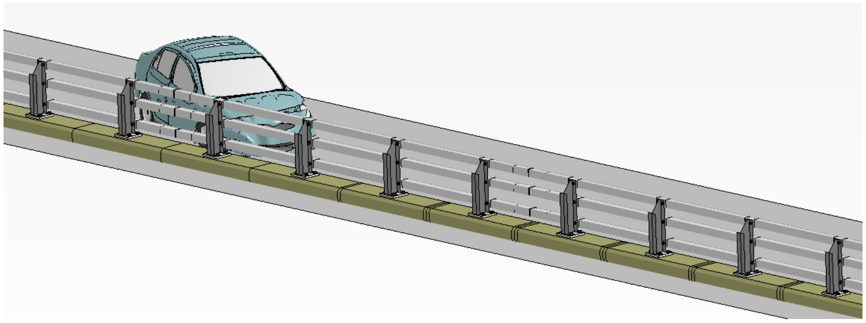

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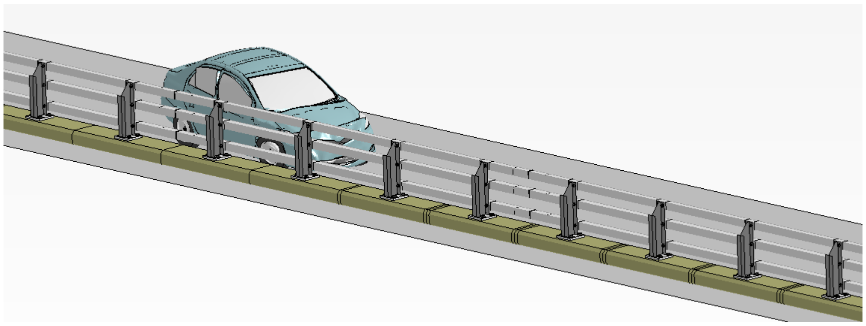

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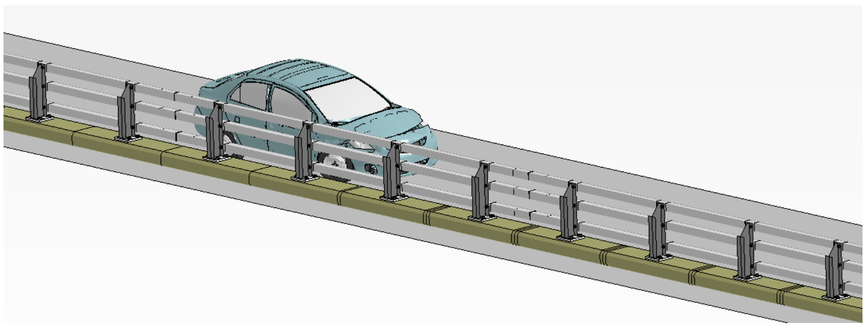
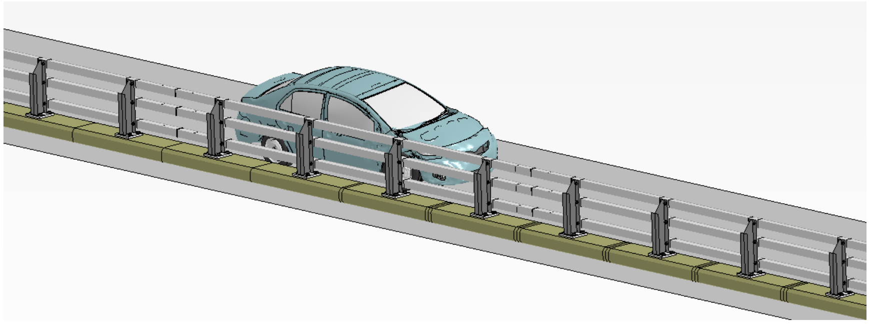


Figure G-3. Sequential views from analysis of MASH Test 4-10 for sidewalk-mounted S3-TL4 from an oblique viewpoint.

0.20 seconds



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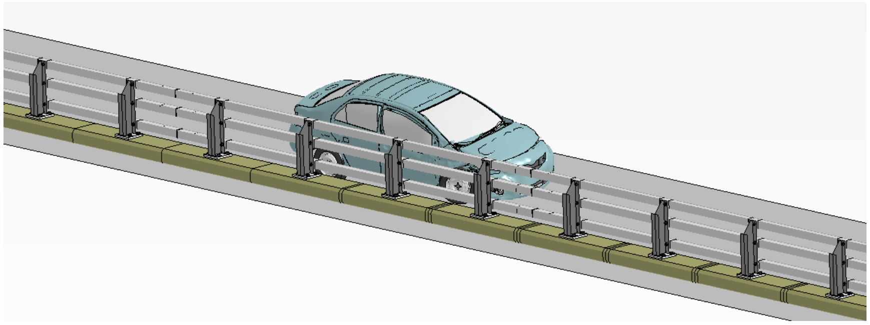

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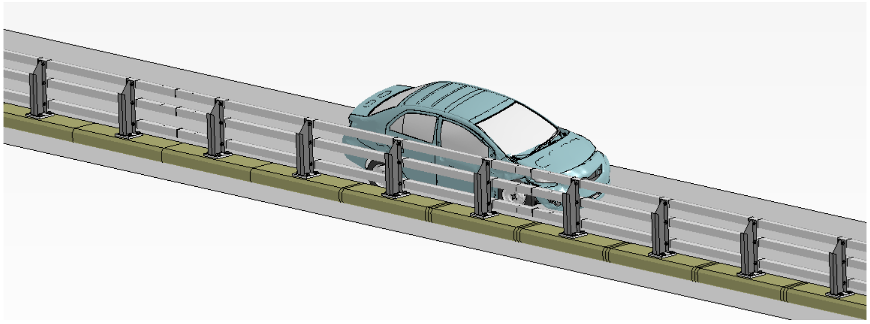

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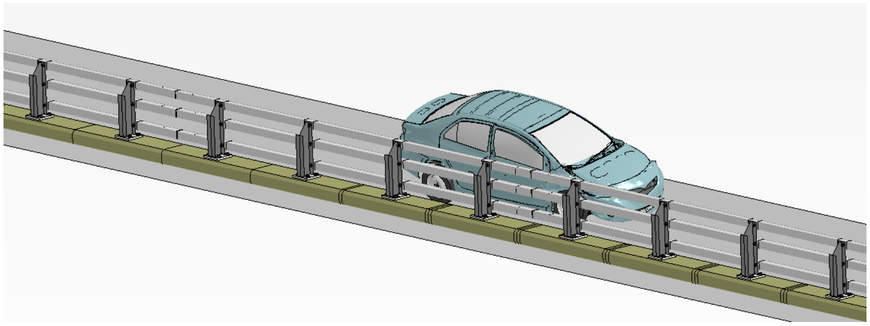
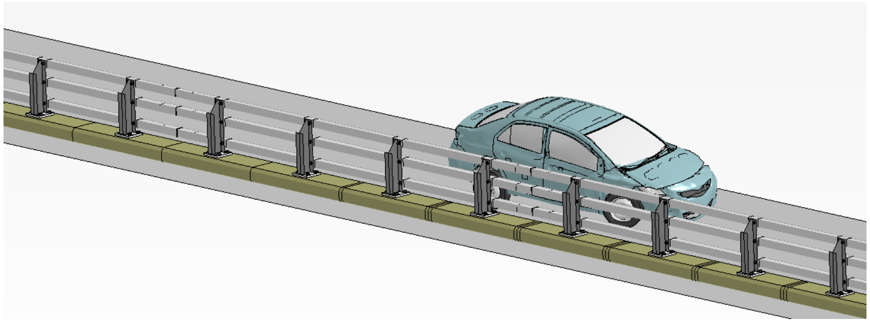


Figure G-3. [Continued] Sequential views from analysis of MASH Test 4-10 for sidewalk-mounted S3-TL4 from an oblique viewpoint.

0.40 seconds



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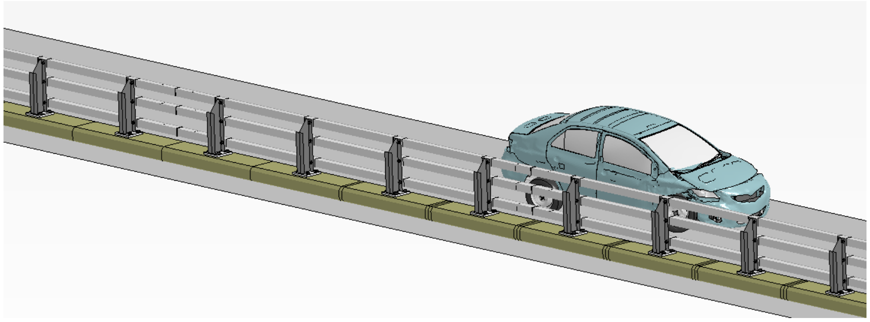

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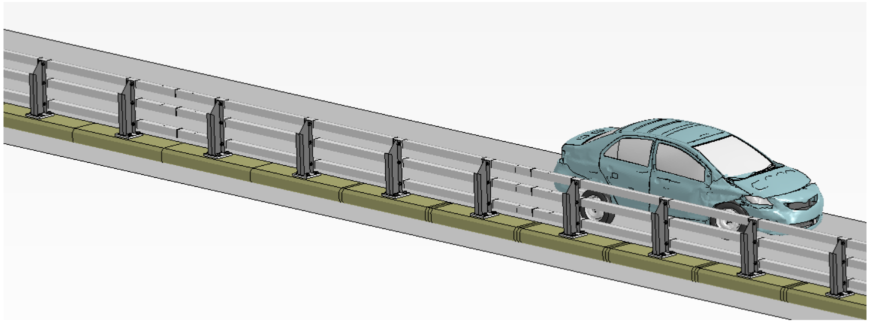

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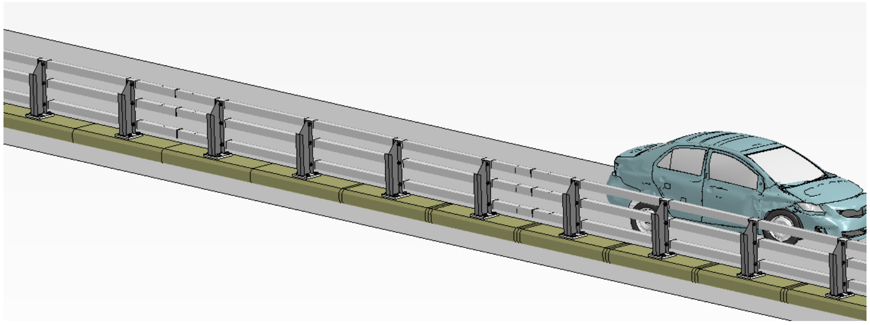


Figure G-3. [Continued] Sequential views from analysis of MASH Test 4-10 for sidewalk-mounted S3-TL4 from an oblique viewpoint.

Appendix H

Sequential Views for MASH Test 4-11 for

Curb-Mounted S3-TL4 Bridge Rail

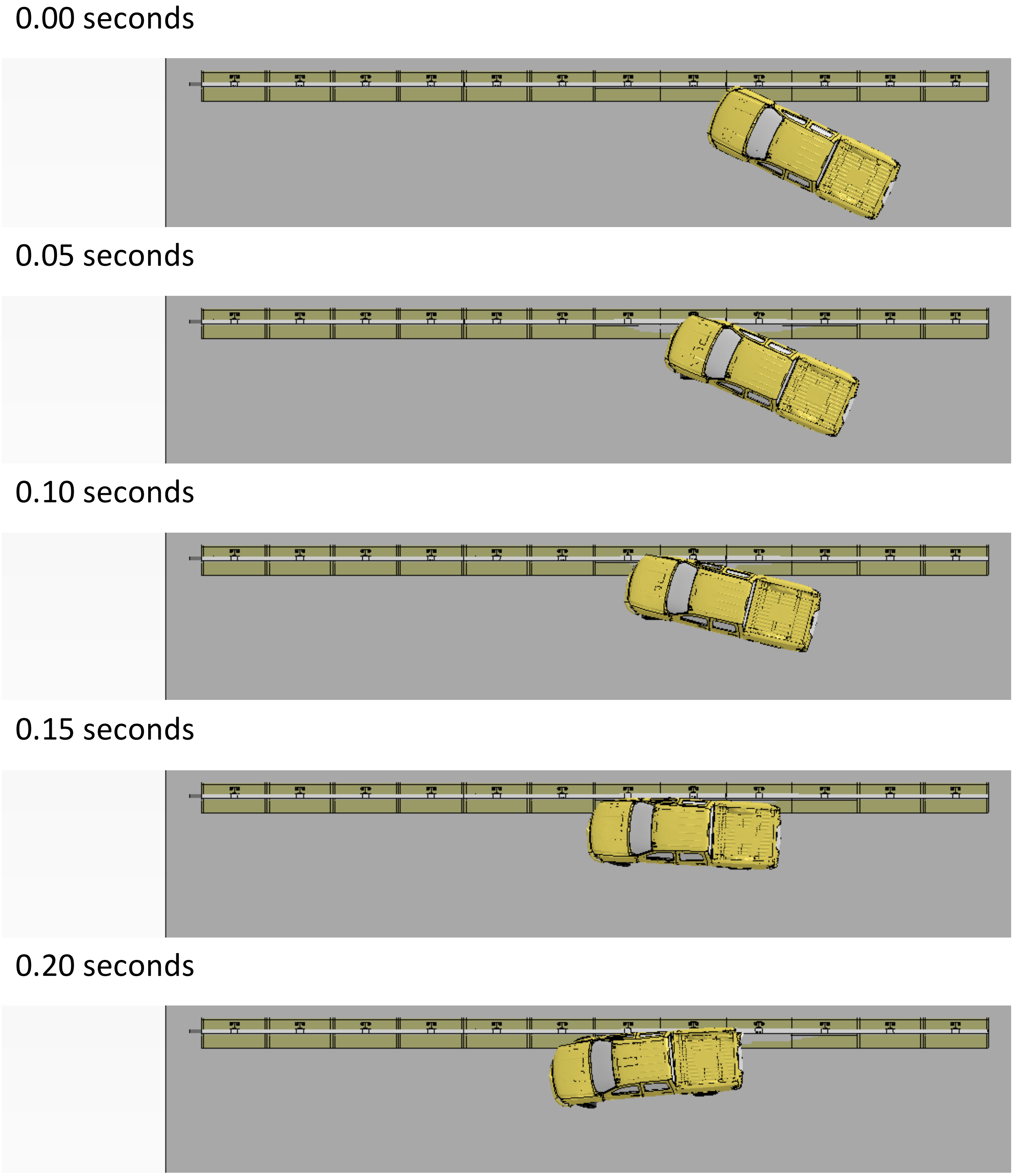
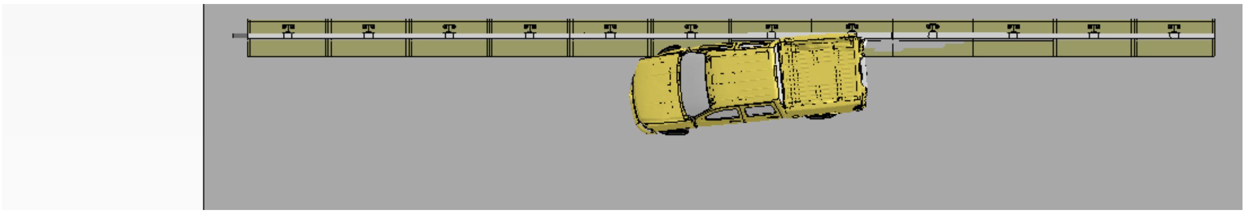


Figure H-1. Sequential views from analysis of MASH Test 4-11 for curb-mounted S3-TL4 from an overhead viewpoint.

0.25 seconds



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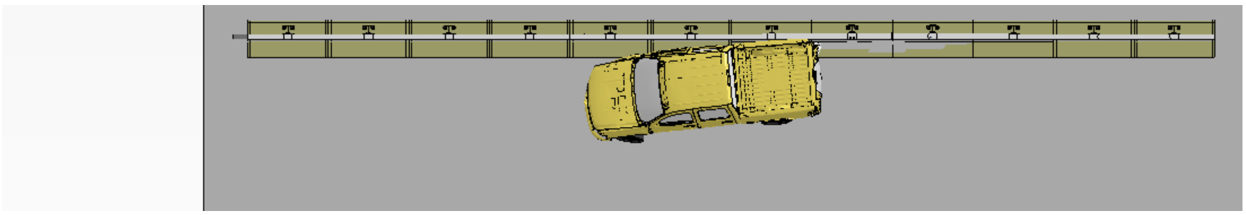

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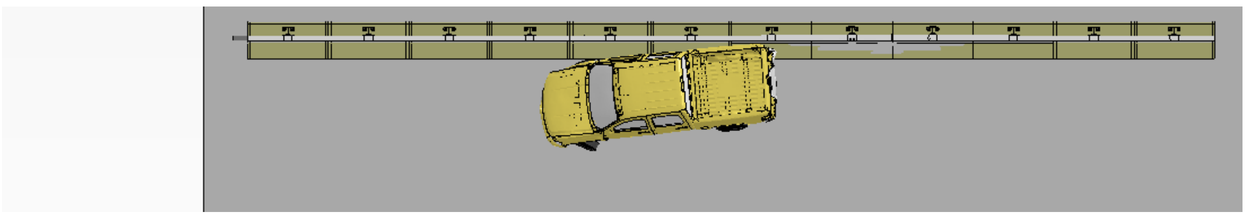

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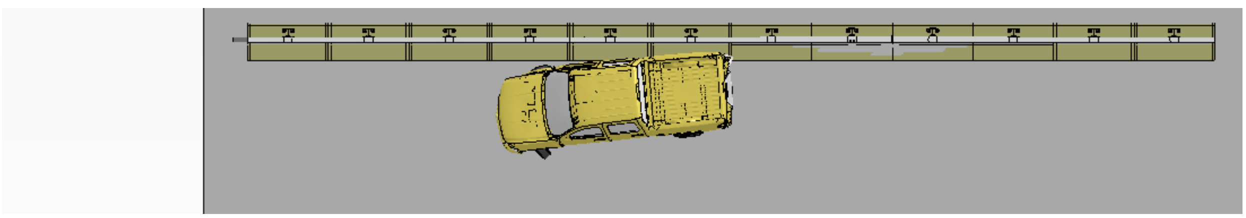

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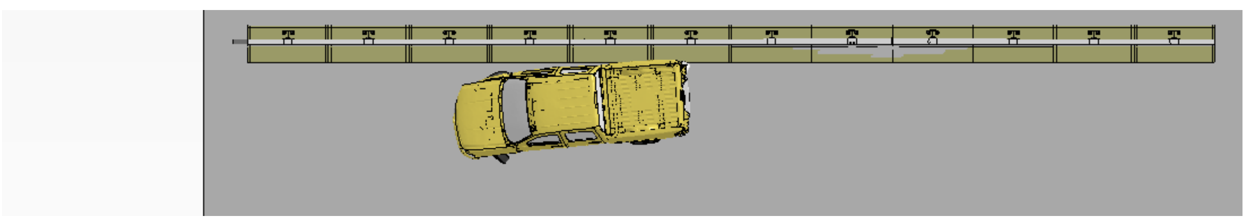
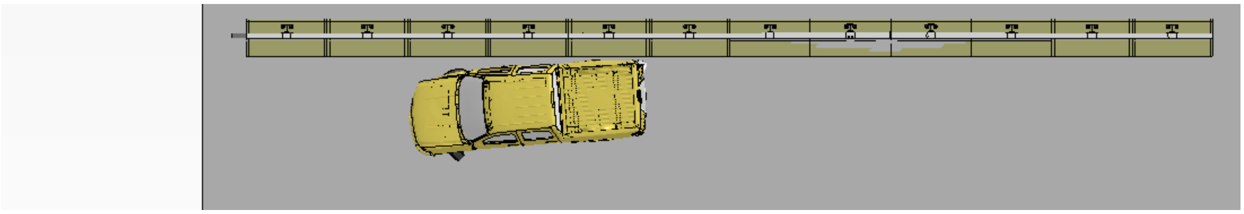


Figure H-1. [Continued] Sequential views from analysis of MASH Test 4-11 for curb-mounted S3-TL4 from an overhead viewpoint.

0.50 seconds



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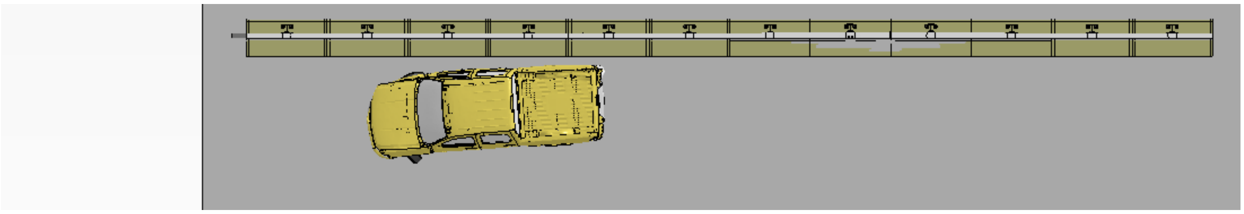

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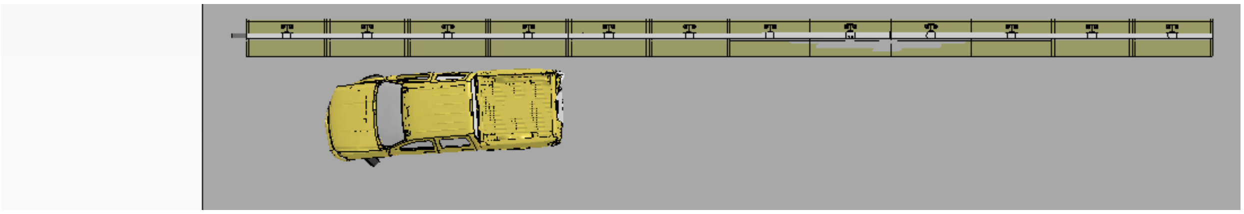

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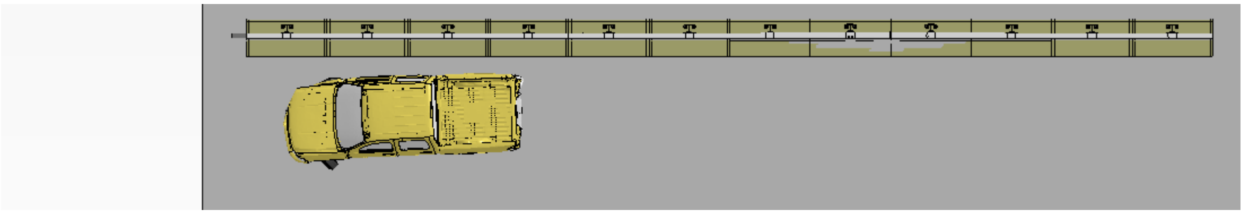

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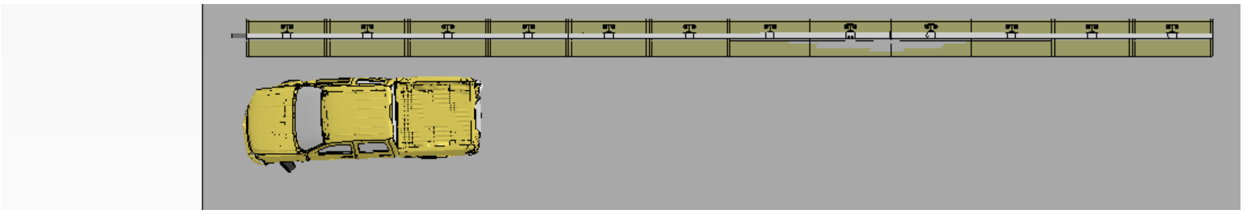
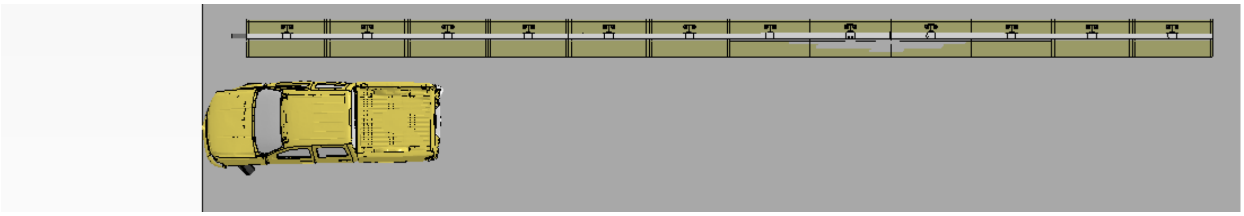


Figure H-1. [Continued] Sequential views from analysis of MASH Test 4-11 for curb-mounted S3-TL4 from an overhead viewpoint.

0.75 seconds



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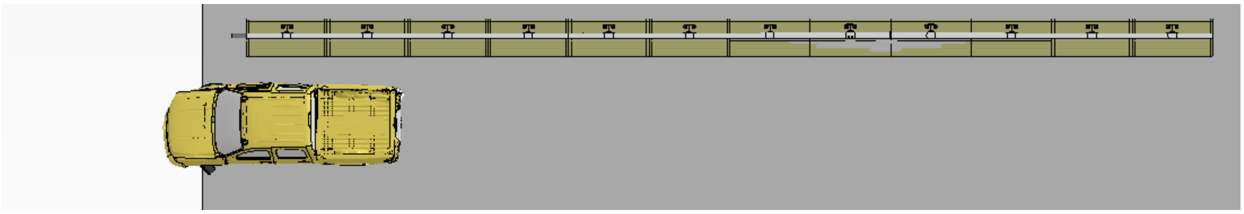

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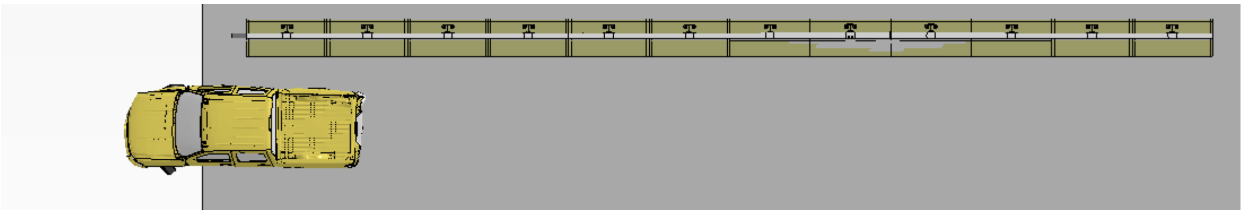

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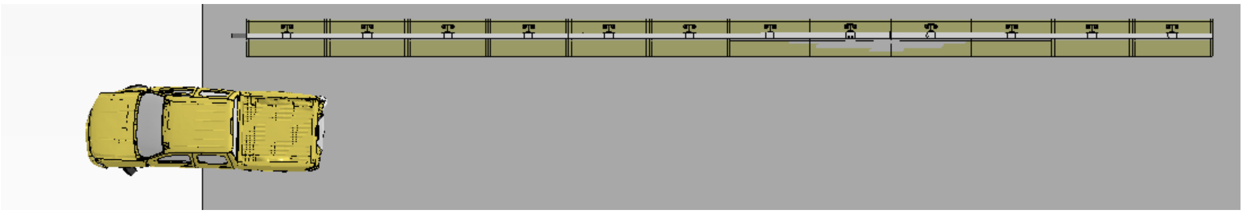

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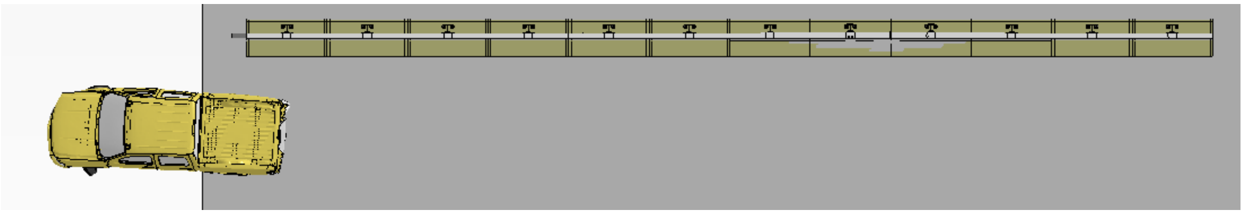
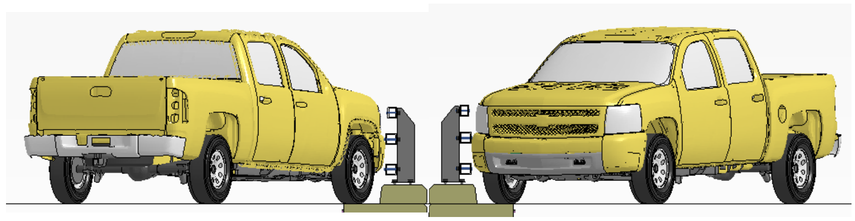


Figure H-1. [Continued] Sequential views from analysis of MASH Test 4-11 for curb-mounted S3-TL4 from an overhead viewpoint.

0.00 seconds



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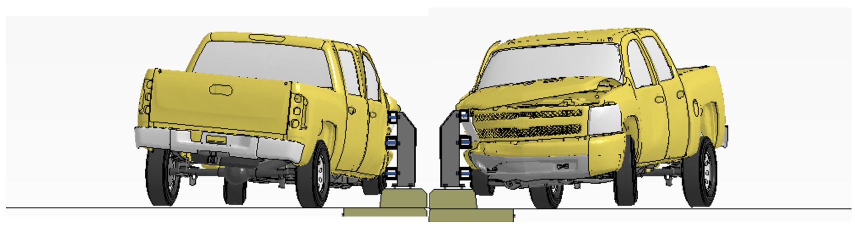

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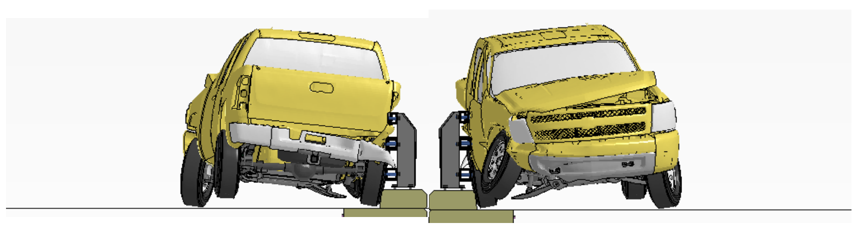

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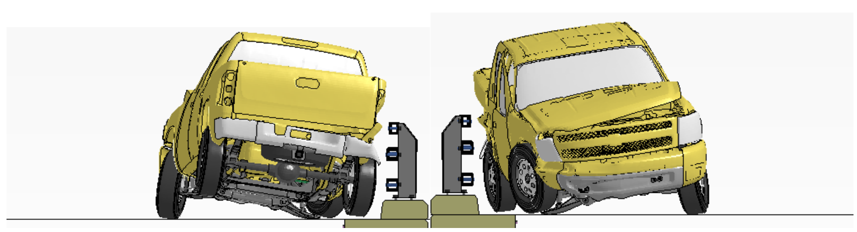

Figure H-2. Sequential views from analysis of MASH Test 4-11 for curb-mounted S3-TL4 from upstream and downstream viewpoints.

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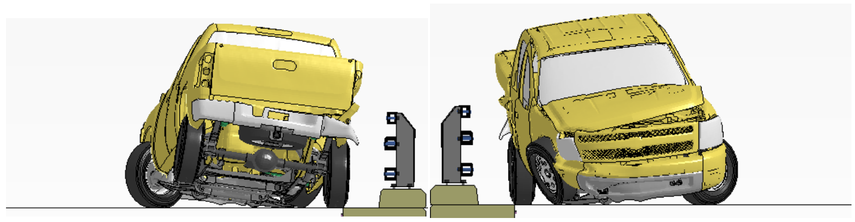

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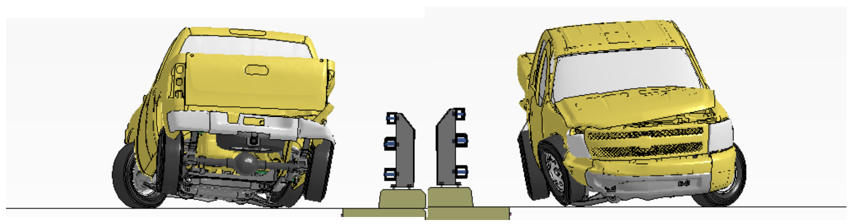

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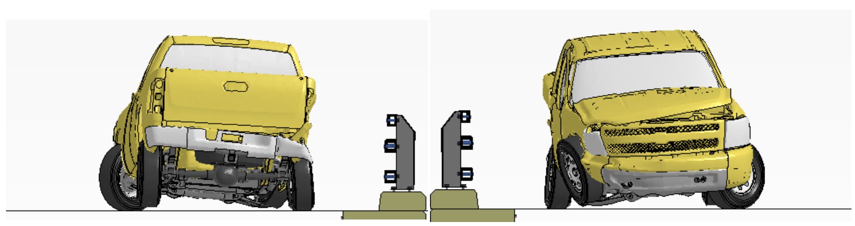

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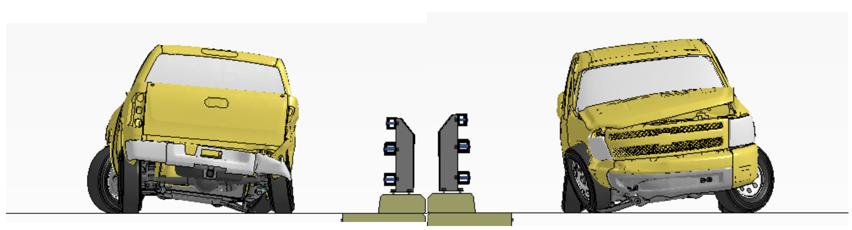

Figure H-2. [Continued] Sequential views from analysis of MASH Test 4-11 for curb-mounted S3-TL4 from upstream and downstream viewpoints.

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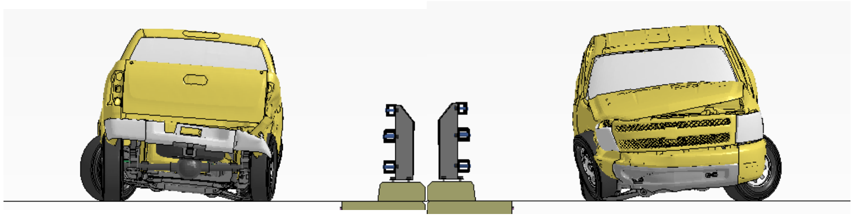

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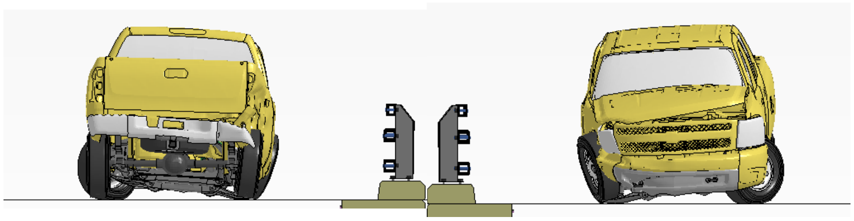

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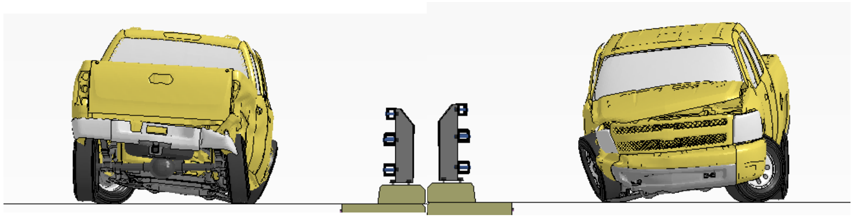

Figure H-2. [Continued] Sequential views from analysis of MASH Test 4-11 for curb-mounted S3-TL4 from upstream and downstream viewpoints.

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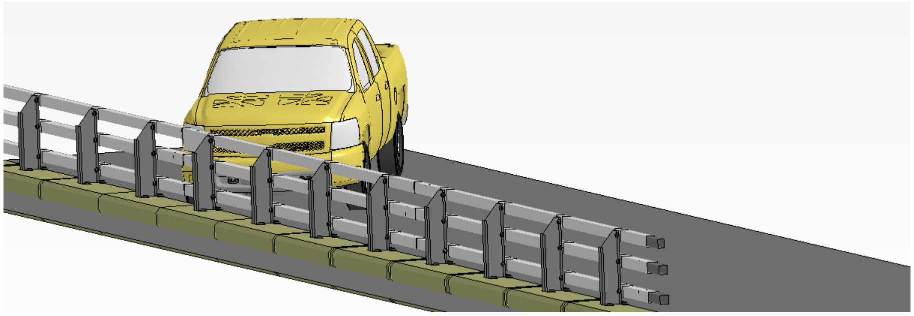

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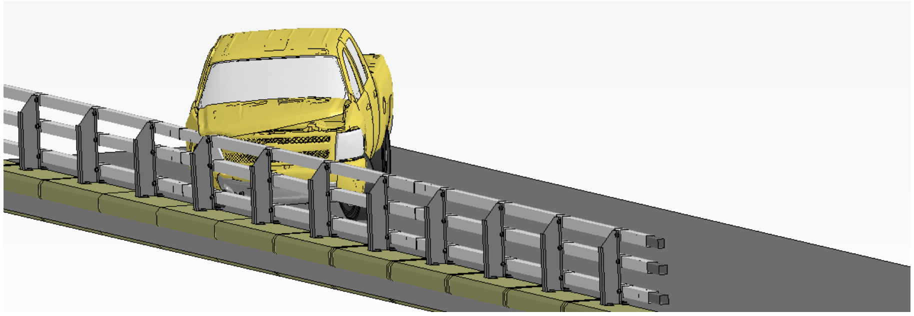

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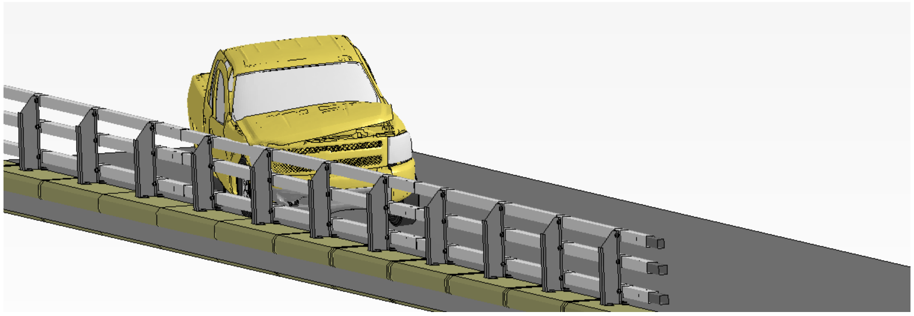

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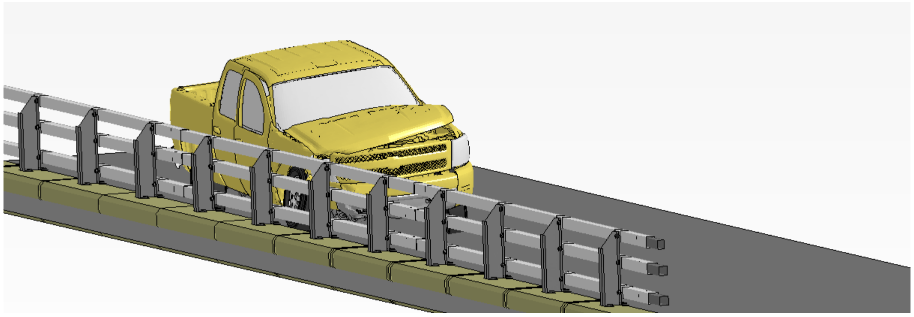
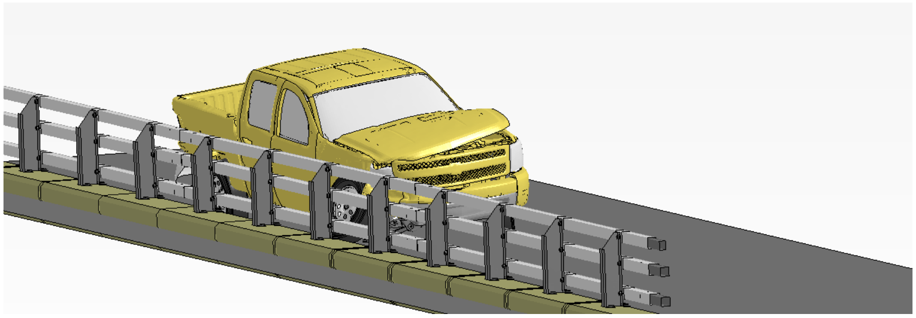


Figure H-3. Sequential views from analysis of MASH Test 4-11 for curb-mounted S3-TL4 from an oblique viewpoint.

0.20 seconds



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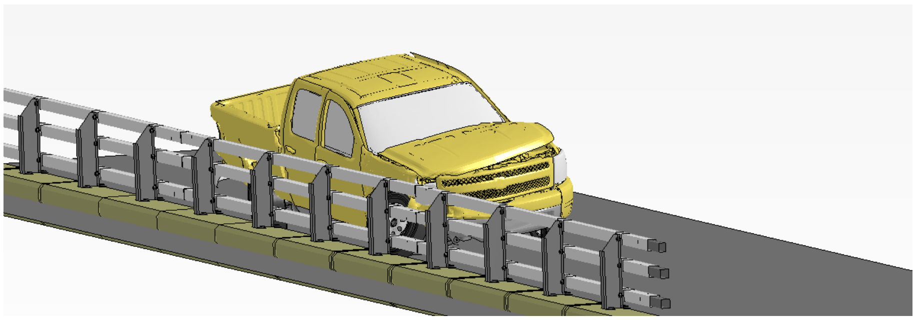

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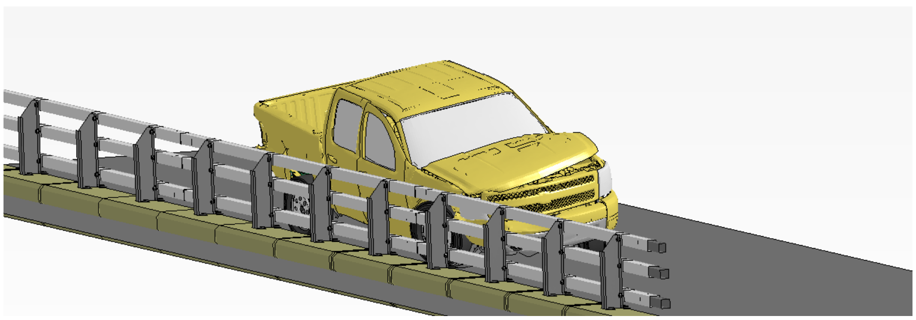

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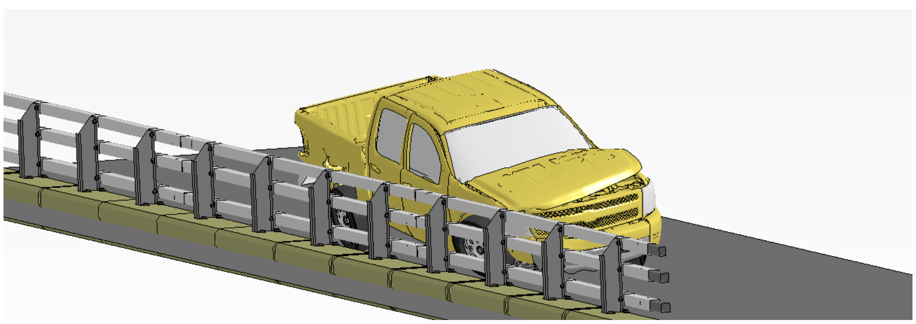
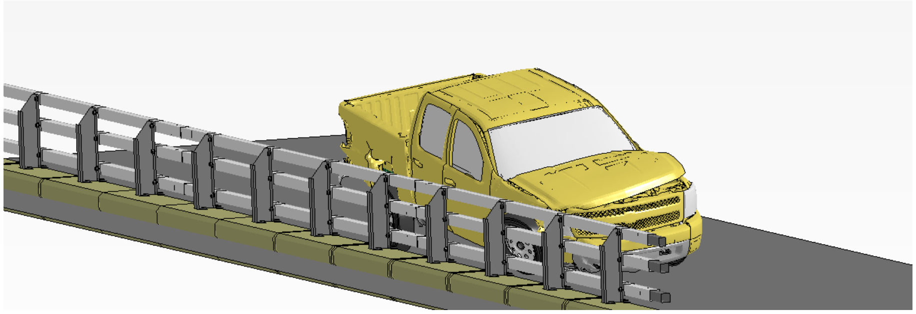


Figure H-3. [Continued] Sequential views from analysis of MASH Test 4-11 for curb-mounted S3-TL4 from an oblique viewpoint.

0.40 seconds



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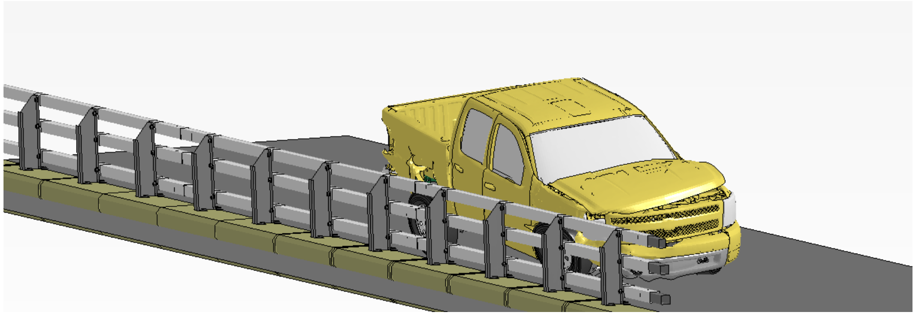

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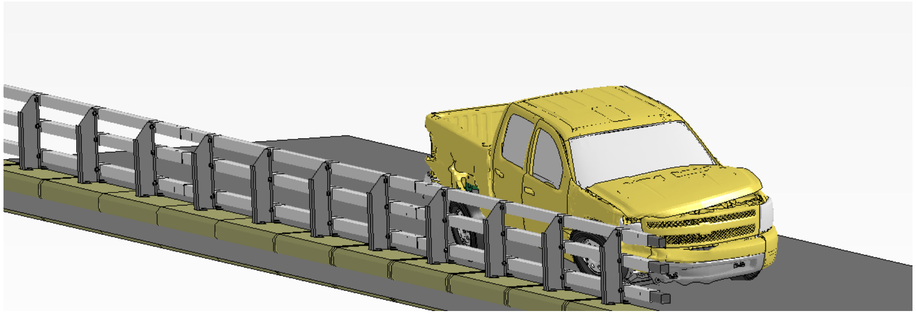

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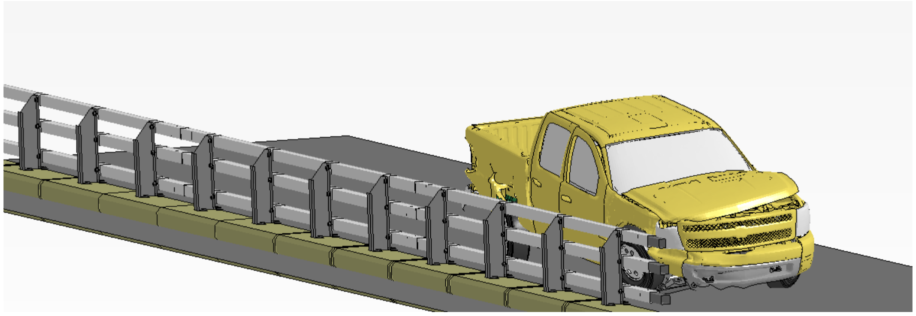


Figure H-3. [Continued] Sequential views from analysis of MASH Test 4-11 for curb-mounted S3-TL4 from an oblique viewpoint.

Appendix I

Sequential Views for MASH Test 4-11 for

Sidewalk-Mounted S3-TL4 Bridge Rail

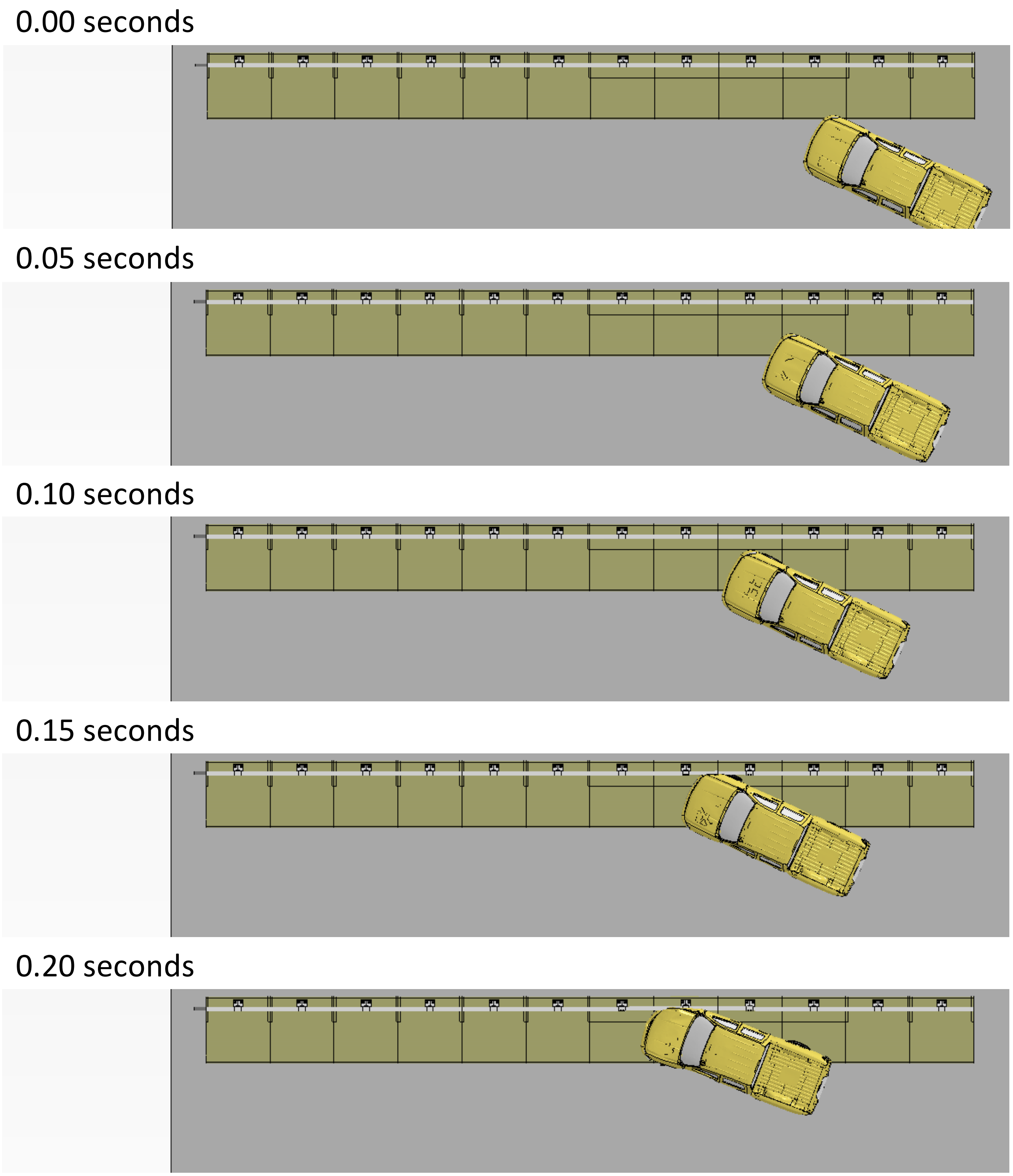
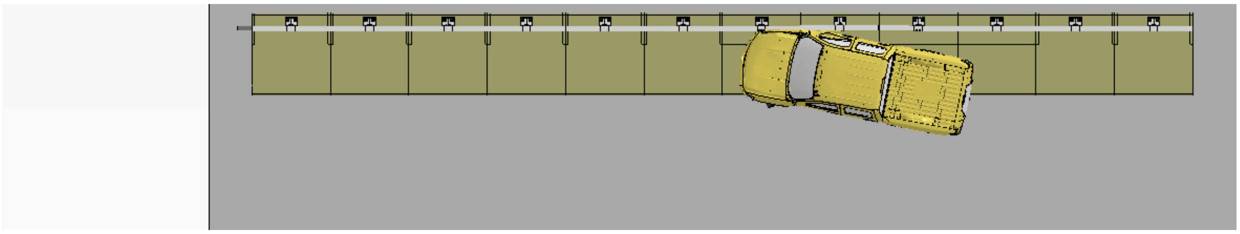


Figure I-1. Sequential views from analysis of MASH Test 4-11 for sidewalk-mounted S3-TL4 from an overhead viewpoint.

0.25 seconds



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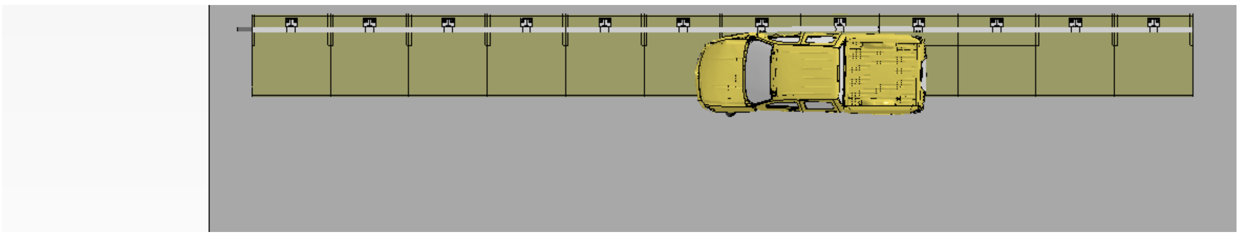

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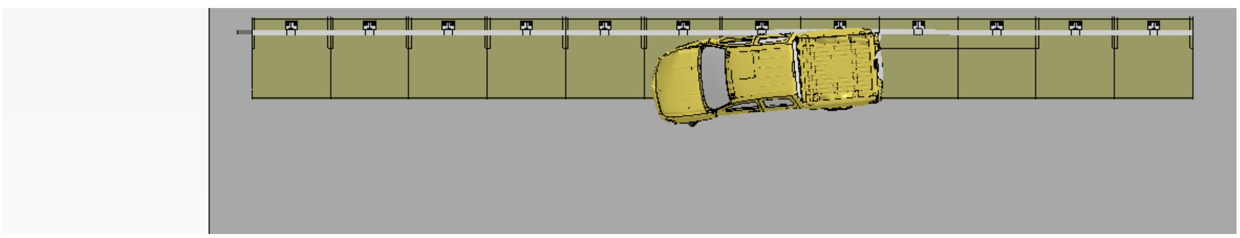

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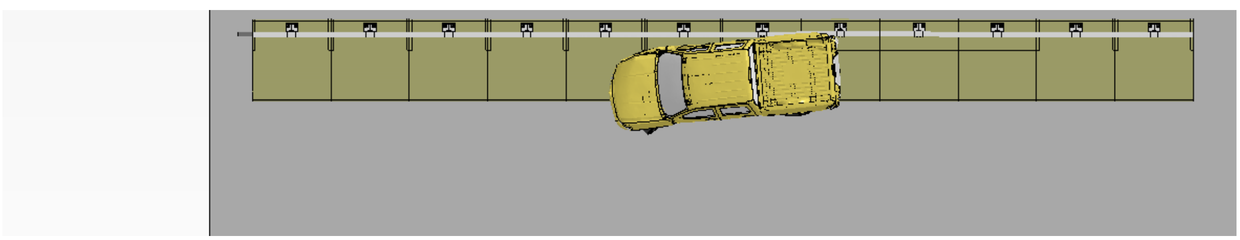

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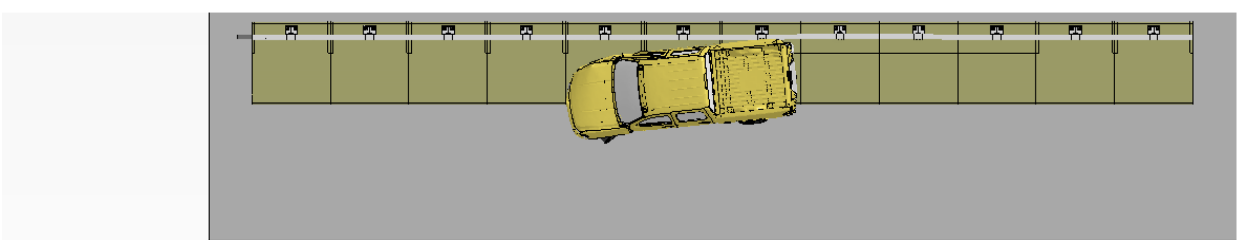

Figure I-1. [Continued] Sequential views from analysis of MASH Test 4-11 for sidewalk-mounted S3-TL4 from an overhead viewpoint.

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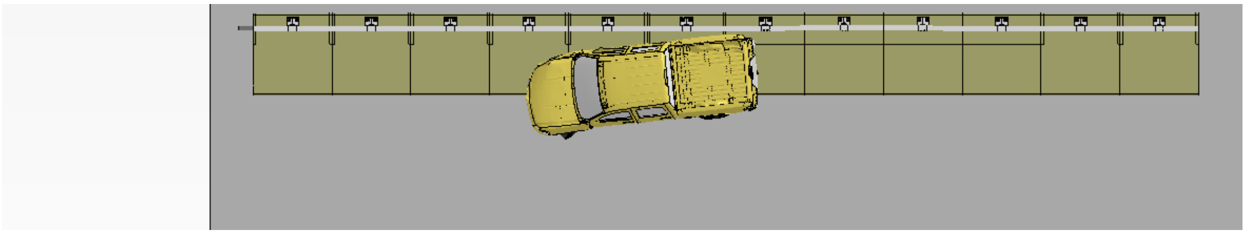

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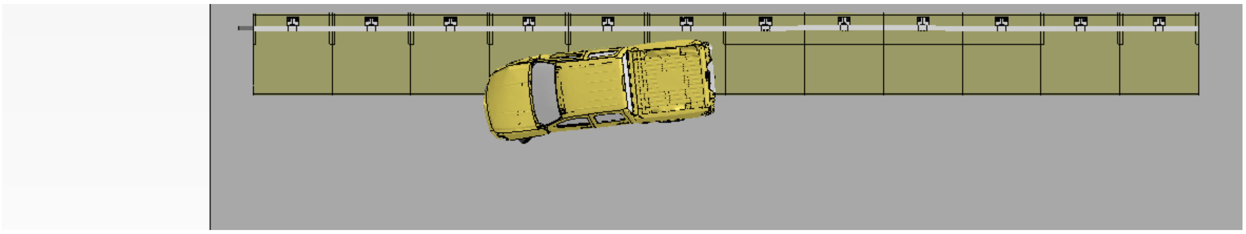

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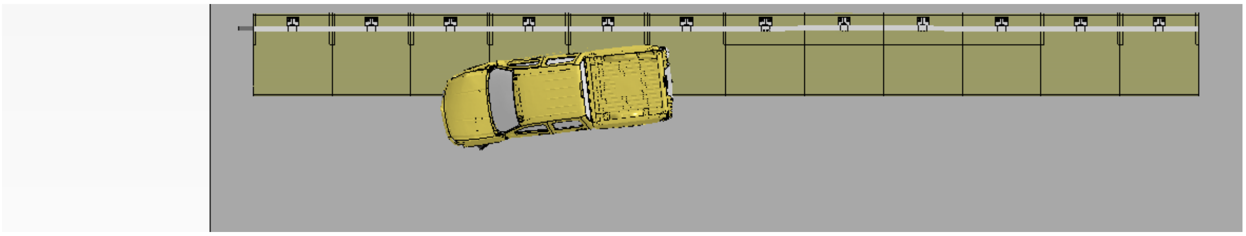

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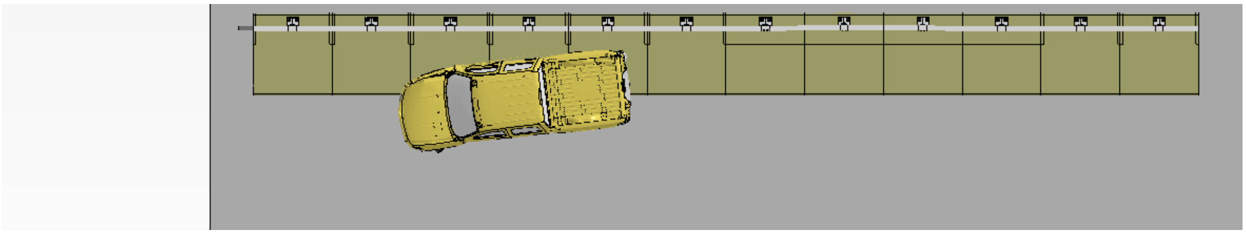

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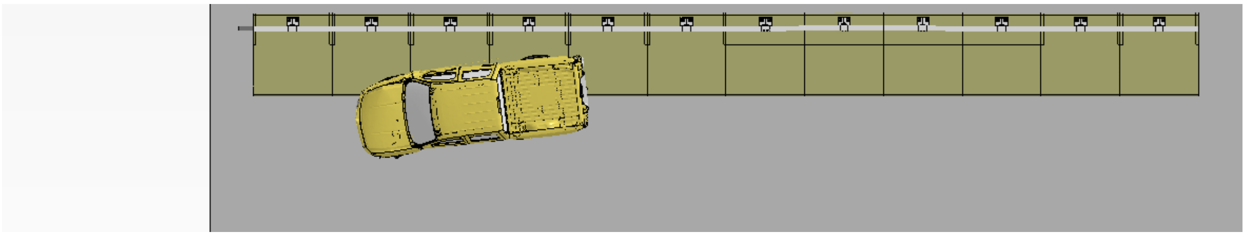

Figure I-1. [Continued] Sequential views from analysis of MASH Test 4-11 for sidewalk-mounted S3-TL4 from an overhead viewpoint.

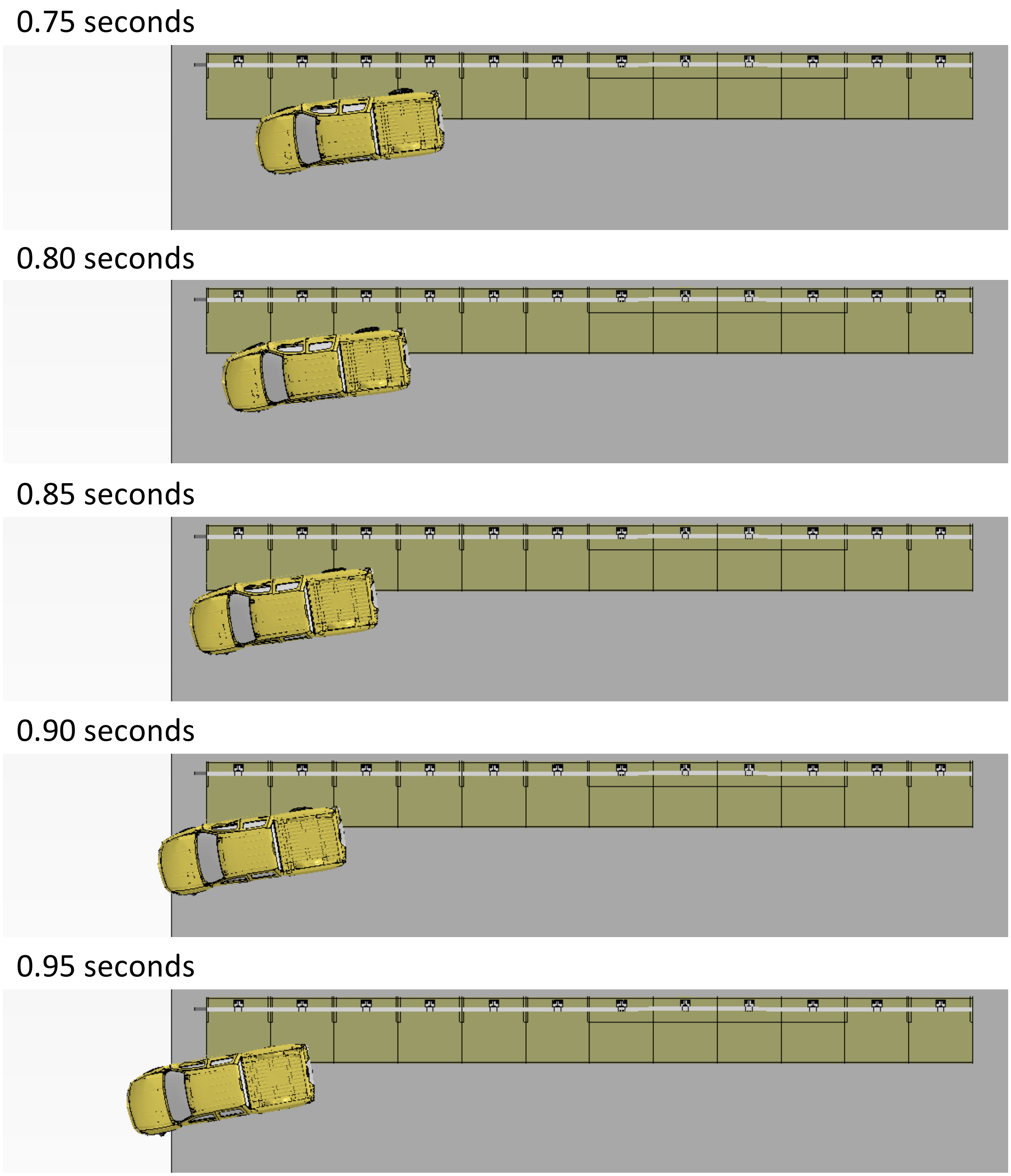

Figure I-1. [Continued] Sequential views from analysis of MASH Test 4-11 for sidewalk-mounted S3-TL4 from an overhead viewpoint.

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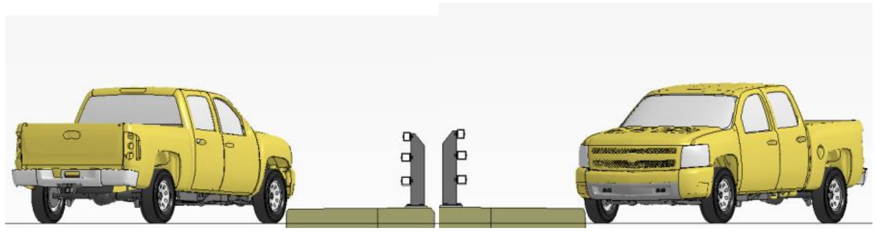

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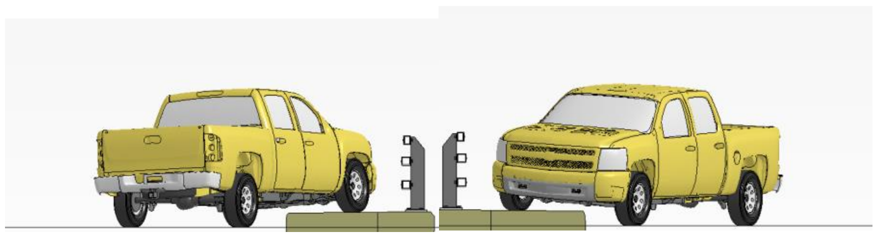

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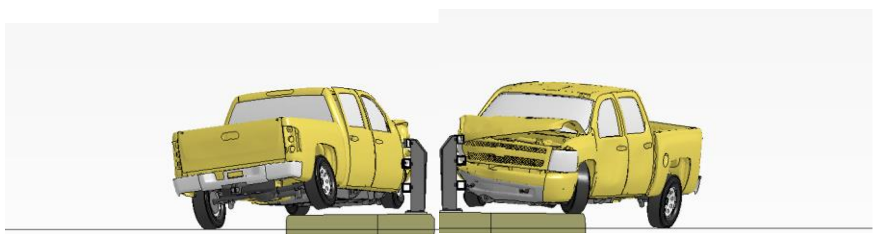

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Figure I-2. Sequential views from analysis of MASH Test 4-11 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints.

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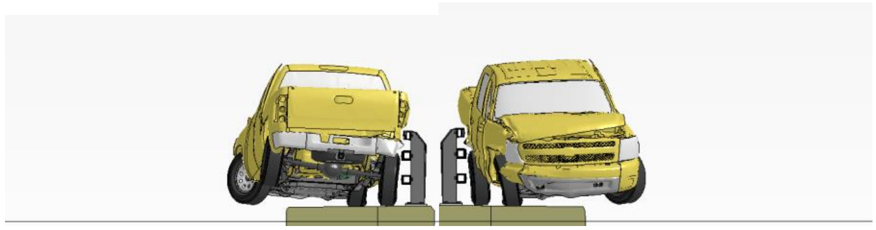

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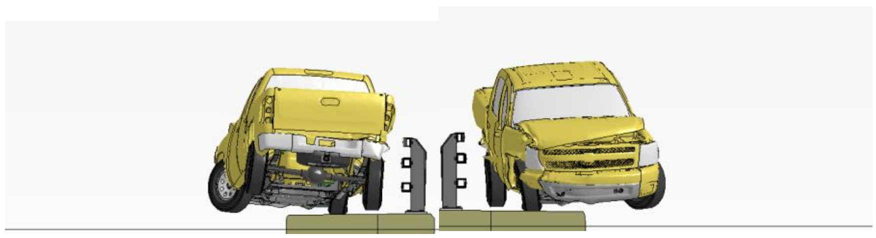

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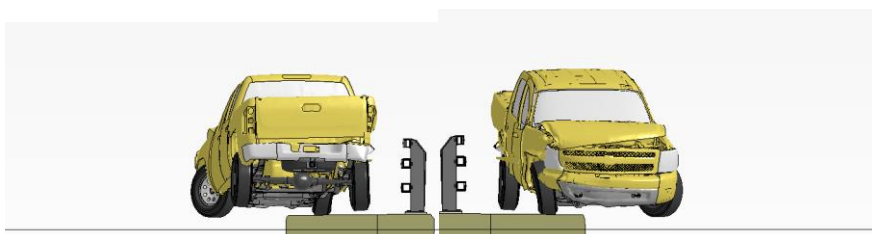

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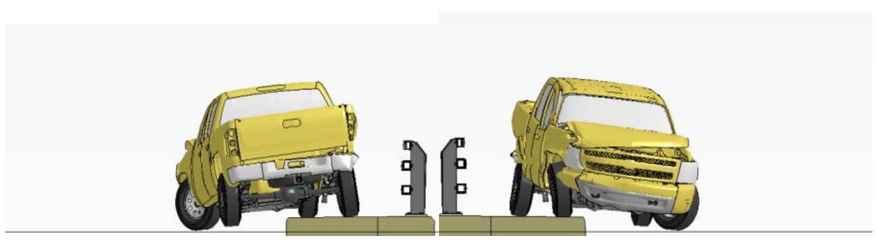

Figure I-2. [Continued] Sequential views from analysis of MASH Test 4-11 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints.

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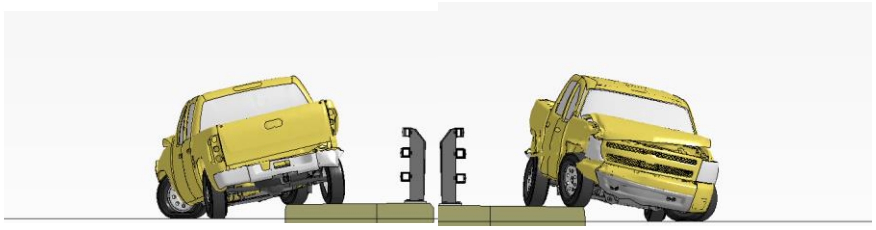

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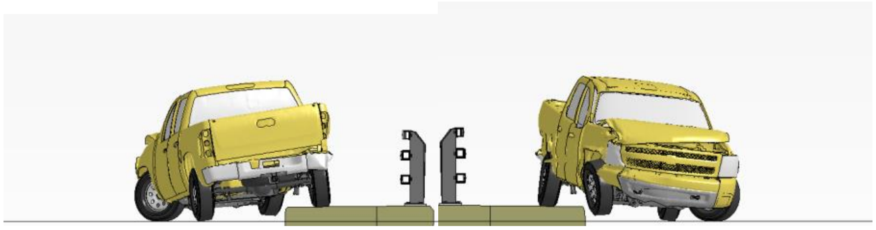

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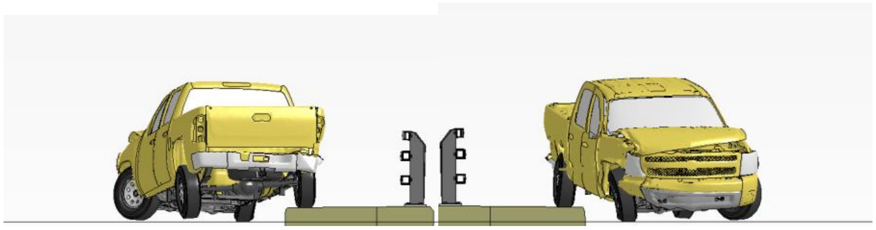

Figure I-2. [Continued] Sequential views from analysis of MASH Test 4-11 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints.

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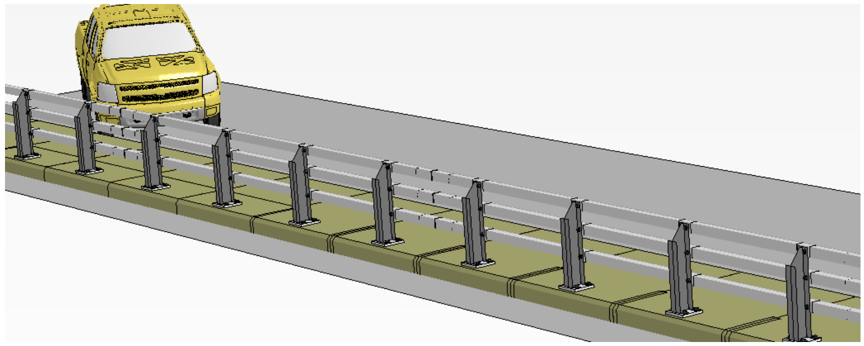

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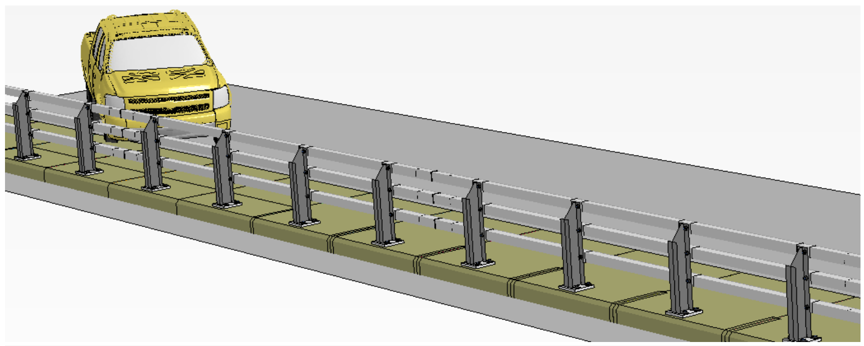

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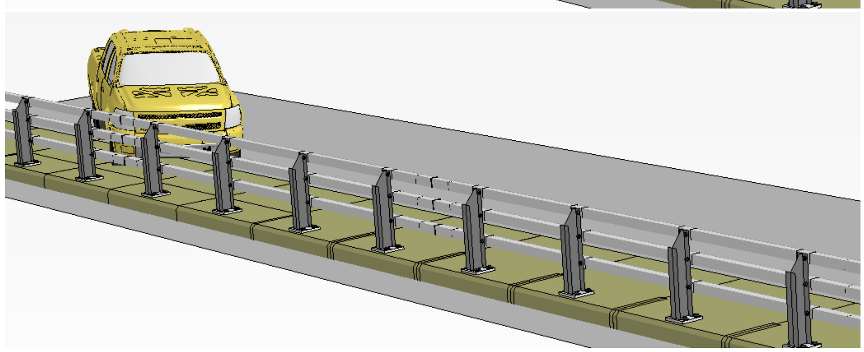

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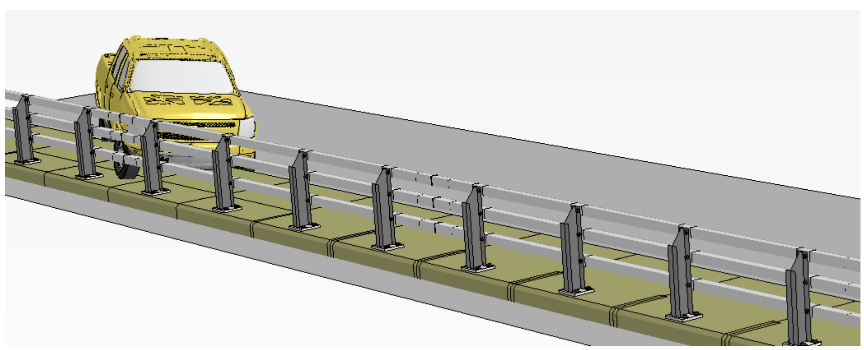
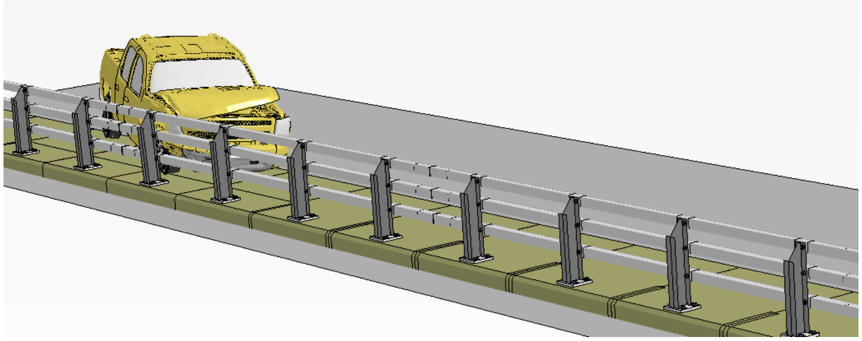


Figure I-3. Sequential views from analysis of MASH Test 4-11 for sidewalk-mounted S3-TL4 from an oblique viewpoint.

0.20 seconds



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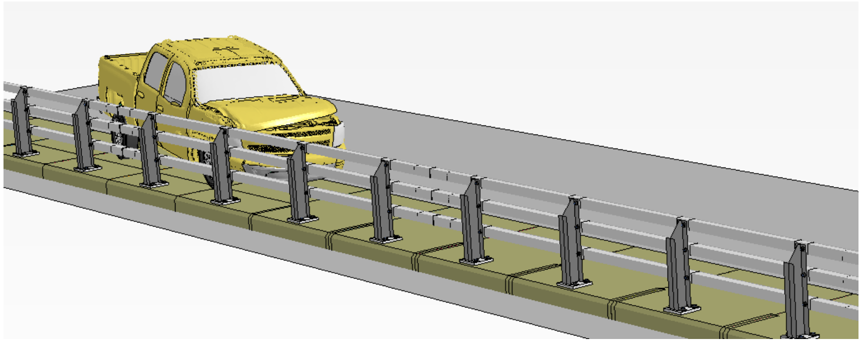

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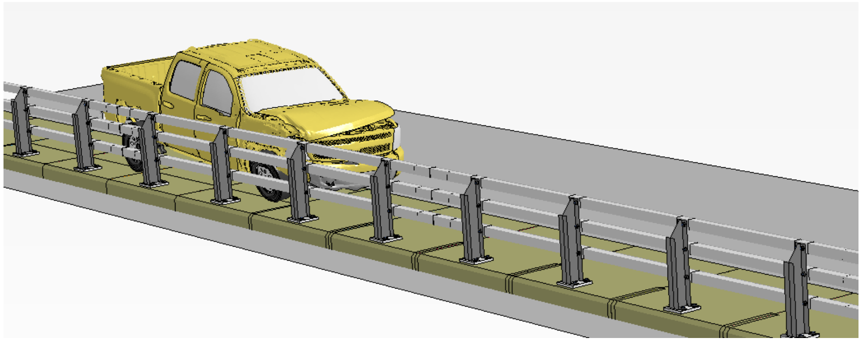

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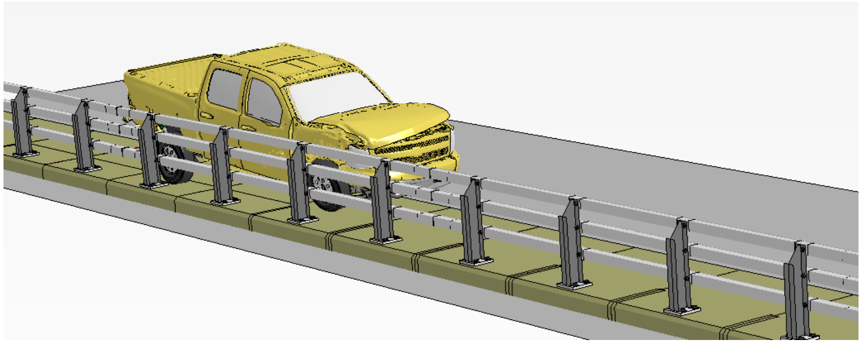

Figure I-3. [Continued] Sequential views from analysis of MASH Test 4-11 for sidewalk-mounted S3-TL4 from an oblique viewpoint.

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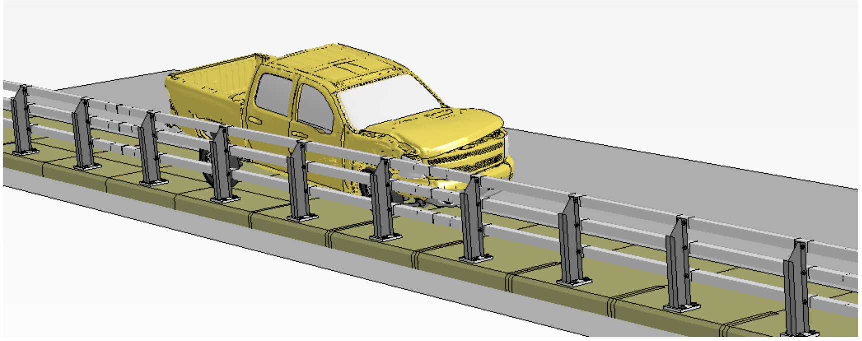

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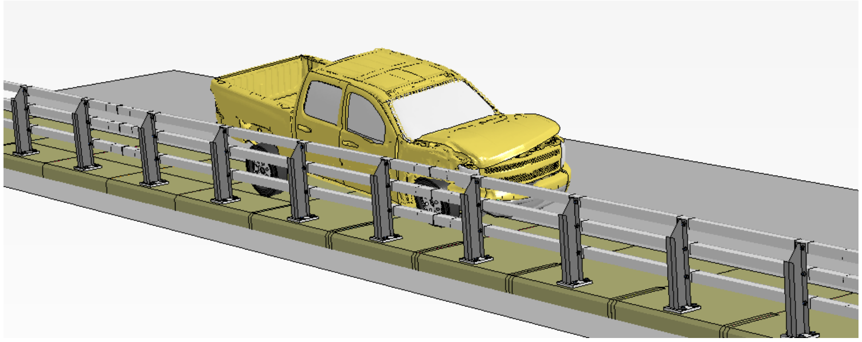

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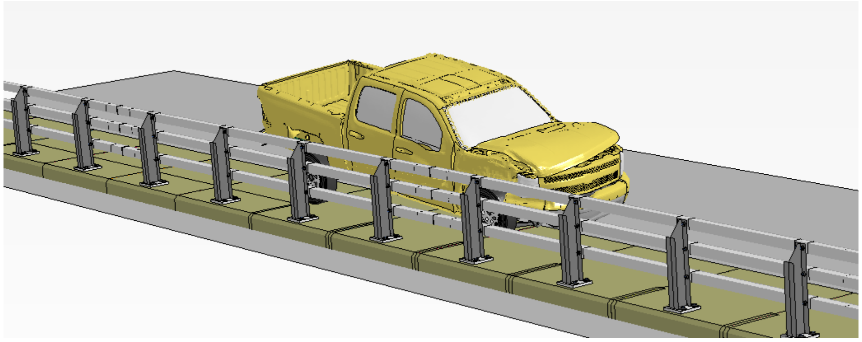

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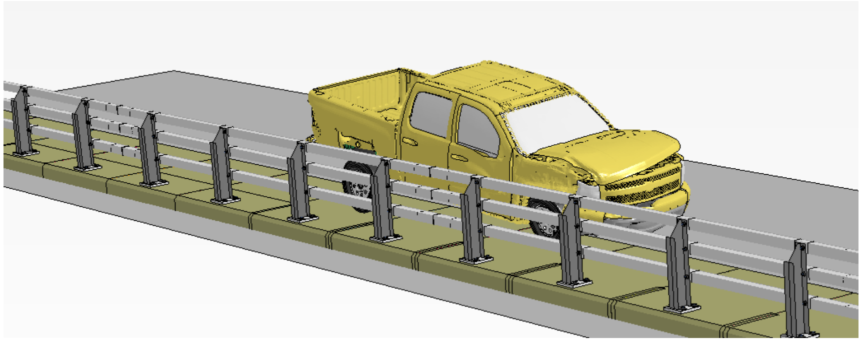


Figure I-3. [Continued] Sequential views from analysis of MASH Test 4-11 for sidewalk-mounted S3-TL4 from an oblique viewpoint.

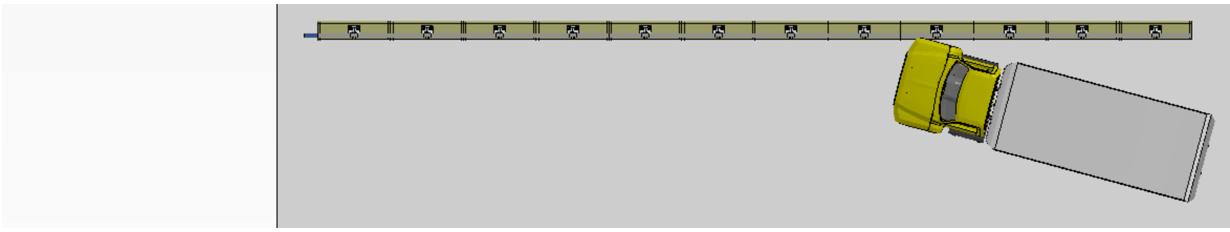
Appendix J

Sequential Views for MASH Test 4-12 for

Curb-Mounted S3-TL4 Bridge Rail

(Case 1)

0.00 seconds



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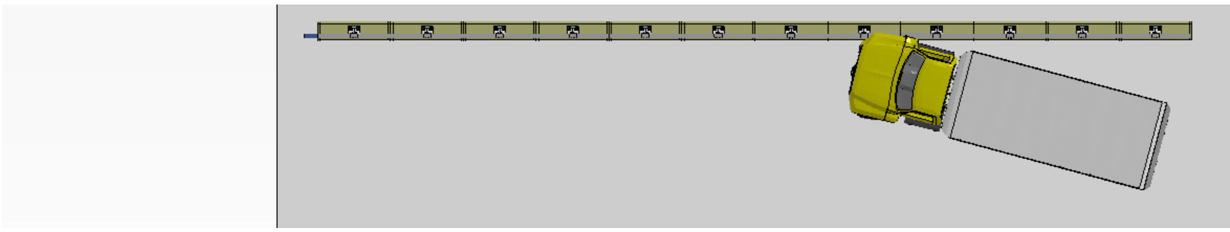

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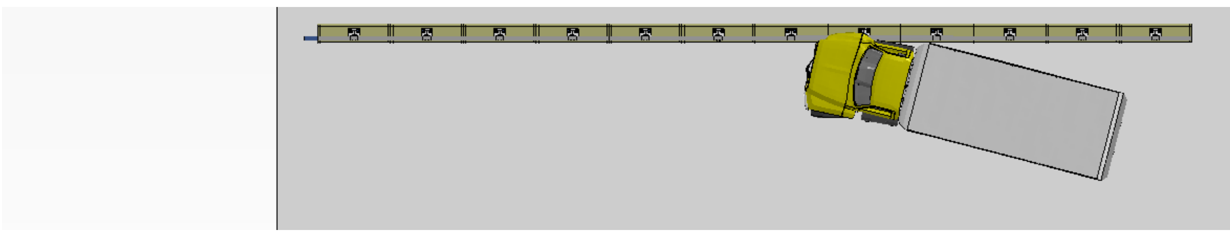

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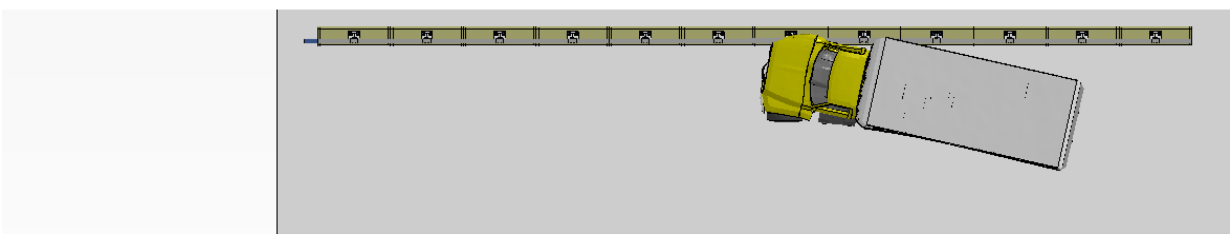

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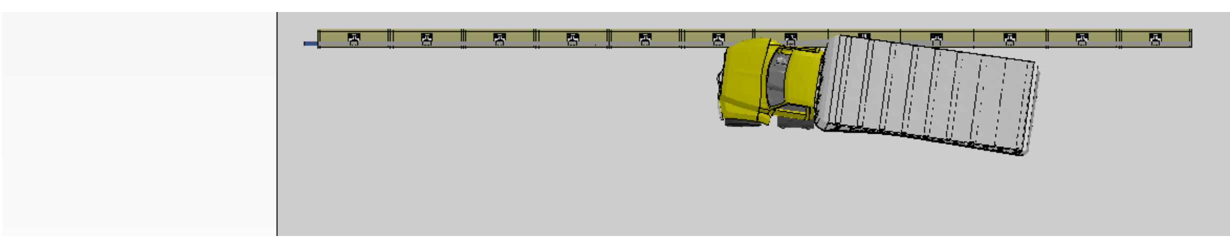
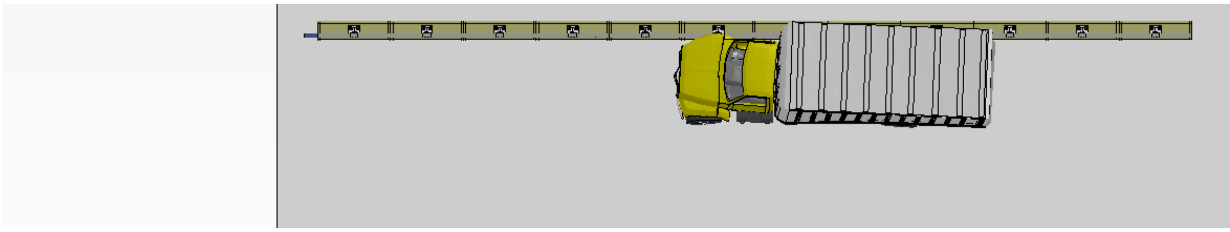


Figure J-1. Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 1).

0.25 seconds



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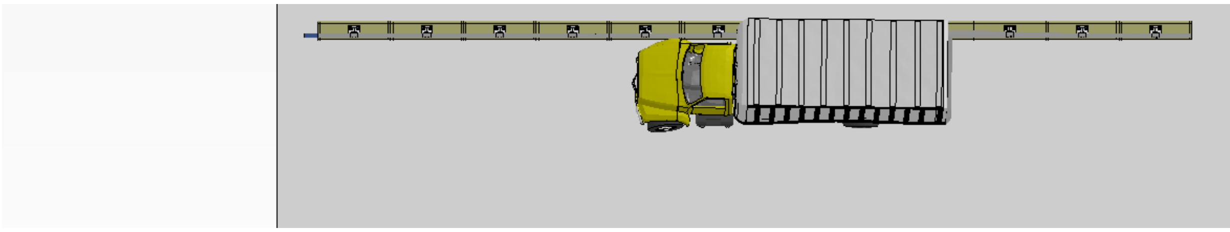

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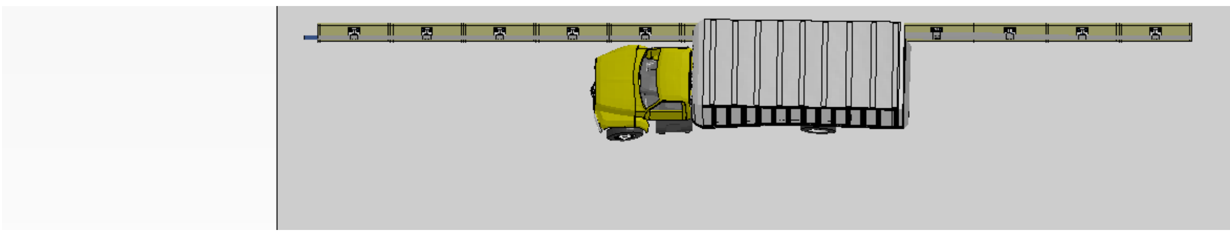

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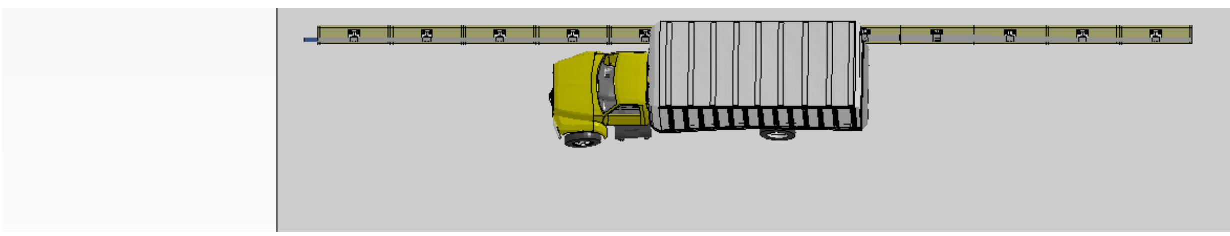

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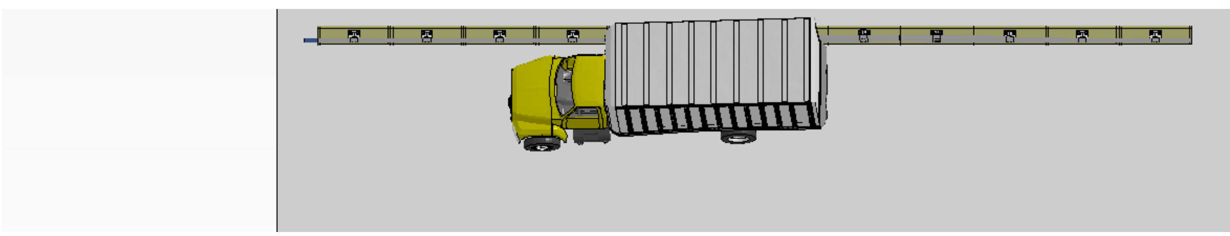

Figure J-1. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 1).

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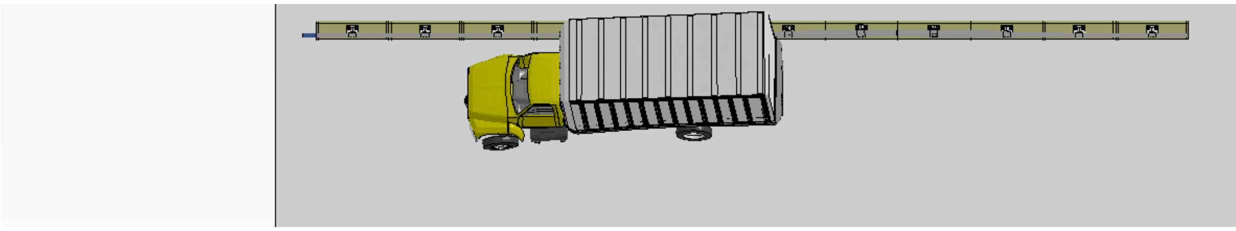

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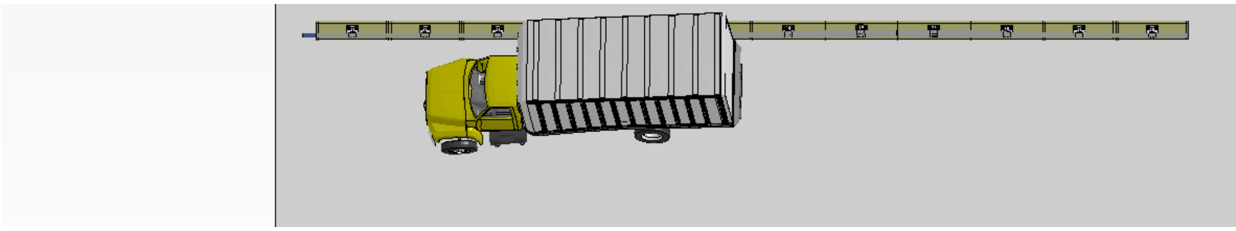

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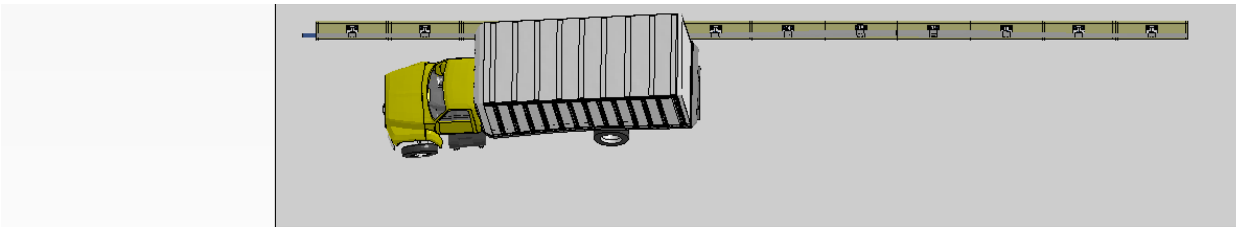

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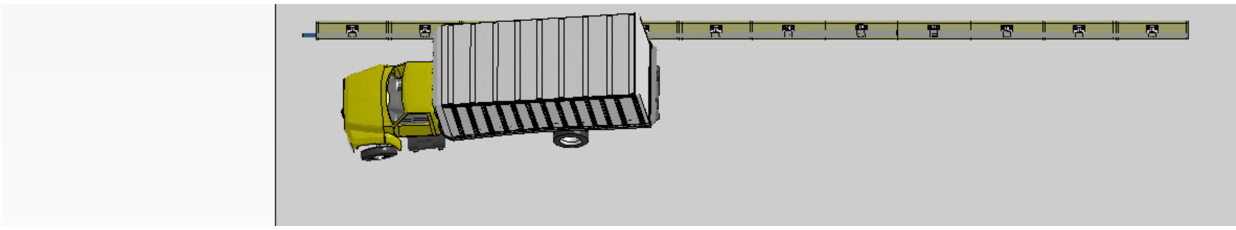

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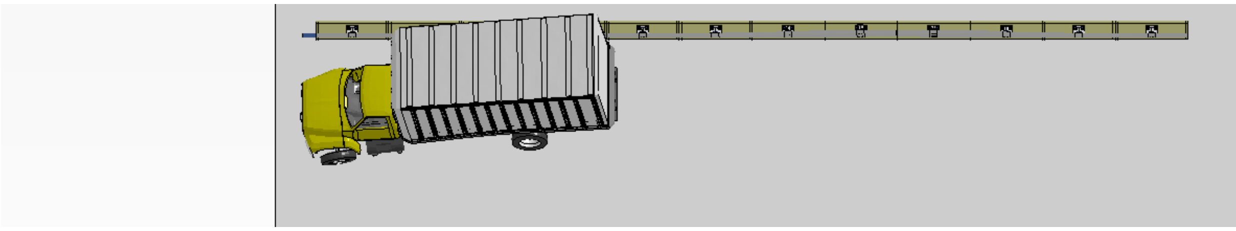

Figure J-1. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 1).

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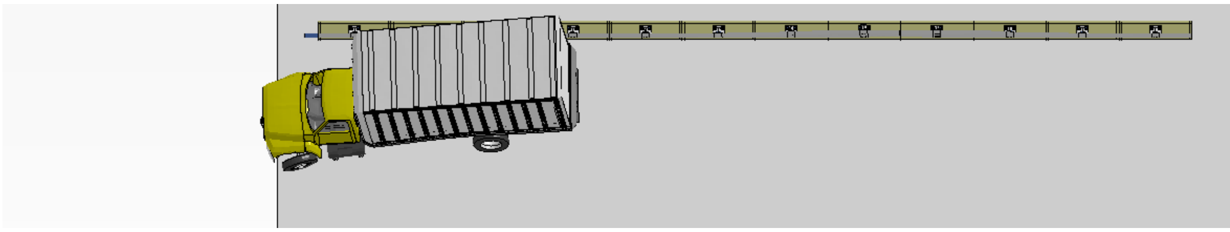

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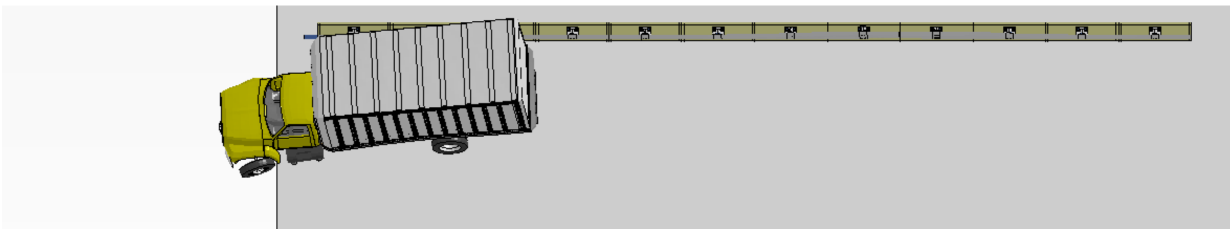

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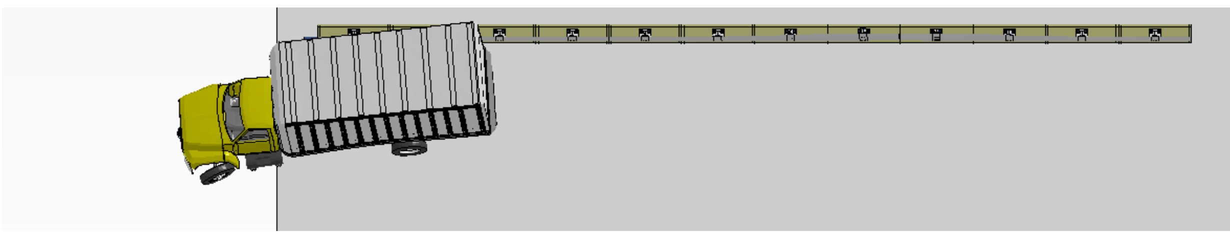

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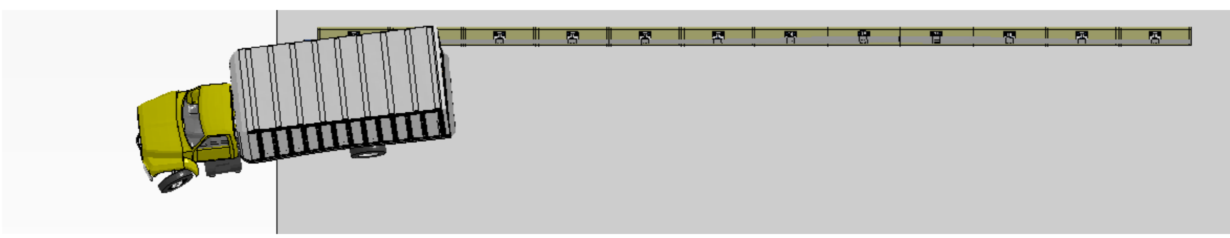

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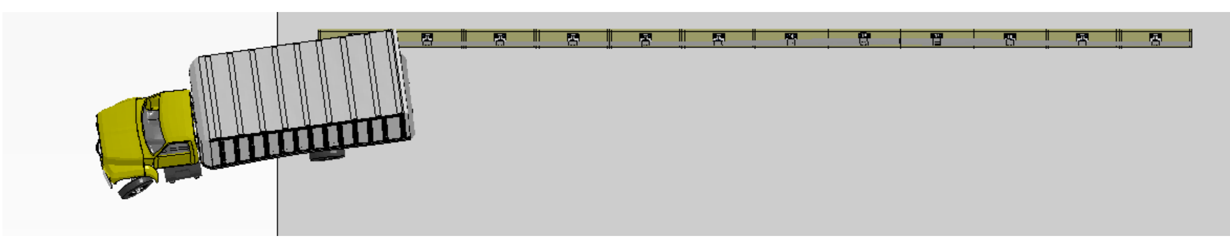

Figure J-1. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 1).

0.00 seconds

0.10 seconds

0.20 seconds

0.30 seconds

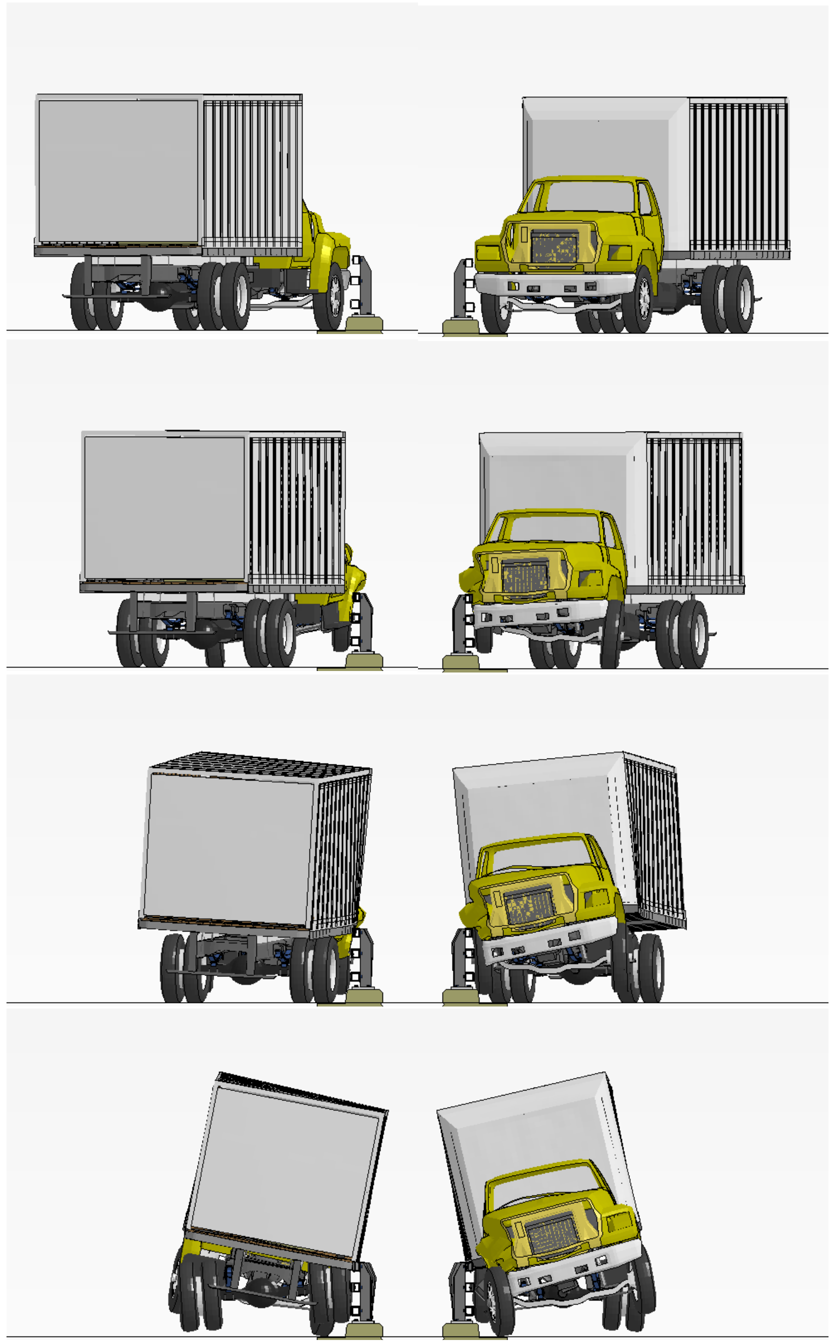

Figure J-2. Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from upstream and downstream viewpoints (Case 1).

0.40 seconds

0.50 seconds

0.60 seconds

0.70 seconds

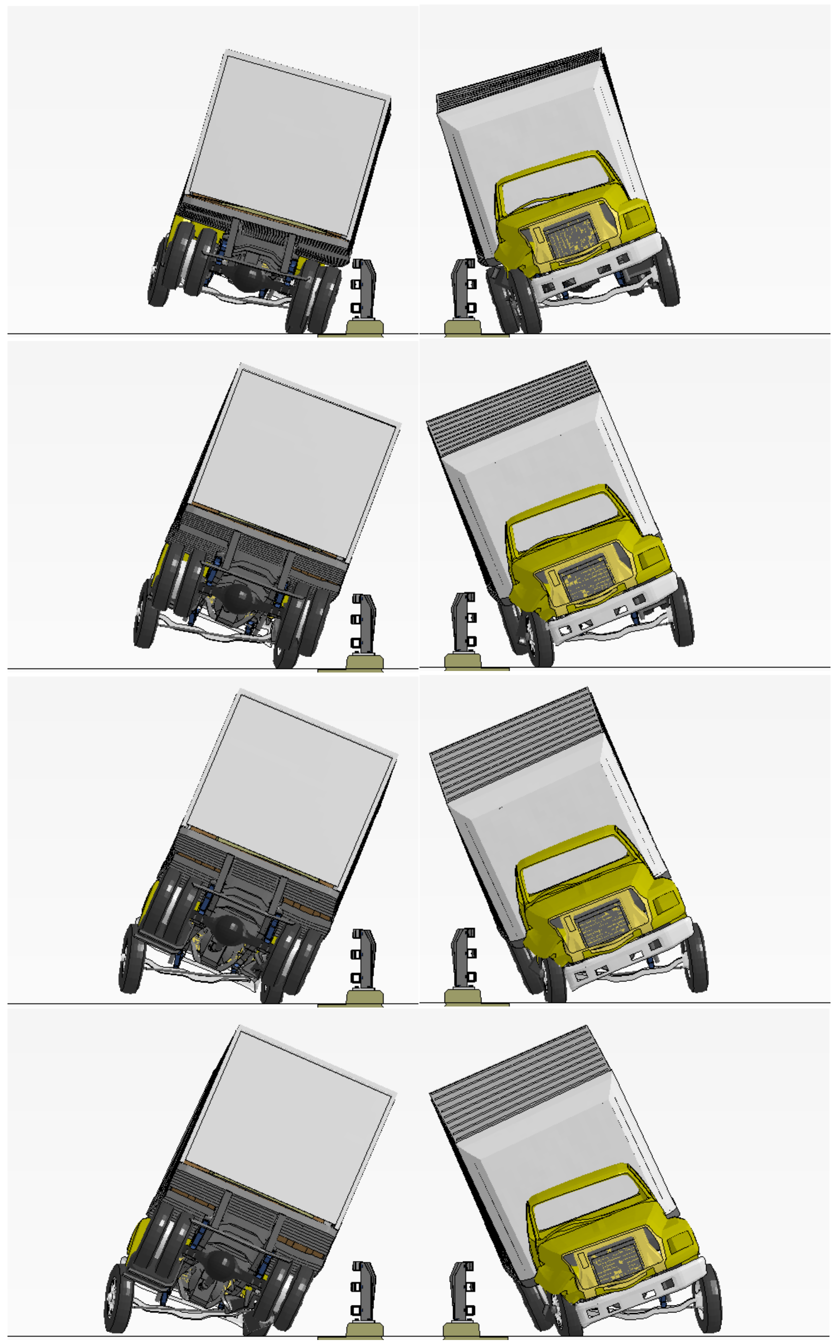

Figure J-2. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from upstream and downstream viewpoints (Case 1).

0.80 seconds

0.90 seconds

1.00 seconds

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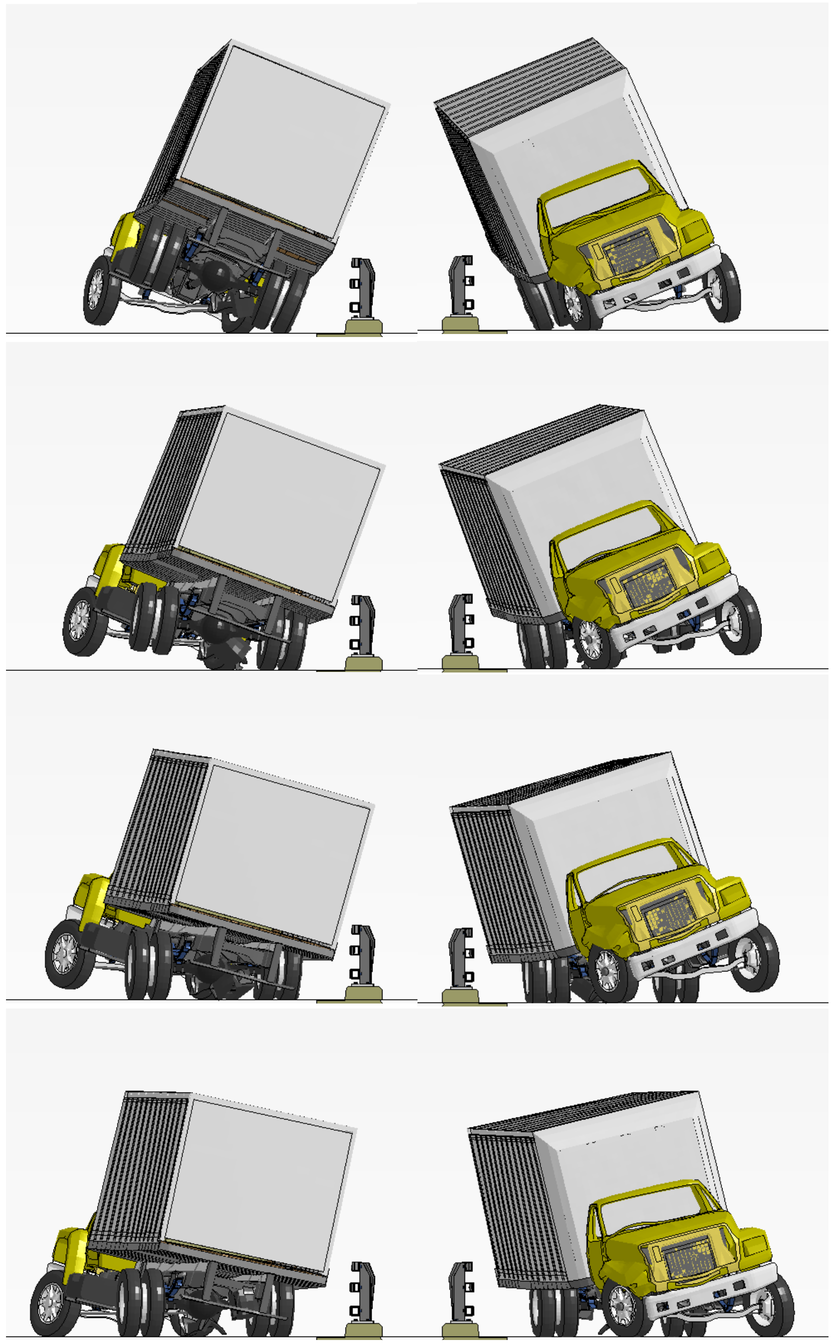
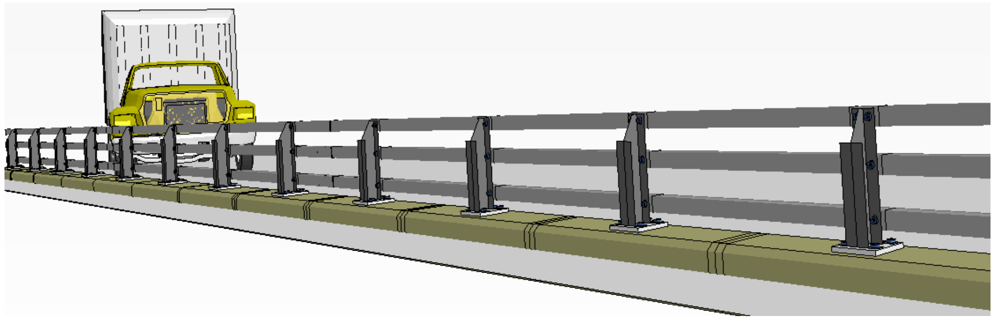


Figure J-2. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from upstream and downstream viewpoints (Case 1).

0.00 seconds



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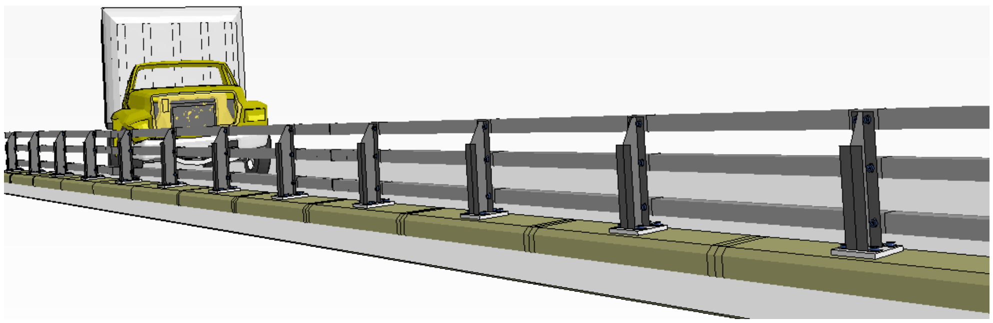

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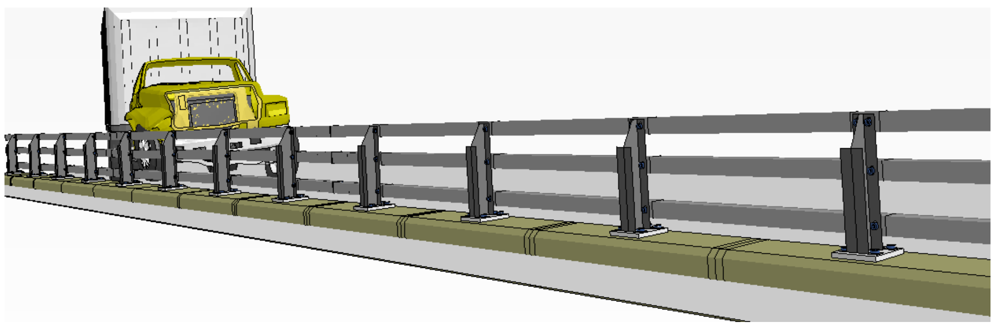


0.15 seconds

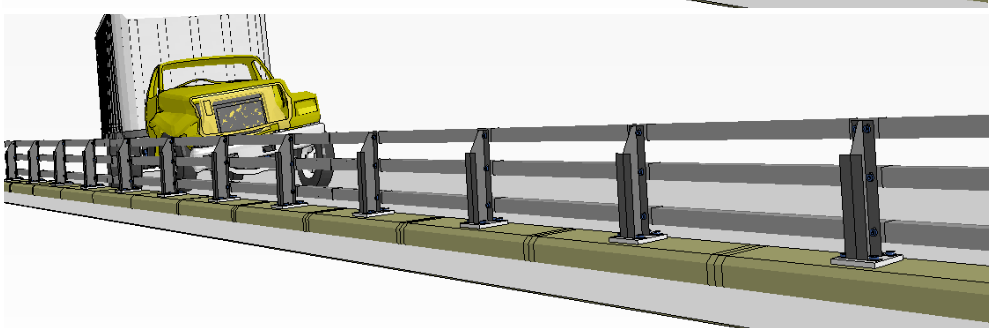
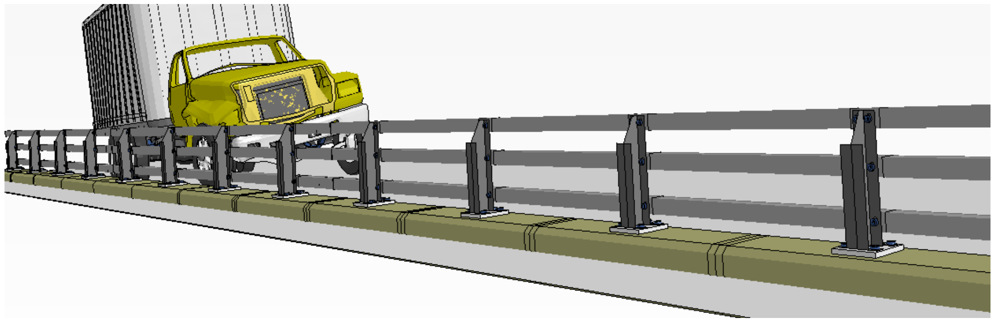


Figure J-3. Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an oblique viewpoint (Case 1).

0.20 seconds



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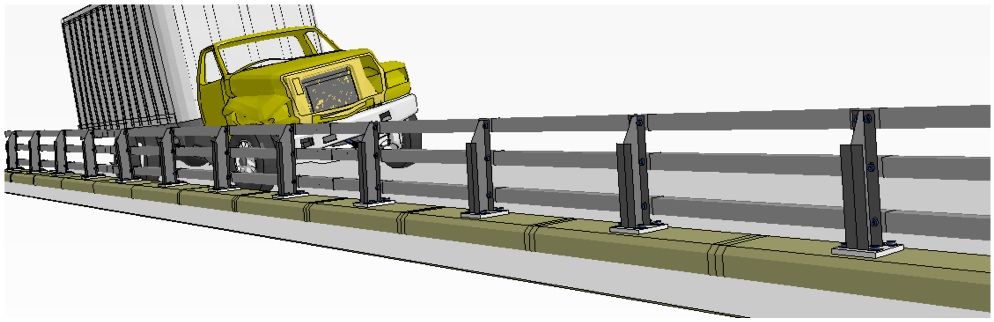

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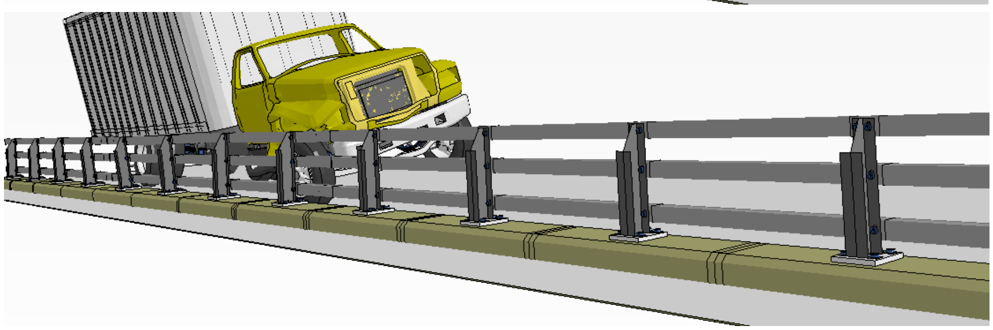

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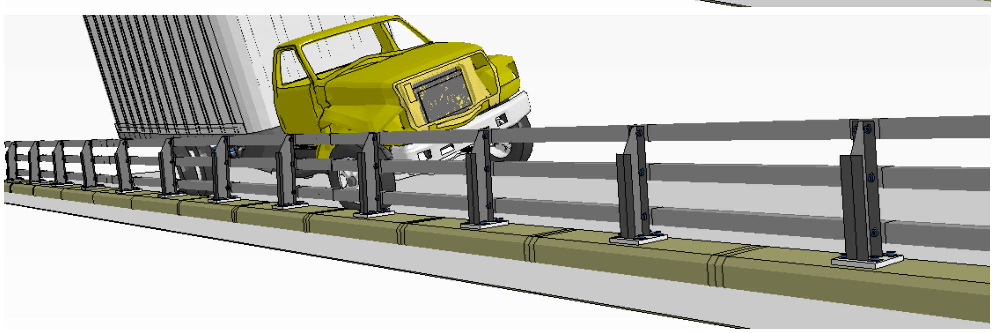
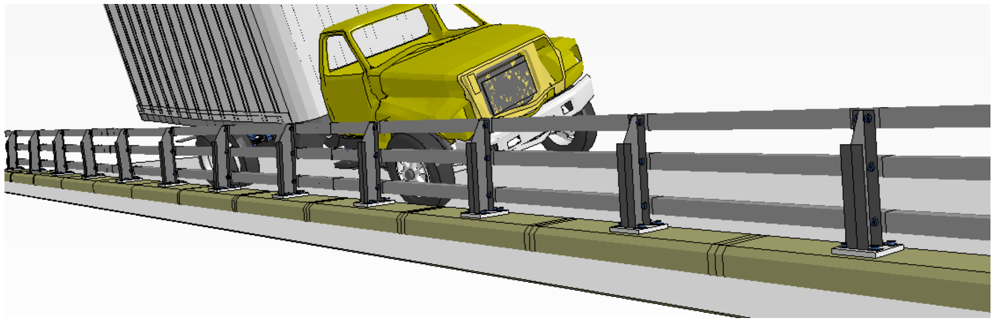


Figure J-3. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an oblique viewpoint (Case 1).

0.40 seconds



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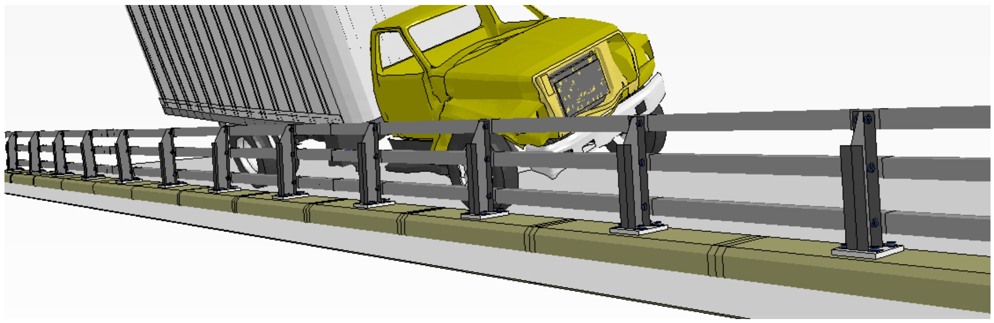

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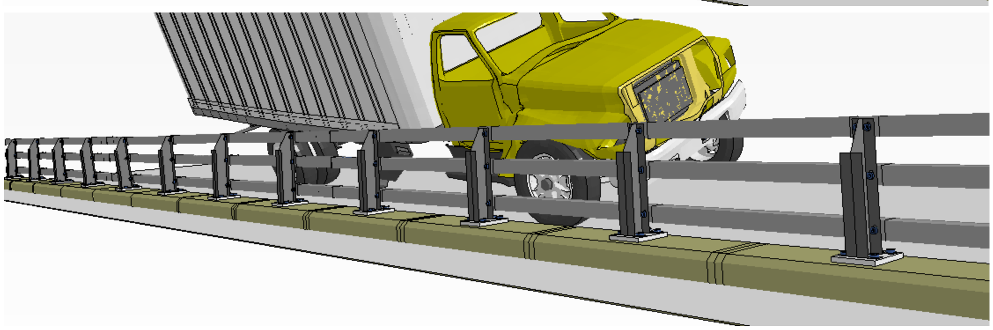

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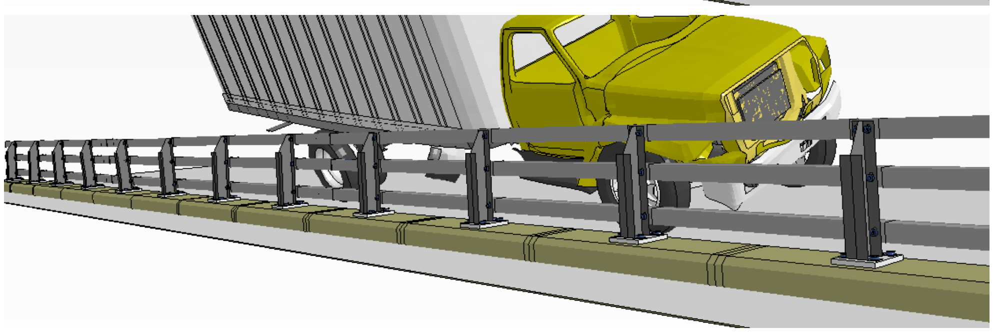


Figure J-3. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an oblique viewpoint (Case 1).

Appendix K

Sequential Views for MASH Test 4-12 for

Curb-Mounted S3-TL4 Bridge Rail

(Case 2)

0.00 seconds

0.05 seconds

0.10 seconds

0.15 seconds

0.20 seconds

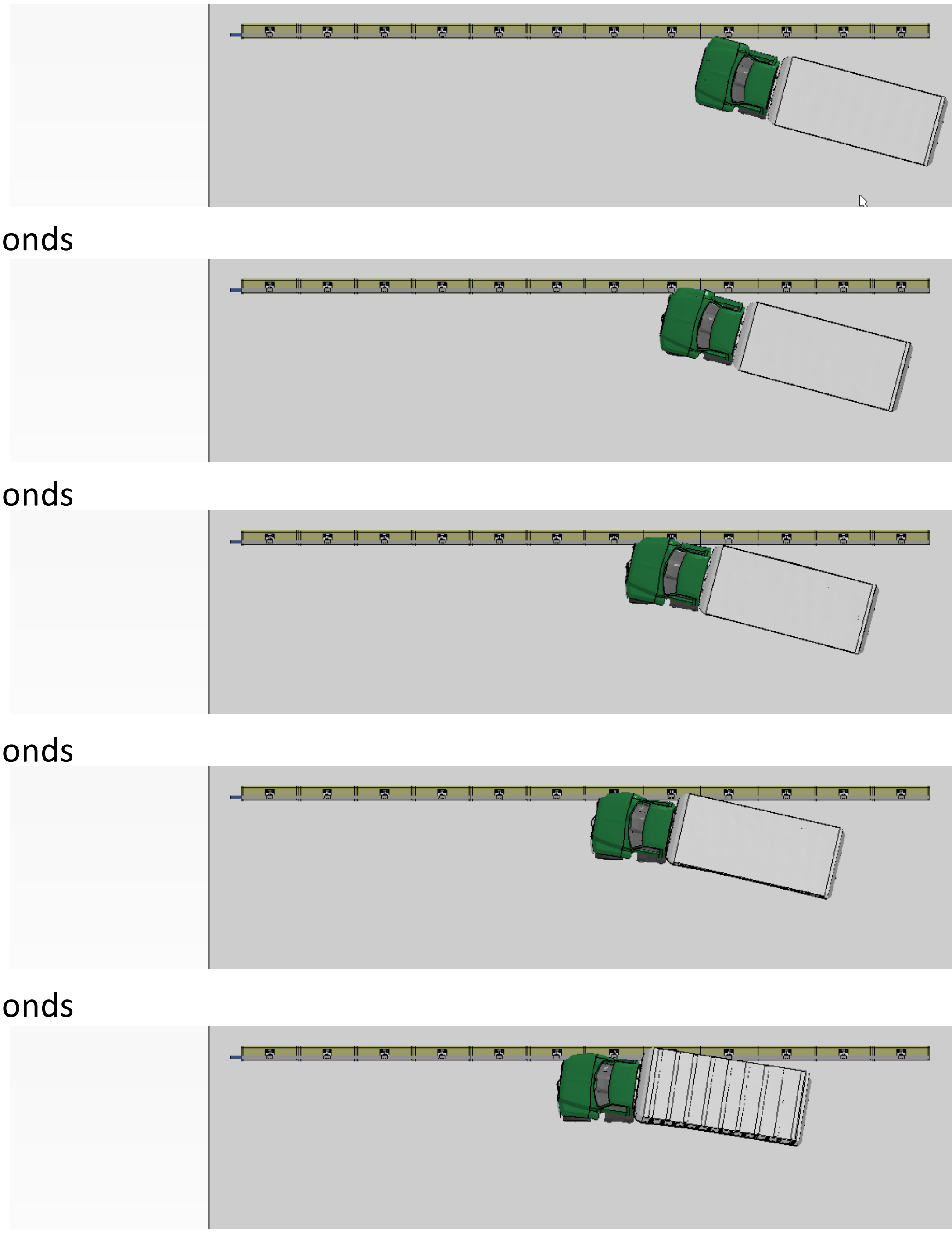
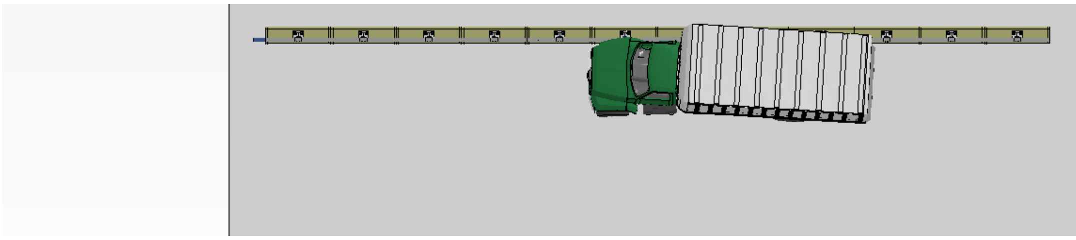


Figure K-1. Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 2).

0.25 seconds



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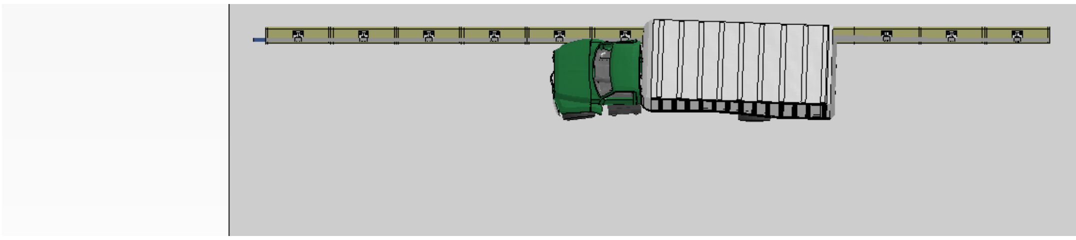

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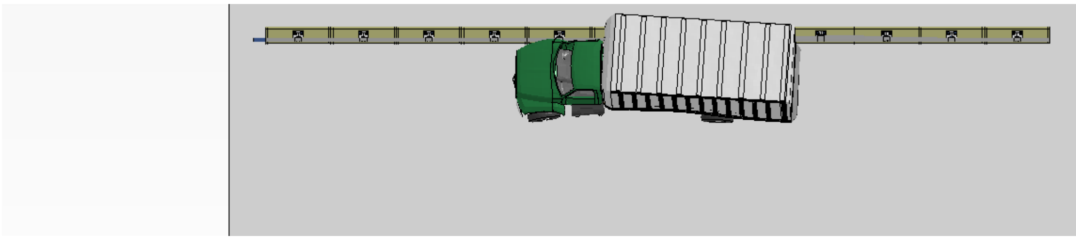

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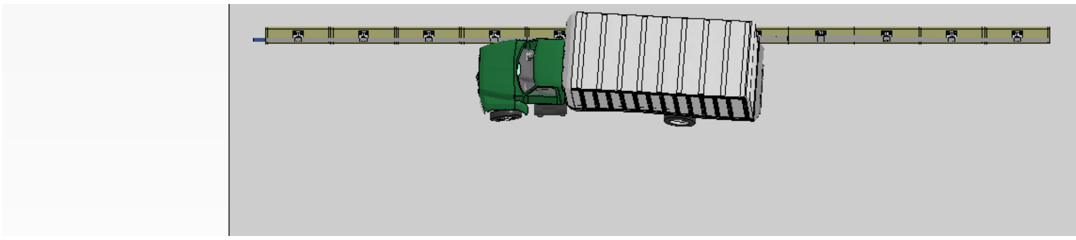

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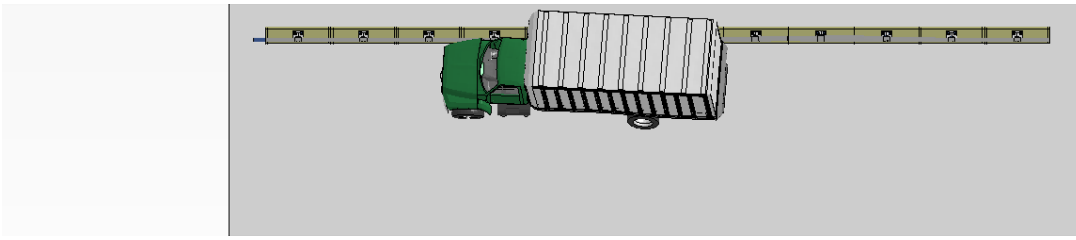


Figure K-1. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 2).

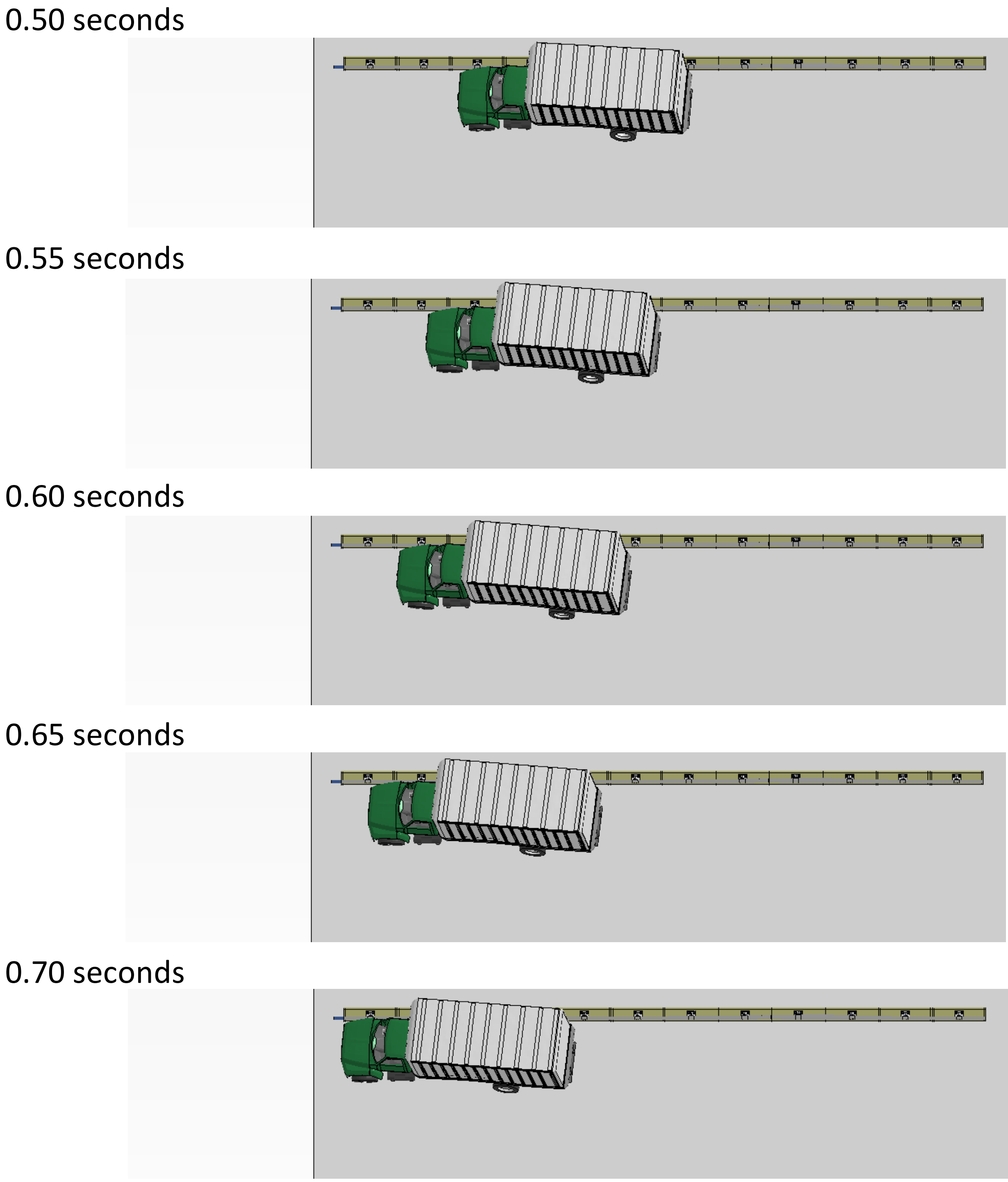
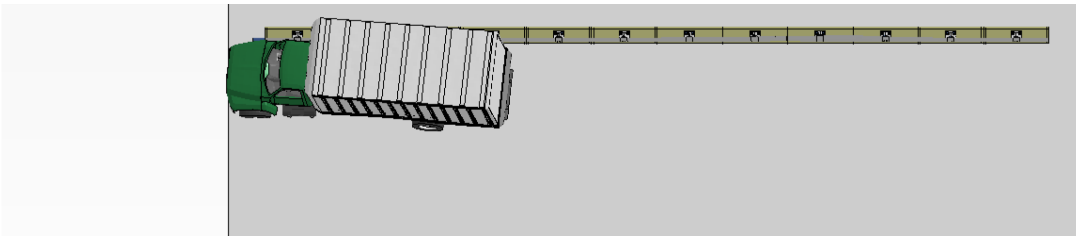


Figure K-1. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 2).

0.75 seconds



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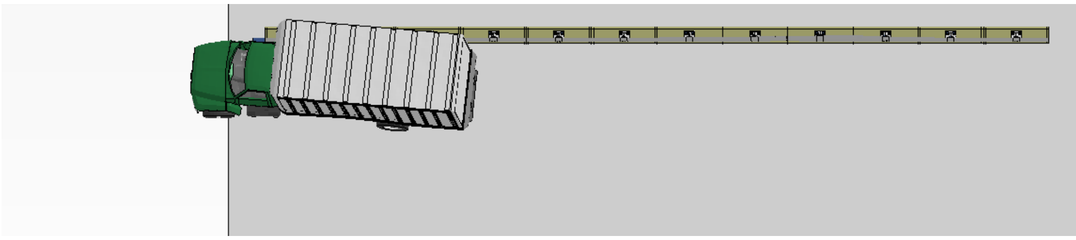

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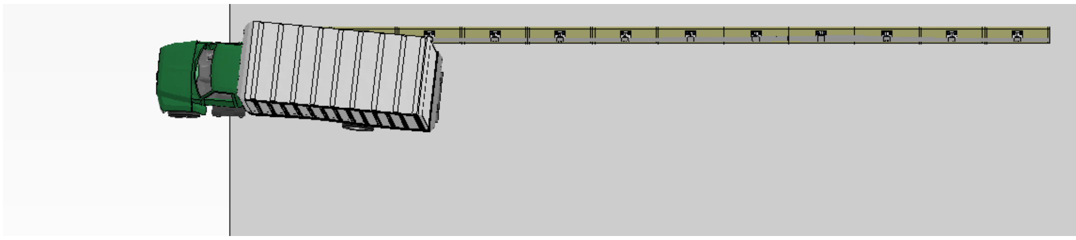

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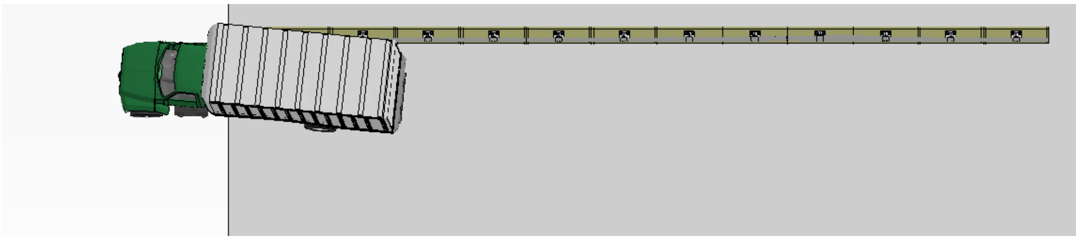

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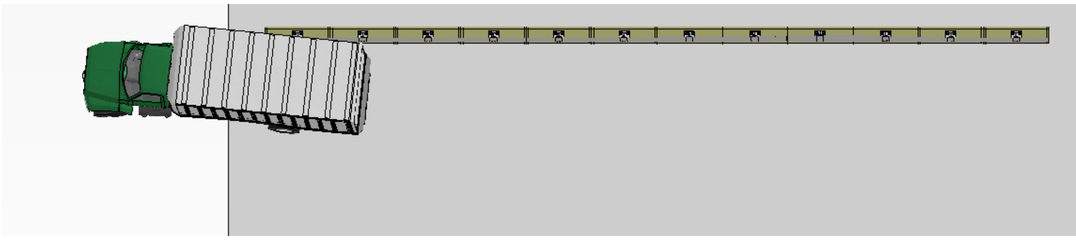
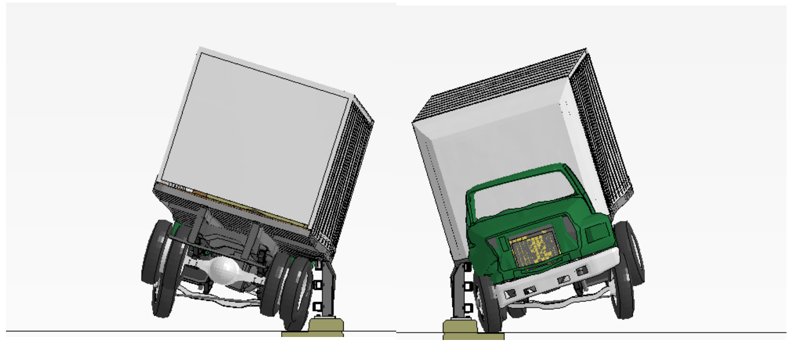


Figure K-1. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 2).

Figure K-2. Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from upstream and downstream viewpoints (Case 2).

0.40 seconds



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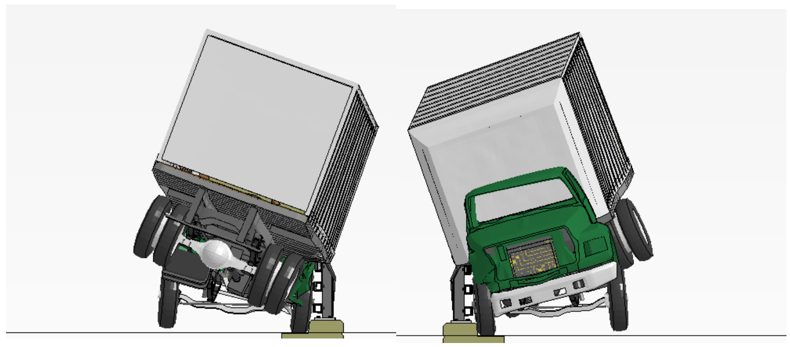

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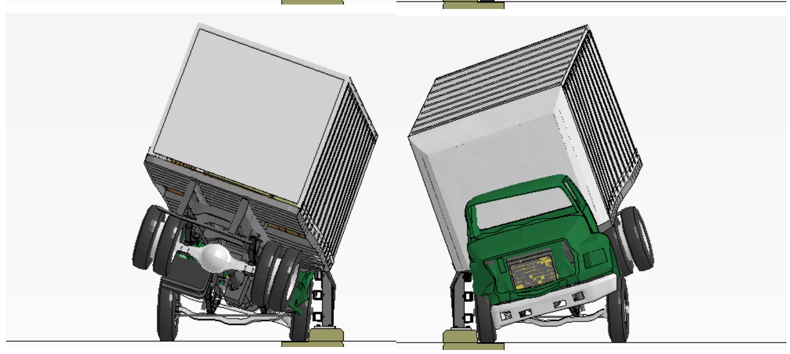

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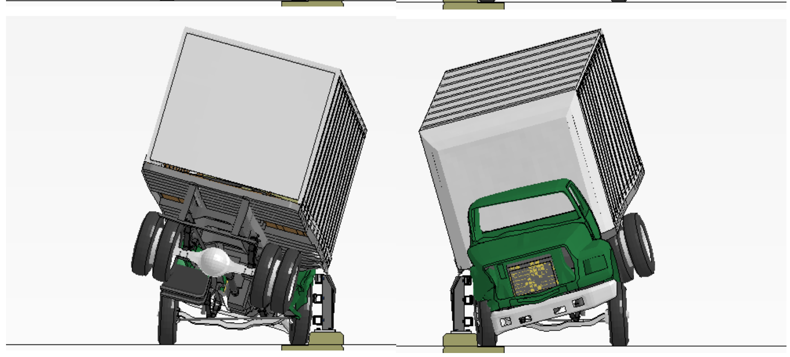
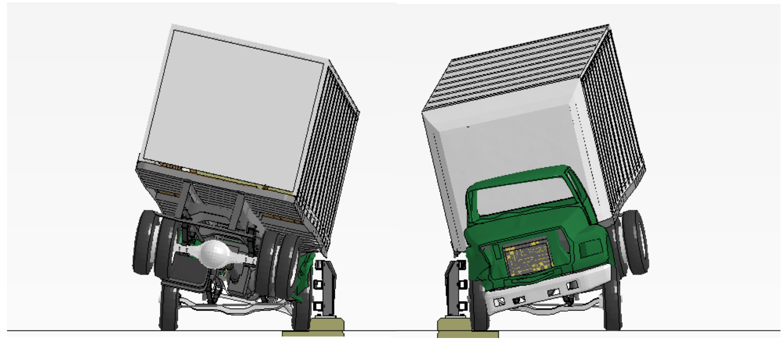


Figure K-2. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from upstream and downstream viewpoints (Case 2).

0.80 seconds



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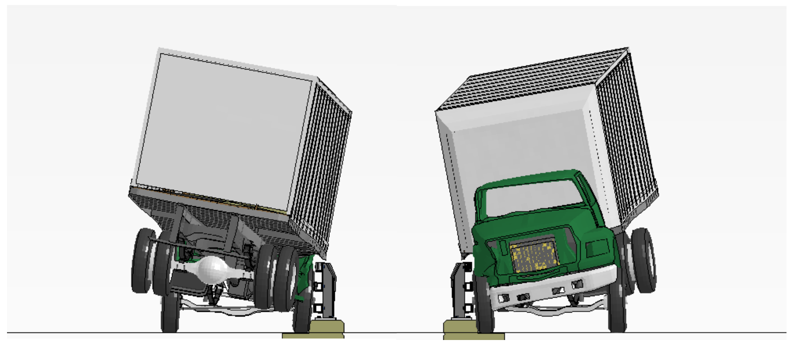

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1.05 seconds

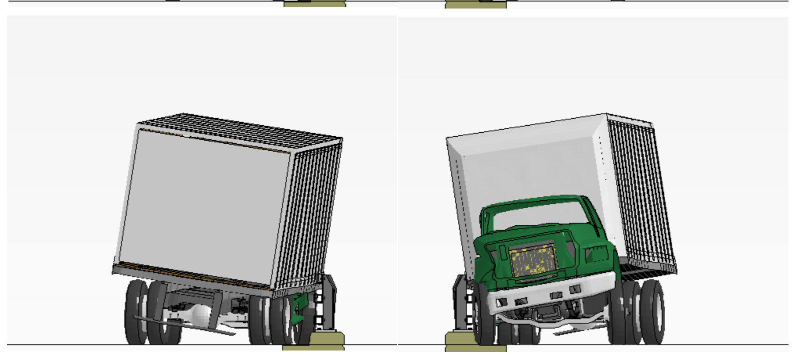


Figure K-2. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from upstream and downstream viewpoints (Case 2).

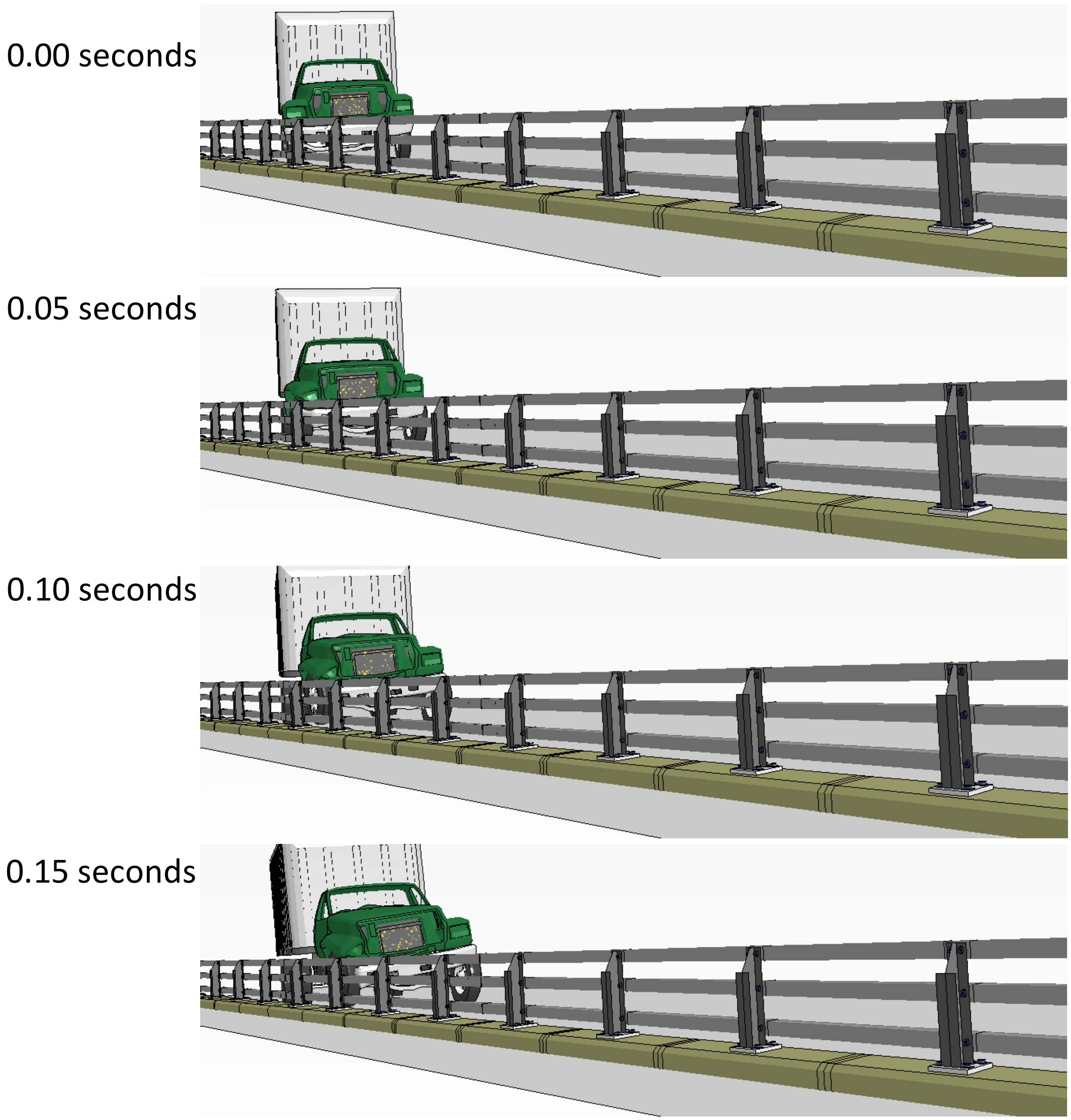


Figure K-3. Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an oblique viewpoint (Case 2).

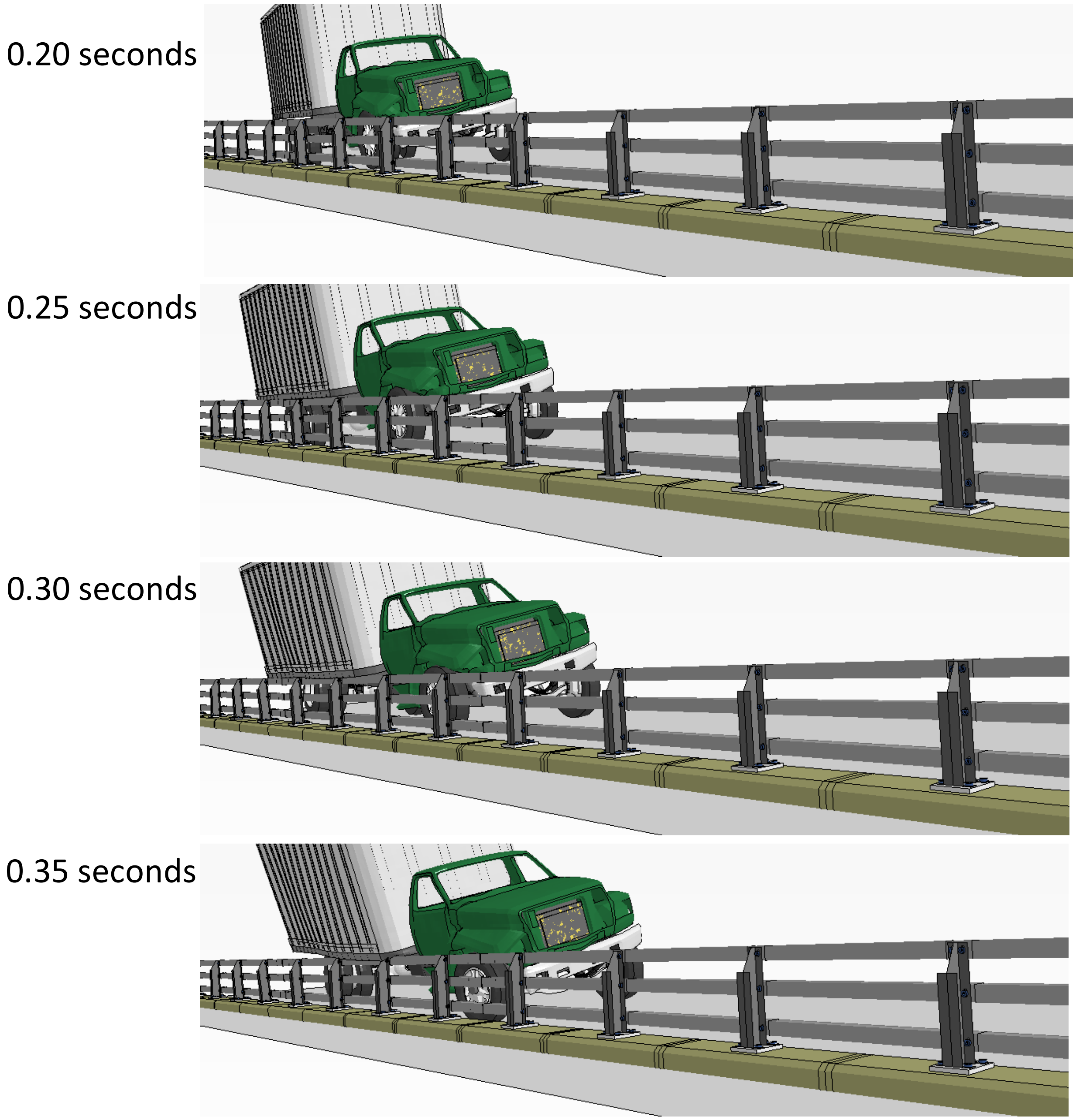
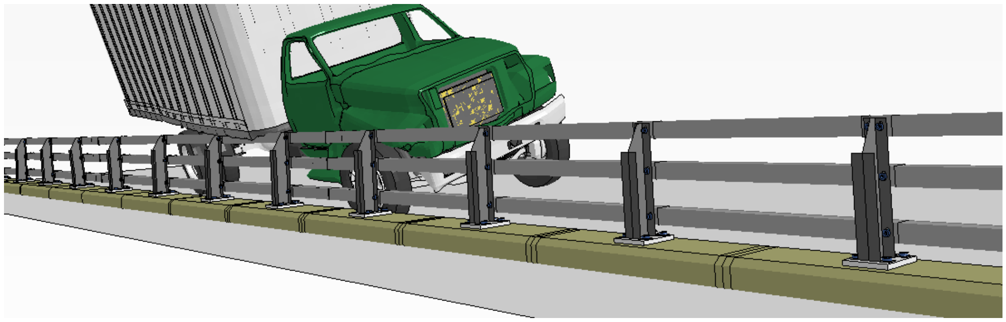


Figure K-3. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an oblique viewpoint (Case 2).

0.40 seconds



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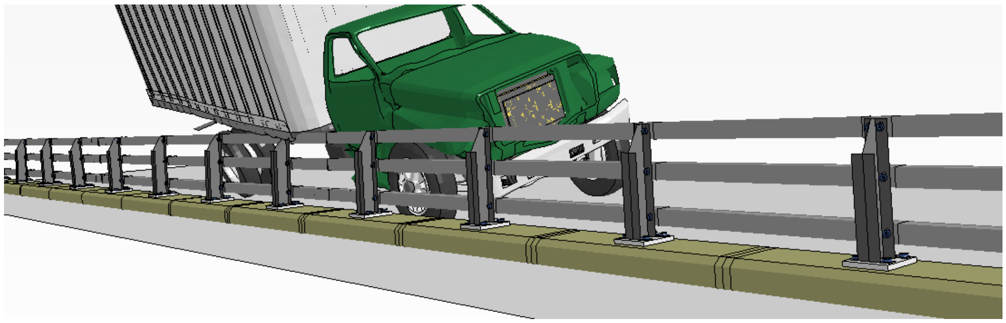

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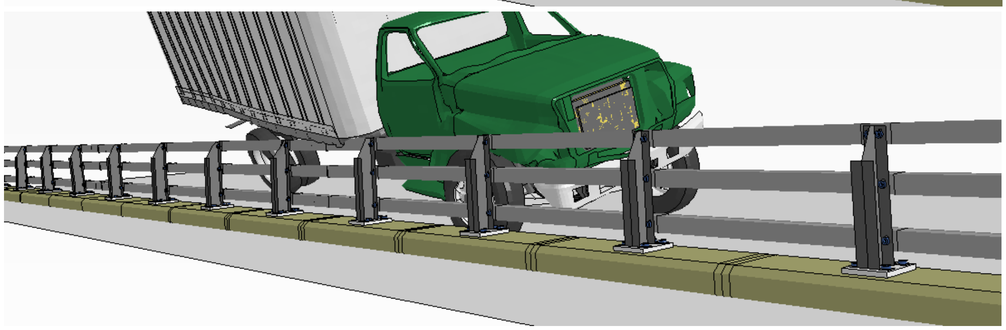

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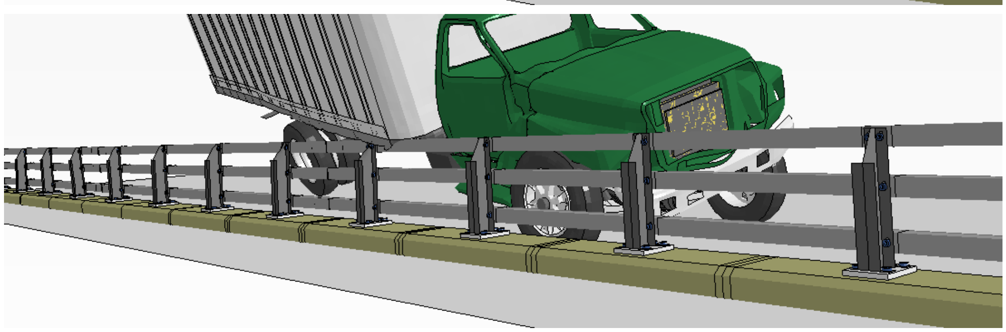


Figure K-3. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an oblique viewpoint (Case 2).

Appendix L

Sequential Views for MASH Test 4-12 for

Curb-Mounted S3-TL4 Bridge Rail

(Case 3)

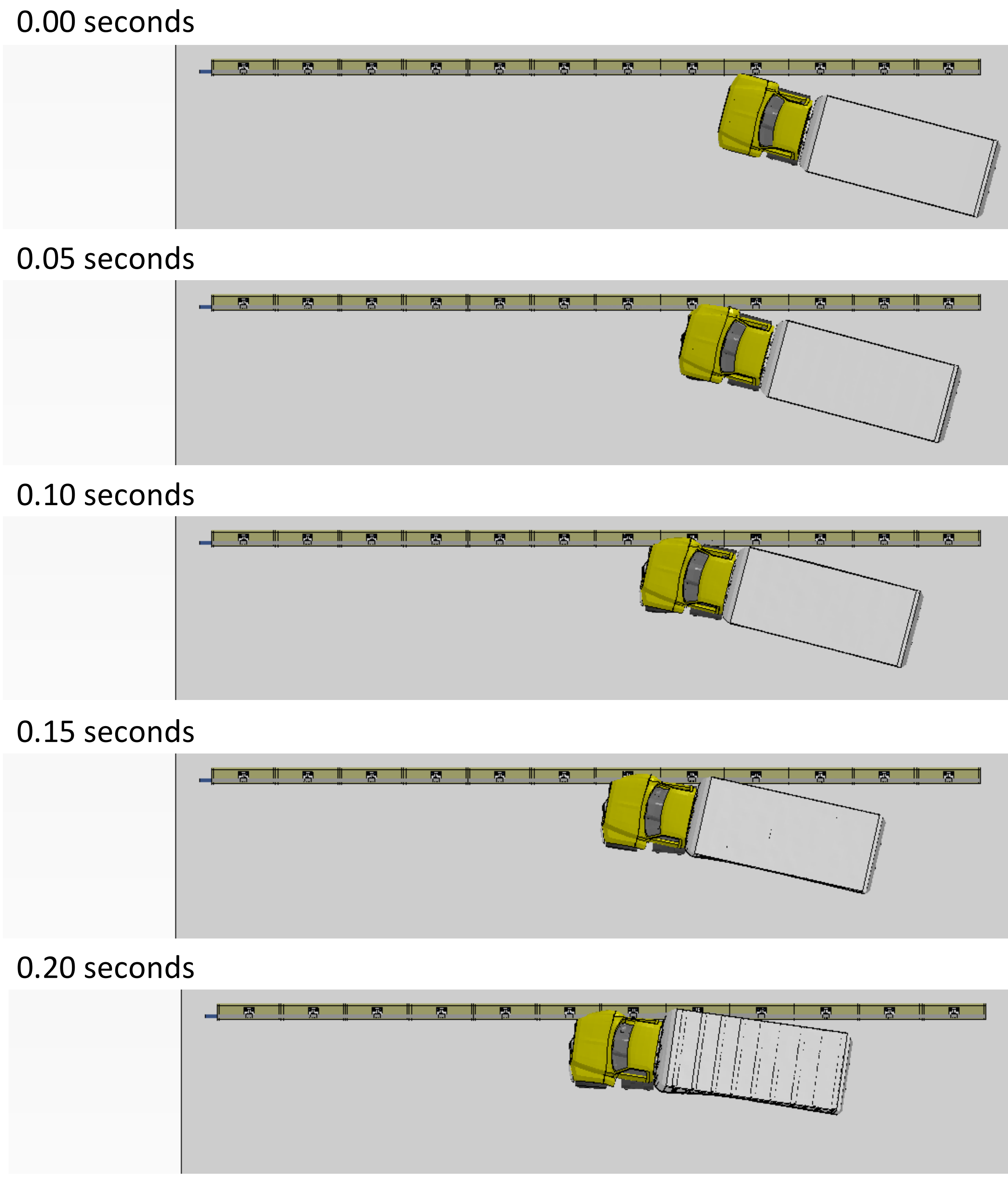
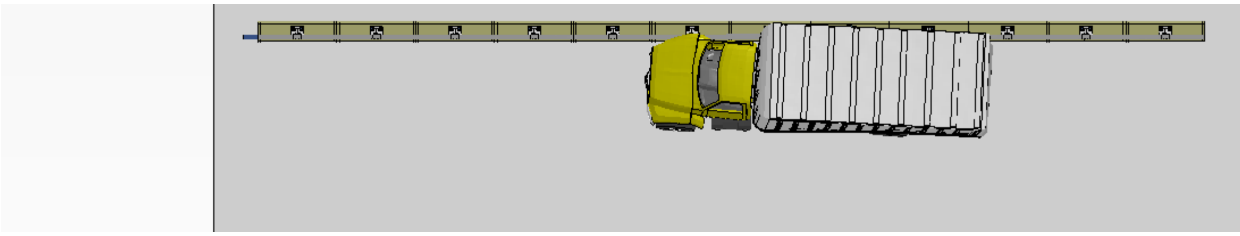


Figure L-1. Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 3).

0.25 seconds



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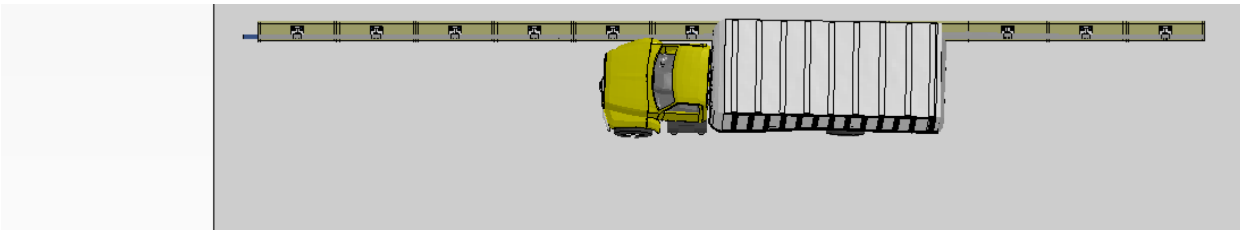

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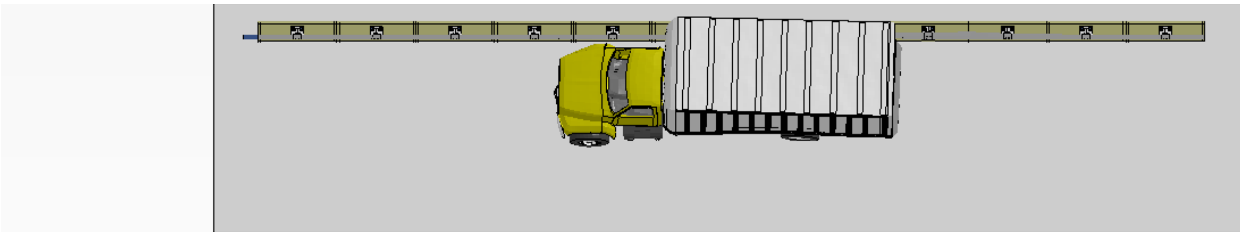

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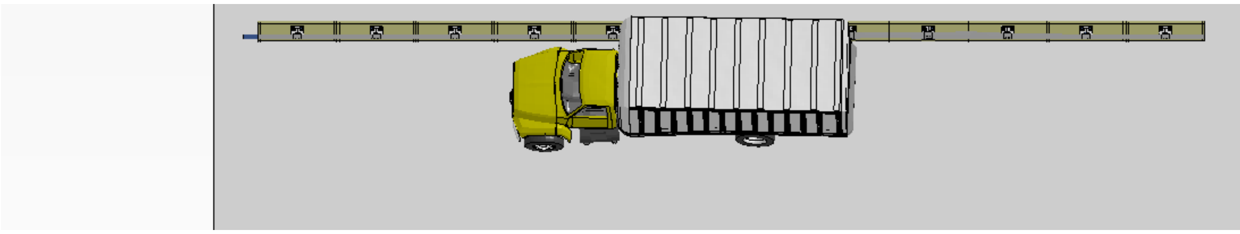

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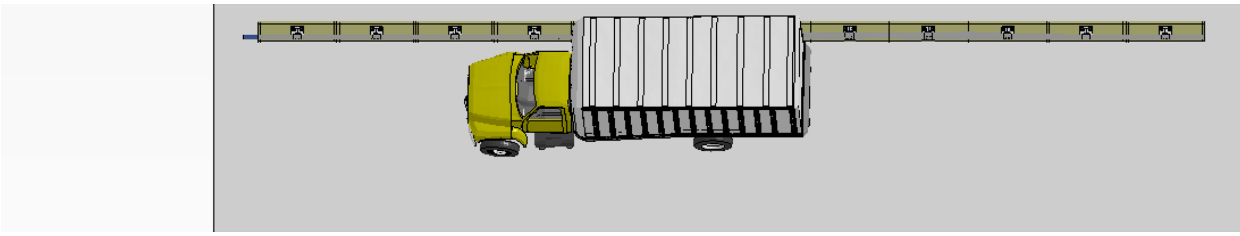
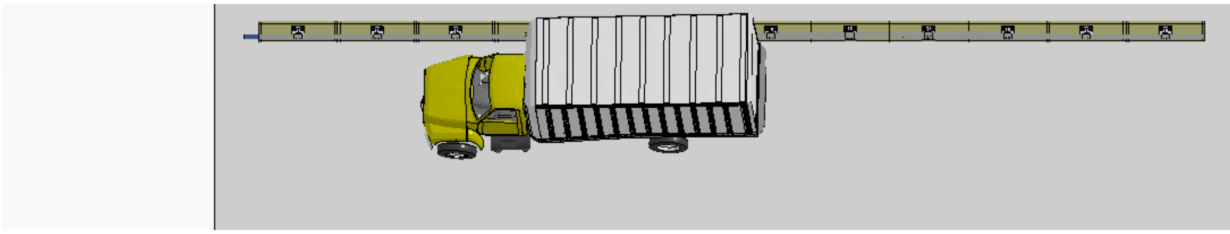


Figure L-1. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 3).

0.50 seconds



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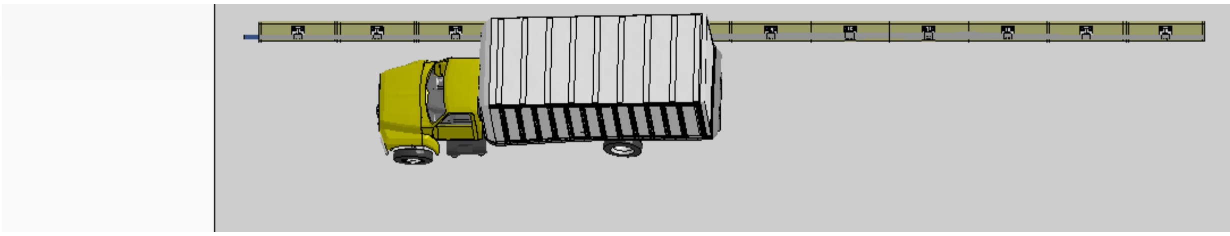

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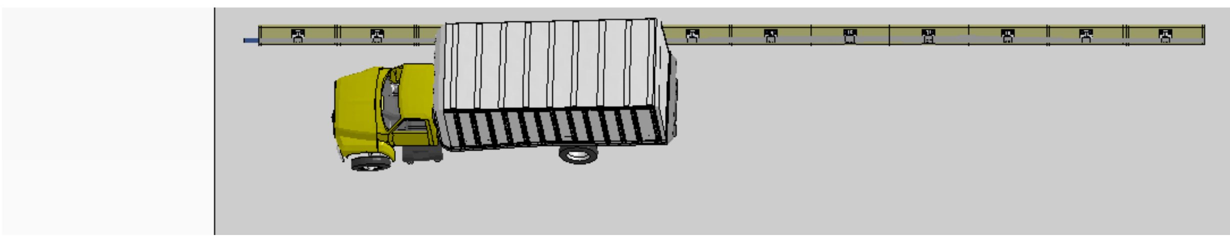

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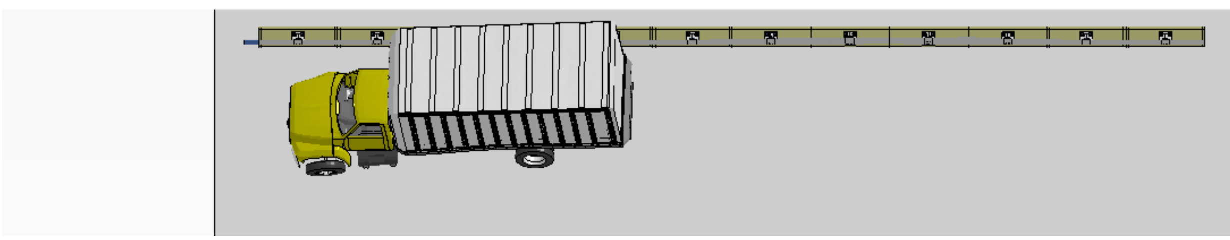

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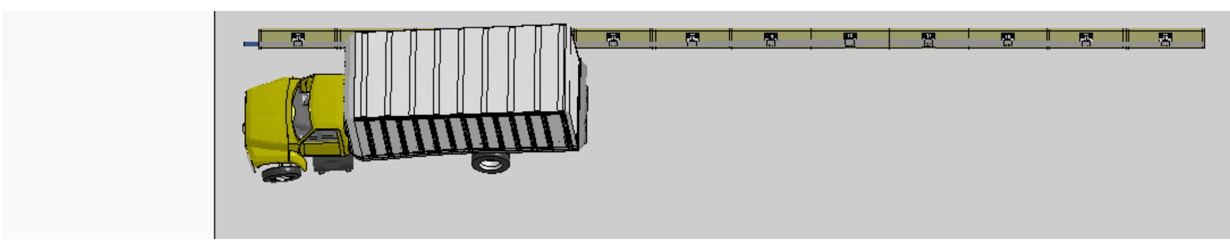
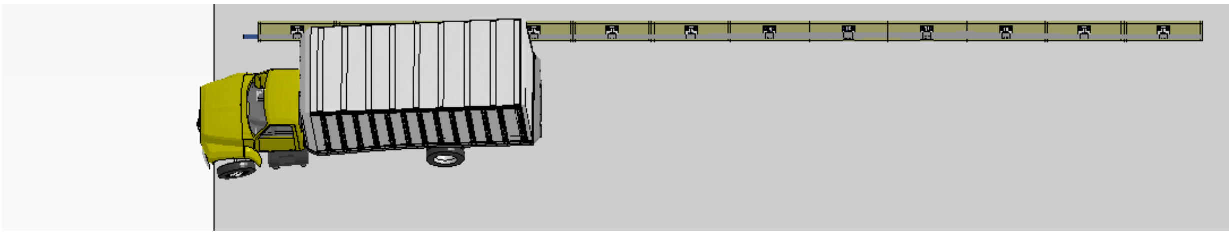


Figure L-1. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 3).

0.75 seconds



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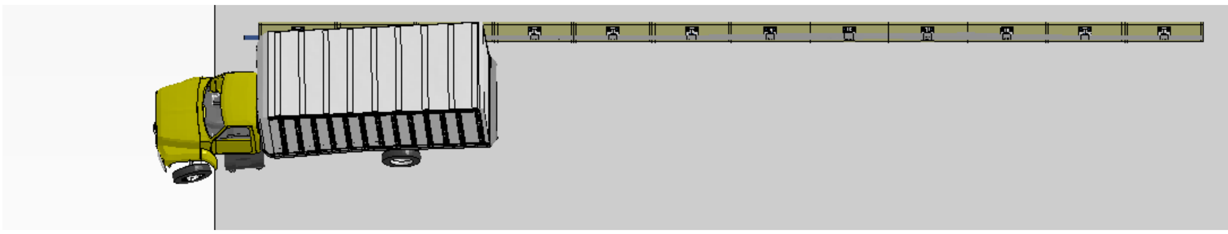

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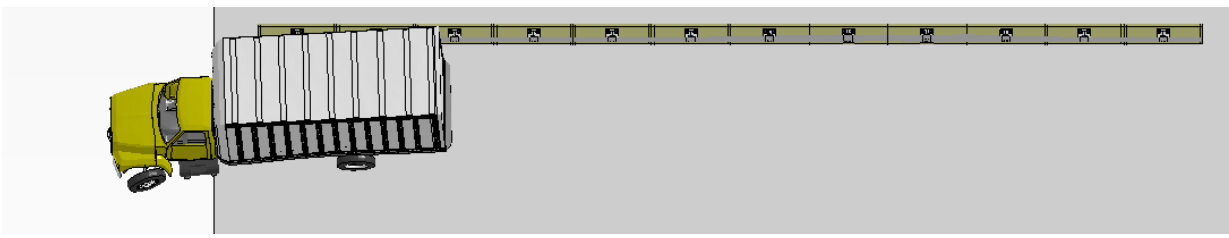

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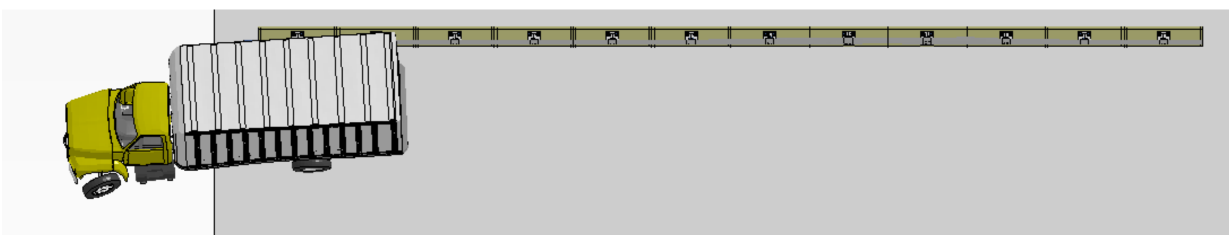

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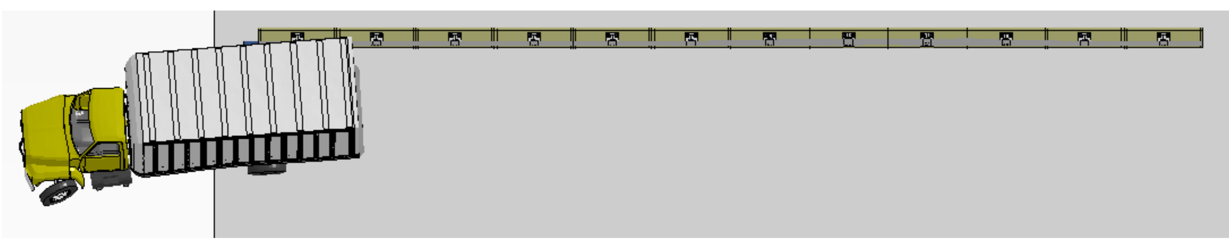

Figure L-1. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an overhead viewpoint (Case 3).

0.00 seconds

0.10 seconds

0.20 seconds

0.30 seconds

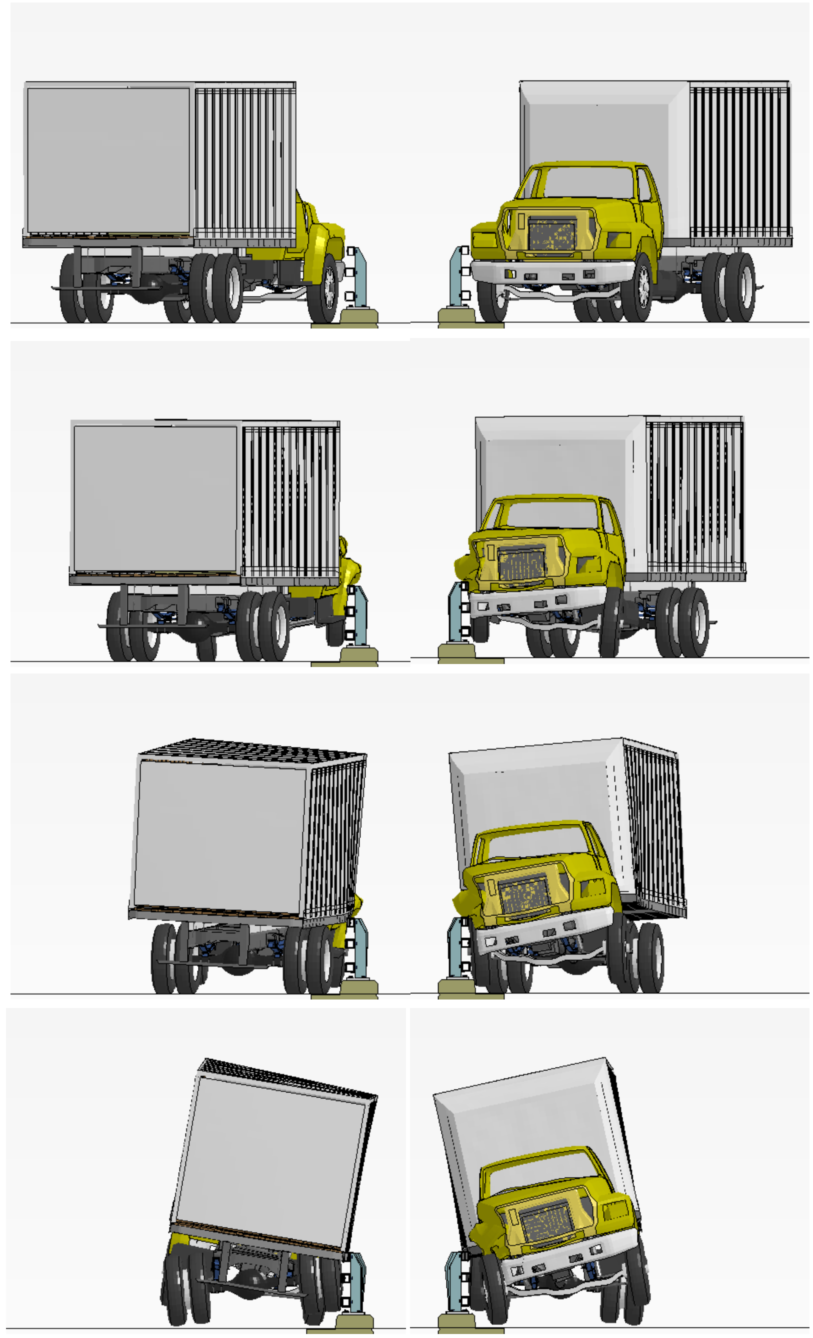

Figure L-2. Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from upstream and downstream viewpoints (Case 3).

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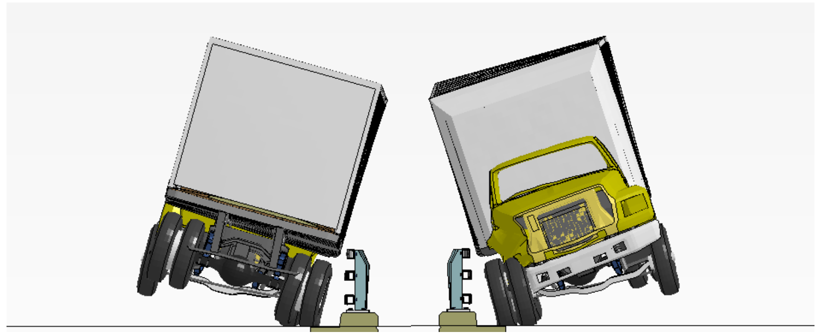

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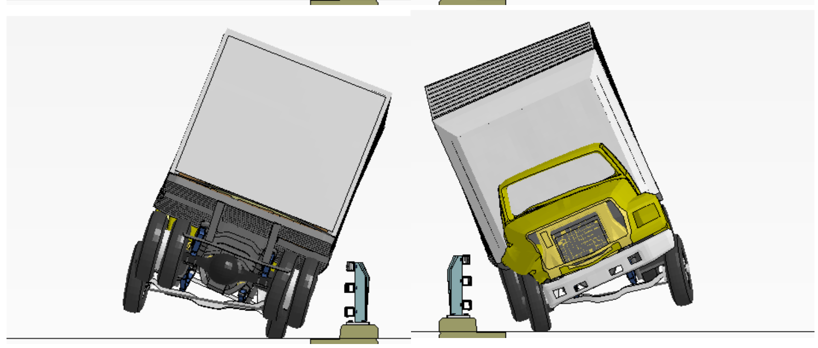

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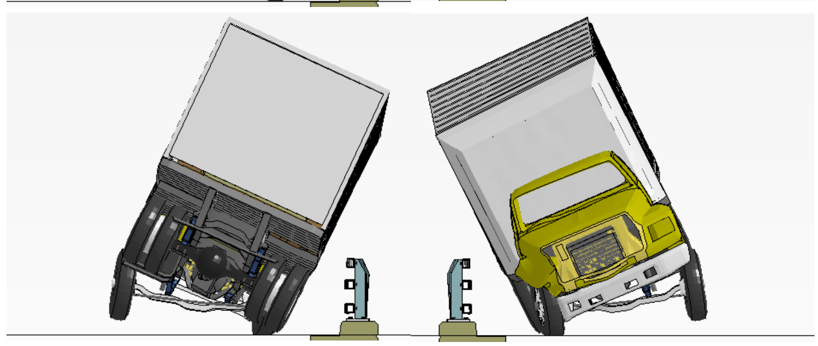

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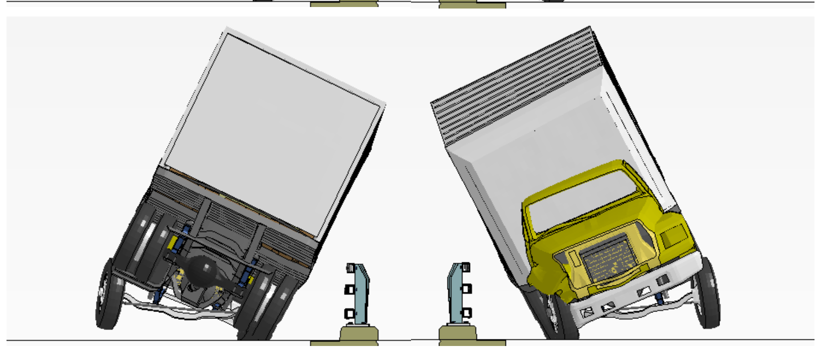
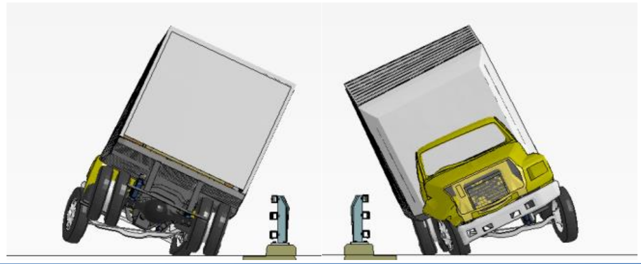


Figure L-2. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from upstream and downstream viewpoints (Case 3).

0.80 seconds



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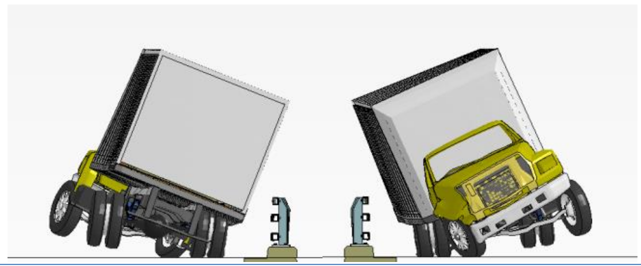

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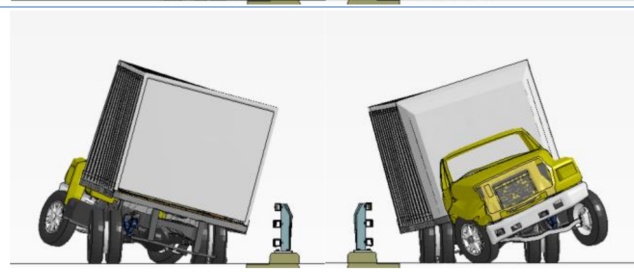

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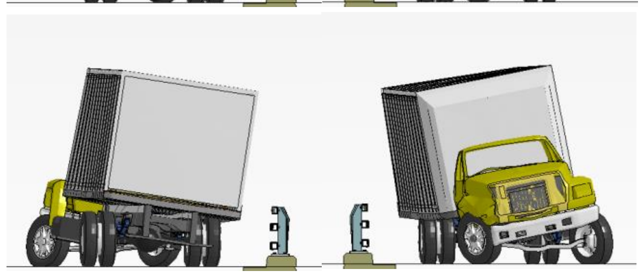

Figure L-2. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from upstream and downstream viewpoints (Case 3).

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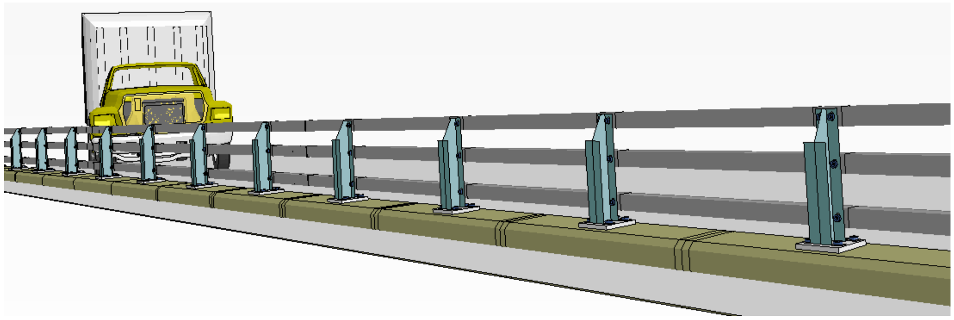

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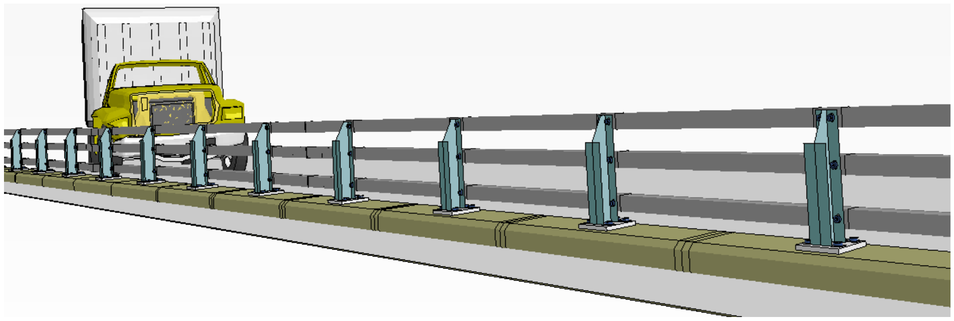

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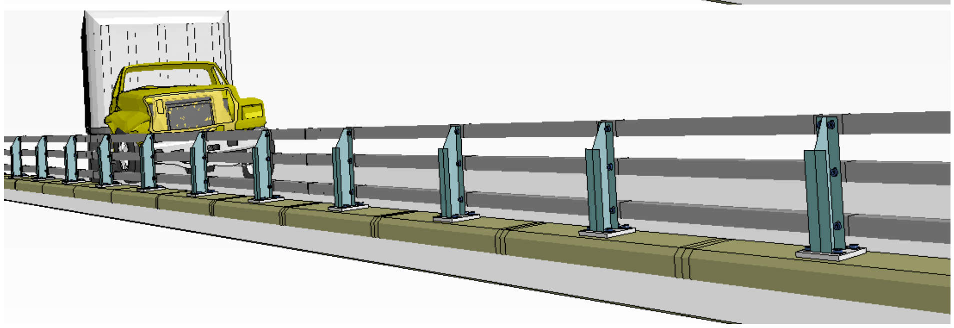

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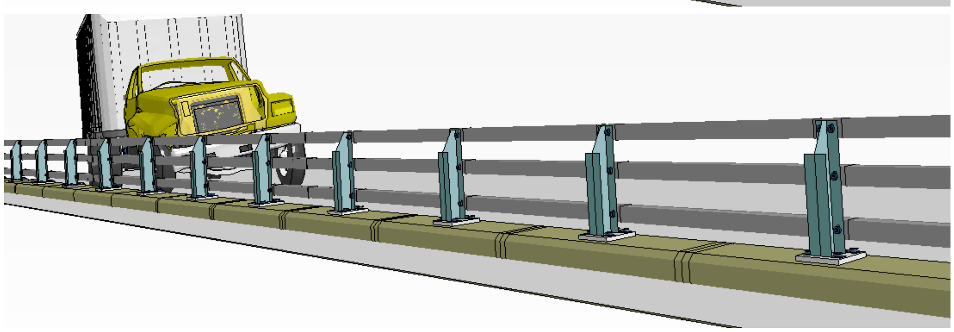

Figure L-3. Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an oblique viewpoint (Case 3).

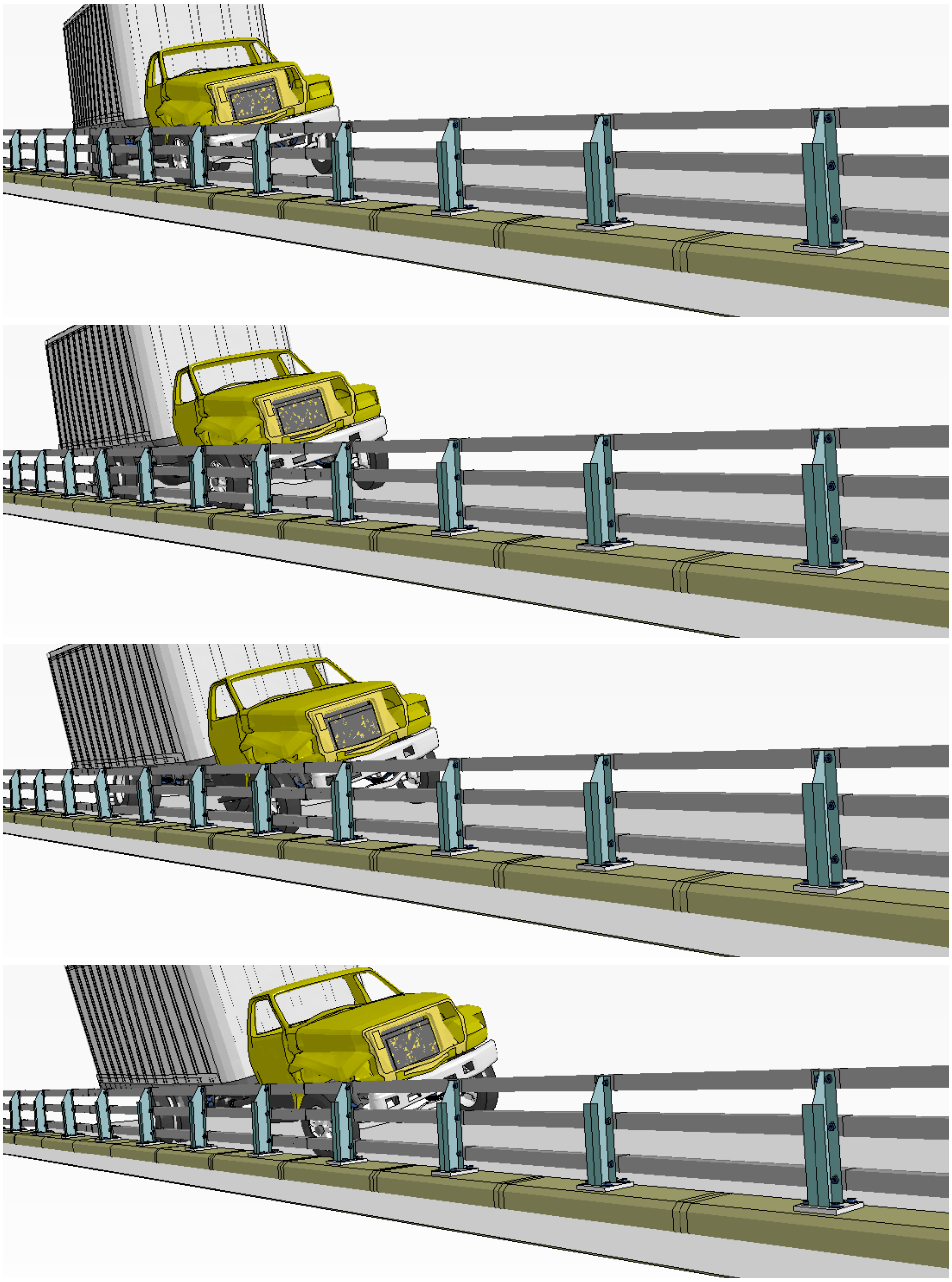

Figure L-3. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an oblique viewpoint (Case 3).

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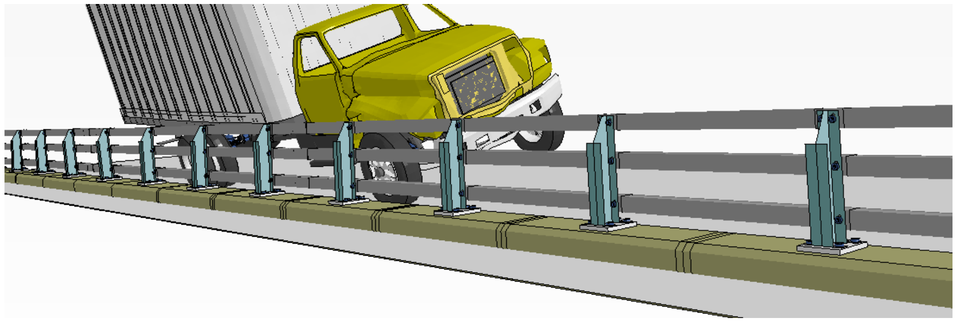

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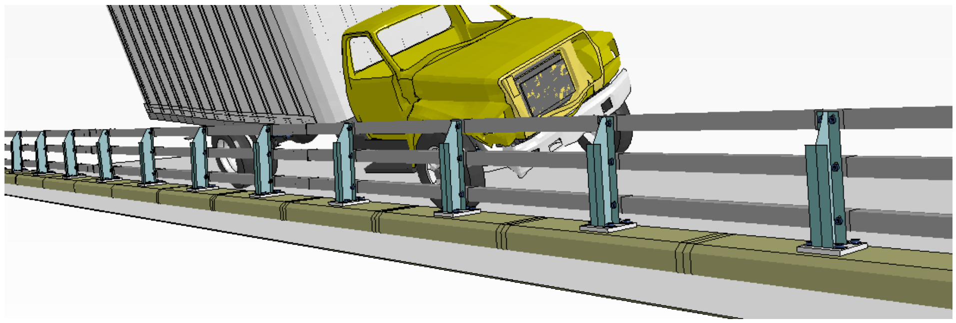

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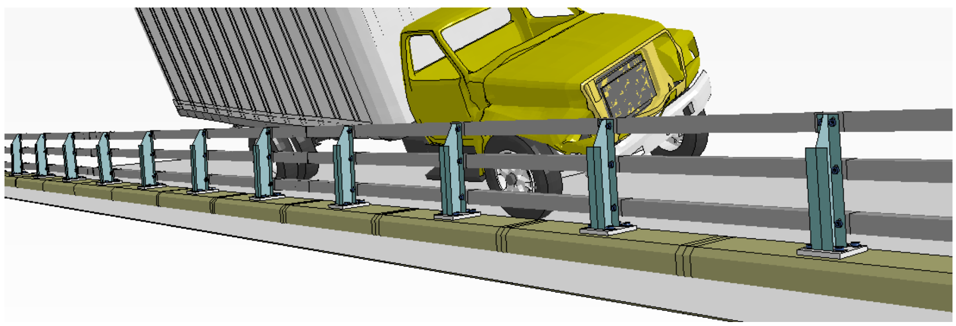

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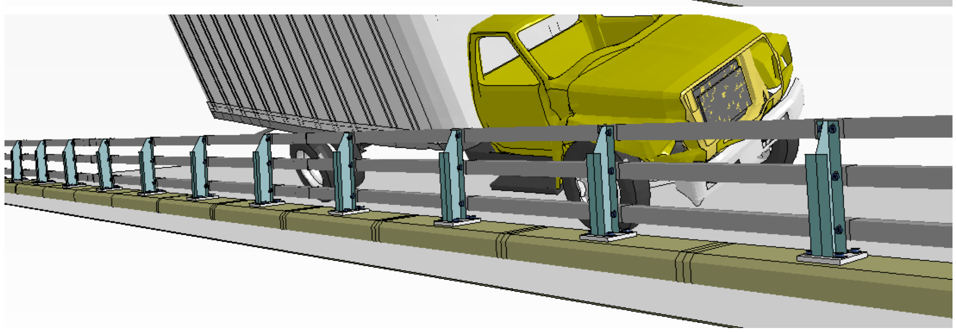
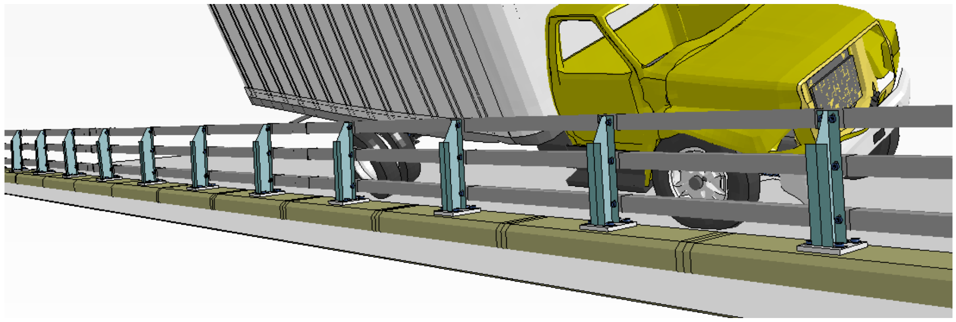


Figure L-3. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an oblique viewpoint (Case 3).

0.60 seconds



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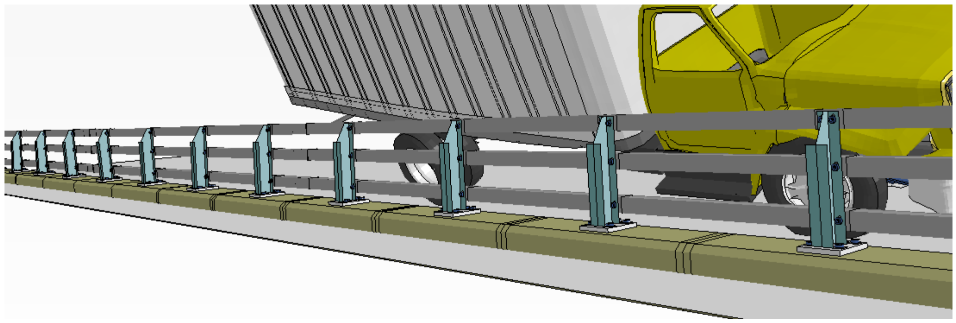

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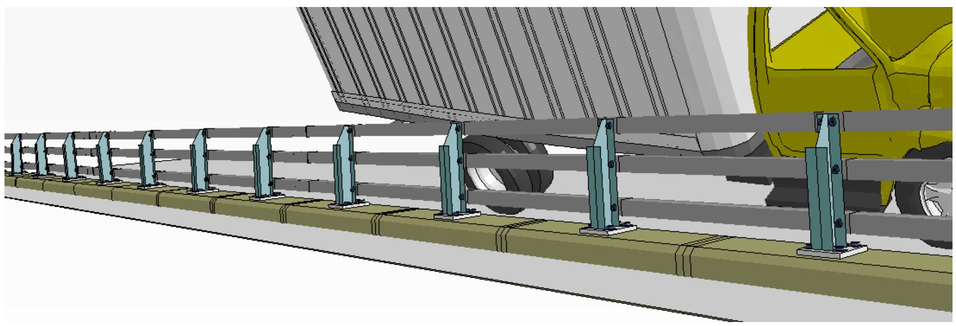

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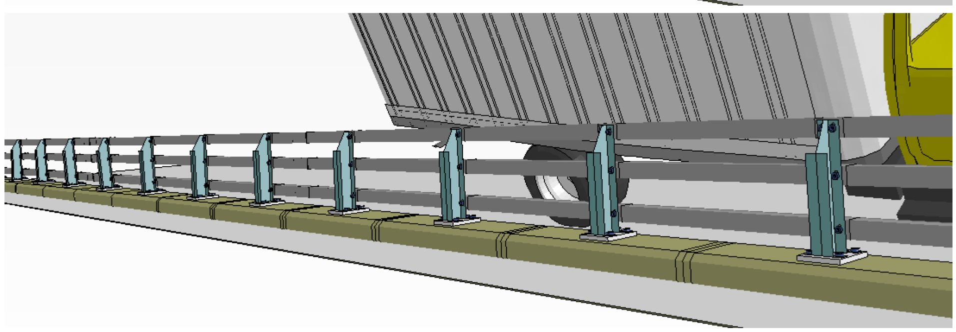


Figure L-3. [Continued] Sequential views from analysis of MASH Test 4-12 for curb-mounted S3-TL4 from an oblique viewpoint (Case 3).

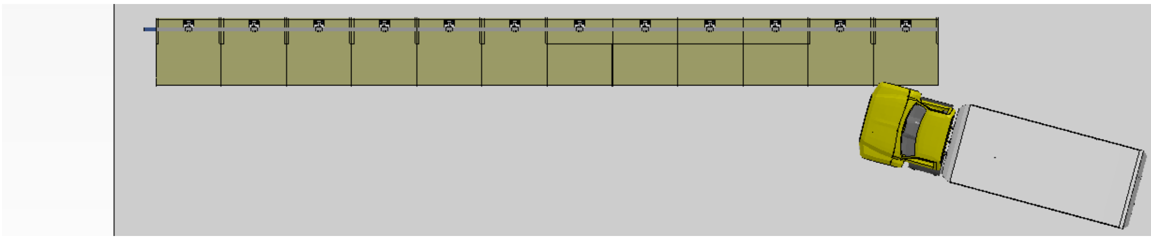
Appendix M

Sequential Views for MASH Test 4-12 for

Sidewalk-Mounted S3-TL4 Bridge Rail

(Case 1)

0.00 seconds



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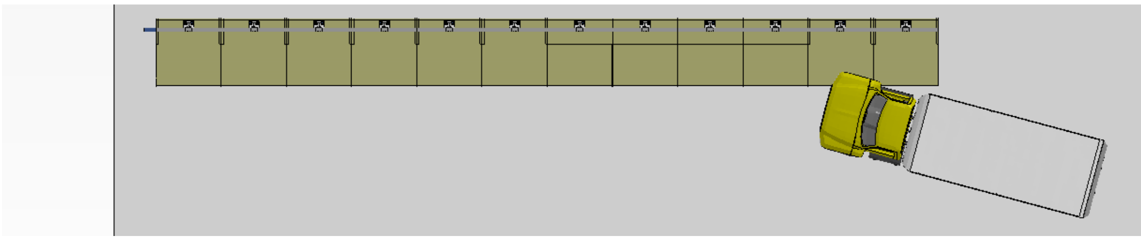

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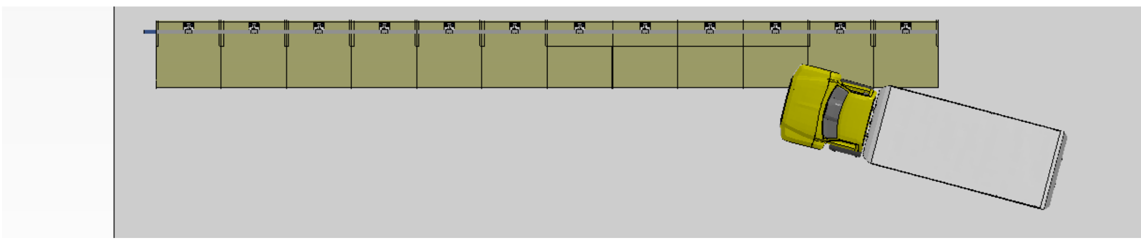

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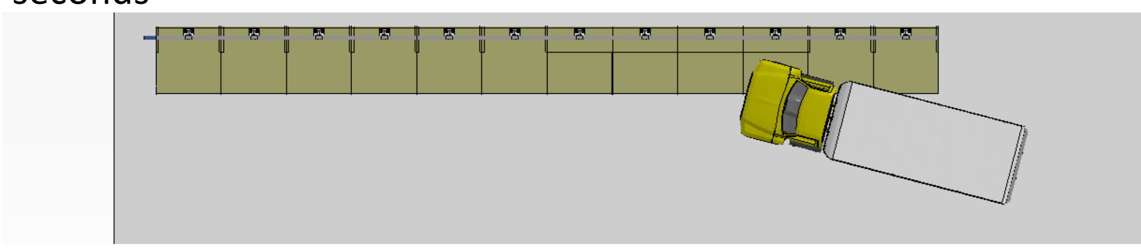

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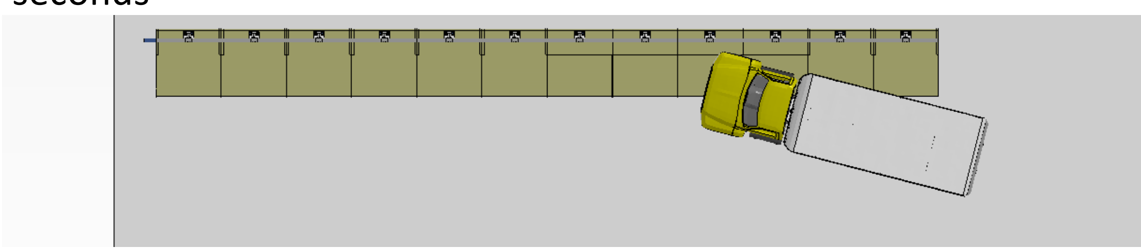
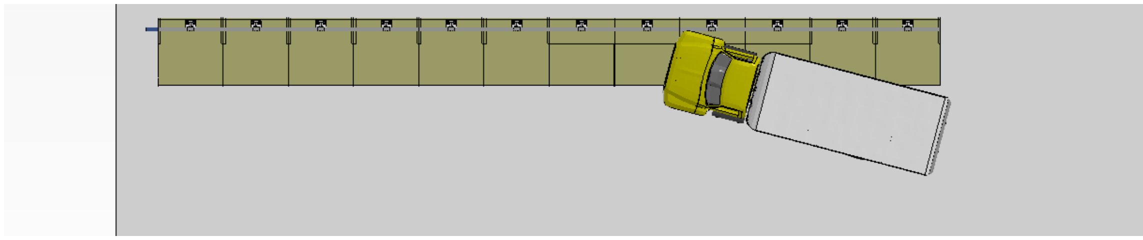


Figure M-1. Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an overhead viewpoint (Case 1).

0.25 seconds



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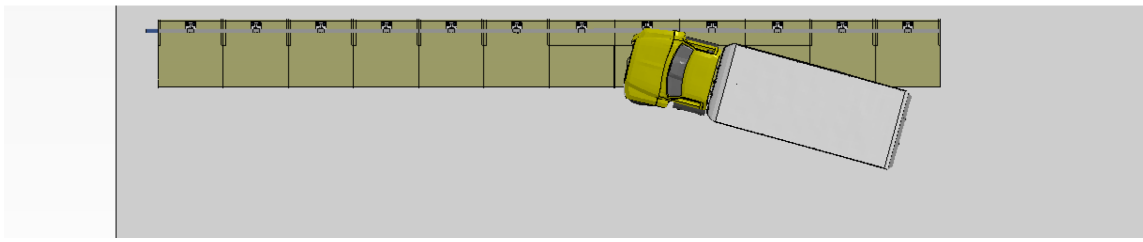

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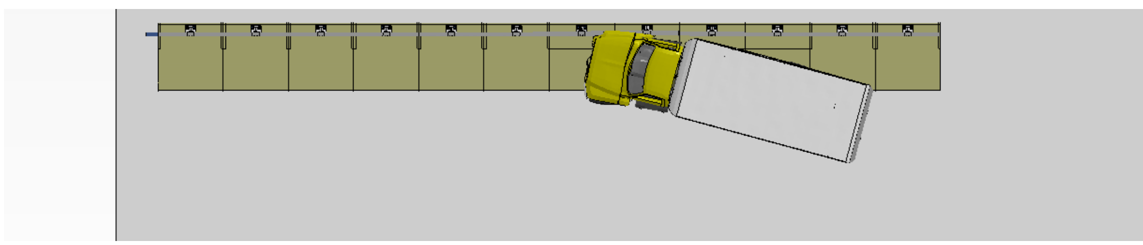

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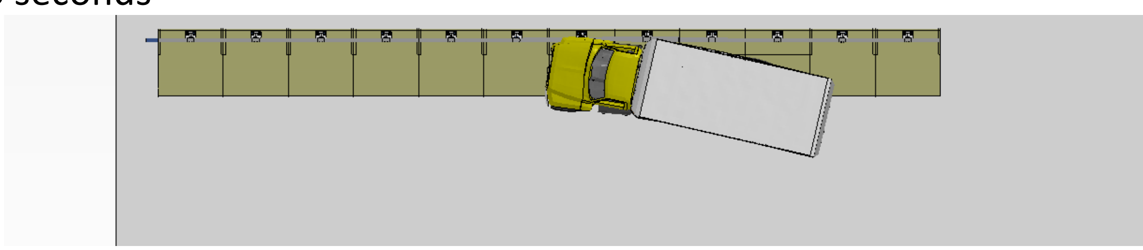

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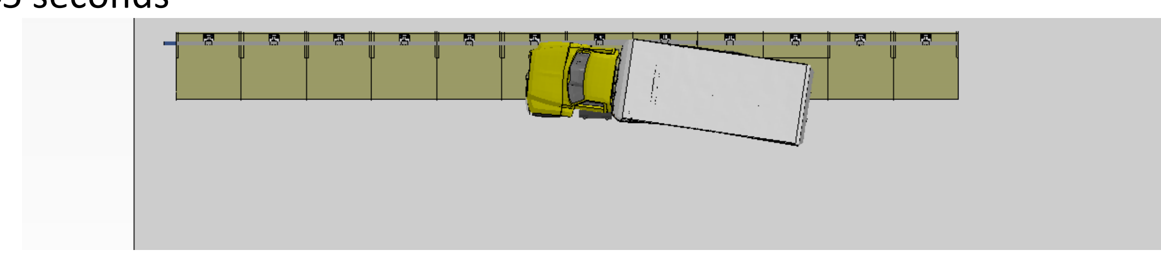
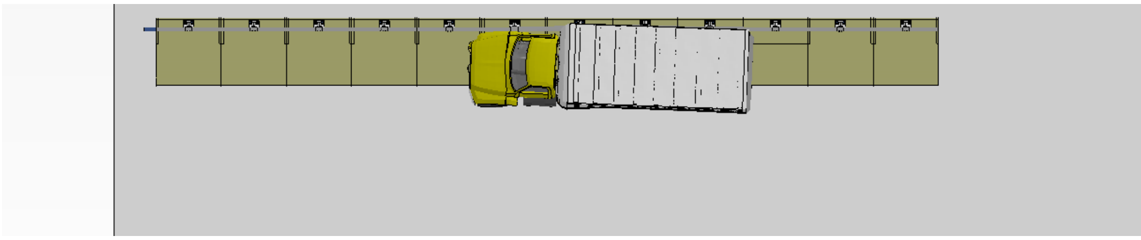


Figure M-1. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an overhead viewpoint (Case 1).

0.50 seconds



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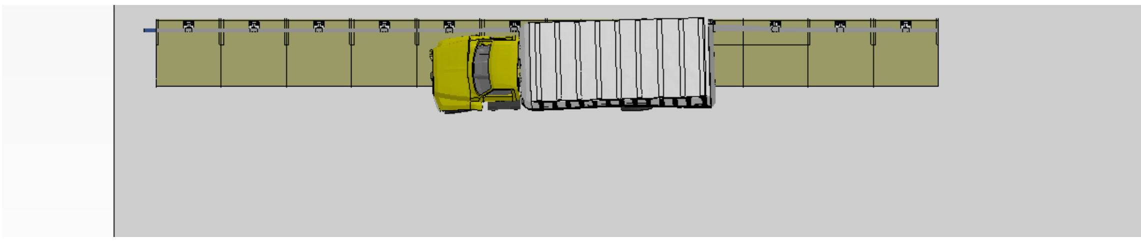

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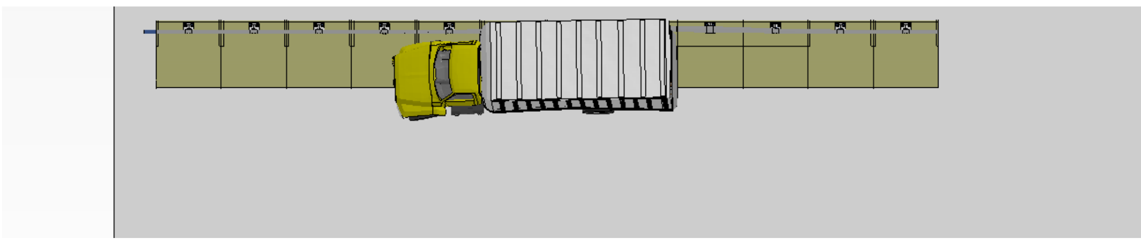

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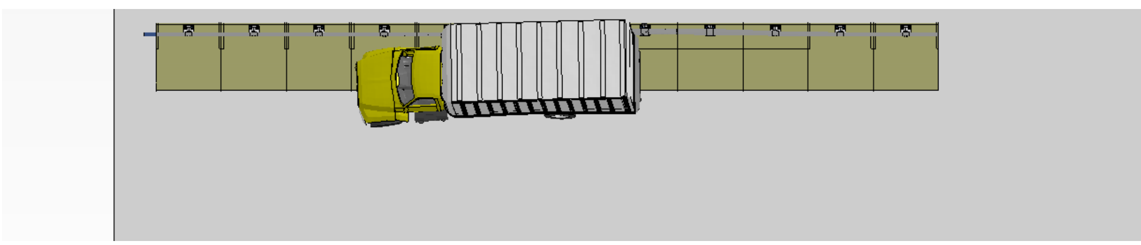

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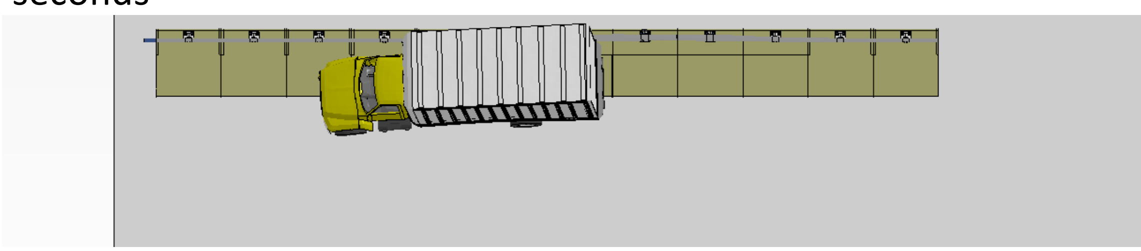
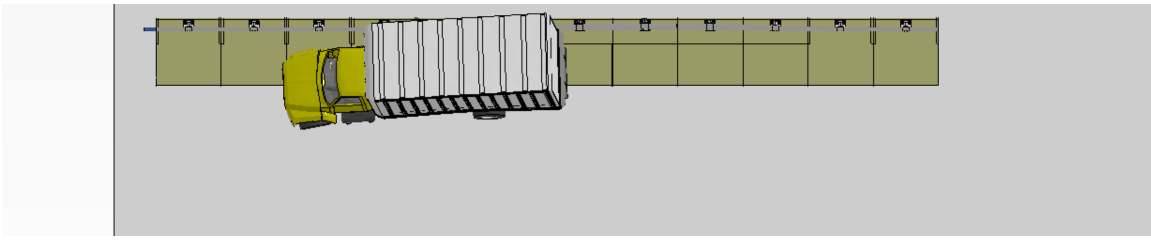


Figure M-1. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an overhead viewpoint (Case 1).

0.75 seconds



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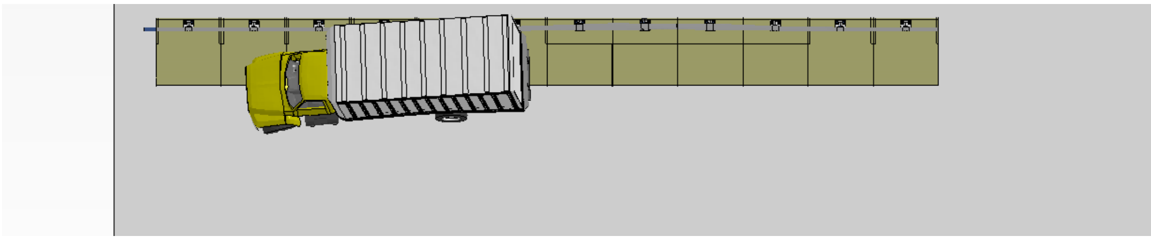

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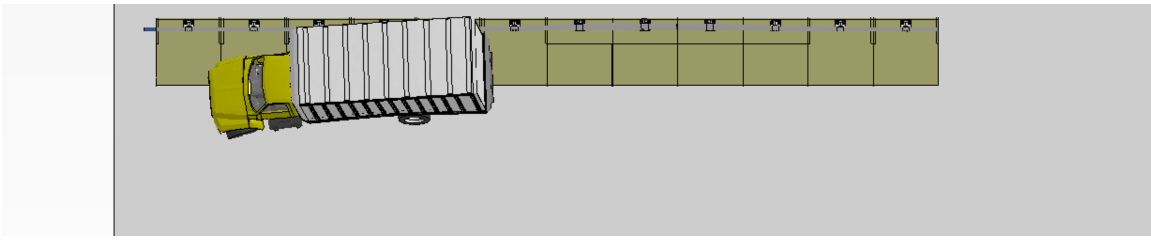

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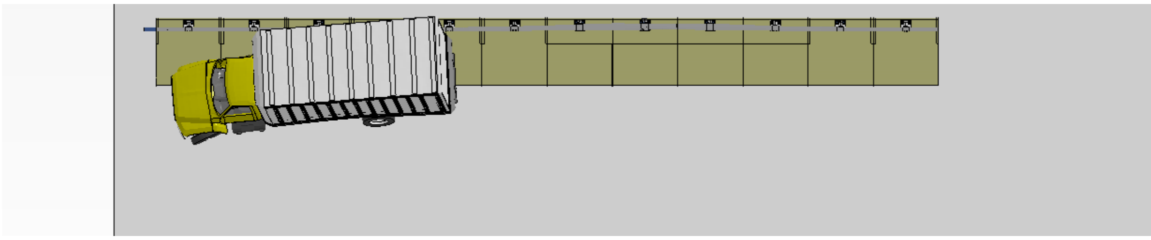

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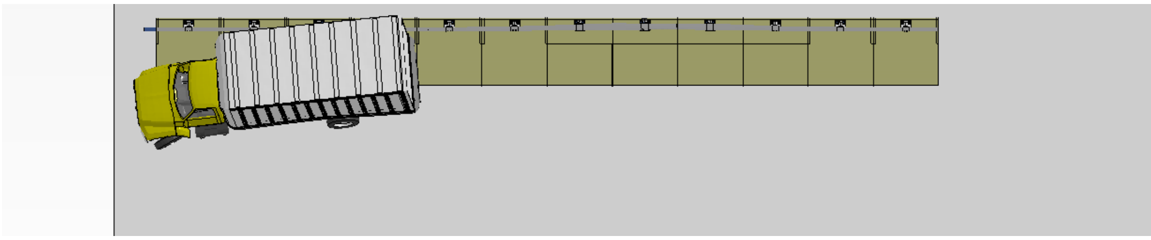


Figure M-1. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an overhead viewpoint (Case 1).

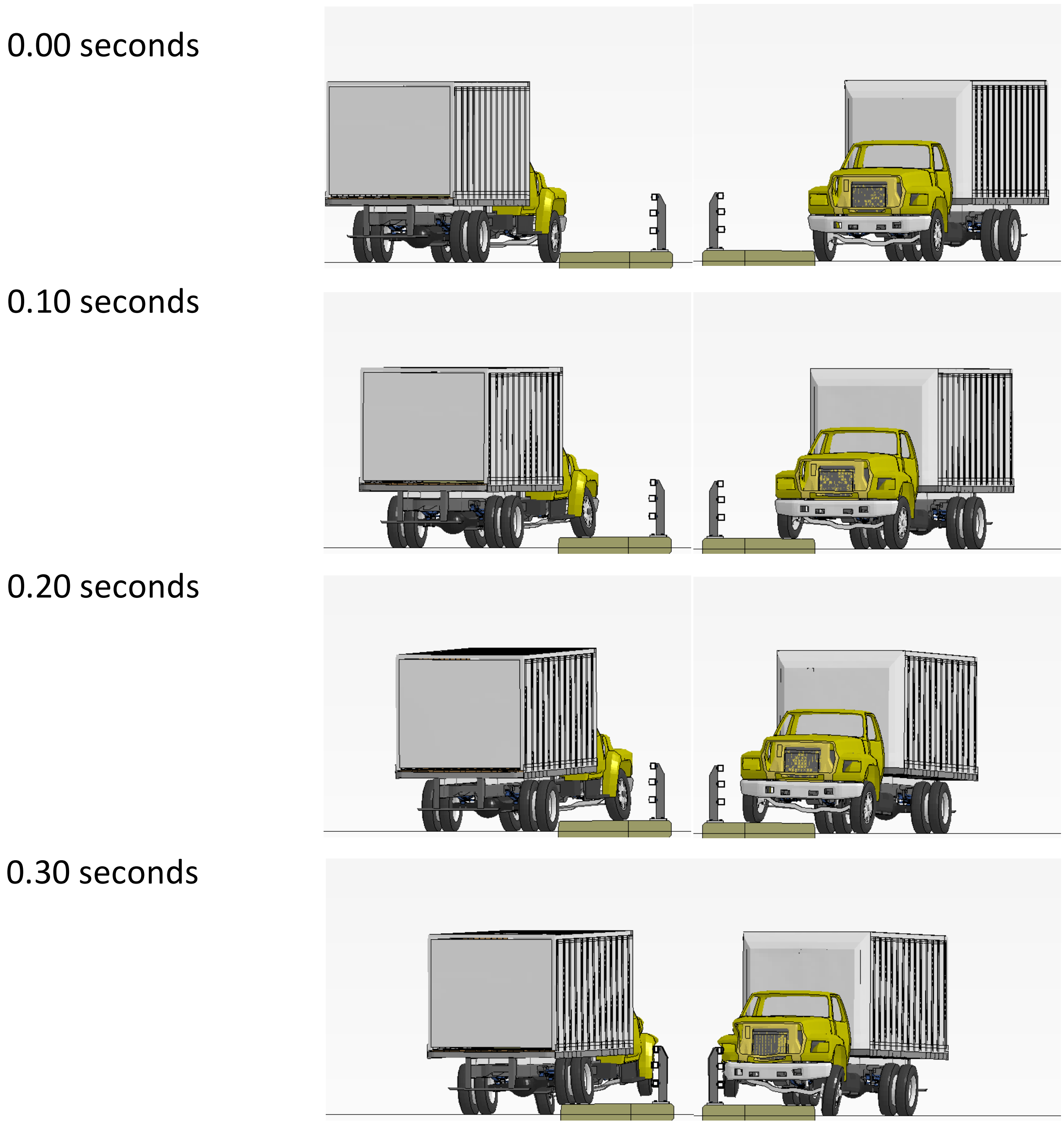


Figure M-2. Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints (Case 1).

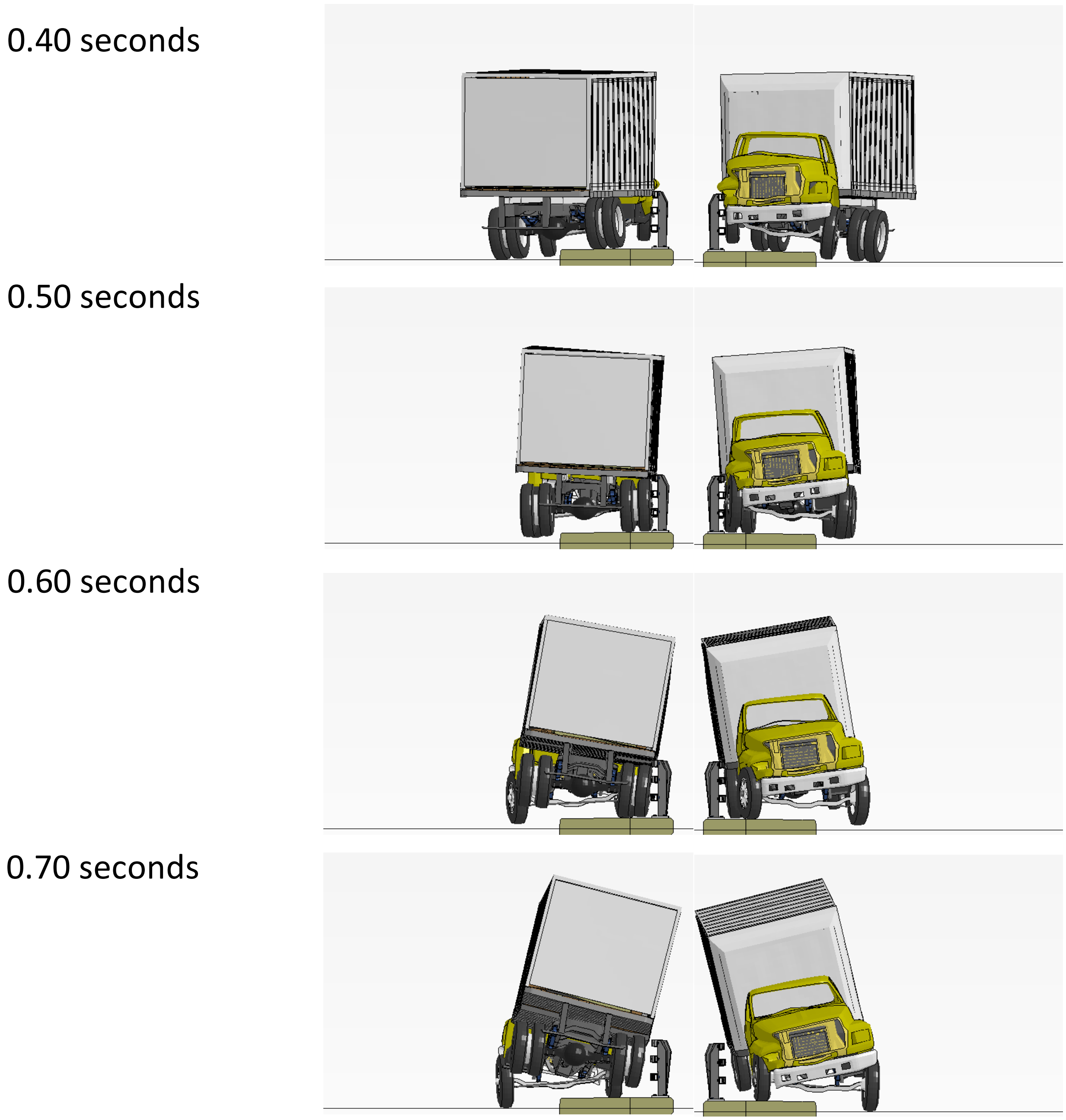
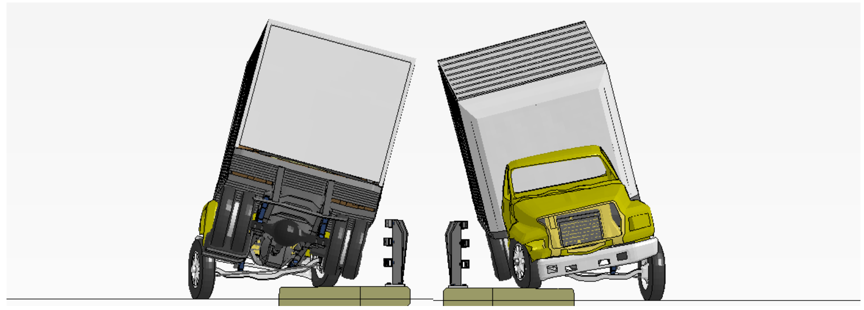


Figure M-2. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints (Case 1).

0.80 seconds



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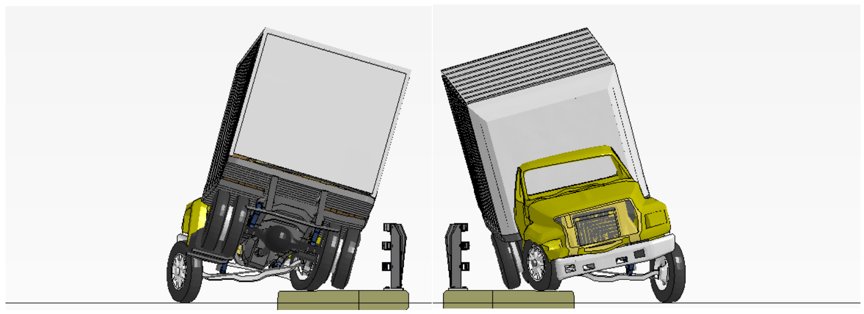

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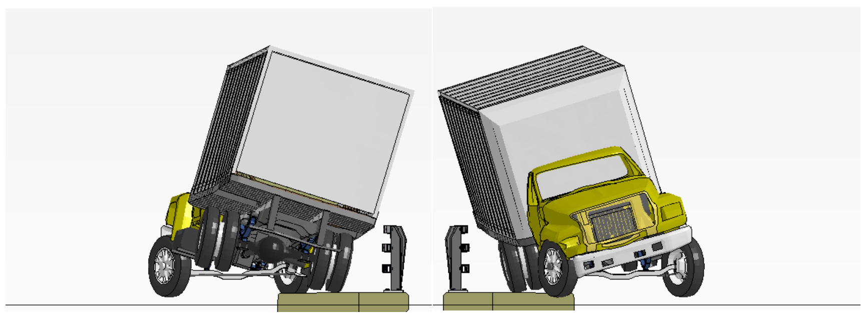

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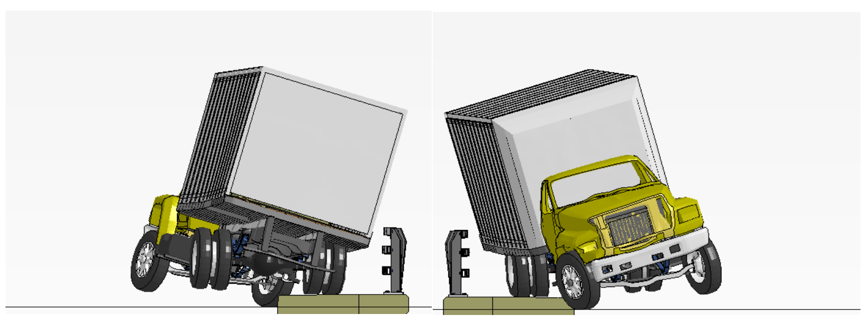


Figure M-2. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints (Case 1).

0.00 seconds

0.05 seconds

0.10 seconds

0.15 seconds

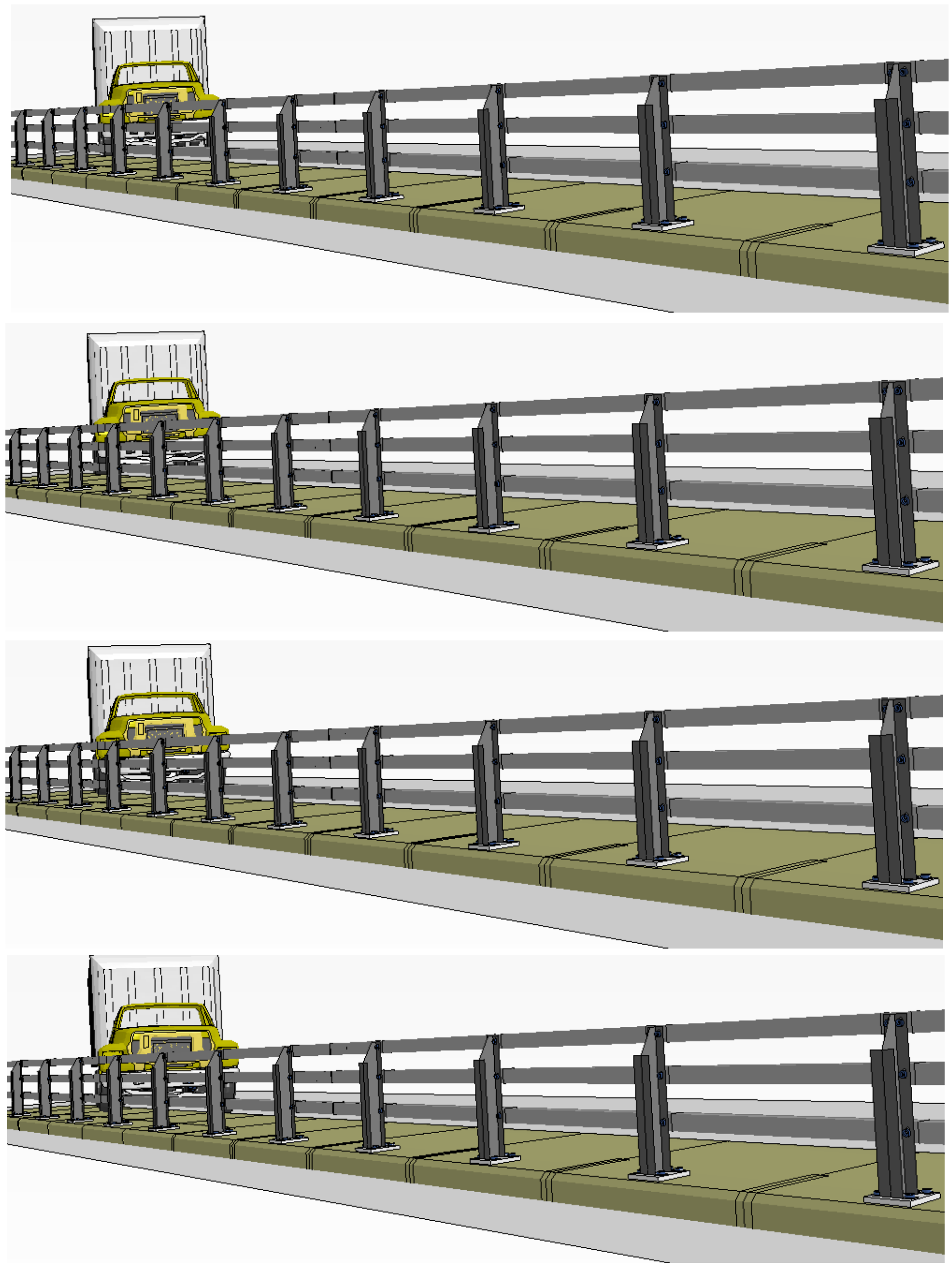
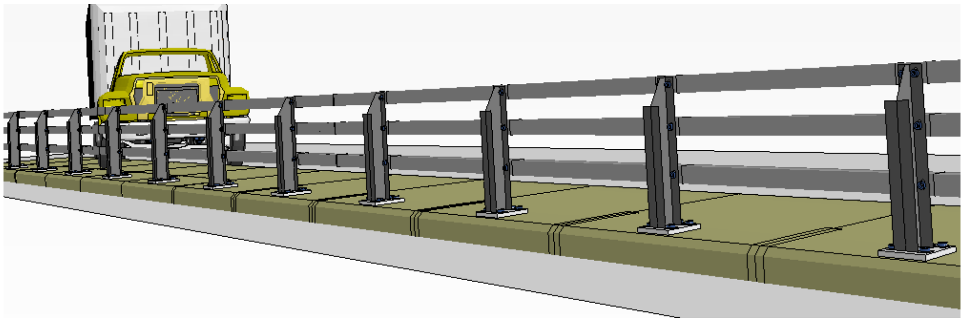


Figure M-3. Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an oblique viewpoint (Case 1).

0.20 seconds



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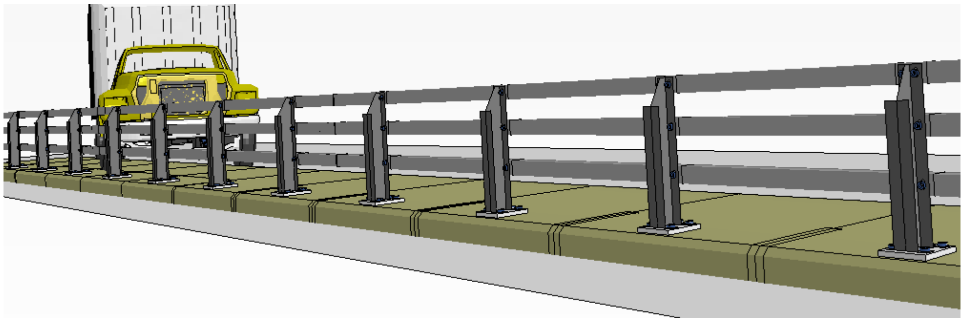

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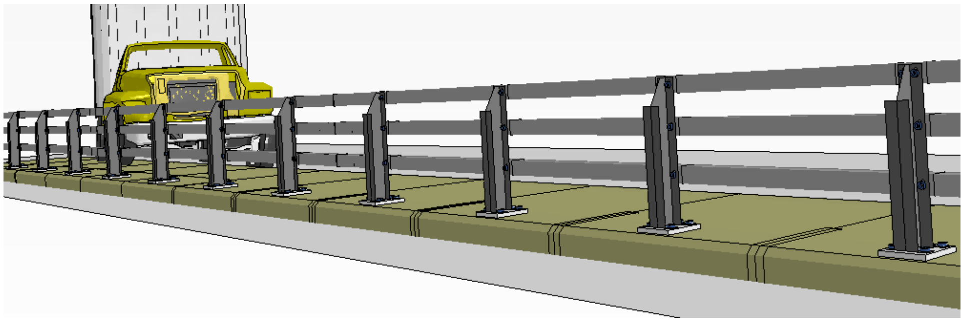

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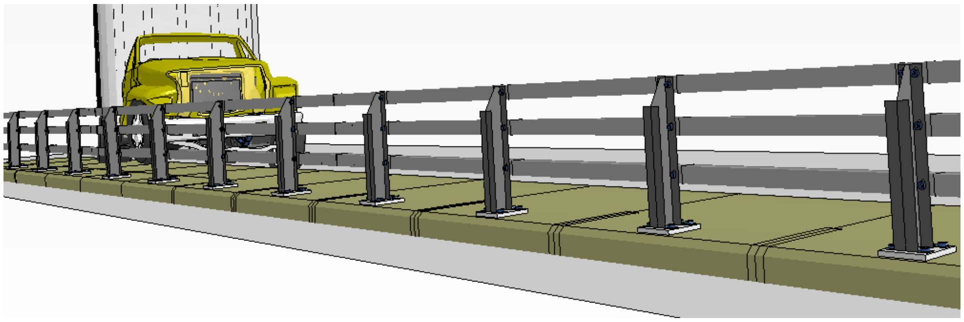
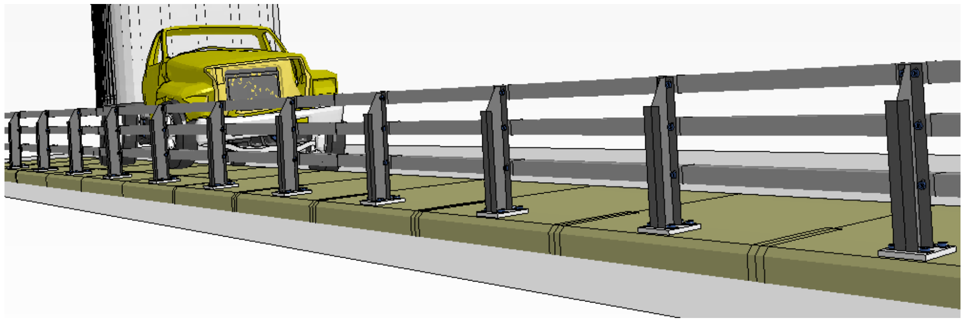


Figure M-3. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an oblique viewpoint (Case 1).

0.40 seconds



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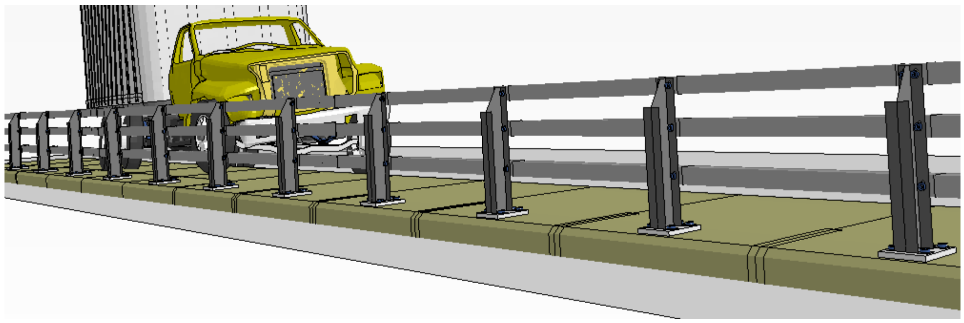

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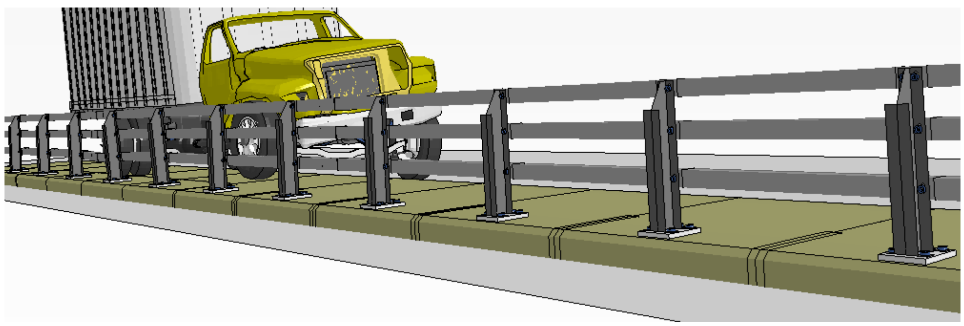

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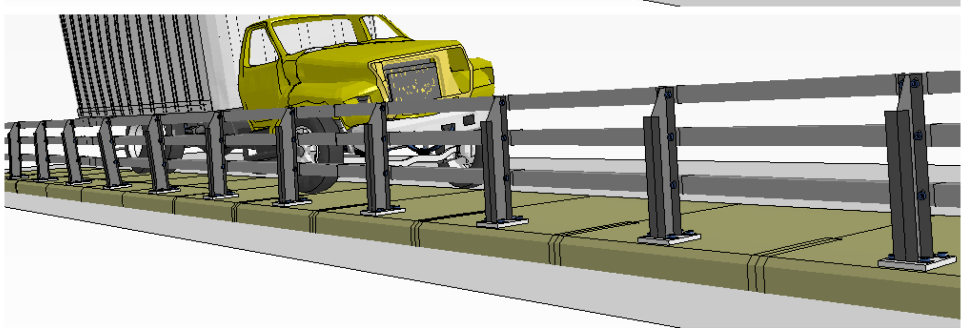

Figure M-3. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an oblique viewpoint (Case 1).

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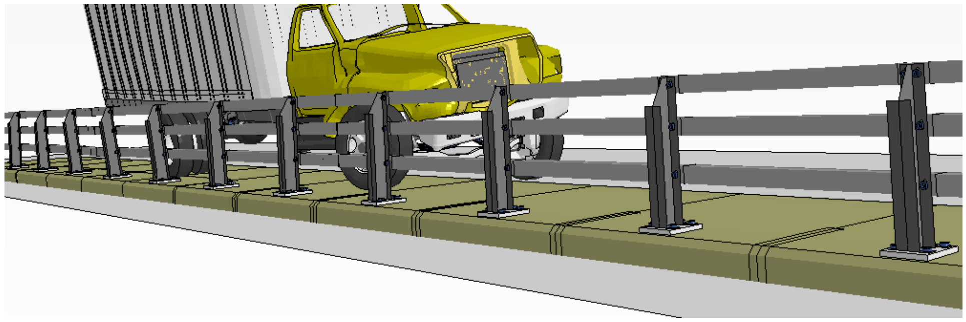

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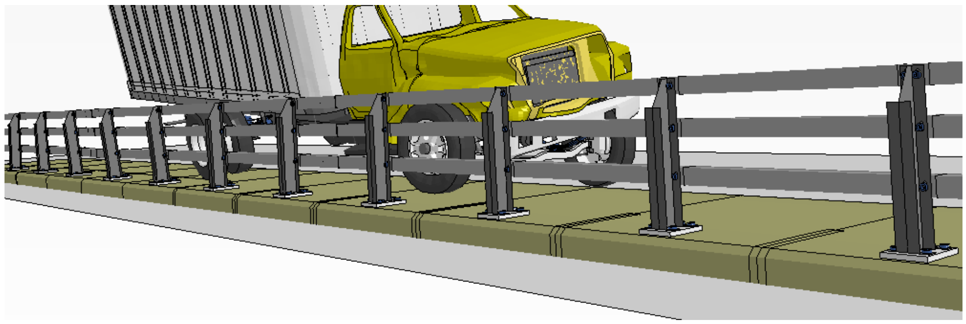

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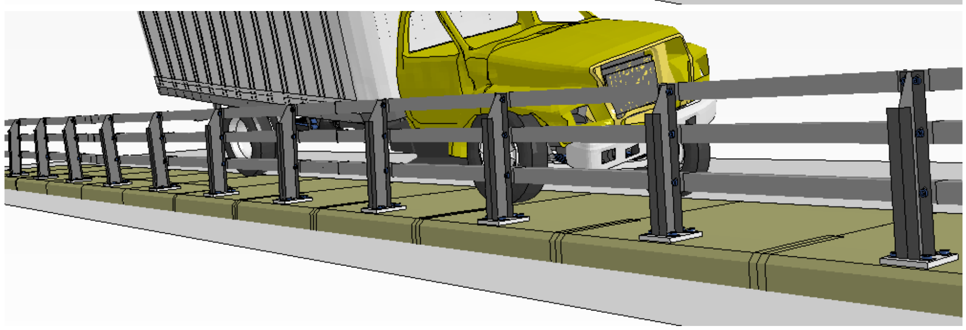

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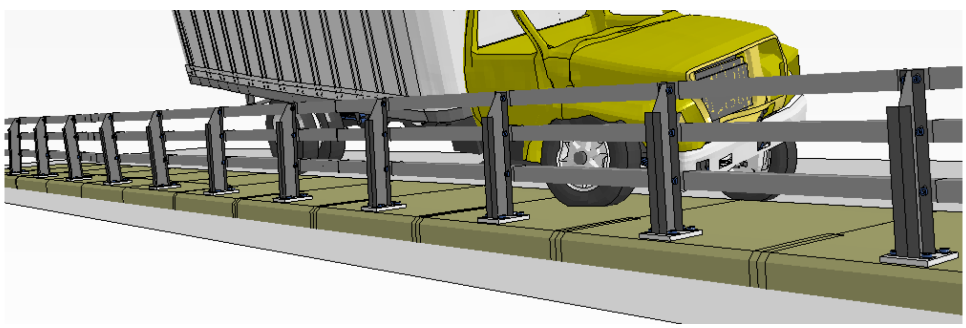


Figure M-3. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an oblique viewpoint (Case 1).

Appendix N

Sequential Views for MASH Test 4-12 for

Sidewalk-Mounted S3-TL4 Bridge Rail

(Case 2)

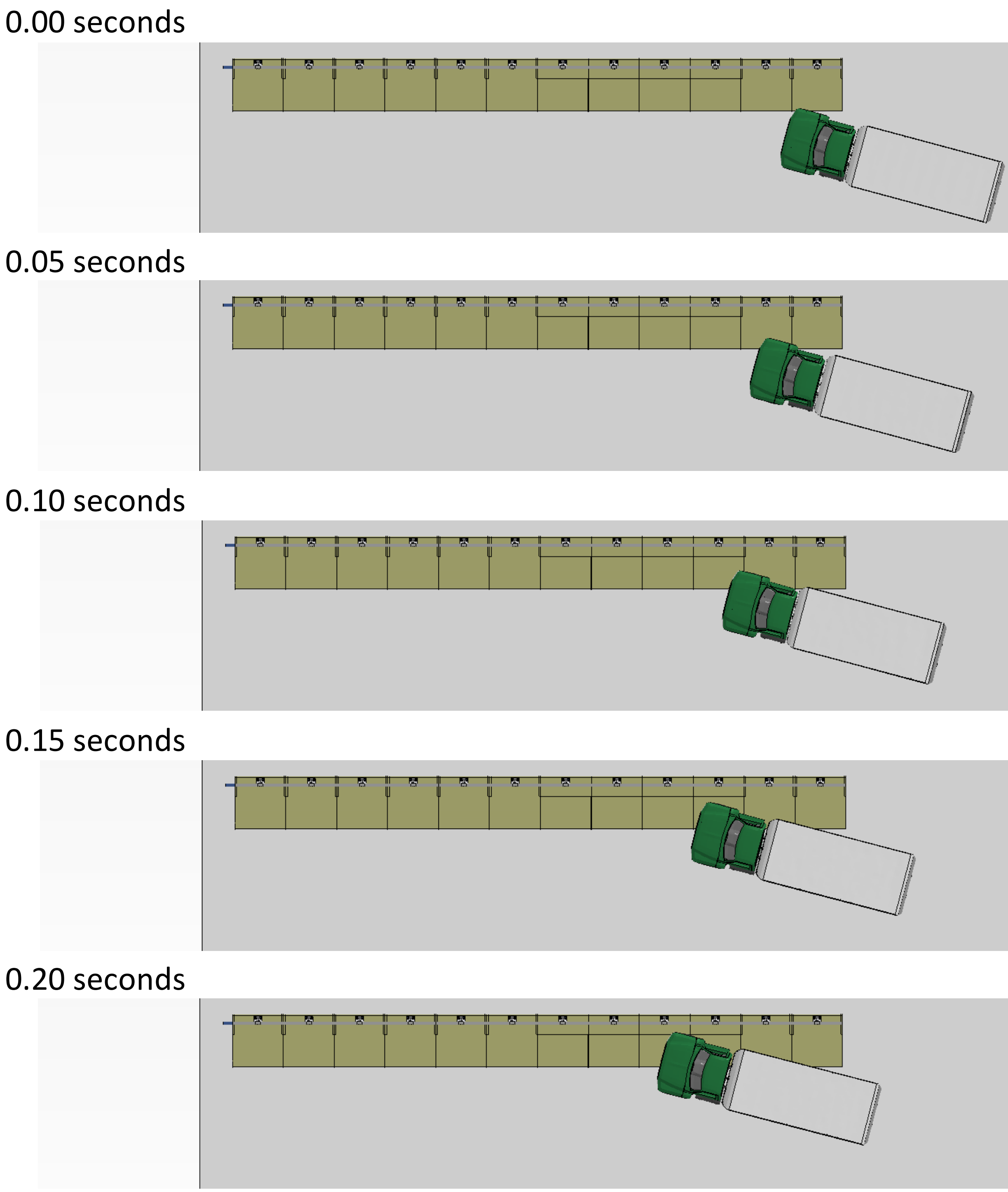
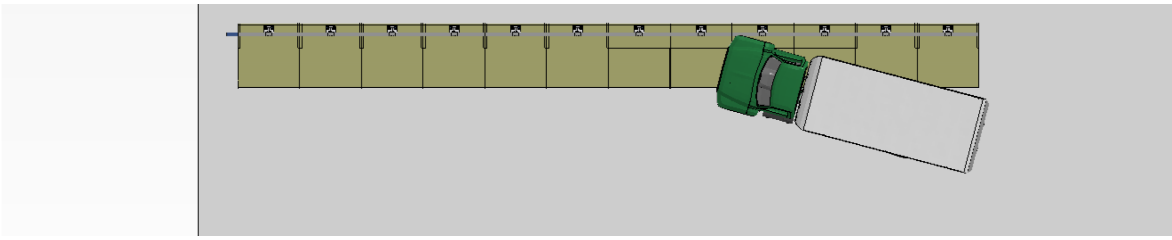


Figure N-1. Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an overhead viewpoint (Case 1).

0.25 seconds



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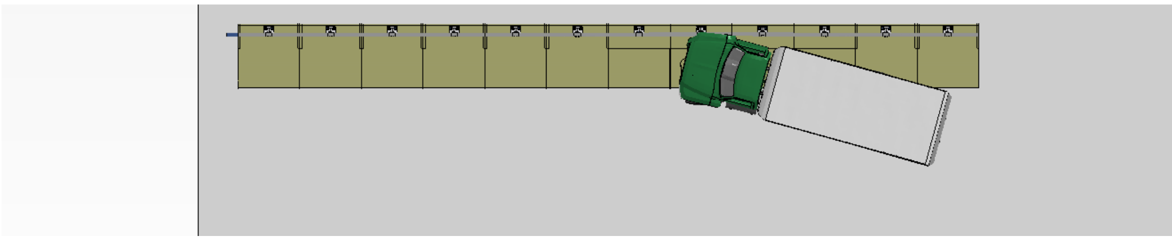

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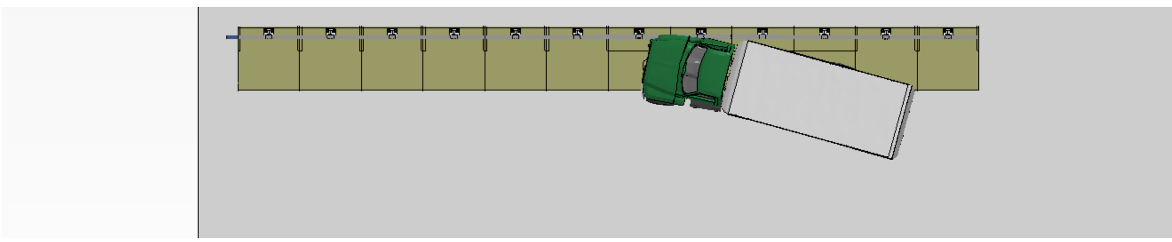

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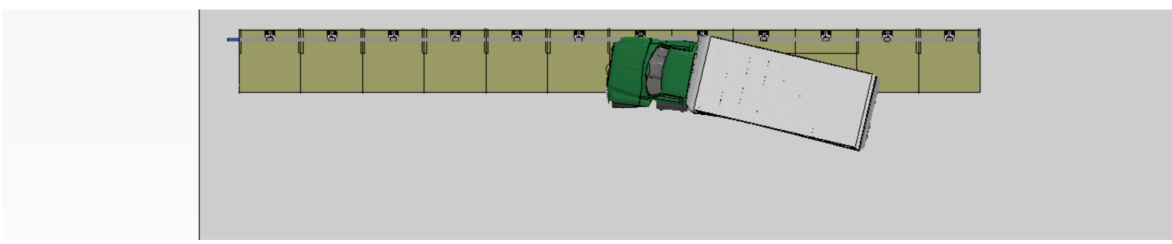

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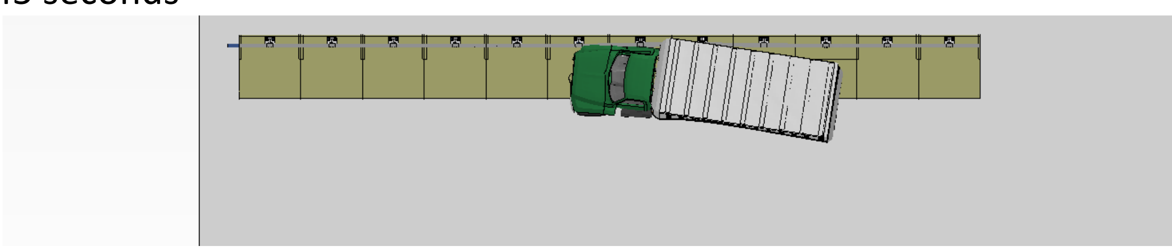
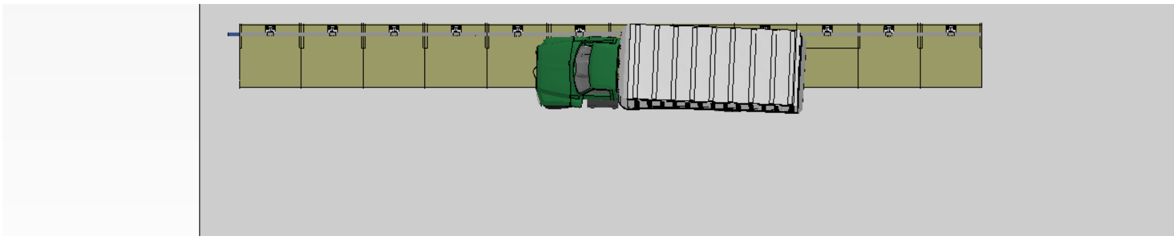


Figure N-1. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an overhead viewpoint (Case 1).

0.50 seconds



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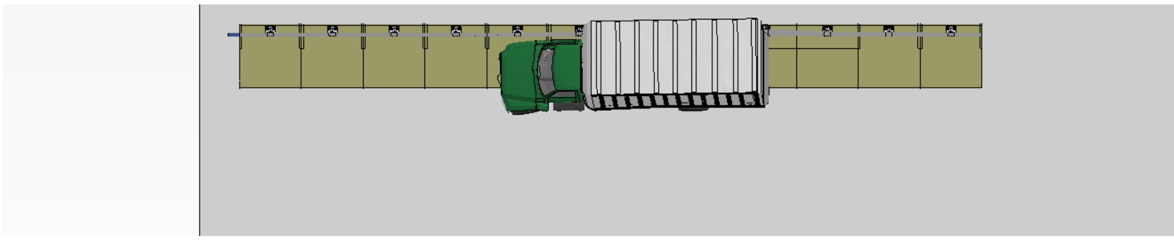

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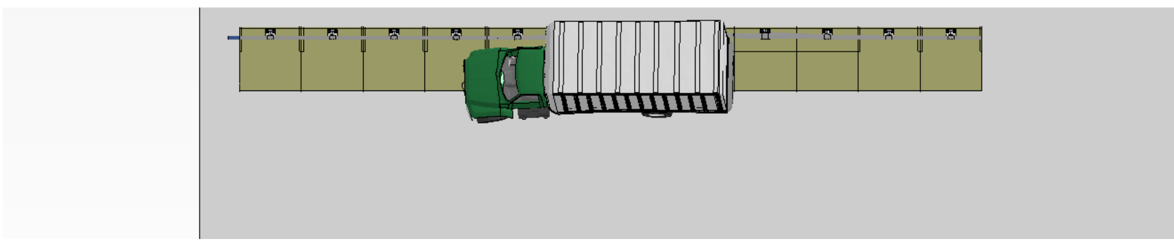

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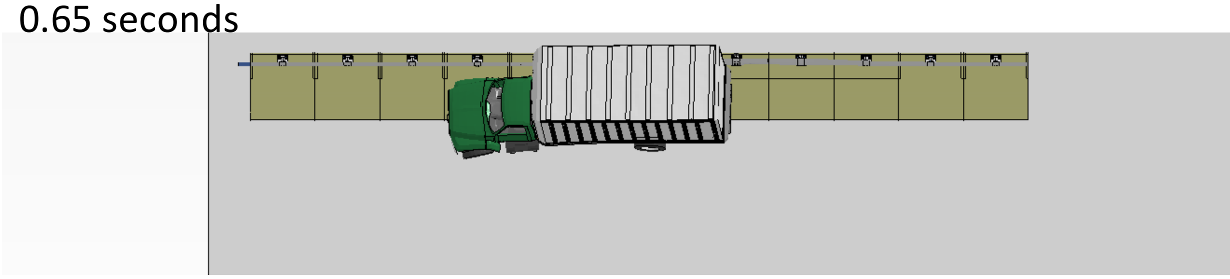

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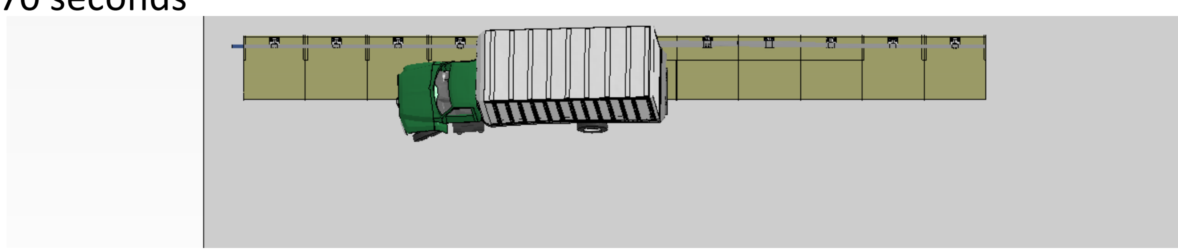
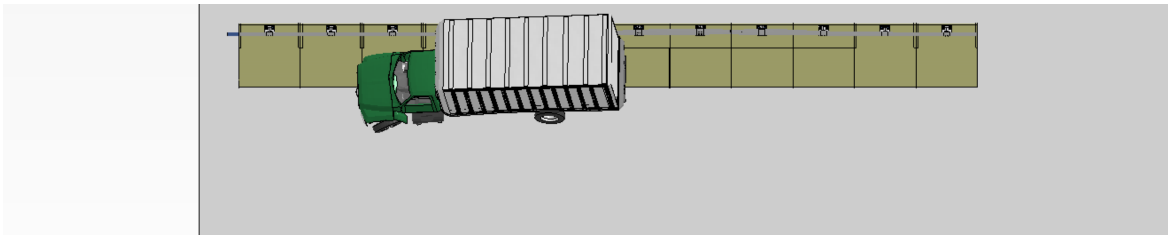


Figure N-1. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an overhead viewpoint (Case 1).

0.75 seconds



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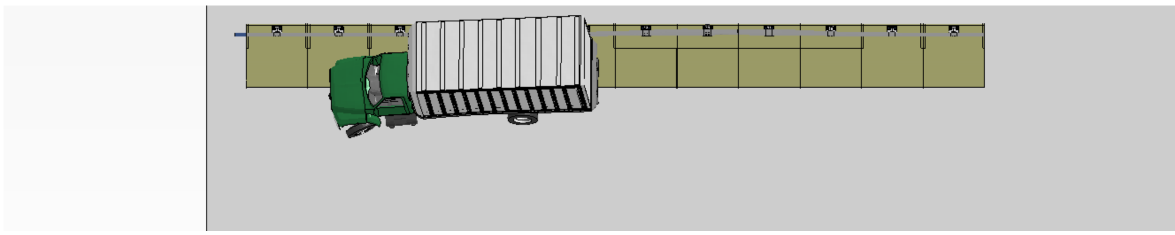

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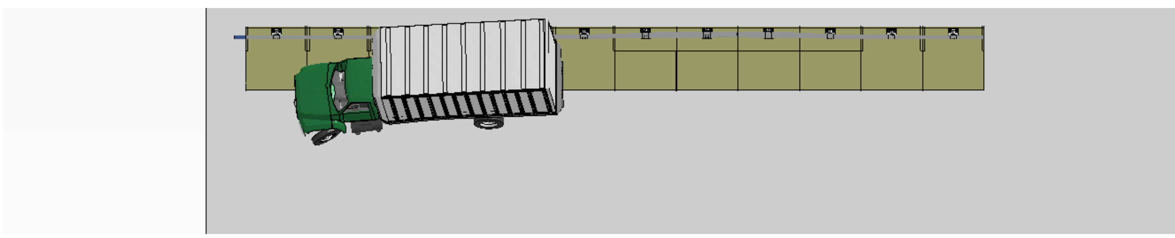

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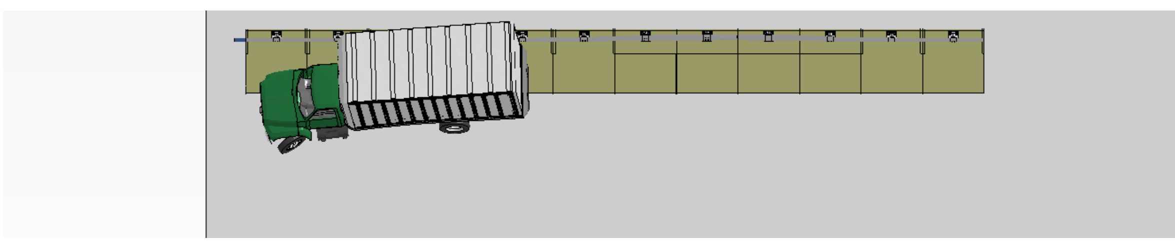

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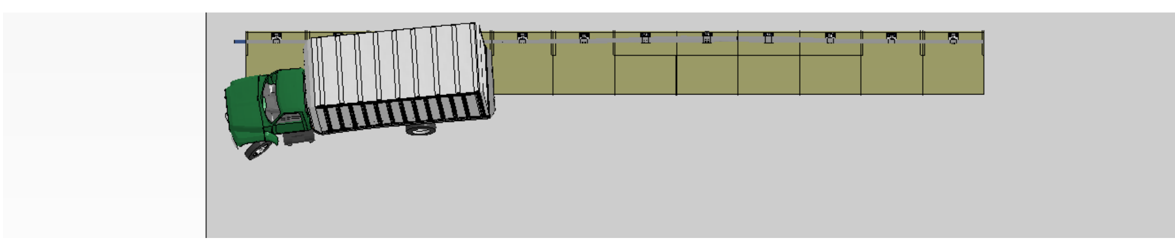

Figure N-1. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an overhead viewpoint (Case 1).

0.00 seconds

0.10 seconds

0.20 seconds

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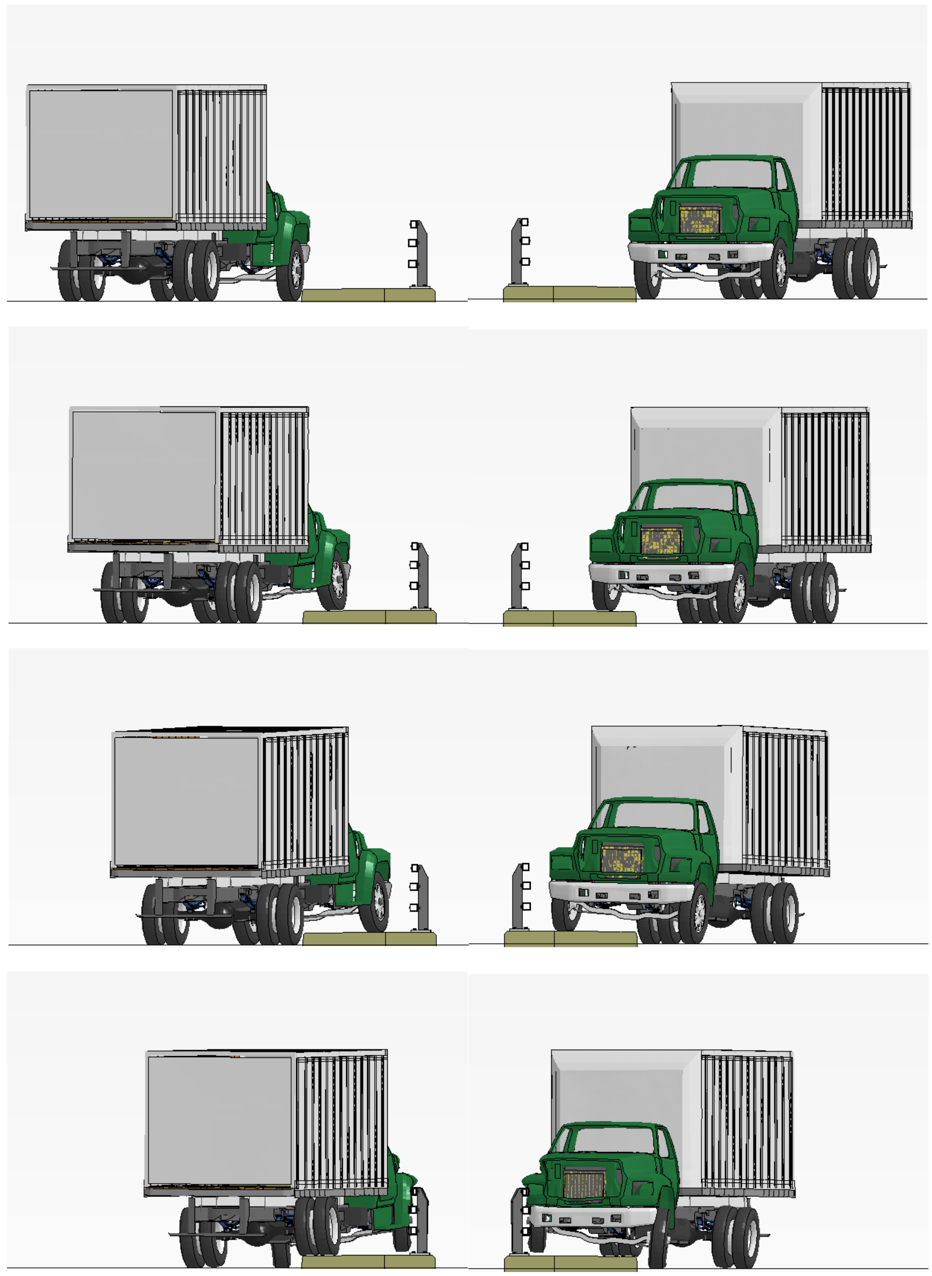

Figure N-2. Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints (Case 1).

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0.60 seconds

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Figure N-2. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints (Case 1).

Figure N-2. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from upstream and downstream viewpoints (Case 1).

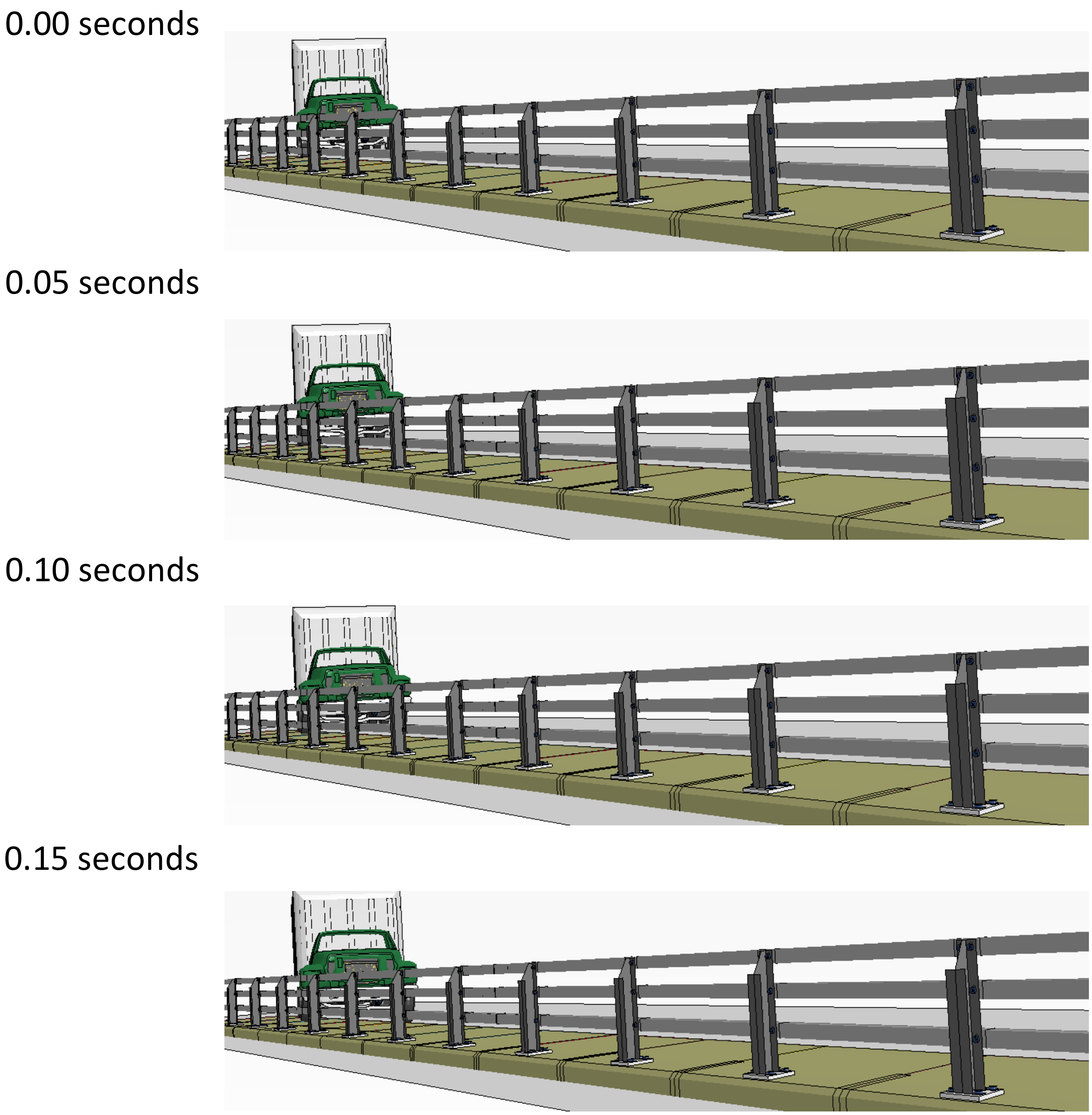

Figure N-3. Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an oblique viewpoint (Case 1).

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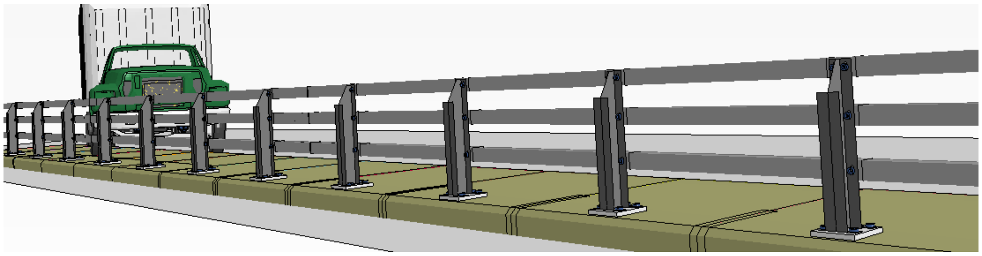

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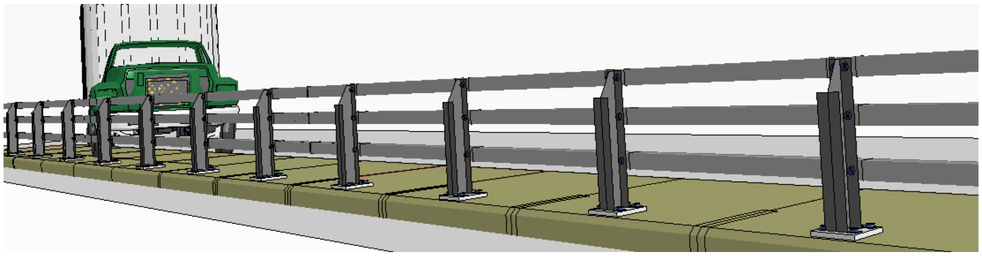

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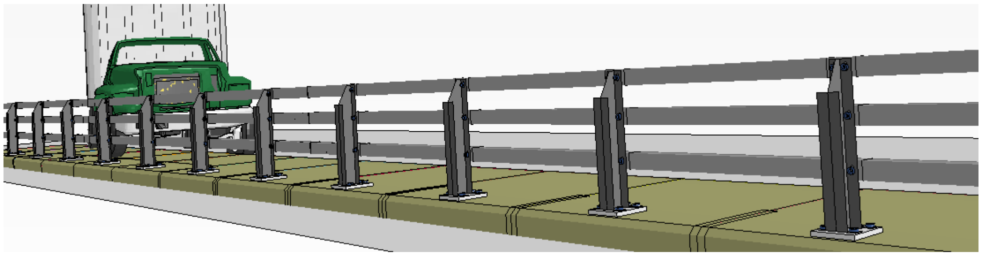

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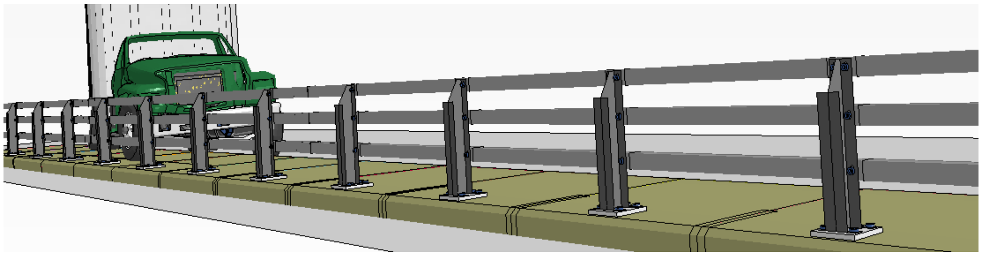

Figure N-3. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an oblique viewpoint (Case 1).

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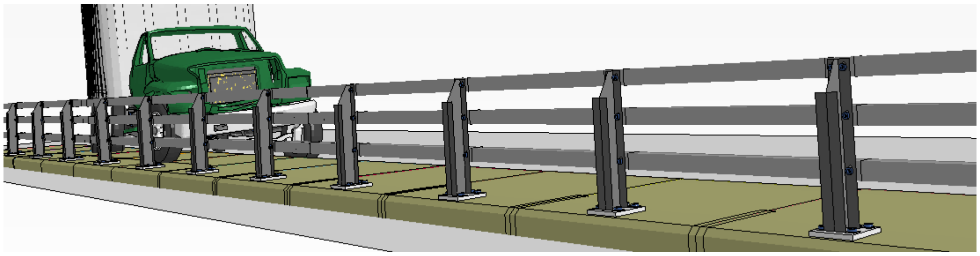

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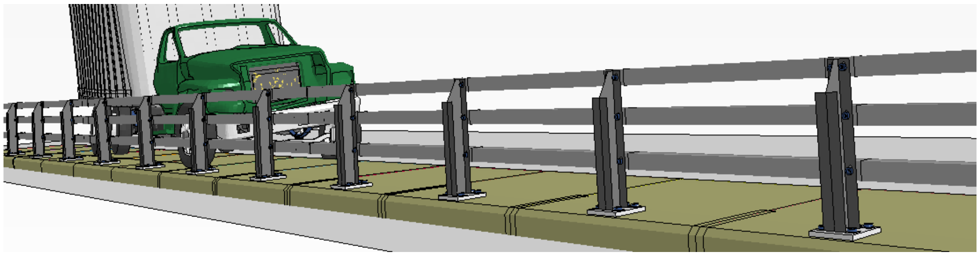

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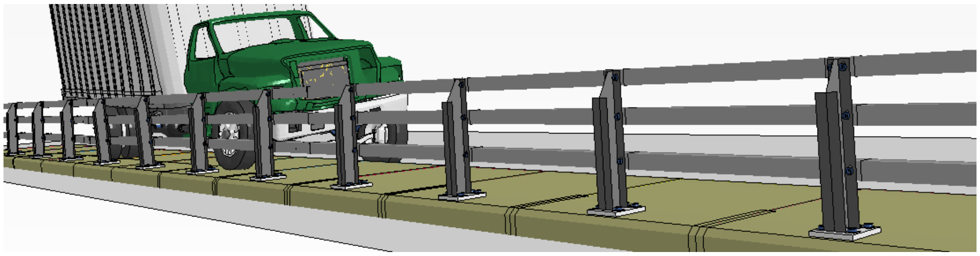

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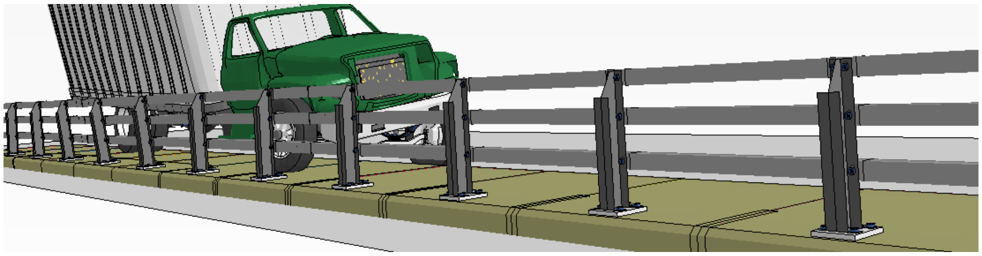

Figure N-3. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an oblique viewpoint (Case 1).

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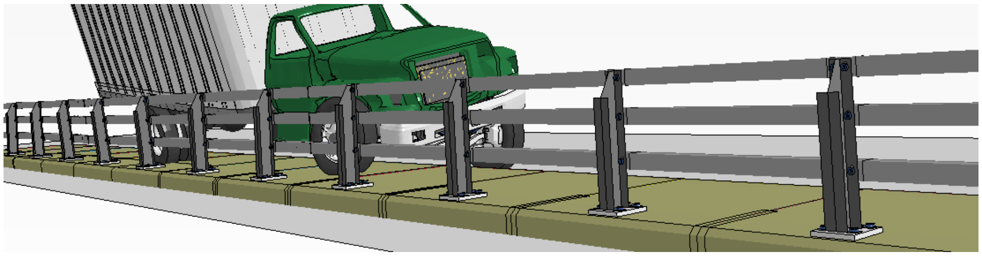

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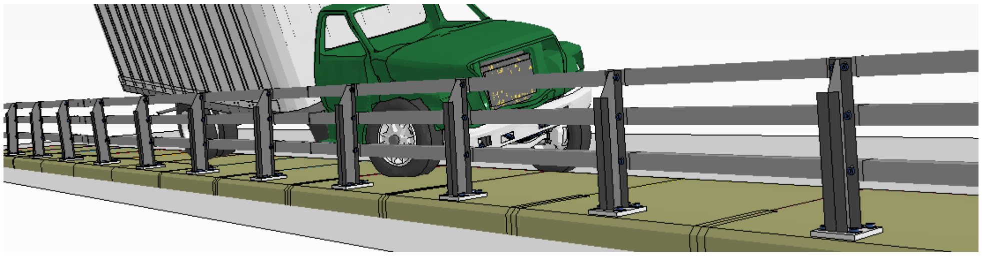

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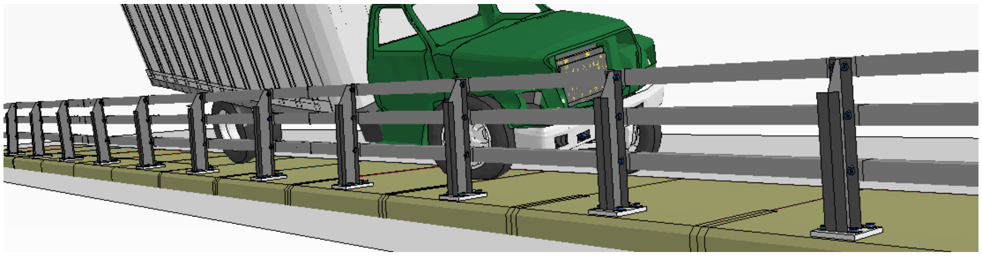

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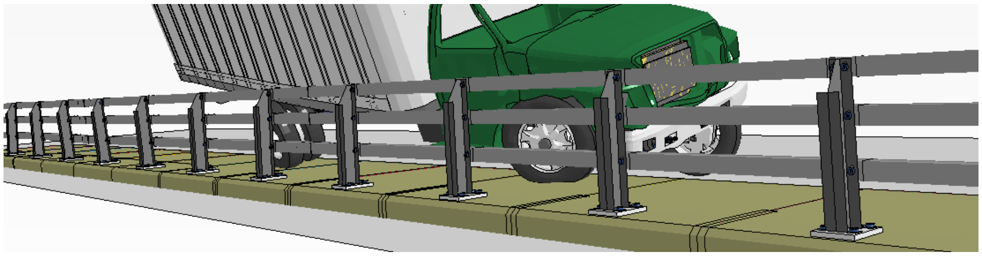

Figure N-3. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an oblique viewpoint (Case 1).

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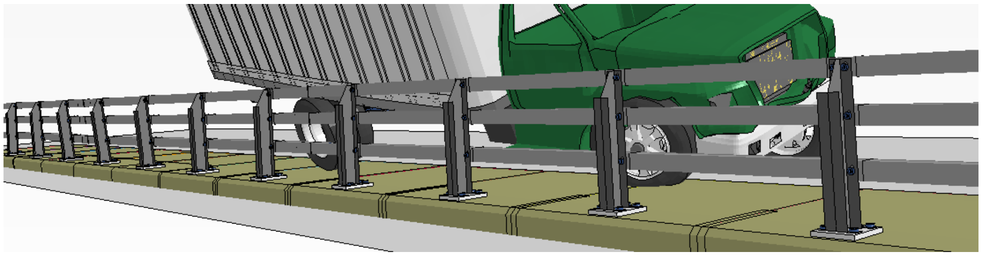

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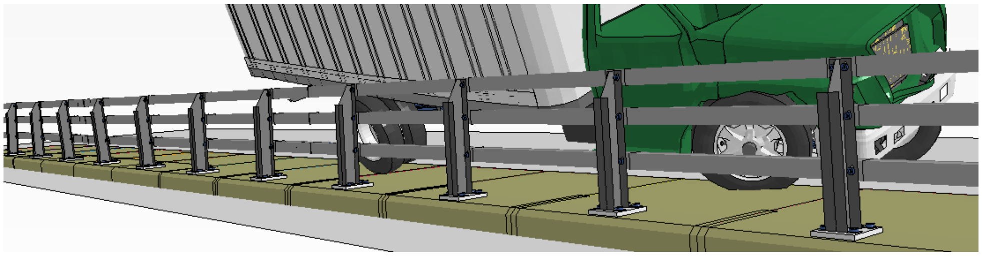

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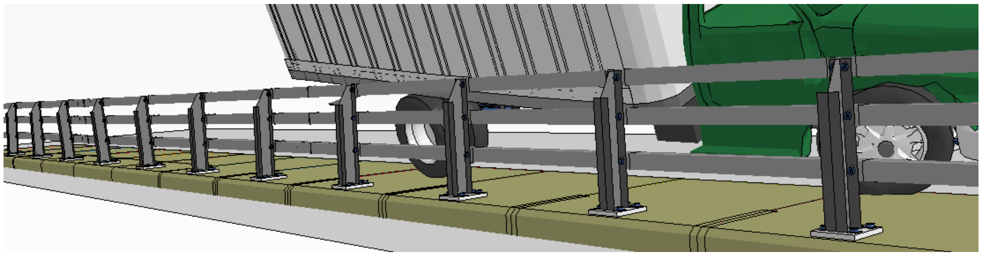

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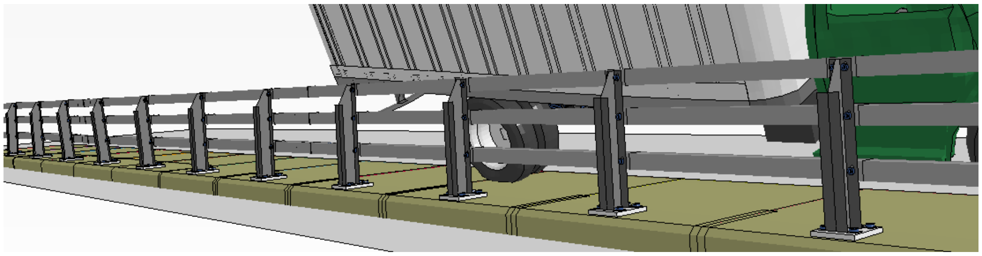

Figure N-3. [Continued] Sequential views from analysis of MASH Test 4-12 for sidewalk-mounted S3-TL4 from an oblique viewpoint (Case 1).

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