Final Report

MASH TL3 EVALUATION OF MASSDOT'S CM-MTL3 BRIDGE RAIL USING FINITE ELEMENT ANALYSIS

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16. Abstract

The crash performance of the MassDOT CM-MTL3 combination concrete barrier with steel top rail 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 3 (TL3). Two design options for the bridge rail were evaluated: 1) Integral safety-curb design, 2) Vertical face on concrete. Both designs were found to meet *MASH* performance criteria for TL3. The vertical face design is recommended for future installations.

17. Key Words	18. Distribution Statement
CM-MTL3, Combination Rail, Concrete Barrier, Steel Top Rail, Integral Curb, Vertical Face Barrier, MASH TL3, Finite Element Analysis	**No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161**

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CHAPTER 1 – INTRODUCTION

The purpose of this project was to evaluate the crash performance of MassDOT's CM-MTL3 bridge rail design under AASHTO Manual for Assessing Safety Hardware (*MASH*) test level 3 (TL-3) impact conditions and performance criteria using finite element analysis (FEA). The original design (i.e., CM-TL3) was developed by researchers at Worcester Polytechnic Institute (WPI), and its crash performance was evaluated under impact and evaluation criteria specified in NCHRP Report 350 for test level 3 (TL3). [*Ray07*] The system received eligibility status for use on federally funded roadways in 2008 based on the results from that study (see Eligibility Letter B-168).

Drawings details for the modified design for the CM-MTL3 are shown in Appendix A. The design includes a 15-1/8 inches tall steel post-and-beam railing mounted onto the top of a 17-inch tall continuous reinforced concrete barrier, as illustrated in Figures 1-3. The overall height of the barrier is 32-1/8 inches measured from the top of the roadway to the top of the steel rail. The steel post-and-beam rail is composed of a HSS 8"x3"x1/4" longitudinal beam supported by HSS 5"x5"x1/4" posts which are spaced at 6 feet on centers. The longitudinal beam is welded to the top of the posts. A 3/4-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 four ¾-inch diameter ASTM A4495 anchor bolts that are 12-inch long, as shown in Figure 2. Two bolts are positioned on the front side of the posts and two bolts positioned at the back of the base plate and closely aligned with the back edge of the posts. A 3/8" x 9½" x14½" anchor plate is attached at the bottom of the anchor bolts to secure the anchors and to prevent pullout during impact.

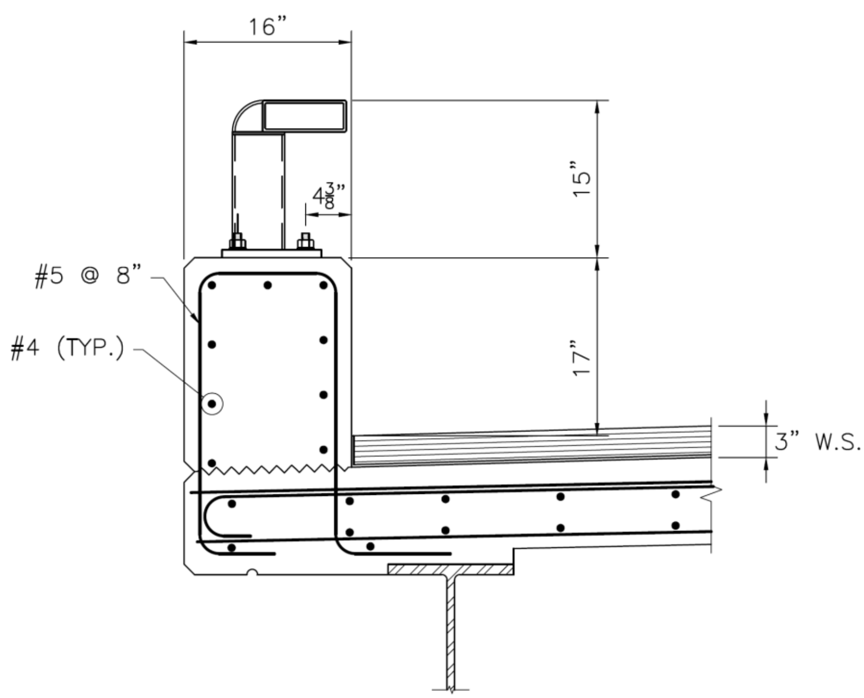


Figure 1. Section drawing for CM-MTL3.

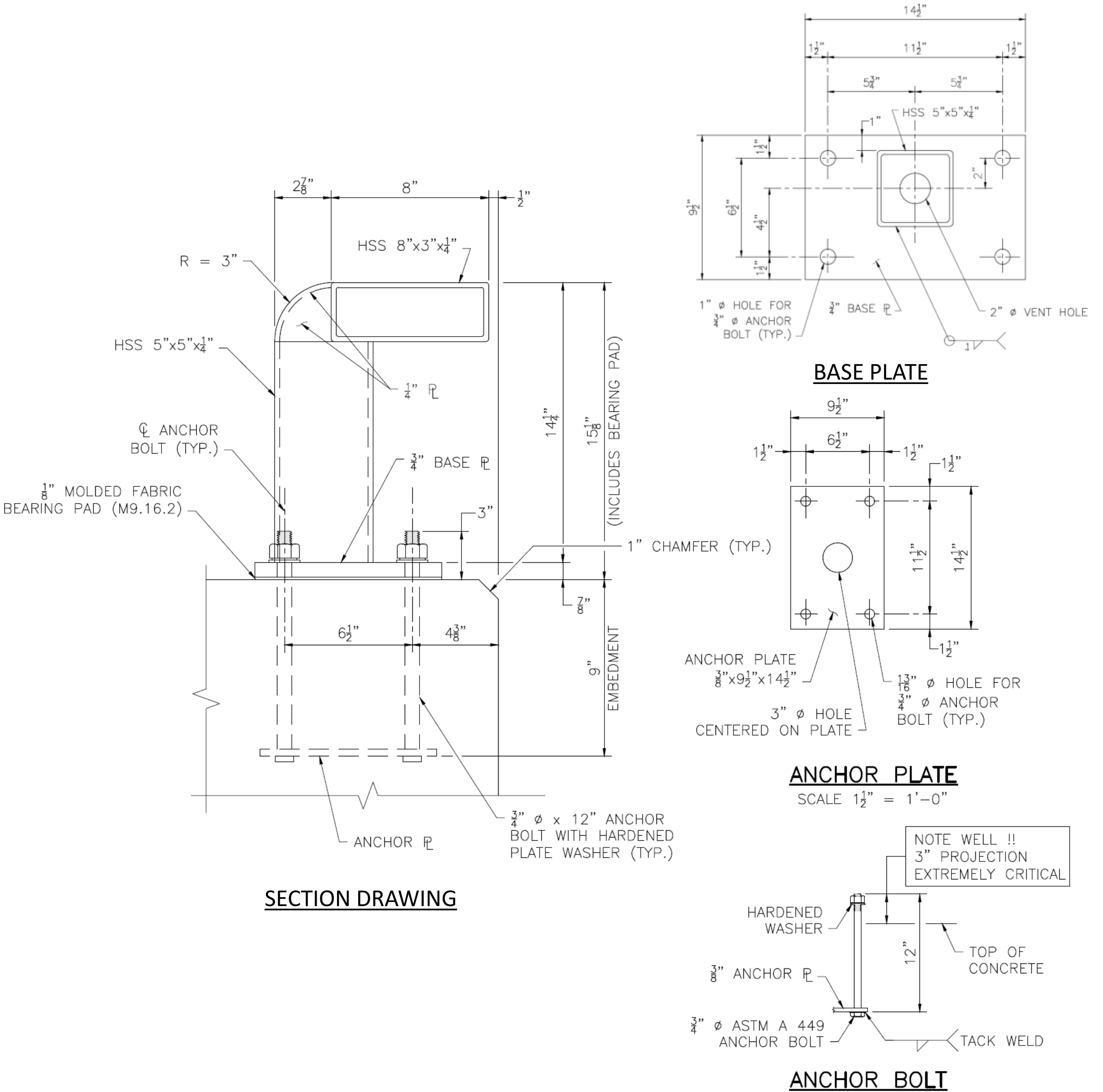


Figure 2. Section drawing and anchor details for the CM-MTL3.

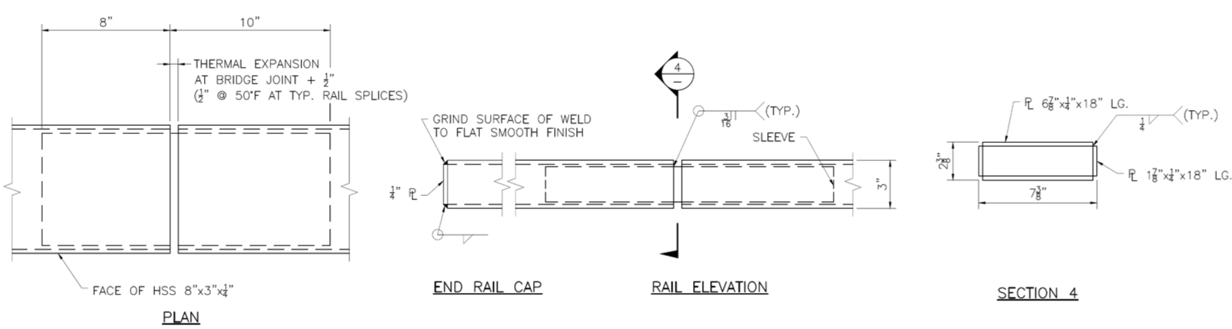


Figure 3. Splice details for the CM-MTL3.

The most significant change for the modified CM-MTL3 design compared to the original CM-TL3 design is a decreased offset distance for the post. The offset distance is 5-7/8" for the CM-MTL3 compared to 7-1/4" for the original CM-TL3. Geometric evaluation criteria for bridge railings are contained in Figures A13.1.1-2 and A13.1.1-3 of Section 13 of the AASHTO LRFD Bridge Design Specifications and are reproduced here in Figure 4 for convenience.[*AASHTO12*] The geometric criteria were developed based on a review of NCHRP Report 230 crash test data to relate impact performance to the geometric characteristics of bridge railing systems. The rail geometric criteria correlate the potential for the wheel, bumper, or hood to snag against a bridge rail post during impact, which could potentially lead to high vehicle decelerations and occupant compartment intrusions. These criteria have not yet been correlated to *MASH* criteria but are still commonly applied to bridge rail design. The rail-geometric assessment for the original and modified designs are illustrated in Figure 4, which shows that both designs meet preferred conditions for the *ratio of rail contact width to height* relative to *post setback distance* and are both borderline for preferred-marginal for the *vertical clear opening relative to post setback distance* criteria.

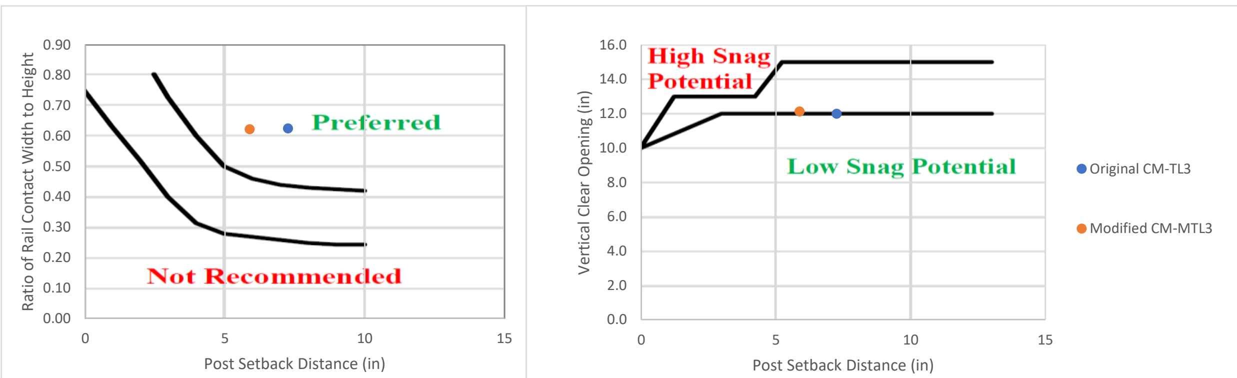


Figure 4. AASHTO Section 13 Figures A13.1.1-2 and A13.1.1-3 including Original CM-TL3 and Modified CM-MTL3.

Objectives and Scope

The objective of this project was to use finite element analysis (FEA) computer simulation to evaluate the crash performance of the MassDOT CM-MTL3 bridge rail design under the current impact and evaluation criteria of *MASH* TL3. The crash evaluations were carried out using the non-linear, dynamic, explicit finite element analysis software LS-DYNA. [*LSDYNA17*]. The assessment procedures included evaluations of structural capacity, risk of occupant injury and vehicle stability during impact and redirection. Two design options were evaluated: (1) integral safety-curb on concrete barrier and (2) vertical slope on concrete barrier, as shown in Figure 5.

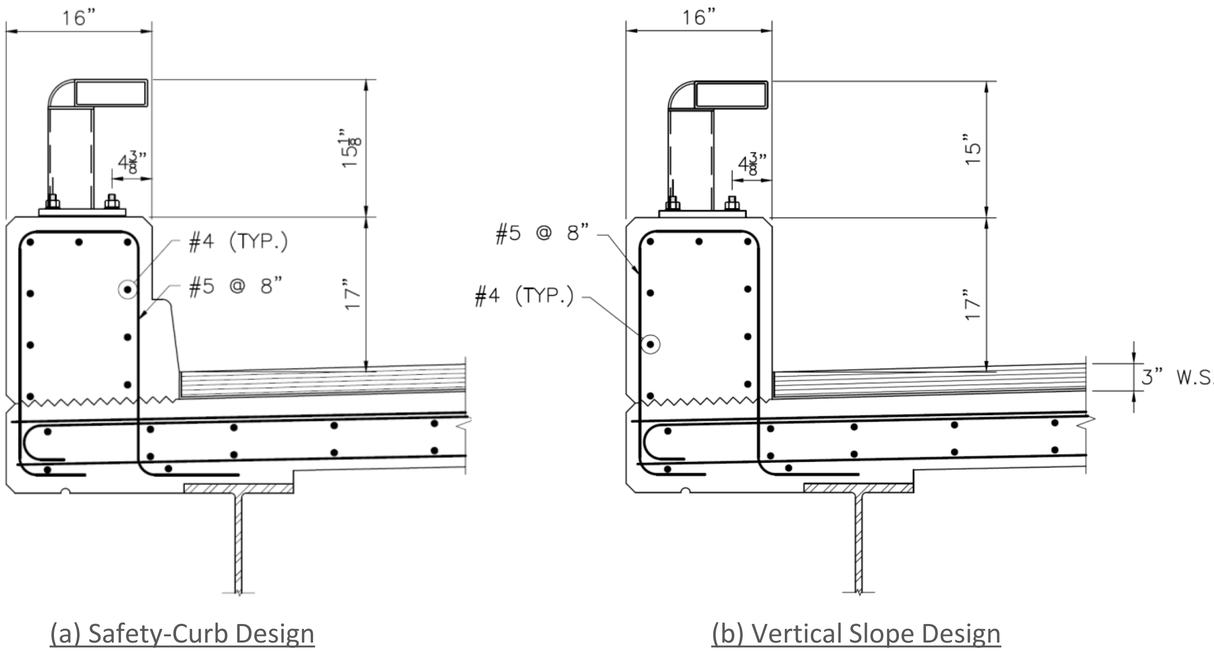


Figure 5. Section drawing for (a) safety-curb design and (b) vertical slope design.

CHAPTER 2 – RESEARCH APPROACH AND EVALUATION CRITERIA

The basic approach for the study was to develop a finite element model of the CM-MTL3 bridge rail (see Chapter 4) and to use FEA to simulate *MASH* TL3 tests (see Chapters 5 and 6). The crash performance of the system was evaluated for structural capacity, occupant risk, vehicle stability and trajectory during impact and redirection according to the recommended procedures and criteria contained in *MASH*. The FEA model was not directly validated against full-scale testing in this study; however, the same methodologies used in the development and validation of the FEA models used in early phases of this project, which were validated against full-scale crash testing using NCHRP Report 179 procedures, were implemented here.[*Ray10*] The FEA model for HSS tube, the steel anchor plate, and the anchor rods were based on the validated models developed in Phase II for the S3-TL4 bridge rail, and the FEA model for concrete and steel reinforcement were based on the validated models developed in Phase III for the CT-TL2.[*Plaxico19; Plaxico21*]

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 TL3 outlined with a red box. Table 2 shows the details for each criterion. The required test conditions specified in *MASH* for test level 3 evaluation of longitudinal barrier include:

- Test 3-10 – 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.
- Test 3-11 – 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.

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 3-10	Test 3-11
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.	Y	Y
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. Deformations of, or intrusions into, occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Y	Y
	F.	The vehicle should remain upright during and after the collision. The maximum roll and pitch angles are not to exceed 75 degrees.	Y	Y
	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)	Y	Y
	I.	The longitudinal and lateral occupant ridedown acceleration (ORA) shall not exceed 20.49 G, with a preferred limit of 15.0 G.	Y	Y

Accelerometers were positioned between the front seat occupants for both the 1100C and 2270P vehicles at the center of gravity for each vehicle models. The acceleration-time histories and angular rate-time histories were collected 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), occupant 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*]

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 trajectory, 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. The width of the exit box is the lateral distance "A" in Figure 6, which is defined as 7.2 feet plus the width of the vehicle plus 16 percent of the length of the vehicle. The length of the exit box is the longitudinal distance “B” in Figure 6 which is 32 feet. All wheel tracks of the vehicle should remain within the exit box throughout distance “B”. [*AASHTO16*] A graphical representation of the exit box is shown in Figure 6.

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

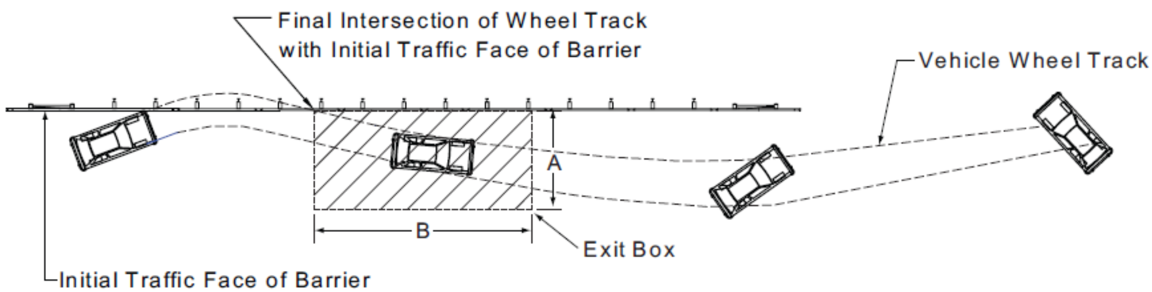


Figure 6. *MASH* exit box. [*AASHTO16*]

The exit box values were calculated based on the dimensions of the finite element analysis vehicle models that are further described in Chapter 3. 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)
2-10	5.5	14.1	15	32.8
2-11	6.02	16.8	15.86	32.8

CHAPTER 3 – FEA VEHICLE MODELS

The vehicle models used in the crash performance evaluations include:

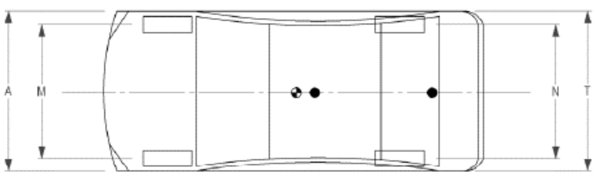
- YarisC version 1L (i.e., 1100C vehicle)
- Ram2018_V02u_RSTire (i.e., 2270P vehicle)

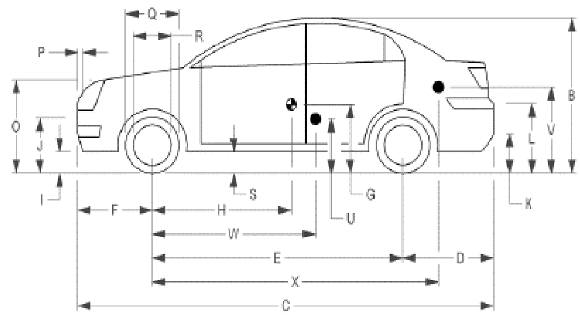
The models for the 1100C and 2270P vehicles used for the *MASH* analysis cases were the YarisC_v1L model (based on a 2010 Toyota Yaris) and the Ram2018_V02u model (based on a 2018 quad-cab Dodge Ram). These vehicles closely represent the two test vehicles specified in *MASH*. [*AASHTO16*] The vehicle 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. The models also include validated suspension and steering subsystems. The Dodge Ram model is relatively new and is continually being improved by GMU as well as the user community. The Yaris model has been used extensively by the research team and has routinely provided good results. [*Plaxico19; Plaxico20*] The validation reports for these vehicles can be accessed from the George Mason University's Center for Collision Safety and Analysis website. [*Marzougui12; CCSA16; CCSA18*] Additional modifications were made to the 1100C and the 2270P models in Phase III, which included development of a new tire model.[*Plaxico21*]

A comparison of the physical and inertial properties of the 1100C and 2270P vehicle models with those of recent full-scale test vehicles (i.e., Test 469468-3-1 and Test 469468-3-2) is provided in Figure 7 and Figure 8, respectively.[*Bligh19*] The most notable difference for the 1100C vehicle was that the center of gravity (c.g.) was set 6.15 inches farther back in the model compared to the test vehicle, which resulted in a 17 percent difference, and the height of the model was approximately 12 percent taller than the test vehicle. For the 2270P vehicle model, except for the *bumper extension* and the *wheel-well clearance*, all other measurements were within 10 percent of those measured on the test vehicle. The longitudinal c.g. and the vertical c.g. of the 2270P model was within 4 percent and 1 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.

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	65.67	-1.07
b	Overall Height:	51.5	57.68	11.99
c	Overall Length:	165.75	169.17	2.07
d	Rear Overhang:	34	37.09	9.08
e	Wheel Base:	98.75	99.92	1.19
f	Front Overhang:	33	32.13	-2.65
g	C.G. Height:		21.67	
h	C.G. Horz. Dist.	35.9	42.05	17.12
i	Front Bumper Bottom:	7.75	7.91	2.11
j	Front Bumper Top:	21.5	21.42	-0.38
k	Rear Bumper Bottom:	12.25	13.74	12.16
l	Rear Bumper Top:	25.25	25.20	-0.21
m	Front Track Width:	57.75	58.62	1.51
n	Rear Track Width:	57.7	57.64	-0.11
o	Hood Height:	28.25	31.73	12.33

		Test	Model	% Error
p	Bumper Extension:	4.12	3.66	-11.13
q	Front Tire Width:	22.5	22.99	2.19
r	Front Wheel Width:	15.5	15.08	-2.72
s	Bottom Door Height:	8.25	7.87	-4.56
t	Rear Bumper Width:	66.2	65.83	-0.56

Engine Type:	4 cylinder
Engine Size:	1.6 liter

Accelerometer Location (mm) - measured from front axle and ground

	X	Y	Z
Test Vehicle:	35.9	0	15.8
FEA Vehicle:	41.7	0	13.0

Weights (lbs)

	Curb		
	Test	Model	% Error
$W_{front\ axle}$	1597	0	-100.00
$W_{rear\ axle}$	921	0	-100.00
W_{total}	2518	0	-100.00

	Gross Static		
	Test	Model	% Error
$W_{front\ axle}$	1641	1511.2	-7.91
$W_{rear\ axle}$	971	1097.9	13.07
W_{total}	2612	2609.1	-0.11

GVWR Ratings (lbs)	Test	Model	% Error
Front	1718	0	-100.00
Rear	1874	0	-100.00

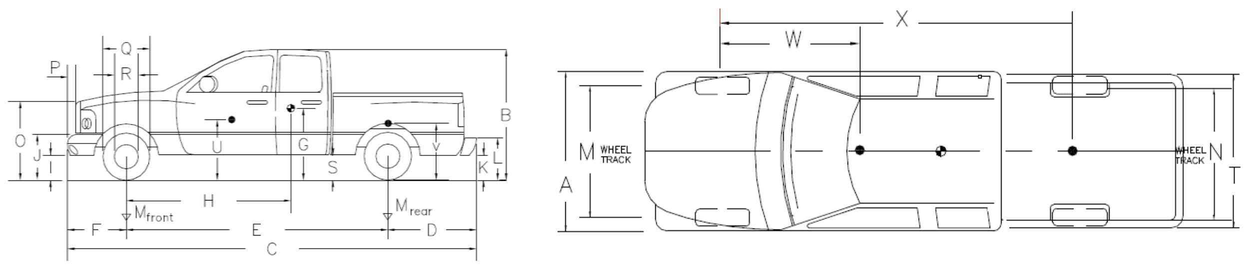
Dummy Data				
	Type	50th Percentile male		
	Mass (lbs)	165	0	-100.00
	Seat Position	Impact Side		

Other Notes:

Figure 7. Vehicle property sheet for the 1100C vehicle model compared with the test vehicle in full-scale test 469468-3-1.

VEHICLE PROPERTIES AND INFORMATION

Date:	10/8/2003	Test No.:	420020-3	Vin No.:	1D7HA18N455243883
Year:	2005	Make:	Dodge	Model:	RAM 1500 Quad-Cab
Odometer:	138200	Tire Size Front:	265/70R17	Tire Size Rear:	245/70R17



Vehicle Geometry (inches)

		Test	Model	% Error			Test	Model	% Error
a	Front Bumper Width:	78.50	76.02	-3.15	p	Bumper Extension:	3.00	2.6	-12.07
b	Overall Height:	74.00	75.51	2.04	q	Front Tire Width:	30.50	31.8	4.17
c	Overall Length:	227.50	229.33	0.80	r	Front Wheel Width:	18.00	18.4	2.36
d	Rear Overhang:	44.00	48.31	9.79	s	Bottom of Body Height:	13.00	13.6	4.78
e	Wheel Base:	140.50	140.20	-0.22	t	Overall Width:	77.00	79.3	2.98
f	Front Overhang:	40.00	40.20	0.49	u	Accelerometer Height:	27.75	27.7	-0.21
g	C.G. Height:	28.87	28.98	0.38	w	Accelerometer from Axle	62.40	62.4	0.00
h	C.G. Horz. Dist.	62.40	60.11	-3.68		Wheel Center Height Front:	14.75	16.0	8.37
i	Front Bumper Bottom:	11.75	12.56	6.89		Wheel Center Height Back:	14.75	16.0	8.37
j	Front Bumper Top:	27.00	25.94	-3.91		Wheel Well Clearance (F):	6.00	NA	
k	Rear Bumper Bottom:	20.00	20.47	2.36		Wheel Well Clearance (R):	9.25	11.9	28.54
l	Rear frame Top:	30.00	31.14	3.81		Frame Height (F):	12.00	12.6	4.66
m	Front Track Width:	68.50	69.49	1.44		Frame Height (R):	25.50	27.0	5.76
n	Rear Track Width:	68.00	67.24	-1.11		Engine Type:	V-8		
o	Hood Height:	46.00	44.84	-2.52		Engine Size:			

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

Weights (lbs)

	Curb Test	Curb Model	% Error
$W_{front\ axle}$	2850	0	-100.00
$W_{rear\ axle}$	2106	0	-100.00
W_{total}	4956	0	-100.00

	Gross Static Test	Gross Static Model	% Error
$W_{front\ axle}$	2870	2960	3.14
$W_{rear\ axle}$	2307	2221	-3.71
W_{total}	5177	5182	0.09

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 Position	Impact Side		

Other Notes:

Figure 8. Vehicle property sheet for the 2270P vehicle model compared with the test vehicle in full-scale test 469468-3-2.

CHAPTER 4 – FEA MODEL DEVELOPMENT

A detailed finite element model of the CM-MTL3 bridge rail was developed, as shown in Figure 9, based on construction drawings provided by MassDOT, which are provided in Appendix A of this report. The overall FEA model included a 48-ft length of the CM-MTL3 bridge rail and a 3-ft width of the bridge deck, as shown in Figure 9. FEA models for two design cases were developed: 1) integral safety-curb design and 2) vertical face design. Both models are identical except for the shape of the traffic face of the concrete barrier, as illustrated in Figure 14. The basic components of the bridge rail model include:

- Eight (8) 5”x5”x1/4” posts spaced at 6-feet on centers,
- Eight (8) 9.5”x14.25”x0.75” base plates (i.e., one at each post),
- Eight (8) 9.5”x14.5”x0.375” anchor plates (i.e., one at each post)
- Thirty-two (32) anchor bolts (i.e., four (4) at each base plate connecting the base plate to the concrete parapet),
- Two (2) HSS 8”x3”x0.25” tube rails that are 24 feet long (each) and hardware,
- One (1) splice tube weldment, 18 inches long (each) made from 1/4-inch thick steel plate, and
- Concrete parapet and bridge deck with steel reinforcement.

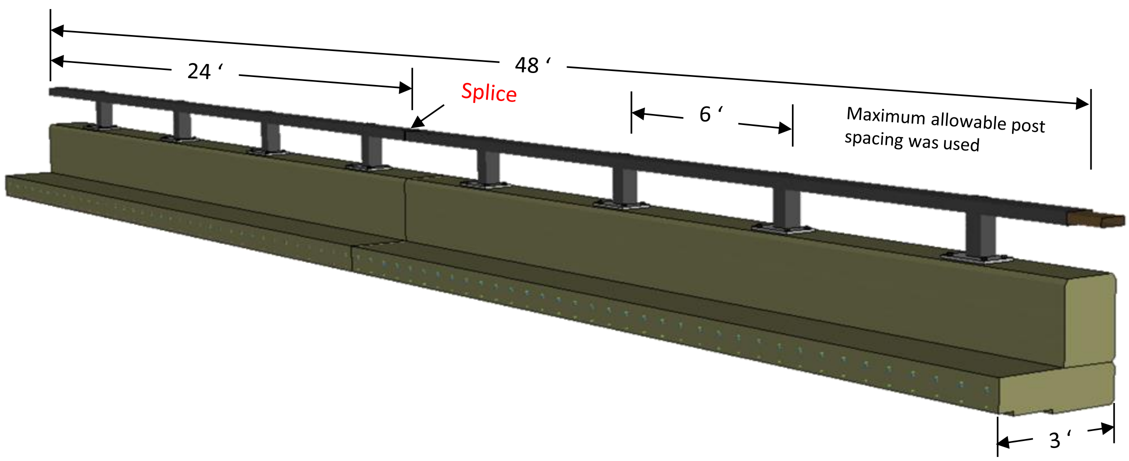


Figure 9. FEA model of the MassDOT CM-MTL3 bridge rail.

Posts

The geometry of the posts was modeled according to the detailed drawings in Appendix A. The FEA model of the post is shown in Figure 10. The material for the HSS portion of the post model conformed to ASTM A500 Grade C; the material for the top weldment portion of the post 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 mesh size was modeled with a nominal element size of 5/8” x 5/8”. The weldment was modeled as *Constrained_Spotwelds in LS-DYNA with no failure.

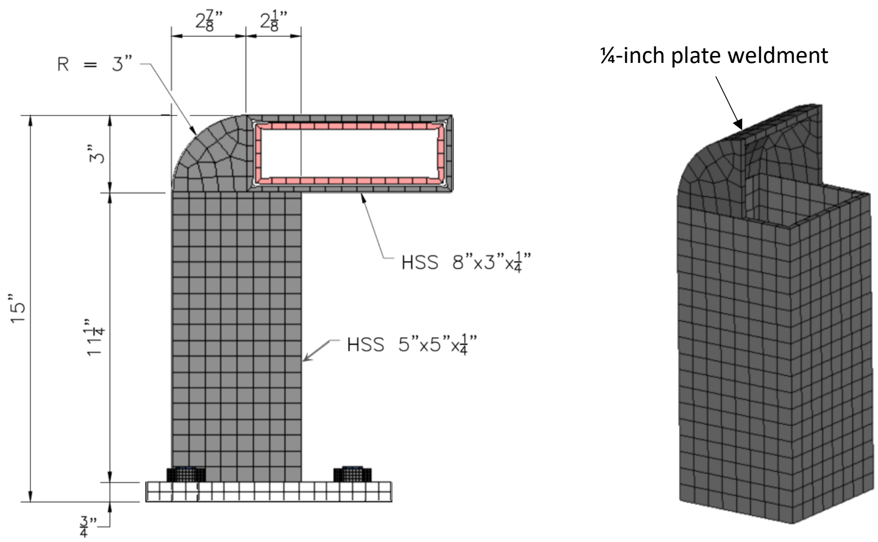


Figure 10. FEA mesh of steel bridge rail post.

Tubular Rail

The tubular rail section was modeled according to the dimensional specifications for HSS 8" x 3" x ¼". A representative portion of the rail model is shown in Figure 11. 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 5/8" x 5/8". The weldment of the rail to the post was modeled using *Contact_Tied_Nodes_to_Surface option in LS-DYNA.

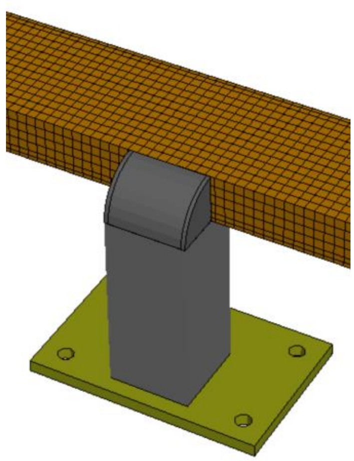


Figure 11. FEA mesh of tubular rail.

The splice connection of the adjoining tube rails included an 18-inch long tubular sleeve inserted 8 inches into the end of the downstream main rail section (see Appendix A for dimension details). The welded connection of the splice-tube to the downstream main rail was modeled using spotweld constraints in LSDYNA. The other end of the splice tube is inserted into the upstream main rail section and does not include any fasteners or weldments, thereby allowing the splice tube to slide freely inside the upstream rail section. A ½-inch gap between the adjoining main-rail sections was included according to the splice design. The modeled splice connection is shown in Figure 12. The splice tubes were modeled with the same material properties and mesh details as the main rail tubes.

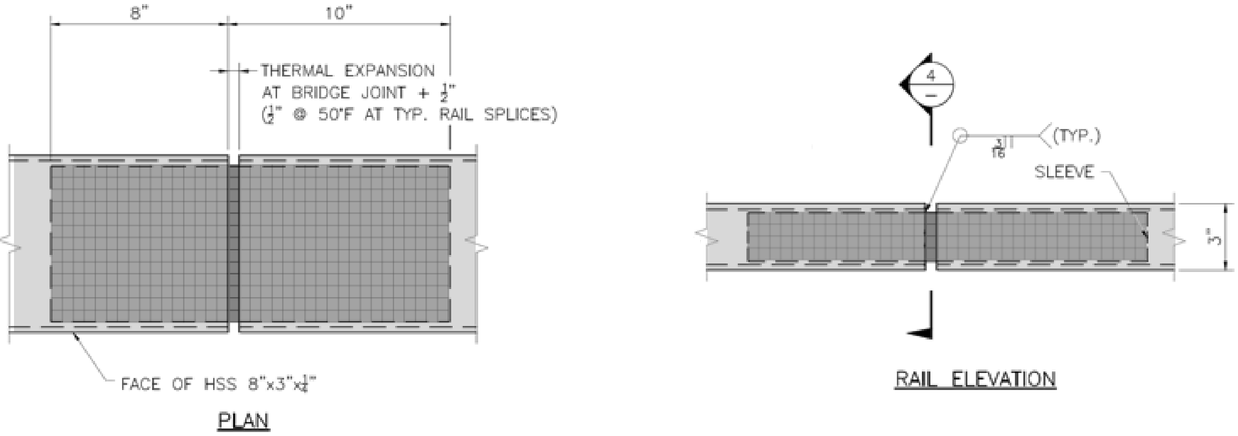


Figure 12. Model of rail splice with rail-tube shown transparent.

Base Plate and Anchor Bolts

The base plate was modeled with dimensions 12½" x 9½" x ¾" and with material properties conforming to ASTM A709 Grade 50. The part was meshed with Type 3 hexahedral element (fully integrated quadratic 8 node element with nodal rotations) with nominal side length of 9/16". The welded connection of the post to the base plated was modeled using *Contact_Tied option in LS-DYNA. The ¾-inch diameter anchor bolts were modeled with Type 1 beam elements in LS-DYNA. The material for the anchor bolts conformed to ASTM A449, which has a minimum yield strength of 105 ksi, ultimate strength of 125 ksi, and 15 percent elongation. The nuts were modeled as rigid. The anchor bolts extended into the rigid deck, as illustrated in Figure 13. 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 so that its constraint to the curb/deck could also be modeled using *Constrained_Beam-in-Solid.

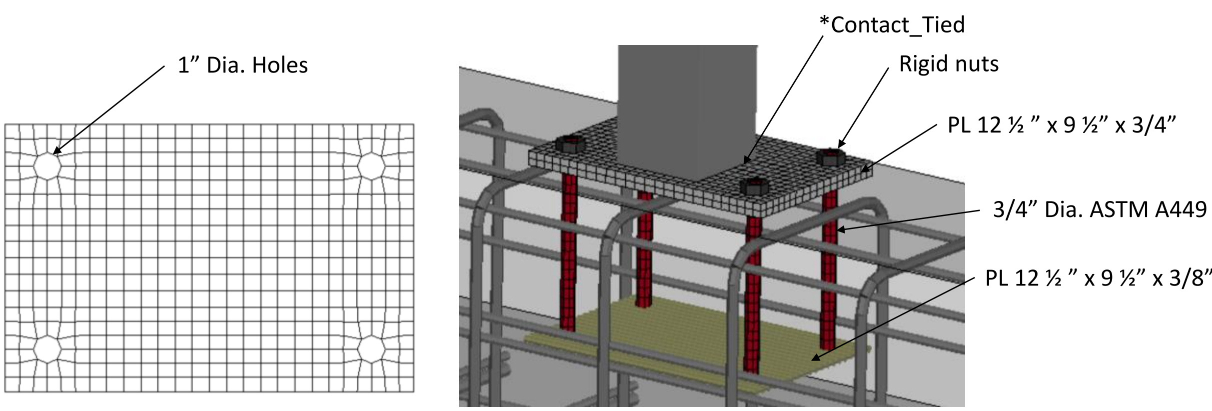


Figure 13. Transparent view of concrete showing model of base plate and anchor bolts.

Concrete Parapet and Deck

The concrete for the parapet and deck was modeled with Type 1 hexahedral elements in LS-DYNA with nominal element size of 1” x 1” x 1” in the regions where the posts are mounted, and are modeled with nominal element size of 1”x1”x1.5” elsewhere, as illustrated in Figures 14 and 15. All reinforcing bars were modeled with Type 1 beam elements with a nominal element length of 13/16 inch. The material properties for the reinforcing steel conformed to ASTM A615 Grade 60 steel.[*TFHRC15*]

The concrete material for the bridge rail and deck was modeled using two different concrete constitutive models in LS-DYNA (i.e., **Mat_RHT* and **MAT_CSCM*) with material properties based on an unconfined compressive strength of 4,000 psi (27.5 MPa), which corresponds to MassDOT’s current minimum strength specification. Bonding of the reinforcing steel within the concrete was modeled using the **Constrained_Beam_in_Solid* option in LS-DYNA.

Fixed constraints were imposed on the boundary ends of deck rebar and on the boundary face of the concrete, as indicated in Figure 14 by “+” symbols. The roadway was model as rigid using the **Rigidwall_Planar_Finite* option in LS-DYNA.

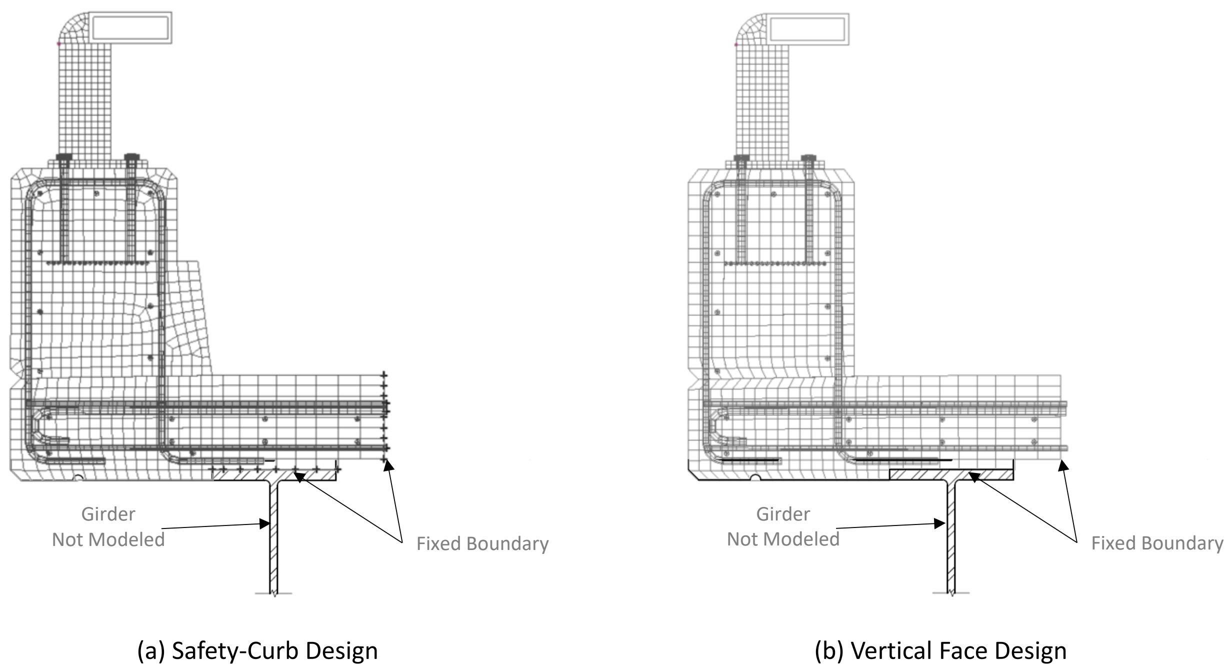


Figure 14. FEA model details for the CM-MTL3 for (a) safety-curb design and (b) vertical face design.

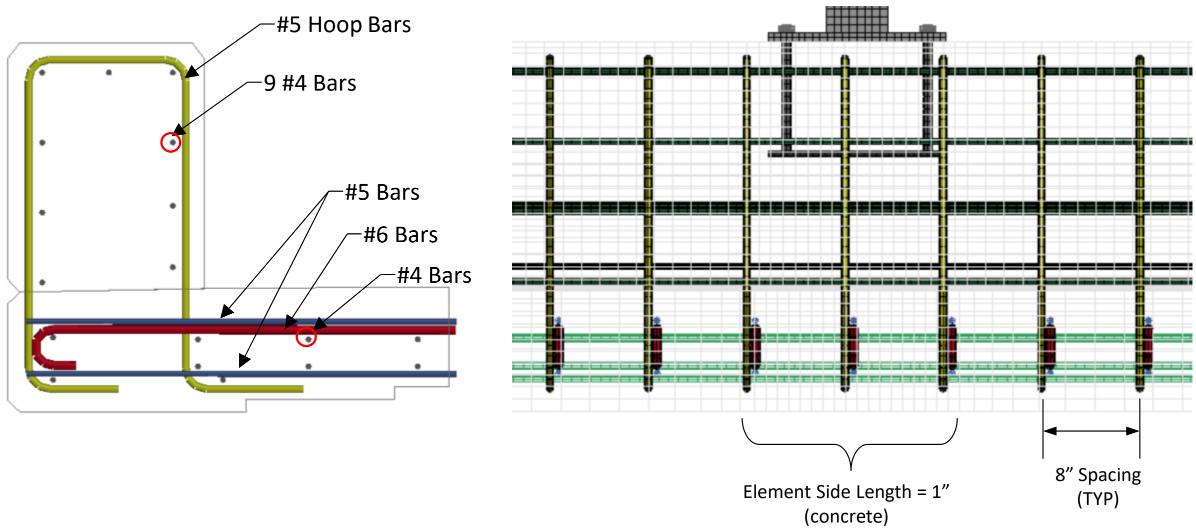


Figure 15. FEA model details for concrete barrier and deck reinforcement.

CHAPTER 5 – *MASH* TEST 3-11 EVALUATION OF THE CM-MTL3 WITH INTEGRAL SAFETY-CURB

FEA was used to evaluate the crash performance of the CM-MTL3 bridge rail with integral safety-curb, as illustrated in Figure 16. The evaluations were based on structural adequacy, vehicle stability during and after redirection, and occupant risk factors using criteria specified in *MASH* for Test Level 3. Simulation of Test 3-11 included the 2270P Dodge Ram model ballasted to 5,182 lb (2,351 kg) impacting the railing at 63.7 mph and 25 degrees. The RHT concrete model in LS-DYNA was used for these analyses with parameters as described in Chapter 4. The analysis in all cases was performed using LS-DYNA version mpp_s_R10.2.0 revision number 135267. The analysis was conducted with a time-step of 1.0 microsecond for a period of 0.735 second of the impact event.

Figure 16. FEA model of Test 3-11 on CM-MTL3 with safety curb.

Two critical impact cases were evaluated: (1) IP01 involved impact point at 4.3 ft upstream from the splice connection to maximize the potential for snagging at the splice and (2) IP02 involved impact point at 4.3 ft upstream of a post to maximize the potential for snagging on the critical bridge rail post (i.e., immediately downstream of rail splice). Each of the impact points are illustrated in Figure 17. A summary of the analysis results is shown in Table 4, which includes assessment of eight key metrics. 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.

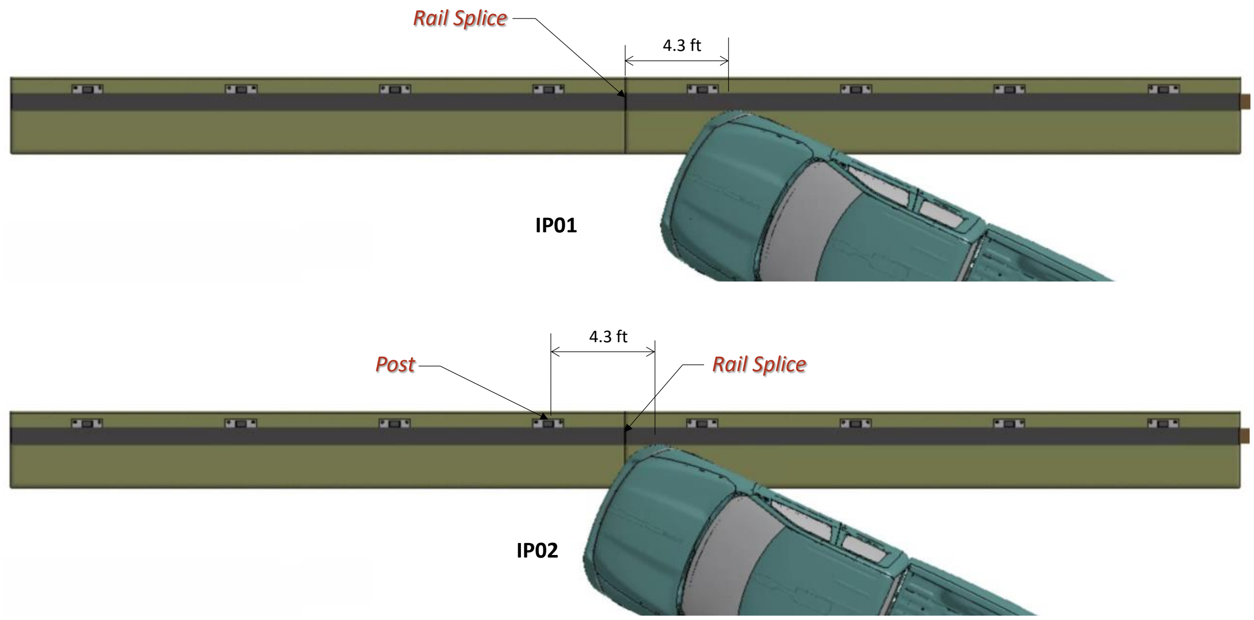


Figure 17. Critical impact point evaluated.

Table 4. Summary of results for CM-MTL3 for D1 (integral curb) design.

MASH Test	Impact Case	Concrete Model	Peak Acceleration X-dir (G)	Peak Acceleration Y-dir (G)	Occupant Risk Metrics OIVx (ft/s)	OIVy (ft/s)	ORAx (ft/s)	ORAy (ft/s)	Vehicle Stability Max Roll (deg)	Max Pitch (deg)	Result
3-11	IP_01	RHT	-17.1	-17.7	28.2	23.6	-10.9	-7.4	-9.5	5.2	Pass
3-11	IP_02	RHT	-17.8	-15.8	29.9	25.6	-5.9	-5.0	-8.7	-4.7	Pass

Test 3-11

The 5,182-lb pickup model struck the barrier at 4.3 feet upstream of the rail splice connection for IP01 and 4.3 feet upstream of the critical post for IP02. The impact speed was 63.7 mph, and the impact angle was 25 degrees. The sequential views of the impact event are shown in Appendices B and C for IP01 and IP02, respectively. Additional details for the sequence of key events for this analysis case are provided in Table 5. The following sections provide time-history data evaluation, occupant risk assessments, and damages sustained by both the barrier and vehicle for these two impact cases.

Table 5. Sequence of key events for Test 3-11 at IP01 for CM-MTL3 with safety curb.

	Event	IP01 - CIP for Rail Splice
1	Initial contact with barrier Right front fender and right front tire impacts vertical wall @ post 4	0.00 sec Impact speed = 63.7 mph Impact angle = 25 deg
2	Front right tire deflates	0.014 sec
3	Right front wheel climbs face of barrier	0.015 sec
4	Peak 50-ms average y-acceleration	11.6 G @ 0.0286 - 0.0786 sec
5	Vehicle begins to yaw counterclockwise	≈ 0.04 sec
6	Vehicle passes critical splice - w/ no apparent snag	0.05 sec
7	Peak 50-ms average x-acceleration	12.7 G @ 0.0506 - 0.1006 sec
8	Max positive pitch (front pitched upward)	≈ 5.10 deg @ 0.08 sec
9	Front right bumper contacts critical post # 5, but no significant snag occurs.	0.08 sec
10	Right rear wheel leaves the ground	0.08 sec
11	Max negative roll (top of vehicle away from barrier)	≈ -9.5 deg @ 0.08 sec
12	Front of vehicle passes critical post	0.09 sec
13	Occupant impact with vehicle interior	0.0962 sec OIV-x = 28.2 ft/s OIV-y = 23.6 ft/s
14	Left front wheel leaves the ground	0.11 sec
15	Maximum ORA-y	7.4 G @ 0.1191 - 0.1291 sec
16	Maximum dynamic barrier deflection occurs at splice	Initial contact: 3.1 in @ 0.12 sec
17	Maximum ORA-x	10.9 G @ 0.1244 - 0.1344 sec
18	Snag potential: front right wheel contacts critical post # 5, but no signifficant snag occurs.	0.13 sec
19	Left rear wheel leaves the ground	0.13 sec
20	Maximum occupant compartment intrusion. Maximum OCI Location Maximum OCI Magnitude	0.22 sec Right-side front panel forward of the A-pillar 7.1 in
21	Vehicle parallel with barrier	0.31 sec
22	Left front wheel returns to ground	0.32 sec
23	Tail slap with barrier Right rear fender and right rear tire impacts vertical wall between posts 4 and 5	0.37 sec Speed = 35.4 mph Angle = -3.0 deg
24	Rear right tire deflates	0.375 sec
25	Vehicle front bumper passes end of barrier	0.40 sec
26	Right front wheel returns to ground	0.43 sec
27	Vehicle body exits barrier	0.43 sec
28	Max negative pitch (front pitched downward)	≈ -4.7 deg @ 0.45 sec
29	Vehicle wheels exit barrier	0.46 sec Exit speed = 34.2 mph Exit angle = -4.66 deg
30	Peak yaw (counter-clockwise)	≈ -29.68 deg @ 0.47 sec
31	Max positive roll (top of vehicle toward barrier)	≈ 1.4 deg @ 0.65 sec
32	Left rear wheel returns to ground	Doesn’t return before end of run
33	Analysis Terminated	0.736 sec Speed = 32.5 mph Yaw angle = 2.6 deg (total angle) Roll angle = 0.7 deg (away from barrier) Pitch angle = 0.8 deg (rear pitched up)

Table 6. Sequence of key events for Test 3-11 at IP02 for CM-MTL3 with safety curb.

Event		IP02 - CIP for Post
1	Initial contact with barrier Right front fender and right front tire impacts vertical wall @ post 4	0.00 sec Impact speed = 63.7 mph Impact angle = 25 deg
2	Front right tire deflates	0.014 sec
3	Right front wheel climbs face of barrier	0.015 sec
5	Vehicle begins to yaw counterclockwise	≈ 0.04 sec
6	Peak 50-ms average y-acceleration	11.9 G @ 0.0441 - 0.0941 sec
7	Peak 50-ms average x-acceleration	13.3 G @ 0.0443 - 0.0943 sec
8	Vehicle front bumper passes critical post	0.04 sec
9	Front, right wheel climbes above concrete barrier	0.05 sec
10	Right rear wheel leaves the ground	0.08 sec
11	Max negative roll (top of vehicle away from barrier)	≈ -8.6 deg @ 0.084 sec
12	Max positive pitch (front pitched upward)	≈ 4.14 deg @ 0.089 sec
13	Front right wheel contacts critical post # 5 resulting in slight snag.	0.09 sec
14	Occupant impact with vehicle interior	0.0984 sec OIV-x = 29.9 ft/s OIV-y = 25.6 ft/s
15	Left front wheel leaves the ground	0.1 sec
16	Maximum occupant compartment intrusion. Maximum OCI Location Maximum OCI Magnitude	0.10 sec Right-side front panel forward of the A-pillar 5.8 in
17	Maximum dynamic barrier deflection occurs at splice	Initial contact: 2.1 in @ 0.11 sec
18	Left rear wheel leaves the ground	0.13 sec
19	Maximum ORA-x	5.9 G @ 0.1696 - 0.1796 sec
20	right rear wheel skips off ground ground	0.20 - 0.23 sec
21	Vehicle parallel with barrier	0.275 sec
22	Rear right tire deflates	0.283 sec
23	Tail slap with barrier Right rear fender and right rear tire impacts vertical wall between posts 5 and 6	0.29 sec Speed = 38.8 mph Angle = -0.87 deg
24	Maximum ORA-y	5.0 G @ 0.3139 - 0.3239 sec
25	Vehicle front bumper passes end of barrier	0.33 sec
26	Left front wheel returns to ground	0.34 sec
27	Vehicle body and wheel exits barrier	0.40 sec Exit speed = 37.8 mph Exit angle = -4.37 deg
28	Right front wheel returns to ground	0.41 sec
29	Max negative pitch (front pitched downward)	≈ -4.7 deg @ 0.453 sec
30	right rear wheel returns to ground	0.51 sec
31	Peak yaw (counter-clockwise)	≈ -30.92 deg @ 0.592 sec
32	Max positive roll (top of vehicle toward barrier)	≈ 4.875 deg @ 0.6 sec
33	Left rear wheel returns to ground	Doesn’t return before end of run
34	Analysis Terminated	0.738 sec Speed = 34.3 mph Yaw angle = 5.6 deg (total angle) Roll angle = 2.3 deg (away from barrier) Pitch angle = 2.3 deg (rear pitched up)

Time History Data Evaluation

Figures 18 through 20 show the longitudinal, transverse, and vertical acceleration-time histories, respectively, computed from the center of gravity of the vehicle; Figures 21 through 23 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.

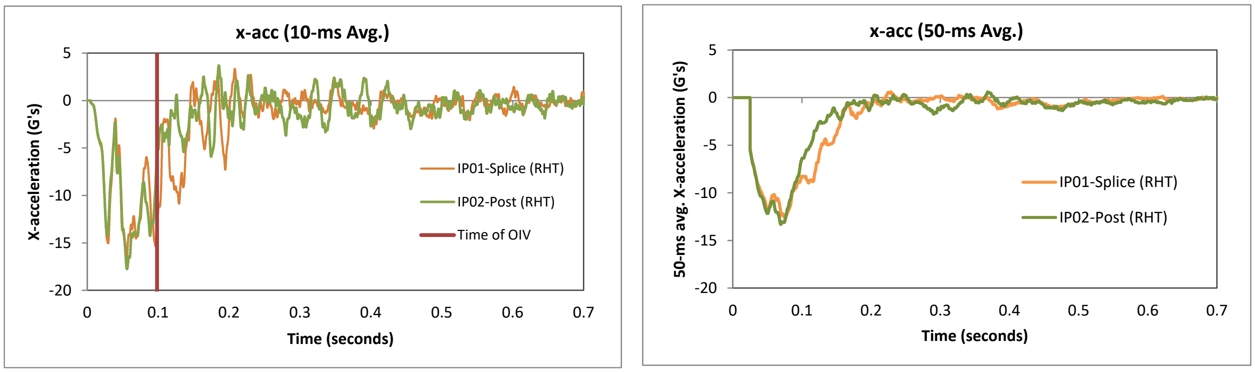


Figure 18. 10- and 50-millisecond average X-acceleration from FEA of Test 3-11 on the CM-MTL3 with safety curb at IP01 and IP02.

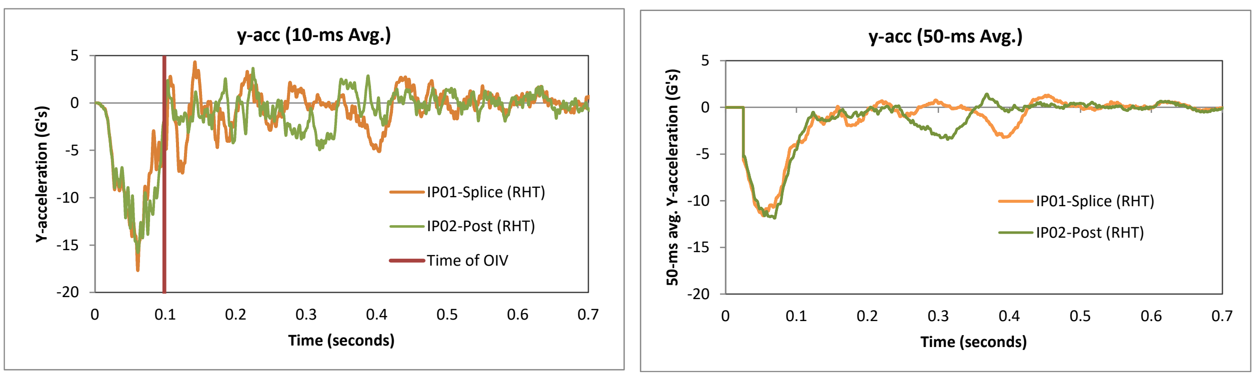


Figure 19. 10- and 50-millisecond average Y-acceleration from FEA of Test 3-11 on the CM-MTL3 with safety curb at IP01 and IP02.

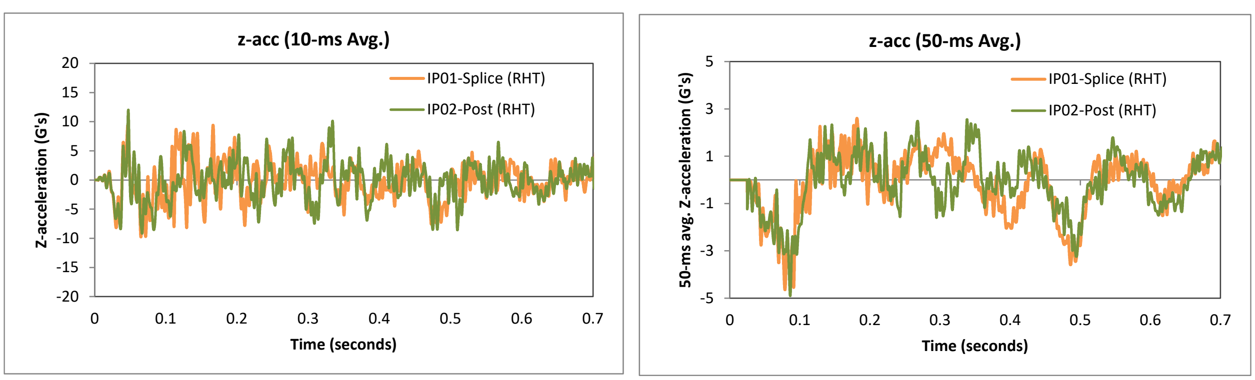


Figure 20. 10- and 50-millisecond average Z-acceleration from FEA of Test 3-11 on the CM-MTL3 with safety curb at IP01 and IP02.

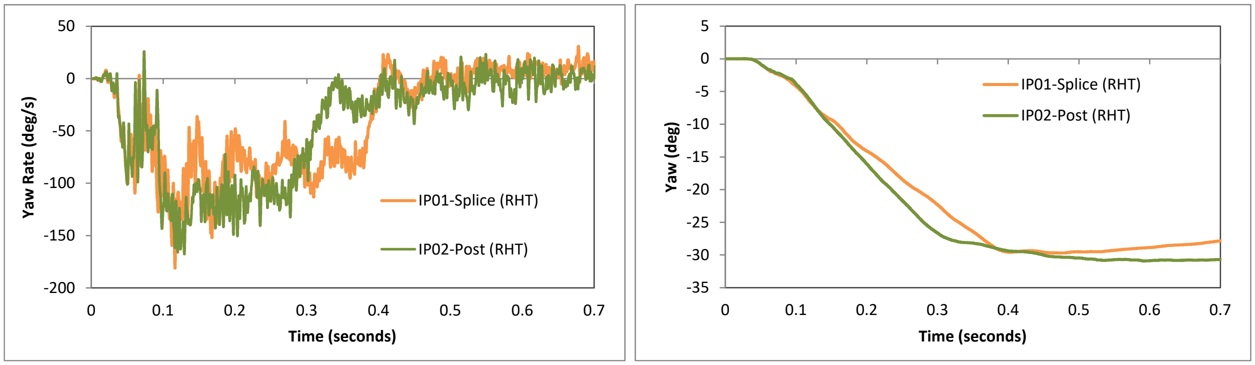


Figure 21. Yaw rate and yaw angle time-history from FEA of Test 3-11 on the CM-MTL3 with safety curb at IP01 and IP02.

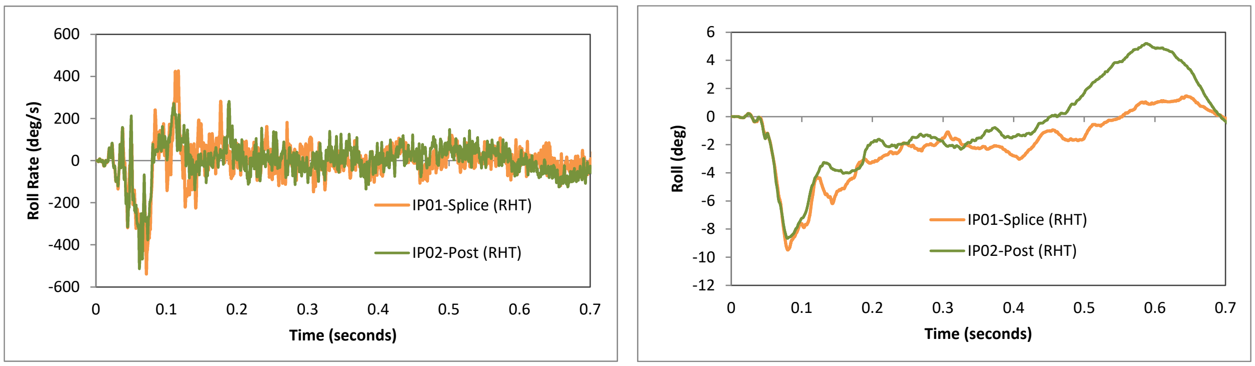


Figure 22. Roll rate and roll angle time-history from FEA of Test 3-11 on the CM-MTL3 with safety curb at IP01 and IP02.

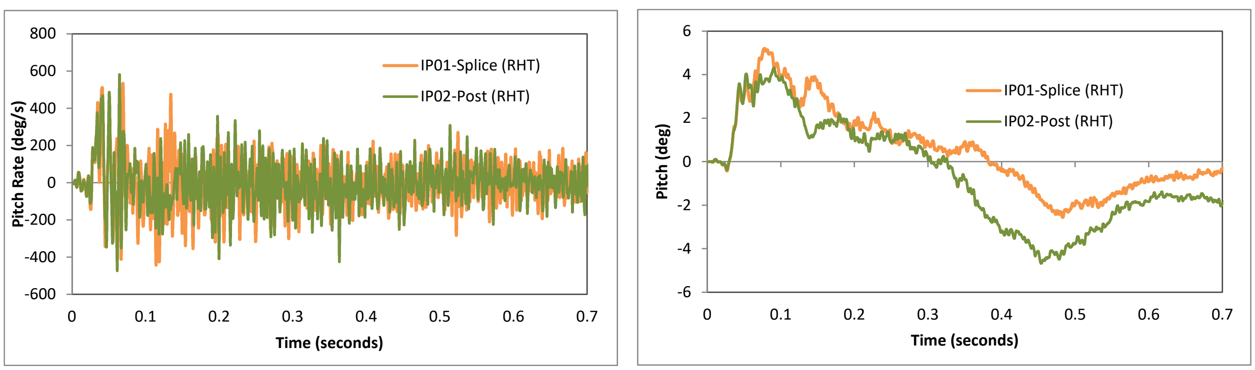


Figure 23. Pitch rate and pitch angle time-history from FEA of Test 3-11 on the CM-MTL3 with safety curb at IP01 and IP02.

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 7 shows the results for the occupant risk calculations. The results indicate that the occupant risk factors meet safety criteria specified in *MASH*.

IP01 – CIP for Snag on Rail Splice

The peak 10-ms running average accelerations were approximately 17 G in the longitudinal direction and approximately 18 G in the lateral direction, as shown in Figures 18 and 19 and Table 4. The occupant impact velocities in the longitudinal and transverse directions for system were 28.2 ft/s and 23.6 ft/s, respectively, which were within preferred limits specified in *MASH*. The highest 0.010-second occupant ridedown acceleration in the longitudinal and transverse directions were -10.9 g and -7.4 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 -12.7 g and -11.6 g, respectively. The maximum roll and pitch angles of the vehicle were -9.5 degrees and -5.2 degrees, respectively, which were well below critical limits in *MASH*.

Note that the maximum roll angle occurred during the early phase of the impact event (i.e., 0.08 seconds) and was the result of a local rotation of the accelerometer mounted to the cabin floor, rather than overall roll of the pickup[1]. As shown in Appendix B, the roll of the vehicle was minimal throughout impact and redirection. This was also the case for IP02 which is detailed below.

IP02 – CIP for Snag on Post

The peak 10-ms running average accelerations were approximately 18 G in the longitudinal direction and approximately 16 G in the lateral direction, as shown in Figures 18 and 19 and Table 4. The occupant impact velocities in the longitudinal and transverse directions for system were 29.9 ft/s and 25.6 ft/s, respectively, which were within preferred limits specified in *MASH*. The highest 0.010-second occupant ridedown acceleration in the longitudinal and transverse directions were -5.9 g and -5.0 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 -13.3 g and -11.9 g, respectively. The maximum roll and pitch angles of the vehicle were -8.7 degrees and -4.7 degrees, respectively, which were well below critical limits in *MASH*.

Damages to the Barrier System

Figure 24 shows images of the barrier at the time of maximum dynamic deflection with a contour plot of lateral displacement on the bridge rail. The dynamic deflection was 3.1 inches for IP01 and was 2.1 inches for IP02. The maximum permanent deflection was 2.6 inches for IP01 and was 1.8 inches for IP02. Figure 25 shows contour plots of the damage parameter, and Figure 26 shows contour plots of the 1st principal strain. Both analysis cases resulted in excessive damage to the upper, front face of the concrete barrier, with notable spalling along the top edge. The spalling was more pronounced for IP01 and resulted from the tire rim snagging at the expansion joint of the concrete when the wheel aggressively steered toward the barrier during impact.

[1] An additional 5 lbs was added to the accelerometer at the center of gravity of the vehicle to alleviate aliasing of data. The additional mass appears to have caused low magnitude motion of the accelerometer relative to the vehicle due to the added inertia of the part.

Table 7. Summary of *MASH* occupant risk metrics for Test 3-11 on the CM-MTL3 with safety curb.

Occupant Risk Factors		MASH 3-11	
		IP01-Splice (RHT)	IP02-Post (RHT)
Occupant Impact Velocity (ft/s)	x-direction	28.2	29.9
	y-direction	23.6	25.6
	at time	at 0.0962 seconds on right side of interior	at 0.0984 seconds on right side of interior
THIV (ft/s)		35.8 at 0.0962 seconds on right side of interior	38.4 at 0.0966 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-10.9 (0.1244 - 0.1344 seconds)	-5.9 (0.1696 - 0.1796 seconds)
	y-direction	-7.4 (0.1191 - 0.1291 seconds)	-5 (0.3139 - 0.3239 seconds)
PHD (g's)		12 (0.0962 - 0.1062 seconds)	5.9 (0.1696 - 0.1796 seconds)
ASI		1.72 (0.0594 - 0.1094 seconds)	1.81 (0.0629 - 0.1129 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-12.7 (0.0506 - 0.1006 seconds)	-13.3 (0.0443 - 0.0943 seconds)
	y-direction	-11.6 (0.0286 - 0.0786 seconds)	-11.9 (0.0441 - 0.0941 seconds)
	z-direction	-4.6 (0.0537 - 0.1037 seconds)	-4.9 (0.0613 - 0.1113 seconds)
Maximum Angular Disp. (deg)	Roll	-9.5 (0.0803 seconds)	-8.7 (0.0796 seconds)
	Pitch	5.2 (0.0780 seconds)	-4.7 (0.4538 seconds)
	Yaw	-29.7 (0.4755 seconds)	-30.9 (0.5919 seconds)

MASH Criteria

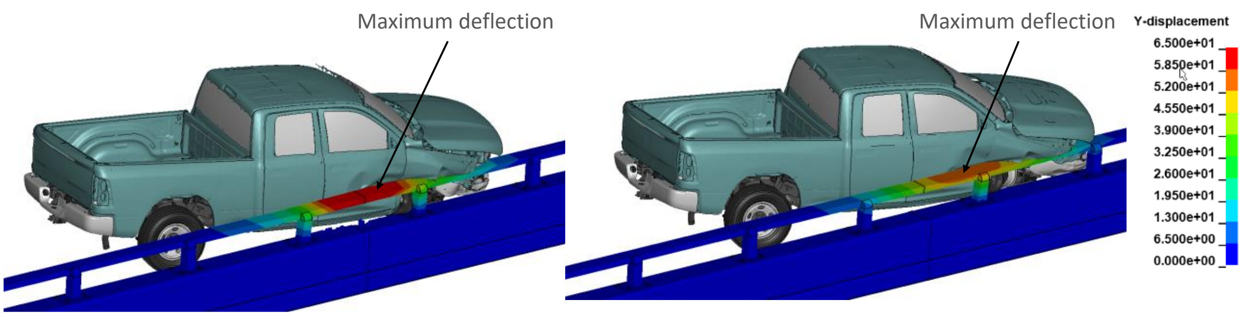
Occupant Impact Velocity: < 30 ft/s (preferred) ✓ < 40 ft/s (limit)

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

Roll and Pitch: < 75 deg ✓

Maximum dynamic deflection = 3.102 in (78.8 mm) @ 0.120 sec
Maximum permanent deflection = 2.579 in (65.5 mm)

Maximum dynamic deflection = 2.134 in (54.2 mm) @ 0.110 sec
Maximum permanent deflection = 1.772 in (45.0 mm)



IP01 Splice

IP02 Post

Figure 24. Contour plot of lateral displacement for Test 3-11 on the curbed CM-MTL3 at the time of maximum dynamic deflection for IP01 and IP02.

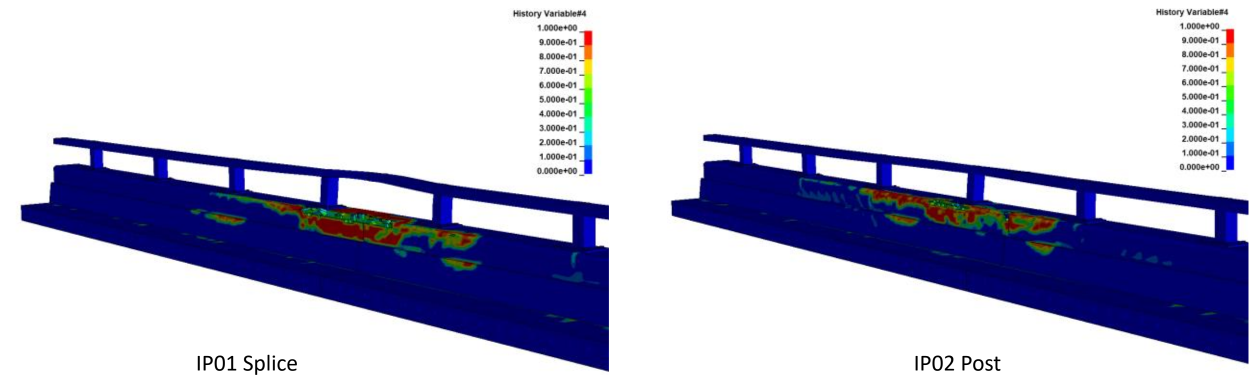


Figure 25. Contour plot of the damage variable for Test 3-11 on the curbed CM-MTL3 for IP01 and IP02.

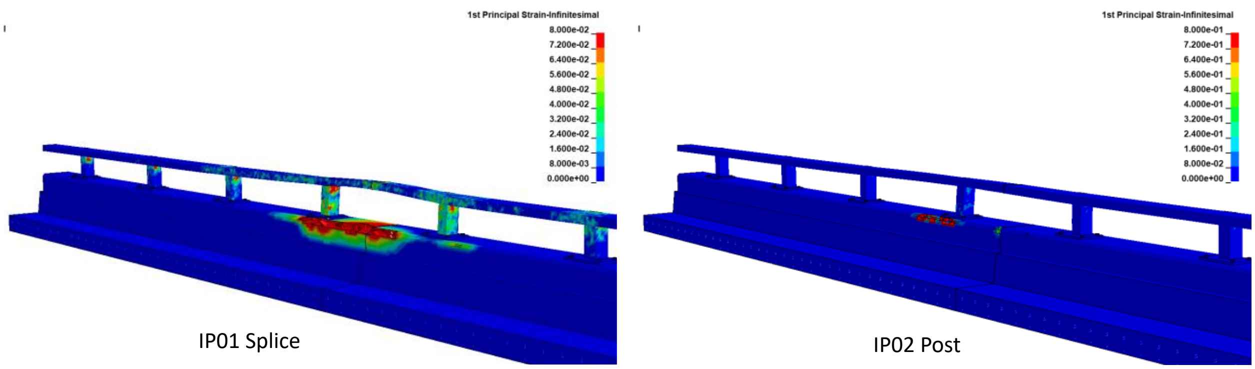


Figure 26. Contour plot of the 1st principal strain for Test 3-11 on the curbed CM-MTL3 for IP01 and IP02.

Damages to Vehicle

Figure 27 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. Damage to the vehicle was limited to the impact side of the front cap, the front impact-side wheel assembly, impact-side doors, and rear section of pickup bed.

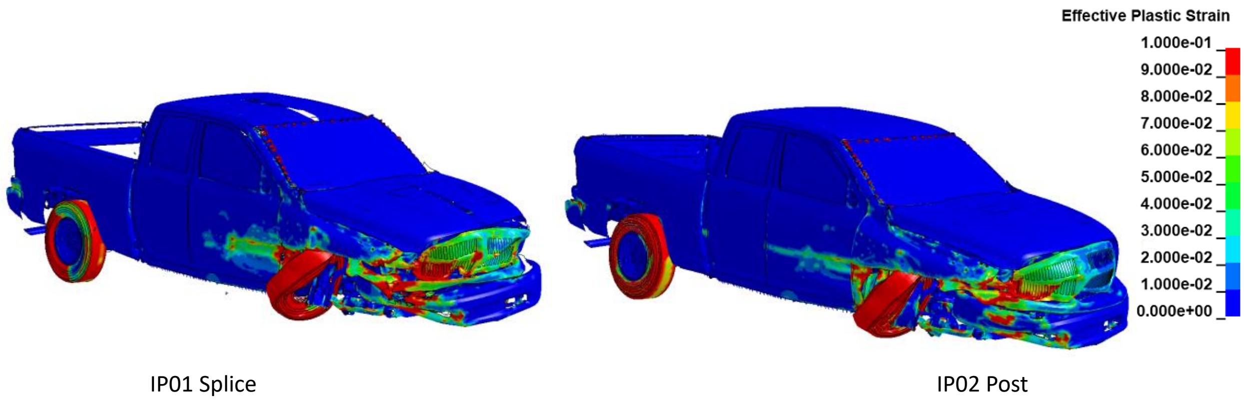


Figure 27. Damages to vehicle in Test 3-11 analysis of curbed CM-MTL3 for IP01 and IP02.

Occupant Compartment Intrusion

The maximum deformation of the occupant compartment was 7.1 inches for IP01 and was 5.8 inches for IP02. In both cases the maximum deformation occurred at the right-side front panel forward of the A-pillar. Figure 28 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 12 inches specified in *MASH* for this area of the occupant compartment.

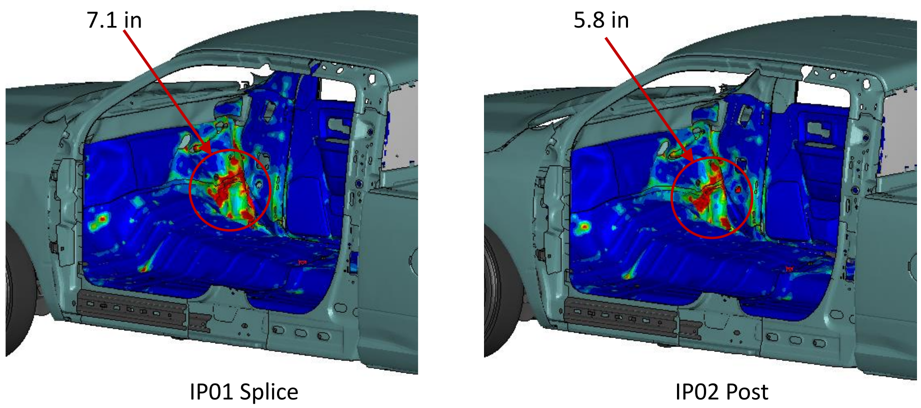


Figure 28. Occupant compartment deformation resulting from Test 3-11 of curbed CM-MTL3 for IP01 and IP02.

Exit Box

Figures 29 and 30 show the exit box for Test 3-11 on the curbed CM-MTL3 for cases IP01 and IP02, respectively. Although the exit box analysis is not required in *MASH*, it was included here for completeness. The vehicle was redirected with its path well within the exit box criteria of *MASH* for both analysis cases.

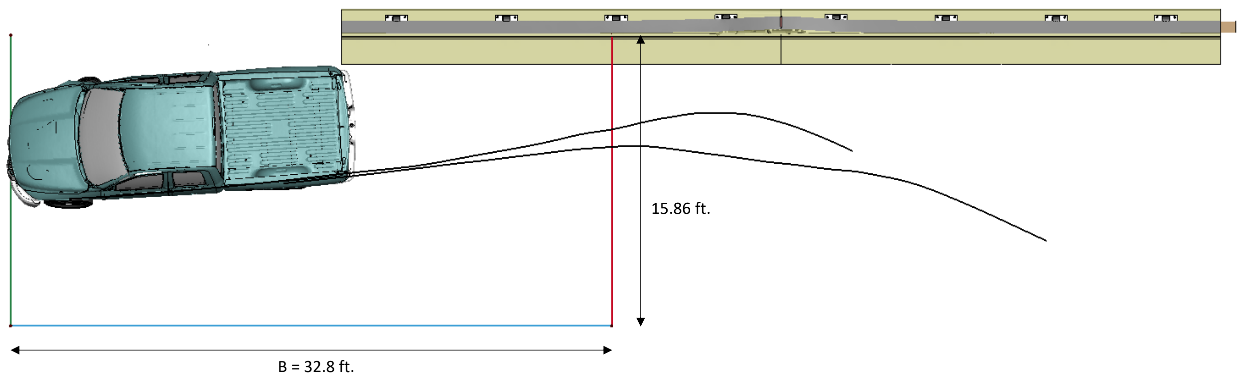


Figure 29. Exit box for Test 3-11 on the curbed CM-MTL3 for IP01.

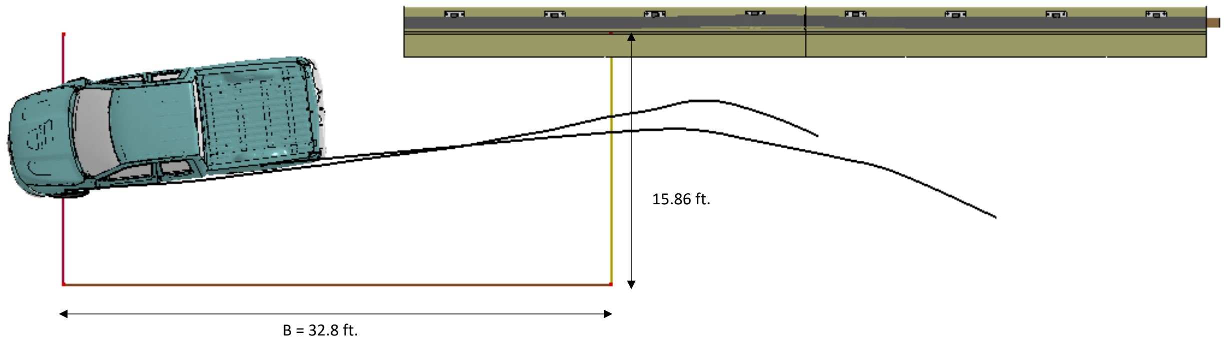


Figure 30. Exit box for Test 3-11 on the curbed CM-MTL3 for IP02.

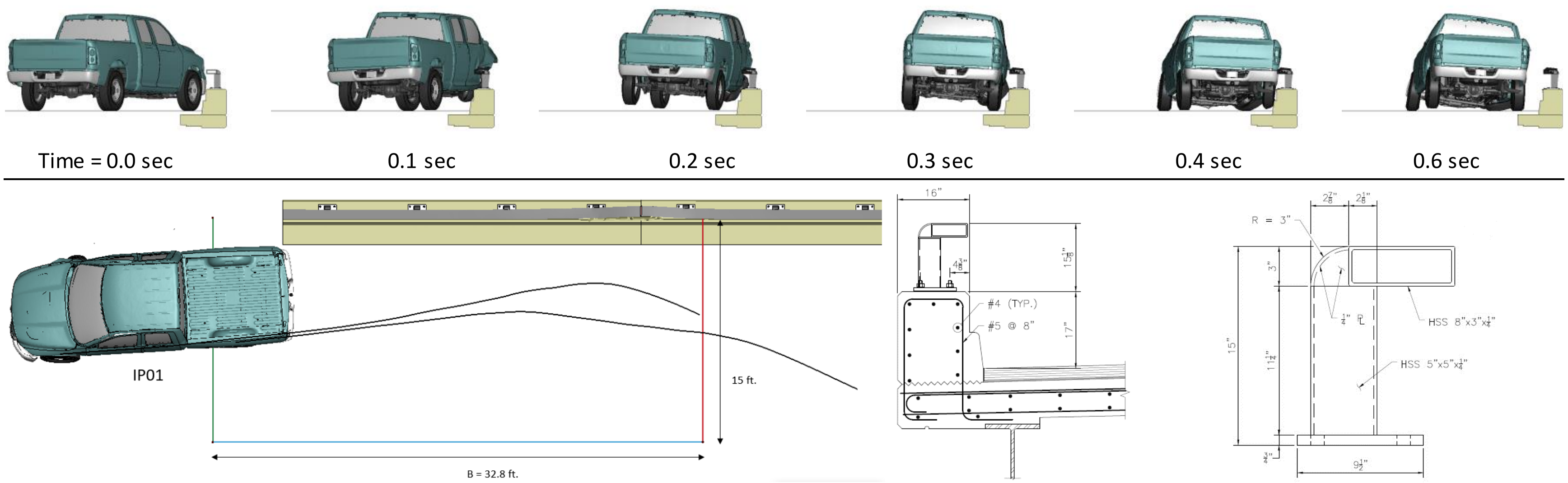
Results Summary

A summary of the *MASH* Test 3-11 results on the curbed CM-MTL3 bridge rail is shown in Table 8 and Figures 31 and 32. The barrier successfully contained and redirected the pickup with moderate damage to the bridge rail. 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 preferred 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 3-11 impact conditions.

Although the analysis results showed that the crash performance of the barrier system met *MASH* TL3 criteria, it was decided that the performance would likely be improved if the integral curb was removed from the barrier. During the early phase of the impact, the front, impact-side tire aggressively climbed and abruptly steered toward the barrier, resulting notable damage to the top edge of the barrier (e.g., significant spalling). Accordingly, the CM-MTL3 design was then modified to replace the integral-curb with a vertical face design for the concrete barrier. The results for the *MASH* TL3 evaluations of the CM-MTL3 with vertical face are presented in Chapter 6.

Table 8. Summary of *MASH* Test 3-11 results on the CM-MTL3 bridge rail with integral safety-curb.

Evaluation Factors		Evaluation Criteria	Results	
			IP01	IP02
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	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	Pass
	F	The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.	Pass	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	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	Pass



General Information

- Analysis Agency .... Roadsafe LLC
- Test Standard Test No. .... MASH Test 3-11
- Analysis No. CM-TL3 D1 IP01-Splice
- Analysis Date 7/19/2021

Test Article

- Type .... Bridge Rail
- Name CM-TL3
- Installation Length .... 48.0 feet
- Material or Key Elements .... Continuous concrete with top mounted steel post-and-beam rail

Soil Type and Condition .... NA

Analysis Vehicle

- Type / Designation 2270P
- FEA Model name .... Ram2018C_V2u.k w/ RS tire
- Mass .... 5,001 lb

Impact Conditions

- Speed .... 63.7 mph
- Angle .... 25 degrees
- Location .... 4.3 ft upstream of critical splice

Impact Severity .... 121.1 kip-ft

Exit Conditions

- Speed .... 34.2 mph
- Angle .... 4.7 degrees
- Time .... 0.46 seconds

Occupant Risk Values

- Longitudinal OIV .... 28.2 ft/s
- Lateral OIV .... 23.6 ft/s
- Longitudinal ORA .... 10.9 g
- Lateral ORA .... 7.4 g
- THIV .... 35.8 ft/s
- PHD .... 12.0 g
- ASI 1.72

Max50-millisecond Avg. (G)

- Longitudinal .... 12.7 g
- Lateral .... 11.6 g
- Vertical .... 4.6 g

Test Article Deflections (in)

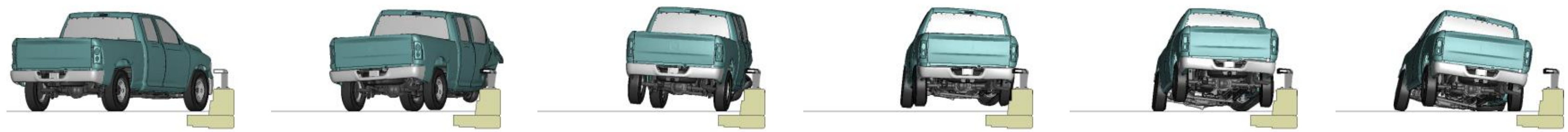
- Dynamic .... 3.1 inches
- Permanent .... 2.6 inches
- Working Width .... 16.0 inches

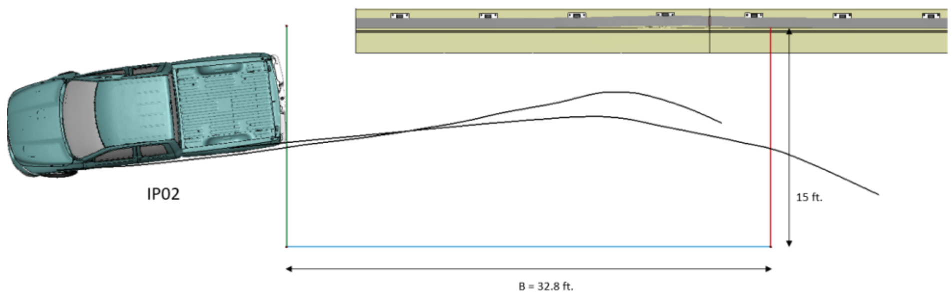
Max. OCI .... 7.1 inches

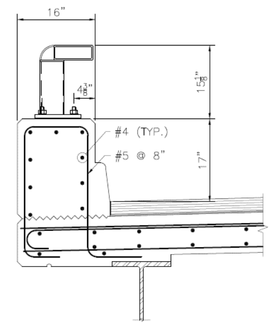
Vehicle Stability

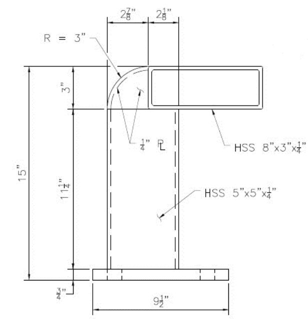
- Roll .... 9.5 degees
- Pitch .... 5.2 degrees
- Yaw .... 29.7 degrees

Figure 31. Summary results for *MASH* Test 3-11 on the CM-MTL3 bridge rail with integral safety curb.









General Information	
Analysis Agency	Roadsafe LLC
Test Standard Test No.	MASH Test 3-11
Analysis No.	CM-TL3 D1 IP02-Post
Analysis Date	7/19/2021
Test Article	
Type	Bridge Rail
Name	CM-TL3
Installation Length	48.0 feet
Material or Key Elements	Continuous concrete with top mounted steel post-and-beam rail
Soil Type and Condition	NA
Analysis Vehicle	
Type / Designation	2270P
FEA Model name	Ram2018C_V2u.k w/ RS tire
Mass	5,001 lb

Impact Conditions	
Speed	63.7 mph
Angle	25 degrees
Location	4.3 ft upstream of critical post
Impact Severity	121.1 kip-ft
Exit Conditions	
Speed	37.3 mph
Angle	4.4 degrees
Time	0.41 seconds
Occupant Risk Values	
Longitudinal OIV	29.9 ft/s
Lateral OIV	25.6 ft/s
Longitudinal ORA	5.9 g
Lateral ORA	5.0 g
THIV	38.4 ft/s
PHD	5.9 g
ASI	1.81

Max50-millisecond Avg. (G)	
Longitudinal	113.3 g
Lateral	11.9 g
Vertical	4.9 g
Test Article Deflections (in)	
Dynamic	2.1 inches
Permanent	1.8 inches
Working Width	16.0 inches
Max. OCI	5.8 inches
Vehicle Stability	
Roll	8.7 degees
Pitch	4.7 degrees
Yaw	30.9 degrees

Figure 32. Summary results for *MASH* Test 3-11 on the CM-MTL3 bridge rail with integral safety curb.

CHAPTER 6 – *MASH* TL3 EVALUATION OF THE CM-MTL3 WITH VERTICAL FACE

Based on the results presented in Chapter 5, the CM-MTL3 design was modified to improve crash performance by replace the integral curb on the face of the barrier with a vertical face design, as shown in Figure 5. FEA was again used to evaluate the crash performance of the bridge rail under *MASH* TL3 performance criteria. The evaluations included:

- Simulation of Test 3-10 with the 1100C Yaris model ballasted to 2,609 lb (1183 kg) impacting the barrier at 62 mph and 25 degrees.
- Simulation of Test 3-11 with the 2270P Chevrolet Silverado model ballasted to 5,182lb (2,351 kg) impacting the railing at 63.7 mph and 25 degrees.

As was done in the previous analyses of the CM-MTL3 barrier with safety-curb (see Chapter 5), two critical impact points were evaluated as illustrated in Figure 17: (1) IP01 maximized the potential for snagging at the splice and (2) IP02 maximized the potential for snagging on the critical post. Each impact scenario also included two different concrete material models in the evaluations: (1) the RHT concrete model and (2) the CSCM concrete model, as defined in Chapter 4. In total, eight analysis cases were evaluated, and a summary of the analysis results is shown in Table 9, which includes assessment of eight key metrics. Additional details of the results are provided in the following sections.

Table 9. Summary of results for CM-MTL3 for D2 (vertical face) design.

MASH Test	Impact Case	Concrete Model	Peak Acceleration		Occupant Risk Metrics				Vehicle Stability		Result
			X-dir (G)	Y-dir (G)	OIVx (ft/s)	OIVy (ft/s)	ORAx (ft/s)	ORAy (ft/s)	Max Roll (deg)	Max Pitch (deg)	
3-10	IP_01	RHT	-25.8	-32.3	23.6	28.5	-4.4	-13.5	6.1	-5.3	Pass
3-10	IP_01	CSCM	-26.8	-32.0	24.9	27.9	-9.0	-9.4	-5.3	-4.9	Pass
3-10	IP_02	RHT	-26.2	-31.2	25.3	28.9	-2.8	-12.6	-5.6	-5.2	Pass
3-10	IP_02	CSCM	-29.7	-29.8	26.9	28.2	-2.8	-10.2	-5.6	-4.7	Pass
3-11	IP_01	RHT	-17.3	-21.7	23.3	24.9	-5.0	-11.7	-10.8	5.2	Pass
3-11	IP_01	CSCM	-16.7	-19.7	23.6	24.9	-4.7	-10.5	-11.5	5.3	Pass
3-11	IP_02	RHT	-16.8	-22.1	22.0	25.9	-4.4	-10.7	13.1	-7.3	Pass
3-11	IP_02	CSCM	-17.6	-18.6	23.3	25.3	-4.4	-10.5	-11.1	5.2	Pass

Test 3-11 at IP01 – CIP for Snag at Rail Splice

The 5,182-lb pickup model struck the face of the barrier at 4.3 feet upstream of the rail splice at a speed of 63.7 mph and at an angle of 25 degrees. The sequential views of the impact event are shown in Appendix D for both the RHT and CSCM models. Additional details regarding the sequence of key events for both the RHT and CSCM analysis cases are provided in Table 10. The following sections provide time-history data evaluation, occupant risk assessments, and damages sustained by both the barrier and vehicle.

Table 10. Sequence of events for Test 3-11 at IP01 for the CM-MTL3 w/vertical face.

	Event	RHT	CSCM
1	Initial contact with barrier Right front fender and right front tire impacts vertical wall @ post 4	0.00 sec Impact speed = 63.7 mph Impact angle = 25 deg	0.00 sec Impact speed = 63.7 mph Impact angle = 25 deg
2	Front right tire deflates	0.013 sec	0.013 sec
3	Right front wheel climbs vertical face of barrier	0.015 sec	0.015 sec
4	Peak 50-ms average y-acceleration	13.1 G @ 0.0283 - 0.0783 sec	13.1 G @ 0.024 - 0.074 sec
5	Peak 50-ms average x-acceleration	11.0 G @ 0.0289 - 0.0789 sec	10.6 G @ 0.024 - 0.0740 sec
6	Vehicle passes critical splice - no snag	0.04 sec	0.04 sec
7	Vehicle begins to yaw counterclockwise	≈ 0.04 sec	≈ 0.04 sec
8	Vehicle passes critical post - no contact with post	0.08 sec	0.08 sec
9	Max positive pitch (front pitched upward)	≈ 5.14 deg @ 0.09 sec	≈ 5.25 deg @ 0.09 sec
10	Occupant impact with vehicle interior	0.092 sec OIV-x = 23.3 ft/s OIV-y = 24.9 ft/s	0.093 sec OIV-x = 23.6 ft/s OIV-y = 24.9 ft/s
11	Maximum ORA-x	5.0 G @ 0.0953 - 0.1053 sec	4.7 G @ 0.1092 - 0.1192 sec
12	Left front wheel leaves the ground	0.10 sec	0.10 sec
13	Left rear wheel leaves the ground	0.11 sec	0.10 sec
14	Maximum occupant compartment intrusion. Maximum OCI Location Maximum OCI Magnitude	0.13 sec Right front toe pan 7.5 in	0.10 sec Right front toe pan 6.6 in
15	Vehicle parallel with barrier	0.21 sec	0.21 sec
16	Rear right tire deflates	0.223 sec	0.223 sec
17	Tail slap with barrier Right rear fender and right rear tire impacts vertical wall between posts 4 and 5	0.23 sec Speed = 44.5 mph Angle = -1.7 deg	0.23 sec Speed = 44.2 mph Angle = -2.1 deg
18	Maximum ORA-y	11.7 G @ 0.2342 - 0.2442 sec	10.5 G @ 0.2339 - 0.2439 sec
19	Maximum dynamic barrier deflection occurs at splice	Tail slap: 2.1 in @ 0.24 sec	Initial contact: 2.4 in @ 0.11 sec
20	Right rear wheel leaves the ground	0.24 sec	0.24 sec
21	Vehicle wheels exit barrier	0.31 sec	0.31 sec
22	Right rear bumper: slight snag on rail @ post 6	0.32 sec	0.32
23	Right front wheel returns to ground	0.34 sec	0.34 sec
24	Vehicle front bumper passes end of barrier	0.35 sec	0.35 sec
25	Vehicle body exits barrier	0.40 sec Exit speed = 42.7 mph Exit angle = -8.2 deg	0.41 sec Exit speed = 42.1 mph Exit angle = -8.7 deg
26	Max positive roll (top of vehicle toward barrier)	≈ 8.1 deg @ 0.44 sec	≈ 6.7 deg @ 0.40 sec
27	Right rear wheel returns to ground momentarily	0.45 - 0.58 sec	0.45 - 0.59 sec
28	Max negative pitch (front pitched downward)	≈ -4.1 deg @ 0.50 sec	≈ -2.8 deg @ 0.48 sec
29	Left front wheel returns to ground	0.56 sec	0.55 sec
30	Right rear wheel returns to ground	Doesn't return before analysis termination	0.64 sec
31	Peak yaw (counter-clockwise)	≈ -37.5 deg @ 0.65 sec	≈ -38.4 deg @ 0.65 sec
32	Max negative roll (top of vehicle away from barrier)	≈ -3.98 deg @ 0.65 sec	≈ -5.1 deg @ 0.65 sec
33	Left rear wheel returns to ground	Doesn't return before end of run	Doesn't return before end of run
34	Analysis Terminated	0.65 sec Speed = 39.6 mph Yaw angle = 12.5 deg (total angle) Roll angle = 4.0 deg (away from barrier) Pitch angle = 2.3 deg (rear pitched)	0.65 sec Speed = 39.4 mph Yaw angle = 13.4 deg (total angle) Roll angle = 5.1 deg (away from barrier) Pitch angle = 0.3 deg (rear pitched up)

Time History Plots and Occupant Risk Measures

Figures 33 through 35 show the longitudinal, transverse, and vertical acceleration-time histories, respectively, computed from the center of gravity of the vehicle; Figures 36 through 38 show the comparison of the angular rates and angular displacements (i.e., yaw, roll, and pitch) at the center of gravity of the vehicle. Table 11 shows the results for the occupant risk calculations for the two cases.

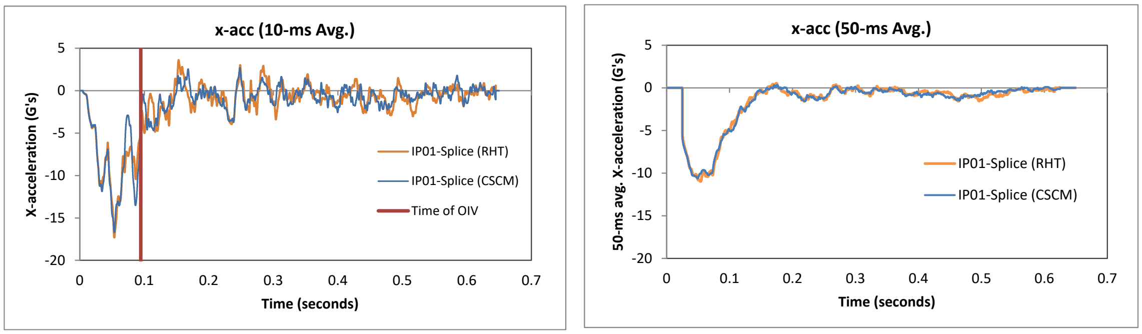


Figure 33. 10- and 50-millisecond average X-acceleration from FEA of Test 3-11 at IP01 on CM-MTL3 with vertical face.

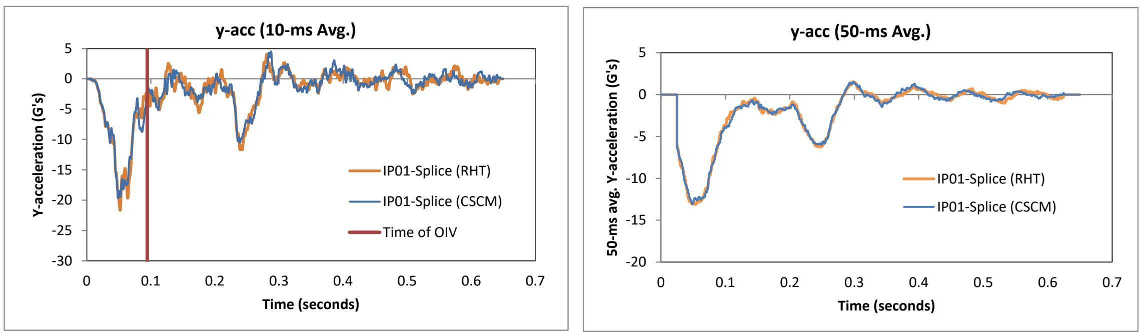


Figure 34. 10- and 50-millisecond average Y-acceleration from FEA of Test 3-11 at IP01 on CM-MTL3 with vertical face.

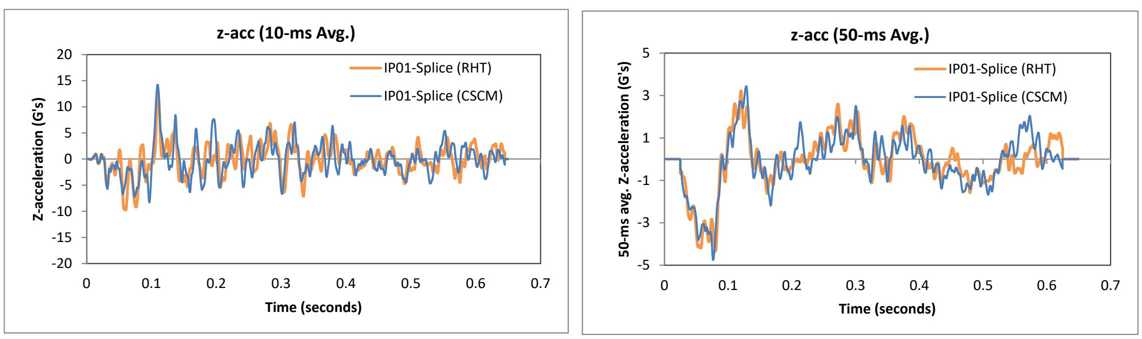


Figure 35. 10- and 50-millisecond average Z-acceleration from FEA of Test 3-11 at IP01 on CM-MTL3 with vertical face.

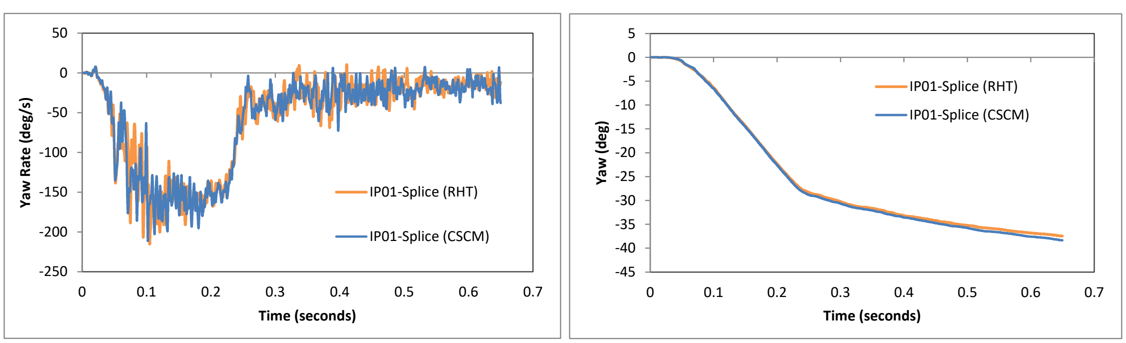


Figure 36. Yaw rate and yaw angle time-history from FEA of Test 3-11 at IP01 on CM-MTL3 with vertical face.

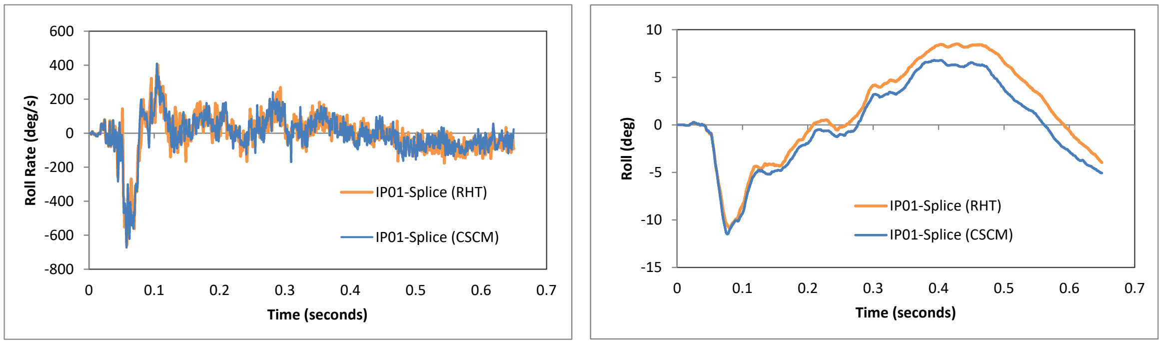


Figure 37. Roll rate and roll angle time-history from FEA of Test 3-11 at IP01 on CM-MTL3 with vertical face.

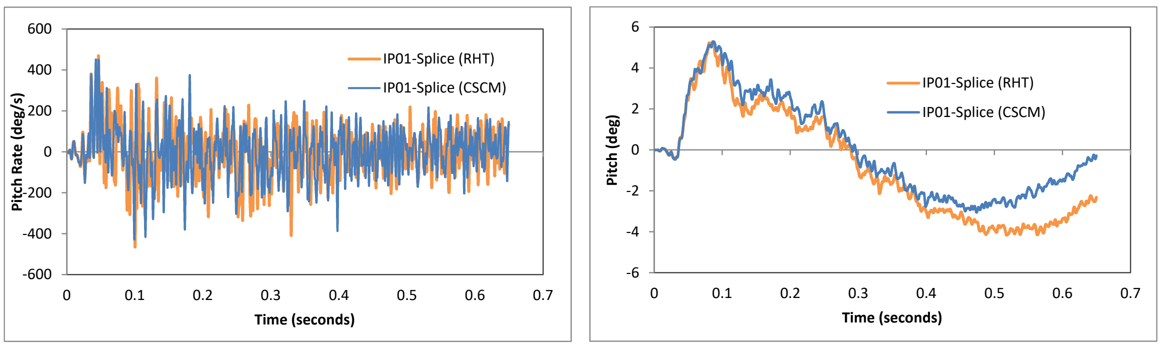


Figure 38. Pitch rate and pitch angle time-history from FEA of Test 3-11 at IP01 on CM-MTL3 with vertical face.

The peak 10-ms running average accelerations were approximately 17 G in the longitudinal direction and approximately 20-22 G in the lateral direction, as shown in Figures 33-35 and Table 9. The OIV value in the longitudinal direction for the RHT and CSCM cases was 23.3 ft/s and 23.6 ft/s, respectively; the occupant impact velocity in the lateral direction was 24.9 ft/s for both cases. The highest ORA in the longitudinal direction was -5.0 g and -4.7 g for the RHT and CSCM cases, respectively; the highest ORA in the lateral direction was -11.7 g and -10.5 g for the RHT and CSCM cases, respectively. The maximum roll angle of the vehicle for the RHT and CSCM cases was -10.8 degrees and -11.5 degrees, respectively; the maximum pitch angle of the vehicle for the RHT and CSCM cases was 5.2 degrees and 5.3 degrees, respectively. All occupant risk metrics were well within the preferred limits of *MASH*.

Table 11. Summary of *MASH* occupant risk metrics for Test 3-11 at IP01 on CM-MTL3 with vertical face.

Occupant Risk Factors		MASH 3-11	
		IP01-Splice (RHT)	IP01-Splice (CSCM)
Occupant Impact Velocity (ft/s)	x-direction	23.3	23.6
	y-direction	24.9	24.9
	at time	at 0.0920 seconds on right side of interior	at 0.0925 seconds on right side of interior
THIV (ft/s)		33.8 at 0.0920 seconds on right side of interior	34.8 at 0.0925 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-5 (0.0953 - 0.1053 seconds)	-4.7 (0.1092 - 0.1192 seconds)
	y-direction	-11.7 (0.2342 - 0.2442 seconds)	-10.5 (0.2339 - 0.2439 seconds)
PHD (g's)		12.2 (0.2341 - 0.2441 seconds)	11.1 (0.2337 - 0.2437 seconds)
ASI		1.93 (0.0557 - 0.1057 seconds)	1.89 (0.0552 - 0.1052 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-11 (0.0289 - 0.0789 seconds)	-10.6 (0.0240 - 0.0740 seconds)
	y-direction	-13.1 (0.0283 - 0.0783 seconds)	-13.1 (0.0240 - 0.0740 seconds)
	z-direction	-4.3 (0.0552 - 0.1052 seconds)	-4.8 (0.0515 - 0.1015 seconds)
Maximum Angular Disp. (deg)	Roll	-10.8 (0.0804 seconds)	-11.5 (0.0770 seconds)
	Pitch	5.2 (0.0810 seconds)	5.3 (0.0863 seconds)
	Yaw	-37.5 (0.6498 seconds)	-38.4 (0.6498 seconds)

MASH Criteria

- < 30 ft/s (preferred) ✓
- < 40 ft/s (limit)
- < 15 G (preferred) ✓
- < 20.49 G (limit)
- < 75 deg ✓

Damages to the Barrier System

Figure 39 shows images of maximum permanent deflection of the barrier with a contour plot of lateral displacement on the bridge rail. The dynamic deflection was 2.1 inches and 2.4 inches for the RHT and CSCM models, respectively. For the RHT case, the maximum deflection occurred at 0.24 seconds during the tail-slap of the vehicle with the barrier; for the CSCM case, the maximum deflection occurred at 0.11 seconds during impact with the front corner of the vehicle. The maximum permanent dynamic deflection was 1.6 inches and 2.0 inches for the RHT and CSCM case, respectively. Figure 40 shows contour plots of the damage parameter computed in LS-DYNA, and Figure 41 shows contour plots of the 1st principal strain. Both models indicated spalling on the front face of barrier, while the CSCM showed additional spalling across the top surface. The CSCM model indicated small crack formation radiating from back-side anchor bolts, while the RHT model showed little to no potential for such cracks.

The damage to the face of the barrier was significantly reduced compared to the results from the analysis of the CM-MTL3 with integral curb. As shown in Figure 42, the wheel climbed the barrier in both cases; however, the case involving the integral curb resulted in abrupt tire-steer toward the barrier causing significant spalling along the top edge of the barrier; this did not occur for the CM-MTL3 with vertical face.

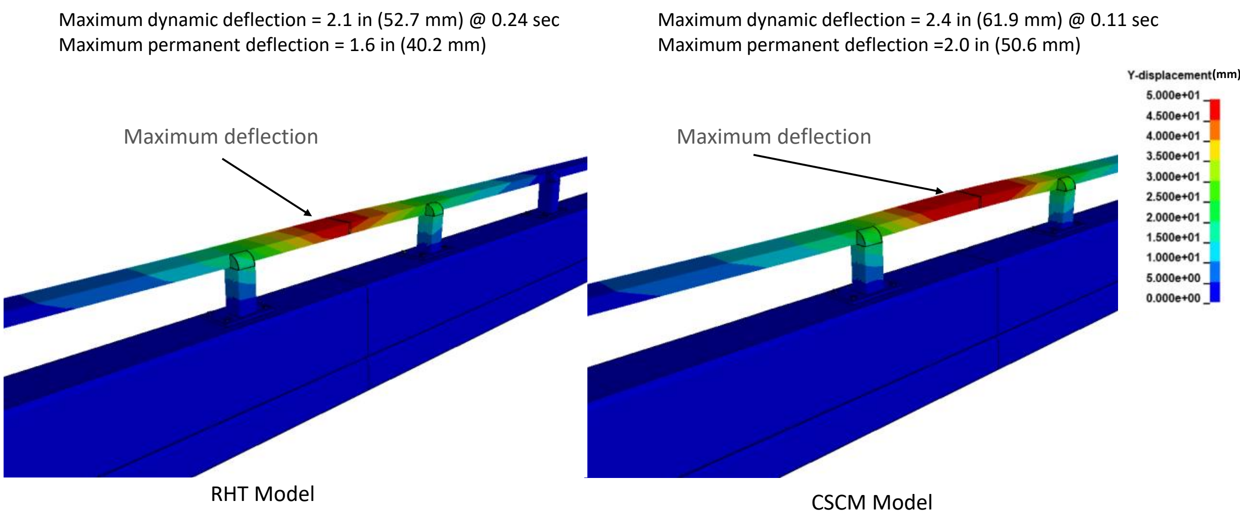


Figure 39. Contour plot of lateral displacement for Test 3-11 at IP01 on CM-MTL3 with vertical face.

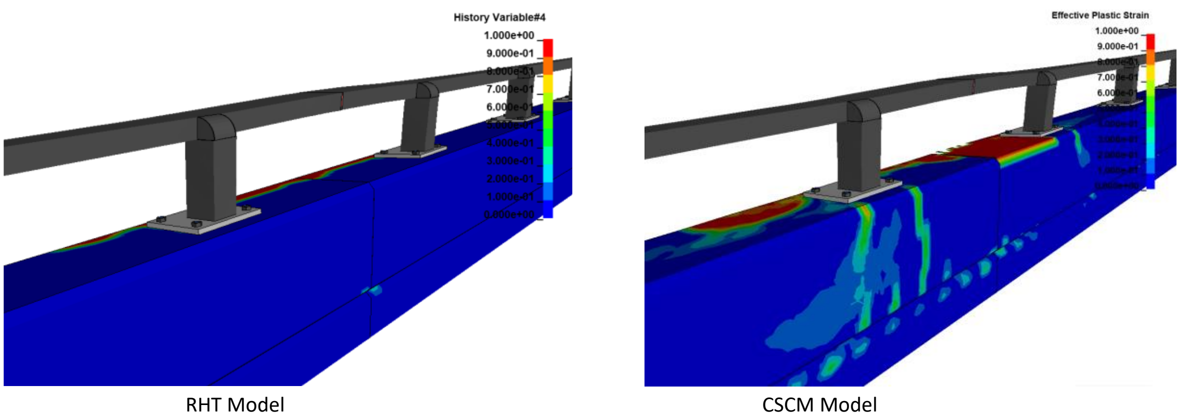


Figure 40. Contour plot of the damage variable for Test 3-11 at IP01 on CM-MTL3 with vertical face.

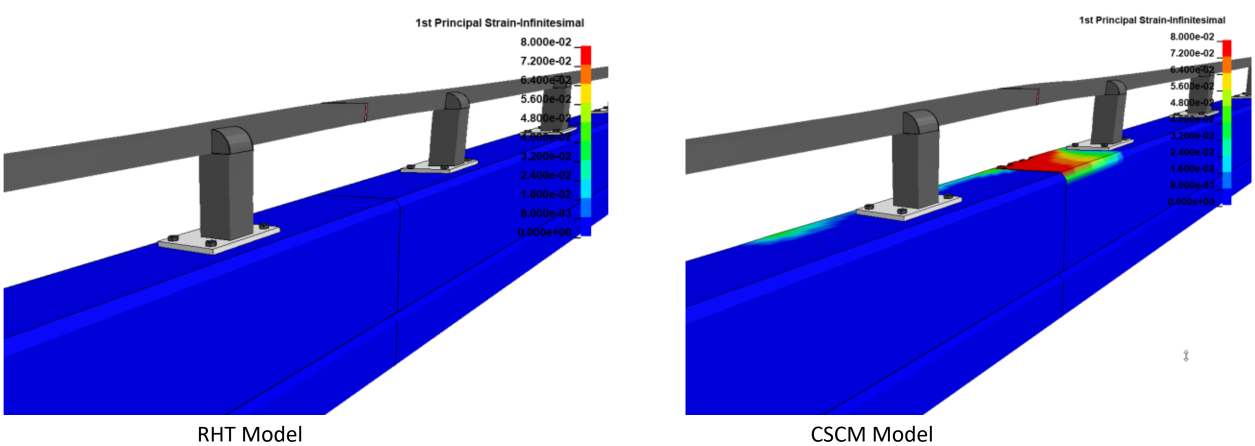


Figure 41. Contour plot of the 1st principal strain for Test 3-11 at IP01 on CM-MTL3 with vertical face.

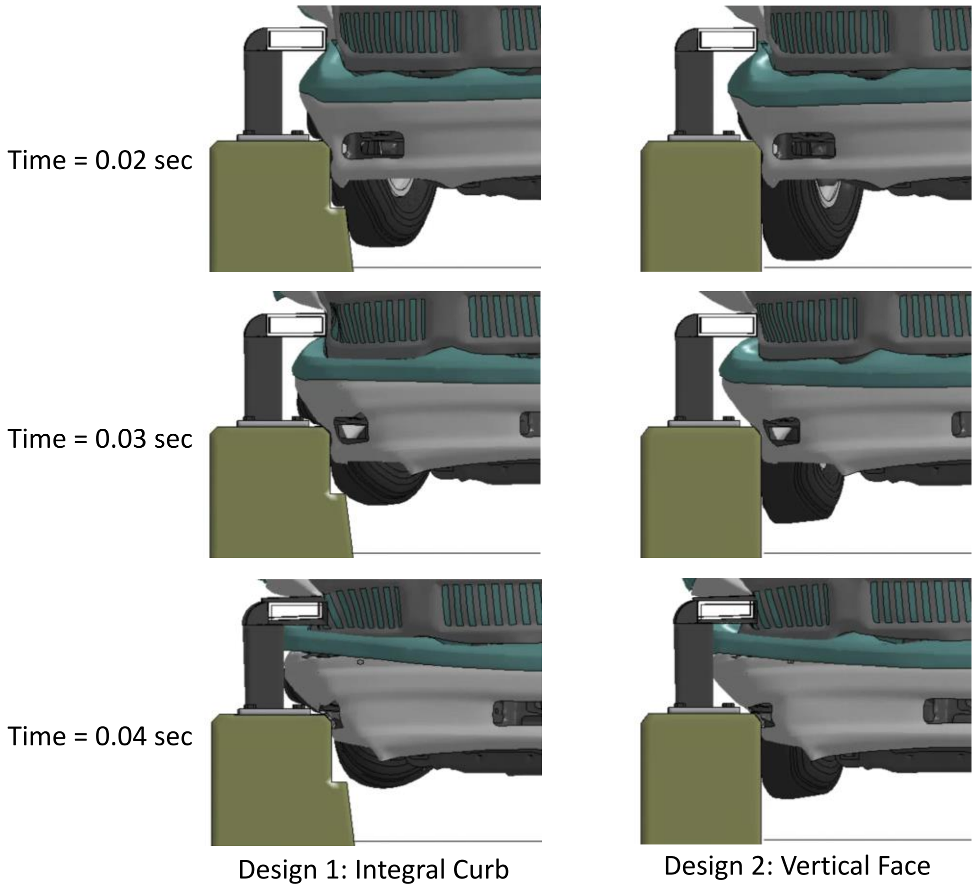


Figure 42. Comparison of wheel response from Test 3-11 impact at IP01 for the CM-MTL3 with and without the integral curb.

Damages to Vehicle

Figure 43 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. Damage to the vehicle was limited to the impact side of the front cap, the front impact-side wheel assembly, impact-side doors, front edge of pickup bed, and rear section of pickup bed.

Occupant Compartment Intrusion

The maximum deformation of the occupant compartment was 6.6 – 7.5 inches at the right-front toe pan at the wheel well. Figure 44 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.

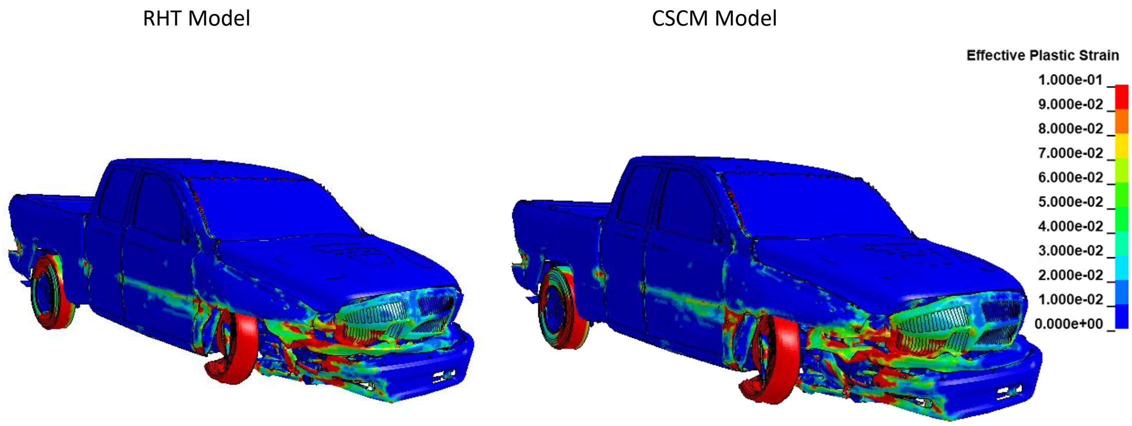


Figure 43. Damages to vehicle in Test 3-11 at IP01 on CM-MTL3 with vertical face.

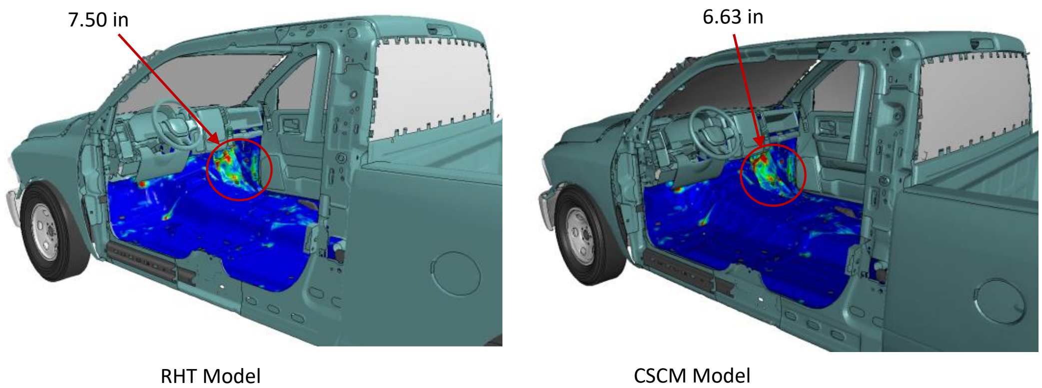


Figure 44. Occupant compartment deformation resulting from Test 3-11 at IP01 on CM-MTL3 with vertical face.

Exit Box

Figures 45 and 46 show the exit box for Test 3-11 on the CM-MTL3 with vertical face. Although the exit box analysis is not required in *MASH*, it was included here for completeness. The post trajectory response was almost identical for both the RHT and CSCM cases. The vehicle was redirected with its path well within the exit box criteria of *MASH*.

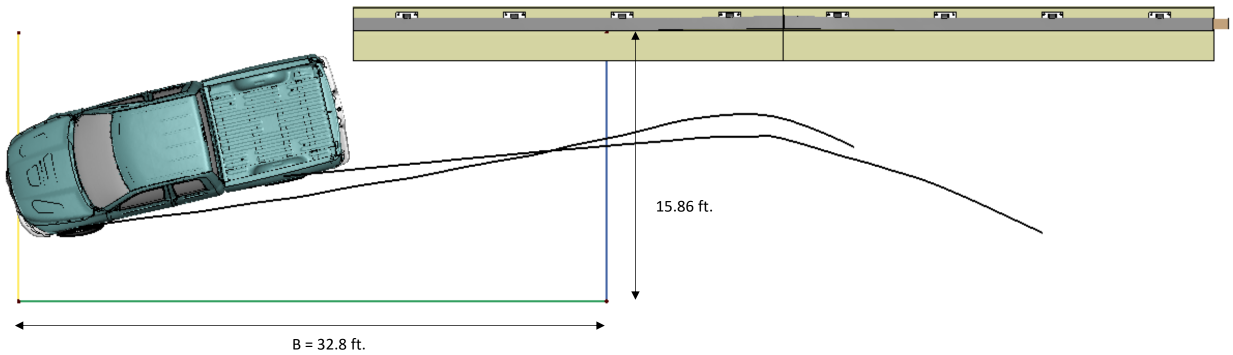


Figure 45. Exit box for Test 3-11 at IP01 on CM-MTL3 with vertical face (RHT model).

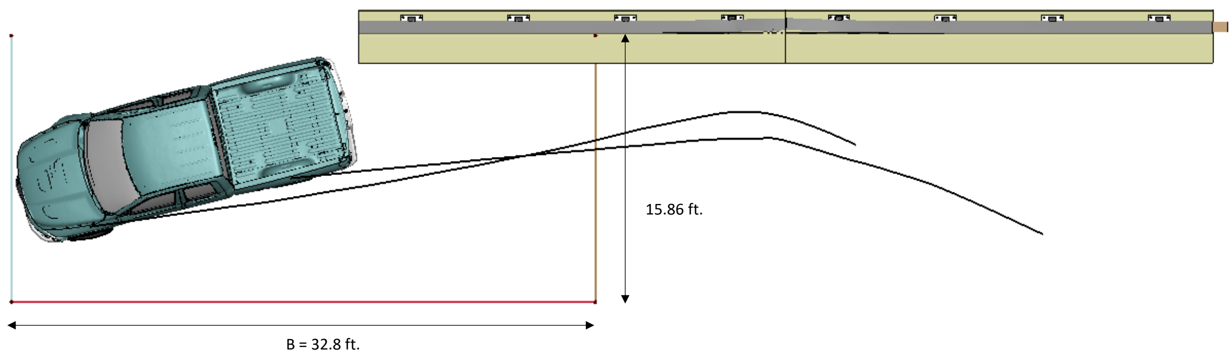


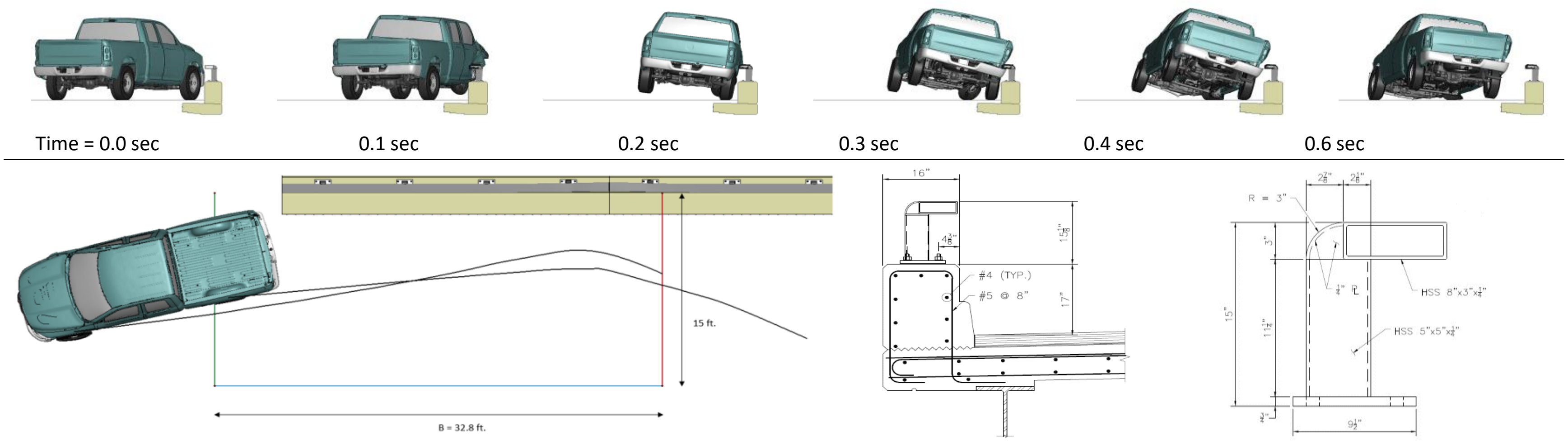
Figure 46. Exit box for Test 3-11 at IP01 on CM-MTL3 with vertical face (CSCM model).

Results Summary

A summary of the *MASH* Test 3-11 results for the CM-MTL3 with vertical face with CIP at 4.3 feet upstream of rail splice is shown in Table 12. The bridge rail successfully contained and redirected the pickup with minimal damage to the concrete barrier and moderate damage to the steel rail components. 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 preferred 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 3-11 impact conditions.

Table 12. Summary of *MASH* Test 3-11 at IP01 on CM-MTL3 with vertical face.

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 3-11
Analysis No.	CM-TL3 D2 IP01-Splice
Analysis Date	6/7/2021
Test Article	
Type	Bridge Rail
Name	CM-TL3
Installation Length	48.0 feet
Material or Key Elements	Continuous concrete with top mounted steel post-and-beam rail
Soil Type and Condition	NA
Analysis Vehicle	
Type / Designation	2270P
FEA Model name	Ram2018C_V2u.k w/ RS tire
Mass	5,001 lb

Impact Conditions	
Speed	63.7 mph
Angle	25 degrees
Location	4.3 ft upstream of splice
Impact Severity	121.1 kip-ft
Exit Conditions	
Speed	42.2 - 42.5 mph
Angle	8.4 - 8.6 degrees
Time	0.4 seconds
Occupant Risk Values	
Longitudinal OIV	23.3 - 23.6 ft/s
Lateral OIV	24.9 ft/s
Longitudinal ORA	4.7 - 5.0 g
Lateral ORA	10.5 - 11.7 g
THIV	33.8 - 34.8 ft/s
PHD	11.1 - 12.2 g
ASI	1.89 - 1.93

Max50-millisecond Avg. (G)	
Longitudinal	10.6 - 11.0 g
Lateral	13.1 g
Vertical	4.3 - 4.8 g
Test Article Deflections (in)	
Dynamic	2.1 - 2.4 inches
Permanent	1.6 - 2.0 inches
Working Width	16.0 inches
Max. OCI	6.6 - 7.5 inches
Vehicle Stability	
Roll	10.8 - 11.5 degees
Pitch	5.2 - 5.3 degrees
Yaw	37.5 - 38.4 degrees

Figure 47: Summary results for *MASH* Test 3-11 at IP01 on CM-MTL3 with vertical face.

Test 3-11 at IP02 – CIP for Snag on Post

The 5,182-lb pickup model struck the face of the barrier at a speed of 63.7 mph and at an angle of 25 degrees. The impact point was 4.3 feet upstream of the post that was located immediately downstream of the rail splice (refer to Figure 17). Table 13 lists the sequence of key events for both the RHT and CSCM analysis cases.

Table 13. Sequence of events for Test 3-11 at IP02 for the CM-MTL3 w/vertical face

Event		RHT	CSCM
1	Initial contact with barrier Right front fender and right front tire impacts vertical wall @ critical splice (between post 4 and 5)	0.00 sec Impact speed = 63.7 mph Impact angle = 25 deg	0.00 sec Impact speed = 63.7 mph Impact angle = 25 deg
2	Right front wheel climbs vertical face of barrier	0.015 sec	0.015 sec
3	Peak 50-ms average y-acceleration	13.7 G @ 0.0263 - 0.0763 sec	12.8 G @ 0.0323 - 0.0823 sec
4	Vehicle begins to yaw counterclockwise	≈ 0.04 sec	≈ 0.04 sec
5	Vehicle passes critical post - slight contact with bumper	0.05 sec	0.05 sec
6	Peak 50-ms average x-acceleration	11.4 G @ 0.0256 - 0.0756 sec	11.1 G @ 0.0170 - 0.0670 sec
7	Max positive pitch (front pitched upward)	≈ 3.36 deg @ 0.085 sec	≈ 4.87 deg @ 0.085 sec
8	Left front wheel leaves the ground	0.09 sec	0.10 sec
9	Occupant impact with vehicle interior	0.0944 sec OIV-x = 22.0 ft/s OIV-y = 25.9 ft/s	0.0932 sec OIV-x = 23.3 ft/s OIV-y = 25.3 ft/s
10	Left rear wheel leaves the ground	0.11 sec	0.11 sec
11	Front right tire deflates	0.013 sec	0.013 sec
12	Maximum occupant compartment intrusion. Maximum OCI Location Maximum OCI Magnitude	0.16 sec Right front toe pan 6.3 in	0.23 sec Right front toe pan 5.5 in
13	Vehicle parallel with barrier	0.21 sec	0.21 sec
14	Rear right tire deflates	0.213 sec	0.218 sec
15	Maximum ORA-x	4.4 G @ 0.2173 - 0.2273 sec	4.4 G @ 0.1235 - 0.1335 sec
16	Tail slap with barrier Right rear fender and right rear tire impacts vertical wall between posts 4 and 5	0.22 sec Speed = 46.0 mph Angle = -0.85 deg	0.23 sec Speed = 44.5 mph Angle = -1.71 deg
17	Maximum ORA-y	10.7 G @ 0.2244 - 0.2344 sec	10.5 G @ 0.2293 - 0.2393 sec
18	Maximum dynamic barrier deflection occurs at splice	Tail slap: 1.6 in @ 0.23 sec	Tail slap: 2.2 in @ 0.23 sec
19	Right rear wheel leaves the ground	0.23 sec	0.23 sec
20	Right rear wheel returns to ground	momentarily: 0.29 - 0.57 sec	0.30 sec
21	Vehicle front bumper passes end of barrier	0.30 sec	0.305 sec
22	Vehicle wheels exit barrier	0.31 sec	0.32 sec
23	Right front wheel returns to ground	0.37 sec	0.35 sec
24	Vehicle body exits barrier	0.40 sec Exit speed = 44.2 mph Exit angle = -8.6 deg	0.39 sec Exit speed = 43.1 mph Exit angle = -8.1 deg
25	Max positive roll (top of vehicle toward barrier)	≈ 12.9 deg @ 0.46 sec	≈ 5.6 deg @ 0.40 sec
26	Max negative pitch (front pitched downward)	≈ -7.2 deg @ 0.57 sec	≈ -3.7 deg @ 0.48 sec
27	Left front wheel returns to ground	0.60 sec	0.46 sec
28	Peak yaw (counter-clockwise)	≈ -38.43 deg @ 0.65 sec	≈ -38.63 deg @ 0.65 sec
29	Max negative roll (top of vehicle away from barrier)	≈ -0.48 deg @ 0.65 sec	≈ -3.1 deg @ 0.65 sec
30	Right rear wheel returns to ground	Doesn't return before end of run after second lift	Had already returned to ground and did not lift again
31	Left rear wheel returns to ground	Doesn't return before end of run	Doesn't return before end of run
32	Analysis Terminated	0.65 sec Speed = 41.0 mph Yaw angle = 13.4 deg (total angle) Roll angle = 0.5 deg (away from barrier) Pitch angle = 6.3 deg (rear pitched up)	0.65 sec Speed = 40.0 mph Yaw angle = 13.6 deg (total angle) Roll angle = 3.1 deg (away from barrier) Pitch angle = 0.6 deg (rear pitched up)

The sequential views of the impact event are shown in Appendix E for both the RHT and CSCM models. The following sections provide time-history data evaluation, occupant risk assessments, and damages sustained by both the barrier and vehicle.

Time History Plots and Occupant Risk Measures

Figures 48 through 50 show the longitudinal, transverse, and vertical acceleration-time histories, respectively, computed from the center of gravity of the vehicle; Figures 51 through 53 show the comparison of the angular rates and angular displacements (i.e., yaw, roll, and pitch) at the center of gravity of the vehicle. Table 14 shows the results for the occupant risk calculations for the two cases.

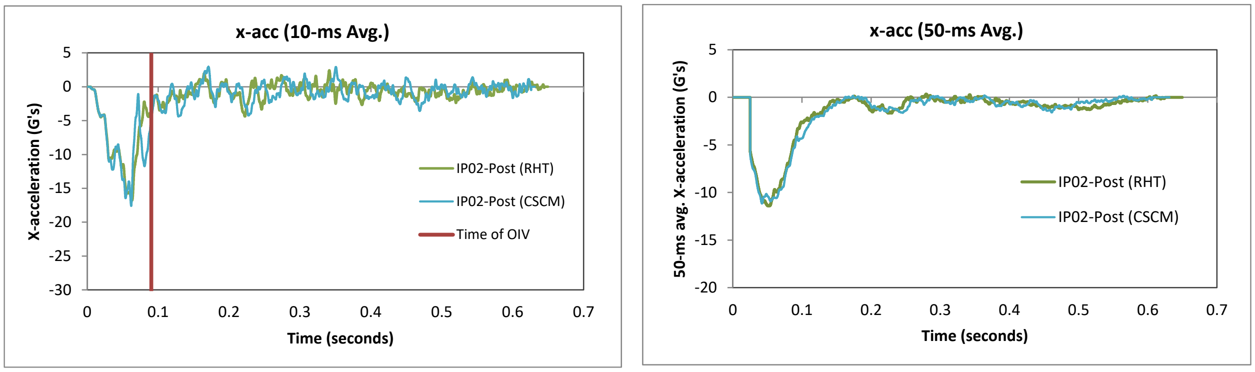


Figure 48. 10- and 50-millisecond average X-acceleration from FEA of Test 3-11 at IP02 on CM-MTL3 with vertical face.

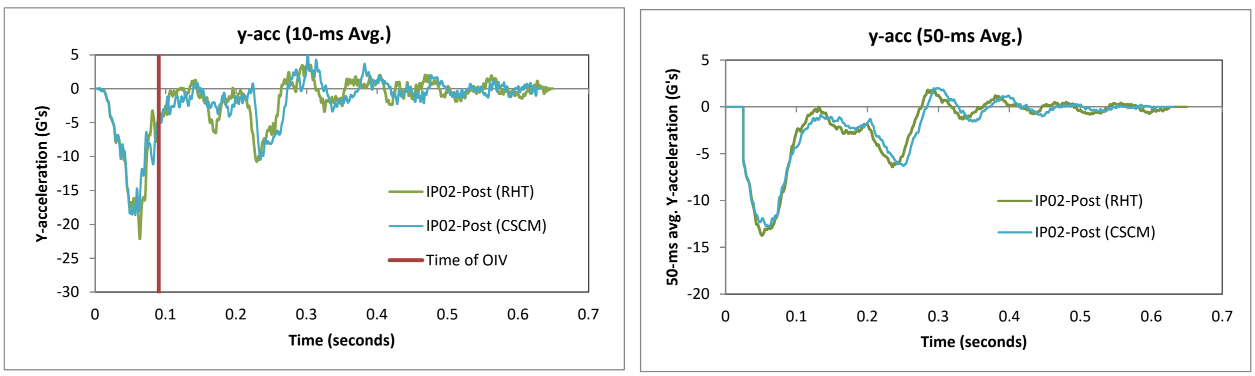


Figure 49. 10- and 50-millisecond average Y-acceleration from FEA of Test 3-11 at IP02 on CM-MTL3 with vertical face.

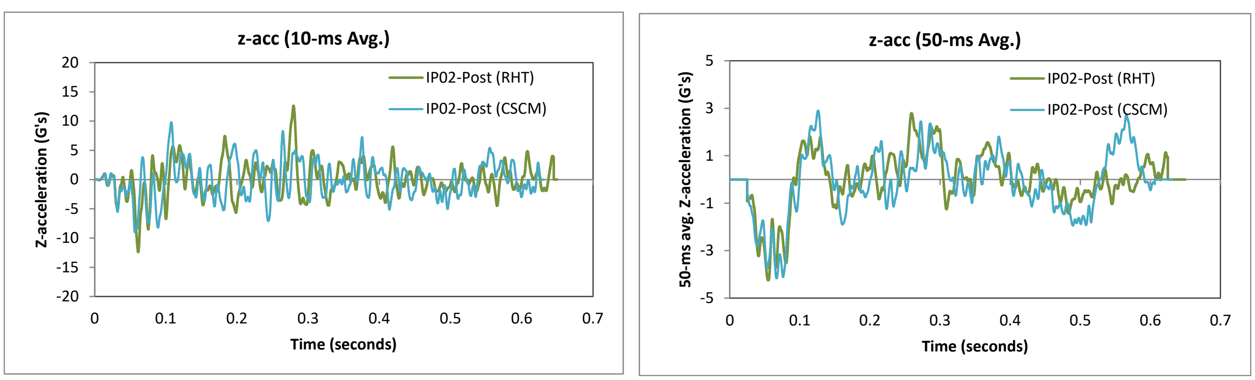


Figure 50. 10- and 50-millisecond average Z-acceleration from FEA of Test 3-11 at IP02 on CM-MTL3 with vertical face.

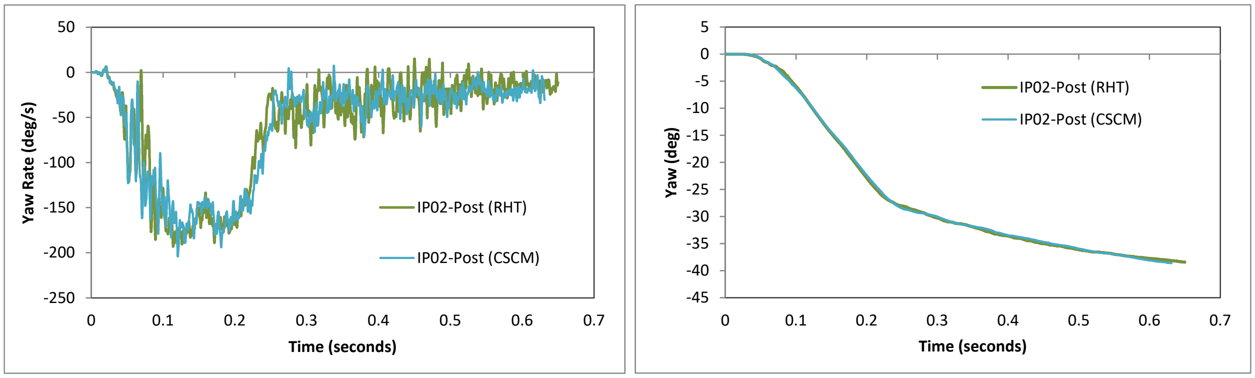


Figure 51. Yaw rate and yaw angle time-history from FEA of Test 3-11 at IP02 on CM-MTL3 with vertical face.

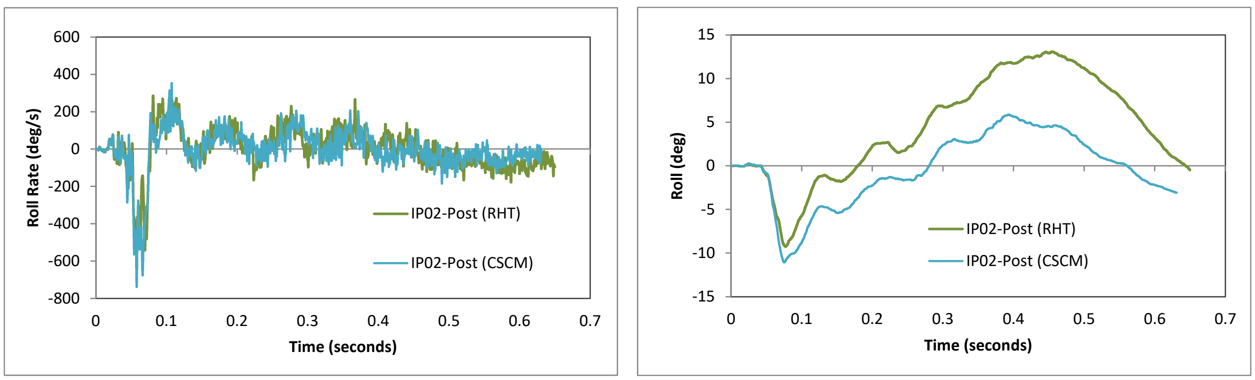


Figure 52. Roll rate and roll angle time-history from FEA of Test 3-11 at IP02 on CM-MTL3 with vertical face.

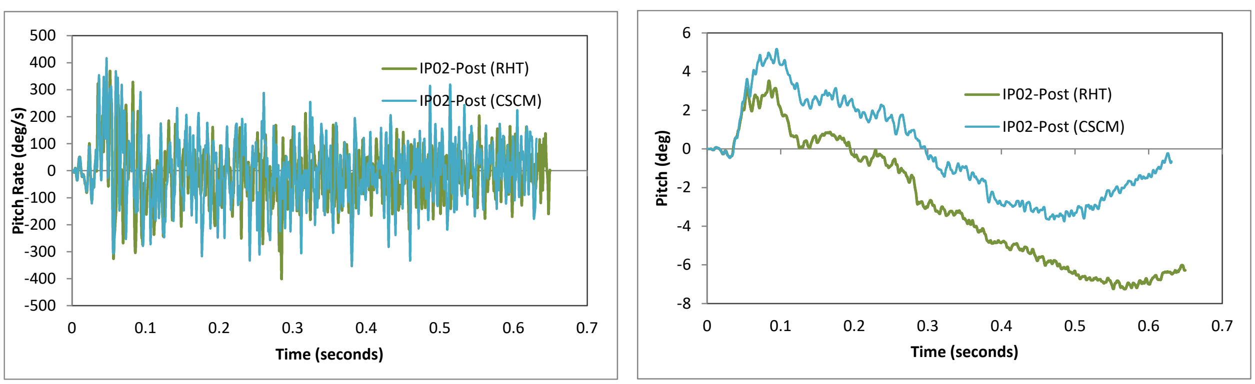


Figure 53. Pitch rate and pitch angle time-history from FEA of Test 3-11 at IP02 on CM-MTL3 with vertical face.

Table 14. Summary of *MASH* occupant risk metrics for Test 3-11 at IP02 on CM-MTL3 with vertical face.

Occupant Risk Factors		MASH 3-11 IP02-Post (RHT)	MASH 3-11 IP02-Post (CSCM)
Occupant Impact Velocity (ft/s)	x-direction	22.0	23.3
	y-direction	25.9	25.3
	at time	at 0.0944 seconds on right side of interior	at 0.0932 seconds on right side of interior
THIV (ft/s)		34.1 at 0.0922 seconds on right side of interior	34.4 at 0.0932 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-4.4 (0.2173 - 0.2273 seconds)	-4.4 (0.1235 - 0.1335 seconds)
	y-direction	-10.7 (0.2244 - 0.2344 seconds)	-10.5 (0.2293 - 0.2393 seconds)
PHD (g's)		10.8 (0.2242 - 0.2342 seconds)	10.7 (0.2293 - 0.2393 seconds)
ASI		1.98 (0.0572 - 0.1072 seconds)	1.87 (0.0557 - 0.1057 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-11.4 (0.0256 - 0.0756 seconds)	-11.1 (0.0170 - 0.0670 seconds)
	y-direction	-13.7 (0.0263 - 0.0763 seconds)	-12.8 (0.0323 - 0.0823 seconds)
	z-direction	-4.2 (0.0300 - 0.0800 seconds)	-4.2 (0.0418 - 0.0918 seconds)
Maximum Angular Disp. (deg)	Roll	13.1 (0.4545 seconds)	-11.1 (0.0753 seconds)
	Pitch	-7.3 (0.5679 seconds)	5.2 (0.0945 seconds)
	Yaw	-38.4 (0.6498 seconds)	-38.6 (0.6312 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 ✓

The peak 10-ms running average accelerations were approximately 17 G in the longitudinal direction and approximately 20-22 G in the lateral direction, as shown in Figures 48 through 50 and Table 9. The OIV value in the longitudinal direction for the RHT and CSCM cases was 22.0 ft/s and 23.3 ft/s, respectively; the occupant impact velocity in the lateral direction was 25.9 ft/s and 25.3 ft/s for the RHT and CSCM cases, respectively. The highest ORA in the longitudinal direction was -4.4 g for both the RHT and CSCM cases; the highest ORA in the lateral direction was -10.7 g and -10.5 g for the RHT and CSCM cases, respectively. The maximum roll angle of the vehicle for the RHT and CSCM cases was -13.1 degrees and -11.1 degrees, respectively; the maximum pitch angle of the vehicle for the RHT and CSCM cases was 7.3 degrees and 5.2 degrees, respectively. All occupant risk metrics were well within the preferred limits of *MASH*.

Damages to the Barrier System

Figure 54 shows images of maximum permanent deflection of the barrier with a contour plot of lateral displacement on the bridge rail. The dynamic deflection was 1.6 inches and 2.2 inches for the RHT and CSCM models, respectively. For both cases, the maximum deflection occurred at 0.23 seconds during the tail-slap of the vehicle with the barrier. The maximum permanent dynamic deflection was 1.2 inches and 1.8 inches for the RHT and CSCM case, respectively. Figure 55 shows contour plots of the damage parameter computed in LS-DYNA, and Figure 56 shows contour plots of the 1st principal strain. Similar to the previous analysis case, both models indicated spalling on the front face of barrier, while the CSCM showed additional spalling across the top surface. The CSCM model indicated small crack formation radiating from back-side anchor bolts, while the RHT model showed little to no potential for such cracks.

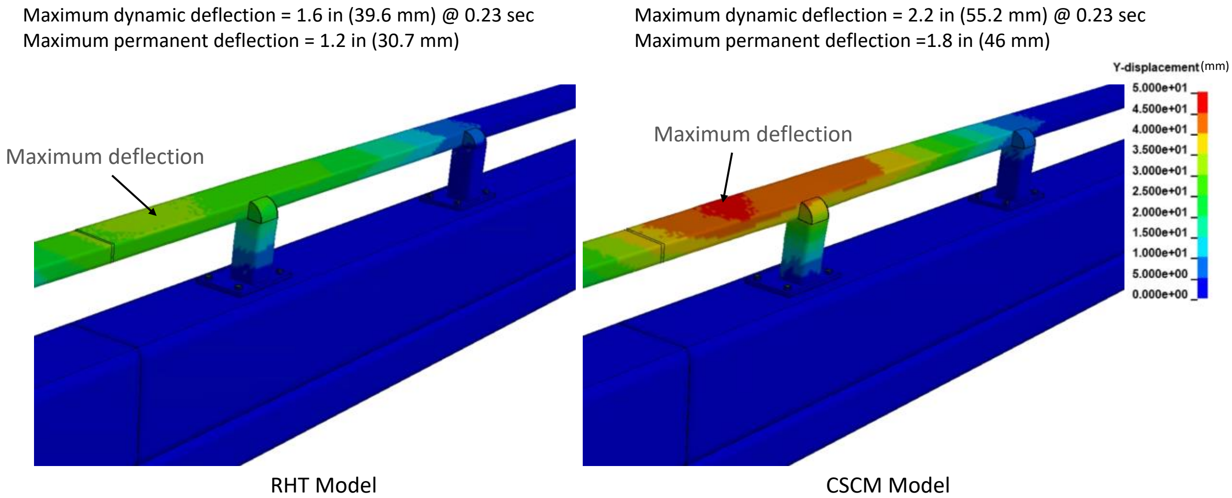


Figure 54. Contour plot of lateral displacement for Test 3-11 at IP02 on CM-MTL3 with vertical face.

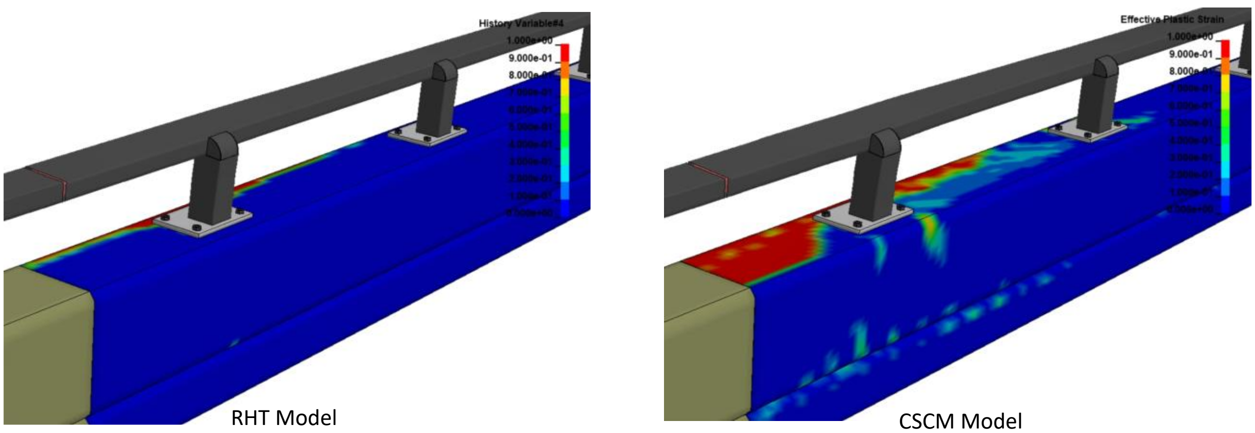


Figure 55. Contour plot of the damage variable for Test 3-11 at IP02 on CM-MTL3 with vertical face.

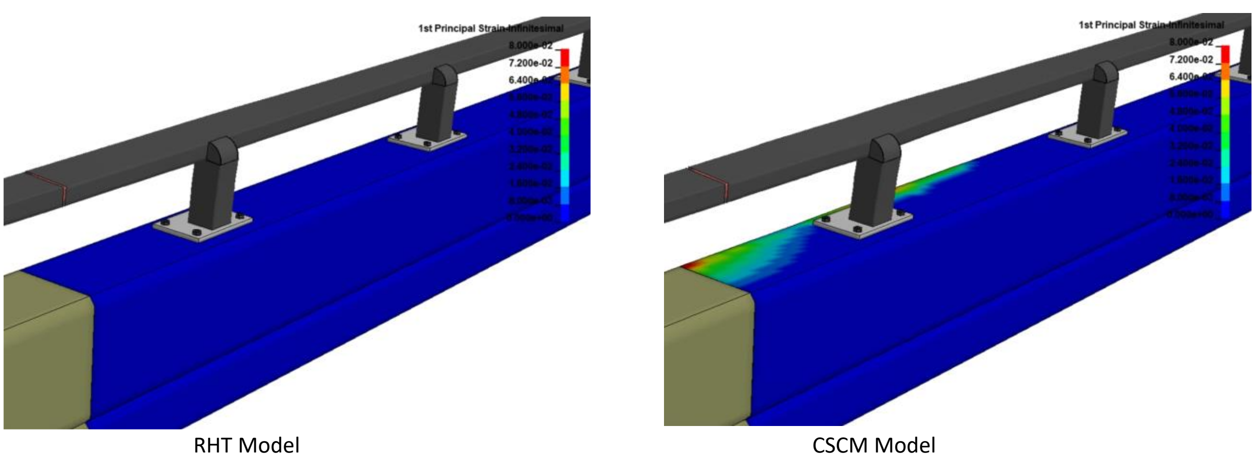


Figure 56. Contour plot of the 1st principal strain for Test 3-11 at IP02 on CM-MTL3 with vertical face.

Damages to Vehicle

Figure 57 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. Damage to the vehicle was limited to the impact side of the front cap, the front impact-side wheel assembly, impact-side doors, front edge of pickup bed, and rear section of pickup bed.

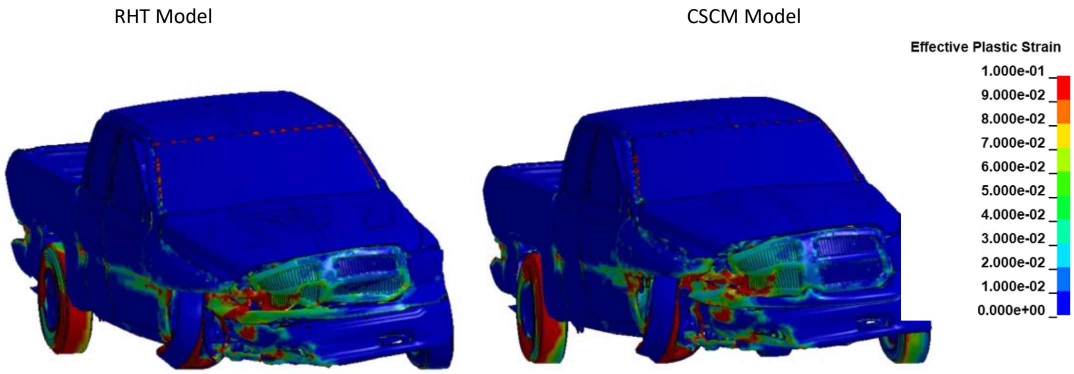


Figure 57. Damages to vehicle in Test 3-11 at IP02 on CM-MTL3 with vertical face.

Occupant Compartment Intrusion

The maximum deformation of the occupant compartment was 5.5 – 6.3 inches at the right-front toe pan at the wheel well. Figure 58 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.

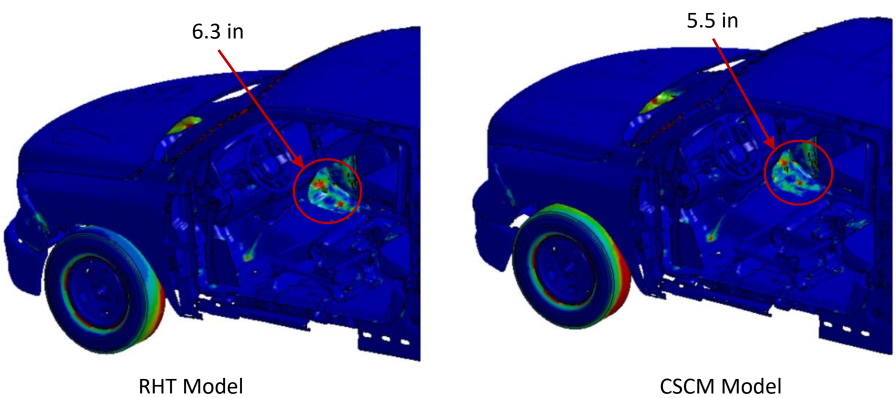


Figure 58. Occupant compartment deformation resulting from Test 3-11 at IP02 on CM-MTL3 with vertical face.

Exit Box

Figures 59 and 60 show the exit box for Test 3-11 on the CM-MTL3 with vertical face. The post trajectory path was essentially identical for both cases; however, the CSCM model case resulted in slightly less exit velocity (i.e., slightly higher friction response with barrier). The vehicle was redirected with its trajectory path well within the exit box criteria of *MASH* for both analysis cases.

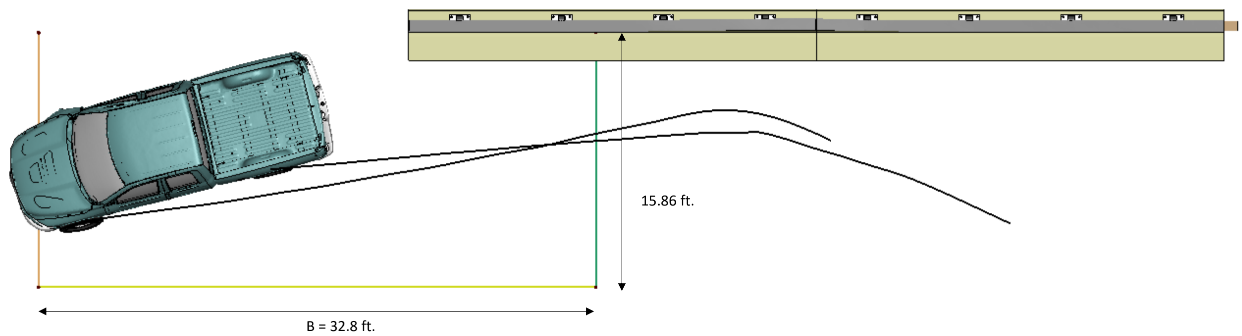


Figure 59. Exit box for Test 3-11 at IP02 on CM-MTL3 with vertical face (RHT model).

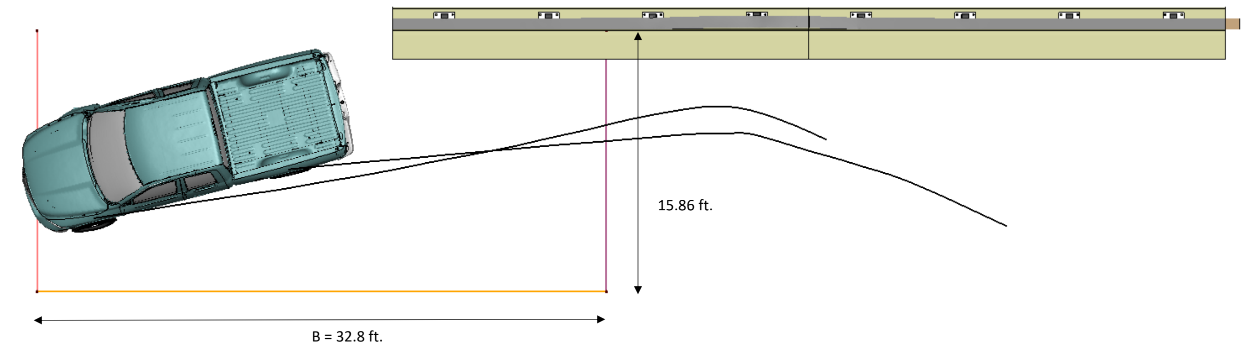


Figure 60. Exit box for Test 3-11 at IP02 on CM-MTL3 with vertical face (CSCM model).

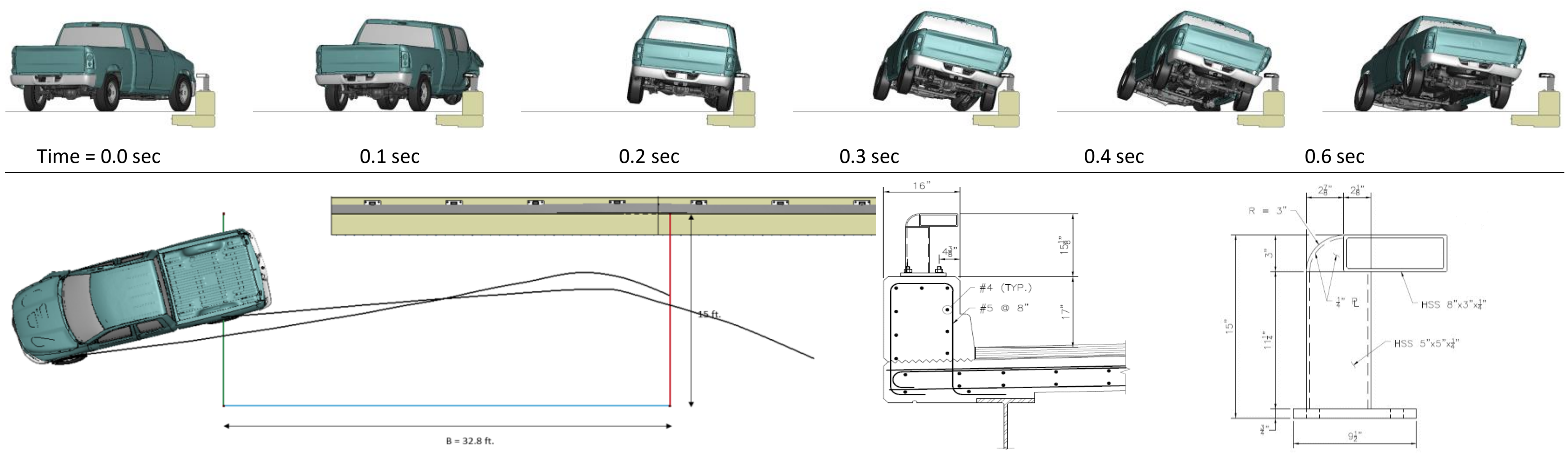
Results Summary

A summary of the *MASH* Test 3-11 results for the CM-MTL3 with vertical face with CIP at 4.3 feet upstream of critical post is shown in

Table 15. The bridge rail successfully contained and redirected the pickup with minimal damage to the concrete barrier and moderate damage to the steel rail components. 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 preferred 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 3-11 impact conditions.

Table 15. Summary of *MASH* Test 3-11 at IP02 on CM-MTL3 with vertical face.

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 3-11
Analysis No.	CM-TL3 D2 IP02-Post
Analysis Date	6/13/2021

Test Article

Type	Bridge Rail
Name	CM-TL3
Installation Length	48.0 feet
Material or Key Elements	Continuous concrete with top mounted steel post-and-beam rail
Soil Type and Condition	NA

Analysis Vehicle

Type / Designation	2270P
FEA Model name	Ram2018C_V2u.k w/ RS tire
Mass	5,001 lb

Impact Conditions

Speed	63.7 mph
Angle	25 degrees
Location	4.3 ft upstream of critical post
Impact Severity	121.1 kip-ft

Exit Conditions

Speed	40.6 - 41.2 mph
Angle	7.8 degrees
Time	0.39 seconds

Occupant Risk Values

Longitudinal OIV	22.0 - 22.3 ft/s
Lateral OIV	25.3 - 25.9 ft/s
Longitudinal ORA	4.40 g
Lateral ORA	10.5 - 10.7 g
THIV	34.1 - 34.4 ft/s
PHD	10.7 - 10.8 g
ASI	1.87 - 1.98

Max50-millisecond Avg. (G)

Longitudinal	11.1 - 11.4 g
Lateral	12.8 - 13.7 g
Vertical	4.2 g

Test Article Deflections (in)

Dynamic	1.6 - 2.2 inches
Permanent	1.2 - 1.8 inches
Working Width	16.0 inches
Max. OCI	5.5 - 6.3 inches

Vehicle Stability

Roll	11.1 - 13.1 degees
Pitch	5.2 - 7.3 degrees
Yaw	38.4 - 38.6 degrees

Figure 61: Summary results for *MASH* Test 3-11 at IP02 on CM-MTL3 with vertical face.

Test 3-10 at IP01 – CIP for Snag on Splice

Simulation of Test 3-10 involved the 2,609-lb Yaris model impacting the bridge rail at 62 mph and 25 degrees. The critical impact condition for Test 3-10 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 the rail splice and was selected to maximize potential for snagging at the rail splice. [*AASHTO16*] The analysis cases included two concrete models, RHT and CSCM. Table 16 lists the sequence of key events for both the RHT and CSCM analysis cases.

Table 16. Sequence of events for Test 3-10 at IP01 for the CM-MTL3 w/vertical face.

Event		RHT	CSCM
1	Initial contact with barrier Right front fender and right front tire impacts vertical wall @ post 4	0.00 sec Impact speed = 62.0 mph Impact angle = 25 deg	0.00 sec Impact speed = 62.0 mph Impact angle = 25 deg
2	Peak 50-ms average x-acceleration	14.6 G @ 0.0046 - 0.0546 sec	15.1 G @ 0.0175 - 0.0675 sec
3	Front right tire deflates	0.008 sec	0.007 sec
4	Peak 50-ms average y-acceleration	17.9 G @ 0.0144 - 0.0644 sec	17.8 G @ 0.0155 - 0.0655 sec
	Vehicle passes critical splice - no snag	0.04 sec	0.04 sec
5	Lower right edged of windshield begins to crack	0.040 sec	0.04 sec
6	Maximum dynamic barrier deflection occurs at splice	0.5 in @ 0.04 sec	0.6 in @ 0.05 sec
7	Vehicle begins to yaw counterclockwise	≈ 0.05 sec	≈ 0.05 sec
8	Both passenger windows begin to fail	0.05 sec	0.05 sec
9	Left rear wheel leaves the ground	0.06 sec	0.06 sec
10	Max positive pitch (front pitched upward)	≈ 0.26 deg @ 0.06 sec	≈ 0.29 deg @ 0.06 sec
11	Occupant impact with vehicle interior	0.069 sec OIV-x = 23.6 ft/s OIV-y = 28.5 ft/s	0.069 sec OIV-x = 24.9 ft/s OIV-y = 27.9 ft/s
12	Maximum ORA-x	4.4 G @ 0.0711 - 0.0811 sec	9.0 G @ 0.0713 - 0.0813 sec
	Vehicle passes critical post - no contact with post	0.08 sec	0.07 sec
13	Left front wheel leaves the ground	0.08 sec	0.08 sec
14	Maximum occupant compartment intrusion. Maximum OCI Location Maximum OCI Magnitude	0.14 sec Right front toe pan 2.5 in	0.14 sec Right front toe pan 2.7 in
15	Vehicle parallel with barrier	0.17 sec	0.18 sec
16	Tail slap with barrier Right rear fender and right rear tire impacts vertical wall between posts 4 and 5	0.19 sec Speed = 44.2 mph Angle = -3.6 deg	0.21 sec Speed = 42.5 mph Angle = -3.9 deg
17	Maximum ORA-y	13.5 G @ 0.1931 - 0.2031 sec	9.4 G @ 0.2234 - 0.2334 sec
18	Vehicle exits barrier (body and wheels)	0.27 sec Exit speed = 42.8 mph Exit angle = -6.2 deg	0.31 sec Exit speed = 41.0 mph Exit angle = -7.7 deg
19	Max positive roll (top of vehicle toward barrier)	≈ 6.14 deg @ 0.28 sec	≈ 4.85 deg @ 0.32 sec
20	Peak yaw (counter-clockwise) and begins to reverse yaw direction	≈ -31.36 deg @ 0.3 sec	≈ -32.83 deg @ 0.36 sec
21	Left front wheel returns to ground	0.32 sec	0.32 sec
22	Vehicle front bumper passes end of barrier	0.36 sec	0.37 sec
23	Right rear wheel leaves the ground	0.36 sec	0.41 sec
24	Max negative pitch (front pitched downward)	≈ -5.3 deg @ 0.40 sec	≈ -5.0 deg @ 0.36 sec
25	Left rear wheel returns to ground	0.51 sec	0.50 sec
26	Right rear wheel returns to ground	0.54 sec	0.46 sec
27	Max negative roll (top of vehicle away from barrier)	≈ -5.34 deg @ 0.56 sec	≈ -4.59 deg @ 0.56 sec
28	Analysis Terminated	0.65 sec Speed = 40.4 mph Yaw angle = 0.77 deg (total angle) Roll angle = 3.72 deg (away from barrier) Pitch angle = 1.10 deg (rear pitched up)	0.65 sec Speed = 38.8 mph Yaw angle = 2.68 deg (total angle) Roll angle = 4.00 deg (away from barrier) Pitch angle = 1.00 deg (rear pitched up)

The sequential views of the impact event are shown in Appendix F for both the RHT and CSCM models. The following sections provide time-history data evaluation, occupant risk assessments, and damages sustained by both the barrier and vehicle.

Time History Plots and Occupant Risk Measures

Figures 62 through 64 show the longitudinal, transverse, and vertical acceleration-time histories, respectively, computed from the center of gravity of the vehicle; Figures 65 through 67 show the comparison of the angular rates and angular displacements (i.e., yaw, roll, and pitch) at the center of gravity of the vehicle. Table 17 shows the results for the occupant risk calculations for the two cases.

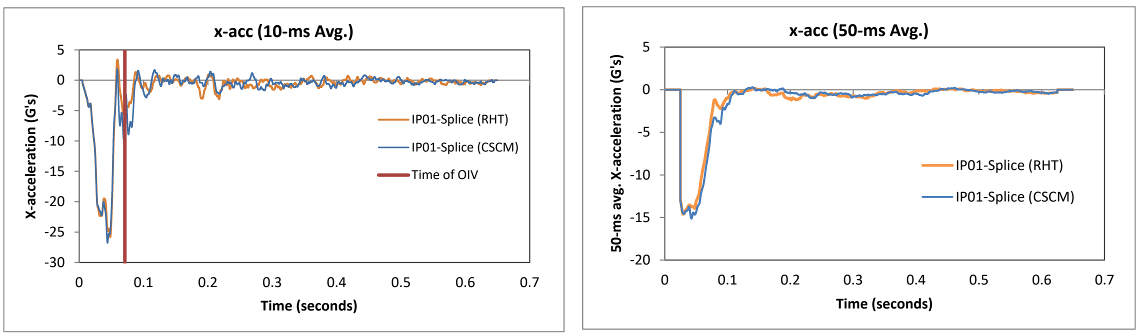


Figure 62. 10- and 50-millisecond average X-acceleration from FEA of Test 3-10 at IP01 on CM-MTL3 with vertical face.

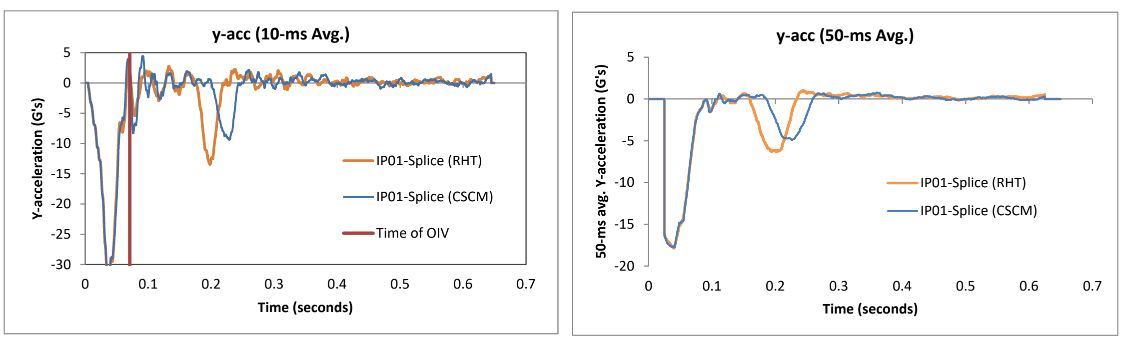


Figure 63. 10- and 50-millisecond average Y-acceleration from FEA of Test 3-10 at IP01 on CM-MTL3 with vertical face.

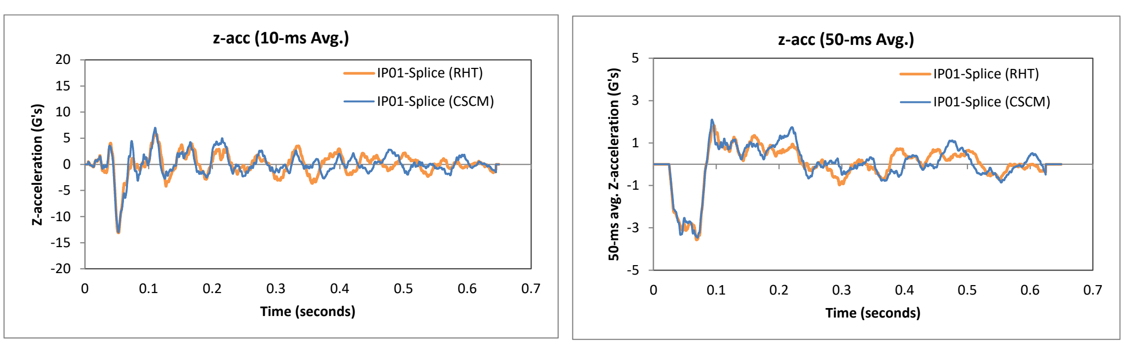


Figure 64. 10- and 50-millisecond average Z-acceleration from FEA of Test 3-10 at IP01 on CM-MTL3 with vertical face.

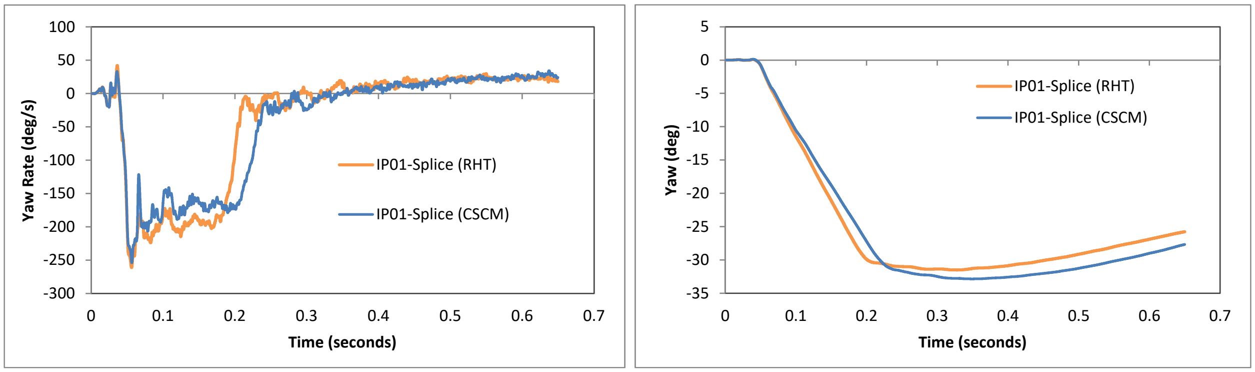


Figure 65. Yaw rate and yaw angle time-history from FEA of Test 3-10 at IP01 on CM-MTL3 with vertical face.

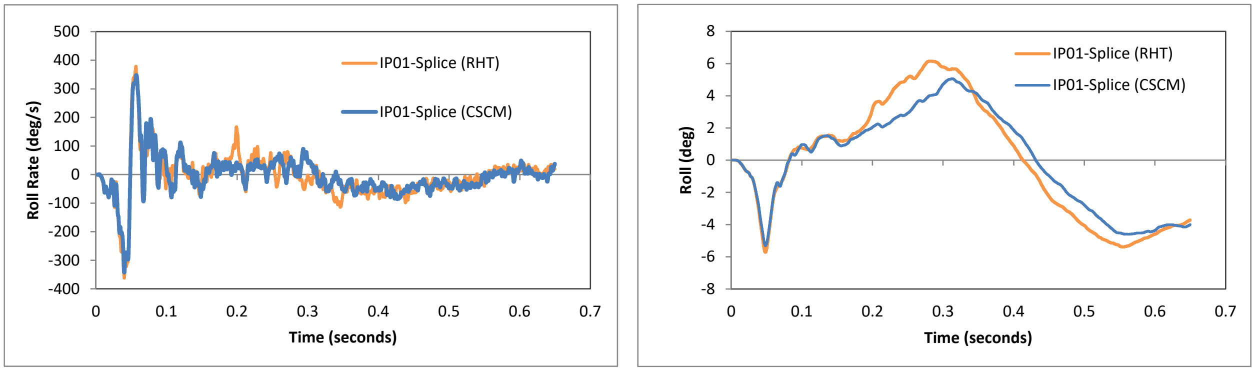


Figure 66. Roll rate and roll angle time-history from FEA of Test 3-10 at IP01 on CM-MTL3 with vertical face.

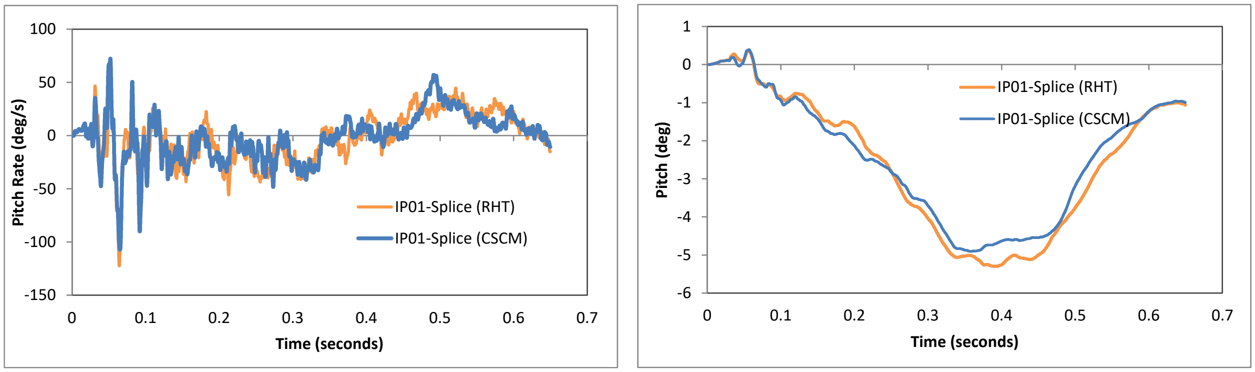


Figure 67. Pitch rate and pitch angle time-history from FEA of Test 3-10 at IP01 on CM-MTL3 with vertical face.

Table 17. Summary of *MASH* occupant risk metrics for Test 3-10 at IP01 on CM-MTL3 with vertical face.

Occupant Risk Factors		MASH 3-10 IP01-Splice (RHT)	MASH 3-10 IP01-Splice (CSCM)	MASH Criteria
Occupant Impact Velocity (ft/s)	x-direction	23.6	24.9	< 30 ft/s (preferred) ✓ < 40 ft/s (limit)
	y-direction	28.5	27.9	
	at time	at 0.0685 seconds on right side of interior	at 0.0686 seconds on right side of interior	
THIV (ft/s)		37.7 at 0.0685 seconds on right side of interior	38.4 at 0.0686 seconds on right side of interior	
Ridedown Acceleration (g's)	x-direction	-4.4 (0.0711 - 0.0811 seconds)	-9 (0.0713 - 0.0813 seconds)	< 15 G (preferred) ✓ < 20.49 G (limit)
	y-direction	-13.5 (0.1931 - 0.2031 seconds)	-9.4 (0.2234 - 0.2334 seconds)	
PHD (g's)		13.5 (0.1931 - 0.2031 seconds)	12.2 (0.0712 - 0.0812 seconds)	
ASI		2.6 (0.0393 - 0.0893 seconds)	2.63 (0.0397 - 0.0897 seconds)	
Max 50-ms moving avg. acc. (g's)	x-direction	-14.6 (0.0046 - 0.0546 seconds)	-15.1 (0.0175 - 0.0675 seconds)	
	y-direction	-17.9 (0.0144 - 0.0644 seconds)	-17.8 (0.0155 - 0.0655 seconds)	
	z-direction	-3.6 (0.0435 - 0.0935 seconds)	-3.5 (0.0451 - 0.0951 seconds)	
Maximum Angular Disp. (deg)	Roll	6.1 (0.2833 seconds)	-5.3 (0.0486 seconds)	< 75 deg ✓
	Pitch	-5.3 (0.3899 seconds)	-4.9 (0.3586 seconds)	
	Yaw	-31.5 (0.3278 seconds)	-32.9 (0.3502 seconds)	

The peak 10-ms running average accelerations in the longitudinal direction was approximately 26-27g, and the peak lateral acceleration was approximately 32 g for the analysis, as shown in Figure 62, Figure 63, and Table 9. The OIV value in the longitudinal direction for the RHT and CSCM cases was 23.6 ft/s and 24.9 ft/s, respectively; the occupant impact velocity in the lateral direction was 28.5 ft/s and 27.9 ft/s for the RHT and CSCM cases, respectively. The highest ORA in the longitudinal direction was -4.4 g and -9.0 g for the RHT and CSCM cases, respectively; the highest ORA in the lateral direction was -13.5 g and -9.4 g for the RHT and CSCM cases, respectively. There were two primary peak roll events during the analysis, as shown in Figure 66 (i.e., excluding the first peak at 0.5 seconds which appears to be an anomaly of the accelerometer mounting during initial impact with barrier caused by local deformation of the floor pan). The maximum positive roll angle for the RHT case was 6.1 degrees (i.e., roll toward barrier) and occurred at 0.28 seconds; the maximum positive roll angle for the CSCM case was 4.9 degrees and occurred at 0.32 seconds. The maximum negative roll angle for the RHT case was -5.3 degrees (i.e., roll away from barrier) and occurred at 0.56 seconds; the maximum negative roll angle for the CSCM case was -4.59 degrees which also occurred at 0.56 seconds. The maximum pitch angle of the vehicle for the RHT and CSCM case was -5.3 degrees and -4.9 degrees (rear pitching upward), respectively. All occupant risk metrics were well within the preferred limits of *MASH*.

Damages to the Barrier System

Figure 68 shows images of maximum permanent deflection of the barrier with a contour plot of lateral displacement on the bridge rail. The dynamic deflection was 0.5 inches and 0.6 inches for the RHT and CSCM models, respectively. The maximum permanent dynamic deflection was 0.2 inches for both cases. Figure 69 shows contour plots of the damage parameter computed in LS-DYNA, and Figure 70 shows contour plots of the 1st principal strain. Both models indicated spalling on the front face of barrier, while the CSCM showed additional spalling across the top surface. The CSCM model indicated potential for crack initiation with contours for damage reaching 0.9 (note: value of 1 indicates crack opening) starting at the back-side anchor bolts and extending down the backside of the barrier to the deck joint. The RHT model indicated very low potential for concrete cracks on the backside of the barrier but did result in damage metric values reaching 0.5 at the barrier-deck joint. The first principal strain values were less than 0.008 on the backside for both models, which further indicate that concrete damage is minimal.

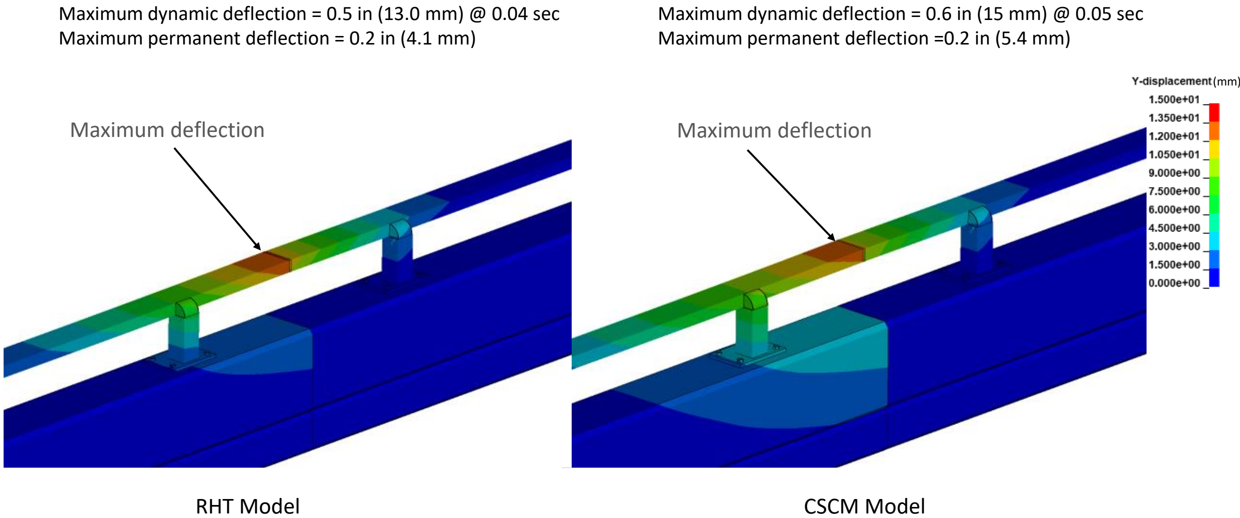


Figure 68. Contour plot of lateral displacement for Test 3-10 at IP01 on CM-MTL3 with vertical face.

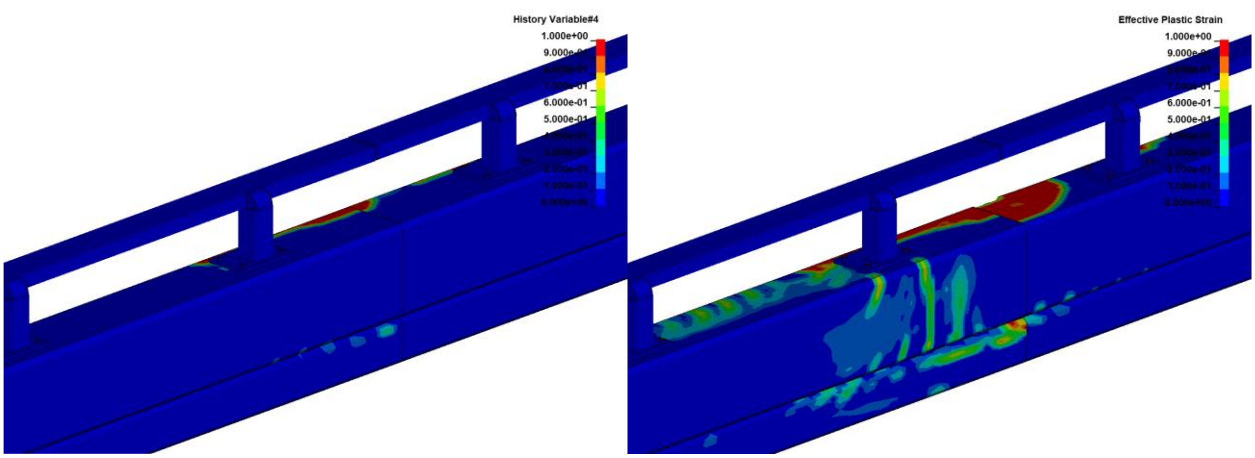


Figure 69. Contour plot of the damage variable for Test 3-10 at IP01 on CM-MTL3 with vertical face.

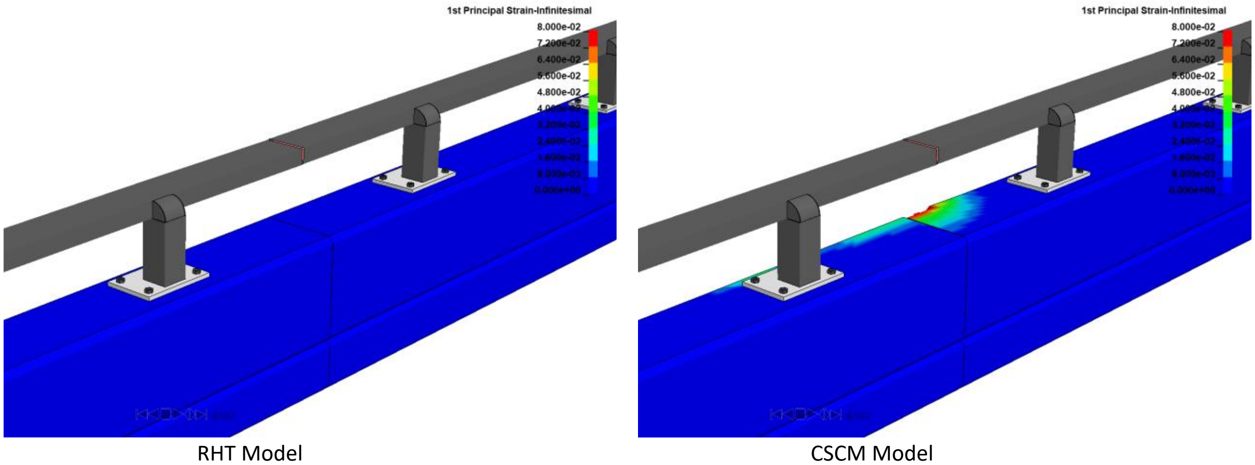


Figure 70. Contour plot of the 1st principal strain for Test 3-10 at IP01 on CM-MTL3 with vertical face.

Damages to Vehicle

Figure 71 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. Damage to the vehicle was limited to the impact side of the front cap, the front impact-side wheel assembly, front edge of front door, rear section of vehicle, edge of windshield on impact side, and side windows. The damages to the side windows and windshield were not caused by direct contact between the vehicle and barrier.

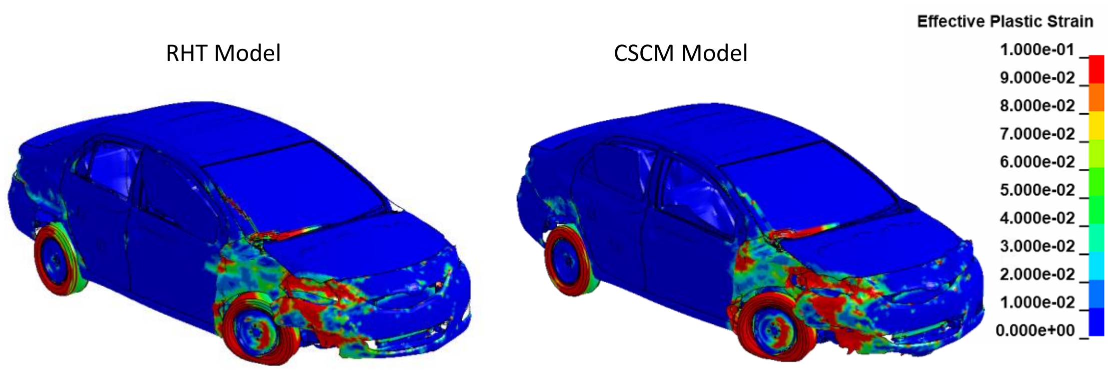


Figure 71. Damages to vehicle in Test 3-10 at IP01 on CM-MTL3 with vertical face.

Occupant Compartment Intrusion

The maximum deformation of the occupant compartment was 2.5 – 2.7 inches at the right-front toe pan at the wheel well. Figure 72 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.

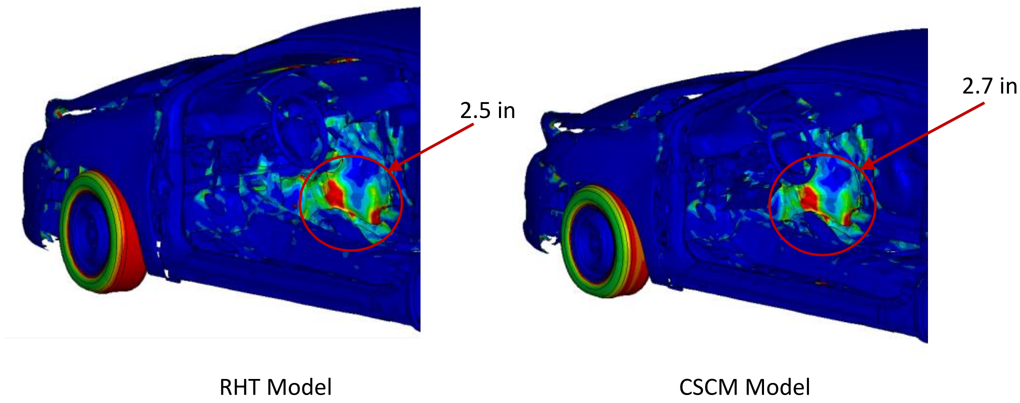


Figure 72. Occupant compartment deformation resulting from Test 3-10 at IP01 on CM-MTL3 with vertical face.

Exit Box

Figures 73 and 74 show the exit box for Test 3-10 at IP01 for the CM-MTL3 with vertical face. The post trajectory path was similar for both cases; however, the CSCM model resulted in slightly less exit velocity. The vehicle was safely redirected with its trajectory path well within the exit box criteria of *MASH* for both analysis cases.

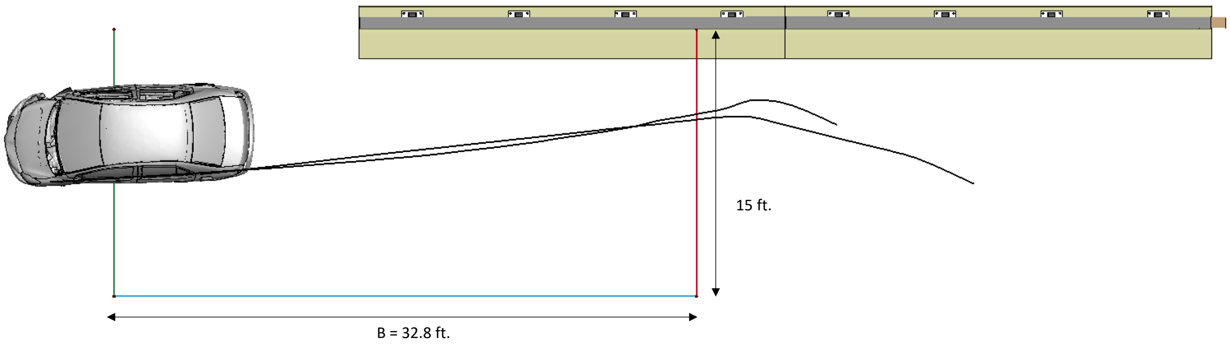


Figure 73. Exit box for Test 3-10 at IP01 on CM-MTL3 with vertical face (RHT model).

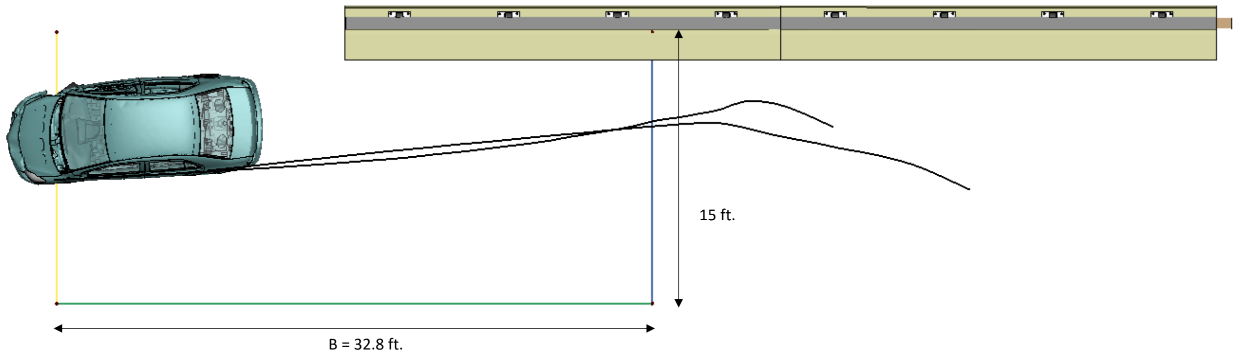


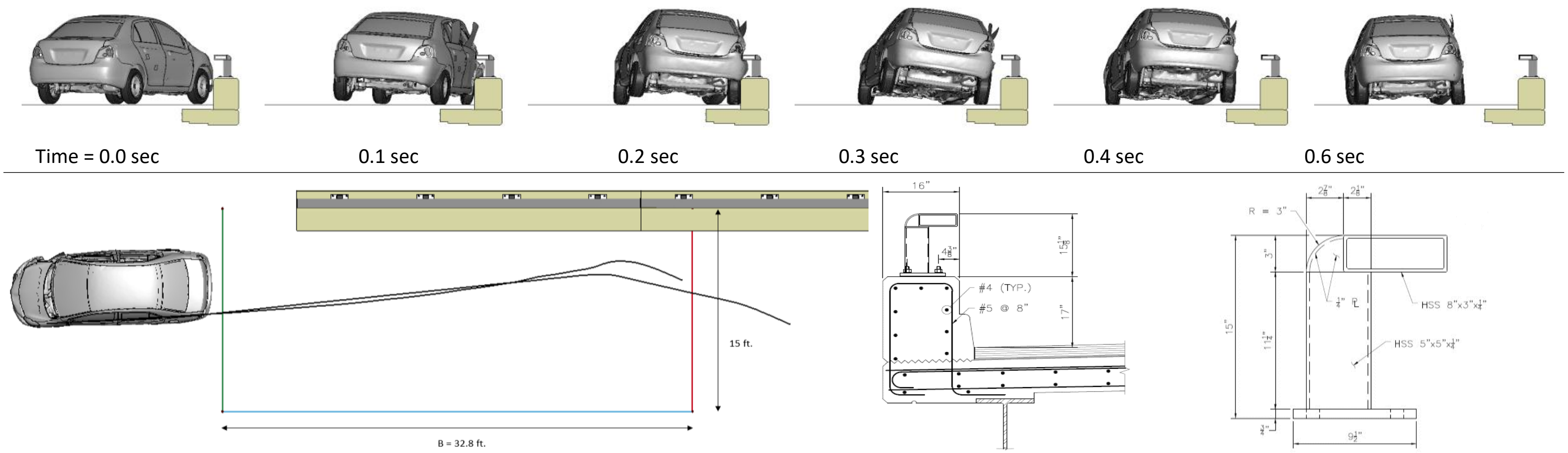
Figure 74. Exit box for Test 3-10 at IP01 on CM-MTL3 with vertical face (CSCM model).

Results Summary

A summary of *MASH* Test 3-10 results for the CM-MTL3 with vertical face with CIP at 3.6 feet upstream of the rail splice is shown in Table 18. The bridge rail successfully contained and redirected the small car with minimal damage to the concrete barrier and steel rail components. 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 preferred 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 3-10 impact conditions.

Table 18. Summary of *MASH* Test 3-10 at IP01 on CM-MTL3 with vertical face.

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		Impact Conditions		Max50-millisecond Avg. (G)	
Analysis Agency	Roadsafe LLC	Speed	62 mph	Longitudinal	14.6 - 15.1 g
Test Standard Test No.	MASH Test 3-10	Angle	25 degrees	Lateral	17.8 - 17.9 g
Analysis No.	CM-TL3 D2 IP01-Splice	Location	3.6 ft upstream of splice	Vertical	3.5 - 3.6 g
Analysis Date	6/8/2021				
Test Article		**Impact Severity**	59.5 kip-ft	**Test Article Deflections (in)**	
Type	Bridge Rail	**Exit Conditions**		Dynamic	0.5 - 0.6 inches
Name	CM-TL3	Speed	41.5 - 42.4 mph	Permanent	0.2 inches
Installation Length	48.0 feet	Angle	6.4 - 6.9 degrees	Working Width	16.0 inches
Material or Key Elements	Continuous concrete with top mounted steel post-and-beam rail	Time	0.26 - 0.30 seconds	**Max. OCI**	2.5 - 2.7 inches
Soil Type and Condition	NA	**Occupant Risk Values**		**Vehicle Stability**	
Analysis Vehicle		Longitudinal OIV	23.6 - 24.9 ft/s	Roll	5.3 - 6.1 degees
Type / Designation	1100C	Lateral OIV	27.9 - 28.5 ft/s	Pitch	4.9 - 5.3 degrees
FEA Model name	YarisC_V1l_R200522.k w/ RS tire	Longitudinal ORA	4.4 - 9.0 g	Yaw	31.5 - 32.9 degrees
Mass	2,595 lb	Lateral ORA	9.4 - 13.5 g		
		THIV	37.7 - 38.4 ft/s		
		PHD	12.2 - 13.5 g		
		ASI	2.6		

Figure 75: Summary results for *MASH* Test 3-10 at IP01 on CM-MTL3 with vertical face.

Test 3-10 at IP02 – CIP for Snag on Steel Post

Simulation of Test 3-10 included the 2,609-lb Yaris model impacting the bridge rail at 62 mph and 25 degrees. The target impact point was 3.6 feet upstream of the first post downstream of the splice and was selected to maximize potential for snagging at the bridge rail post based on the *MASH* recommended CIP for rigid barrier tests (see Table 2-7 of *MASH*). [*AASHTO16*] The analysis was performed using both the RHT and CSCM concrete models in LS-DYNA. Table 19 lists the sequence of key events for both the RHT and CSCM analysis cases.

Table 19. Sequence of events for Test 3-10 at IP02 for the CM-MTL3 w/vertical face.

Event		RHT	CSCM
1	Initial contact with barrier Right front fender and right front tire impacts vertical wall @ critical splice (between post 4 and 5)	0.00 sec Impact speed = 62.0 mph Impact angle = 25 deg	0.00 sec Impact speed = 62.0 mph Impact angle = 25 deg
3	Front right tire deflates	0.007 sec	0.008 sec
4	Peak 50-ms average y-acceleration	17.8 G @ 0.0110 - 0.0610 sec	17.6 G @ 0.0095 - 0.0595 sec
2	Peak 50-ms average x-acceleration	15.0 G @ 0.0221 - 0.0721 sec	15.6 G @ 0.0222 - 0.0722 sec
	Vehicle passes critical post - slight contact w/bumper	0.03 sec	0.03 sec
5	Lower right edged of windshield begins to crack	0.040 sec	0.04 sec
6	Maximum dynamic barrier deflection occurs at splice	0.5 in @ 0.04 sec	0.5 in @ 0.04 sec
10	Max positive pitch (front pitched upward)	≈ 0.12 deg @ 0.04 sec	≈ 0.40 deg @ 0.04 sec
7	Vehicle begins to yaw counterclockwise	≈ 0.05 sec	≈ 0.05 sec
8	Both passenger windows begin to fail	0.05 sec	0.05 sec
9	Left rear wheel leaves the ground	0.06 sec	0.06 sec
11	Occupant impact with vehicle interior	0.071 sec OIV-x = 25.3 ft/s OIV-y = 28.9 ft/s	0.070 sec OIV-x = 26.9 ft/s OIV-y = 28.2 ft/s
13	Left front wheel leaves the ground	0.08 sec	0.08 sec
14	Maximum occupant compartment intrusion. Maximum OCI Location Maximum OCI Magnetude	0.11 sec Right front toe pan 4.3 in	0.12 sec Right front toe pan 2.7 in
15	Vehicle parallel with barrier	0.17 sec	0.18 sec
16	Tail slap with barrier Right rear fender and right rear tire impacts vertical wall between posts 4 and 5	0.20 sec Speed = 43.9 mph Angle = -3.6 deg	0.21 sec Speed = 43.2 mph Angle = -3.9 deg
17	Maximum ORA-y	12.6 G @ 0.2068 - 0.2168 sec	10.2 G @ 0.2226 - 0.2326 sec
12	Maximum ORA-x	2.8 G @ 0.2239 - 0.2339 sec	2.8 G @ 0.0722 - 0.0822 sec
21	Left front wheel returns to ground	0.24 sec	0.24 sec
18	Vehicle exits barrier (body and wheels)	0.28 sec Exit speed = 42.6 mph Exit angle = -7.2 deg	0.29 sec Exit speed = 41.7 mph Exit angle = -7.3 deg
19	Max positive roll (top of vehicle toward barrier)	≈ 5.3 deg @ 0.30 sec	≈ 4.7 deg @ 0.32 sec
22	Vehicle front bumper passes end of barrier	0.31 sec	0.31 sec
20	Peak yaw (counter-clockwise) and begins to reverse yaw direction	≈ -32.85 deg @ 0.36 sec	≈ -32.96 deg @ 0.36 sec
23	Right rear wheel leaves the ground	0.39 sec	N/A
24	Max negative pitch (front pitched downward)	≈ -5.0 deg @ 0.46 sec	≈ -4.7 deg @ 0.46 sec
25	Left rear wheel returns to ground	0.51 sec	0.51 sec
26	Right rear wheel returns to ground	0.52 sec	N/A
27	Max negative roll (top of vehicle away from barrier)	≈ -4.10 deg @ 0.56 sec	≈ -3.7 deg @ 0.56 sec
28	Analysis Terminated	0.65 sec Speed = 40.1 mph Yaw angle = 3.8 deg (total angle) Roll angle = 1.73 deg (away from barrier) Pitch angle = 2.80 deg (rear pitched up)	0.65 sec Speed = 39.3 mph Yaw angle = 3.6 deg (total angle) Roll angle = 1.15 deg (away from barrier) Pitch angle = 2.7 deg (rear pitched up)

The sequential views of the impact event are shown in Appendix G for both the RHT and CSCM models. The following sections provide time-history data evaluation, occupant risk assessments, and damages sustained by both the barrier and vehicle.

Time History Plots and Occupant Risk Measures

Figures 76 through 78 show the longitudinal, transverse, and vertical acceleration-time histories, respectively, computed from the center of gravity of the vehicle; Figures 79 through 81 show the comparison of the angular rates and angular displacements (i.e., yaw, roll, and pitch) at the center of gravity of the vehicle. Table 20 shows the results for the occupant risk calculations for these two cases.

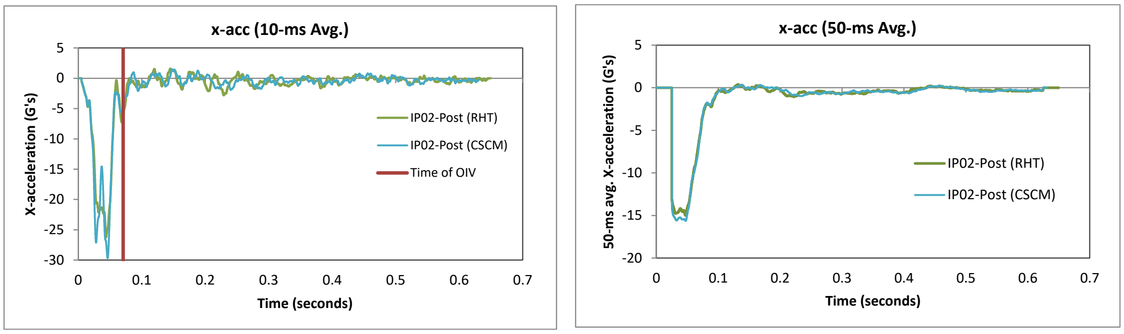


Figure 76. 10- and 50-millisecond average X-acceleration from FEA of Test 3-10 at IP02 on CM-MTL3 with vertical face.

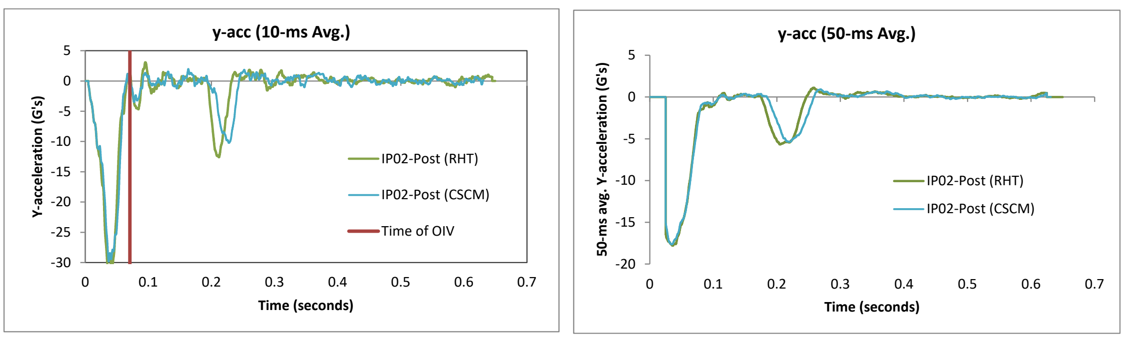


Figure 77. 10- and 50-millisecond average Y-acceleration from FEA of Test 3-10 at IP02 on CM-MTL3 with vertical face.

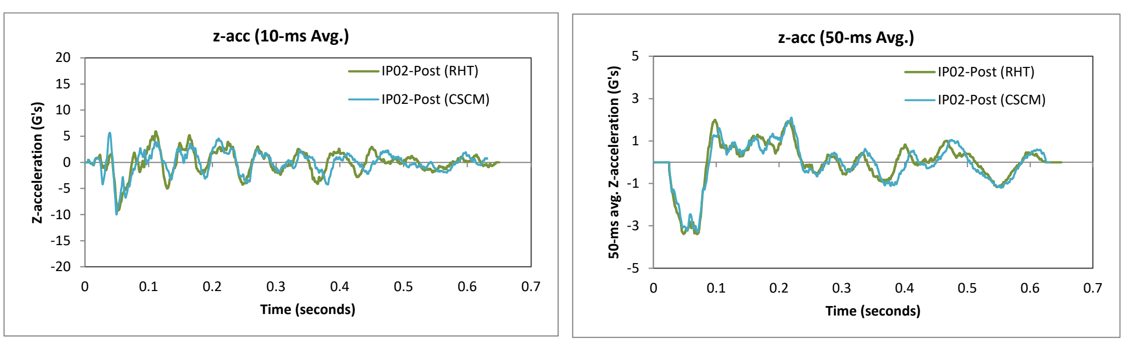


Figure 78. 10- and 50-millisecond average Z-acceleration from FEA of Test 3-10 at IP02 on CM-MTL3 with vertical face.

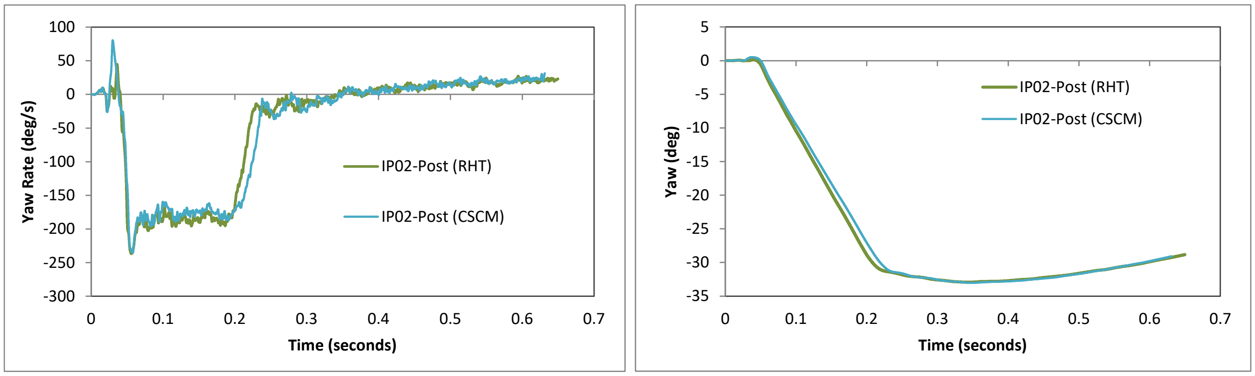


Figure 79. Yaw rate and yaw angle time-history from FEA of Test 3-10 at IP02 on CM-MTL3 with vertical face.

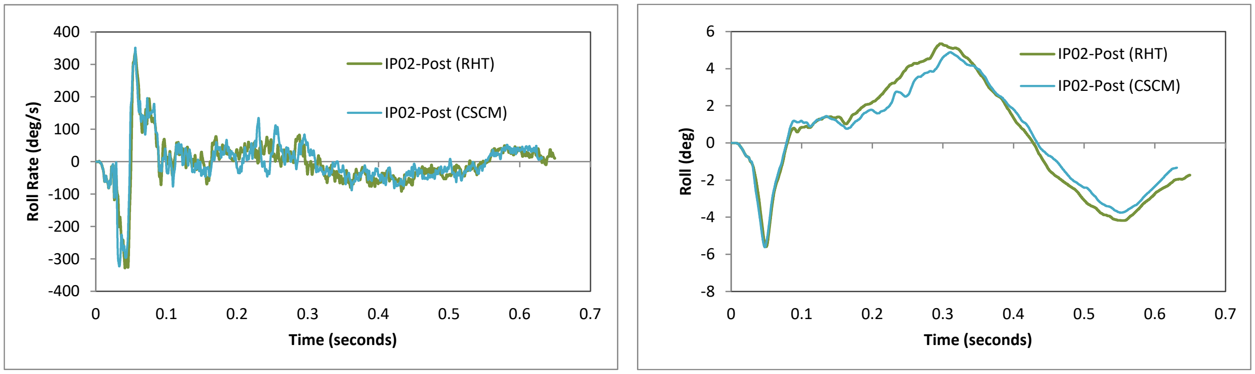


Figure 80. Roll rate and roll angle time-history from FEA of Test 3-10 at IP02 on CM-MTL3 with vertical face.

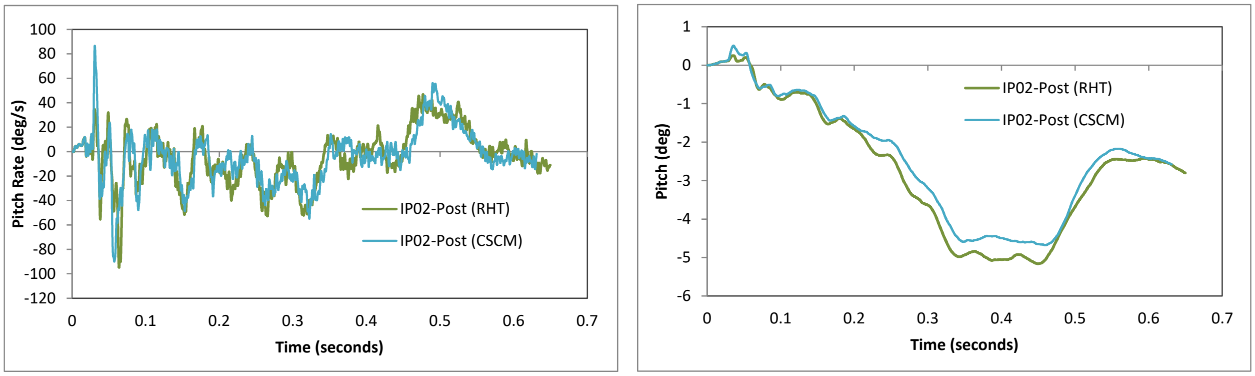


Figure 81. Pitch rate and pitch angle time-history from FEA of Test 3-10 at IP02 on CM-MTL3 with vertical face.

Table 20. Summary of *MASH* occupant risk metrics for Test 3-10 at IP02 on CM-MTL3 with vertical face.

Occupant Risk Factors		MASH 3-10	
		IP02-Post (RHT)	IP02-Post (CSCM)
Occupant Impact Velocity (ft/s)	x-direction	25.3	26.9
	y-direction	28.9	28.2
	at time	at 0.0707 seconds on right side of interior	at 0.0702 seconds on right side of interior
THIV (ft/s)		38.1 at 0.0687 seconds on right side of interior	39.0 at 0.0702 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-2.8 (0.2239 - 0.2339 seconds)	-2.8 (0.0722 - 0.0822 seconds)
	y-direction	-12.6 (0.2068 - 0.2168 seconds)	-10.2 (0.2226 - 0.2326 seconds)
PHD (g's)		12.6 (0.2068 - 0.2168 seconds)	10.3 (0.2226 - 0.2326 seconds)
ASI		2.64 (0.0399 - 0.0899 seconds)	2.63 (0.0407 - 0.0907 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-15 (0.0221 - 0.0721 seconds)	-15.6 (0.0222 - 0.0722 seconds)
	y-direction	-17.8 (0.0110 - 0.0610 seconds)	-17.6 (0.0095 - 0.0595 seconds)
	z-direction	-3.4 (0.0443 - 0.0943 seconds)	-3.3 (0.0452 - 0.0952 seconds)
Maximum Angular Disp. (deg)	Roll	-5.6 (0.0498 seconds)	-5.6 (0.0479 seconds)
	Pitch	-5.2 (0.4496 seconds)	-4.7 (0.4593 seconds)
	Yaw	-32.9 (0.3438 seconds)	-33 (0.3490 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 ✓

The peak 10-ms running average accelerations in the longitudinal direction was approximately 26-30 g, and the peak lateral acceleration was approximately 30-31 g for the analyses, as shown in Figure 76, Figure 77 and in Table 9. The OIV value in the longitudinal direction for the RHT and CSCM cases was 25.3 ft/s and 26.9 ft/s, respectively; the occupant impact velocity in the lateral direction was 28.9 ft/s and 28.2 ft/s for the RHT and CSCM cases, respectively. The highest ORA in the longitudinal direction was -2.8 g for both the RHT and CSCM cases; the highest ORA in the lateral direction was -12.6 g and -10.3 g for the RHT and CSCM cases, respectively. As was seen in the previous analysis case, there were two primary peak roll events during the analysis, as shown in Figure 80 (i.e., excluding the first peak at 0.5 seconds which appears to be an anomaly of the accelerometer mounting during initial impact with barrier). The maximum positive roll angle for the RHT case was 5.3 degrees (i.e., roll toward barrier) and occurred at 0.30 seconds; the maximum positive roll angle for the CSCM case was 4.7 degrees and occurred at 0.32 seconds. The maximum negative roll angle for the RHT case was -4.1 degrees (i.e., roll away from barrier) and occurred at 0.56 seconds; the maximum negative roll angle for the CSCM case was -3.7 degrees which also occurred at 0.56 seconds. The maximum pitch angle of the vehicle for the RHT and CSCM cases was -5.2 degrees and -4.7 degrees (rear pitching upward), respectively. All occupant risk metrics were well within the preferred limits of *MASH*.

Damages to the Barrier System

Figure 82 shows images of maximum permanent deflection of the barrier with a contour plot of lateral displacement on the bridge rail. The dynamic deflection was 0.5 inches, and the maximum permanent dynamic deflection was 0.1 inches for both the RHT and CSCM models. Figure 83 shows contour plots of the damage parameter computed in LS-DYNA, and Figure 84 shows contour plots of the 1st principal strain. Both models indicated spalling on the front face of barrier, while the CSCM showed additional spalling across the top surface. The CSCM model indicated minor crack formation initiating on the backside, while the RHT model indicated a low potential for concrete cracks on the backside of the barrier. The first principal strain values were less than 0.008 on the backside for both models, which further indicate that concrete damage is minimal.

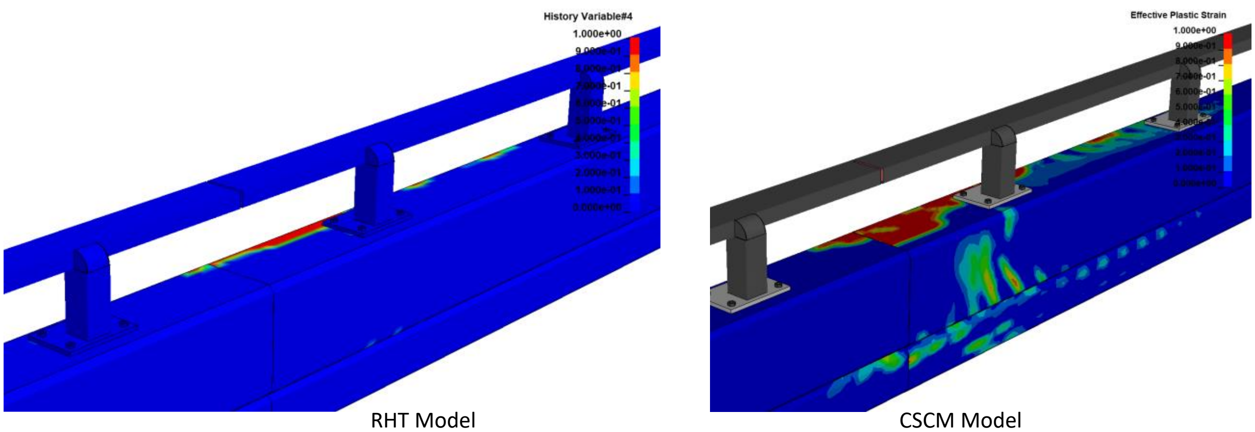


Figure 82. Contour plot of lateral displacement for Test 3-10 at IP02 on CM-MTL3 with vertical face.

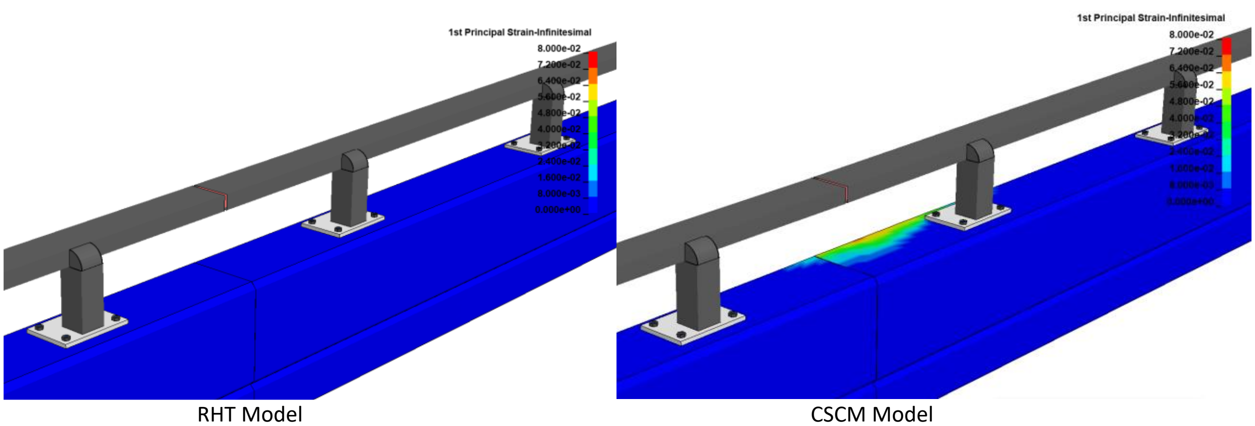


Figure 83. Contour plot of the damage variable for Test 3-10 at IP02 on CM-MTL3 with vertical face.

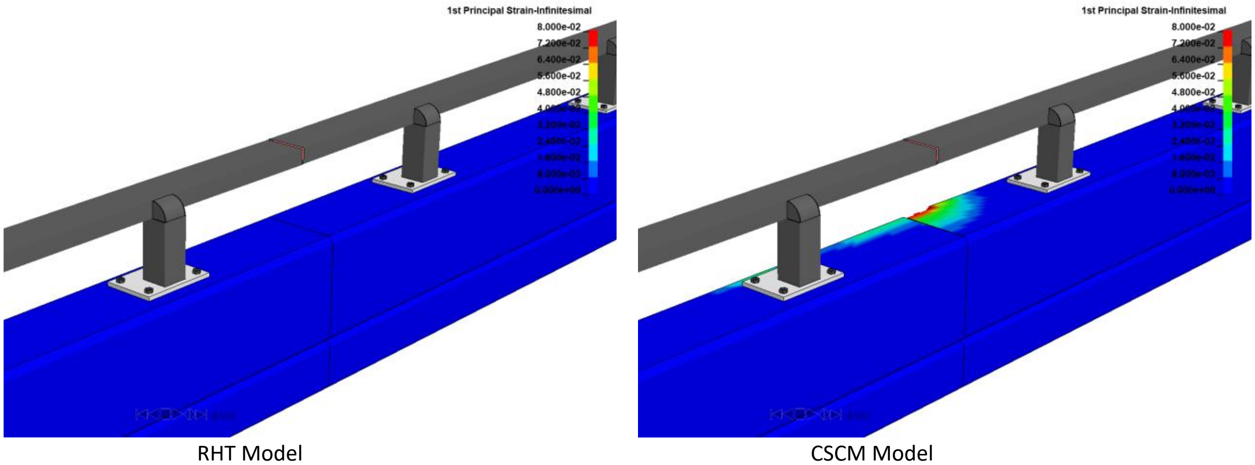


Figure 84. Contour plot of the 1st principal strain for Test 3-10 at IP02 on CM-MTL3 with vertical face.

Damages to Vehicle

Figure 85 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. Damage to the vehicle was limited to the impact side of the front cap, the front impact-side wheel assembly, front edge of front door, rear section of vehicle, edge of windshield on impact side, and side windows. The damages to the side windows and windshield were not caused by direct contact between the vehicle and barrier.

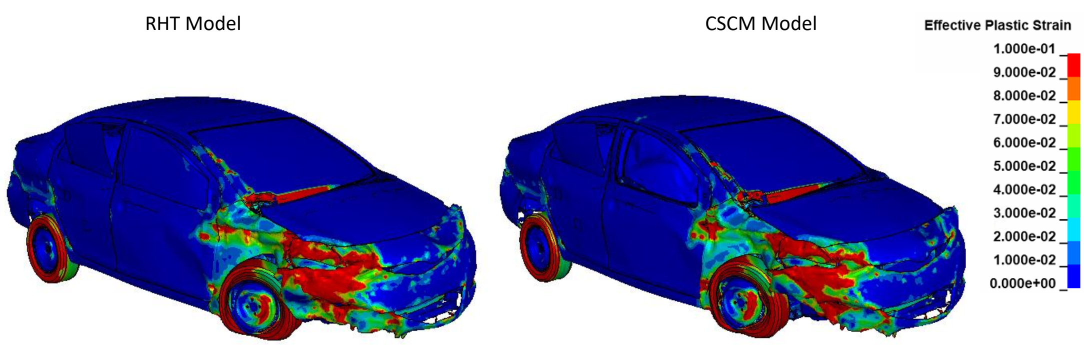


Figure 85. Damages to vehicle in Test 3-10 at IP02 on CM-MTL3 with vertical face

Occupant Compartment Intrusion

The maximum deformation of the occupant compartment was 2.7 – 4.3 inches at the right-front toe pan at the wheel well. Figure 86 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.

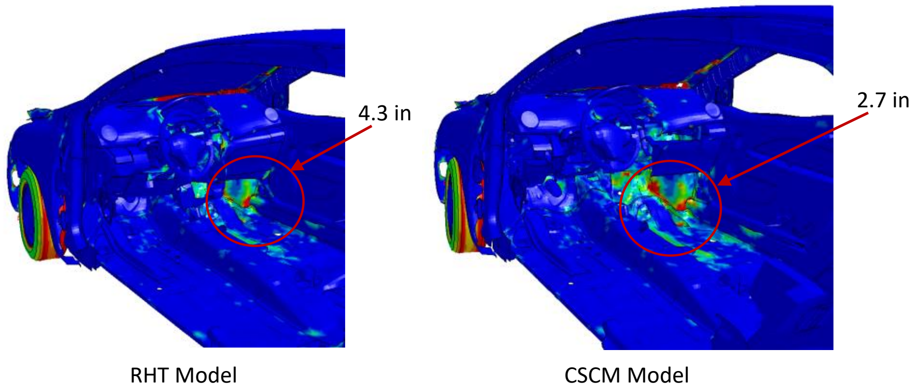


Figure 86. Occupant compartment deformation resulting from Test 3-10 at IP02 on CM-MTL3 with vertical face.

Exit Box

Figures Figure 87 and Figure 88 show the exit box for Test 3-10 at IP02 for the CM-MTL3 with vertical face. The post trajectory path was essentially the same for both cases similar for both cases. The vehicle was safely redirected with its trajectory path well within the exit box criteria of *MASH* for both analysis cases.

Results Summary

A summary of the *MASH* Test 3-10 results for the CM-MTL3 with vertical face with CIP at 3.6 feet upstream of critical post is shown in Table 21. The bridge rail successfully contained and redirected the small car with minimal damage to the concrete barrier and steel rail components. 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 preferred 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 3-10 impact conditions.

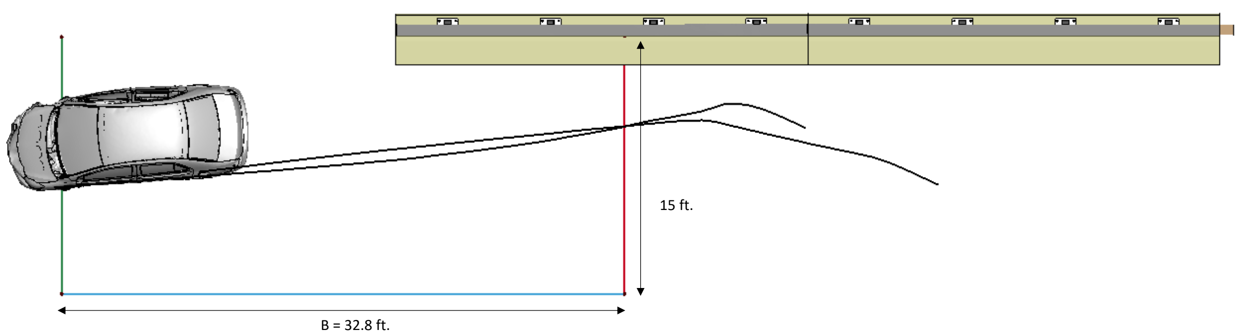


Figure 87. Exit box for Test 3-10 at IP02 on CM-MTL3 with vertical face (RHT model).

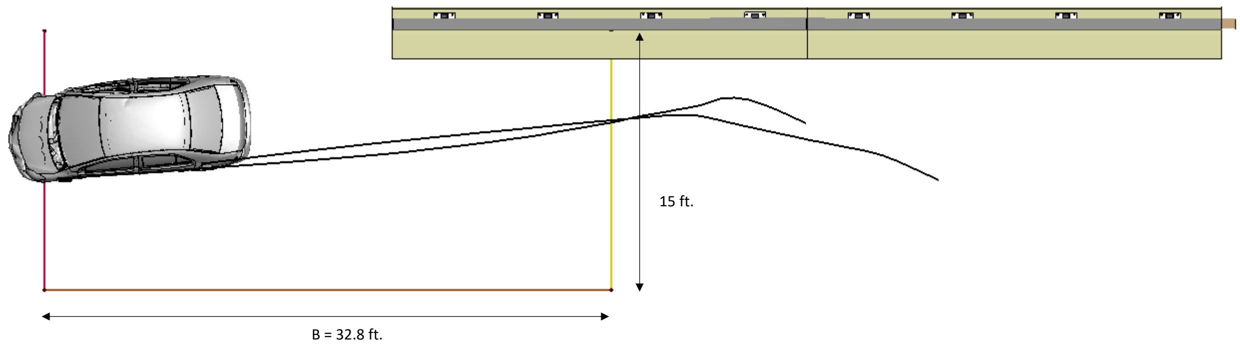
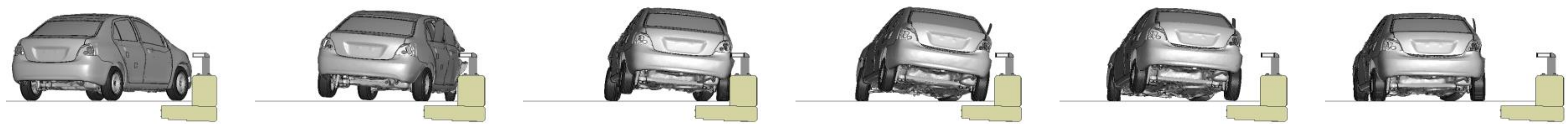
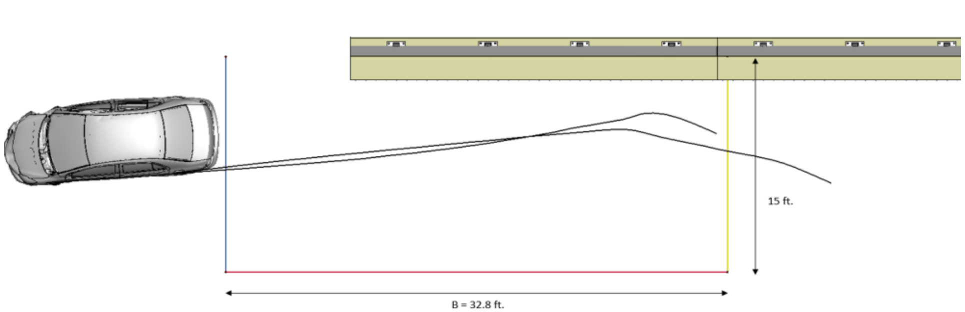


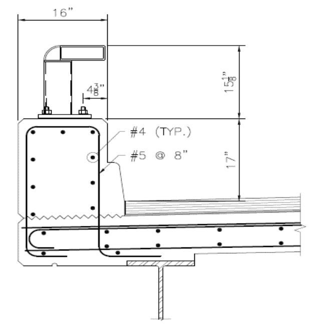
Figure 88. Exit box for Test 3-10 at IP02 on CM-MTL3 with vertical face (CSCM model).

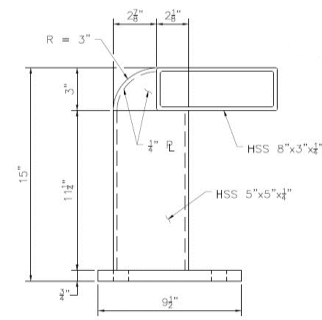
Table 21. Summary of *MASH* Test 3-10 at IP02 on CM-MTL3 with vertical face.

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 3-10
Analysis No.	CM-TL3 D2 IP02-Post
Analysis Date	6/8/2021

Test Article

Type	Bridge Rail
Name	CM-TL3
Installation Length	48.0 feet
Material or Key Elements	Continuous concrete with top mounted steel post-and-beam rail

Soil Type and Condition .... NA

Analysis Vehicle

Type / Designation	1100C
FEA Model name	YarisC_V1I_R200522.k w/ RS tire
Mass	2,595 lb

Impact Conditions

Speed	62 mph
Angle	25 degrees
Location	3.6 ft upstream of critical post

Impact Severity .... 59.5 kip-ft

Exit Conditions

Speed	41.6 - 42.8 mph
Angle	7.1 - 7.3 degrees
Time	0.27 - 0.29 seconds

Occupant Risk Values

Longitudinal OIV	25.3 - 26.9 ft/s
Lateral OIV	28.2 - 28.9 ft/s
Longitudinal ORA	2.8 g
Lateral ORA	10.2 - 12.6 g
THIV	38.1 - 39.0 ft/s
PHD	10.3 - 12.6 g
ASI	2.63 - 2.64

Max50-millisecond Avg. (G)

Longitudinal	15 - 15.6 g
Lateral	17.6 - 17.8 g
Vertical	3.3 - 3.4 g

Test Article Deflections (in)

Dynamic	0.5 inches
Permanent	0.1 inches
Working Width	16.0 inches

Max. OCI .... 2.7 - 4.3 inches

Vehicle Stability

Roll	5.6 degees
Pitch	4.7 - 5.2 degrees
Yaw	32.9 - 33.0 degrees

Figure 89: Summary results for *MASH* Test 3-10 at IP02 on CM-MTL3 with vertical face.

CHAPTER 9 – S UMMARY AND CONCLUSIONS

The objective of this project was to use finite element analysis (FEA) computer simulation to evaluate the crash performance of the MassDOT CM-MTL3 bridge rail design. The impact conditions and assessment procedures for the CM-MTL3 bridge rail evaluations conformed to the specifications in *MASH* for TL3. Two primary design options for the bridge rail were evaluated:

- Design 1: Integral safety-curb design on face of concrete barrier,
- Design 2: Vertical face design on concrete barrier

In total, ten analysis cases were evaluated, including two cases for Design 1 and eight cases for Design 2. A summary of the analysis results regarding eight key metrics is shown in Table 22. Based on the results of the analyses, the CM-MTL3 is expected to meet all structural and occupant risk criteria in *MASH* TL3.

Design 1 – CM-MTL3 with integral safety curb

Only Test 3-11 was evaluated for the CM-MTL3 with the integral safety curb for two CIP cases: (1) IP01 involved impact point at 4.3 ft upstream from the splice connection to maximize the potential for snagging at the splice and (2) IP02 involved impact point at 4.3 ft upstream of a post to maximize the potential for snagging on the critical bridge rail post (i.e., immediately downstream of rail splice). The barrier successfully contained and redirected the 2270P vehicle. There were no detached elements from the barrier that showed potential for penetrating or significantly deforming the occupant compartment or presenting undue hazard to other traffic. The vehicles remained upright and did not experience excessive roll or pitch angle displacements. The OIV and maximum ORA values were within preferred limits specified in *MASH*.

The damage to the bridge rail was notable for this case and included maximum dynamic deflections of 3.1 inches for IP01 and 2.1 inches for IP02. The maximum permanent deflection was 2.6 inches for IP01 and was 1.8 inches for IP02. The maximum barrier deflections were corresponded to the steel rail portion of the barrier. Both analysis cases resulted in excessive damage to the upper, front face of the concrete barrier, with notable spalling along the top edge. The spalling was more pronounced for IP01 and resulted from the tire rim snagging at the expansion joint of the concrete when the wheel aggressively steered toward the barrier during impact.

Although the analysis results showed that the crash performance of the barrier system met *MASH* criteria for Test 3-11, it was determined that barrier performance would likely be improved by removing the integral curb from the face of barrier. During the early phase of the impact, the front, impact-side tire aggressively climbed the face of the barrier and abruptly steered toward the barrier, resulting notable damage to the top edge of the barrier (e.g., significant spalling). This event also caused higher loading on the steel rail that is mounted on top of the barrier and showed higher propensity for wheel snag at the concrete expansion joint and on the steel posts.

Design 2 – CM-MTL3 with vertical face barrier

Based on the results of Design 1, the integral curb was removed from the face of the barrier and replaced with a vertical face design. The barrier successfully contained and redirected both the vehicle for both Test 3-10 and Test 3-11 for both the IP01 and IP02 critical impact point cases. There were no detached elements from the barrier that showed potential for penetrating or significantly deforming the occupant compartment or presenting undue hazard to other traffic. The vehicles remained upright and did not experience excessive roll or pitch angle displacements. The OIV and maximum ORA values were within preferred limits specified in *MASH*.

The damage to the face of the barrier was significantly reduced for this design case compared to the results for the design involving the integral curb. The wheel climbed the barrier in both design cases; however, the integral curb design (i.e., Design 1) resulted in abrupt tire-steer toward the barrier which caused significant spalling along the top edge of the barrier. This did not occur for the vertical face design (i.e., Design 2), thus the potential for wheel snag on the barrier was considerably reduced.

Recommendations

Based on the results of this study, it is recommended that the vertical face design be used for the CM-MTL3 barrier. Note that the crash performance was very similar for both CIP locations with no significant snagging of the vehicle against the barrier for either case. However, the CIP was selected to maximize snagging against the post based on the premise that, if such an event occurred, it would result in the most severe outcome regarding crash performance. If full-scale testing is to be conducted, it is suggested that the critical impact point for Test 3-10 be taken as 3.6 feet upstream of the critical post location (i.e., immediately downstream of the rail splice), and that the critical impact point for Test 3-11 be 4.2 feet upstream of the critical post location.

Table 22. Summary of results for CM-MTL3 for D1 (integral curb) and D2 (vertical face) design.

Design Case	*MASH* Test	Impact Case	Concrete Model	Deflection		Peak Acceleration		Occupant Risk Metrics				Vehicle Stability		Result
				Dynamic (in)	Final (in)	X-dir (G)	Y-dir (G)	OIVx (ft/s)	OIVy (ft/s)	ORAx (ft/s)	ORAy (ft/s)	Max Roll (deg)	Max Pitch (deg)	
D1	3-11	IP_01	RHT	3.1	2.6	-17.1	-17.7	28.2	23.6	-10.9	-7.4	-9.5	5.2	Pass
	3-11	IP_02	RHT	2.1	1.8	-17.8	-15.8	29.9	25.6	-5.9	-5.0	-8.7	-4.7	Pass
D2	3-11	IP_01	RHT	2.1	1.6	-17.3	-21.7	23.3	24.9	-5.0	-11.7	-10.8	5.2	Pass
	3-11	IP_01	CSCM	2.4	2.0	-16.7	-19.7	23.6	24.9	-4.7	-10.5	-11.5	5.3	Pass
	3-11	IP_02	RHT	1.6	1.2	-16.8	-22.1	22.0	25.9	-4.4	-10.7	13.1	-7.3	Pass
	3-11	IP_02	CSCM	2.2	1.8	-17.6	-18.6	23.3	25.3	-4.4	-10.5	-11.1	5.2	Pass
	3-10	IP_01	RHT	0.5	0.2	-25.8	-32.3	23.6	28.5	-4.4	-13.5	6.1	-5.3	Pass
	3-10	IP_01	CSCM	0.6	0.2	-26.8	-32.0	24.9	27.9	-9.0	-9.4	-5.3	-4.9	Pass
	3-10	IP_02	RHT	0.5	0.1	-26.2	-31.2	25.3	28.9	-2.8	-12.6	-5.6	-5.2	Pass
	3-10	IP_02	CSCM	0.5	0.1	-29.7	-29.8	26.9	28.2	-2.8	-10.2	-5.6	-4.7	Pass

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Appendix A

Detail Drawings for the MassDOT CM-MTL3 Bridge Rail

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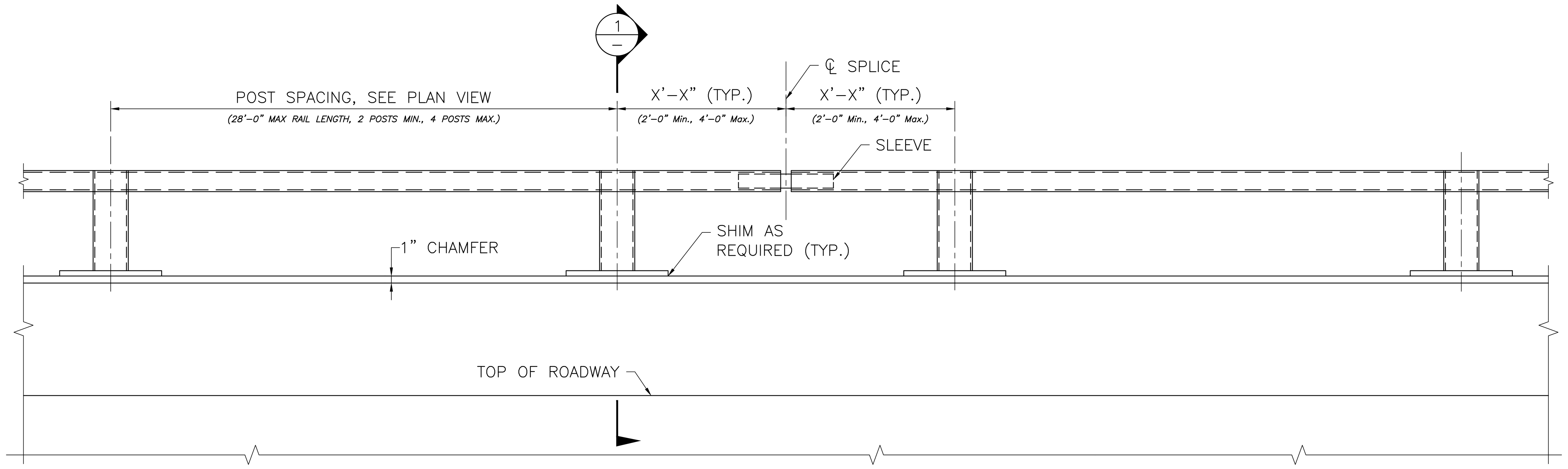
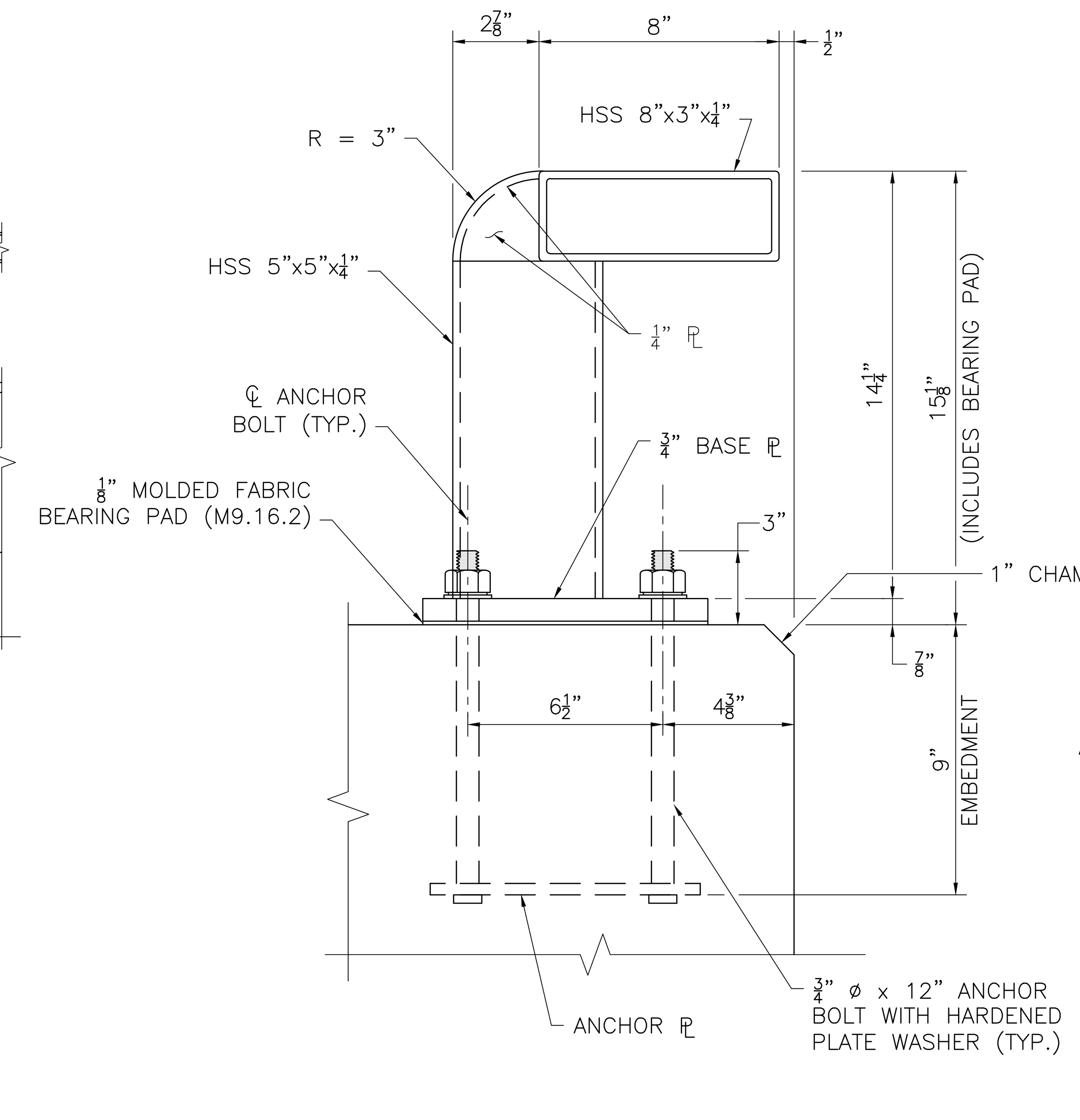
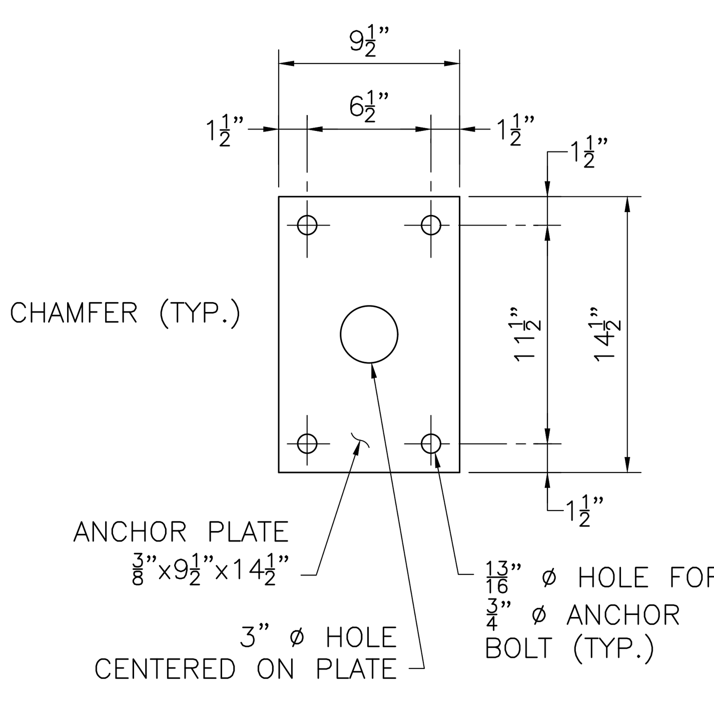


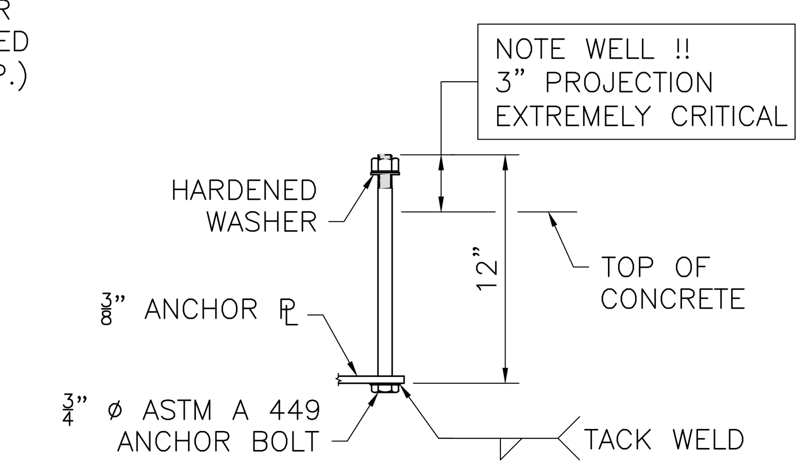
ELEVATION
SCALE: 1" – 1'-0"



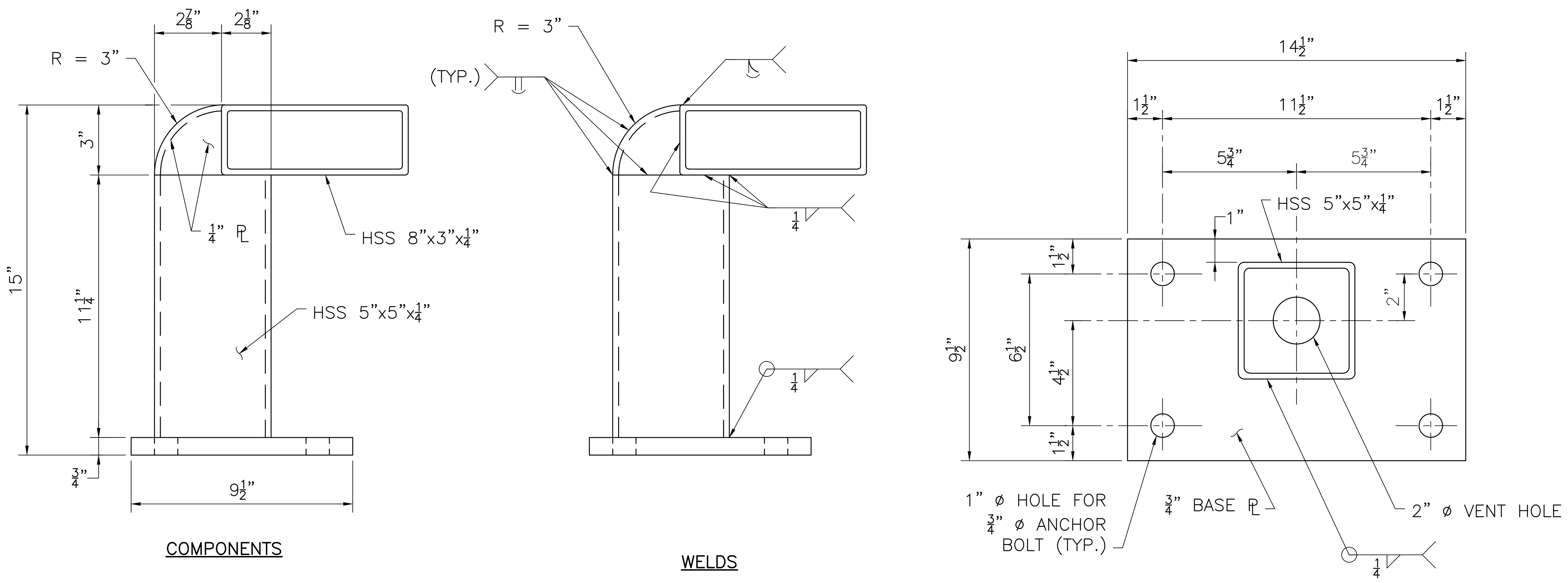
SECTION 1
SCALE: 3" = 1'-0"



ANCHOR PLATE
SCALE 1 1/2" = 1'-0"



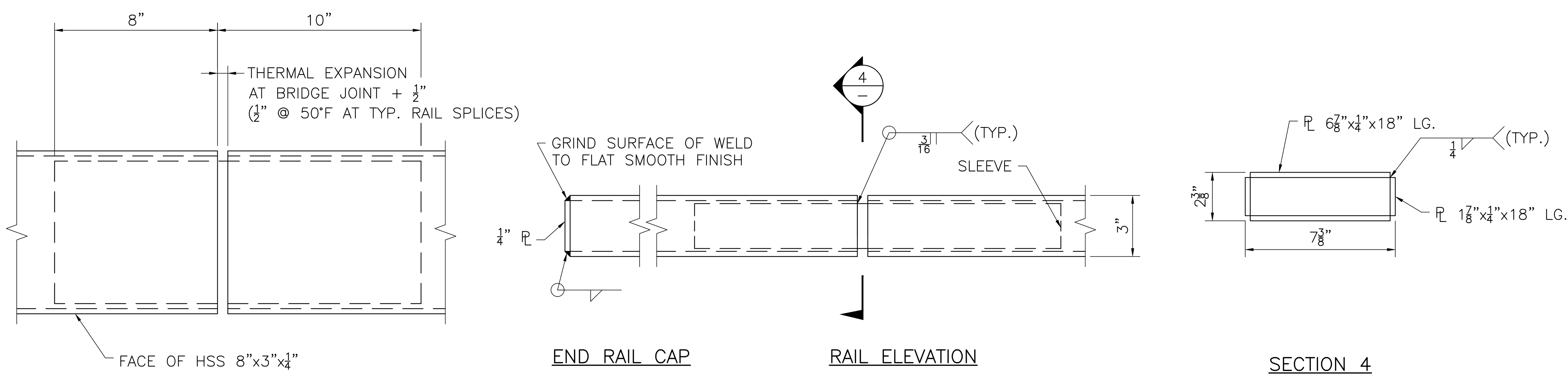
ANCHOR BOLT



SECTION

BASE PLATE

RAIL POST DETAILS
SCALE: 3" = 1'-0"



TYPICAL SPLICE DETAILS
SCALE: 3" = 1'-0"

MATERIALS:

STRUCTURAL STEEL TUBING — ASTM A 500 GRADE B (GALVANIZED)
POST AND BASE PLATE — AASHTO M 270 GRADE 36 OR GRADE 50 (GALVANIZED)
ANCHOR BOLTS — ASTM F1554 GRADE 105 TYPE 2A (GALVANIZED)

GENERAL NOTES:

1. RAILS SHALL BE CONTINUOUS OVER A MINIMUM OF TWO AND A MAXIMUM OF 4 POSTS.
2. RAILS SHALL HAVE A TUBE SPLICE BETWEEN CONTINUOUS LENGTHS OF RAIL AND IN THE PANEL OVER A BRIDGE EXPANSION JOINT.
3. ALL STEEL (EXCEPT THE ANCHOR PLATE AND FASTENERS) SHALL BE GALVANIZED AND PAINTED DARK BRONZE (AMS STANDARD 595A COLOR NUMBER 10045 OF THE FEDERAL STANDARD 595B).
4. 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 A ADDITIONAL 1/8 TURN AFTER STEEL IS IN PLACE.
5. ALL POSTS SHALL BE SET PERPENDICULAR TO GRADE.
6. END TUBE SECTIONS SHALL BE SAWED. GRIND SMOOTH EXPOSED EDGES. ALL CUT ENDS SHALL BE TRUE AND SMOOTH.
7. WELDING SHALL CONFORM TO THE REQUIREMENTS OF ANSI/AASHTO/AWS D.1.5, EXCEPT THAT WELDING OF THE TUBE-WELDED SPLICE SHALL CONFORM TO THE REQUIREMENTS OF ANSI/AWS D.1.1

CM–TL3 BRIDGE RAILING

MONTH DD, YYYY	ISSUED FOR CONSTRUCTION
DATE	DESCRIPTION
USE ONLY PRINTS OF LATEST DATE	

SHEET XX OF XX SHEETS BRIDGE NO. X–XX–XXX (XXX)

Date: June 2013

CITY/TOWN
STREET/ROUTE # OR NAME

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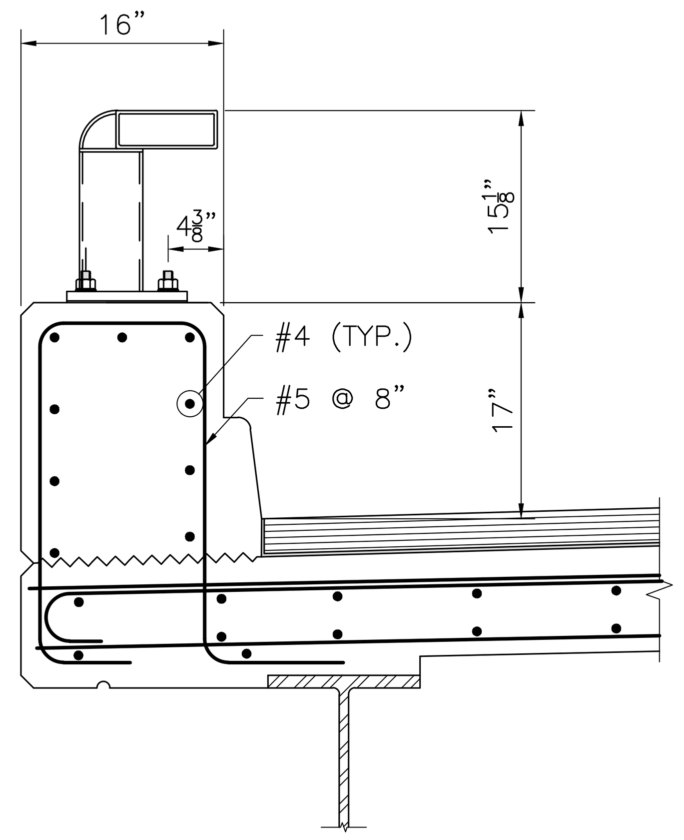
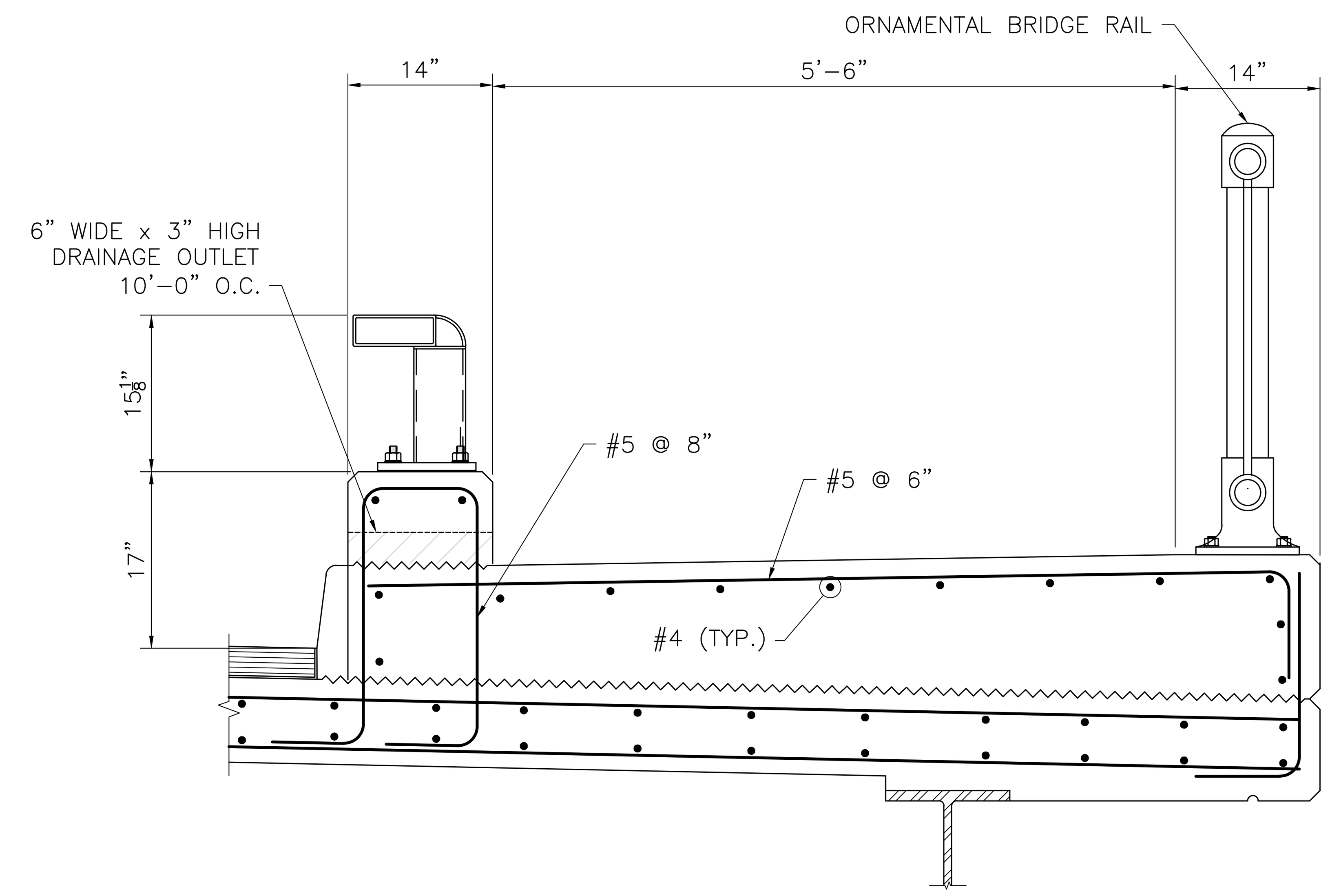
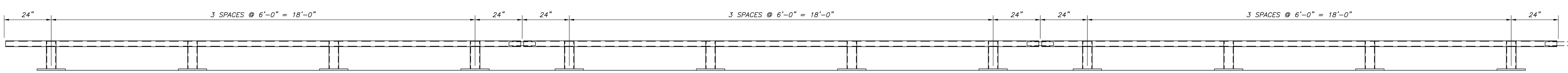
PROJECT FILE NO. XXXXXX			



SECTION AT SAFETY CURB



SECTION THRU SIDEWALK



NOT INTENDED FOR STANDARD DRAWINGS JUST AN EXPLAINATION OF POST SPACING

SAMPLE POST SPACING

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DATE	DESCRIPTION
USE ONLY PRINTS OF LATEST DATE	

SHEET XX OF XX SHEETS BRIDGE NO. X–XX–XXX (XXX)

Date: June 2013

CM-TL3_BRIDGE_RAILING.DWG 7-Apr-2021

Xxxxxx Structural Submittal (S#) DD-Month-YYYY

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CITY/TOWN
STREET/ROUTE # OR NAME

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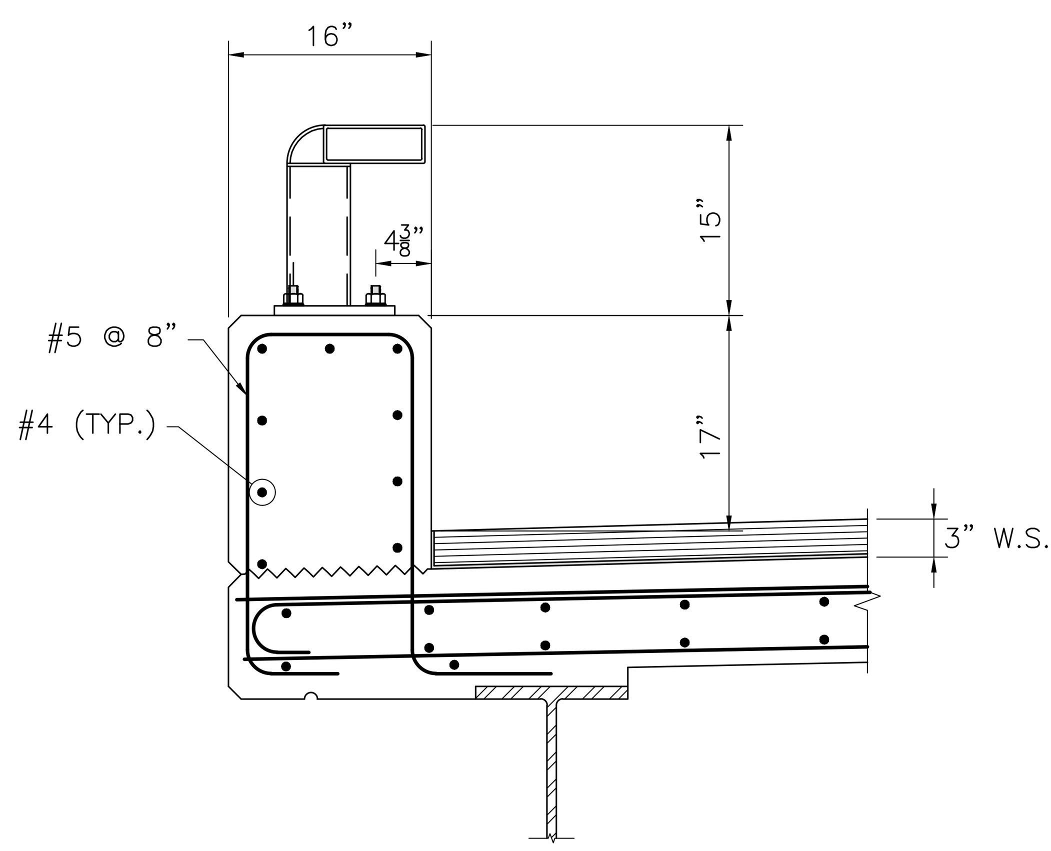

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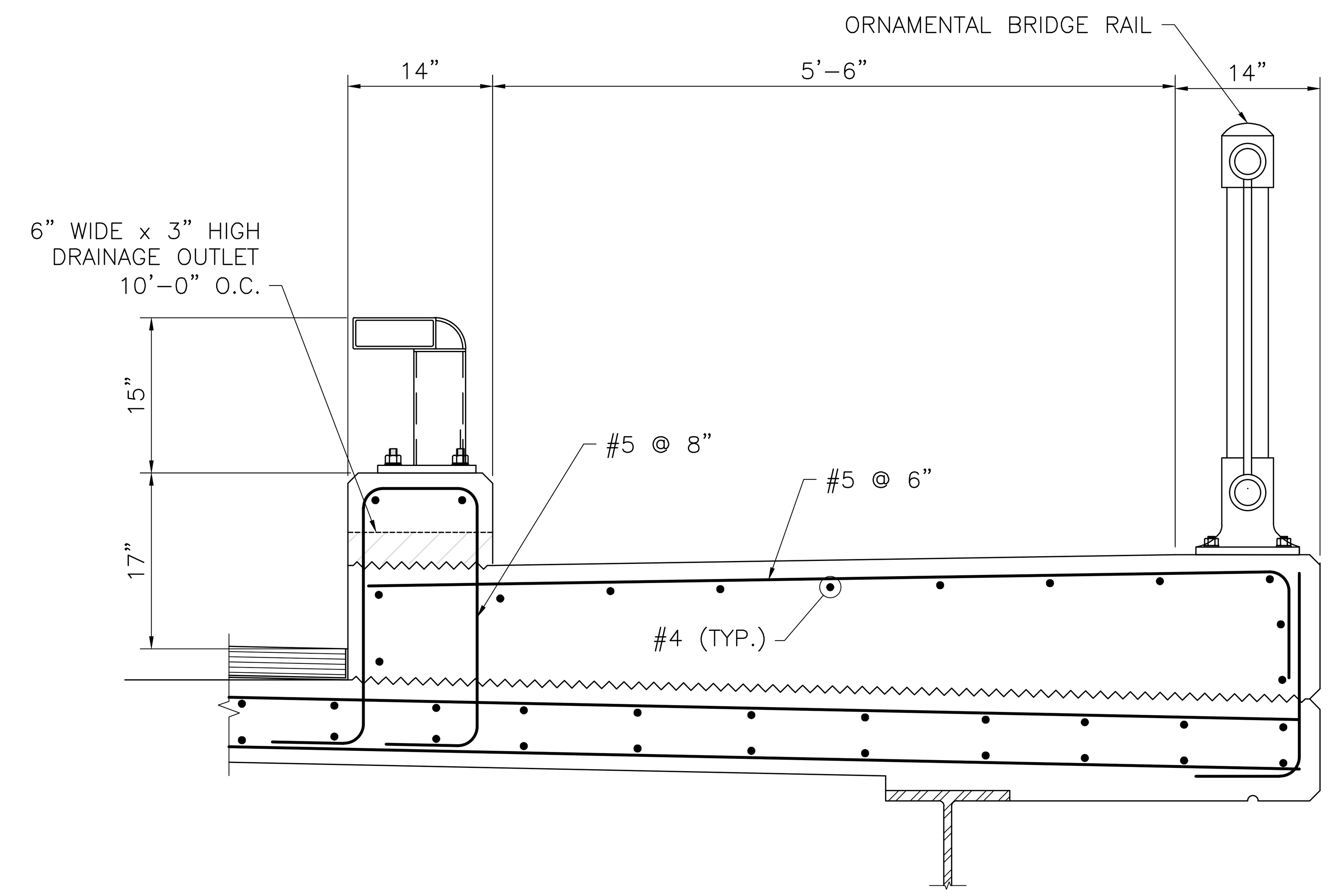

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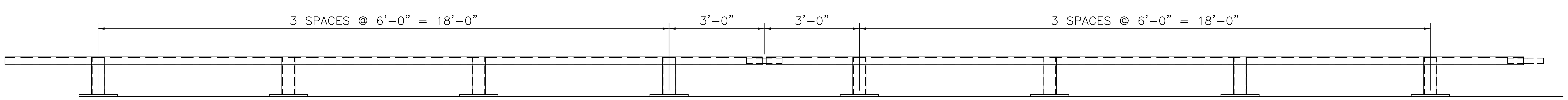

SAMPLE POST SPACING

MONTH DD, YYYY	ISSUED FOR CONSTRUCTION
DATE	DESCRIPTION
USE ONLY PRINTS OF LATEST DATE	

SHEET XX OF XX SHEETS BRIDGE NO. X–XX–XXX (XXX)

Date: June 2013

CM-TL3_BRIDGE_RAILING.DWG 22-Jul-2021

Xxxxxx Structural Submittal (S#) DD-Month-YYYY

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Appendix B

Sequential Views for Test 3-11 at IP01

CM-MTL3 Bridge Rail with Safety-Curb Design

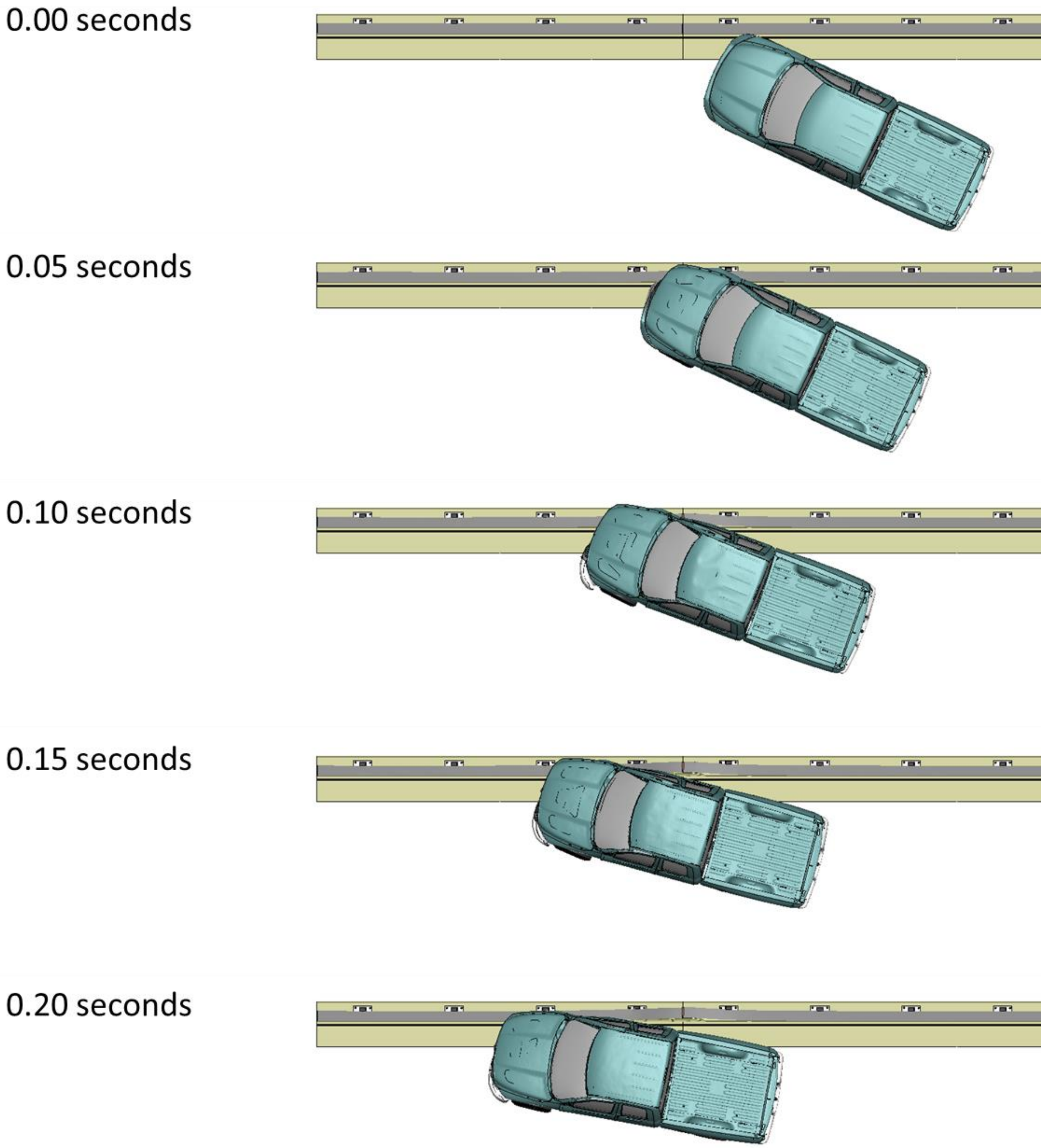


Figure B-1. Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Safety-Curb Design from an overhead viewpoint.

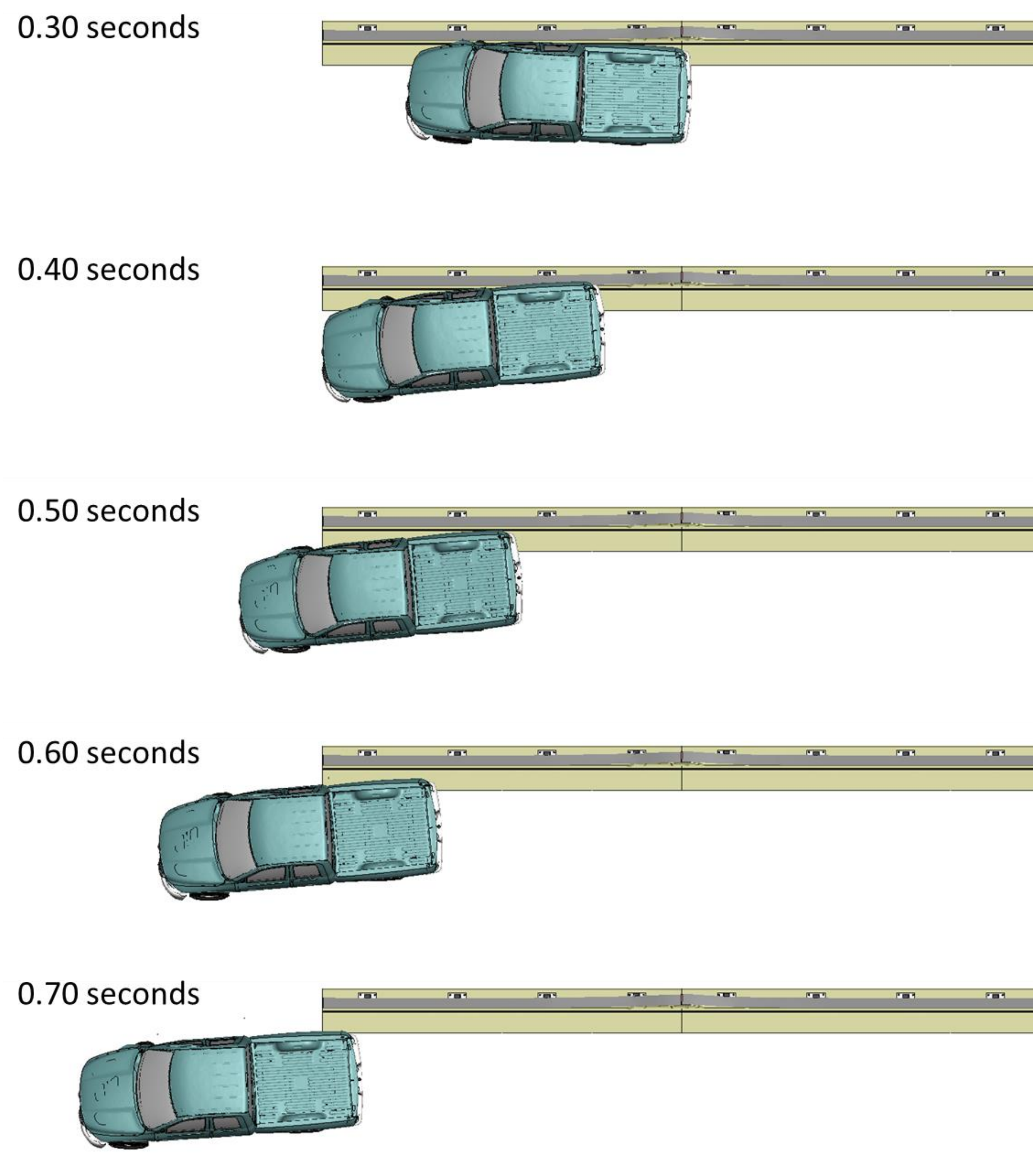
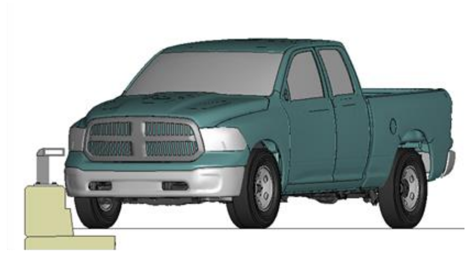


Figure B-1. [Continued] Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Safety-Curb Design from an overhead viewpoint.

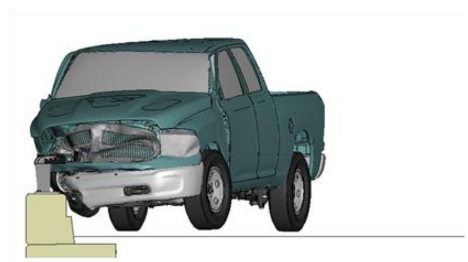
0.00 seconds



0.05 seconds

0.10 seconds

0.15 seconds



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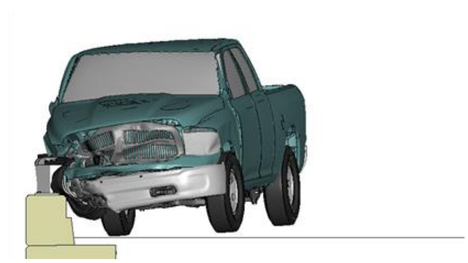


Figure B-2. Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Safety-Curb Design from downstream viewpoint.

0.30 seconds

0.40 seconds

0.50 seconds

0.60 seconds

0.70 seconds

Figure B-2. [Continued] Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Safety-Curb Design from downstream viewpoint.

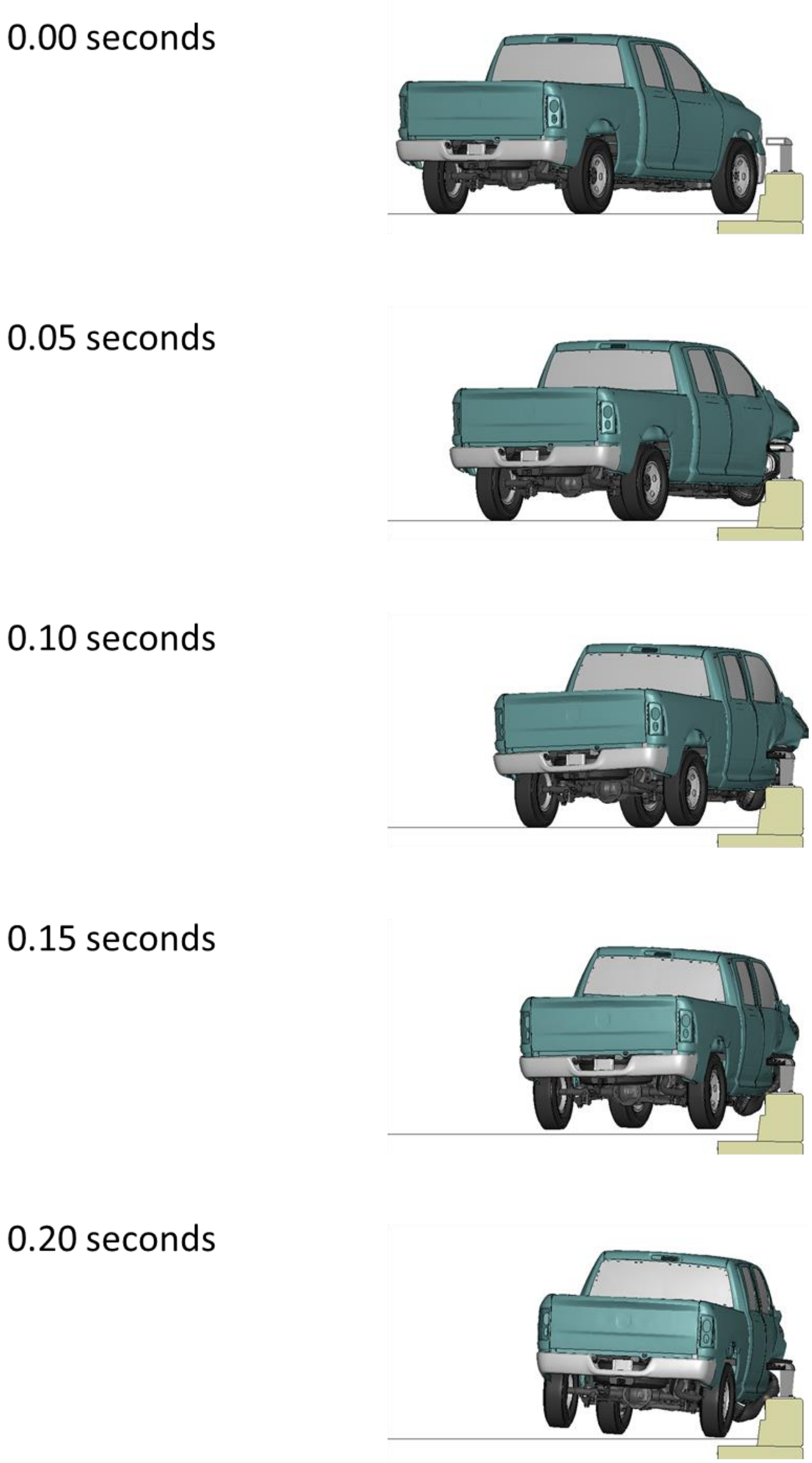


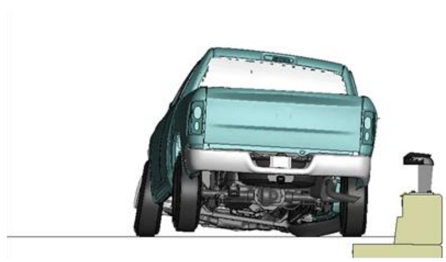
Figure B-3. Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Safety-Curb Design from upstream viewpoint.

0.30 seconds

0.40 seconds

0.50 seconds

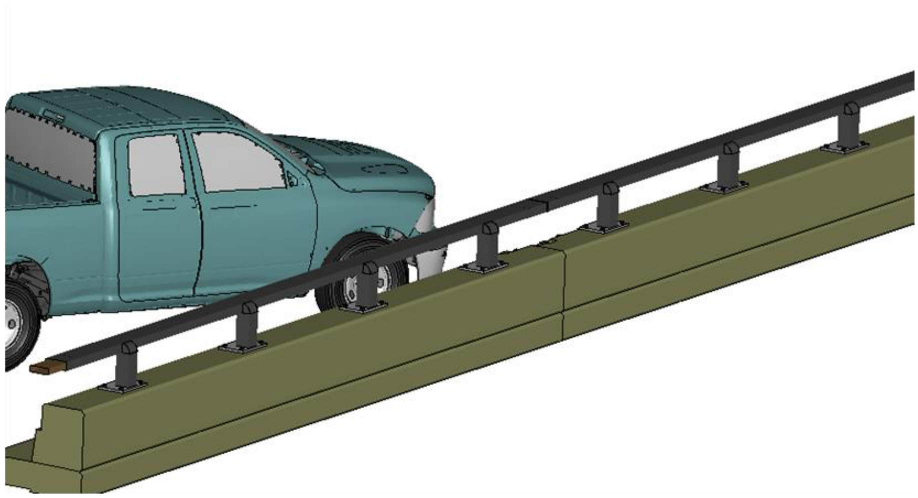
0.60 seconds



0.65 seconds

Figure B-3. [Continued] Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Safety-Curb Design from upstream viewpoint.

0.00 seconds



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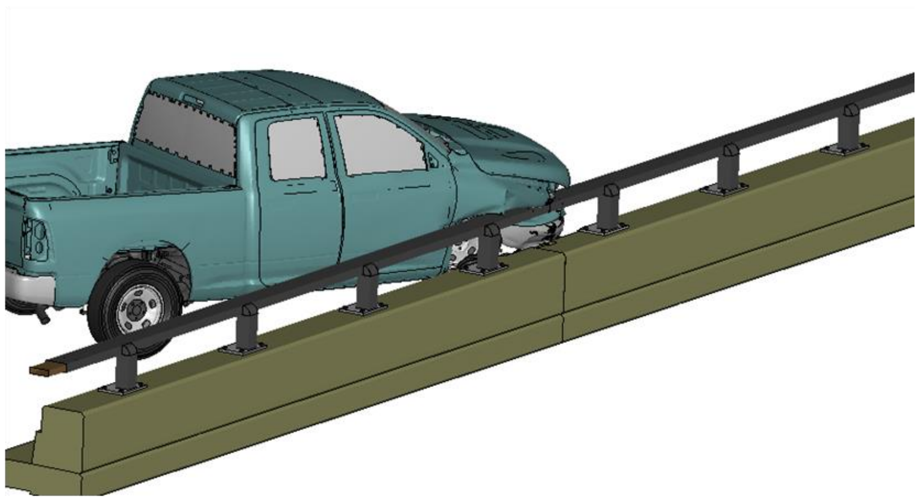

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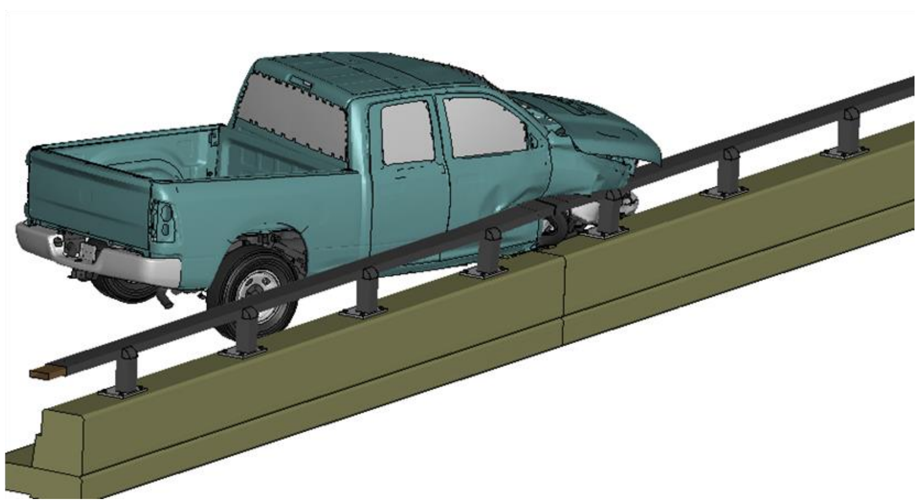
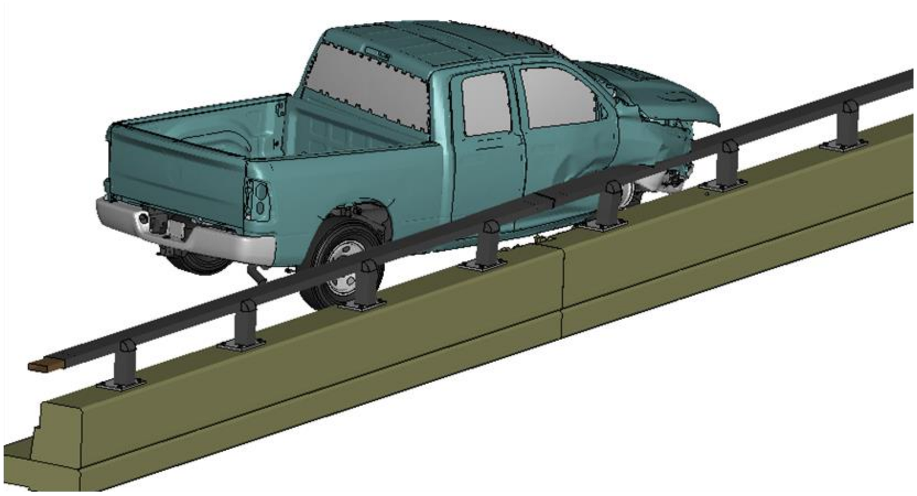
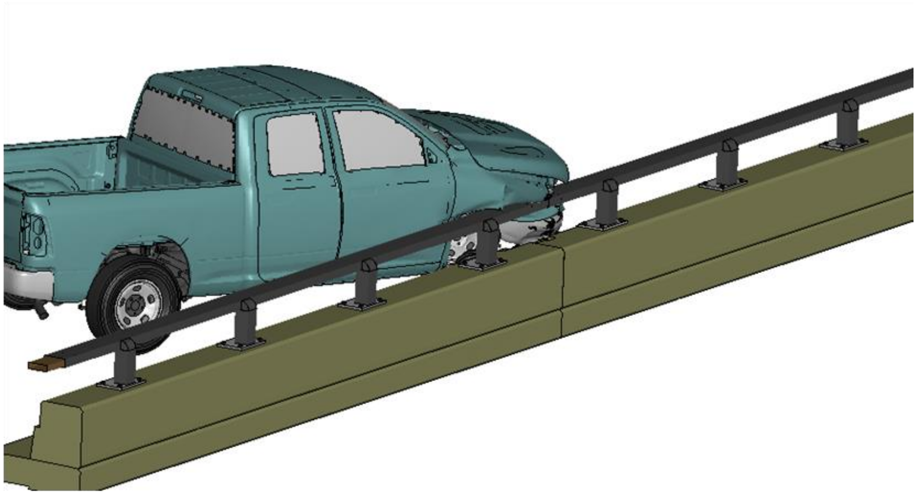


Figure B-4. Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Safety-Curb Design from oblique viewpoint.

0.15 seconds



0.20 seconds



0.25 seconds

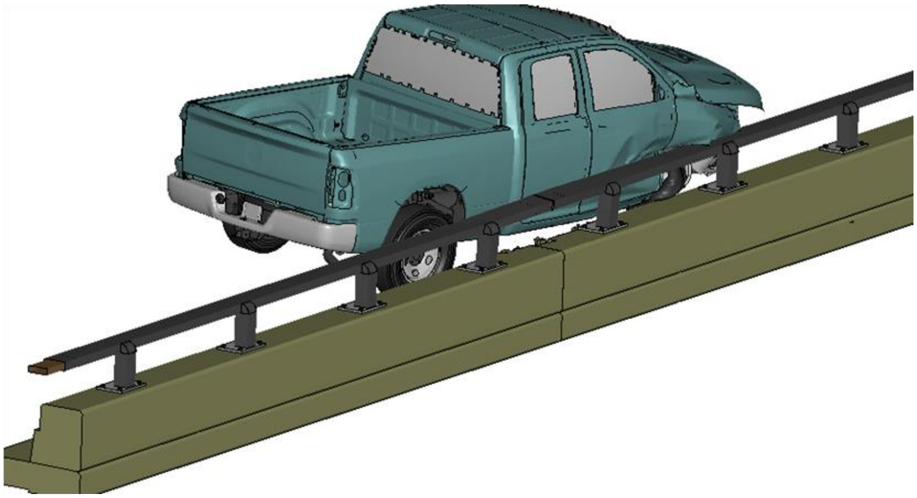


Figure B-4. [Continued] Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Safety-Curb Design from oblique viewpoint.

Appendix C

Sequential Views for Test 3-11 at IP02

CM-MTL3 Bridge Rail with Safety-Curb Design

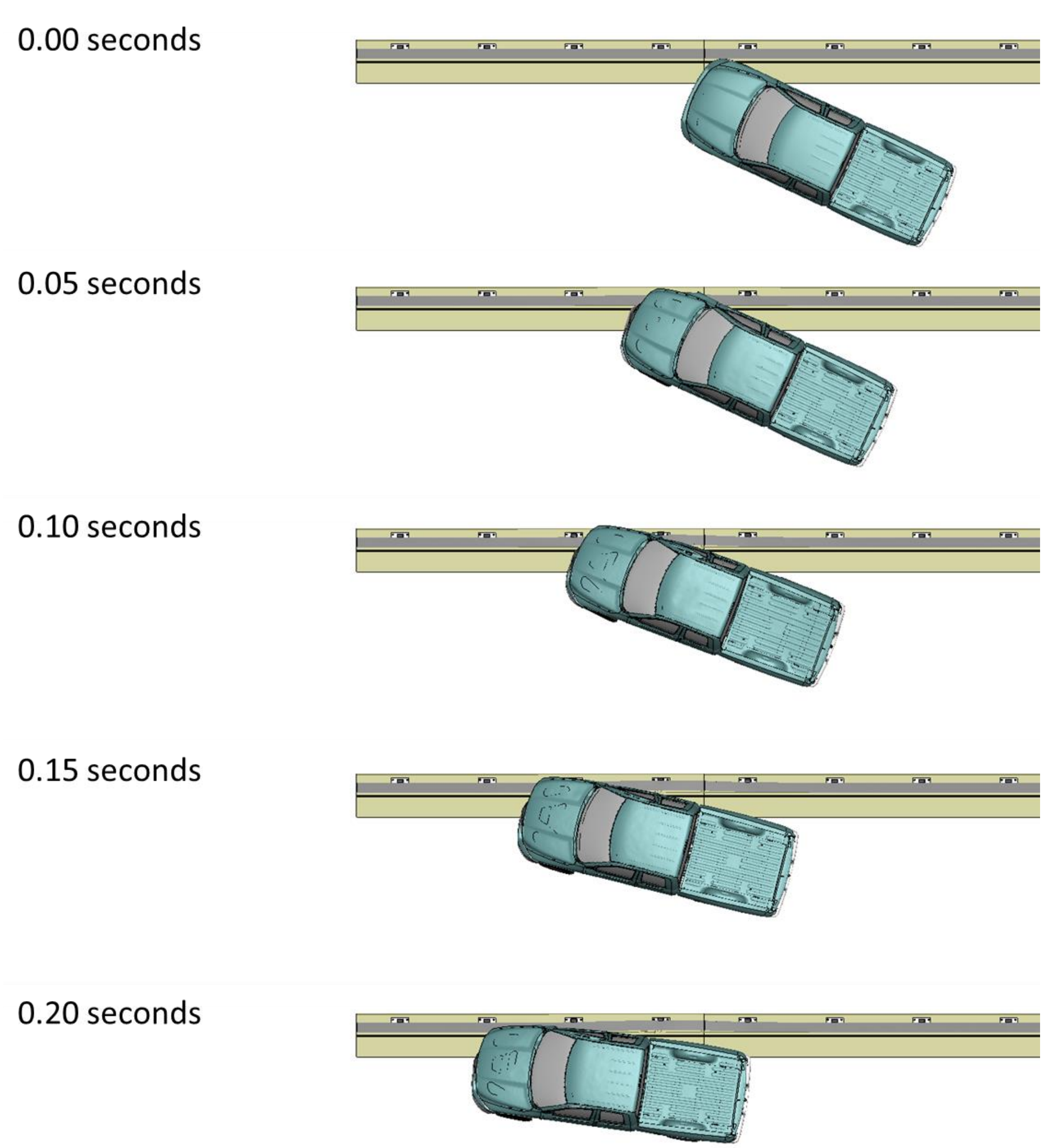


Figure C-1. Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Safety-Curb Design from an overhead viewpoint.

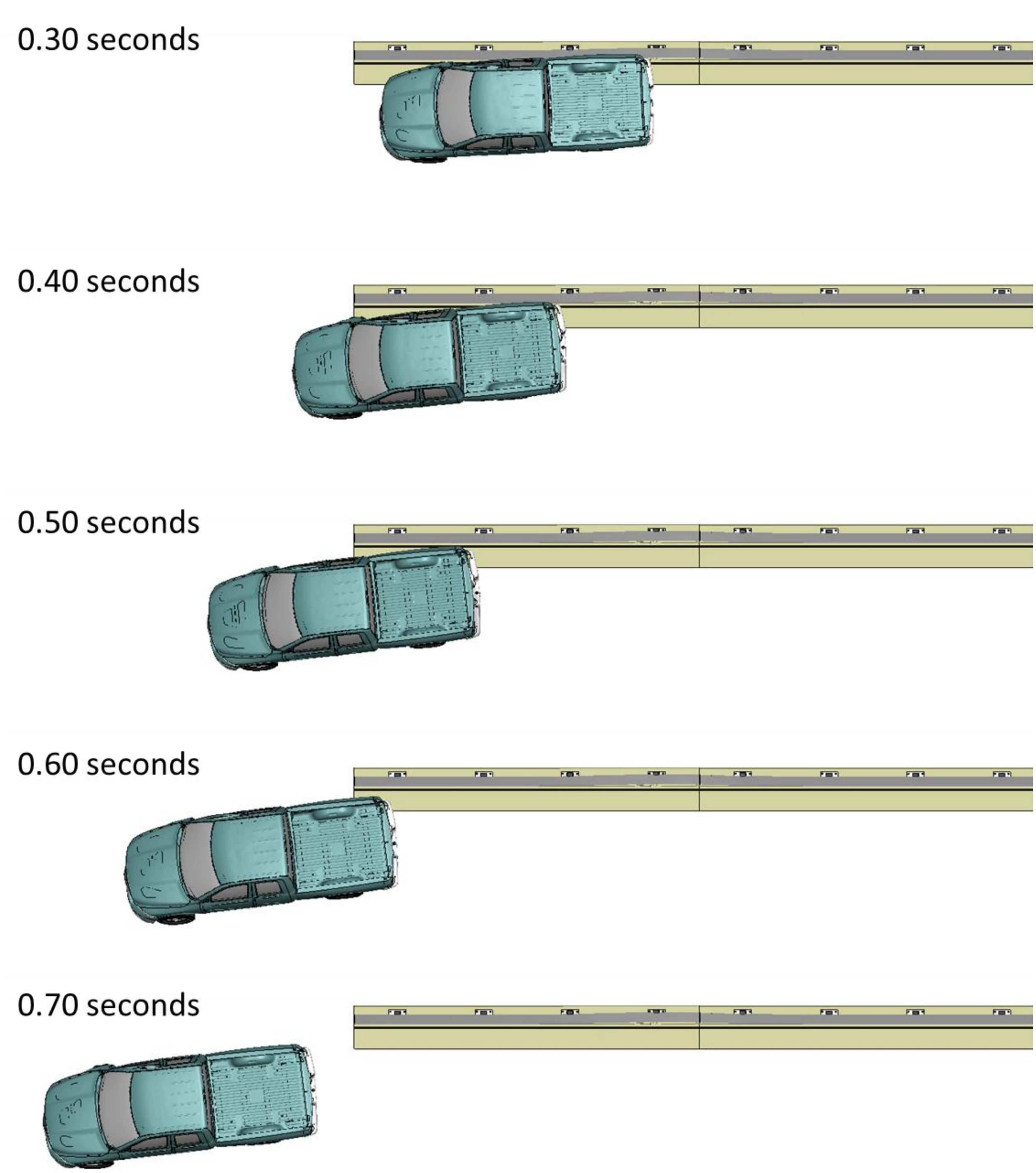


Figure C-1. [Continued] Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Safety-Curb Design from an overhead viewpoint.

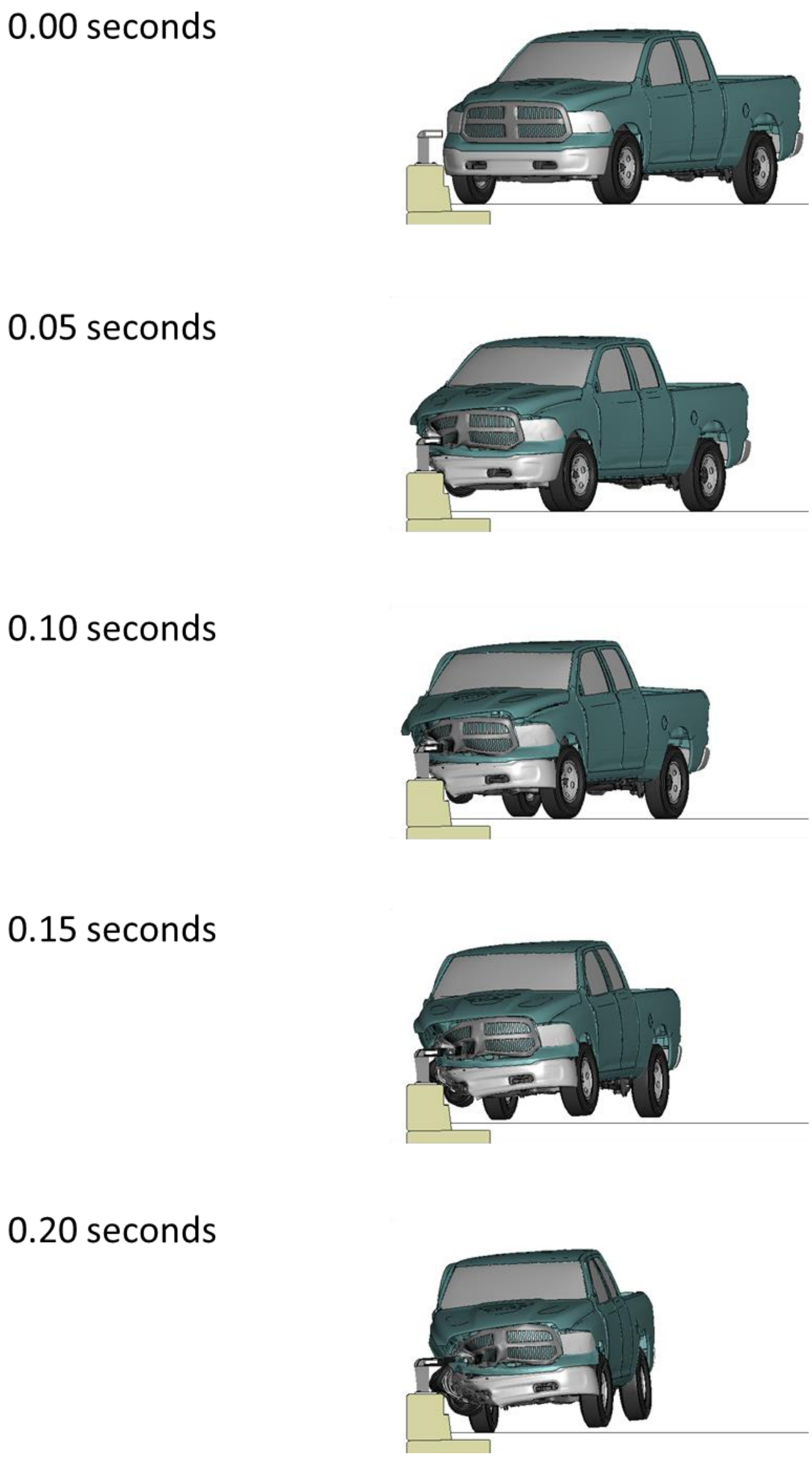


Figure C-2. Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Safety-Curb Design from downstream viewpoint.

0.30 seconds

0.40 seconds

0.50 seconds

0.60 seconds

0.70 seconds

Figure C-2. [Continued] Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Safety-Curb Design from downstream viewpoint.

0.00 seconds

0.05 seconds

0.10 seconds

0.15 seconds

0.20 seconds

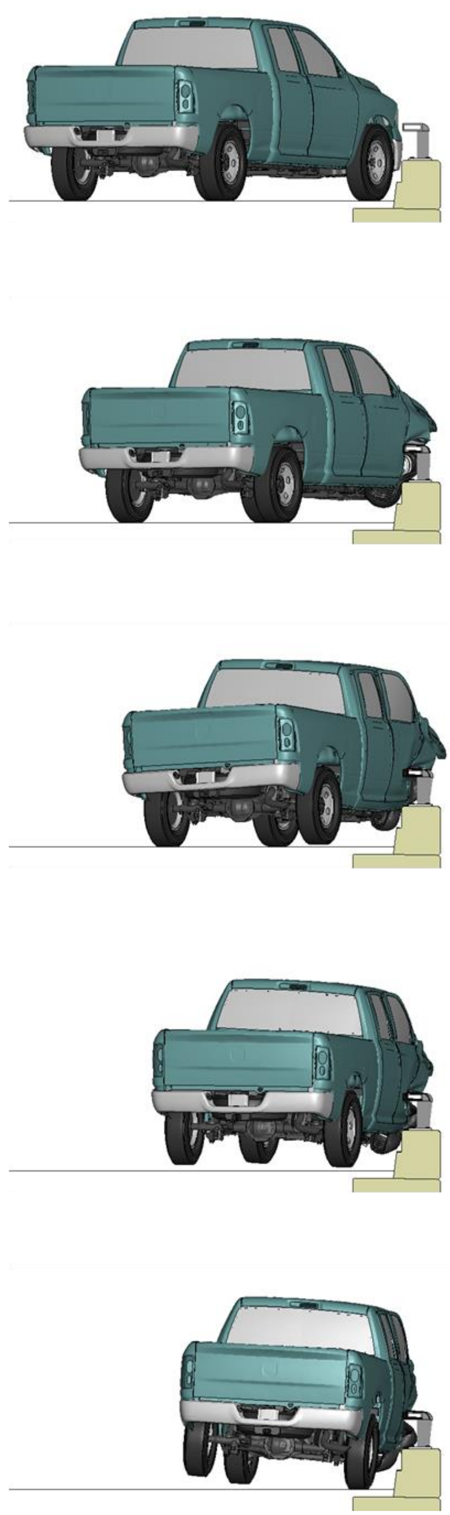


Figure C-3. Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Safety-Curb Design from upstream viewpoint.

0.30 seconds

0.40 seconds

0.50 seconds

0.60 seconds

0.65 seconds

Figure C-3. [Continued] Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Safety-Curb Design from upstream viewpoint.

0.00 seconds

0.05 seconds

0.10 seconds

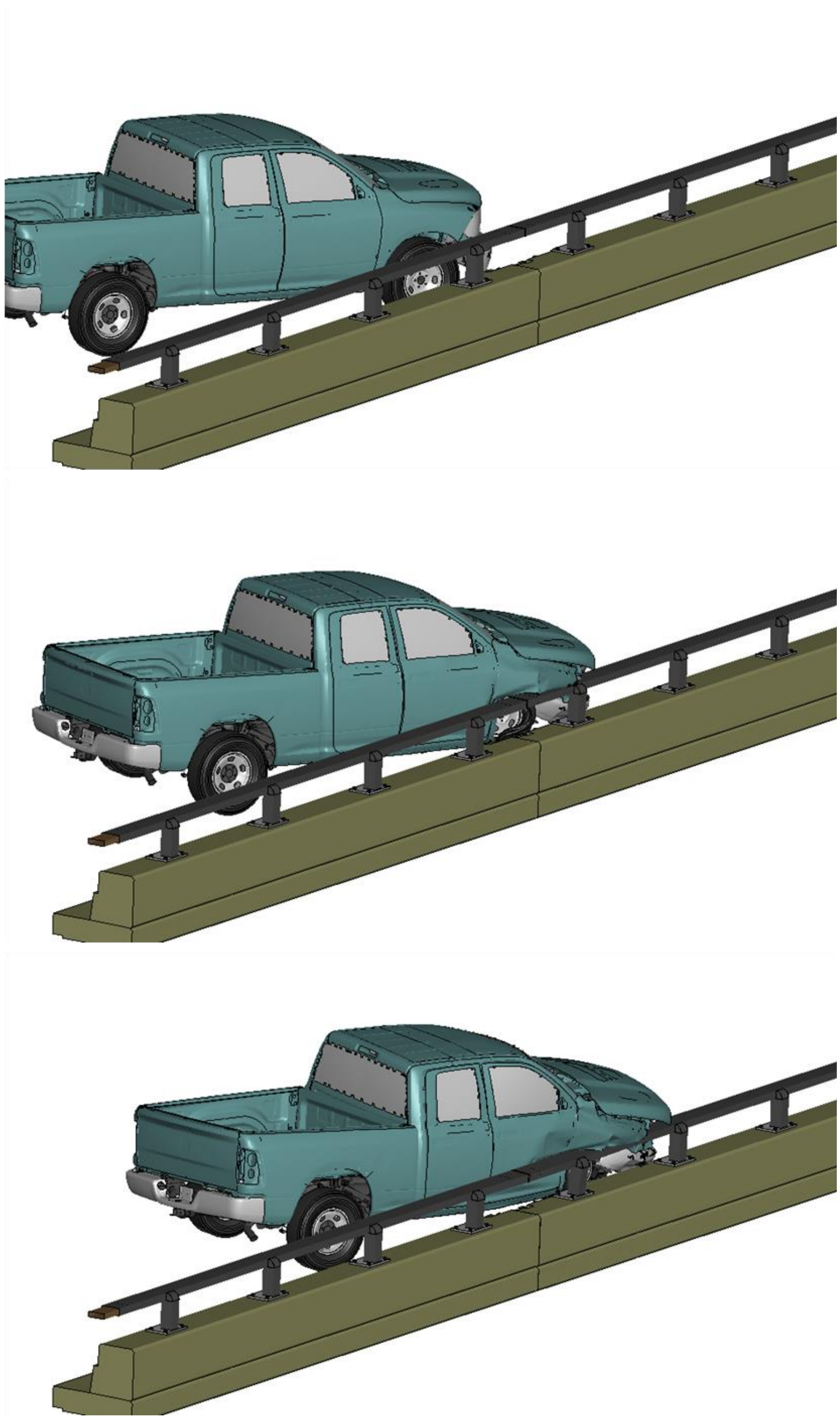
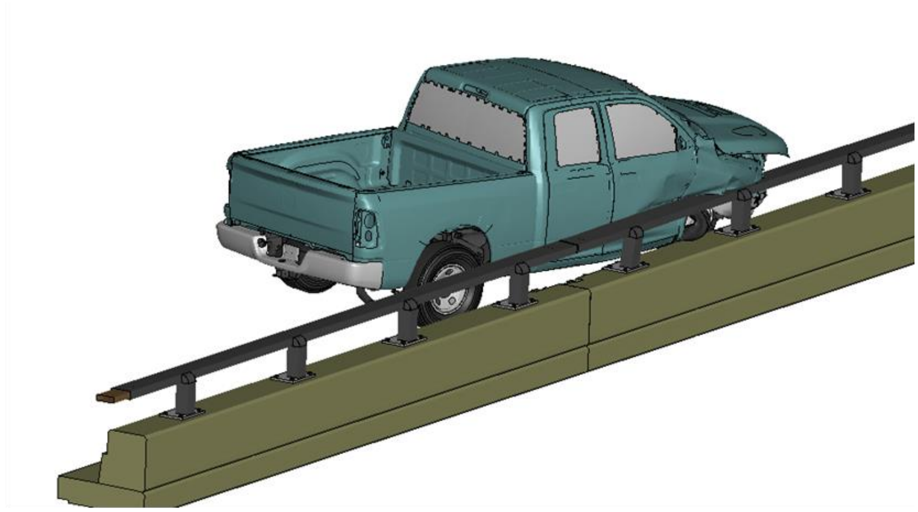


Figure C-4. Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Safety-Curb Design from oblique viewpoint.

0.15 seconds



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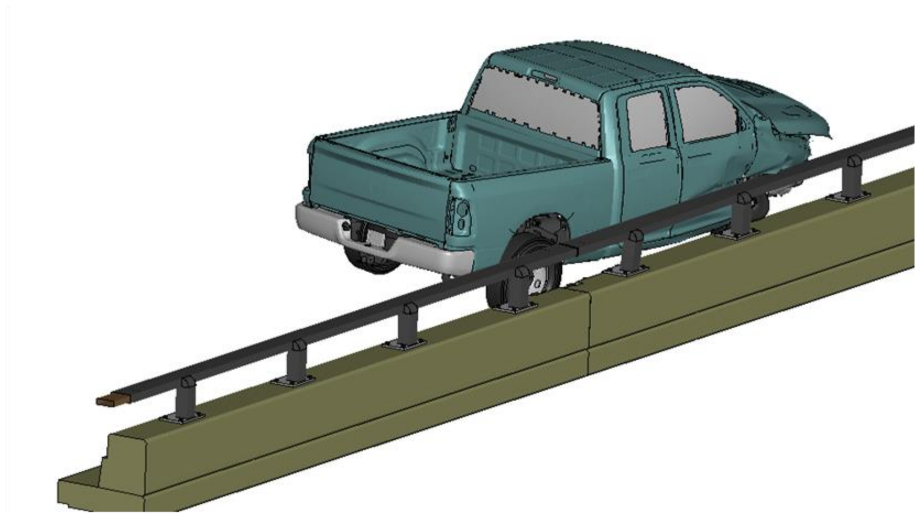

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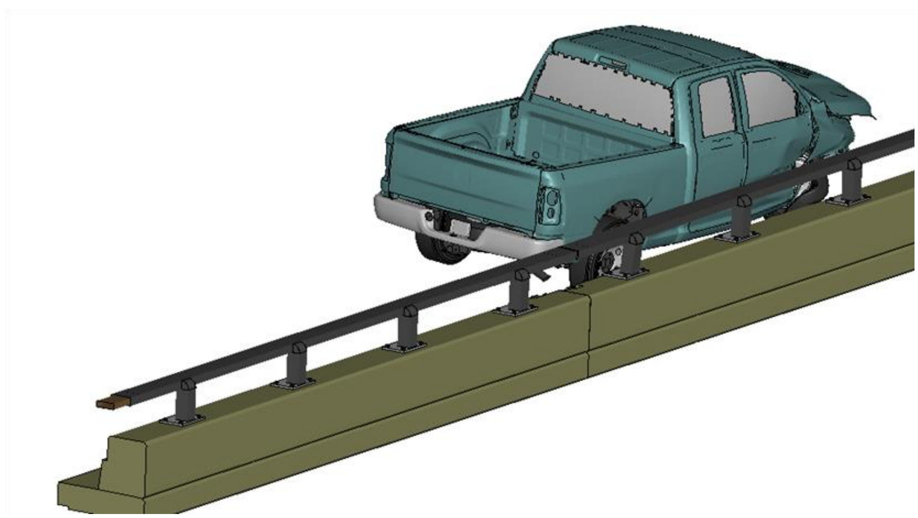


Figure C-4. [Continued] Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Safety-Curb Design from oblique viewpoint.

Appendix D

Sequential Views for Test 3-11 at IP01

CM-MTL3 Bridge Rail with Vertical Face Design

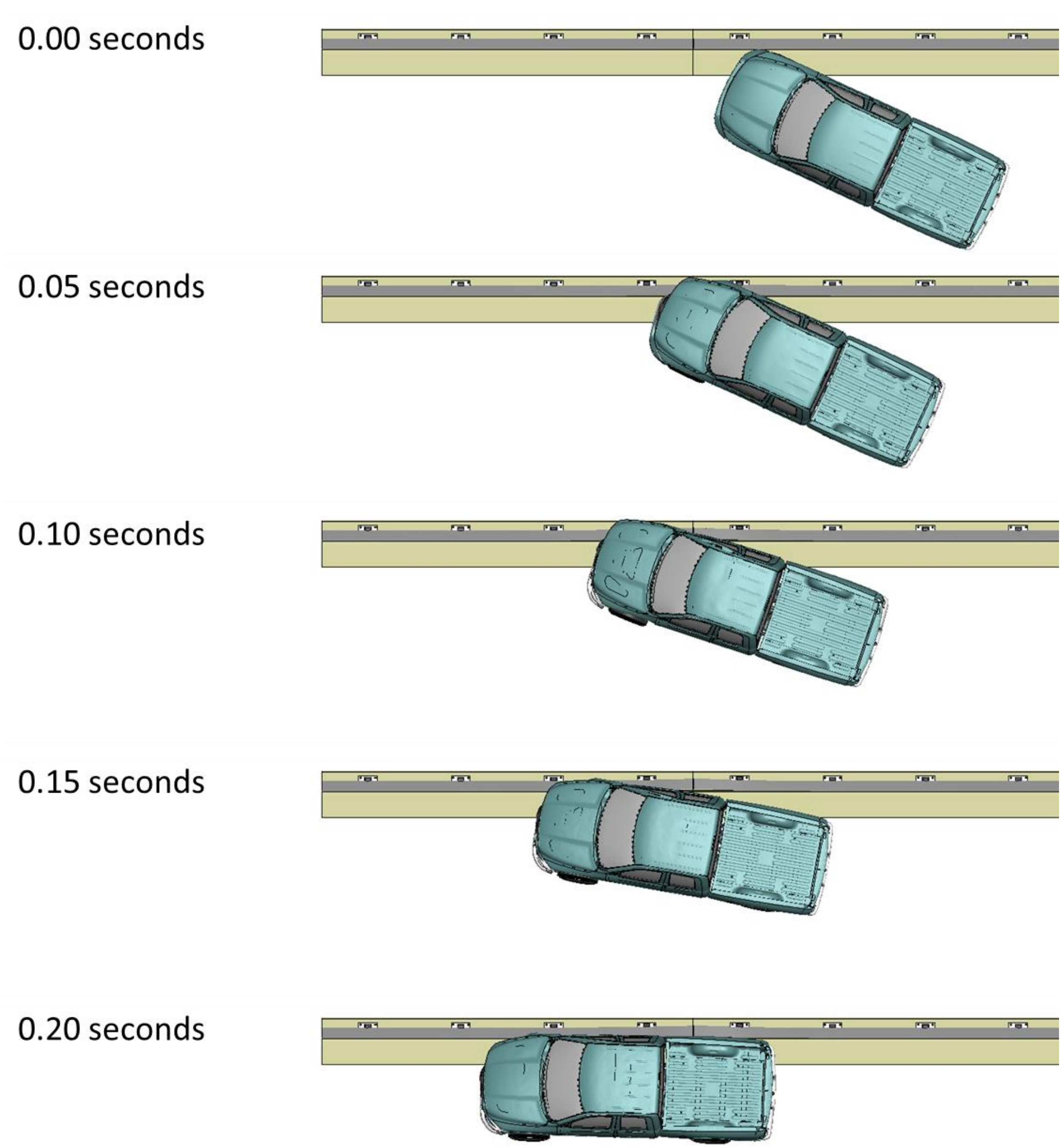


Figure D-1. Sequential views from analysis of MASH Test 3-11 RHT at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

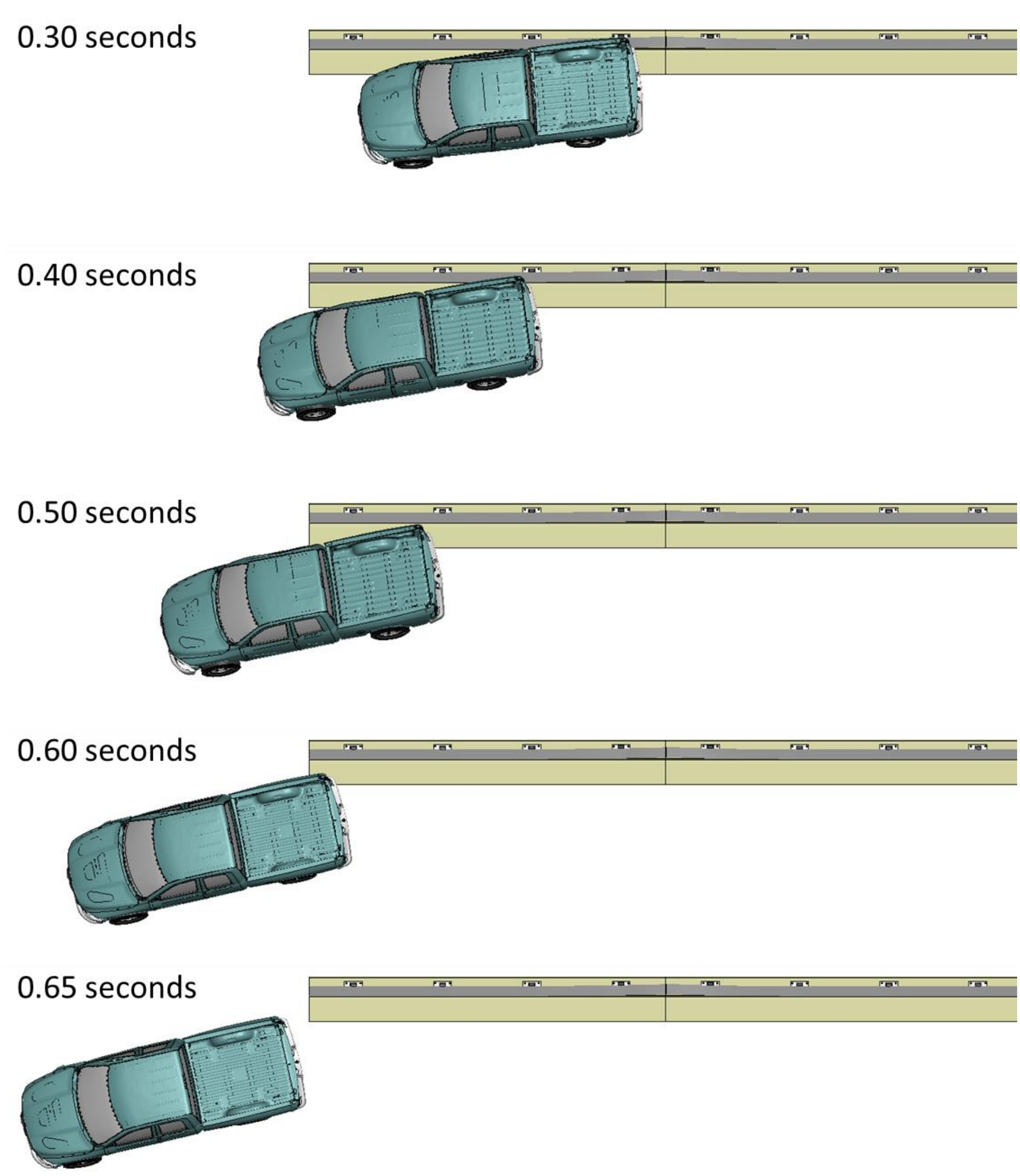


Figure D-1. [Continued] Sequential views from analysis of MASH Test 3-11 RHT at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

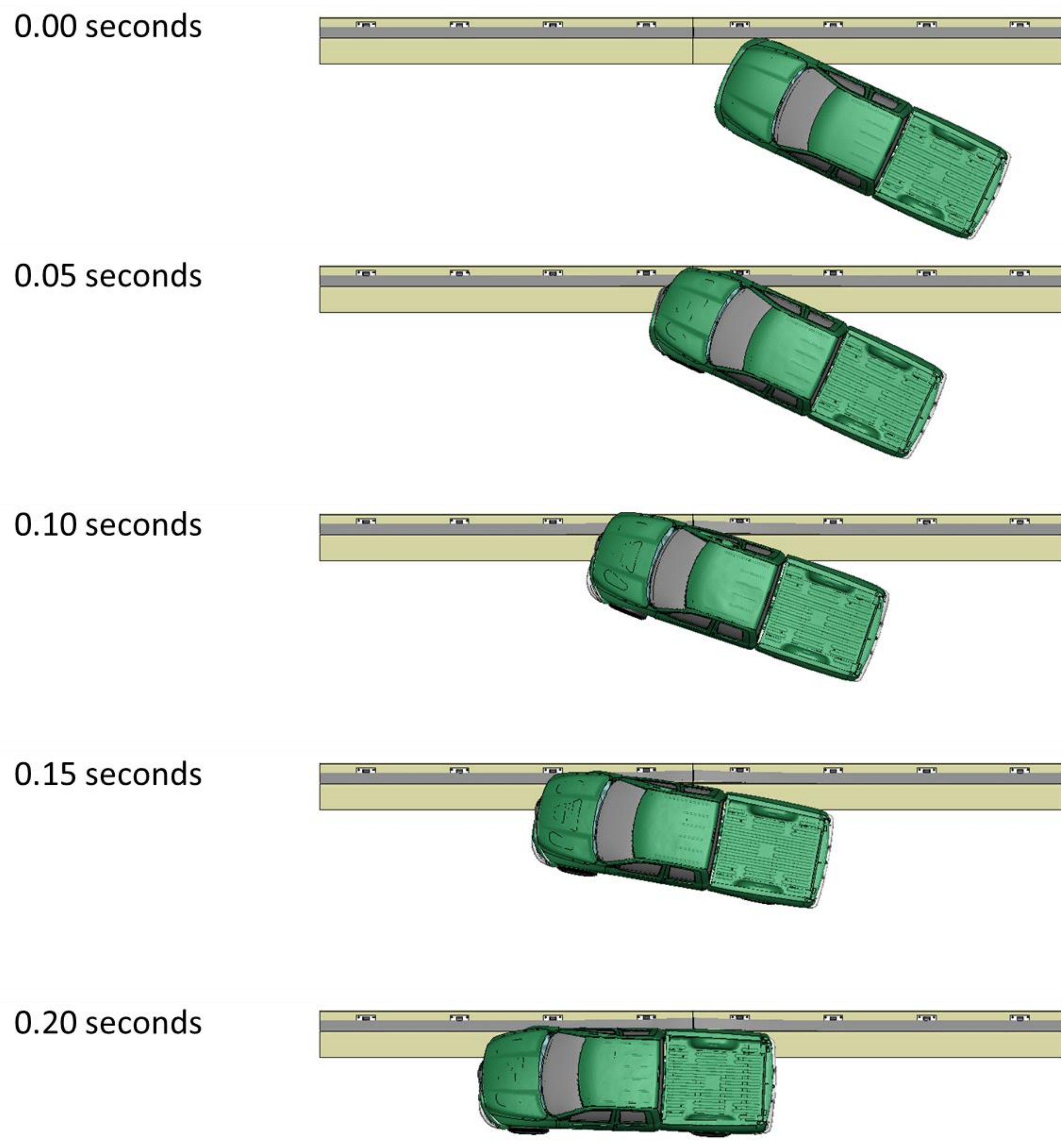


Figure D-2. Sequential views from analysis of MASH Test 3-11 CSCM at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

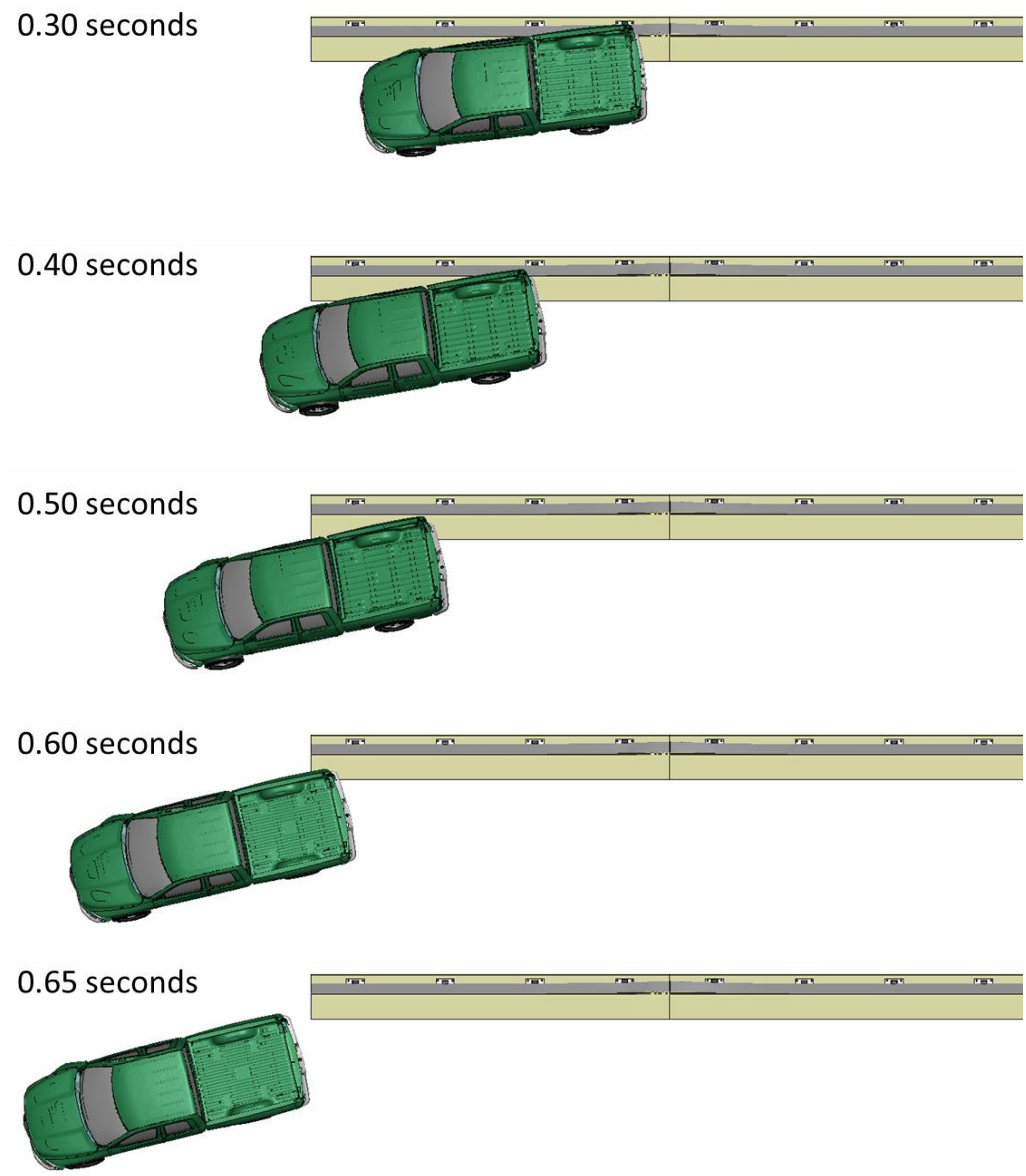


Figure D-2. [Continued] Sequential views from analysis of MASH Test 3-11 CSCM at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

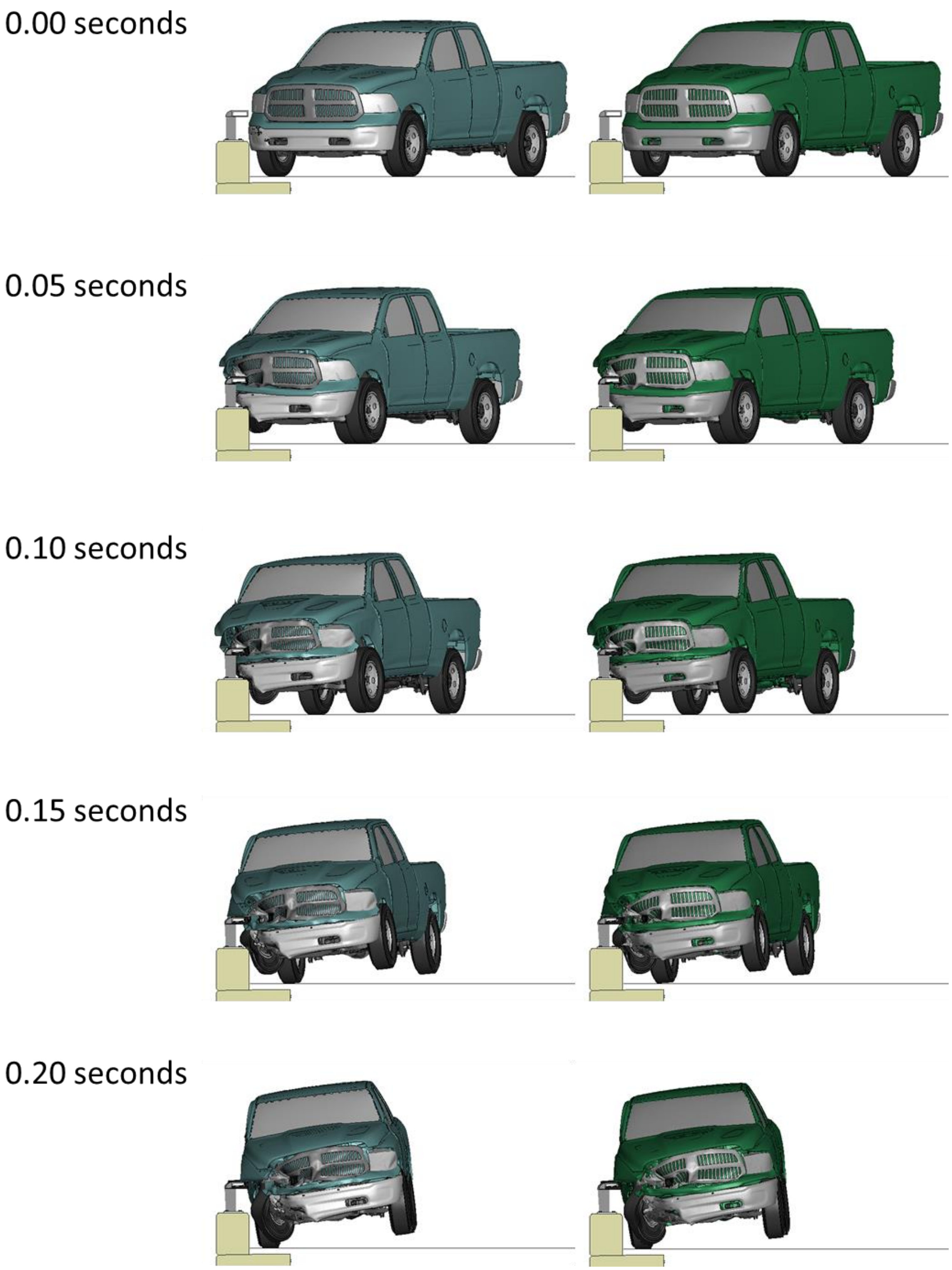
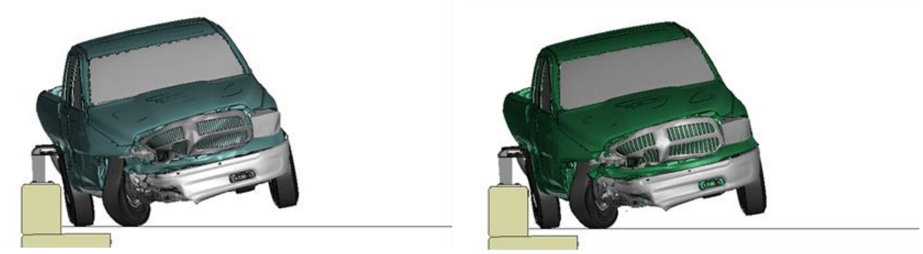


Figure D-3. Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from a downstream viewpoint. RHT on left, CSCM on right.

0.30 seconds



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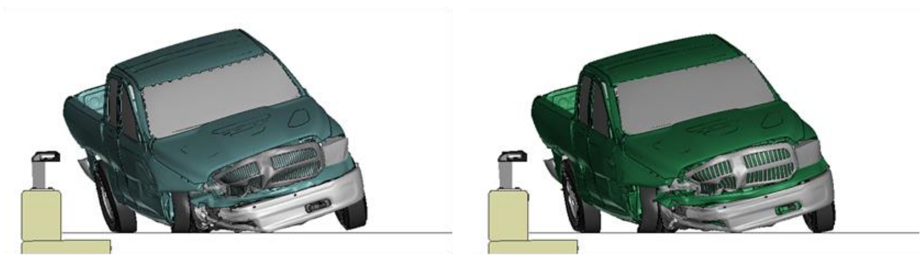

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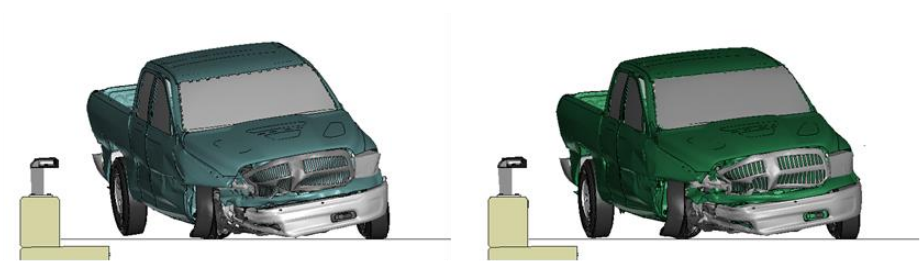


0.65 seconds

Figure D-3. [Continued] Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from a downstream viewpoint. RHT on left, CSCM on right.

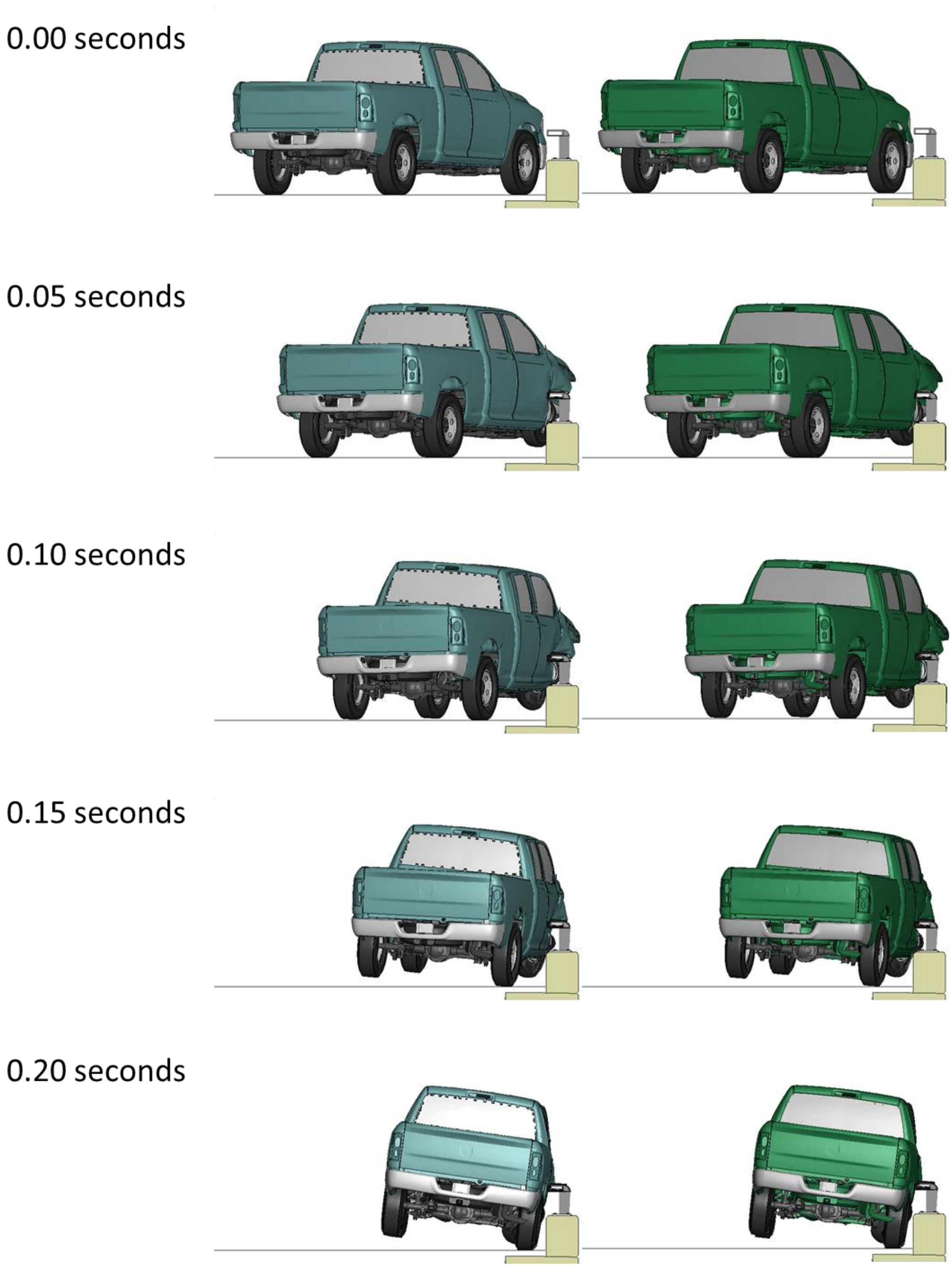
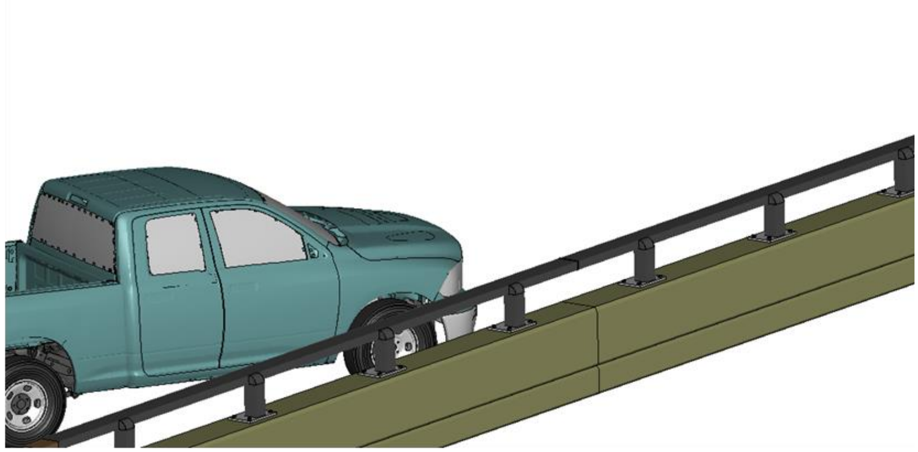


Figure D-4. Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an upstream viewpoint. RHT on left, CSCM on right.

Figure D-4. [Continued] Sequential views from analysis of MASH Test 3-11 at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an upstream viewpoint. RHT on left, CSCM on right.

0.00 seconds



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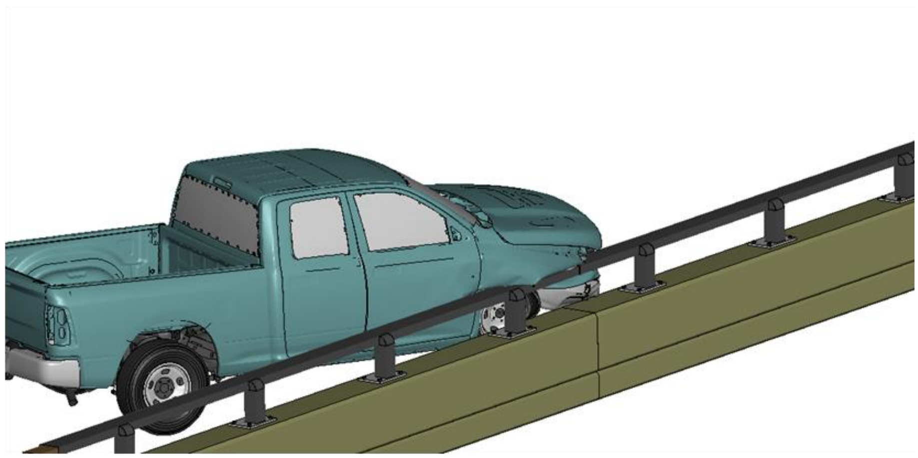

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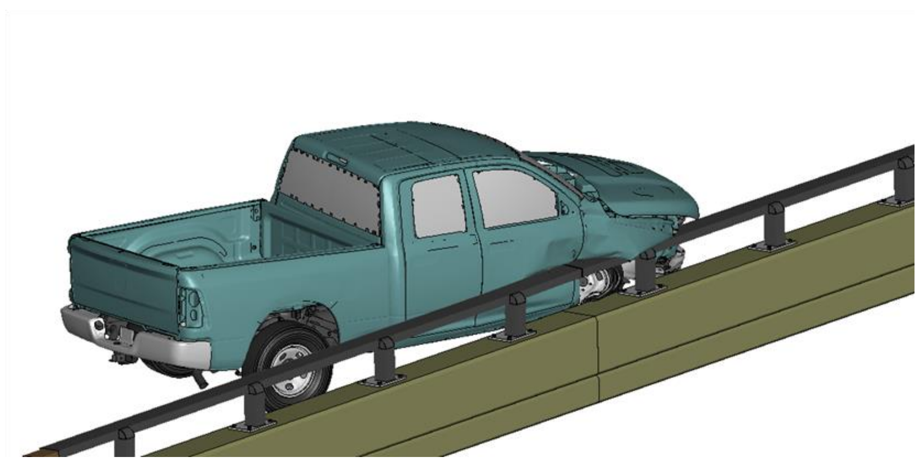
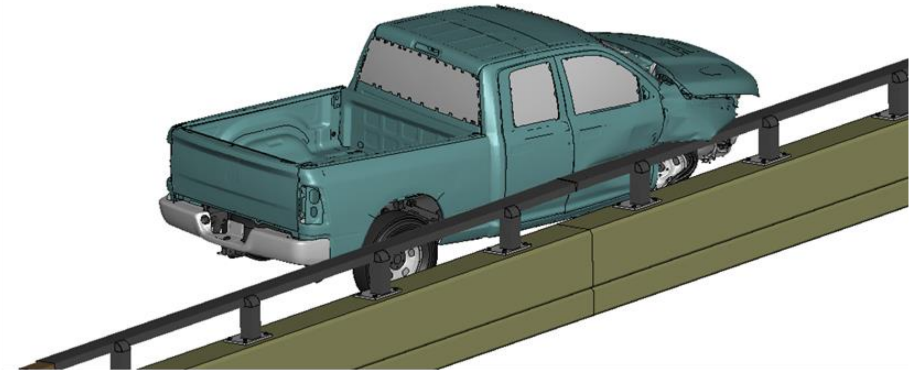


Figure D-5. Sequential views from analysis of MASH Test 3-11 RHT at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

0.15 seconds



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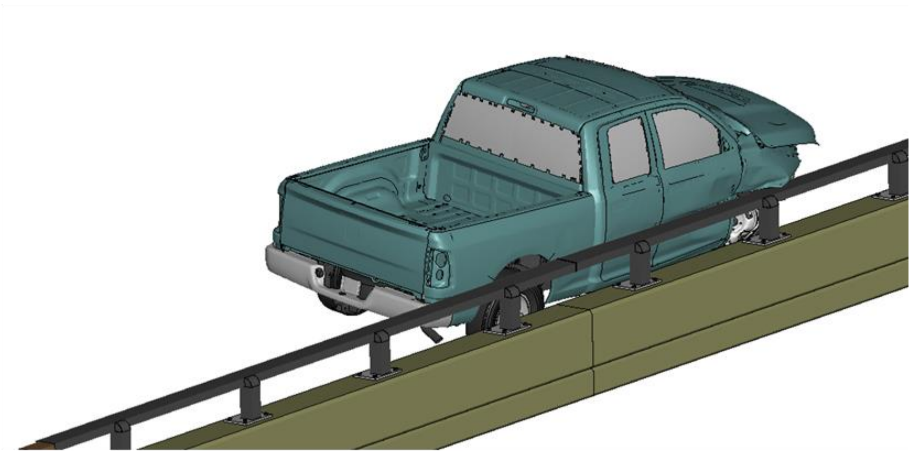


0.25 seconds

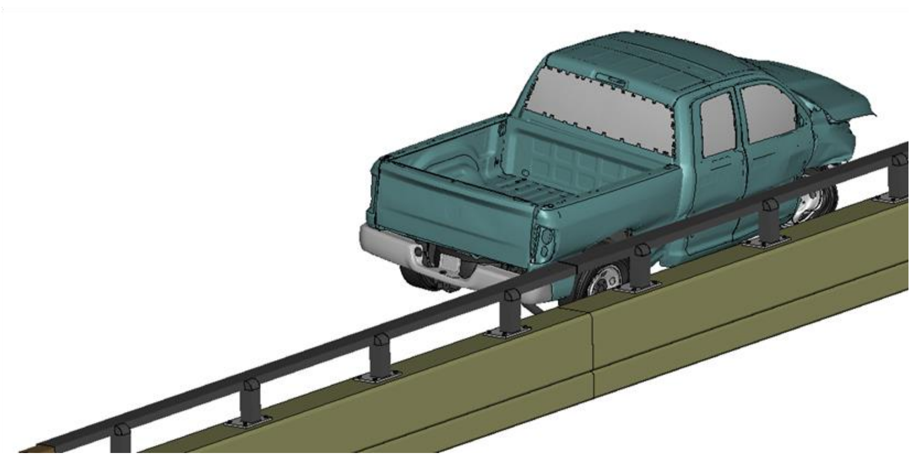


Figure D-5. [Continued] Sequential views from analysis of MASH Test 3-11 RHT at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

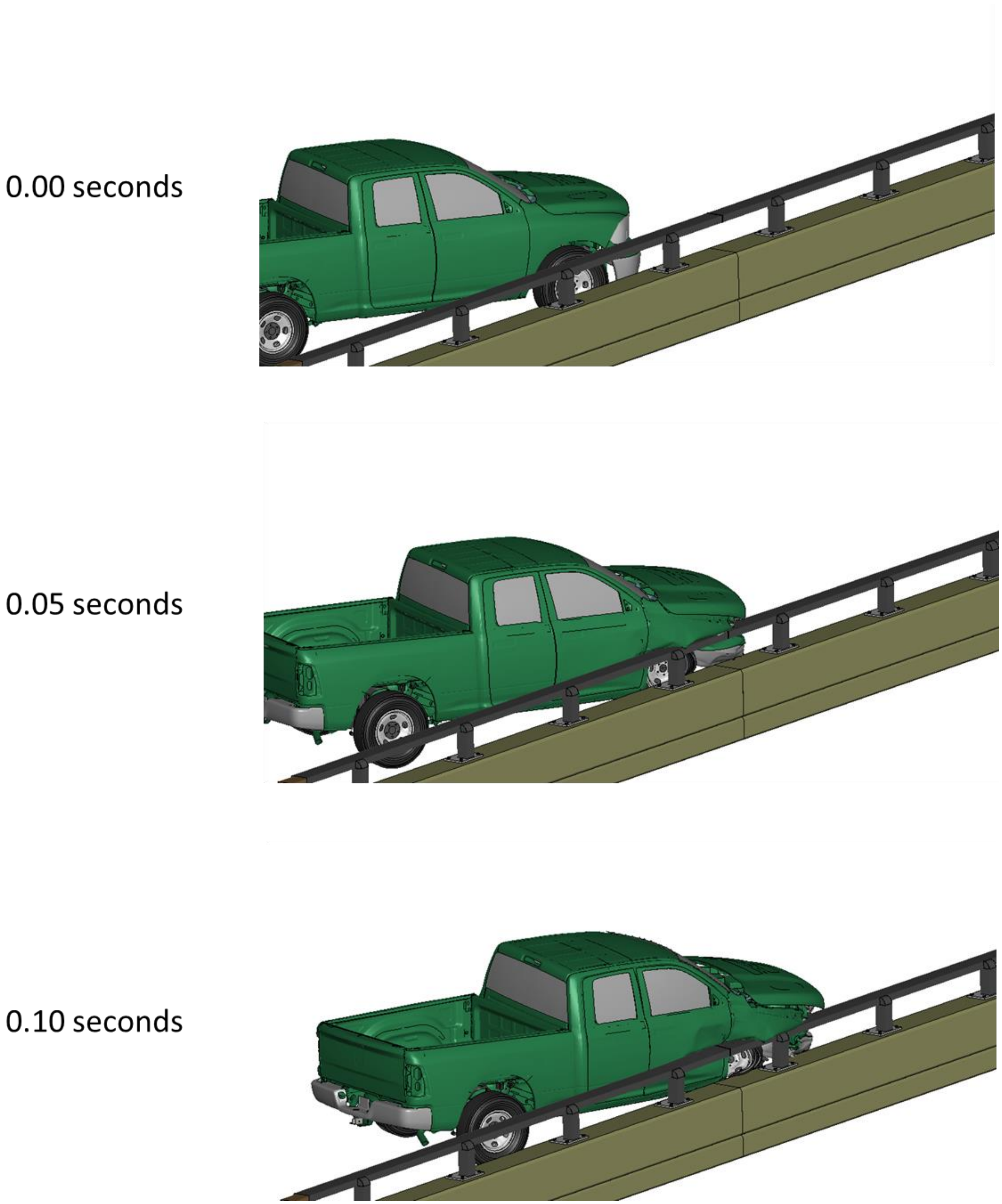
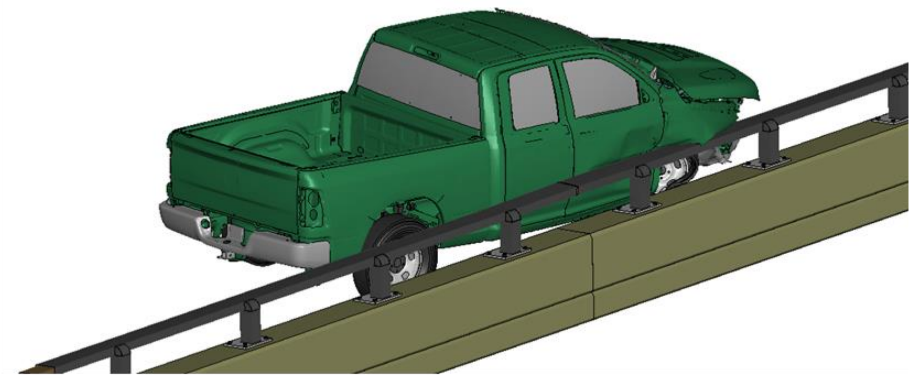


Figure D-6. Sequential views from analysis of MASH Test 3-11 CSCM at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

0.15 seconds



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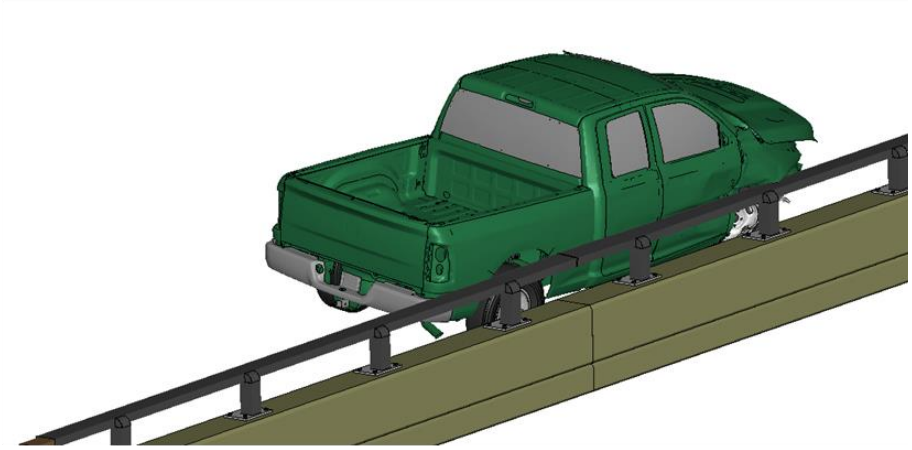

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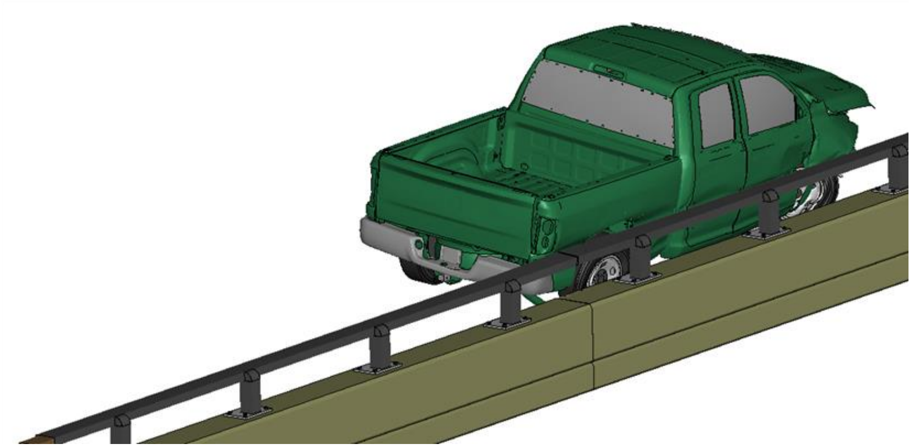


Figure D-6. [Continued] Sequential views from analysis of MASH Test 3-11 CSCM at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

Appendix E

Sequential Views for Test 3-11 at IP02

CM-MTL3 Bridge Rail with Vertical Face Design

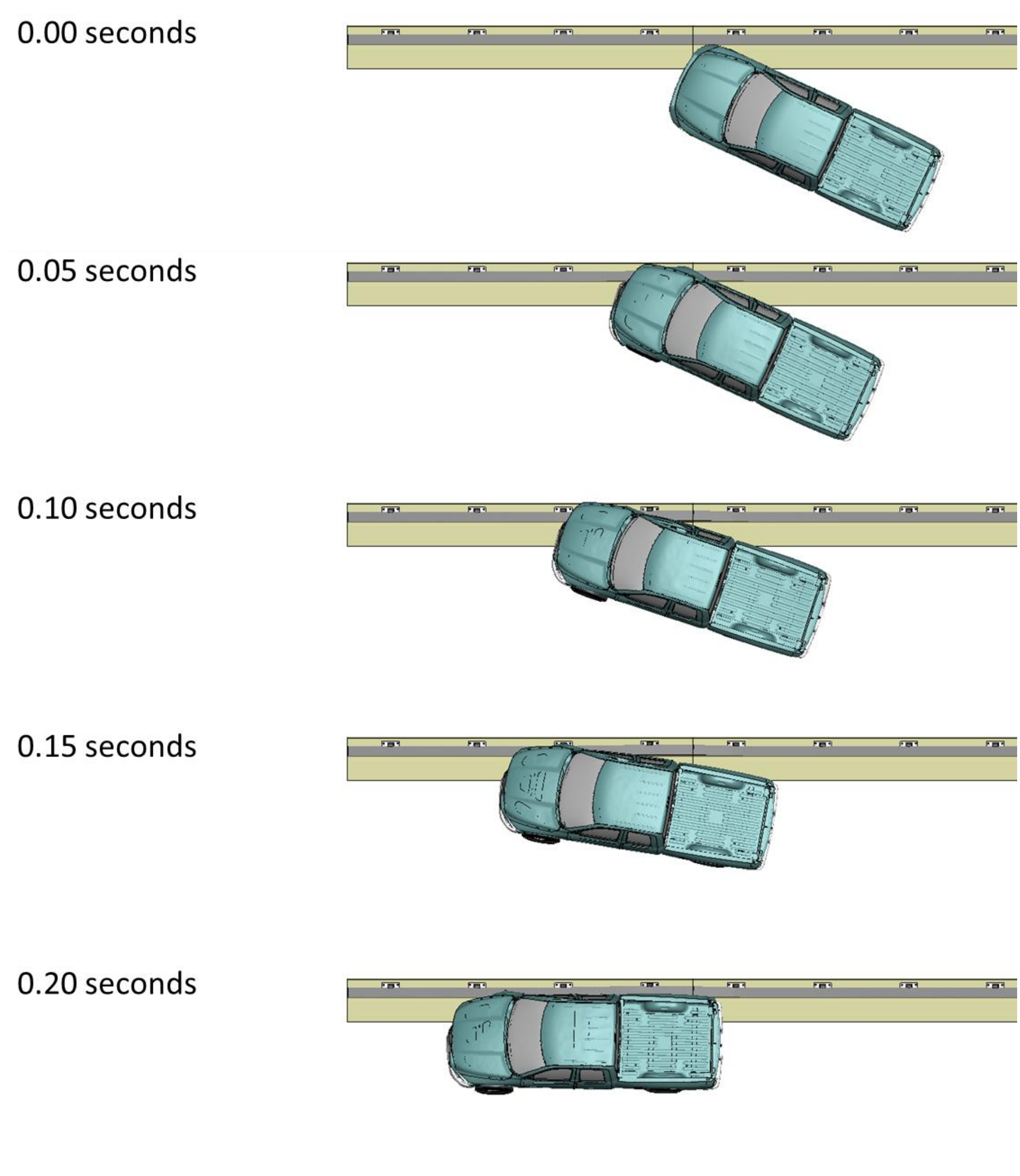


Figure E-1. Sequential views from analysis of MASH Test 3-11 RHT at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

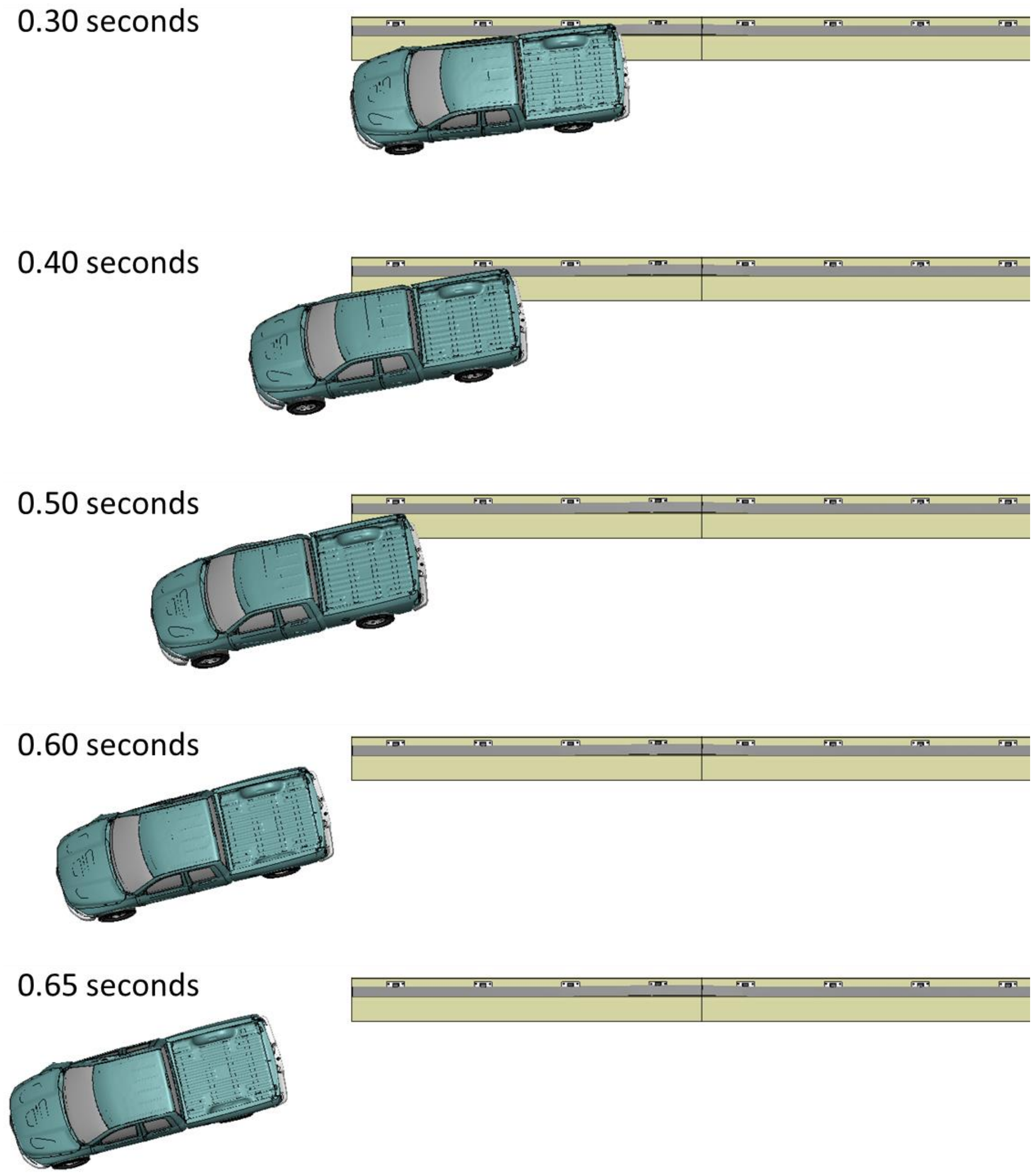


Figure E-1. [Continued] Sequential views from analysis of MASH Test 3-11 RHT at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

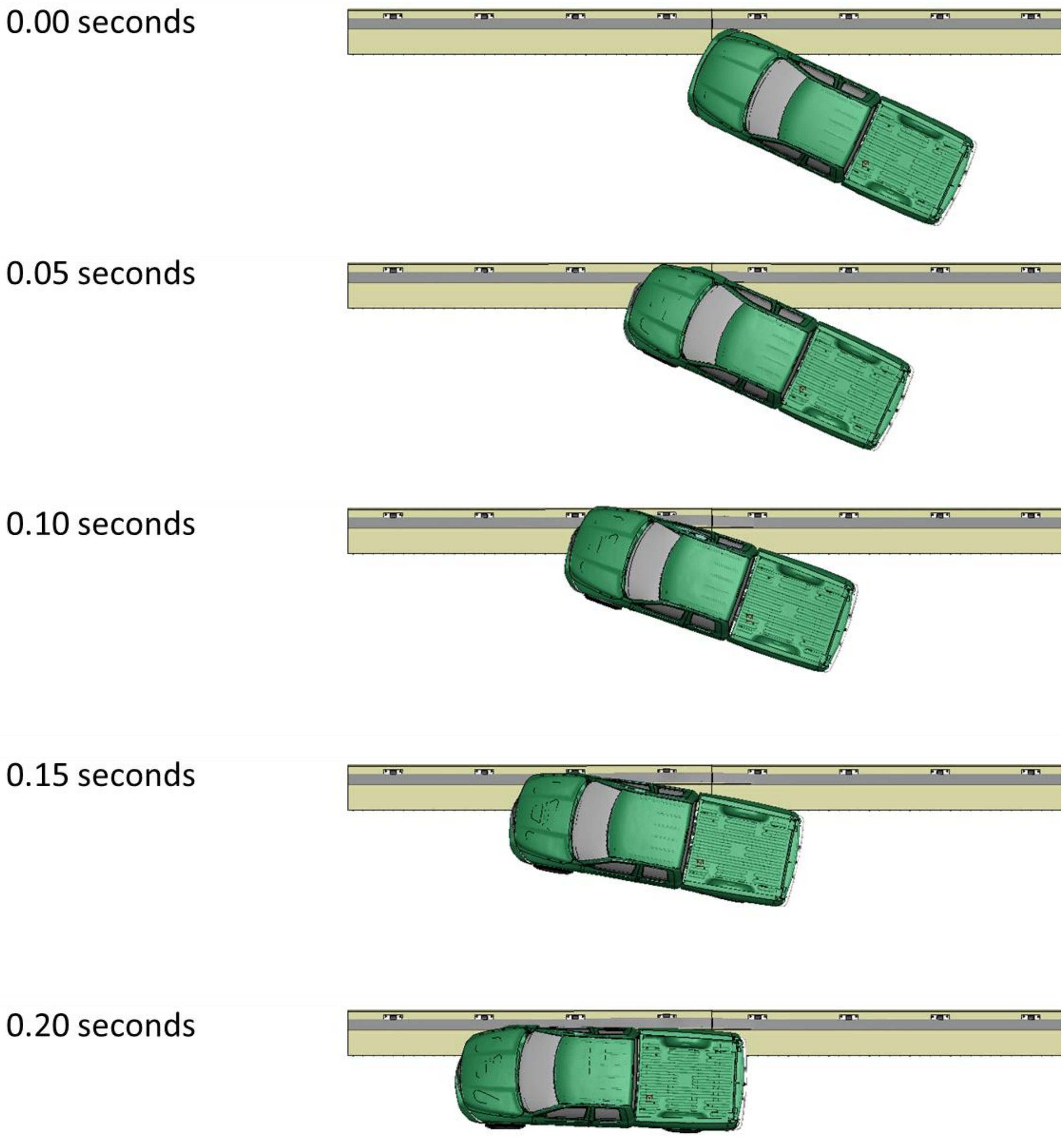


Figure E-2. Sequential views from analysis of MASH Test 3-11 CSCM at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

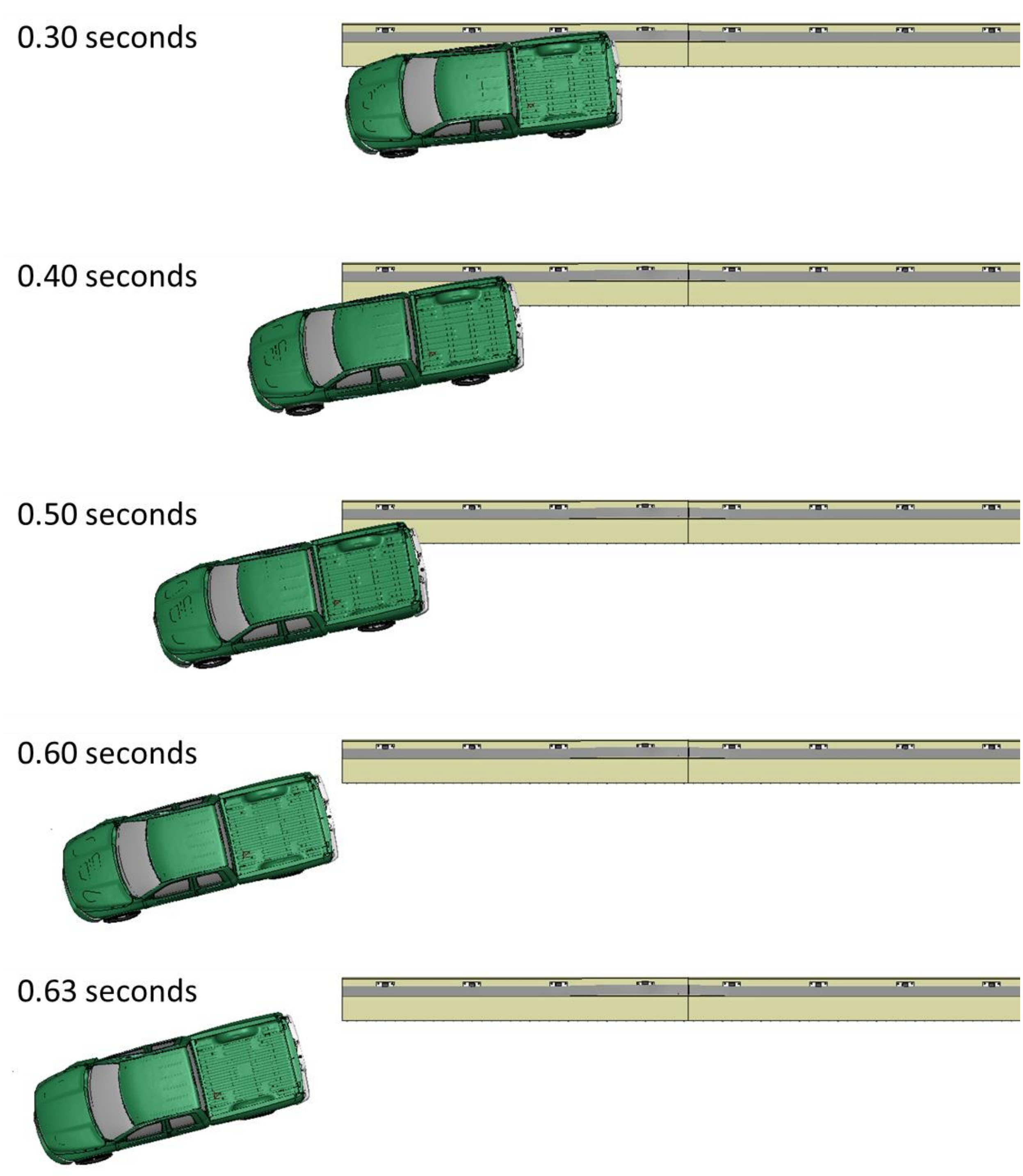


Figure E-2. [Continued] Sequential views from analysis of MASH Test 3-11 CSCM at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

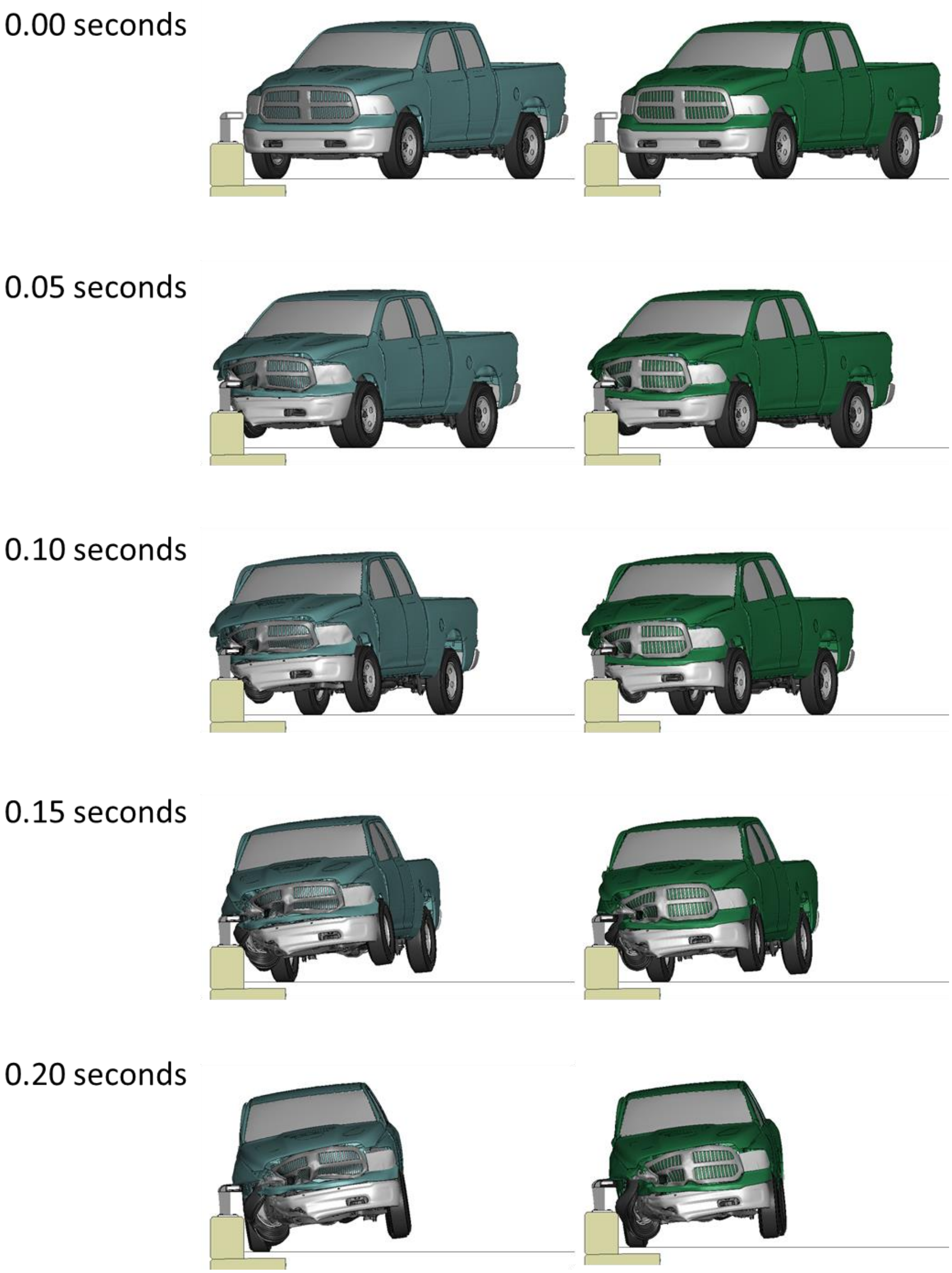


Figure E-3. Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from a downstream viewpoint. RHT on left, CSCM on right.

Figure E-3. [Continued] Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from a downstream viewpoint. RHT on left, CSCM on right.

Figure E-4. Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an upstream viewpoint. RHT on left, CSCM on right.

Figure E-4. [Continued] Sequential views from analysis of MASH Test 3-11 at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an upstream viewpoint. RHT on left, CSCM on right.

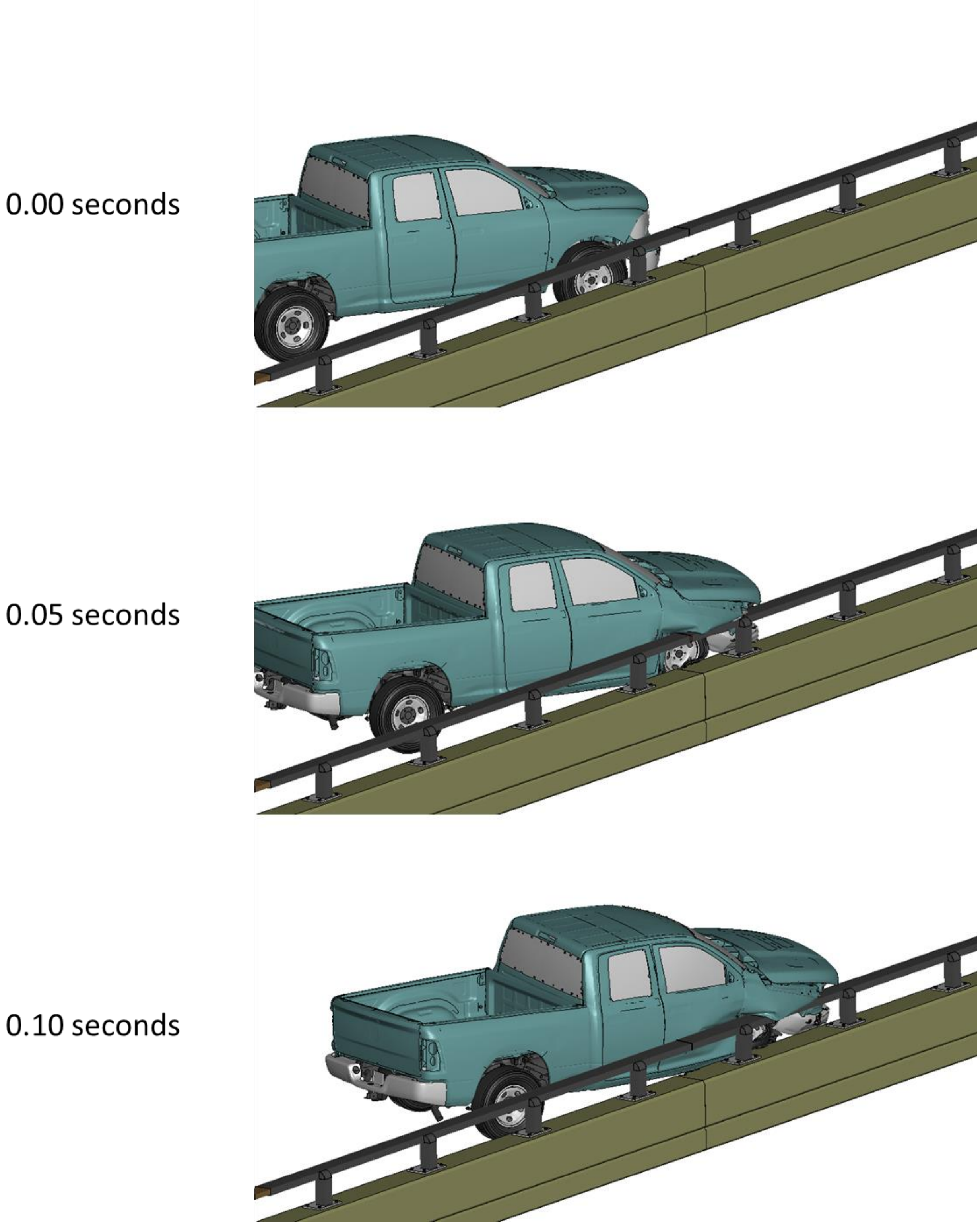
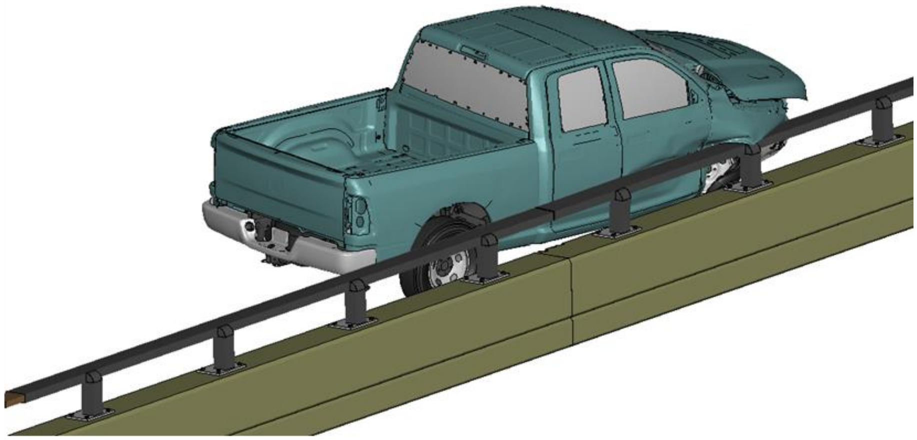
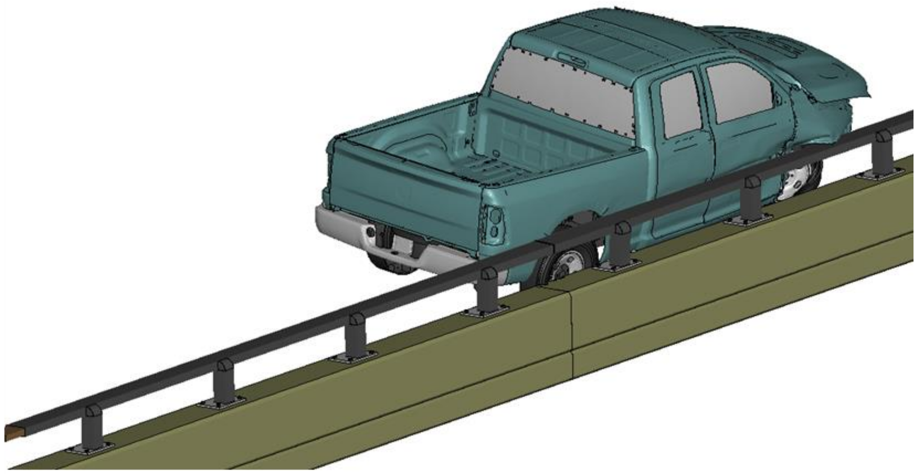


Figure E-5. Sequential views from analysis of MASH Test 3-11 RHT at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

0.15 seconds



0.20 seconds



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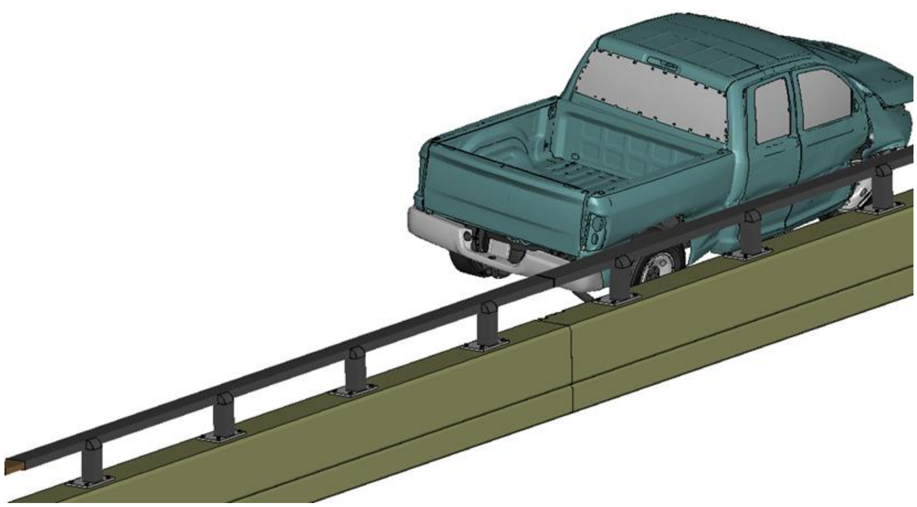


Figure E-5. [Continued] Sequential views from analysis of MASH Test 3-11 RHT at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

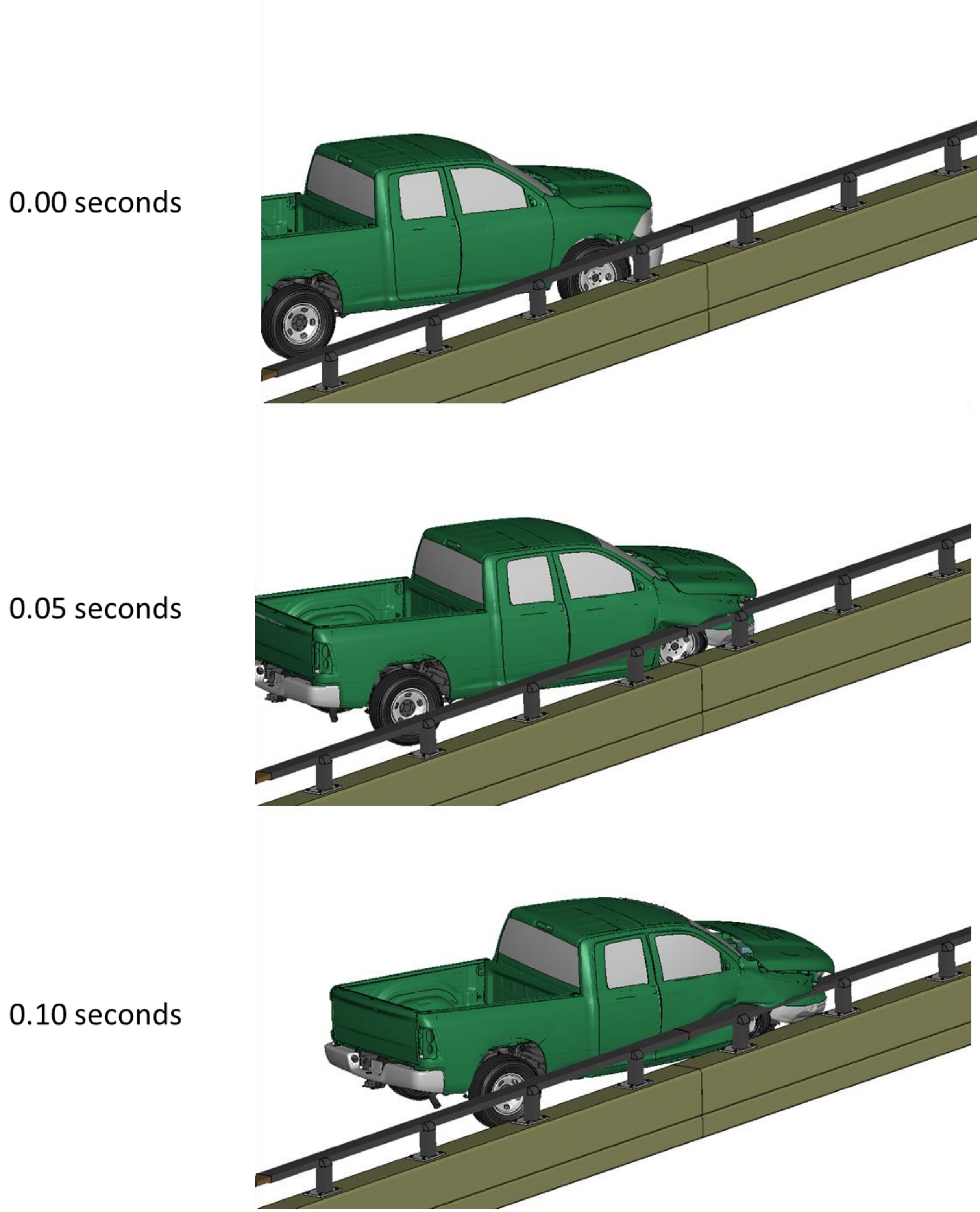


Figure E-6. Sequential views from analysis of MASH Test 3-11 CSCM at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

0.15 seconds

0.20 seconds

0.25 seconds

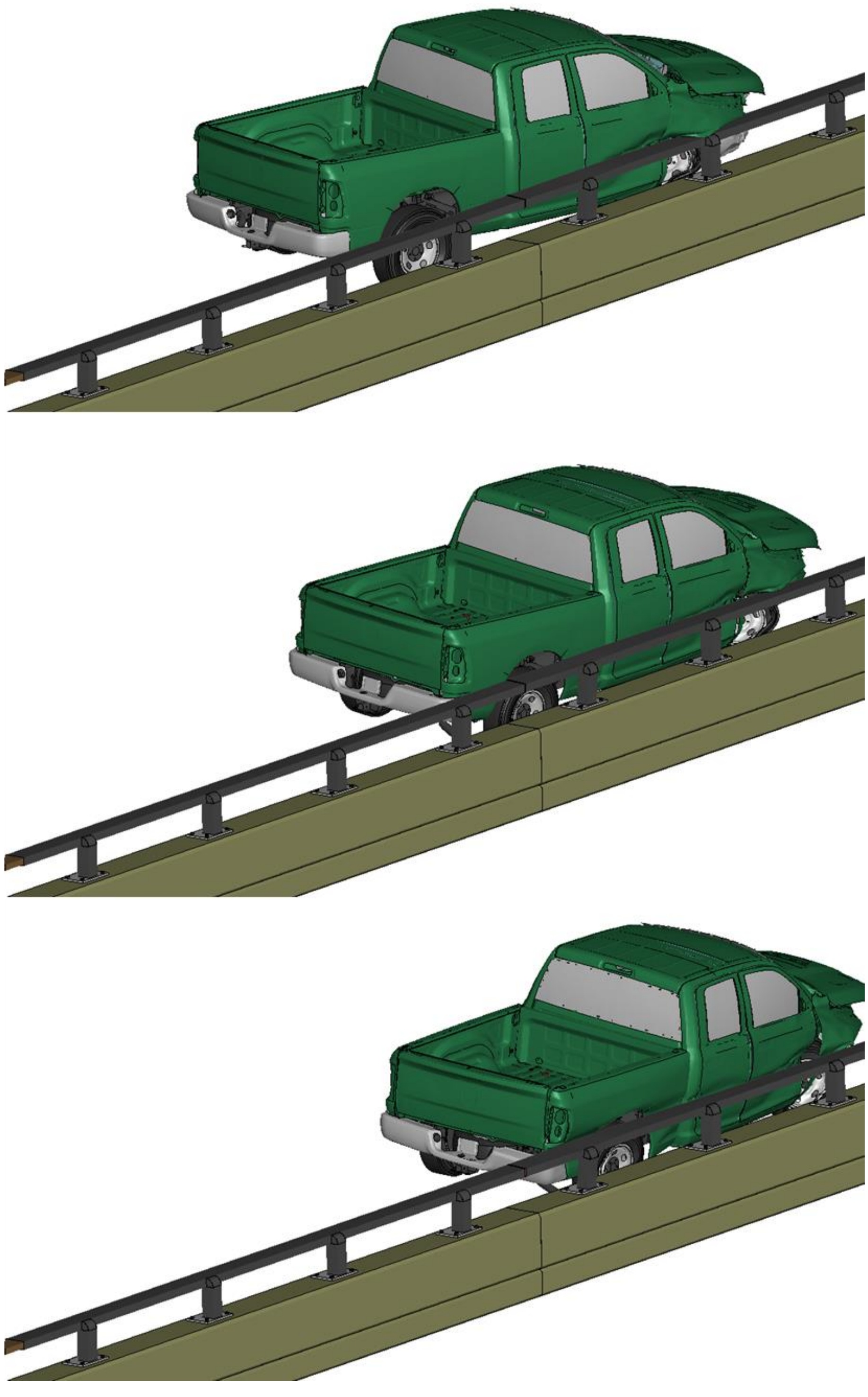


Figure E-6. [Continued] Sequential views from analysis of MASH Test 3-11 CSCM at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

Appendix F

Sequential Views for Test 3-10 at IP01

CM-MTL3 Bridge Rail with Vertical Face Design

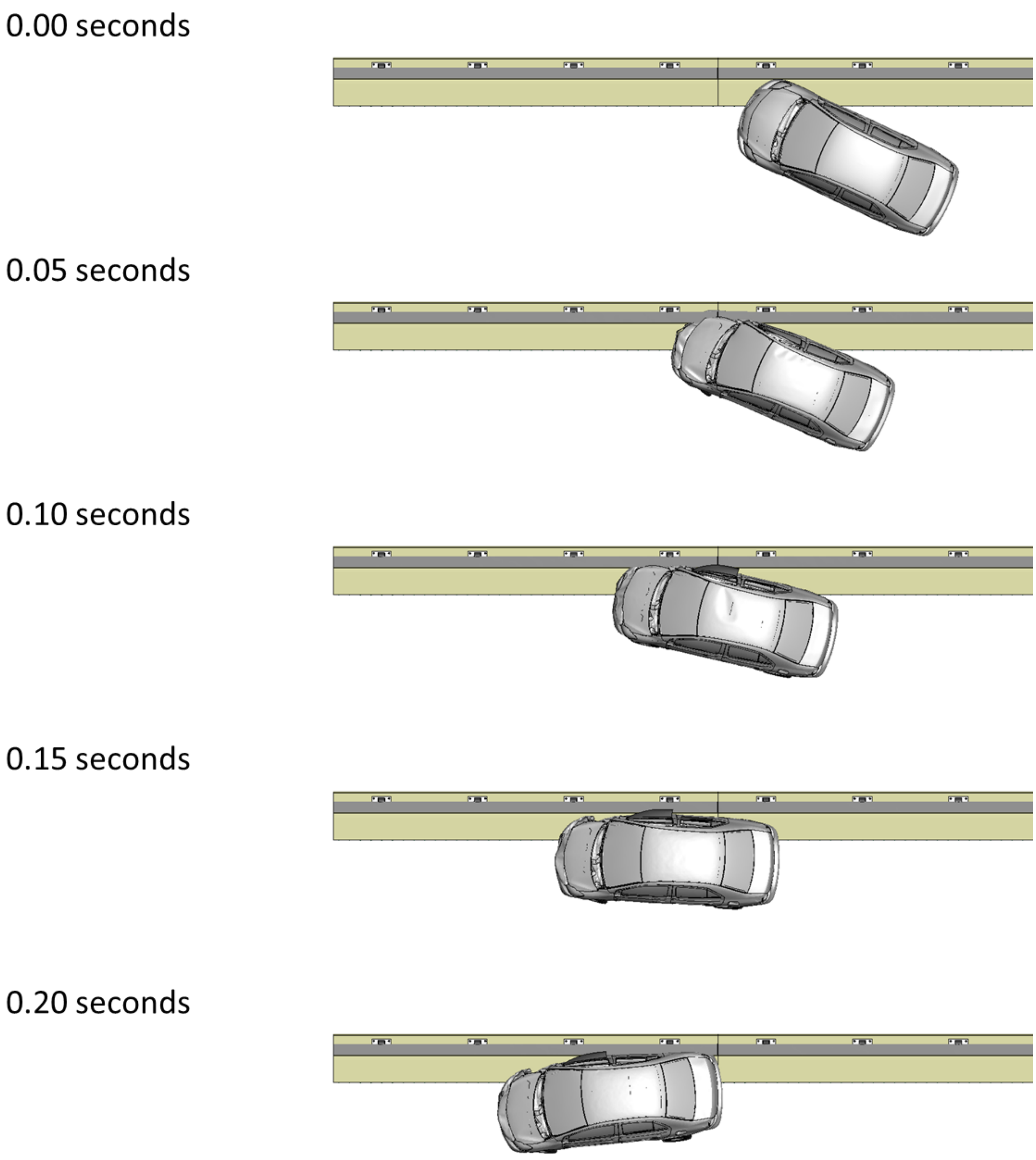


Figure F-1. Sequential views from analysis of MASH Test 3-10 RHT at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

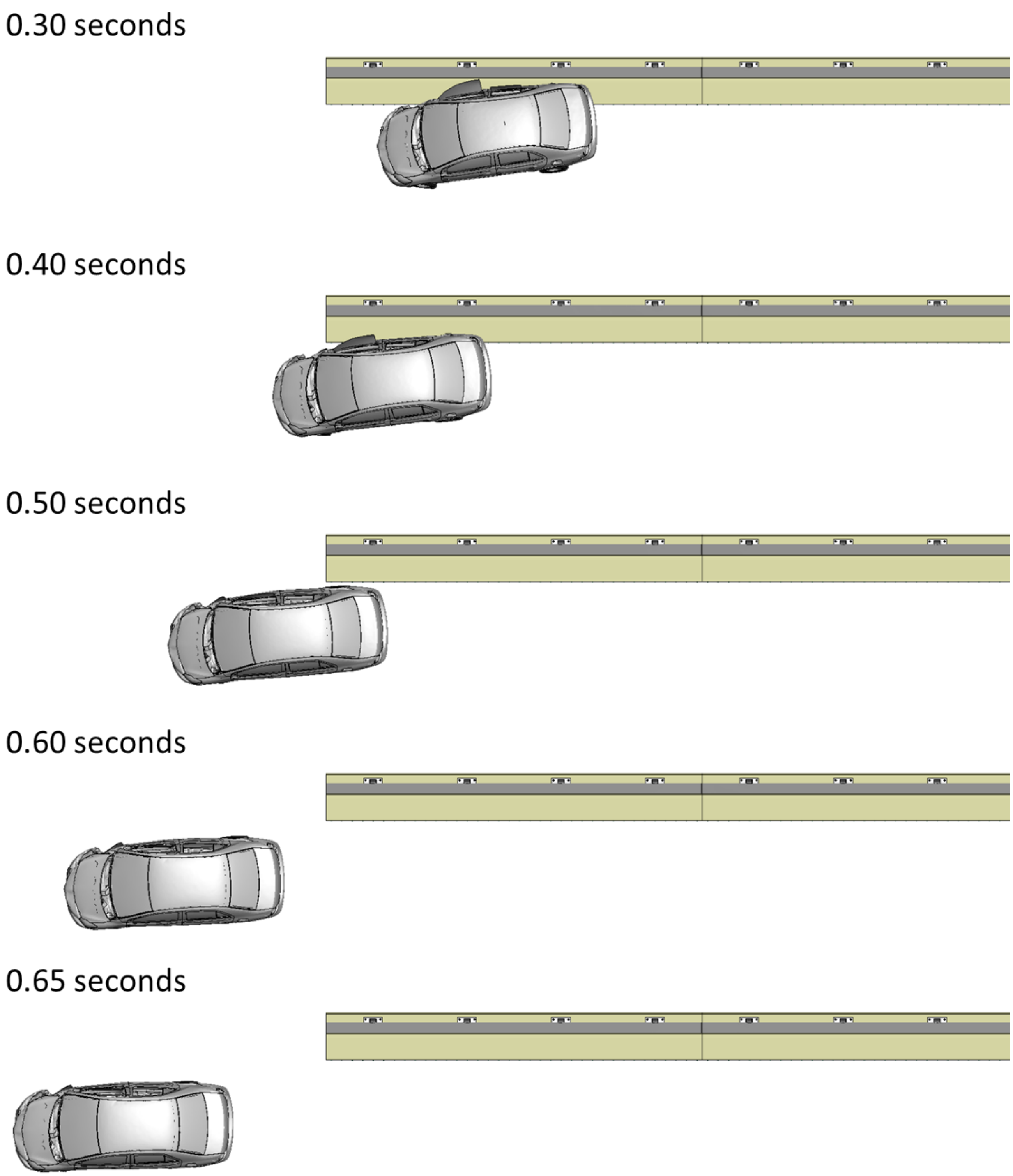


Figure F-1. [Continued] Sequential views from analysis of MASH Test 3-10 RHT at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

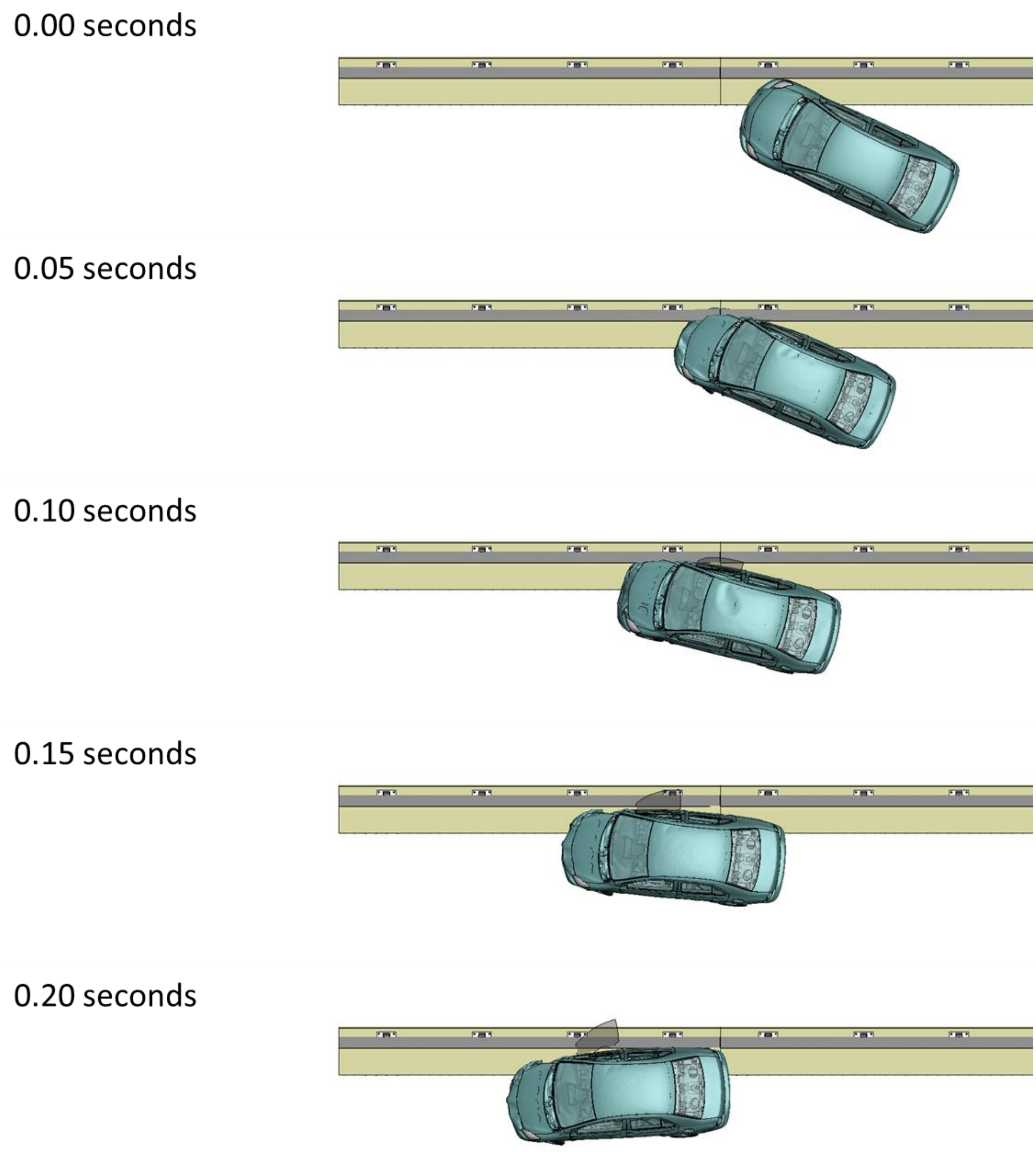
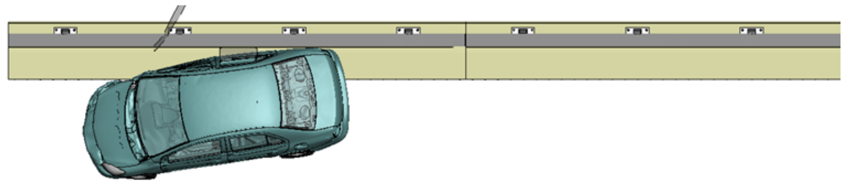


Figure F-2. Sequential views from analysis of MASH Test 3-10 CSCM at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

0.30 seconds



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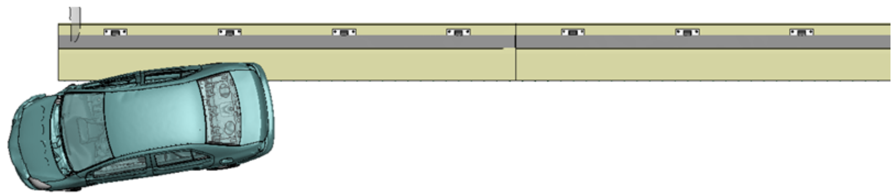

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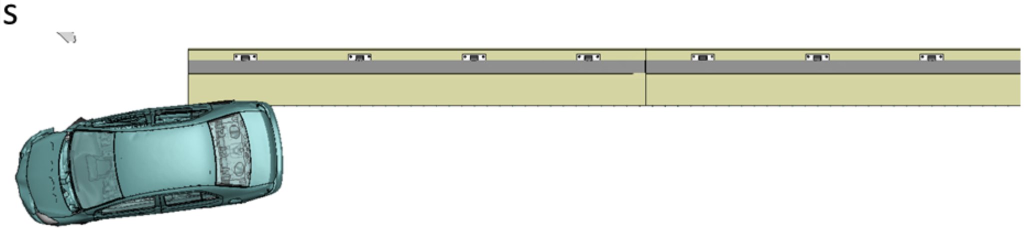


0.60 seconds

0.65 seconds

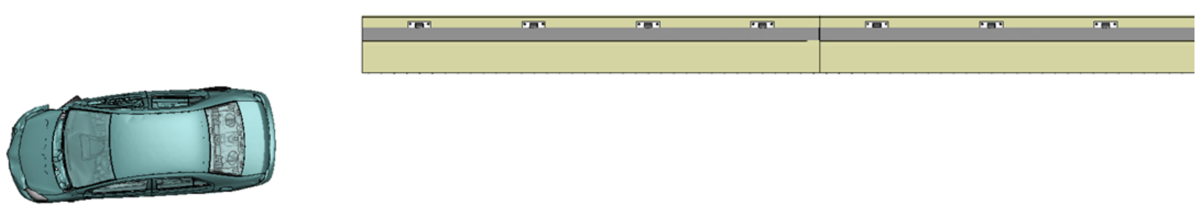


Figure F-2. [Continued] Sequential views from analysis of MASH Test 3-10 CSCM at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

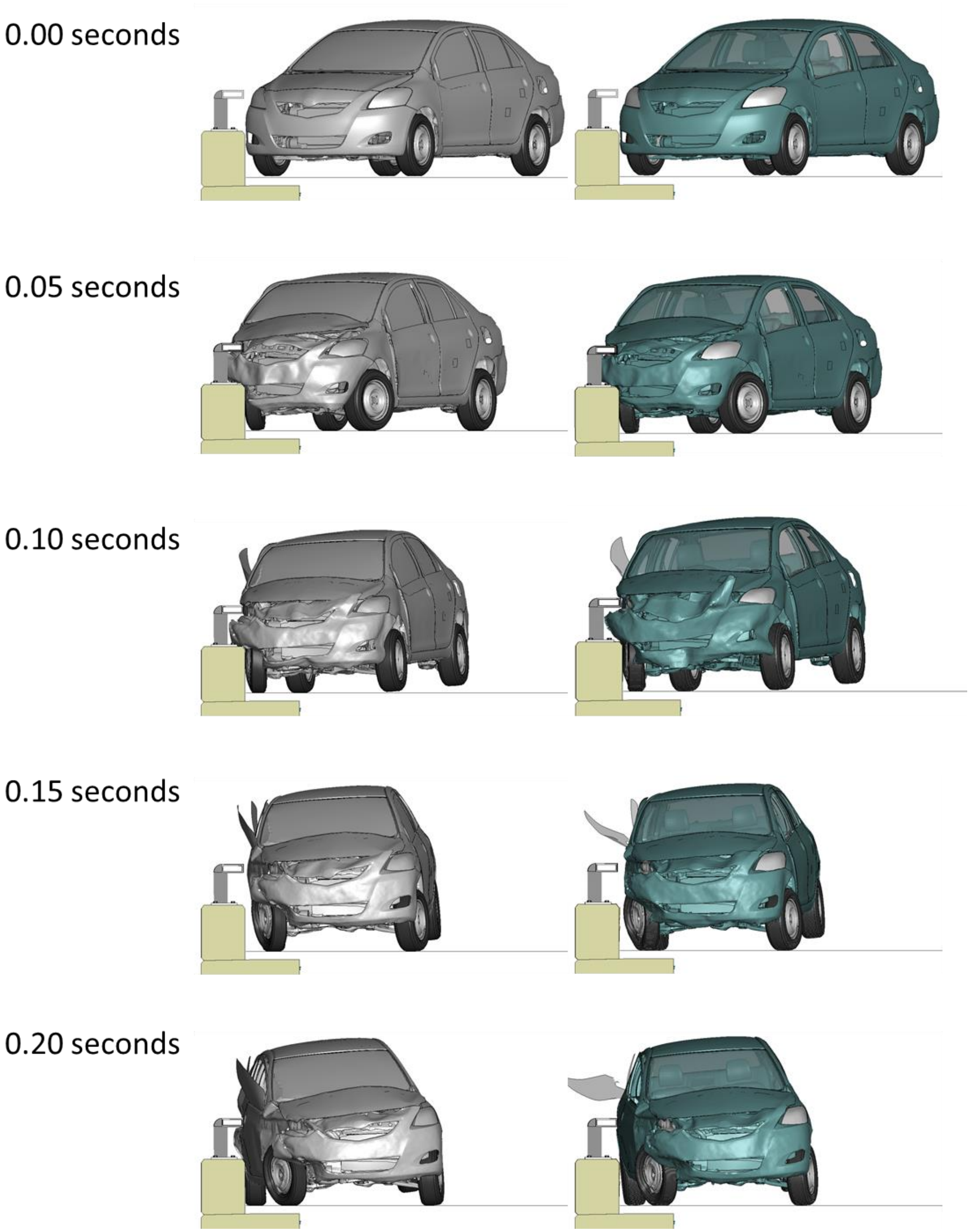


Figure F-3. Sequential views from analysis of MASH Test 3-10 at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from a downstream viewpoint. RHT on left, CSCM on right.

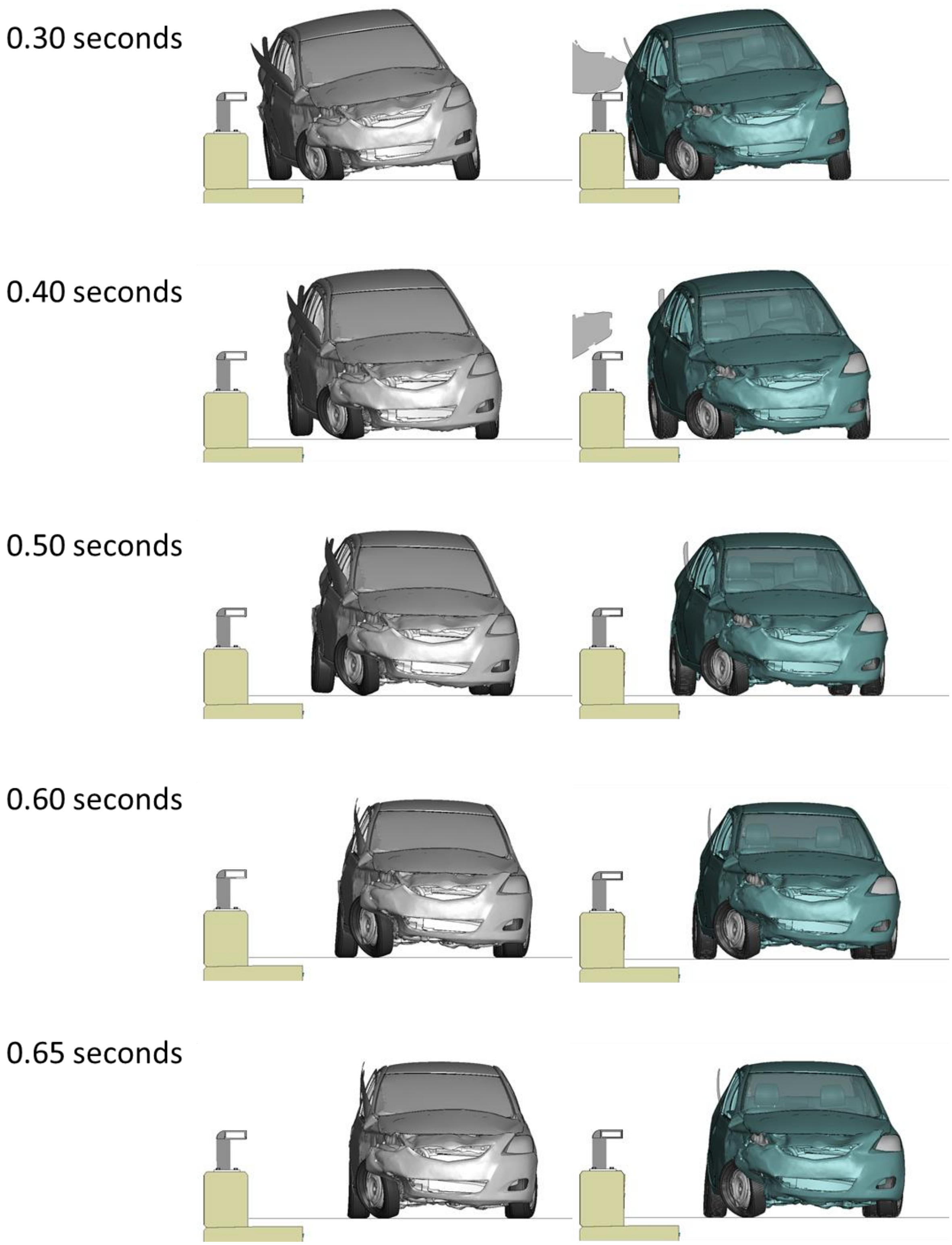


Figure F-3. [Continued] Sequential views from analysis of MASH Test 3-10 at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from a downstream viewpoint. RHT on left, CSCM on right.

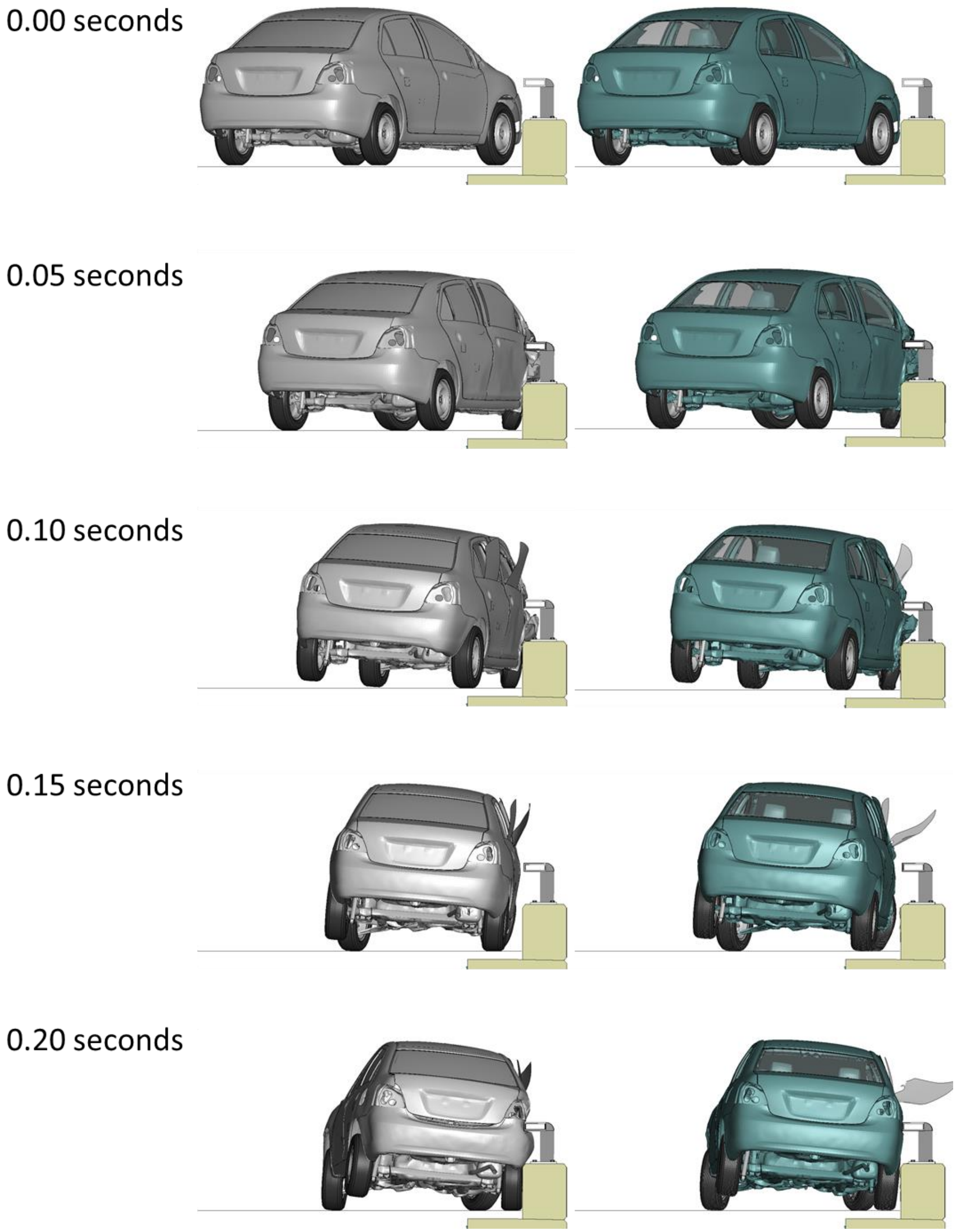


Figure F-4. Sequential views from analysis of MASH Test 3-10 at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an upstream viewpoint. RHT on left, CSCM on right.

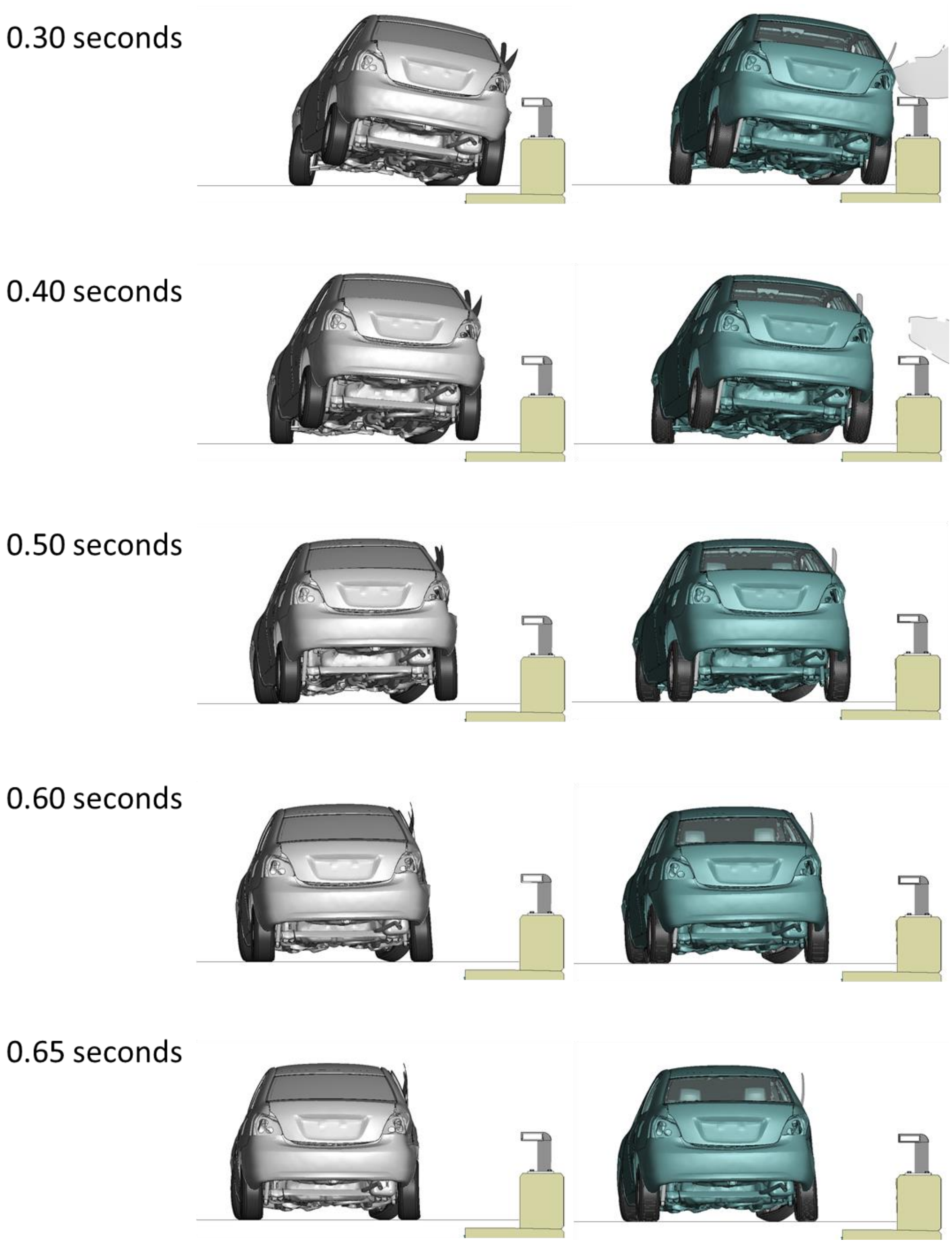


Figure F-4. [Continued] Sequential views from analysis of MASH Test 3-10 at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an upstream viewpoint. RHT on left, CSCM on right.

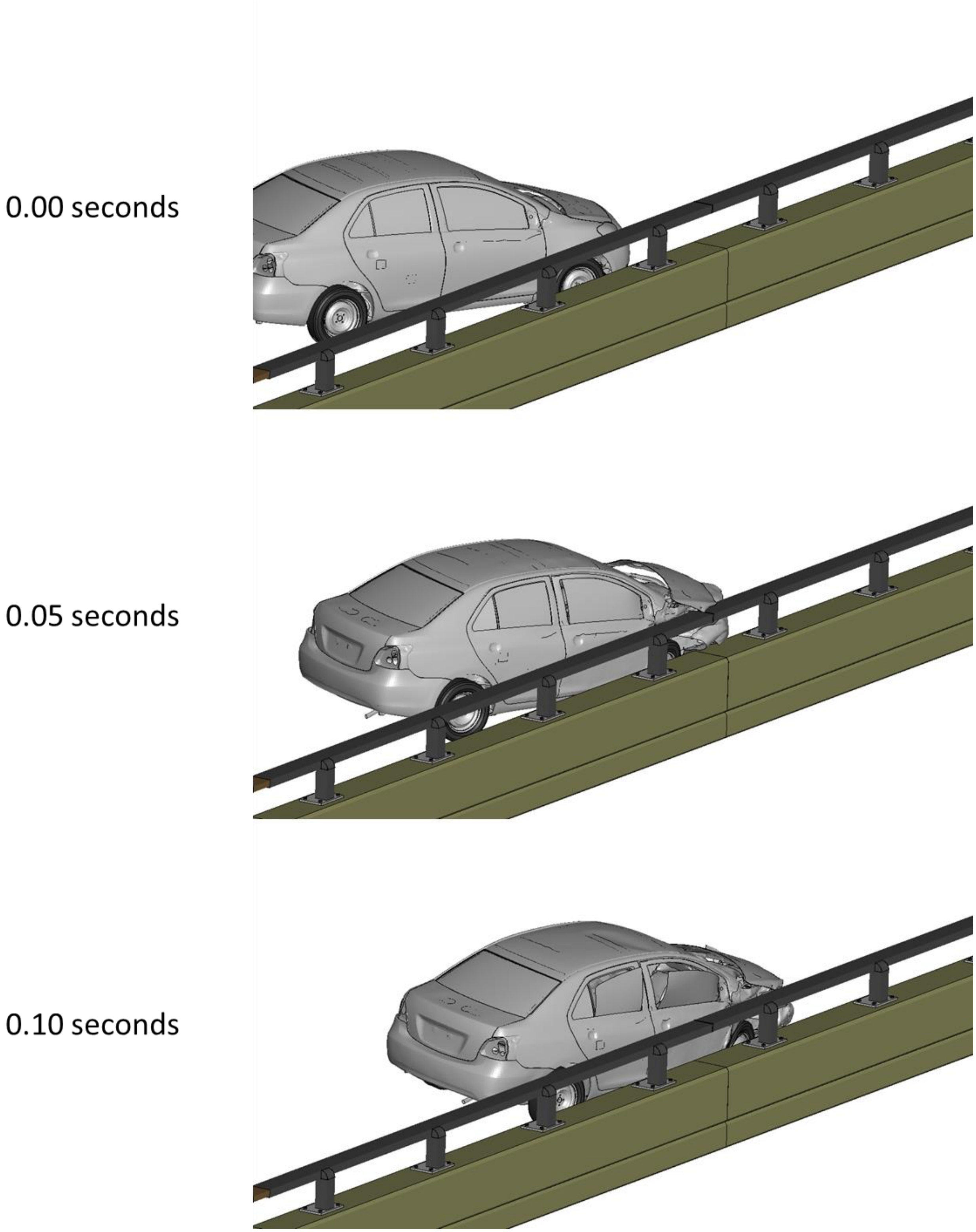
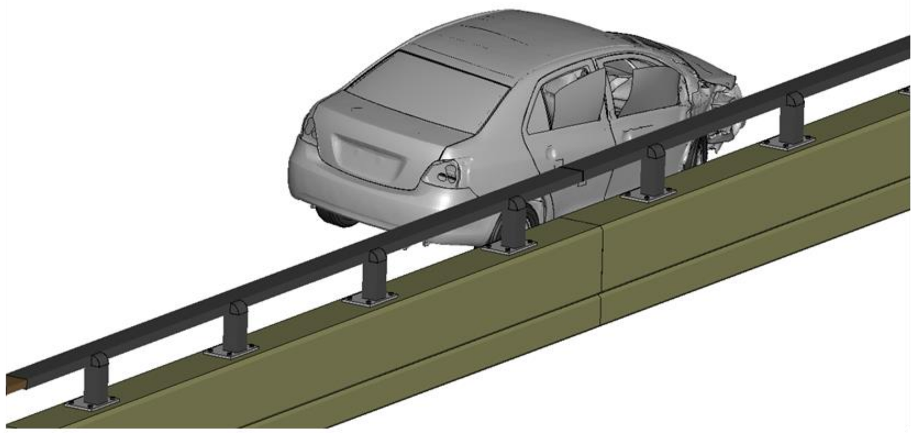


Figure F-5. Sequential views from analysis of MASH Test 3-10 RHT at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

0.15 seconds



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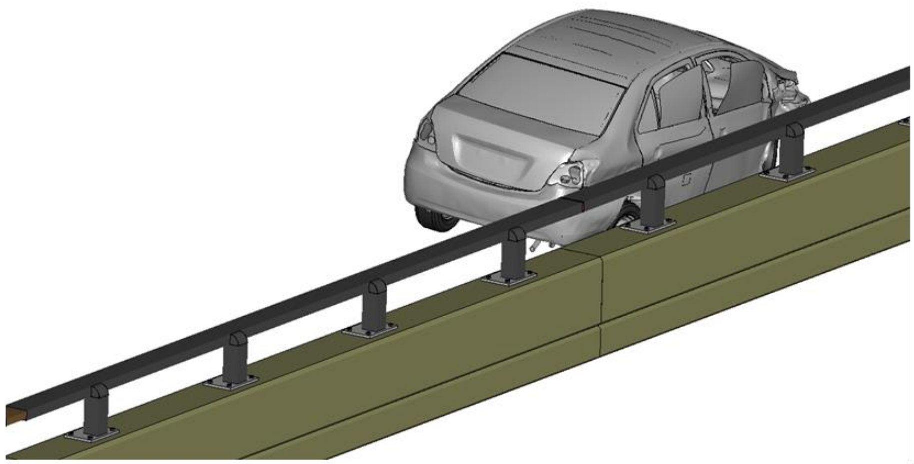

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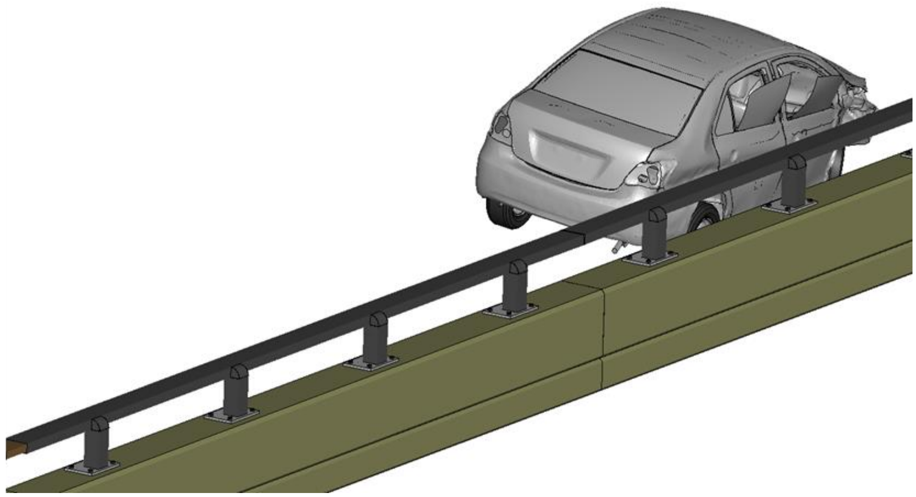
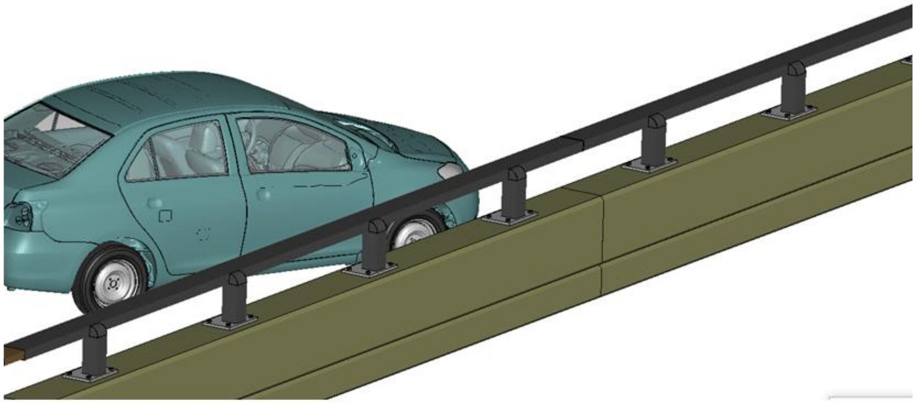


Figure F-5. [Continued] Sequential views from analysis of MASH Test 3-10 RHT at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

0.00 seconds



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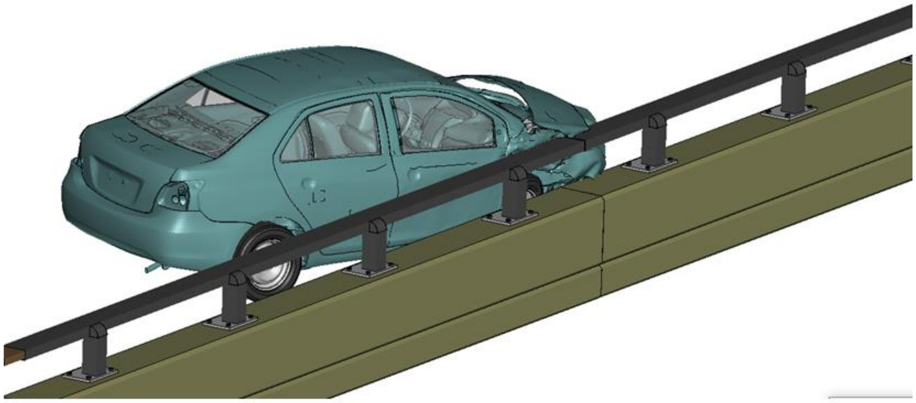

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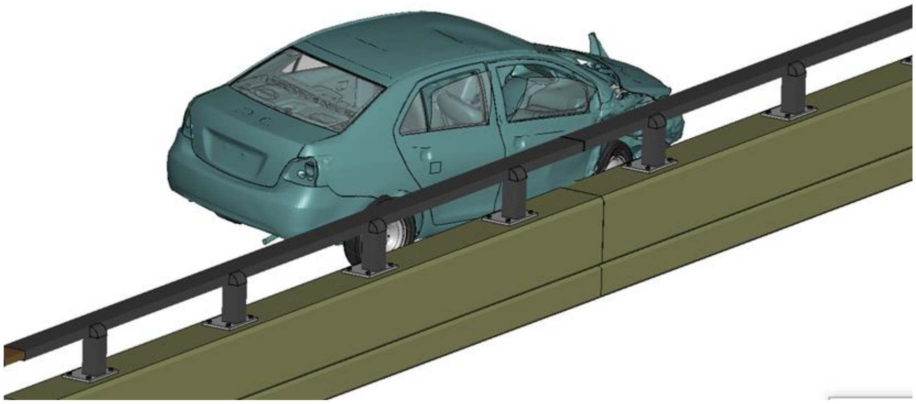
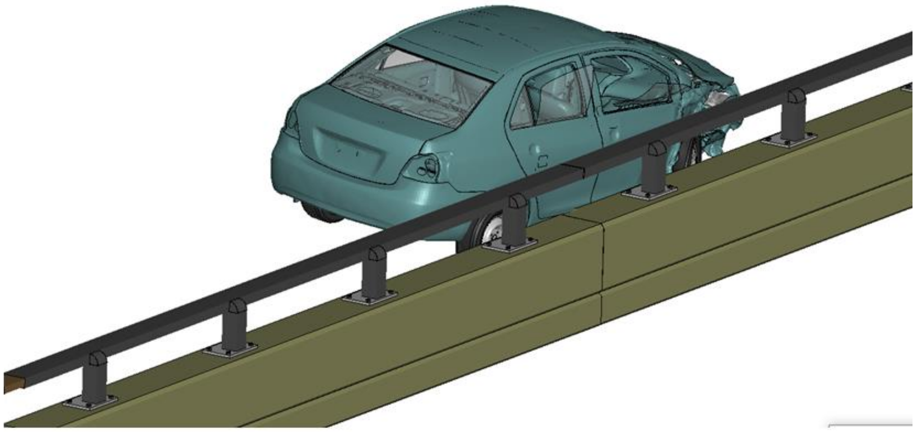


Figure F-6. Sequential views from analysis of MASH Test 3-10 CSCM at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

0.15 seconds



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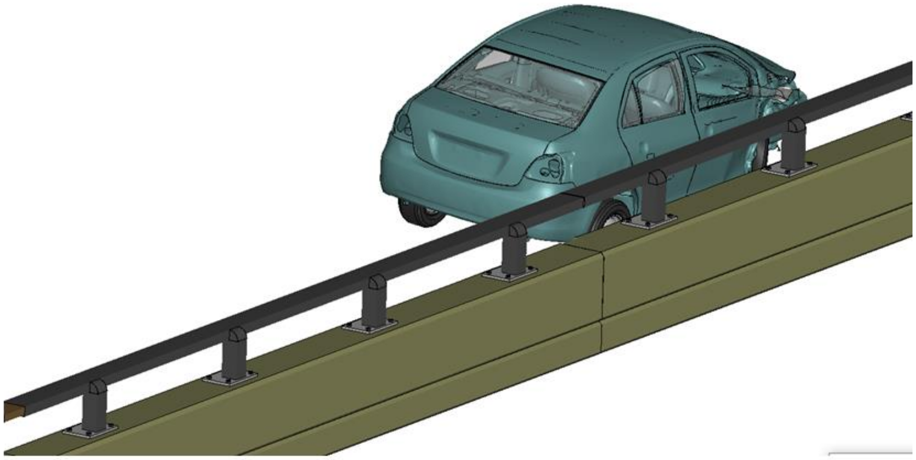

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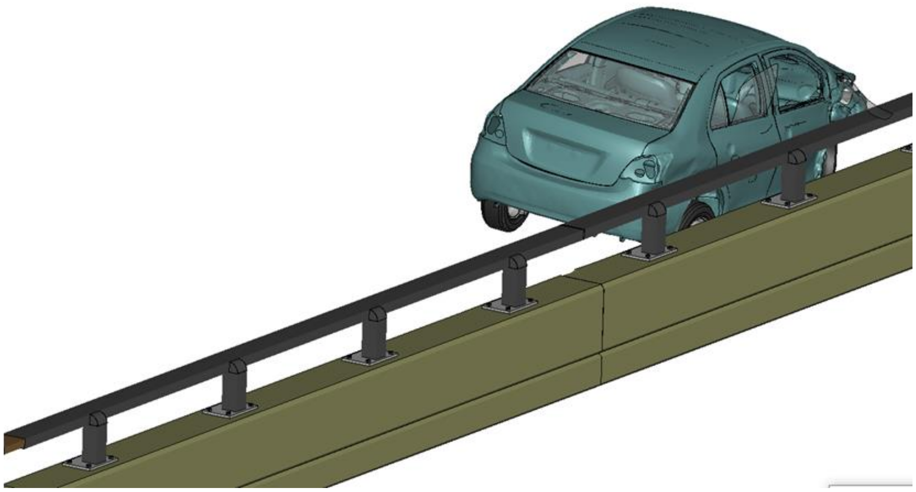


Figure F-6. [Continued] Sequential views from analysis of MASH Test 3-10 CSCM at IP01 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

Appendix G

Sequential Views for Test 3-10 at IP02

CM-MTL3 Bridge Rail with Vertical Face Design

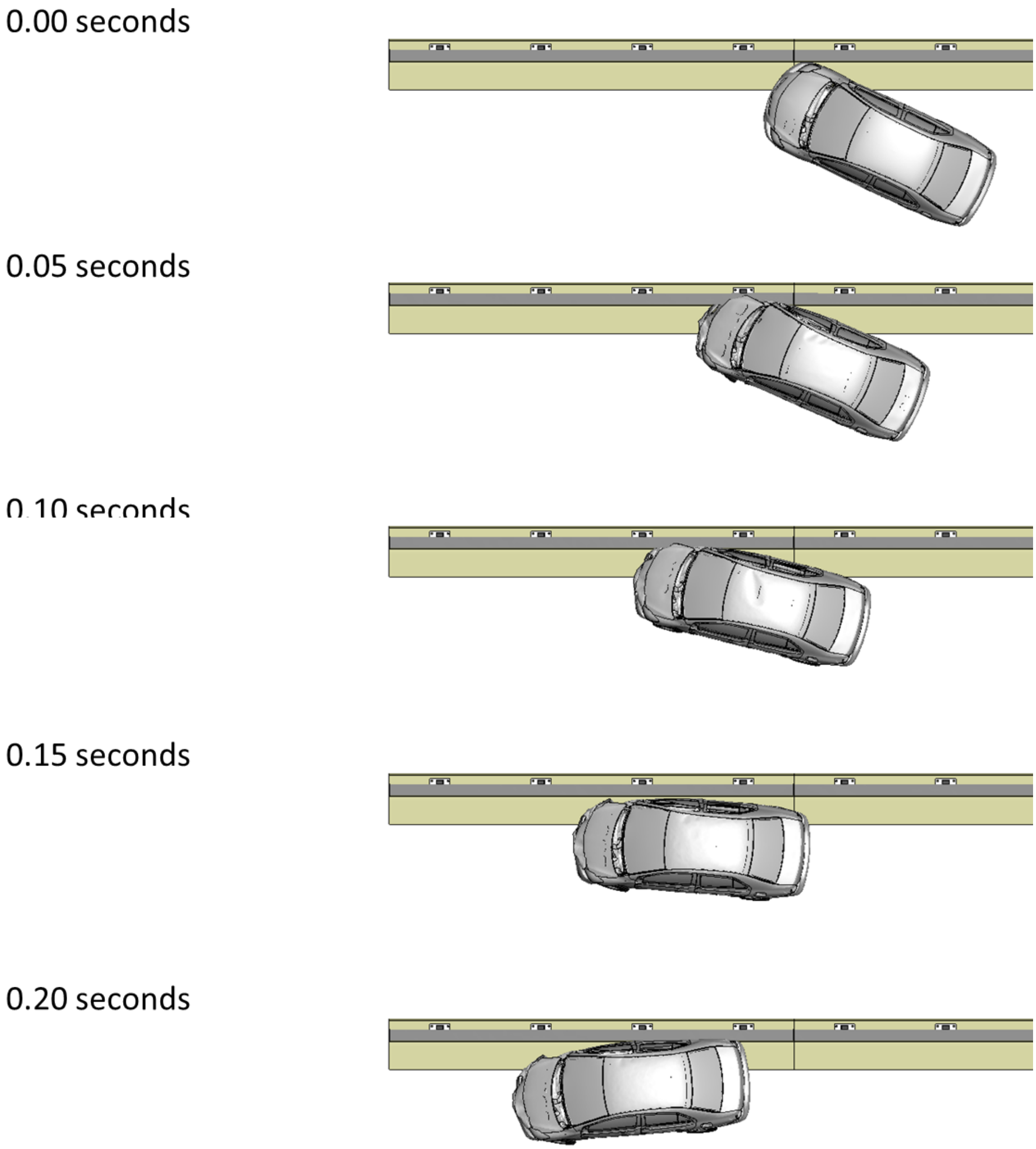


Figure G-1. Sequential views from analysis of MASH Test 3-10 RHT at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

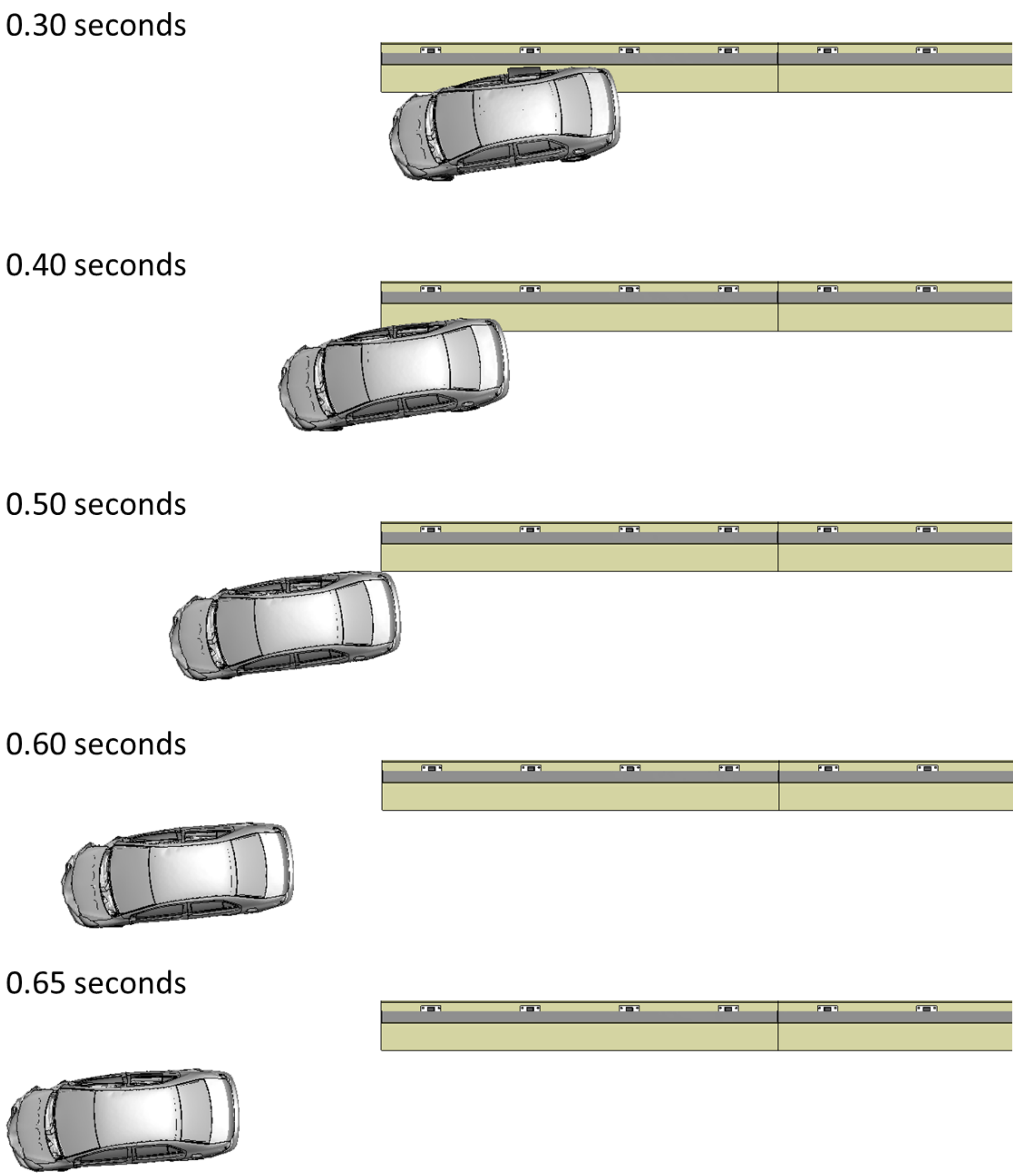


Figure G-1. [Continued] Sequential views from analysis of MASH Test 3-10 RHT at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

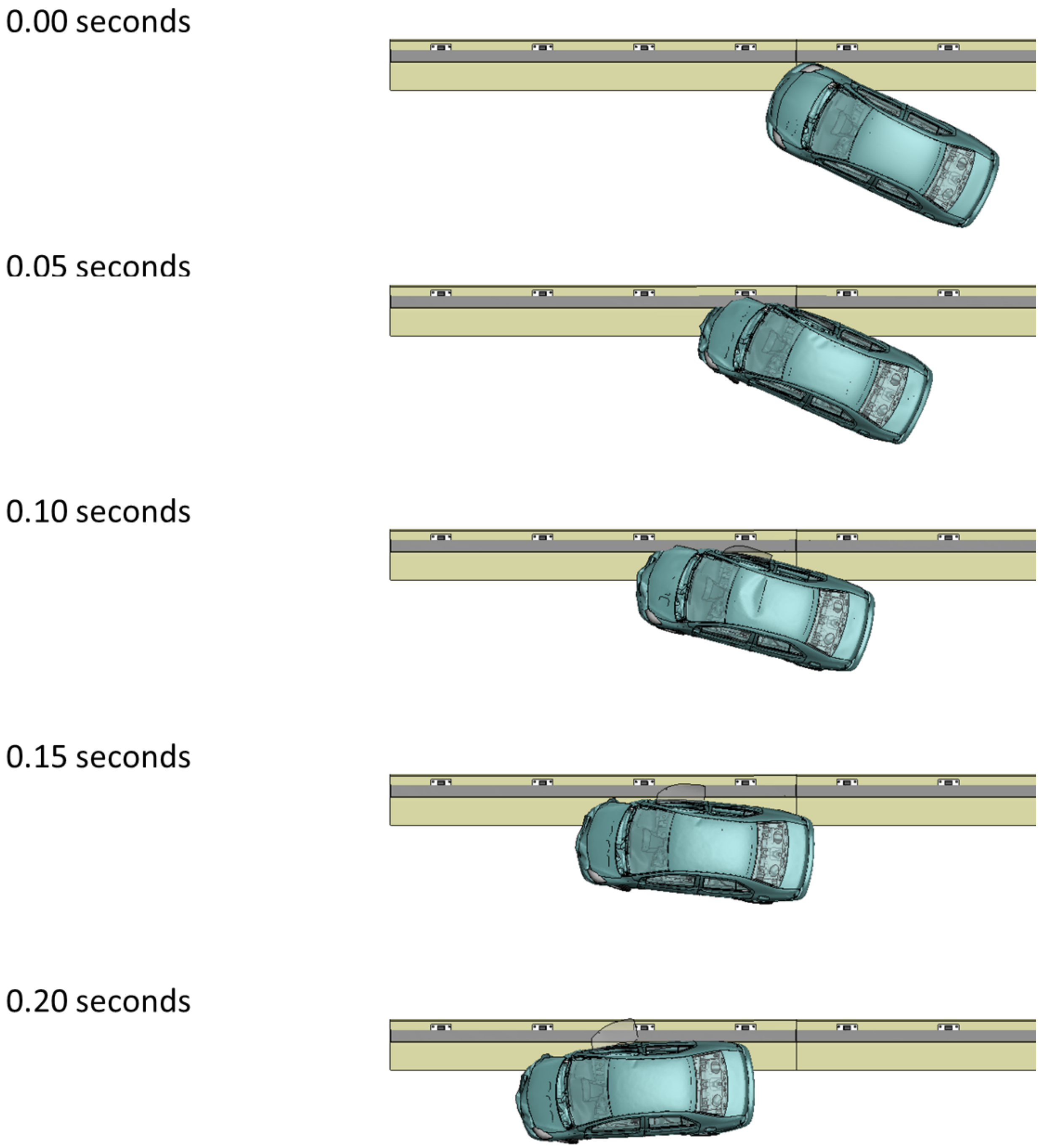


Figure G-2. Sequential views from analysis of MASH Test 3-10 CSCM at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

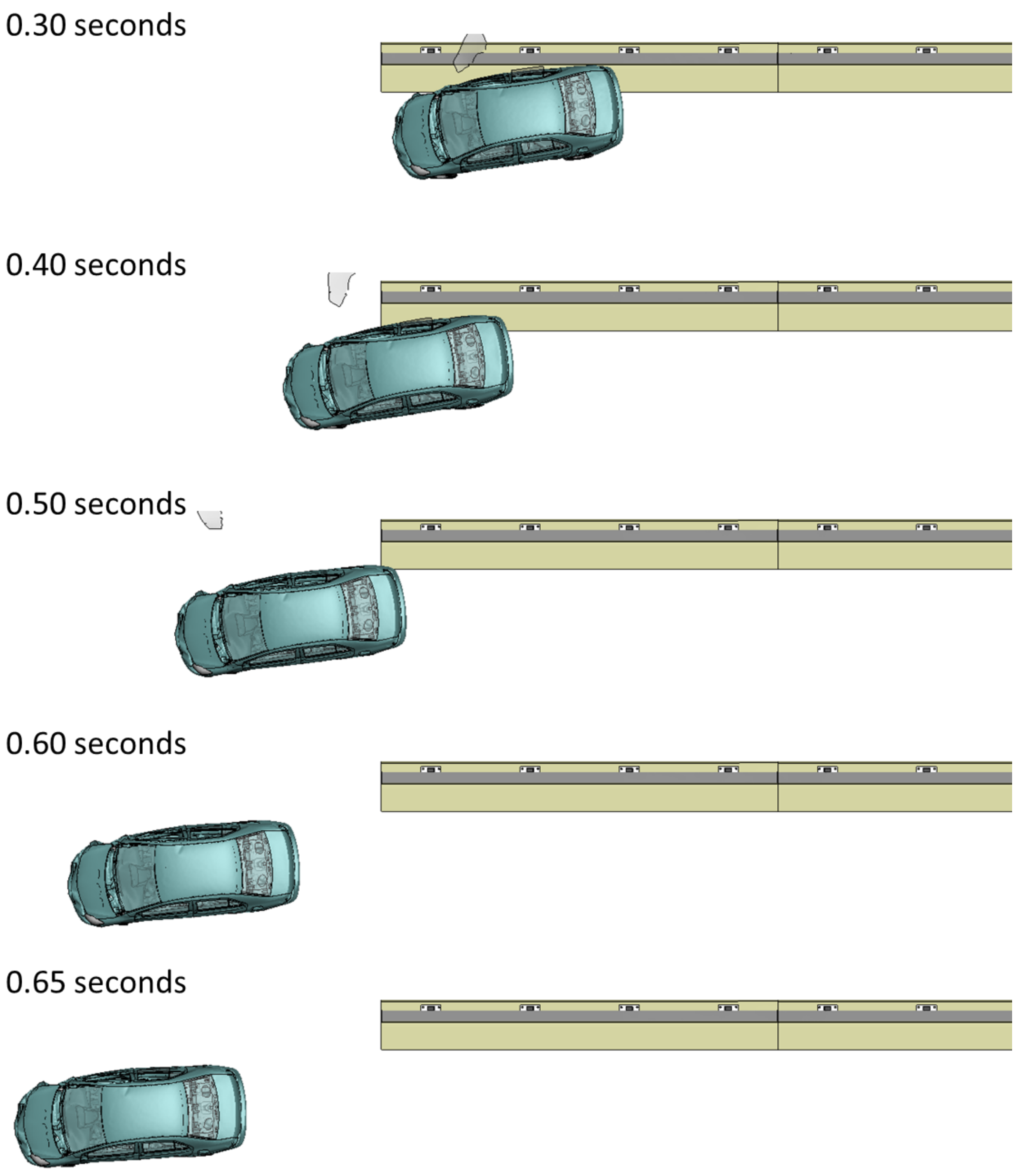


Figure G-2. [Continued] Sequential views from analysis of MASH Test 3-10 CSCM at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an overhead viewpoint.

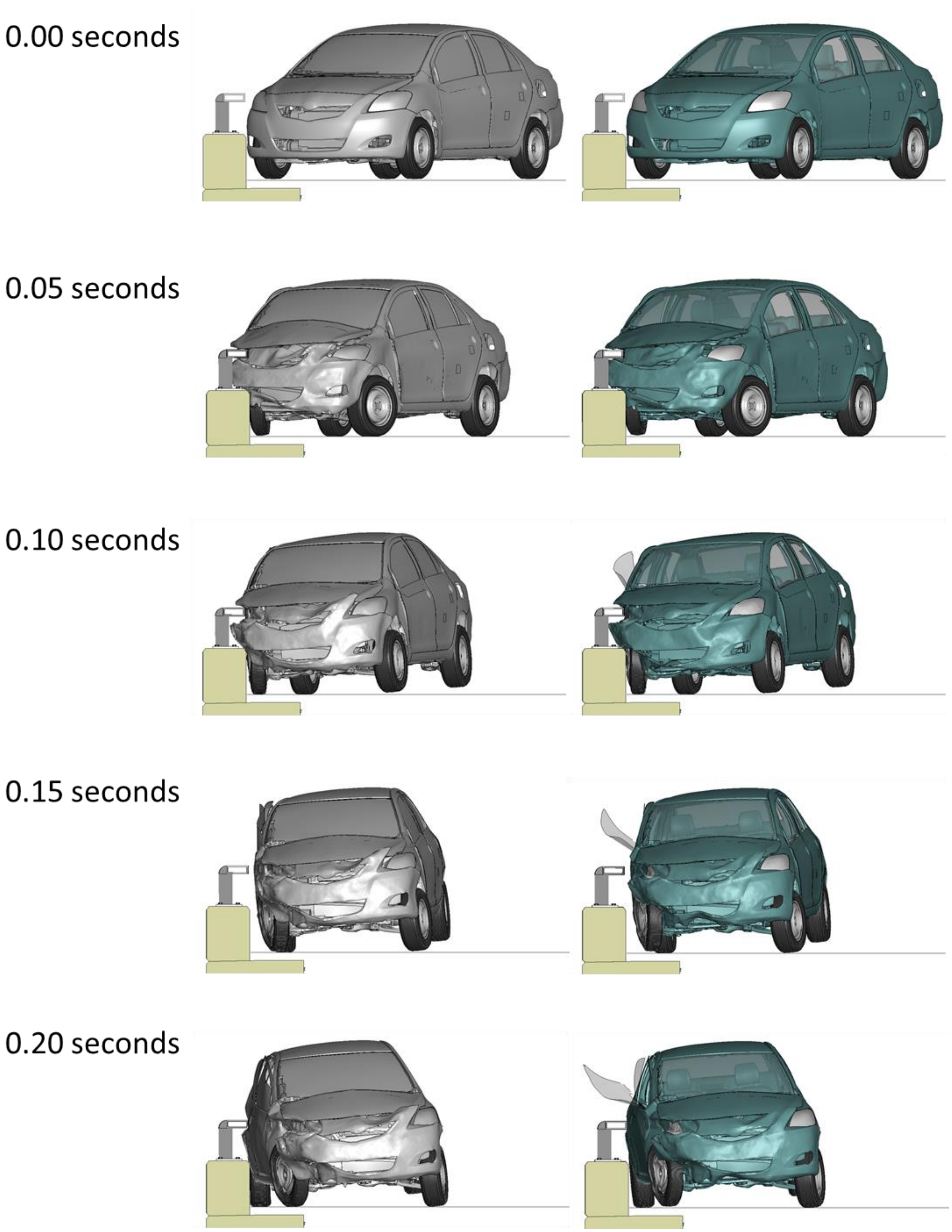


Figure G-3. Sequential views from analysis of MASH Test 3-10 at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from a downstream viewpoint. RHT on left, CSCM on right.

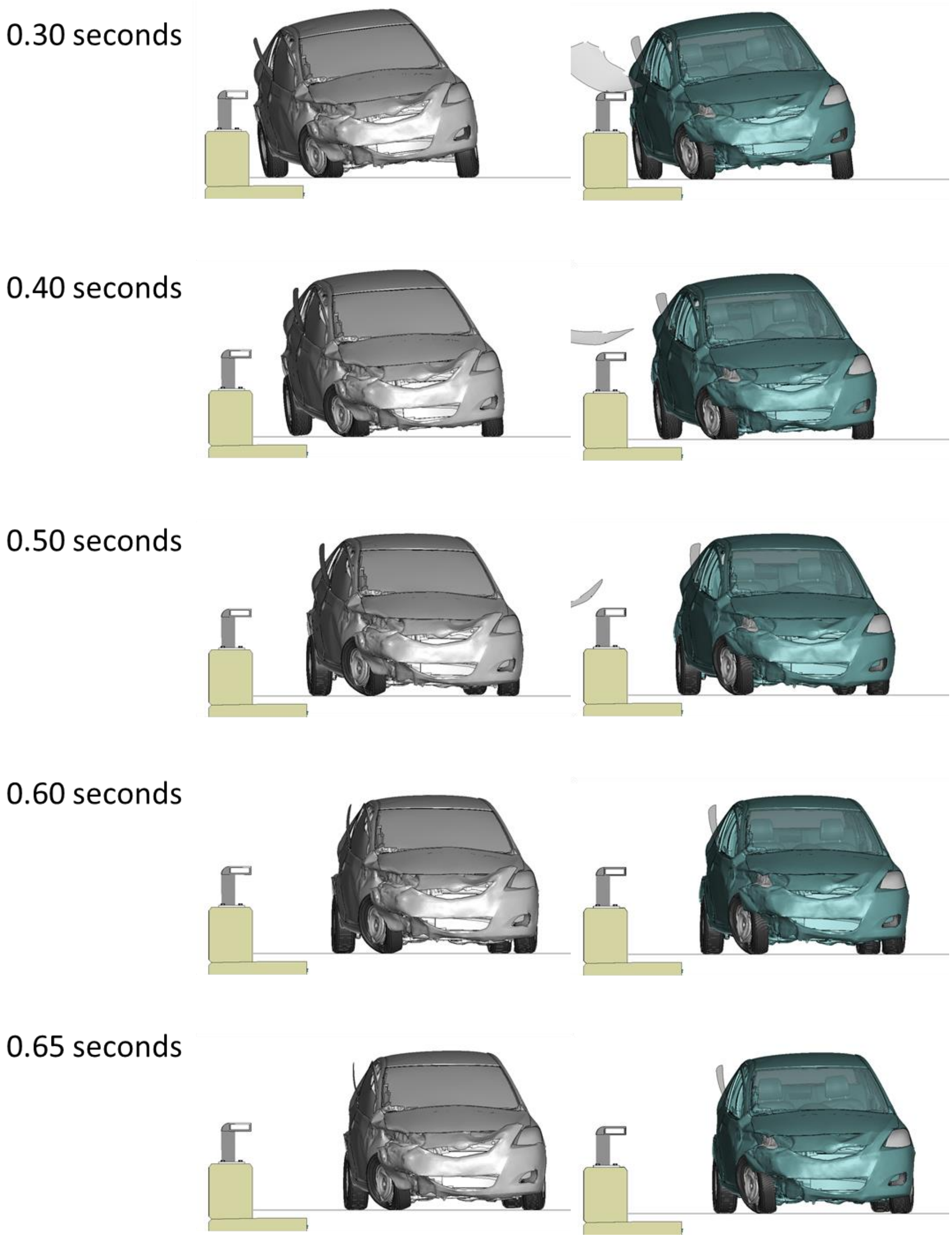


Figure G-3. [Continued] Sequential views from analysis of MASH Test 3-10 at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from a downstream viewpoint. RHT on left, CSCM on right.

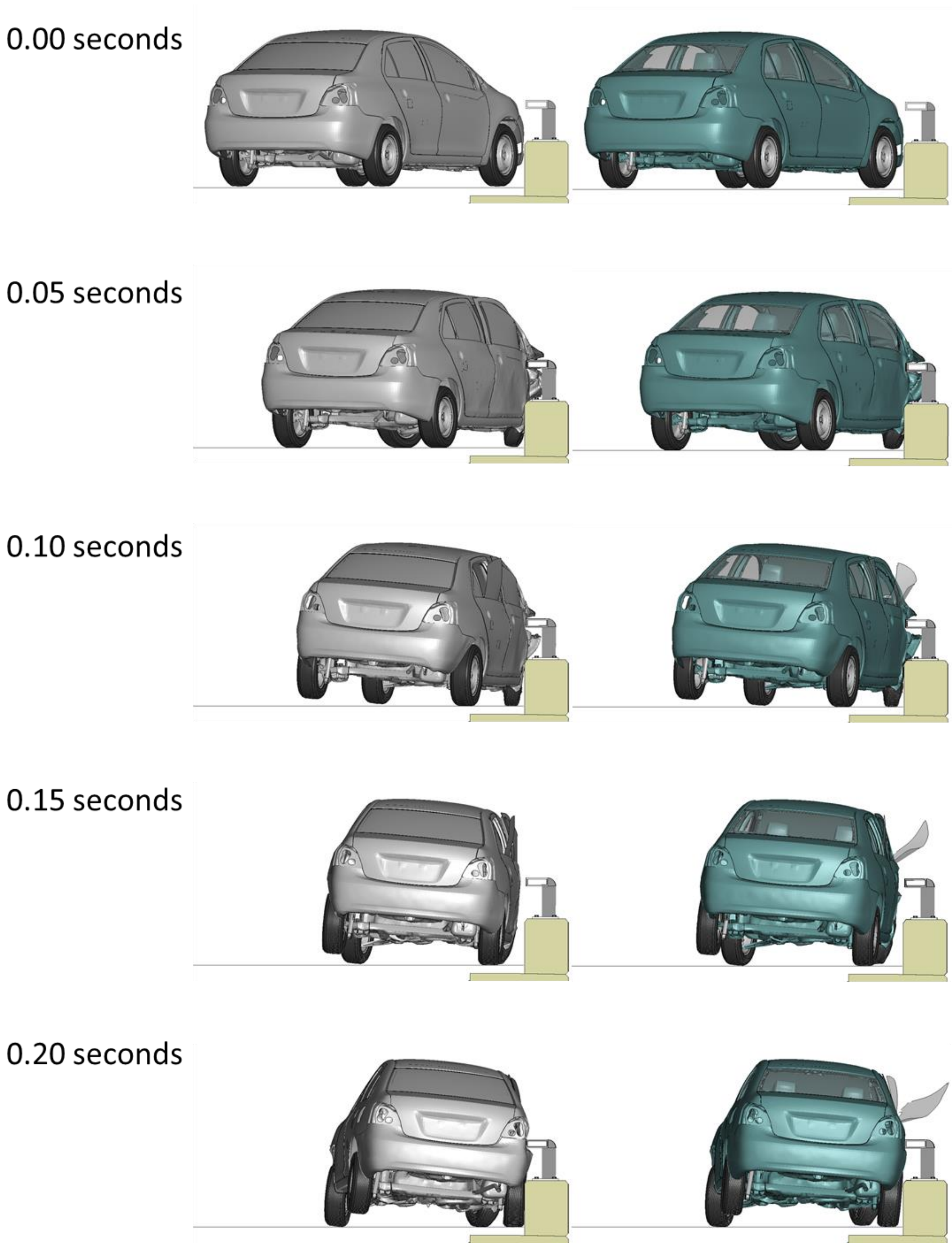


Figure G-4. Sequential views from analysis of MASH Test 3-10 at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an upstream viewpoint. RHT on left, CSCM on right.

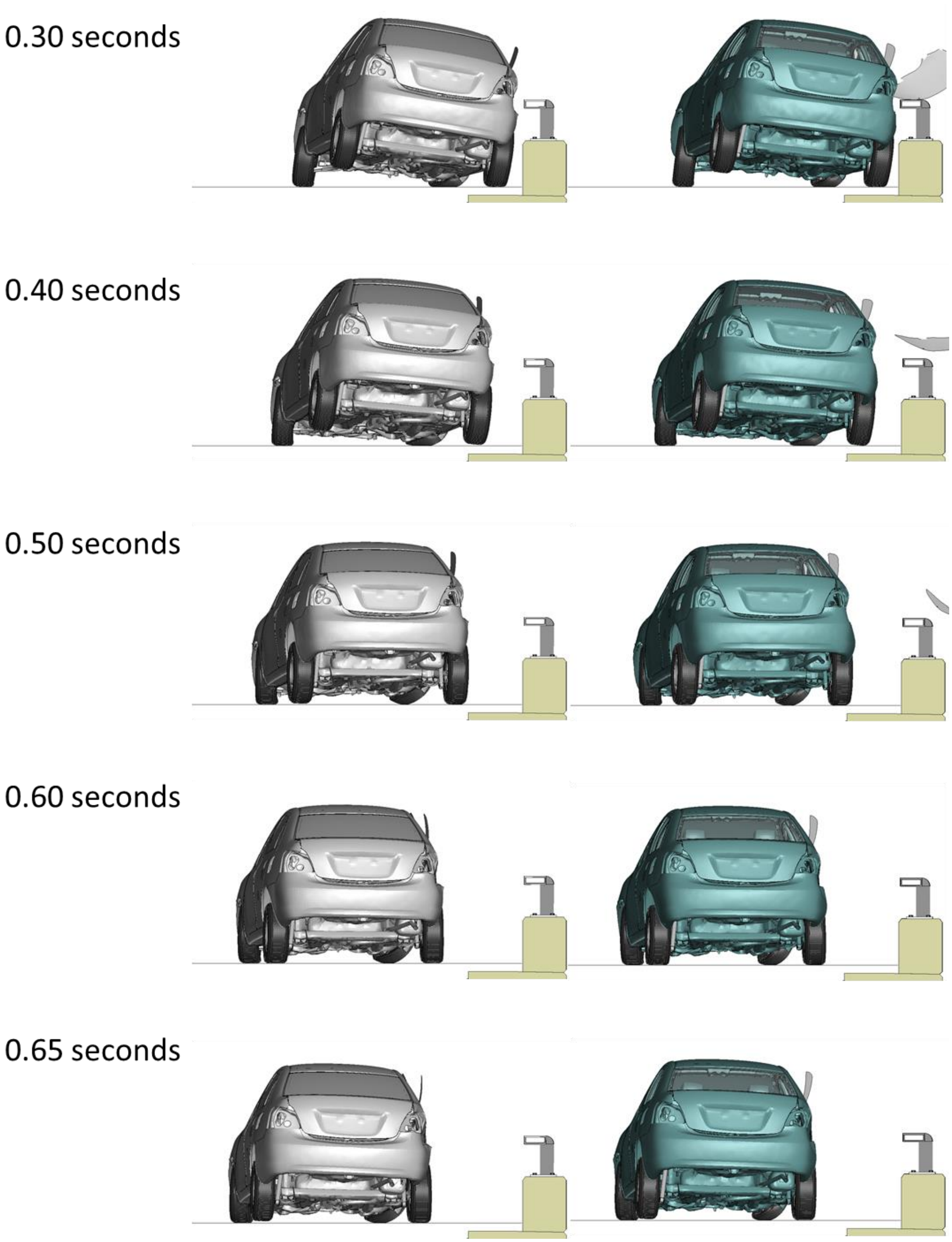


Figure G-4. [Continued] Sequential views from analysis of MASH Test 3-10 at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an upstream viewpoint. RHT on left, CSCM on right.

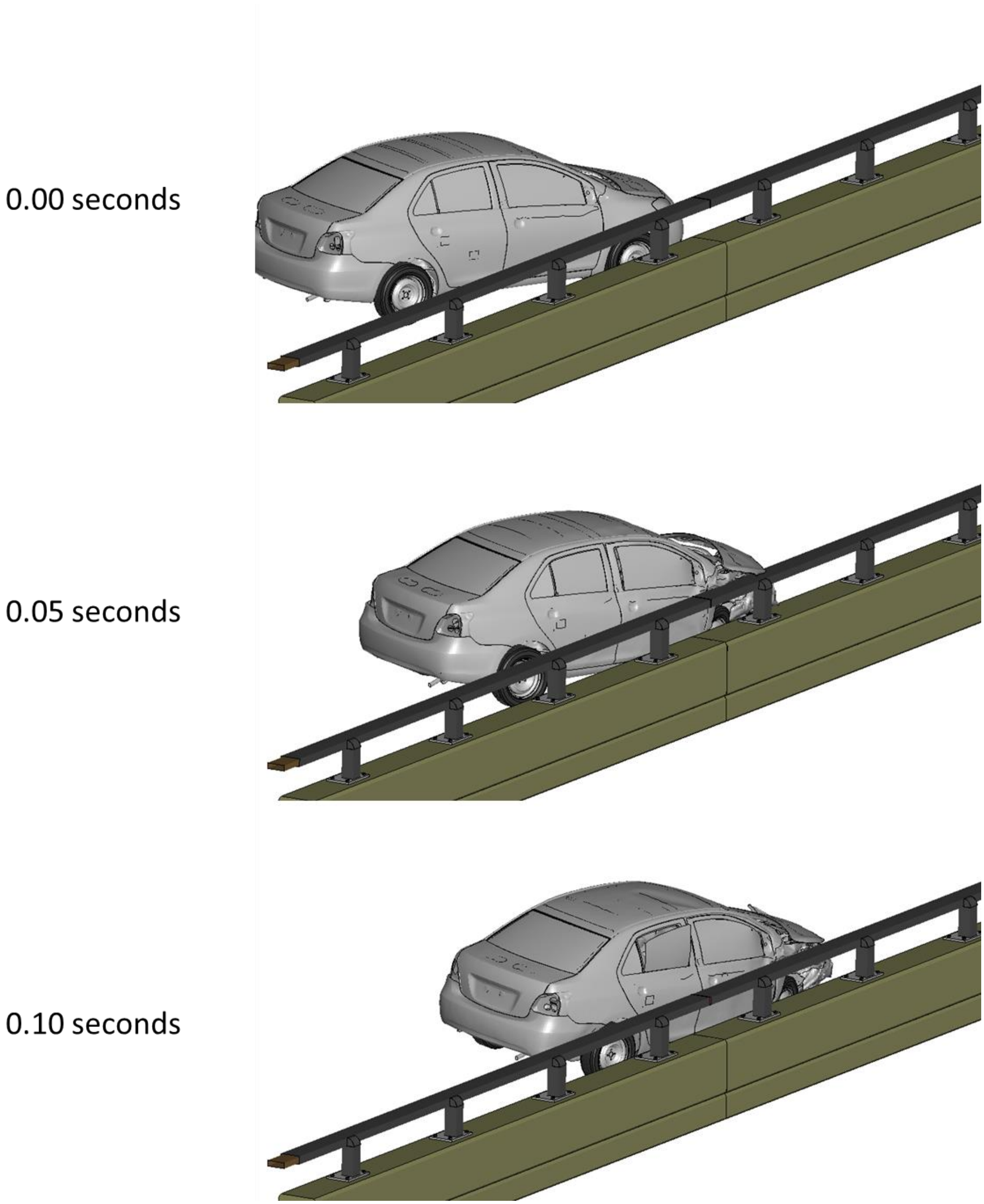
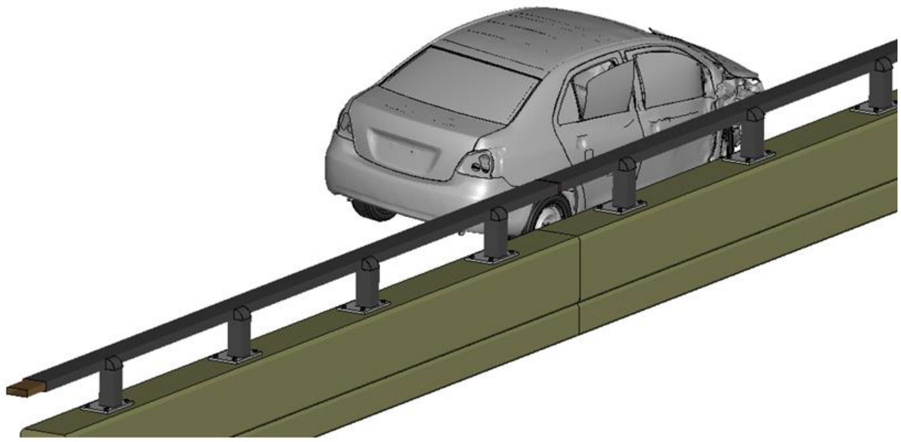


Figure G-5. Sequential views from analysis of MASH Test 3-10 RHT at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

0.15 seconds



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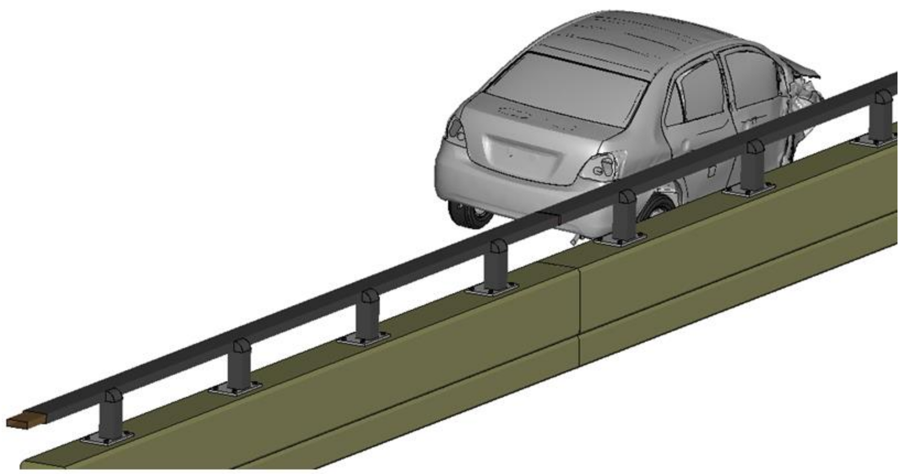

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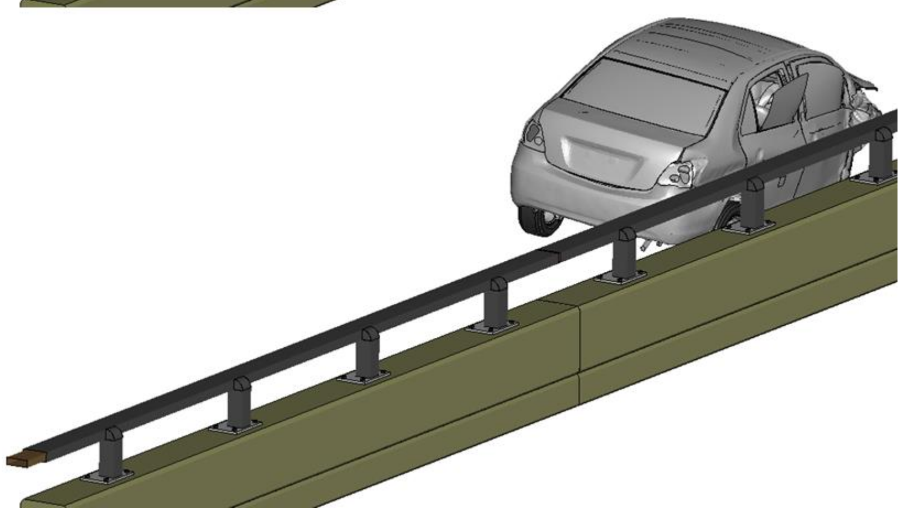

Figure G-5. [Continued] Sequential views from analysis of MASH Test 3-10 RHT at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

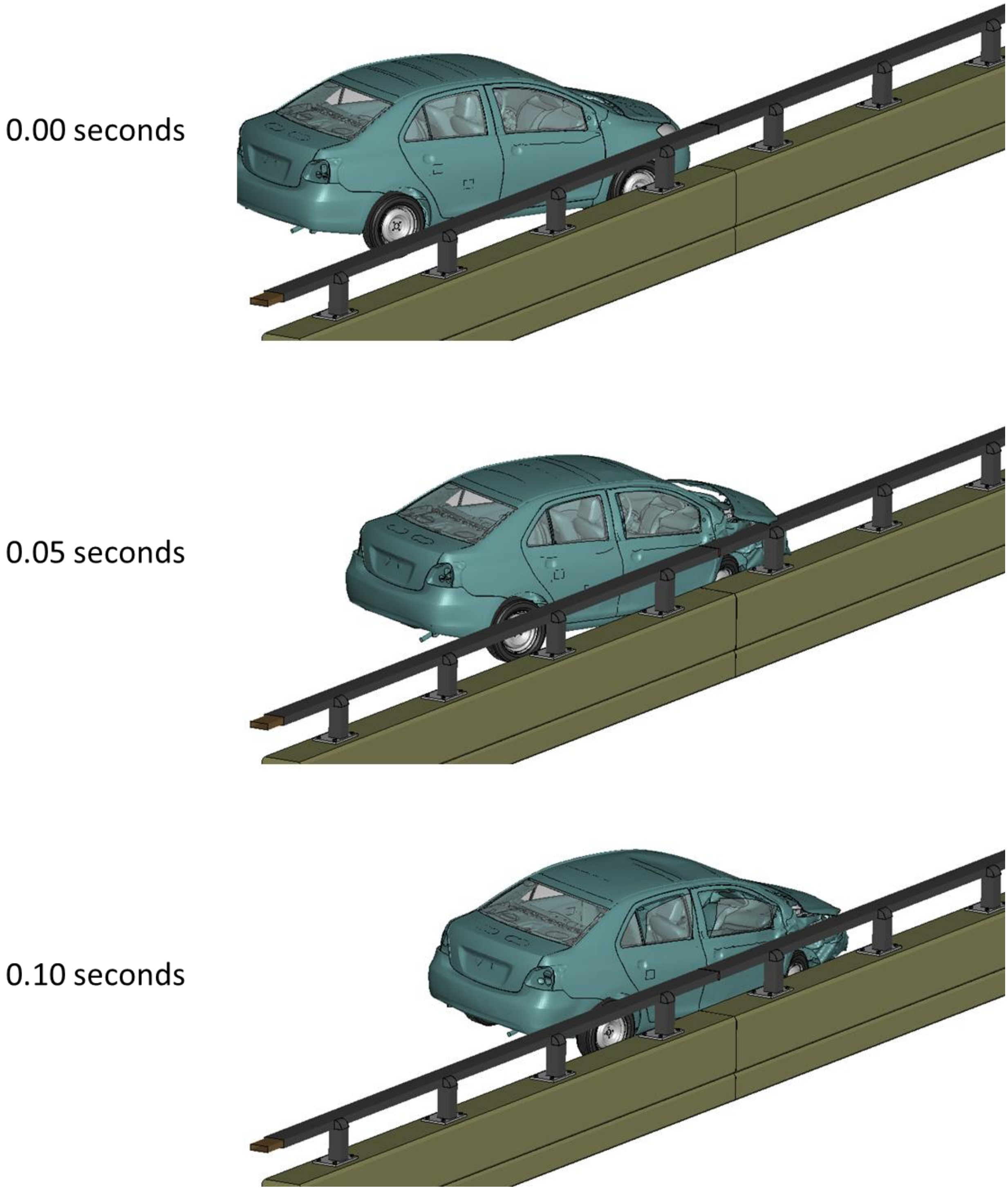

Figure G-6. Sequential views from analysis of MASH Test 3-10 CSCM at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.

0.15 seconds

0.20 seconds

0.25 seconds

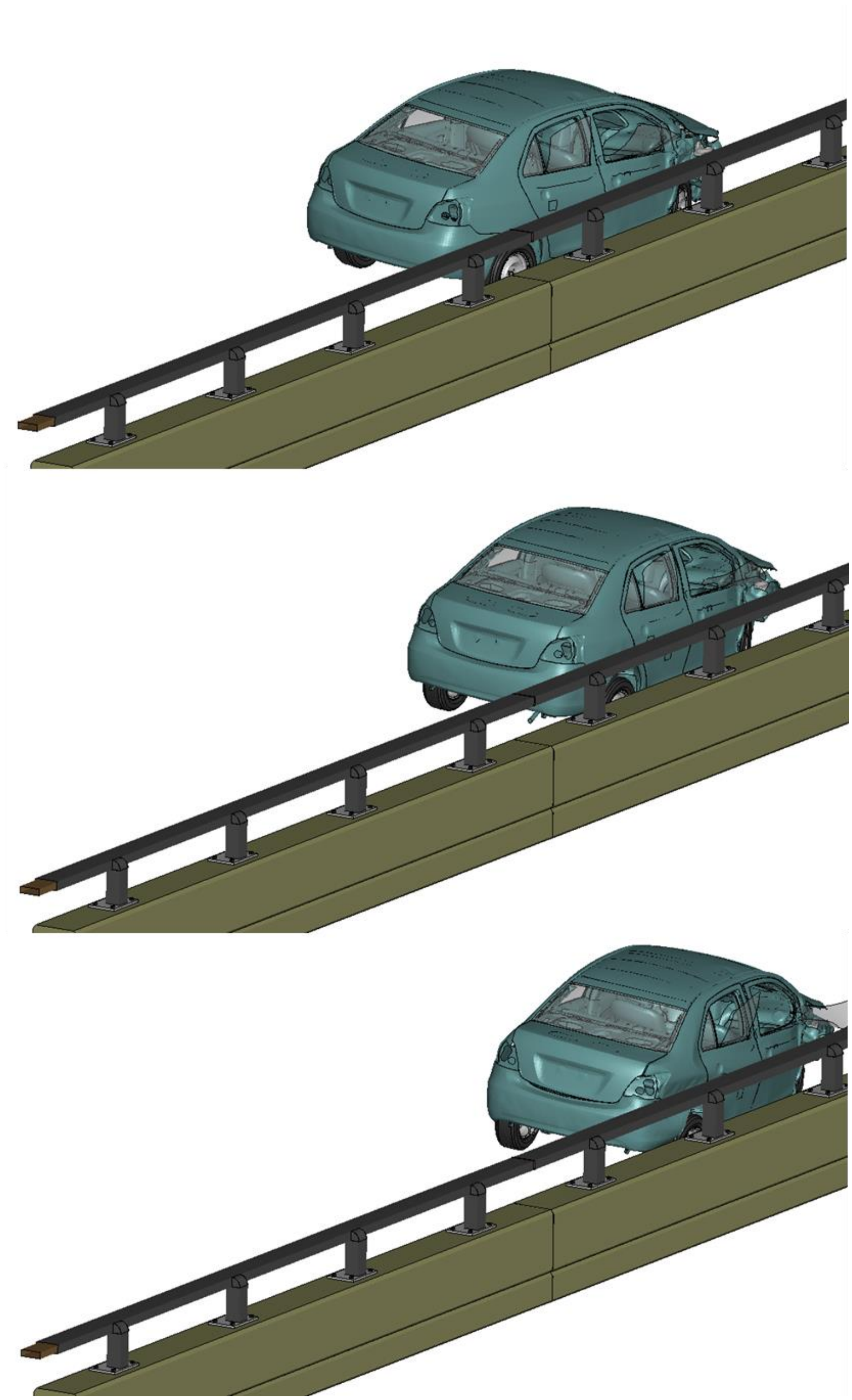

Figure G-6. [Continued] Sequential views from analysis of MASH Test 3-10 CSCM at IP02 on CM-MTL3 Bridge Rail with Vertical Face Design from an oblique viewpoint.