Crash Performance Evaluation of MassDOT and NETC Steel Bridge Rail and Transition Designs Using FEA

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NETC Symposium June 19, 2019

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Background

- Sunset date for MASH implementation for bridge rails and transitions is December 31, 2019.
- Currently, New England DOTs are specifying steel bridge rails that were tested, or otherwise approved, under previous test standards (e.g., NCHRP Report 350 or AASHTO GSBR).
- There are some NCHRP and pooled fund initiatives to evaluate bridge rail, but it is unknown if any of these systems will be included.
- Further, a recent NCHRP 20-07/Task 395 study concluded that several existing NETC systems do not meet MASH – (i.e., can't not be "grandfathered").
- It was of interest to determine if these existing systems meet the new crash testing standards of *MASH*, which involve higher impact severities for each of the required test cases; and, if not, what design changes are needed to meet those requirements.

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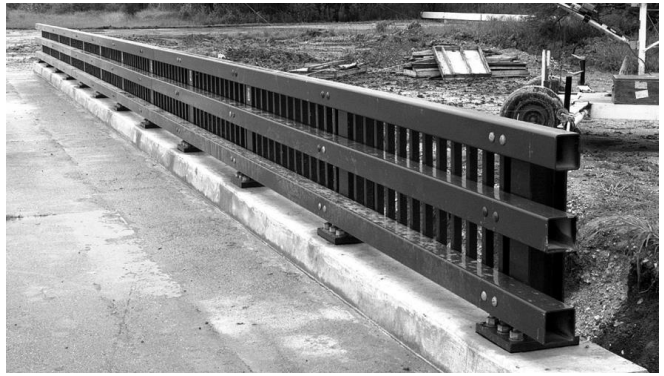
Objectives

- The objectives were to use FEA (computer simulation) to evaluate the crash performance of various MassDOT and NETC bridge rail and Transition designs under MASH testing conditions and criteria.



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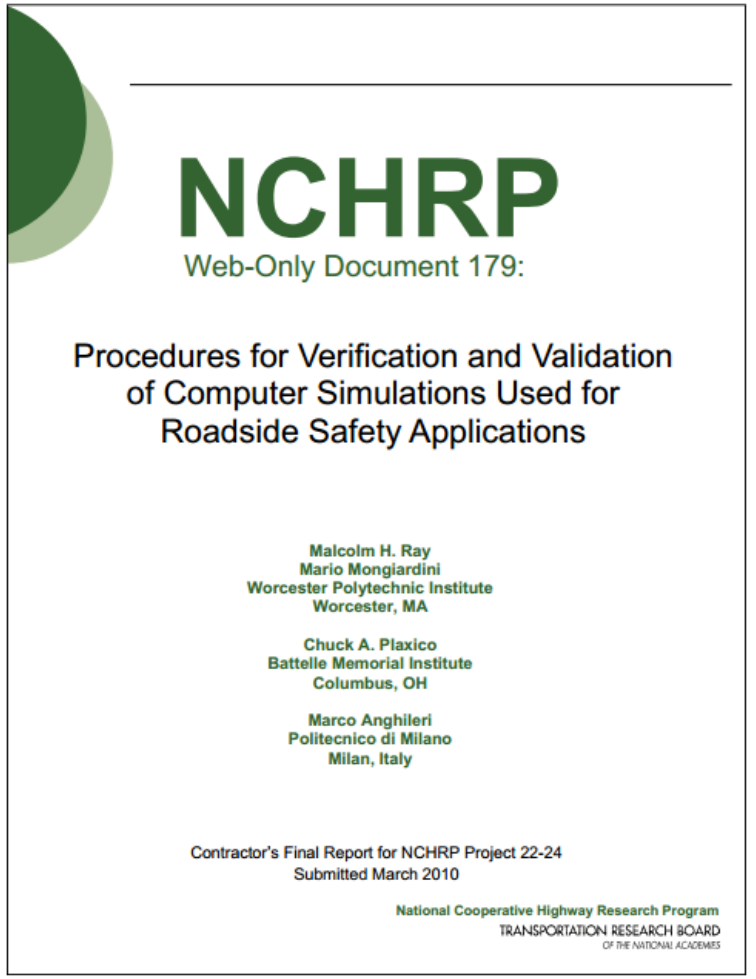
Research Approach

The basic approach for the study was to:

- Develop finite element models of existing hardware.
- Validate the models using the procedures outlined in NCHRP Web Document 179 by comparing results to existing full-scale crash tests on the system.
- Update models to include MASH vehicle types and impact conditions
- And then use FEA to simulate MASH TL4 tests and evaluate the system's performance.


NCHRP

Web-Only Document 179:

Procedures for Verification and Validation of Computer Simulations Used for Roadside Safety Applications

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Contractor's Final Report for NCHRP Project 22-24
Submitted March 2010

National Cooperative Highway Research Program
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MASH Test Level 3 and 4

- *MASH* specifies two **(2) tests** for assessing **TL-3 performance** and three **(3) tests** for assessing **TL-4 crash performance** for bridge rails and transitions:

Test Level 4

Test Level 3

- ***Test 3-10/3-20***: Involves a 2425-lb passenger car (1100C vehicle) impacting the critical impact point at a nominal speed and angle of 62 mph and 25 degrees. Test optional for transitions.
- ***Test 3-11/3-21:*** Involves a 5,000-lb ½-ton quad-cab pickup truck (2270P vehicle) impacting the critical impact point at a nominal speed and angle of 62 mph and 25 degrees.
- ***Test 4-12/4-22:*** Involves a 22,000-lb single unit truck (SUT) (10,000S vehicle) impacting the critical impact point at a nominal speed and angle of 56 mph and 15 degrees.

1100C

2270P

10000S

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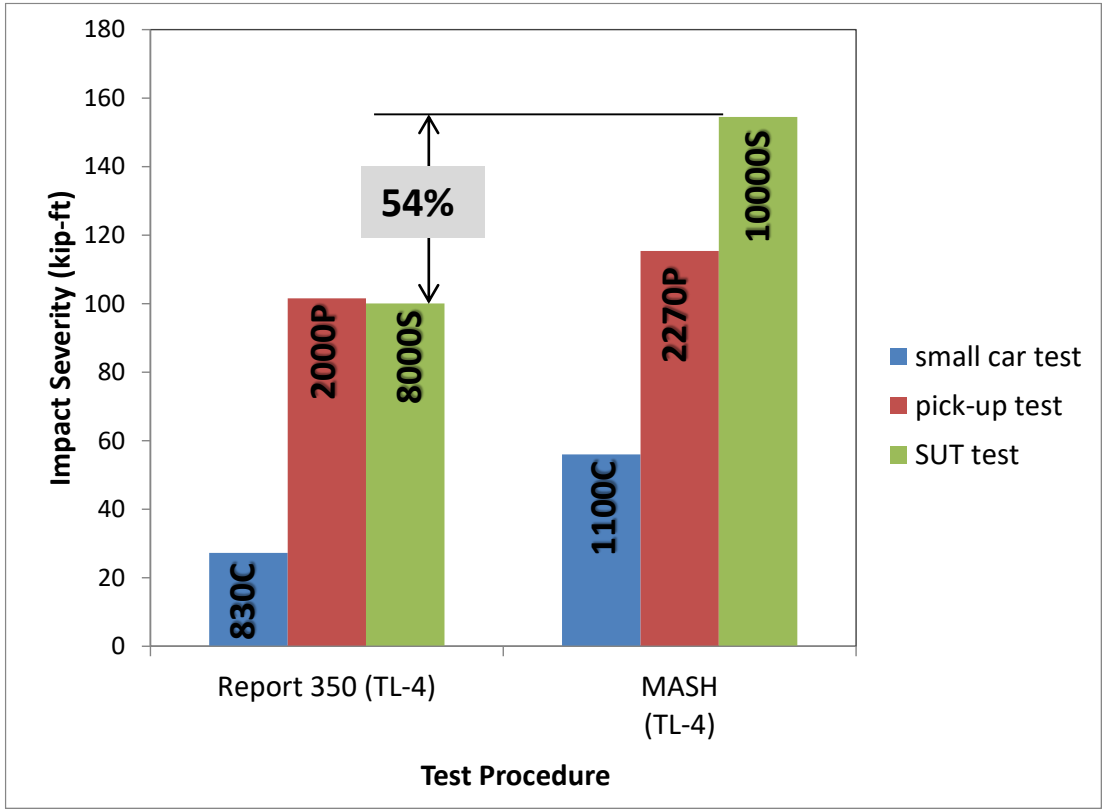
Comparing Impact Severity (Report 350 and MASH)



Test Vehicles		
Report 350		MASH
830C 1.8 kip 62 mph 20 deg.		**1100C** 2.4 kip 62 mph 25 deg.
2000P 4.4 kip 62 mph 25 deg.		**2270P** 5.0 kip 62 mph 25 deg.
8000S 18 kip 50 mph 15 deg.		**10000S** 22 kip 56 mph 15 deg.

33% > mass

25% > angle

14% > mass

22% > mass

12% > speed

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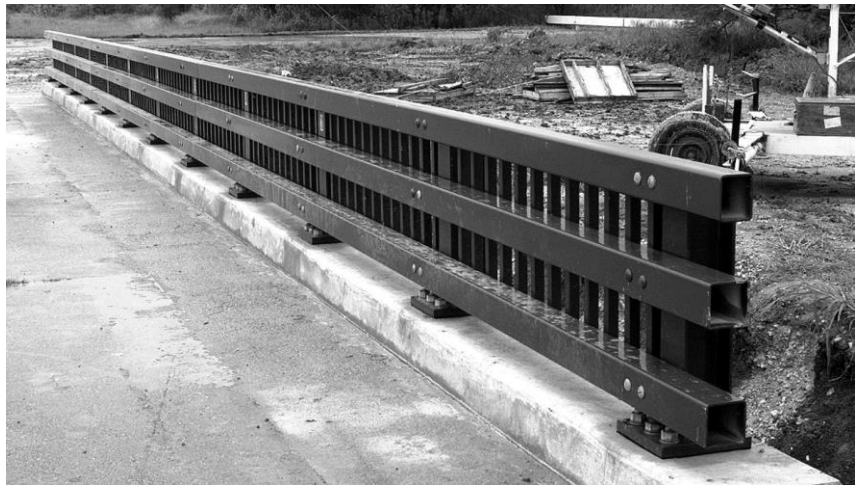
MassDOT 3-Bar Bridge Rail S3-TL4

Two design options were evaluated:

1. Curb-mounted option in which the bridge rail was mounted onto the top of an 8-inch tall concrete curb, and
2. Sidewalk-mounted option in which the bridge rail was mounted onto the top of a 5-ft wide sidewalk with an 8-inch curb face.



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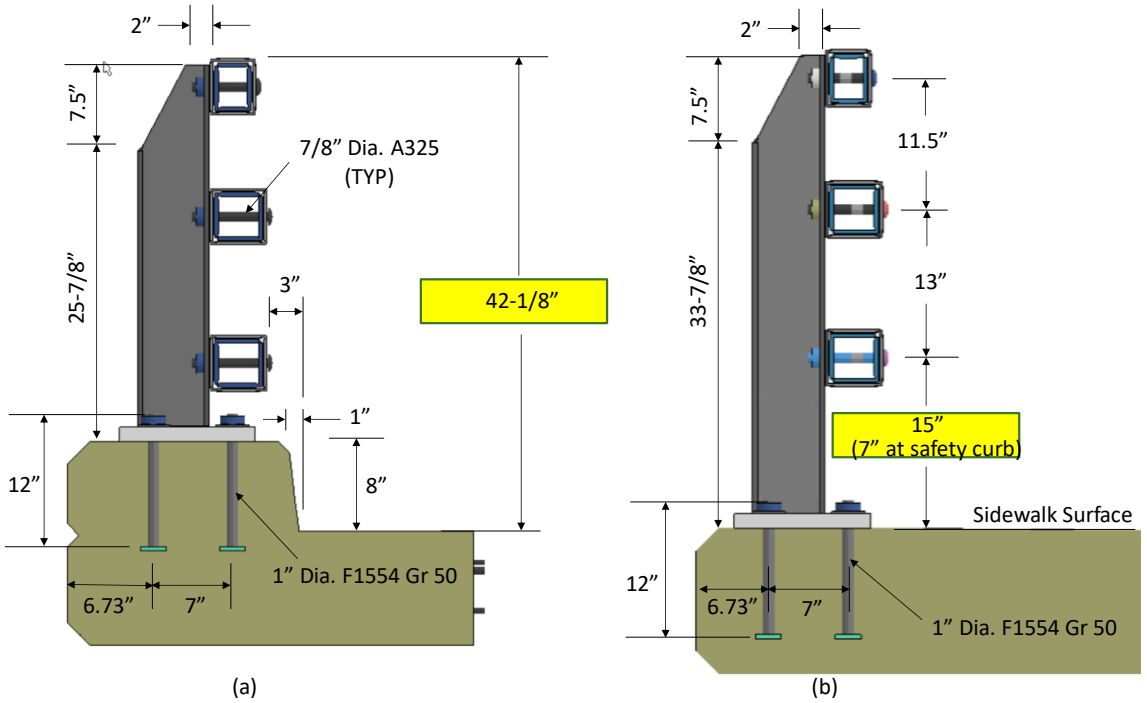
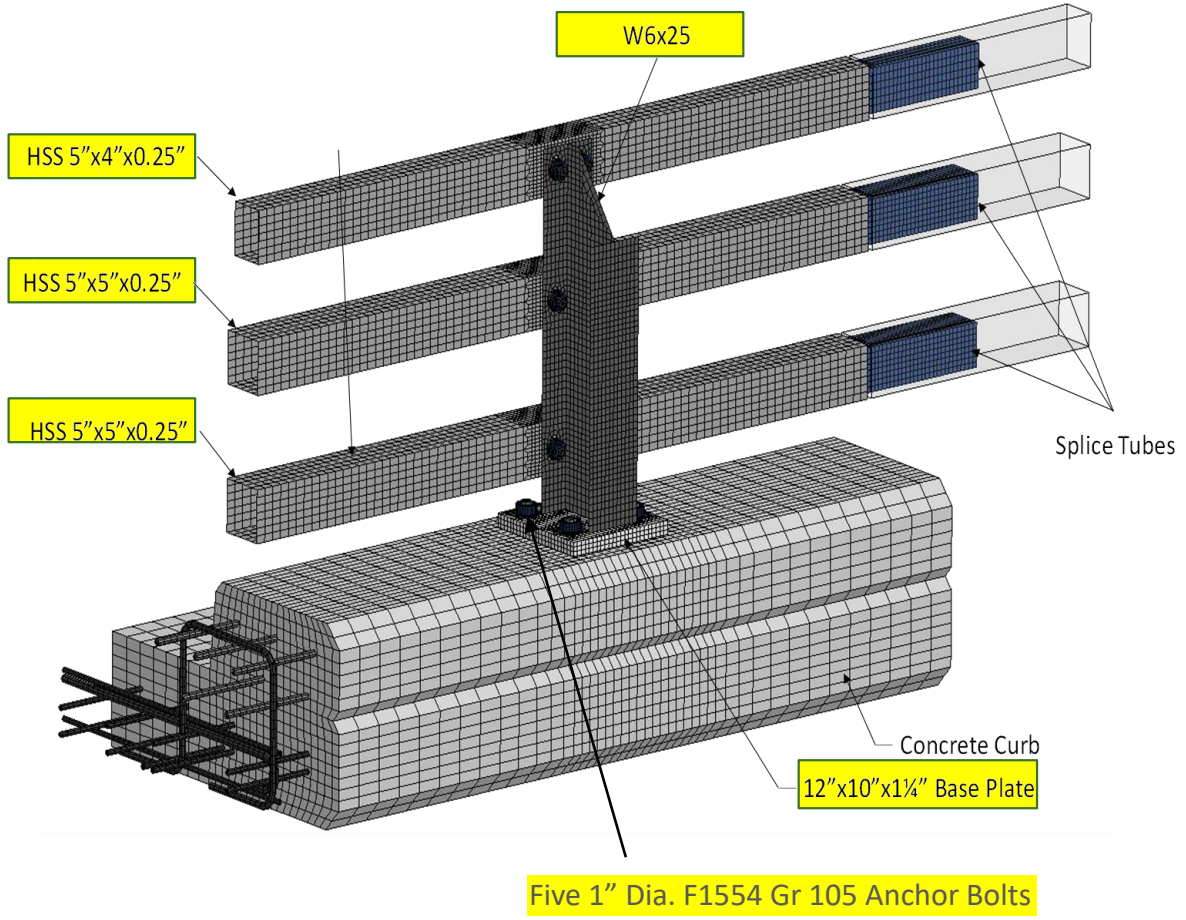
S3-TL4 Bridge Rail FEA Model





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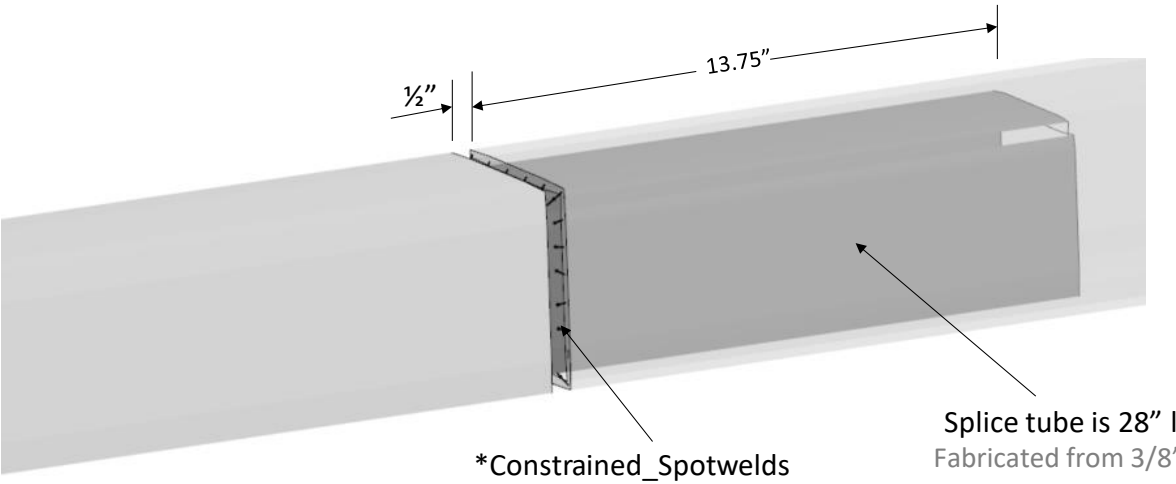
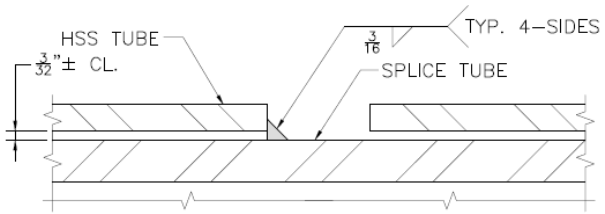
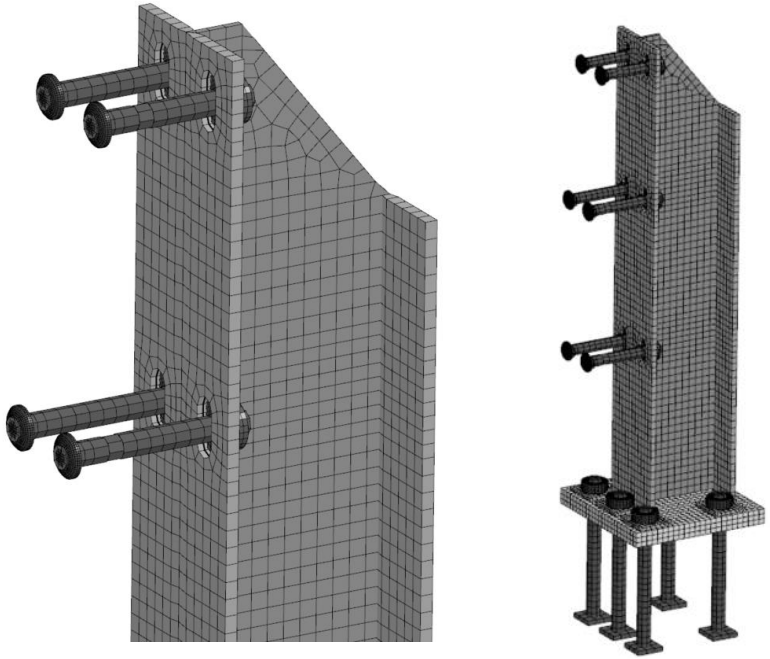
Component Models

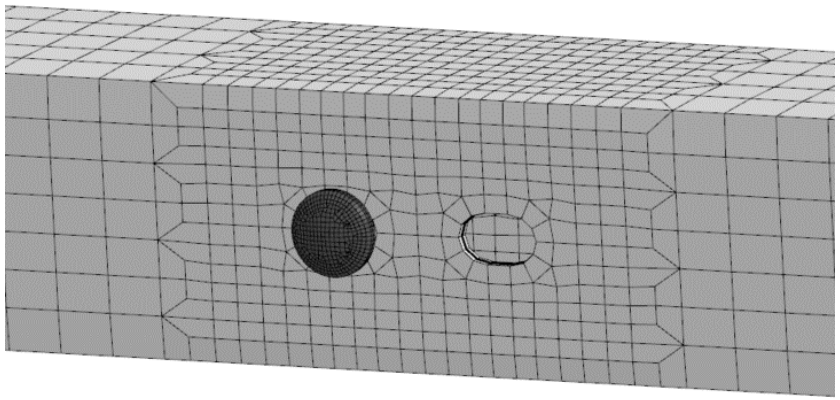


Splice Model

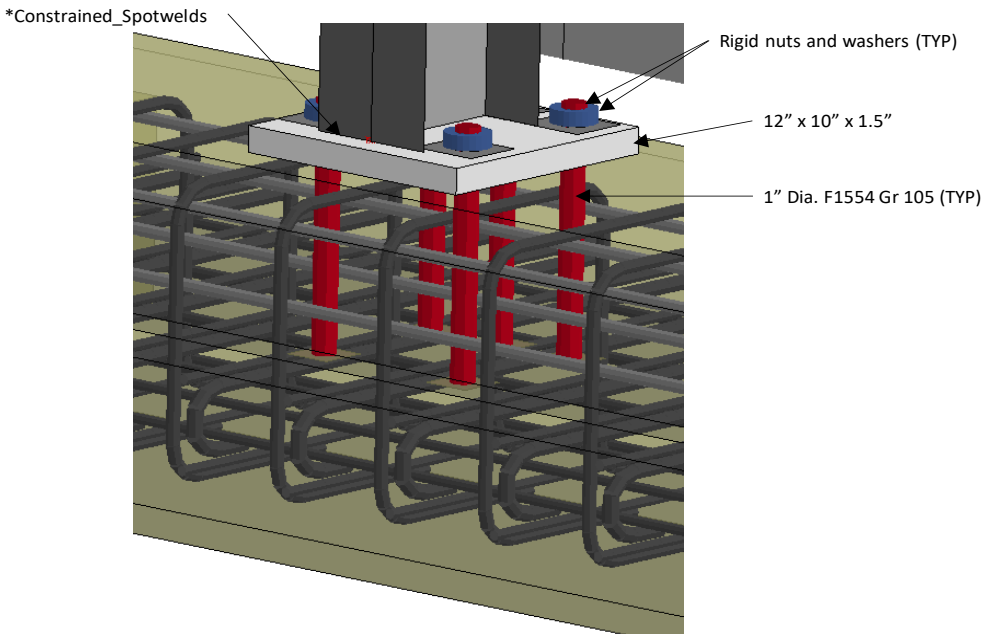




Post and Base Plate Model

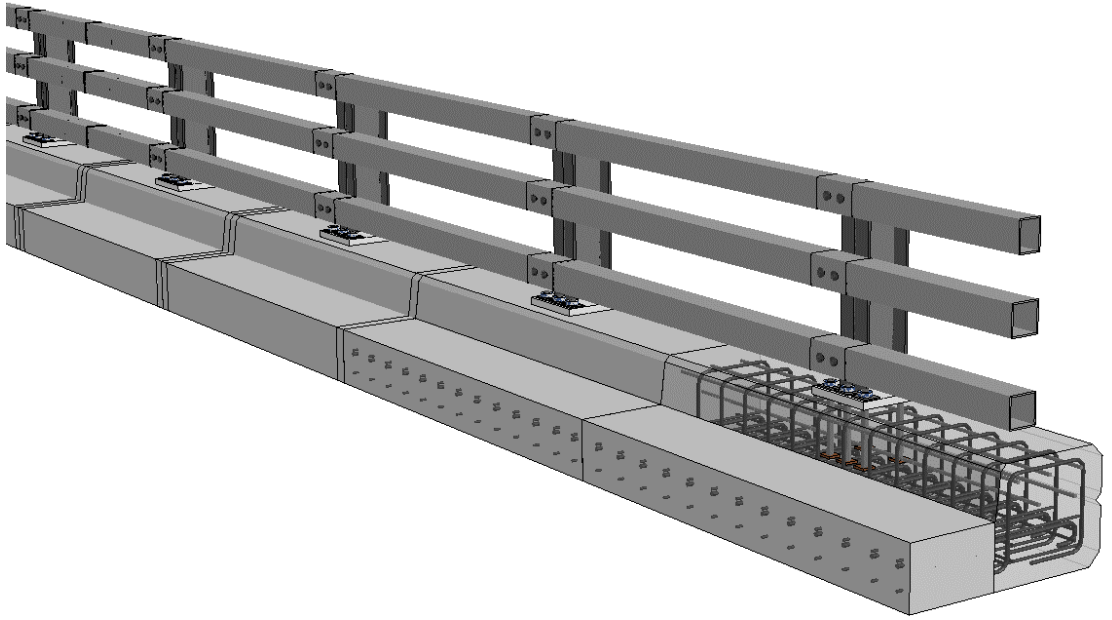


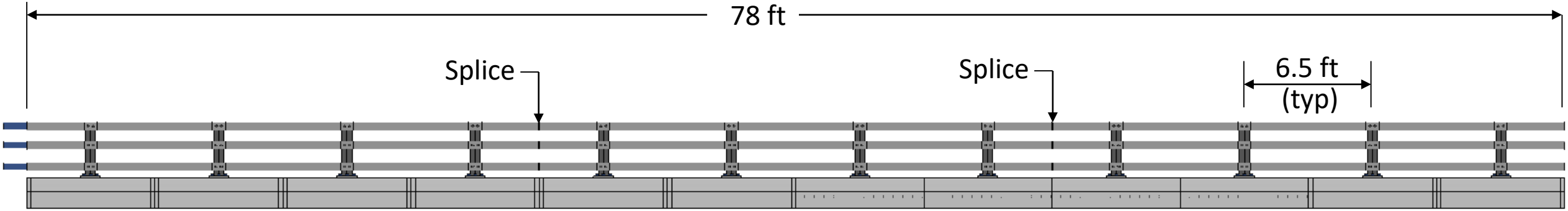
Tube Rail Model



Bridge Rail FEA Model

- A 78-ft section of the S3-TL4 bridge rail was developed
- Post spacing was set to maximum allowable
- Included two splice connections





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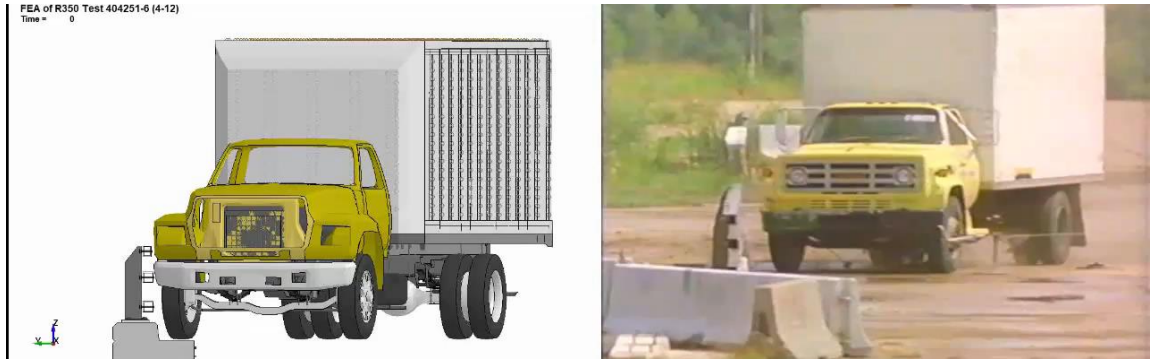
Model Validation with Previous Full-Scale Tests

- The available full-scale test data for the validation task included tests performed according to NCHRP *Report 350*:
  - **Sidewalk-Mounted:**
    - Test 404251-3 (Test 4-12): 8000-kg single unit truck (SUT) test on sidewalk-mounted system
  - **Curb-Mounted:**
    - Test 404251- 6 (Test 4-12): 8000-kg SUT test on curb-mounted system.

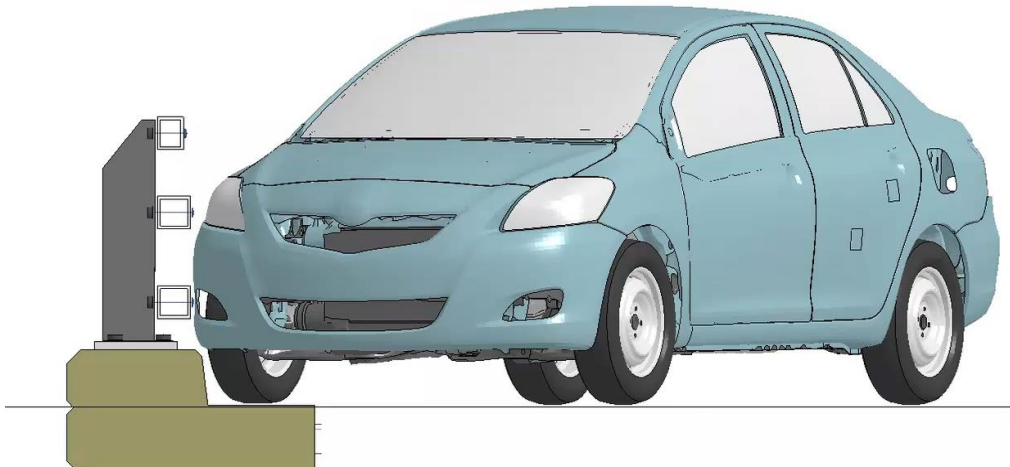


Final Report: http://www.roadsafellc.com/MADOT/S3-TL4/Final_Report/_FinalReport_MDOT-X129053P11_190429.pdf

MASH FEA Results for Curb-Mounted S3-TL4

Test 4-10

- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 3.6 ft upstream from critical Post



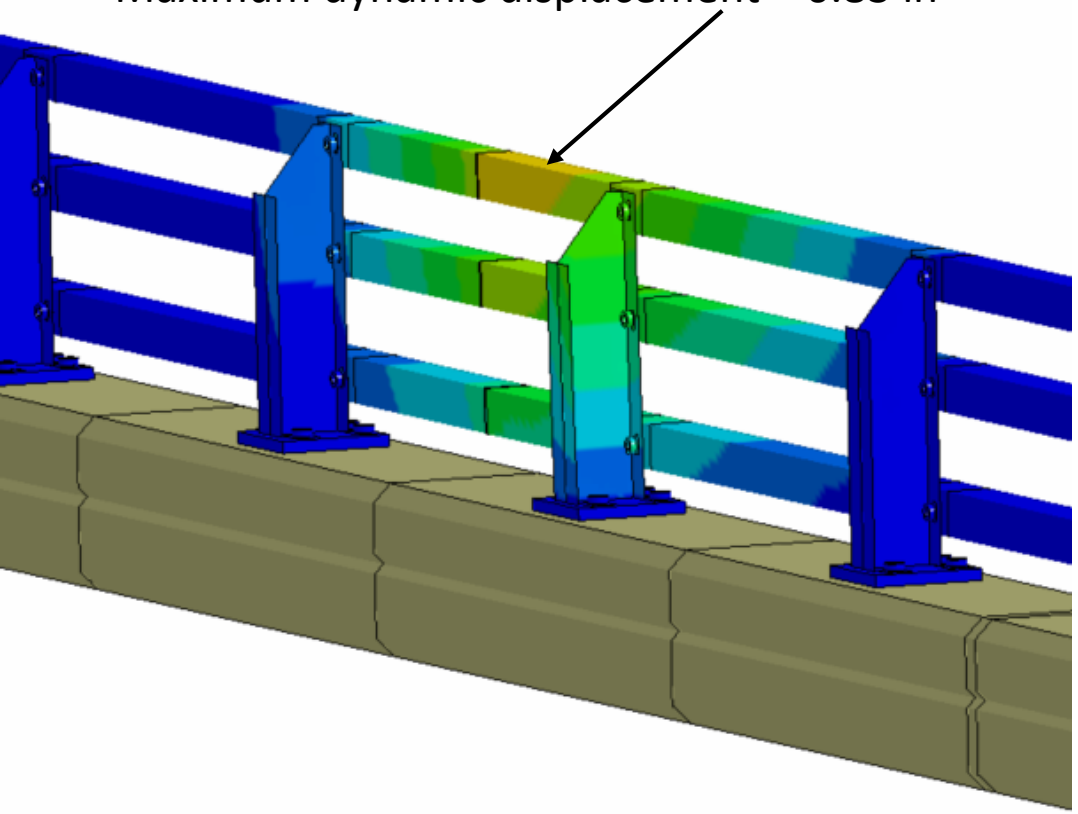
Test 4-11

- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 4.3 ft upstream from critical Post

Barrier Deflections

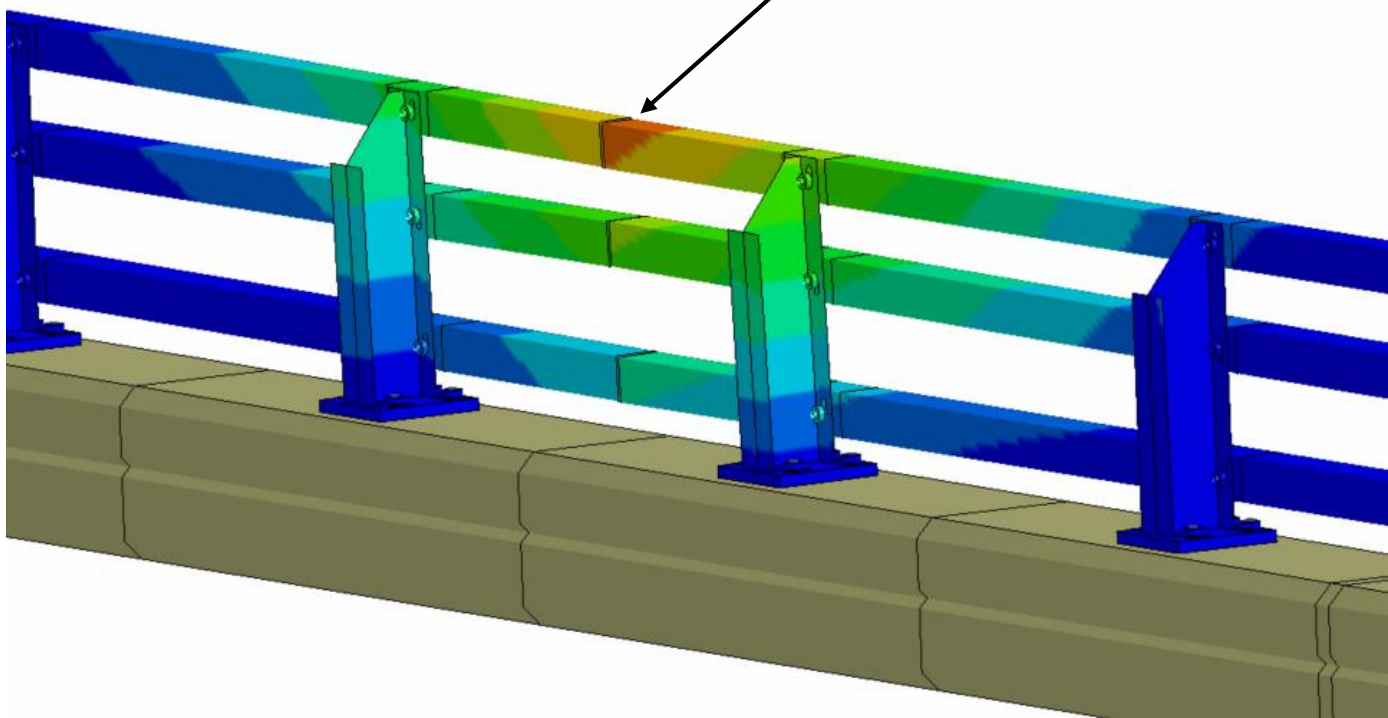
Test 4-10
(small car)

Maximum dynamic displacement = 0.83 in



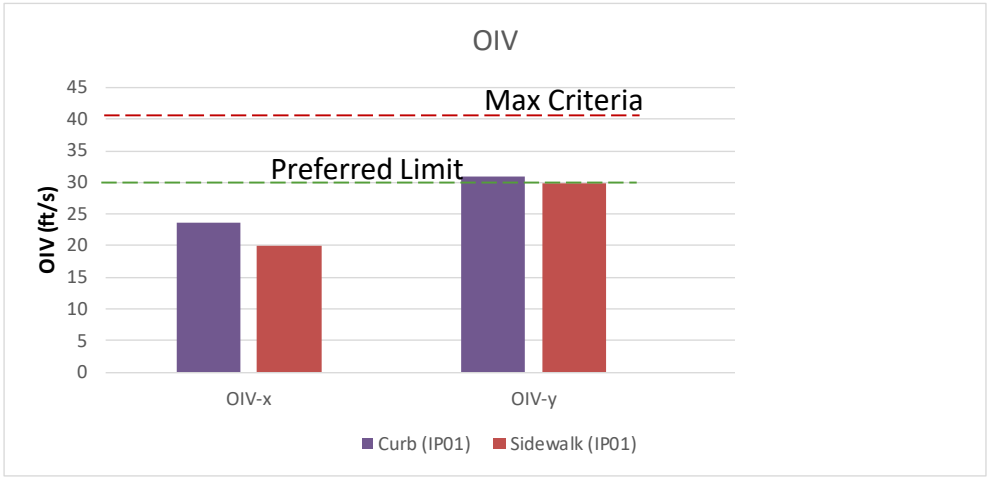
Test 4-11
(pickup)

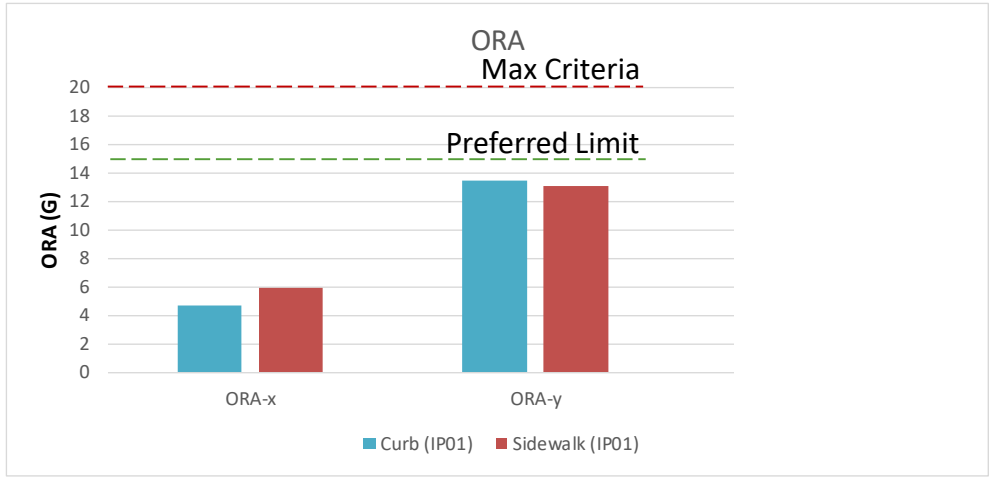
Maximum dynamic deflection = 1.73 in



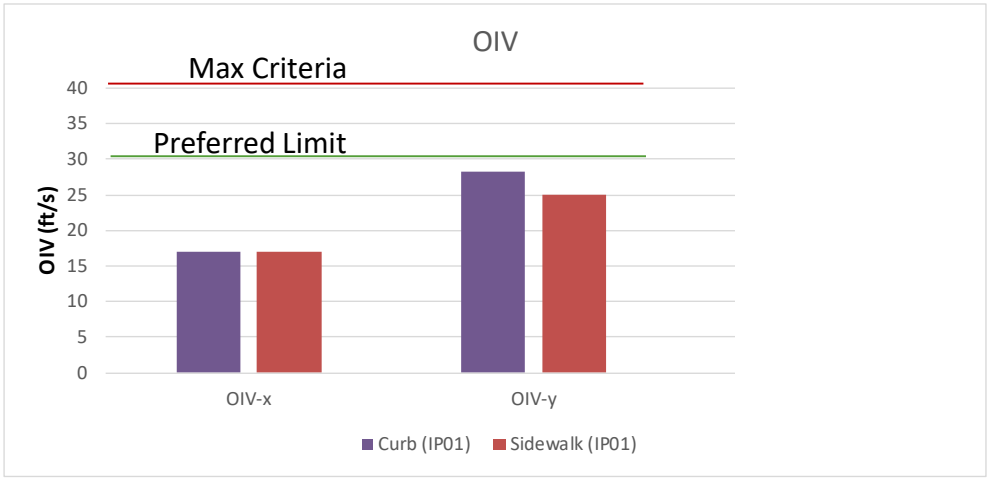
Occupant Risk Metrics

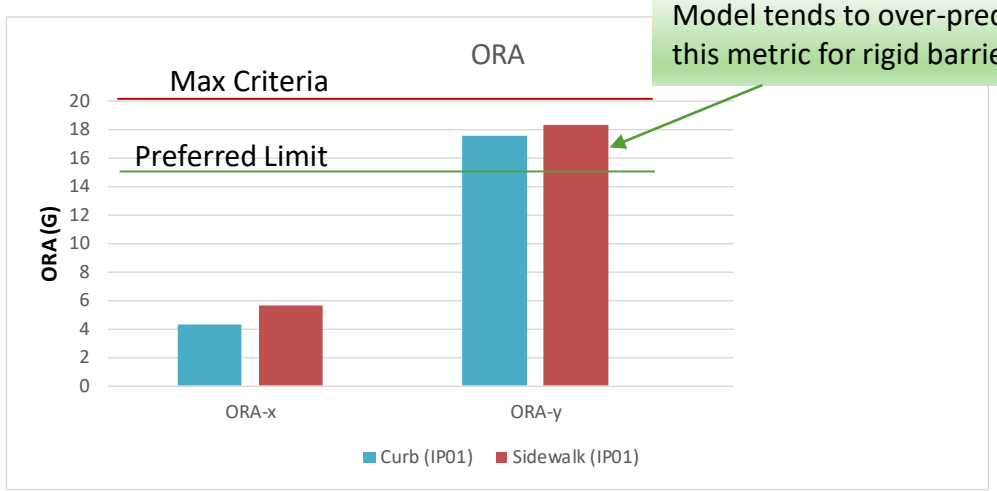
Test 4-10
(small car)





Test 4-11
(pickup)





Model tends to over-predict this metric for rigid barriers

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Conclusions for Overall Barrier Performance

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 with a preferred limit of 30 ft/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

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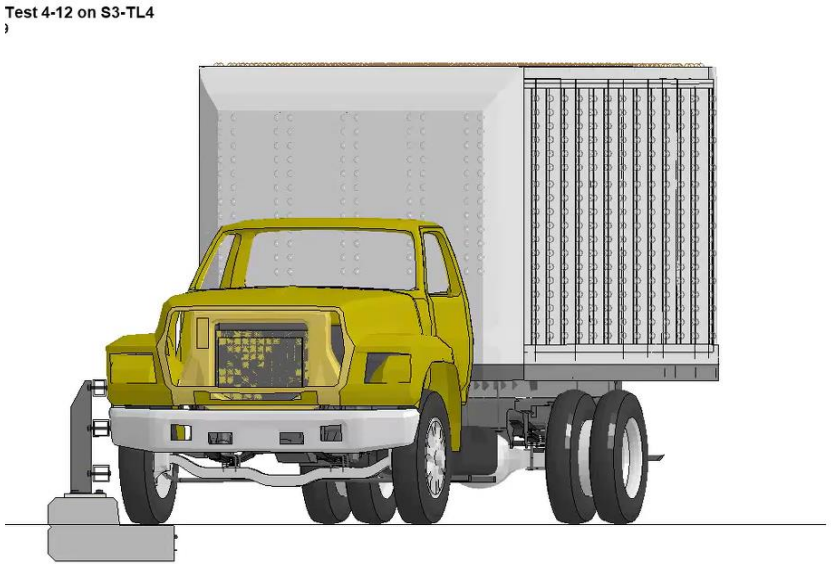
Results for Curb-Mounted S3-TL4

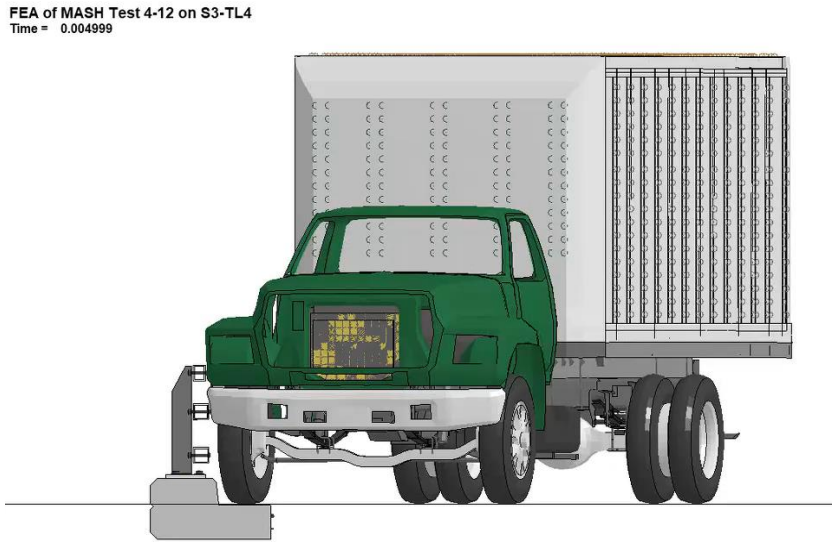
Test 4-12 (Case 1)

- Impact Speed = 56 mph
- Impact Angle = 15 degrees
- Impact Point = 5.0 ft upstream from critical Post
- Bed Height = 47.5” (e.g., Ford F800)
- Post Yield = 51 ksi



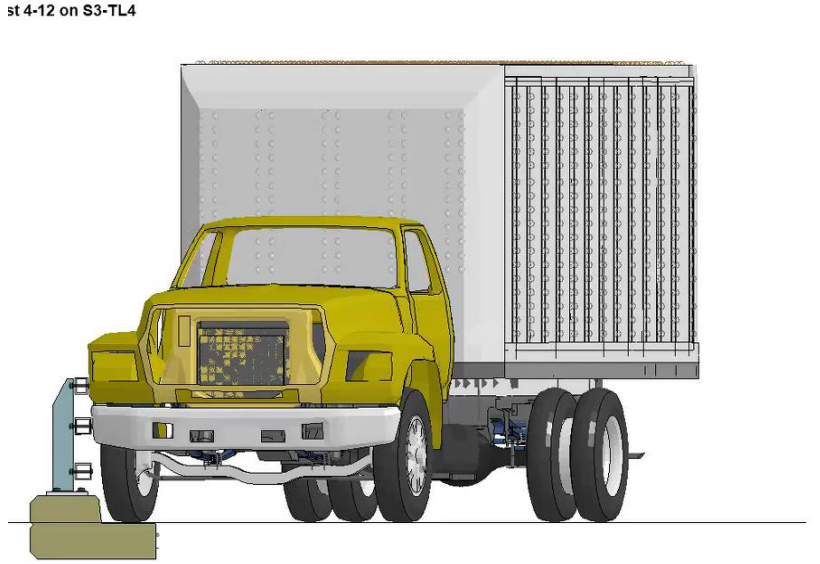
Test 4-12 (Case 2)

- Impact Speed = 56 mph
- Impact Angle = 15 degrees
- Impact Point = 5.0 ft upstream from critical Post
- Bed Height = 50” (e.g., GMC)
- Post Yield = 51 ksi



Test 4-12 (Case 3)

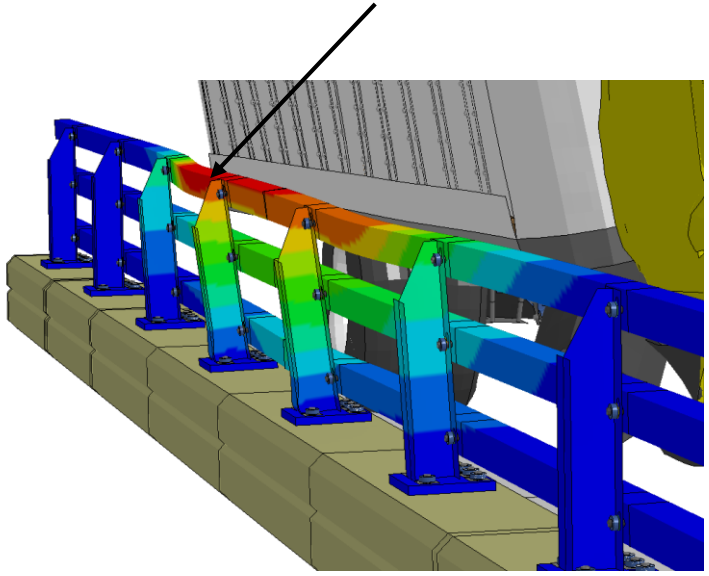
- Impact Speed = 56 mph
- Impact Angle = 15 degrees
- Impact Point = 5.0 ft upstream from critical Post
- Bed Height = 47.5” (e.g., Ford F800)
- Post Yield = 60 ksi



Barrier Deflections

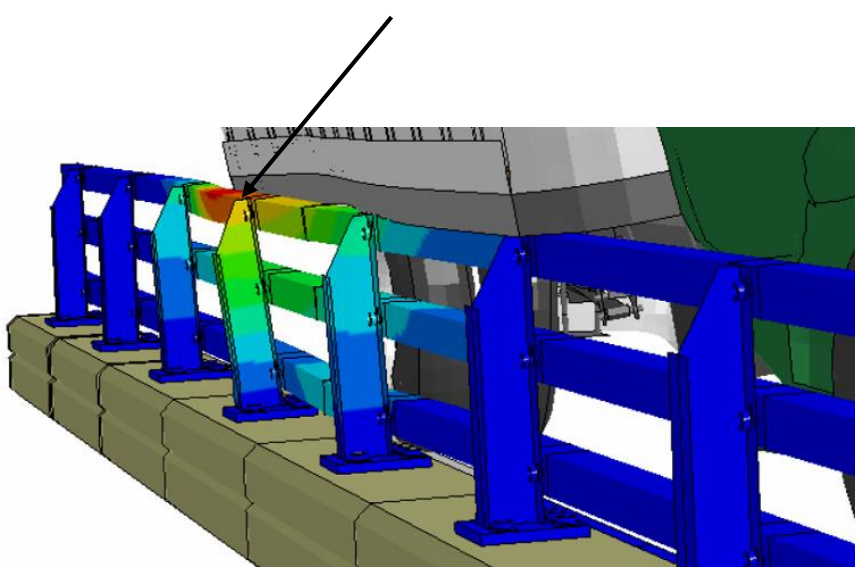
Test 4-12
(Case 1)

Maximum dynamic deflection = 5 in (127 mm)



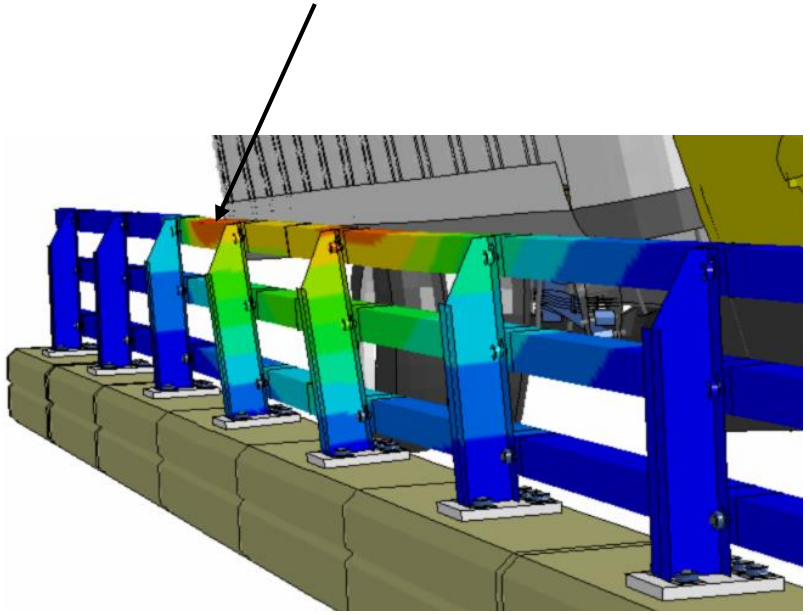
Test 4-12
(Case 2)

Maximum dynamic deflection = 4.5 in (115mm)



Test 4-12
(Case 3)

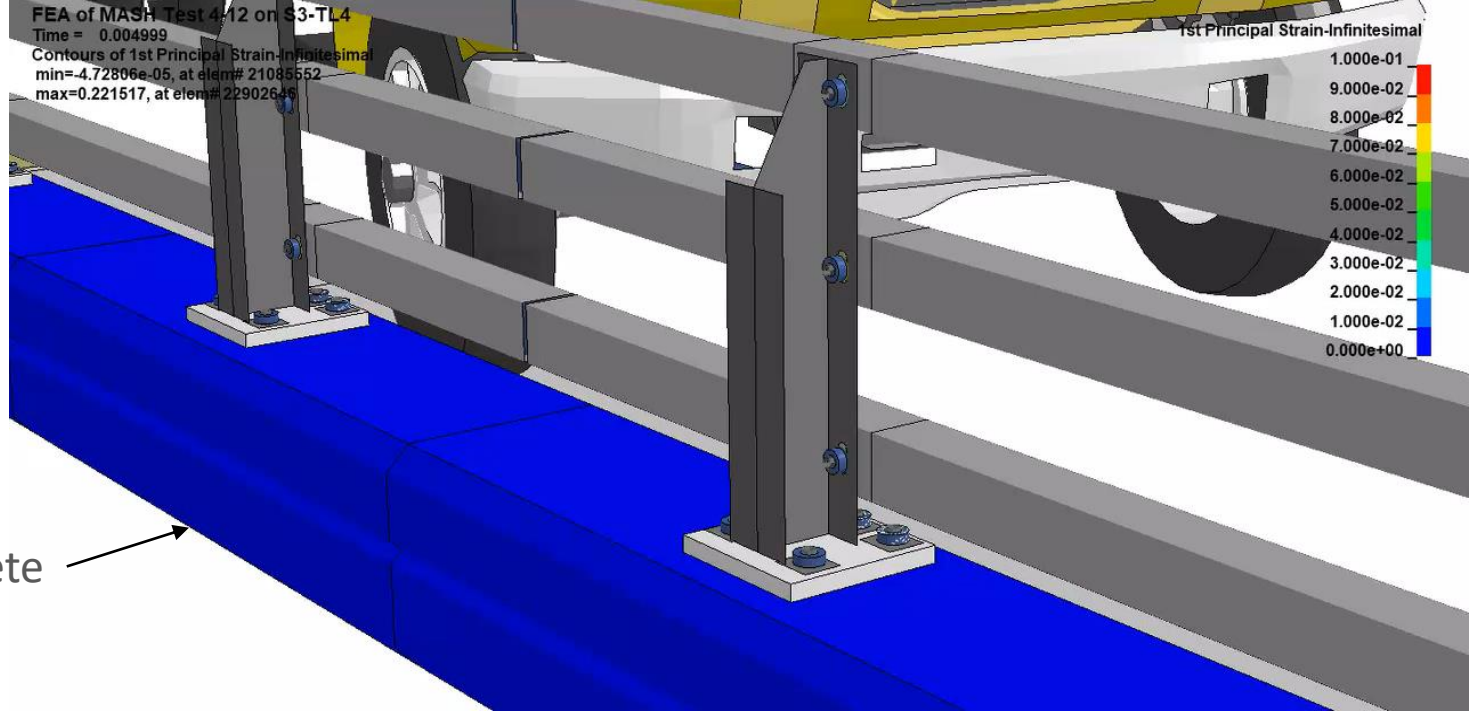
Maximum dynamic deflection = 4.44 in (113 mm)



Curb-Mounted S3-TL4 Test 4-12 Simulation

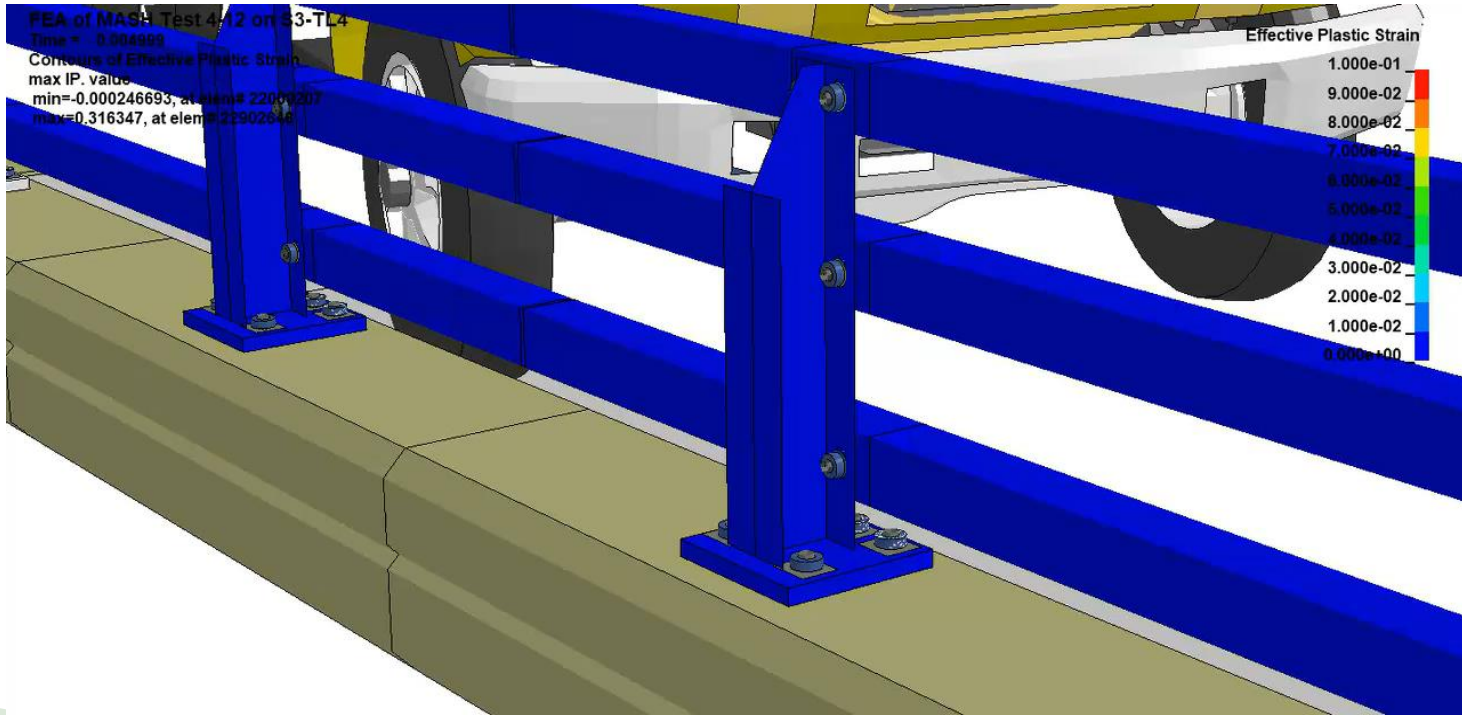
Case 3:
- *47.5” Bed*
- *60 ksi Posts*

- The damage to the concrete was isolated to the front anchor bolts, with the possibility of cracks for the stronger post case.
- The higher strength post, which frequently occurs, increases the loading on the anchor bolts and welds.



4 ksi Concrete

Case 3:
- *47.5” Bed*
- *60 ksi Posts*



Sidewalk-Mounted Transition to Buttress Test 4-22

Conclusions

Evaluation Factors		Evaluation Criteria – MASH Test 4-12	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass
	G	It is preferable, although not essential, that the vehicle remain upright during and after collision.	Pass

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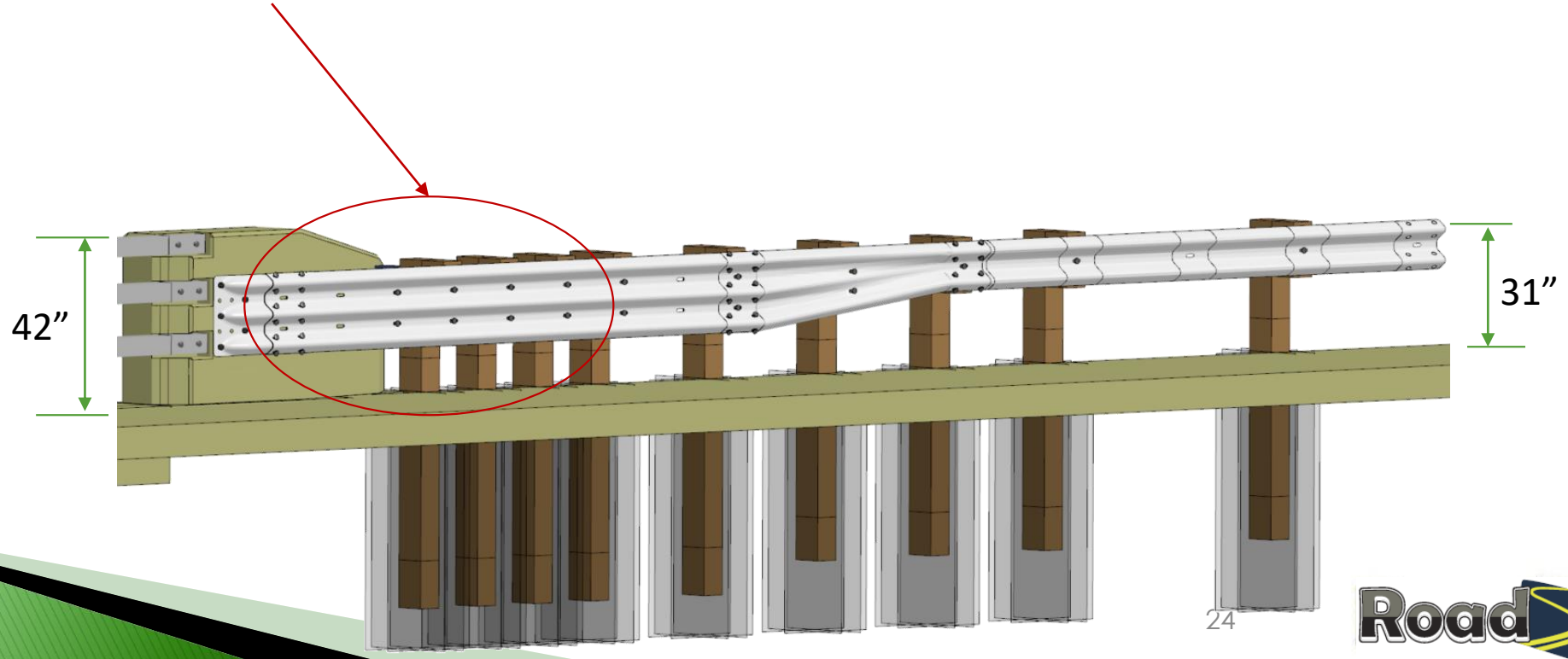
MassDOT Transition

Two design options were evaluated:

1. Curb-mounted option (no photo), and
2. Sidewalk-mounted option with continuous 5-ft wide sidewalk with an 8-inch curb face integral with bridge section.

MassDOT Transition for the S3-TL4

- The AGT system is used to transition from a 31-inch tall w-beam guardrail to a 42-inch tall steel open-faced bridge rail.
- The focus of this evaluation was on the transition to the shaped buttress.



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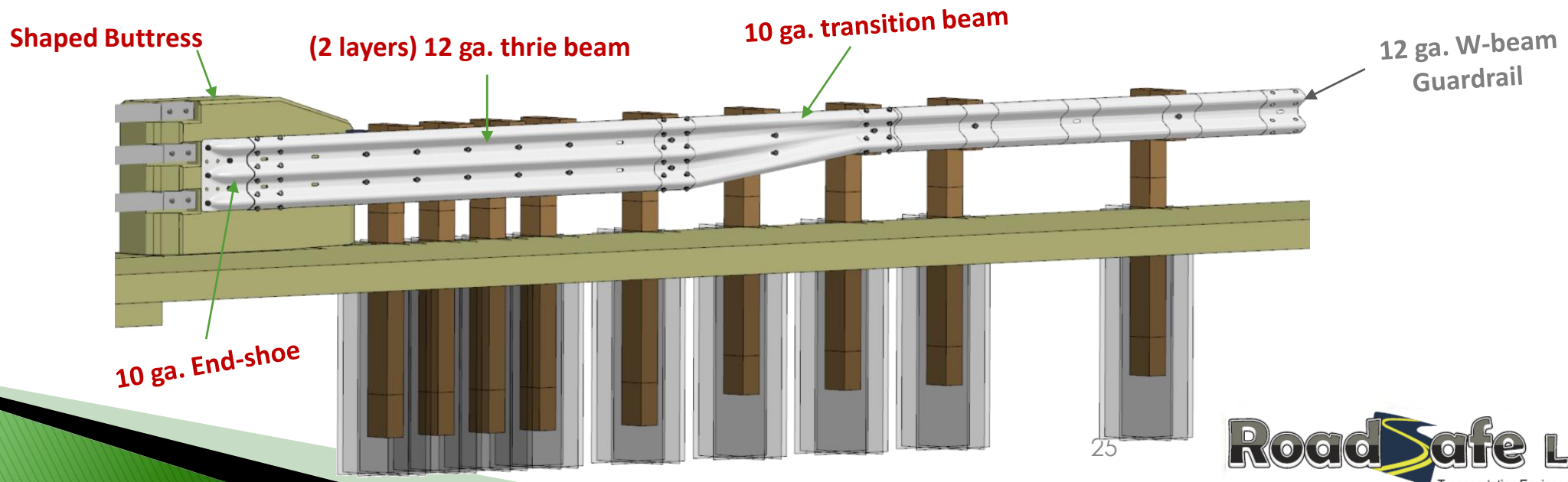
Basic Design

The AGT design includes four primary elements:

1) 10-gauge w-beam to thrie-beam transition with decreased post-spacing,
2) A two-layer, 12-gauge thrie-beam section with further decreased post spacing,
3) 10-gauge terminal connector, and
4) a shaped concrete buttress.



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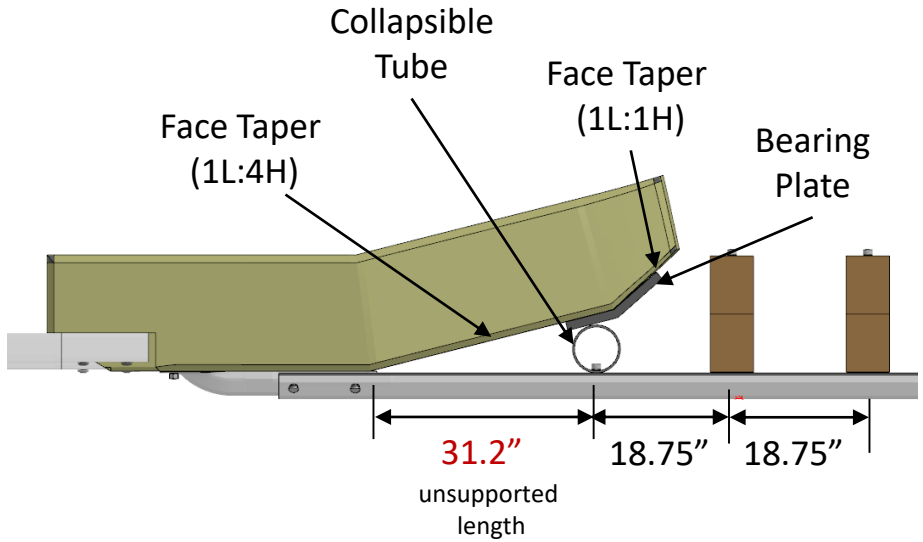
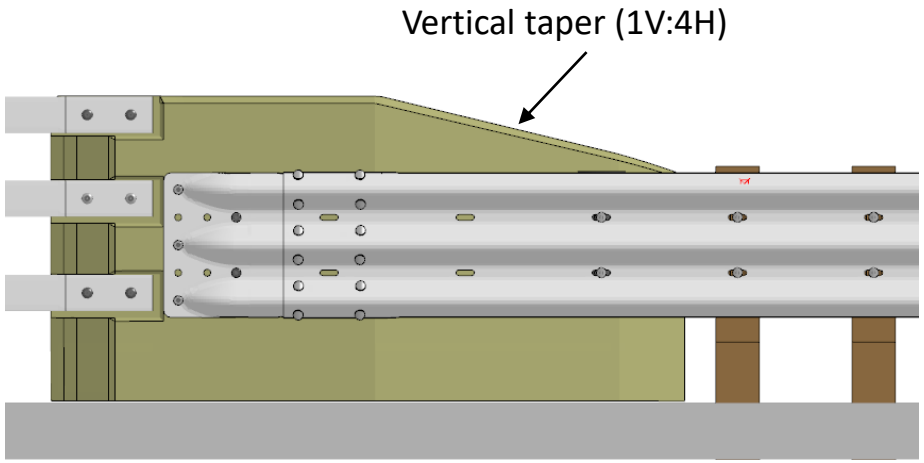
MassDOT Transition

A key aspect of this design is the shaped buttress, which serves to transition from the thrie-beam rail to the bridge rail.

- The top surface on the leading end of the buttress gradually tapers from 31 inches tall at the thrie-beam end to 42 inches tall as it approaches the bridge rail.
- The buttress also includes a double taper on the front face at the leading end to mitigate potential snag points for the vehicle during impacts.
- A collapsible tube spacer block is placed between the thrie-beam and the tapered face.
- The location of the spacer block results in 31.2 inches of unsupported length of thrie-beam between the spacer block and the tangent section of the buttress.





MassDOT Transition

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

Test 401181-2
4/15/2005

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Analysis Matrix

Impact Direction	AGT System	Critical Impact Points		
		Test 4-20	Test 4-21	Test 4-22
Transition to Buttress	Curb-Mounted	3.6 ft	4.3 ft 5.5 ft	5.5 ft
	Sidewalk-Mounted	3.6 ft	4.3 ft 5.5 ft *6.5 ft 7.1 ft	5.5 ft 7.5 ft 10.0 ft 11.0 ft
Bridge Rail to Buttress	Curb-Mounted	-	-	-
	Sidewalk-Mounted	-	4.3 ft	5.0 ft

* Allowing tire deflation

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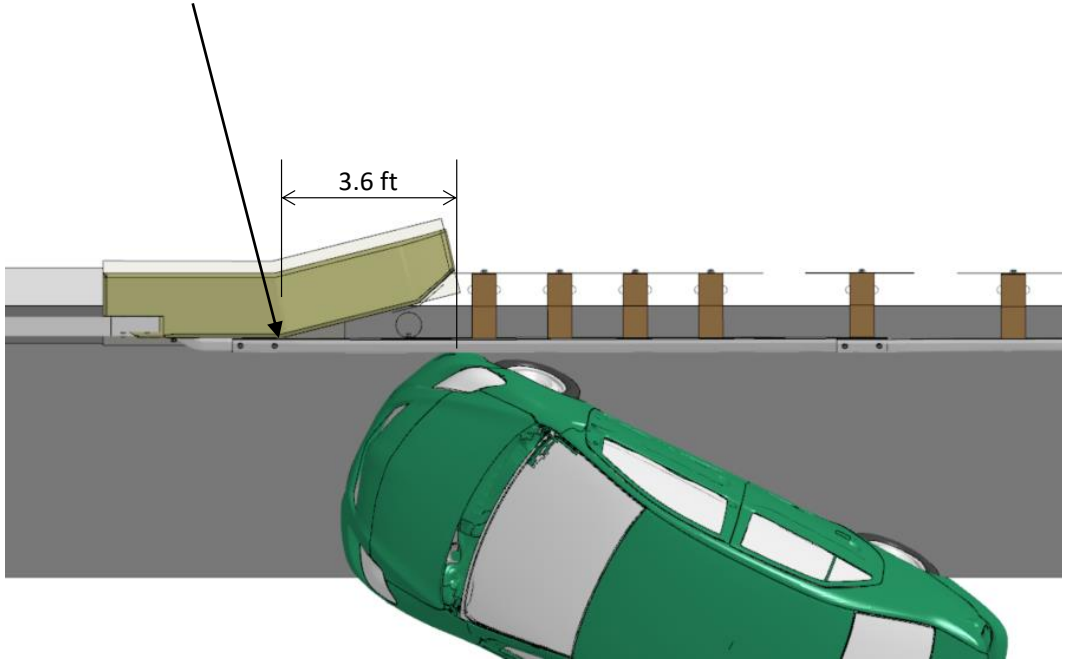
Sidewalk-Mounted Transition to Buttress

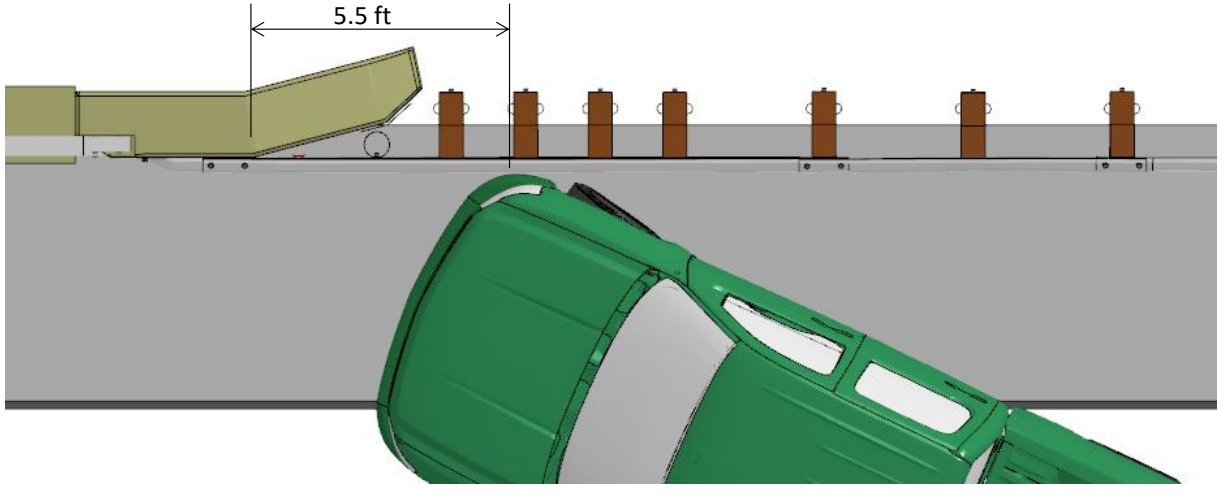
Test 4-20

- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 3.6 ft upstream from tangent breakpoint of buttress



Test 4-21

- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 5.5 ft upstream tangent breakpoint of buttress



Sidewalk-Mounted Transition to Buttress

Test 4-20

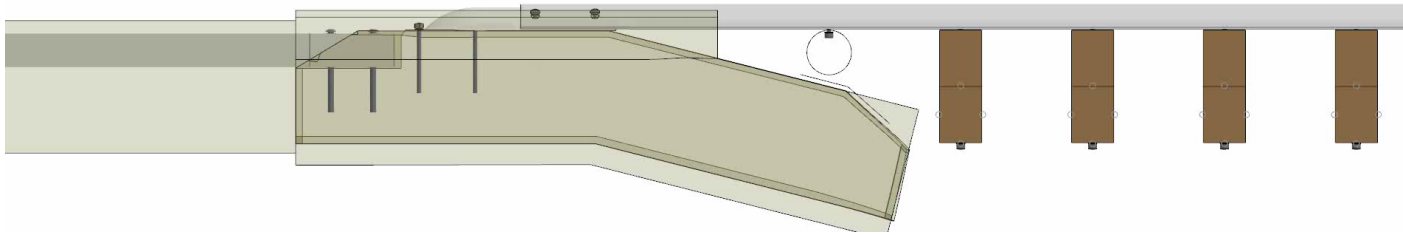
- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 3.6 ft upstream from tangent breakpoint of buttress

Test 4-21

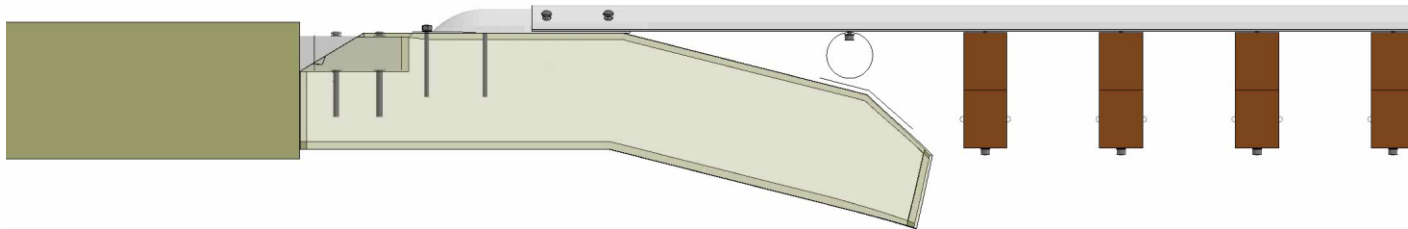
- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 5.5 ft upstream tangent breakpoint of buttress

Sidewalk-Mounted Transition to Buttress

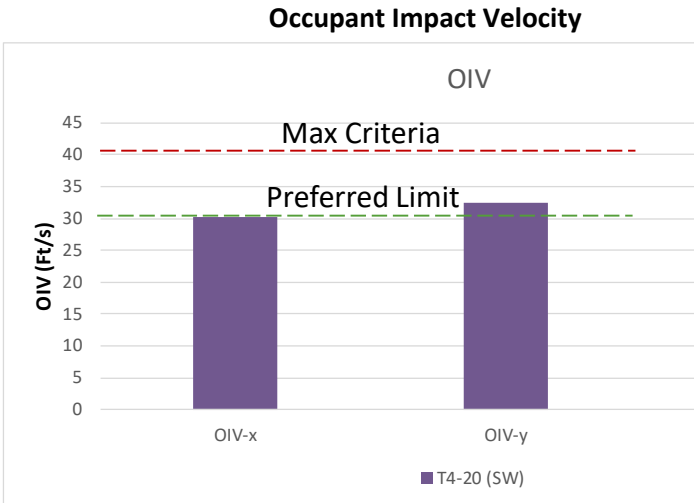
Test 4-20
(small car)

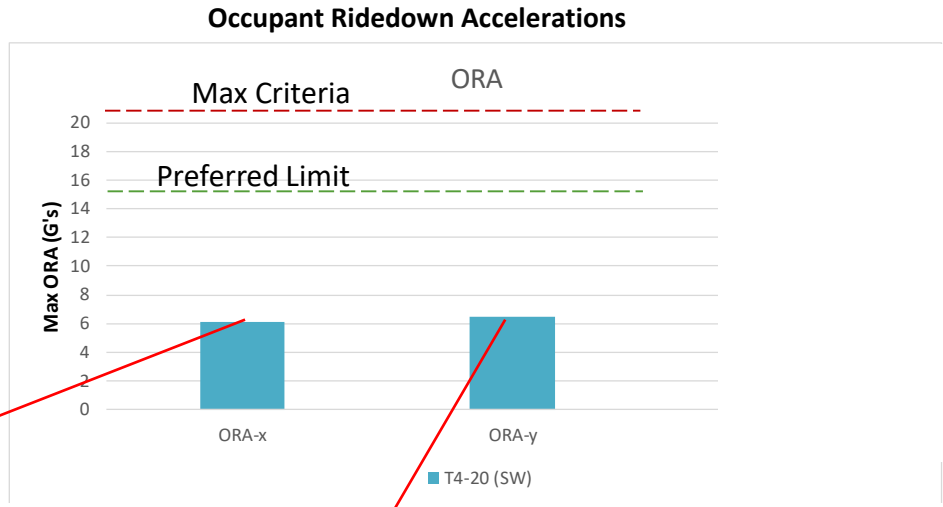


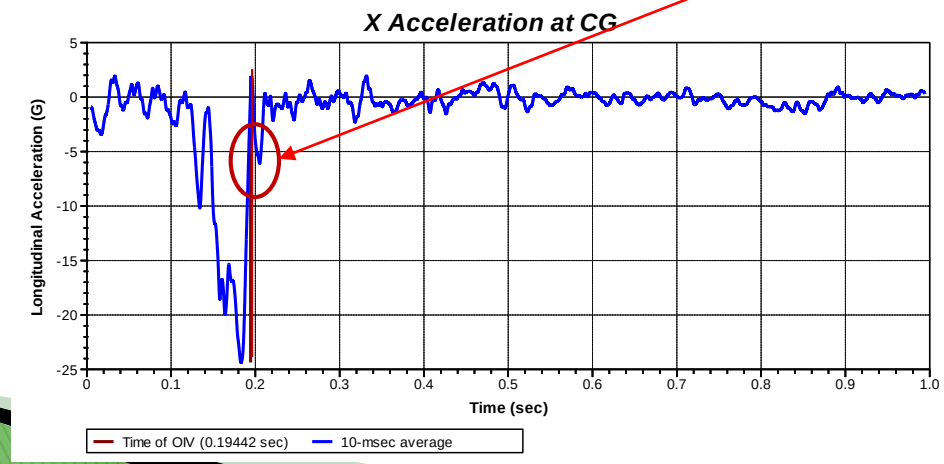
Test 4-21
(pickup)

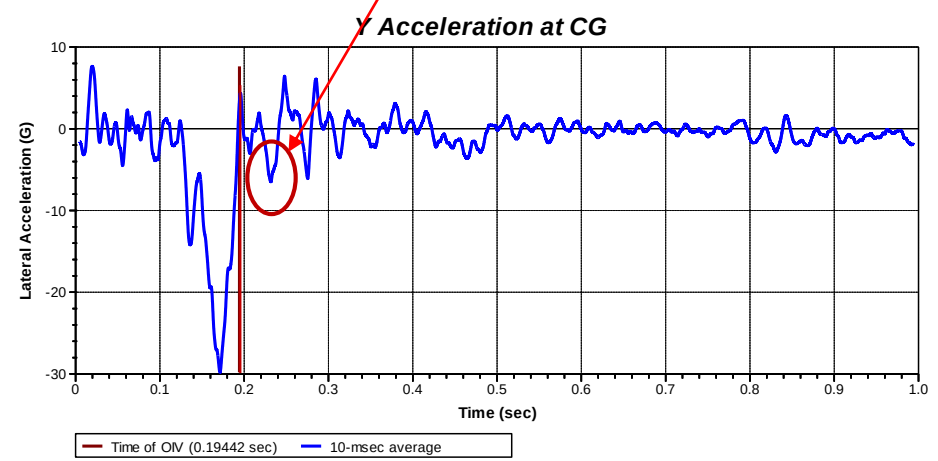


Sidewalk-Mounted Transition to Buttress Test 4-20









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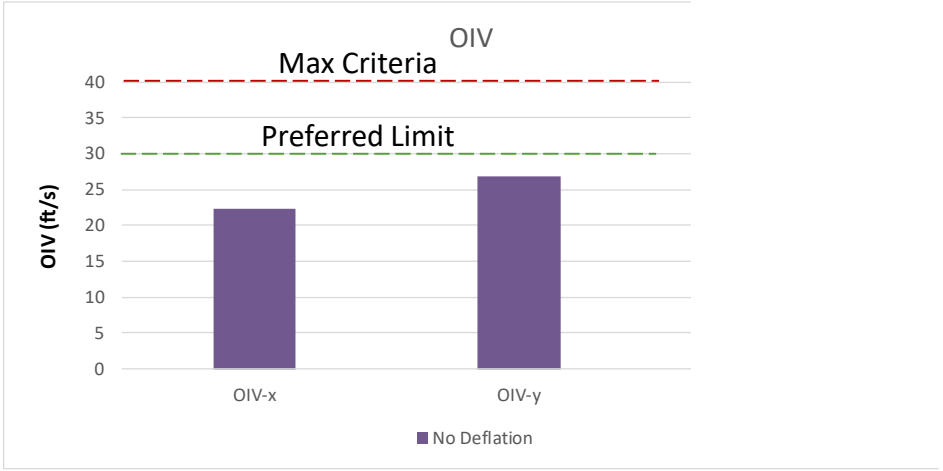
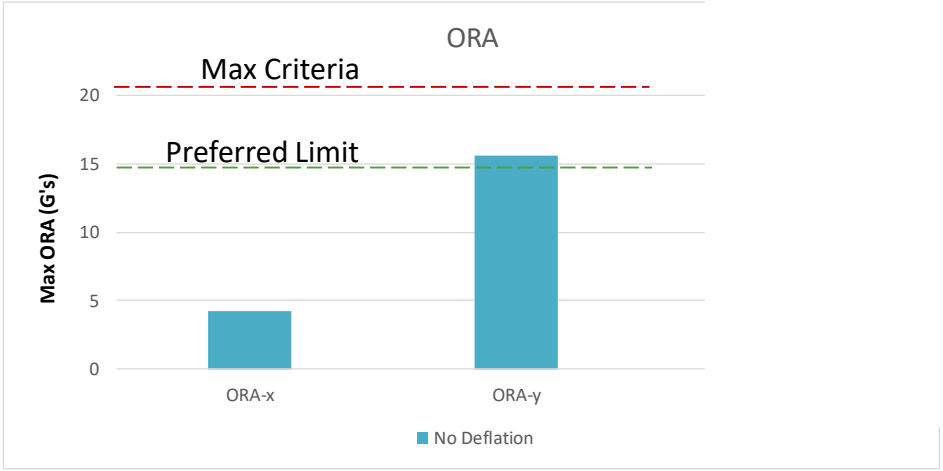
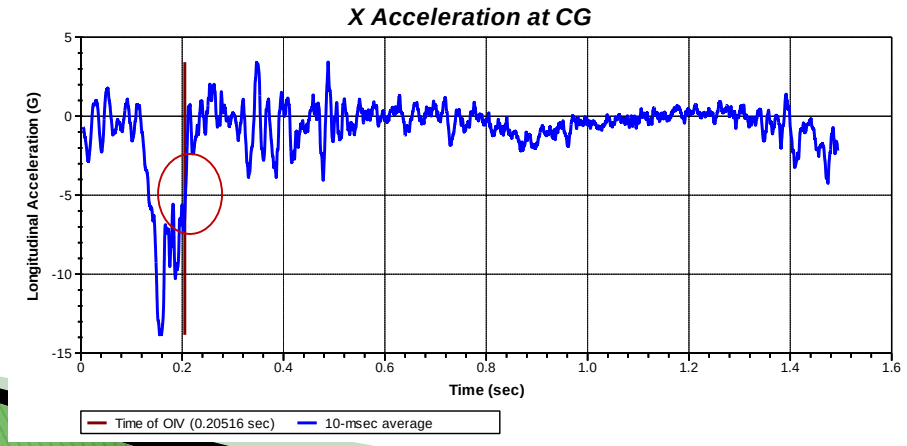
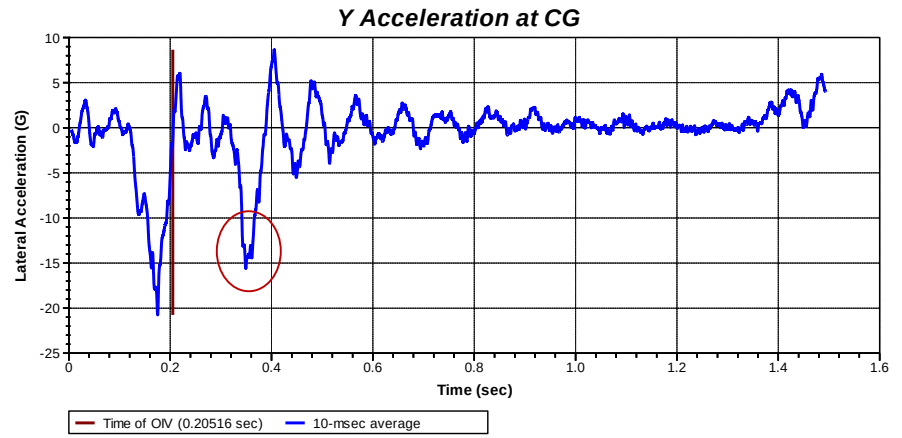
Sidewalk-Mounted Transition to Buttress Test 4-21

Occupant Risk Metrics









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Sidewalk-Mounted Transition to Buttress Test 4-20 and Test 4-21

Conclusions

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 with a preferred limit of 30 ft/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

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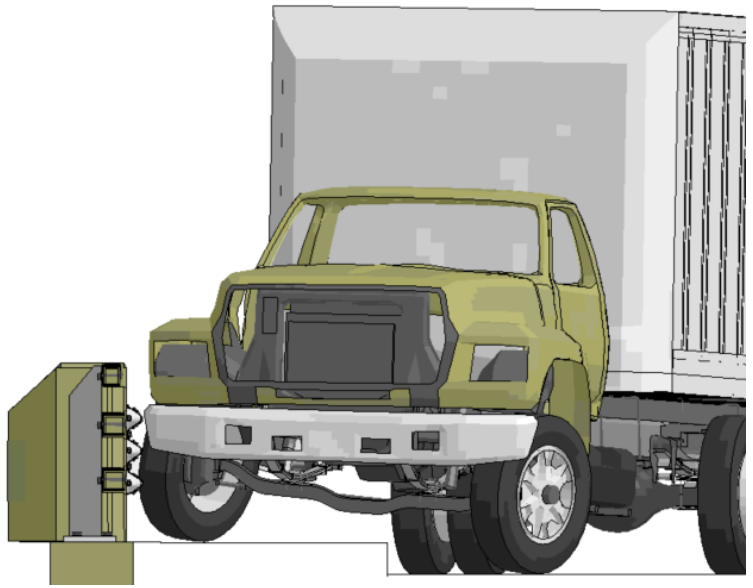
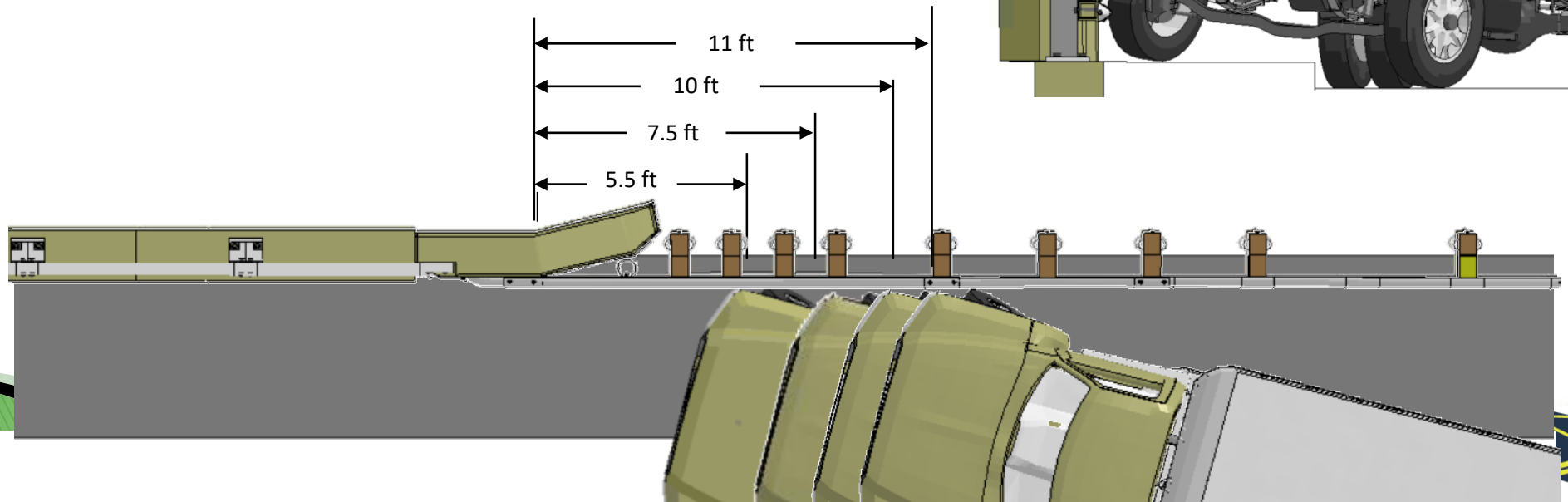
Sidewalk-Mounted Transition to Buttress
Test 4-22

- Impact Conditions
  - Mass = 22,046 lb
  - Impact Speed = 56 mph
  - Impact Angle = 15 degrees
  - Target Impact Point
    - 5.5 ft
    - 7.5 ft
    - 10 ft
    - 11 ft





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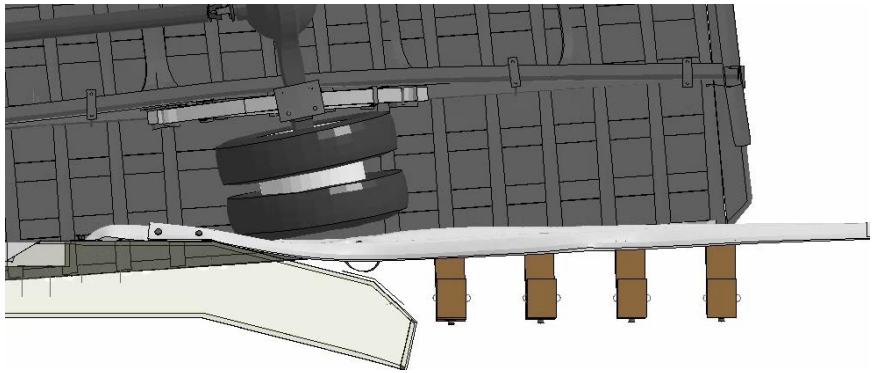
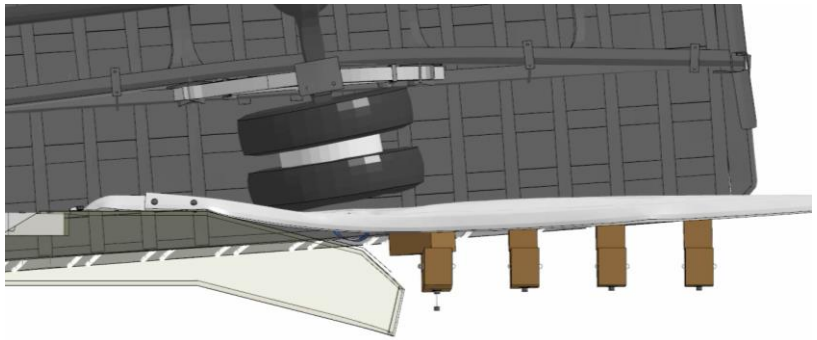
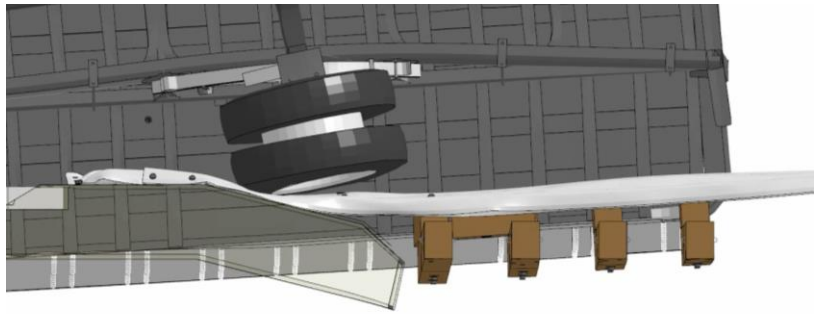
Comparison

Impact Point	Max Wheel Penetration
IP = 5.5 ft	3.0 inches
IP = 7.5 ft	3.3 inches
IP = 10.0 ft	5.3 inches
IP = 11.0 ft	5.9 inches







Video not Shown

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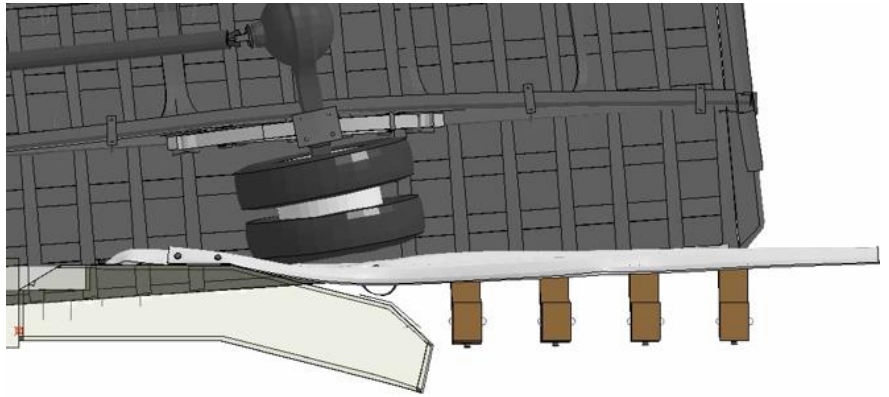
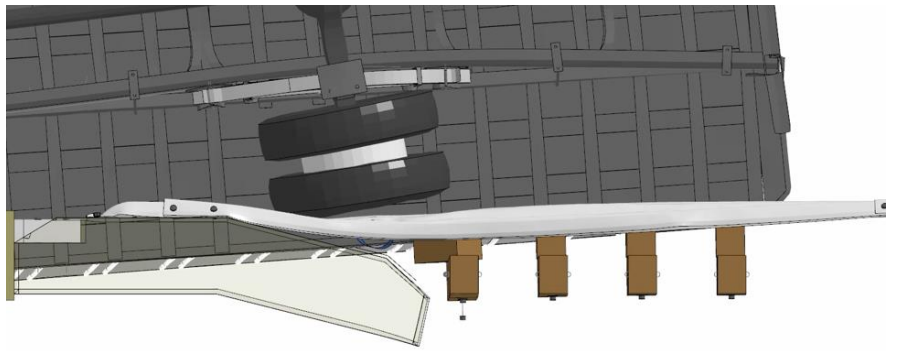
Comparison

Impact Point	Max Wheel Penetration
IP = 5.5 ft	3.0 inches
IP = 7.5 ft	3.3 inches
IP = 10.0 ft	5.3 inches
IP = 11.0 ft	5.9 inches





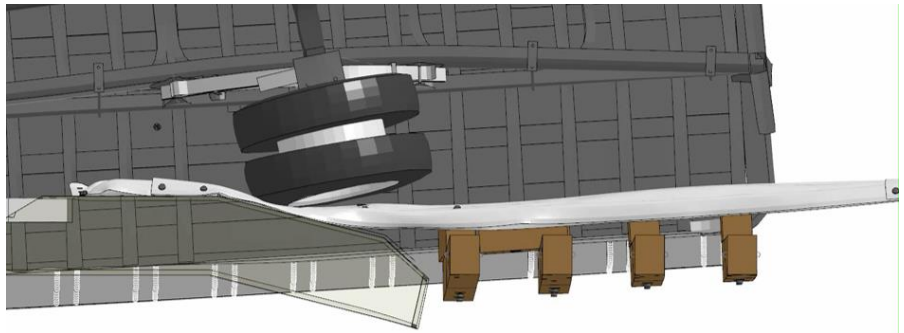


Image not Shown

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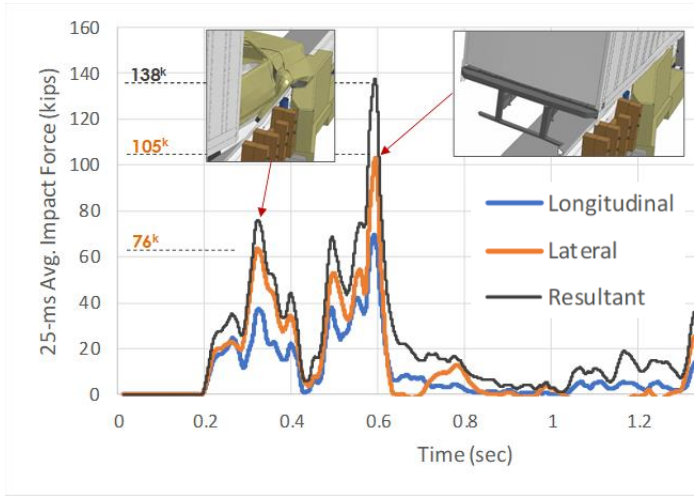
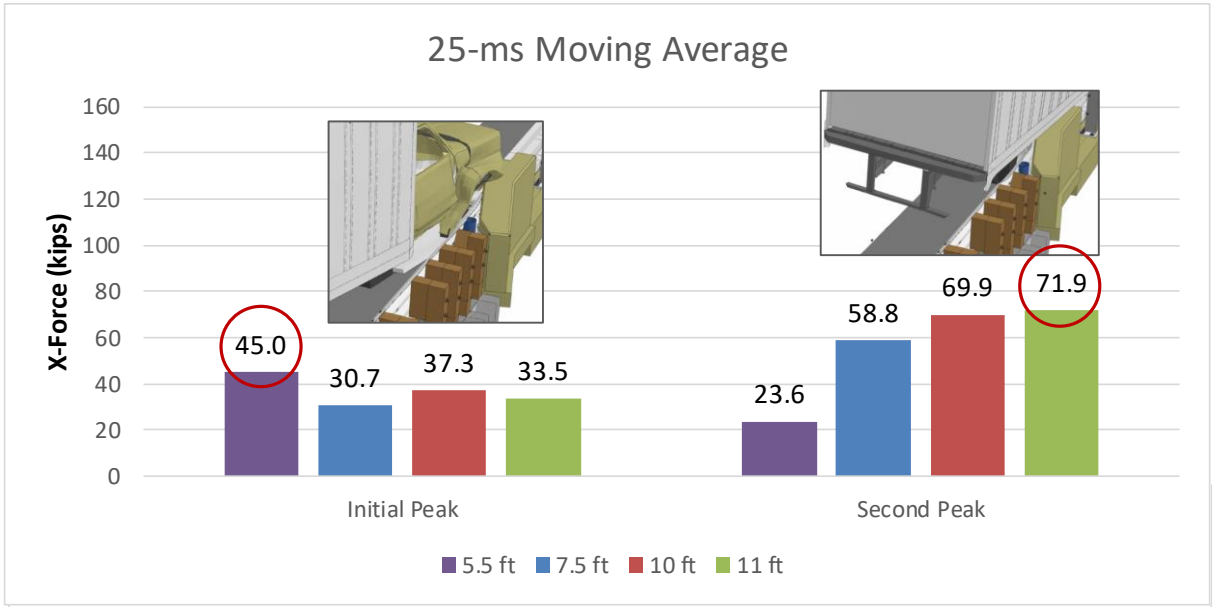
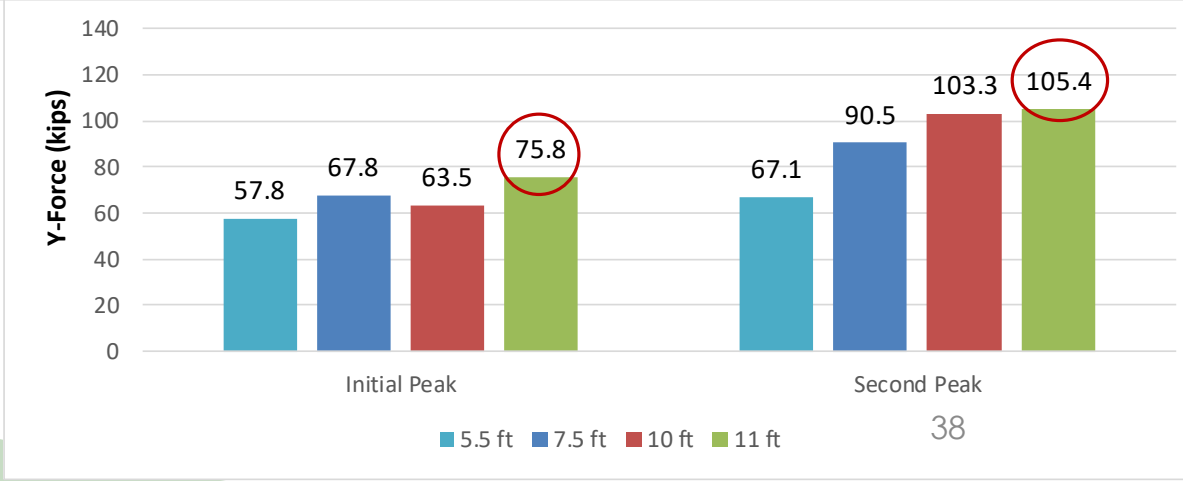
Sidewalk-Mounted Transition to Buttress Test 4-22

Impact Forces
(for Buttress Design)







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Sidewalk-Mounted Transition to Buttress Test 4-22

Conclusions

Evaluation Factors		Evaluation Criteria – MASH Test 4-12	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass
	G	It is preferable, although not essential, that the vehicle remain upright during and after collision.	Likely Pass

CIP = 11.0 ft

Deflection = 9.4”
Min design strength for buttress
$F_x > 72^k$
$F_y > 105^k$

OCI (negligible)

Max roll = 24 deg
Max pitch = 7 deg.

But possible that vehicle could roll onto its side

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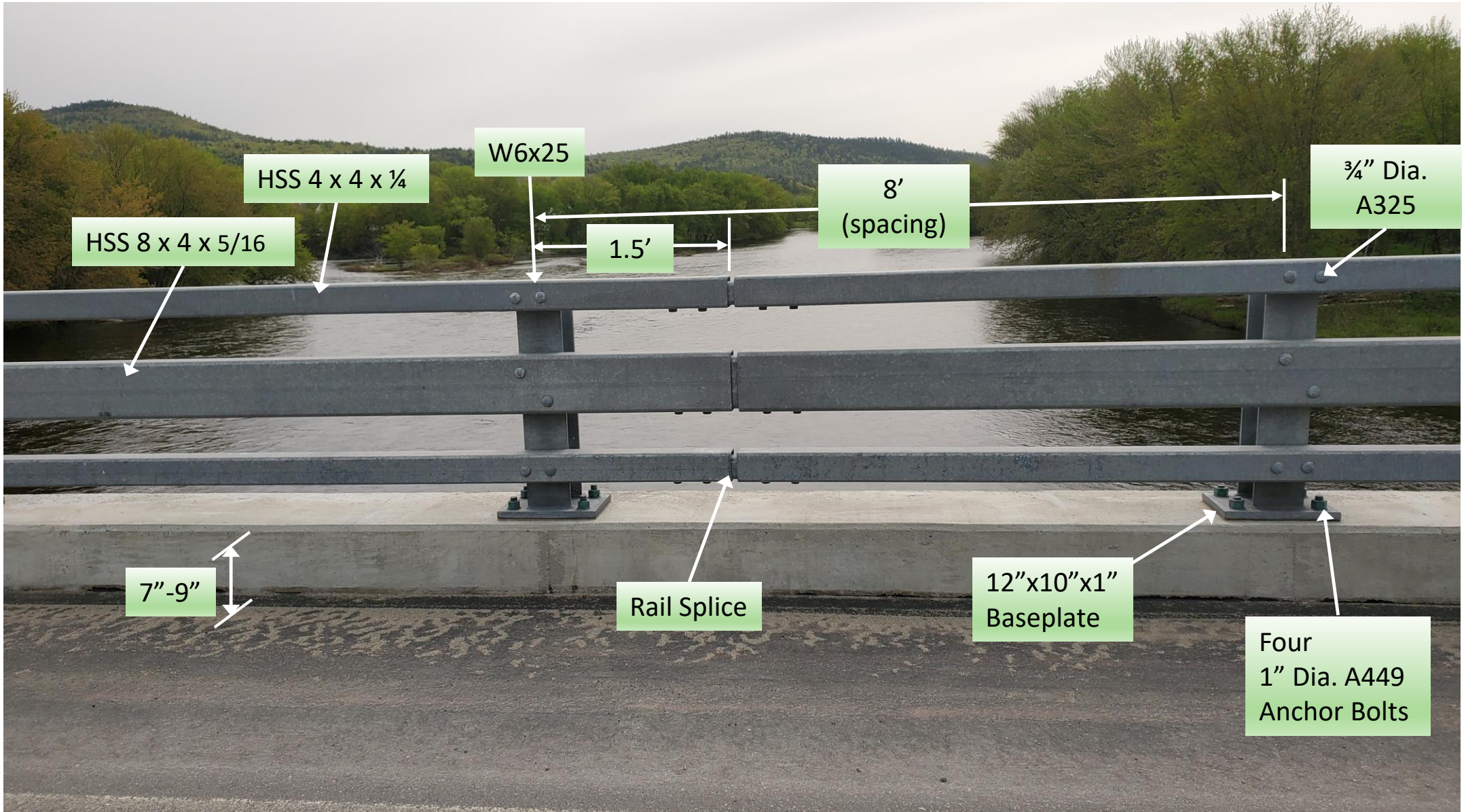
NETC Bridge Rails

Three design options were evaluated:

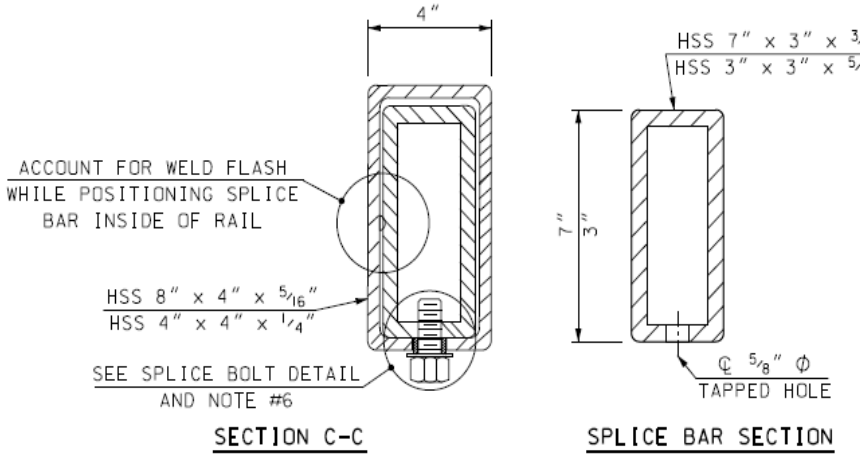
1. NETC curb-mounted 2-Bar Rail (TL3)
2. NETC curb-mounted 3-Bar Rail (TL4)
3. NETC sidewalk-mounted 4-Bar Rail (TL4)

Slight variations in design details depending on State

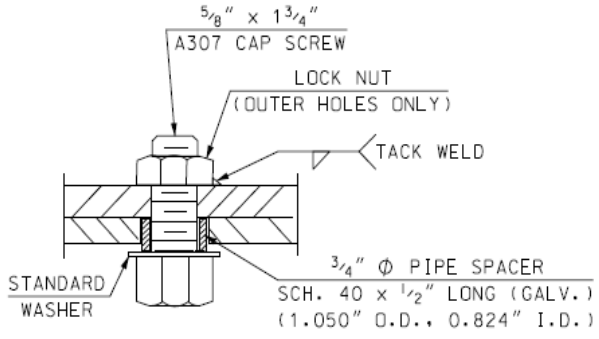
NETC Bridge Rails



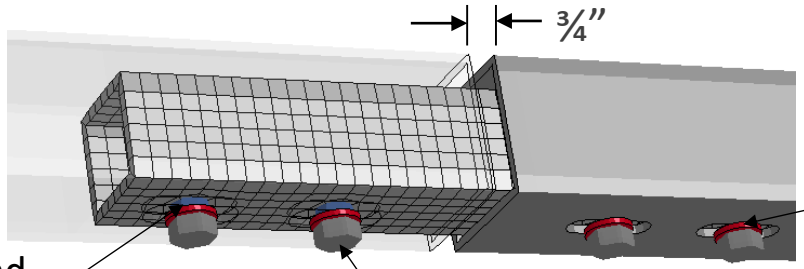
NETC Bridge Rails



RAIL SPLICE DETAILS
SCALE: 3” = 1’-0”



SPLICE BOLT DETAIL
SCALE: 6” = 1’-0”



Washer and
Bushing/Spacer

Washer Only
(bolt tension = 20 kip)

5/8”-Diameter A307 Cap Screws

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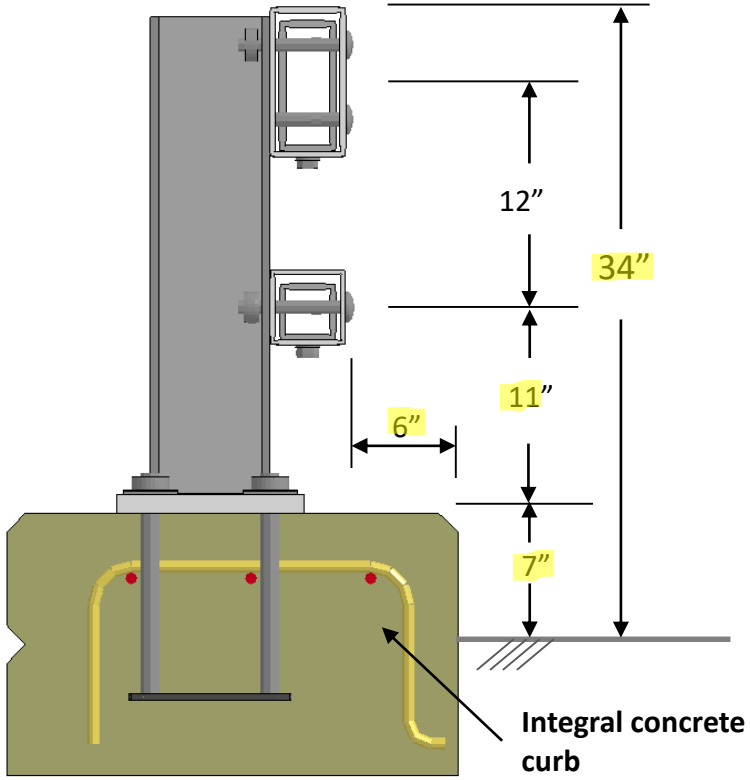
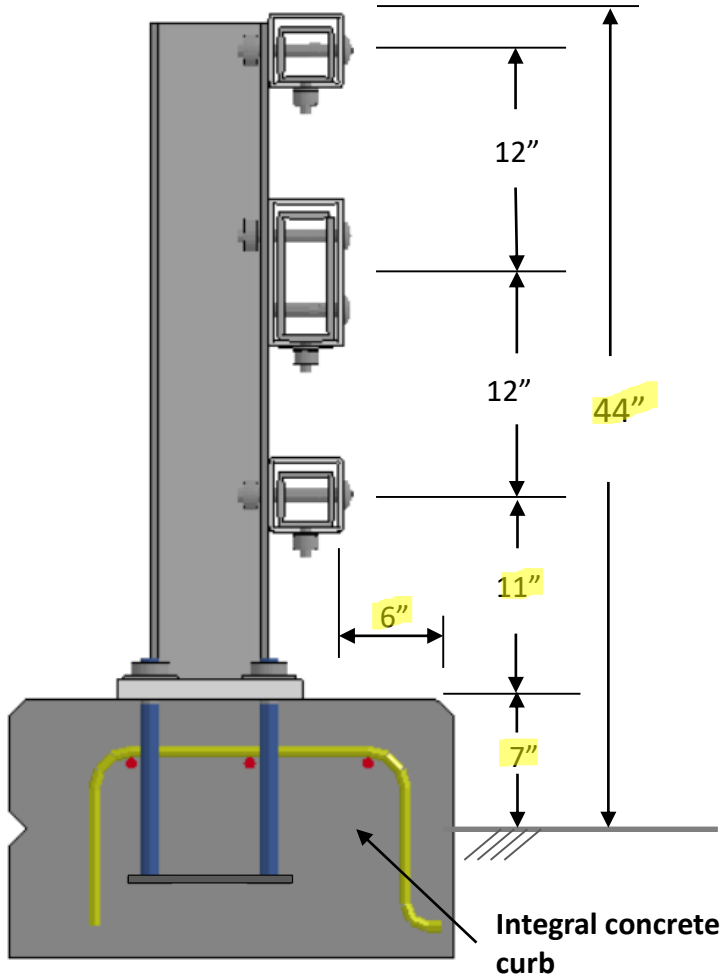
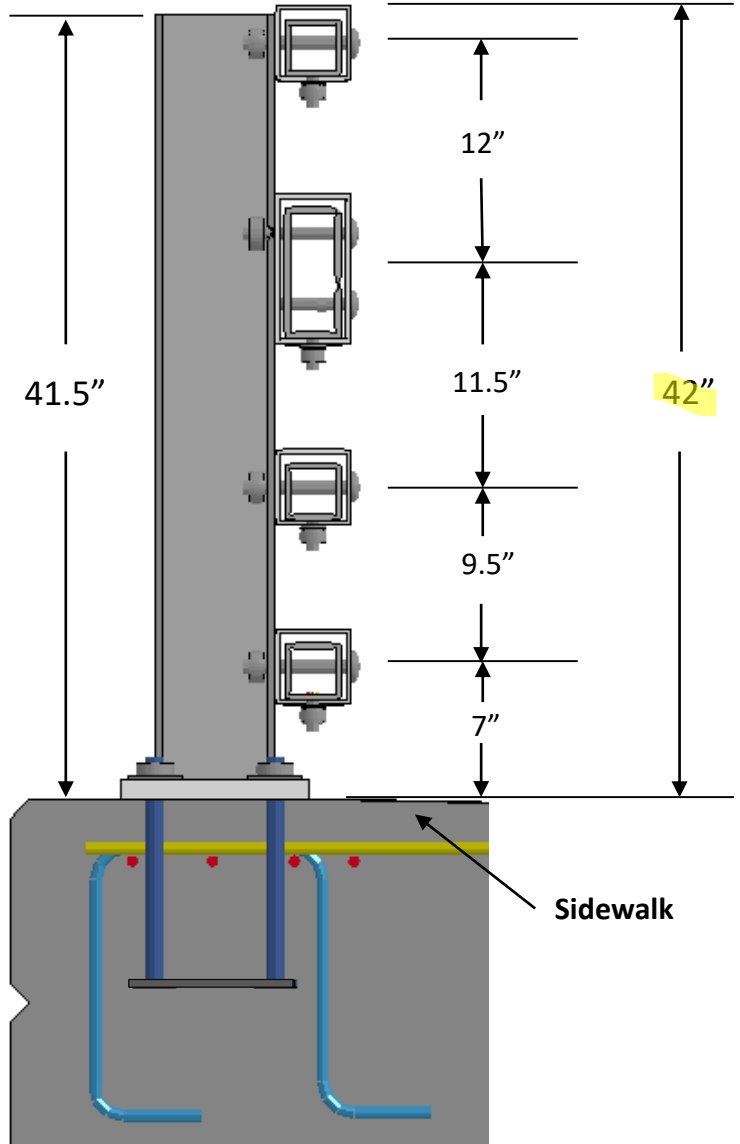
NETC Bridge Rails



NETC 2-Bar BR



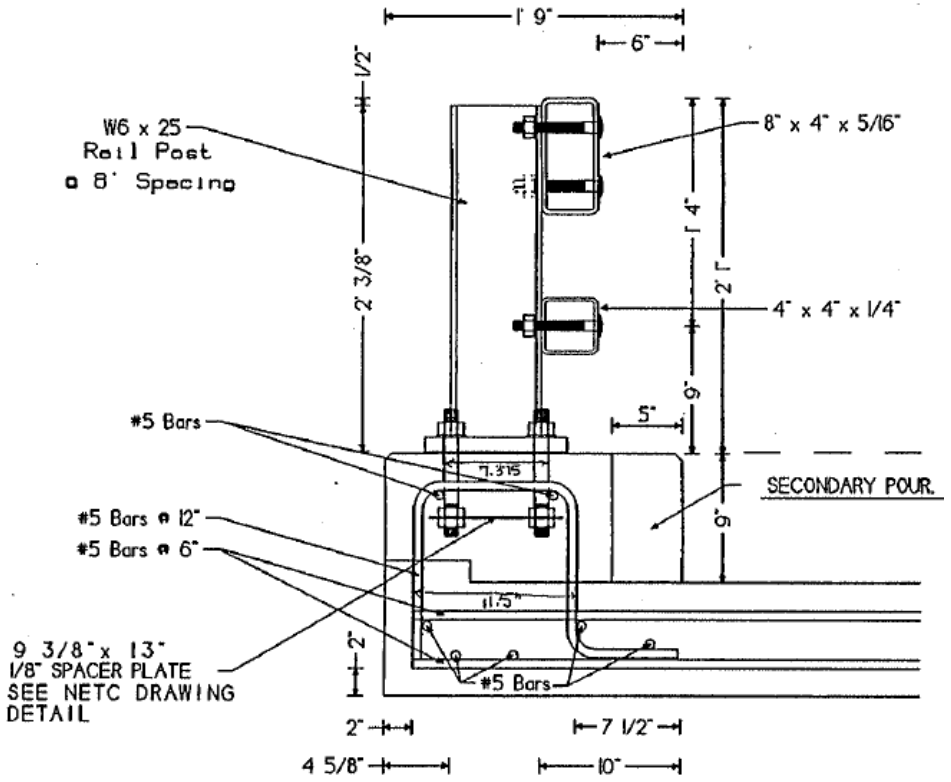
NETC 3-Bar BR



NETC 2-Bar

Previous Testing (TTI)

	471470-18	471470-19	471470-20	Preferred Limits
Test Designation	PL2-car	PL2-Pickup	R350 Test 4-12	
Test Vehicle	1986 Yugo GV	1984 Ford F25	1980 GMC 6000	
Gross Vehicle Weight (lb)	1,970	5,568	17,621	
Impact Speed (mph)	62.7	57.3	50.8	
Impact Angle (deg)	20.6	20.6	15.5	
Exit Speed (mph)	55.1	48.6	-	
Exit Angle (deg)	2.2	2.2	2	
Occupant Impact Velocity				
Longitudinal (ft/s)	16.9	12.2	7.5	< 30 ft/s
Lateral (ft/s)	27.5	21.5	12	
Ridedown Accel				
Longitudinal (g's)	1.6	2.5	4	< 15 G
Lateral (g's)	6.8	12.2	3.2	
Maximum 50 msec Avg Accel				
Longitudinal (g's)	6.1	3.4	1.8	
Lateral (g's)	15.2	10.3	2.6	
Max Deflection (in)	0.25	0.25	-	
Vehicle Trajectory				
Maximum YawAngle (deg)	15	25	16	
Maximum Roll Angle (deg)	15	26	19	< 75°
Maximum Pitch Angle (deg)	32	5	6	
NCHRP Report 350 Evaluation				
Structural Adequacy	Pass	Pass	Pass	
Ocupant Risk	Pass	Pass	Pass	
Vehicle Trajectory	Pass	Pass	Pass	



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NETC 4-Bar

Previous Testing (SwRI)

	NETC-1	NETC-2	NETC-3	
Report 350 Test No.	Test 4-10	Test 4-11	Test 4-12	
Test Vehicle	1991 Ford Festiva	1991 Ford F-250	1993 International 4600 LP	
Gross Vehicle Weight (lb)	1823	4484	17,875	
Impact Speed (mph)	62.1	62.1	49.7	
Impact Angle (deg)	20	25	15	
Exit Speed (mph)	11.4	10.6	35.8	
Exit Angle (deg)	6.6	8.2	4.1	
Occupant Impact Velocity				Preferred Limits
Longitudinal (ft/s)	*	13.1	5.41	< 30 ft/s
Lateral (ft/s)	*	*	9.48	
Ridedown Accel				
Longitudinal (g's)	*	2.55	8.95	< 15 G
Lateral (g's)	*	*	14.3	
Maximum 50 msec Avg Accel				
Longitudinal (g's)	-	-	2.7	
Lateral (g's)	-	-	5.8	
Max Deflection (in)	0	1	1	
Vehicle Trajectory				
Maximum YawAngle (deg)	34	*	*	
Maximum Roll Angle (deg)	10	20	20	< 75°
Maximum Pitch Angle (deg)	5	15	5	
NCHRP Report 350 Evaluation				
Structural Adequacy	Pass	Pass	Pass	
Ocupant Risk	*	Pass	Pass	
Vehicle Trajectory	Pass	Pass	Pass	

** No occupant risk data - lateral accelerometer malfunctioned during test.*

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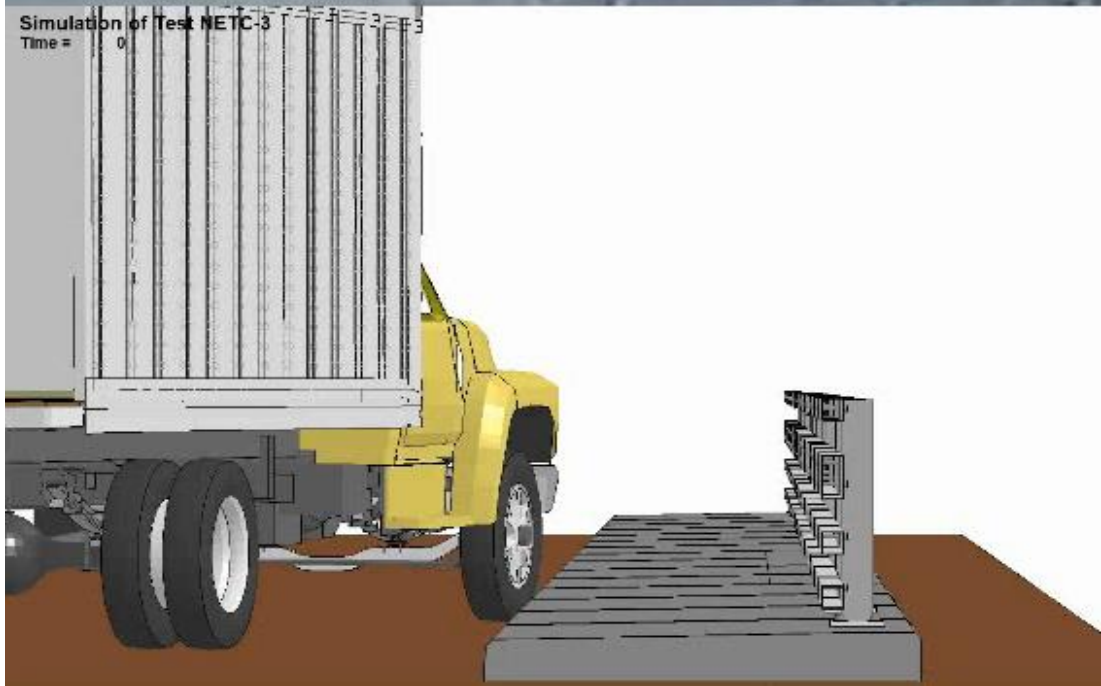
NETC 4-Bar

Validation

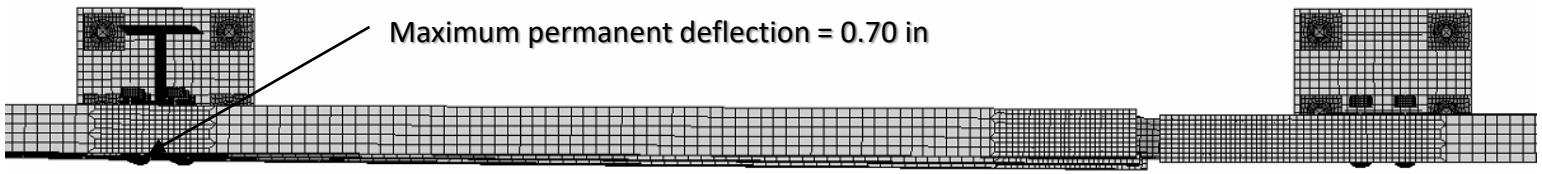
- Test No. NETC-3 on the bridge rail was performed by SwRI on 12/18/1997.
- Total length of bridge rail was 108 feet.
- Impact conditions:
  - Mass = 17,875 lb (8,108 kg)
  - Speed = 49.8 mph (80.1 km/hr)
  - Angle = 15 deg.
  - Impact point = 2 ft (0.61 m) upstream of Post 6.

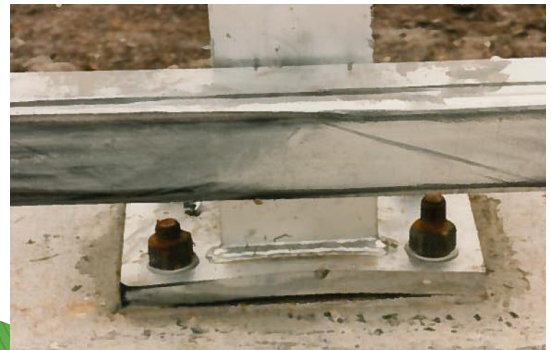


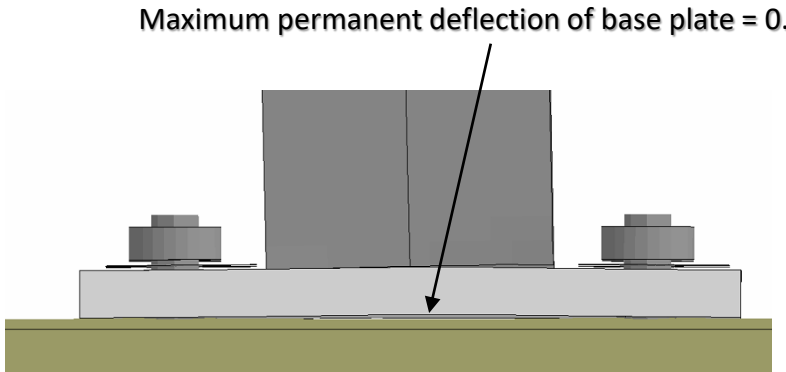
NETC 4-Bar

Validation

- The maximum dynamic deflection of the bridge rail model occurred at the top rail at the splice connection between posts 6 and 7.
  - FEA = 1.77 in (45 mm)
  - Test = 1.00 in (25 mm)
- The resulting permanent deflection at this location was:
  - FEA = 0.7 in (17.5 mm)
  - Test = 0.5 in (13 mm).
- Posts 6 and 7 were tilted back and the base plates of both posts were raised upward at the center:
  - FEA: Dynamic = 0.28 in (7 mm) ; Permanent = 0.11 in (2.75 mm)
  - Test: Dynamic = (not reported) ; Permanent = 0.14 in (3.5 mm).



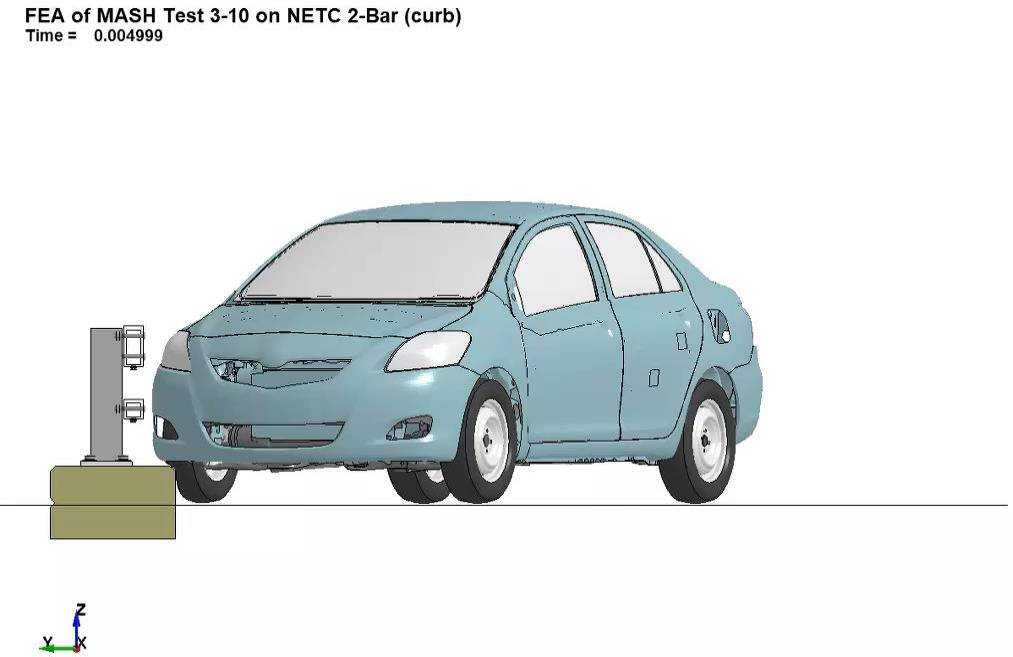




MASH TL-3 for NETC 2-Bar Bridge Rail

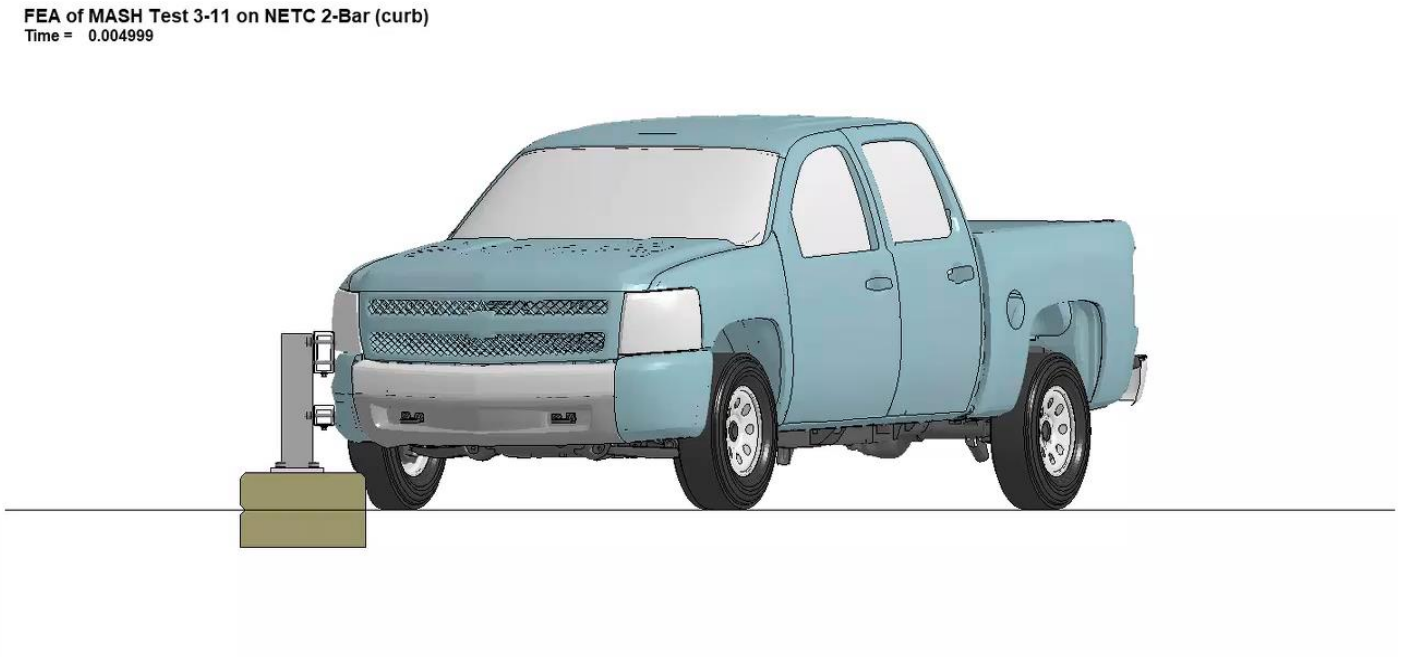
Test 4-10

- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 3.6 ft upstream from critical Post



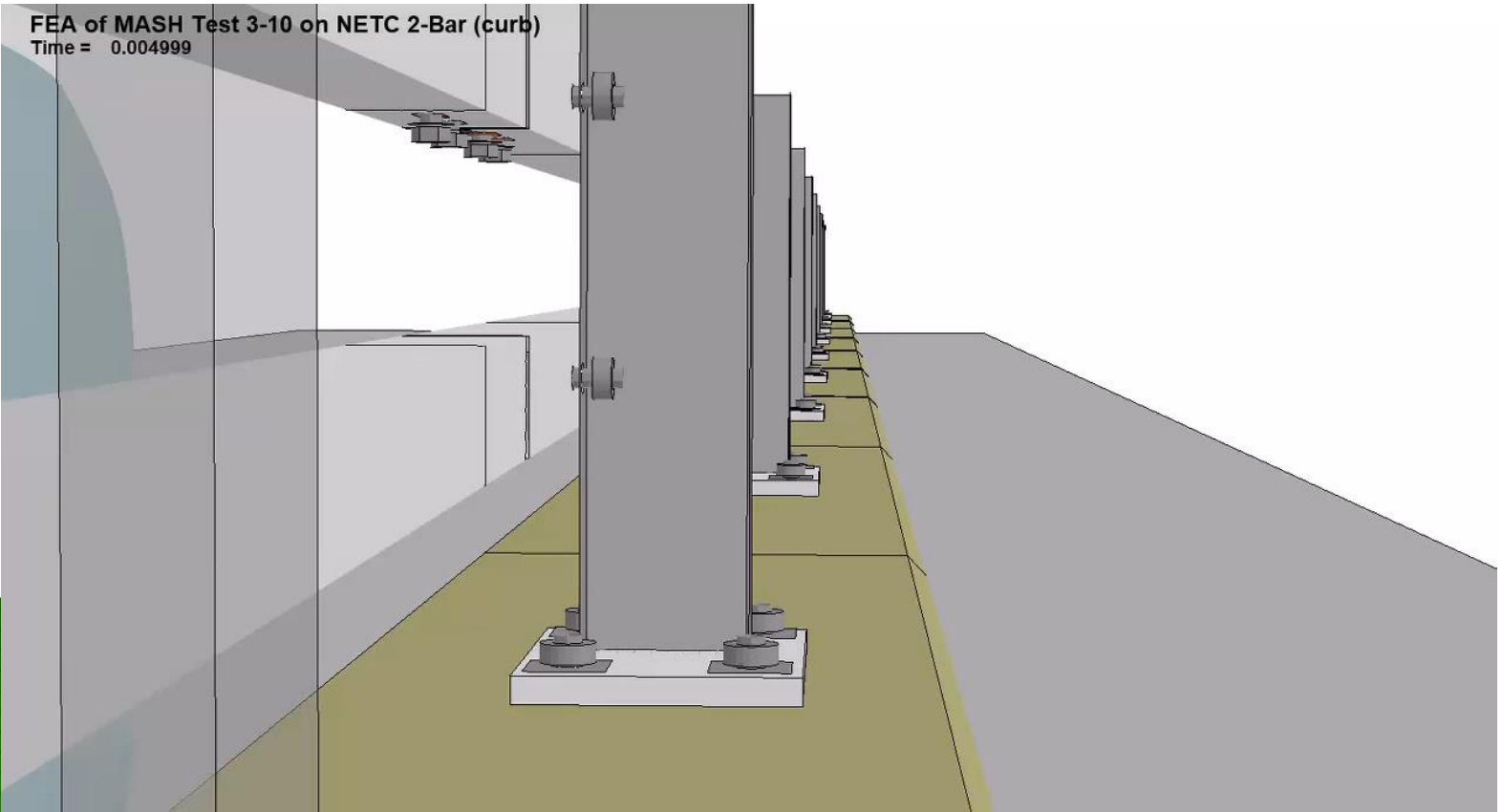
Test 4-11

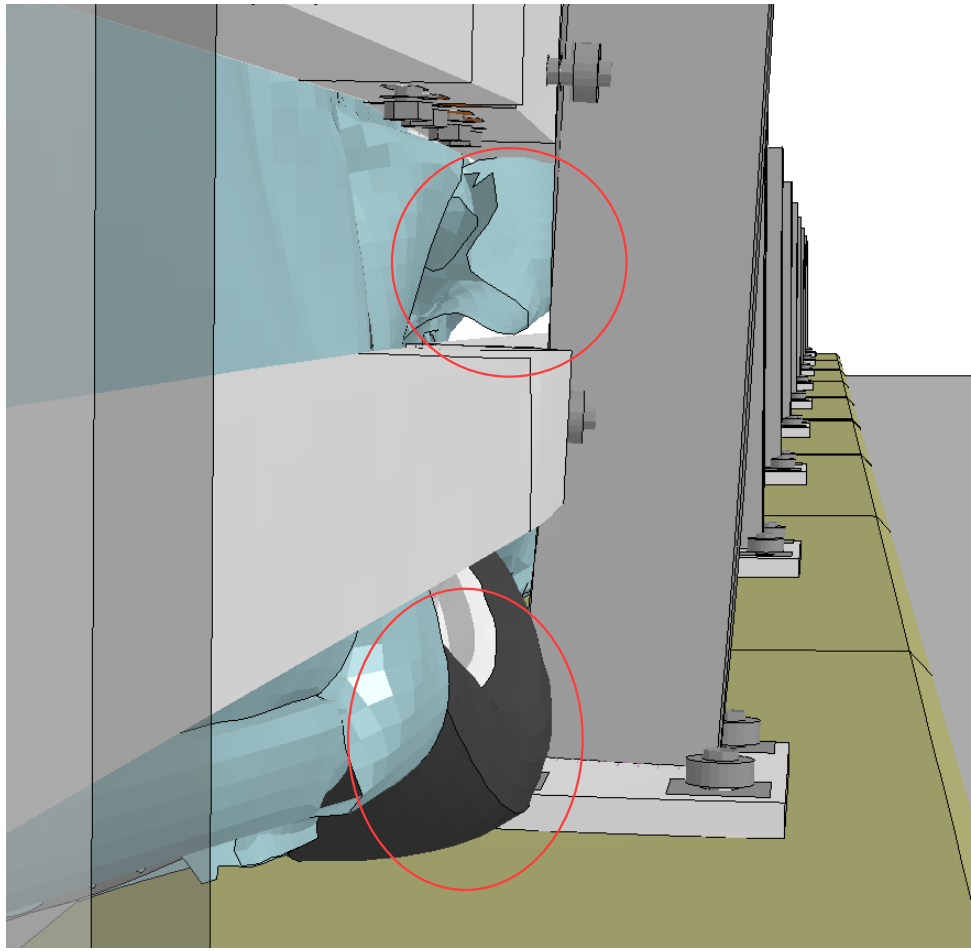
- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 4.3 ft upstream from critical Post



Assessment of Potential Vehicle Contact with Post

- The front fender made slight contact with the post.
- The contact between the front tire and post was moderate.
  - Tire deflation was not included in the model, so an accurate assessment on the potential for wheel rim snag on the post could not be made; however, a moderate snag is possible.





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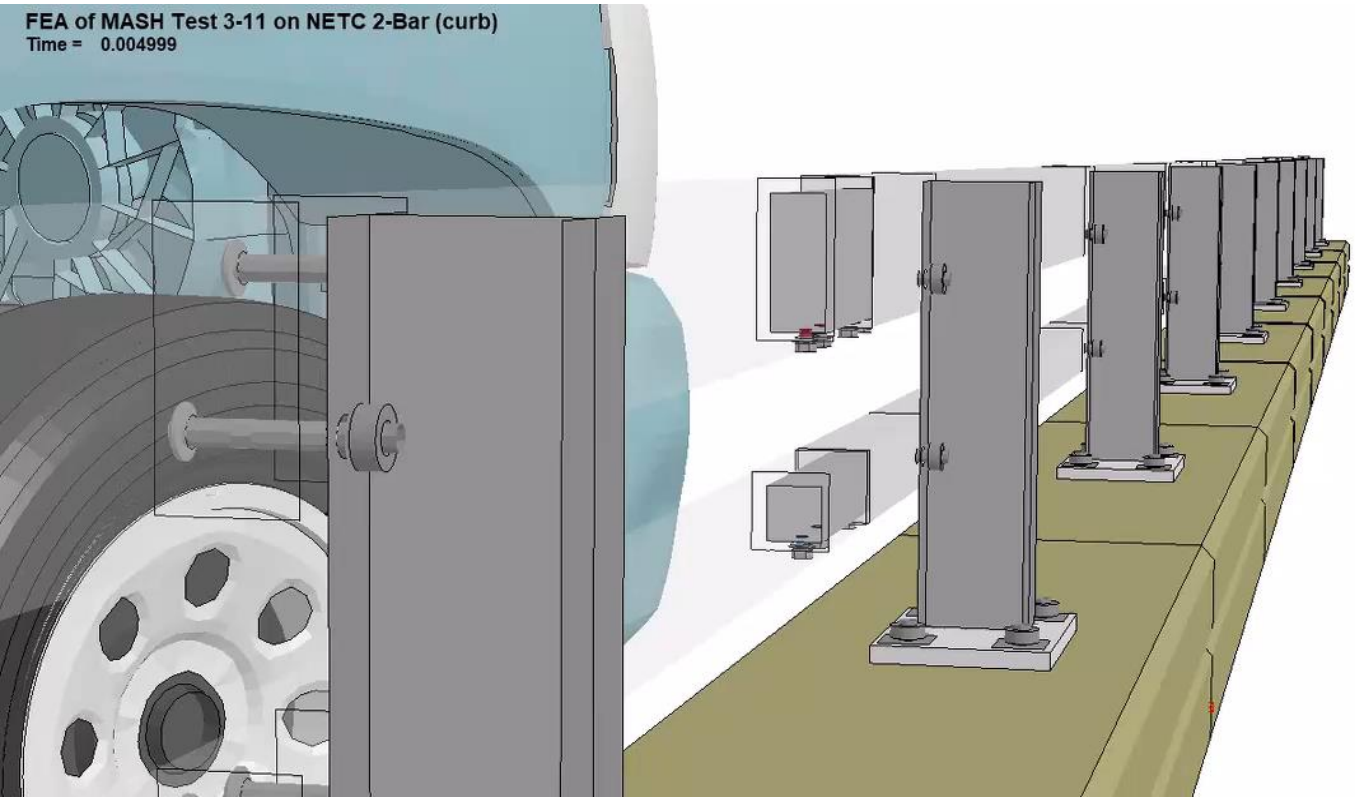
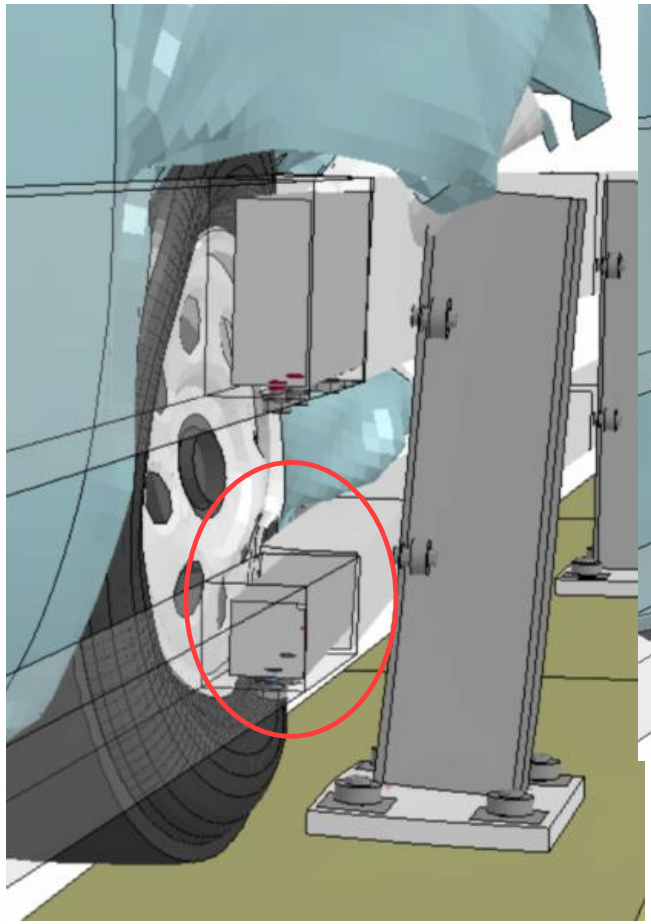
Assessment of Potential Vehicle Snag

- The front fender and bumper made slight contact with the post, but the contact force was negligible.
- The front wheel and the front edge of the passenger door snagged on the rail tube at the splice but resulting accelerations did not affect occupant risk.



Front Wheel Snag



Door Snag

Occupant Risk

Occupant Risk Factors		MASH Test 3-10	MASH Test 3-11
Occupant Impact Velocity (ft/s)	x-direction	26.2	20.7
	y-direction	33.1	26.9
	at time	at 0.0793 seconds on right side of interior	at 0.0919 seconds on right side of interior
THIV (ft/s)		42.0 at 0.0793 seconds on right side of interior	33.5 at 0.0893 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-5.5 (0.0812 - 0.0912 seconds)	-4.6 (0.2233 - 0.2333 seconds)
	y-direction	-6.4 (0.2169 - 0.2269 seconds)	-15.4 (0.1905 - 0.2005 seconds)
PHD (g's)		6.4 (0.2169 - 0.2269 seconds)	15.4 (0.1905 - 0.2005 seconds)
ASI		2.51 (0.0257 - 0.0757 seconds)	1.63 (0.0308 - 0.0808 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-14.8 (0.0241 - 0.0741 seconds)	-9.6 (0.0320 - 0.0820 seconds)
	y-direction	-19.8 (0.0263 - 0.0763 seconds)	-12.7 (0.0303 - 0.0803 seconds)
	z-direction	-3.2 (0.0603 - 0.1103 seconds)	3.3 (0.2342 - 0.2842 seconds)
Maximum Angular Disp. (deg)	Roll	7 (0.5291 seconds)	9 (0.7864 seconds)
	Pitch	-5.4 (0.3745 seconds)	-10.1 (0.4644 seconds)
	Yaw	-39.8 (0.4896 seconds)	-28.8 (0.3265 seconds)

MASH Criteria

< 30 ft/s (preferred)
< 40 ft/s (limit) ✓

< 15 G (preferred)
< 20.49 G (limit) ✓

< 75 deg ✓

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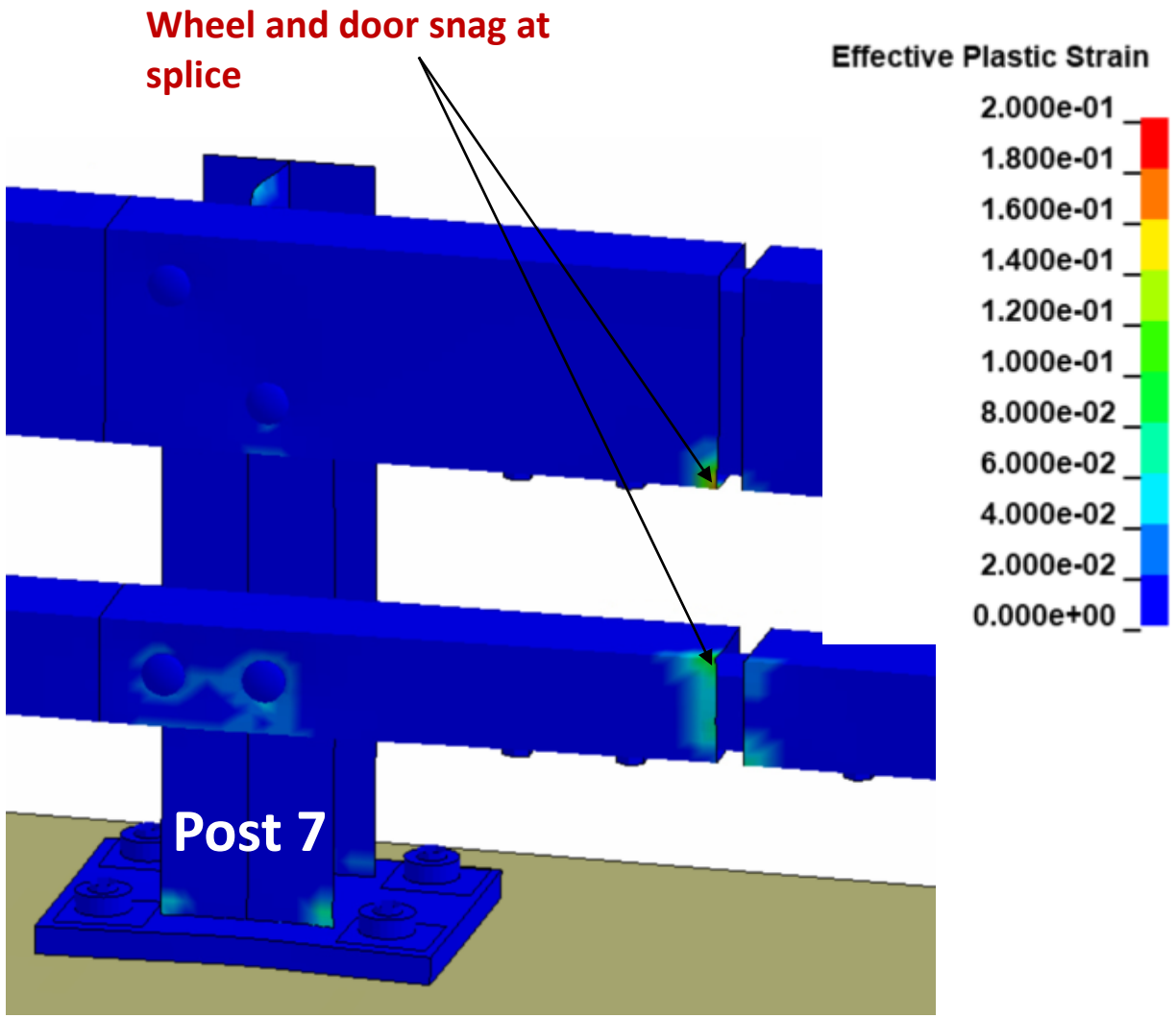
Barrier Damage (Pickup Test)

- There was moderate damage to the rail tubes between Post 6 and 7, with additional damage at the end of the rails at the splice.
- There was moderate damage to Post 6 and 7 and their base plates.
  - There was plastic deformation of at the lower part of the posts and to the base plates.
  - True plastic strain = 0.1 at outer edge of post flange at the weld.
  - Vertical deflection of base plate (Post 7):
    - Dynamic = 0.62 inches (15.7 mm)
    - Permanent = 0.24 inches (6.2 mm)



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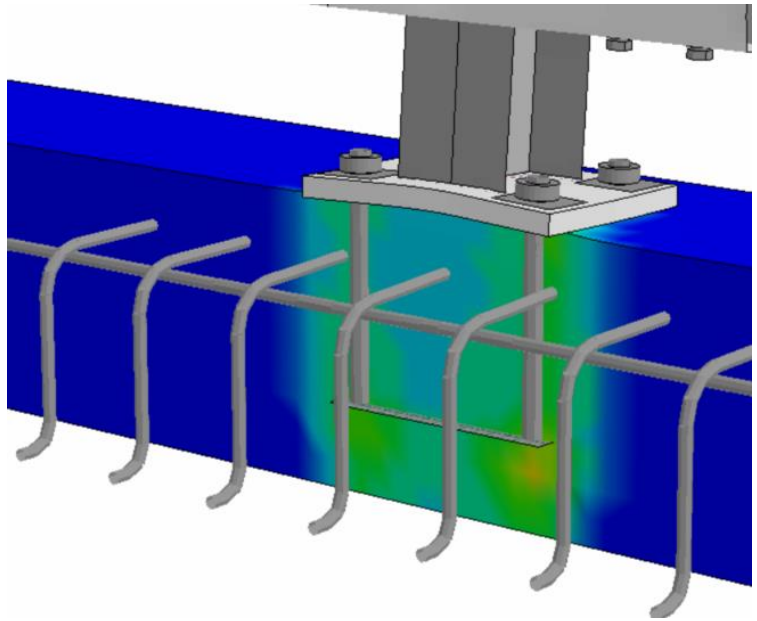
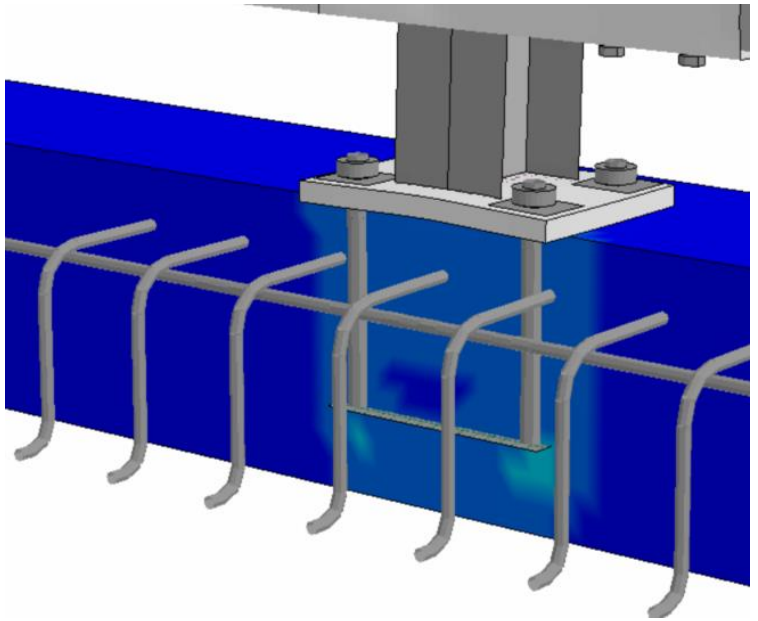
Barrier Damage
(Pickup Test)

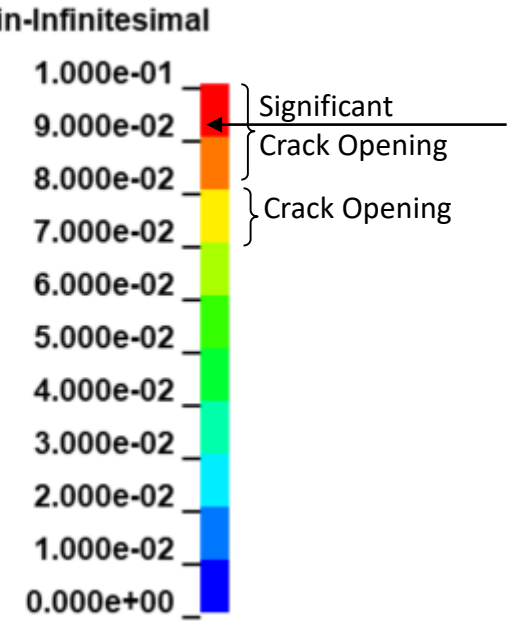
- Analysis indicated potential for significant crack opening in concrete due to anchor pryout around front anchor bolts.
  - Max dynamic 1st Prin. Strain = 0.092
  - Final 1st Prin. Strain = 0.076



Dynamic at time = 0.075 seconds



Final Static



Conclusions for the NETC 2-BAR Bridge Rail

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

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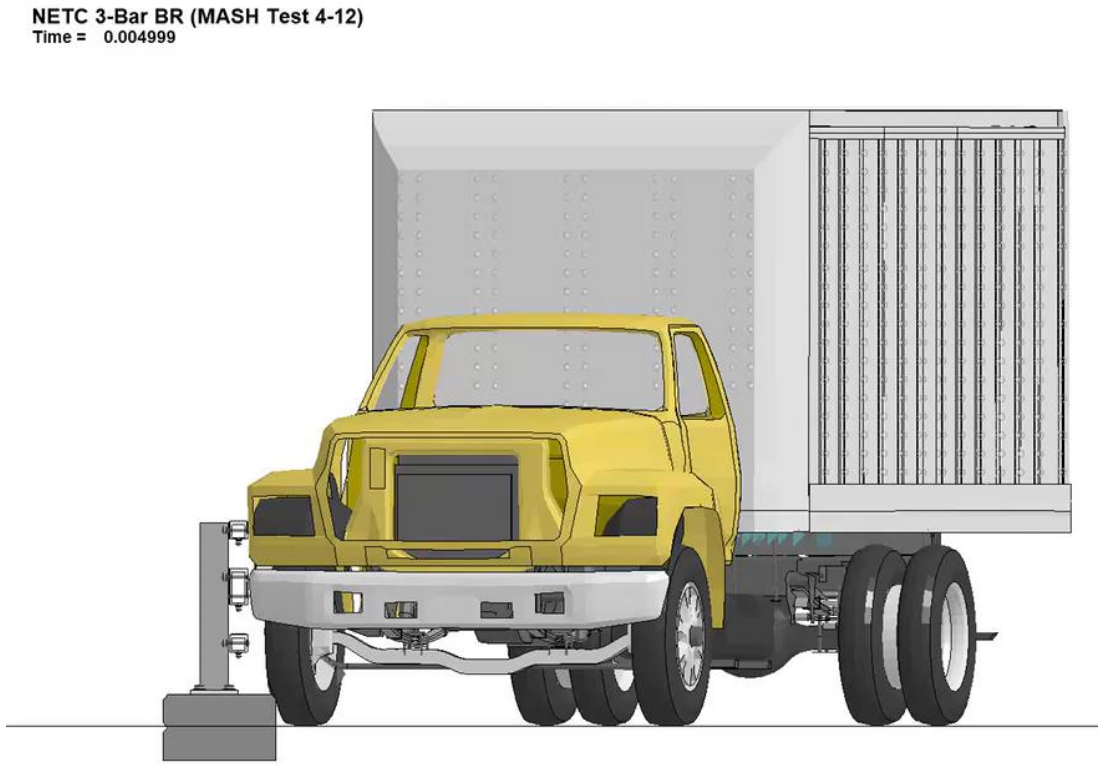
MASH TL-4 for NETC 3-Bar Bridge Rail

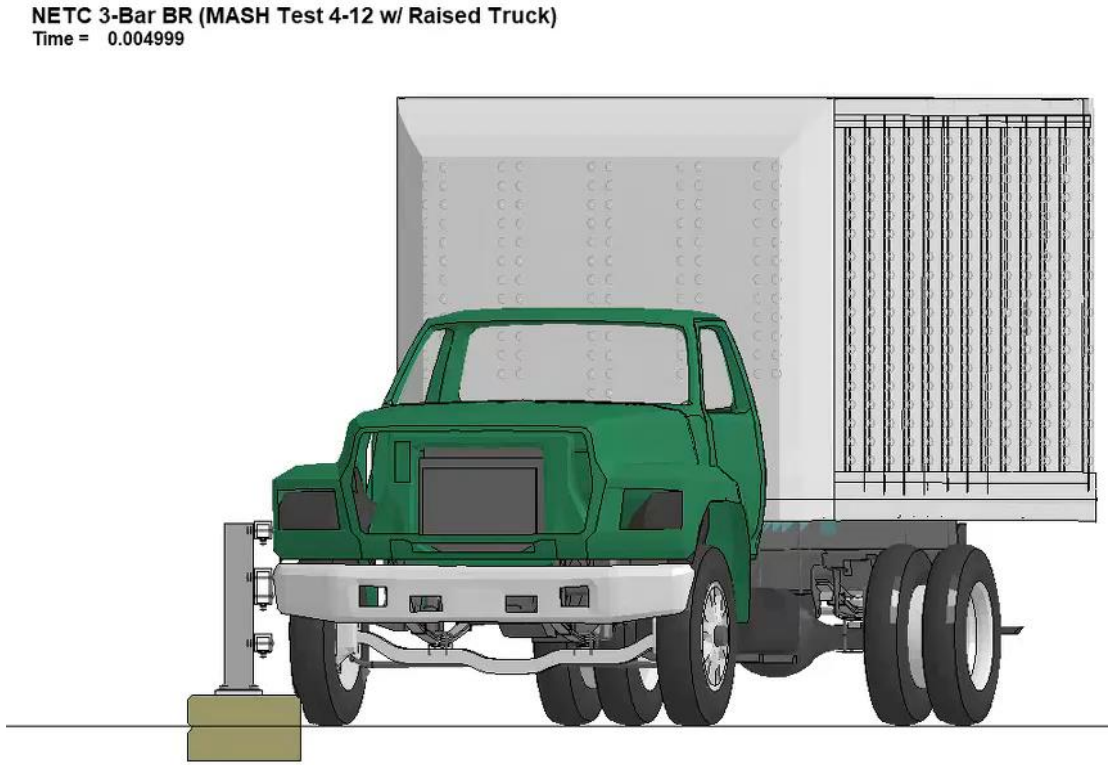
Test 4-12 (Case 1)

- Impact Speed = 56 mph
- Impact Angle = 15 degrees
- Impact Point = 5.0 ft upstream from critical Post
- Bed Height = 47.5” (e.g., Ford F800)

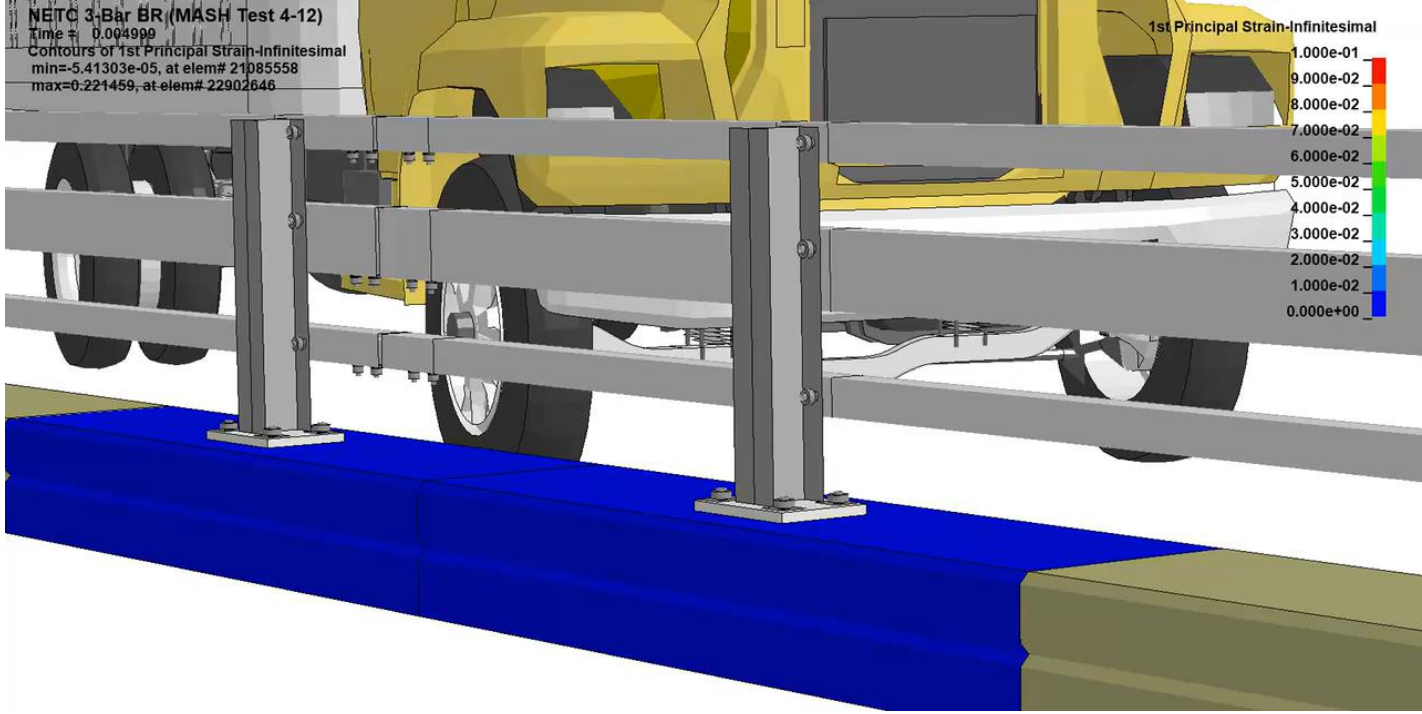


Test 4-12 (Case 2)

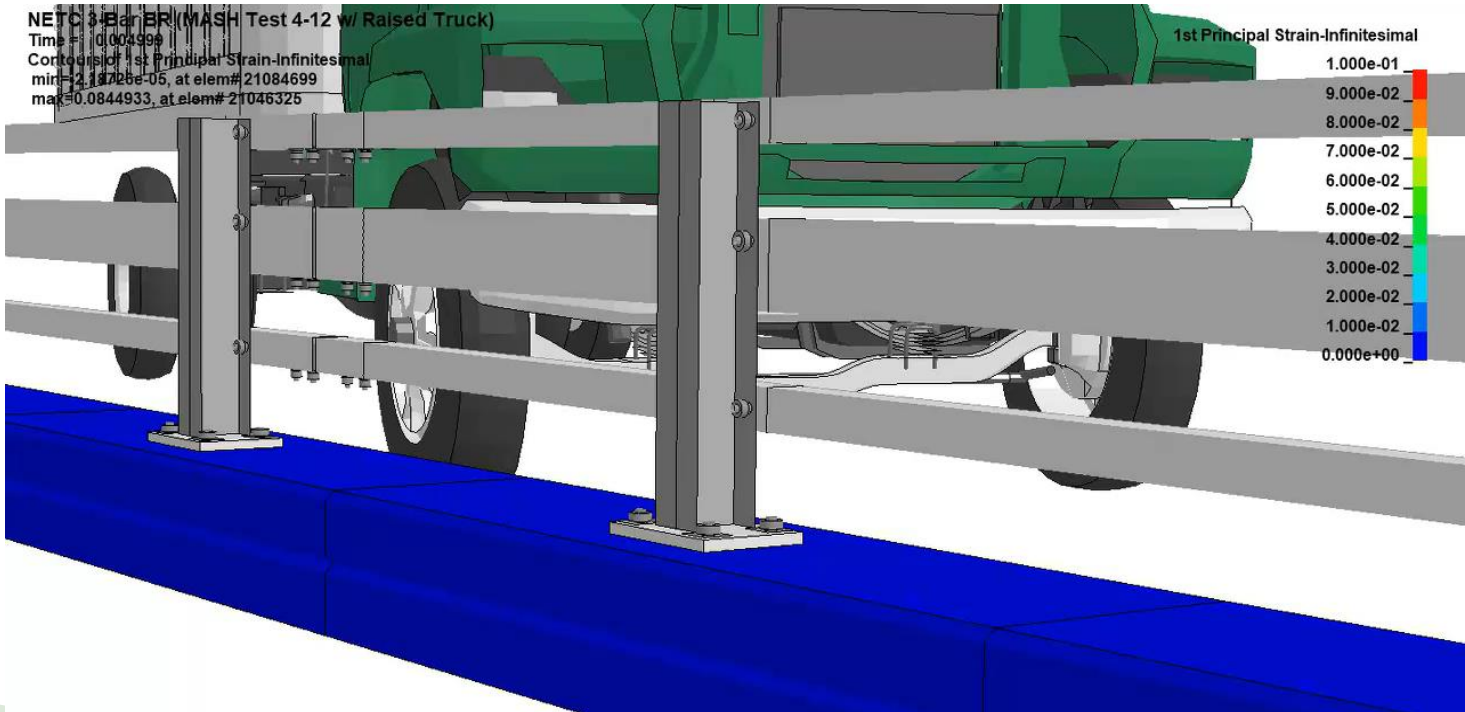
- Impact Speed = 56 mph
- Impact Angle = 15 degrees
- Impact Point = 5.0 ft upstream from critical Post
- Bed Height = 50” (e.g., GMC)



Bed Height = 47.5 inches

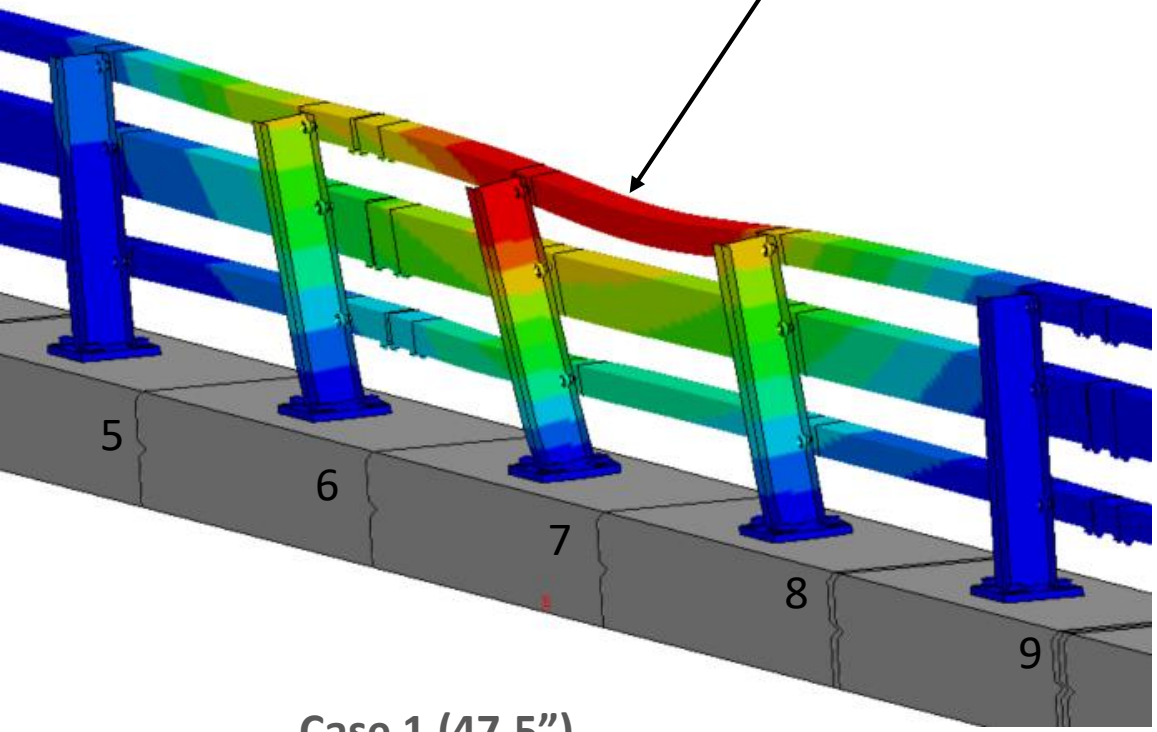


Bed Height = 50 inches



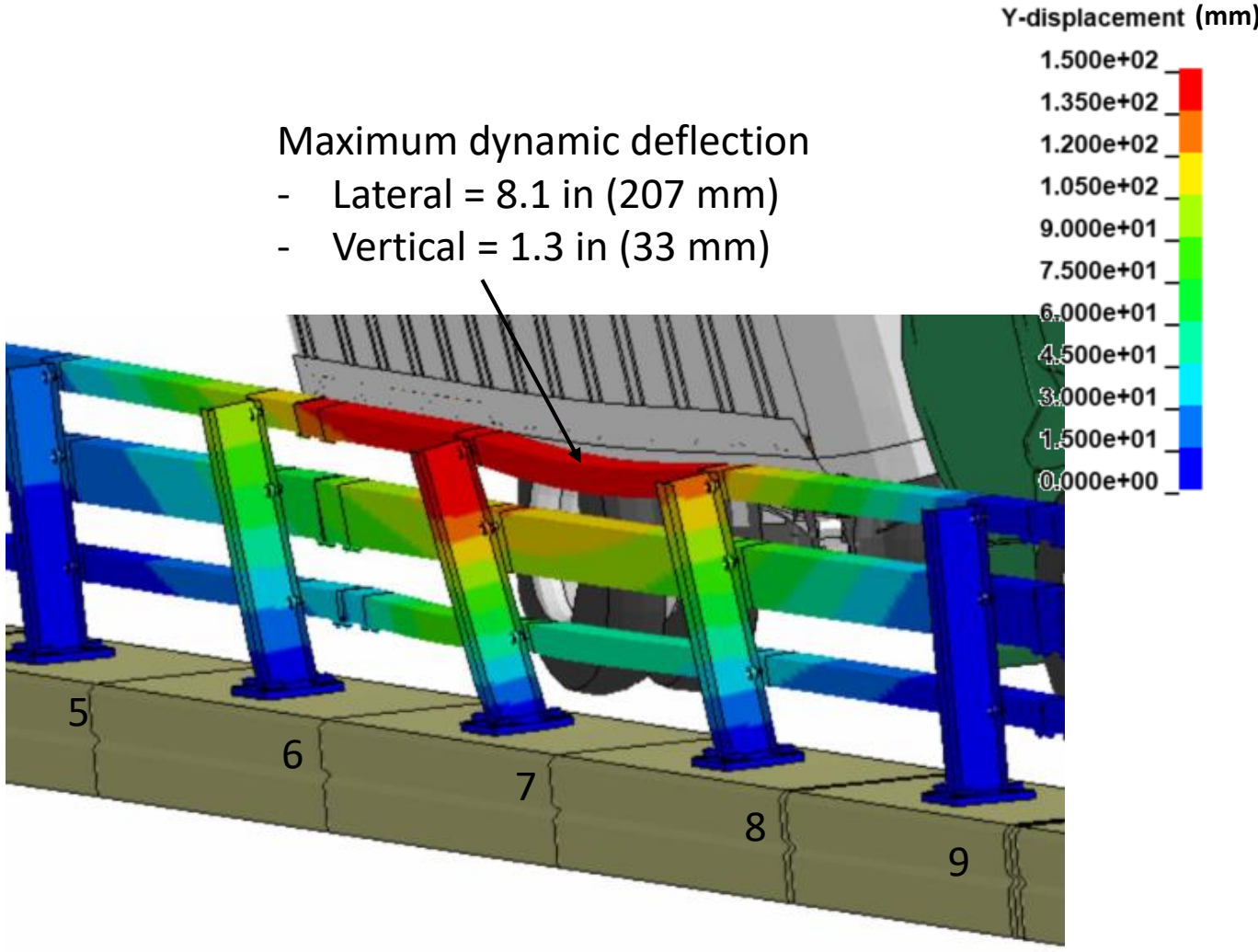
Lateral Dynamic Deflection

Maximum dynamic deflection = 7.64 in (194 mm)



Case 1 (47.5”)

Maximum dynamic deflection
- Lateral = 8.1 in (207 mm)
- Vertical = 1.3 in (33 mm)



Case 2 (50”)

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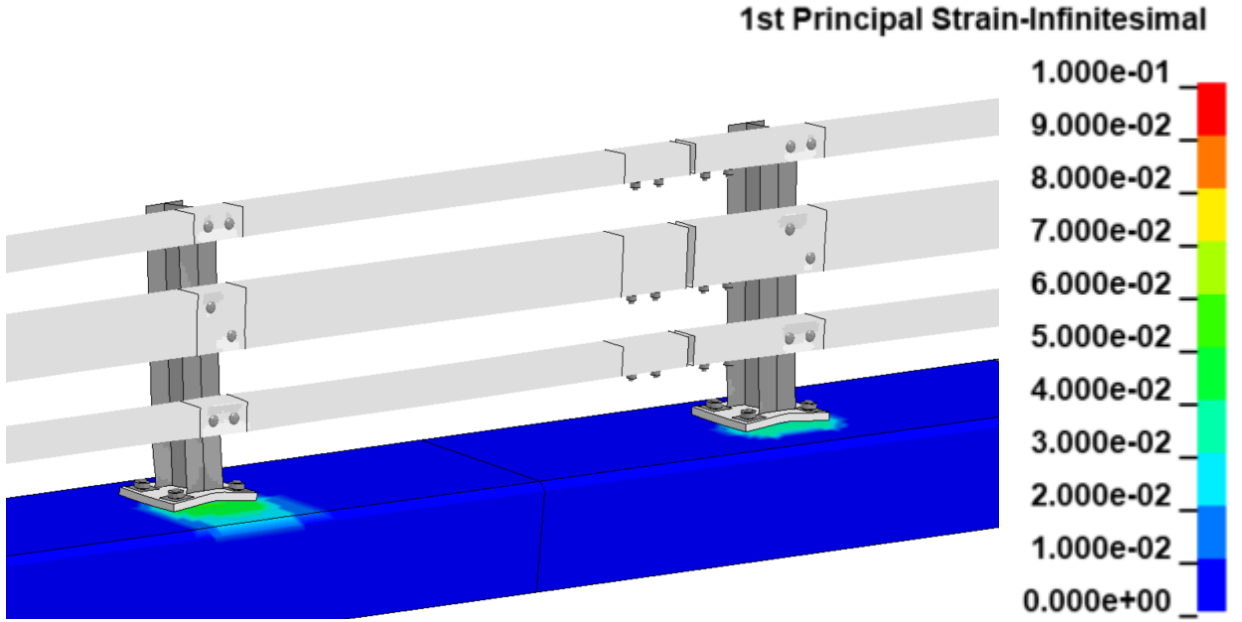
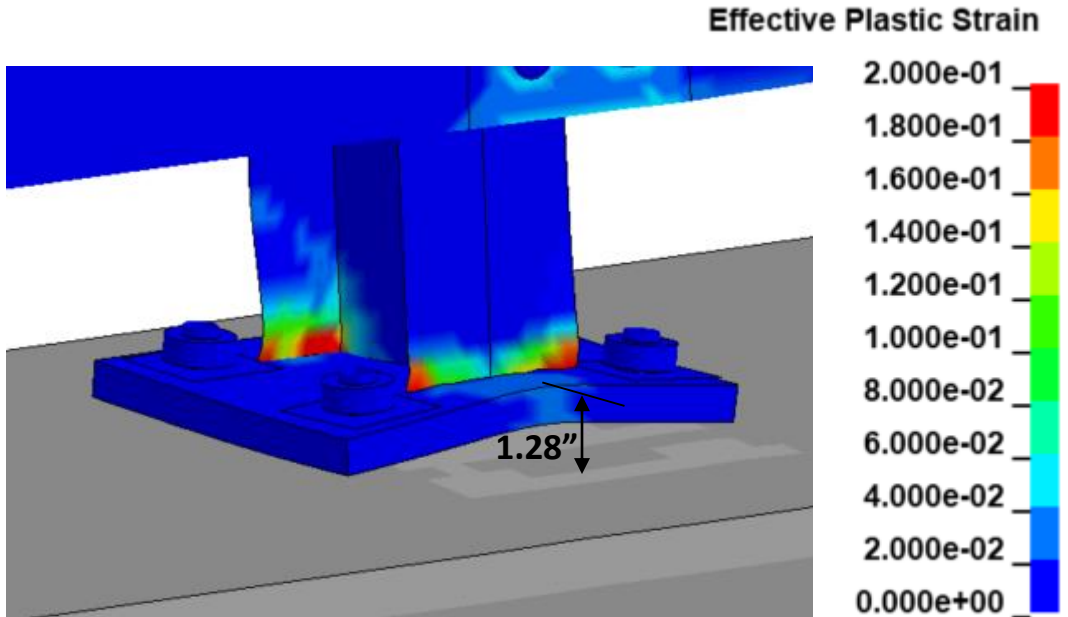
Barrier Damage

Case 1 – Bed Height = 47.5”:

- Analysis resulted in moderate concrete damage at two posts.
  - The damages correspond to high potential cracks around the front anchor bolts and/or anchor pullout.
- There was also significant damage to the posts and base plates at these two post locations.
  - The post flanges buckled at the welded connection to the base plate.
  - Vertical deflection of base plate:
    - Dynamic = 1.28 inches
    - Permanent = 0.9 inches
  - The vertical deflection of the base-plate also increases the stress at the outer edges of the front flange of the post at the weld location.
  - Weld forces were not computed in the analysis but may be of concern.





Conclusions on Test 4-12 on the NETC 3-Bar

Evaluation Factors		Evaluation Criteria – MASH Test 4-12	Results Case 1/ Case 2
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
	G	It is preferable, although not essential, that the vehicle remain upright during and after collision.	Pass/Fail

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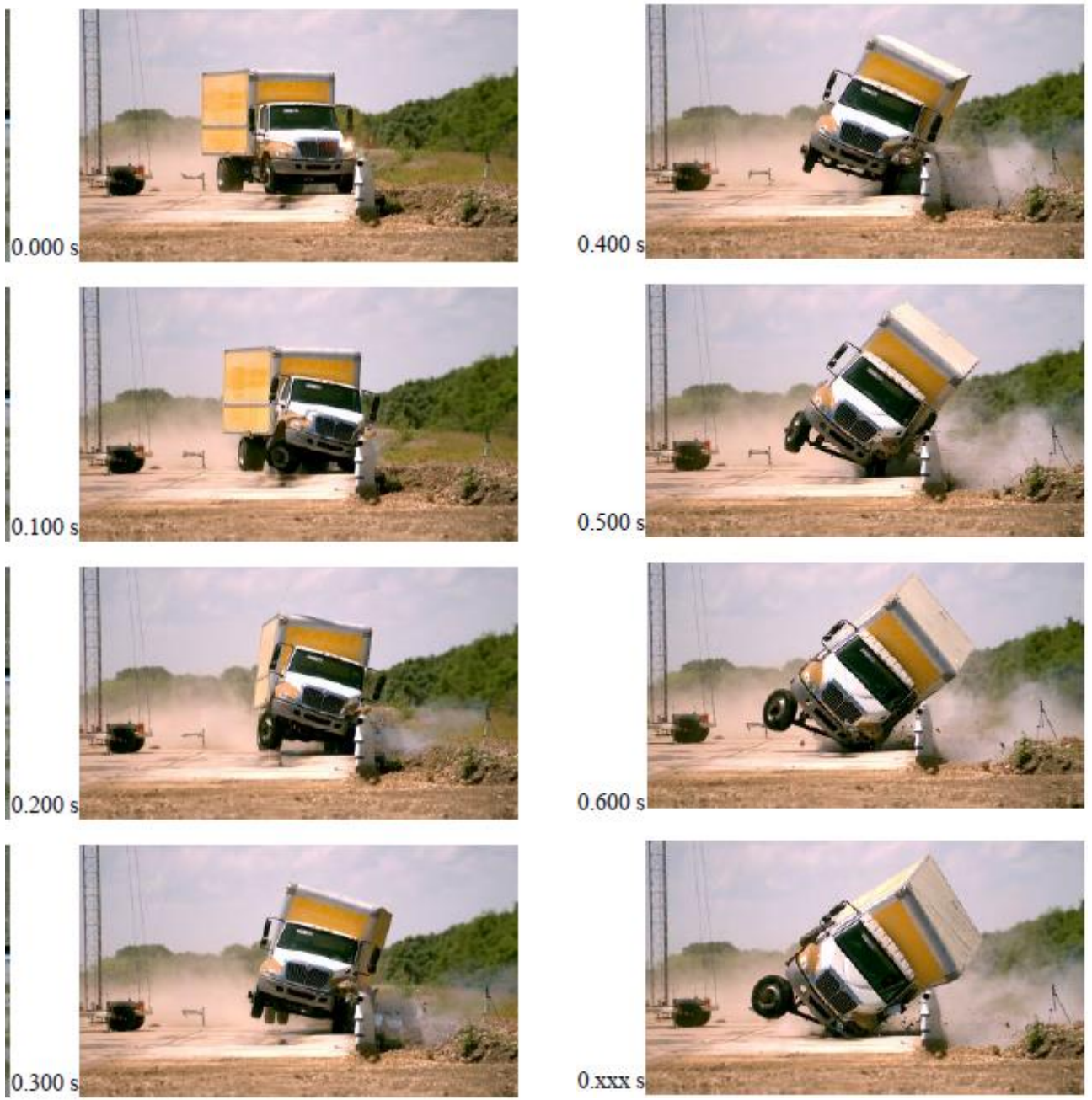
7.5 DAMAGE TO TEST INSTALLATION

Figure 7-3 shows the damage to the TxDOT Type C2P Bridge Rail. The welds failed at the base plates of post 5, 6, and 7. It was determined that the welds were not constructed correctly by the fabricator. After the welds failed at Posts 5, 6, and 7, the post plates rotated toward the field side 10 degrees, 13 degrees, and 7 degrees, respectively. The picket section between posts 5 and 6 released at the center and downstream locations but remained attached to the rail. Cracks radiated through the curb at posts 3 and 4, through the curb and deck at posts 5, 6, and 7, and through the curb at post 8. Working width was 62.3 inches. Maximum dynamic deflection during the test was 11.4 inches. Maximum permanent deformation as 7.25 inches at the joint between posts 5 and 6.

Figure 7-3. TxDOT Type C2P Bridge Rail after Test No. 490026-4-3.

International (bed Height = 50”)



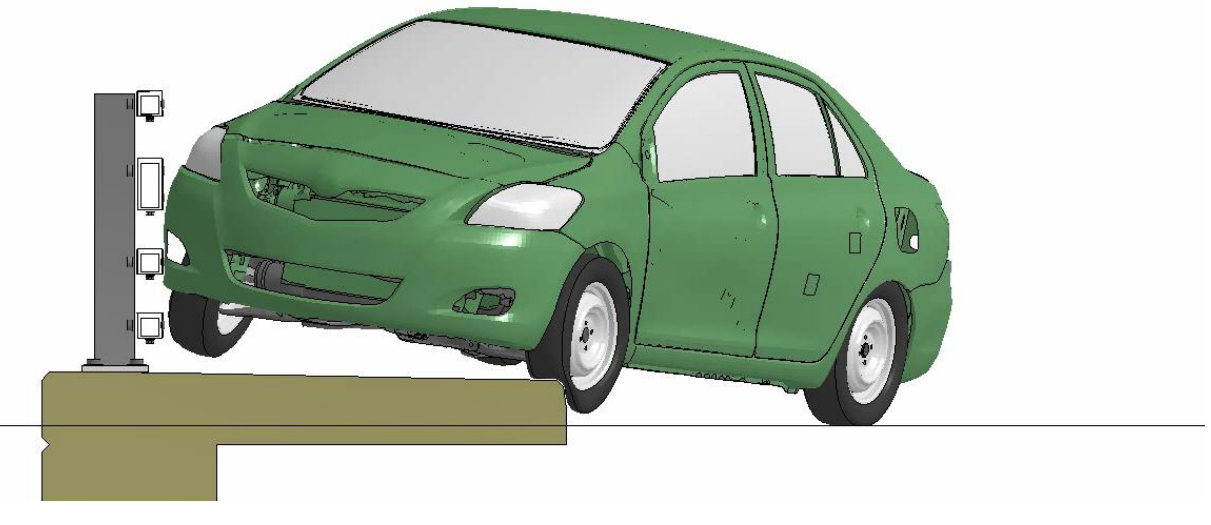
MASH TL-4 for NETC 4-Bar Bridge Rail

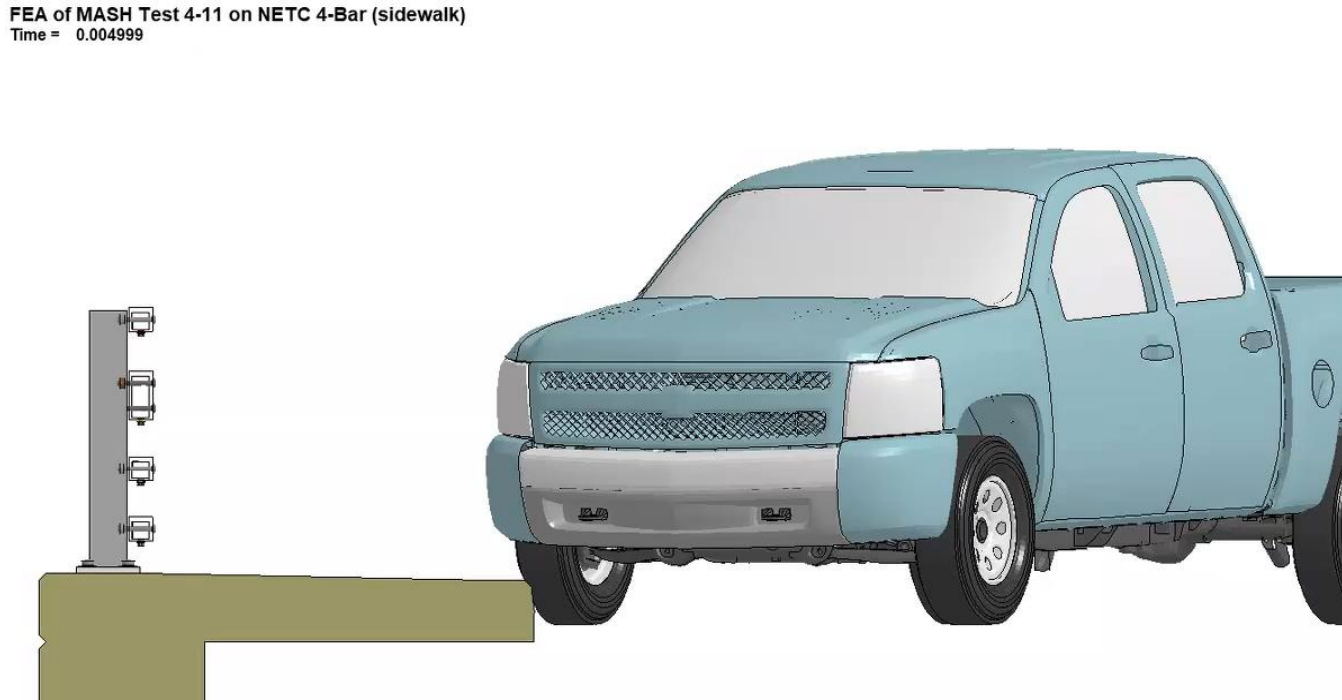
Test 4-10

- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 3.6 ft upstream from critical Post

Test 4-11

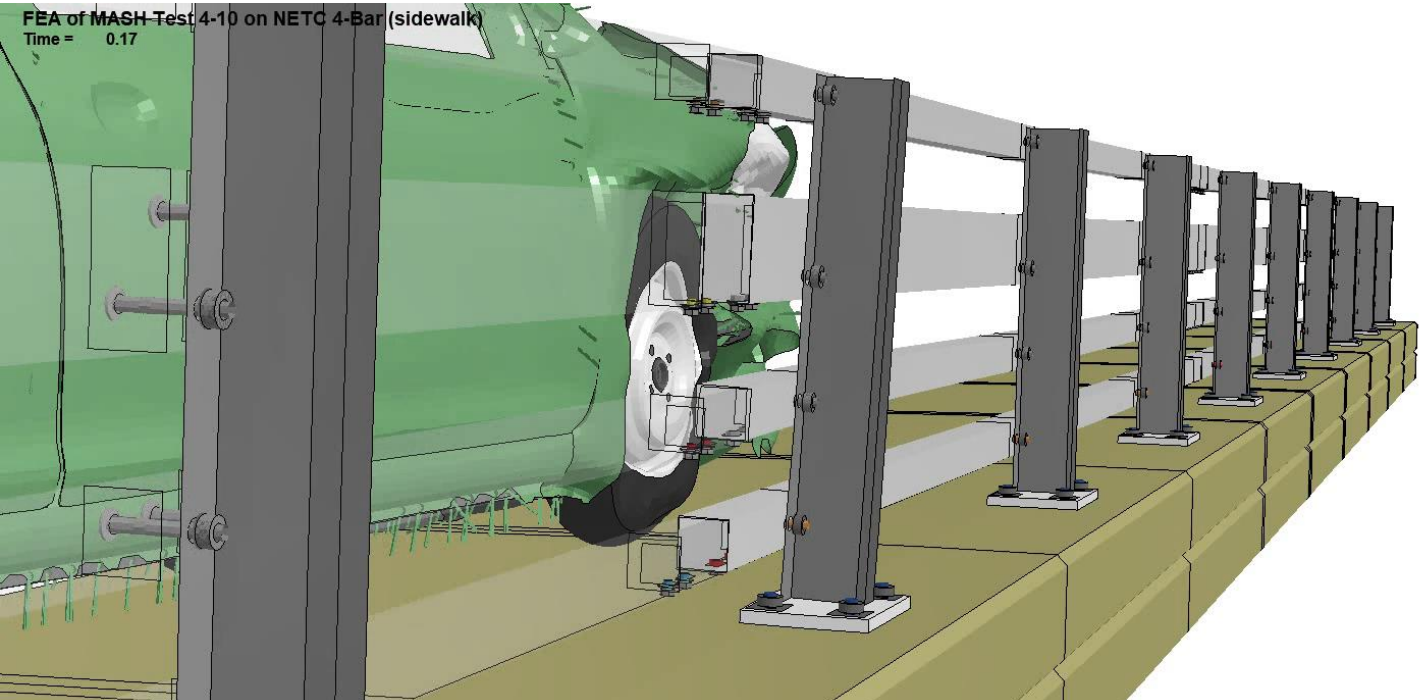
- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 4.3 ft upstream from critical Post

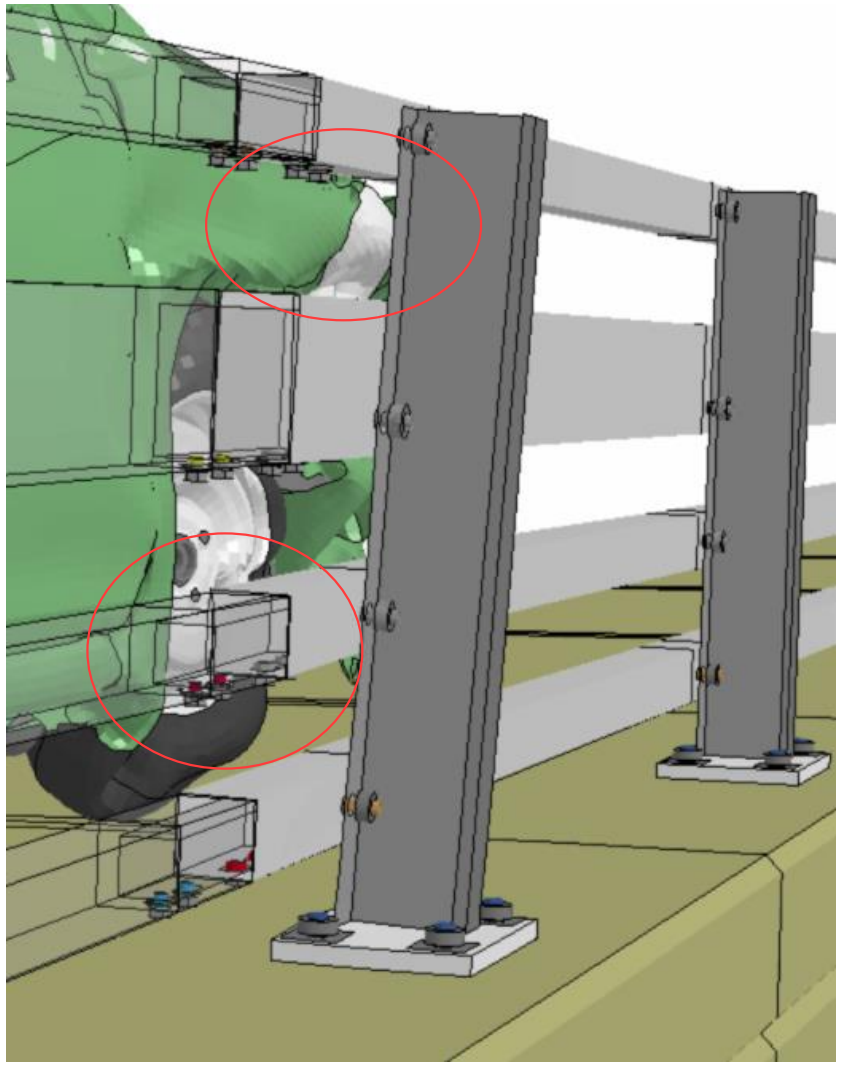




Assessment of Potential Vehicle Contact with Post

- The top of the front fender made slight contact with the post, but the contact force was negligible.
- The tire rim snagged on the splice at the lower-middle tube rail, which resulted in peak longitudinal acceleration of 21.6 G and Peak lateral acceleration of 25.8 G.
- Tires did not contact post.
- Also, the trajectory of the vehicle was affected by the tire remaining inflated and impacted higher on the railing than would be expected.





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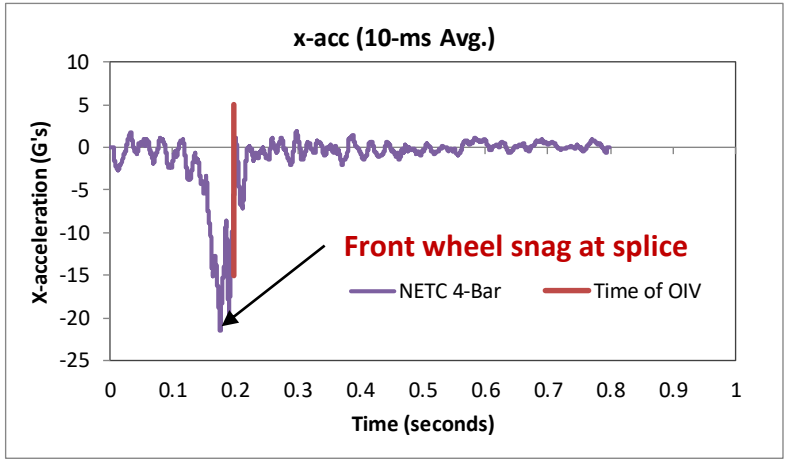
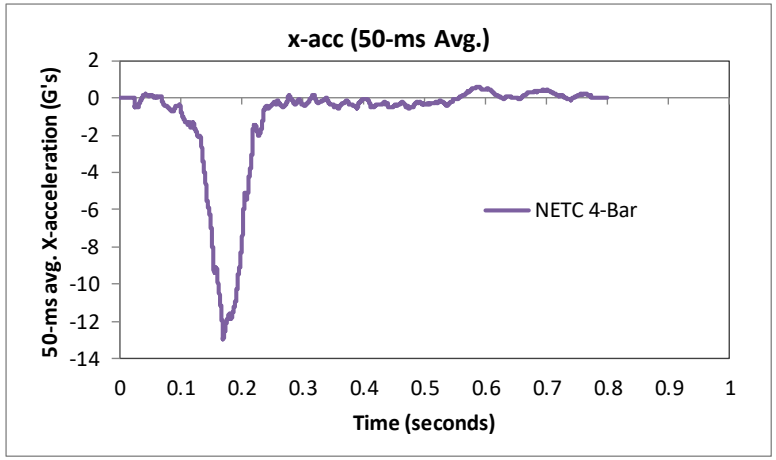
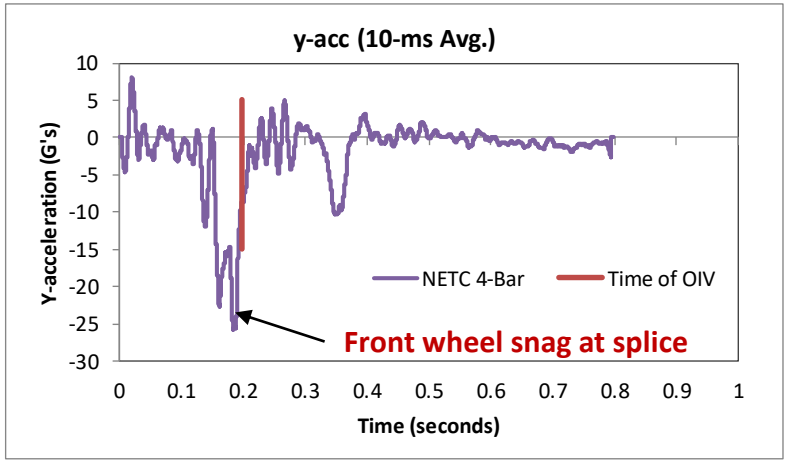
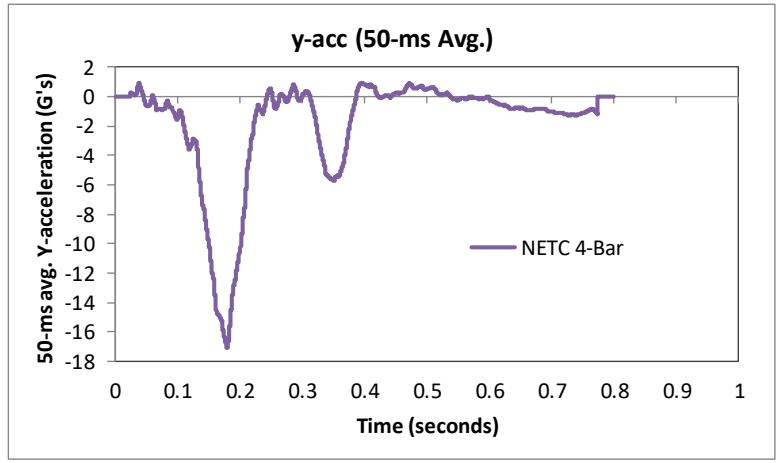
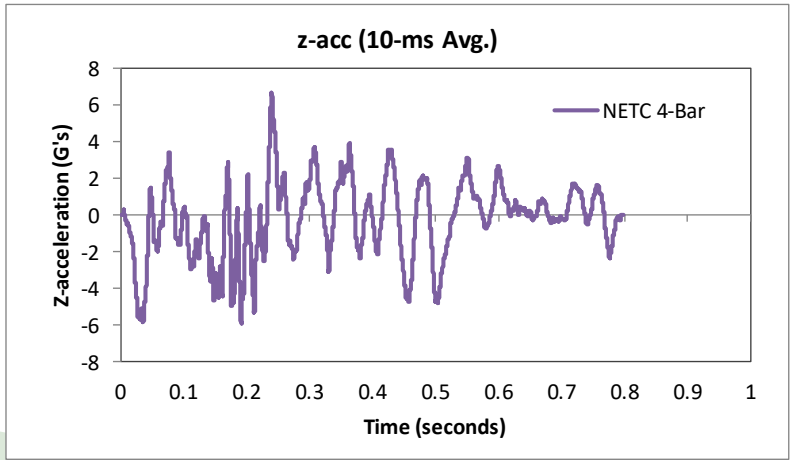
Test 4-10

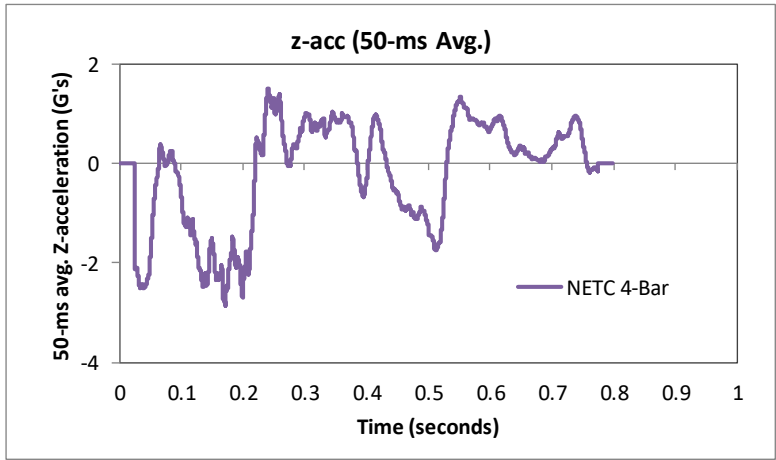

x-acc (10-ms Avg.)
X-acceleration (G's)
Time (seconds)
Front wheel snag at splice
NETC 4-Bar
Time of OIV


x-acc (50-ms Avg.)
50-ms avg. X-acceleration (G's)
Time (seconds)
NETC 4-Bar


y-acc (10-ms Avg.)
Y-acceleration (G's)
Time (seconds)
NETC 4-Bar
Time of OIV
Front wheel snag at splice

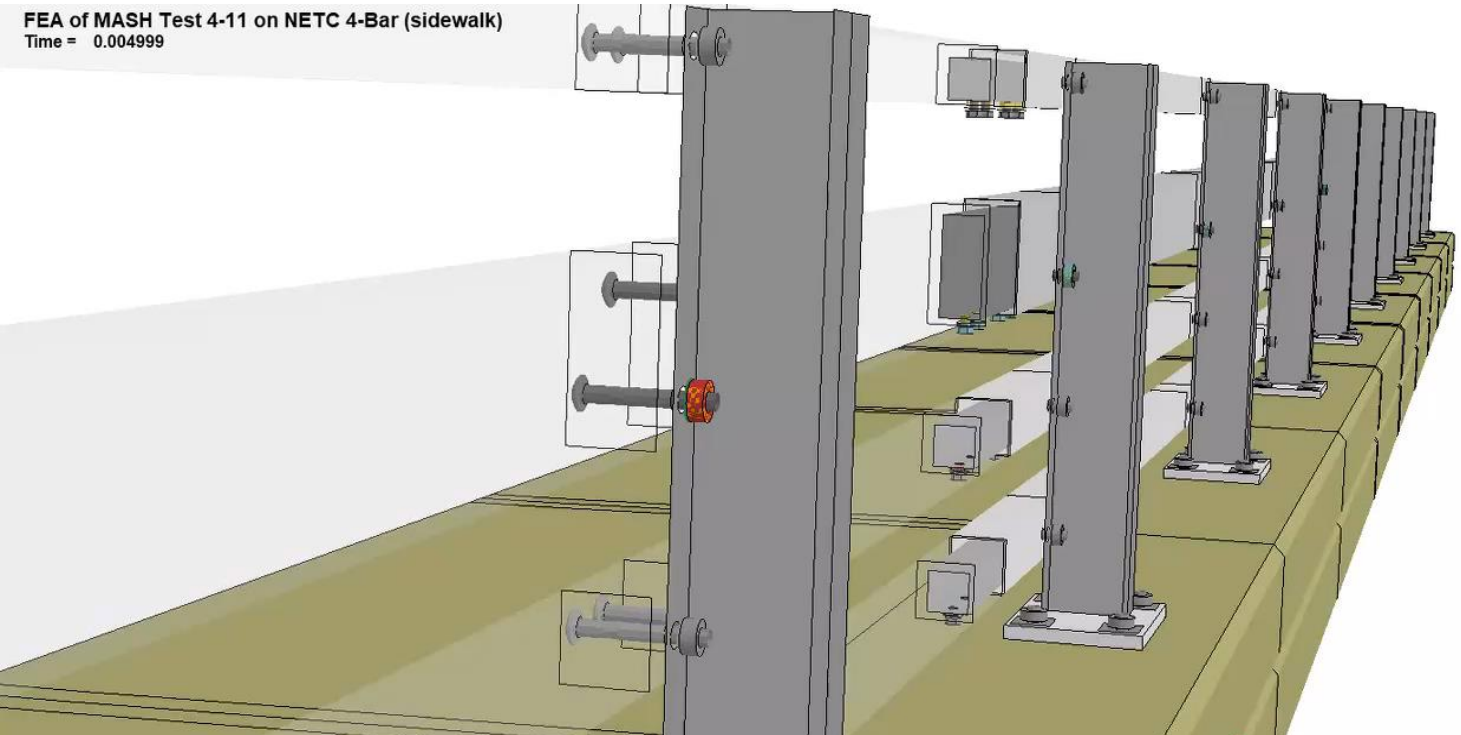

y-acc (50-ms Avg.)
50-ms avg. Y-acceleration (G's)
Time (seconds)
NETC 4-Bar


z-acc (10-ms Avg.)
Z-acceleration (G's)
Time (seconds)
NETC 4-Bar

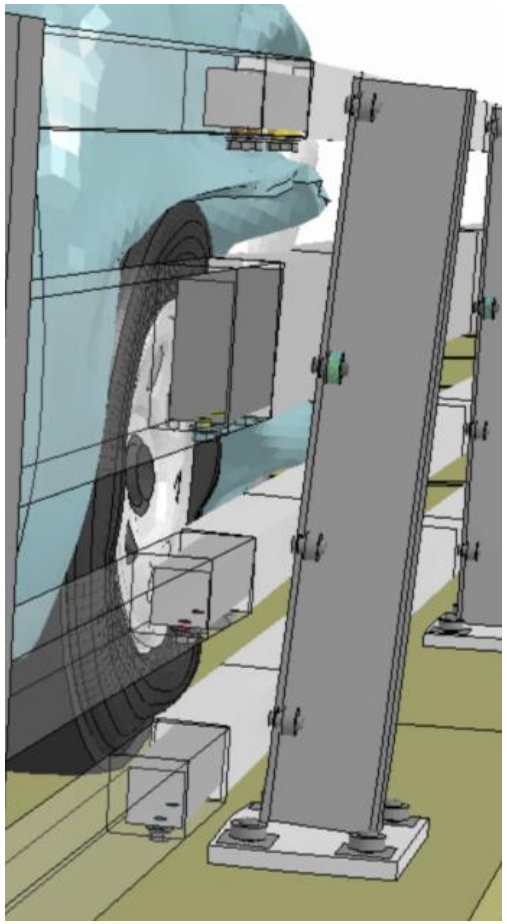

z-acc (50-ms Avg.)
50-ms avg. Z-acceleration (G's)
Time (seconds)
NETC 4-Bar

Assessment of Potential Vehicle Snag

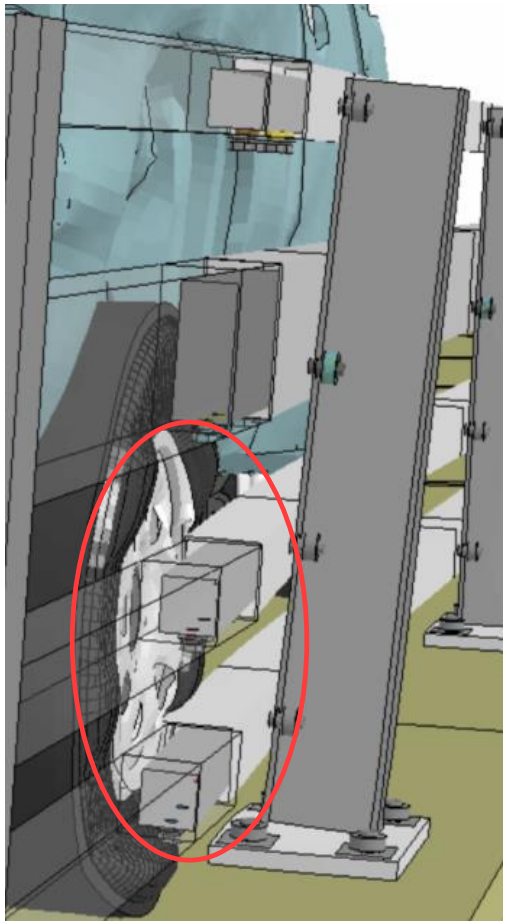
- The front fender and bumper made slight contact with the post, but the contact force was negligible.
- The rear wheel tire and rim snagged on the rail tube at the splice, resulting in maximum ORA.



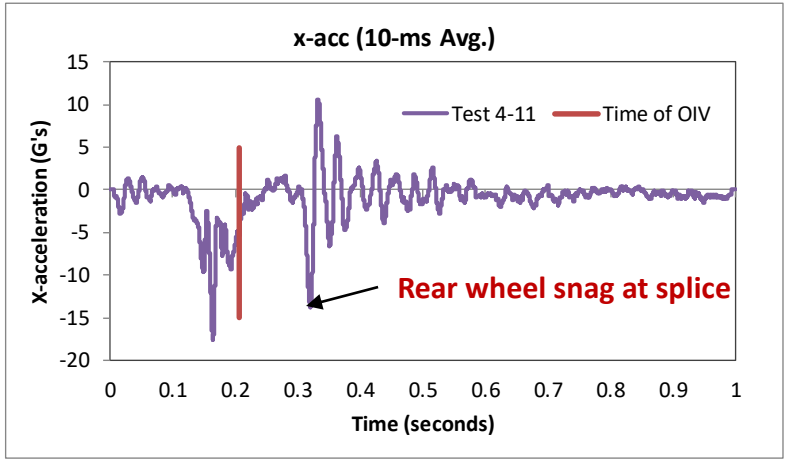
Front of Vehicle

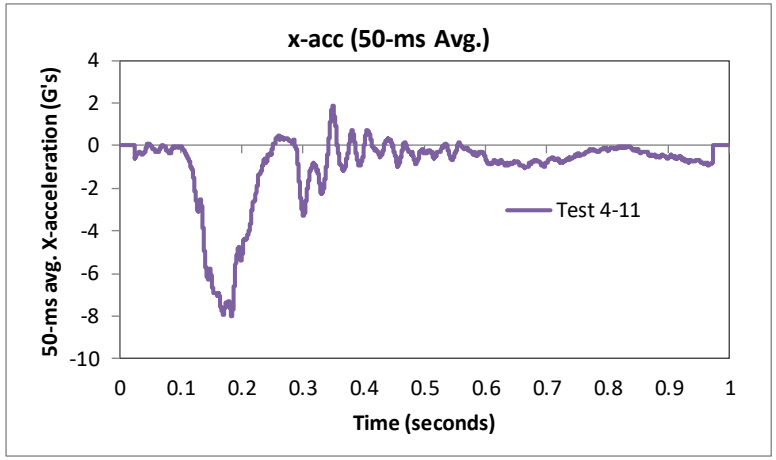


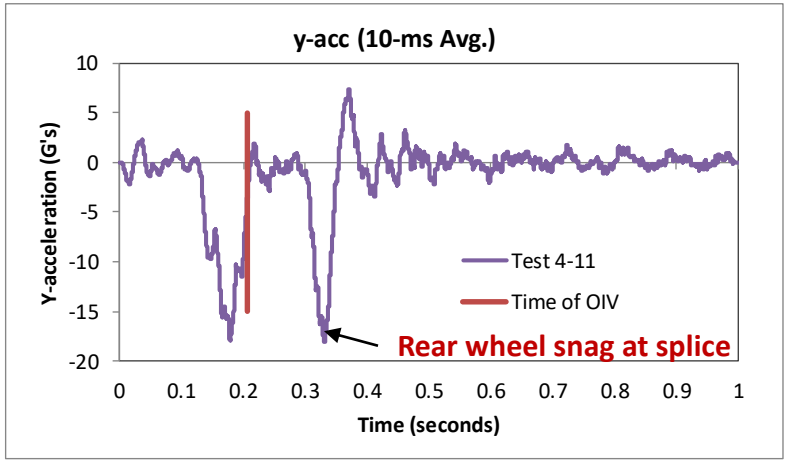
Rear Tire

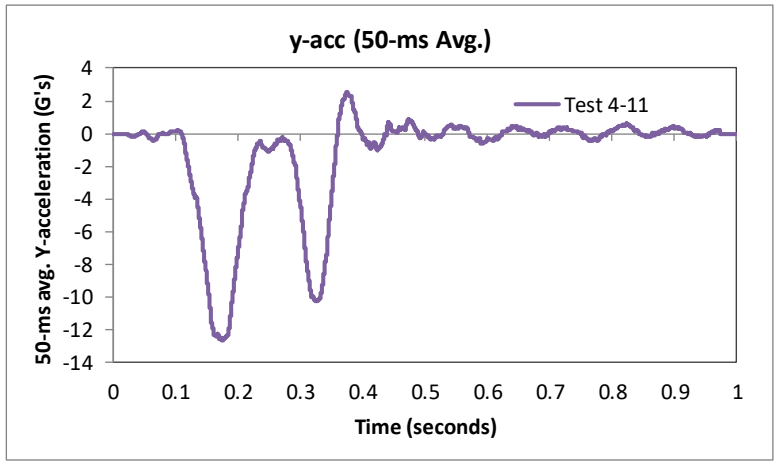


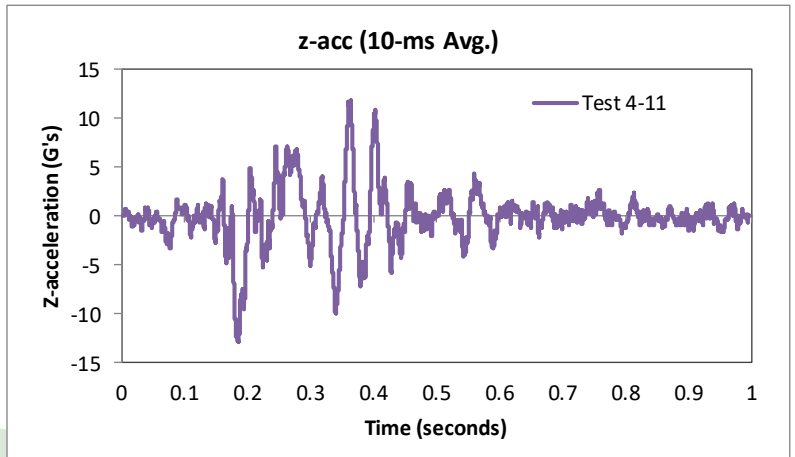
Test 4-11

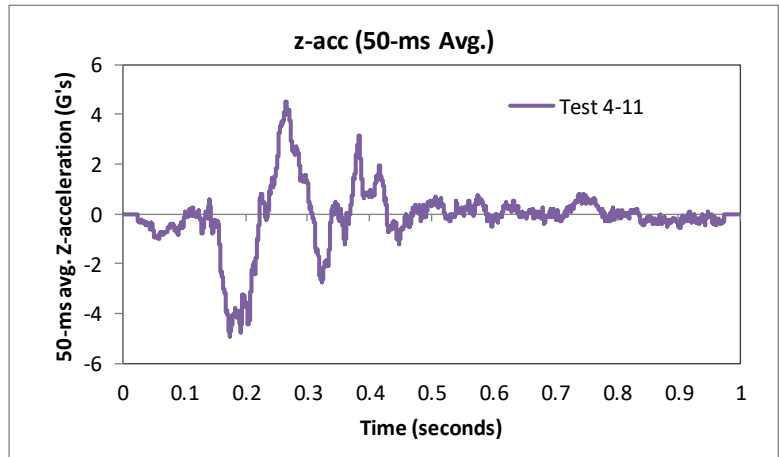

x-acc (10-ms Avg.)
X-acceleration (G's)
Time (seconds)
Test 4-11
Time of OIV
Rear wheel snag at splice


x-acc (50-ms Avg.)
50-ms avg. X-acceleration (G's)
Time (seconds)
Test 4-11


y-acc (10-ms Avg.)
Y-acceleration (G's)
Time (seconds)
Test 4-11
Time of OIV
Rear wheel snag at splice


y-acc (50-ms Avg.)
50-ms avg. Y-acceleration (G's)
Time (seconds)
Test 4-11


z-acc (10-ms Avg.)
Z-acceleration (G's)
Time (seconds)
Test 4-11


z-acc (50-ms Avg.)
50-ms avg. Z-acceleration (G's)
Time (seconds)
Test 4-11

Conclusions for Test 4-10 and 4-11 on the NETC 4-BAR

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

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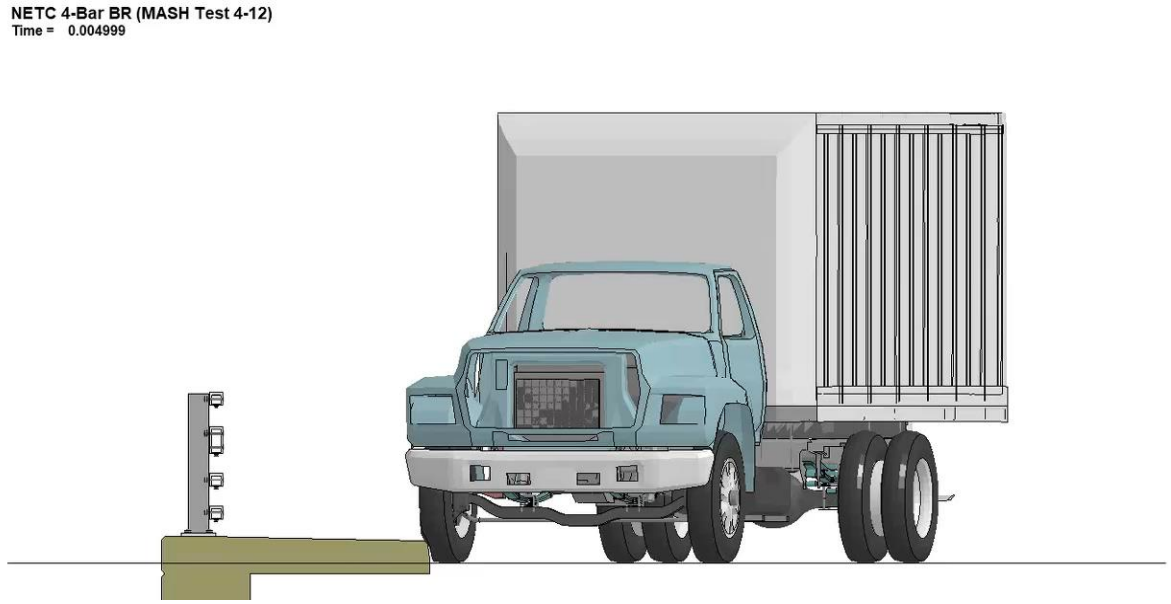
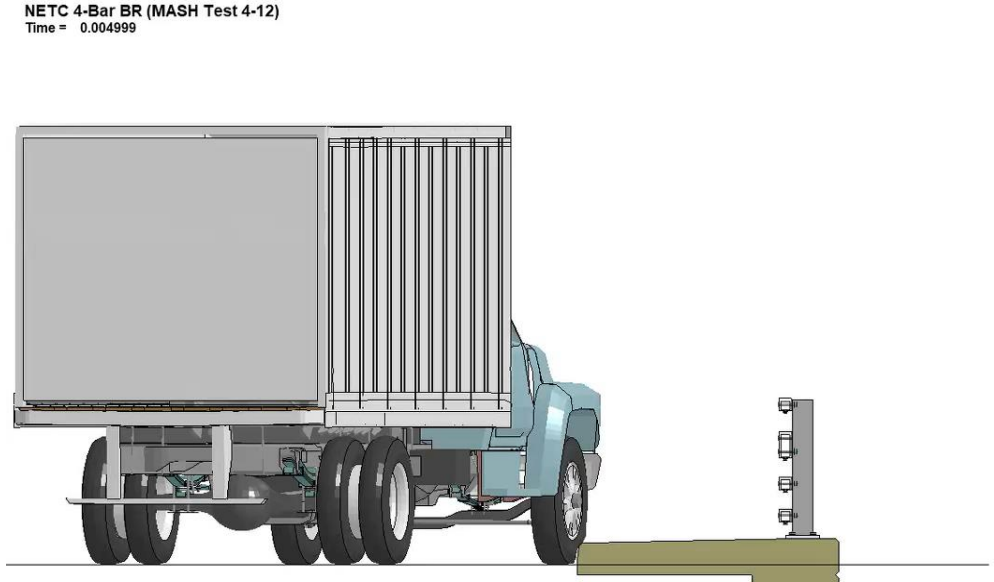
MASH Test 4-12 Simulation

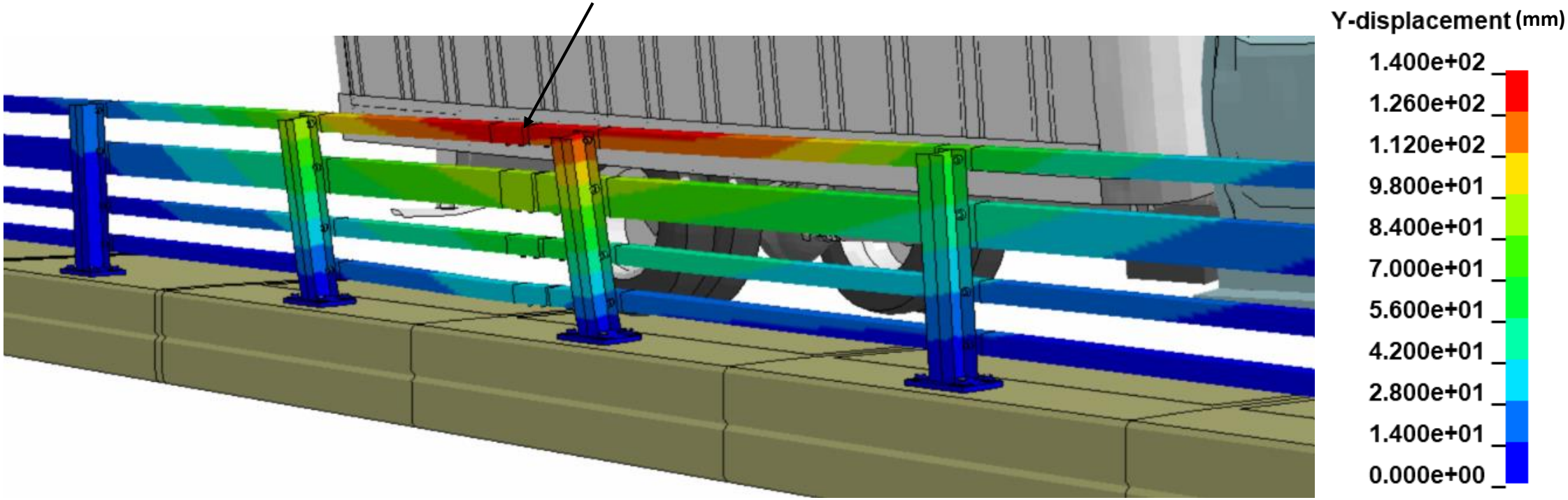
- **Impact Conditions**
  - Mass = 22,061 lb
  - Impact Speed = 56 mph (90 km/hr)
  - Impact Angle = 15 degrees
  - Target Impact Point = 5.0 ft upstream of Post 7
  - **Actual Impact Point = 4.4 ft upstream of Post 7**





Lateral Dynamic Deflection

Maximum dynamic deflection = 8.15 in (207 mm) @ 0.51 seconds



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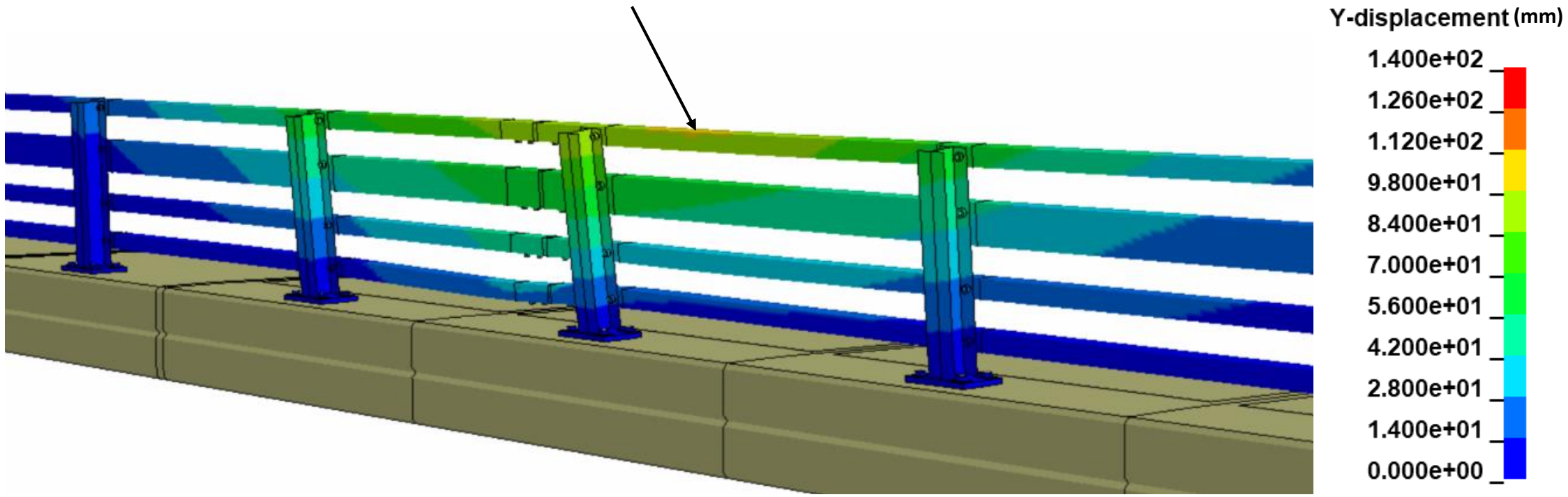
Lateral Permanent Deflection

Maximum permanent deflection = 5.8 in (147 mm)



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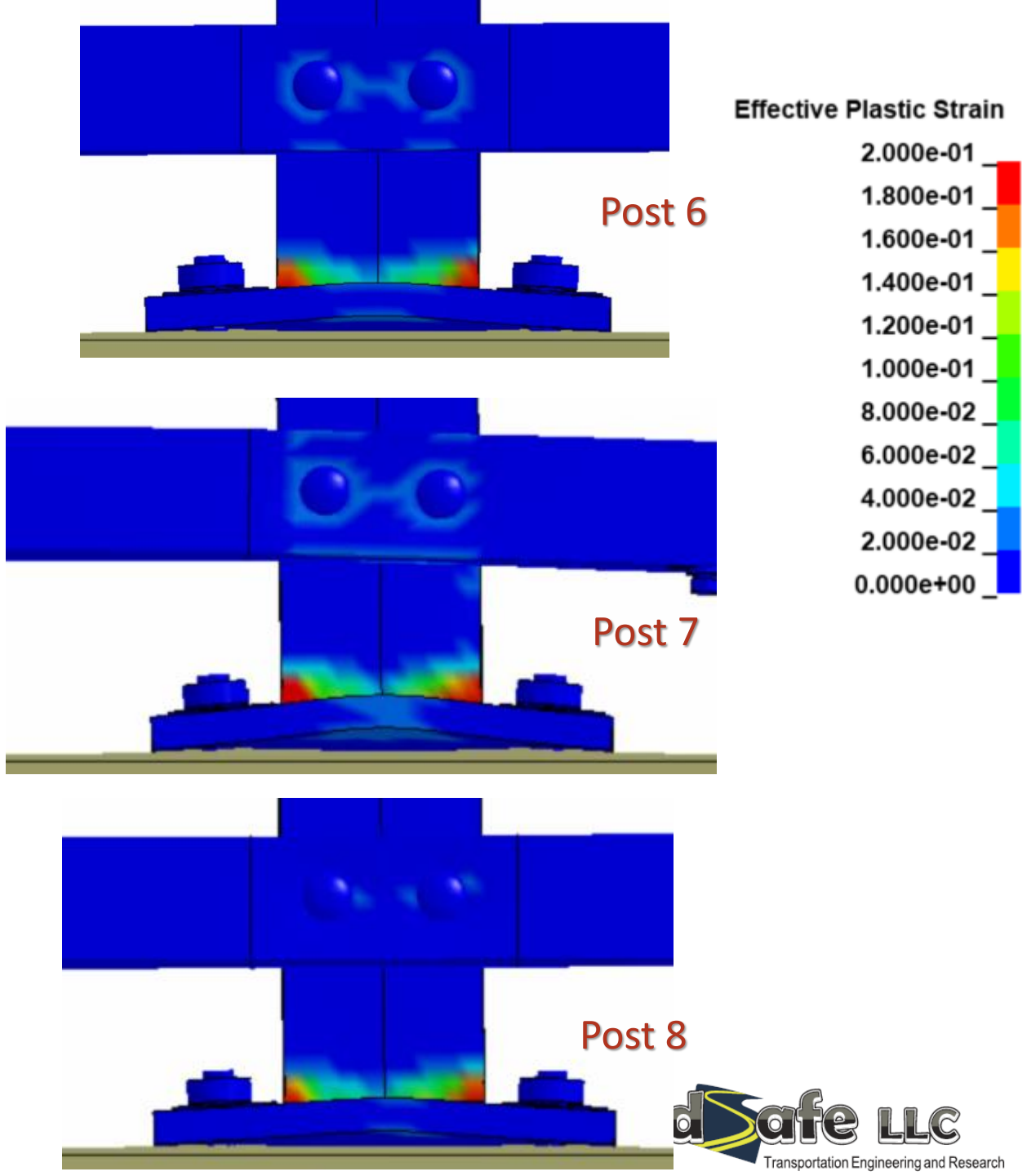
Damage to Base Plates

- Vertical deflection of base plates
  - Post 6:
    - Dynamic = 0.82” (21 mm)
    - Permanent = 0.53” (13.5 mm)
  - Post 7:
    - Dynamic = **1.11” (28 mm)**
    - Permanent = **0.82” (21 mm)**
  - Post 8:
    - Dynamic = 0.78” (20 mm)
    - Permanent = 0.52” (13 mm)



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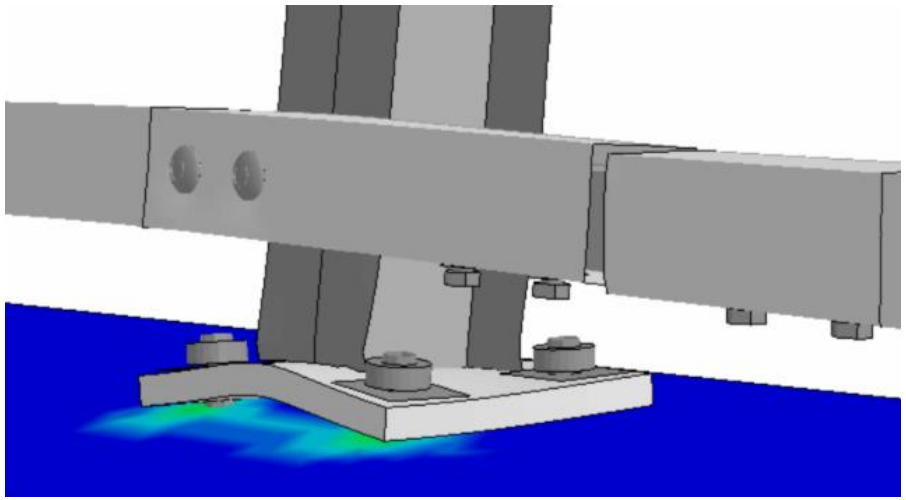
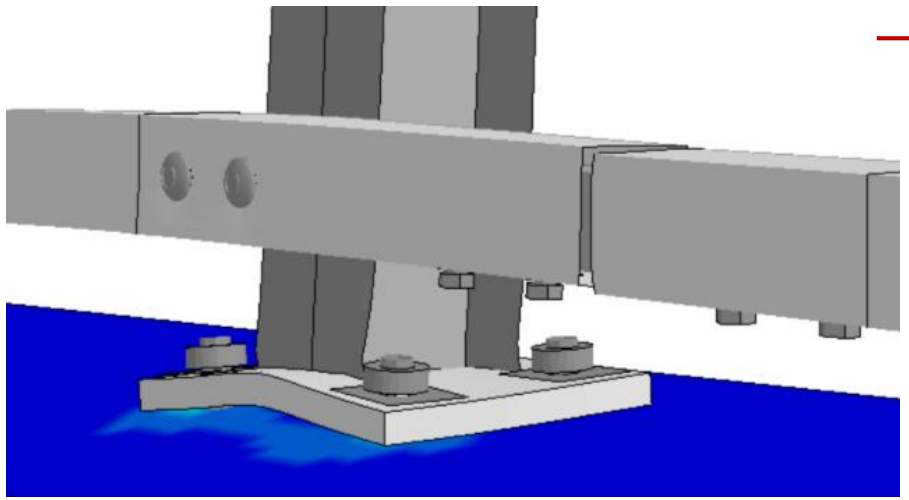
Barrier Damage

- Analysis indicated probable crack opening in concrete at front anchor bolts at Post 7 at maximum dynamic deflection.
  - Max dynamic 1st Prin. Strain = 0.079
  - Final 1st Prin. Strain = 0.054

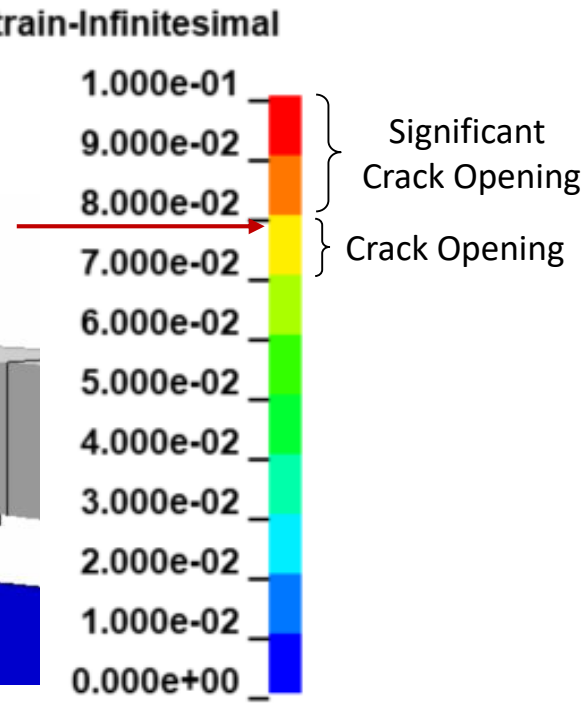
Anchor tensile forces will increase as post strength increases



Dynamic at time = 0.515 seconds



Final Static



Conclusions on Test 4-12 on the NETC 4-Bar

Evaluation Factors		Evaluation Criteria – MASH Test 4-12	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass
	G	It is preferable, although not essential, that the vehicle remain upright during and after collision.	Pass

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Summary/Conclusion for all NETC Systems

- **NETC 2-Bar:**
  - Meets MASH TL3 criteria with only moderate barrier damages.
  - Concrete curb damage at Post 7 was likely for Test 3-11.
- **NETC 3-Bar and 4-Bar:**
  - The barrier system meets MASH TL4 criteria; however, relatively high barrier damages are likely under these conditions.

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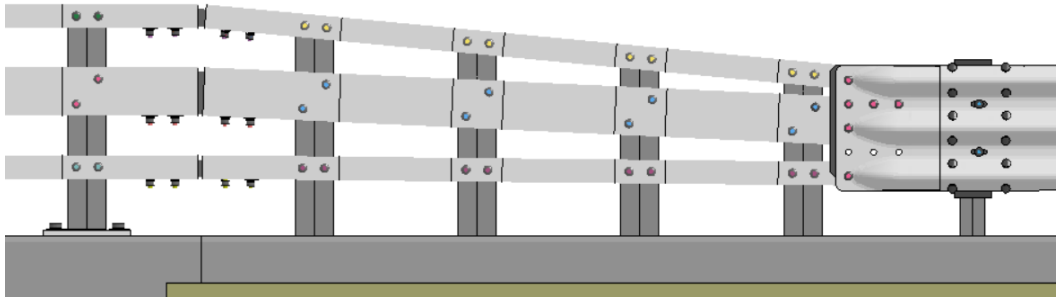
NETC Transition Systems

- Three design options are being evaluated:
  1. NETC Style 2-Bar Rail and Thrie Beam (TL3) (NHDOT steel rail transition)
  2. NETC Style 3-Bar Rail and Thrie Beam (TL4) (NHDOT steel rail transition)
  3. Concrete Transition Barrier and Thrie Beam (TL4) (MaineDOT standard detail)

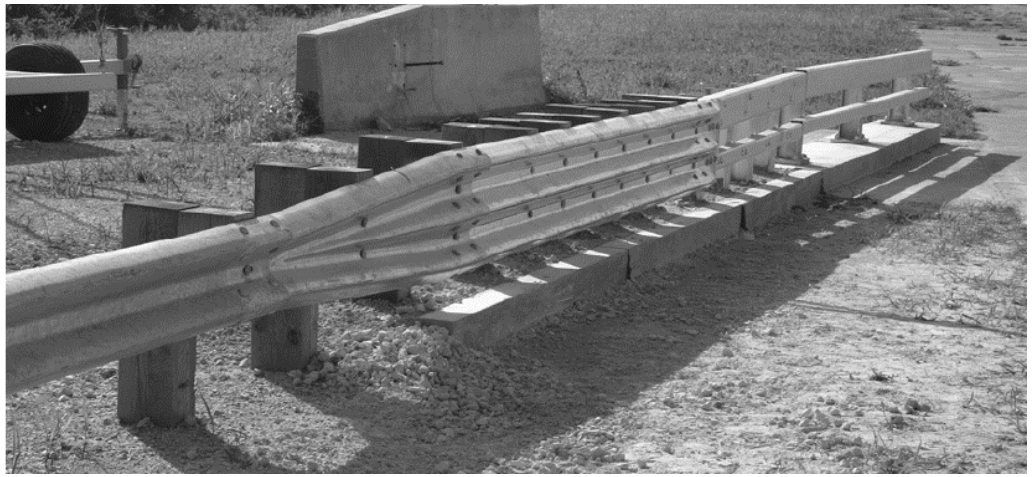


- Single taper on top
- No face taper

NETC 2-Bar to Thrie-Beam AGT

Report 350 Test Level 3

	401181-1	Preferred Limits
Test Designation	Test 3-21	
Test Vehicle	2000 Chevrolet 2500	
Gross Vehicle Weight (lb)	4,706	
Impact Speed (mph)	63.6	
Impact Angle (deg)	24.9	
Exit Speed (mph)	52.9	
Exit Angle (deg)	11.7	
Occupant Impact Velocity		
Longitudinal (ft/s)	17.1	< 30 ft/s
Lateral (ft/s)	24.6	
Ridedown Accel		
Longitudinal (g's)	8.3	< 15 G
Lateral (g's)	10	
Maximum 50 msec Avg Accel		
Longitudinal (g's)	8.1	
Lateral (g's)	13.5	
Max Deflection (in)	7.87	
Vehicle Trajectory		
Maximum YawAngle (deg)	56	
Maximum Roll Angle (deg)	14	< 75°
Maximum Pitch Angle (deg)	19	
NCHRP Report 350 Evaluation		
Structural Adequacy	Pass	
Ocupant Risk	Pass	
Vehicle Trajectory	Pass	



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NETC 2-Bar to Thrie-Beam AGT

Validation

Occupant Risk Factors		MASH Test 3-11		Error		W179 Criteria	
		Test 401181-1	FEA				
		(0 - 1.0 seconds)	(0 - 1.0 seconds)	%	Absolute	Criteria	Pass
Occupant Impact Velocity (ft/s)	x-direction	17.06	19.68	15.4%	2.62	<20% or < 6.6 f/s	Y
	y-direction	-24.61	-24.93	1.3%	-0.33	<20% or < 6.6 f/s	Y
	at time	at 0.0948 seconds on left side of interior	at 0.1005 seconds on left side of interior				
THIV (m/s)		29.9 at 0.0948 seconds on left side of interior	31.5 at 0.0986 seconds on left side of interior	5.5%	1.64	<20% or < 6.6 f/s	Y
Ridedown Acceleration (g's)	x-direction	-8.3 (0.1153 - 0.1253 seconds)	-8.3 (0.1018 - 0.1118 seconds)	0.0%	0.00	<20% or < 4G	Y
	y-direction	10 (0.1182 - 0.1282 seconds)	7.5 (0.1388 - 0.1488 seconds)	25.0%	-2.50	<20% or < 4G	Y
PHD (g's)		11.9 (0.1180 - 0.1280 seconds)	9.1 (0.1344 - 0.1444 seconds)	23.5%	-2.80	<20% or < 4G	Y
ASI		1.74 (0.0216 - 0.0716 seconds)	1.48 (0.0355 - 0.0855 seconds)	14.9%	-0.26	<20% or < 0.2	Y
Max 50-ms moving avg. acc. (g's)	x-direction	-8.1 (0.0334 - 0.0834 seconds)	-9.6 (0.0342 - 0.0842 seconds)	18.5%	-1.50	<20% or < 4G	Y
	y-direction	13.5 (0.0216 - 0.0716 seconds)	11 (0.0448 - 0.0948 seconds)	18.5%	-2.50	<20% or < 4G	Y
	z-direction	-7.6 (0.0209 - 0.0709 seconds)	-3.8 (0.0359 - 0.0859 seconds)	50.0%	3.80	<20% or < 4G	Y
Maximum Angular Disp. (deg)	Yaw	55.6 (1.0000 seconds)	48.2 (0.9426 seconds)	13.3%	-7.40	<20% or < 5 deg	Y
	Roll	-19.4 (0.5914 seconds)	-17 (0.4713 seconds)	12.4%	2.40	<20% or < 5 deg	Y
	Pitch	-13.7 (0.6647 seconds)	-16.5 (0.5674 seconds)	20.4%	-2.80	<20% or < 5 deg	Y

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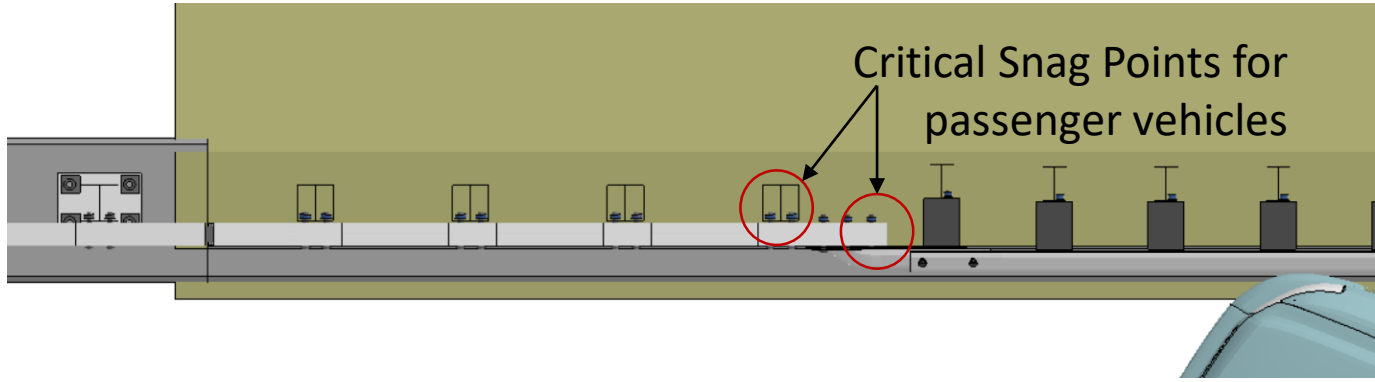
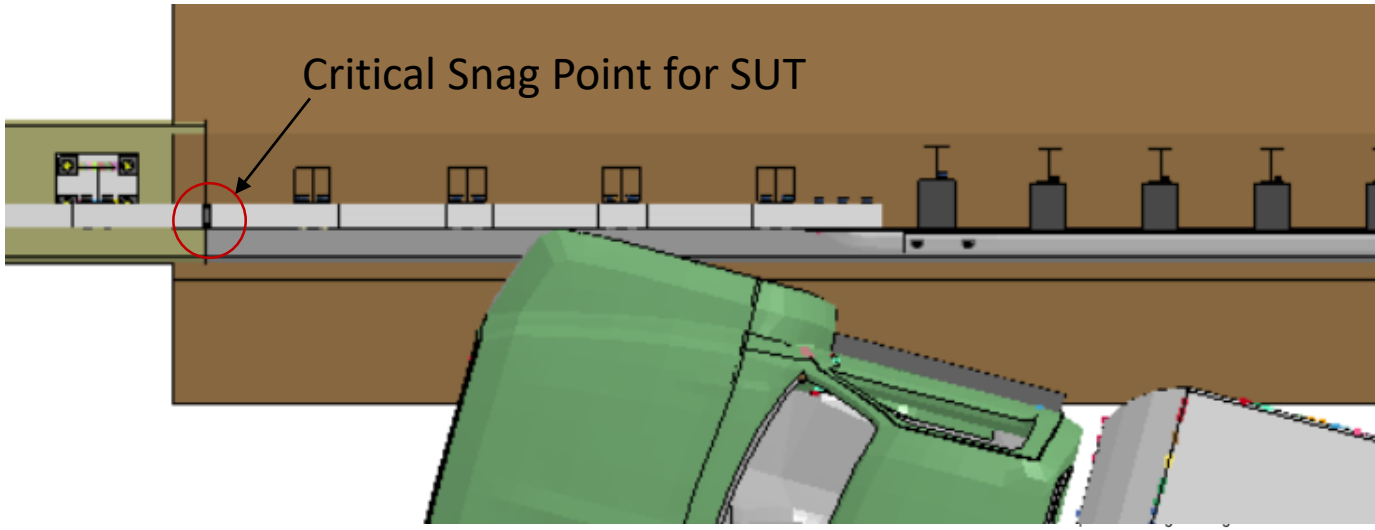
Determining Critical Impact Point for MASH

- Test 4-20 (small Car) and
- Test 4-21 (pickup):
  - Maximize potential for snag on end of transition tube railing
  - Maximize potential for snag on first post of tube rail transition
- Test 4-22 (SUT):
  - Maximize potential for snag on end of bridge rail
    - (i.e., TL4 end of the transition)

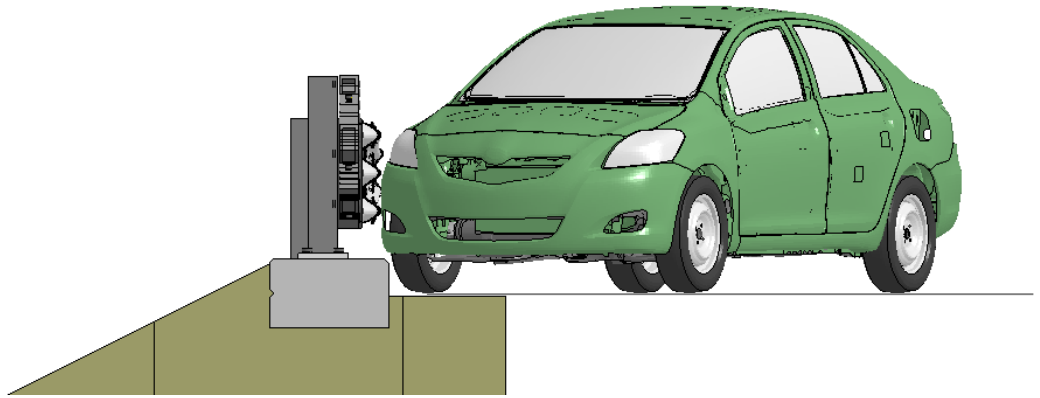


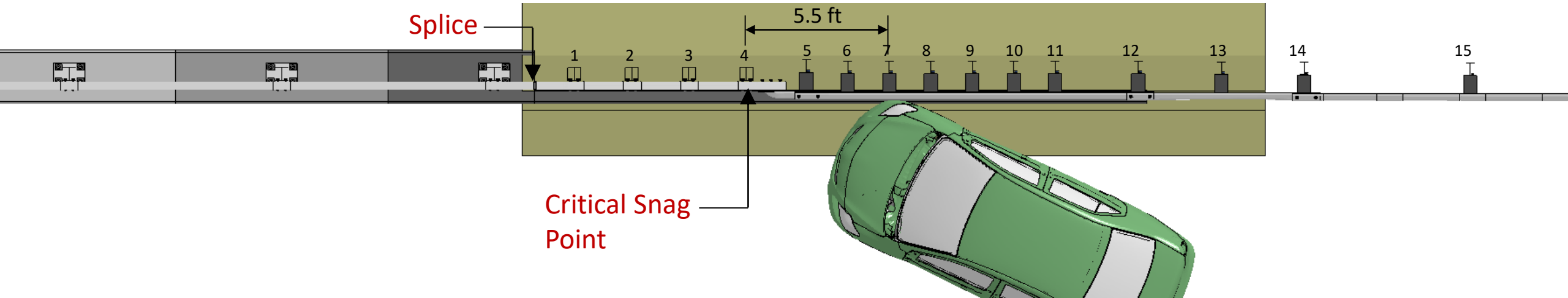


MASH Test 4-20 Simulation on the 3-Bar Trans

- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point = 5.5 ft upstream from critical Post

- Vehicle Model
  - YarisC_V1l_R160407.k
  - Vehicle Mass = 1,177 kg (2,595 lb)

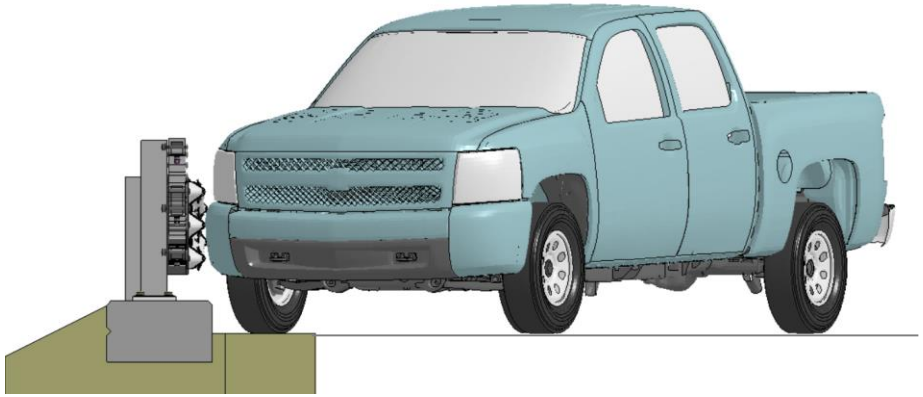


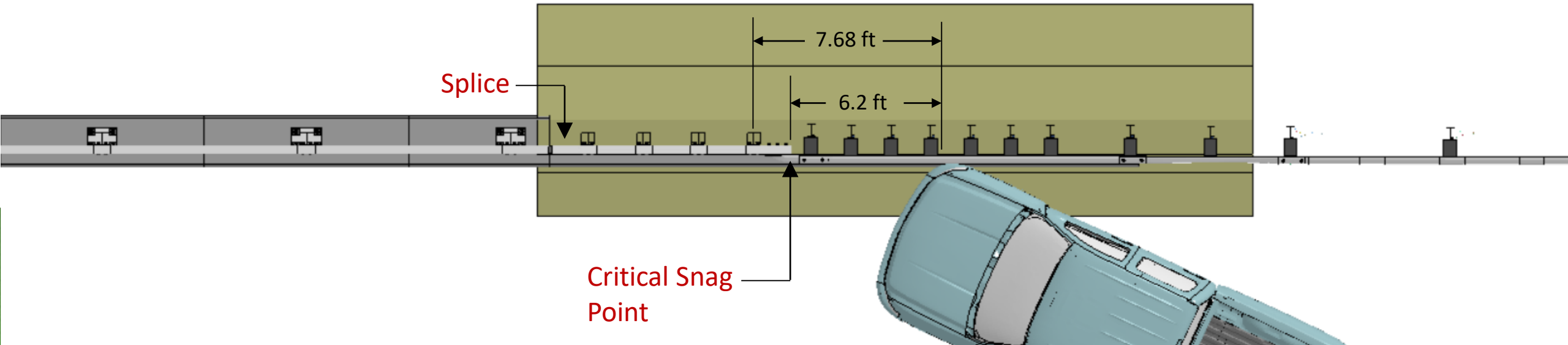


MASH Test 4-21 Simulation on the 3-Bar Trans

- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point = 6.2 ft upstream from end of tube-rail

- Vehicle Model
  - SilveradoC_V3a_V180201_TireRS_35psi.k
  - Vehicle Mass = 2,268 kg (5,001 lb)

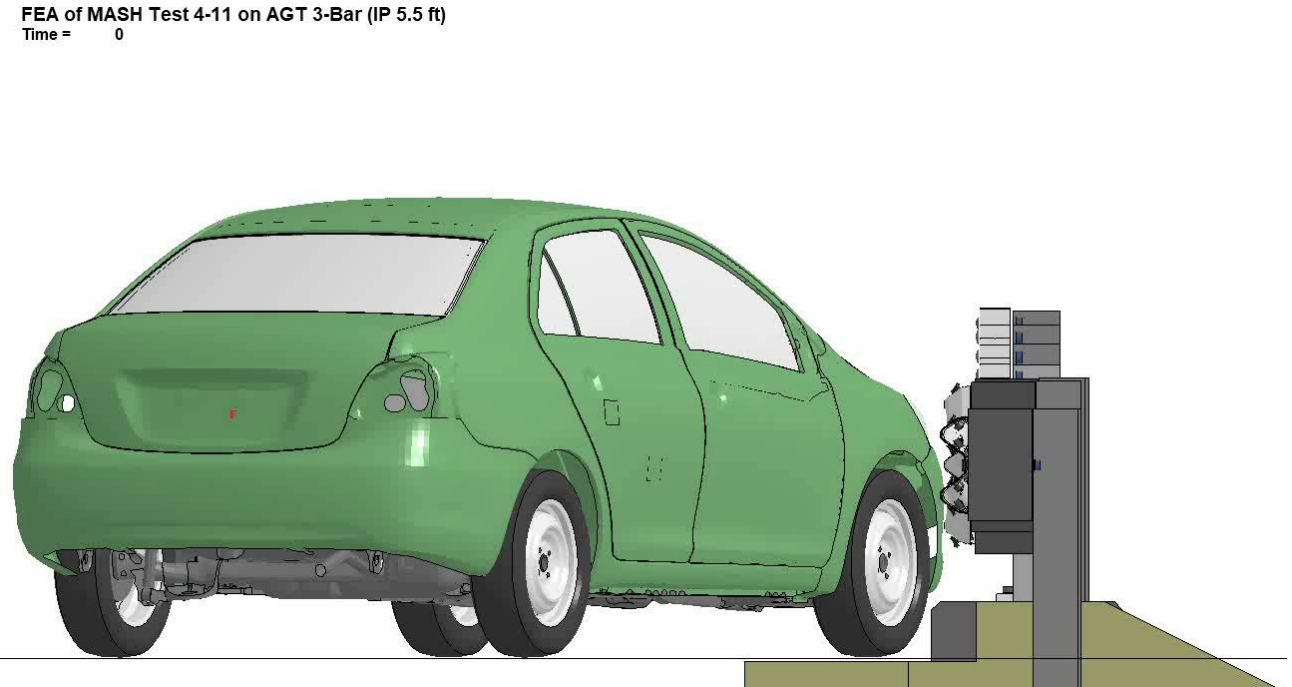




MASH TL-4 for NETC 3-Bar Transition

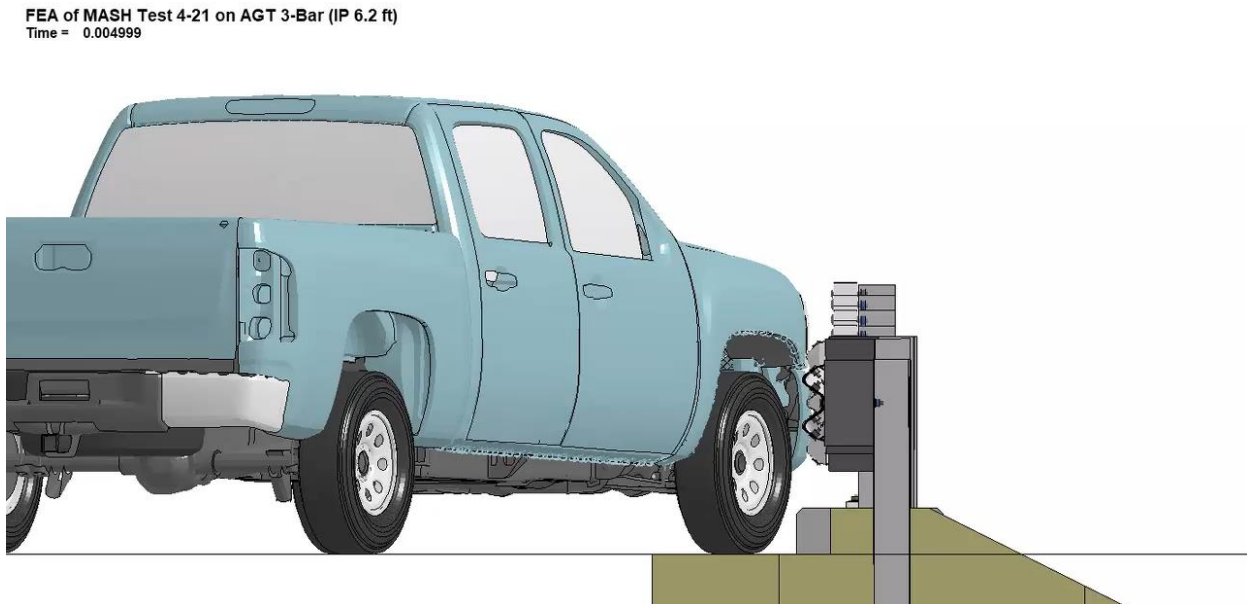
Test 4-20

- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 5.5 ft upstream from critical Post



Test 4-21

- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 6.2 ft upstream from end of tube rail



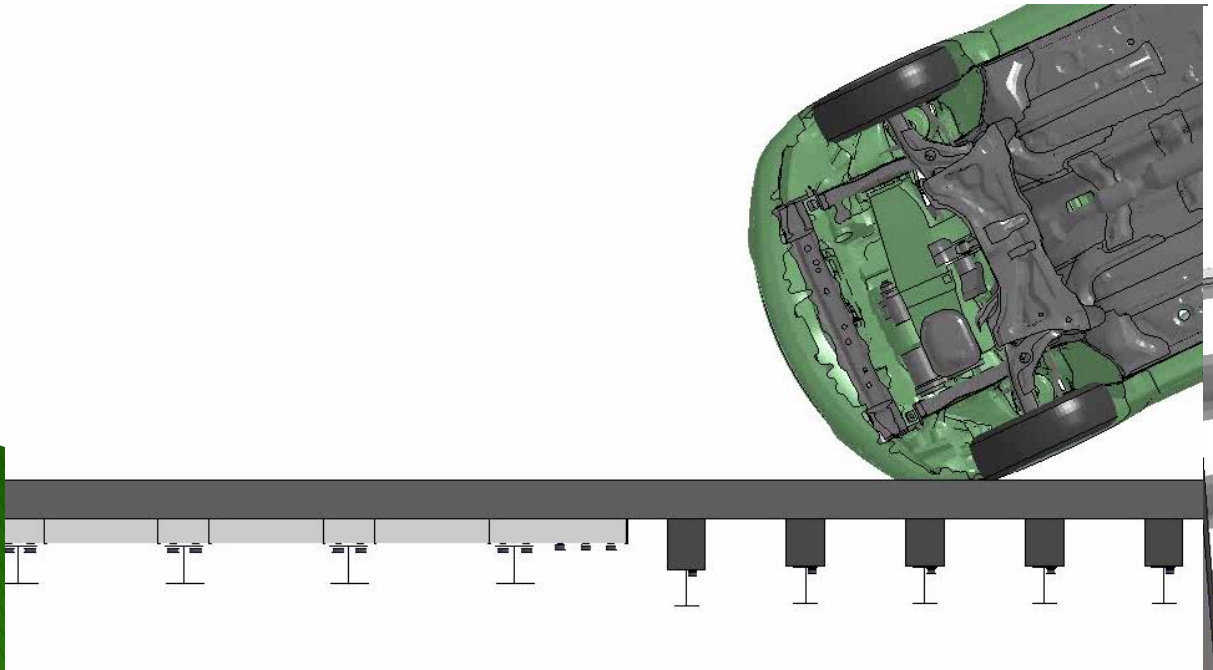
MASH TL-4 for NETC 3-Bar Transition

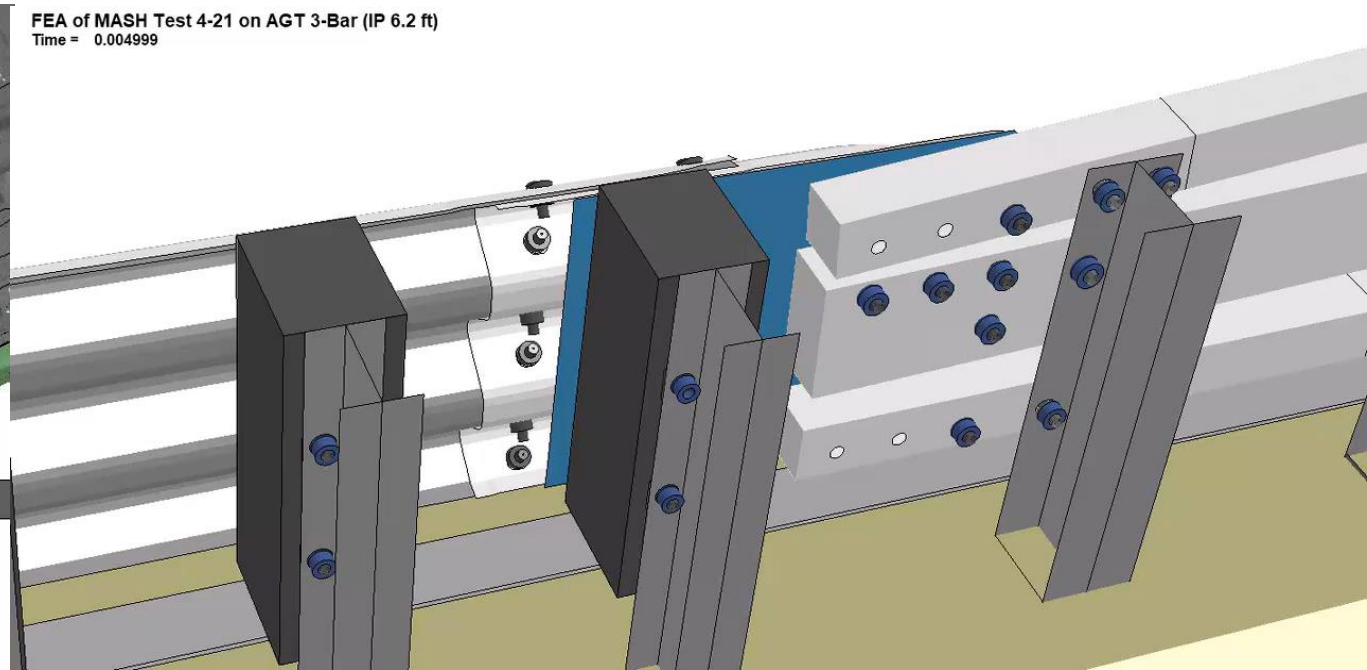
Test 4-20

- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 5.5 ft upstream from critical Post

Test 4-21

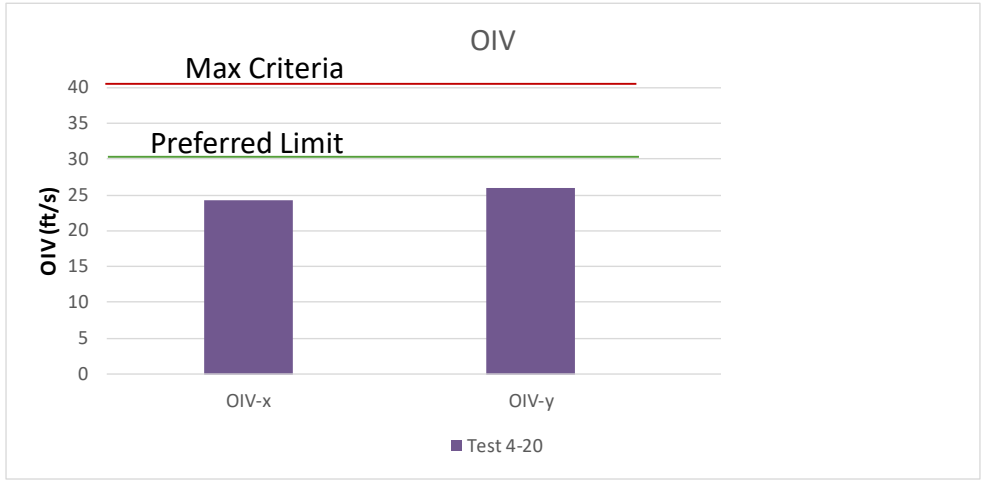
- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 6.2 ft upstream from end of tube rail

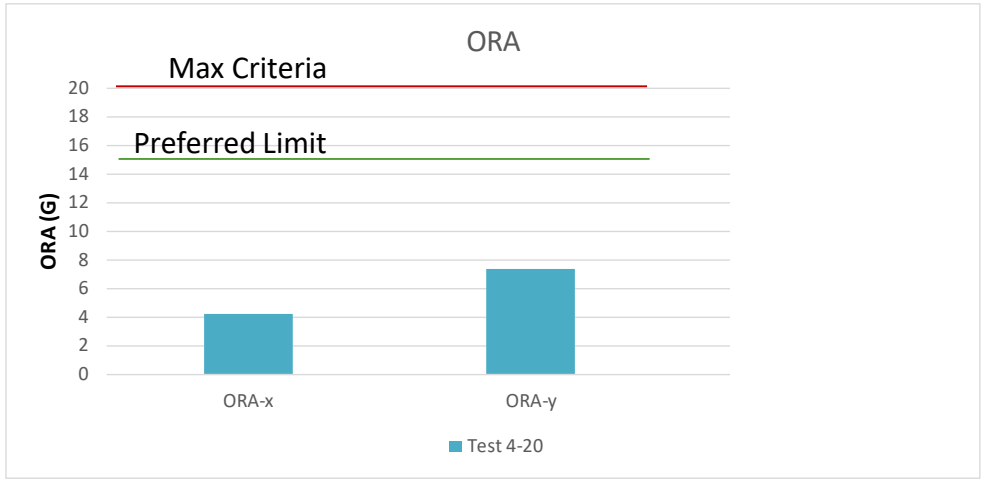




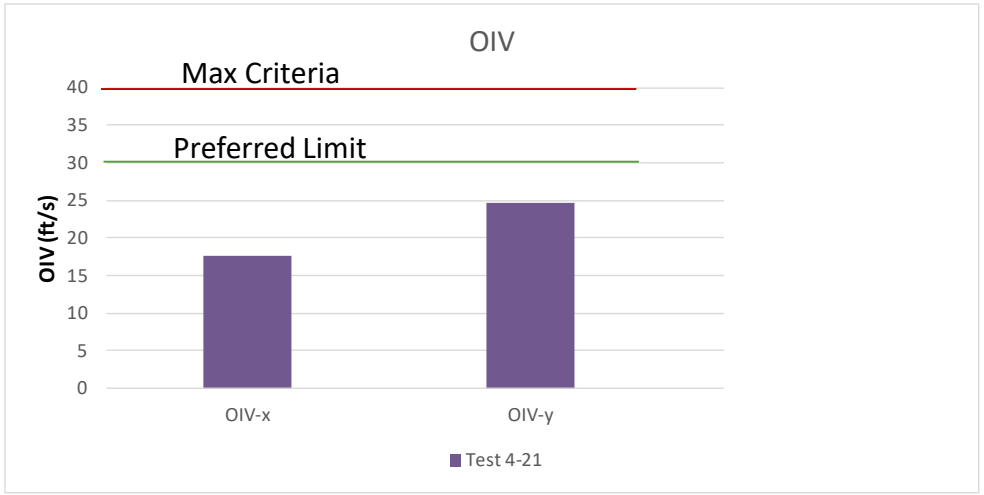
Occupant Risk

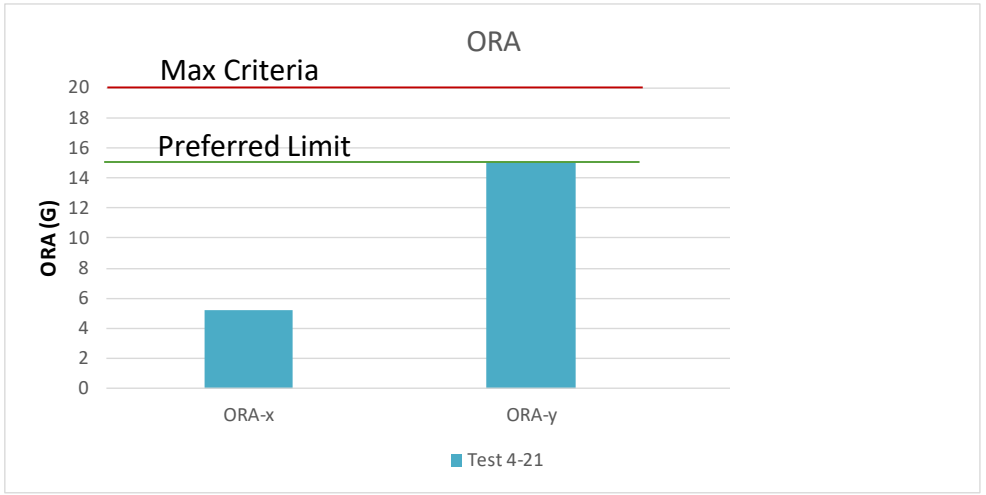
Test 4-10
(small car)





Test 4-11
(pickup)





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Conclusions on Tests 4-20 and 4-21 3-Bar Transition

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

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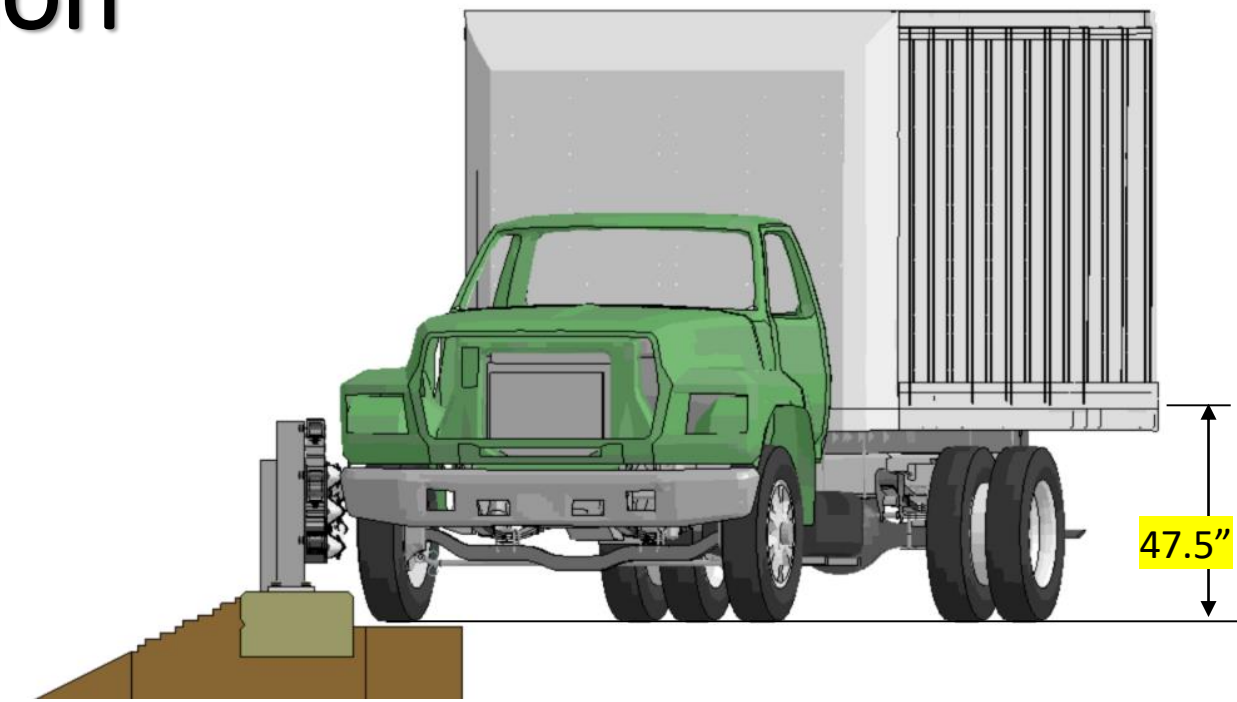
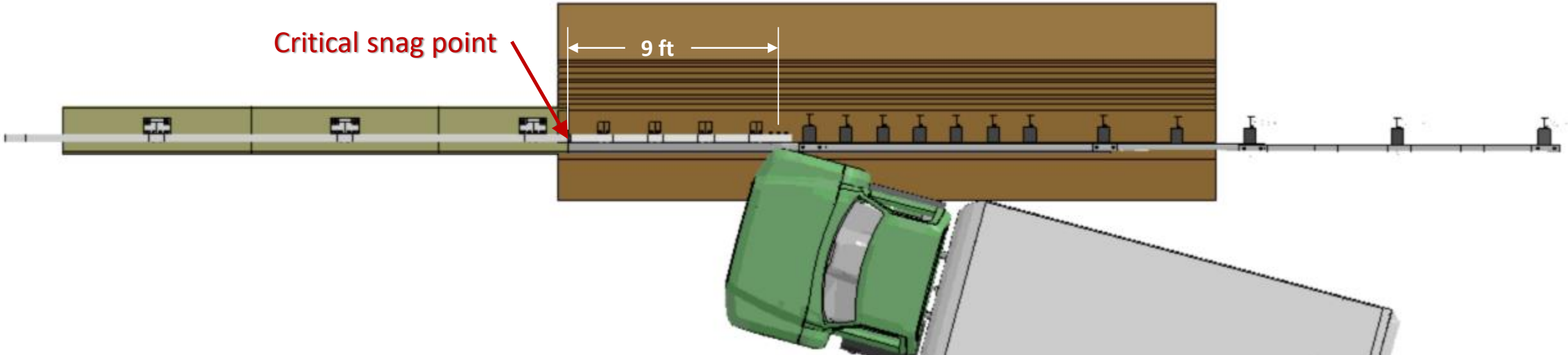
MASH Test 4-22 Simulation

- **Impact Conditions**
  - Mass = 22,061 lb
  - Impact Speed = 56 mph (90 km/hr)
  - Impact Angle = 15 degrees
  - Impact Point = 9 ft upstream of Bridge Rail tube ends
- **Vehicle Model**
  - F800_No-Box_181114_UboltF0p17.k
  - TruckBox_181114.k
  - F800-SuspenStress_FRONT_35N.k
  - F800-SuspenStress_REAR_60N.k
  - Vehicle Mass = 10,000 kg (22,046 lb)

Ford 800 Surrogate





MASH Test 4-22 Simulation

- **Impact Conditions**
  - Mass = 22,061 lb
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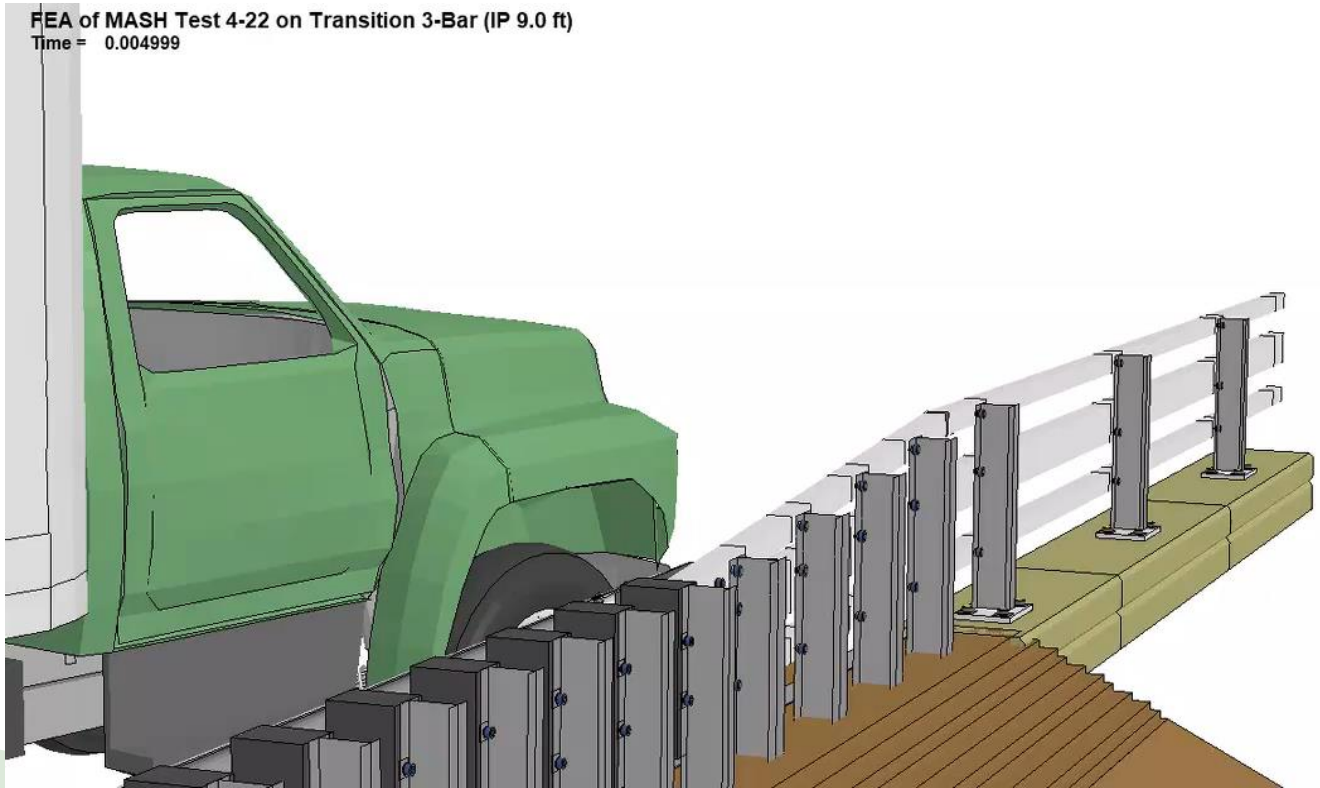
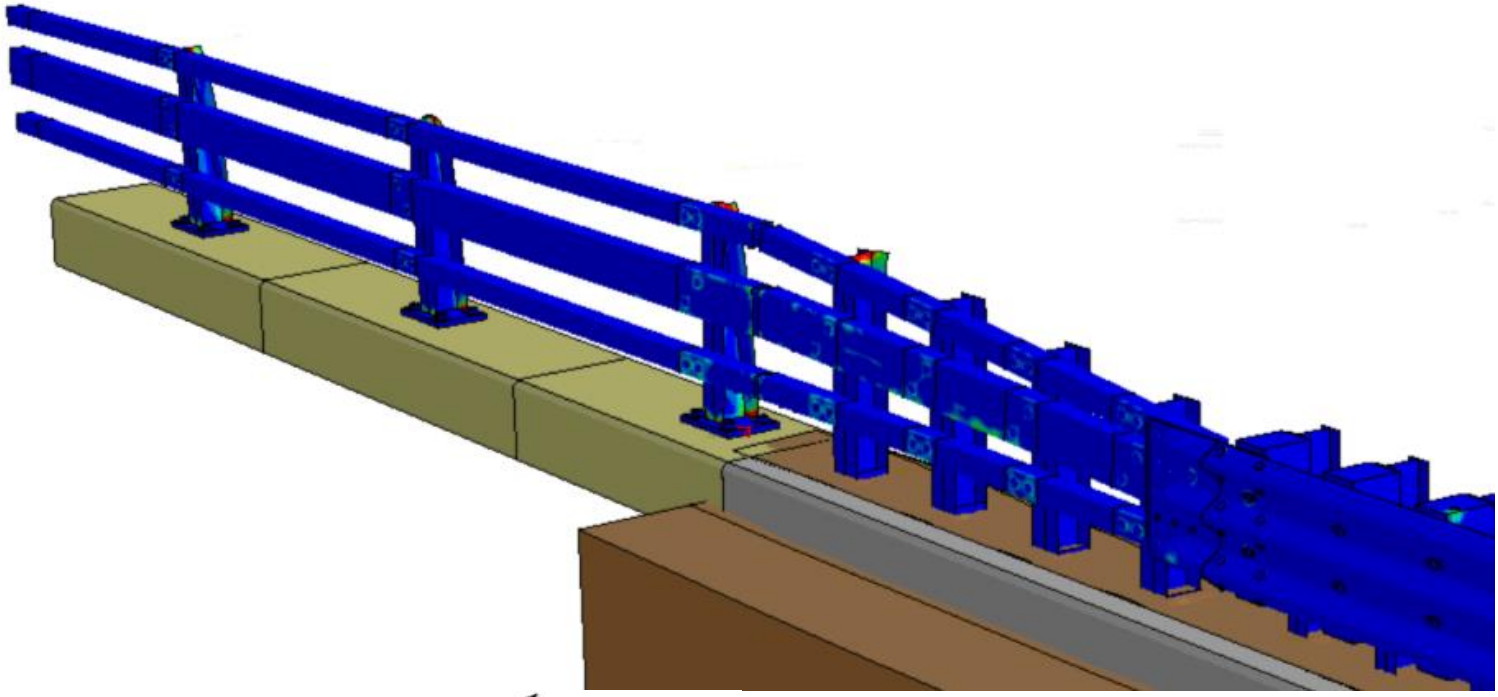
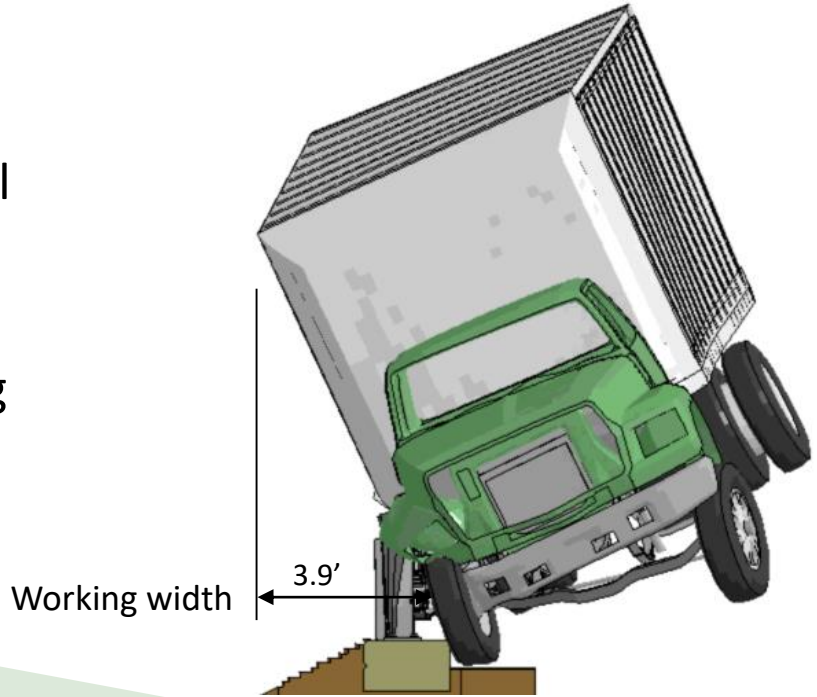
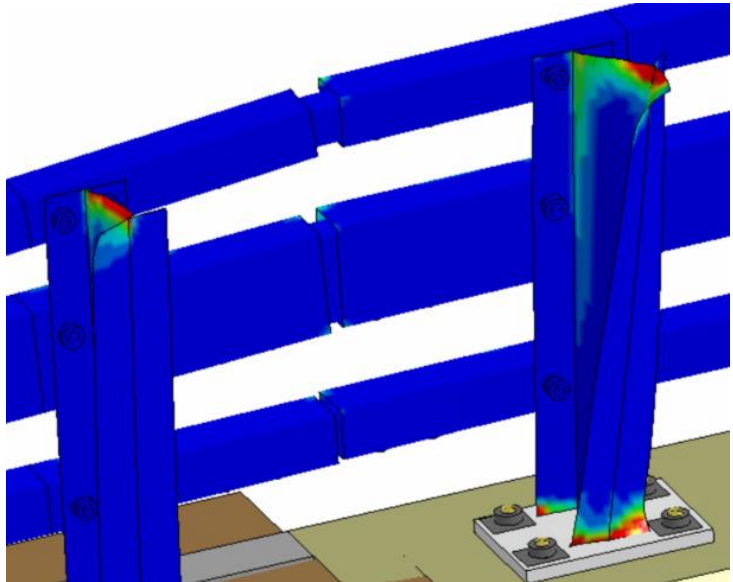


Barrier Damage

- Plastic deformations of the steel components were primarily to the top of Post 1 of the transition and to all three (3) bridge rail posts.
- There was some plastic deformation of the transition rail elements.
- The damage to the posts were due to the bottom of the cargo-box snagging on the top of the posts. This caused torque rotation and longitudinal deformation of the posts.
- The vehicle was in contact with the barrier from the point of contact until the truck box slid off the end of the bridge rail at 0.55 seconds.
- The maximum working width prior to exiting the barrier was 3.9 ft resulting from the top of the cargo box extending over the bridge rail.







Conclusions on Test 4-22 on the 3-Bar Trans

Evaluation Factors		Evaluation Criteria – MASH Test 4-12	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass
	G	It is preferable, although not essential, that the vehicle remain upright during and after collision.	Pass

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Project Status

- **Transition for NETC 4-Bar**
  - Evaluations almost complete
  - Expect Task Report to be submitted at end of this month
- **Transition for NETC 2-Bar**
  - Work begins next month
  - Expect Task Report to be submitted at end of July
- **Final Report**
  - Draft due September 30, 2019
  - Final due December 31 , 2019

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