Development of MASH Computer Simulated Steel Bridge Rail and Transition Details

Project: NETC 18-1

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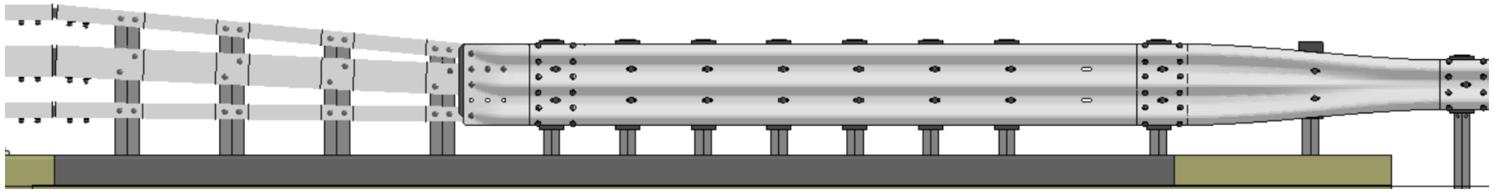
Roadsafe LLC

NETC Webinar July 16, 2020



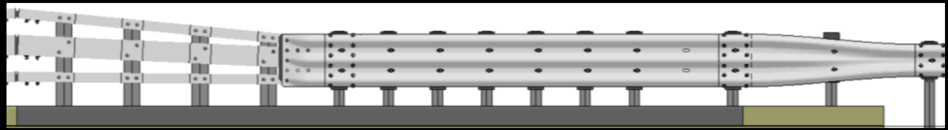
Background and Project Motivation

- The current policy for roadside hardware installed on federal-aid projects requires upgrading non-conforming systems to MASH acceptance level for situations involving full system replacements, certain structural rehabilitations (e.g., deck replacements), or repairing a critically damaged bridge rail system.
- The predominate bridge rail and approach guardrail transition (AGT) systems used in the New England states, include details for 2-bar, 3-bar and 4-bar designs, which were developed and tested under prior crash testing and evaluation standards.
- It was of interest to the New England Transportation Agencies to determine if these existing NETC designs meet the strength and safety criteria of the current test standard (i.e., MASH), which involve higher impact severities than the previous crash testing standards.



Objectives

- Review of NETC style bridge rail and AGT designs to:
  1) Determine preliminary MASH compliance/equivalency:
     - AASHTO LRFD Bridge Design Specifications
     - Procedures outlined in NCHRP Project 20-07 (395)
  2) Determine the least conservative designs for further evaluation using FEA crash simulation.
- Evaluate the crash performance of these systems using finite element analysis (FEA) computer simulation using *MASH* test conditions and criteria:
  - Structural capacity
  - Risk of occupant injury
  - Vehicle stability



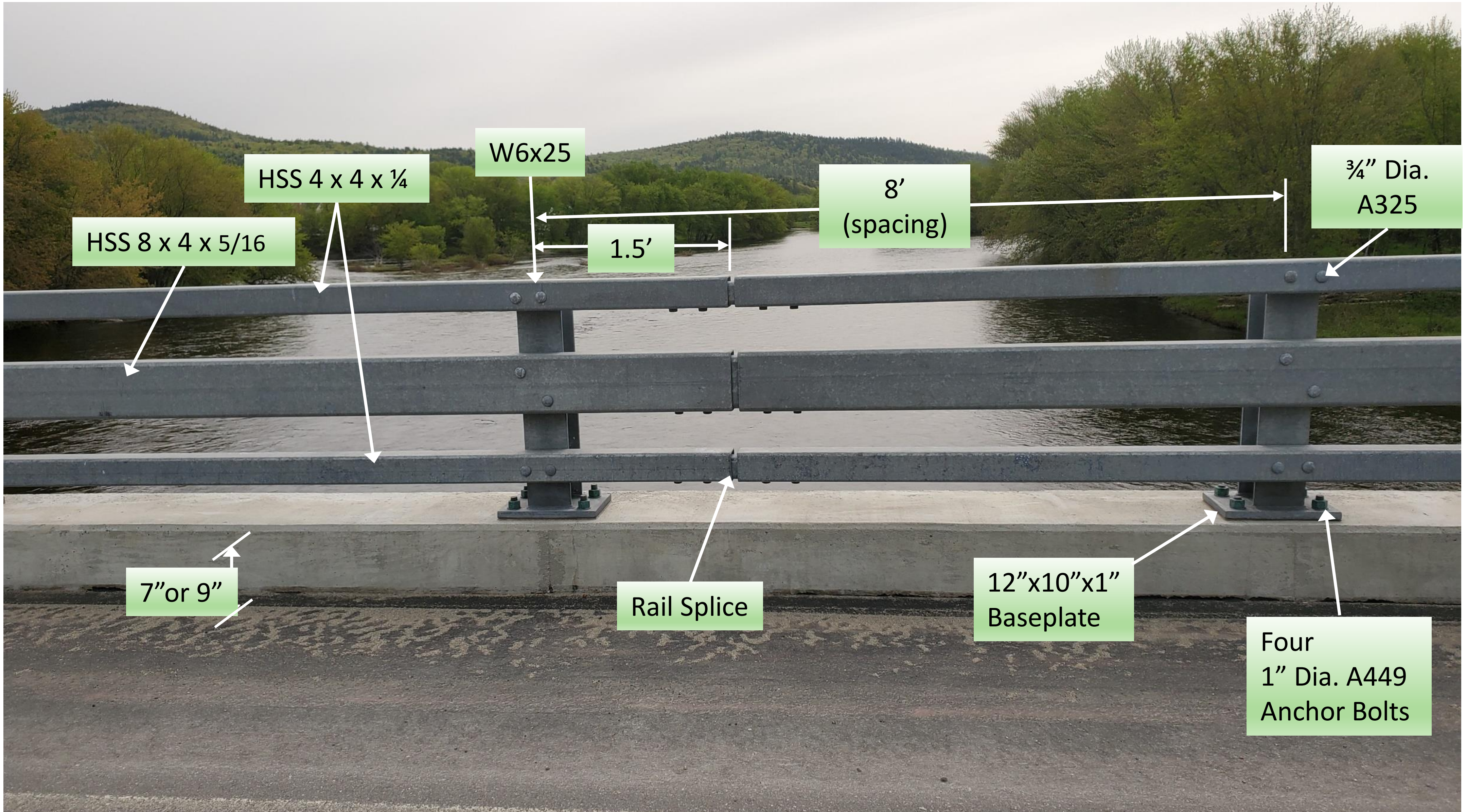
NETC Bridge Rails

Slight variations in design details depending on State

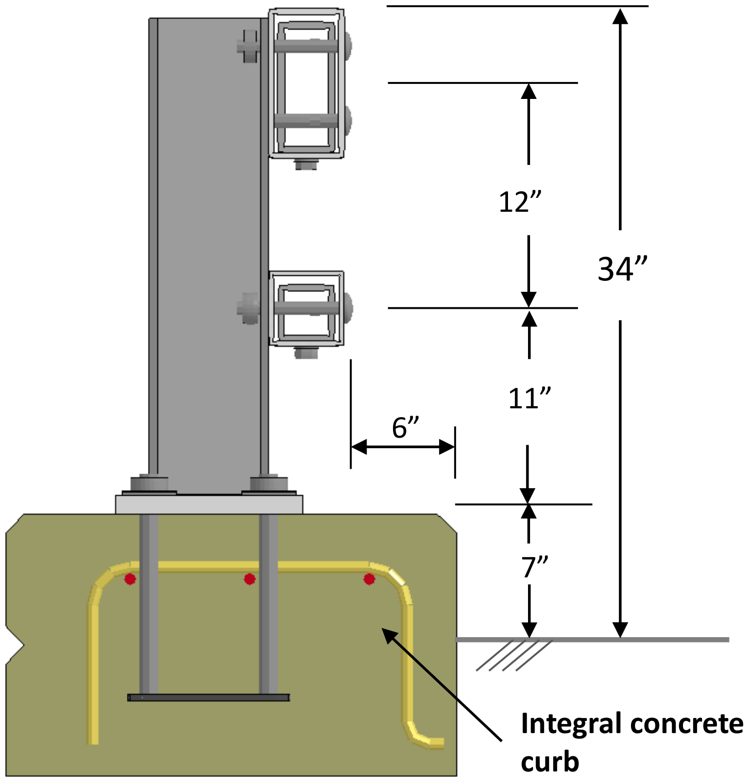
Three design details were evaluated:

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

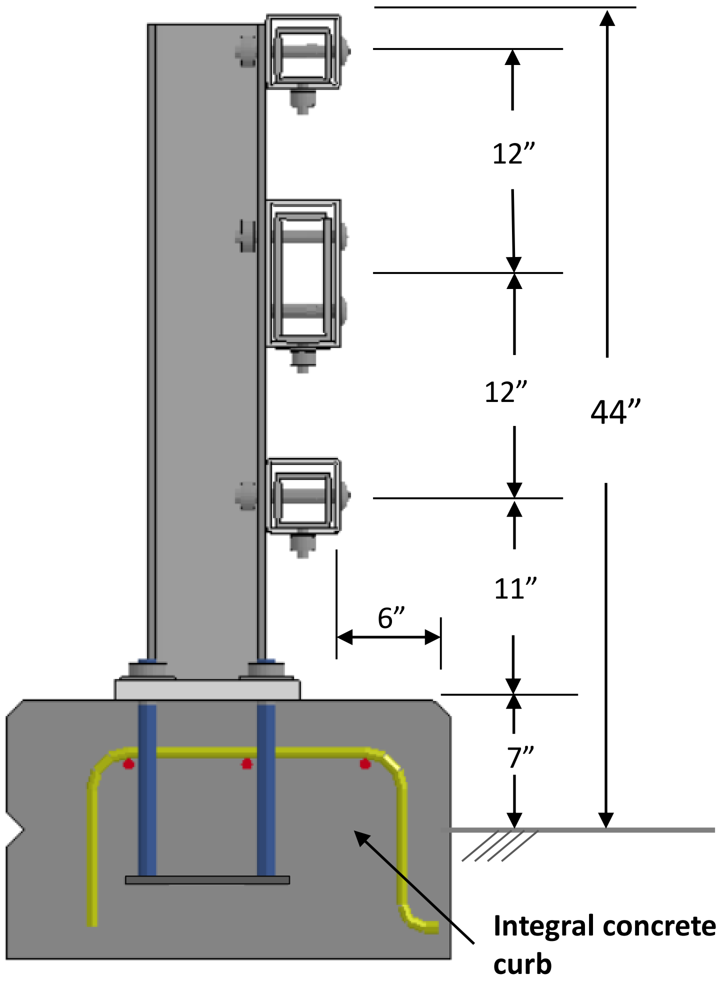
NETC Bridge Rails



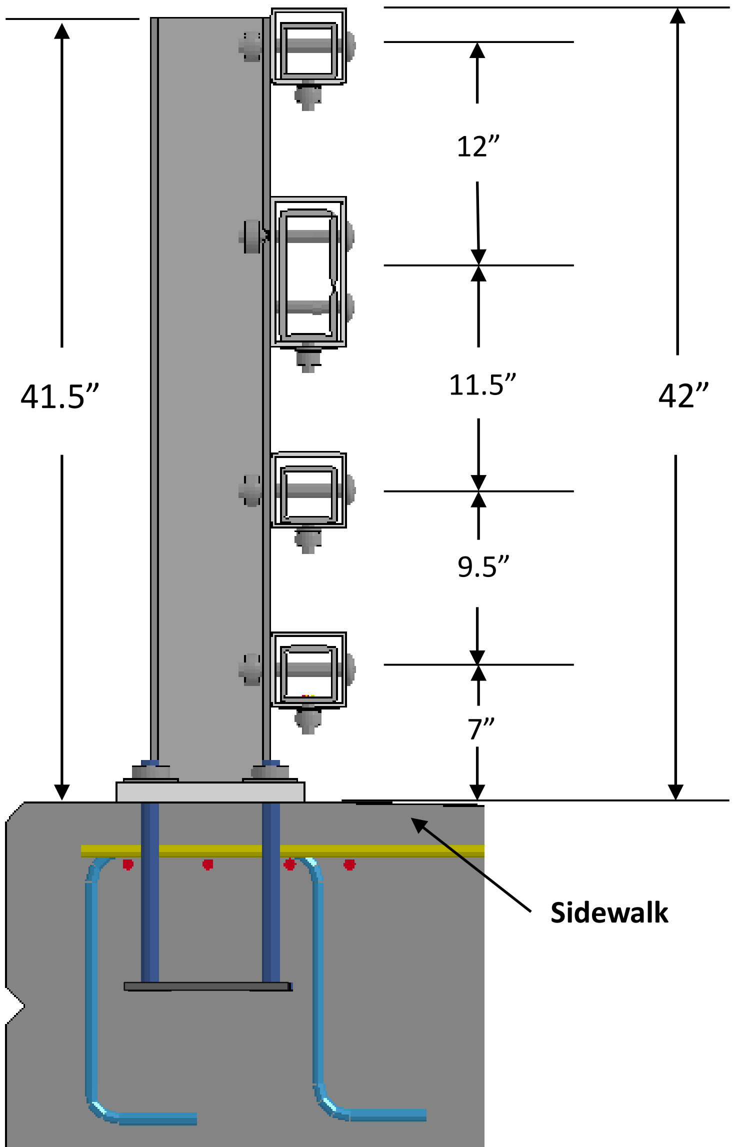
NETC Bridge Rails



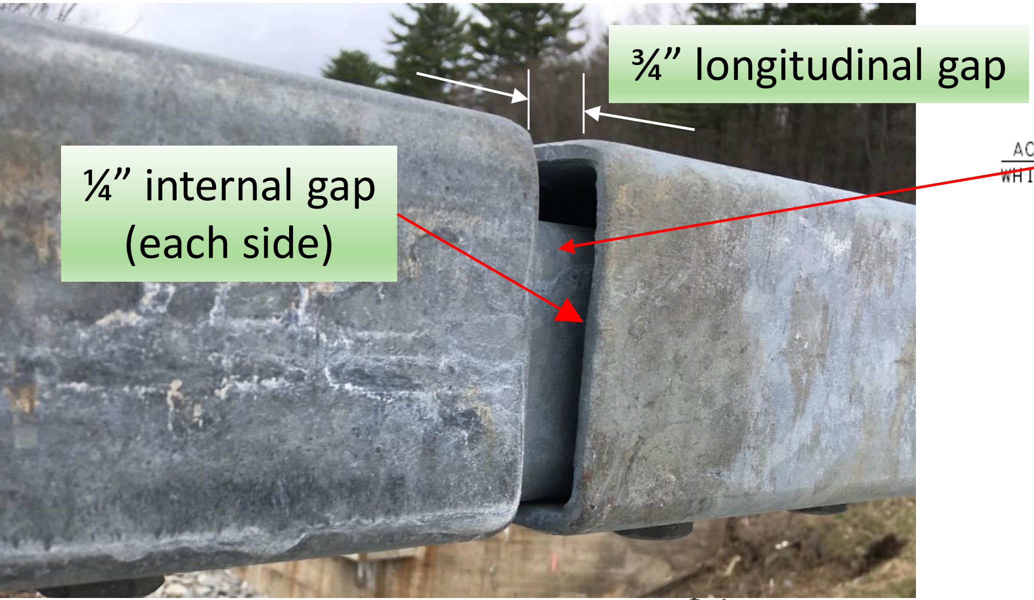
NETC 2-Bar BR

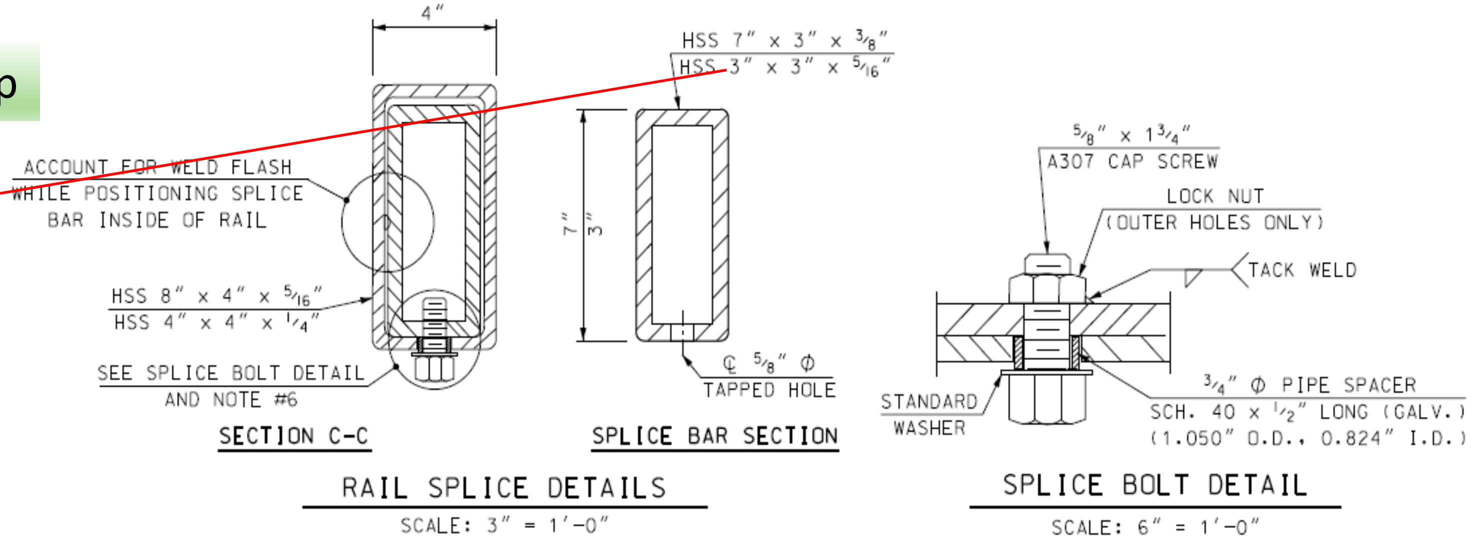


NETC 3-Bar BR

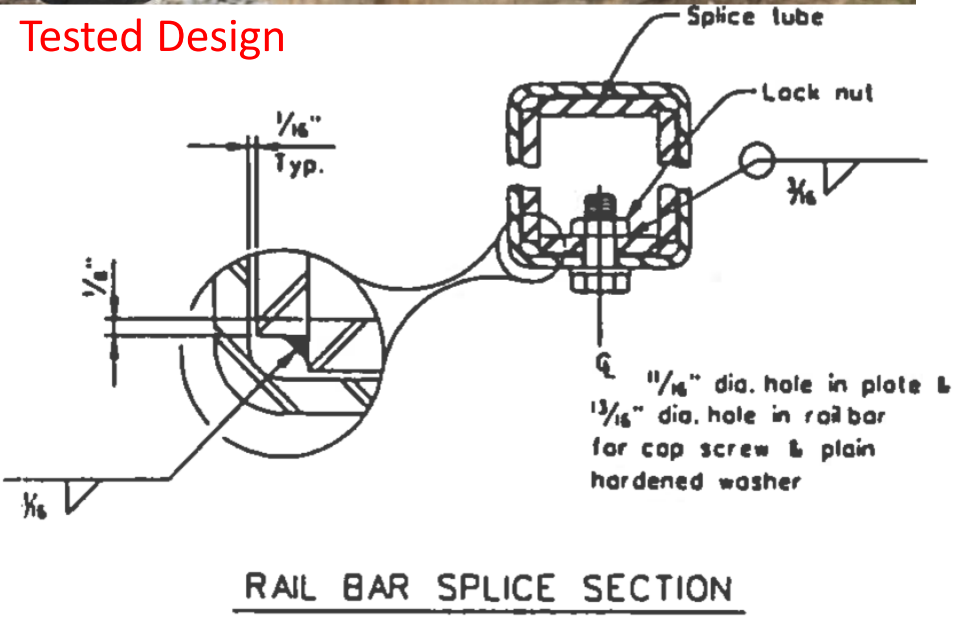


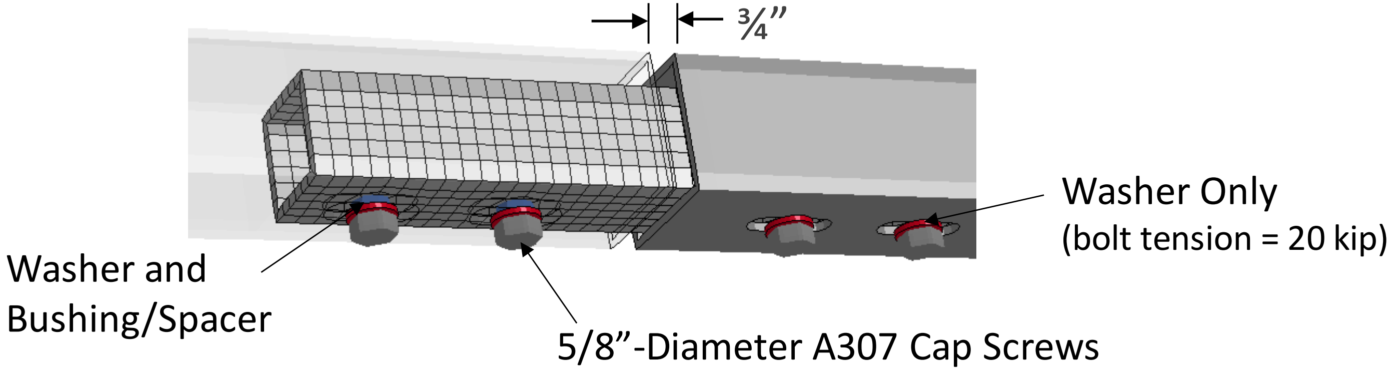
NETC Bridge Rails





Tested Design





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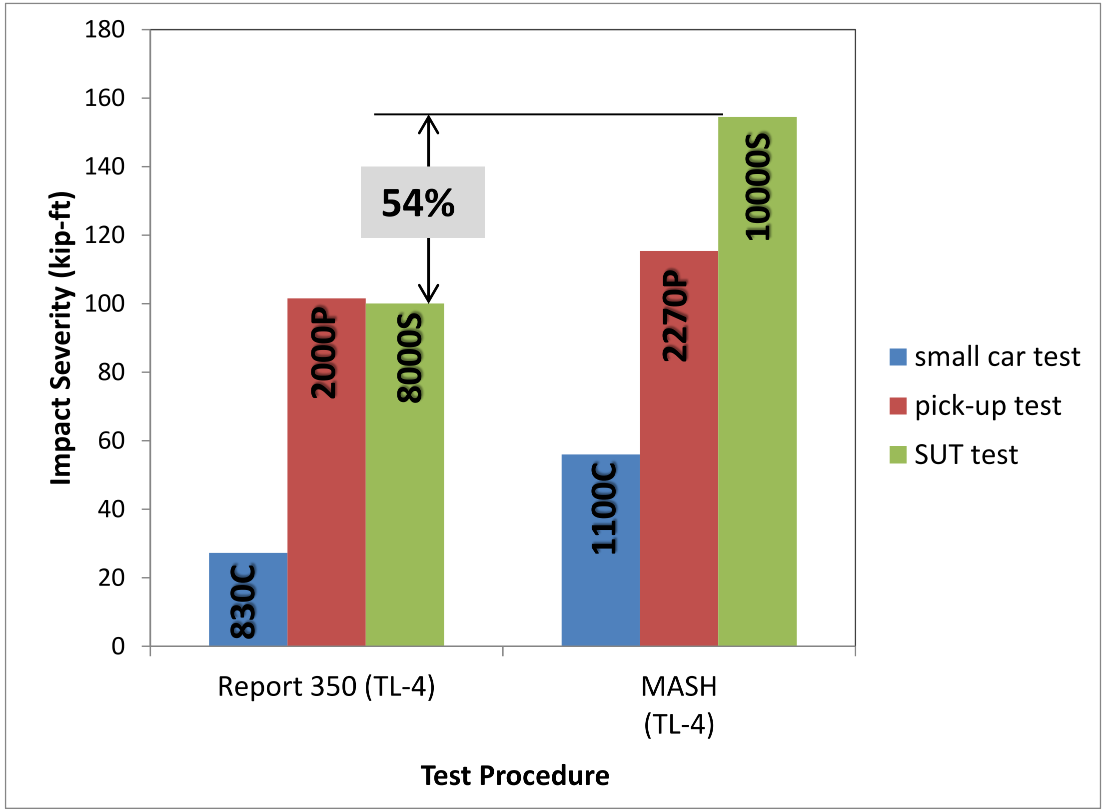
Comparing Impact Severity
(Report 350 and MASH)



Test Vehicles			
Report 350		**MASH**	
830C 1.8 kip 62 mph 20 deg.		**1100C** 2.4 kip 62 mph 25 deg.	33% > mass 25% > angle
2000P 4.4 kip 62 mph 25 deg.		**2270P** 5.0 kip 62 mph 25 deg.	14% > mass
8000S 18 kip 50 mph 15 deg.		**10000S** 22 kip 56 mph 15 deg.	22% > mass 12% > speed

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MASH Equivalency Assessment

LRFD Assessments

	NETC 2-Bar (TL3)		
	Rail Height	Rail Geometrics	Strength
Required	29	(see Table 5)	71 k
Actual	34		109 k
Assessment	S	S	S(1)

NS - Not Satisfactory

M - Marginal

S - Satisfactory

S (1) - Satisfactory Rating for TL-3 Only

S (2) - Satisfactory when 9" curb is used

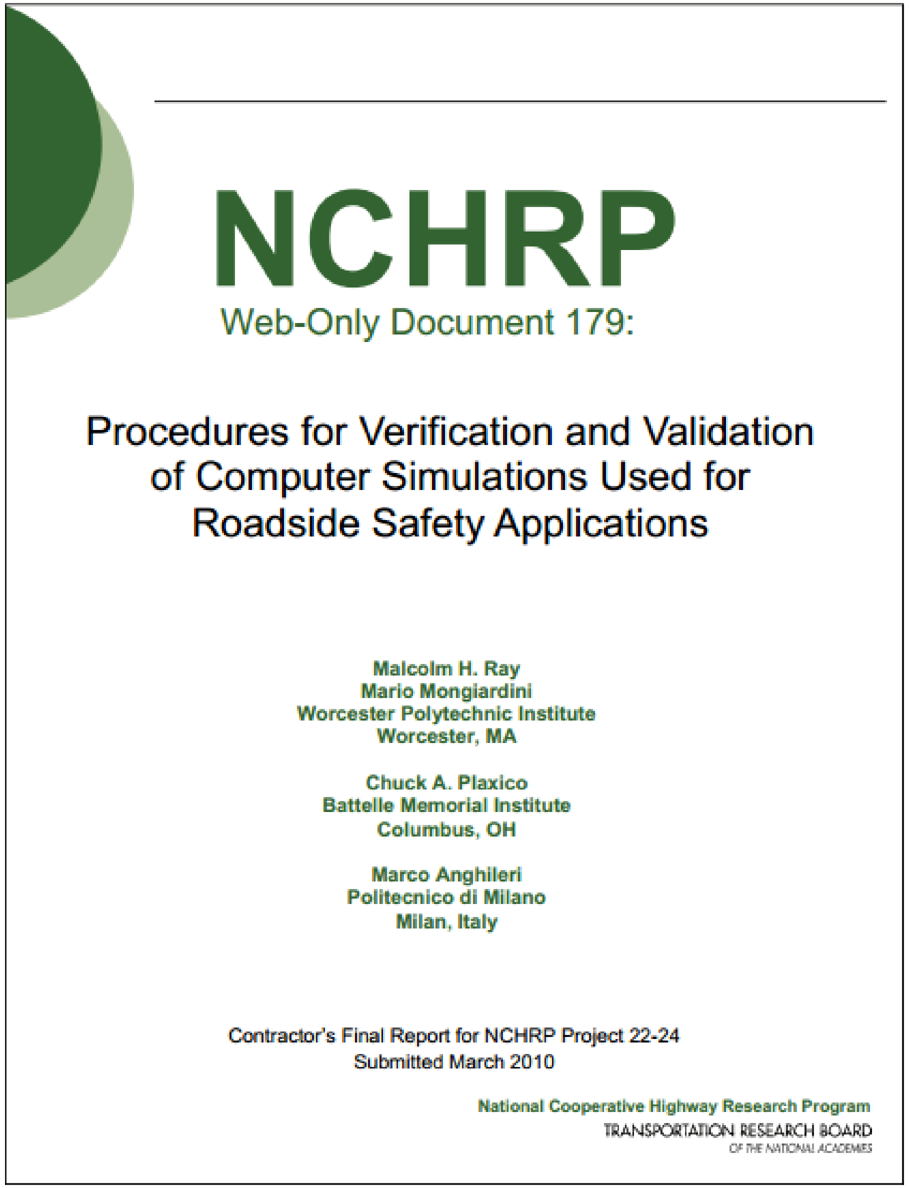
** - Differs from 20-07(395) report*

- Rail geometrics are used to assess potential for vehicle snag on posts and considers:
  - post-offset distance
  - Max vertical clear opening between rails
  - Contact surface w.r.t. overall barrier height

S – 9” curb
M – 7” curb

Research Approach for FEA Crash Simulations

- 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
- Then use FEA to simulate MASH 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
TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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

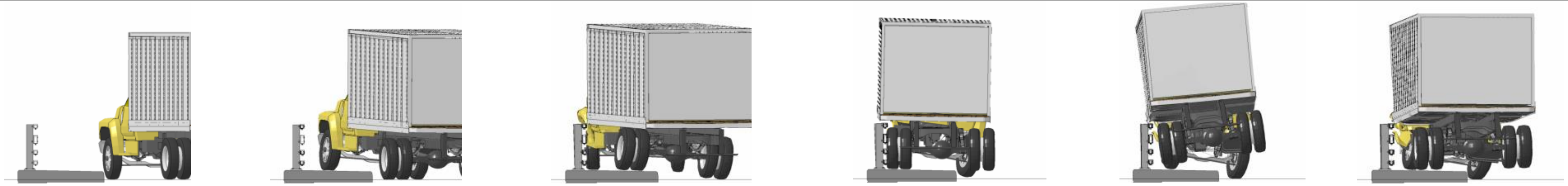
Summary of FEA vs. Test Validation Metrics

System Type:	Bridge Rail	Comparison:	Crash tested original design to FEA of original design	
Device Name:/Variant:	NETC 4-Bar sidewalk-mounted	Submissions Type:		Non-Significant -- Effect is Uncertain
Testing Criterion:	Report 350			Non-Significant -- Effect is Positive
Test Level:	TL4			Non-Significant -- Effect is Inconsequential
FHWA Letter:			X	Baseline Validation of Crash Test to FEA Analysis.

Crash Test

Time = 0.0 sec | 0.2 sec | 0.4 sec | 0.6 sec | 0.9 sec | 1.2 sec

FEA Analysis



Baseline Crash Test	
Test Number:	SwRI NETC-3
Vehicle:	1993 International 4600 LP
Vehicle Mass:	17,875 lbs
Impact Speed:	49.8 mph
Impact Location:	2 ft upstream of Post 6
Tested Hardware:	Original Design
FEA Hardware:	Original Design

W-179 Table E-1: Verification Evaluation Summary

Total Energy:	0%	Pass
Hourglass Energy:	0%	Pass
Mass Added:	0%	Pass
Shooting Nodes:	no	Pass
Negative Volumes:	no	Pass

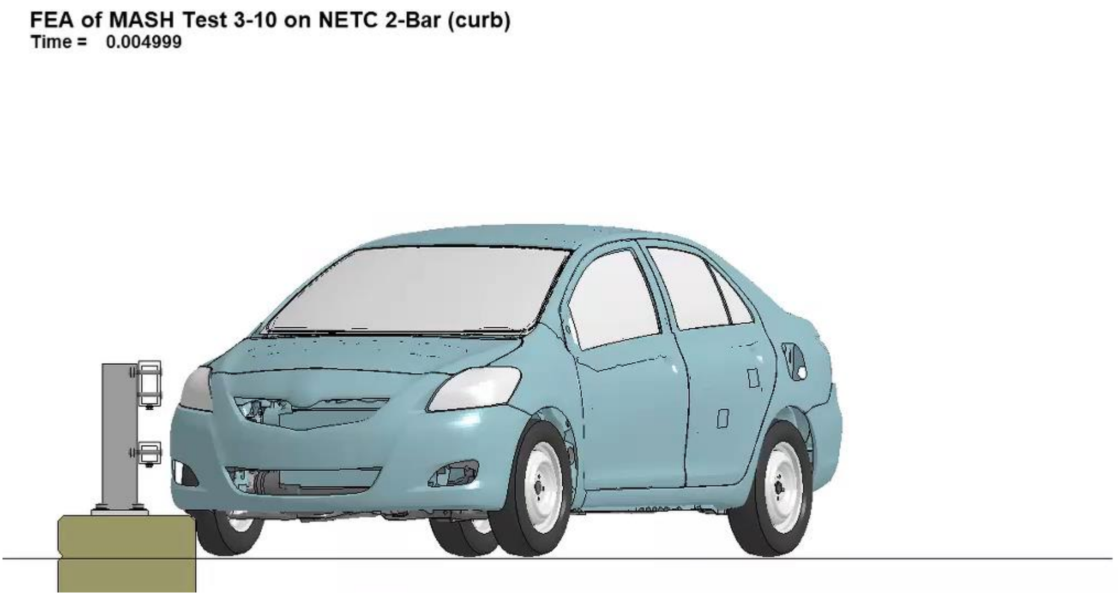
W-179 Table E-5: Roadside PIRTS

Structural Adequacy	Test	FEA	Occupant Risk (cont.)	Test	FEA
A1 - Acceptable perf.?	yes	yes	H2 – Long. OIV	5.4 ft/s	5.9 ft/s
A2 – Permanent Deflection:	0.51 in	0.7 in	H3 – Lat. OIV	9.5 ft/s	12.1 ft/s
A3 – Contact Length	-	42 ft	I2 – Long. ORA	8.95 g	4.95 g
A4 - Component Failure	no	no	I3 – Lat. ORA	14.3 g	12.1 g
A5 – Barrier Rupture?	no	no	**Vehicle Trajectory**		
A7 – Wheel Snagging?	no	no	K – Intruded into travel lanes?	no	no
A8 – Vehicle Snagging?	no	no	N – Travel behind barrier?	no	no
Occupant Risk	**Test**	**FEA**	**W-179 Table E-3 (Multi-Channel Method)**		
D – Detached elements?	no	no	Sprague-Geer Magnitude < 40	-	-
F2 – Max. Vehicle Roll	20	14.7	Sprague-Geer Phase < 40	-	-
F3 – Max. Vehicle Pitch	5	5.4	ANOVA Mean	-	-
F4 – Max. Vehicle Yaw	14.8	16.2	ANOVA Standard Deviation	-	-

MASH TL-3 for NETC 2-Bar Bridge Rail

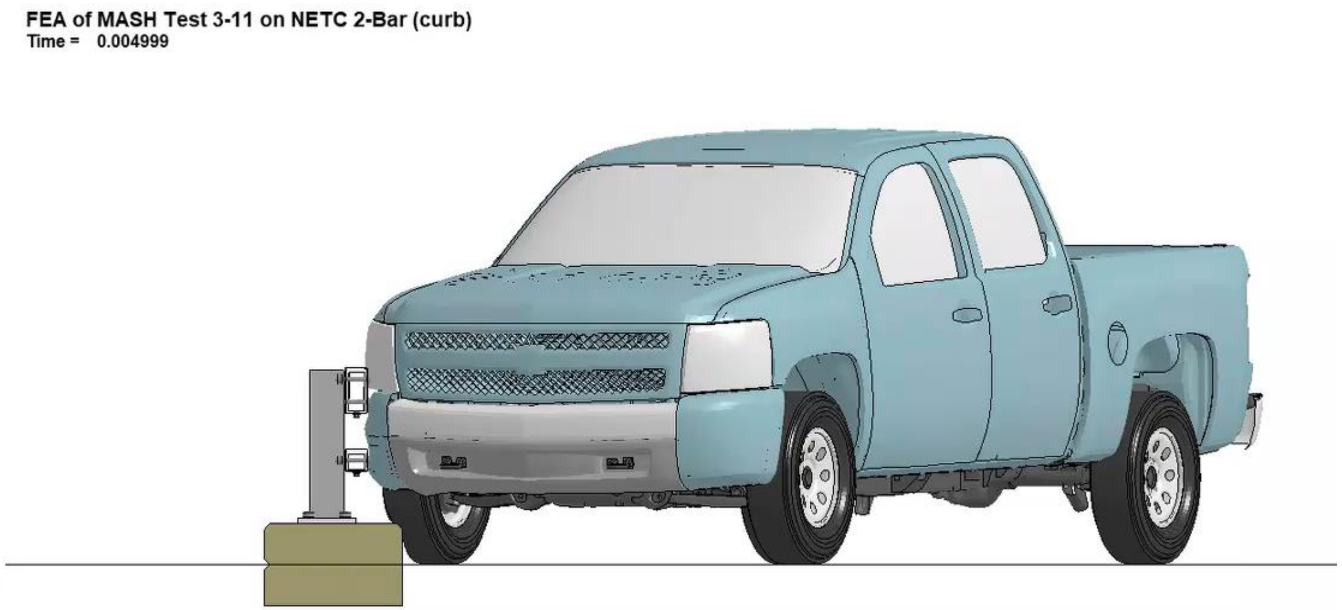
<u>Test 3-10</u>

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



<u>Test 3-11</u>

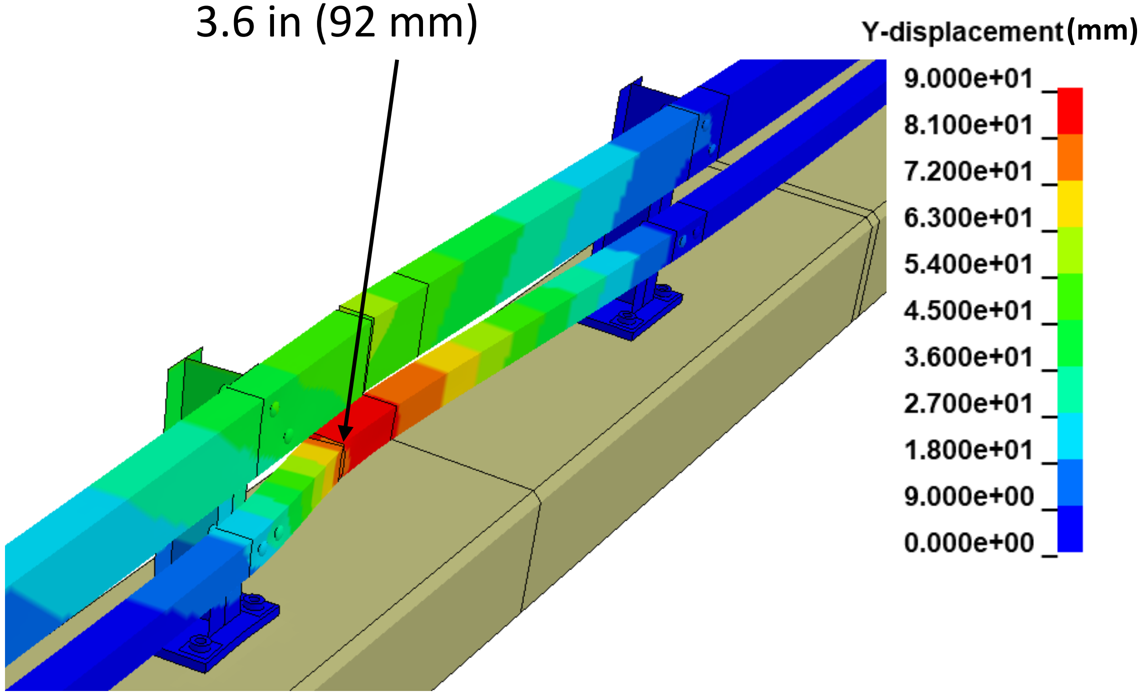
- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 4.3 ft upstream from critical Post



Lateral Dynamic Deflection

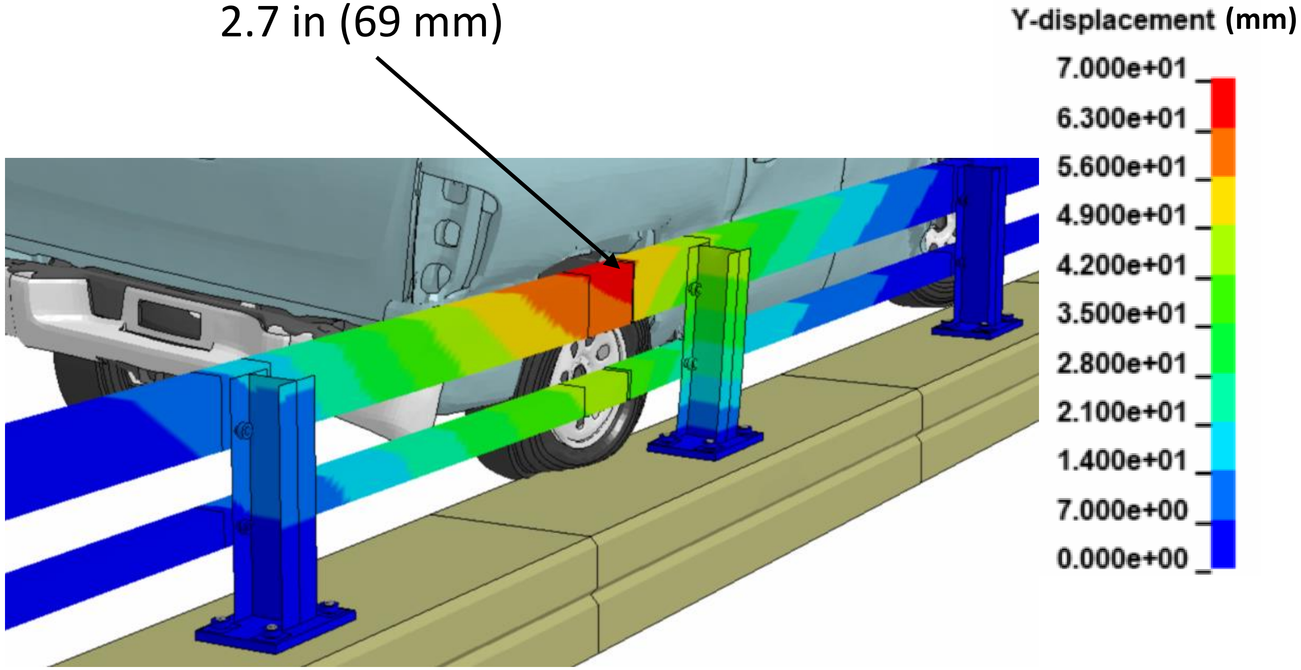
Test 3-10

Maximum dynamic deflection =
3.6 in (92 mm)



Test 3-11

Maximum dynamic deflection =
2.7 in (69 mm)



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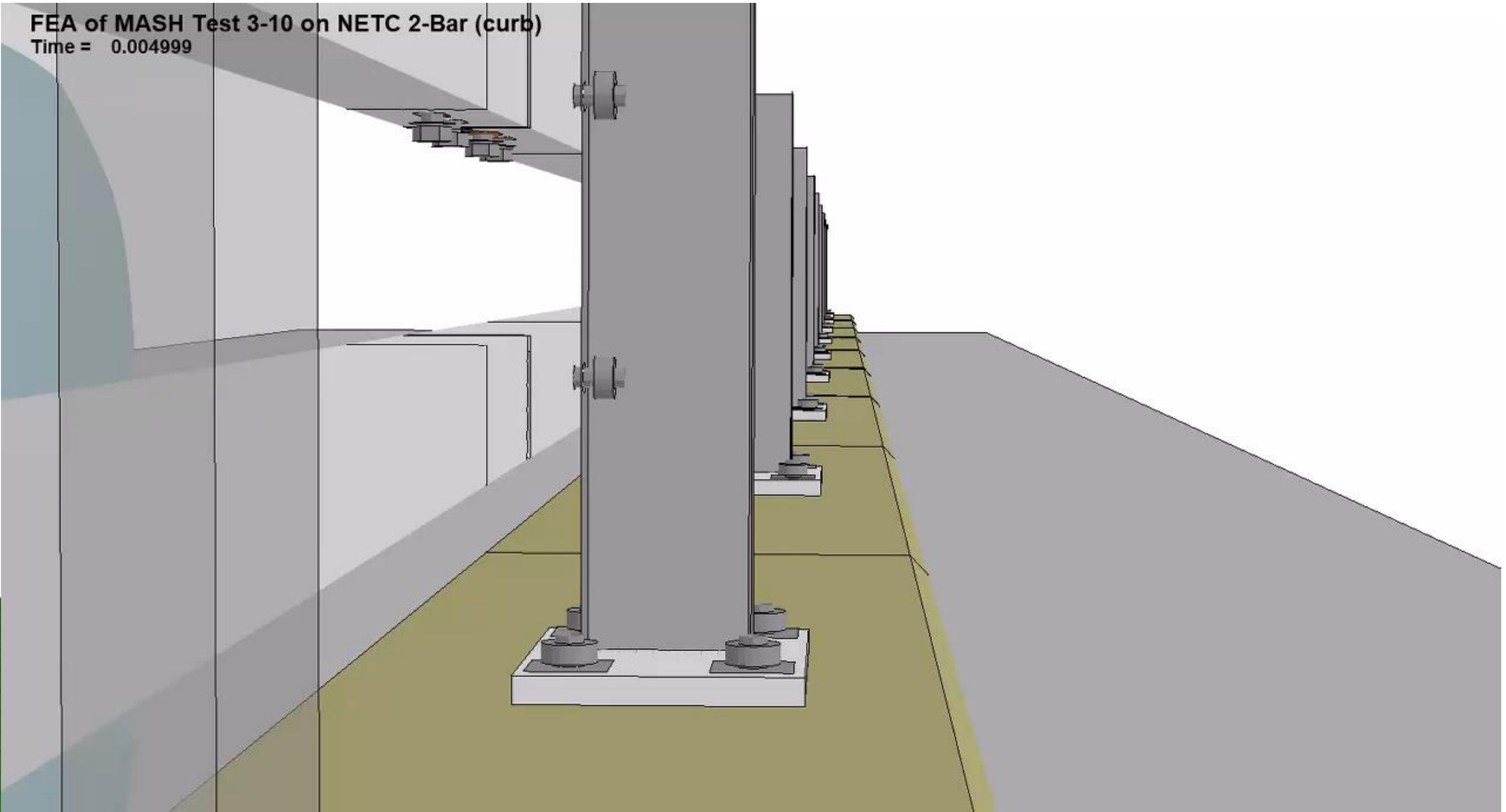
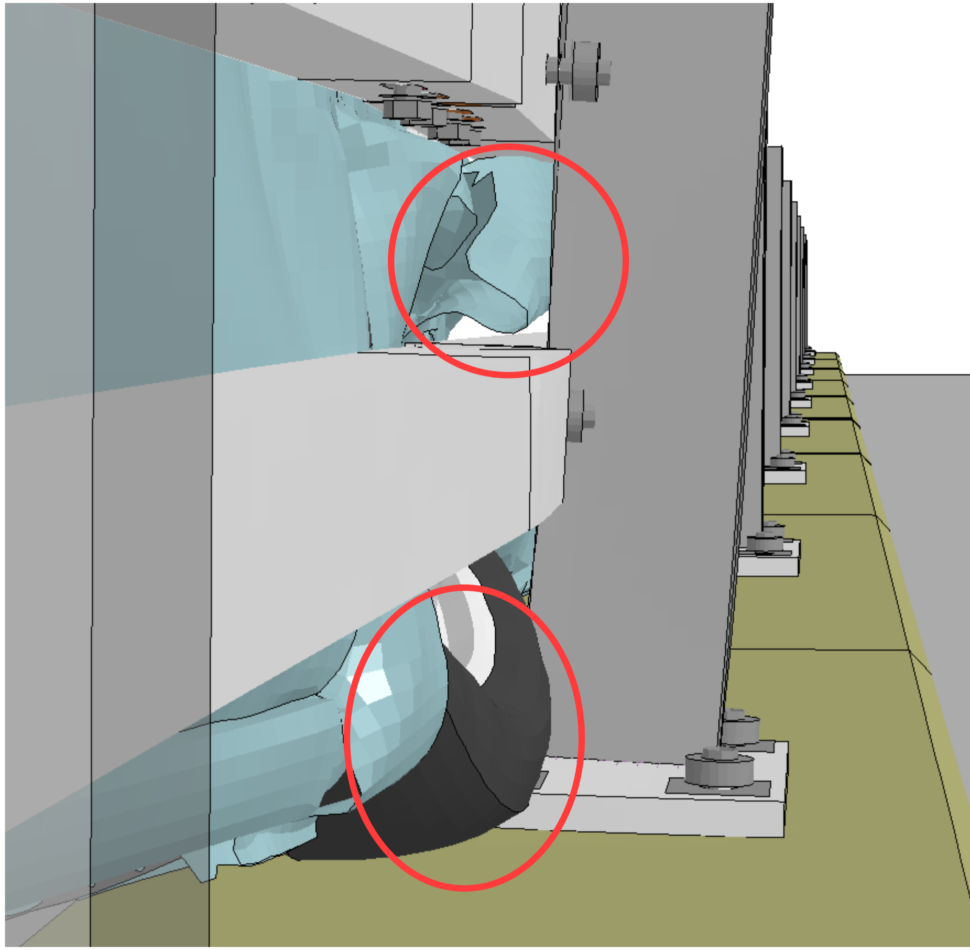
Assessment of Potential Vehicle Contact with Post

- 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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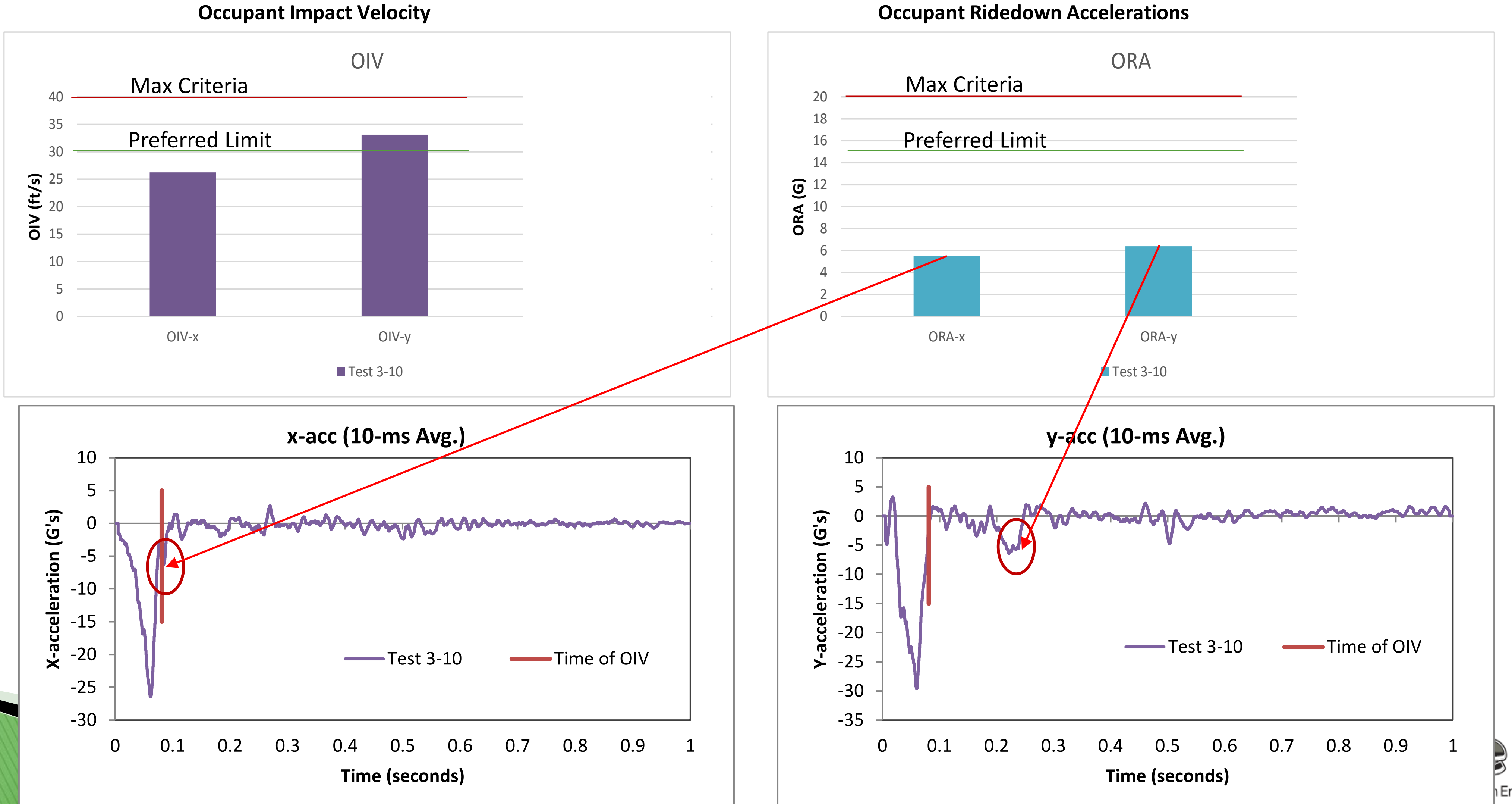
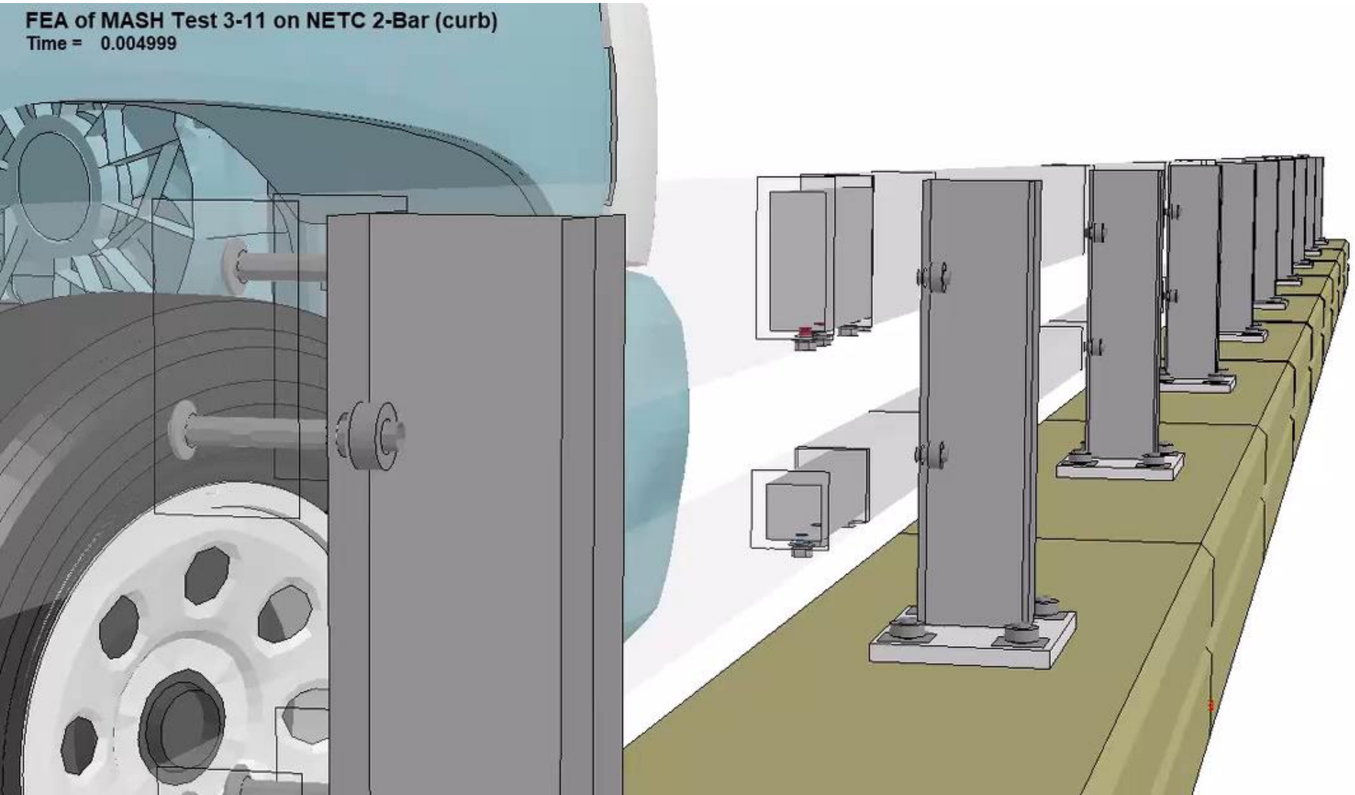
Occupant Risk
Test 3-10

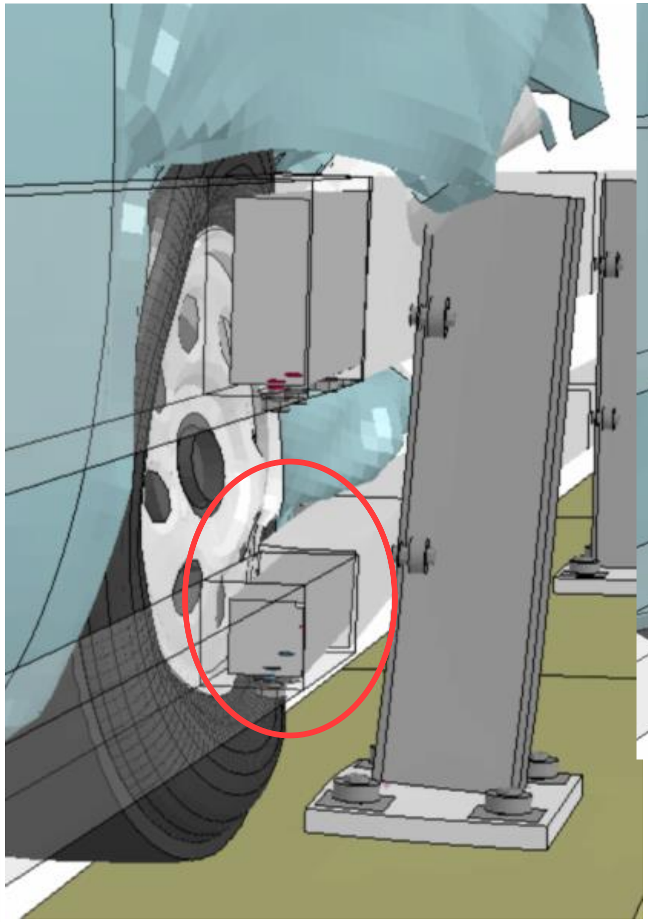


Assessment of Potential Vehicle Snag

- 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 exceed occupant risk criteria.

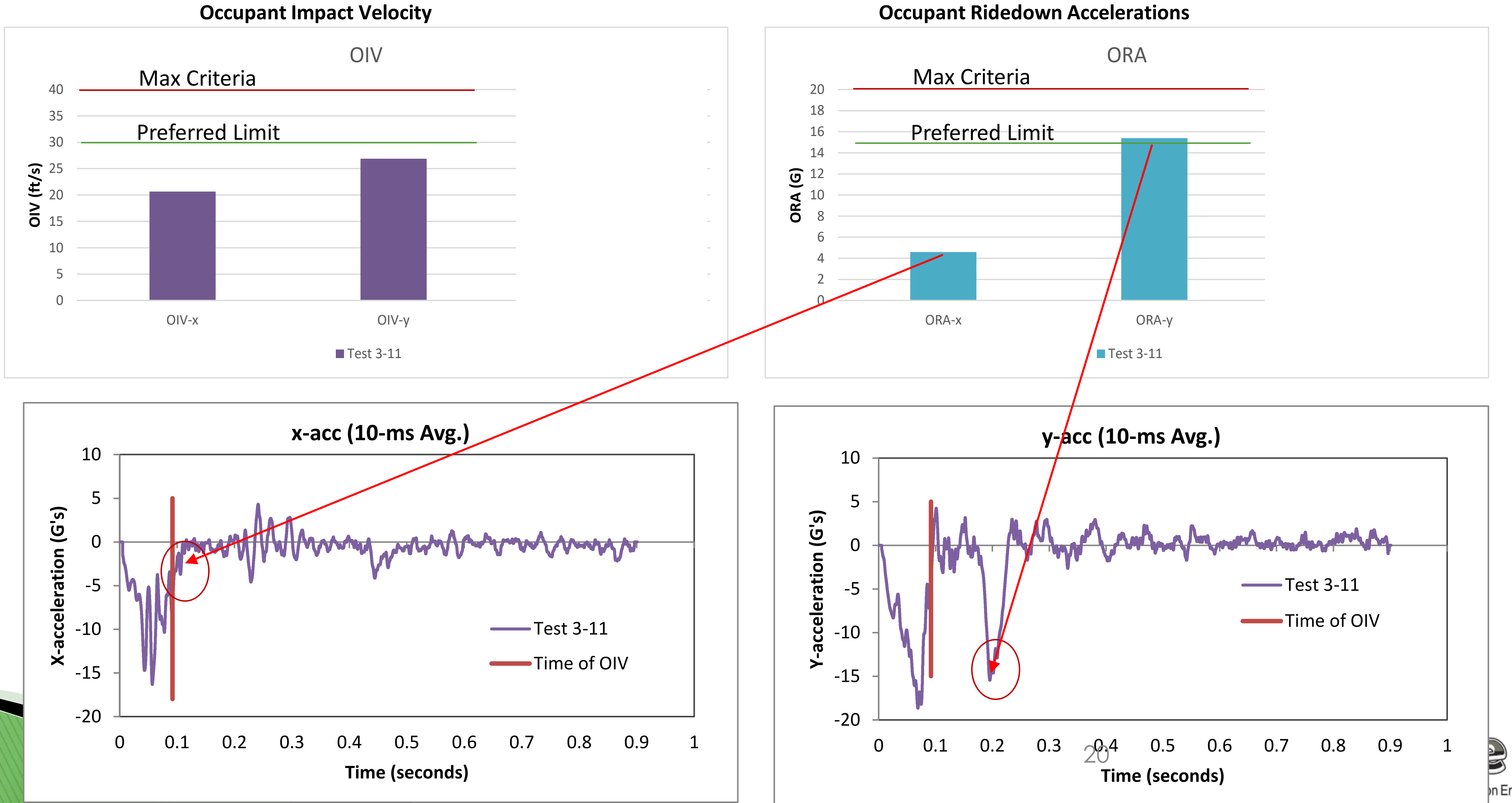


Front Wheel Snag



Door Snag

Occupant Risk
Test 3-11



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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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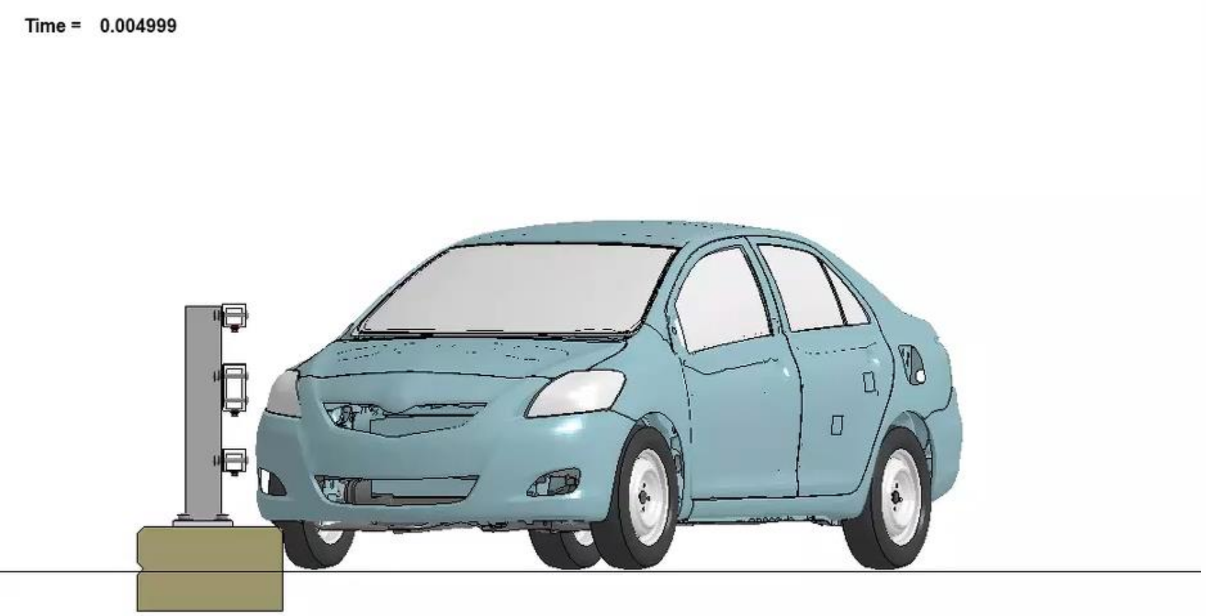
MASH TL-4 for NETC 3-Bar Bridge Rail

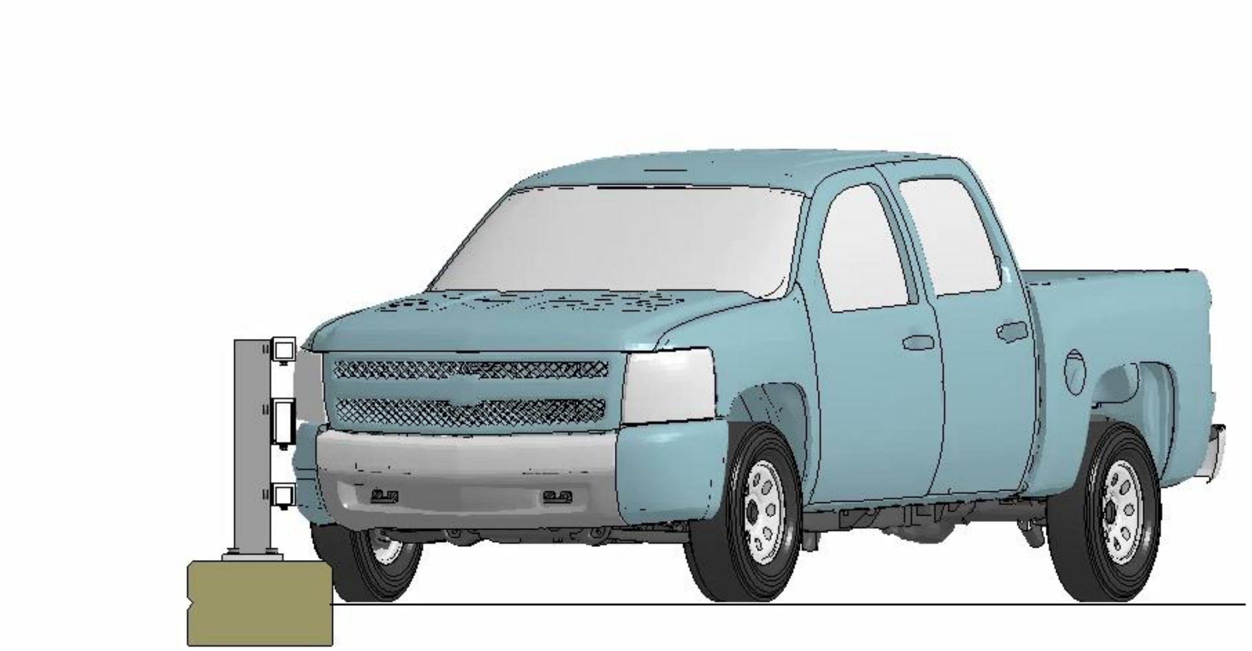
Test 4-10

- 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

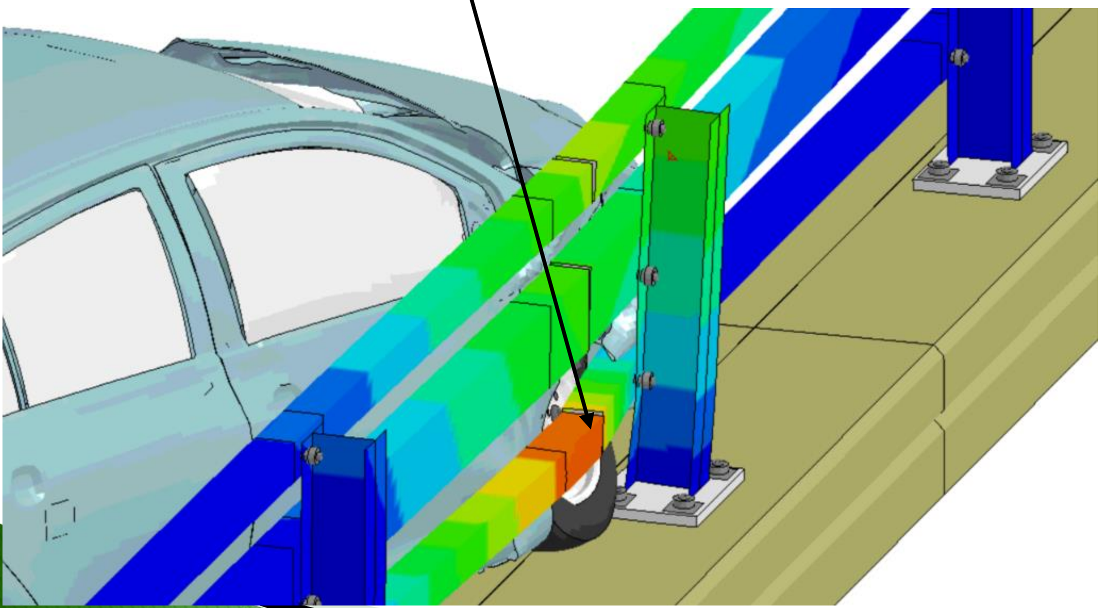




Lateral Dynamic Deflection

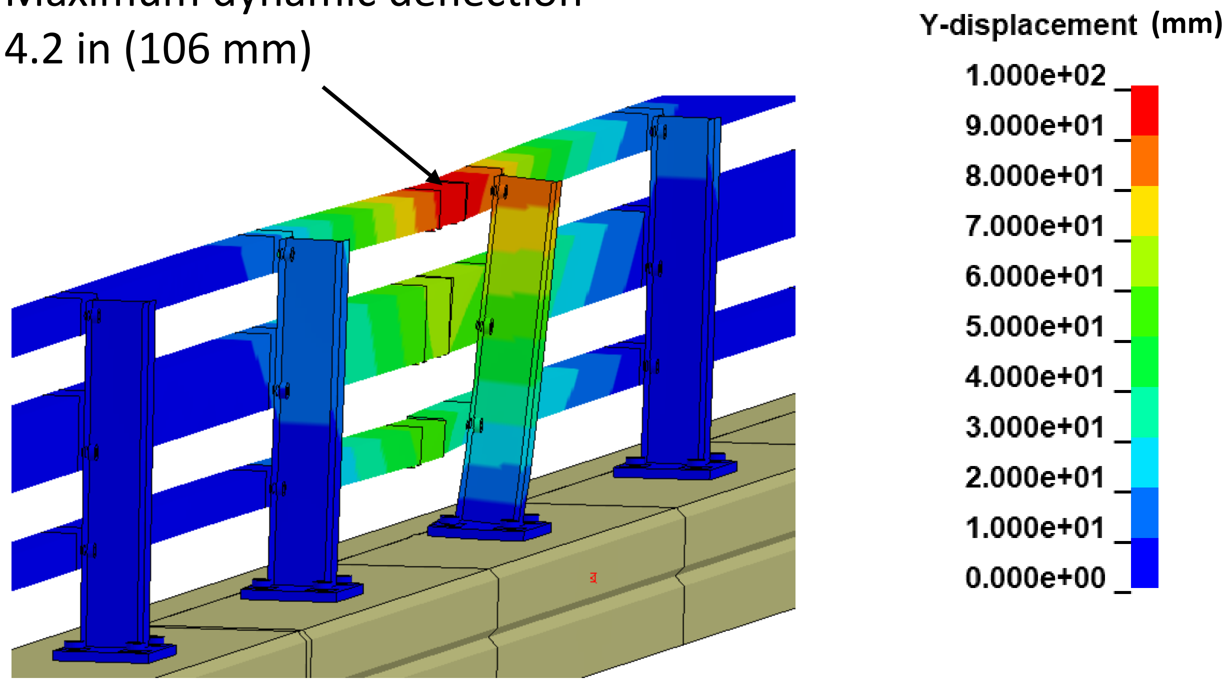
Test 4-10

Maximum dynamic deflection =
3.35 in (85 mm)



Test 4-11

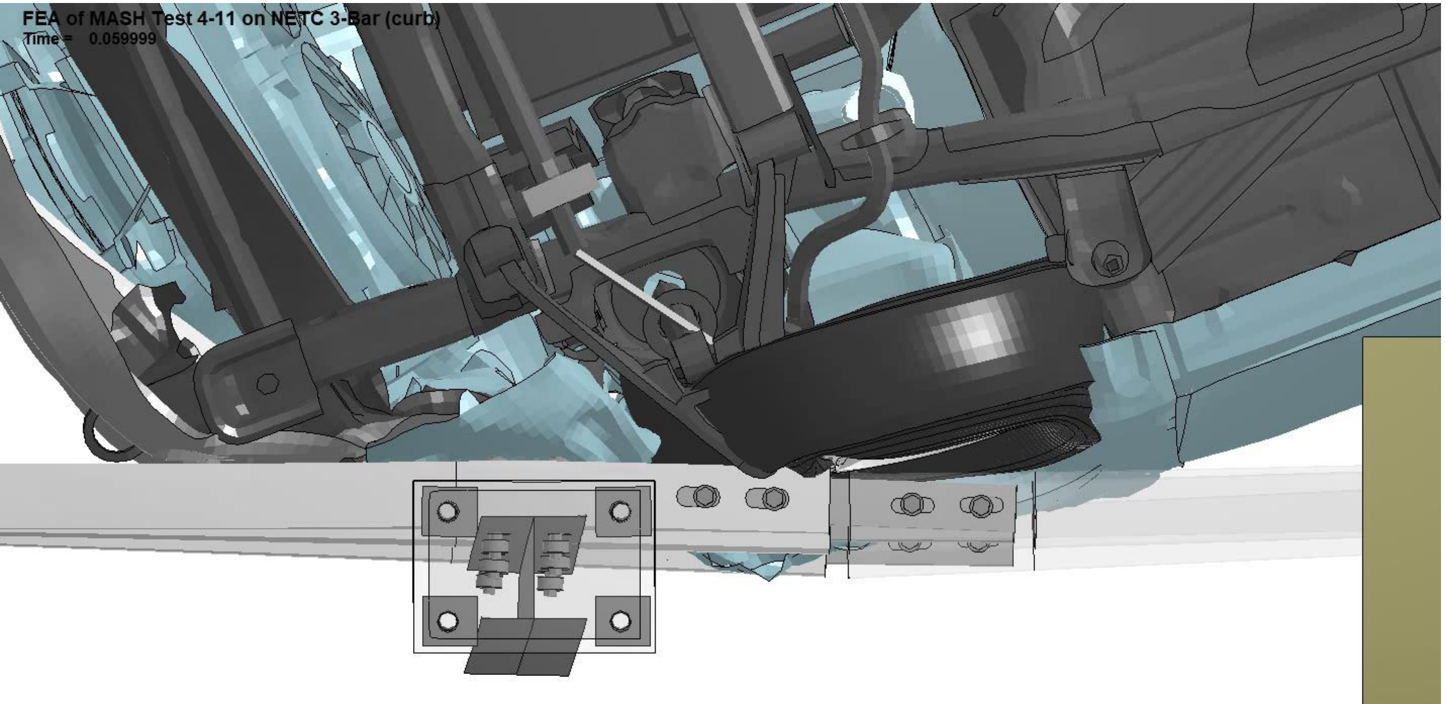
Maximum dynamic deflection =
4.2 in (106 mm)

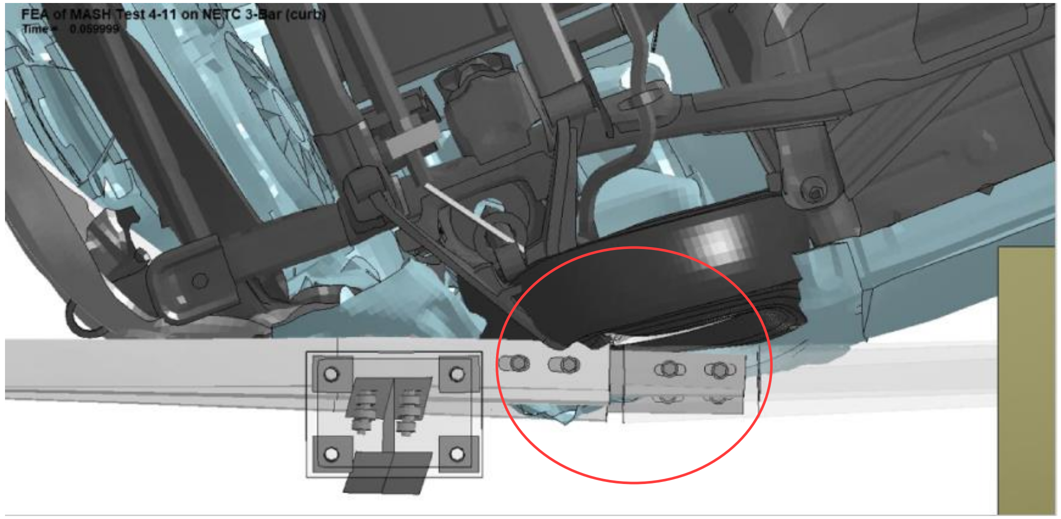


Movies

Assessment of Potential Vehicle Snag

- The tire rim snagged on the splice
- Tires did not contact post.





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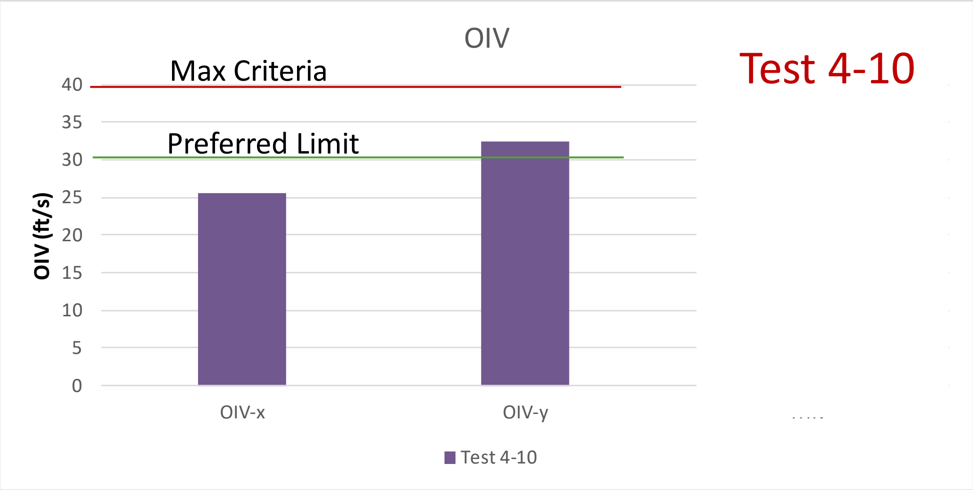
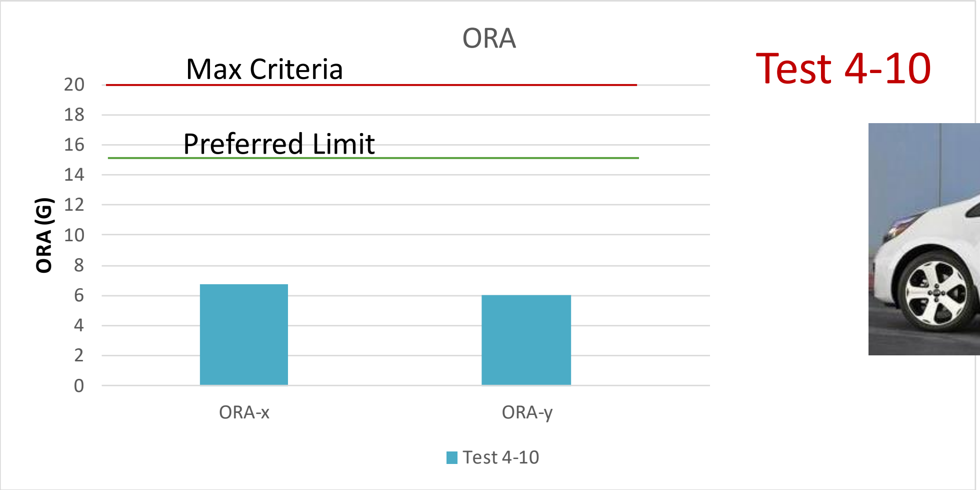
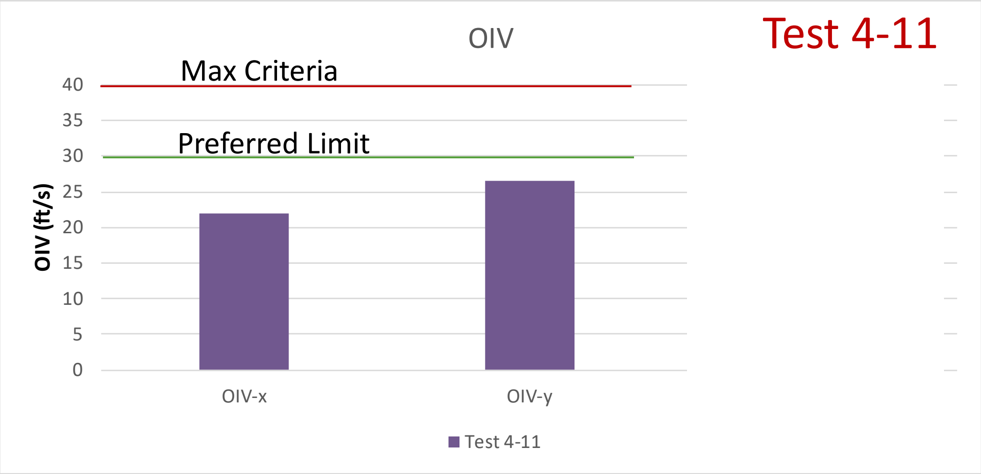
Occupant Risk

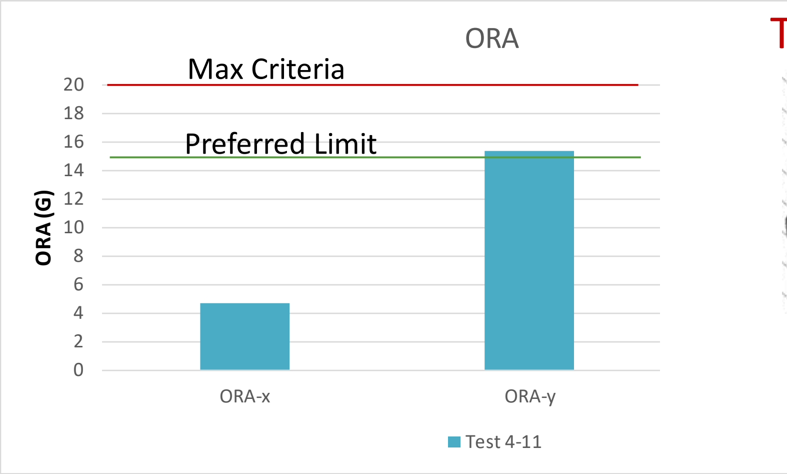
Occupant Impact Velocity



Occupant Ridedown Accelerations







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Conclusions on Test 4-10 and 4-11 on the NETC 3-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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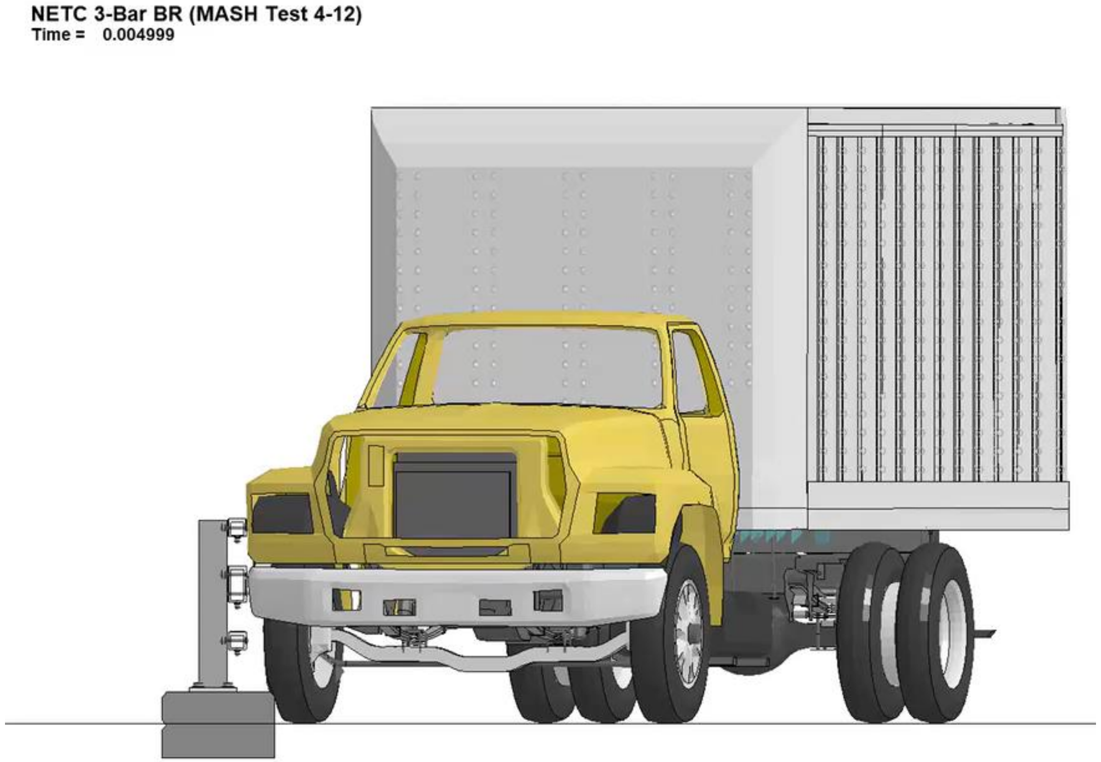
MASH Test 4-12 for NETC 3-Bar Bridge Rail

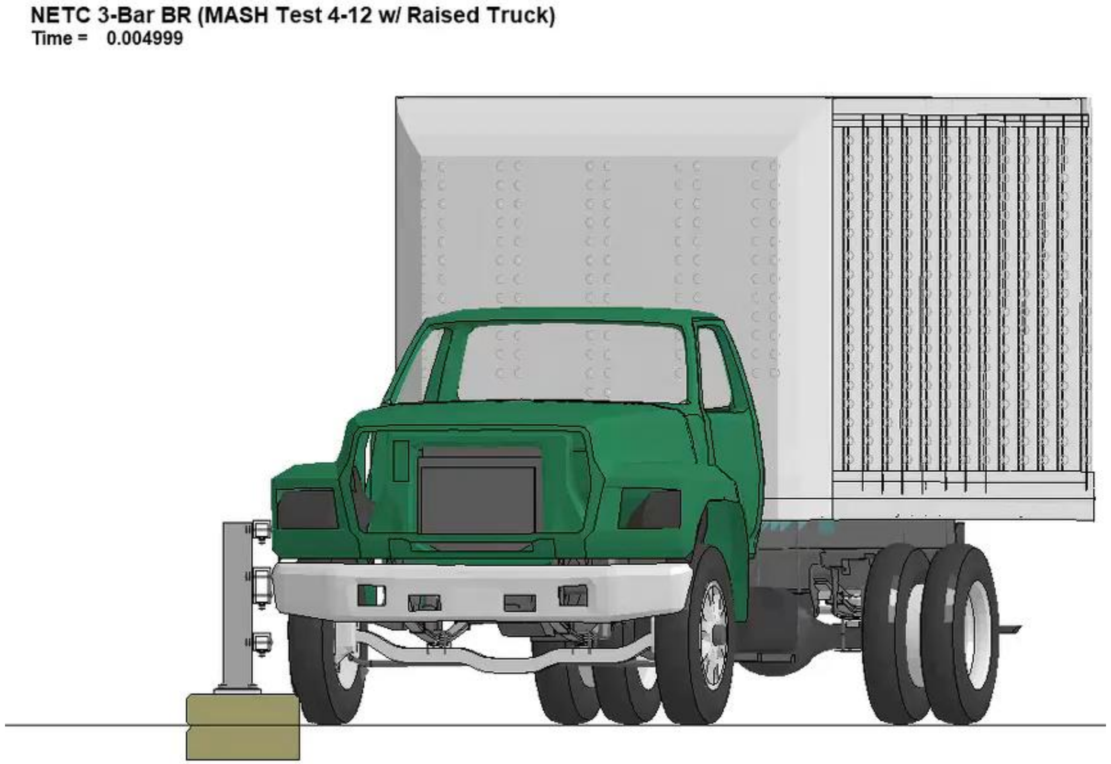
Test 4-12 (Case 1)

- 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)

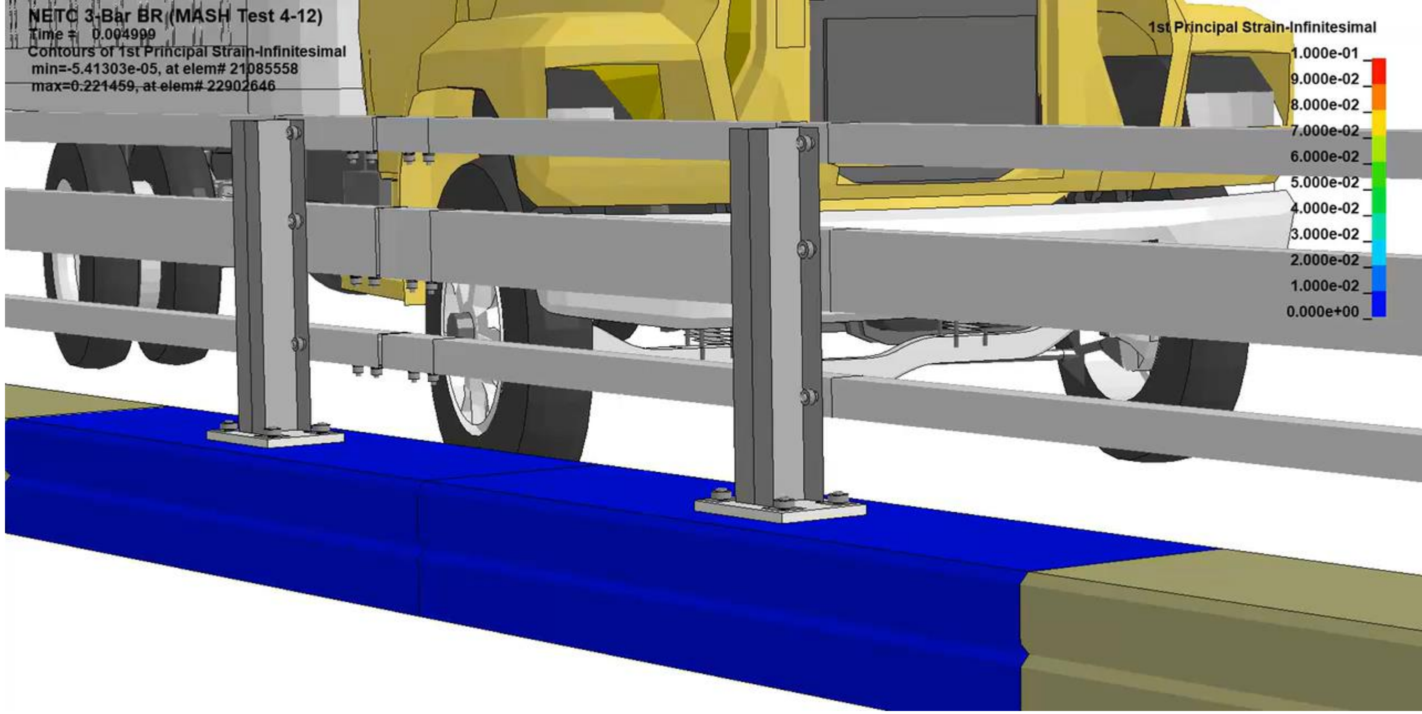


Test 4-12 (Case 2)

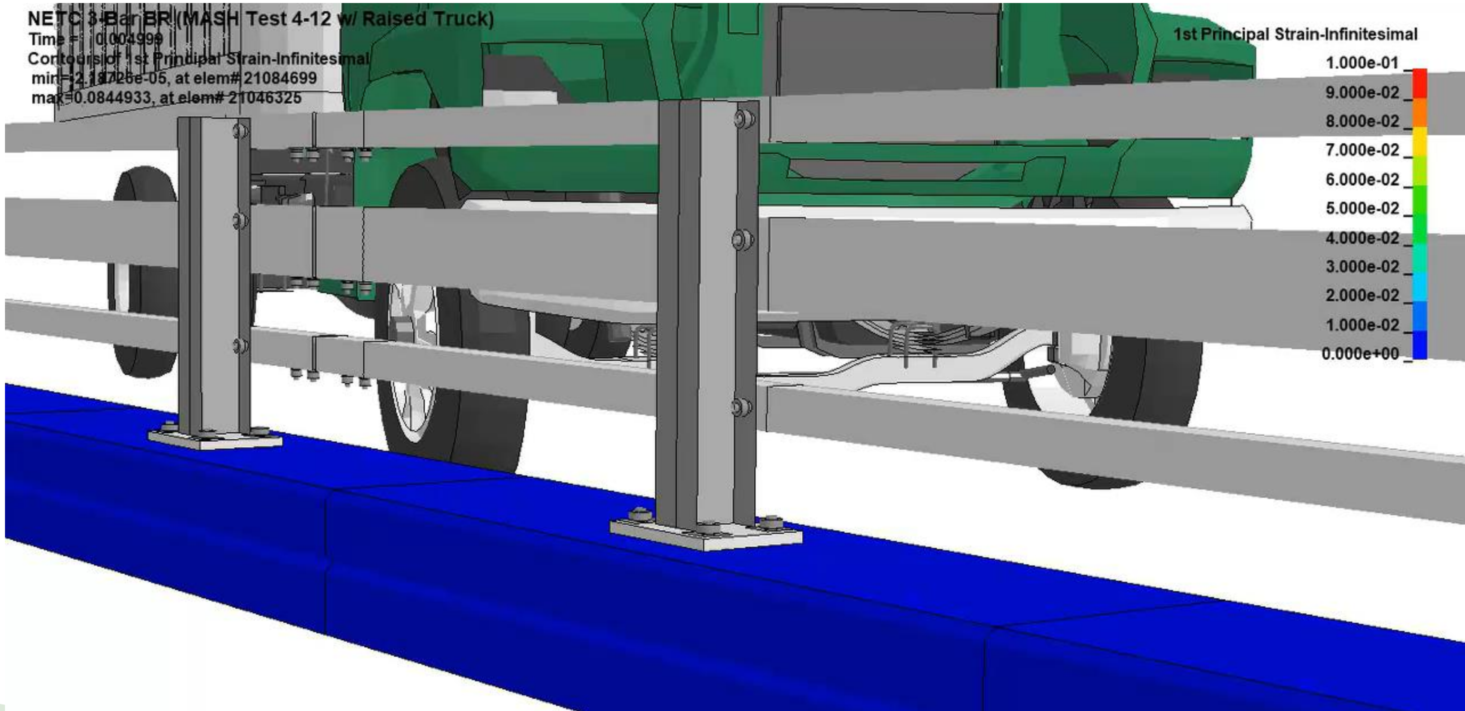
- Impact Speed = 56 mph
- Impact Angle = 15 degrees
- Impact Point = 5.0 ft upstream from critical Post
- Bed Height = 50” (e.g., GMC)



Bed Height = 47.5 inches

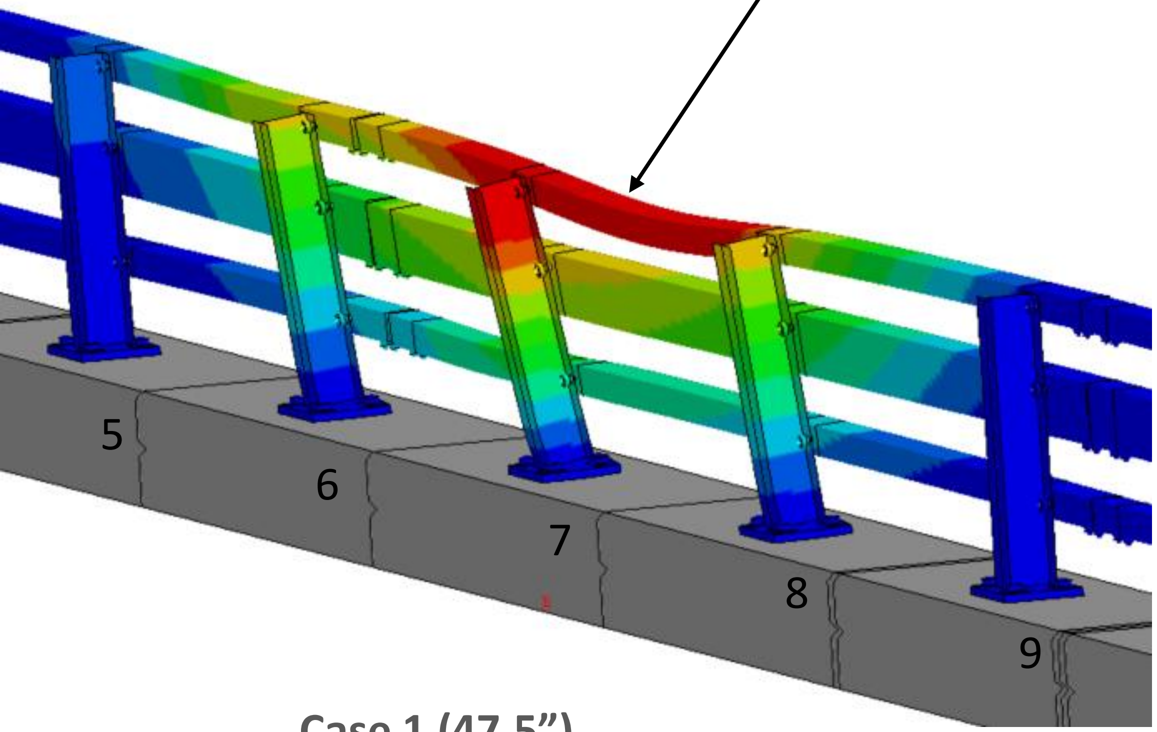


Bed Height = 50 inches



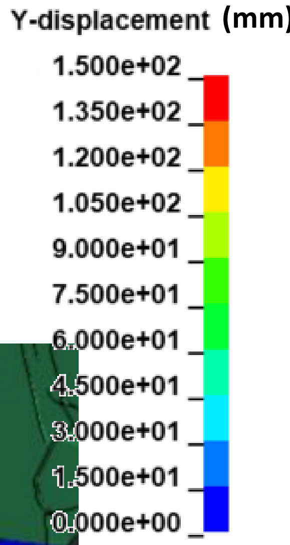
Lateral Dynamic Deflection

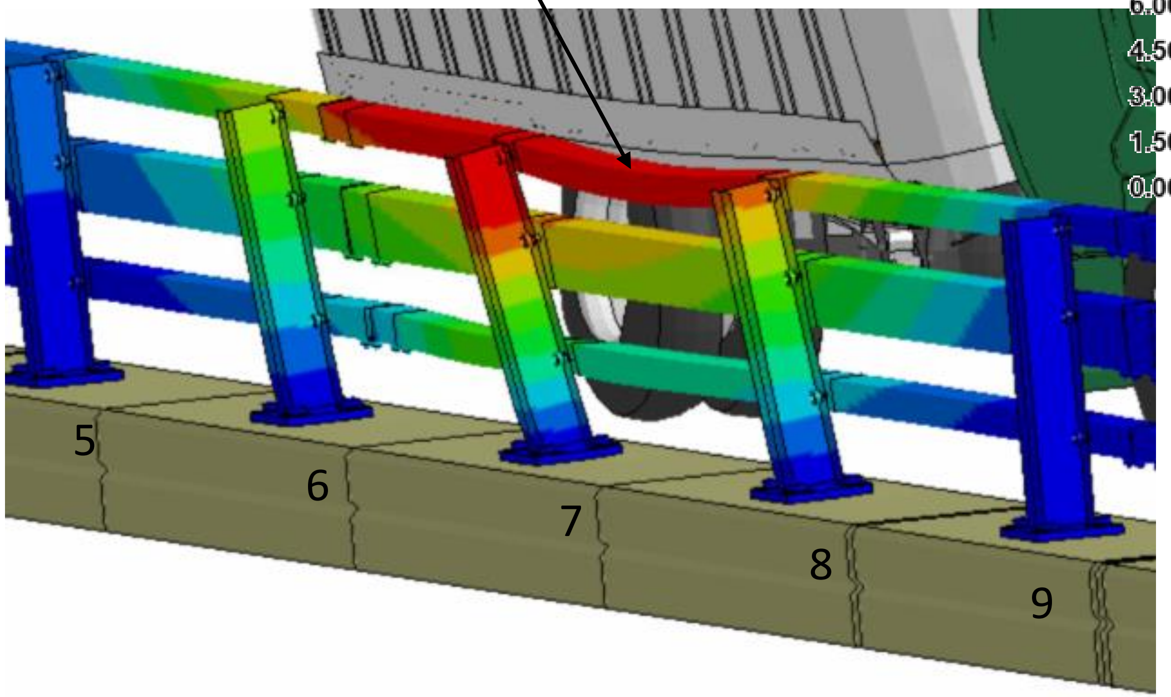
Maximum dynamic deflection = 7.64 in (194 mm)



Case 1 (47.5”)

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





Case 2 (50”)

Transportation Engineering and Research

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

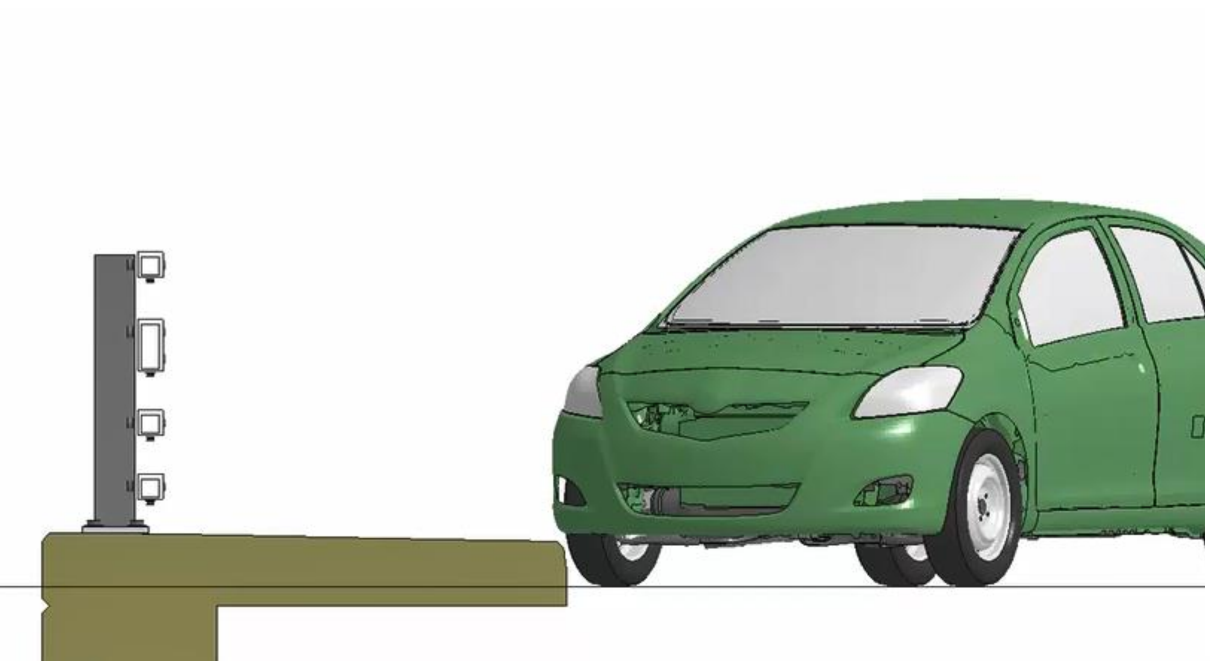
MASH TL-4 for NETC 4-Bar Bridge Rail

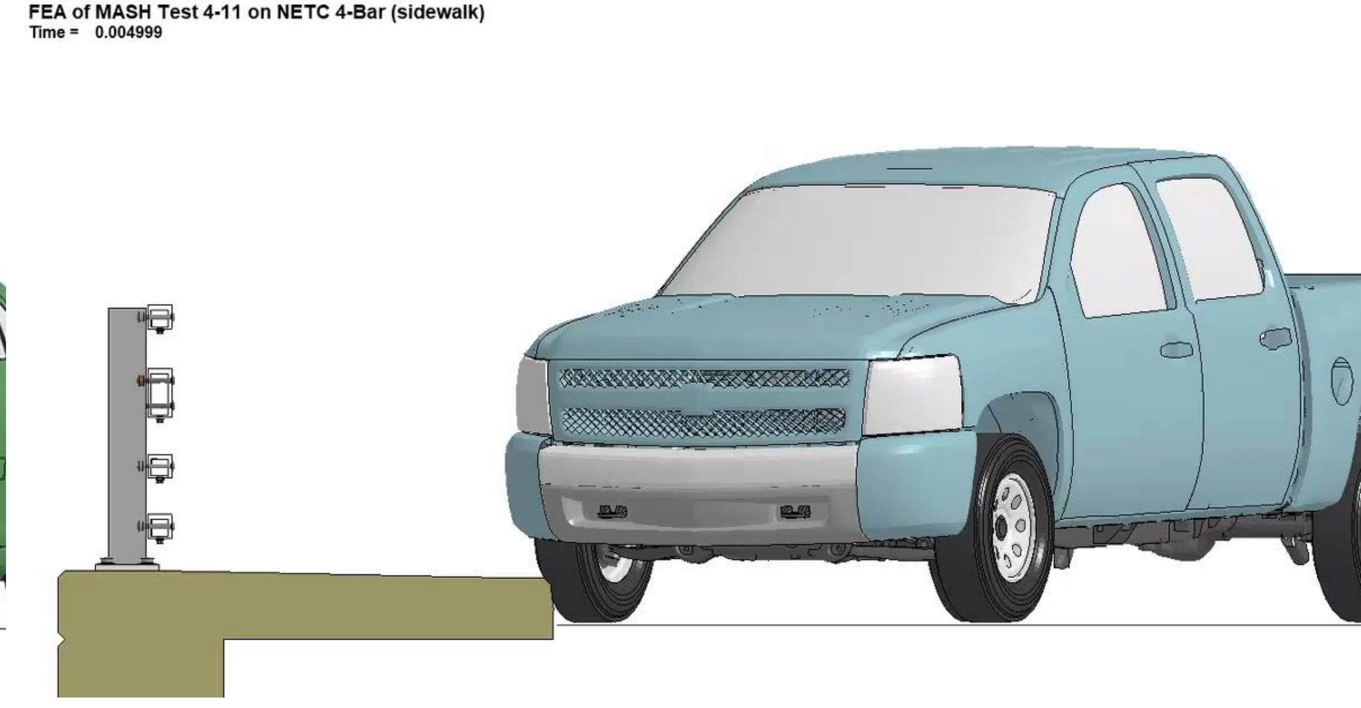
Test 4-10

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

Test 4-11

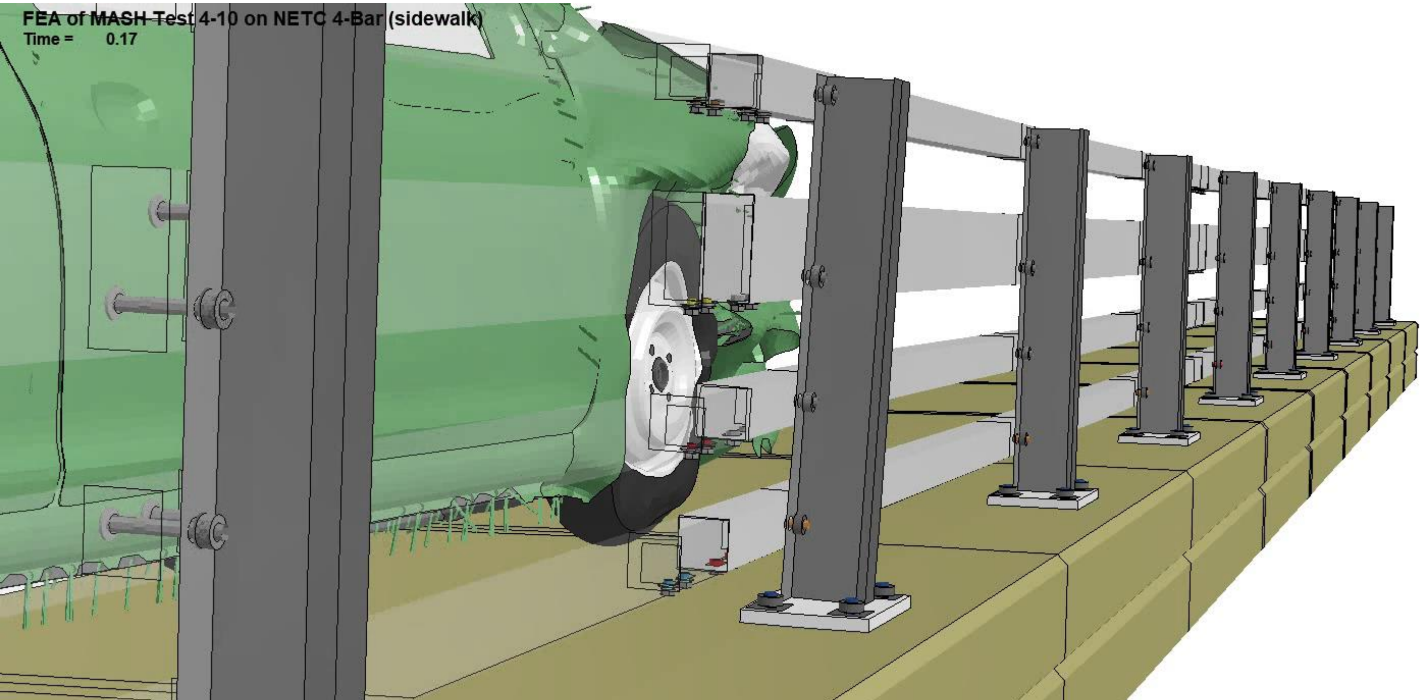
- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 4.3 ft upstream from critical Post

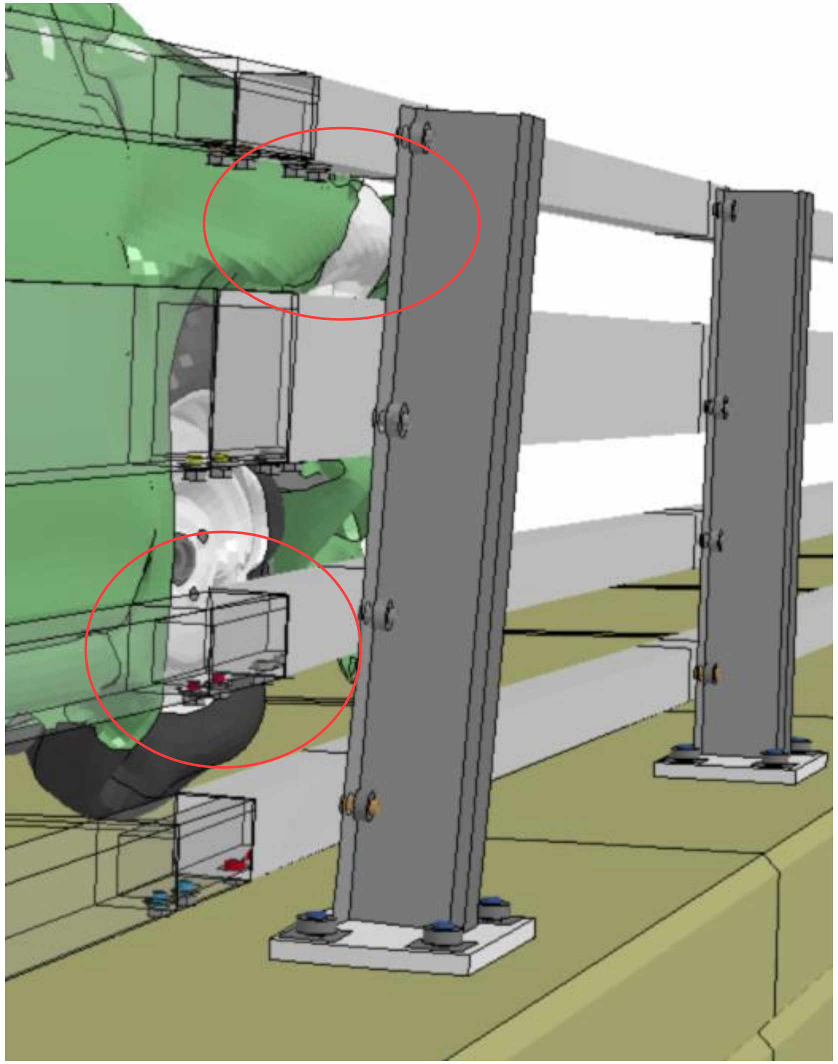




Assessment of Potential Vehicle Snag

- 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 <u>not</u> contact post.





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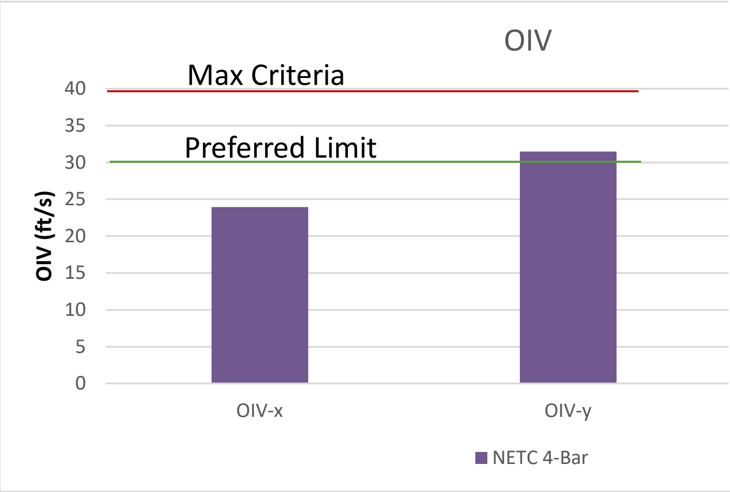
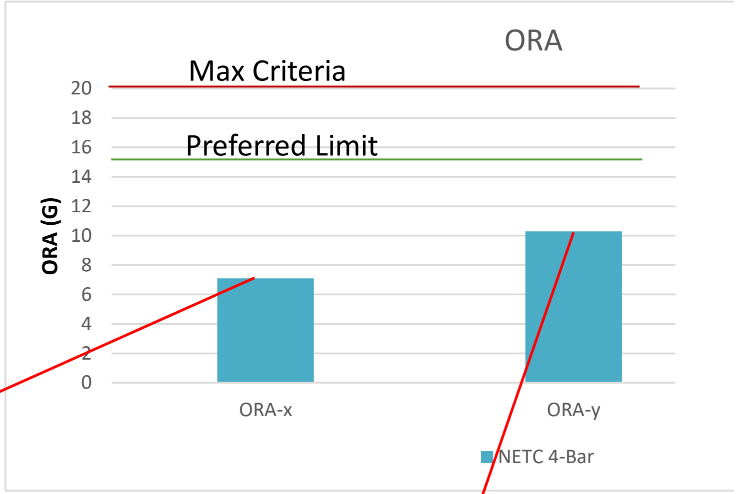
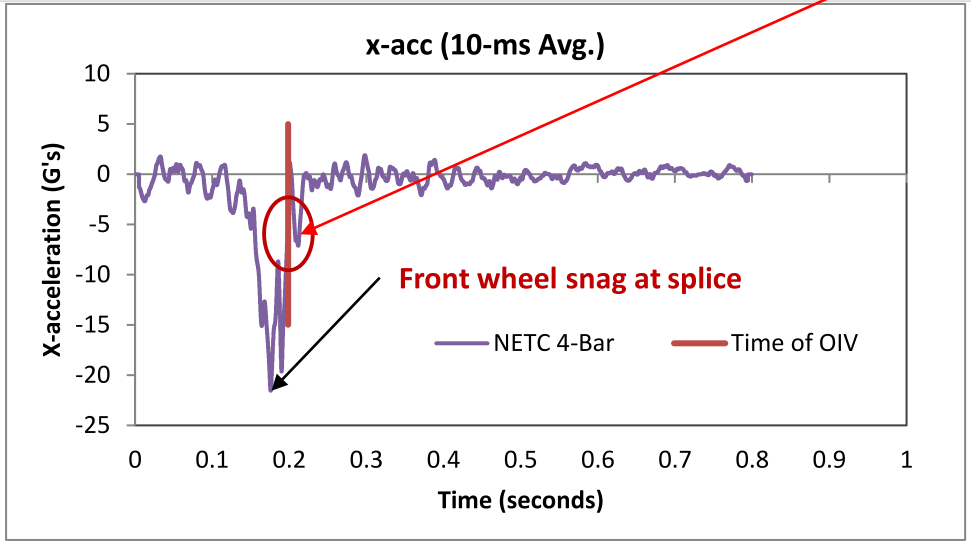
Occupant Risk
Test 4-20

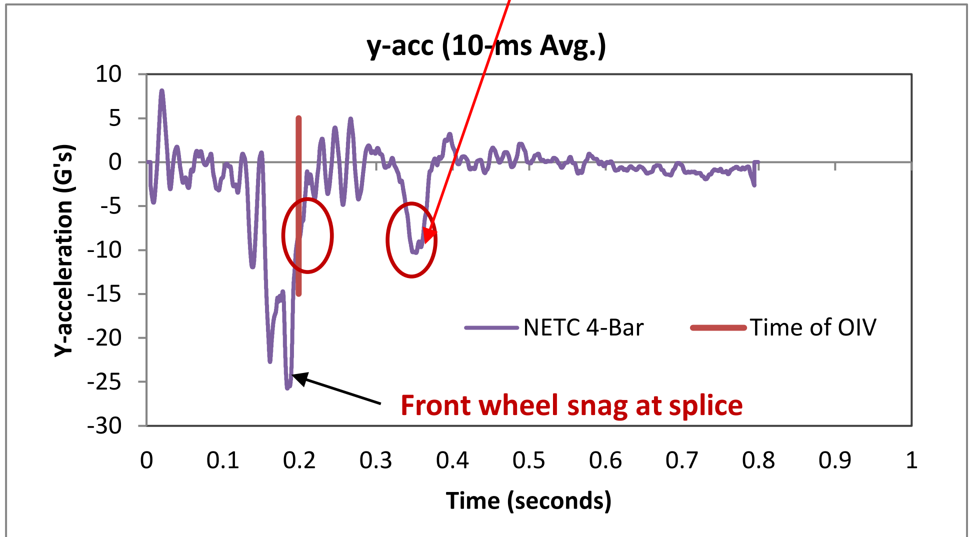
Occupant Impact Velocity



Occupant Ridedown Accelerations

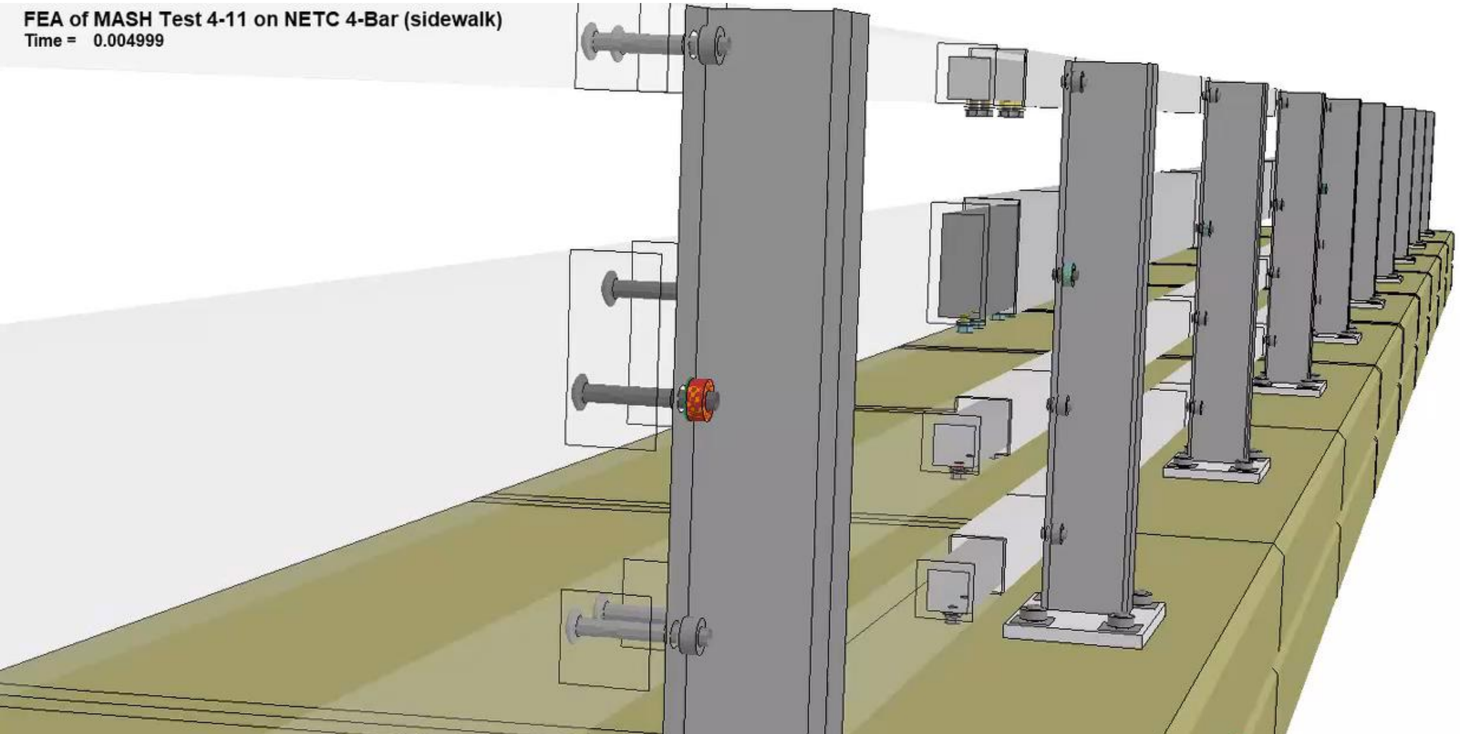




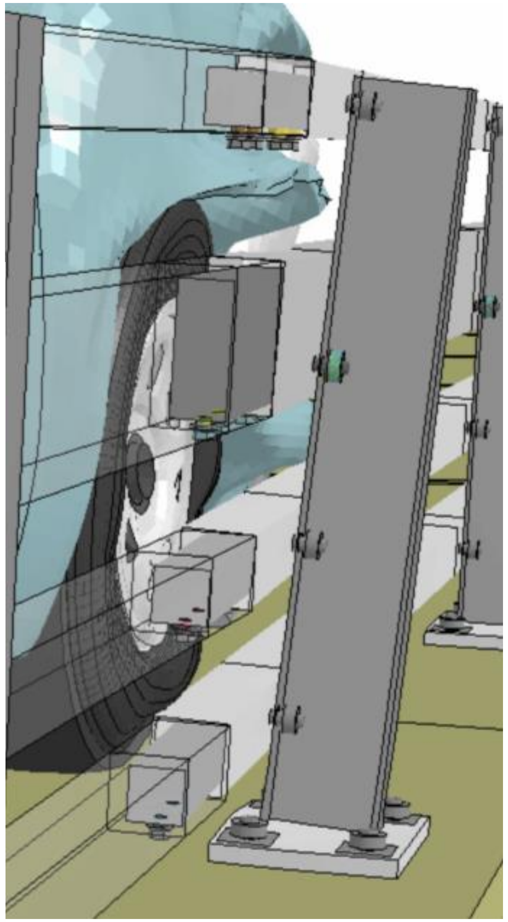


Assessment of Potential Vehicle Snag

- 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.

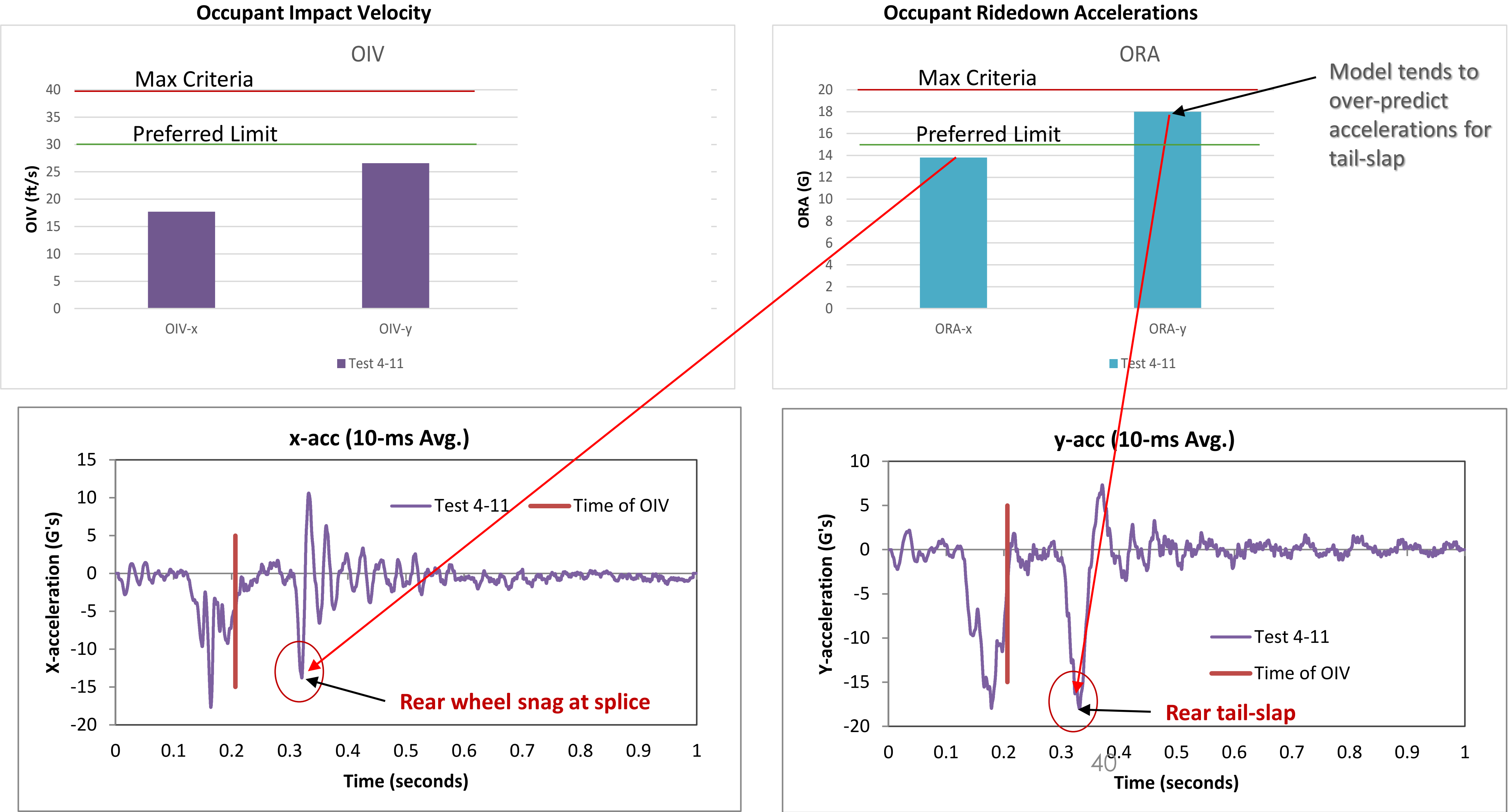


Front of Vehicle



Rear Tire

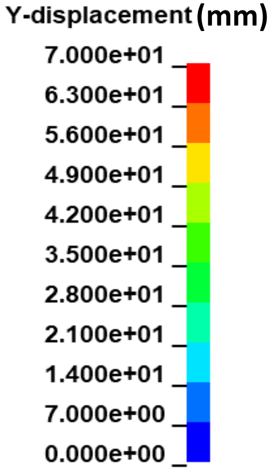
Occupant Risk
Test 4-21

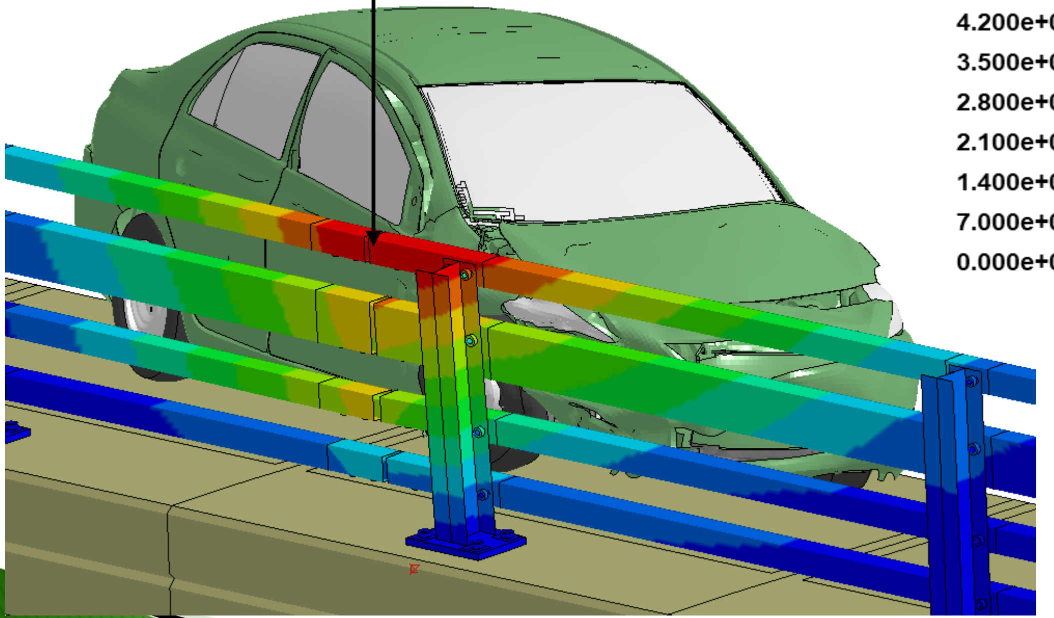


Lateral Dynamic Deflection

Test 4-10

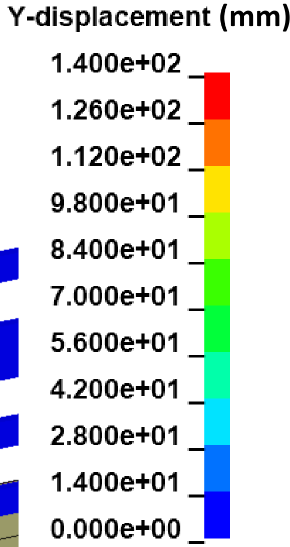
Maximum dynamic deflection = 2.8 in (72 mm)

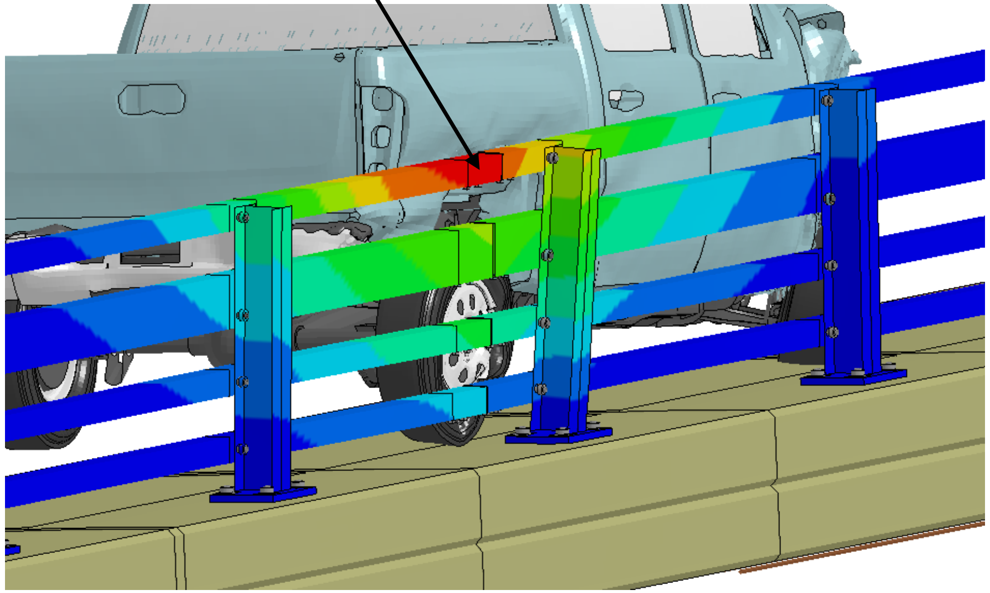




Test 4-11

Maximum dynamic deflection = 5.4 in (138 mm)



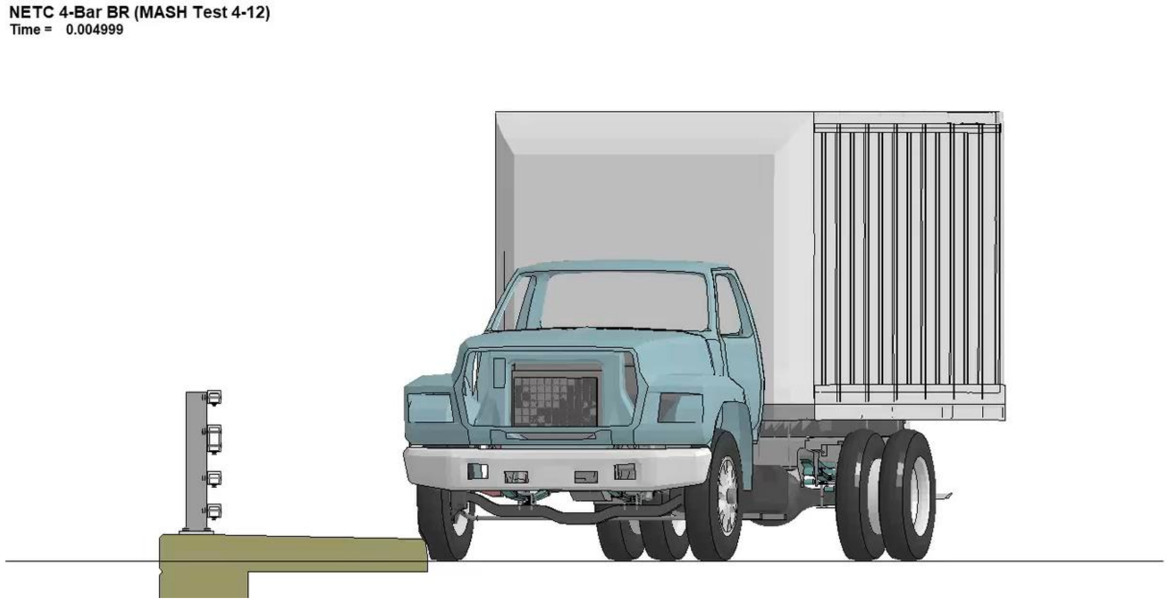


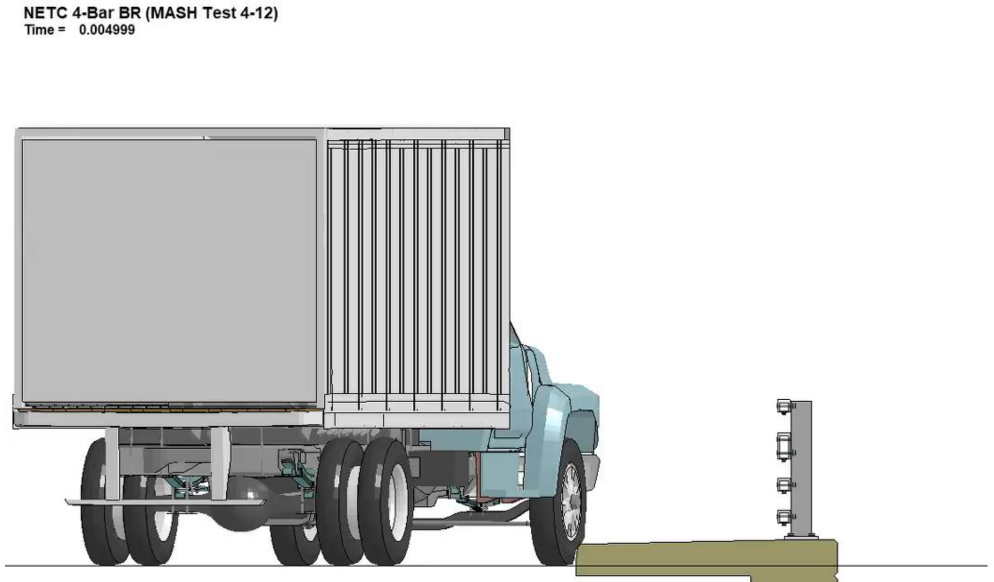
Conclusions for Test 4-10 and 4-11 on the NETC 4-BAR

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

MASH Test 4-12 Simulation

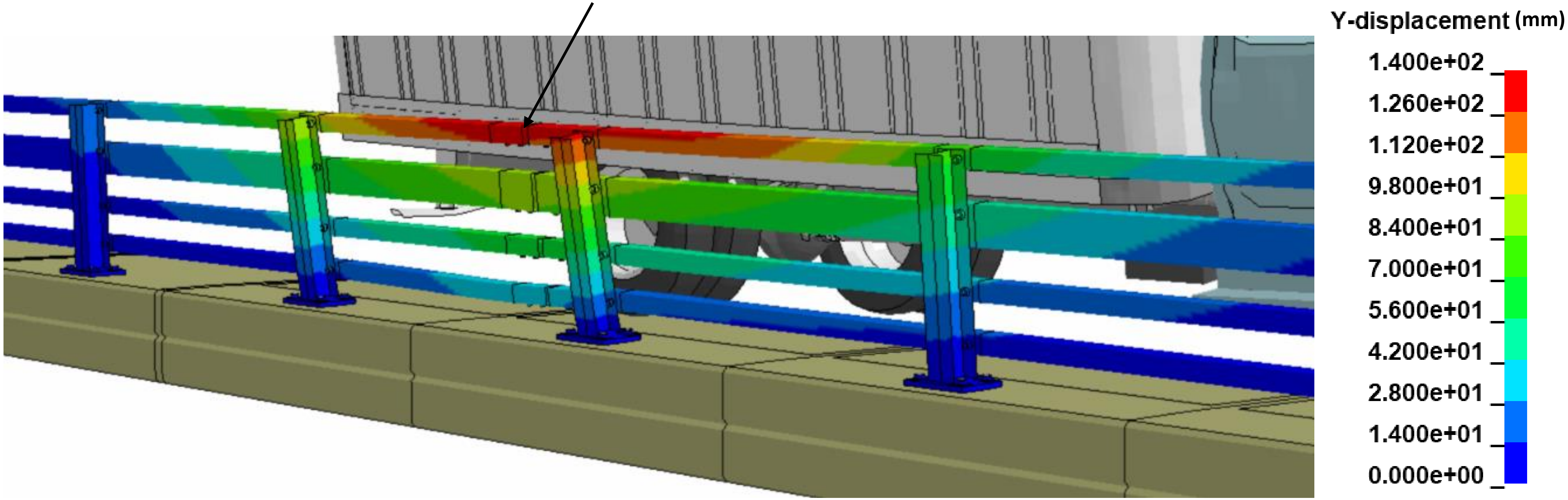
- **Impact Conditions**
  - Mass = 22,061 lb
  - Impact Speed = 56 mph (90 km/hr)
  - Impact Angle = 15 degrees
  - Target Impact Point = 5.0 ft upstream of Post 7





Lateral Dynamic Deflection

Maximum dynamic deflection = 8.15 in (207 mm)



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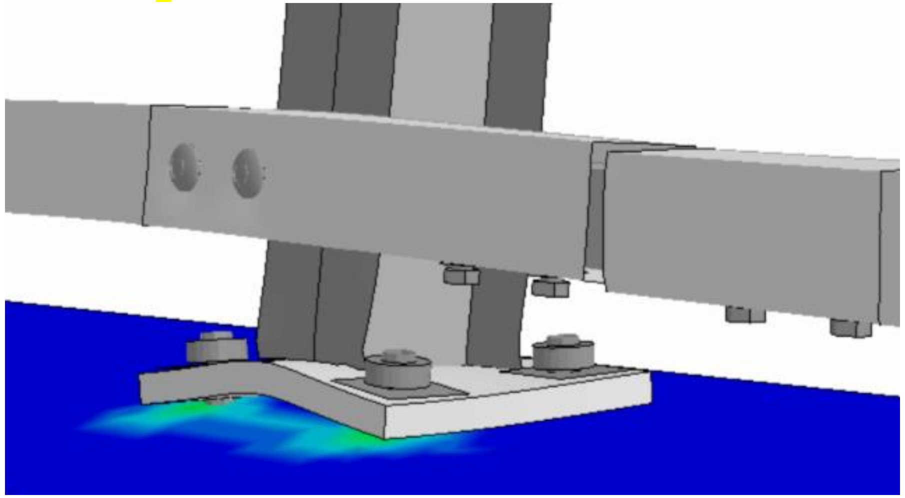
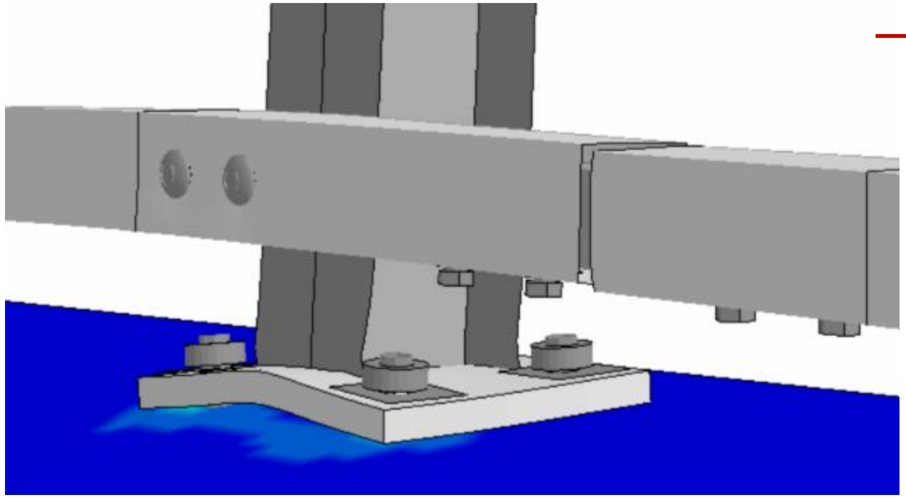
Barrier Damage

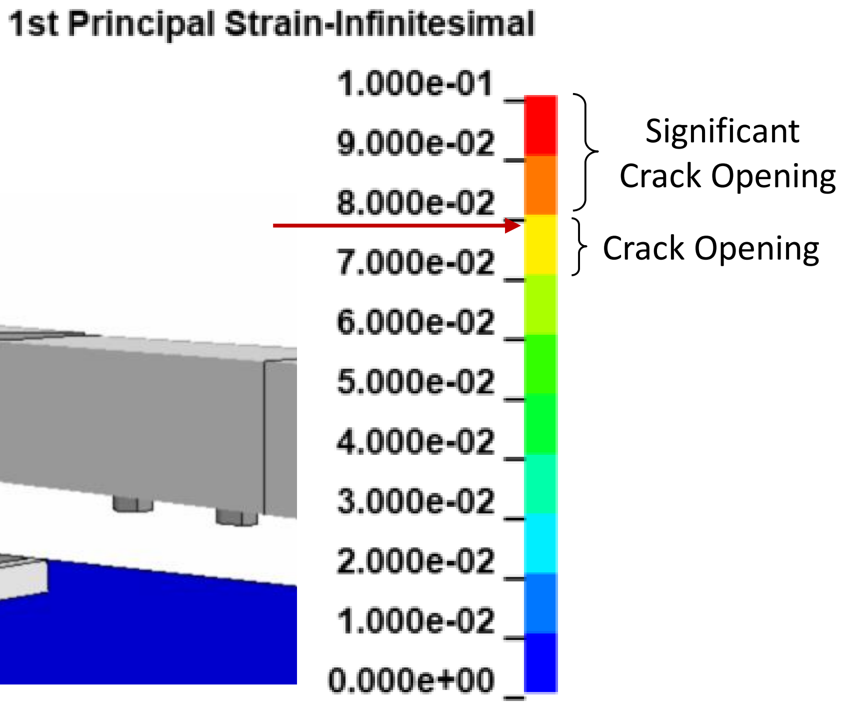
- Analysis indicated probable crack opening in concrete at front anchor bolts at maximum dynamic deflection.
  - Max dynamic 1^{st} Prin. Strain = 0.079
  - Final 1^{st} Prin. Strain = 0.054



Dynamic at time = 0.515 seconds



Final Static



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

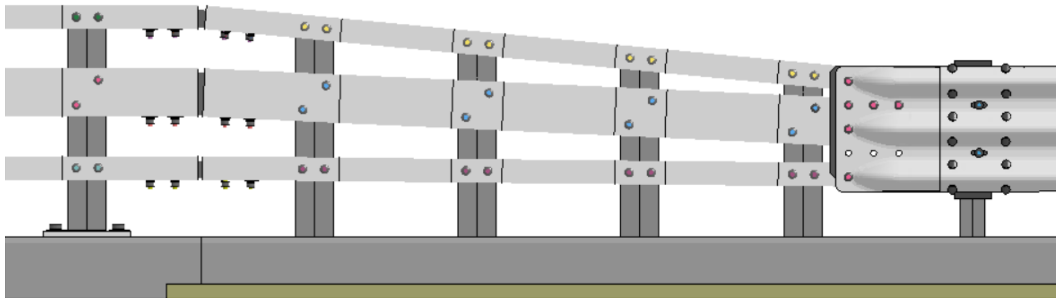
Evaluation Factors		Evaluation Criteria – MASH Test 4-12	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the 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

Summary for NETC Bridge Rail Designs

- **NETC 2-Bar:**
  - Meets MASH TL3 criteria with only moderate barrier damages.
  - Concrete curb damage 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.

NETC Transition Systems

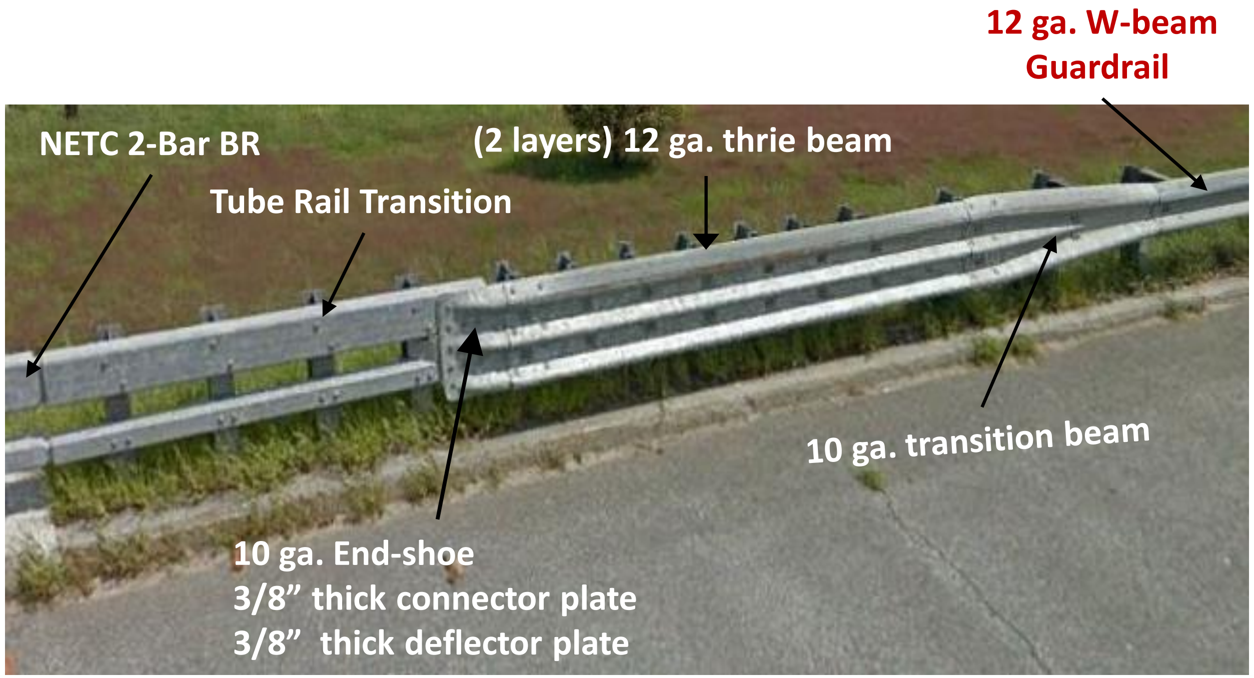
- Three design options were evaluated:
  1. NETC Style 2-Bar Rail and Thrie Beam (TL3) (NHDOT steel rail transition)
  2. NETC Style 3-Bar Rail and Thrie Beam (TL4) (NHDOT steel rail transition)
  3. Concrete Transition Barrier and Thrie Beam (TL4) (MaineDOT standard detail)

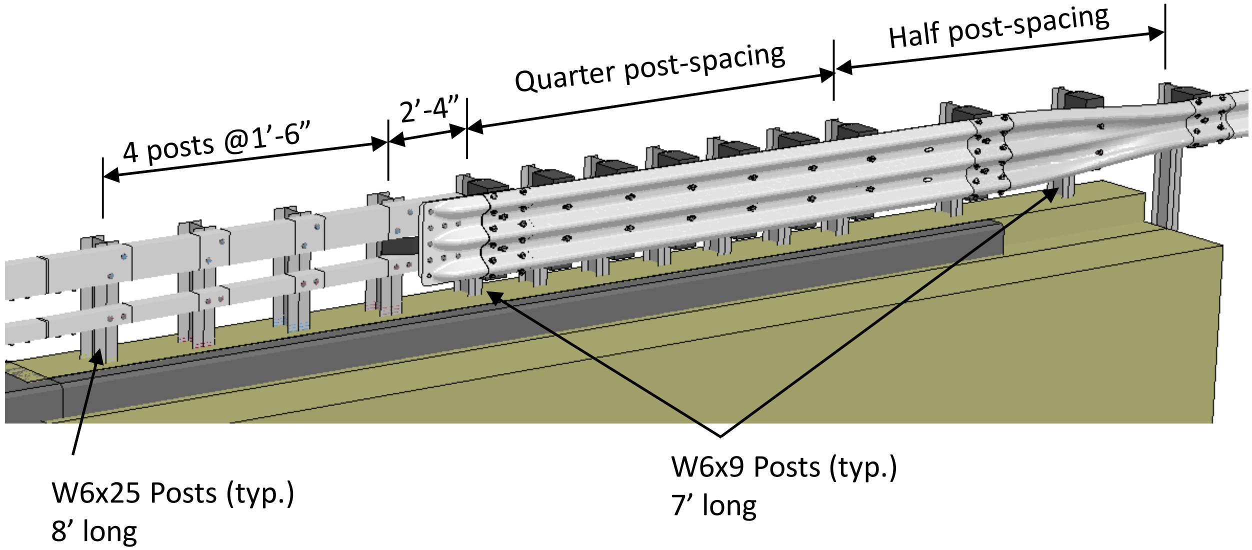


- Single taper on top
- No face taper

NETC 2-Bar Transition

The transition system for the 2-Bar bridge rail was modeled based on the detailed drawing from NHDOT

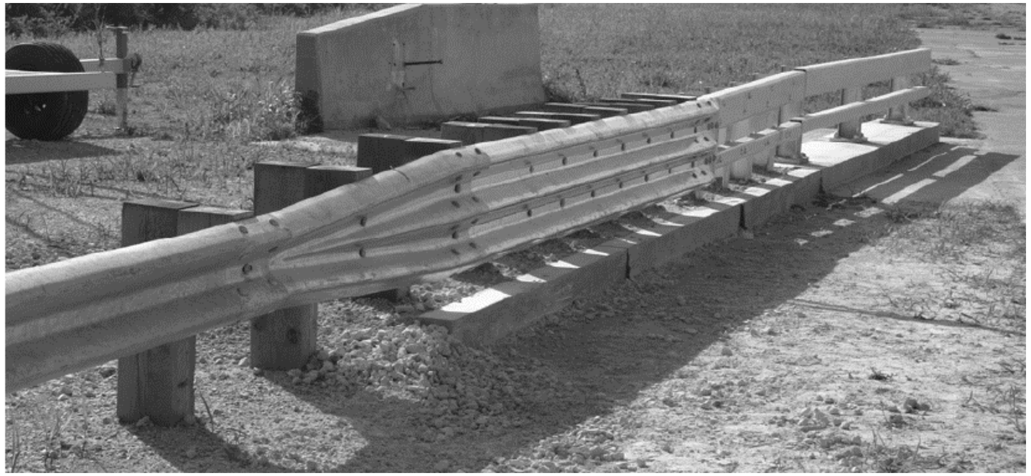




NETC 2-Bar to Thrie-Beam AGT

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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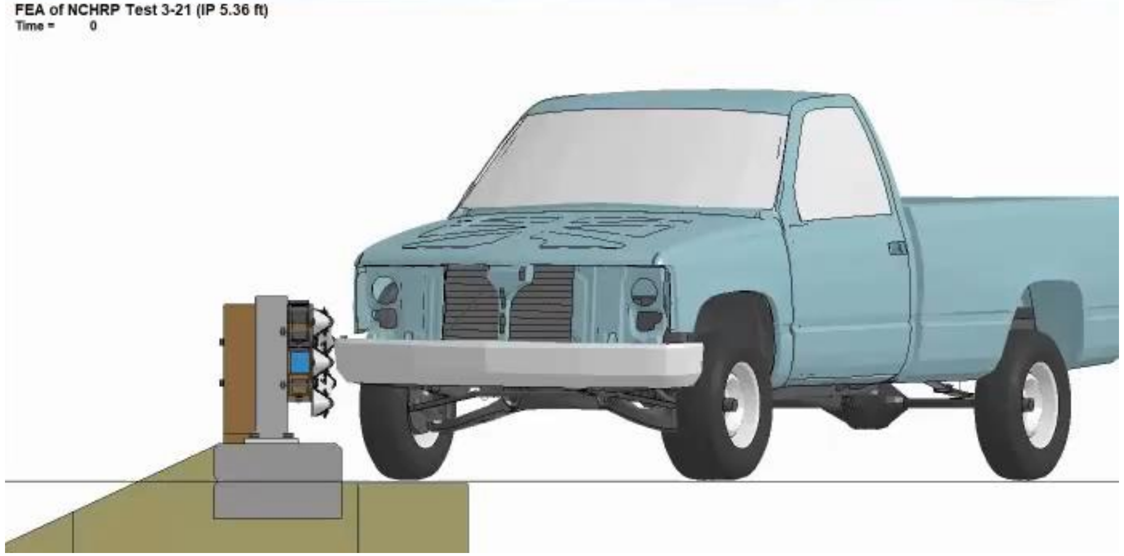
NETC 2-Bar to Thrie-Beam AGT

Validation

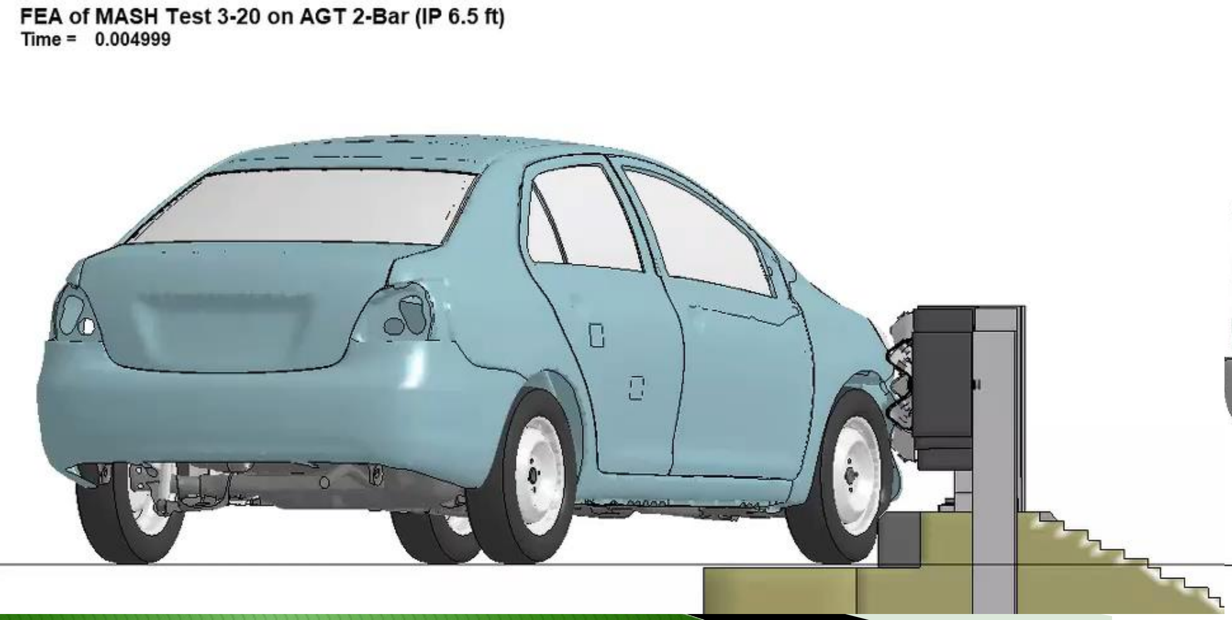
Occupant Risk Factors		MASH Test 3-11		Error		W179 Criteria	
		Test 401181-1	FEA				
		(0 - 1.0 seconds)	(0 - 1.0 seconds)	%	Absolute	Criteria	Pass
Occupant Impact Velocity (ft/s)	x-direction	17.06	19.68	15.4%	2.62	<20% or < 6.6 f/s	Y
	y-direction	-24.61	-24.93	1.3%	-0.33	<20% or < 6.6 f/s	Y
	at time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



MASH TL-4 for NETC **2-Bar** Transition

Test 4-20

- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 6.5 ft upstream from critical Post



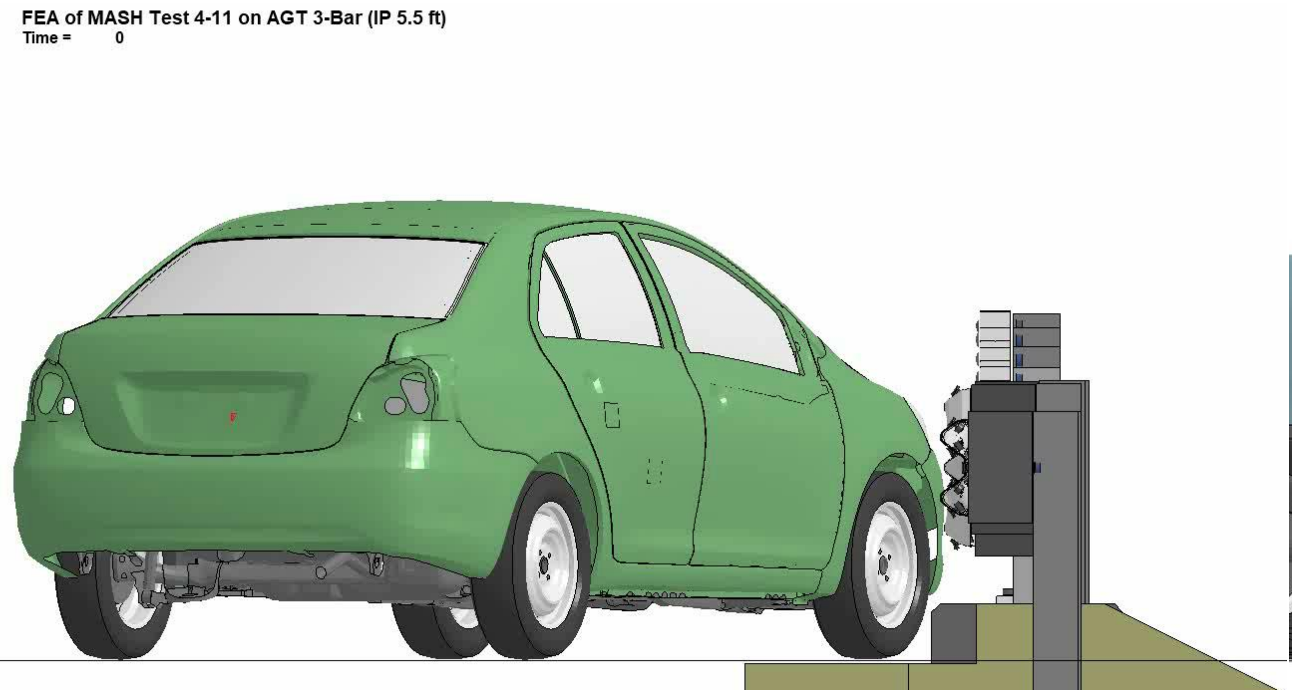
Test 4-21

- Impact Speed = 62.1 mph
- Impact Angle = 25 degrees
- Impact Point = 9 ft upstream from end of tube rail

MASH TL-4 for NETC 3-Bar Transition

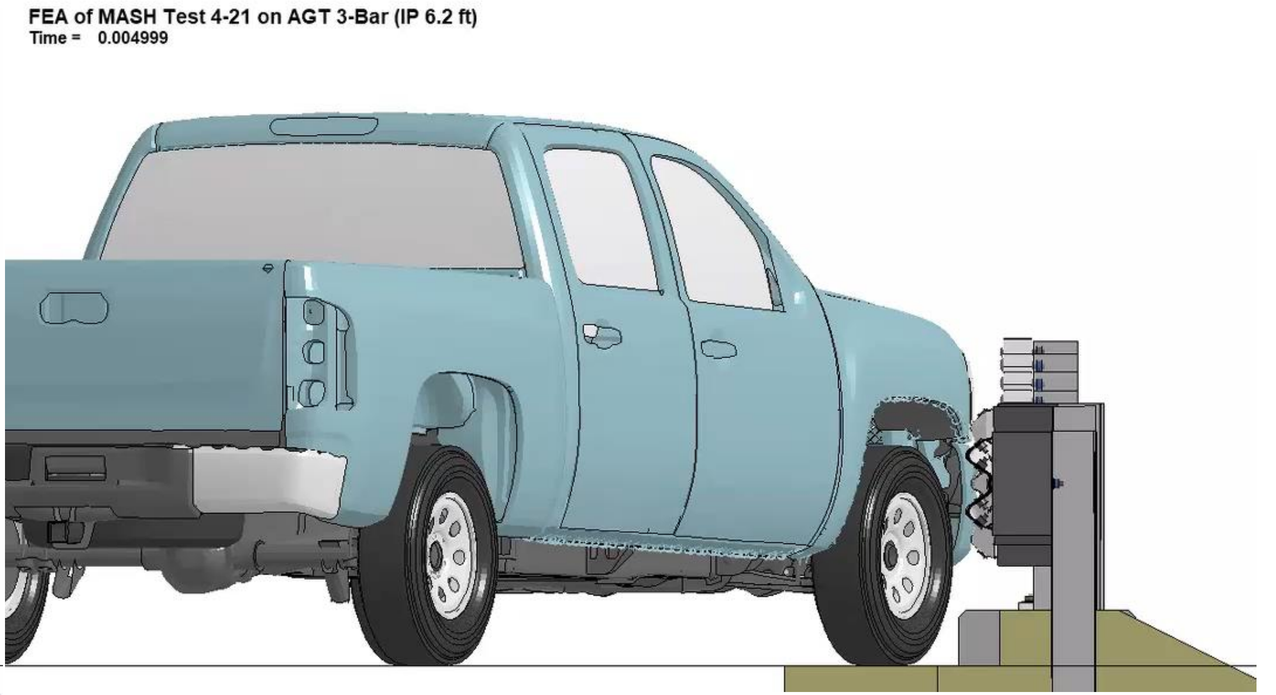
Test 4-20

- 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



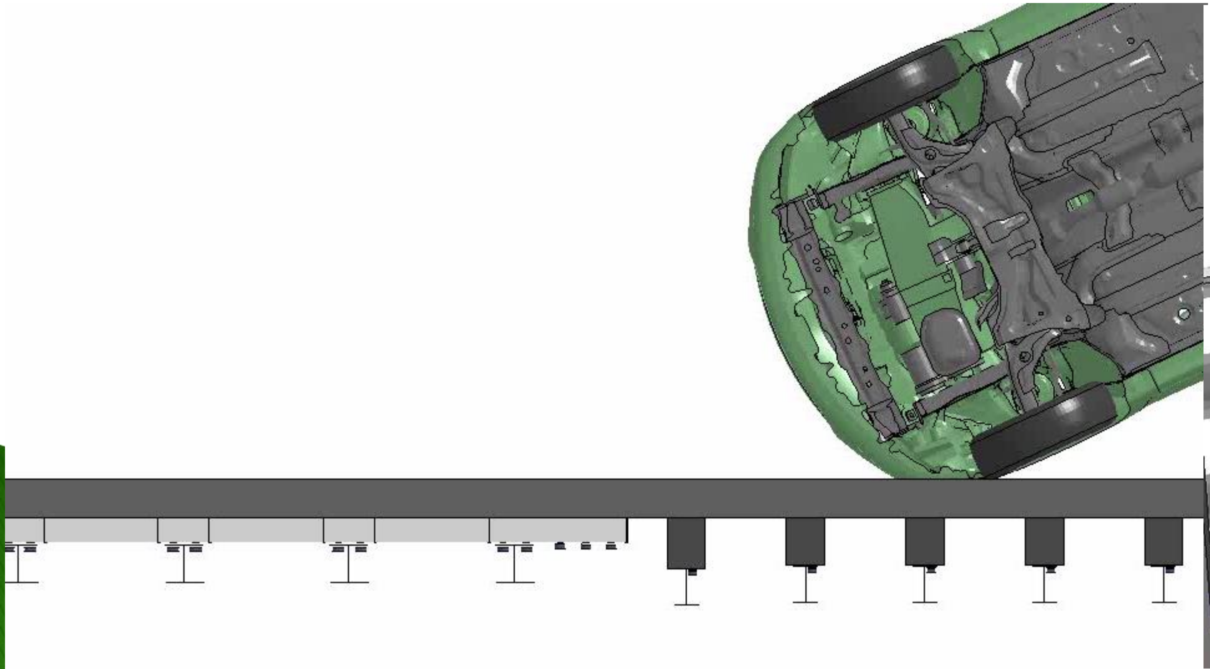
MASH TL-4 for NETC 3-Bar Transition

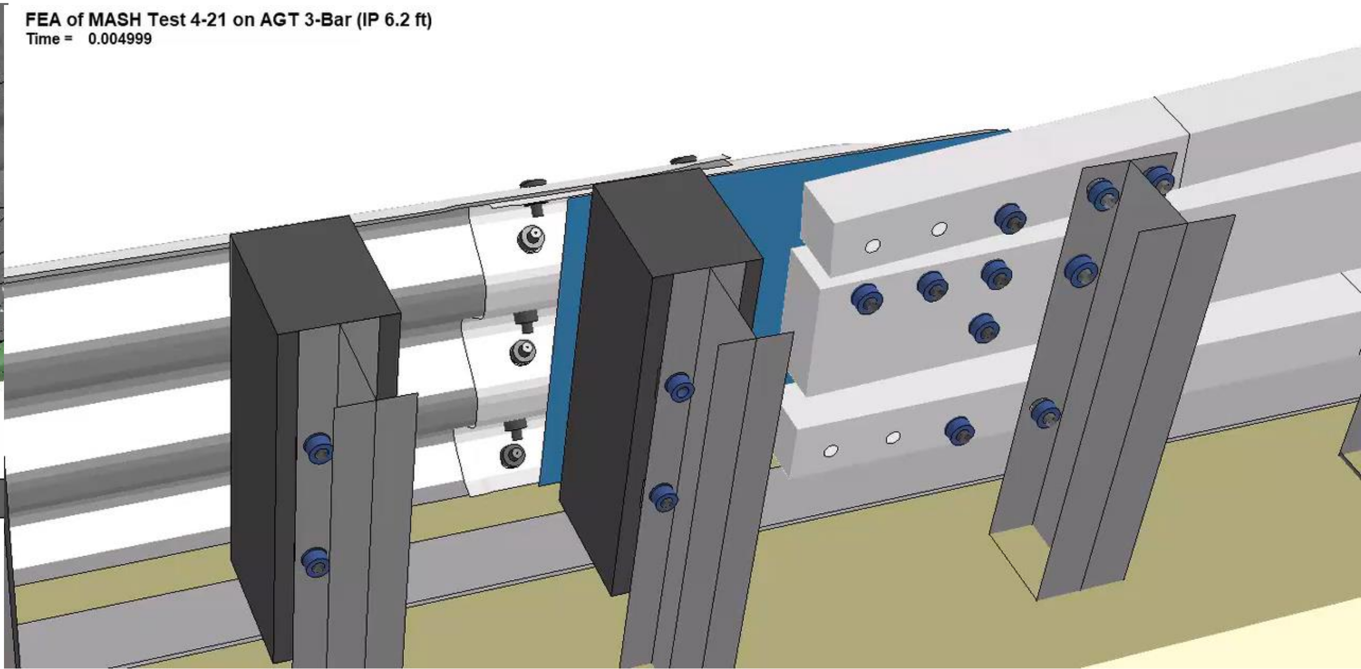
Test 4-20

- 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





Conclusions on Tests 3-20 and 3-21 on 2-Bar and 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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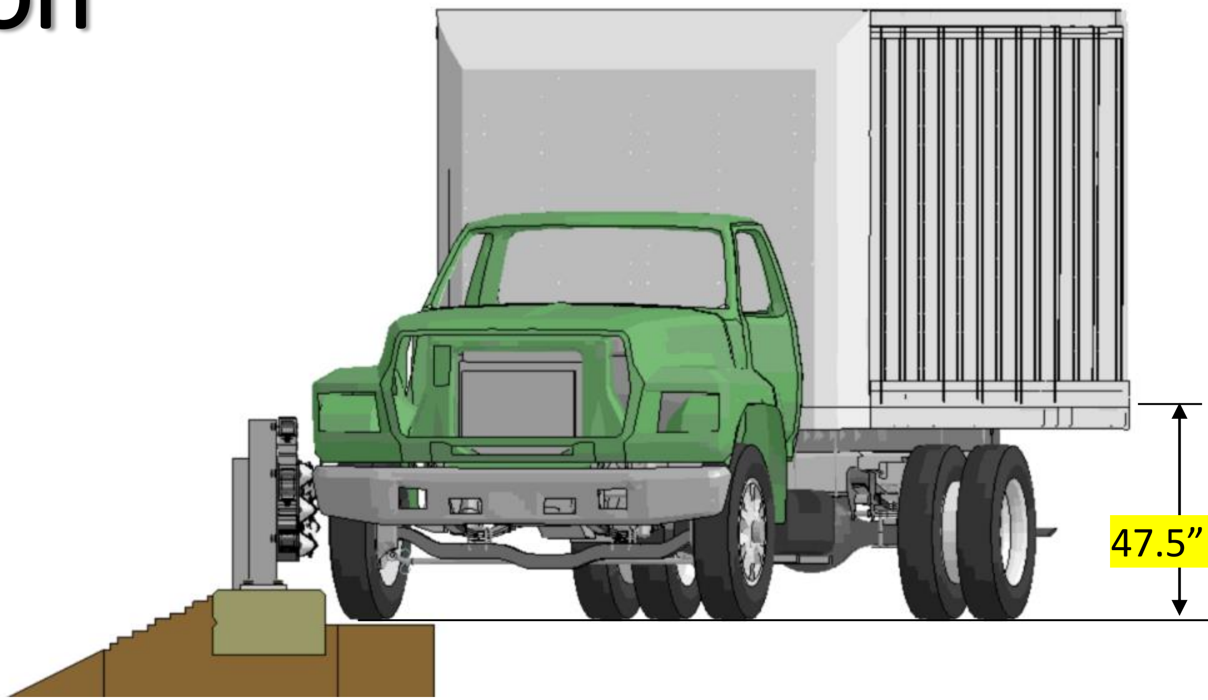
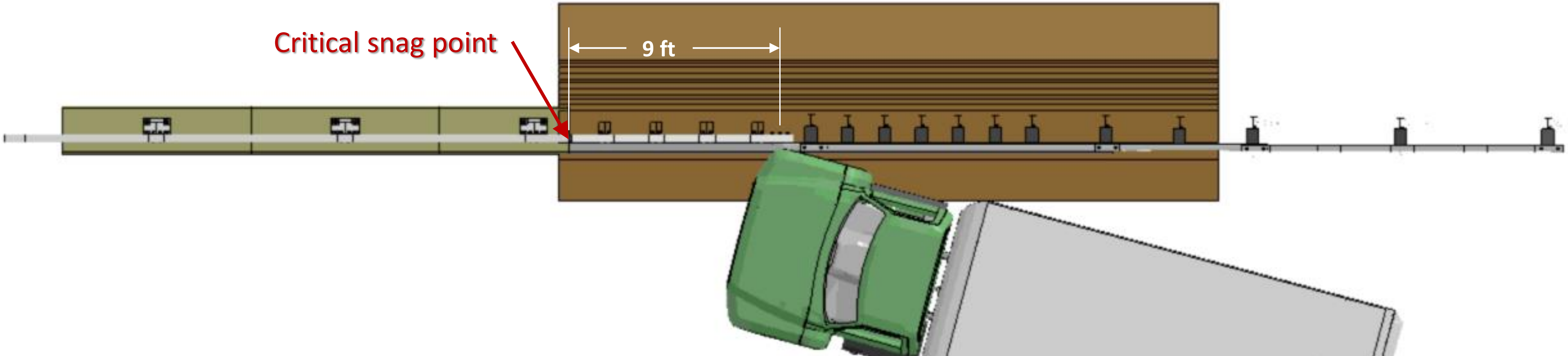
MASH Test 4-22 Simulation

- **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

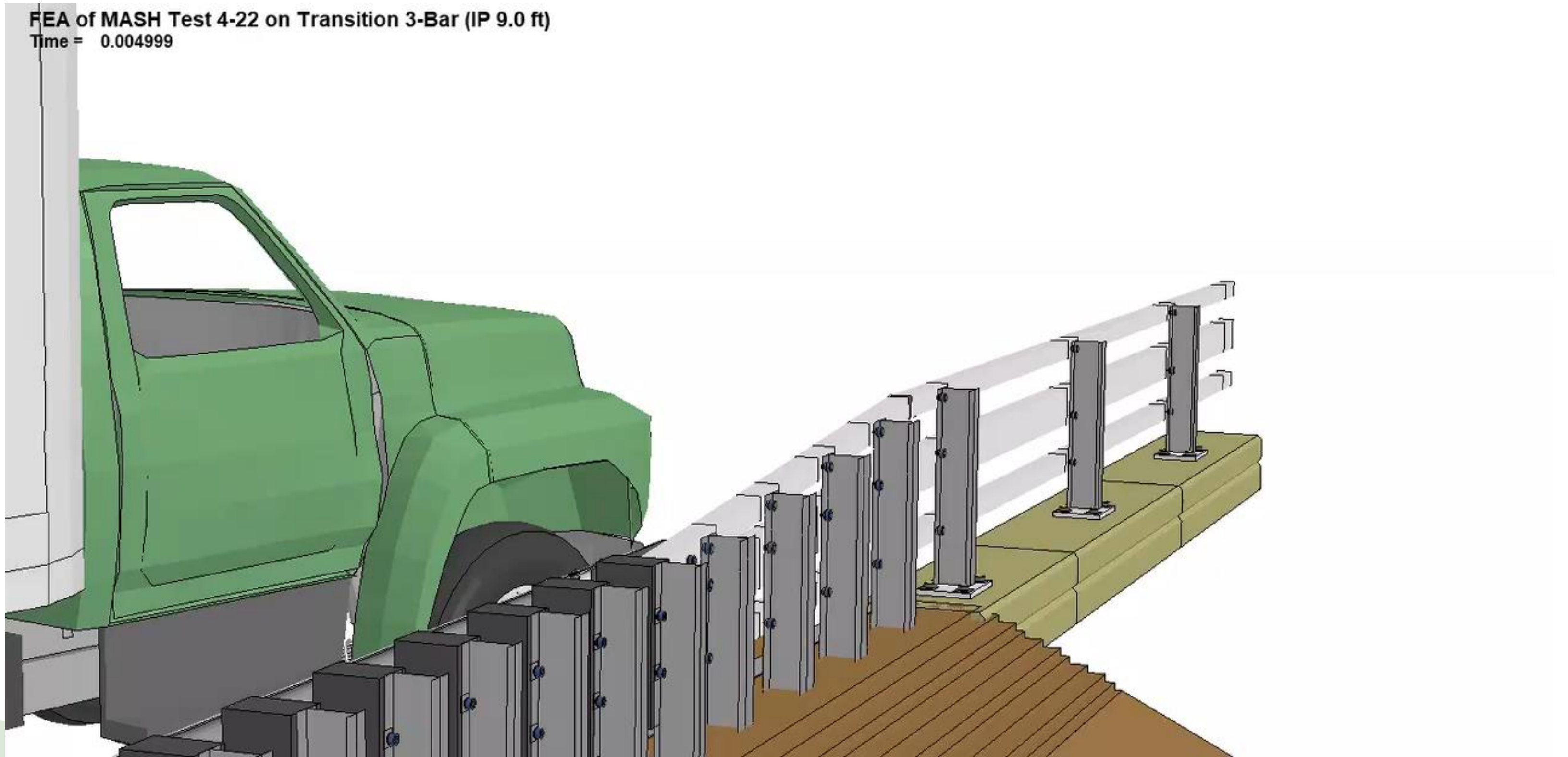
Ford 800 Surrogate





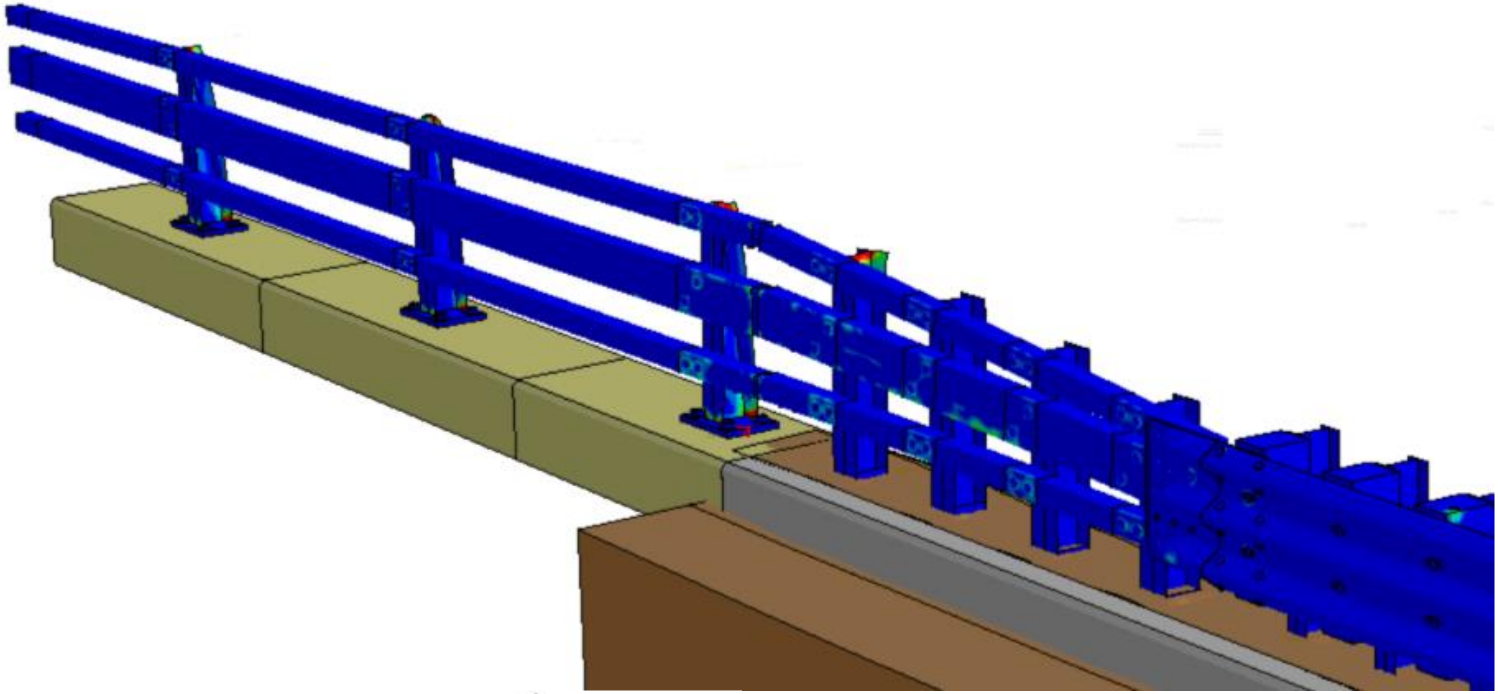
MASH Test 4-22 Simulation

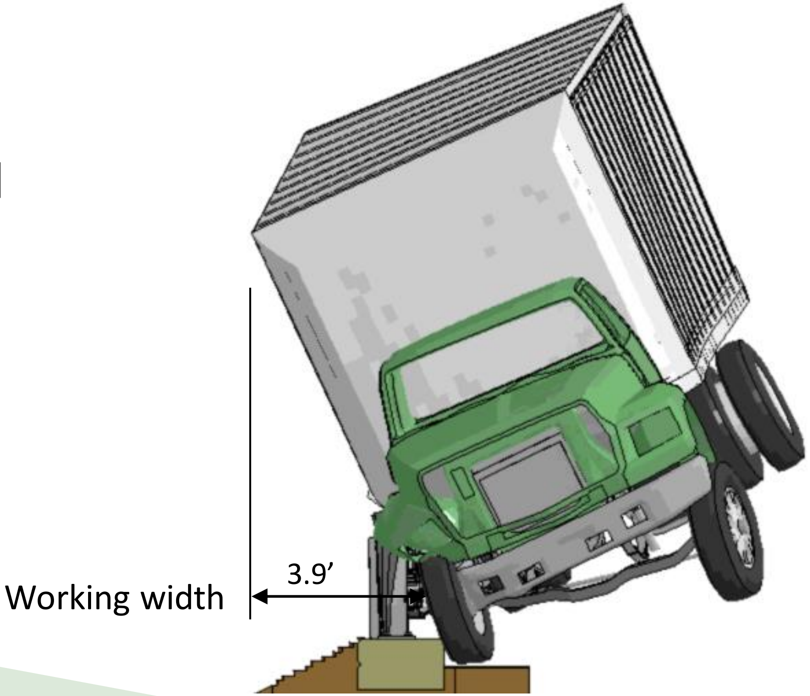
- **Impact Conditions**
  - Mass = 22,061 lb
  - Impact Speed = 56 mph (90 km/hr)
  - Impact Angle = 15 degrees
  - Impact Point = 9 ft upstream of Bridge Rail tube ends

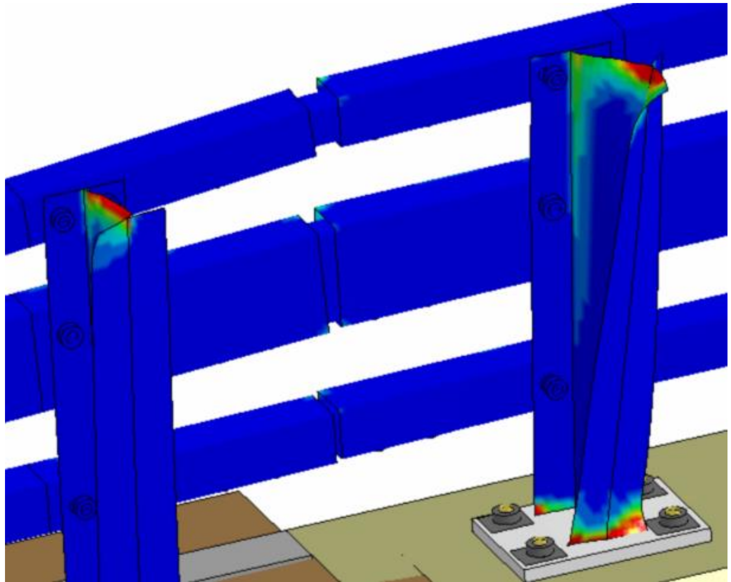


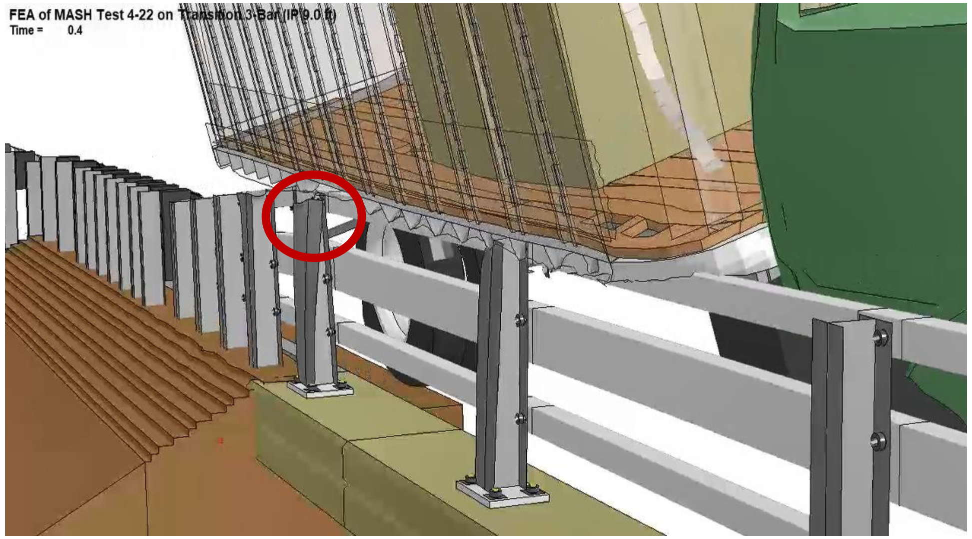
Barrier Damage

- 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.

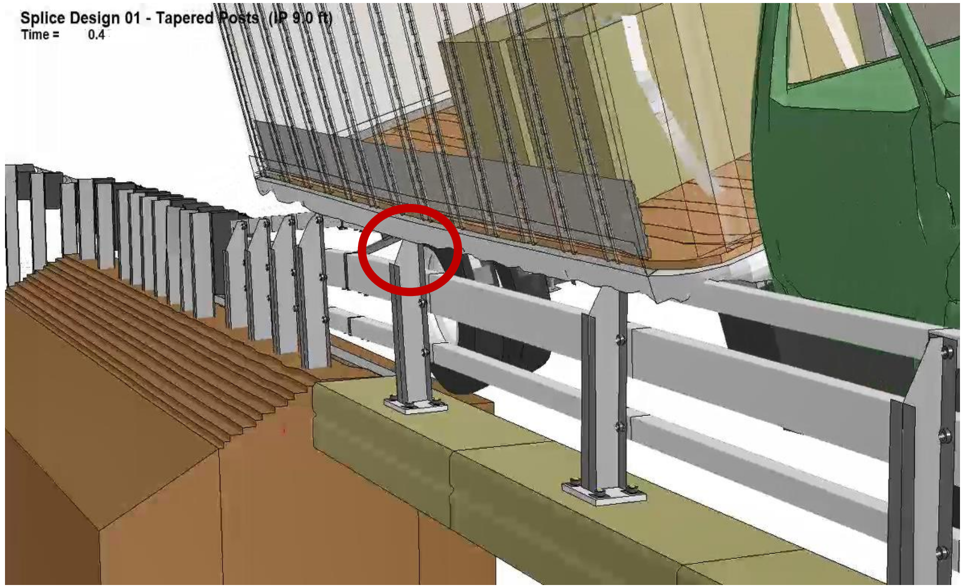








Baseline Original Design (3 ft)



Case 2 – ¾” Splice Gap and Tapered Post (5.5 ft)

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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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Overall Project Conclusions

The results of this study showed that for:

- NETC Bridge Rail Designs
  - 2-bar curb-mounted system meets MASH TL3
  - 3-bar curb-mounted system meets MASH TL4
  - 4-bar sidewalk-mounted system meets MASH TL4
  - However, the 3-bar and 4-bar design resulted in considerable damage to the system, particularly in the SUT test.
- NETC AGT Designs
  - 2-bar to thrie-beam AGT meets MASH TL3
  - 3-bar to thrie-beam AGT meets MASH TL4
  - The concrete buttress to thrie-beam did not meet MASH requirements due to snag and high decelerations for small car test

Overall Project Conclusions

- Redesign of the bridge rail system was not a focus of this study; however, general recommendations were provided to further improve crash performance, including:
  - Revising the splice design to minimize lateral movement in the splice connections.
  - Increasing the size of the HSS rails to improve geometric attributes and strength.
  - Tapering the tops of the posts to mitigate snagging on the top of the posts when parts of a vehicle (e.g., cargo-box on single-unit trucks) overhang the top rail.
- Final Report is posted on the NETC website at:

  https://www.newenglandtransportationconsortium.org/research/netc-research-projects/netc-18-1/

System Type	System	MASH Test No.	Impact Conditions			RESULTS										
						Structural Adequacy		Occupant Risk Metrics						Vehicle Stability		Overall Result
			Speed (mph)	Angle (deg)	CIP ft	Contain	Max. Disp. (in)	OCI Location	OCI (in)	OIV_x (ft/s)	OIV_y (ft/s)	ORA_x (g)	ORA_y (g)	Roll (deg)	Pitch (deg)	
Bridge Rail	NETC 2-Bar	Test 3-10	62	25	3.6	Pass	3.6	Wheel Well/ Toe Pan	3.3	26.2	33.1	5.5[(1)]	6.4	7	5.4	Pass
		Test 3-11	62	25	4.3	Pass	2.7	Wheel Well/ Toe Pan	2.8	20.7	26.9	4.6	15.4[(2)]	9	10.1	Pass
	NETC 3-Bar	Test 4-10	62	25	3.6	Pass	3.4	Wheel Well/ Toe Pan	2.8	25.6	32.5	6.7[(1)]	6	7.3	5.2	Pass
		Test 4-11	62	25	4.3	Pass	4.2	Wheel Well/ Toe Pan	3.3	22	26.6	4.7	15.4[(2)]	9.9	7.5	Pass
		Test 4-12[(3)]	56	15	5	Pass	7.6	Wheel Well/ Toe Pan	1	2	14.8	7	5.3	20.8	7.8	Pass
		Test 4-12[(4)]	56	15	5	Pass	8.1	Wheel Well / lower edge of door	3.3	3	14.1	5.7	5.9	90*	6.9	Pass
	Mod 3-Bar[†]	Test 4-10	62	25	3.6	Pass	2.3	-	-	24.3	32.5	3.5[(1)]	7.7	-	-	Pass
	NETC 4-Bar	Test 4-10	62	25	3.6	Pass	2.8	Wheel Well/ Toe Pan	3.4	24	31.5	7.1[(1)]	10.3	10.9	6.5	Pass
		Test 4-11	62	25	4.3	Pass	5.4	Wheel Well/ Toe Pan	2.2	17.7	26.6	13.8	18[(2)]	7.2	8.3	Pass
		Test 4-12[(3)]	56	15	5	Pass	8.2	Wheel Well/ Toe Pan	1	3.9	16.7	4.3	6.7	18.8	5.6	Pass
	Mod 4-Bar[‡]	Test 4-12[(3)]	56	15	5	Pass	8.2	Not Evaluated	1	3.9	16.7	4.3	6.7	18.8	5.6	Pass
AGT	2-Bar (Tube Rails)	Test 3-20	62	25	6.5	Pass	6.3	Wheel weel / Toe Pan	1.4	25.3	28.2	7.9[(1)]	4.8	6.7	3.6	Pass
		Test 3-21	62	25	9	Pass	11.8	negligible	-	17.4	23.3	4.8	17.2[(2)]	9.3	5.5	Pass
	3-Bar (Tube Rails)	Test 4-20	62	25	5.5	Pass	5.8	Wheel Well/ Toe Pan	1	24.3	25.9	4.2[(1)]	7.4	6.2	3.9	Pass
		Test 4-21	62	25	5.5	Pass	8	negligible	-	17.7	24.6	5.2	15.1[(2)]	8.1	3.7	Pass
		Test 4-22	56	15	9	Pass	7.6	Wheel Well/ Toe Pan	1	2.3	14.8	8.9	5.5	90*	11.9	Pass**
	4-Bar (Concrete Butress)	Test 4-20	62	25	5.5	Pass	6.9	Wheel Well/ Toe Pan	3.4	29.2	32.8	26	7.9[(2)]	5.4	6.8	Fail
		Test 4-21	62	25	6.5	Pass	8.3	Wheel Well/ Toe Pan	1	21	28.2	9.4	17.3	15.4	9.6	Pass
		Test 4-22	56	15	12	Pass	17.0	Wheel Well/ Toe Pan	5.5	8.9	14.4	13.9	8.7	8.7	12	Pass***
	3-Bar (Tube Rails) w/ 5.5-ft Post Space	Test 4-20[§]	62	25	4	Pass	3.25	-	-	25.3	33.1	4.9	2.9[(2)]	-	-	Pass
		Test 4-20[§§]	62	25	4	Pass	2.65	-	-	23.6	32.8	3.7	7.9[(2)]	4.4	5.1	Pass
		Test 4-21[§]	62	25	6	Pass	-	-	-	22.6	27.9	5.8	≈18-19	-	-	Pass
		Test 4-22[Ł]	56	15	9	Pass	5.4	-	-	-	-	-	-	-	-	Pass**

** The vehicle was still upright when the analysis was terminated, but 90-degree roll was expected.*

*** Resulted in significant snagging on and damage to bridge rail posts.*

**** The analysis showed that the barrier contained and redirected the 10,000S vehicle, but with significant damage to the transition and bridge rail elements.*

(1) Maximum ORA occurred on tail-end of a major acceleration pulse. Would have been higher if OIV had occured slightly sooner.

(2) Vehicle model tends to over-predict lateral accelerations associated with "tail-slap".

(3) Cargo-box Bed Height = 47.5 ".

(4) Cargo-box Bed Height = 50 ".

† NETC 3-bar with HSS 5x4x5/16 lower rail

‡ NETC 4-bar with W8x28 posts

§ 3-bar AGT with original components

§§ 3-bar AGT with HSS5x4x5/16 lower rail

Ł 3-bar AGT with 2-inch splice gap and top of posts tapered

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- Project Manager – **Kirsten Seeber**, CTC & Associates
- Chair – **Jeff Folsom**, Maine DOT
- **Dale Peabody**, Maine DOT
- **David Kilpatrick**, Connecticut DOT
- **Alex Bardow**, Massachusetts DOT
- **Robert Landry**, New Hampshire DOT
- **Michael Savella**, Rhode Island DOT
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