Development of MASH Computer Simulated Steel Bridge Rail and Transition Details

Task 4B: 3-Bar Transition w/ Wider Post Spacing MASH TL4

Project # : NETC 18-1
Federal Project No. : 2343018

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Task 4B – MASH TL4 Evaluation of NETC 3-Bar Transition with 5.5’ First-Post Spacing

The objective of this task was to use FEA simulations to determine if increasing the post-spacing for the first bridge rail post from 3’ to 5.5’ would adversely affect crash performance of the 3-Bar AGT for MASH TL-4.

It was expected that the increased spacing would reduce the strength of the railing and have the greatest effect on performance for Tests 4-22 (i.e., SUT vehicle) and 4-20 (i.e., small car).

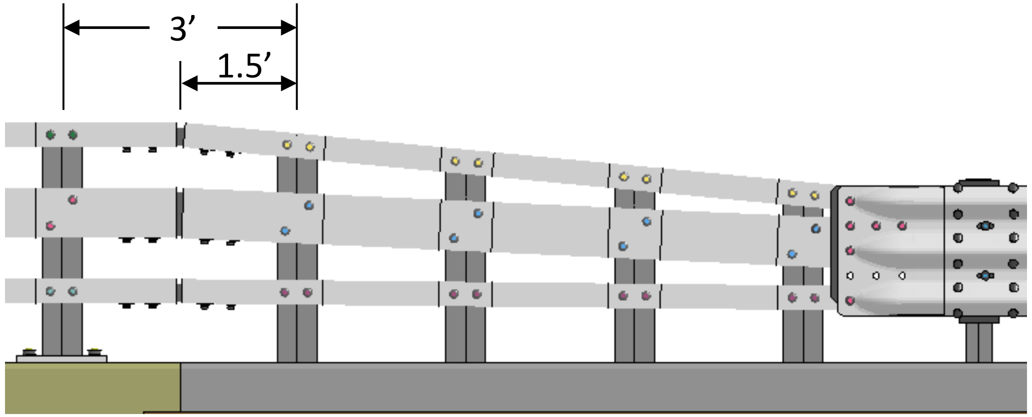
- Test 4-22 subjects the barrier to the greatest loading conditions overall,
- Test 4-20 tends to impart a concentrated load onto the lower railing, which can result in excessive pocketing at the approach to the first bridge rail post (as described in Task 3B).

The evaluation of the baseline NETC 3-Bar transition was performed in Task 4.

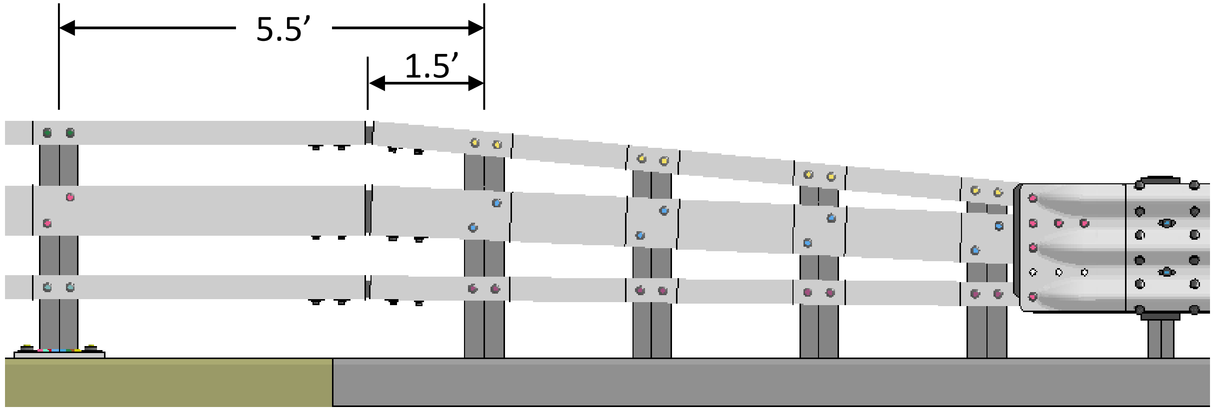
- The original design met MASH TL-4 performance criteria based on the FEA crash simulations.
- The only recommended design change was to taper the tops of the transition posts and bridge rail posts down and toward the field side to avoid contact with the front-lower edge and bottom of the cargo-box during impacts with single unit trucks.

Design Modification(s) and Research Approach

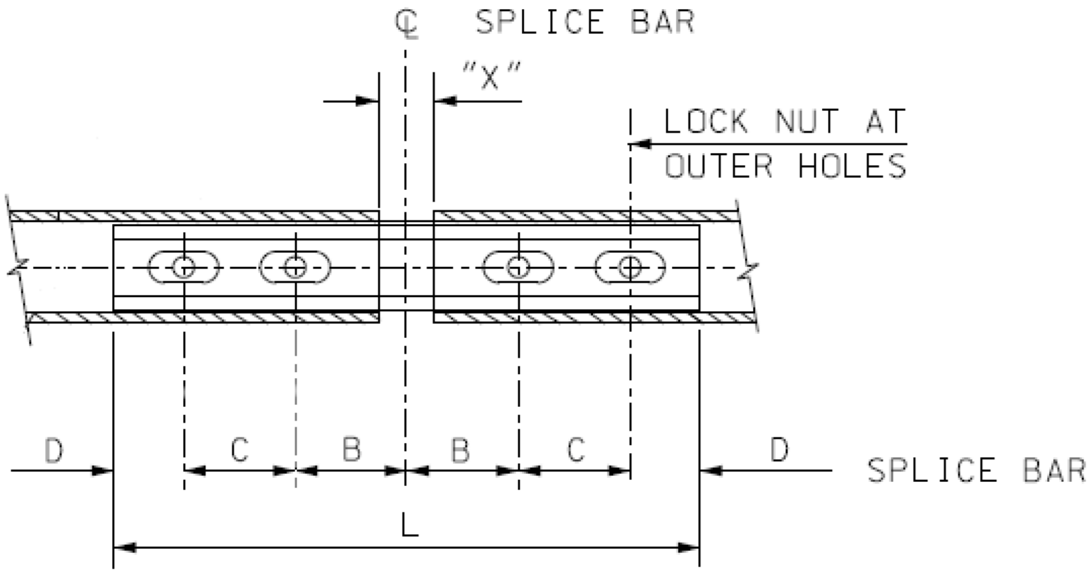
- The evaluations included a **5.5-ft post spacing** with the **splice positioned 1.5-ft** from the approach rail post.
- MASH Test 4-22 was evaluated first, followed by Tests 4-20 and 4-21, each contingent on successful or unsuccessful performance of the previous case.
- The evaluations involved the following modifications to the model:
    - Extending the bridge rail to attain desired post spacing,
    - Tapering the tops of the posts
    - Widening the expansion splice gap from 0.75” to 2”.



(a) Original Design



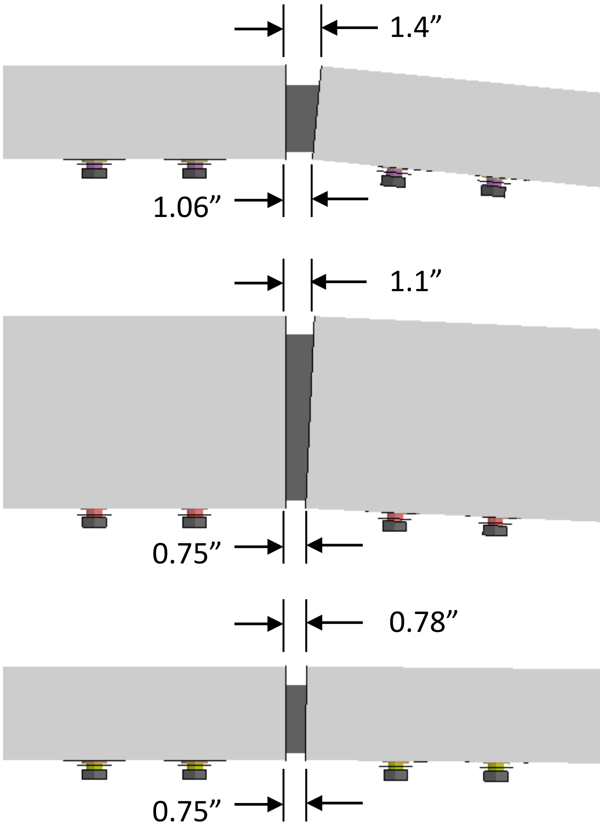
(b) Increased Post Spacing



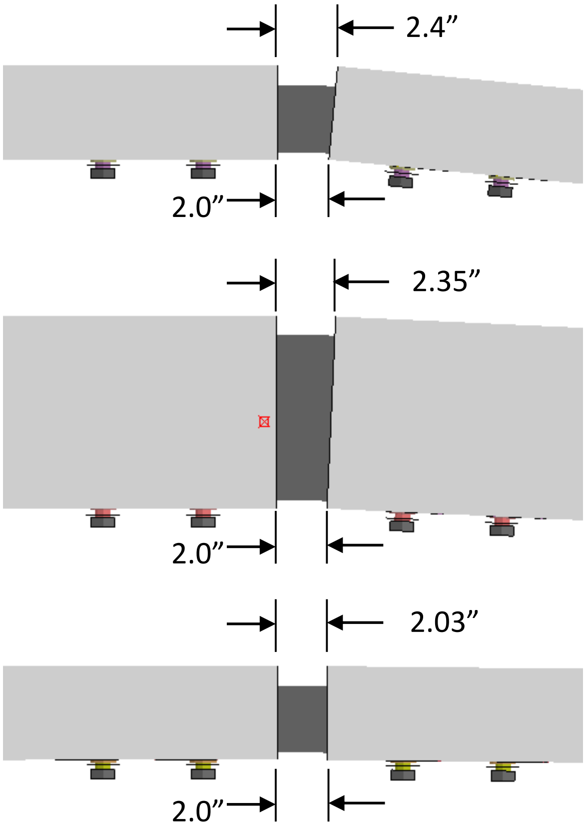
SPLICE BAR DIMENSION TABLE							
	T	A	B	C	D	X	L
	INTERIOR	2 1/2"	4"	4"	2"	3/4"	1'–8"
*	<3 1/4"	2 1/2"	4"	4"	2"	2"	1'–8"
*	3 1/4" TO 5 1/4"	3 1/2"	5"	5"	2 1/2"	3"	2'–1"

T = TOTAL MOVEMENT OF BRIDGE
* = END SPLICE BAR

Expansion Splice Model01



Expansion Splice Model02



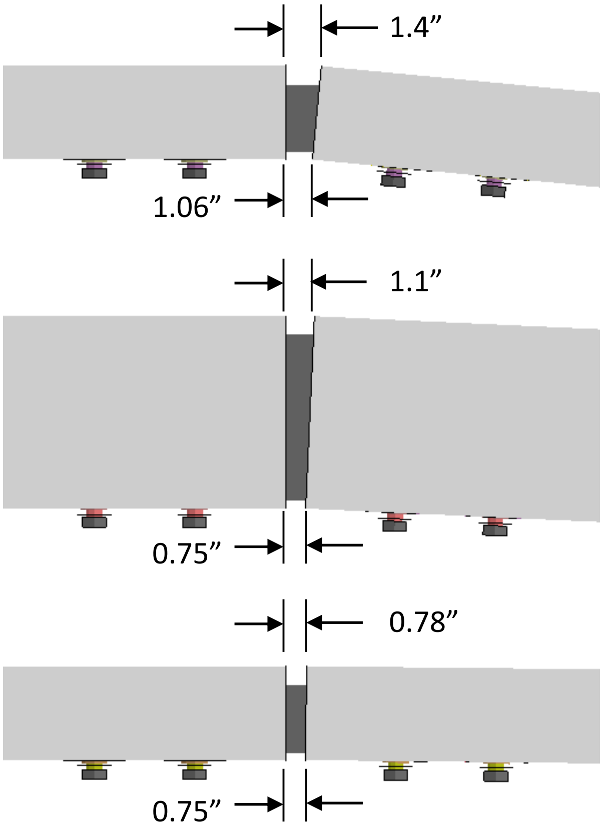
Expansion Splice

Two expansion splice models were evaluated

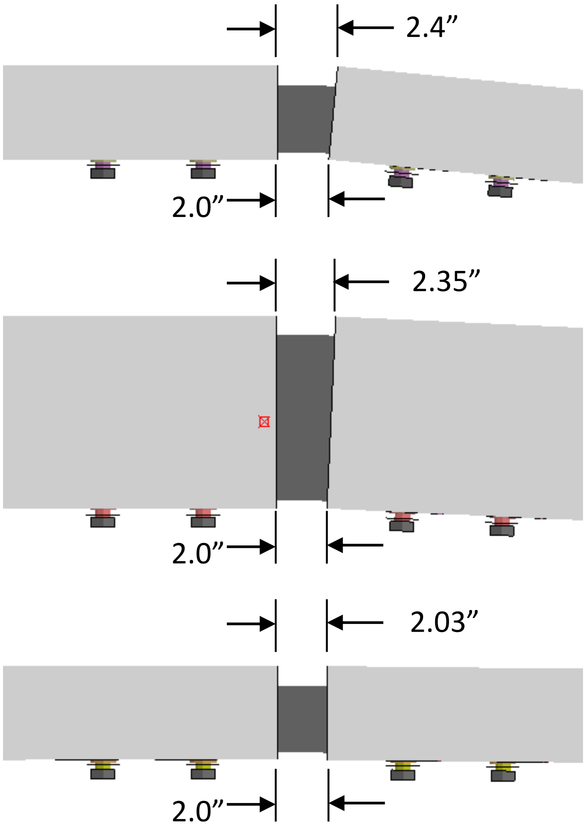
1) Model01:
   - Expansion gap = 0.75” (nominal)
   - Test 4-22 only - to be consistent with previous evaluation on original design
2) Model02:
   - Expansion gap = 2.0” (nominal)
   - Test 4-20 and 4-21 to maximize snagging hazard for passenger vehicles

Note:
Because the splice is located on the downstream side of the transition post, snag on the splice is not expected to be an issue unless reverse direction impacts are considered.

Expansion Splice Model01



Expansion Splice Model02



Expansion Splice

TTI Test 404531-7

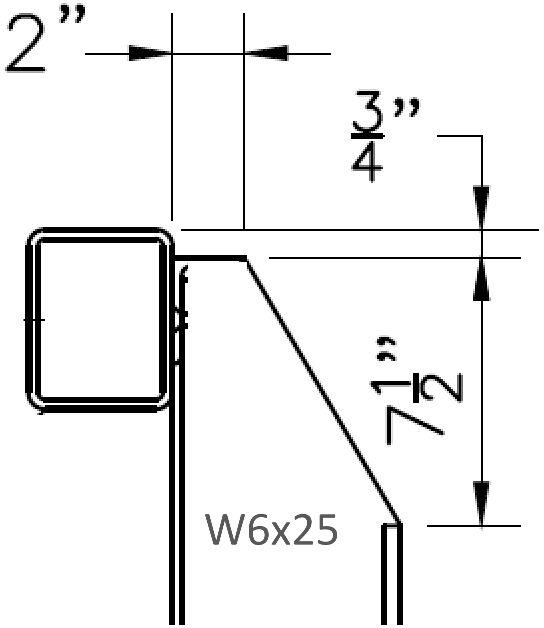
Expansion Splice Gap and Crash Performance

- Based on the results of an earlier study by the research team and previous full-scale testing on a **<u>3¾-inch wide splice gap</u>** it was shown that the vehicle was likely to snag on the ends of the rail tubes at the expansion splice and result in significant deceleration forces.[*Plaxico16; Buth99*]

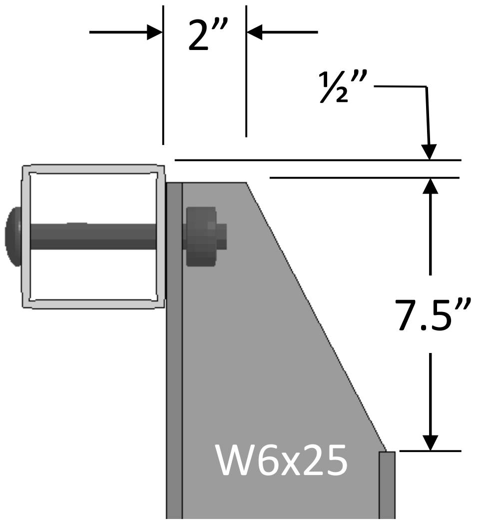
Buth, C.E., W.L. Menges, and W.F. Williams, "Testing and Evaluation of the New York Two-Rail Curbless and Four-Rail Curbless Bridge Railing and the Box-Beam Transition," Report No. 404531-F, for the Federal Highway Administration, Performed by the Texas Transportation Institute, College Station, TX (1999).

Posts

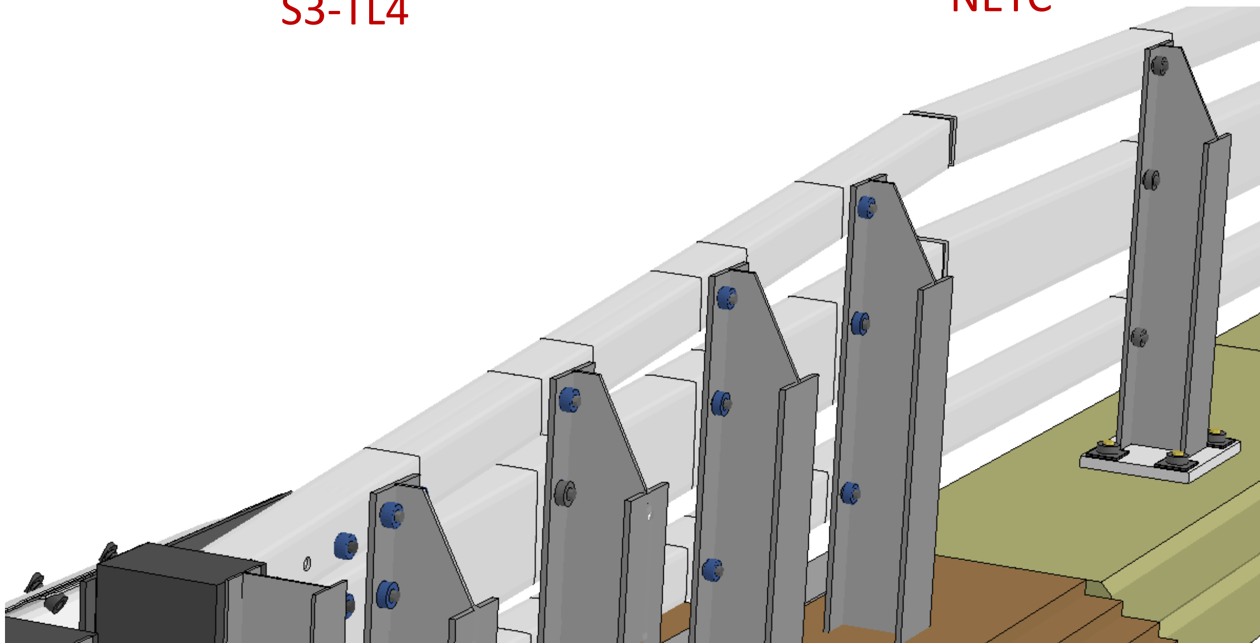
- Two post designs were evaluated:
  - No taper (Original)
  - Tapered (Modified)
- The tapper design was adopted from the MassDOT S3-TL4 bridge rail, as illustrated here.



S3-TL4

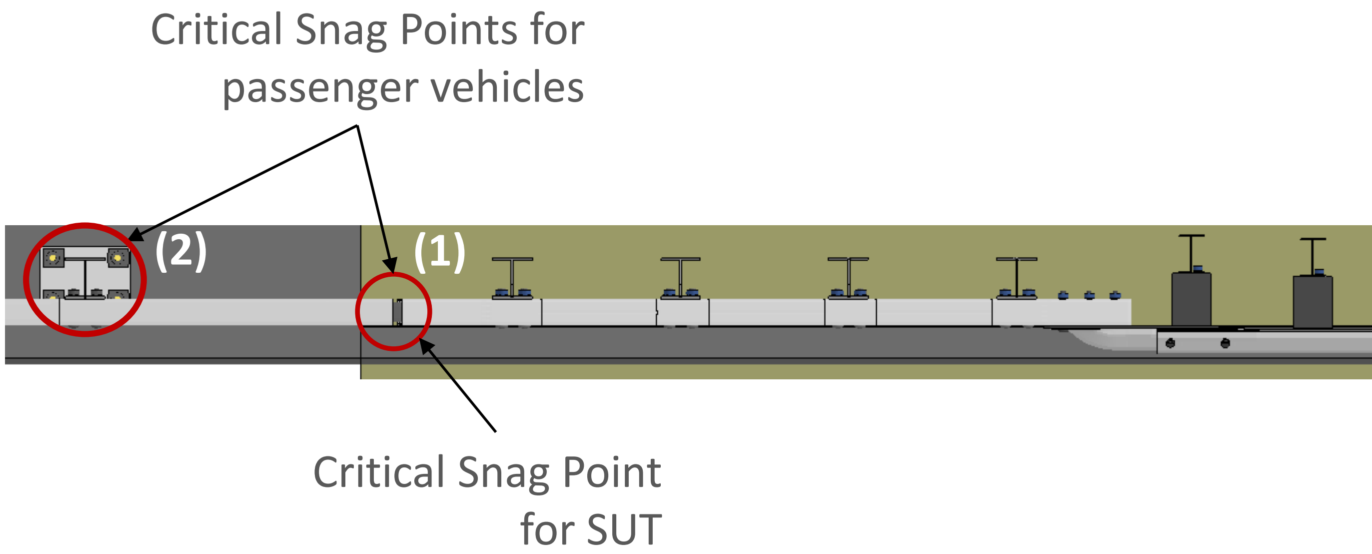


NETC



Determining Critical Impact Point

- Test 4-20 (small Car) and Test 4-21 (pickup):
  - (1) Maximize potential for <u>snag on splice joint</u> at end of bridge rail
  - (2) Maximize potential for <u>snag on first post</u> of bridge rail transition
- Test 4-22 (SUT):
  - (1) Maximize potential for <u>snag on end of bridge rail</u>



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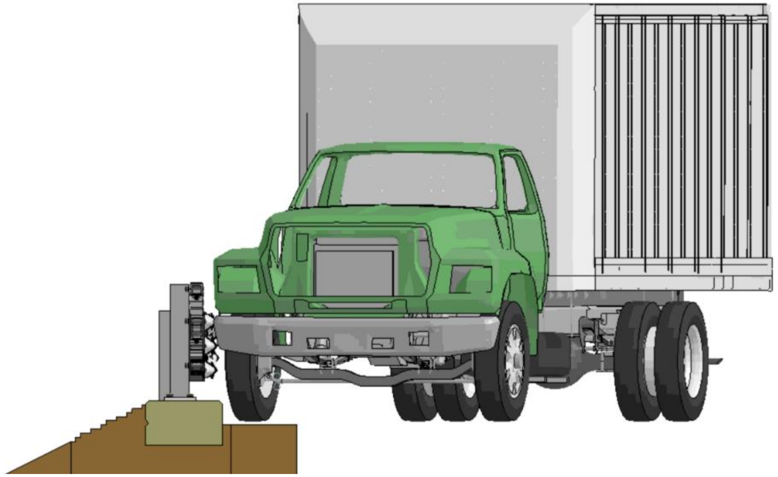
Evaluation Cases for Test 4-22



- CIP was adopted from earlier analysis of original design (see Task 4) with respect to maximizing potential for snag on the end of bridge rail at the spice connection.
- Analysis cases evaluated here:
  - **Splice Design 01 (3/4" expansion gap) w/ original non-tapered post**
    - **IP = 9.0 ft** – CIP for original design
  - **Splice Design 01 w/ tapered post**
    - **IP = 9.0 ft** – CIP for original design
  - **Splice Design 02 (2" expansion gap) w/ tapered post**
    - **IP = 9.0 ft** – CIP for original design

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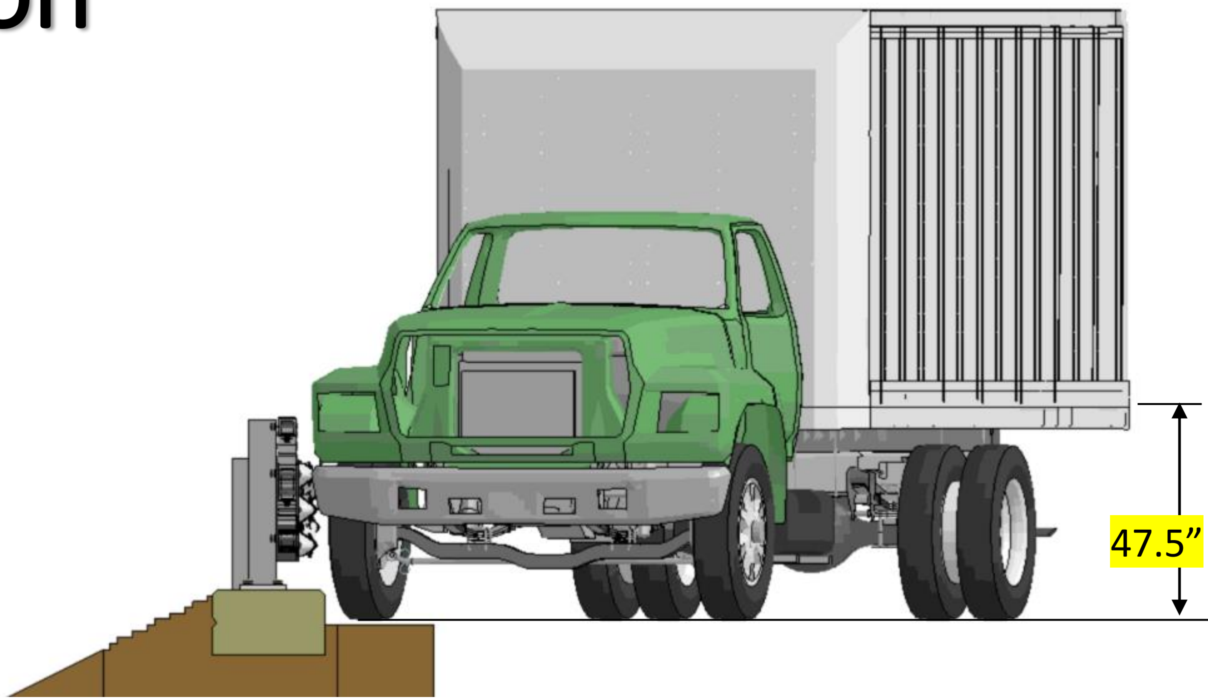
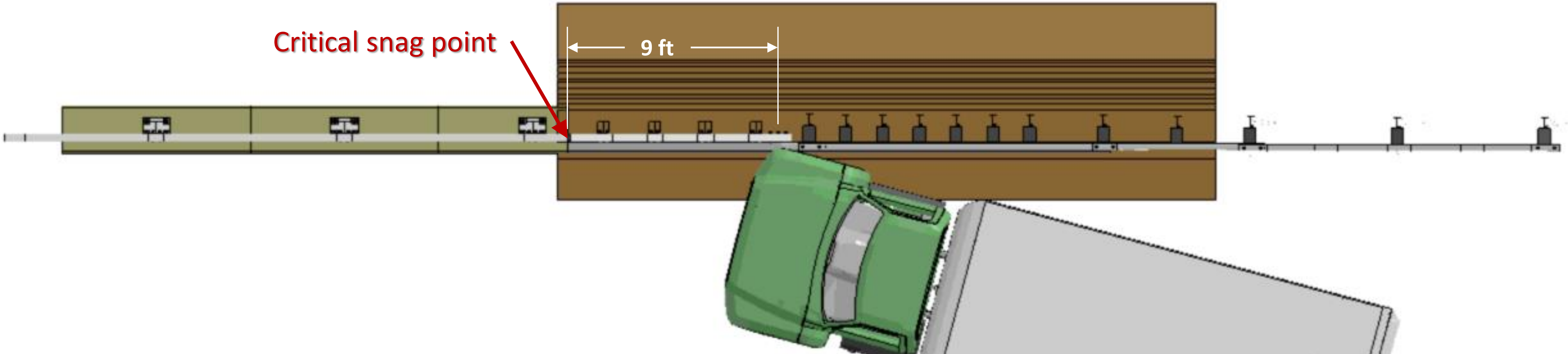
MASH Test 4-22 Simulation

- **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)

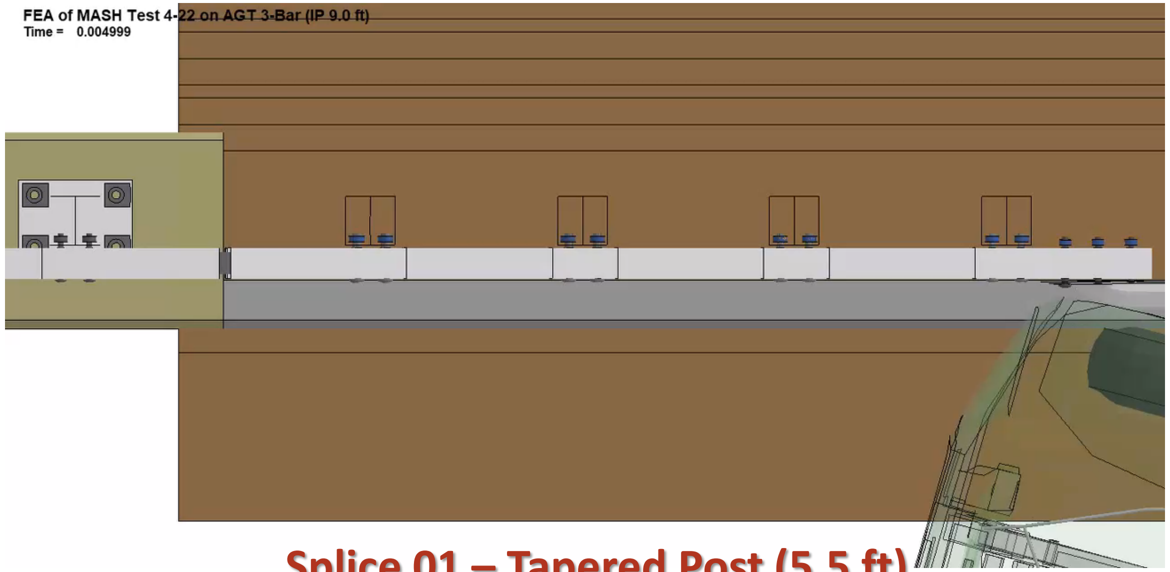
Ford 800 Surrogate



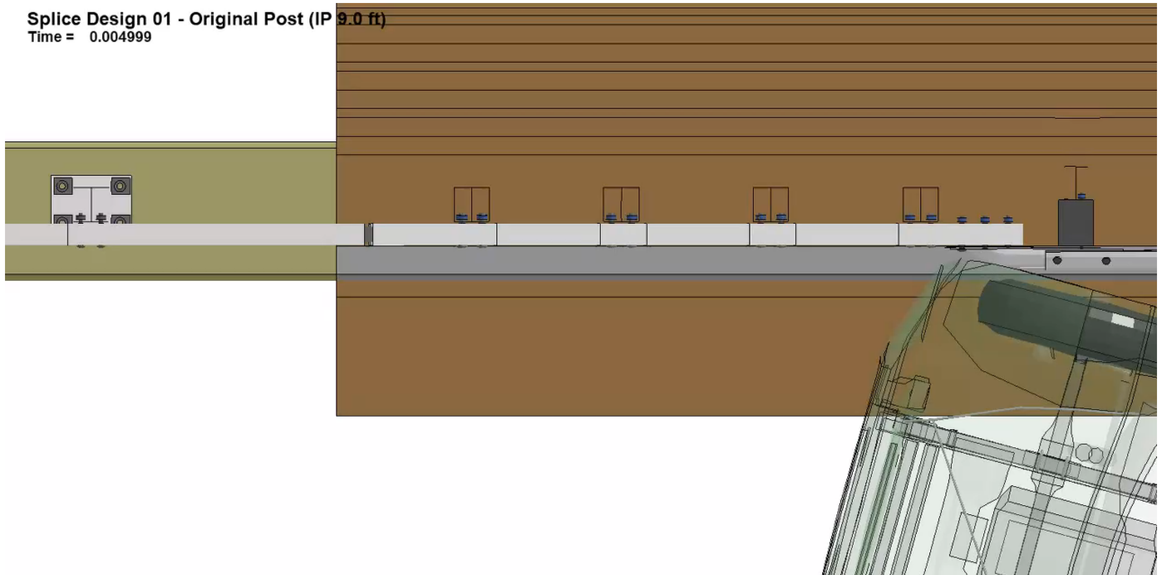


Test 4-22 Results

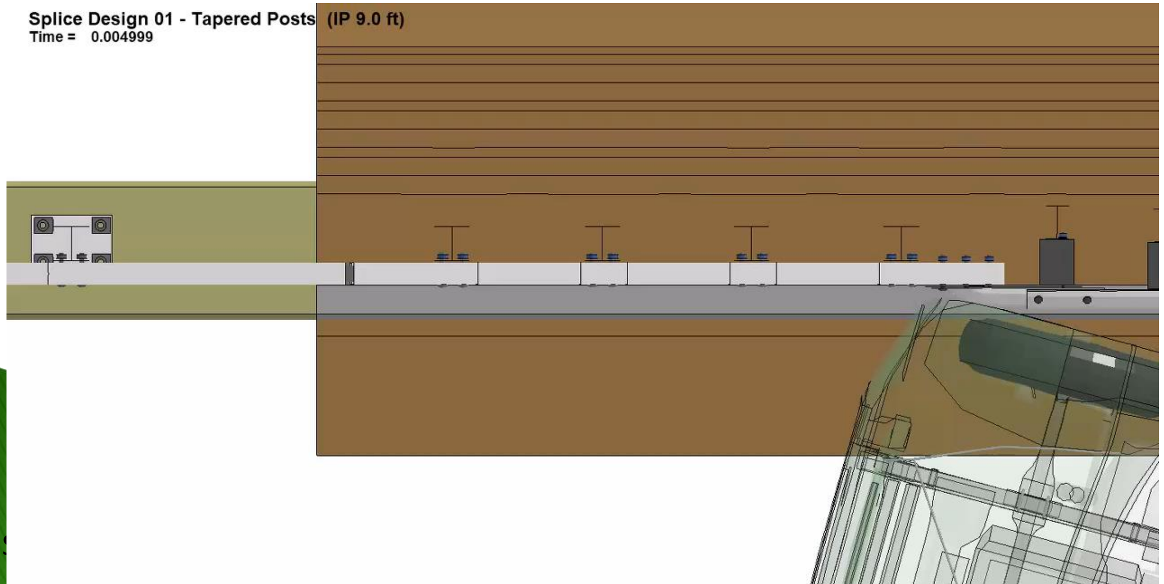
Baseline Original Design (3 ft)



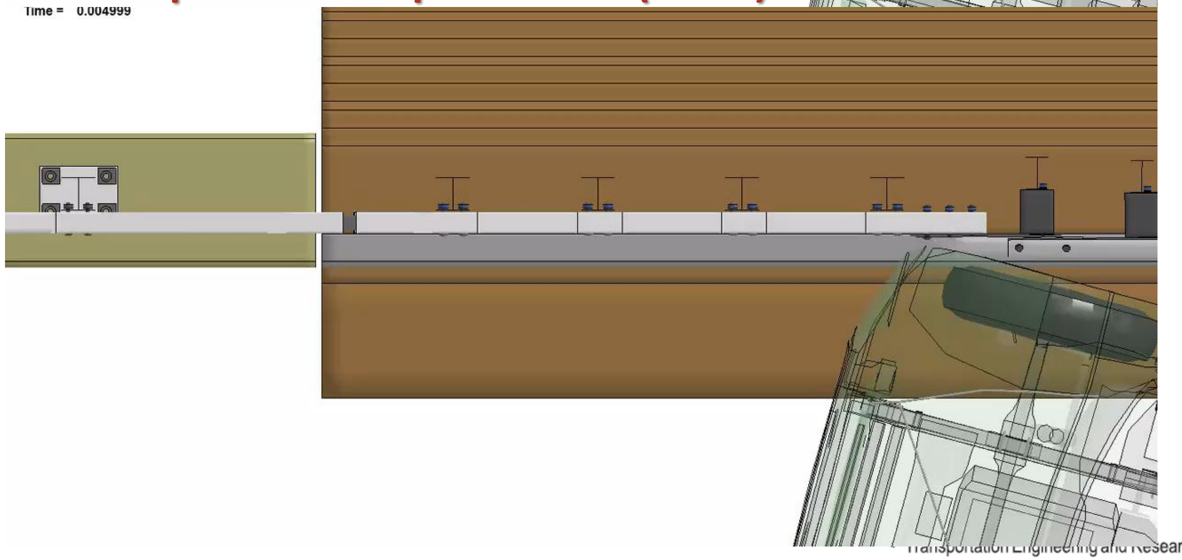
Splice 01 – Original Post (5.5 ft)



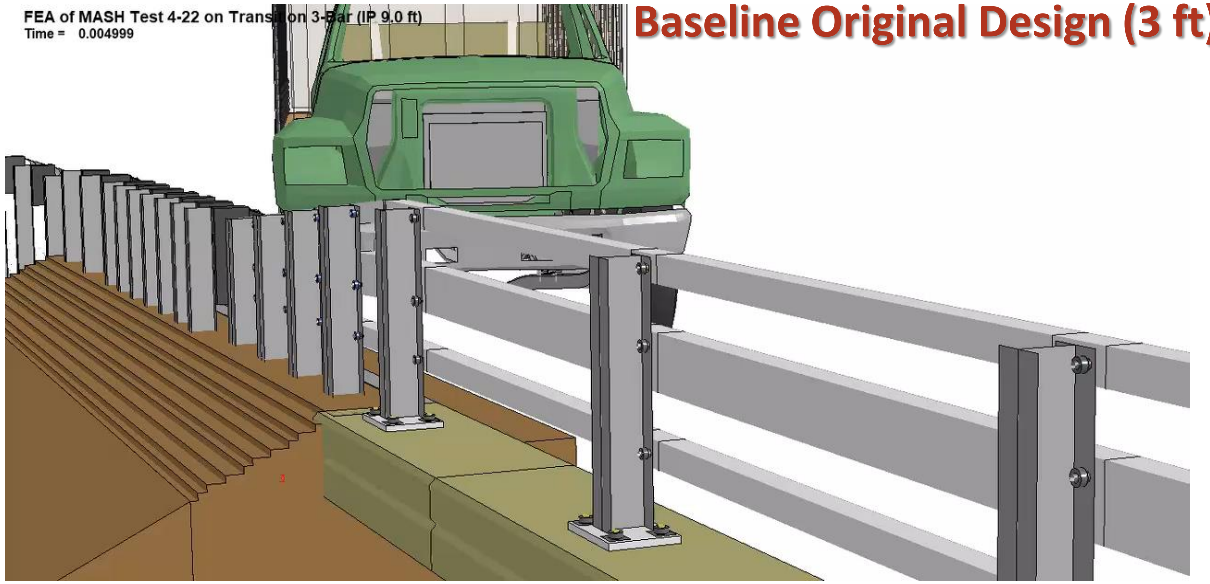
Splice 01 – Tapered Post (5.5 ft)



Splice 02 – Tapered Post (5.5 ft)



Test 4-22 Results



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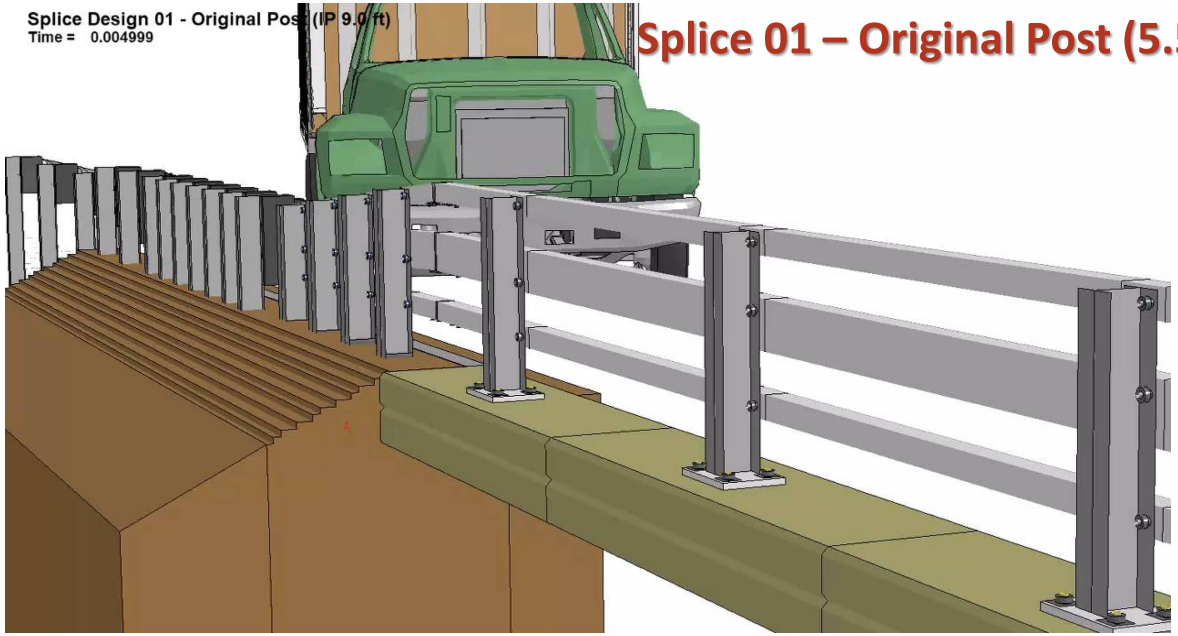

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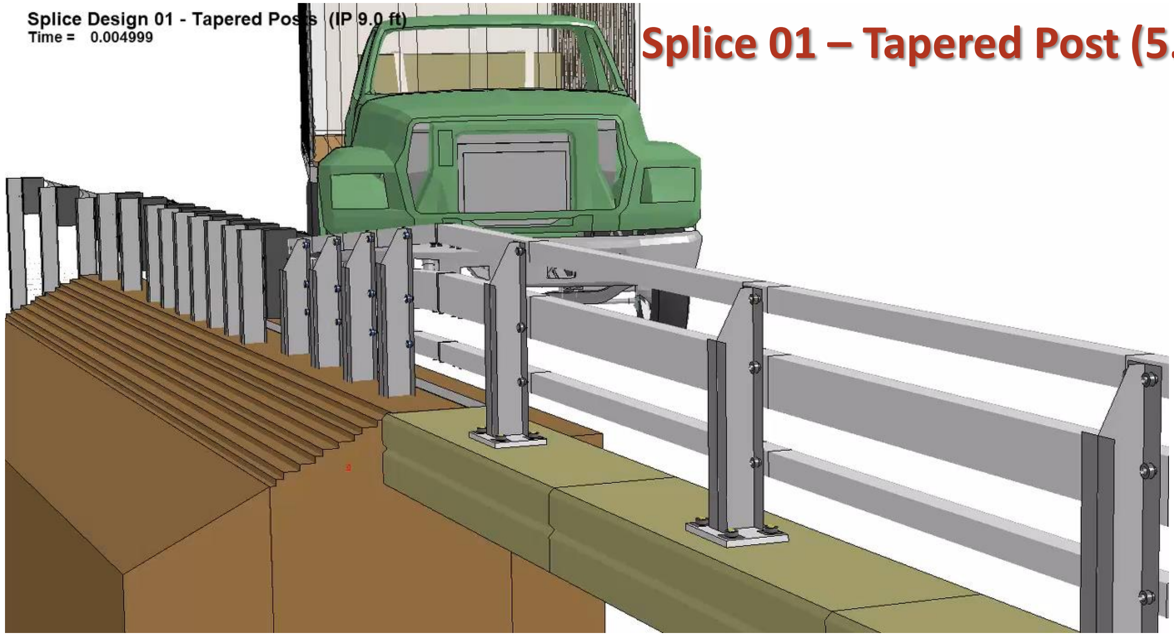

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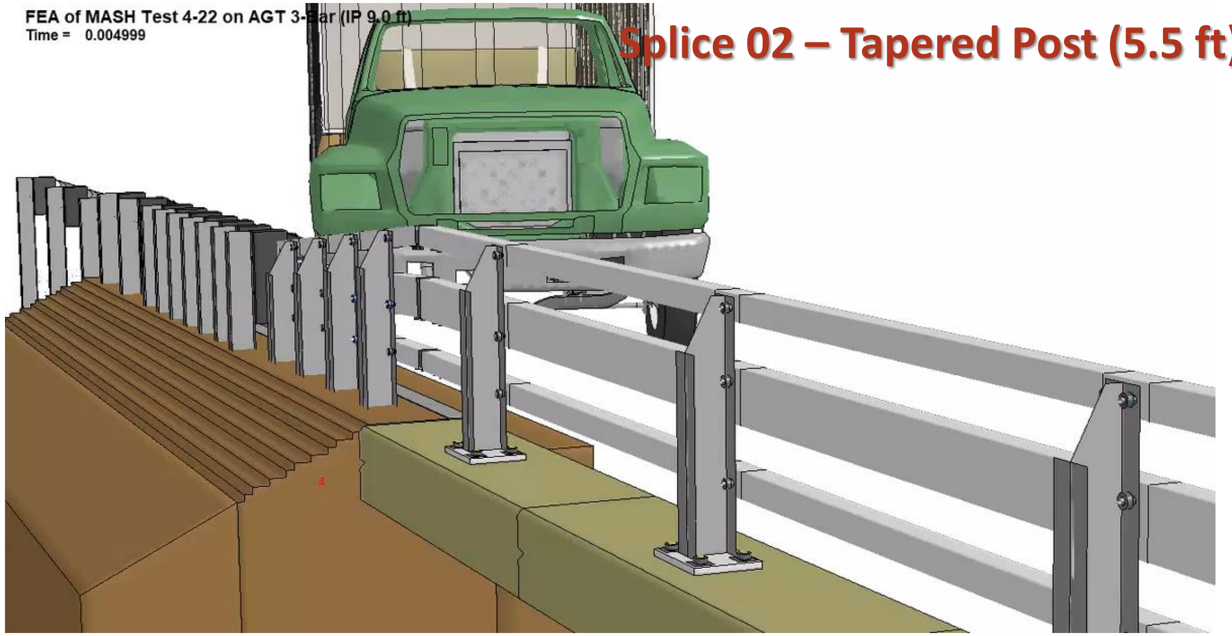

Splice 02 – Tapered Post (5.5 ft)

Test 4-22 Results

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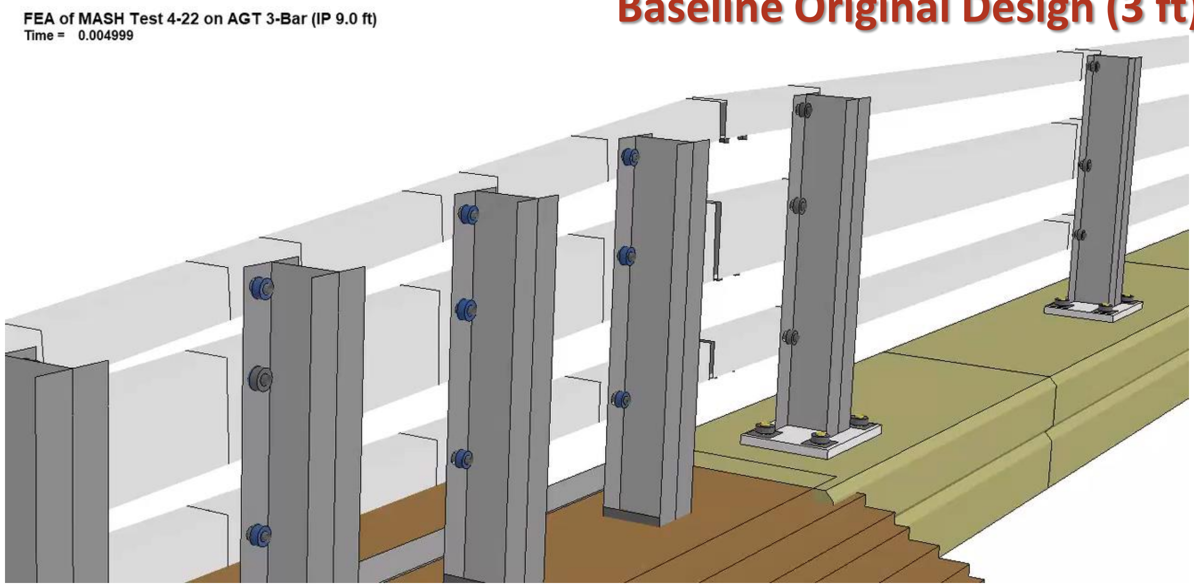

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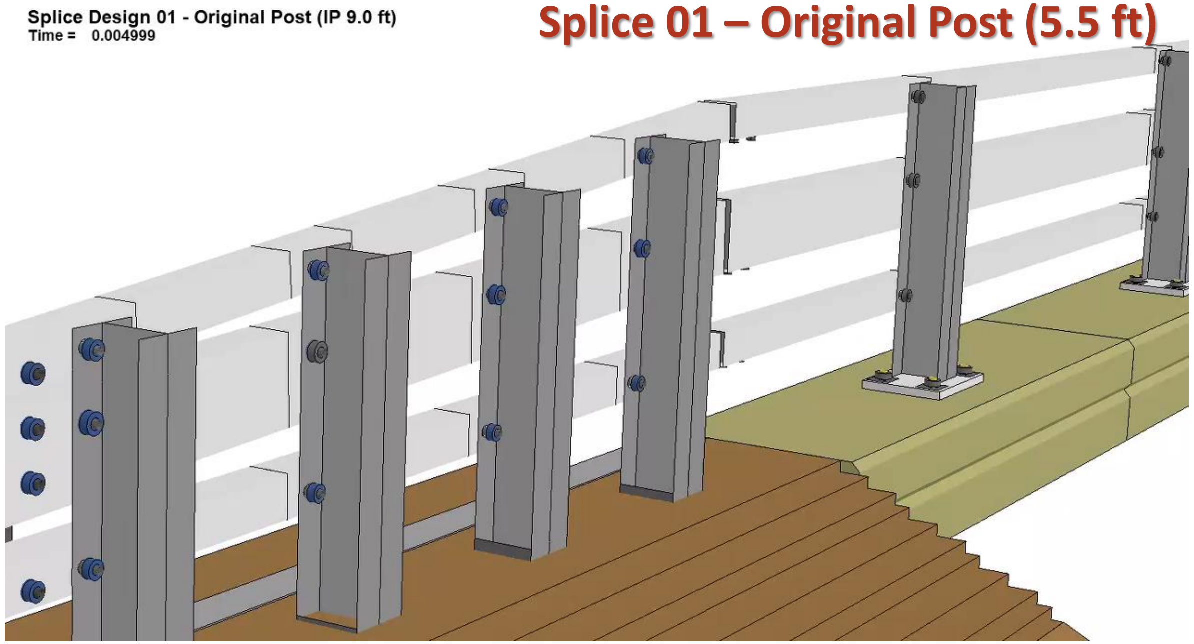

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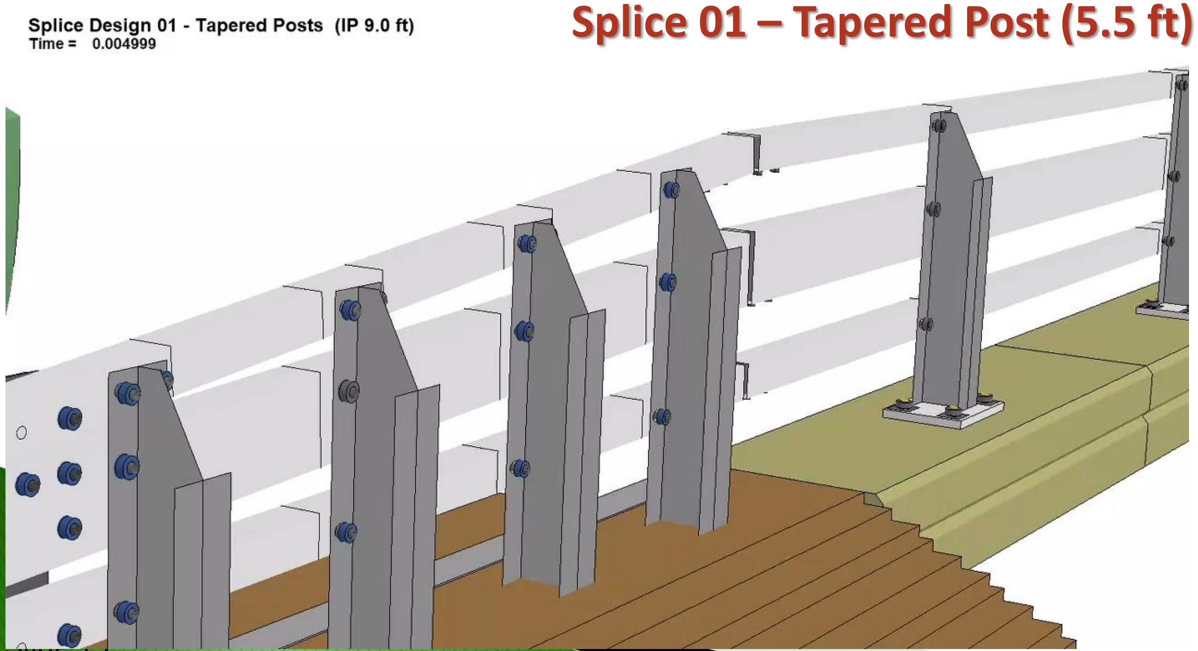

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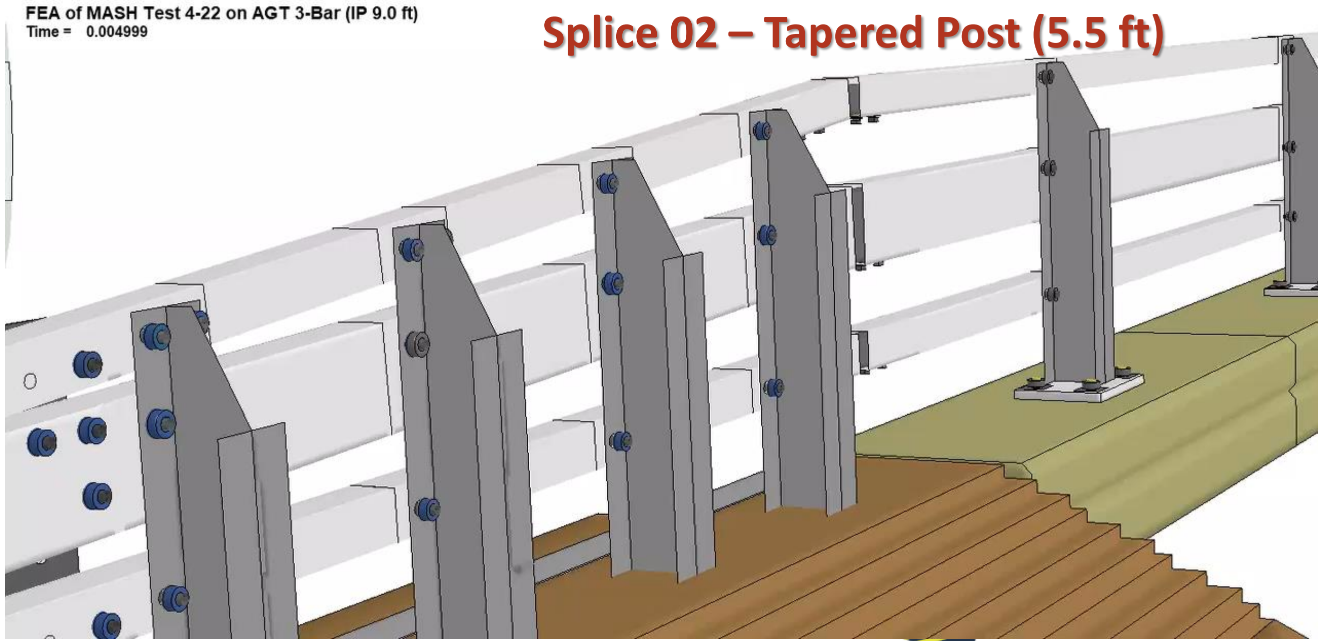

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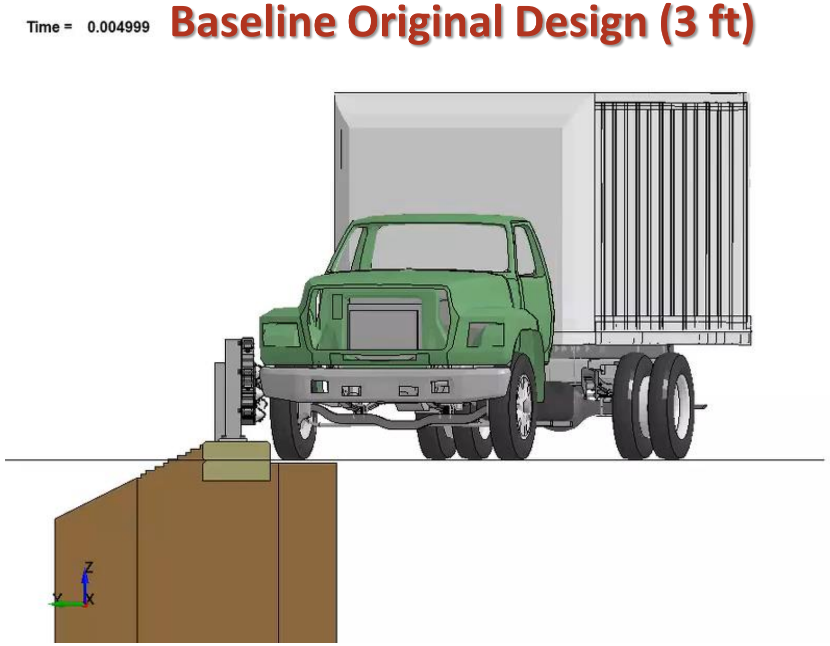

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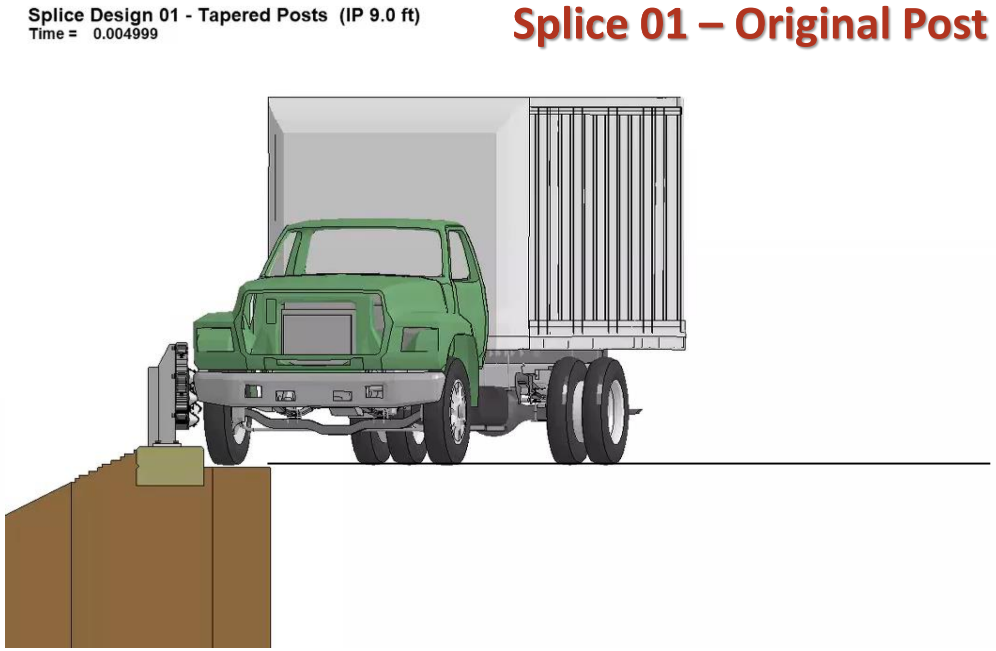

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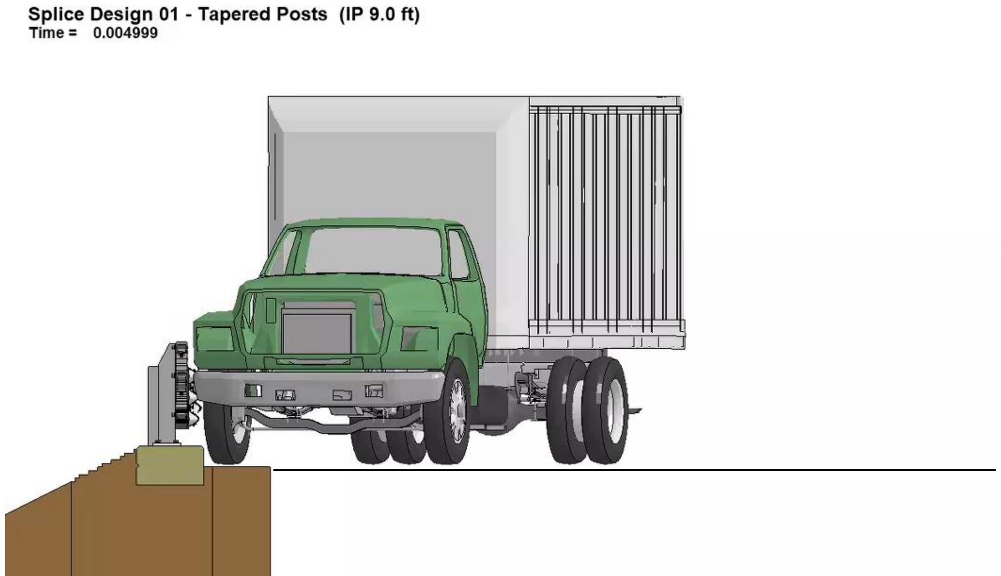

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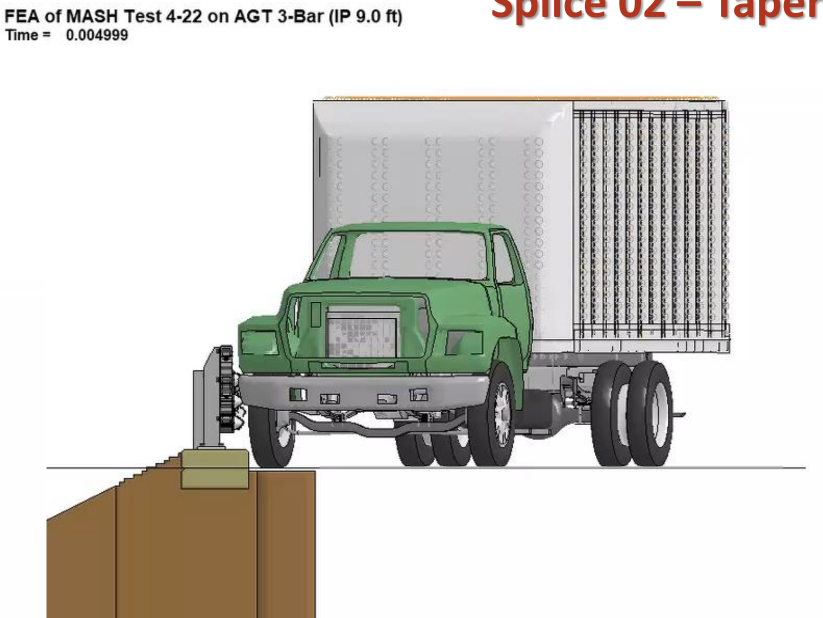

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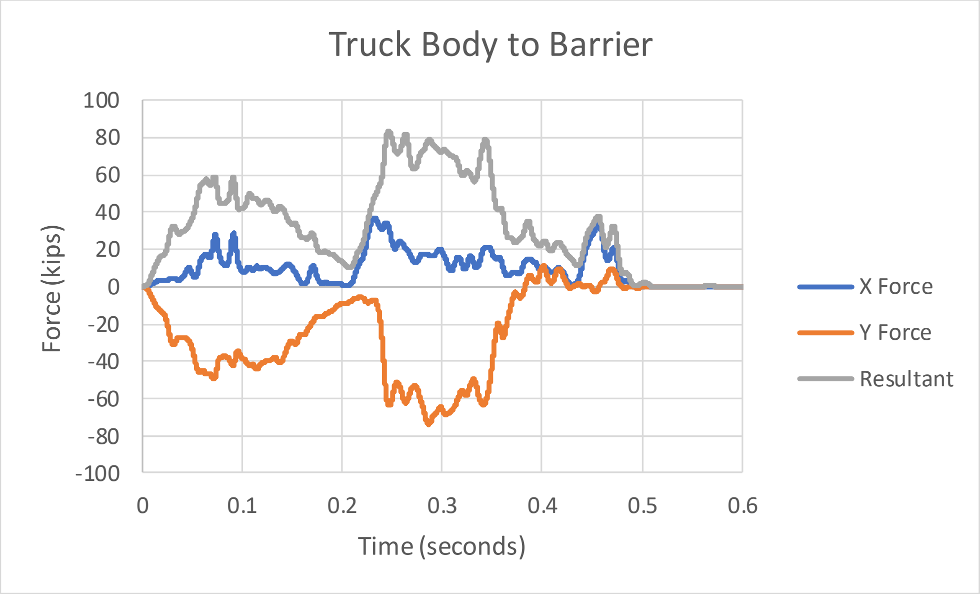

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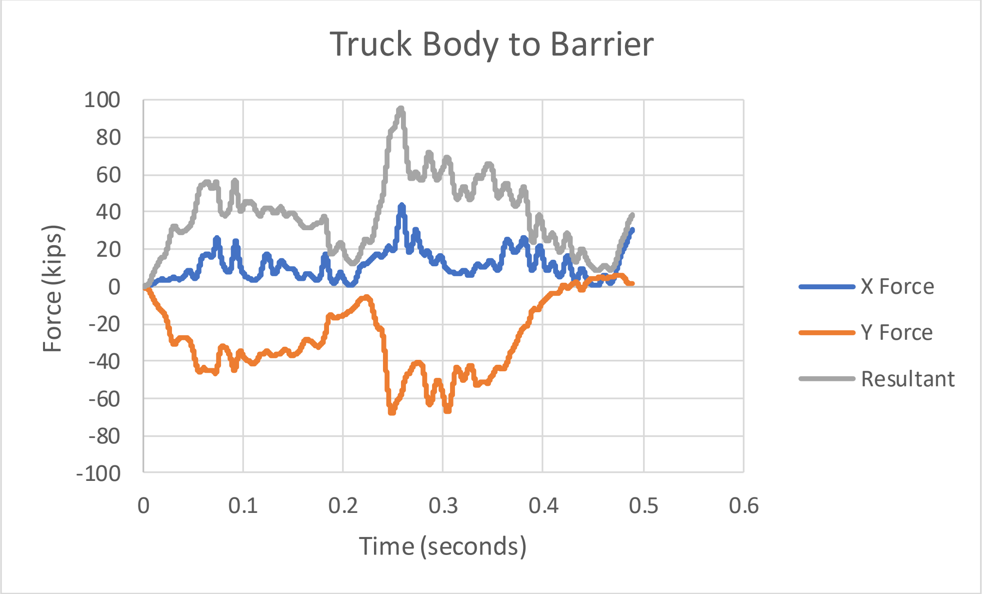

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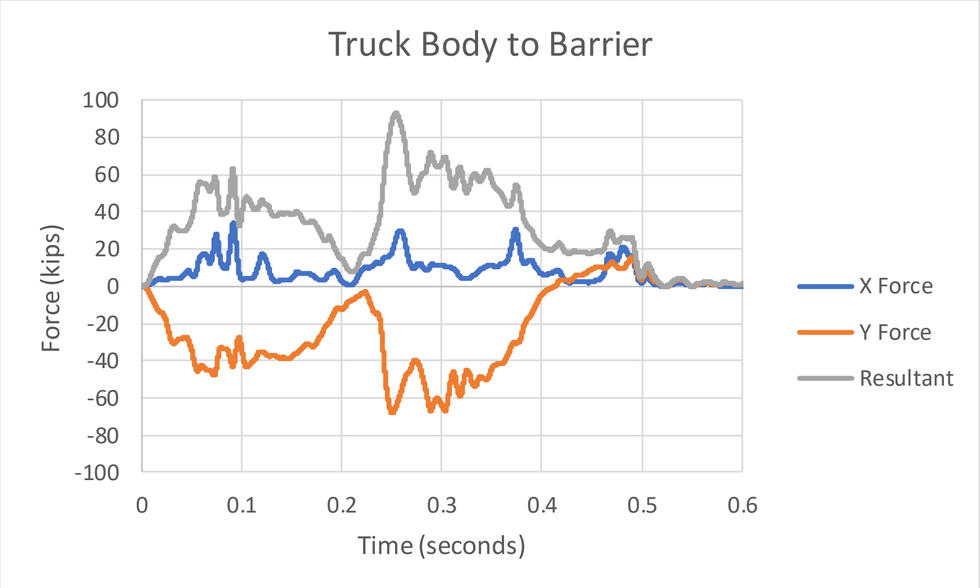
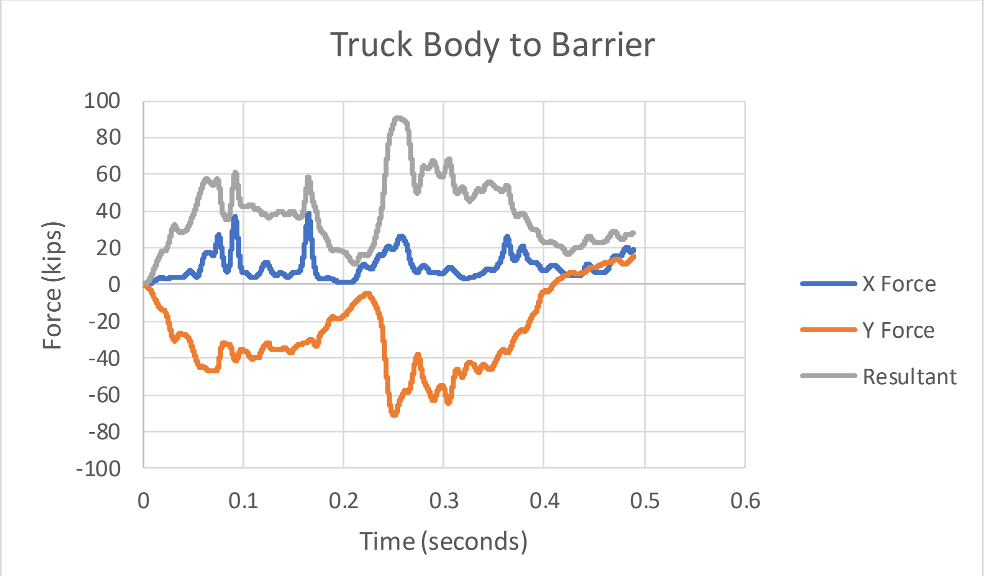
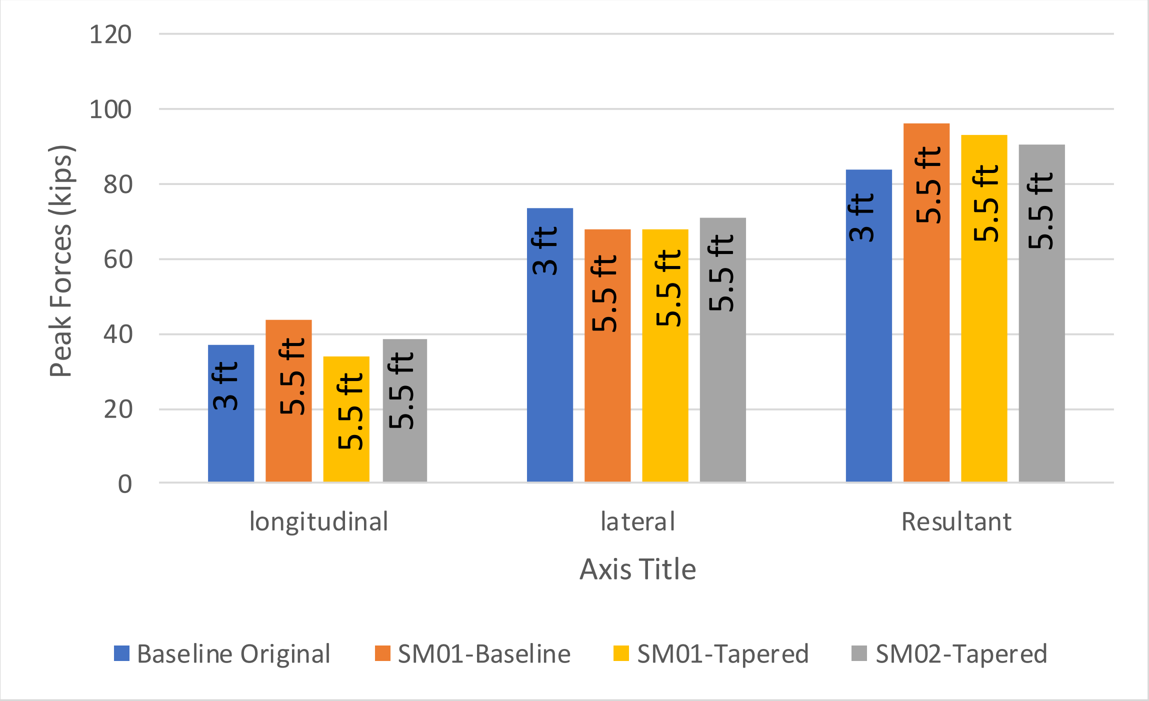


Splice 02 – Tapered Post



Summary of Peak Forces

	Peak Forces (kips)		
	longitudinal	lateral	Resultant
Baseline Original	36.9	73.6	84
SM01-Baseline	43.8	68.1	96.2
SM01-Tapered	34.1	67.9	93.2
SM02-Tapered	38.6	71.3	90.7



TRAP – Summary Table (cabin)

Occupant Risk Factors		MASH Baseline	MASH SM01-Baseline	MASH SM01-Tapper	MASH SM02-Tapper
Occupant Impact Velocity (ft/s)	x-direction	2.3	2.3	2.0	2.0
	y-direction	-14.8	-14.1	-14.1	-14.1
	at time	at 0.1553 seconds on left side of interior	at 0.1565 seconds on left side of interior	at 0.1571 seconds on left side of interior	at 0.1575 seconds on left side of interior
THIV (ft/s)		15.1 at 0.1553 seconds on left side of interior	14.4 at 0.1565 seconds on left side of interior	14.8 at 0.1571 seconds on left side of interior	14.4 at 0.1575 seconds on left side of interior
Ridedown Acceleration (g's)	x-direction	-8.9 (0.3536 - 0.3636 seconds)	-7.2 (0.4366 - 0.4466 seconds)	-6.2 (0.4959 - 0.5059 seconds)	-5.9 (0.2470 - 0.2570 seconds)
	y-direction	-5.5 (1.4779 - 1.4879 seconds)	4.7 (0.1632 - 0.1732 seconds)	6.1 (0.1708 - 0.1808 seconds)	5.5 (0.1820 - 0.1920 seconds)
PHD (g's)		9 (0.3536 - 0.3636 seconds)	7.3 (0.4366 - 0.4466 seconds)	6.4 (0.4959 - 0.5059 seconds)	7.1 (0.2473 - 0.2573 seconds)
ASI		0.69 (0.0757 - 0.1257 seconds)	0.66 (0.0689 - 0.1189 seconds)	0.68 (0.0693 - 0.1193 seconds)	0.67 (0.0710 - 0.1210 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-2.9 (0.1877 - 0.2377 seconds)	-2.3 (0.1883 - 0.2383 seconds)	-2.6 (0.3494 - 0.3994 seconds)	-2.6 (0.2095 - 0.2595 seconds)
	y-direction	5.9 (0.0750 - 0.1250 seconds)	5.6 (0.0761 - 0.1261 seconds)	5.6 (0.0713 - 0.1213 seconds)	5.7 (0.0716 - 0.1216 seconds)
	z-direction	-3.7 (0.0552 - 0.1052 seconds)	-3.5 (0.0561 - 0.1061 seconds)	-3.6 (0.0556 - 0.1056 seconds)	-3.5 (0.0558 - 0.1058 seconds)
Maximum Angular Disp. (deg)	Roll	-26.3 (0.7569 seconds)	-19.9 (0.5000 seconds)	-27.1 (0.7010 seconds)	-23.8 (0.5714 seconds)
	Pitch	-11.9 (0.8730 seconds)	4.8 (0.2857 seconds)	-9.8 (0.7033 seconds)	-6.3 (0.5714 seconds)
	Yaw	-35.3 (1.4987 seconds)	17.1 (0.3761 seconds)	17.2 (0.3639 seconds)	17.4 (0.3684 seconds)

MASH Criteria

Not Applicable

TRAP – Summary Table (c.g.)

MASH Criteria

Not Applicable

Occupant Risk Factors		MASH Baseline	MASH SM01-Baseline	MASH SM01-Taper	MASH SM02-Tapper
Occupant Impact Velocity (ft/s)	**x-direction**	4.9	4.9	4.6	4.59312
	y-direction	-11.2	-11.5	-11.5	-10.82664
	at time	at 0.2265 seconds on left side of interior	at 0.2244 seconds on left side of interior	at 0.2252 seconds on left side of interior	at 0.2250 seconds on left side of interior
THIV (ft/s)		11.8 at 0.2265 seconds on left side of interior	12.5 at 0.2244 seconds on left side of interior	12.8 at 0.2252 seconds on left side of interior	12.79512 at 0.2250 seconds on left side of interior
Ridedown Acceleration (g's)	**x-direction**	-6.5 (0.2667 - 0.2767 seconds)	-9.9 (0.2644 - 0.2744 seconds)	-5.4 (0.4855 - 0.4955 seconds)	-7.4 (0.2636 - 0.2736 seconds)
	y-direction	-10.9 (0.4046 - 0.4146 seconds)	-9.8 (0.4511 - 0.4611 seconds)	7.6 (0.3067 - 0.3167 seconds)	8.6 (0.3054 - 0.3154 seconds)
PHD (g's)		10.9 (0.4046 - 0.4146 seconds)	12.2 (0.2647 - 0.2747 seconds)	8.3 (0.2728 - 0.2828 seconds)	8.9 (0.2633 - 0.2733 seconds)
ASI		0.57 (0.1129 - 0.1629 seconds)	0.56 (0.1116 - 0.1616 seconds)	0.56 (0.1135 - 0.1635 seconds)	0.54 (0.1080 - 0.1580 seconds)
Max 50-ms moving avg. acc. (g's)	**x-direction**	-2.7 (0.2275 - 0.2775 seconds)	-3 (0.2241 - 0.2741 seconds)	-2.3 (0.2335 - 0.2835 seconds)	-2.6 (0.2238 - 0.2738 seconds)
	y-direction	5.1 (0.1128 - 0.1628 seconds)	5 (0.1115 - 0.1615 seconds)	5 (0.1134 - 0.1634 seconds)	4.8 (0.1079 - 0.1579 seconds)
	z-direction	-4.5 (1.2839 - 1.3339 seconds)	-3 (0.2388 - 0.2888 seconds)	-2.7 (0.2450 - 0.2950 seconds)	-2.3 (0.2457 - 0.2957 seconds)
Maximum Angular Disp. (deg)	**Roll**	-34 (0.8269 seconds)	-23.6 (0.5000 seconds)	-32.1 (0.7109 seconds)	-27.5 (0.5714 seconds)
	Pitch	-11.8 (0.8103 seconds)	-4.4 (0.5000 seconds)	-9.8 (0.7109 seconds)	-6.2 (0.5714 seconds)
	Yaw	-33.6 (1.4987 seconds)	17.6 (0.3517 seconds)	17.5 (0.3788 seconds)	17.5 (0.3764 seconds)

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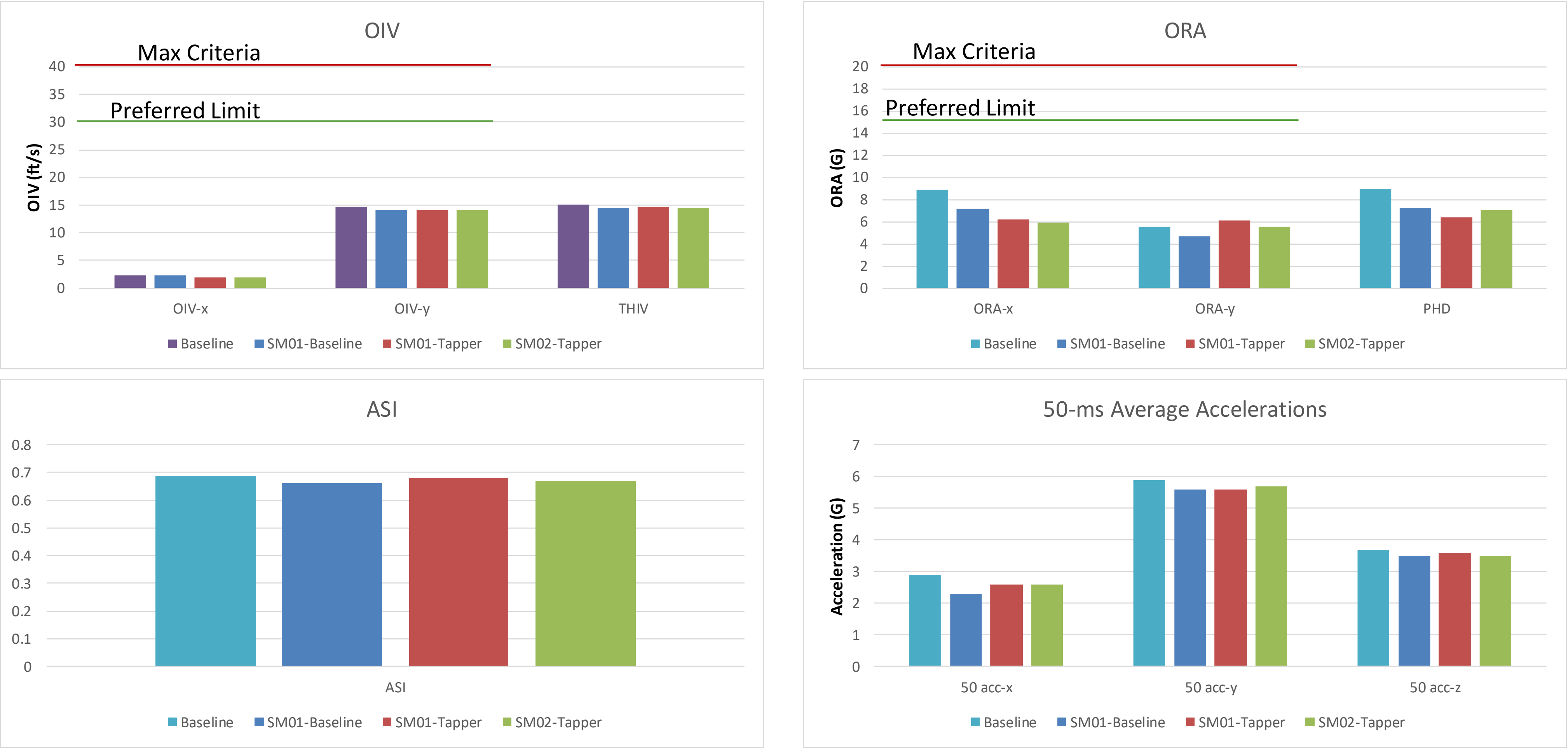
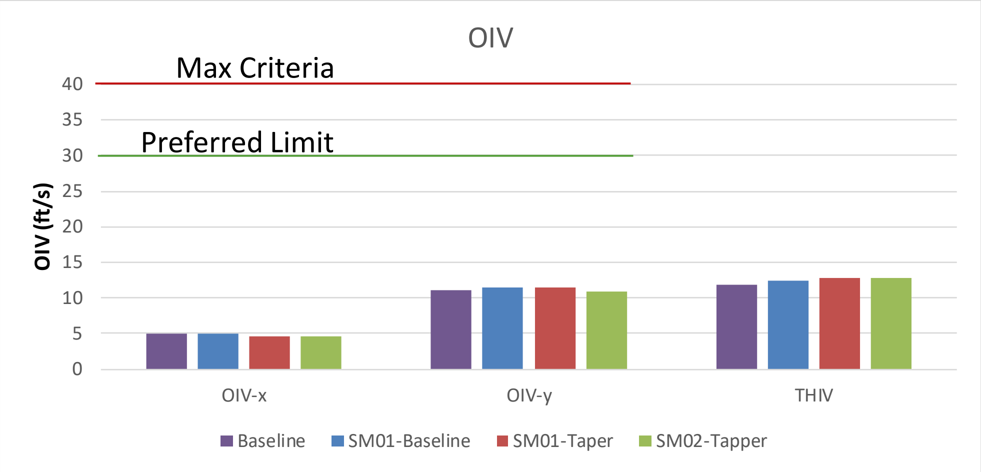
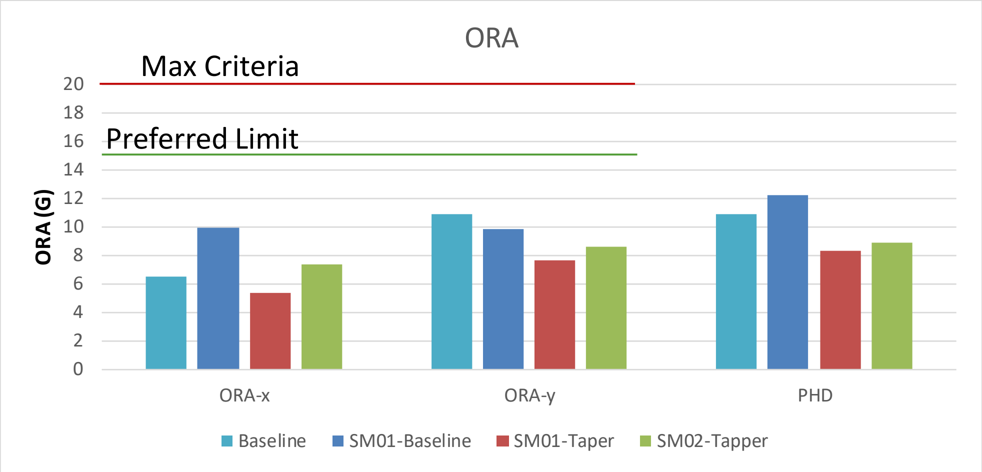
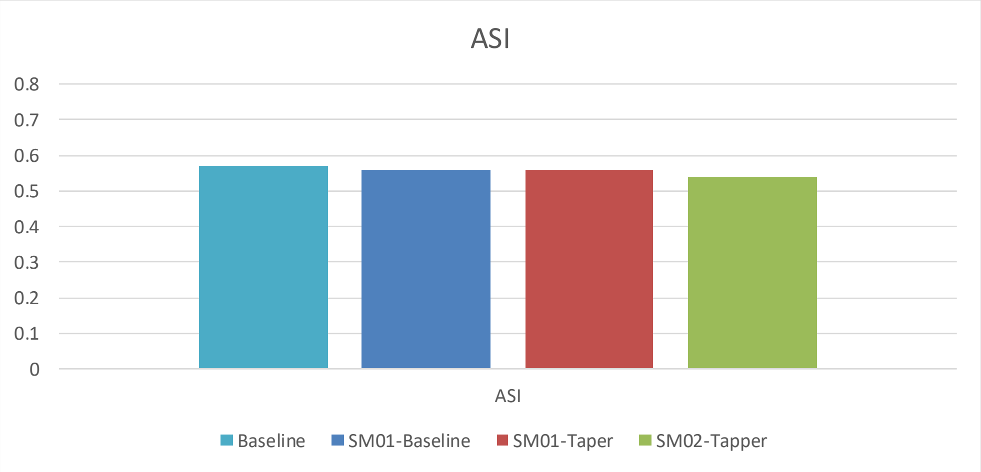
TRAP – Summary Plots (cabin)

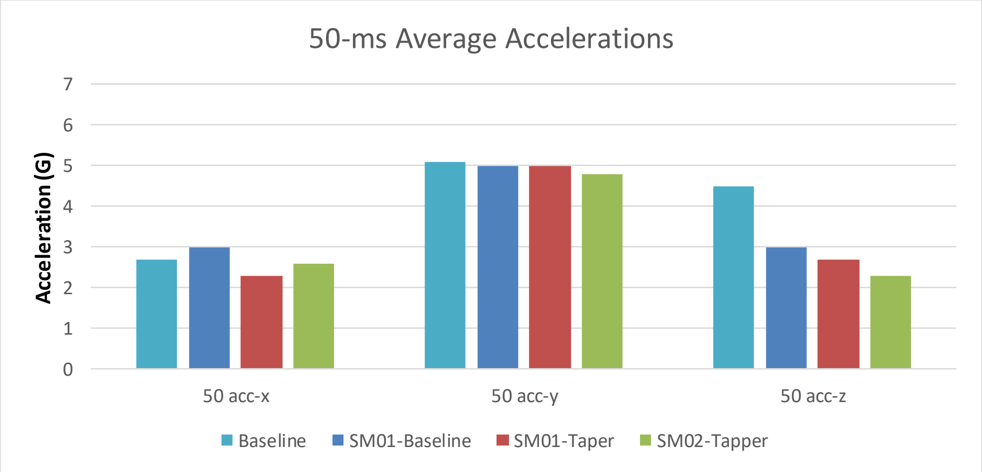


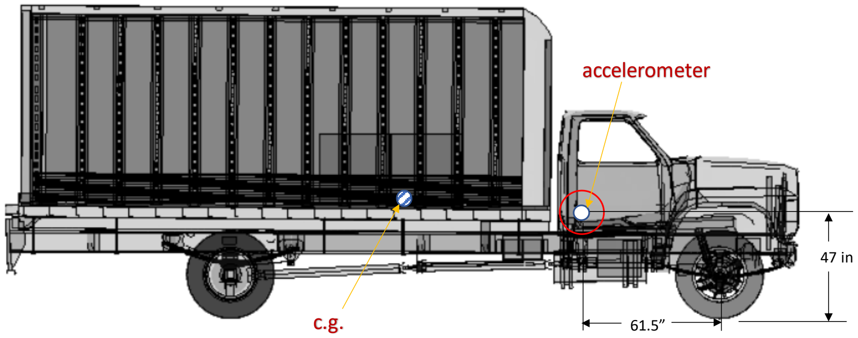
TRAP – Summary Plots (c.g. – cargo box)



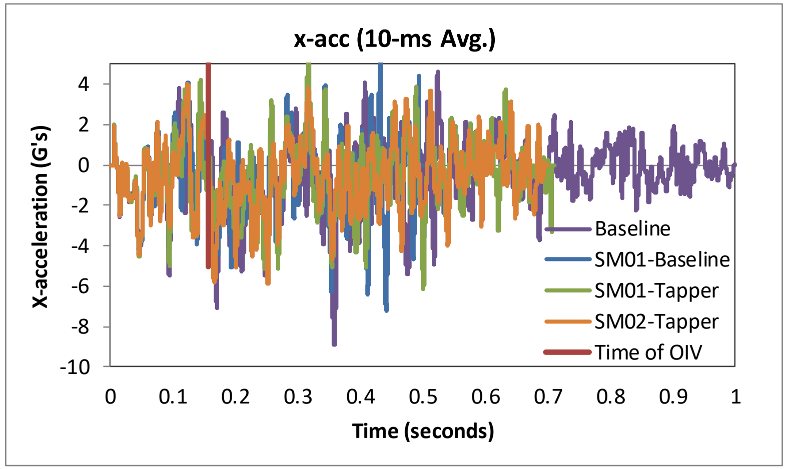


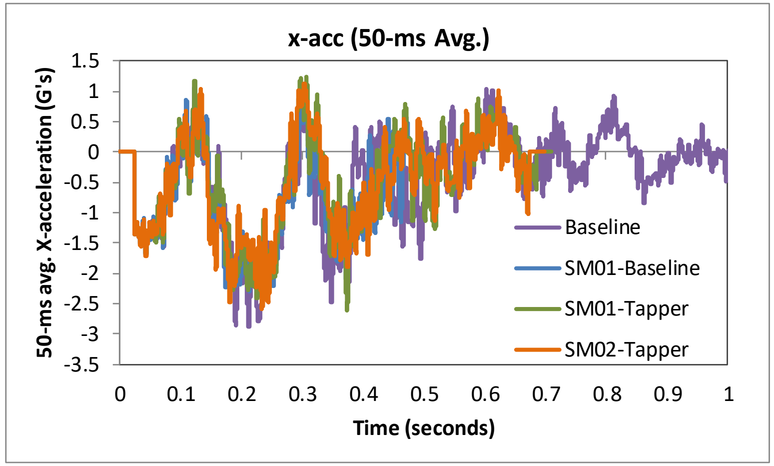


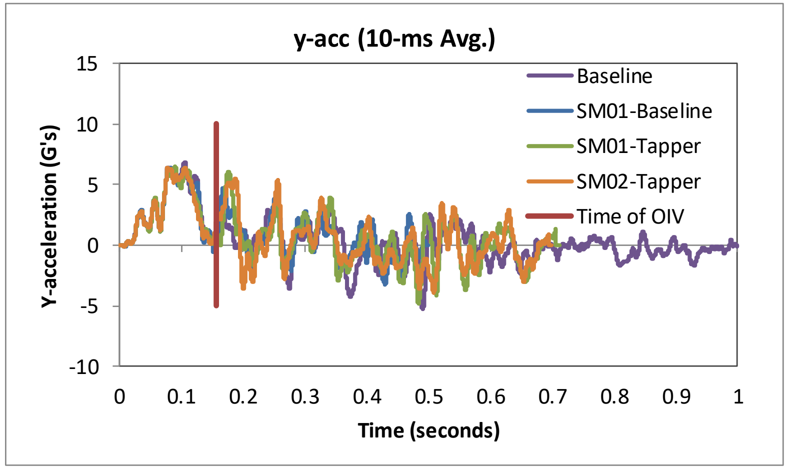


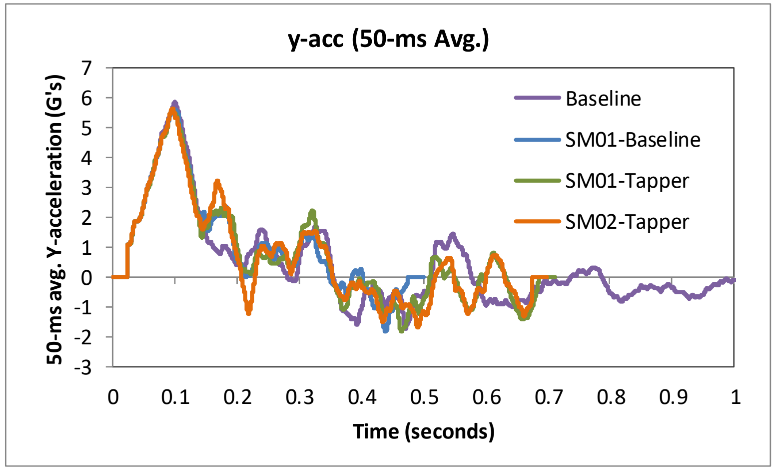


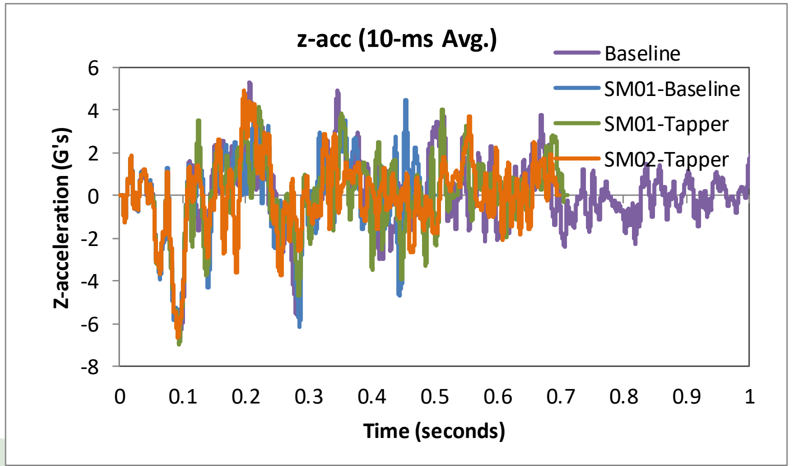
Acceleration Plots (cabin)

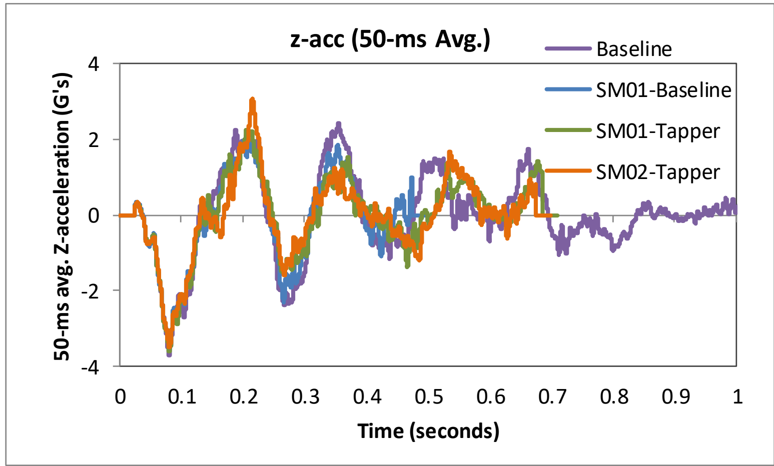


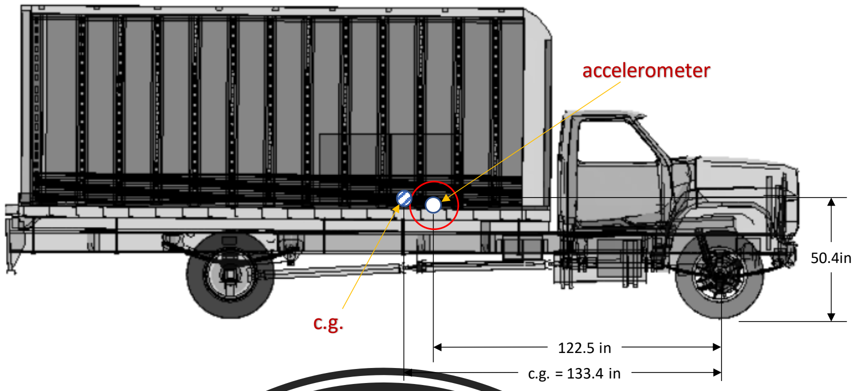




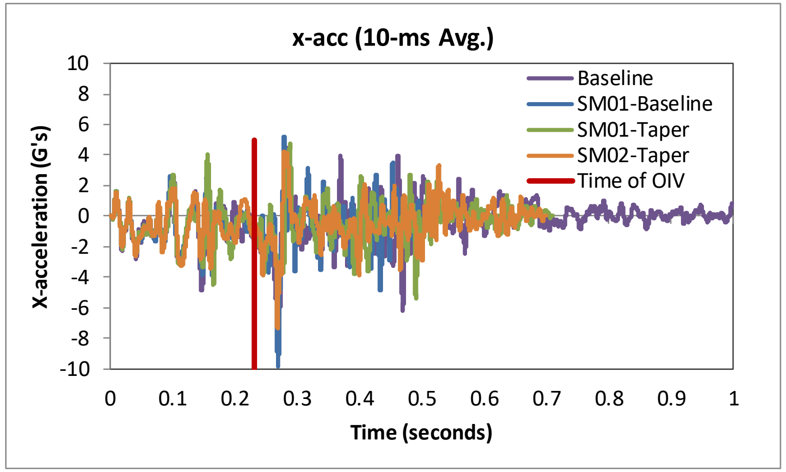


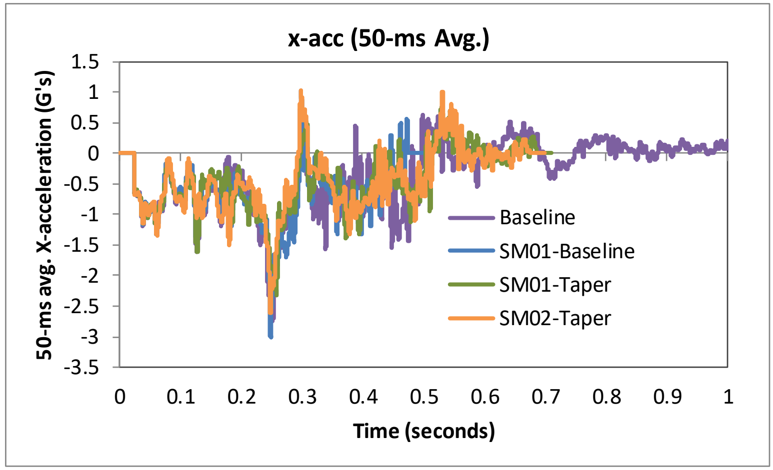


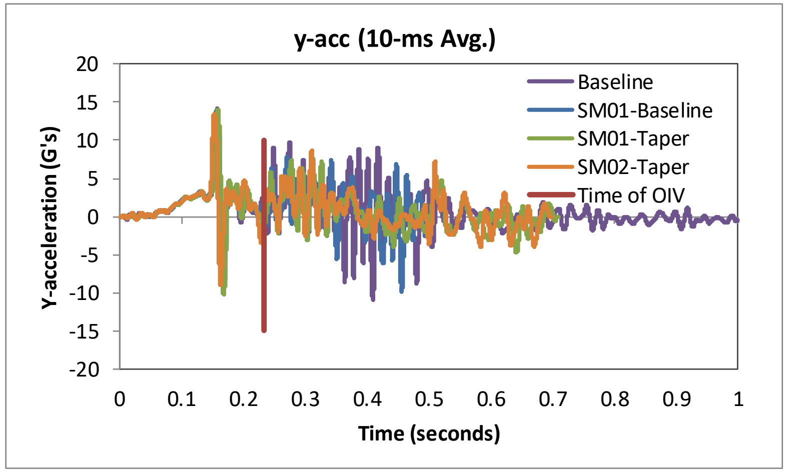


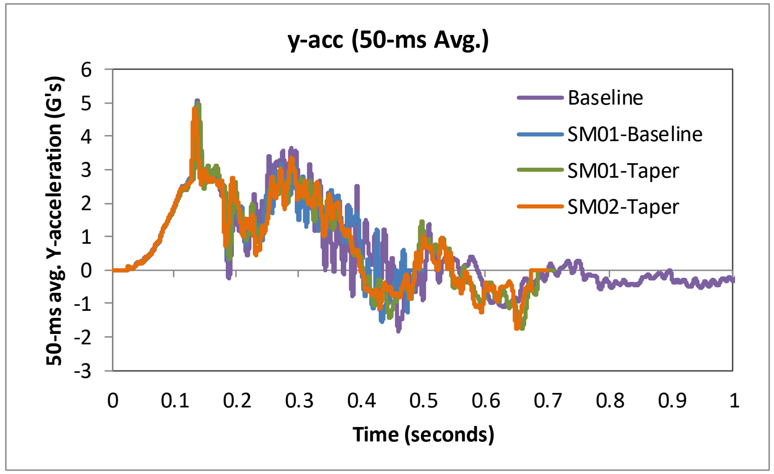


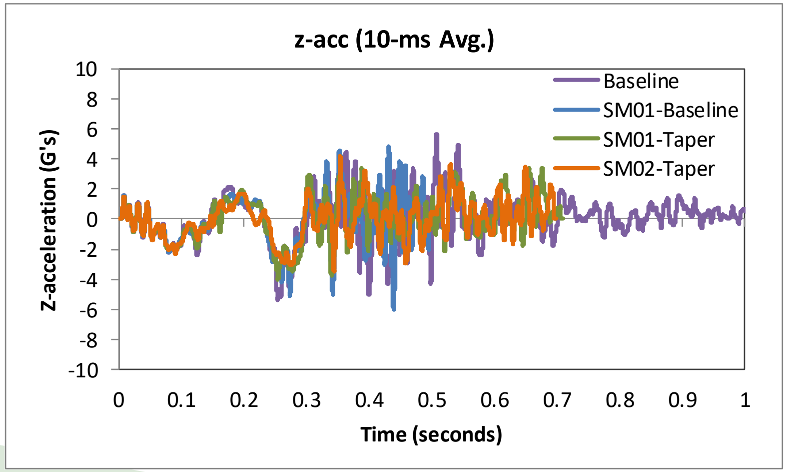
Acceleration Plots (c.g.)

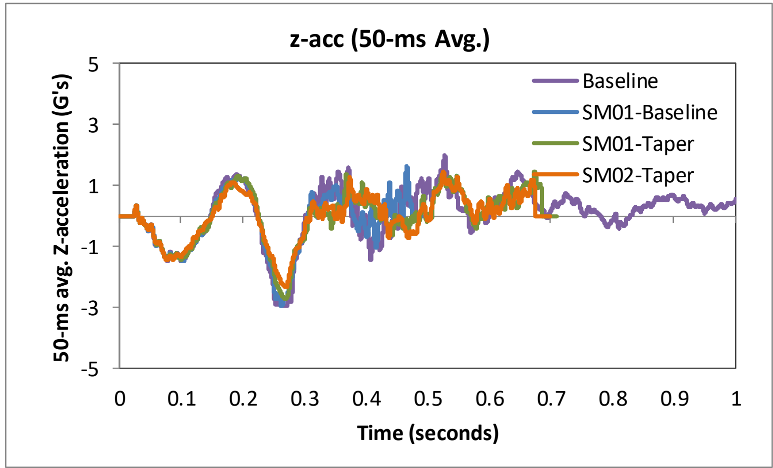


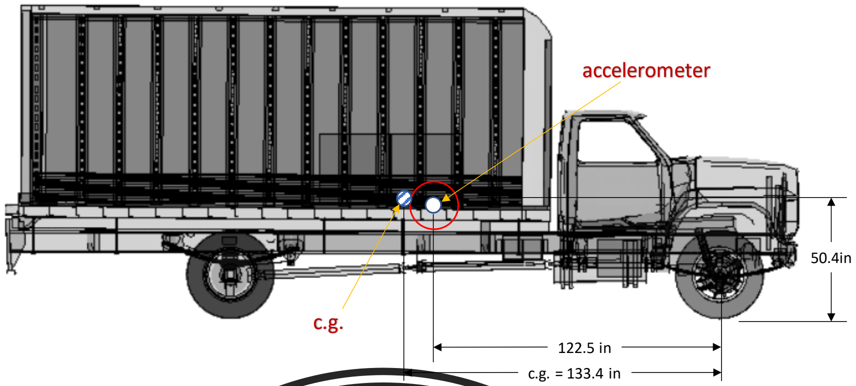




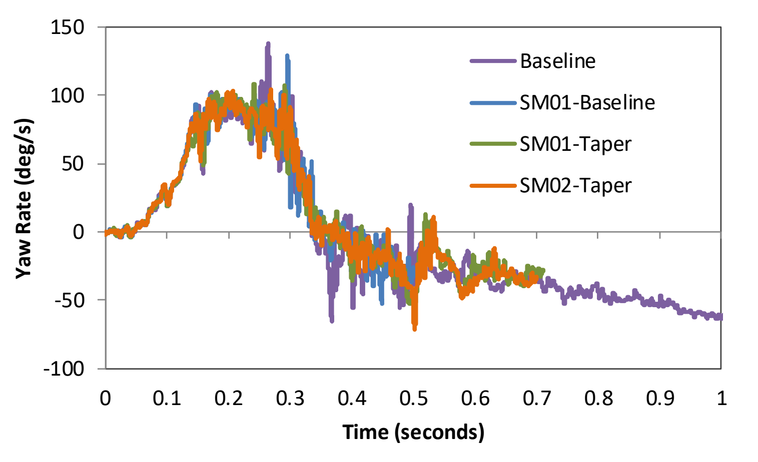


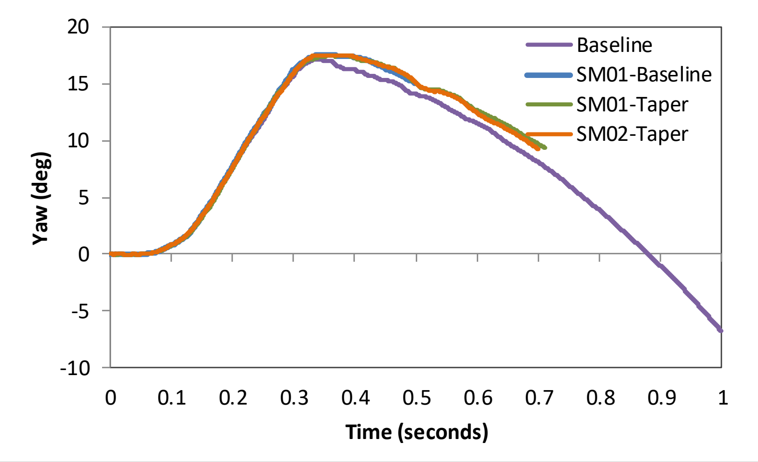


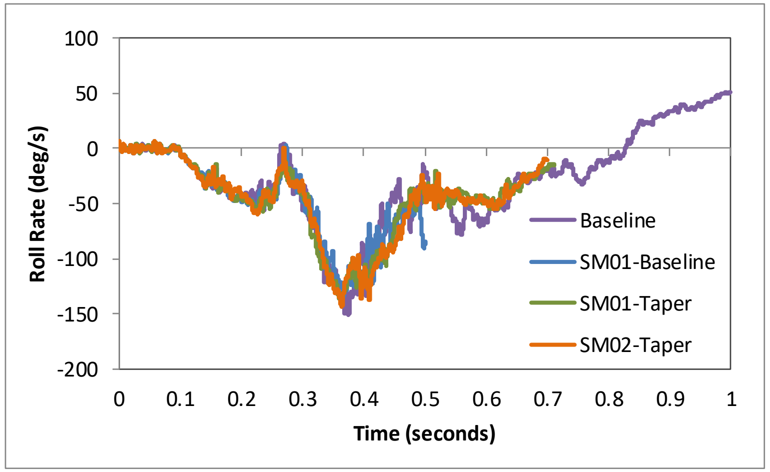


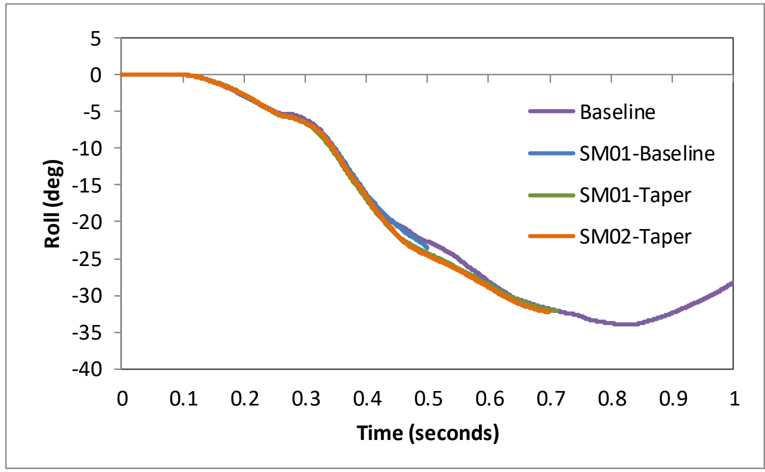


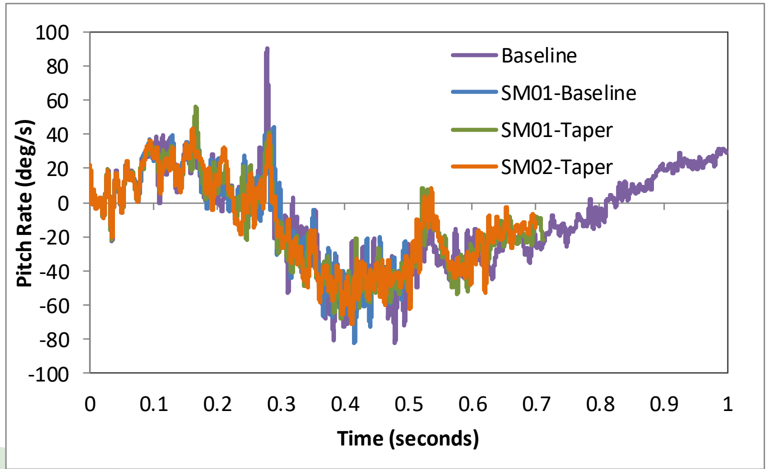
Angular Rate and Displacement Plots (cabin)

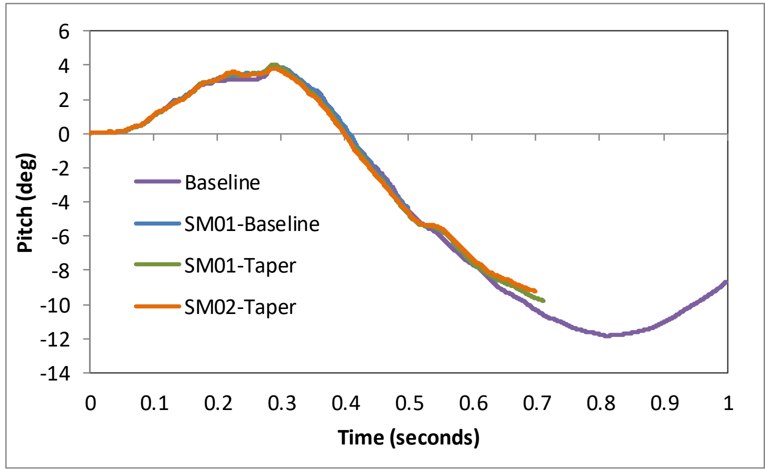






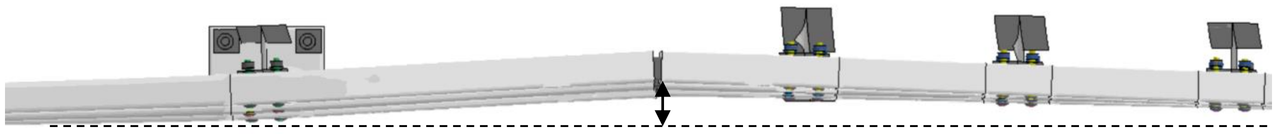


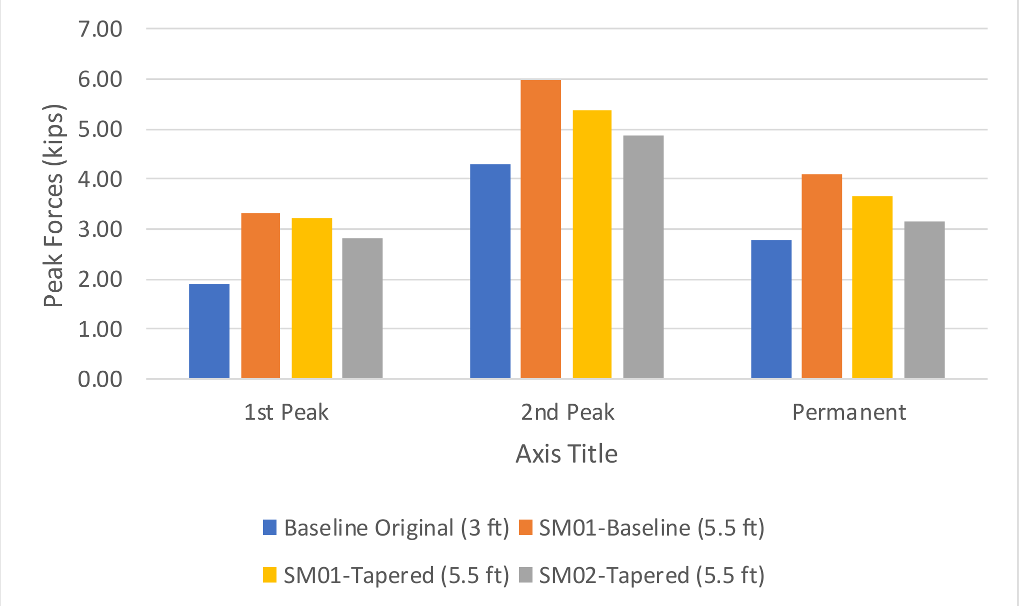


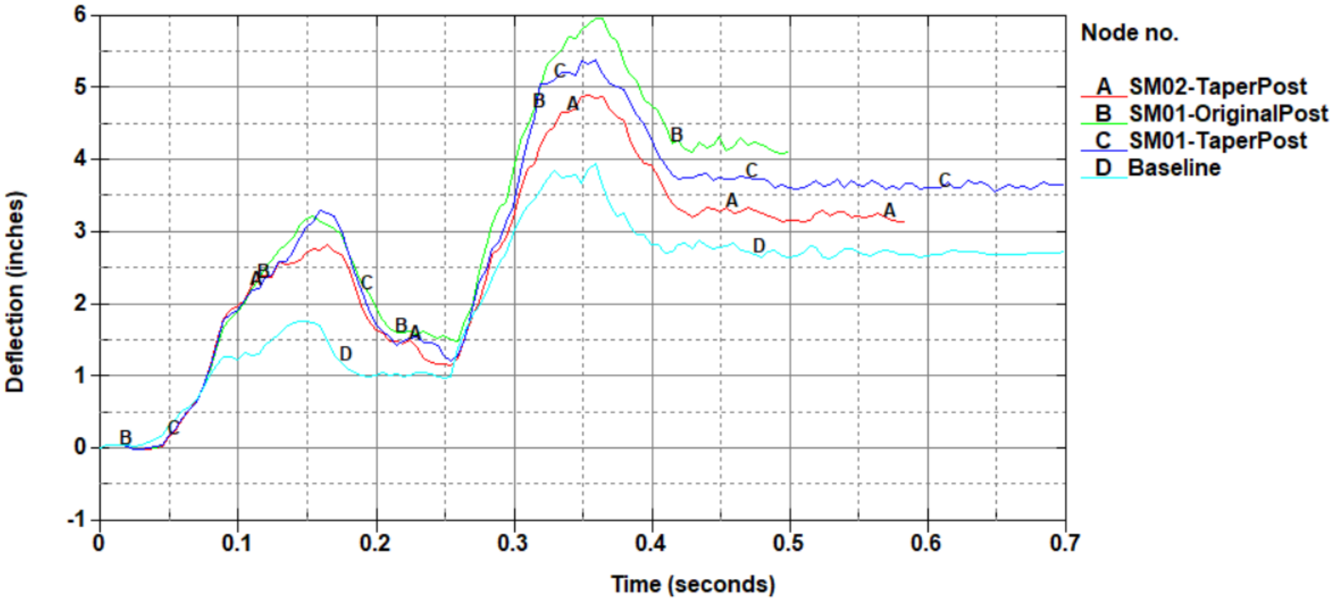


Peak Lateral Deflections

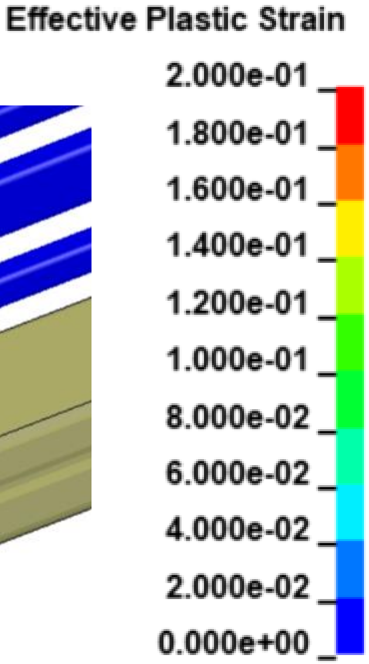
Peak Deflection (in)			
	Dynamic		
	1st Peak	2nd Peak	Permanent
Baseline Original (3 ft)	1.89	4.29	2.80
SM01-Baseline (5.5 ft)	3.31	5.98	4.09
SM01-Tapered (5.5 ft)	3.23	5.39	3.66
SM02-Tapered (5.5 ft)	2.82	4.88	3.15



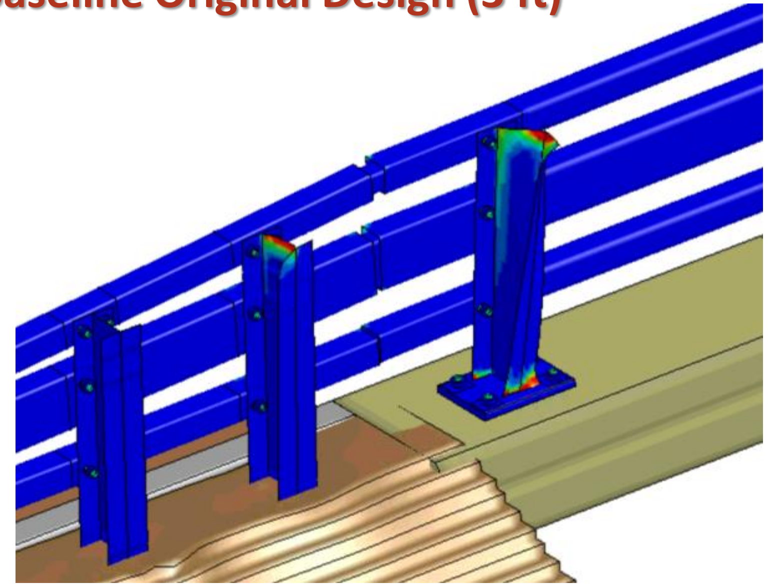




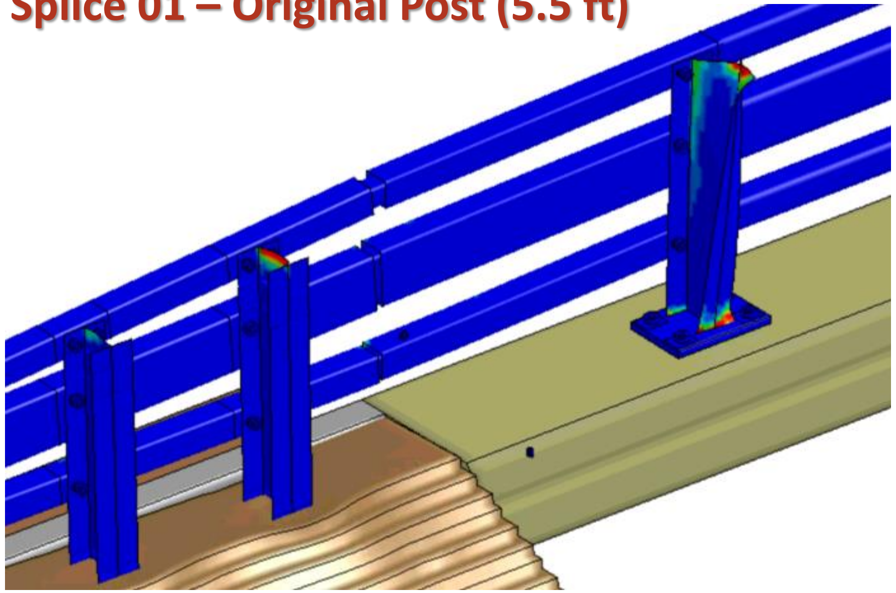
Post-Impact Barrier Damage



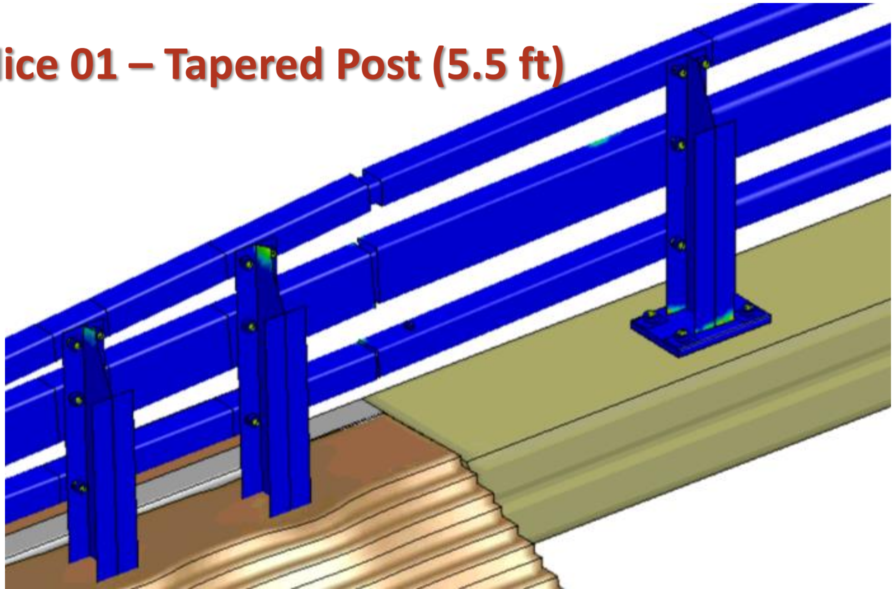
Baseline Original Design (3 ft)



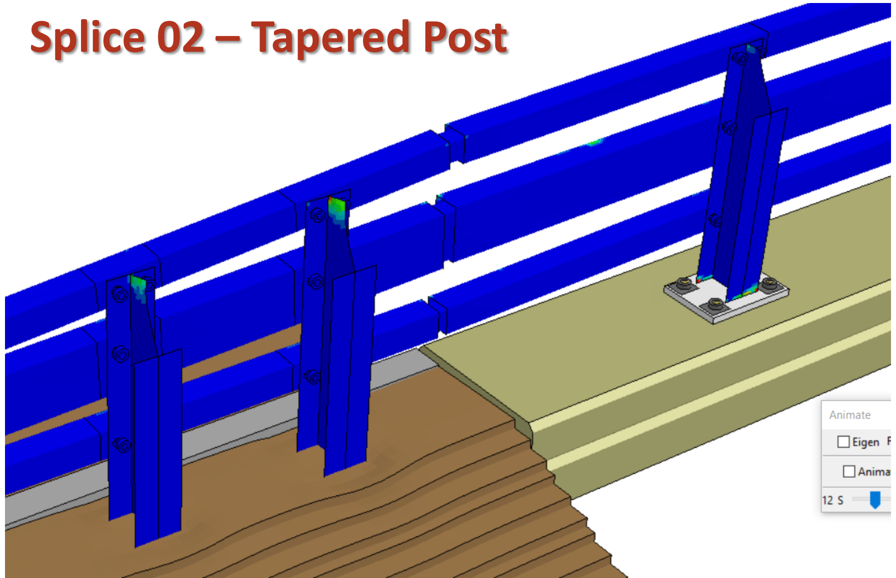
Splice 01 – Original Post (5.5 ft)



Splice 01 – Tapered Post (5.5 ft)

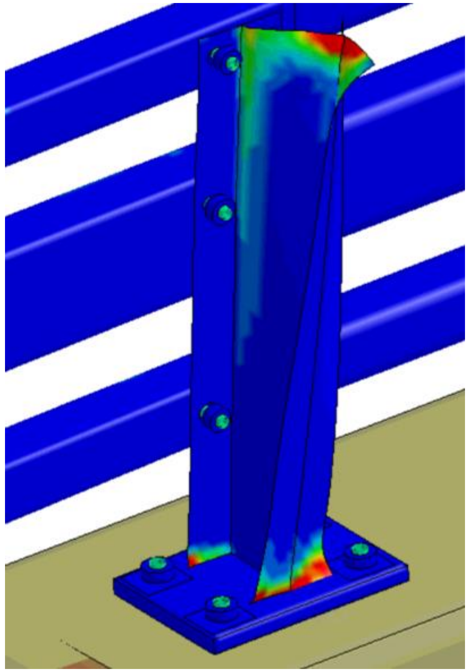


Splice 02 – Tapered Post

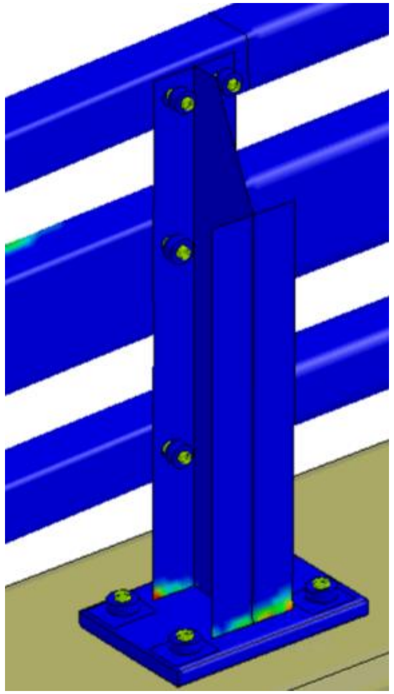


Barrier Damage

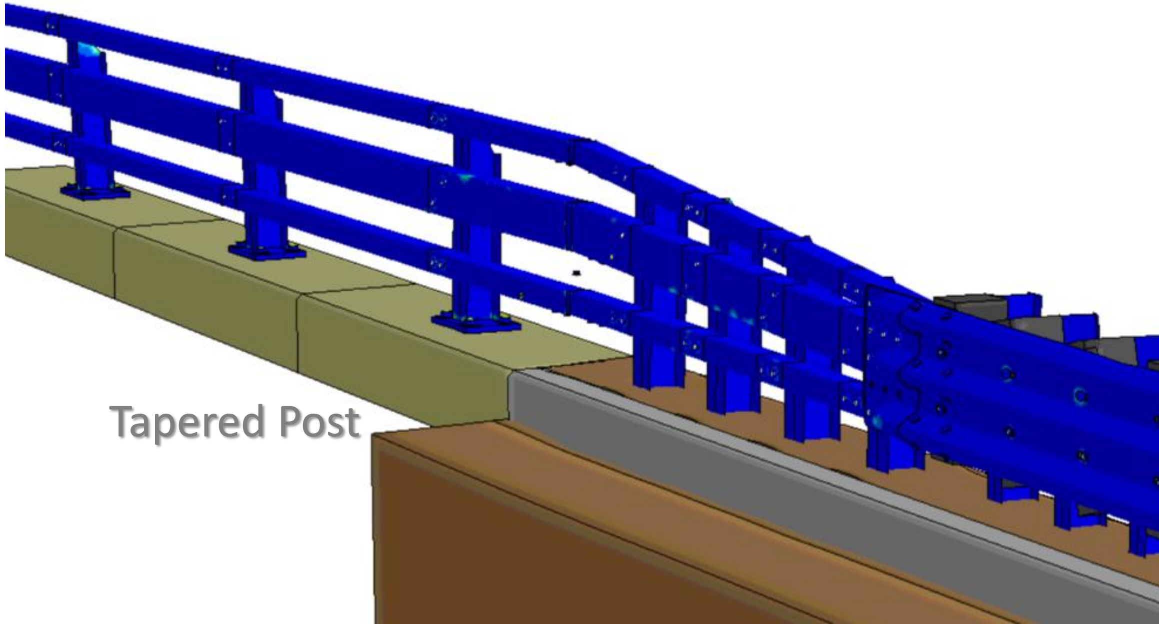
- There was a hard snag on the tops of the posts for the original post cases due to the bottom of the cargo-box snagging on the top of the posts. This caused torque rotation and longitudinal deformation of the posts.
- There was negligible snag on the tops of the posts for the tapered post cases.
- Plastic deformations of the steel components:
  - *Non-Tapered Posts*: Top of Post 1 of the transition and to all three (3) bridge rail posts.
  - *Tapered Posts*: Minimal damage.
- In all cases, 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.



Original Post

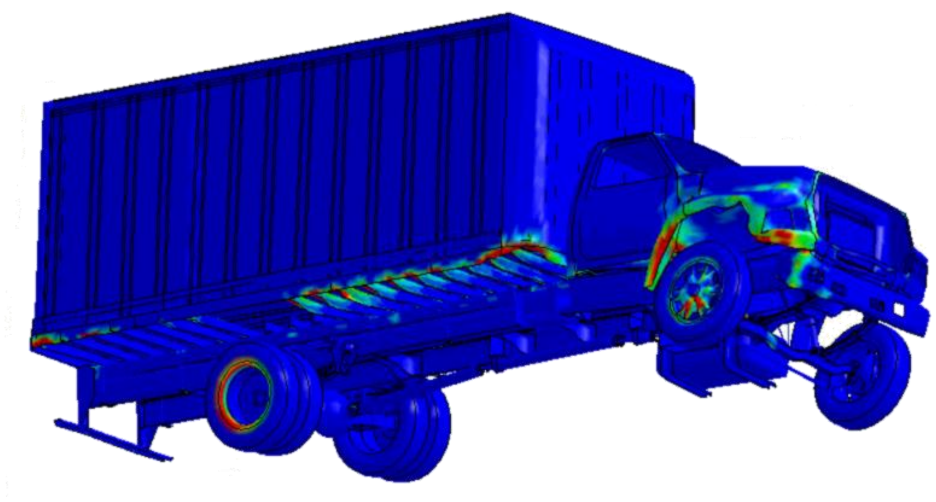


Tapered Post

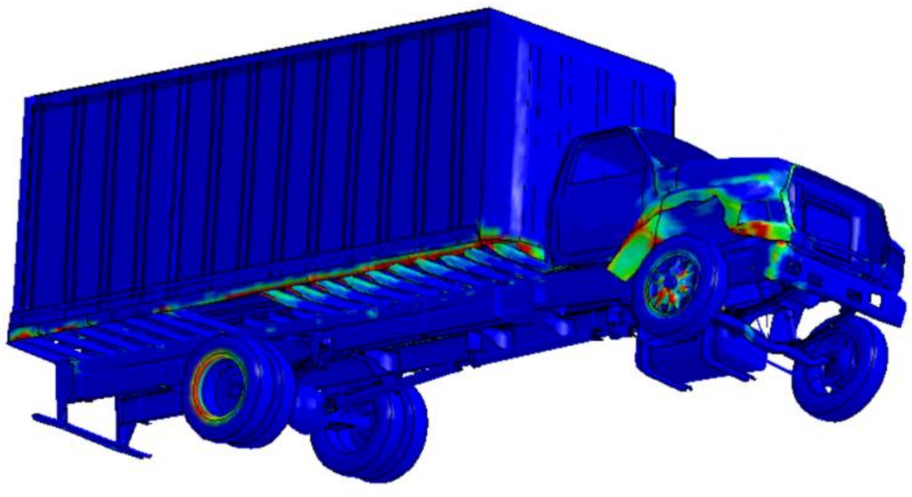


Tapered Post

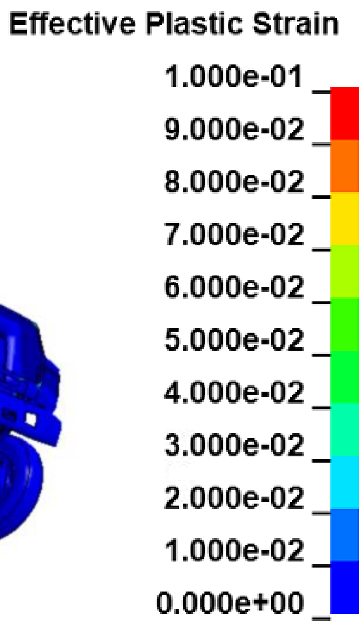
Effective Plastic Strain for SUT Tests



Original Post



Tapered Post



Similar for both cases

<u>Truck Damages</u>:
The front bumper, front fender, front-right suspension, front axle and wheel, and rear wheel.

<u>Cargo-Box Damages</u>:
Front-lower corner of box, lateral floor beams, main bed rail, wood flooring, and side rail.

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

- The 5.5-ft post spacing was evaluated using two expansion splice gaps (i.e., 0.75 inch and 2 inches) and results were compared to the baseline analysis for the original 3.3-ft post spacing.
- The barrier adequately contained and redirected the 10,000S vehicle in all cases.
- There was no snag on the bridge rail at the expansion splice for any case.
  - It is noted that the wheels of the SUT model do not include protruding lug bolts (which are used on many SUT vehicles); therefore, snag from lug bolts was not evaluated.
- Impact Forces:
  - *Longitudinal force*: Increased approximately 19% due to the increase in post spacing with the non-tapered posts (43.8 vs. 36.9 kips); but was slightly reduced for the tapered posts (34.1 vs. 36.9 kips).
  - *Lateral force*: Was reduced with the increase in post spacing.
  - *Resultant force*: Higher for all cases of increased post spacing, but highest for the case with non-tapered posts (96.2 vs. 84 kips).
- Deflections:
  - The maximum lateral deflection occurred at the expansion splice in all cases.
  - The lateral deflection was higher for 5.5-ft post spacing compared to the baseline 3-ft post spacing (i.e., 6” vs. 4.3”).
  - The highest deflection occurred for the 5.5-ft spacing with non-tapered posts.
- The plastic deformations of the transition components were very similar to the baseline case and was low to moderate.
- The plastic deformations of the bridge rail was:
  - *Non-tapered Posts*: Damage to posts was significant due to the bottom of the cargo-box snagging on the tops of the posts (same as baseline case).
  - *Tapered Posts*: Damage was minimal.

General Conclusions Regarding MASH for test 4-22:

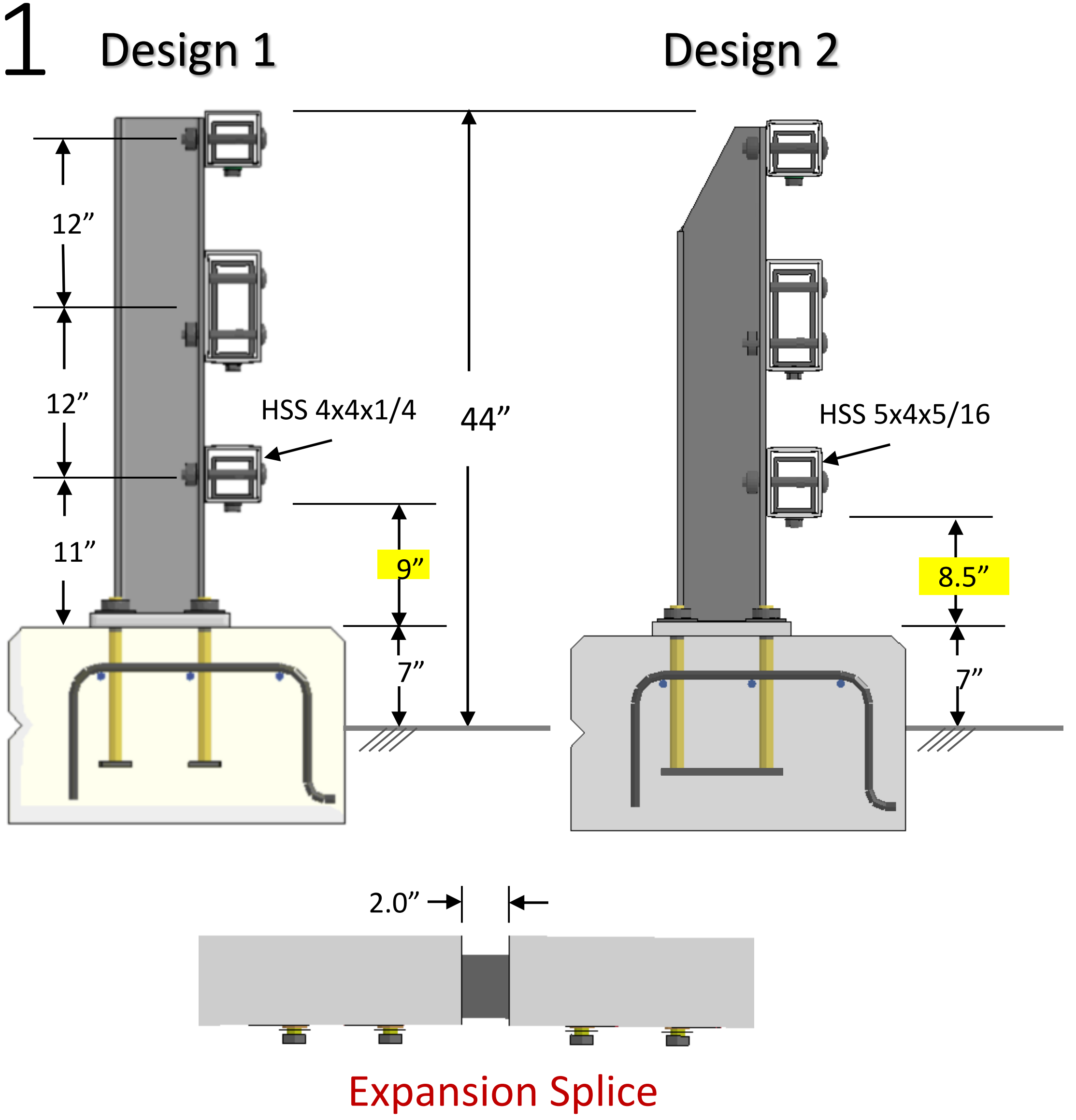
3-Bar Transition with 5.5' Post Spacing All Cases

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.	*Undetermined

** Analysis was terminated before vehicle stability could be determined, but it is probable that the vehicle would roll over onto its side, base on vehicle attitude at termination.*

Analysis for Test 4-20 and 4-21

- Two barrier designs were evaluated:
  1. Design 1 – Original barrier components (e.g., same rails, posts and hardware) with:
     - 5.5’ post spacing for first bridge rail post
     - Expansion Splice Model02 (Gap = 2 inches)
  2. Design 2 – Modified Design with:
     - HSS 5x4x5/16 lower rail
     - Tapered posts
     - 5.5’ post spacing for first bridge rail post
     - Expansion Splice Model02 (Gap = 2 inches)
- The first set of analysis cases were performed to evaluate performance of the existing hardware (i.e., current field installations).
  - Multiple impact points were evaluated to determine CIP for snags on critical post and expansion splice.
- The second analysis case involved only a single impact point [*selected as the CIP from the previous analysis set*] for direct comparison of results with the existing design.



Determination of CIP for Test 4-20

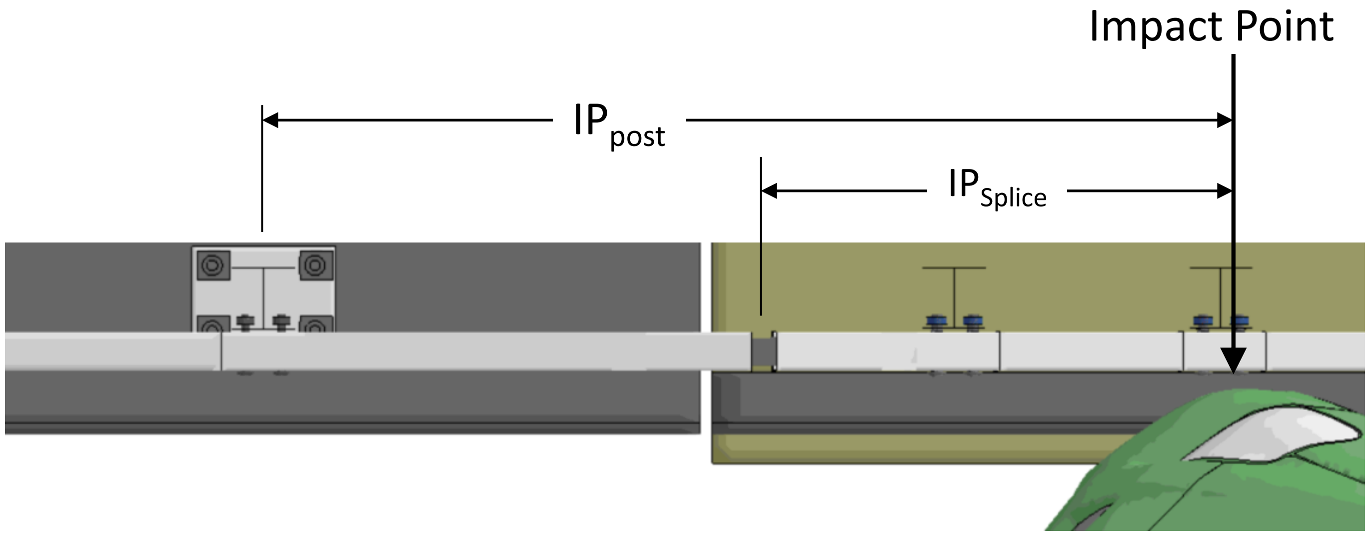
- CIP was determined using FEA with respect to maximizing potential for wheel snag on the first post of the bridge rail and on the splice connection.
- Analysis cases evaluated:

Determine CIP for Post

Determine CIP for Splice

IP	IP_{post} (ft)	IP_{Splice} (ft)
*IP3.6	*3.61	-
IP4.0	4.0	0
IP4.5	4.5	0.5
IP5.0	5.0	1.0
IP5.5	5.5	1.5
IP6.0	6.0	2.0
IP6.5	6.5	2.5
IP7.0	7.0	3.0
*IP7.61	7.61	*3.61
IP8.0	8.0	4.0

**CIP for rigid barriers*



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CIP Analysis Design 1 Analysis Cases

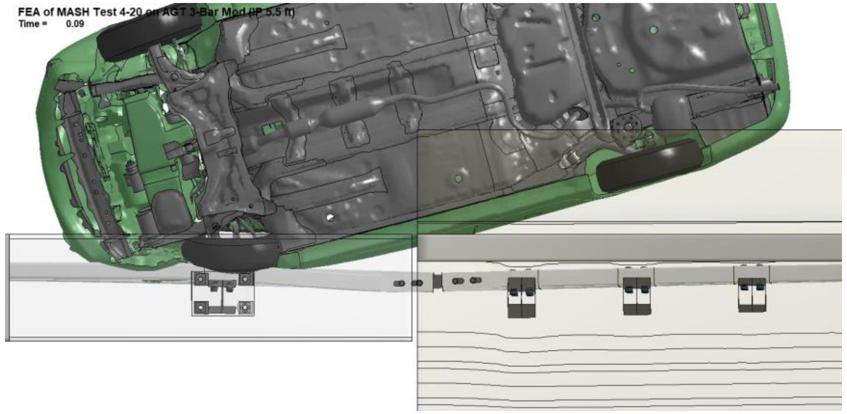
IP 3.6 ft

IP 4.0 ft

IP 4.5 ft

IP 5.0 ft

IP 5.5 ft



IP 6.0 ft

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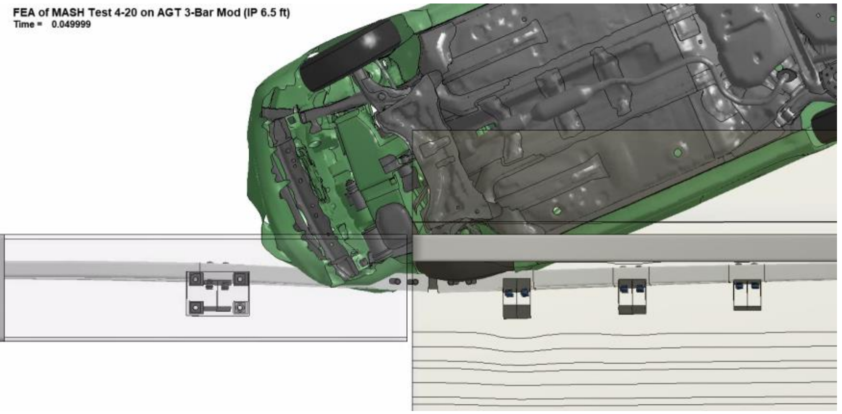
CIP Analysis Design 1 Analysis Cases

IP 6.5 ft



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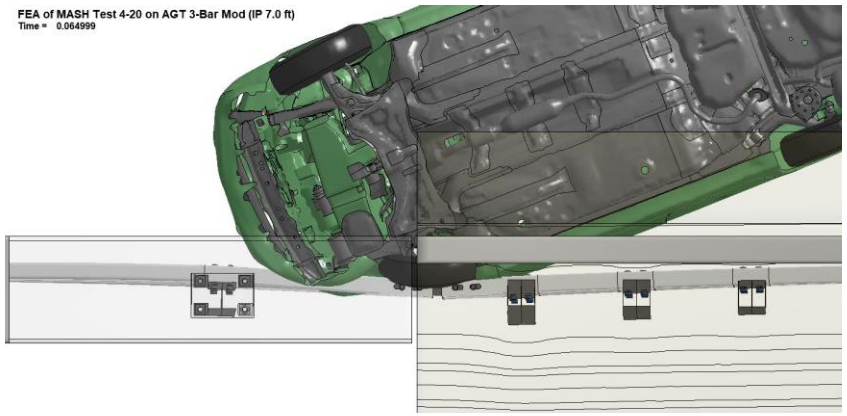
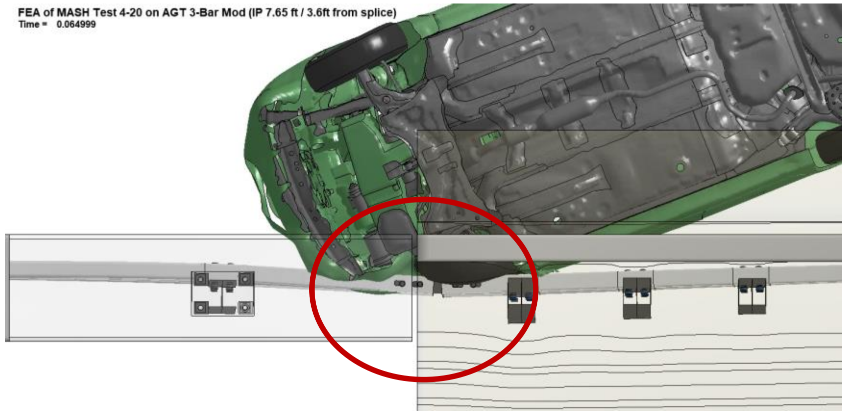
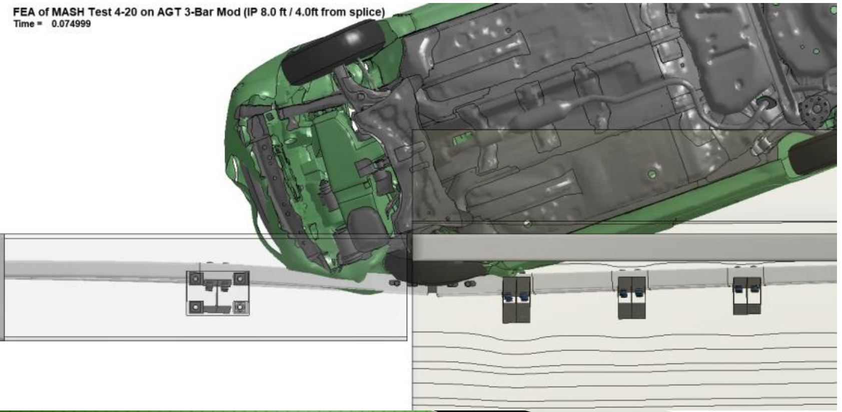


IP 7.65 ft



IP 8.0 ft

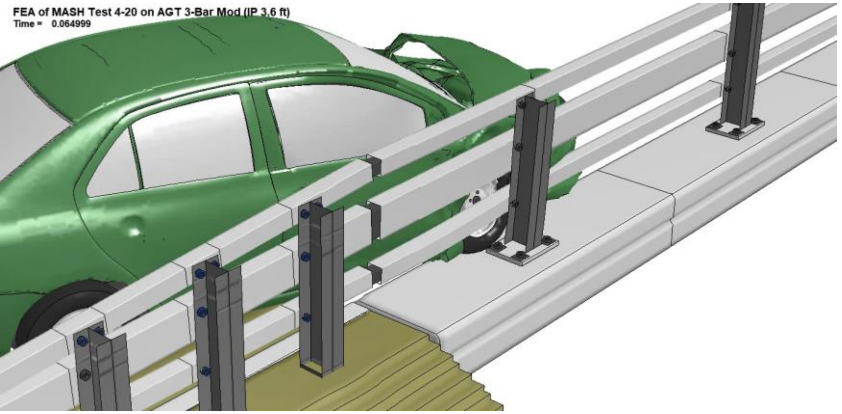


IP 8.5 ft

IP 9.0 ft

CIP Analysis Design 1 Analysis Cases

IP 3.6 ft



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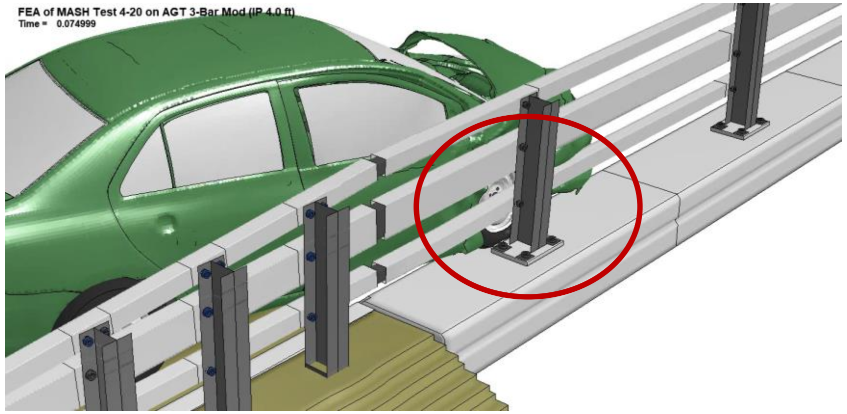

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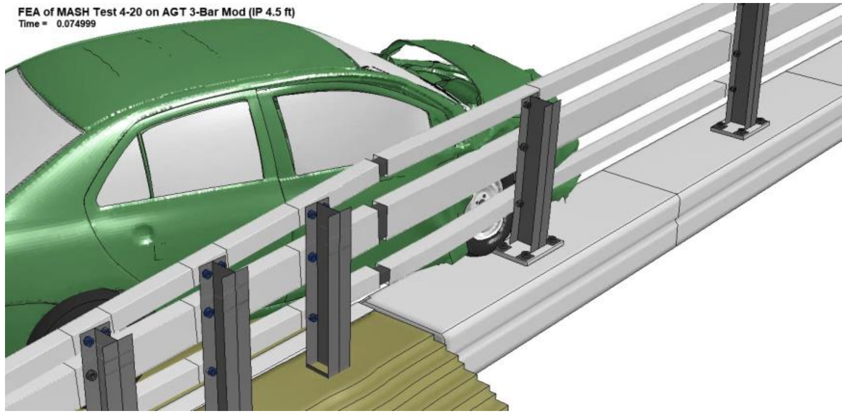

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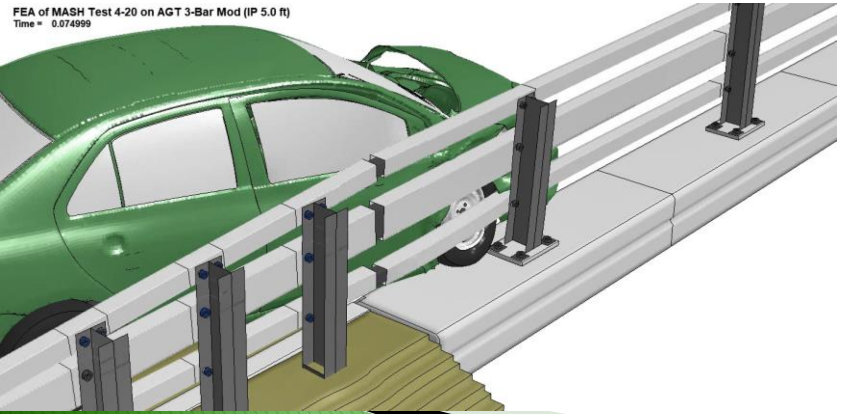

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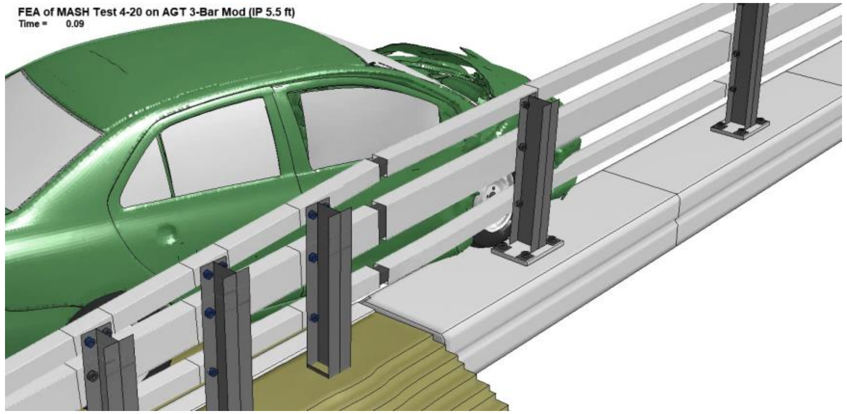

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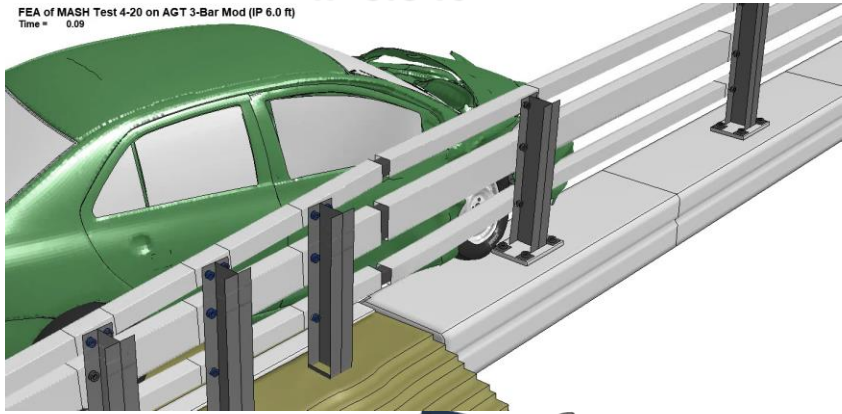
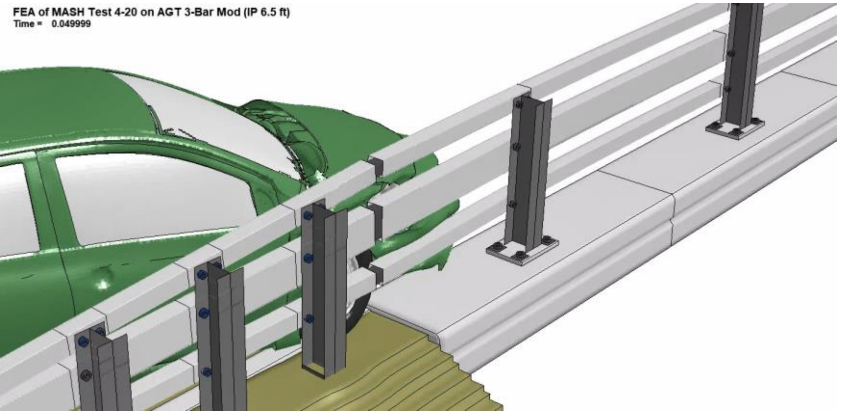


CIP Analysis Design 1 Analysis Cases

IP 6.5 ft



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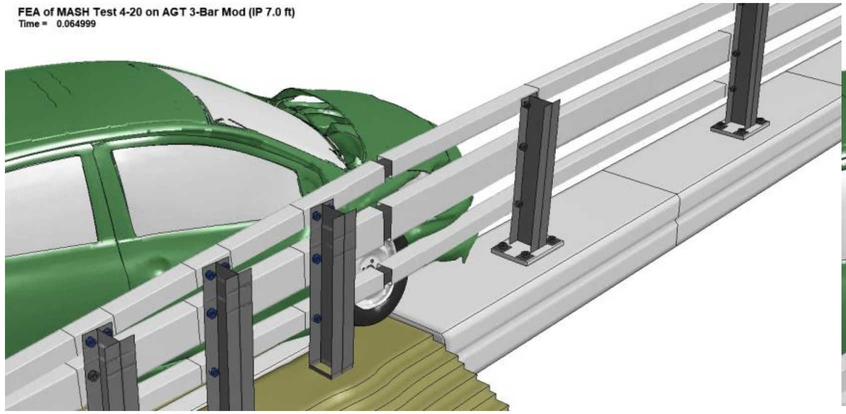

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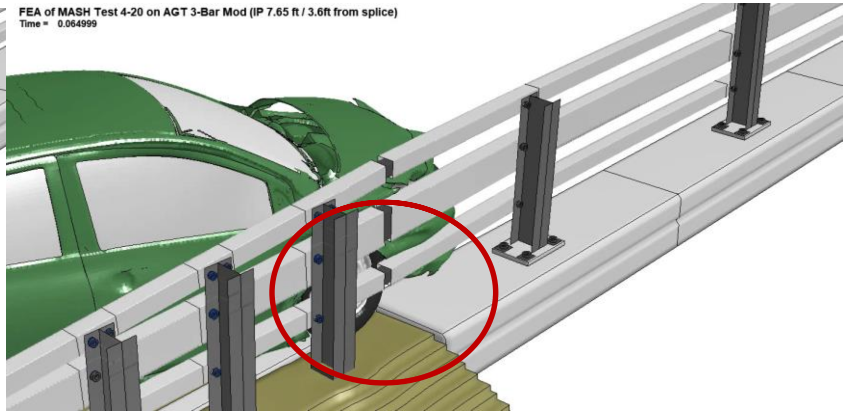

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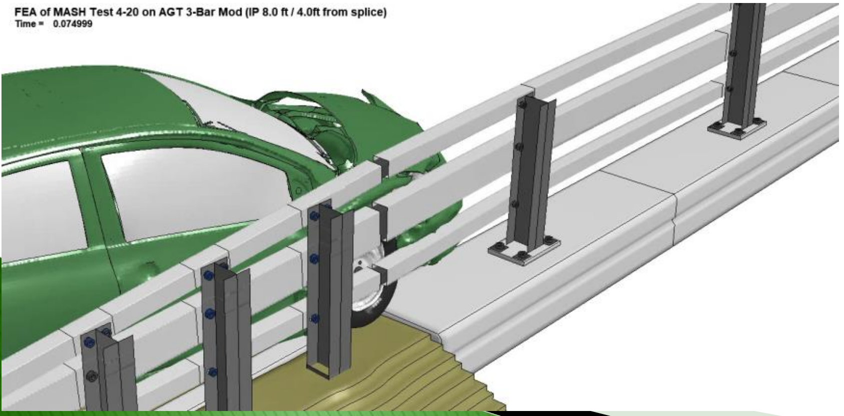

IP 8.5 ft

IP 9.0 ft

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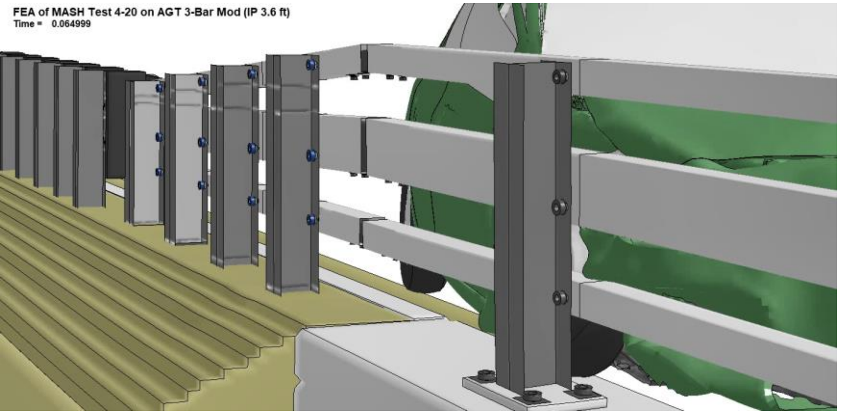
CIP Analysis Design 1 Analysis Cases

IP 3.6 ft



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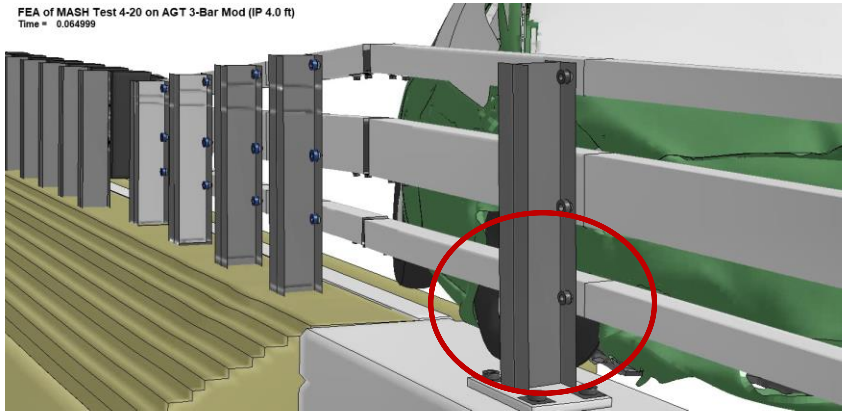

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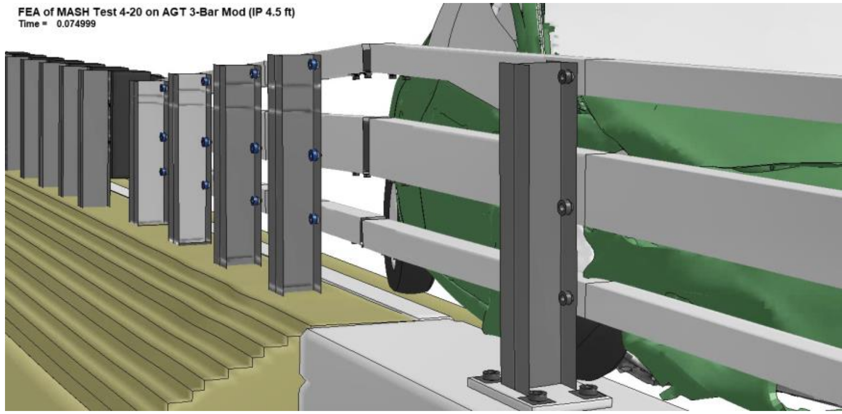

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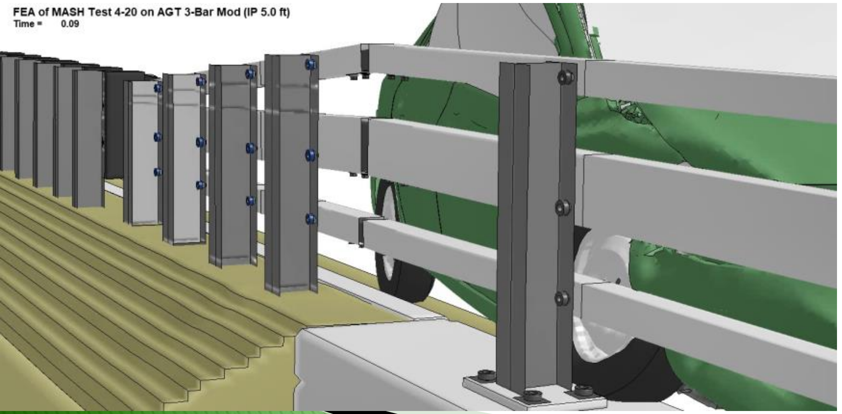

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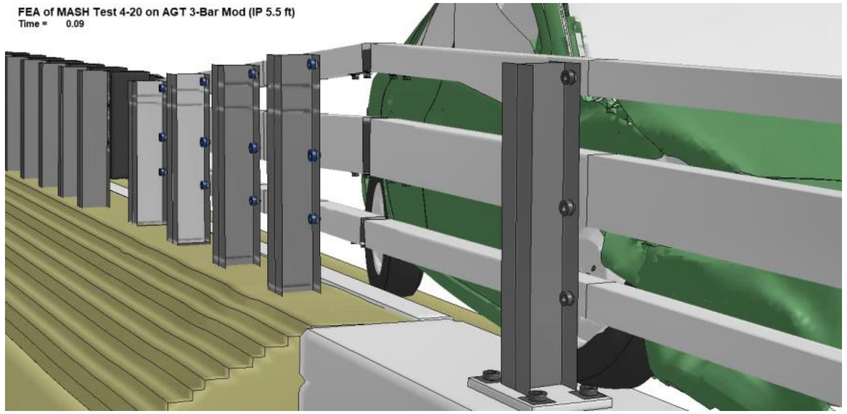

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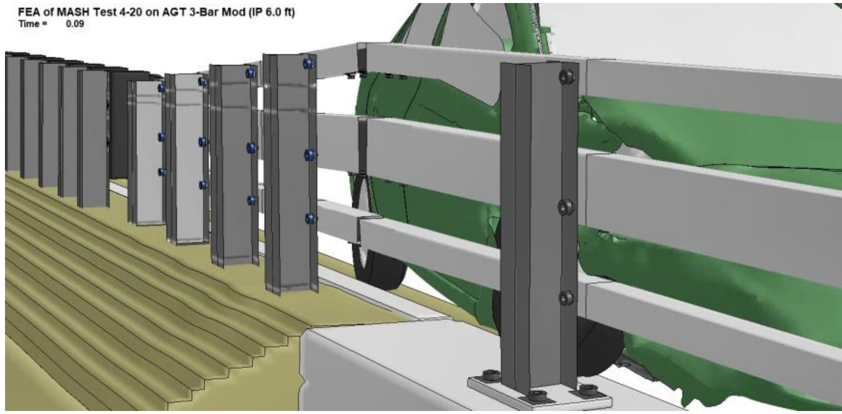

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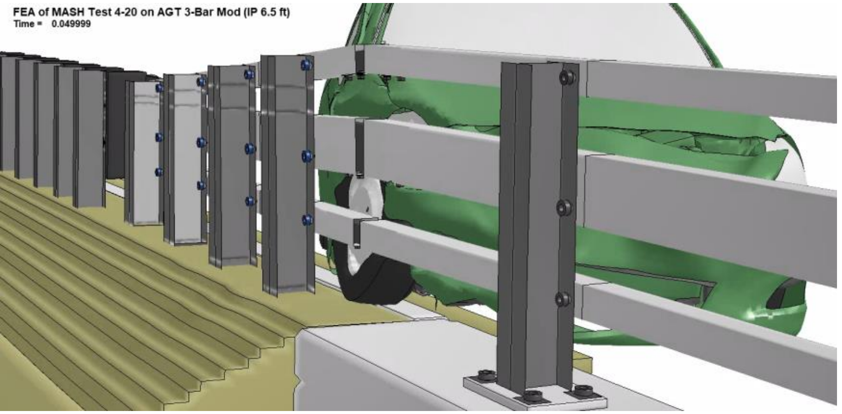
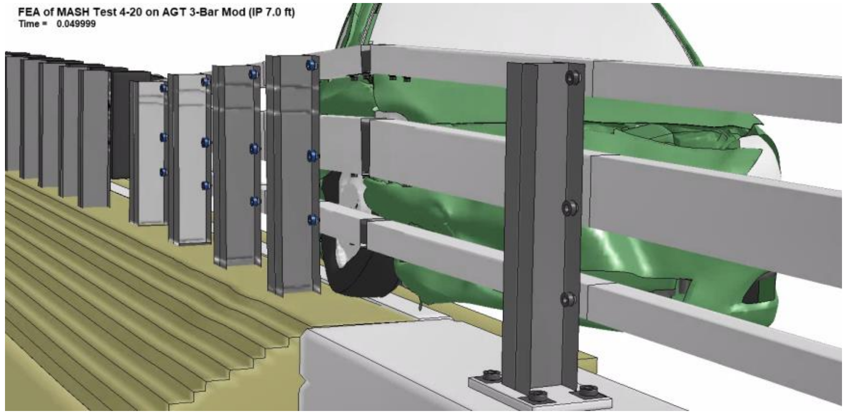
CIP Analysis Design 1 Analysis Cases

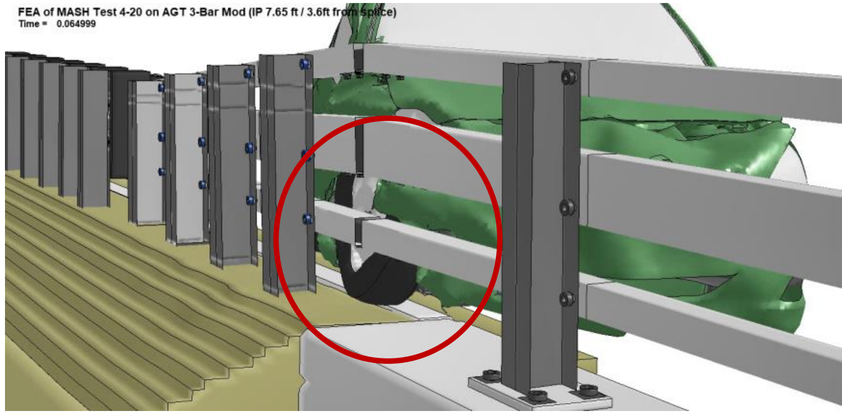
IP 6.5 ft



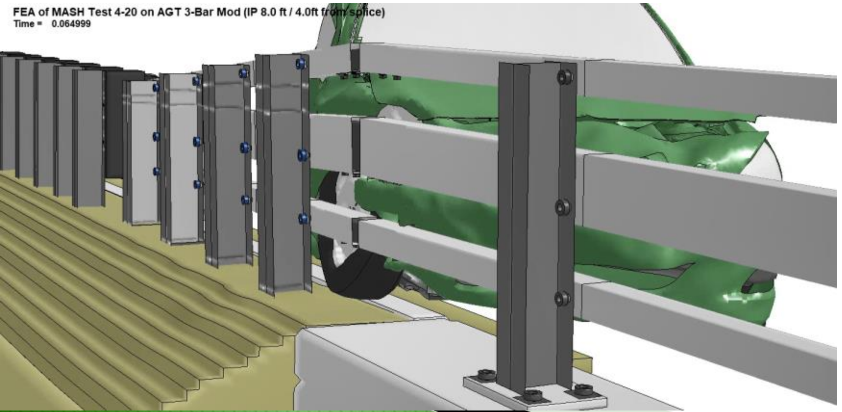
IP 7.0 ft



IP 7.65 ft



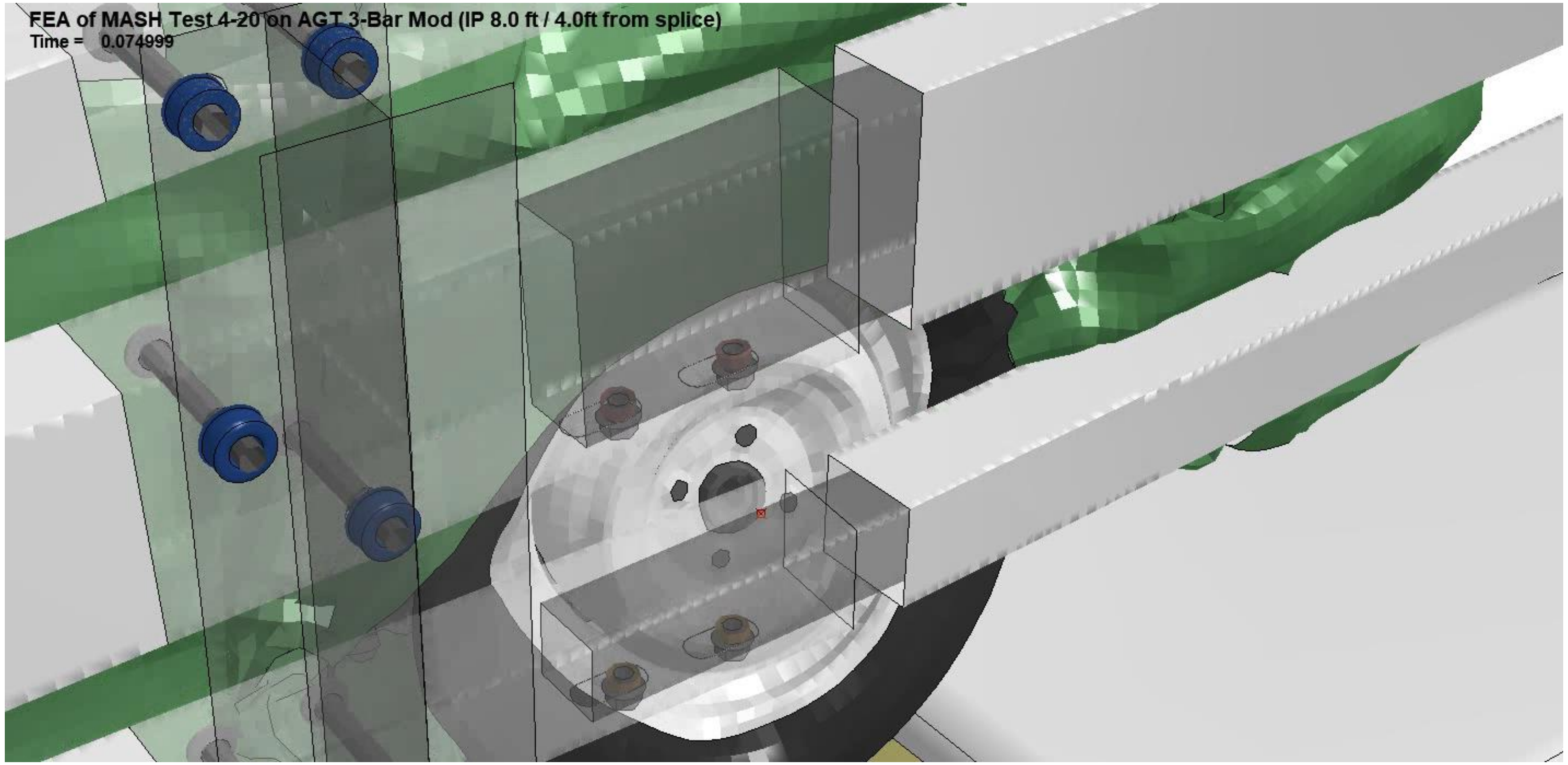
IP 8.0 ft



IP 8.5 ft

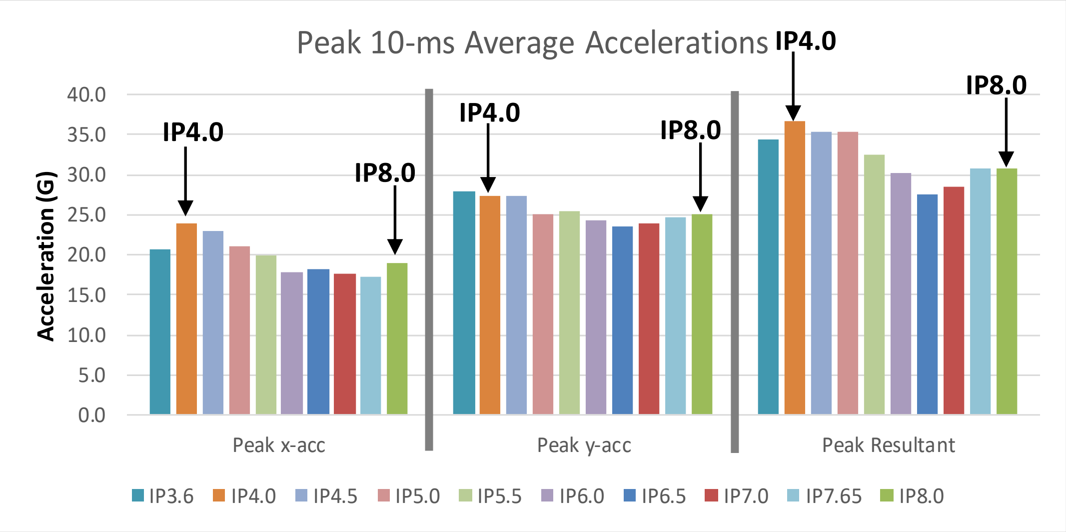
IP 9.0 ft

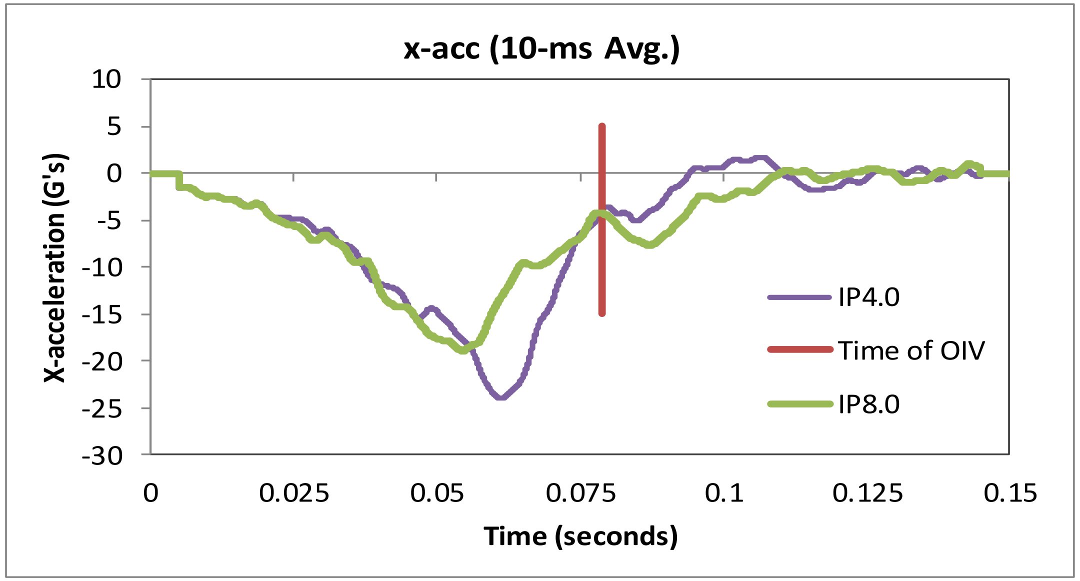
Close-up View of the Splice for Case IP8.0



- The case with impact at 8 ft upstream of critical post appears to be the CIP for assessing potential snag on the splice for Test 4-20 (small car).
- However, the results indicated that there was minimal potential for wheel snag, due to the splice location on the downstream side of the post.
- A reverse impact case may be more critical for assessing snag on the splice.

Vehicle Acceleration-Time History Summary





- Peak Accelerations:
  - IP4.0 – Highest regarding snag on post
    - Highest peak longitudinal acceleration,
    - 2nd highest lateral acceleration and
    - Highest resultant acceleration.
  - IP8.0 – Highest regarding snag on splice
    - As illustrated on the previous slide and confirmed here, snagging on the splice does not appear to be an issue for primary impact direction for Test 4-20

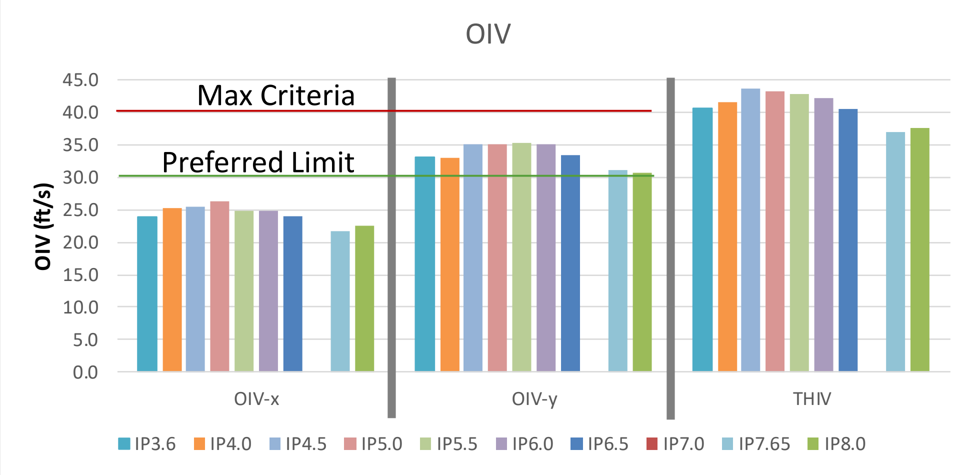
Occupant Risk Metrics

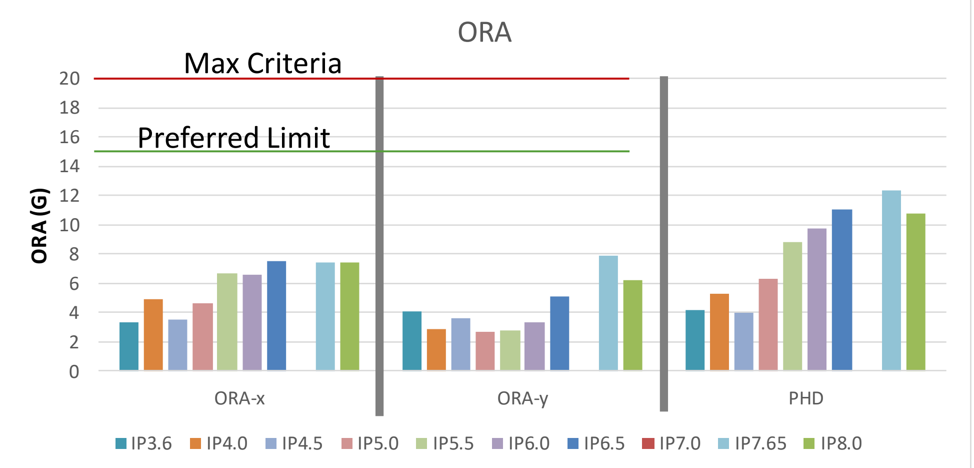
Design 1 Analysis Cases

Occupant Risk Factors		MASH Test 4-20									
		IP3.6	IP4.0	IP4.5	IP5.0	IP5.5	IP6.0	IP6.5	IP7.0	IP7.65	IP8.0
Occupant Impact Velocity (ft/s)	x-direction	24.0	25.3	25.6	26.2	24.9	24.9	23.9	N.A.	21.65328	22.63752
	y-direction	33.1	33.1	35.1	35.1	35.4	35.1	33.5	N.A.	31.1676	30.83952
	at time	at 0.0775 seconds on right side of interior	at 0.0788 seconds on right side of interior	at 0.0789 seconds on right side of interior	at 0.0794 seconds on right side of interior	at 0.0795 seconds on right side of interior	at 0.0804 seconds on right side of interior	at 0.0805 seconds on right side of interior	0	at 0.0810 seconds on right side of interior	at 0.0813 seconds on right side of interior
THIV (ft/s)		40.7 at 0.0775 seconds on right side of interior	41.7 at 0.0788 seconds on right side of interior	43.6 at 0.0789 seconds on right side of interior	43.3 at 0.0794 seconds on right side of interior	43.0 at 0.0795 seconds on right side of interior	42.3 at 0.0804 seconds on right side of interior	40.7 at 0.0805 seconds on right side of interior	0.0 0	37.07304 at 0.0810 seconds on right side of interior	37.7292 at 0.0813 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-3.3 (0.0794 - 0.0894 seconds)	-4.9 (0.0806 - 0.0906 seconds)	-3.5 (0.0813 - 0.0913 seconds)	-4.6 (0.0812 - 0.0912 seconds)	-6.7 (0.0813 - 0.0913 seconds)	-6.6 (0.0822 - 0.0922 seconds)	-7.5 (0.0825 - 0.0925 seconds)	ant does not impact vehi 0	-7.4 (0.0830 - 0.0930 seconds)	-7.4 (0.0834 - 0.0934 seconds)
	y-direction	4.1 (0.0846 - 0.0946 seconds)	2.9 (0.0901 - 0.1001 seconds)	3.6 (0.0950 - 0.1050 seconds)	-2.7 (0.1104 - 0.1204 seconds)	-2.8 (0.1081 - 0.1181 seconds)	-3.3 (0.1169 - 0.1269 seconds)	-5.1 (0.0825 - 0.0925 seconds)	ant does not impact vehi 0	-7.9 (0.0851 - 0.0951 seconds)	-6.2 (0.0834 - 0.0934 seconds)
PHD (g's)		4.2 (0.0846 - 0.0946 seconds)	5.3 (0.0798 - 0.0898 seconds)	4 (0.0789 - 0.0889 seconds)	6.3 (0.0794 - 0.0894 seconds)	8.8 (0.0795 - 0.0895 seconds)	9.8 (0.0803 - 0.0903 seconds)	11.1 (0.0805 - 0.0905 seconds)	ant does not impact vehi 0	12.4 (0.0809 - 0.0909 seconds)	10.8 (0.0812 - 0.0912 seconds)
ASI		2.49 (0.0253 - 0.0753 seconds)	2.53 (0.0251 - 0.0751 seconds)	2.58 (0.0265 - 0.0765 seconds)	2.51 (0.0274 - 0.0774 seconds)	2.47 (0.0266 - 0.0766 seconds)	2.41 (0.0337 - 0.0837 seconds)	2.28 (0.0338 - 0.0838 seconds)	2.07 (0.0231 - 0.0731 seconds)	2.07 (0.0263 - 0.0763 seconds)	2.06 (0.0304 - 0.0804 seconds)
Max 50-ms moving avg. acc.	x-direction	-13.4 (0.0242 - 0.0742 seconds)	-14 (0.0247 - 0.0747 seconds)	-14 (0.0298 - 0.0798 seconds)	-14.6 (0.0352 - 0.0852 seconds)	-13.4 (0.0314 - 0.0814 seconds)	-13.3 (0.0318 - 0.0818 seconds)	-12.9 (0.0377 - 0.0877 seconds)	-11.5 (0.0221 - 0.0721 seconds)	-11.2 (0.0241 - 0.0741 seconds)	-12.1 (0.0239 - 0.0739 seconds)
	y-direction	-20.1 (0.0267 - 0.0767 seconds)	-20.2 (0.0252 - 0.0752 seconds)	-20.7 (0.0266 - 0.0766 seconds)	-20 (0.0271 - 0.0771 seconds)	-19.9 (0.0265 - 0.0765 seconds)	-19.3 (0.0339 - 0.0839 seconds)	-18.2 (0.0266 - 0.0766 seconds)	-16.5 (0.0221 - 0.0721 seconds)	-16.7 (0.0332 - 0.0832 seconds)	-16.3 (0.0335 - 0.0835 seconds)
	z-direction	-2.9 (0.0610 - 0.1110 seconds)	-3.1 (0.0621 - 0.1121 seconds)	-2.8 (0.0608 - 0.1108 seconds)	-2.5 (0.0604 - 0.1104 seconds)	-2.3 (0.0598 - 0.1098 seconds)	-2.3 (0.0573 - 0.1073 seconds)	-2.5 (0.0539 - 0.1039 seconds)	-0.8 (0.0213 - 0.0713 seconds)	-3.1 (0.0554 - 0.1054 seconds)	-2.9 (0.0555 - 0.1055 seconds)
	Resultant	25.6	25.6	25.9	25.9	24.4	24.1	22.8	21.6	22.1	22.1
Peak 10 ms Avg. Accelerations	x-direction	-20.7	-24.0	-22.9	-21.1	-20.0	-17.9	-18.3	-17.6	-17.3	-18.9
	y-direction	-27.9	-27.3	-27.4	-25.1	-25.5	-24.4	-23.5	-23.9	-24.8	-25.0
	Resultant	34.5	36.6	35.3	35.3	32.5	30.2	27.5	28.5	30.8	30.8

Occupant Risk Metrics

Design 1 Analysis Cases





- Occupant impact velocities

  (all cases)
  - OIV-x: Within preferred limits.
  - OIV-y: Exceeded preferred limits but were within critical limits.
- Occupant Ridedown Accelerations (all cases)
  - ORA-x: Well within preferred limits
  - ORA-y: Well within preferred limits
- Highest OIV
  - IP5.0 yielded highest OIV for both x- and y-directions
    - Corresponds to CIP for critical post
- Highest ORA
  - IP7.6 yielded overall highest ORA for both x- and y-directions, as well as highest PHD (resultant post-head deceleration)
    - Corresponds to CIP for critical splice

Conclusions: Test 4-20 on Design 1 for the 3-Bar Transition with 5.5' Post Spacing

- The barrier successfully contained and redirected the 1100P vehicle.
- The OIV's were within critical limits and ORA's were within preferred limits specified in MASH.
  - Max values:
    - OIV_x = **26.2 ft/s** (IP 5.0 ft)
    - OIV_y = **35.4 ft/s** (IP 5.5 ft)
    - ORA_x = **7.5 G** (IP 6.5 ft)
    - ORA_y = **7.9 G** (IP 7.65 ft)
- Peak vehicle accelerations (e.g., relates to impact forces)
  - The highest accelerations of the vehicle occurred for impact at 4'
    - Longitudinal direction = 24 g
    - Lateral direction = 27.3 g
    - Resultant = 36.6 g
  - Note: The occupant was not in contact with the vehicle interior at the time of peak vehicle accelerations, so maximum ORA values were not experienced during that event.
- Barrier damage was moderate and barrier deflections were considered low to moderate.
- The occupant risk metrics in these cases, are comparable to, but slightly higher, than those for the 3-Bar bridge rail.

General Conclusions Regarding MASH for test 4-20:

3-Bar Transition with 5.5’ Post Spacing Design 1

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

* Analysis stopped at 0.15 seconds, but vehicle stability is expected for all cases.

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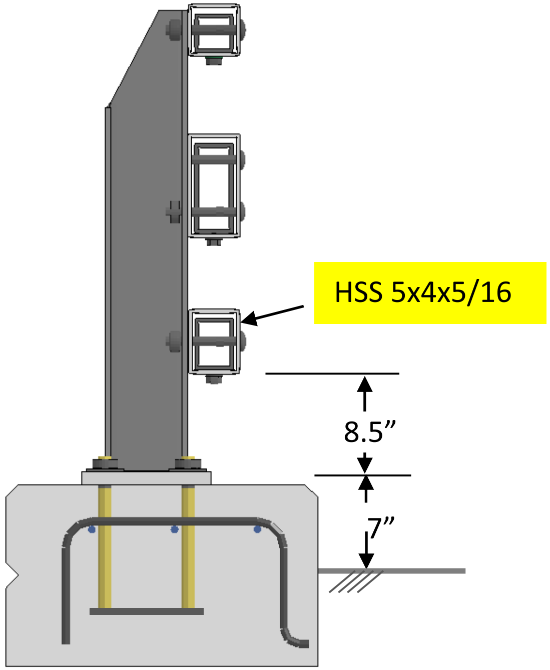
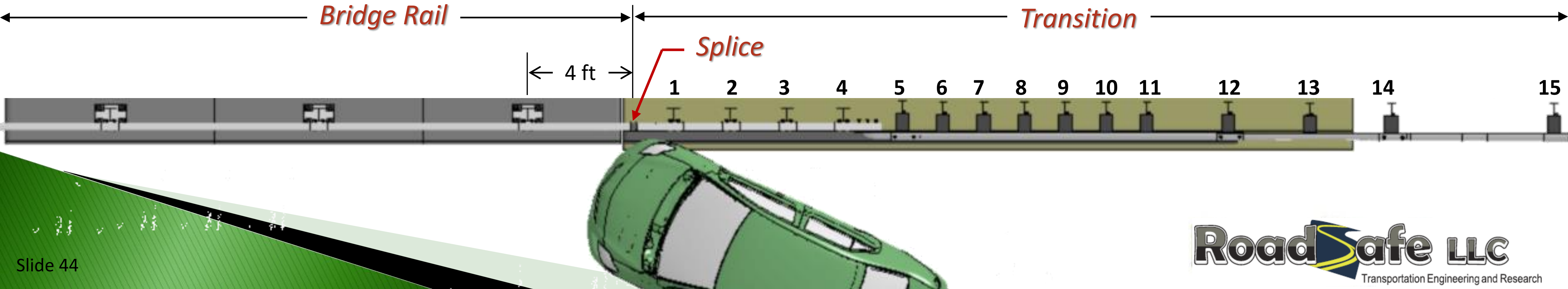
MASH Test 4-10 Simulation on Design 2 for the Modified NETC 3-Bar Transition

- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point = 4 ft upstream from critical Post (at splice)
- Vehicle Model
  - YarisC_V1l_R160407.k
  - Vehicle Mass = 1,177 kg (2,595 lb)





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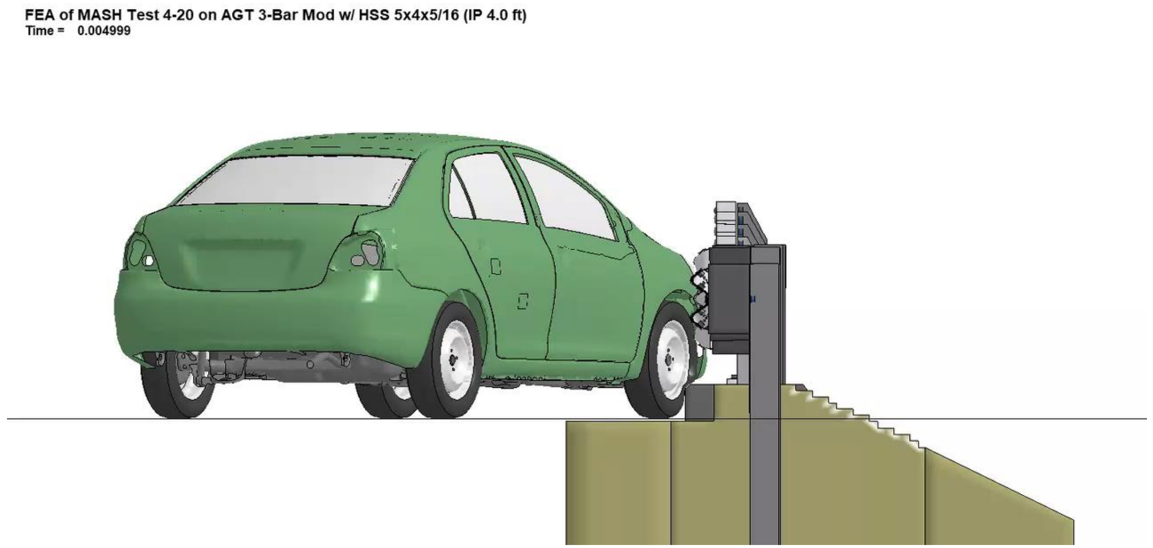

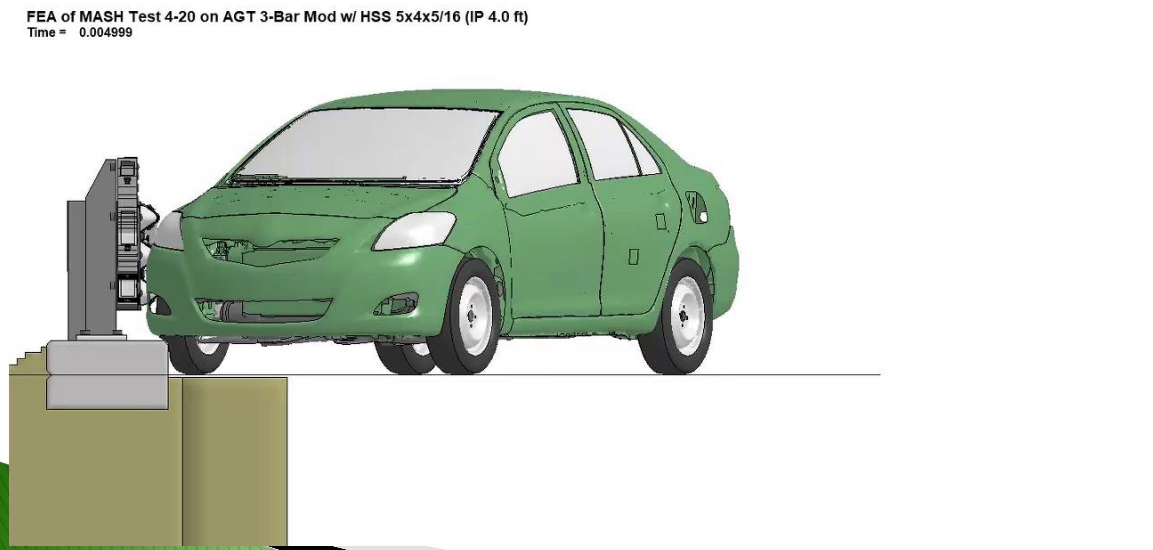

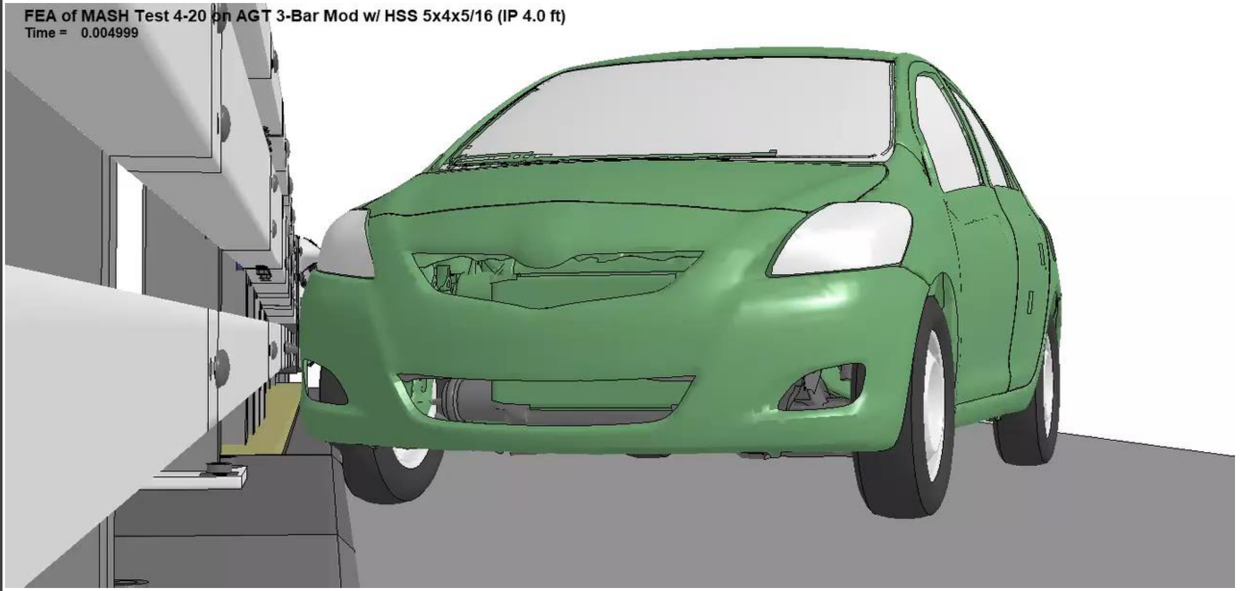

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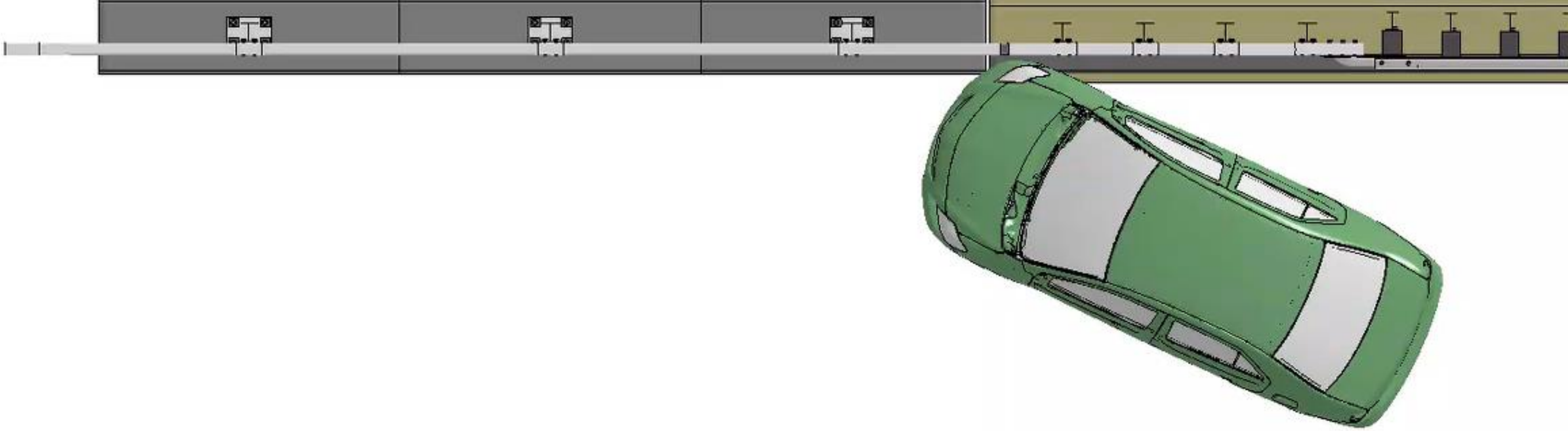
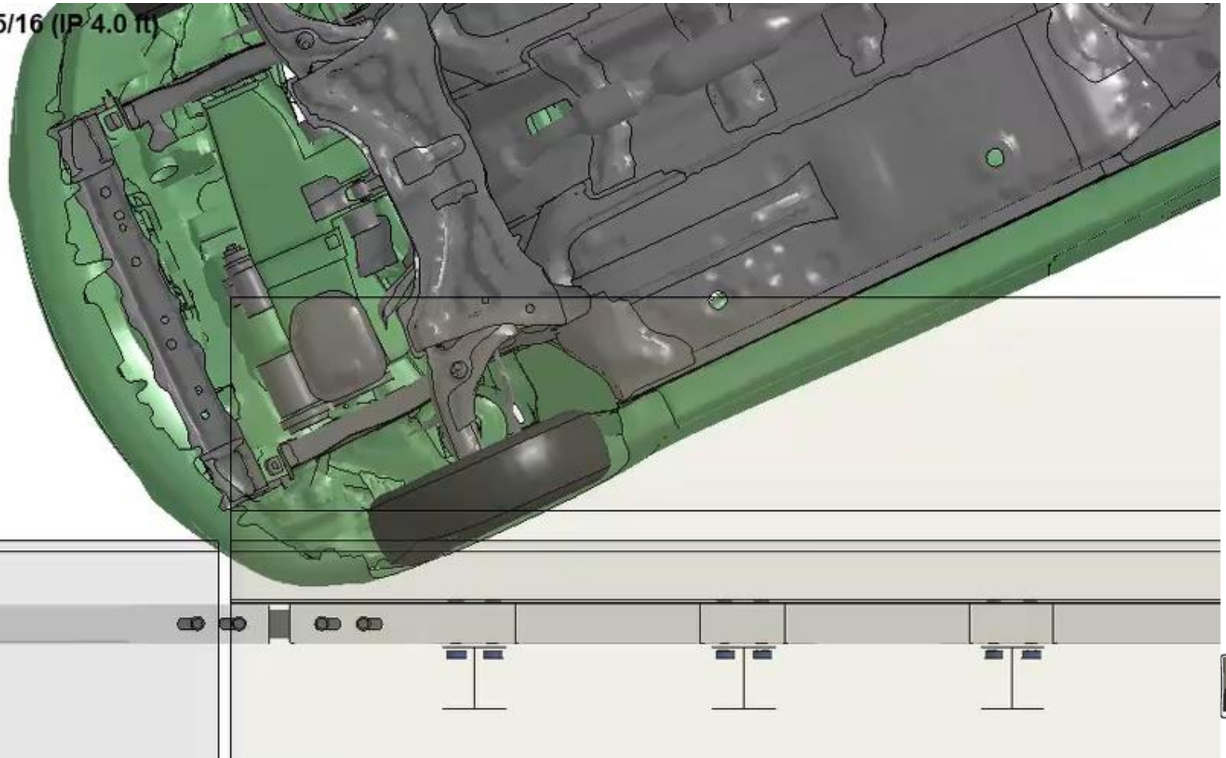
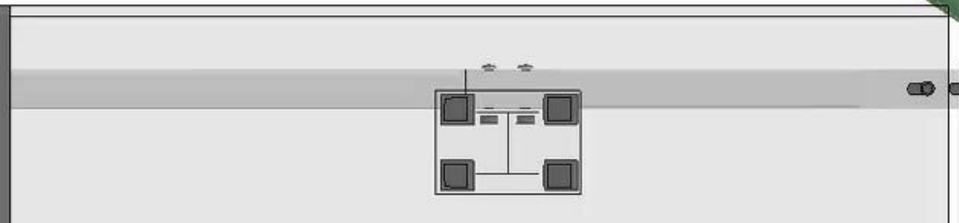
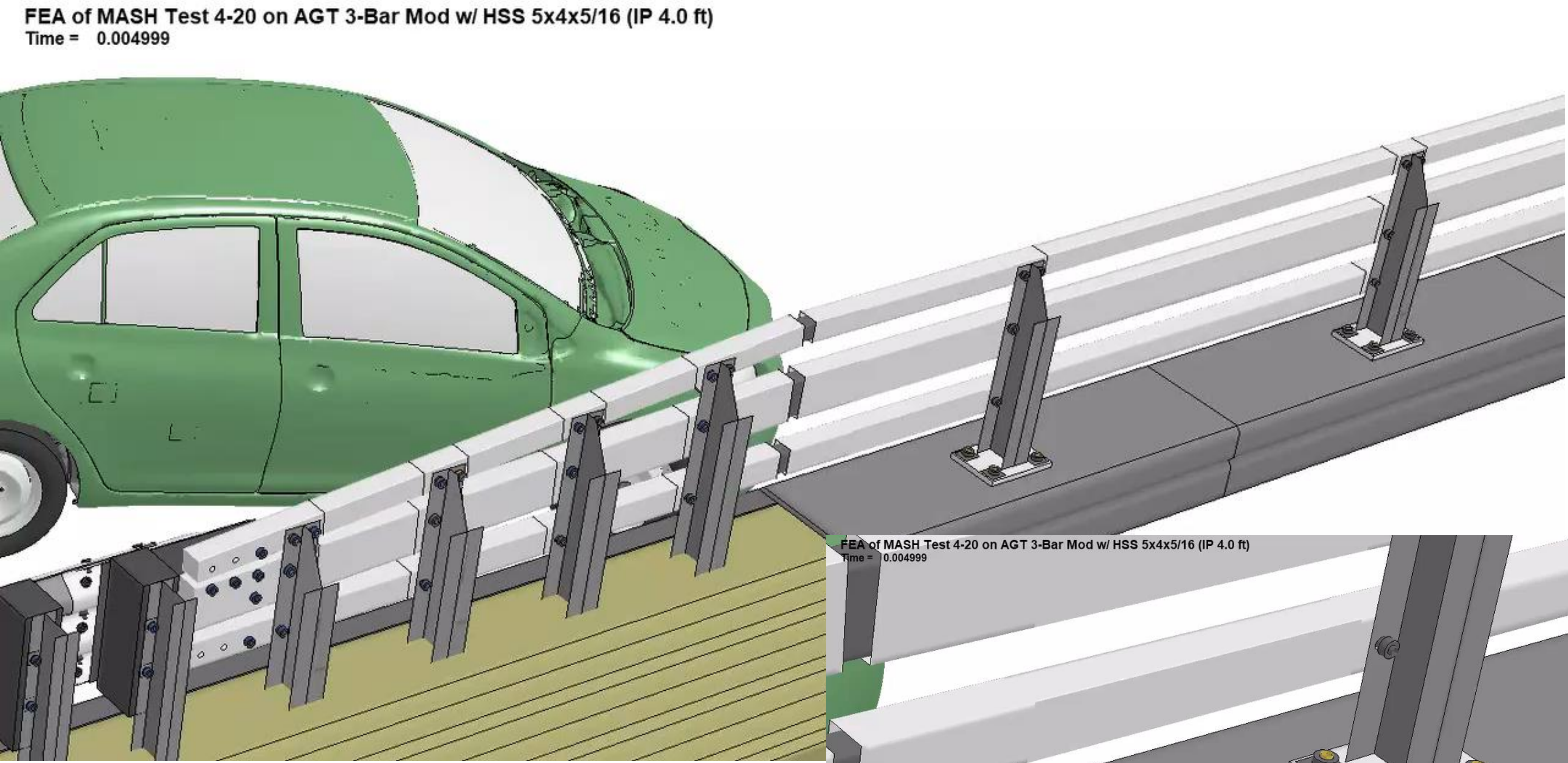


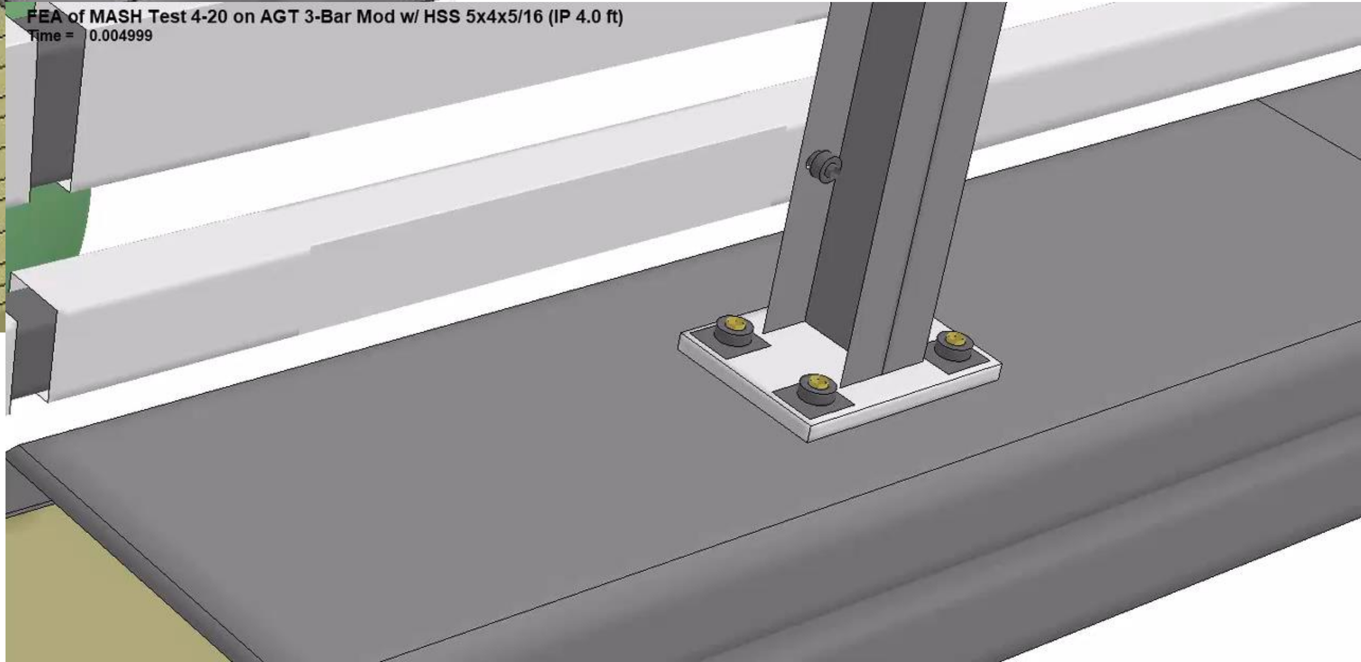
FEA of MASH Test 4-20 on AGT 3-Bar Mod w/ HSS 5x4x5/16 (IP 4.0 ft)
Time = 0.004999






FEA of MASH Test 4-20 on AGT 3-Bar Mod w/ HSS 5x4x5/16 (IP 4.0 ft)
Time =   0.004999


FEA of MASH Test 4-20 on AGT 3-Bar Mod w/ HSS 5x4x5/16 (IP 4.0 ft)
Time = 0.004999


FEA of MASH Test 4-20 on AGT 3-Bar Mod w/ HSS 5x4x5/16 (IP 4.0 ft)
Time = 0.004999

Occupant Risk Summary

Occupant Risk Factors		MASH Design 1	MASH Design 2
Occupant Impact Velocity (ft/s)	x-direction	25.3	23.6
	y-direction	33.1	32.8
	at time	at 0.0788 seconds on right side of interior	at 0.0776 seconds on right side of interior
THIV (ft/s)		41.7 at 0.0788 seconds on right side of interior	40.7 at 0.0776 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-4.9 (0.0806 - 0.0906 seconds)	-3.7 (0.0804 - 0.0904 seconds)
	y-direction	2.9 (0.0901 - 0.1001 seconds)	-7.9 (0.1972 - 0.2072 seconds)
PHD (g's)		5.3 (0.0798 - 0.0898 seconds)	8.2 (0.1966 - 0.2066 seconds)
ASI		2.53 (0.0251 - 0.0751 seconds)	2.49 (0.0241 - 0.0741 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-14 (0.0247 - 0.0747 seconds)	-13.5 (0.0242 - 0.0742 seconds)
	y-direction	-20.2 (0.0252 - 0.0752 seconds)	-20 (0.0241 - 0.0741 seconds)
	z-direction	-3.1 (0.0621 - 0.1121 seconds)	-2.7 (0.0607 - 0.1107 seconds)
Maximum Angular Disp. (deg)	Roll		4.4 (0.5013 seconds)
	Pitch		-5.1 (0.3851 seconds)
	Yaw		-39.4 (0.4683 seconds)

MASH Criteria

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

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

< 75 deg ✓

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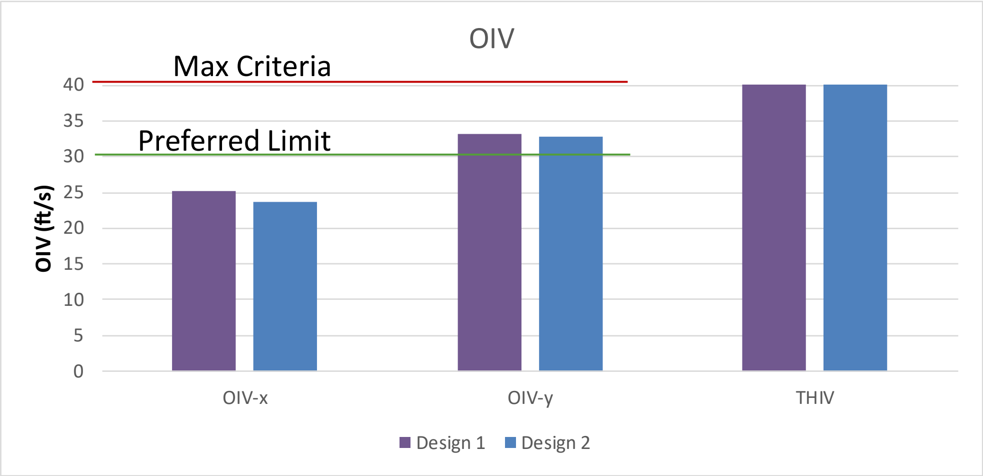
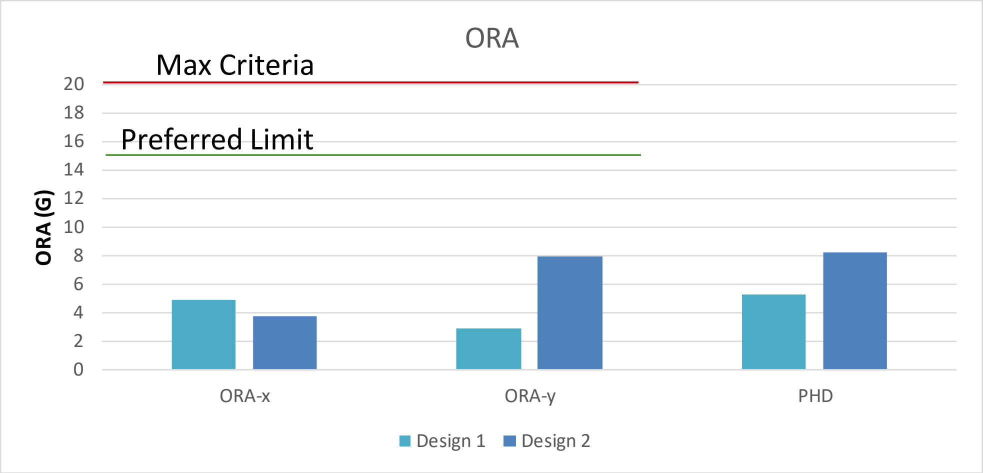
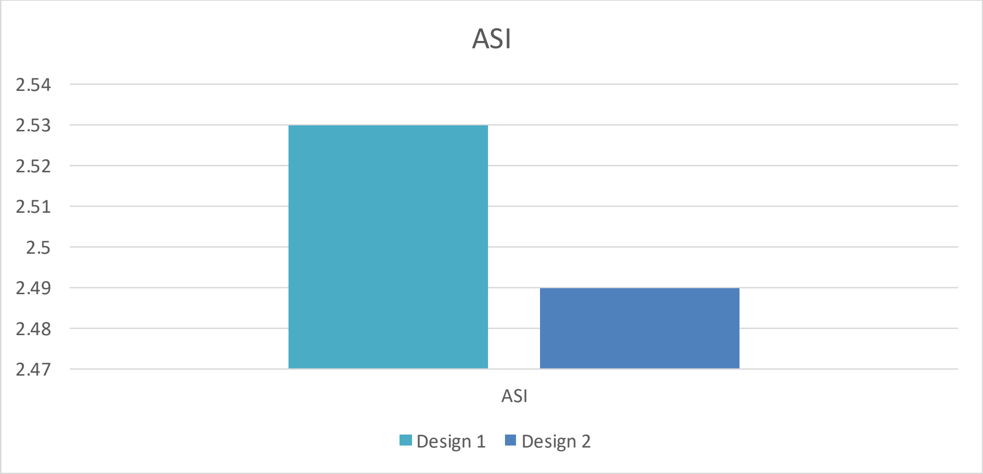
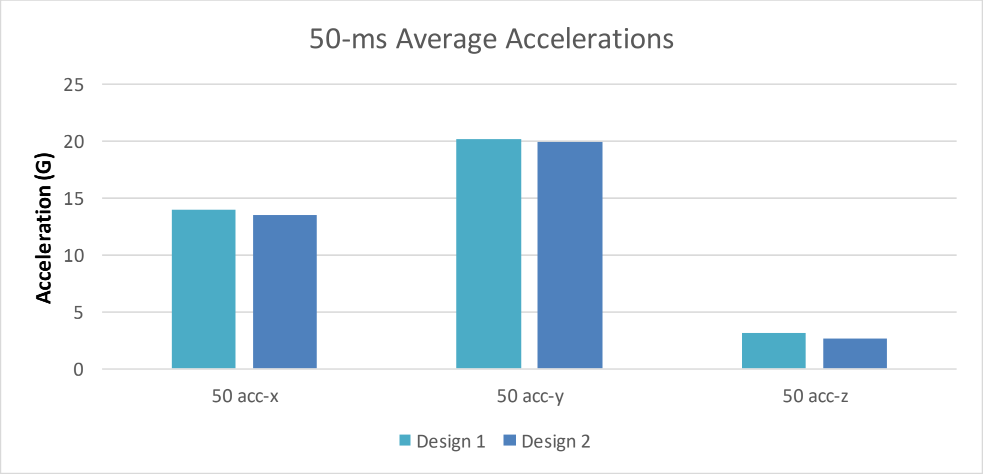
TRAP









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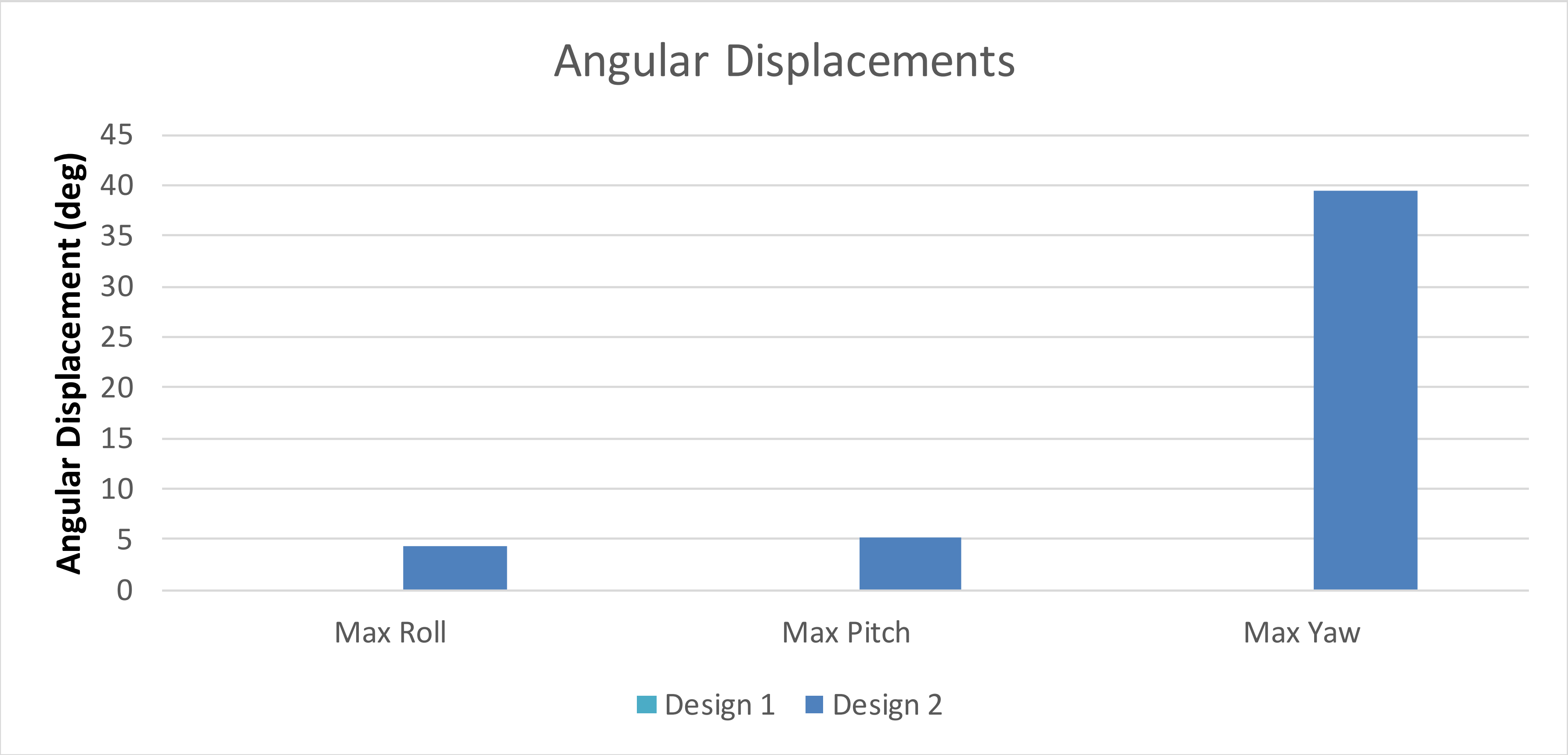
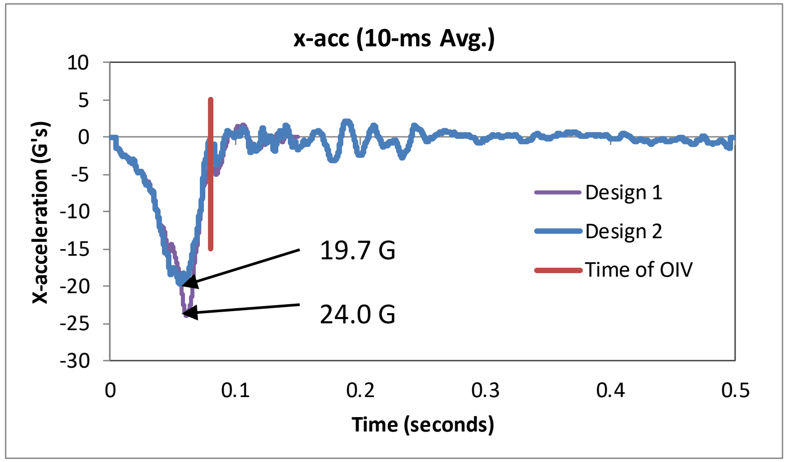
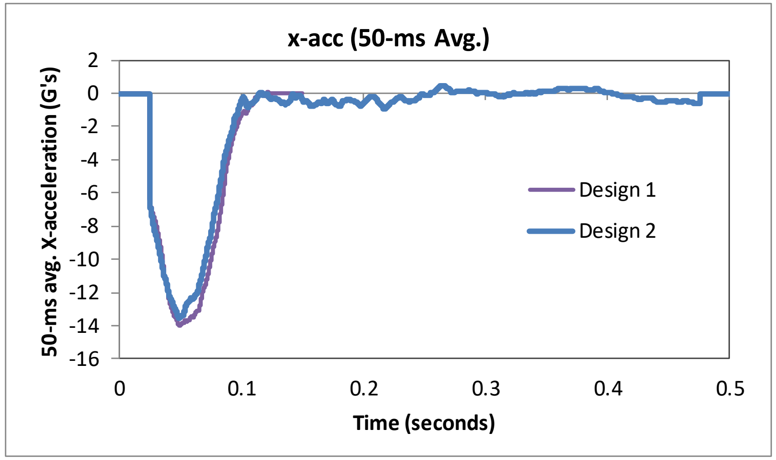
TRAP

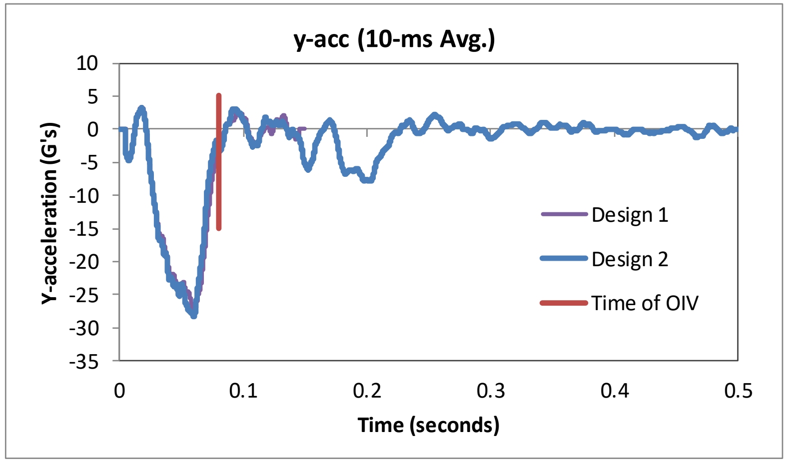


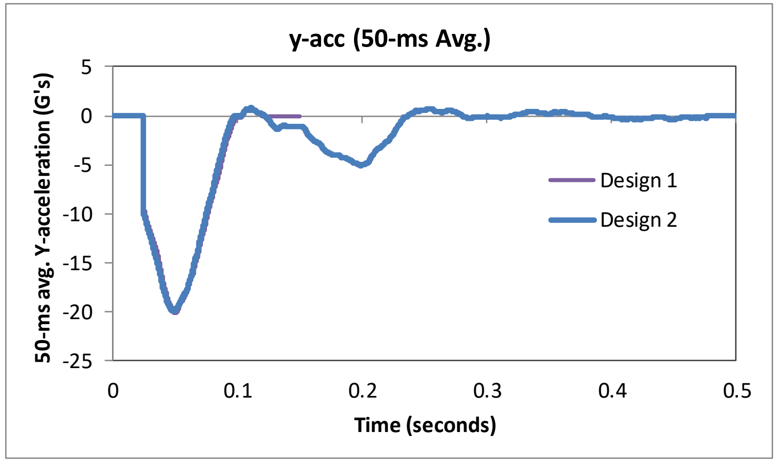
Angular Displacements
Angular Displacement (deg)
45
40
35
30
25
20
15
10
5
0
Max Roll
Max Pitch
Max Yaw
Design 1
Design 2

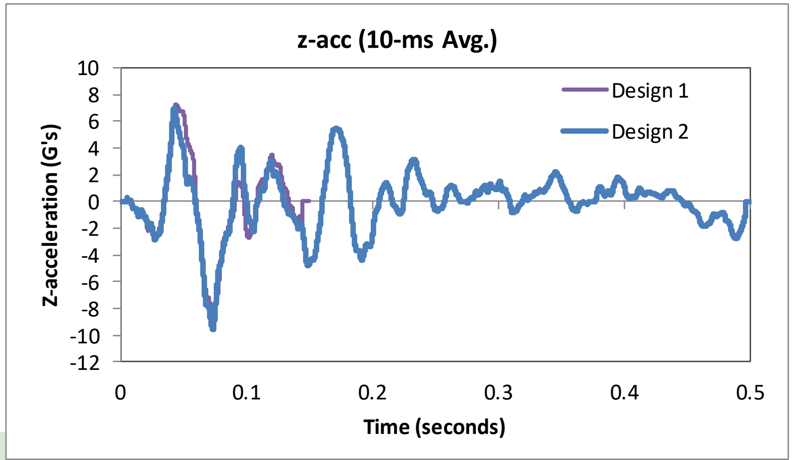
Acceleration Plots

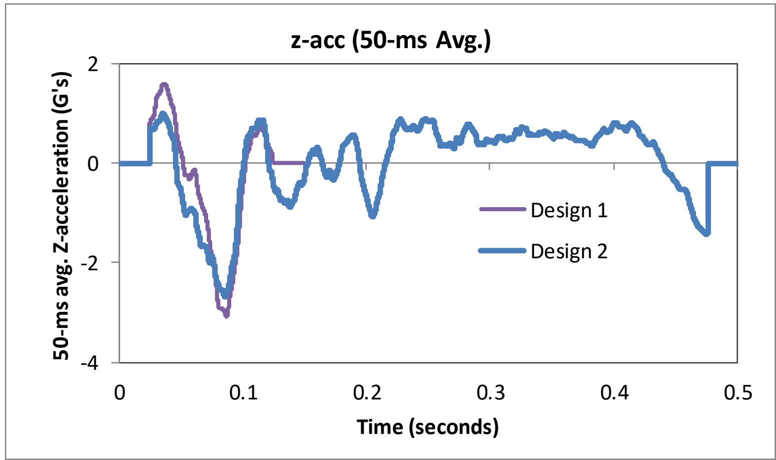




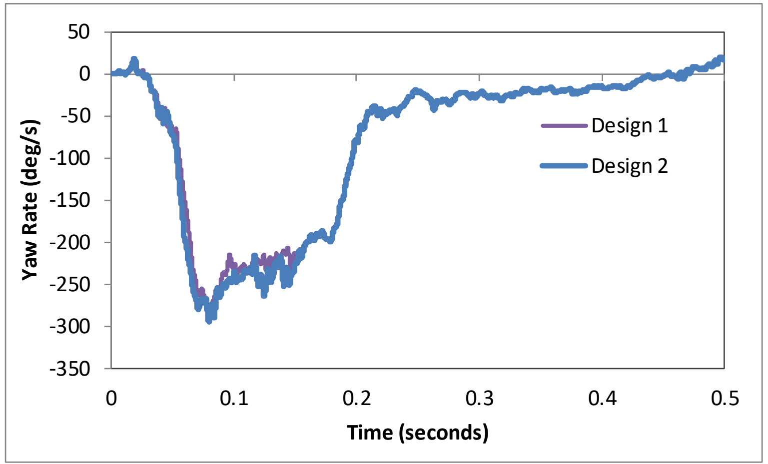


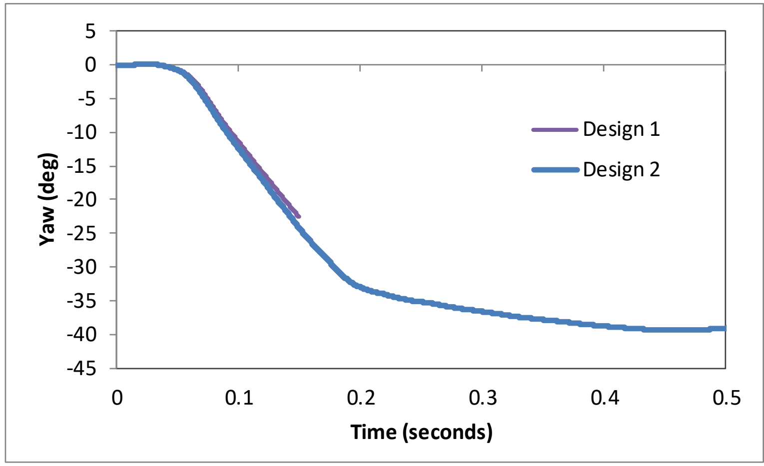


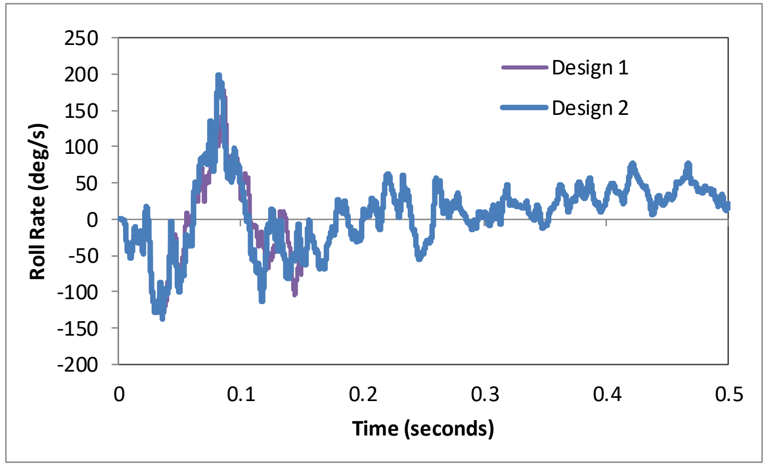


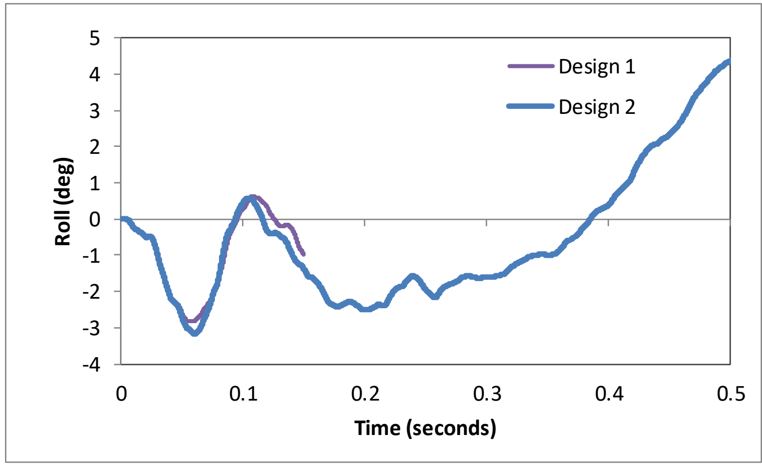


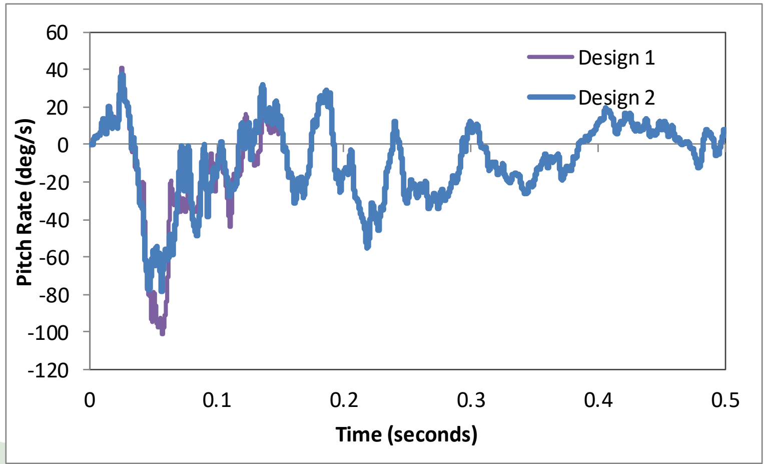
Angular Rate and Displacement Plots

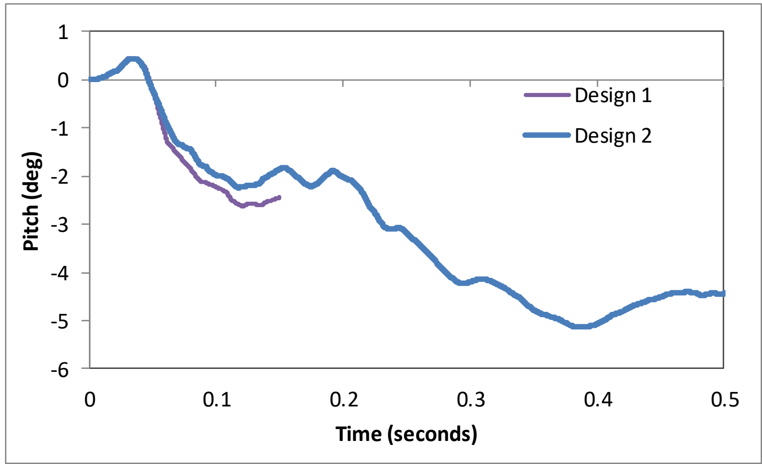






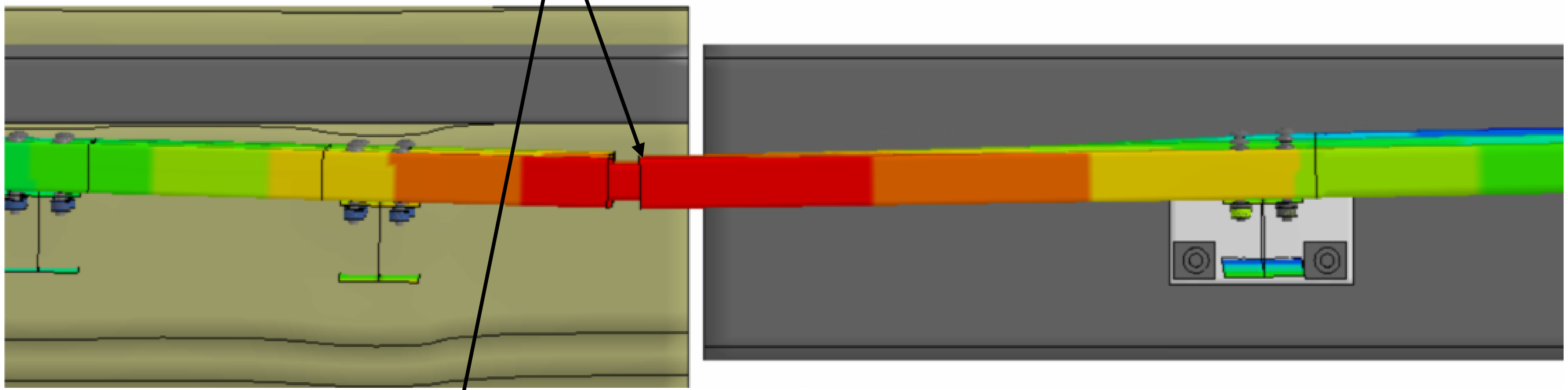


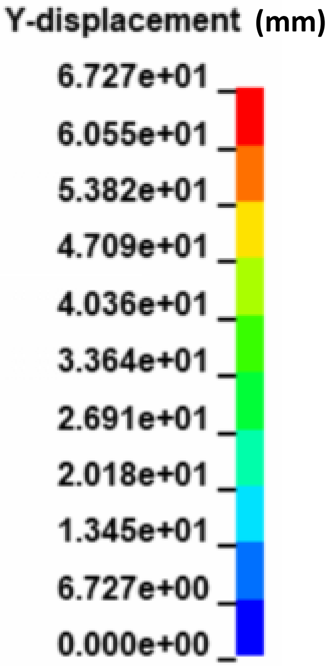


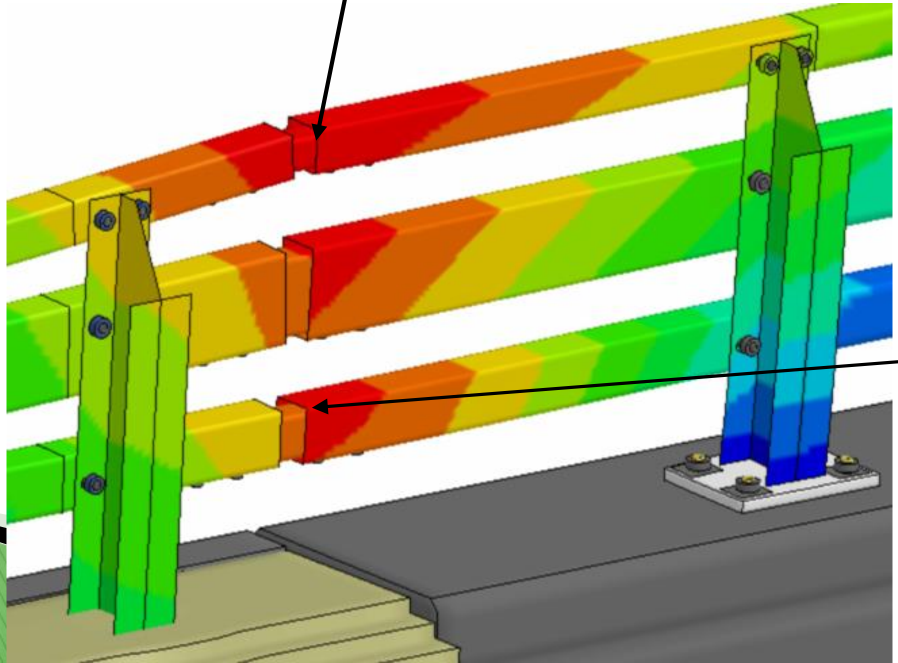


Lateral Dynamic Deflection

Maximum dynamic deflection = 2.65 in (67.3 mm) at 0.06 seconds
Maximum permanent deflection = 1.36 in (34.6 mm)







Peak dynamic deflection of lower rail = 2.44 in
Permanent deflection = 1 in

Compare to Design 1 (HSS 4x4x1/4) with:
Peak dynamic = 3.25 in
Permanent = 1.52 in

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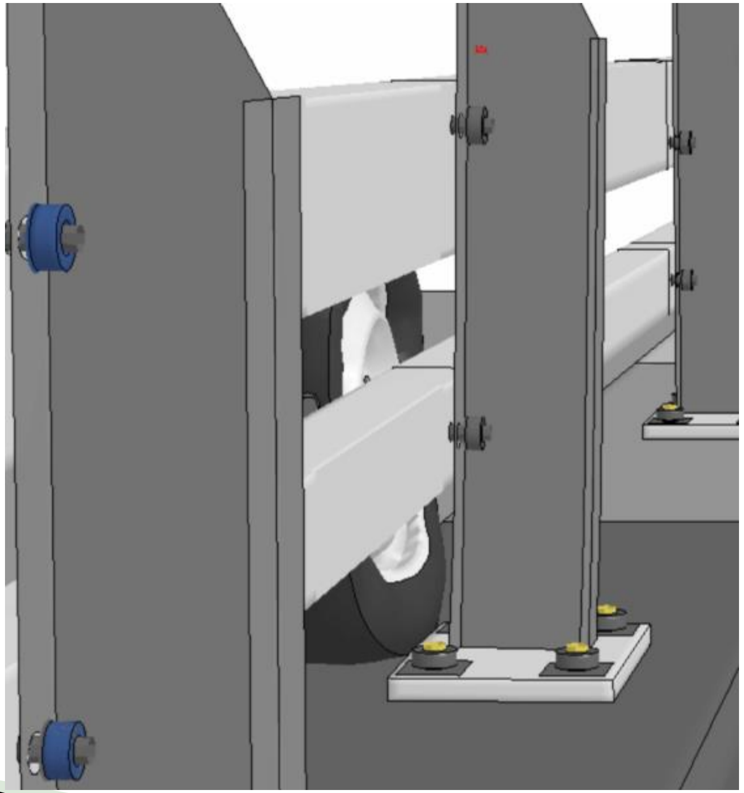
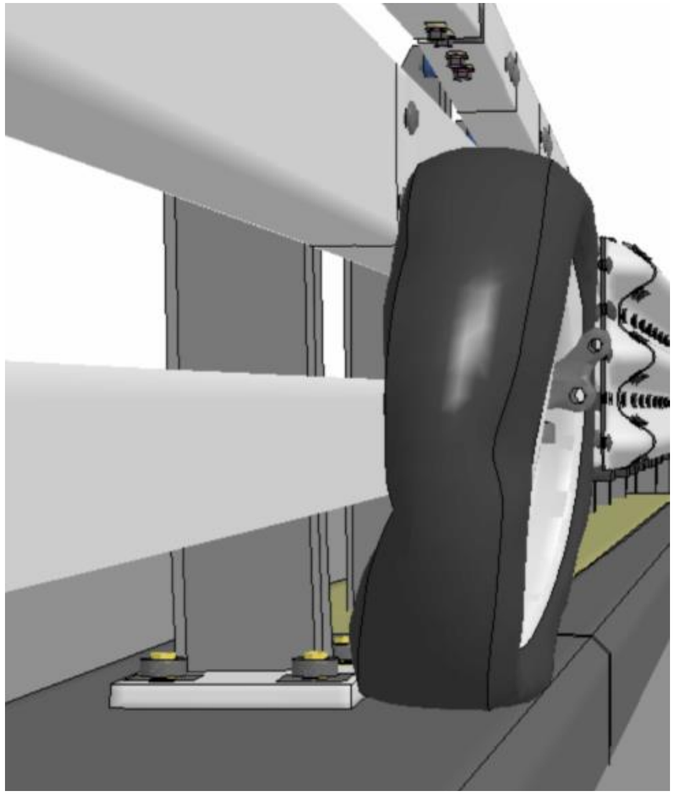
Assessment of Potential Vehicle Contact with Post

- The results of the analysis indicated that the tire would <u>not</u> contact the post during impact.





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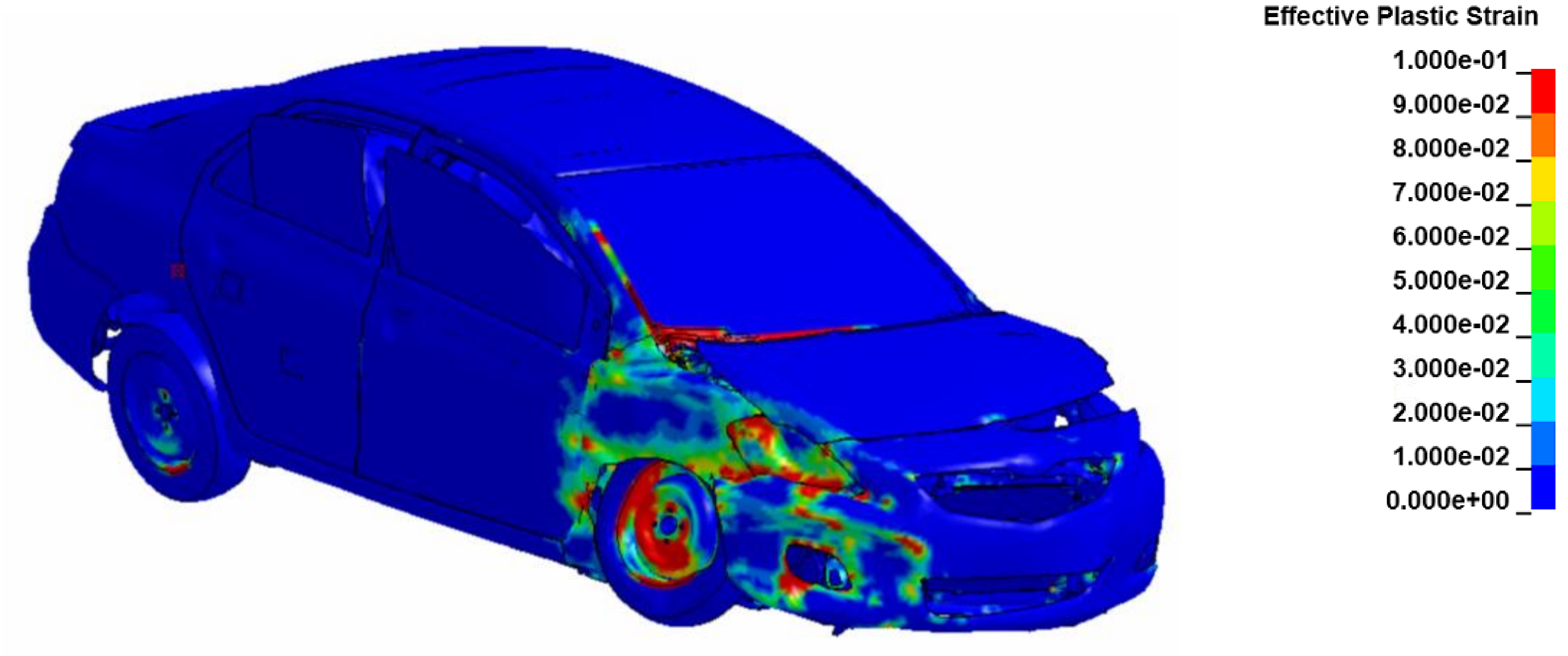
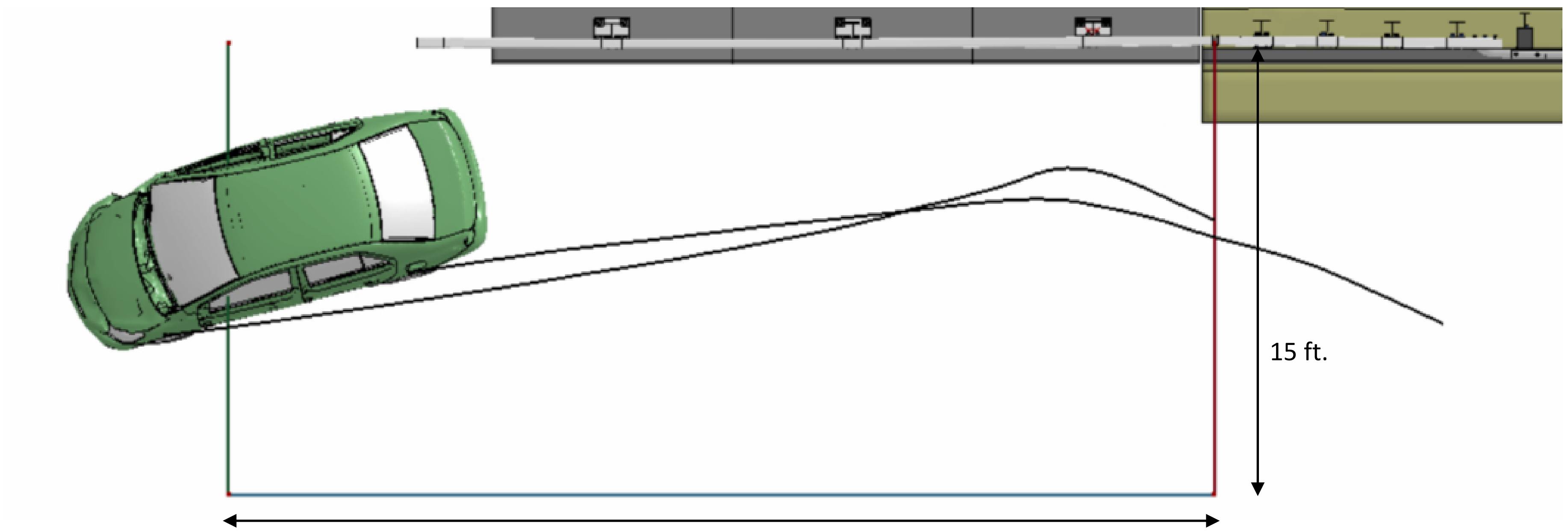
Effective Plastic Strain for Small Car Test



Damages to vehicle were similar to those for the Bridge Rail case. The most severe damages were to the front fender, the upper and lower control arm of front suspension, front wheel, lower- impact edge of windshield (cracking), the rear wheel, and the quarter panel of the vehicle on the impact side.

Exit Box

The driver-side front tire wheel track was used to determine the beginning location of the exit box. From MASH pg. 97: “All wheel tracks of the vehicle should not cross the parallel line within the distance B.”



Conclusions Regarding Test 4-20 on the 3-Bar Transition

- The barrier successfully contained and redirected the 1100P vehicle.
- The vehicle remained upright and stable through impact and redirection, with relatively low angular displacements
  - Max Roll = **4.4 degrees** and Max Pitch = **5.1 degrees**.
- The OIV and ORA were within critical limits specified in MASH.
  - OIV_x = **23.6 ft/s** and OIV_y = **32.8 ft/s**
  - ORA_x = **3.7 G** and ORA_y = **7.9 G**
- The vehicle also **remained within the "exit box"** limits.
- Barrier deflections and damage were minimal to low.
- The greatest deformation of the barrier occurred at the top rail at the expansion splice and was:
  - Max Dynamic = **2.65 inches**; Max Permanent = **1.36 inche**s
  - i.e., approximately 25% less than the baseline case with the HSS 4x4x1/4 rail

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Conclusions on Test 4-20 on the 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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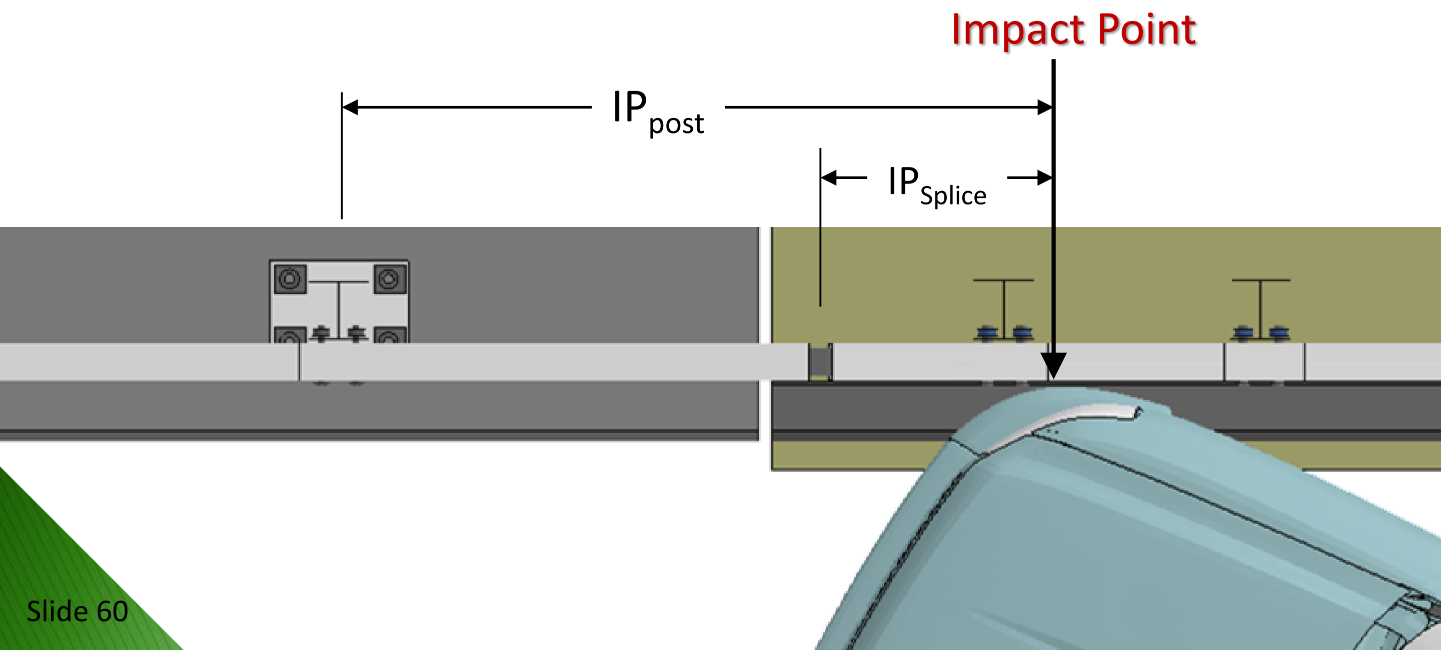
Determination of CIP for Test 4-21

- CIP was determined using FEA with respect to maximizing potential for wheel snag on the first post of the bridge rail and on the splice connection.
- Original system Design 1) with expansion splice gap = 2” (see Slide 29).



- Analysis cases evaluated:

IP	IP_{post} (ft)	IP_{Splice} (ft)
IP5.0	5.0	1.0
IP6.0	6.0	2.0
IP7.0	7.0	3.0
IP8.0	8.0	4.0
IP9.0	9.0	5.0

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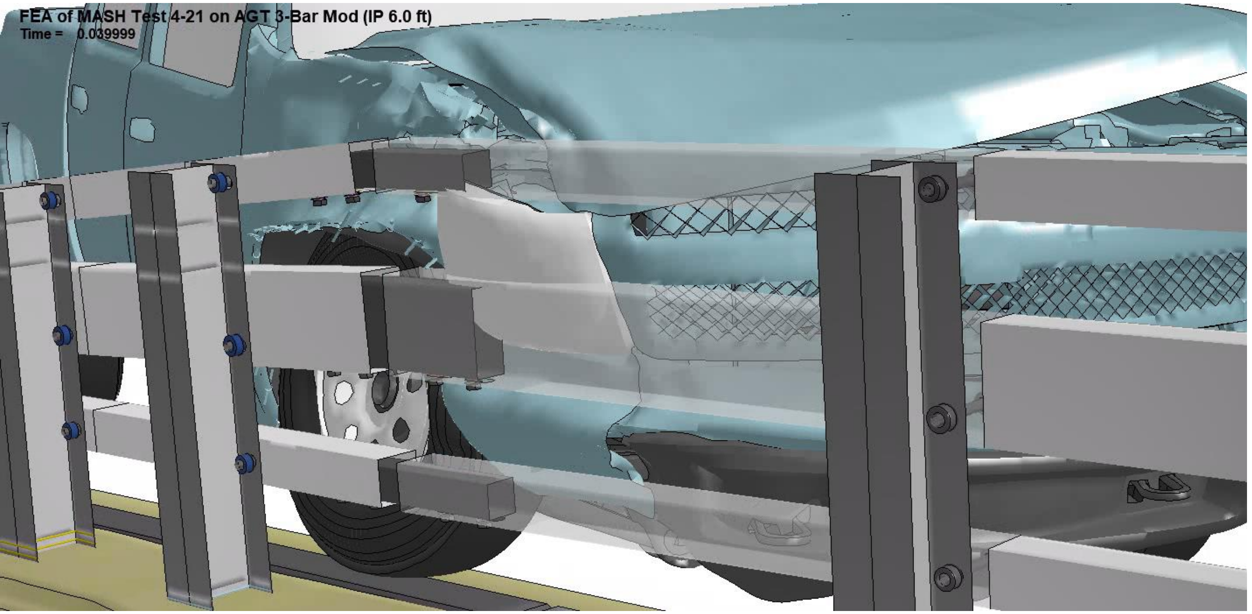
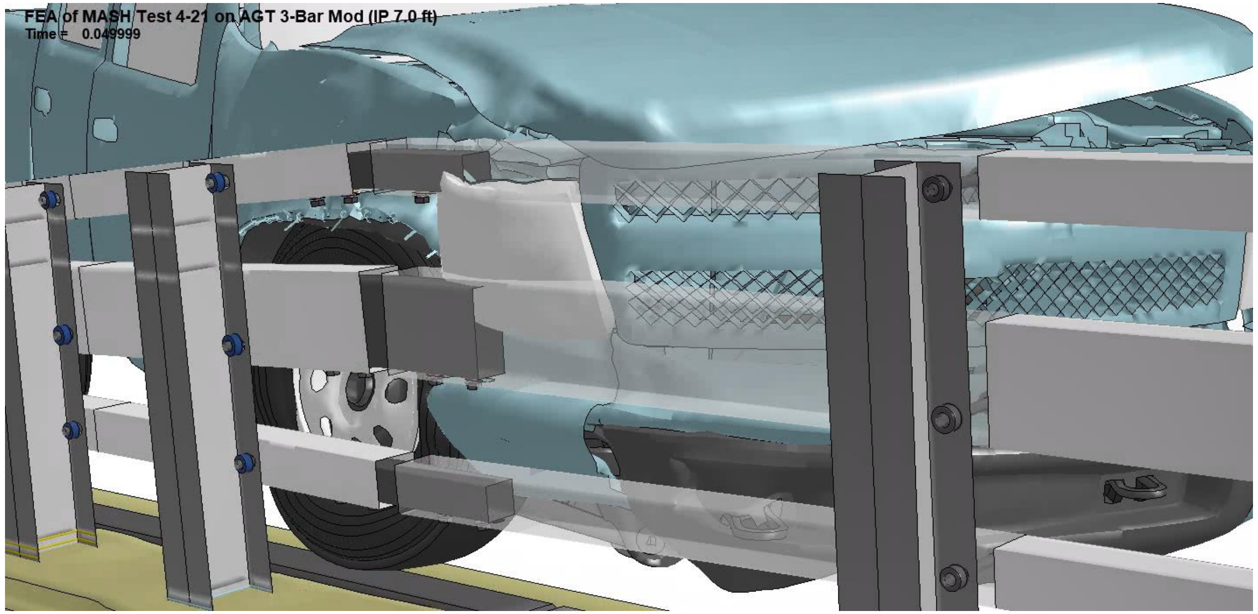
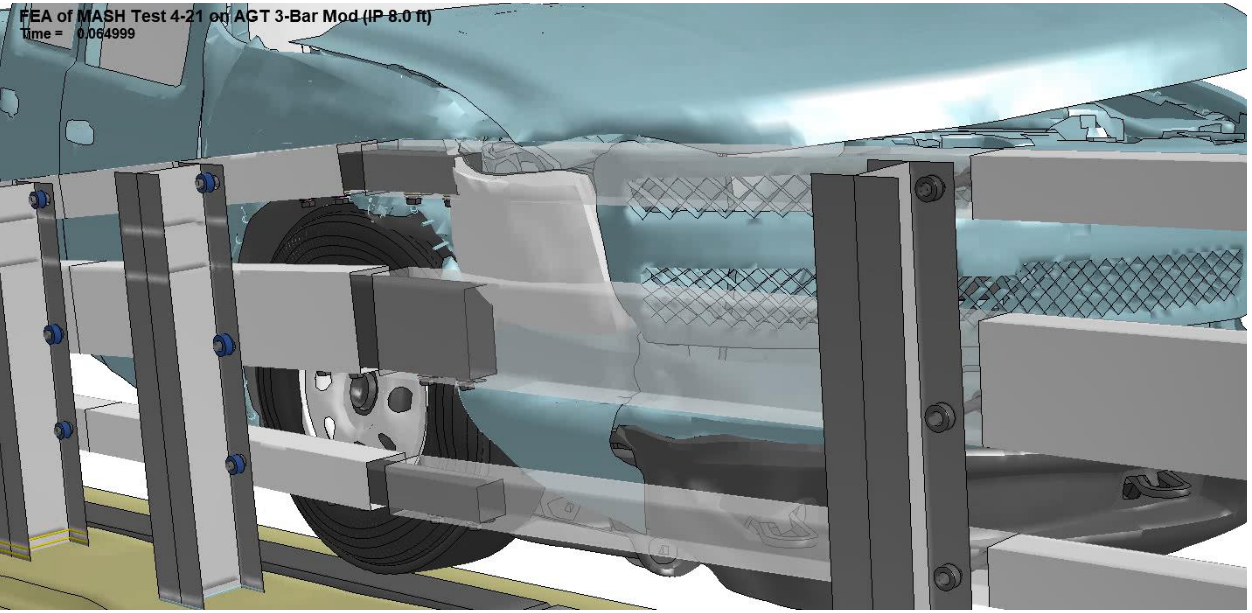
IP 6.0 ft



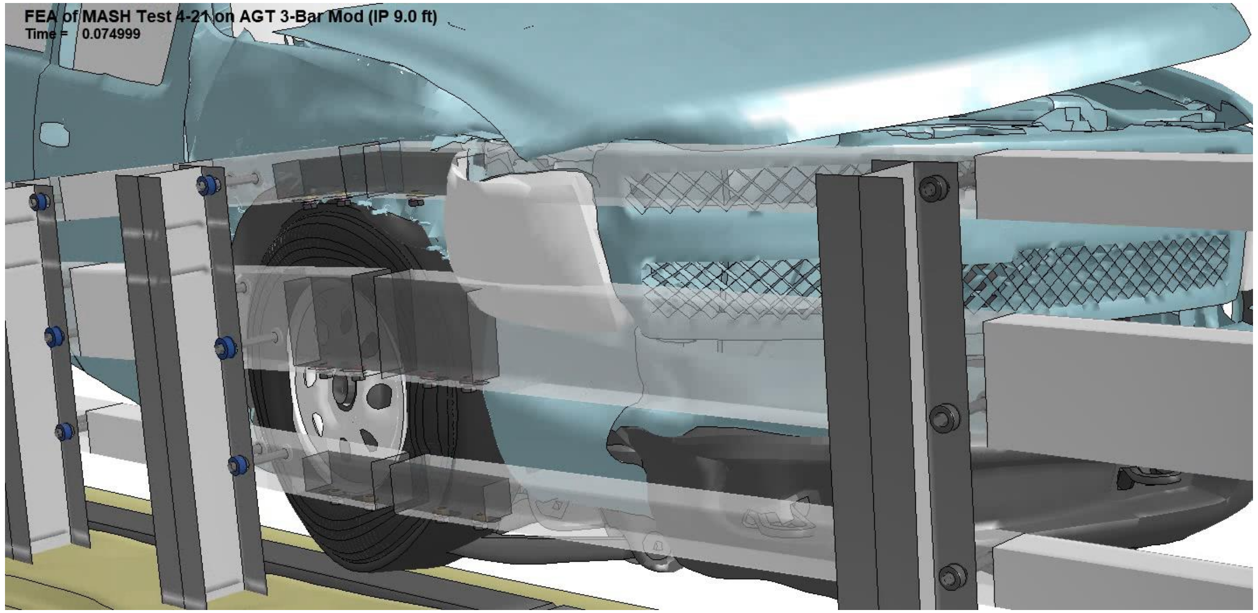
IP 7.0 ft



IP 8.0 ft



IP 9.0 ft



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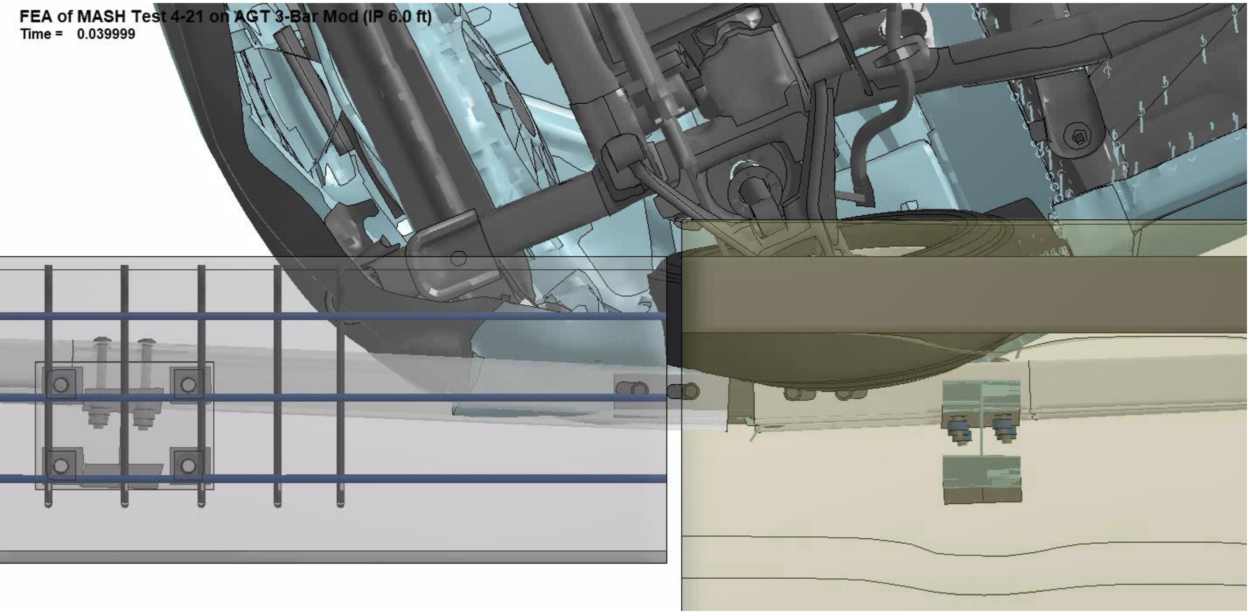

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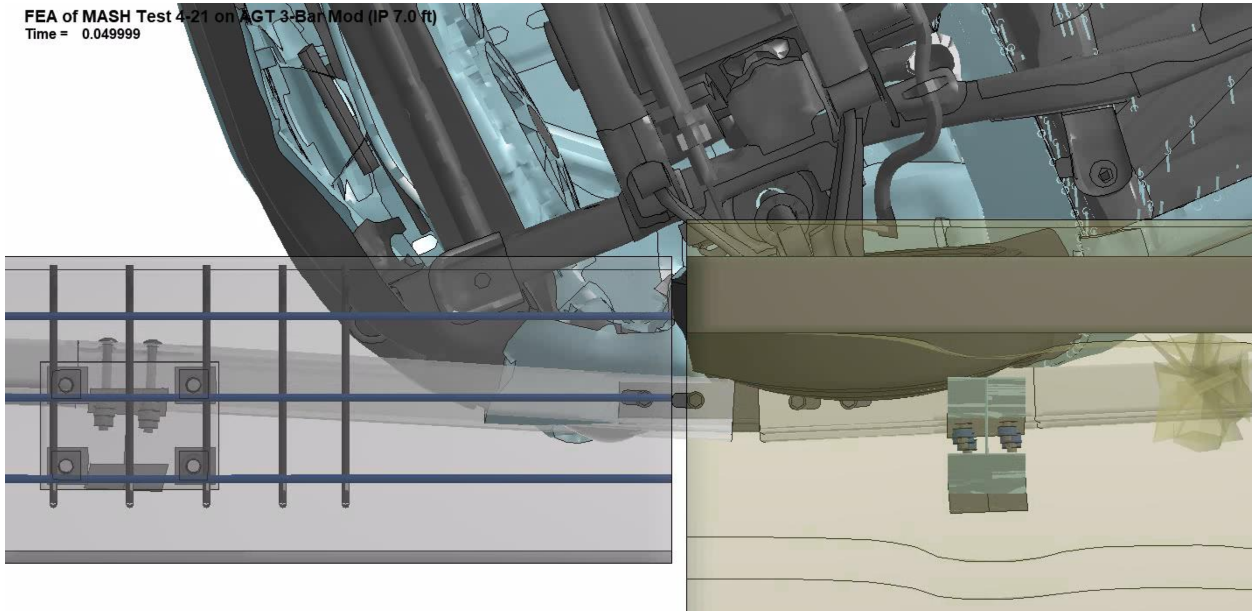
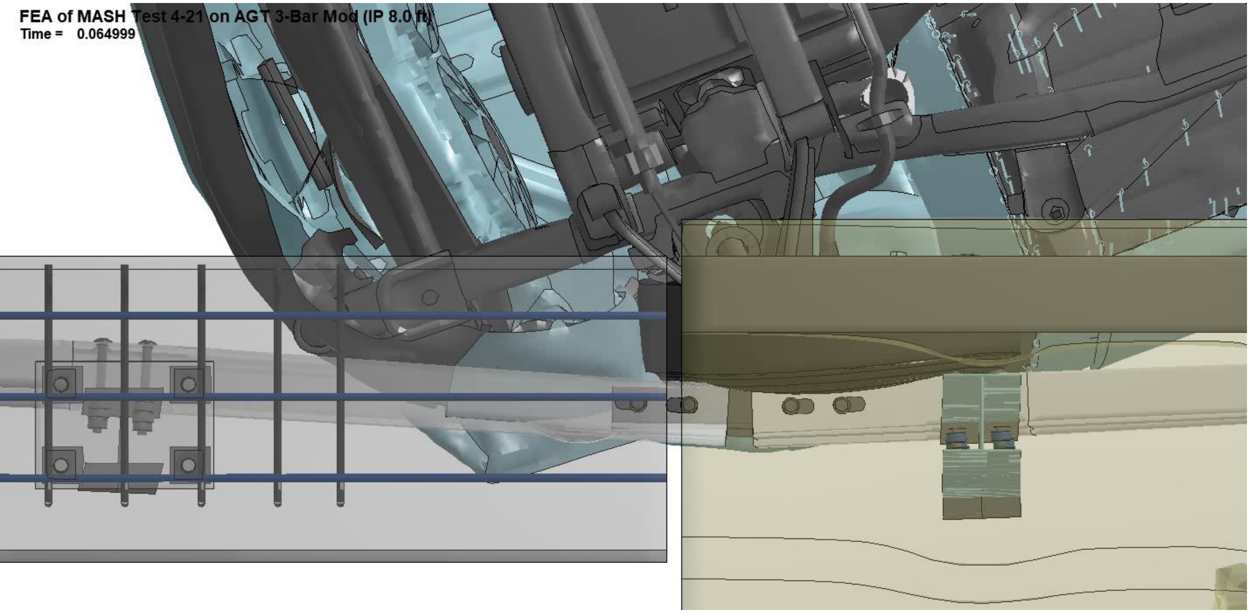
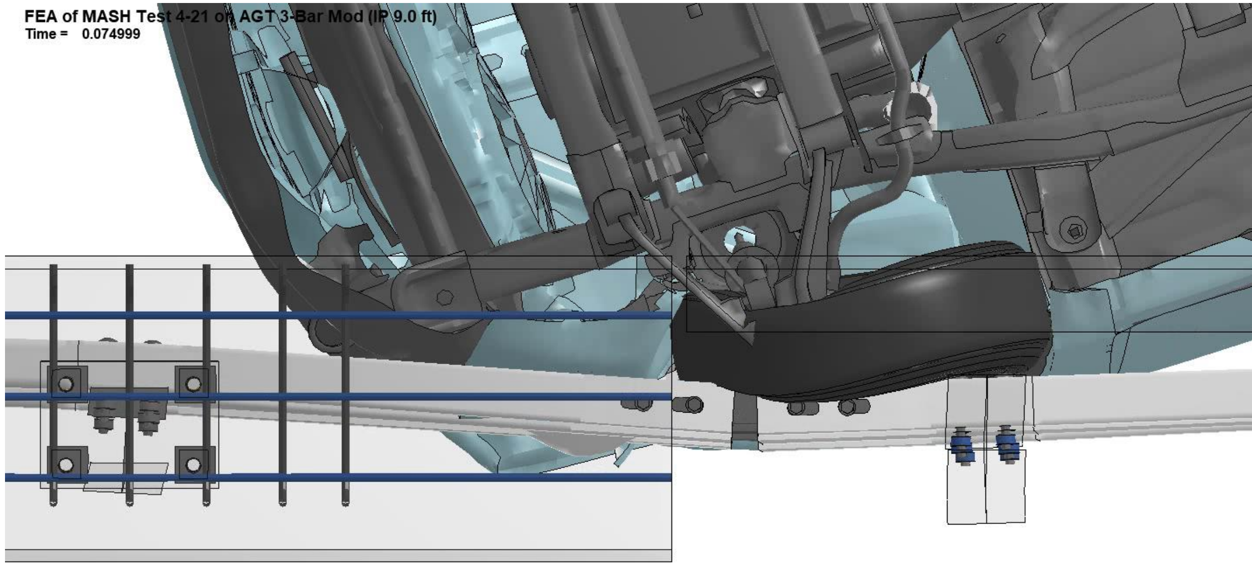


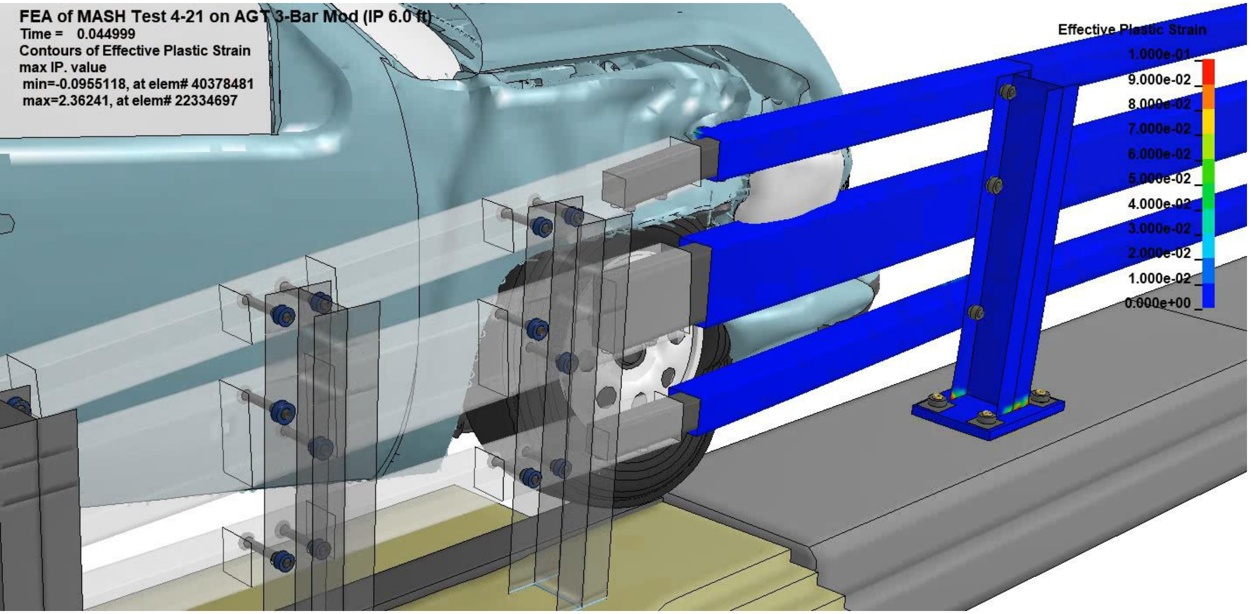
IP 8.0 ft



IP 9.0 ft



IP 6.0 ft



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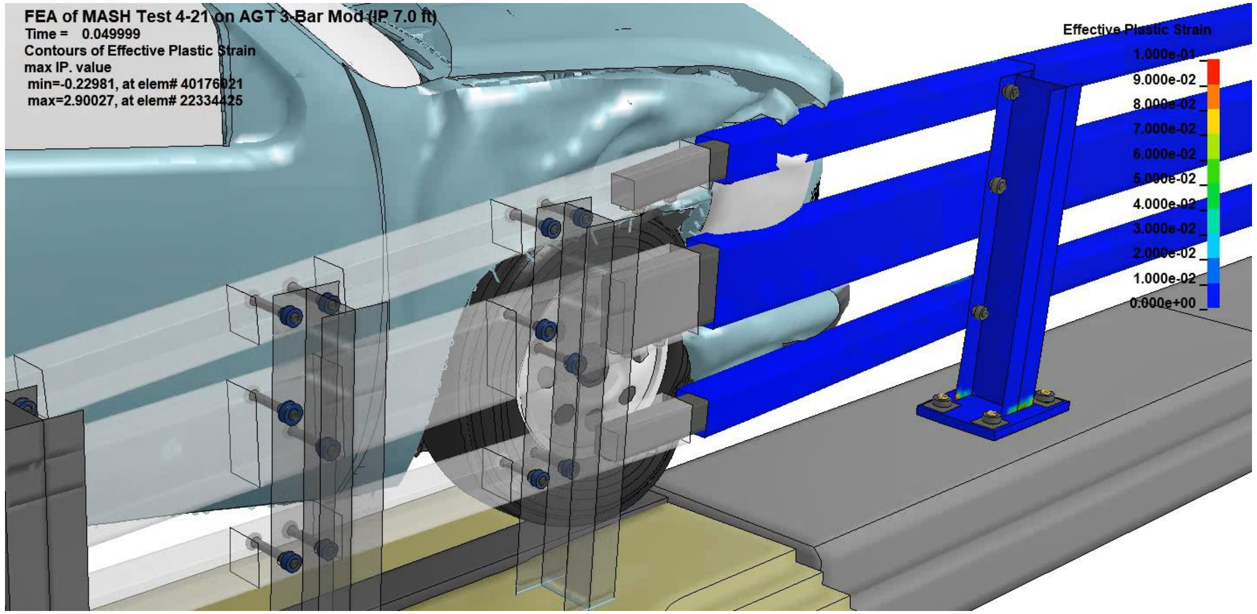
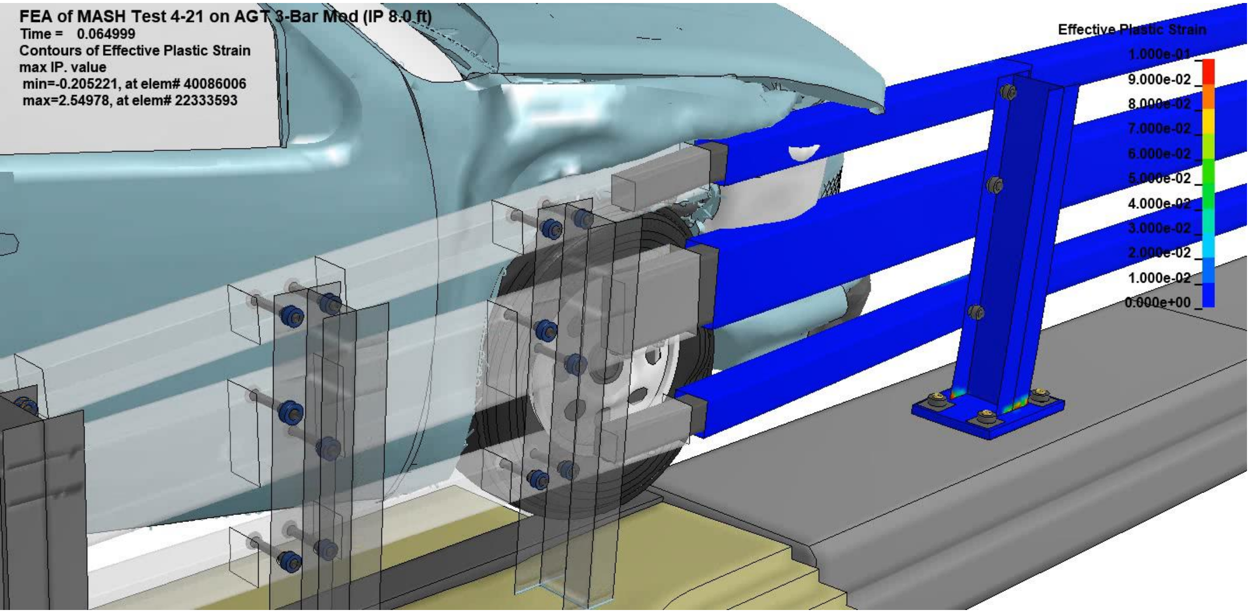


IP 8.0 ft



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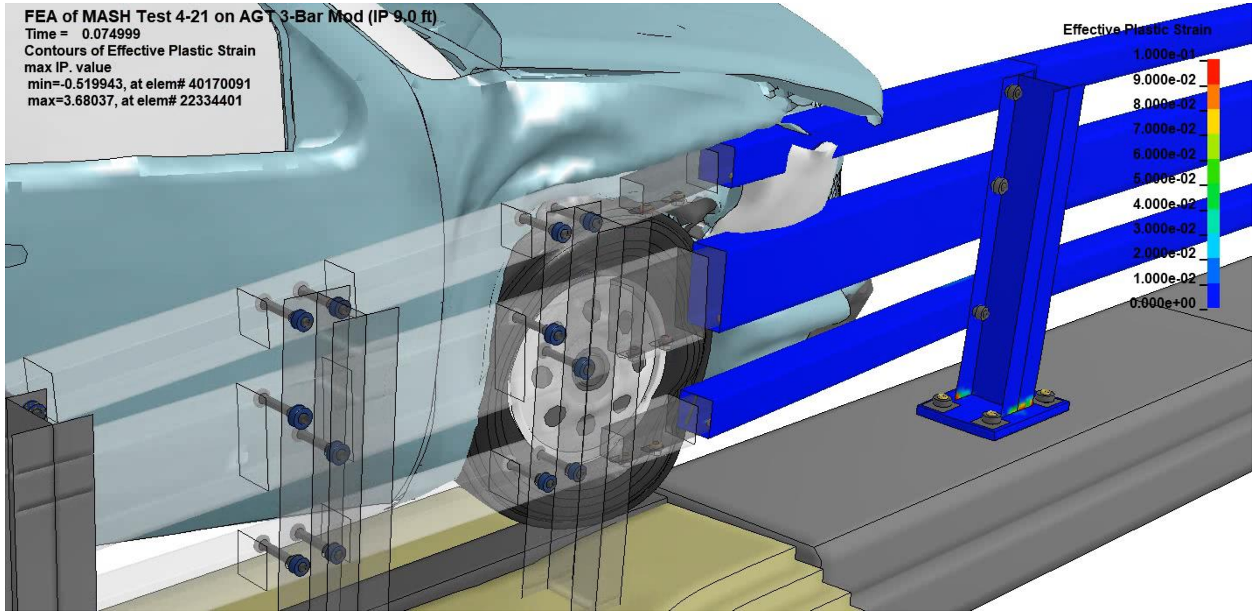

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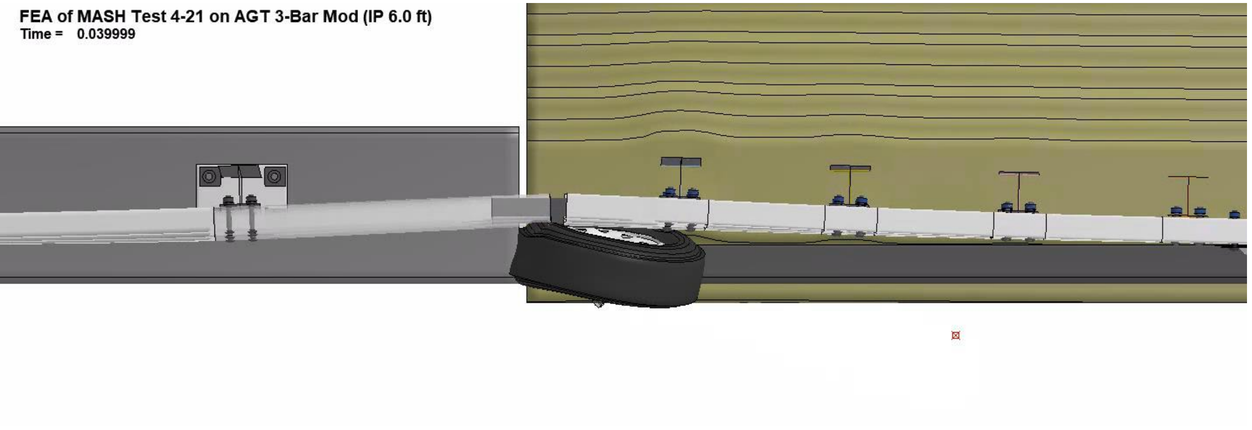
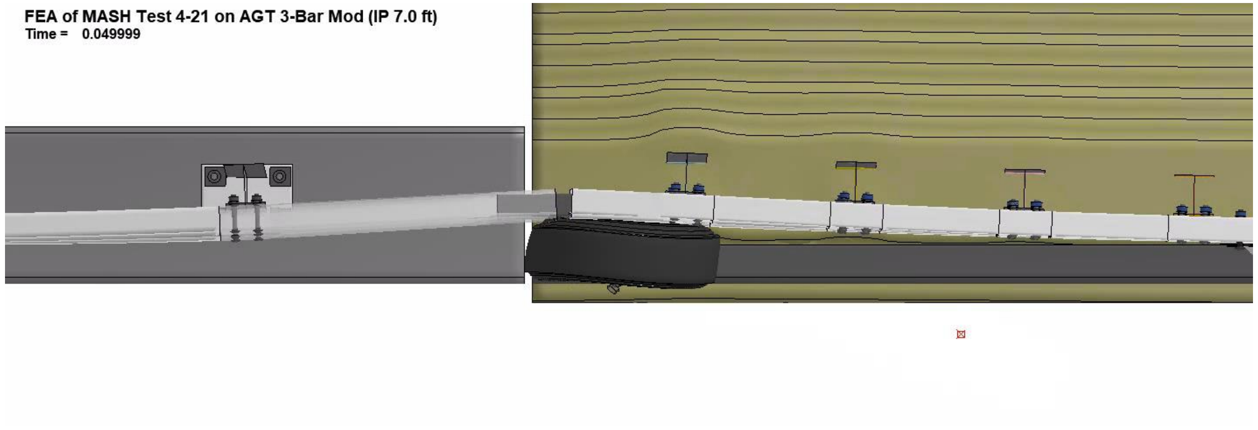
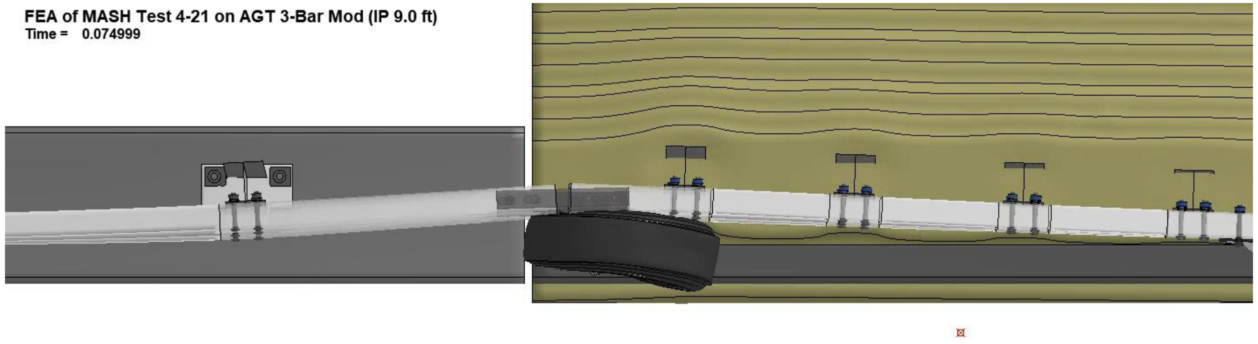


IP 7.0 ft



IP 8.0 ft

IP 9.0 ft



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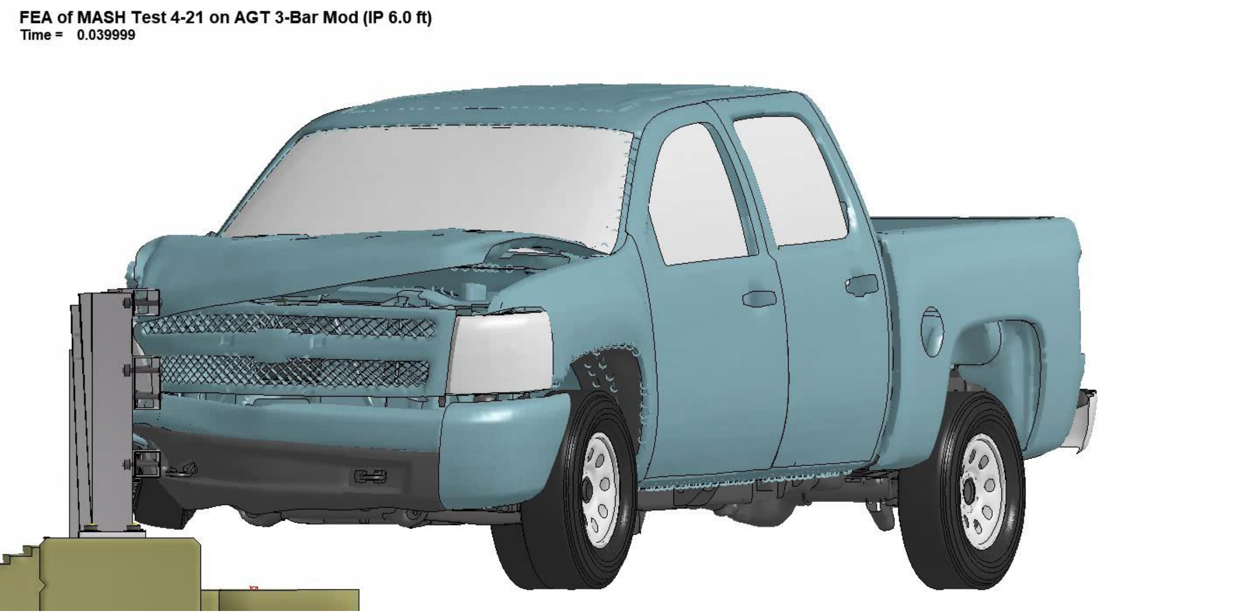
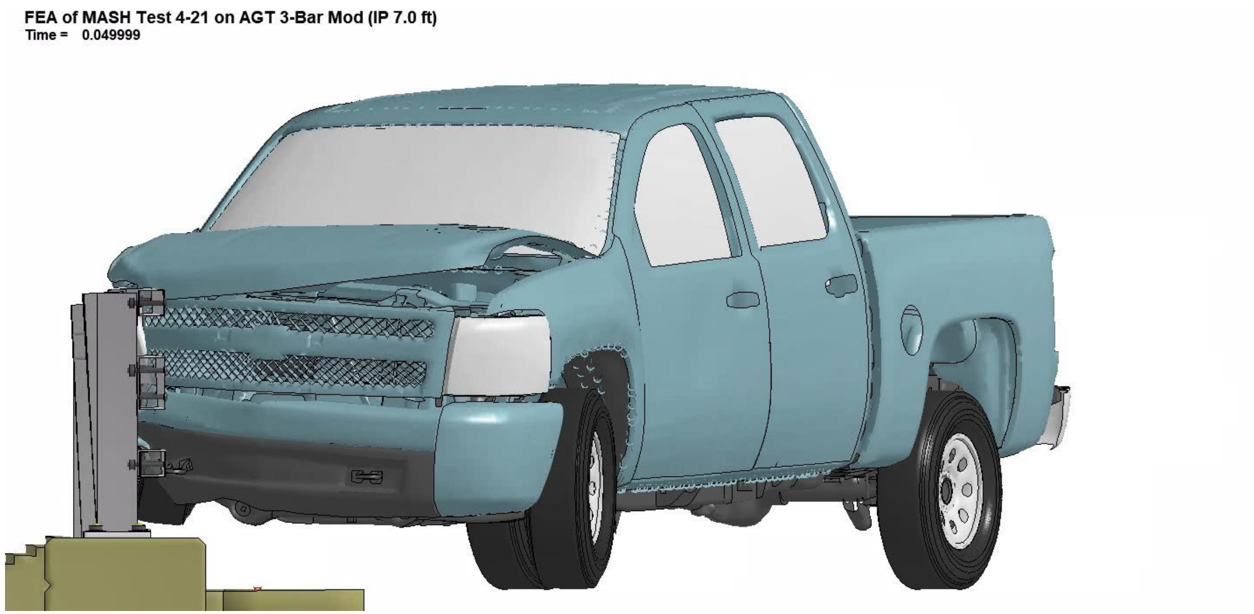
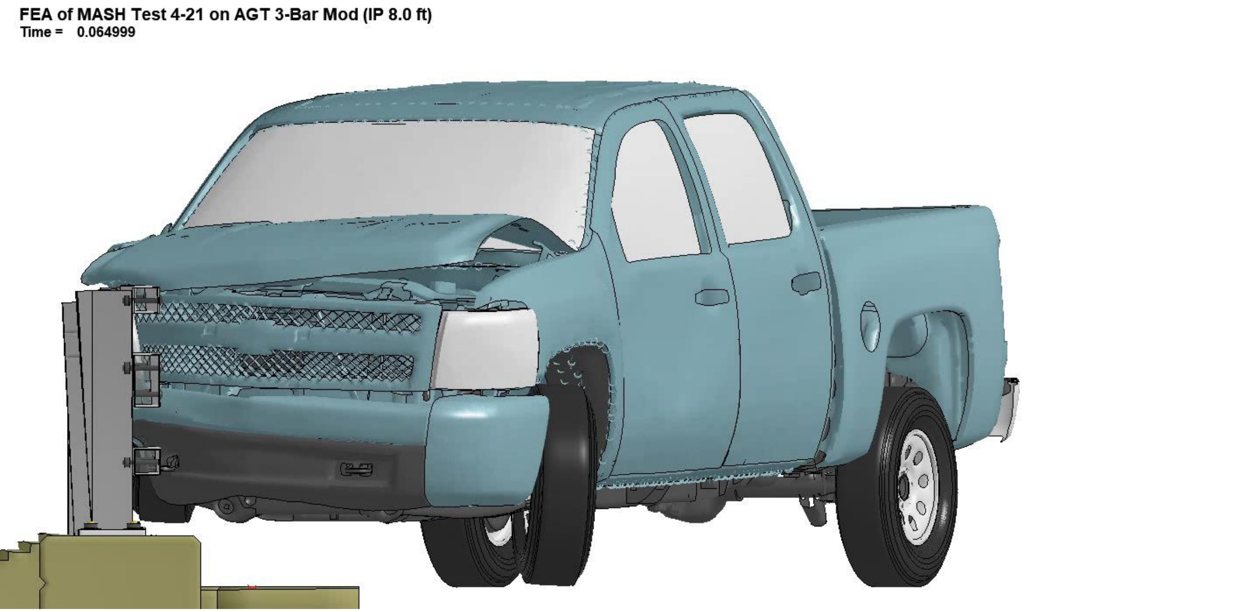


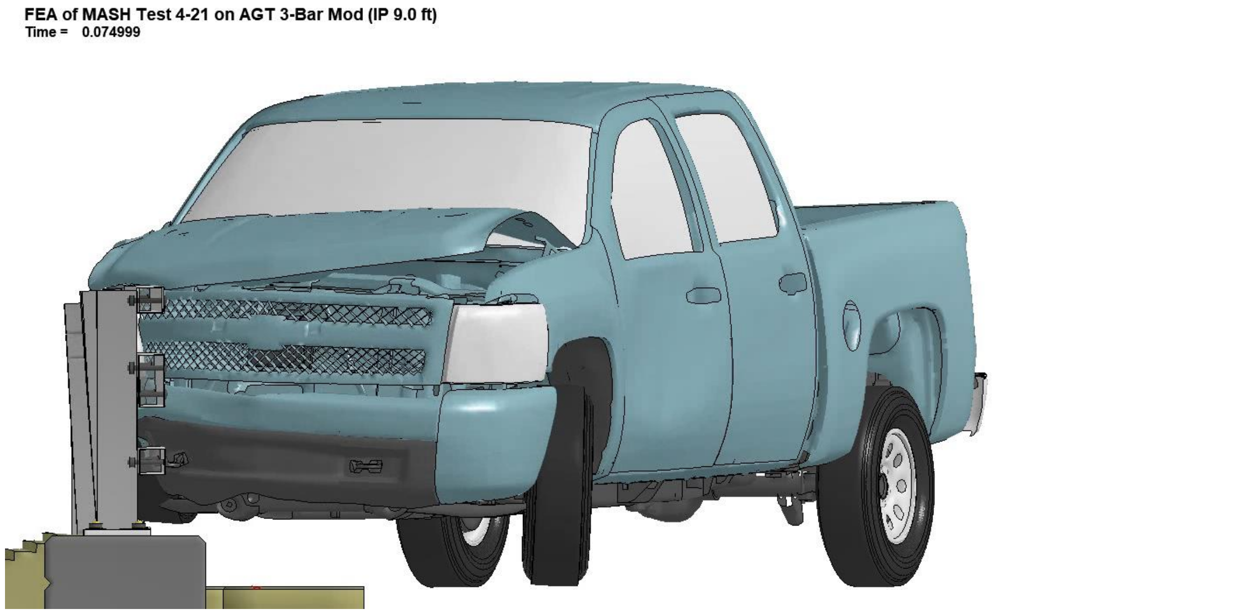
IP 7.0 ft



IP 8.0 ft

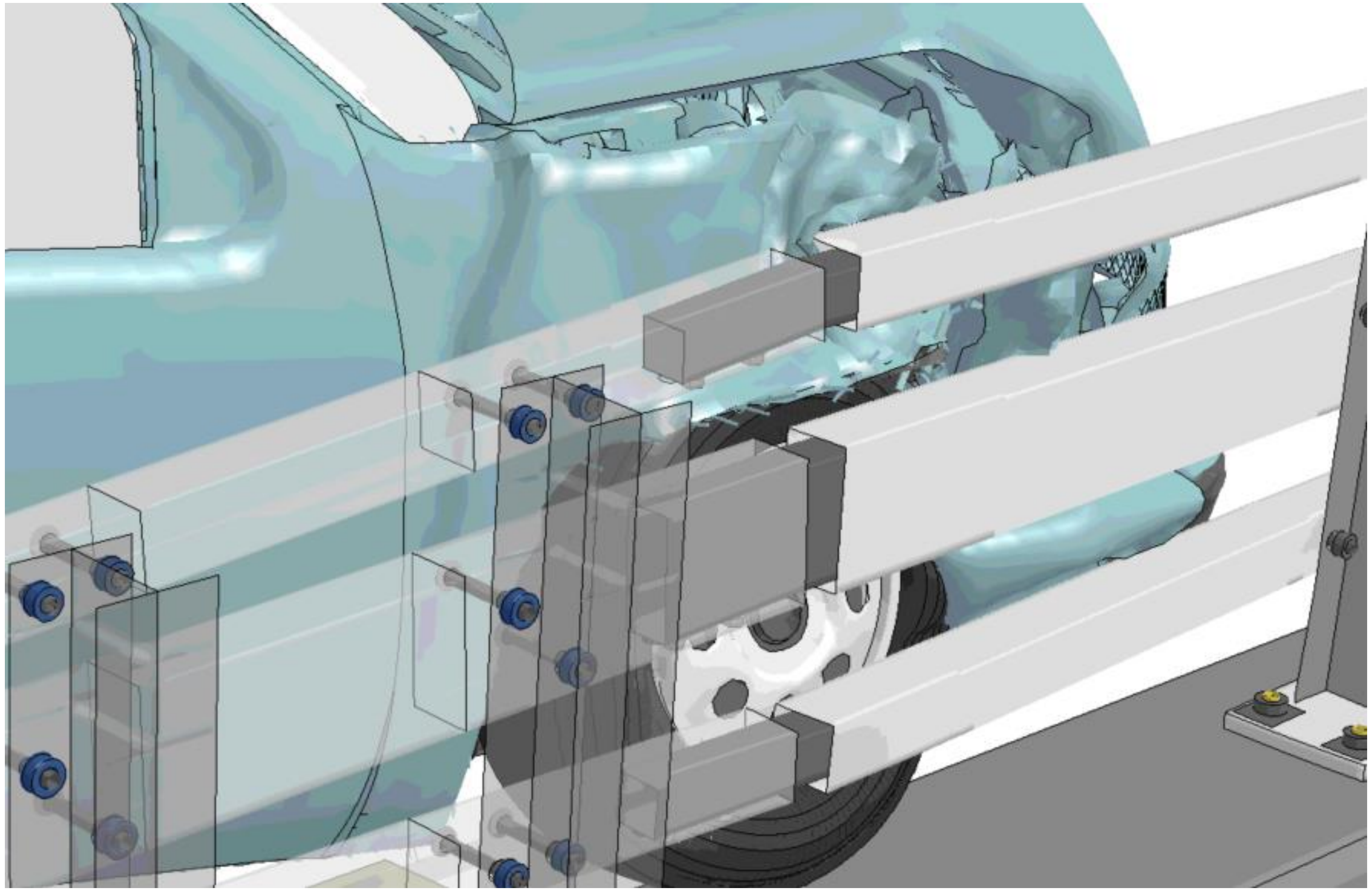


IP 9.0 ft



Close-up View of the Splice for Case IP6.0

- Case IP6.0 appears to be the CIP for the splice for Test 4-21 (pickup).
- The fender snagged on the splice at the top rail, but it did not greatly affect vehicle accelerations.
- Neither the wheel rims nor the leading edge of the door (which would have been a more severe snag) showed propensity for snag in this case.
- Cases IP7.0 and IP8.0 showed higher potential for snag of the leading edge of the door on the splice; however, those analyses did not result in a snag, likely due to the splice location on the downstream side of the post.
- As with the small car test, a reverse impact case may be more critical for assessing snag on the splice.



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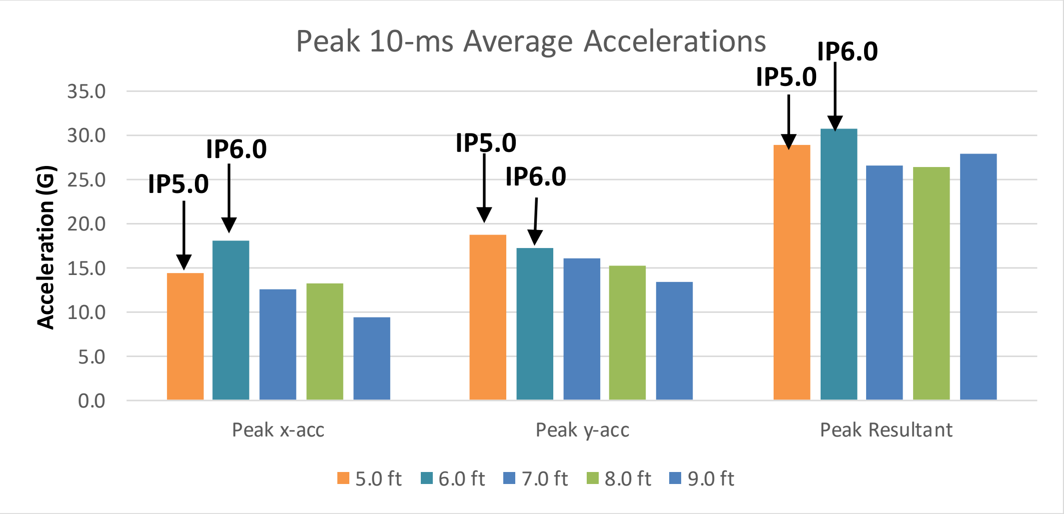
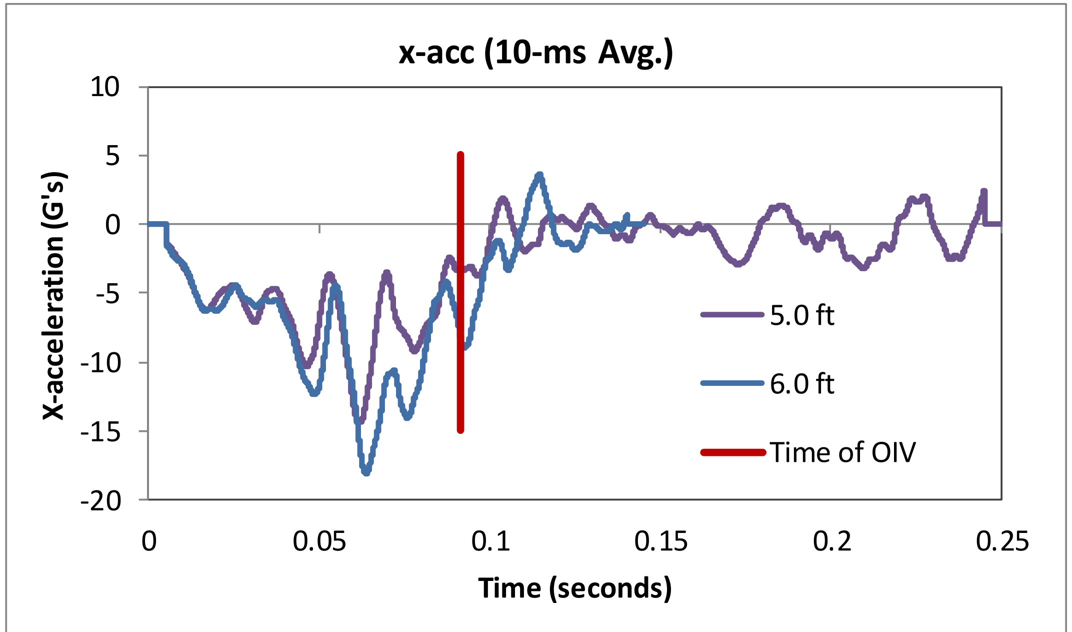
Vehicle Acceleration-Time History Summary





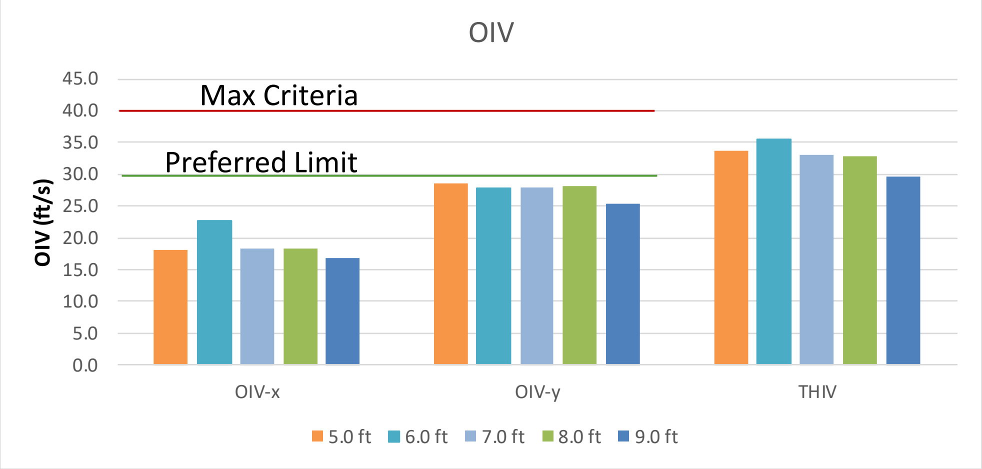
- Peak Accelerations:
  - IP6.0 – Highest regarding snag on both Post and Splice
    - Highest peak longitudinal acceleration
    - 2nd highest lateral acceleration
    - Highest resultant acceleration
    - Fender snag on splice
  - IP5.0 – Highest lateral peak acceleration
  - The snag on the fender may have caused the higher x-acceleration peak for Case IP6.0. *However, the model did not allow for metal tearing of the fender which may have over-predicted the snag force since the material could not fail.*

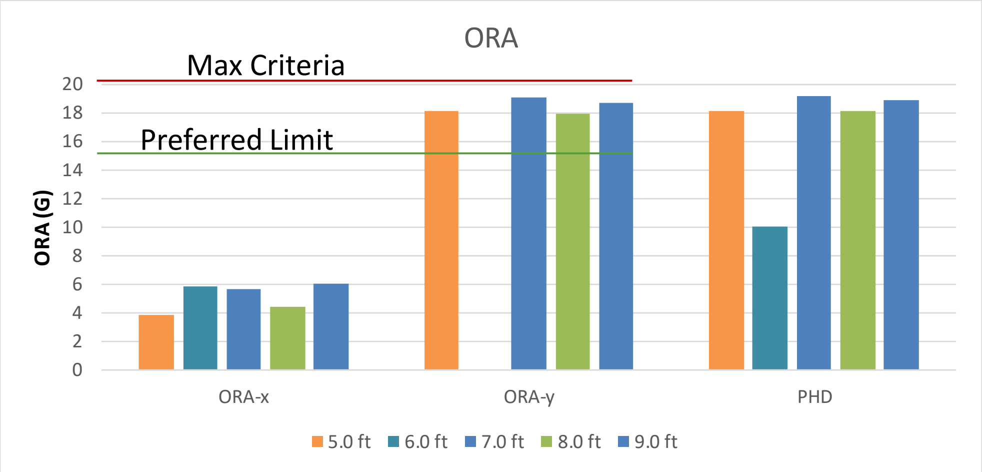
Occupant Risk Metrics

Occupant Risk Factors		MASH Test 4-20				
		5.0 ft	6.0 ft	7.0 ft	8.0 ft	9.0 ft
Occupant Impact Velocity (ft/s)	x-direction	18.0	22.6	18.4	18.4	16.7
	y-direction	28.5	27.9	27.9	28.2	25.3
	at time	at 0.0878 seconds on right side of interior	at 0.0888 seconds on right side of interior	at 0.0898 seconds on right side of interior	at 0.0894 seconds on right side of interior	at 0.0904 seconds on right side of interior
THIV (ft/s)		33.8 at 0.0878 seconds on right side of interior	35.4 at 0.0888 seconds on right side of interior	33.1 at 0.0898 seconds on right side of interior	32.8 at 0.0894 seconds on right side of interior	29.5 at 0.0904 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-3.8 (0.0914 - 0.1014 seconds)	-5.8 (0.0913 - 0.1013 seconds)	-5.6 (0.0923 - 0.1023 seconds)	-4.4 (0.2318 - 0.2418 seconds)	-6 (0.2075 - 0.2175 seconds)
	y-direction	-18.1 (0.1846 - 0.1946 seconds)	N.A.	-19.1 (0.1853 - 0.1953 seconds)	-17.9 (0.1858 - 0.1958 seconds)	-18.7 (0.1823 - 0.1923 seconds)
PHD (g's)		18.1 (0.1846 - 0.1946 seconds)	10 (0.0888 - 0.0988 seconds)	19.2 (0.1852 - 0.1952 seconds)	18.1 (0.1855 - 0.1955 seconds)	18.9 (0.1822 - 0.1922 seconds)
ASI		1.68 (0.0390 - 0.0890 seconds)	1.73 (0.0360 - 0.0860 seconds)	1.59 (0.0388 - 0.0888 seconds)	1.57 (0.0442 - 0.0942 seconds)	1.33 (0.0398 - 0.0898 seconds)
Max 50-ms moving avg. acc.	x-direction	-8 (0.0391 - 0.0891 seconds)	-10.7 (0.0334 - 0.0834 seconds)	-8.2 (0.0378 - 0.0878 seconds)	-7.8 (0.0361 - 0.0861 seconds)	-6.6 (0.0519 - 0.1019 seconds)
	y-direction	-13.9 (0.0354 - 0.0854 seconds)	-13.5 (0.0363 - 0.0863 seconds)	-13 (0.0390 - 0.0890 seconds)	-12.8 (0.0439 - 0.0939 seconds)	-10.8 (0.0391 - 0.0891 seconds)
	z-direction	-2.5 (0.1886 - 0.2386 seconds)	-2.4 (0.0654 - 0.1154 seconds)	-3.3 (0.1813 - 0.2313 seconds)	-2.5 (0.0502 - 0.1002 seconds)	-3 (0.1653 - 0.2153 seconds)
	Resultant	20.6	21.3	20.5	20.4	19.4
Peak 10 ms Avg. Accelerations	x-direction	-14.4	-18.1	-12.6	-13.3	-9.4
	y-direction	-18.7	-17.2	-16.0	-15.2	-13.5
	Resultant	28.9	30.8	26.7	26.4	27.9

Occupant Risk Metrics

Design 1 Analysis Cases





- Occupant impact velocities (all cases)
  - OIV-x: Within preferred limits.
  - OIV-y: Within preferred limits.
- Occupant Ridedown Accelerations (all cases)
  - ORA-x: Well within preferred limits
  - ORA-y: Exceeded preferred limits but were within critical limits.
- Highest OIV
  - IP6.0 yielded highest OIV x-direction and 2nd highest for y-direction
- Highest ORA
  - IP6.0 yielded highest ORA for x-direction.
  - IP6.0 terminated prematurely before peak ORA in y-direction occurred.
  - Also, recall that the Silverado model tends to over-predict the lateral acceleration for the “tail slap”.

Conclusions: Test 4-21 on Design 1 for the 3-Bar Transition with 5.5’ Post Spacing

- The barrier successfully contained and redirected the 1100P vehicle.
- The OIV’s were within critical limits and ORA’s were within preferred limits specified in MASH.
  - Max values:
    - OIV_x = **26.2 ft/s** (IP 5.0 ft)
    - OIV_y = **35.4 ft/s** (IP 5.5 ft)
    - ORA_x = **7.5 G** (IP 6.5 ft)
    - ORA_y = **7.9 G** (IP 7.65 ft)
- Peak vehicle accelerations (e.g., relates to impact forces)
  - The highest accelerations of the vehicle occurred for impact at 4’
    - Longitudinal direction = 24 g
    - Lateral direction = 27.3 g
    - Resultant = 36.6 g
  - The occupant was not in contact with the vehicle interior at the time of peak vehicle accelerations, so maximum ORA values were not experienced during that event.
- Barrier damage was moderate and barrier deflections were considered low to moderate.
- The occupant risk metrics in these cases, are comparable to, but slightly higher, than those for the 3-Bar bridge rail.

General Conclusions Regarding MASH for Test 4-21:

3-Bar Transition with 5.5’ Post Spacing Design 1

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

* Analysis stopped at 0.25 seconds, but vehicle stability is expected for all cases.

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Conclusions
3-Bar Transition w/ 5.5-ft Post Spacing

- The FEA simulations of an increased post spacing of 5.5 ft for the NETC 3-Bar transition was shown to meet MASH TL-4 performance criteria.
- **The increased spacing** resulted in:
  - Increased rail deflections
  - Increased longitudinal forces and accelerations
  - Reduced lateral forces and accelerations
- **Tapering the tops of the posts** notably reduced longitudinal forces for Test 4-22 (SUT test) by mitigating snag on the backs of the post.
- **Expansion splice gap = 2”**
  - The 2” wide expansion splice did not result in notable snag in FEA, but the research team believes a potential exists – particularly for reverse-direction impact scenarios (not evaluated).
  - Previous analysis and full-scale tests on a similar system with 3¾-inch splice gap resulted in significant snag for the pickup test.
- **HSS 5x4x5/16 lower rail** – Increasing the size of the lower rail to HSS 5x4x5/16 resulted in:
  - 25% decease in rail deflection compared to the baseline analysis with HSS4x4x1/4 (small car test)
  - 17.9% decrease in peak longitudinal acceleration (small car test)