Development of MASH Computer Simulated Steel Bridge Rail and Transition Details

Task 5 – NETC 4-Bar MASH TL4

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

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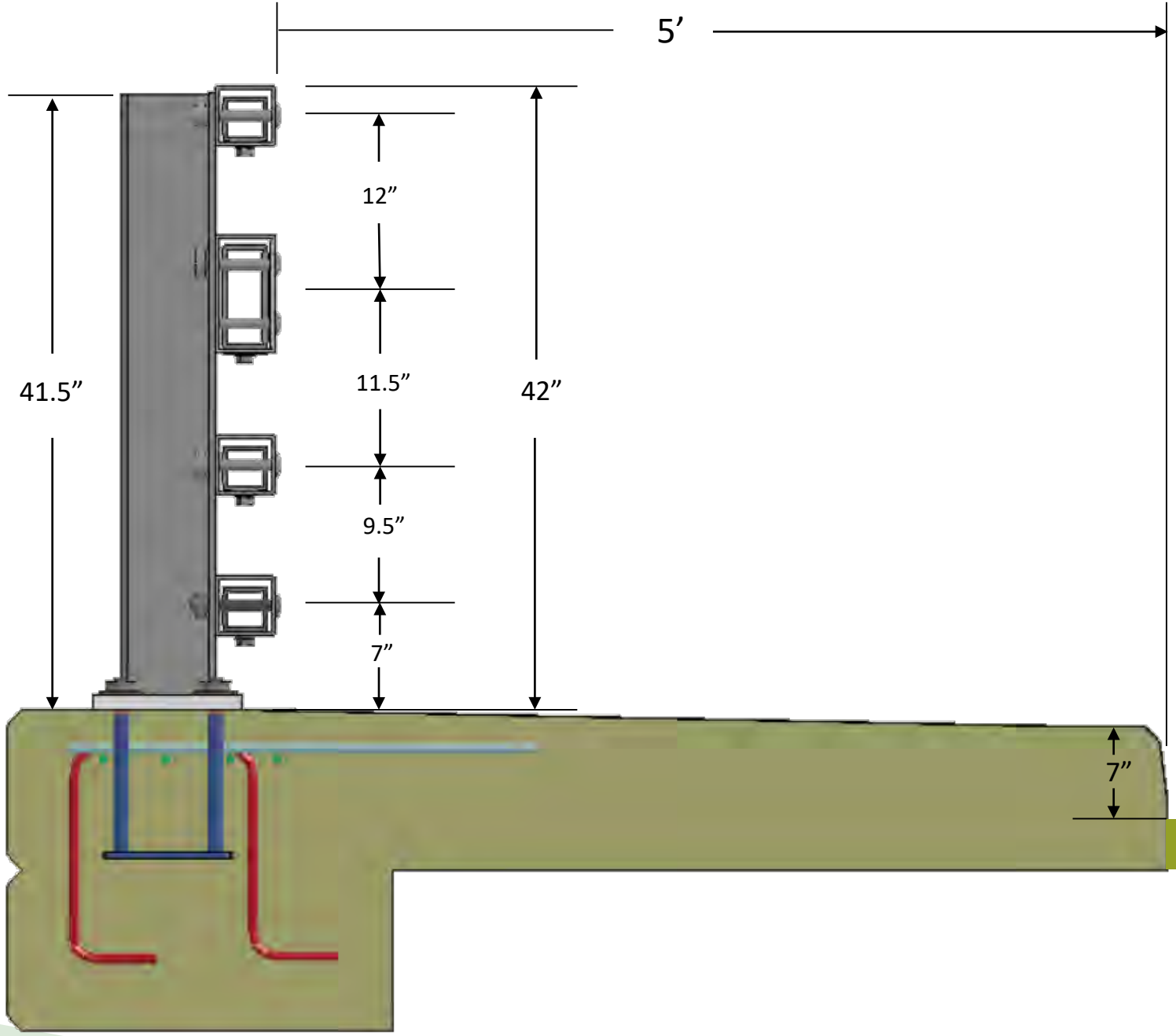
Task 5 – MASH TL-4 Evaluation of NETC 4-Bar Bridge Rail

- The finite element model of the NETC 4-Bar system was developed in Task 2
- That model was used as a baseline and was updated with model improvements developed in Tasks 3 and 4, e.g.:
  - Corrected cap-screw model for splices
  - Splices moved to opposite side of post (to permit CIP for splice from primary direction impact)
  - Revised anchor plate model.



Materials

- **All steel materials were modeled in LS-DYNA using material model *Mat_Piecewise_Linear_Plasticity.** The Young's modulus was set to 29,000 ksi and Poisson's ratio was set to 0.33. The piecewise-linear stress-strain characterization for each component varied depending on steel type and grade.
- The tubular rail sections were modeled with material conforming to **ASTM A500 Grade B**. The minimum yield and tensile strength for the structural tube material is **46 ksi** and **58 ksi**, respectively.
- All **posts and plates** were modeled as **ASTM A572 Grade 50** steel; the material characterization was based on stress-strain curves from tensile tests conducted at the Turner-Fairbank Highway Research Center (TFHRC) in McLean, Virginia in an earlier study performed by Roadsafe. Yield and tensile strength was **50.6 ksi** and **70 ksi,** respectively.
  - Note: Coupon samples from other manufacturers have resulted in 60 ksi yield [*REF MwRSF*].
- All the **post-bolts** in the were modeled as **ASTM A325** with yield strength of 92 ksi and ultimate strength of 120 ksi (engineering stress).
- All anchor rods were modeled as **ASTM A449** with yield strength of 92 ksi and ultimate strength of 120 ksi (engineering stress).
- **Concrete in impact region** was modeled in LS-DYNA using material model ***MAT_RHT** with properties corresponding to **4,000 psi concrete (Impact Zone Only)**.
- **Concrete outside impact region** was modeled with **rigid** material properties.

MASH Test Level 4

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

1100C

2270P

10000S

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Evaluation Criteria

Occupant Compartment Intrusion:

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

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

Evaluation Criteria

Post Impact Vehicle Behavior:

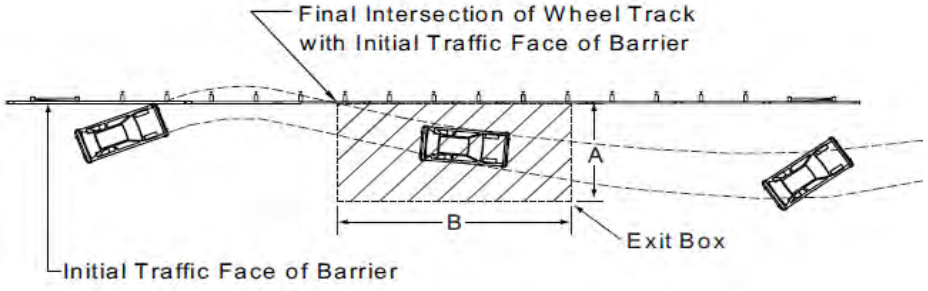
- Although not required by *MASH*, post vehicle trajectory was examined for completeness of the evaluations.
- *MASH* uses the concept of the "exit box" which was adopted directly from CEN standards.
- It is defined by the initial traffic face of the barrier and a line parallel to the initial traffic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

Distance for Exit Box Criterion

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

V_W = Vehicle Width
V_L = Vehicle Length

Test	V_w (ft)	V_L (ft)	A (ft)	B (ft)
4-20	5.5	14.1	15	32.8
4-21	6.02	16.8	15.86	32.8
4-22	8.01	28.15	26.95	65.6



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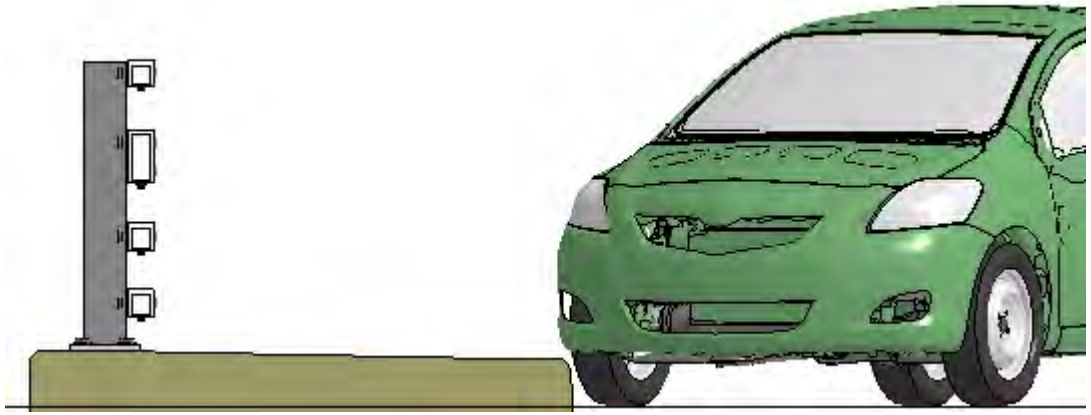
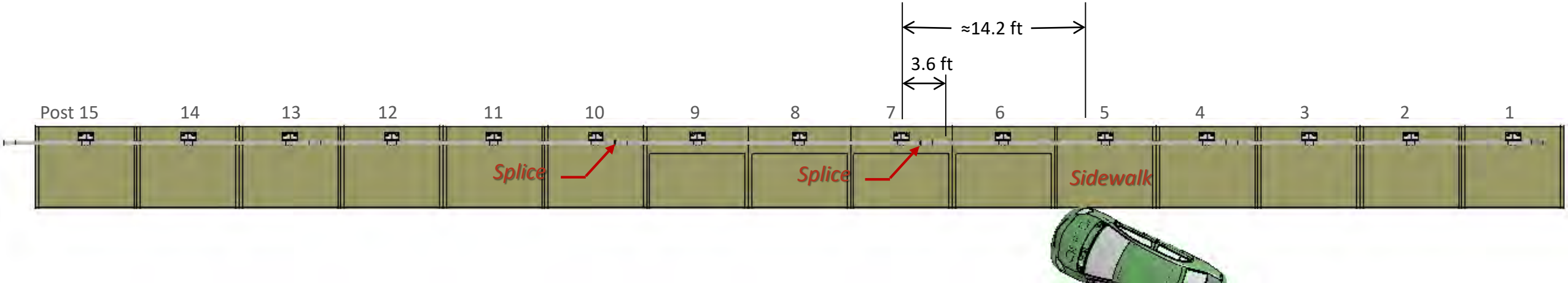
NETC 4-Bar Bridge Rail Test 4-10 Simulation

- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point
    - Target = 3.6 ft upstream of Post 7
    - Actual = 3.8 ft upstream of post 7

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





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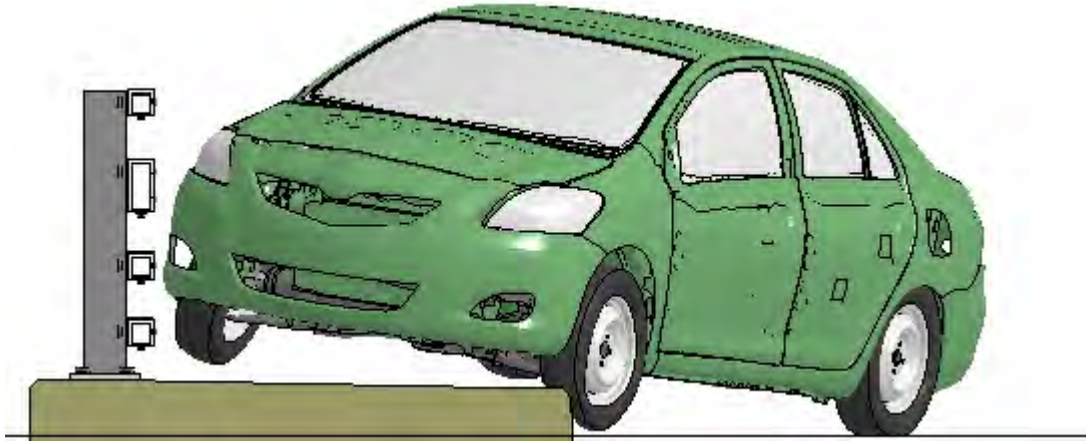

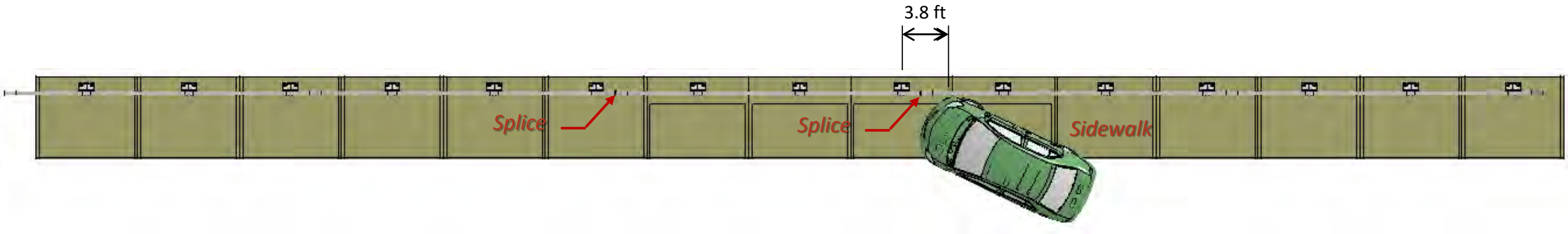

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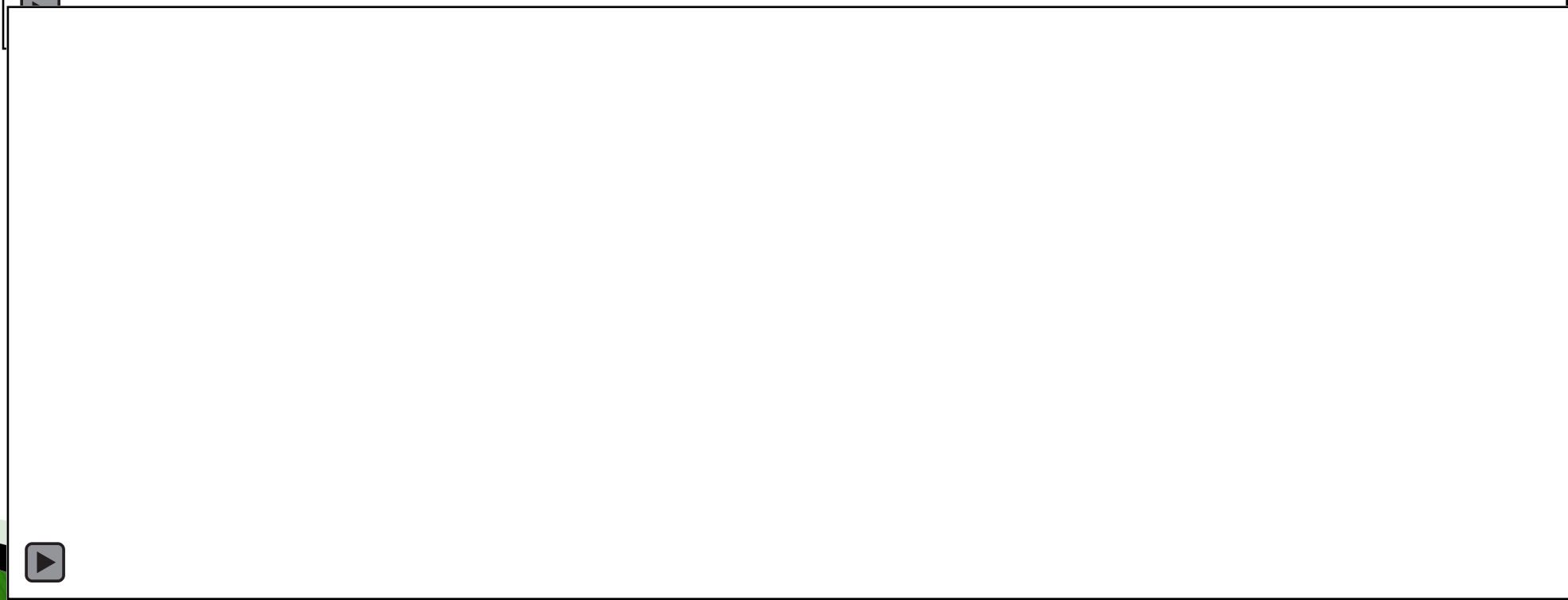

Movies

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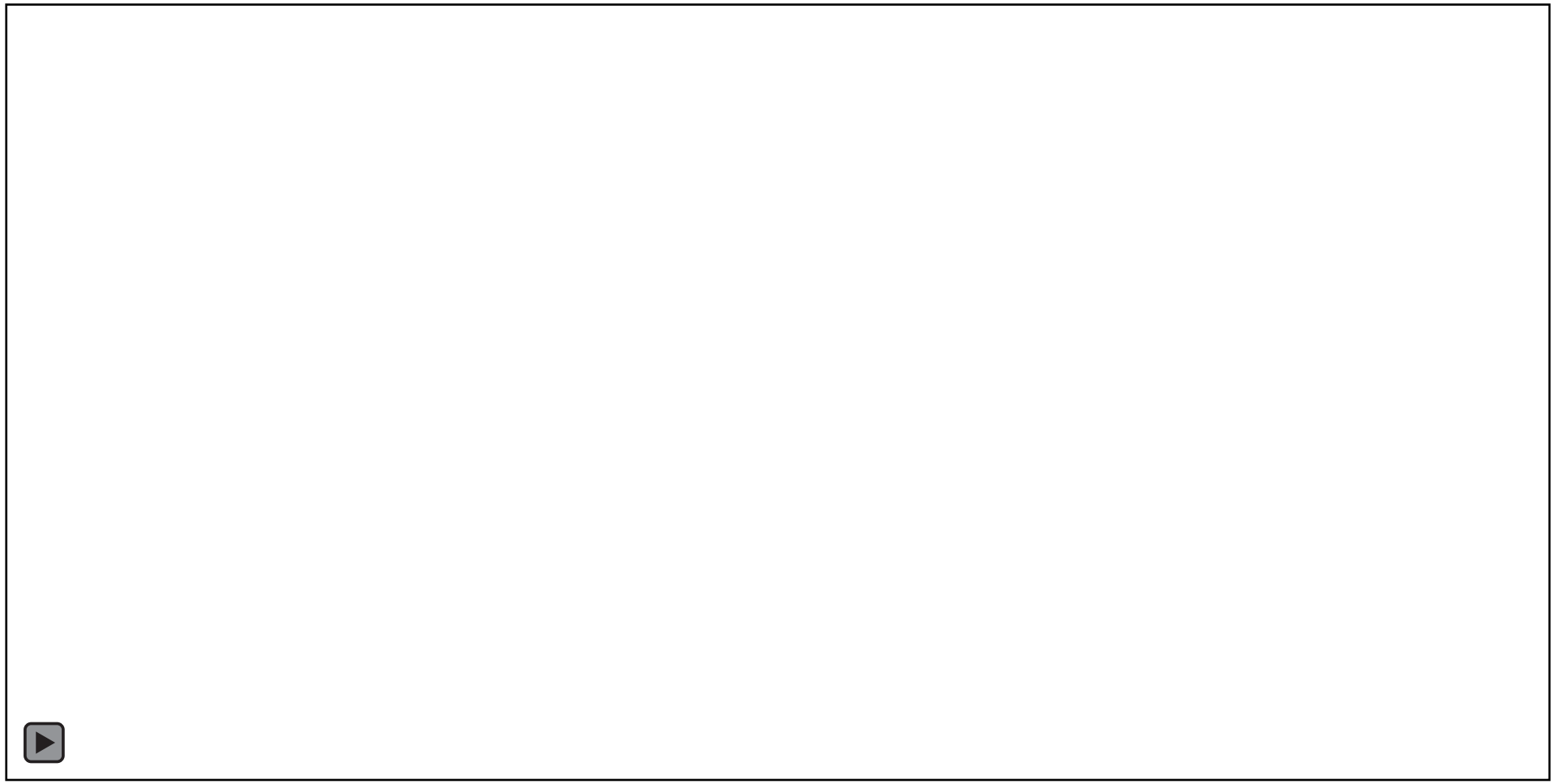

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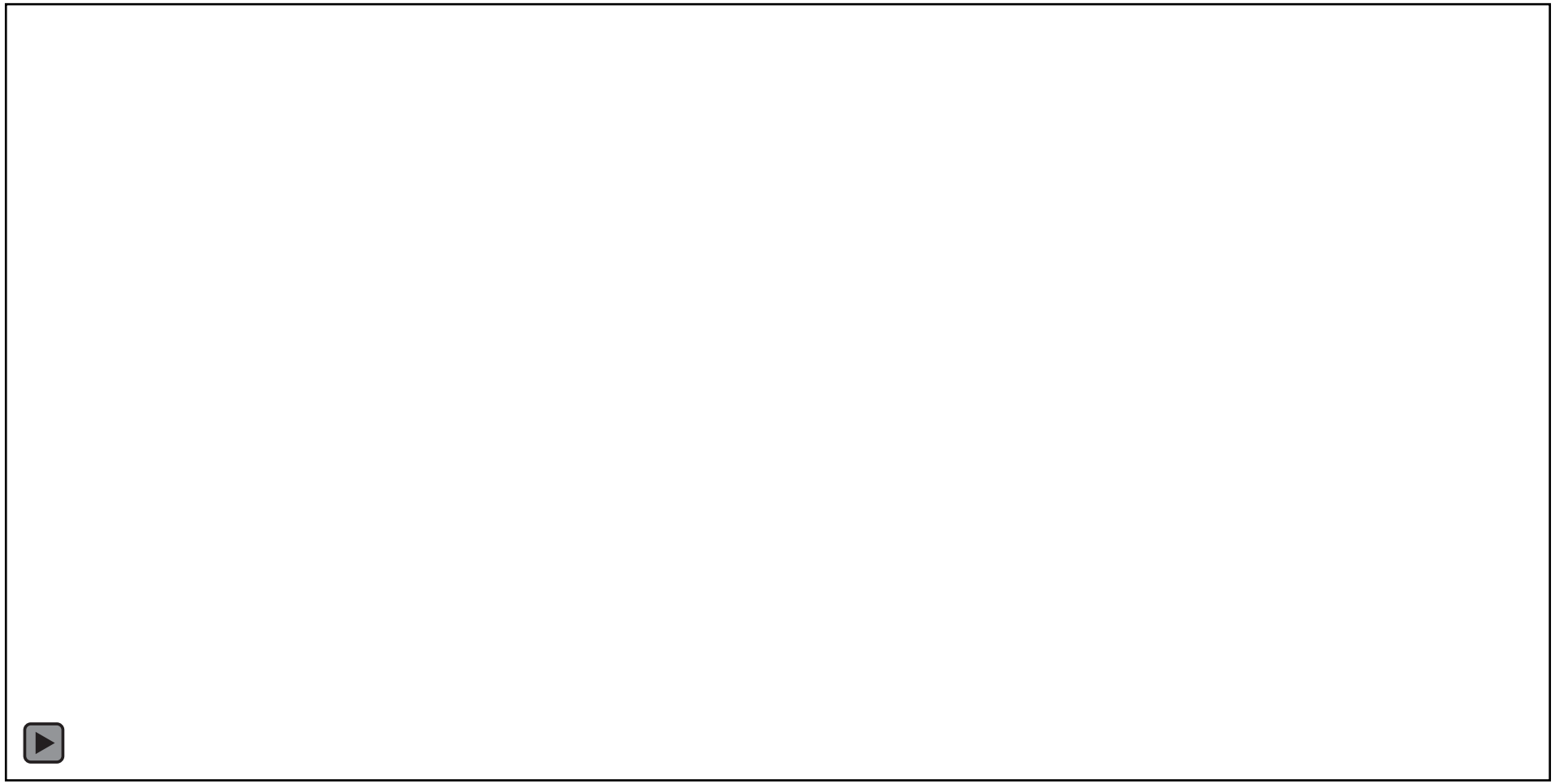
Movies



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TRAP – Summary Table

Occupant Risk Factors		MASH T4-10 NETC 3-Bar
Occupant Impact Velocity (ft/s)	x-direction	24.0
	y-direction	31.5
	at time	at 0.1971 seconds on right side of interior
THIV (ft/s)		39.4 at 0.1971 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-7.1 (0.2064 - 0.2164 seconds)
	y-direction	-10.3 (0.3473 - 0.3573 seconds)
PHD (g's)		10.3 (0.3473 - 0.3573 seconds)
ASI		2.14 (0.1550 - 0.2050 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-12.9 (0.1453 - 0.1953 seconds)
	y-direction	-17.1 (0.1550 - 0.2050 seconds)
	z-direction	-2.9 (0.1463 - 0.1963 seconds)
Maximum Angular Disp. (deg)	Roll	-10.9 (0.6998 seconds)
	Pitch	-6.5 (0.6029 seconds)
	Yaw	-51.8 (0.7996 seconds)

MASH Criteria

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

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

< 75 deg ✓

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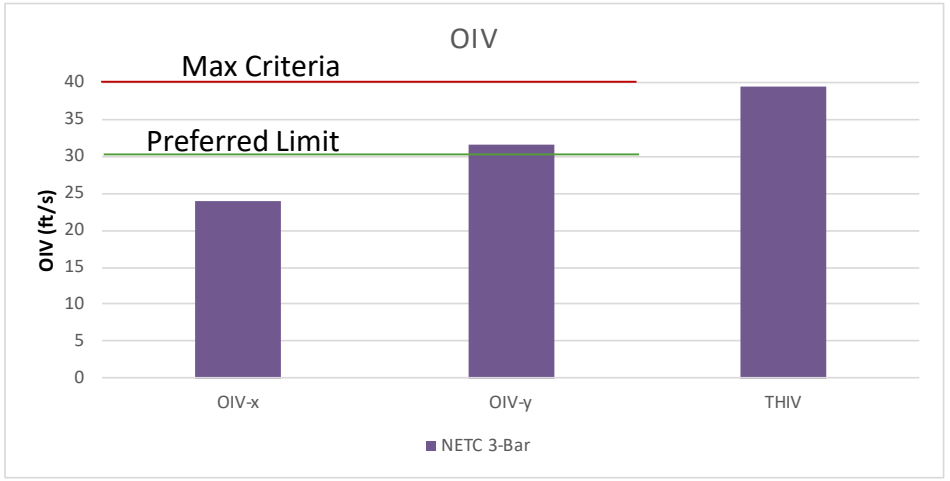
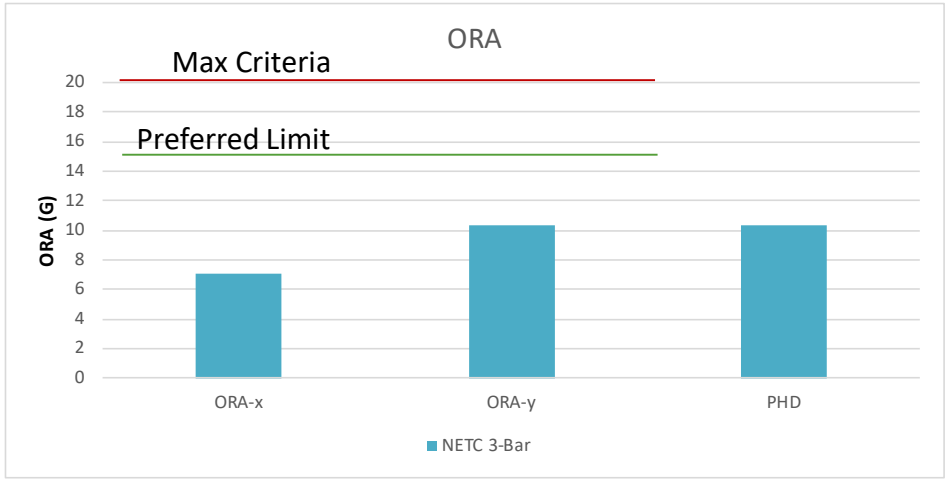
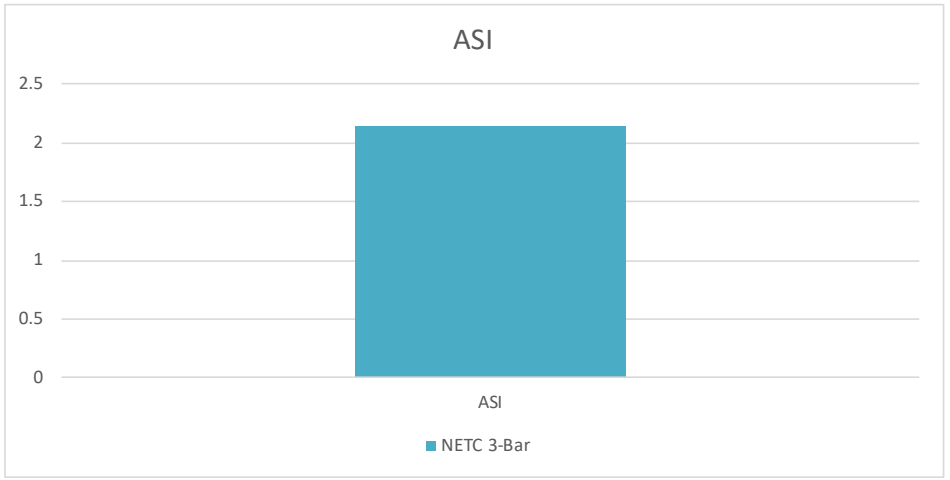
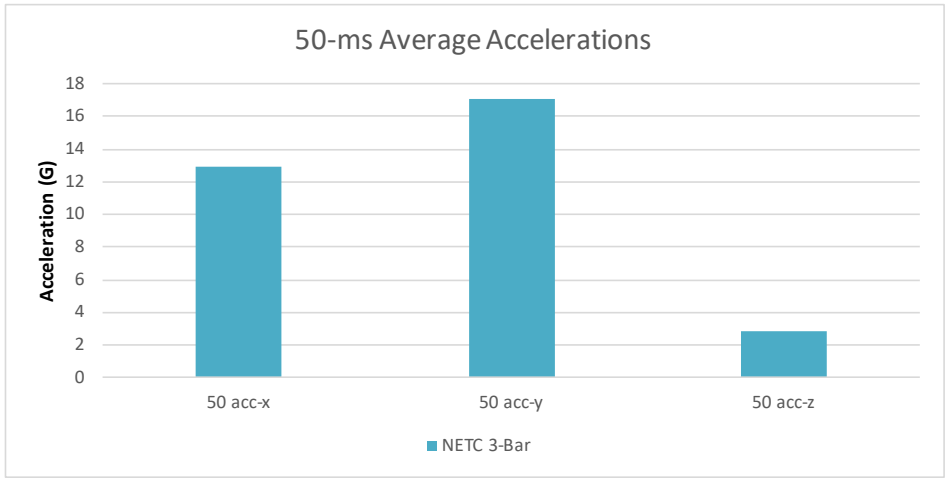
TRAP









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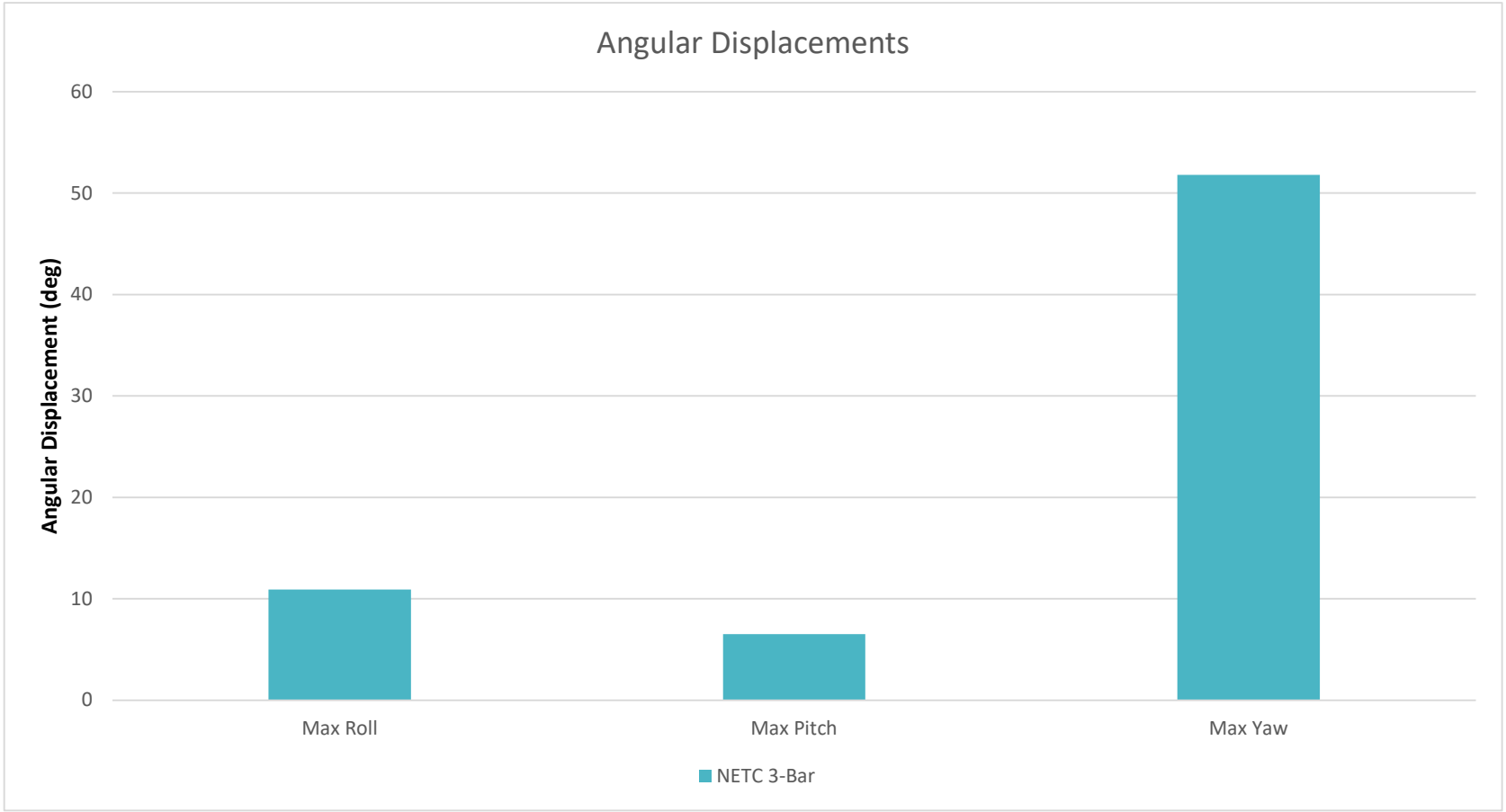
TRAP



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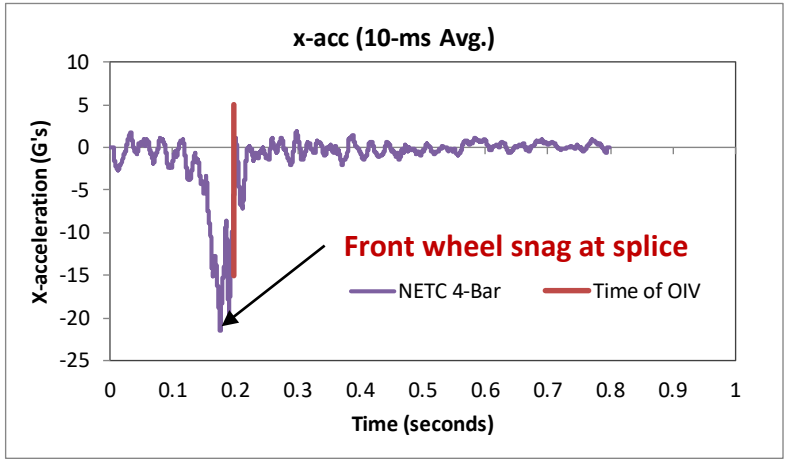
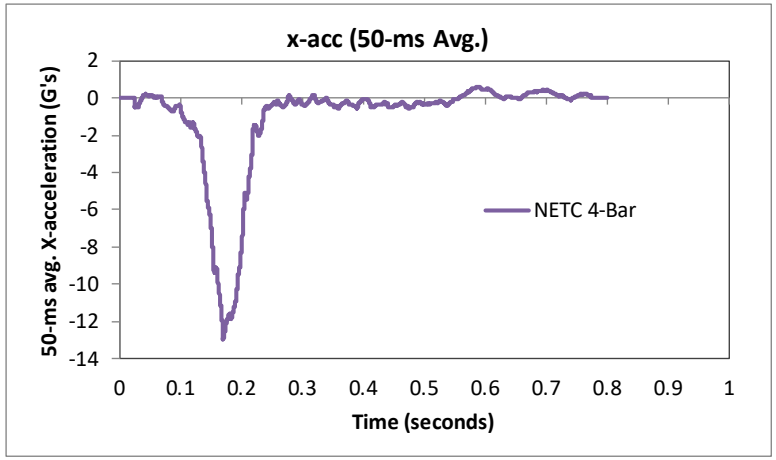
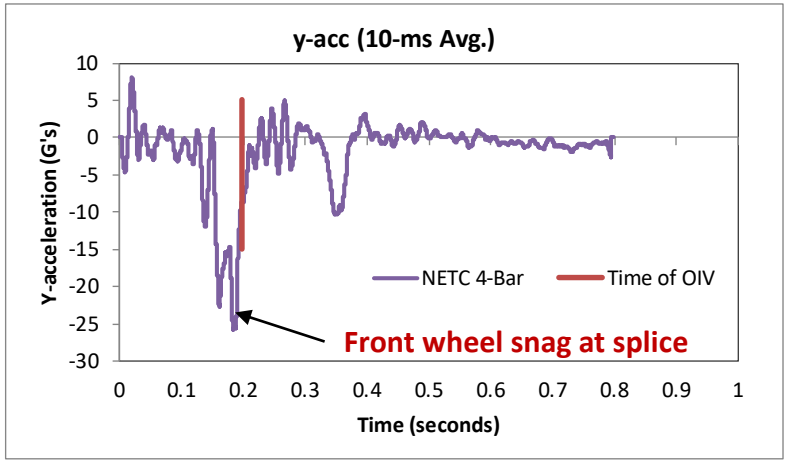
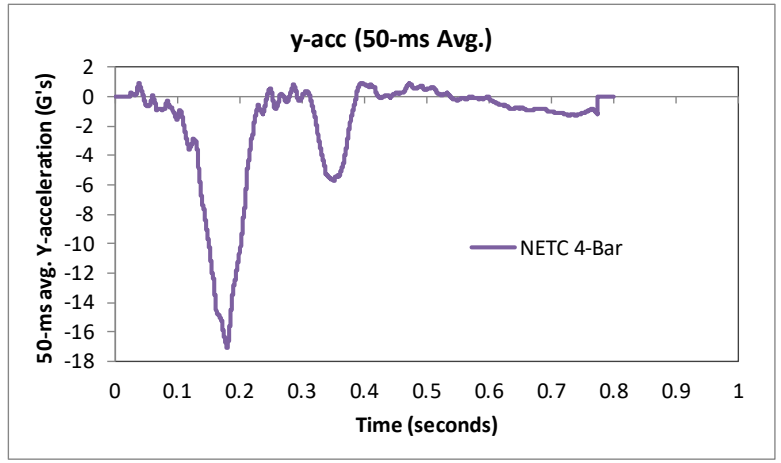
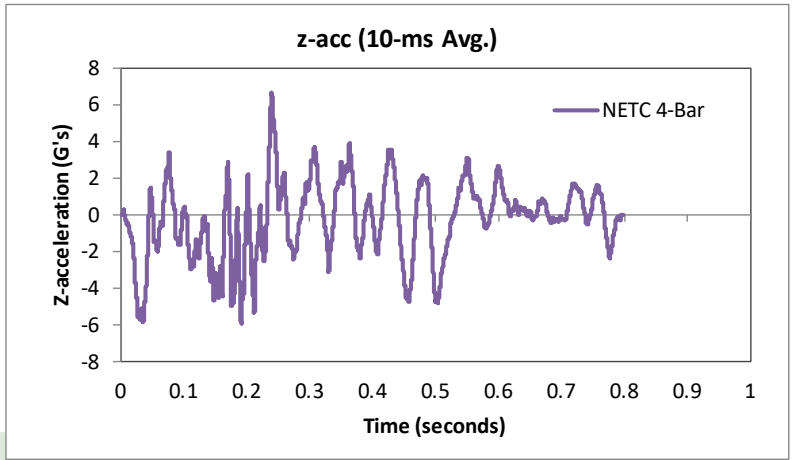
Acceleration Plots

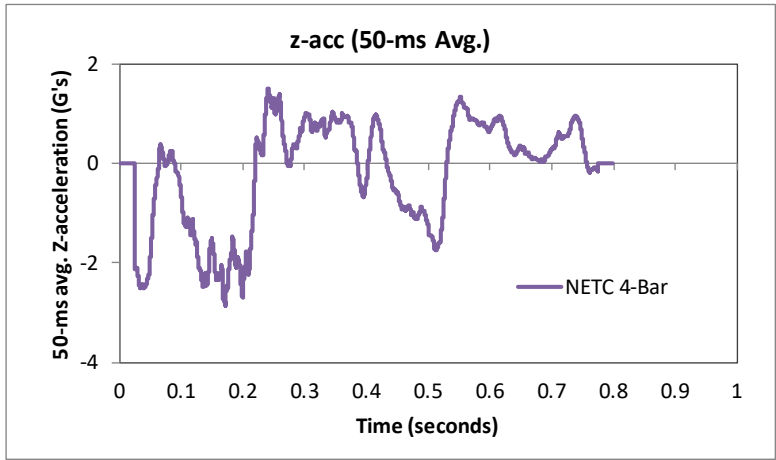




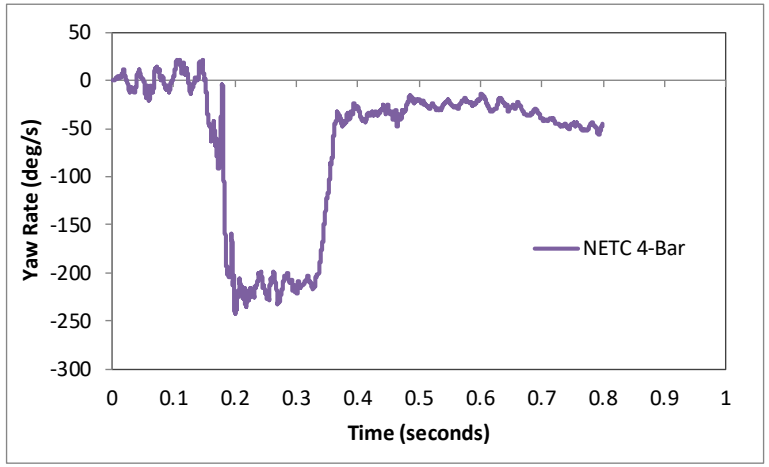


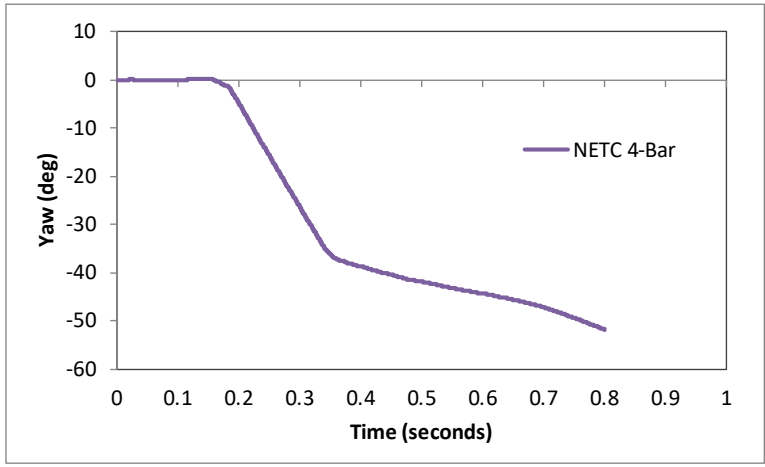


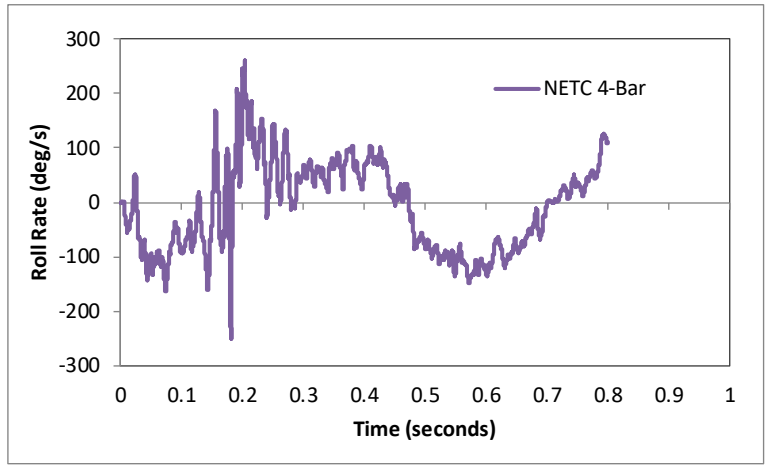


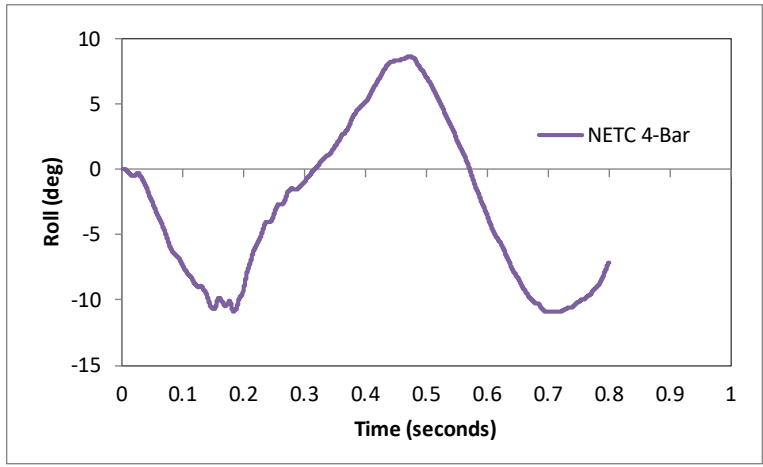


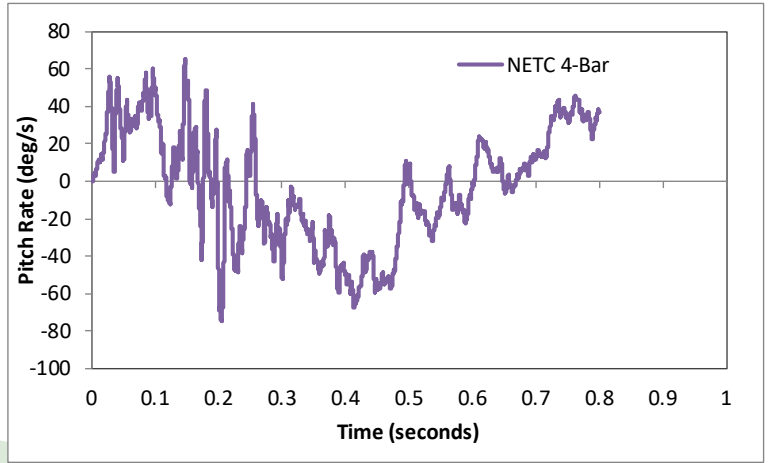
Angular Rate and Displacement Plots

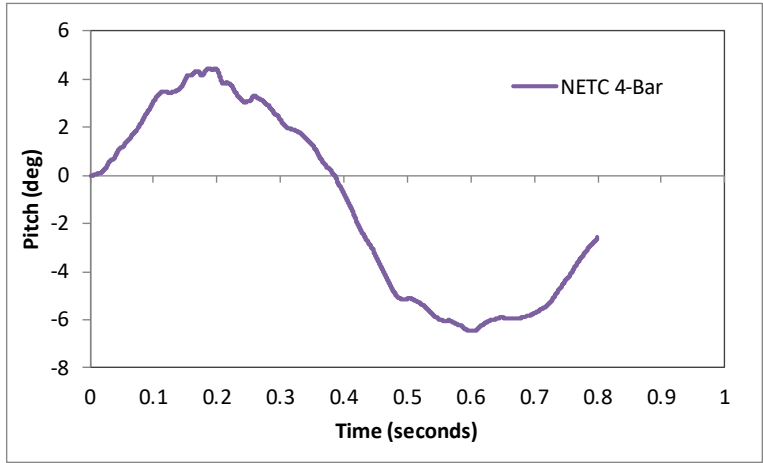






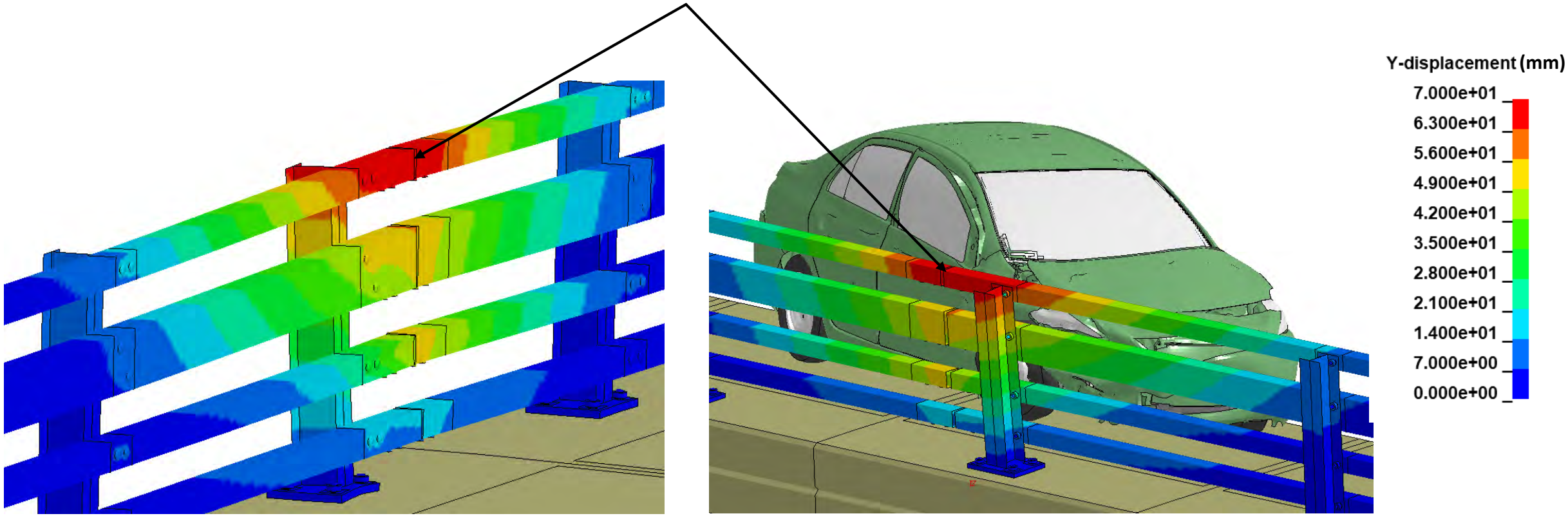






Lateral Dynamic Deflection

Maximum dynamic deflection = 2.8 in (72 mm) at 0.19 seconds



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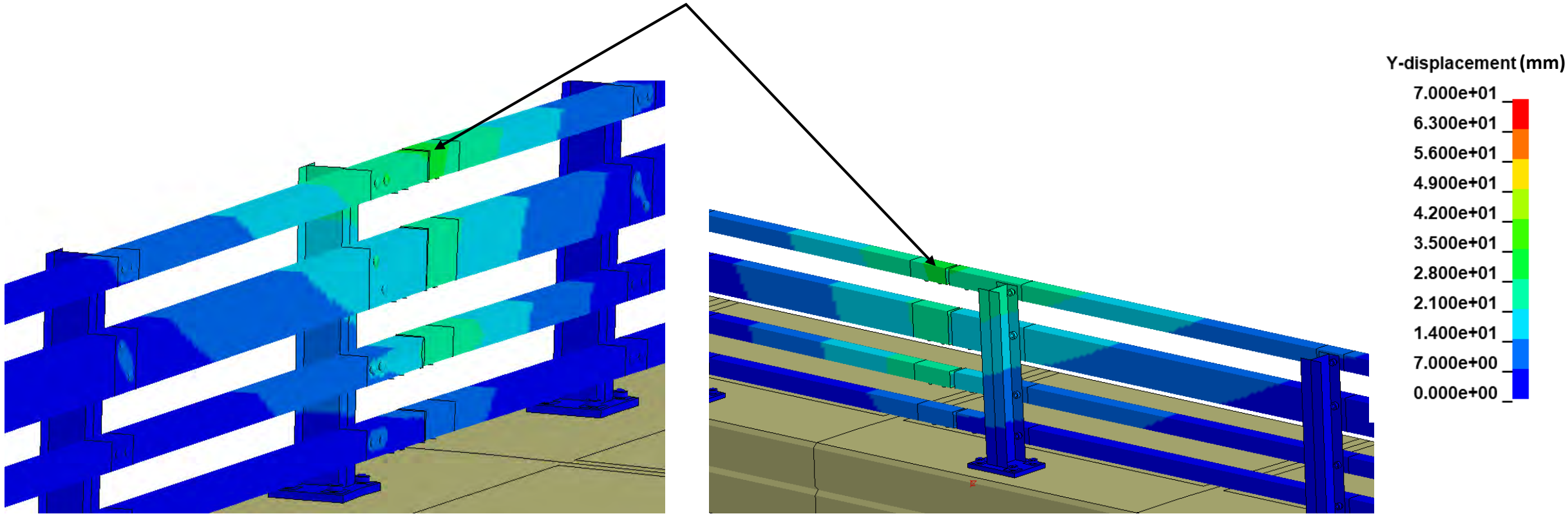
Lateral Permanent Deflection

Maximum permanent deflection = 1.25 in (32 mm)



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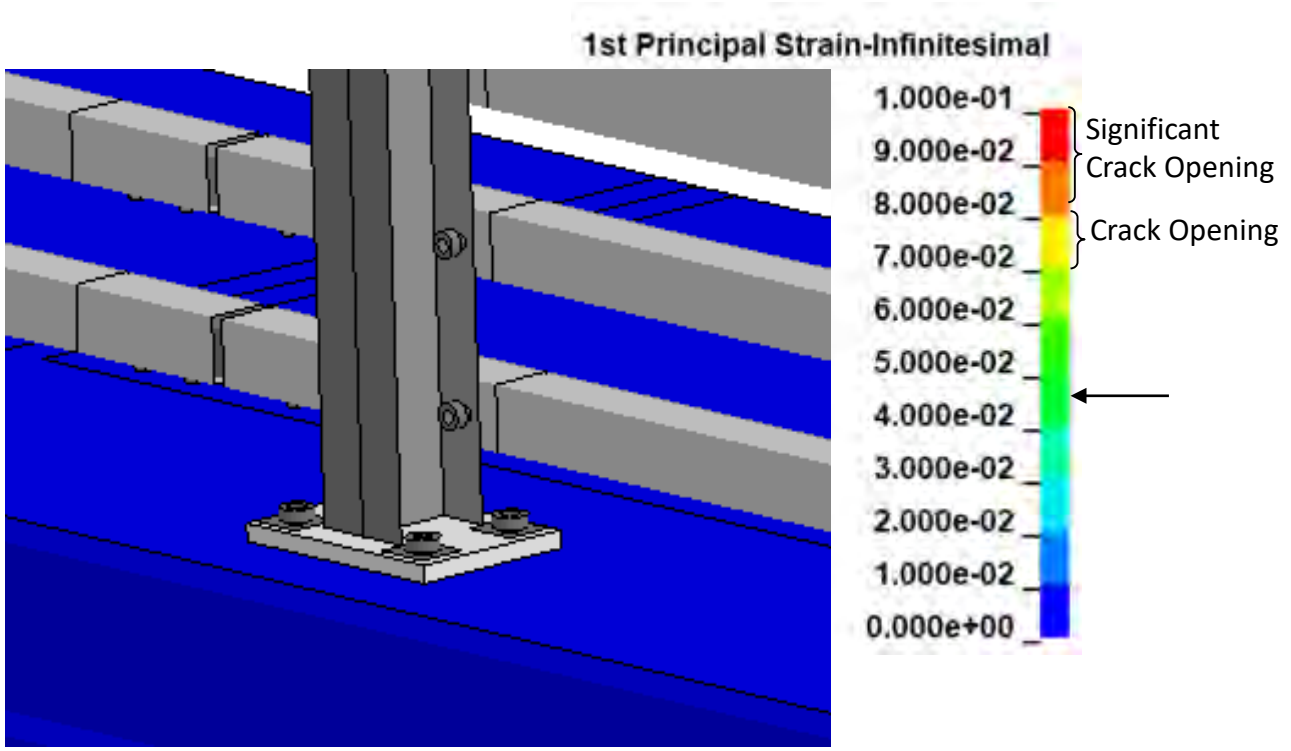
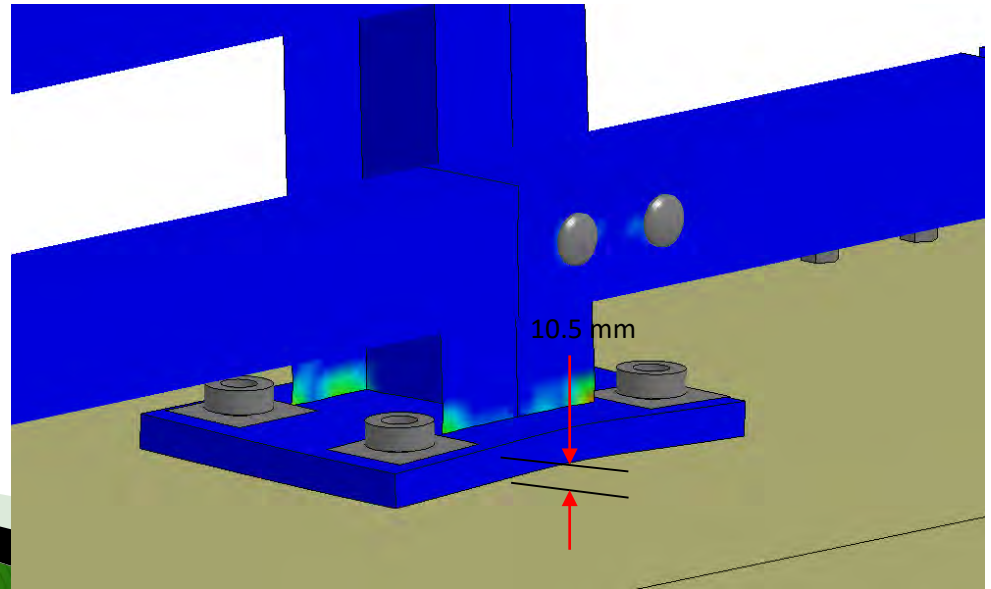
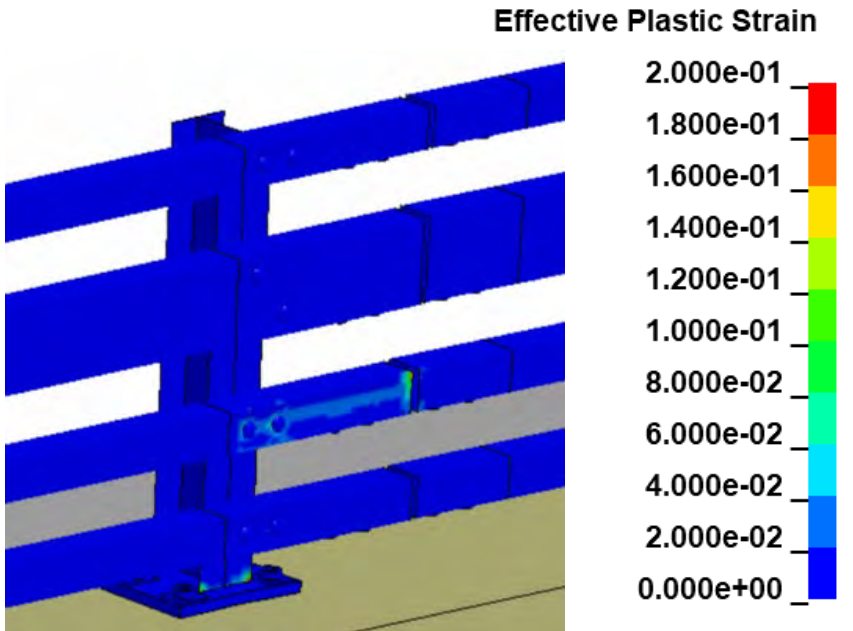
Barrier Damage

- Analysis indicated no damage to the concrete curb/deck.
  - Max dynamic 1st Prin. Strain = 0.046
  - Final 1st Prin. Strain = 0.0
- There was minimal damage to the post and base plates at the critical post location.
- Vertical deflection of the base plate:
  - Dynamic = 0.413 in (10.5 mm) at 0.19 seconds
  - Permanent = 0.18 in (4.5 mm)

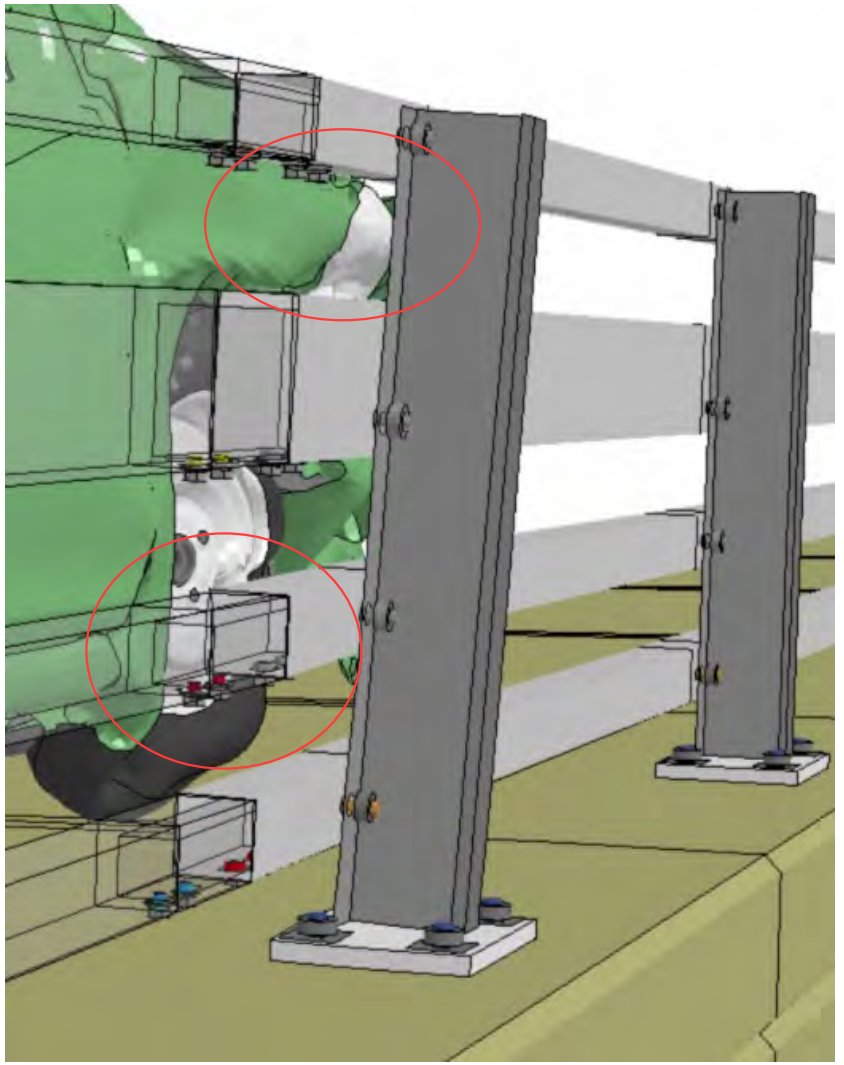






Assessment of Potential Vehicle Contact with Post

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



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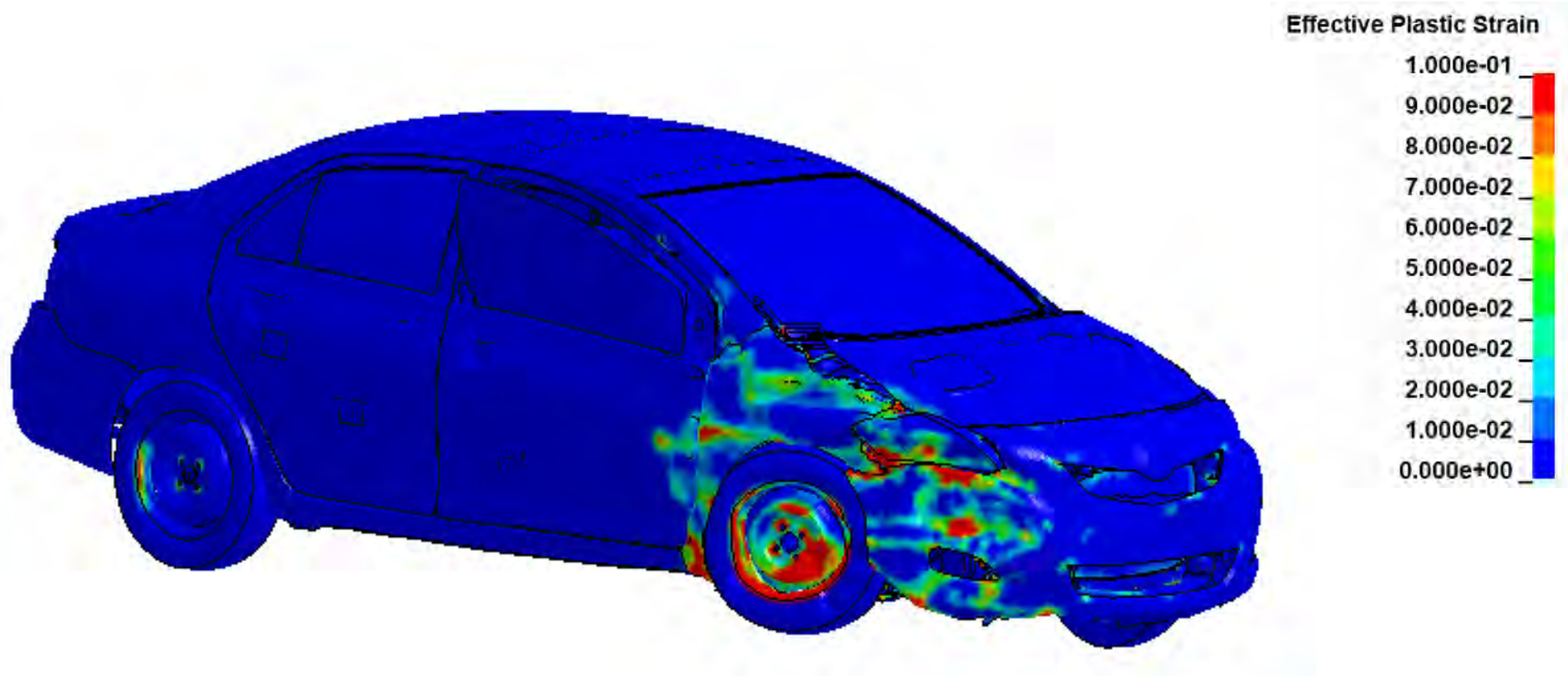
Effective Plastic Strain for Small Car Test



The most severe damages were to the front fender, the upper and lower control arm of front suspension, front wheel, and the leading edge of the front door on the impact side.

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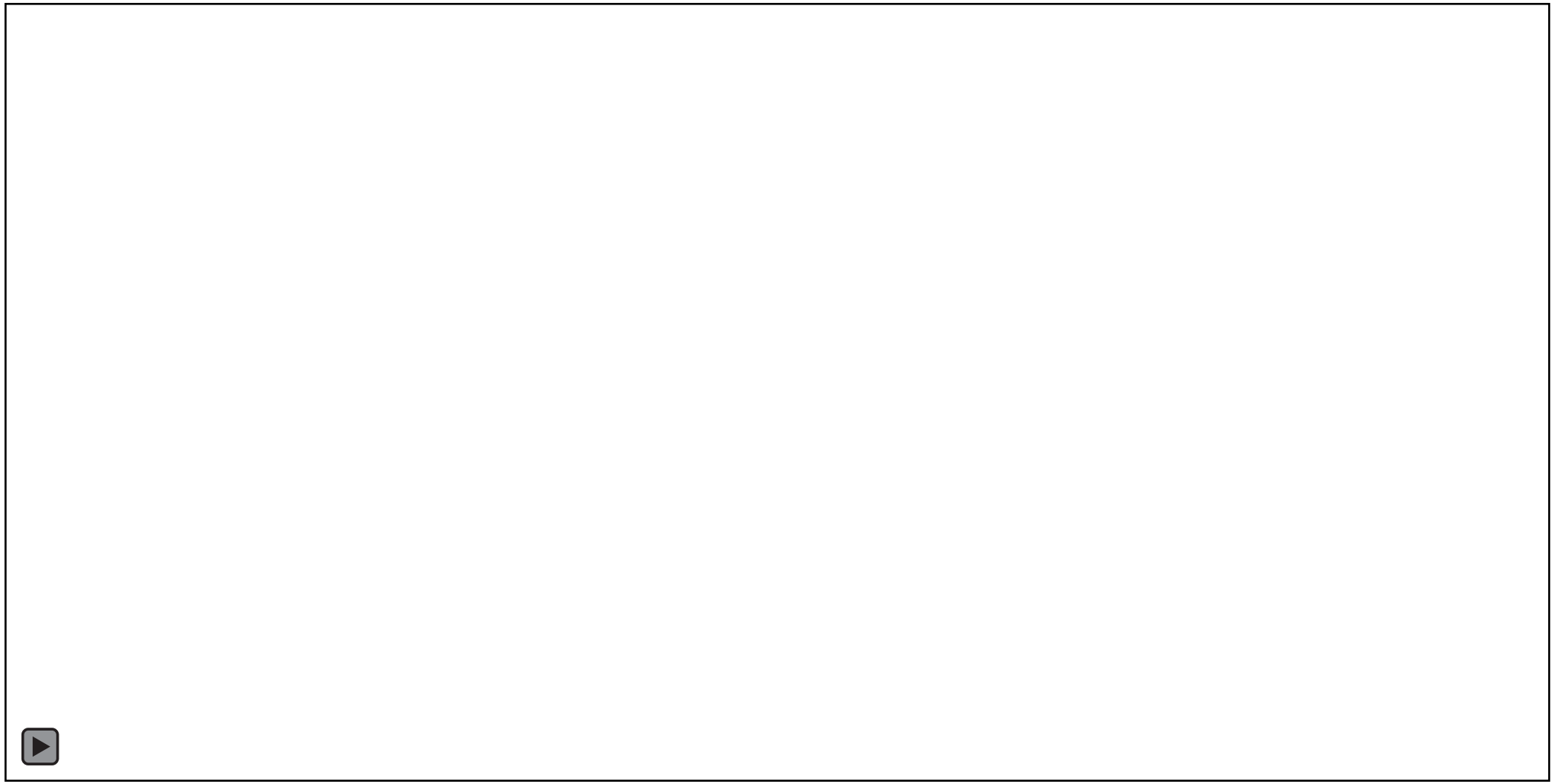
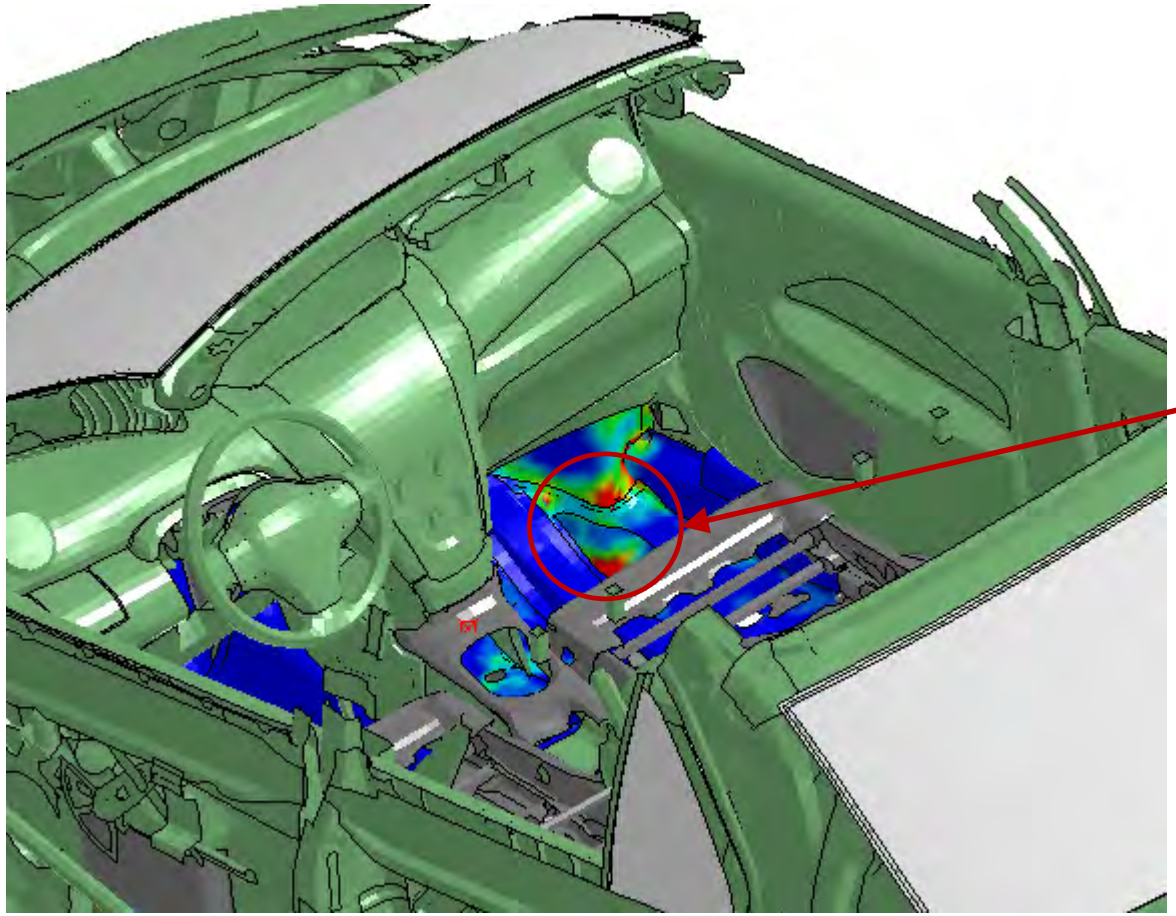
Occupant Compartment Intrusion (OCI) Video



Occupant Compartment Intrusion (OCI)

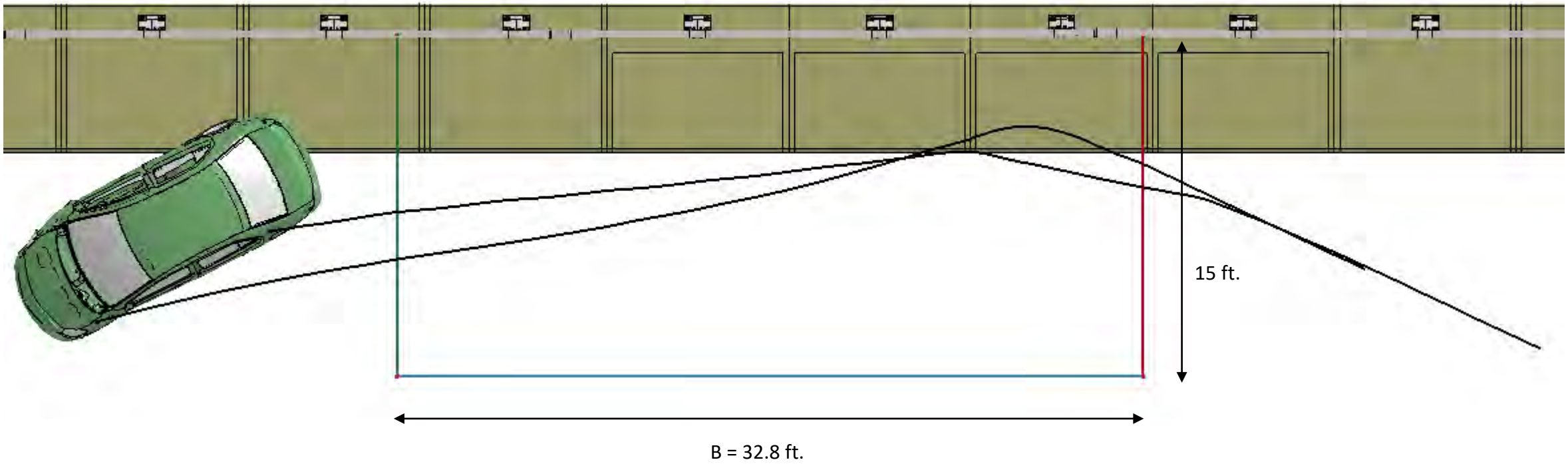


Maximum OCI of the floor, doors, and side panels was ≈**3.4 inches** (87 mm) and occurred at the right-front toe-pan at the wheel well.

Maximum allowable is 9".

Exit Box – NETC 4-Bar – Test 4-10

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."



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Conclusions for Test 4-10 on the NETC 4-BAR Bridge Rail

- 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 = **10.9 degrees** and Max Pitch = **6.5 degrees**.
- The OIV was within critical limits and the maximum ORA was within preferred limits specified in MASH.
  - OIV_x = **24.0 ft/s** and OIV_y = **31.5 ft/s**
  - ORA_x = **7.1 G** and ORA_y = **10.3 G** (*values strongly dependent on time of occupant impact*)
- The maximum **occupant compartment deformation** was approximately **3.4 inches** and occurred at the lower right-front toe pan. This value is well within acceptable limit of 9 inches.
- The vehicle also **remained within the "exit box"** limits.
- **Barrier damage was low to moderate** with the highest deflection occurring on the top railing at the splice connection upstream of the Post 7.
- The greatest deformation of the barrier was:
  - Max Dynamic = **2.8 inches**; Max Permanent = **1.25 inches**

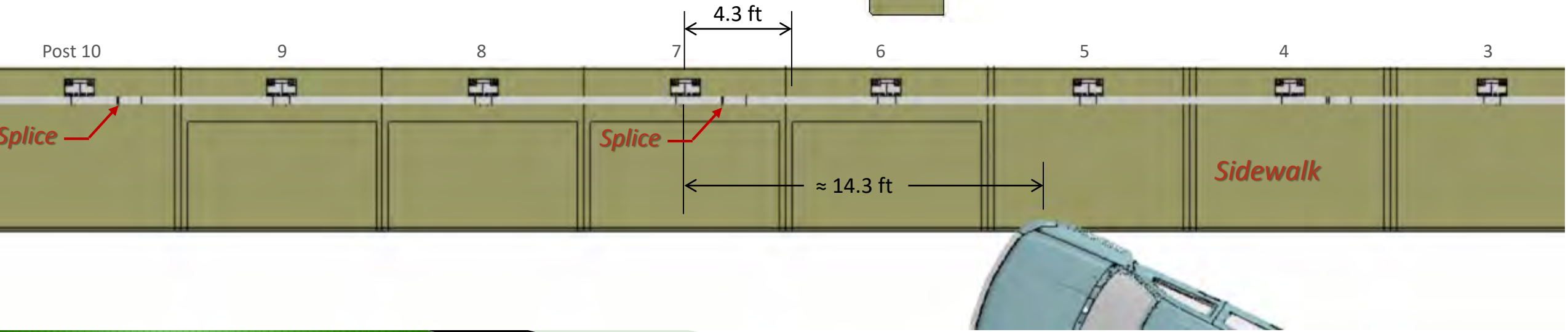
Conclusions for Test 4-10 on the NETC 4-BAR Bridge Rail

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

NETC 4-Bar Bridge Rail Test 4-11 Simulation

- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point
    - Target = 4.3 ft upstream from Post 7
    - Actual = 4.23 ft upstream from critical post

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



NETC 4-Bar Bridge Rail Test 4-11 Simulation

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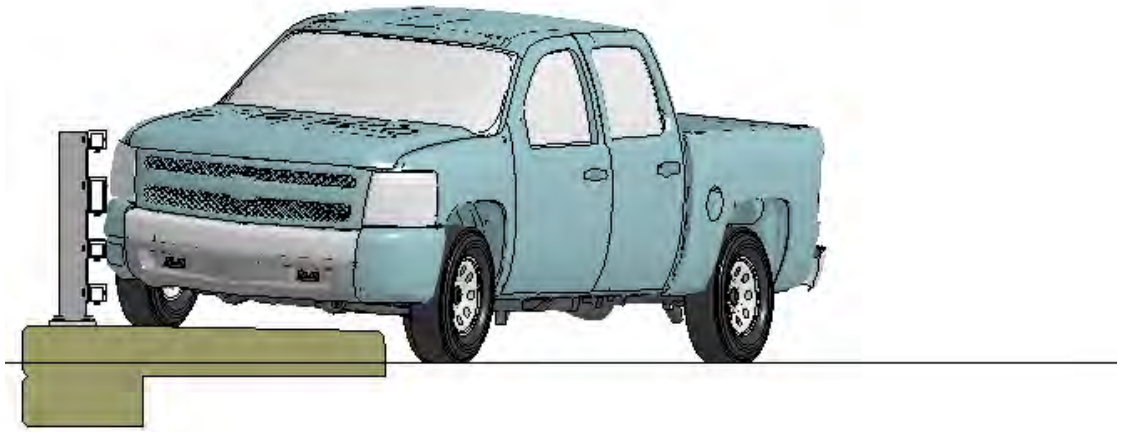
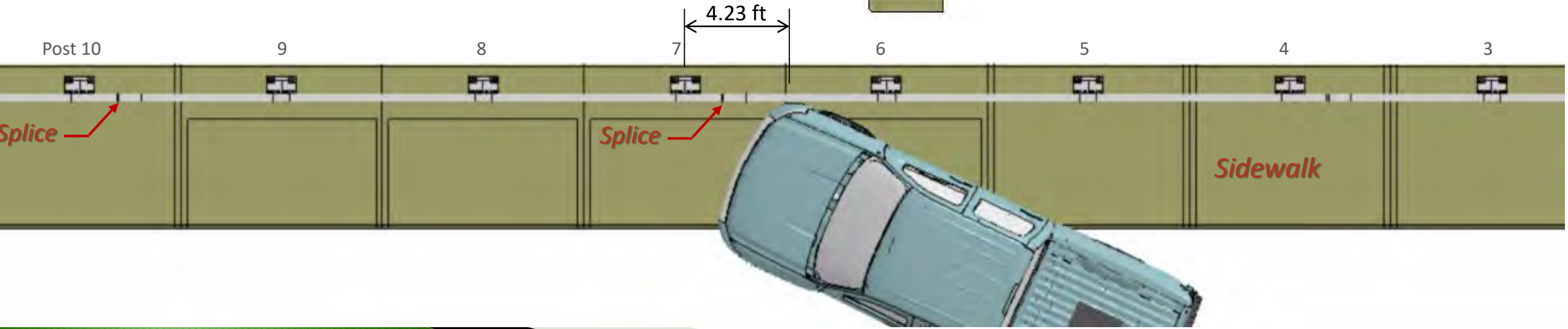
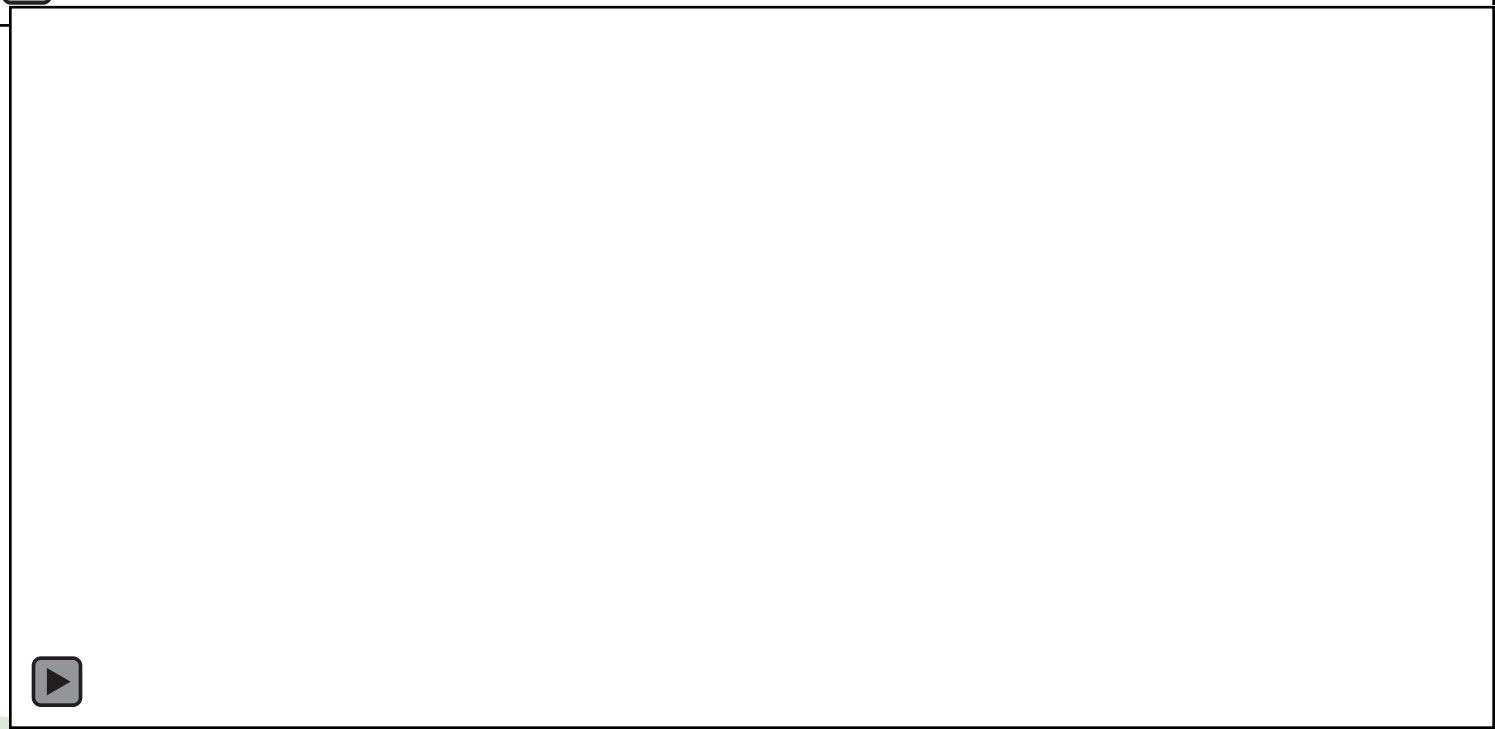
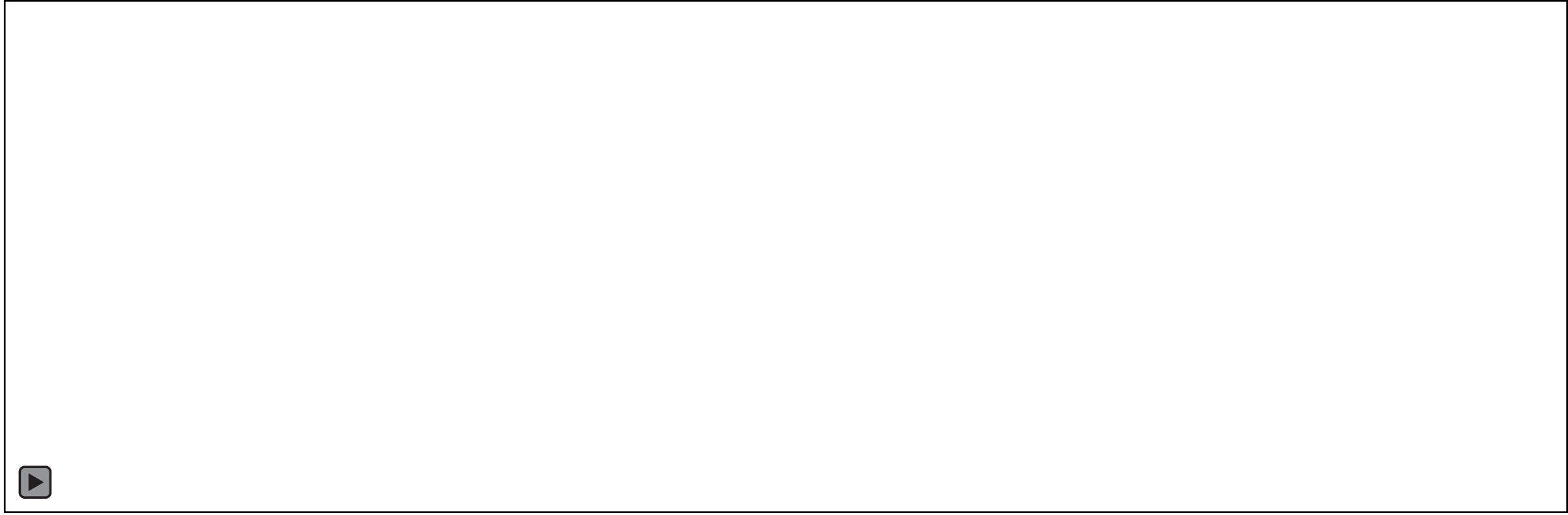


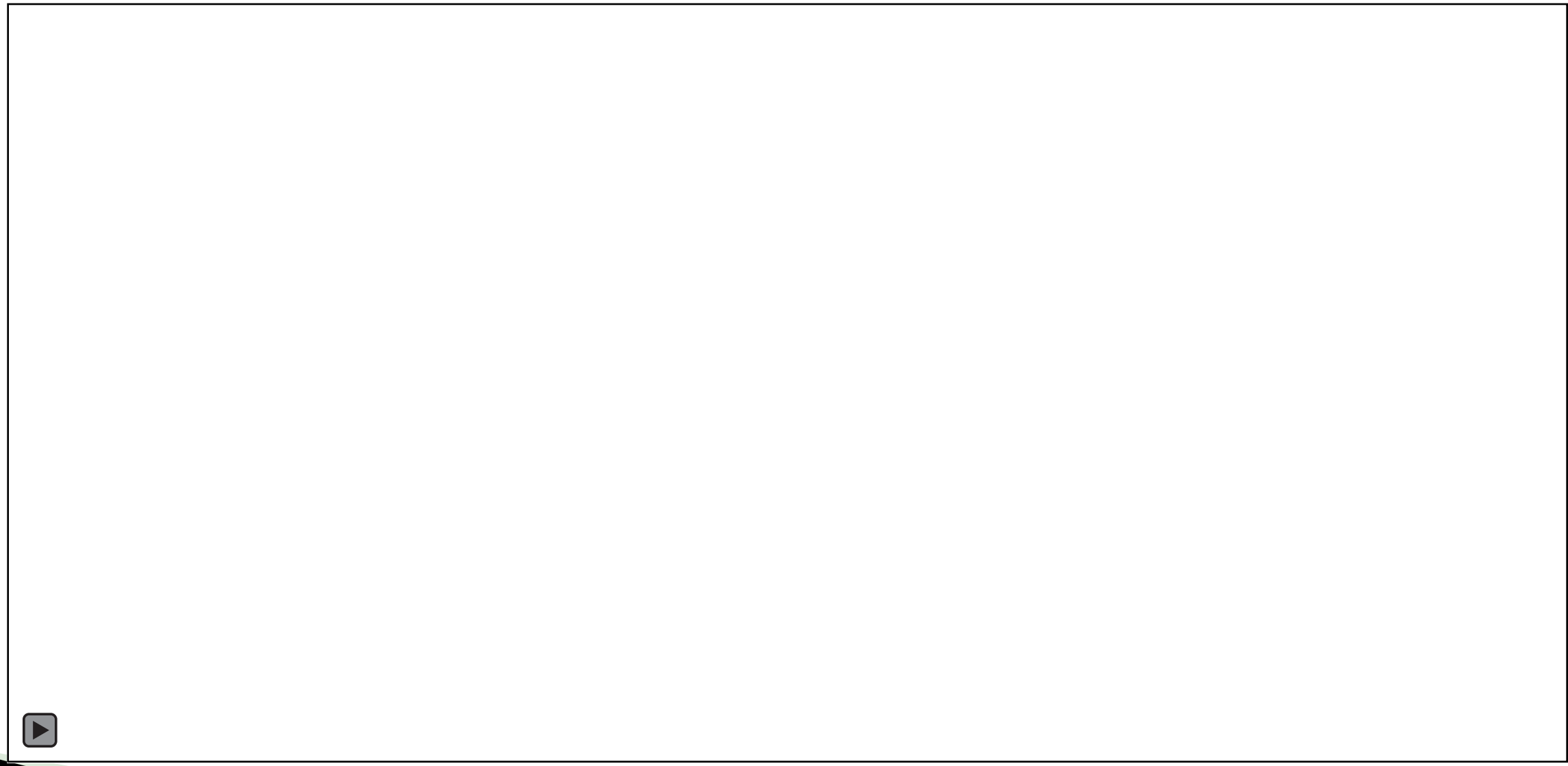


Movies



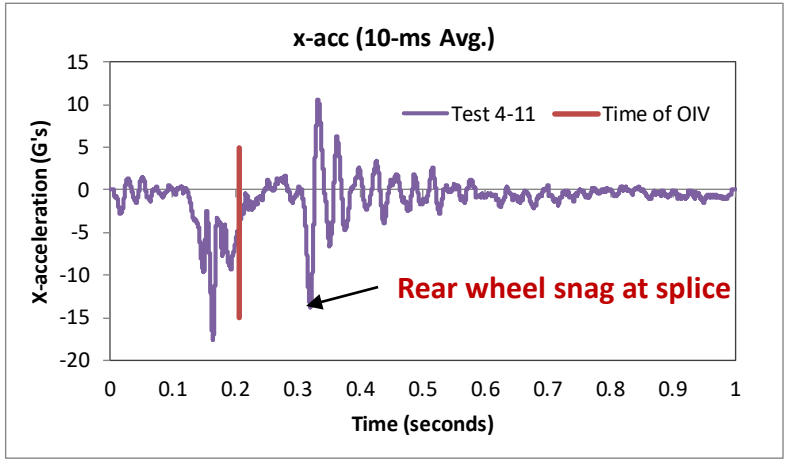


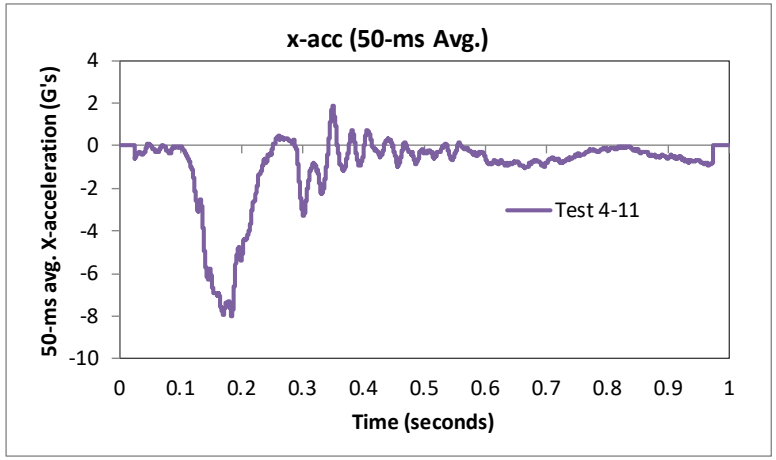
Movies

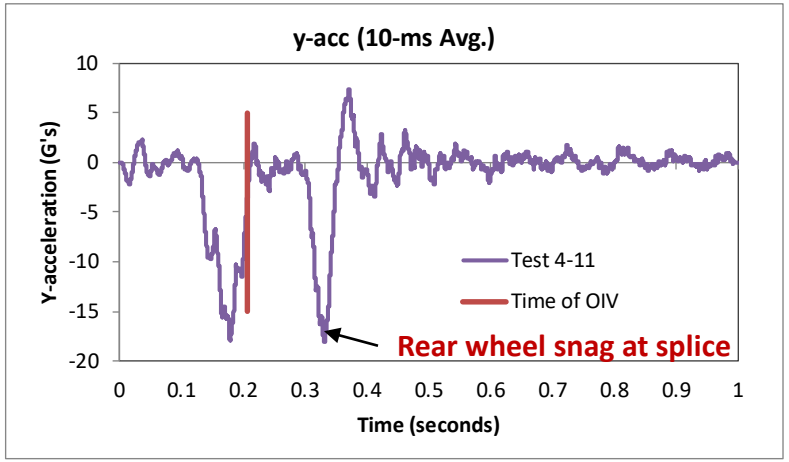


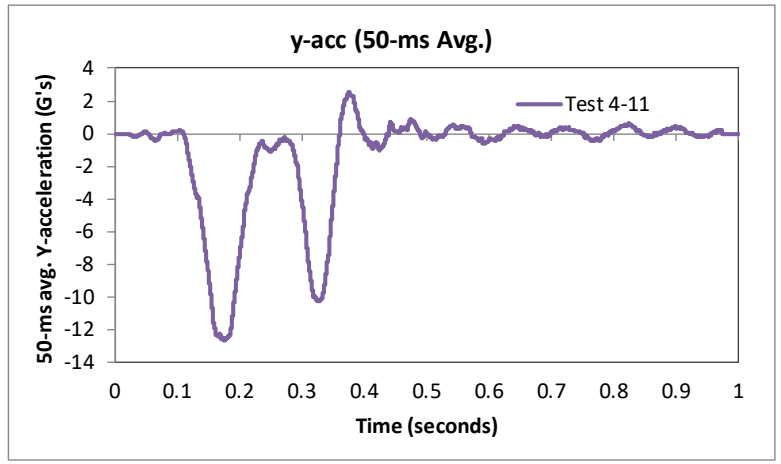
Movies

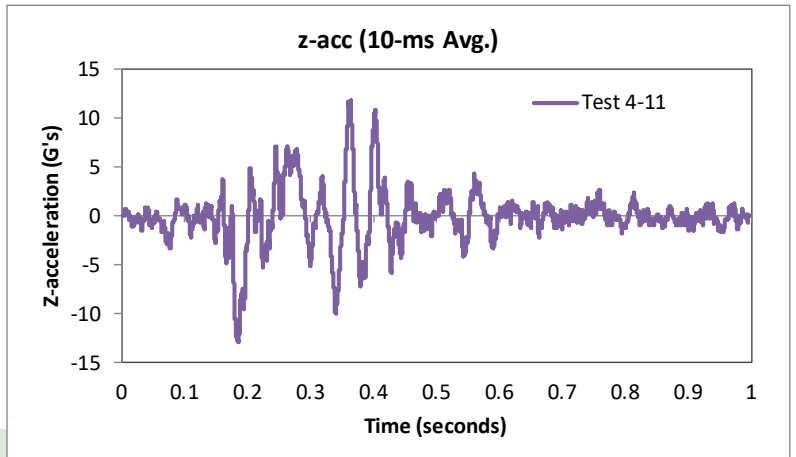
Acceleration Plots

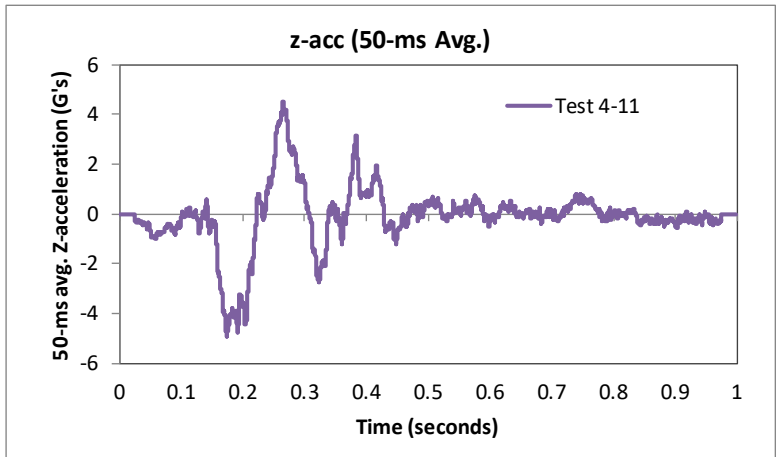












TRAP – Summary Table

Occupant Risk Factors		MASH T4-11 Test 4-11
Occupant Impact Velocity (ft/s)	x-direction	17.7
	y-direction	26.6
	at time	at 0.2039 seconds on right side of interior
THIV (ft/s)		32.2 at 0.2039 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-13.8 (0.3157 - 0.3257 seconds)
	y-direction	-18 (0.3264 - 0.3364 seconds)
PHD (g's)		20.8 (0.3268 - 0.3368 seconds)
ASI		1.61 (0.1482 - 0.1982 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-8 (0.1589 - 0.2089 seconds)
	y-direction	-12.7 (0.1512 - 0.2012 seconds)
	z-direction	-4.9 (0.1487 - 0.1987 seconds)
Maximum Angular Disp. (deg)	Roll	-7.2 (0.1642 seconds)
	Pitch	-8.3 (0.5264 seconds)
	Yaw	-31.4 (0.3422 seconds)

MASH Criteria

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

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

< 75 deg ✓

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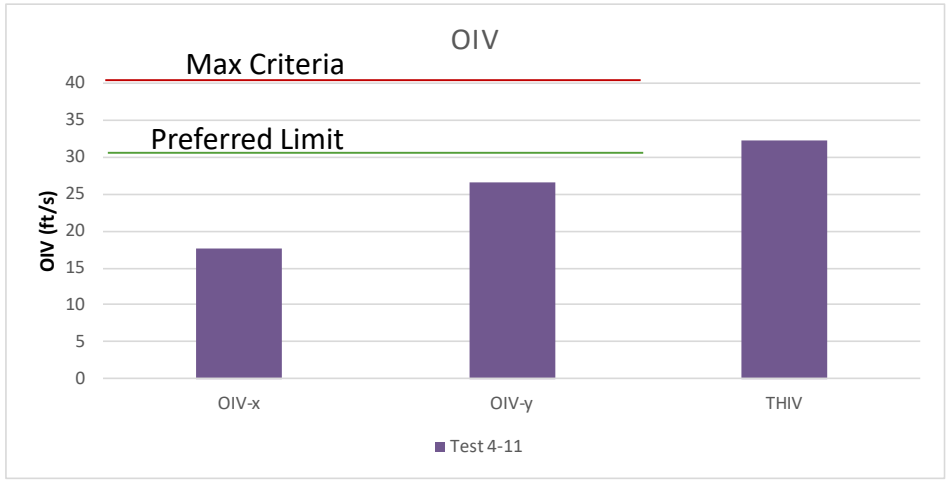
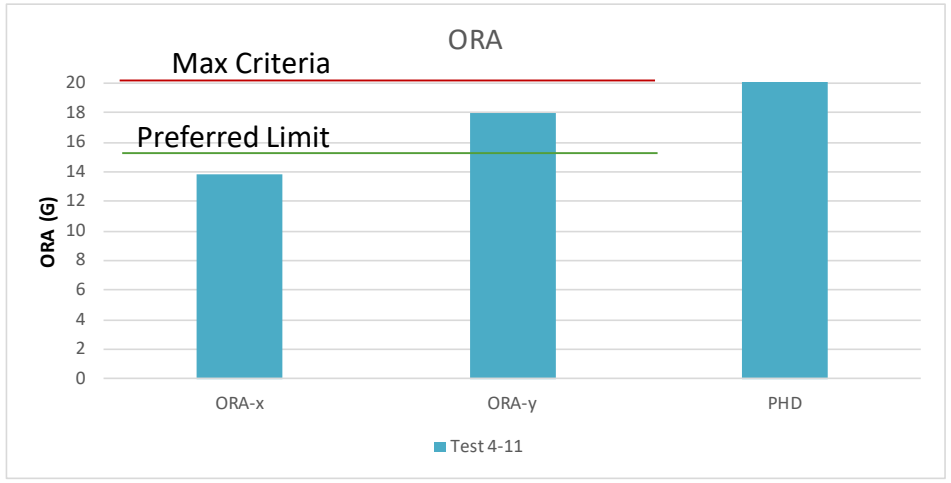
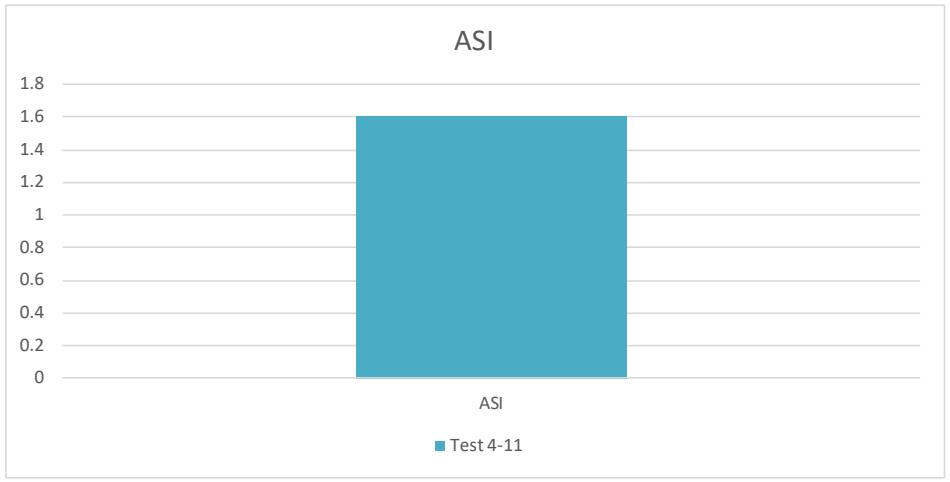
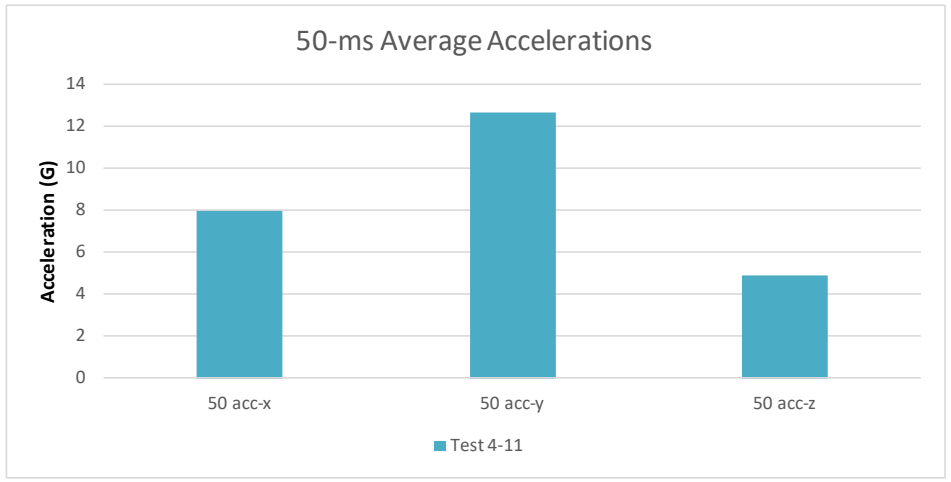
TRAP









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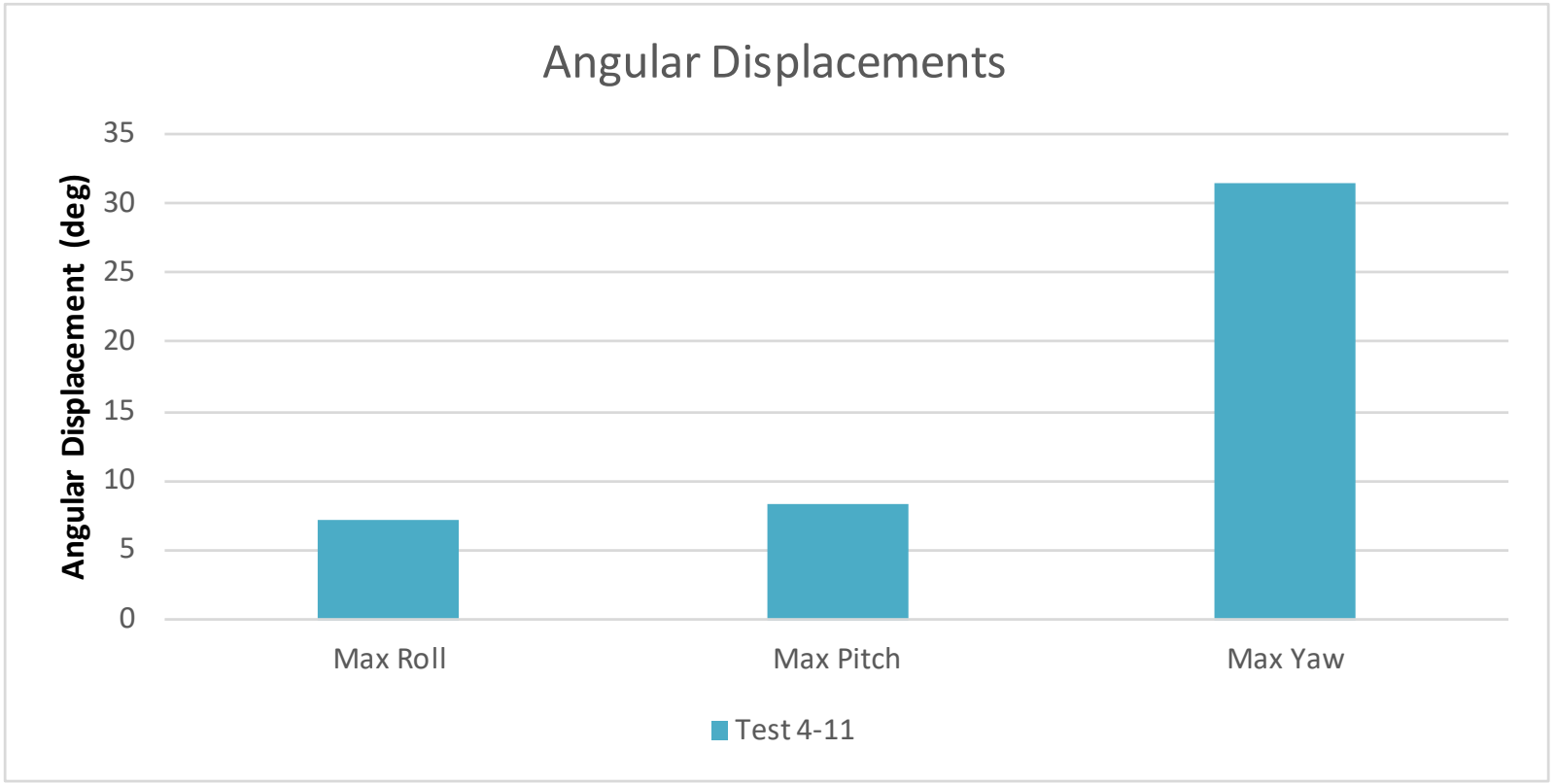
TRAP



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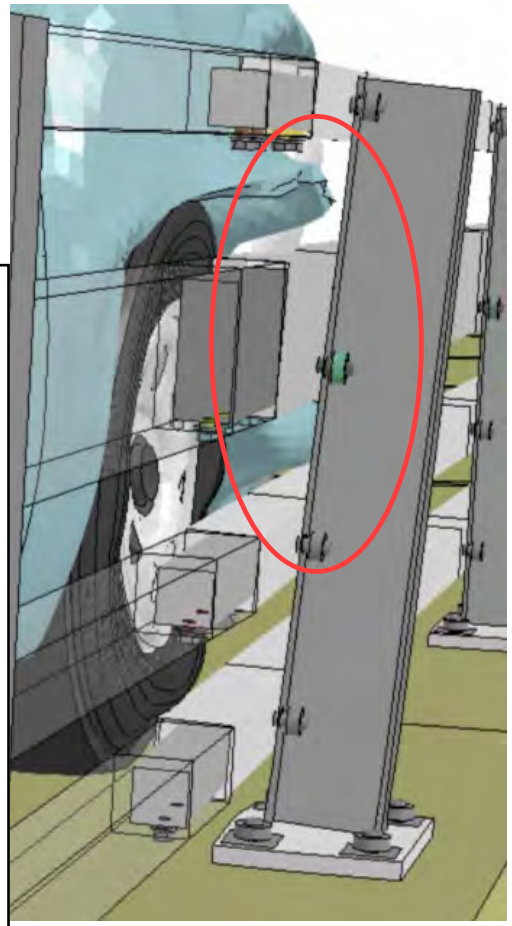
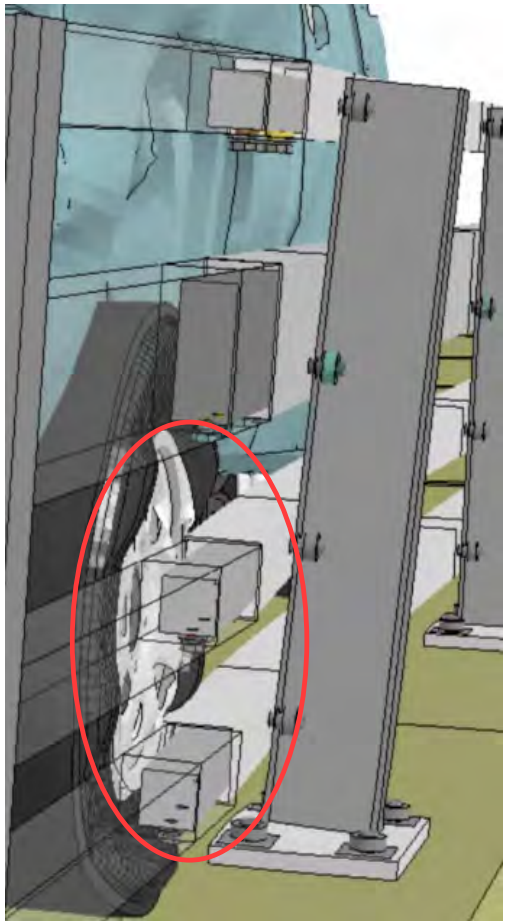
Assessment of Potential Vehicle Snag

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

Front of Vehicle



Rear Tire



Photos of Splice Connection

- PFC Buddy Wendell McLain Memorial Bridge in Dixfield, ME

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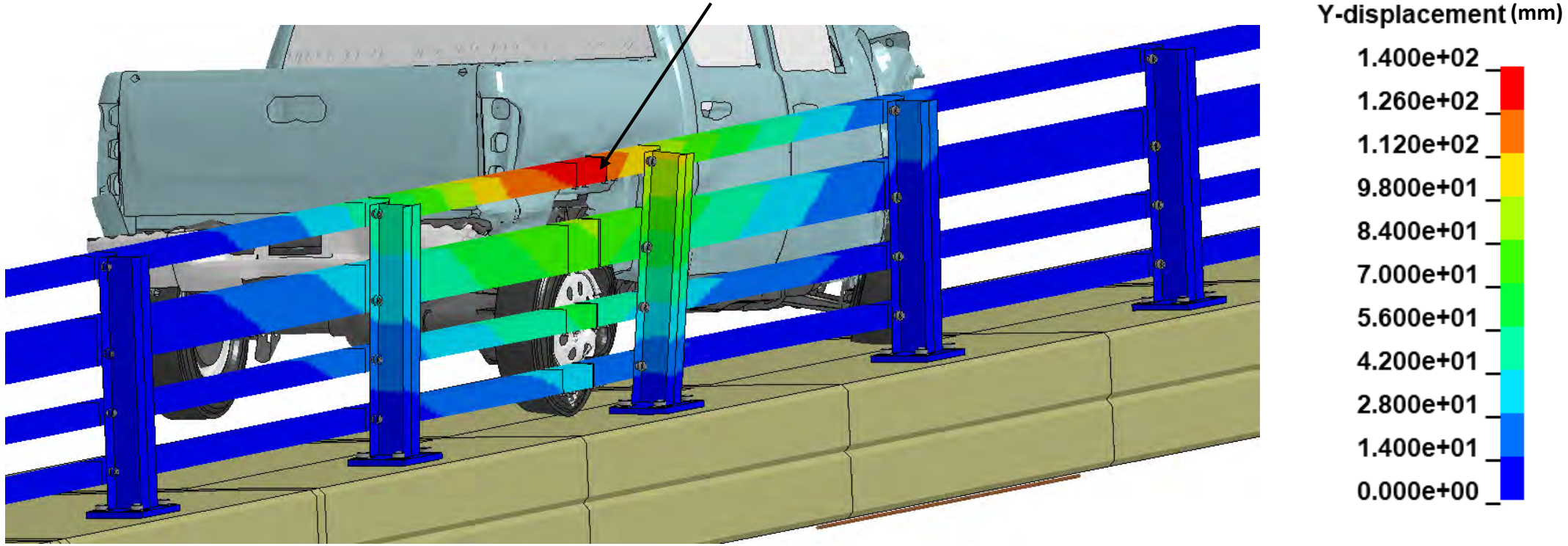
Lateral Dynamic Deflection

Maximum dynamic deflection = 5.4 in (138 mm) @ 0.32 seconds



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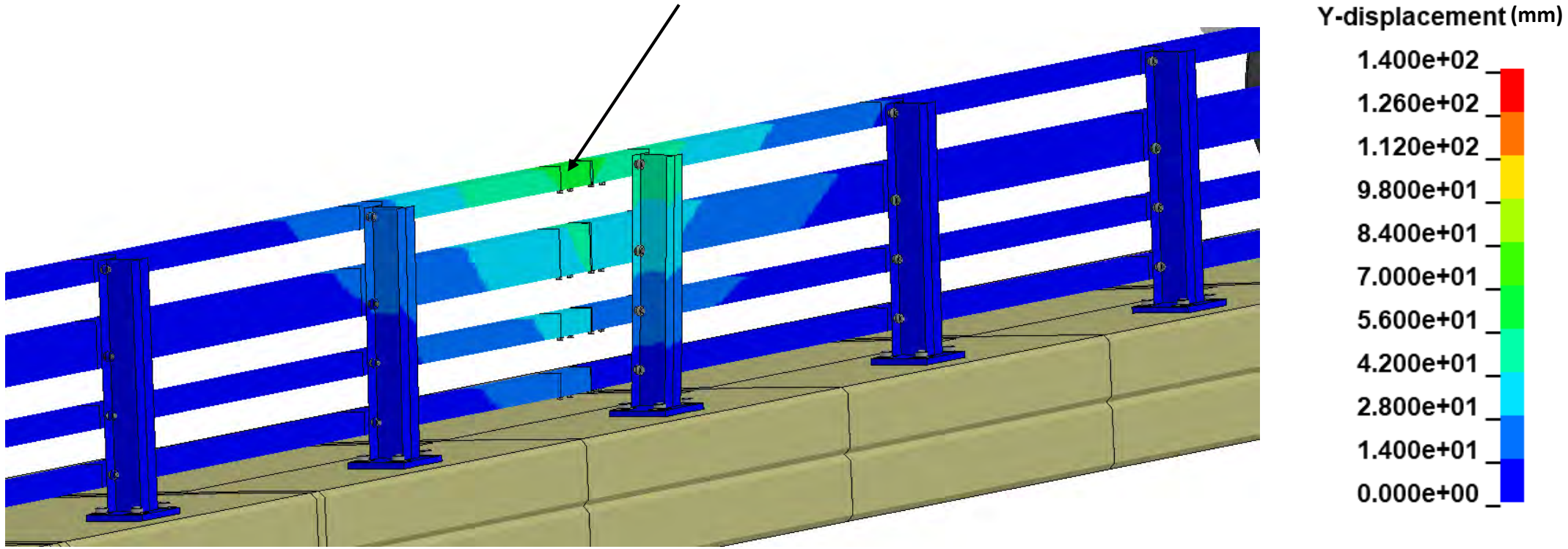
Lateral Permanent Deflection

Maximum permanent deflection = 2.4 in (61.3 mm)



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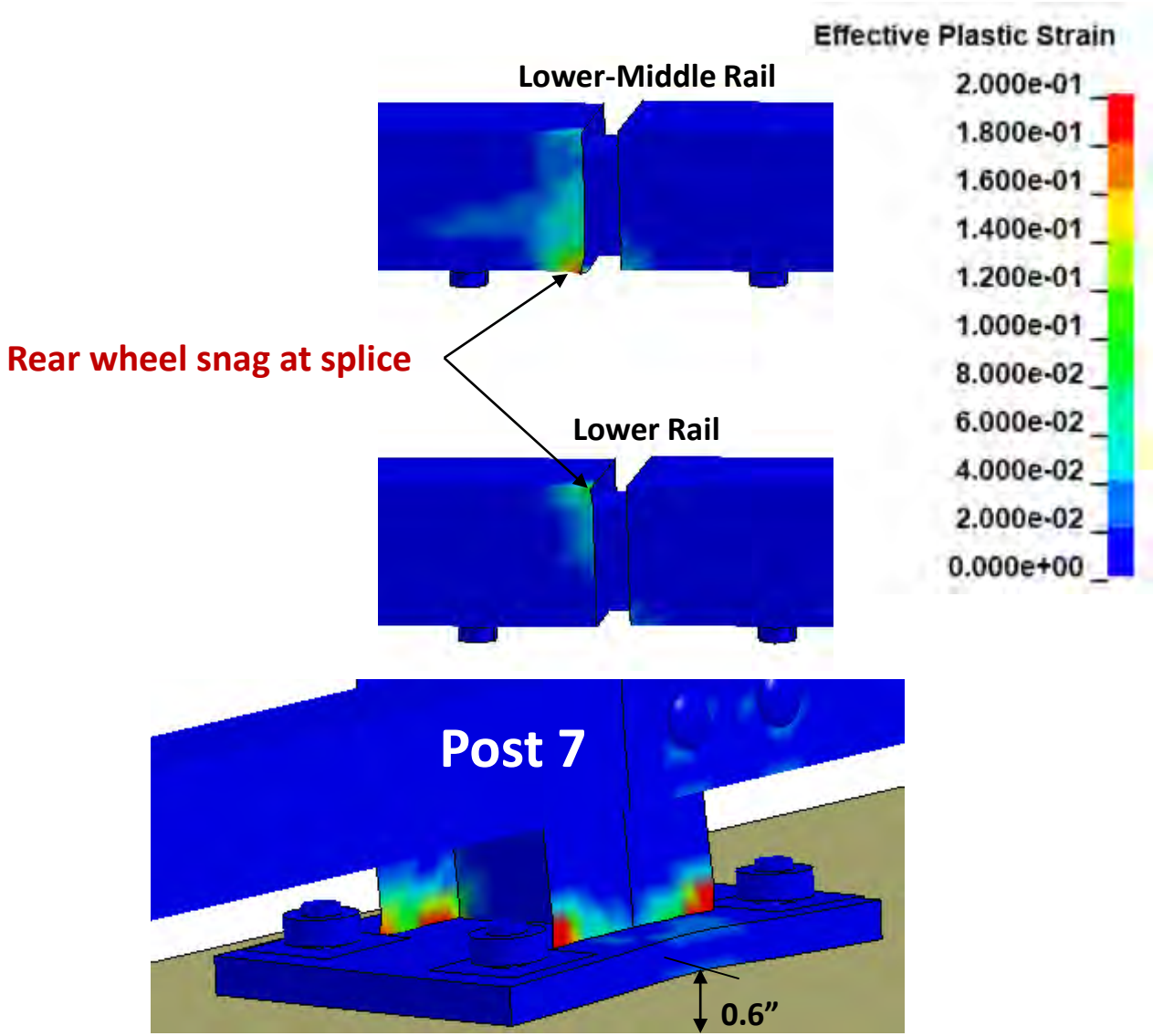
Barrier Damage

- There was moderate damage to the rail tubes between Post 6 and 7, with additional damage at the end of the lower-middle and lower rails at the splice.
- There was moderate damage to Post 6 and 7 and their base plates.
  - There was plastic deformation of at the lower part of the posts and to the base plates.
  - True plastic strain = 0.34 at outer edge of post flange at the weld (possible material failure).
  - Vertical deflection of base plate (Post 6):
    - Dynamic = 0.29 inches (7.5 mm)
    - Permanent = 0.13 inches (3.4 mm)
  - Vertical deflection of base plate (Post 7):
    - Dynamic = 0.6 inches (15 mm)
    - Permanent = 0.31 inches (8 mm)



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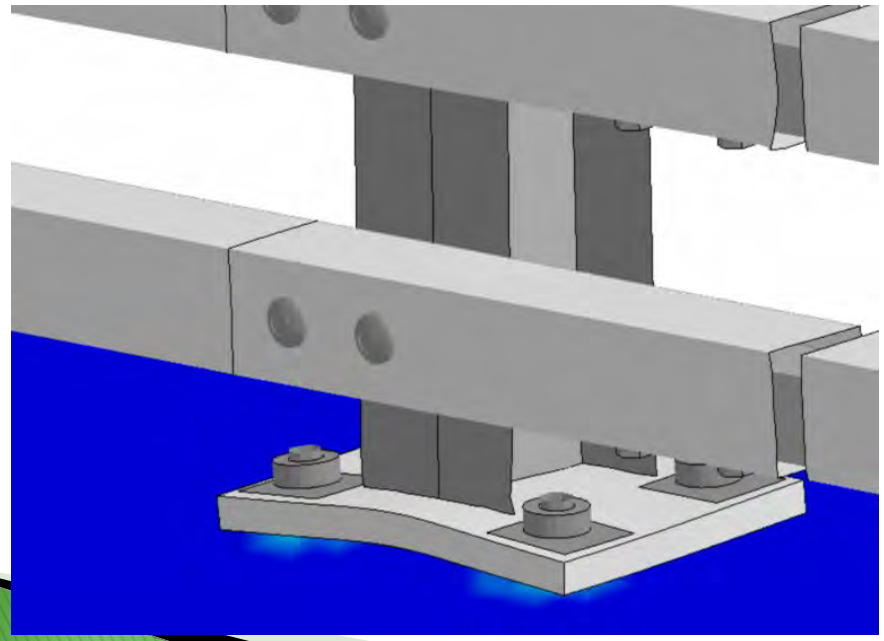
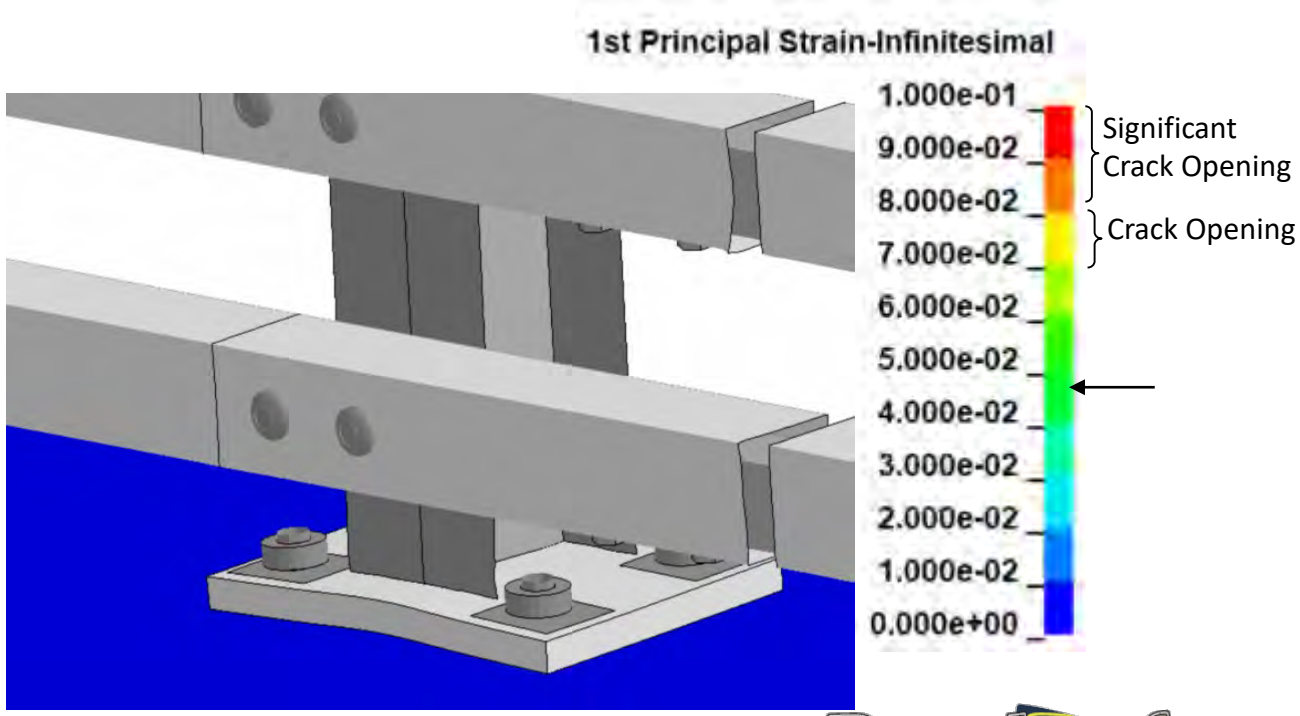
Barrier Damage

- Analysis indicated no damage to the concrete curb/deck.
  - Max dynamic 1st Prin. Strain = 0.048
  - Final 1st Prin. Strain = 0.024



Dynamic at time = 0.32 seconds



Final Static

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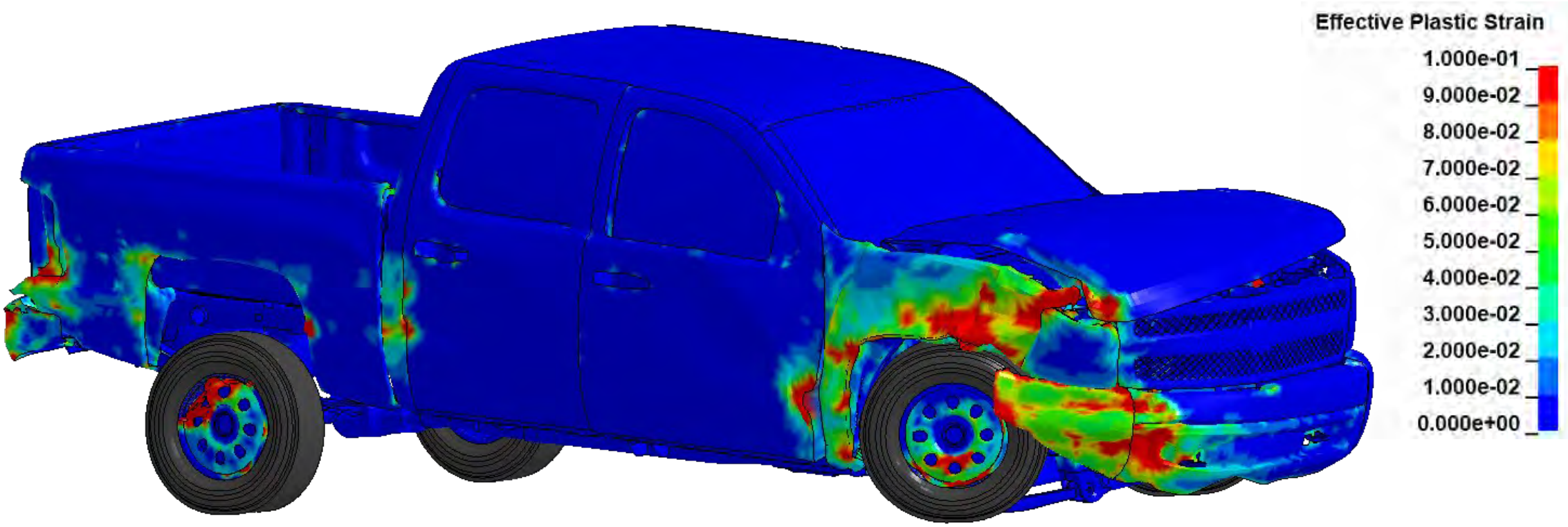
Effective Plastic Strain for Pickup Test



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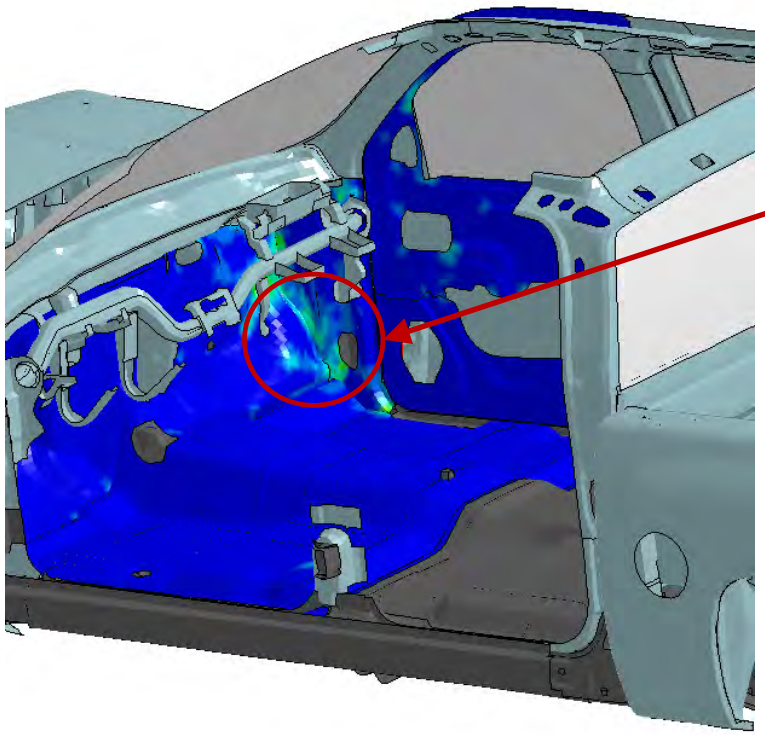
Occupant Compartment Intrusion

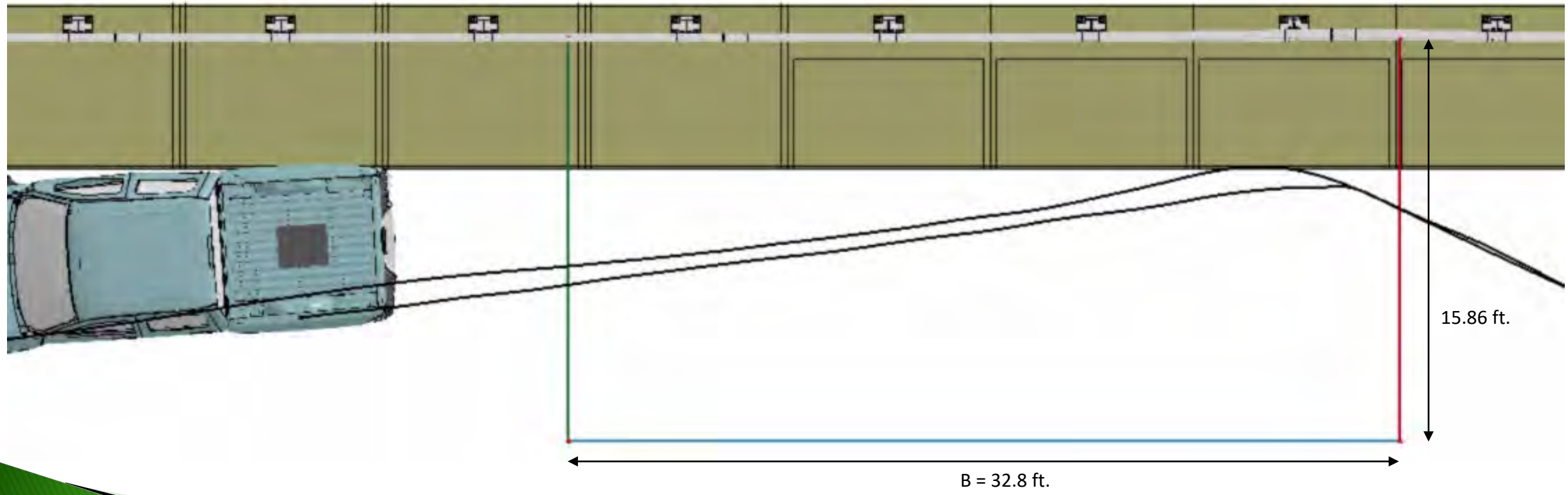
Occupant Compartment Intrusion (OCI)



Maximum OCI was ≈2.2 inches (57 mm) and occurred at the right-front toe-pan at the wheel well.

Exit Box – NETC 4-Bar – Test 4-11

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."



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Conclusions for Test 4-11 on the NETC 4-BAR Bridge Rail

- The barrier successfully contained and redirected the 2270P vehicle.
- The vehicle remained upright and stable through impact and redirection, with relatively low angular displacements
  - Max Roll = **7.2 degrees** and Max Pitch = **8.3 degrees**.
- The OIV was within preferred limits and the maximum ORA was within critical limits specified in MASH.
  - OIV_x = **17.7 ft/s** and OIV_y = **26.6 ft/s**
  - ORA_x = **5.7 G** and ORA_y = **16.4 G**
- The maximum occupant compartment deformation was approximately **2.2 inches** and occurred at the lower right-front toe pan. This value is well within acceptable limit of 9 inches.
- The vehicle also **remained well within the "exit box"** limits and showed no sign of entering back into travel lanes at aggressive angle.
- Barrier damage was moderate.
- The greatest deformation of the barrier occurred at the splice connection and was:
  - Max Dynamic = **5.4 inches**; Max Permanent = **2.4 inches**

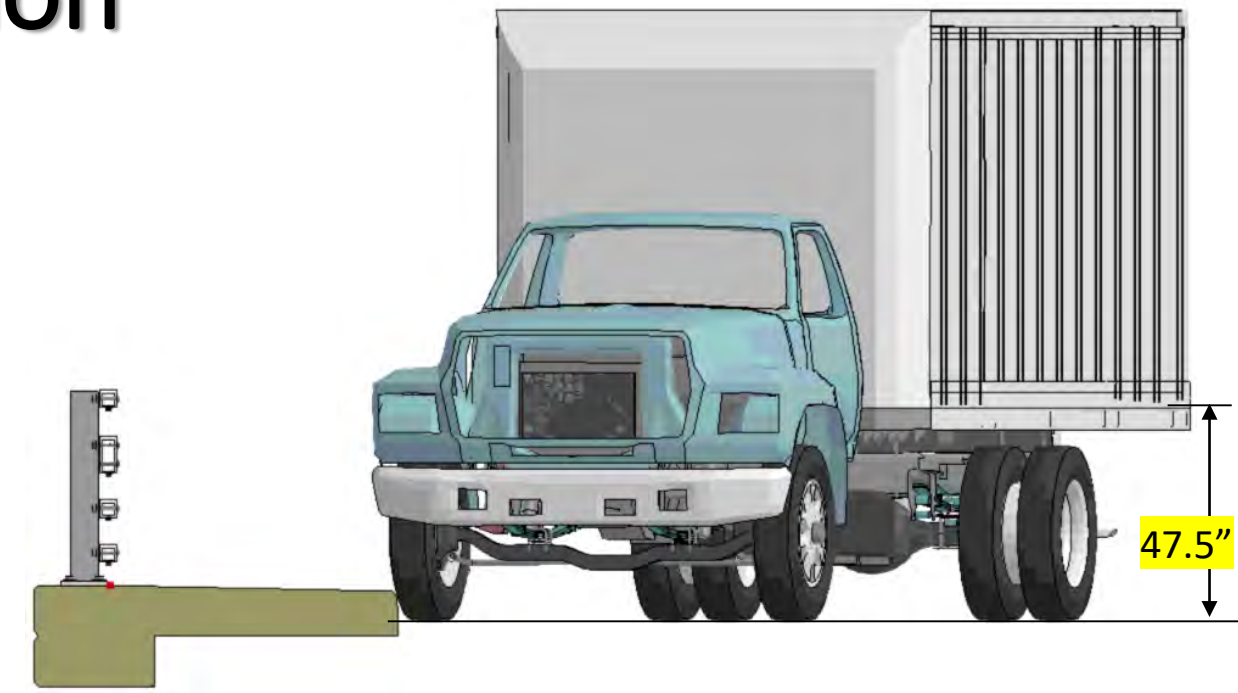
Conclusions for Test 4-11 on the NETC 4-BAR Bridge Rail

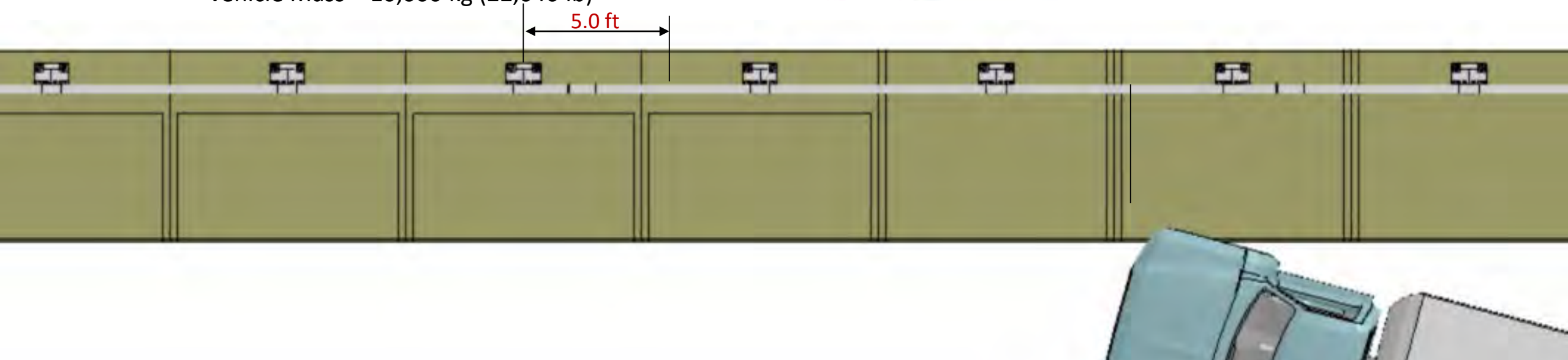
Evaluation Factors		Evaluation Criteria	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is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

MASH Test 4-12 Simulation

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





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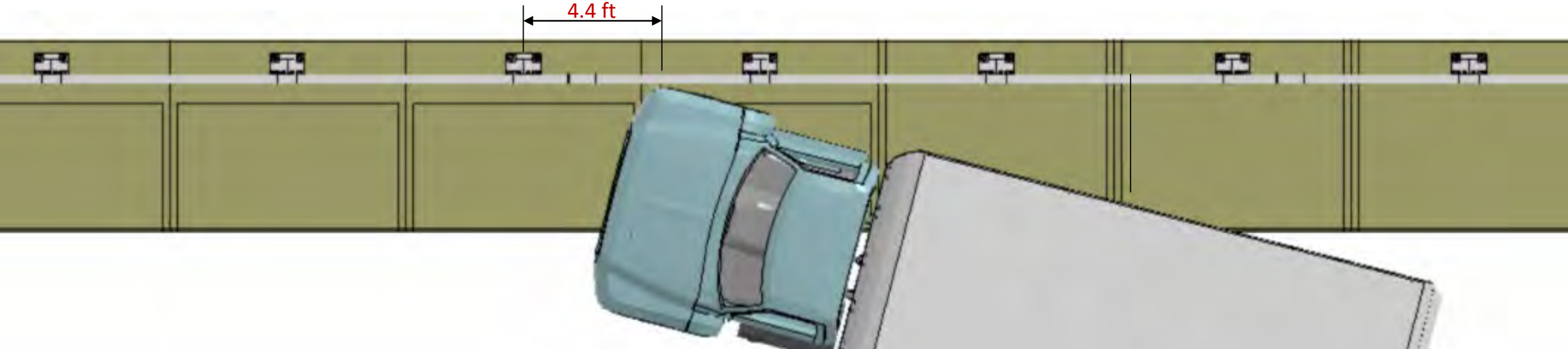
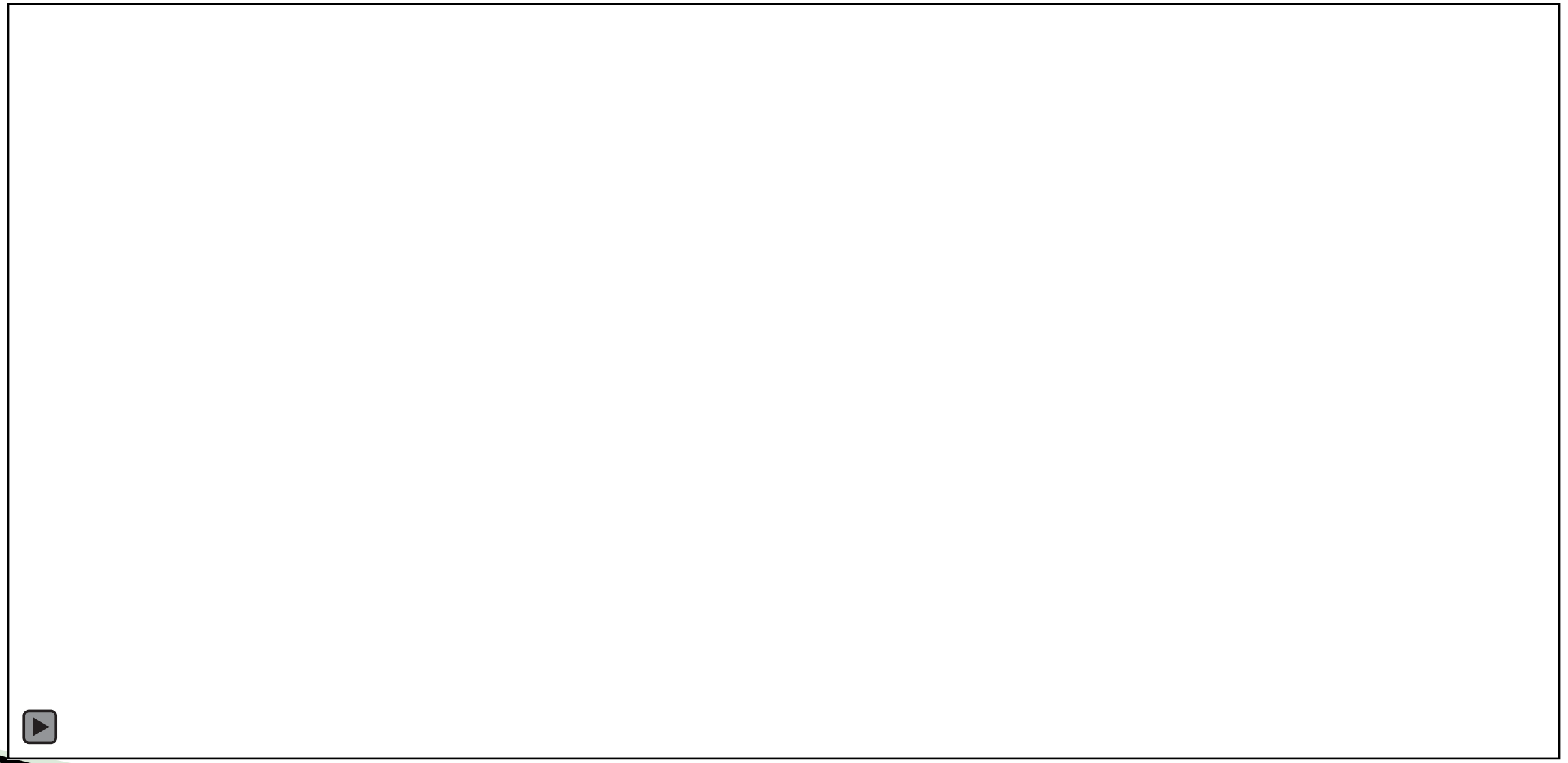
Ford 800 Surrogate



Movies

Movies



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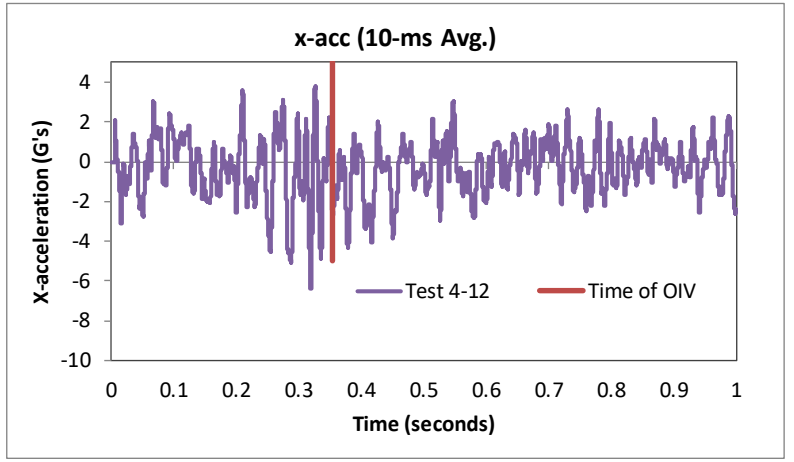
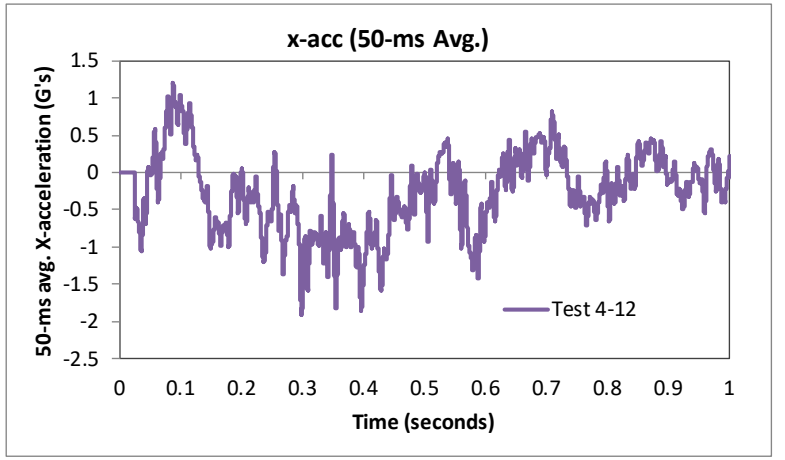
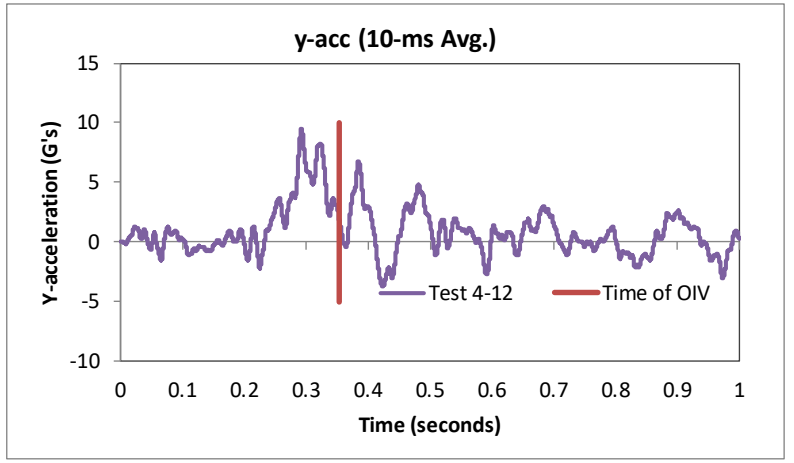
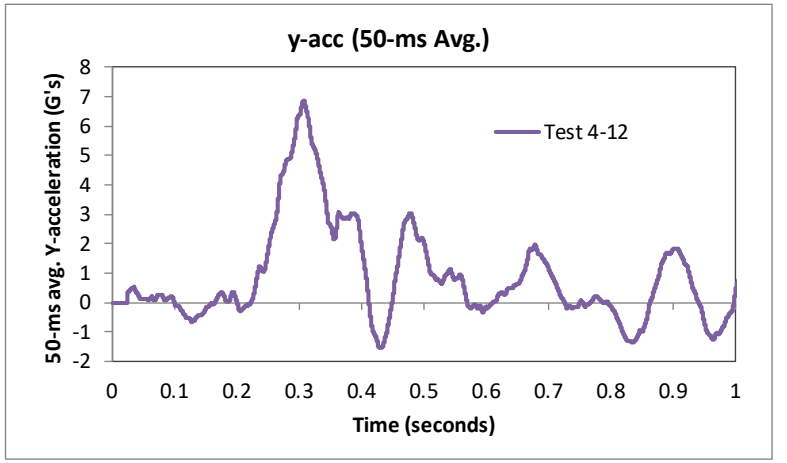
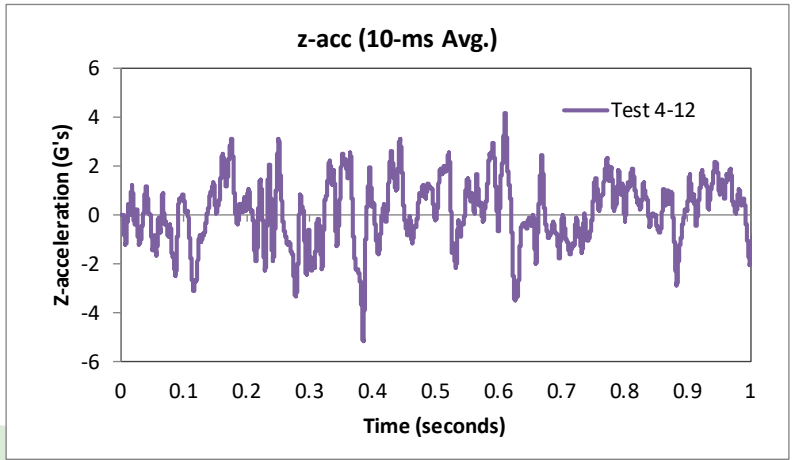
Acceleration Plots

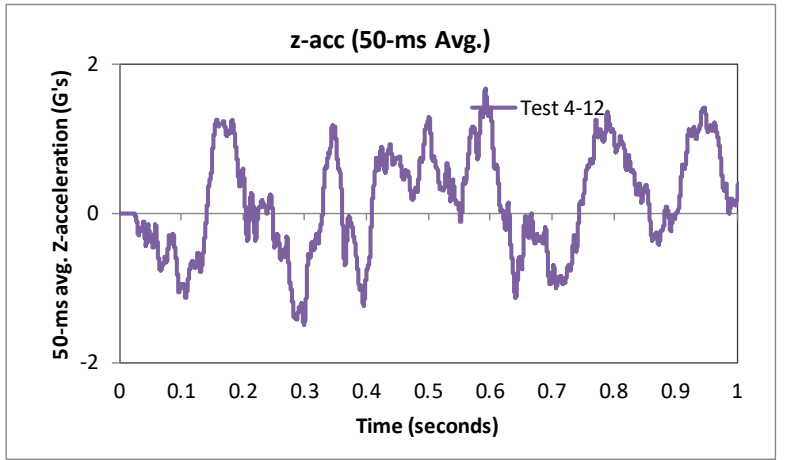




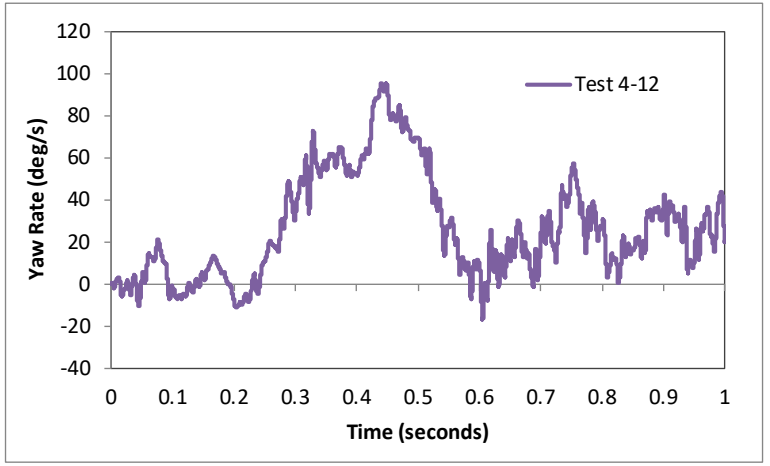


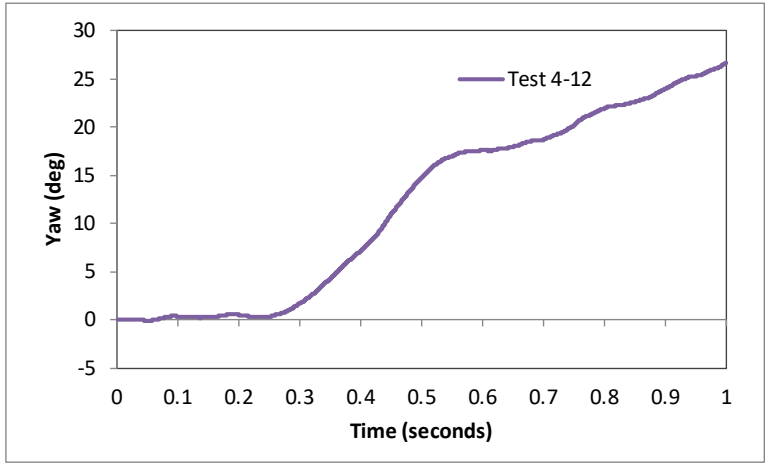


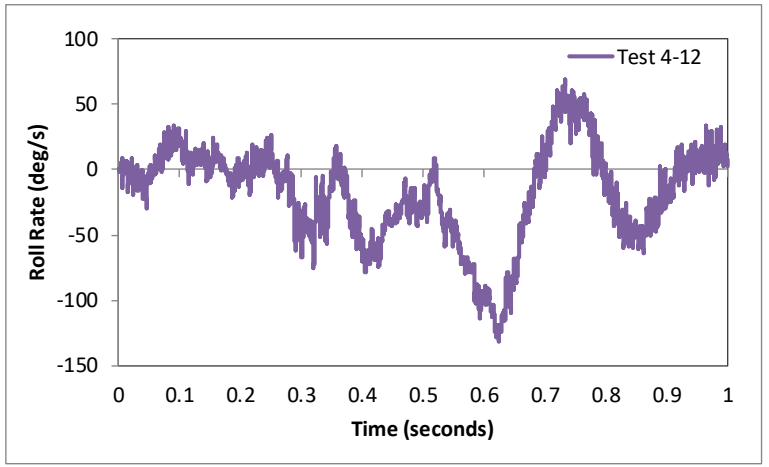


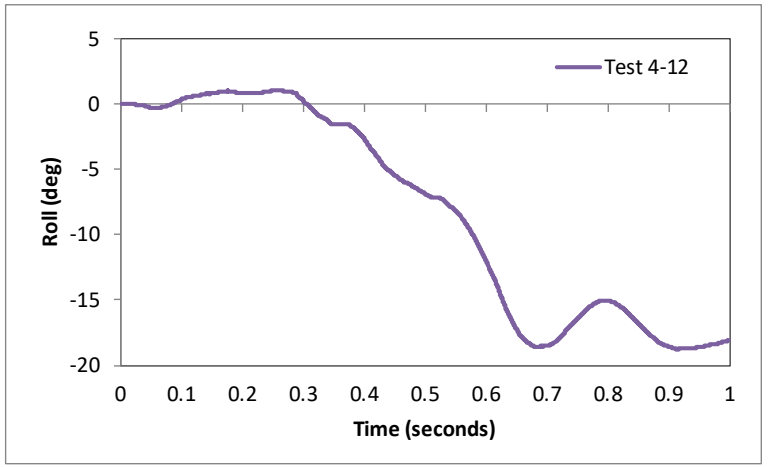


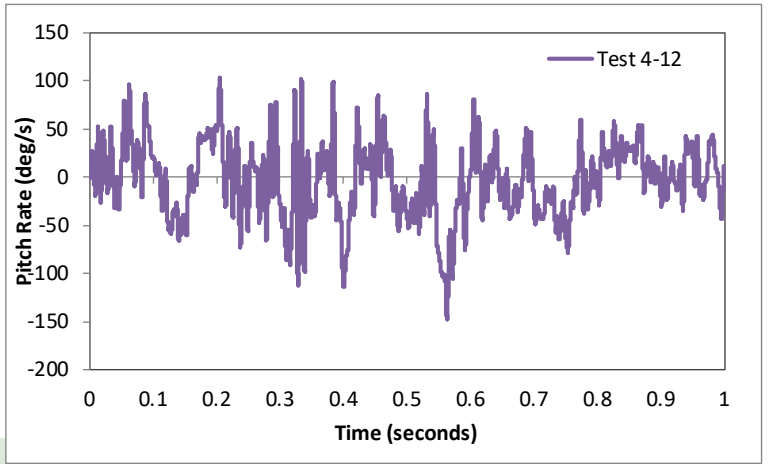
Angular Rate and Displacement Plots

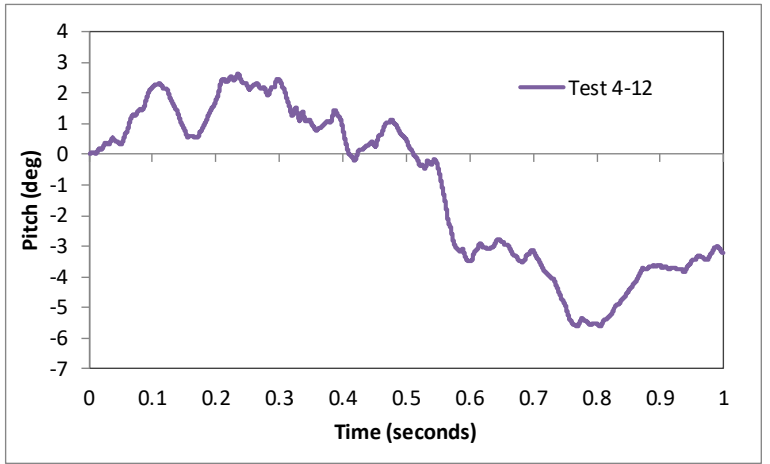












TRAP – Summary Table

Occupant Risk Factors		MASH T4-12 Test 4-12
Occupant Impact Velocity (ft/s)	x-direction	3.9
	y-direction	-16.7
	at time	at 0.3519 seconds on left side of interior
THIV (ft/s)		17.4
		at 0.3519 seconds on left side of interior
Ridedown Acceleration (g's)	x-direction	-4.3 (0.3734 - 0.3834 seconds)
	y-direction	6.7 (0.3793 - 0.3893 seconds)
PHD (g's)		6.7 (0.3791 - 0.3891 seconds)
ASI		0.77 (0.2828 - 0.3328 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-1.9 (0.2735 - 0.3235 seconds)
	y-direction	6.9 (0.2823 - 0.3323 seconds)
	z-direction	1.7 (0.5674 - 0.6174 seconds)
Maximum Angular Disp. (deg)	Roll	-18.8 (0.9140 seconds)
	Pitch	-5.6 (0.8050 seconds)
	Yaw	39.7 (1.4987 seconds)

MASH Criteria

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

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

< 75 deg ✓

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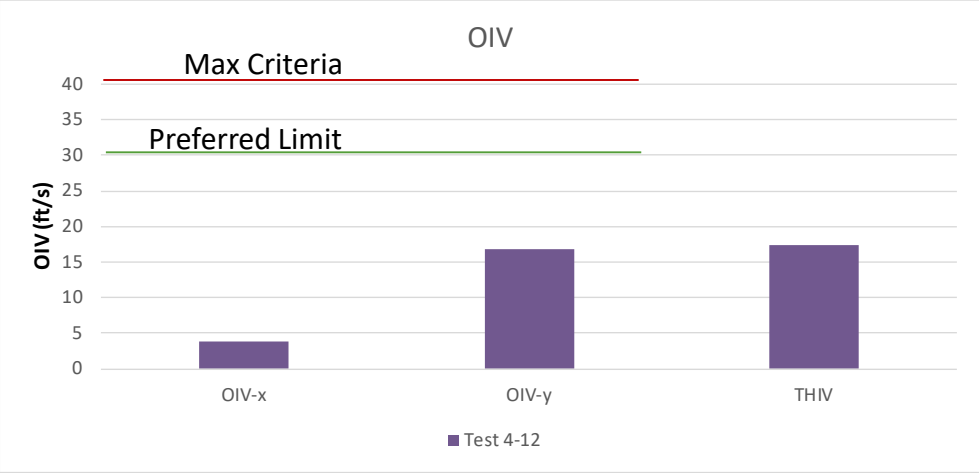
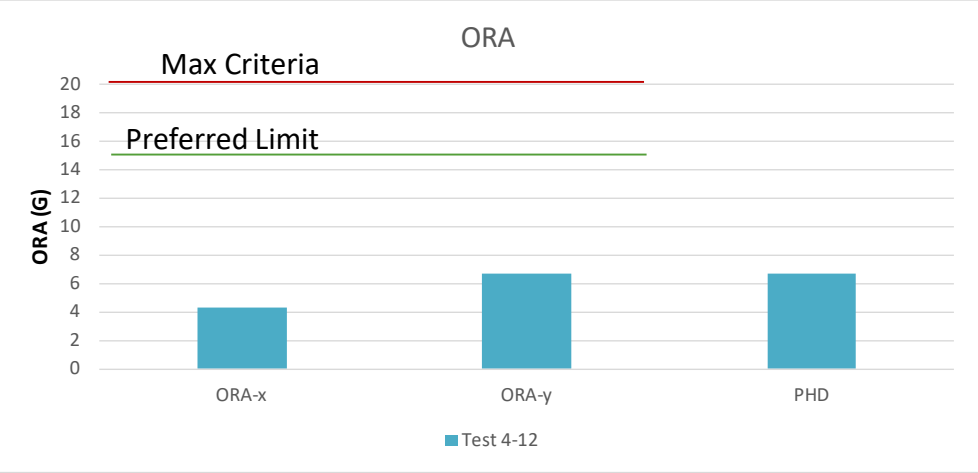
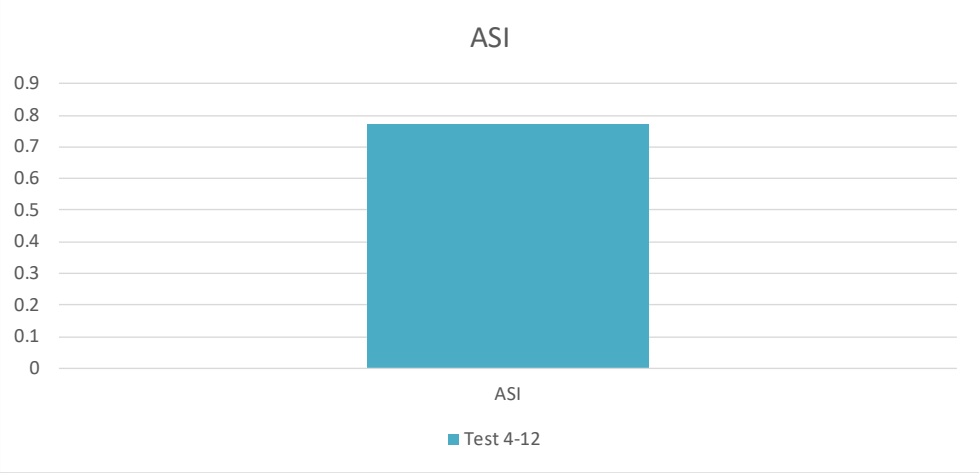
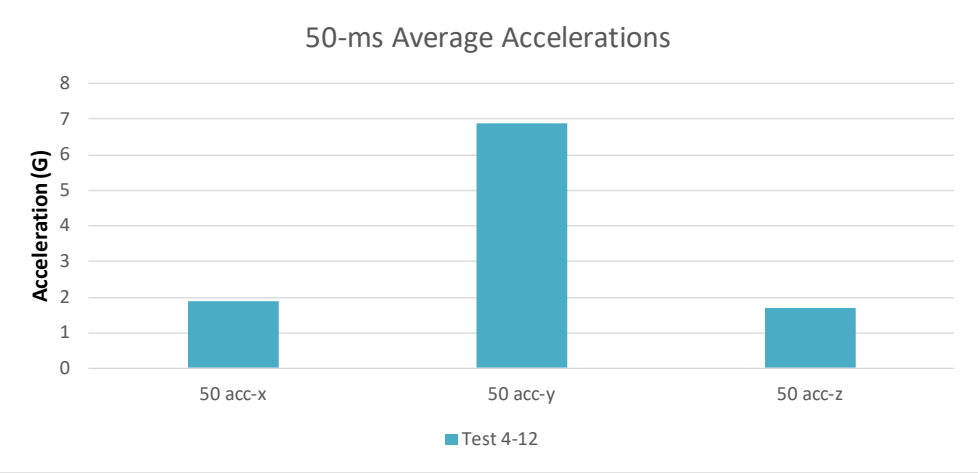
TRAP









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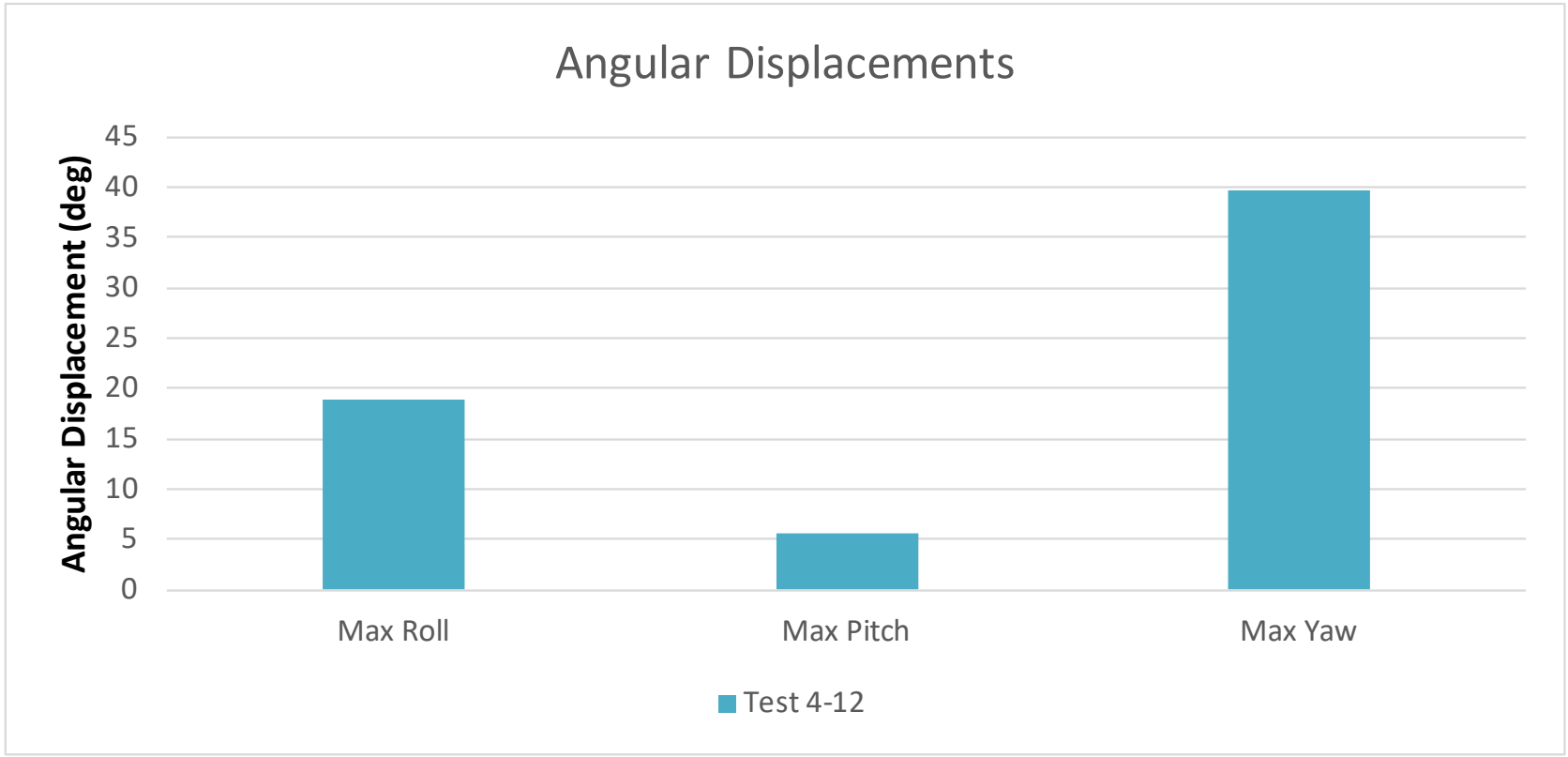
TRAP



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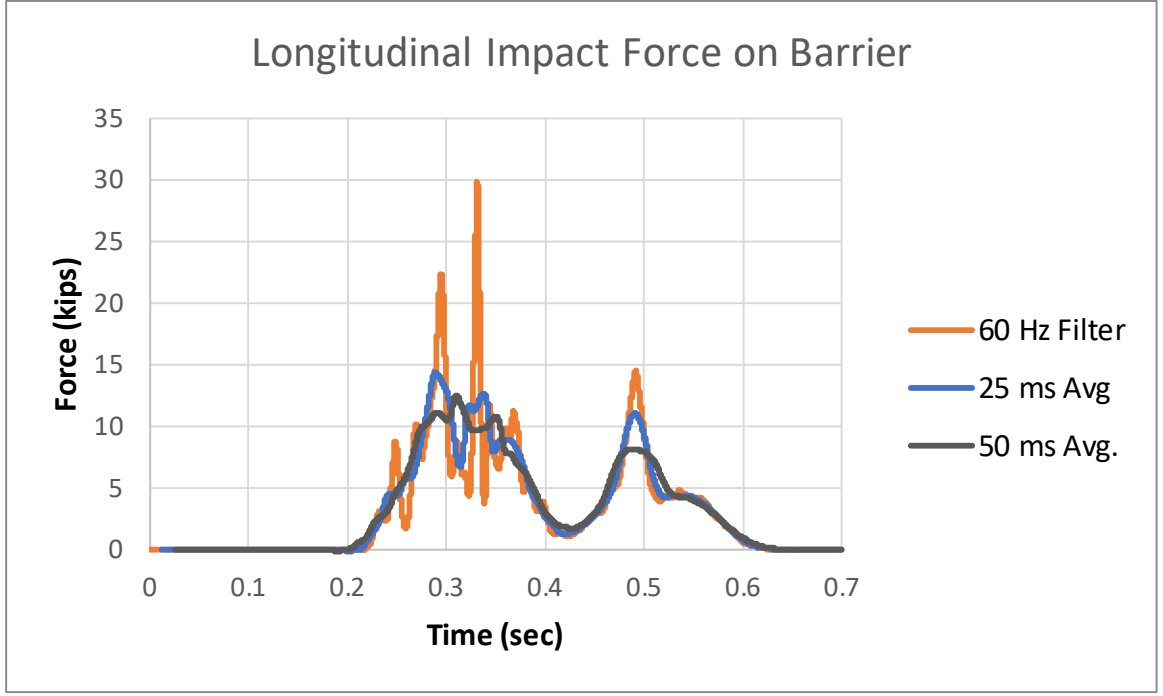
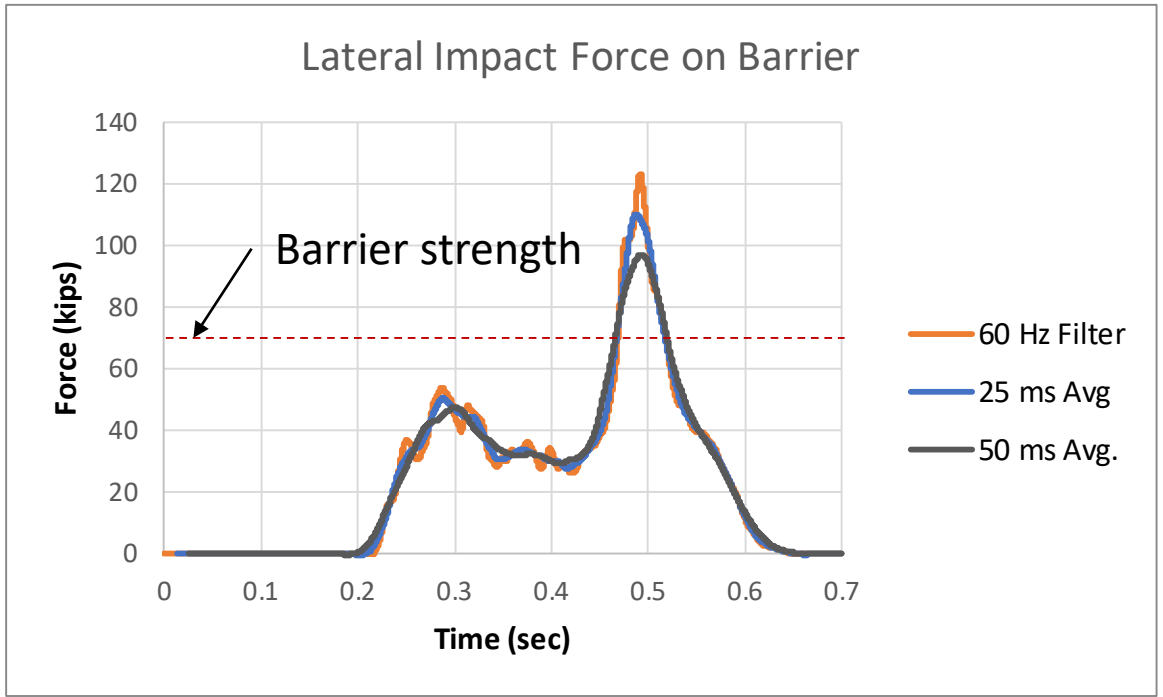
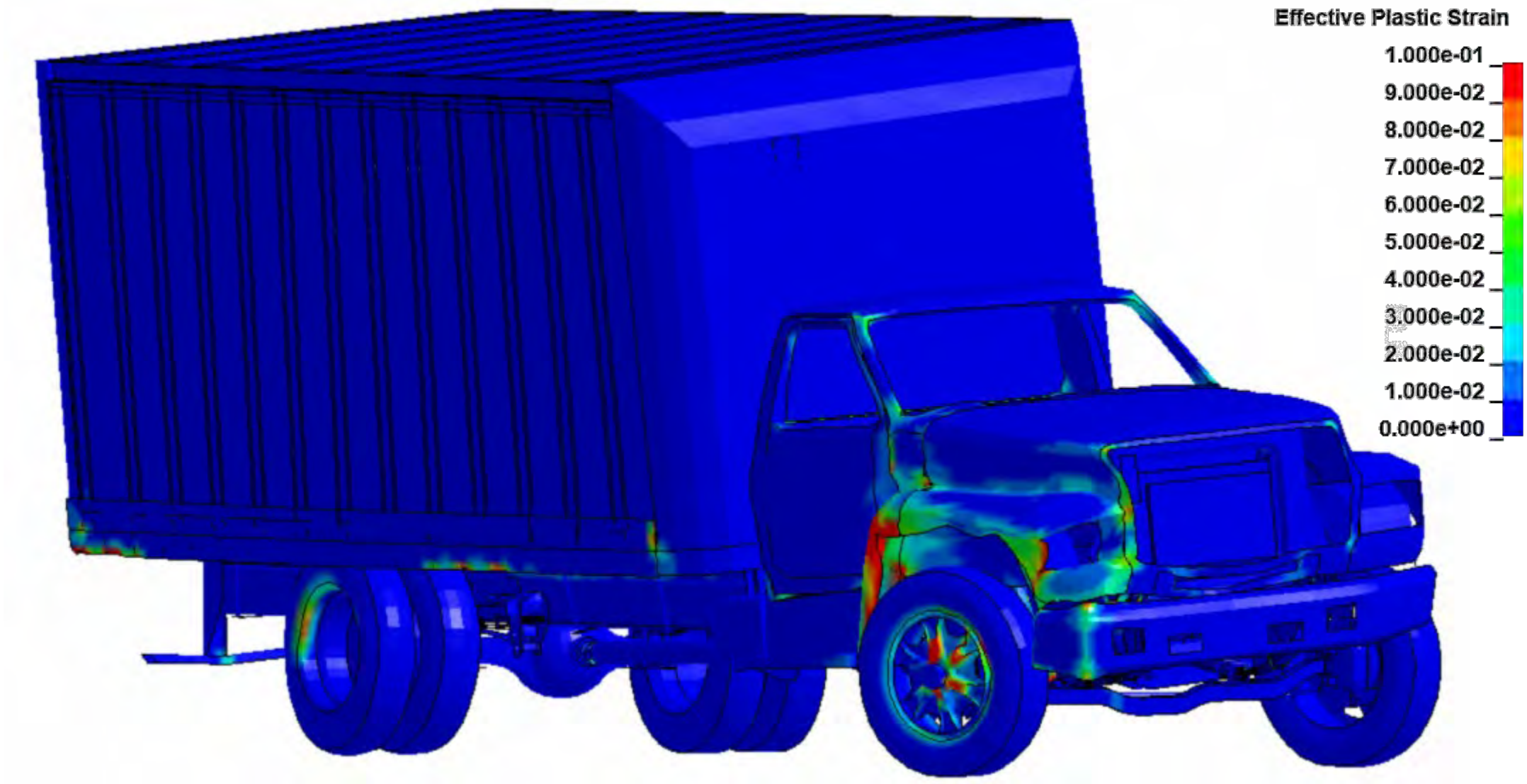
Impact Forces on Bridge Rail from FEA

- Note that the peak lateral loads result from the “tail slap” not the front of the vehicle.
- This is important regarding containment, because the vehicle would already be passing (or passed) the damaged section if failure did occur.





Effective Plastic Strain for SUT Tests



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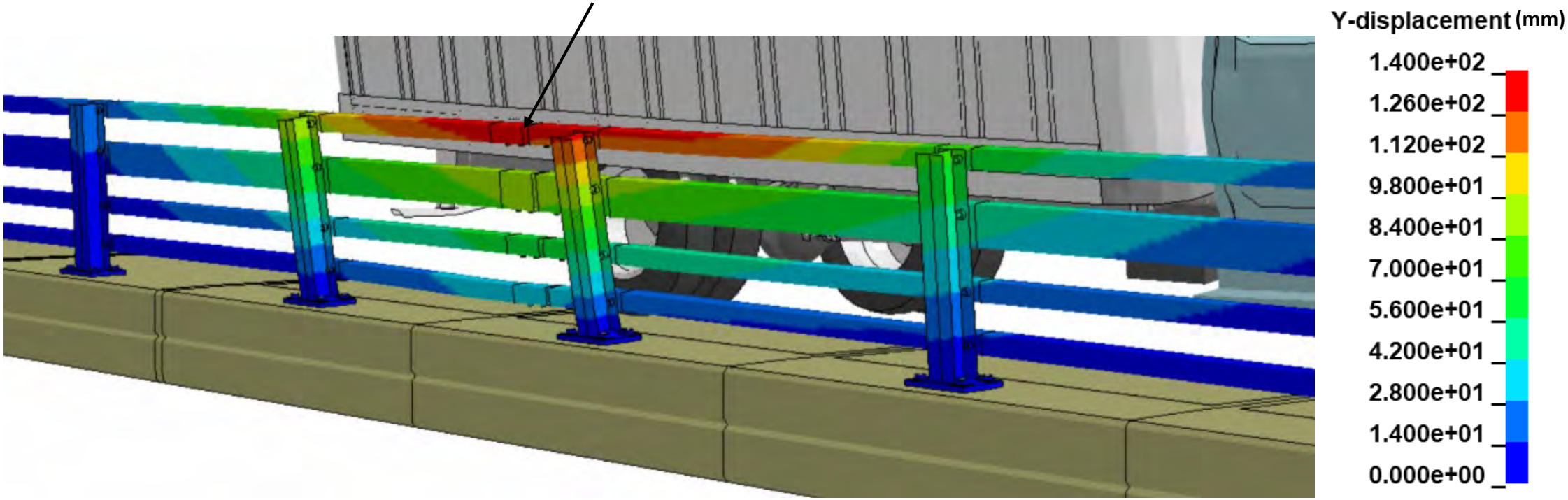
Lateral Dynamic Deflection

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



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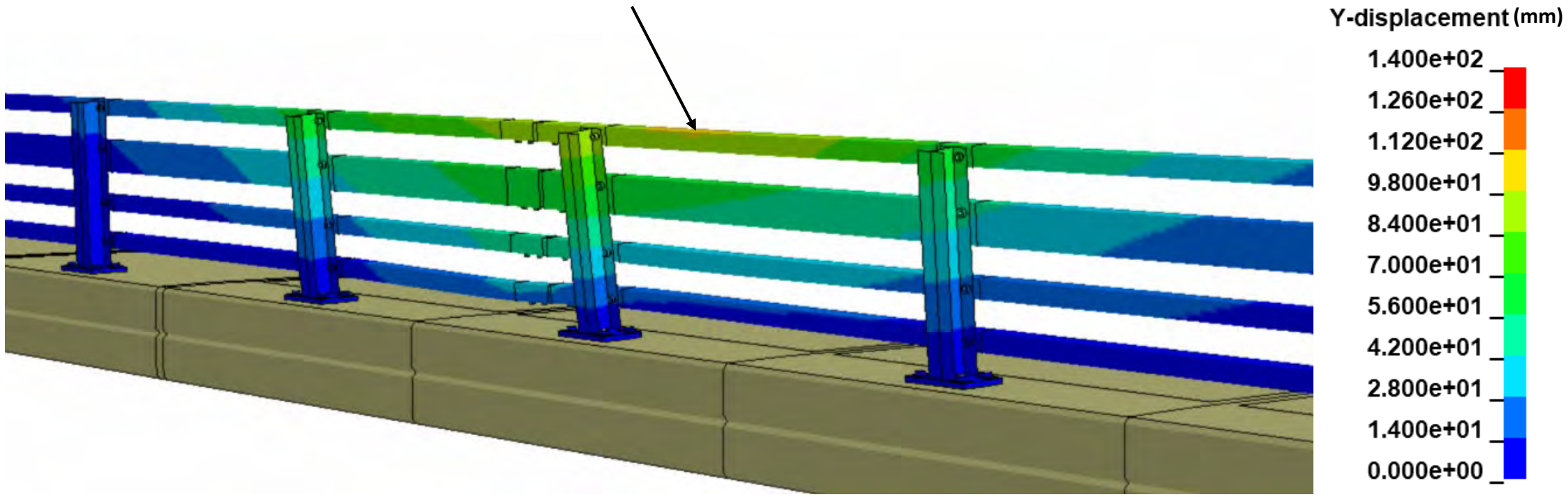
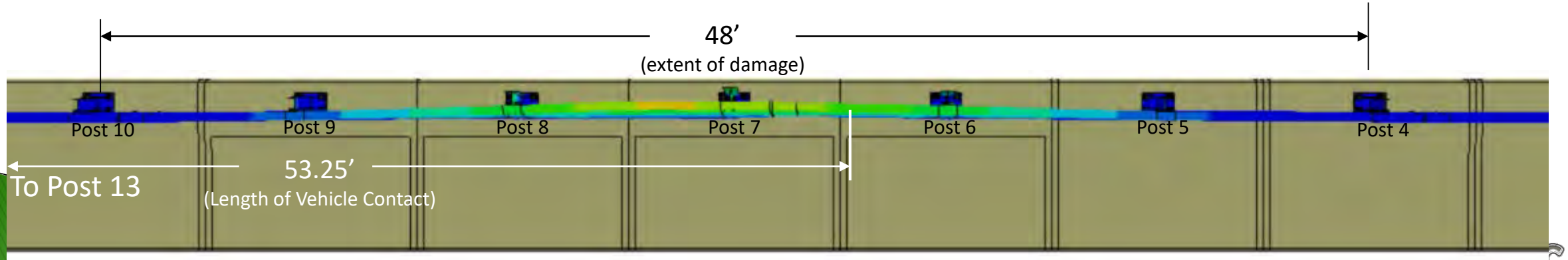
Lateral Permanent Deflection

Maximum permanent deflection = 5.8 in (147 mm)



Barrier Damage

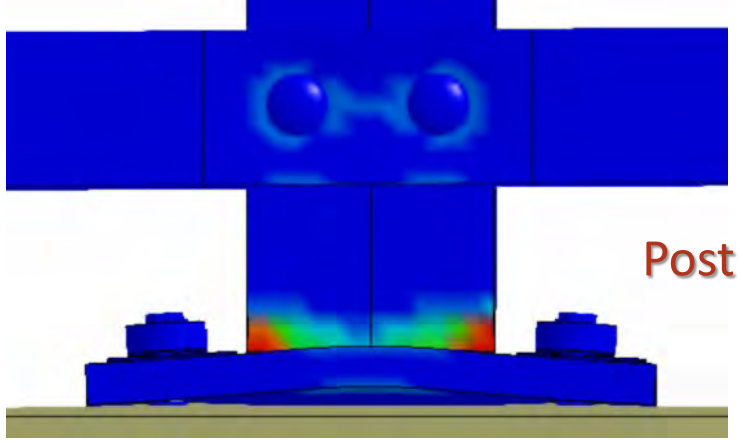
- There was moderate damage to the rail tubes between Post 4 and 10.
- The extent of permanent lateral deformation was 48’ starting at approximately 2.8’ upstream of Post 5.
- The vehicle was in contact with the barrier for 53.25’ starting at the point of impact and extending to Post 13.

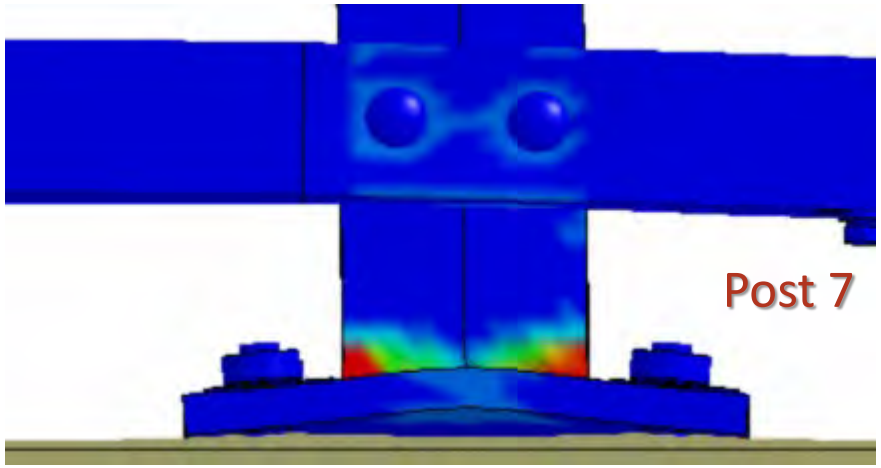


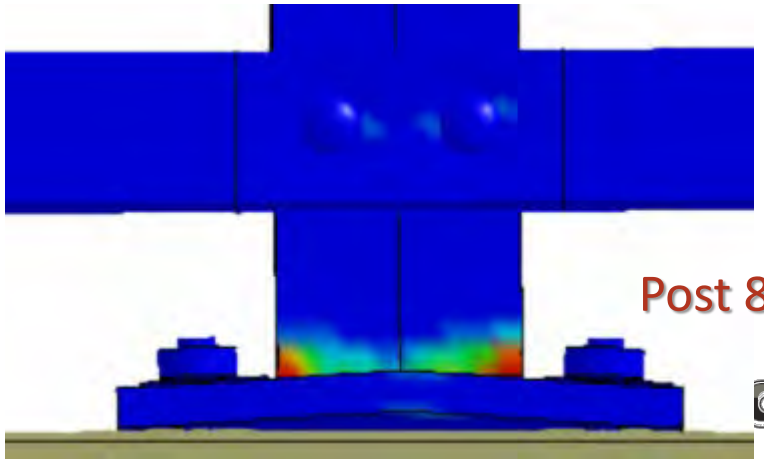
Damage to Posts

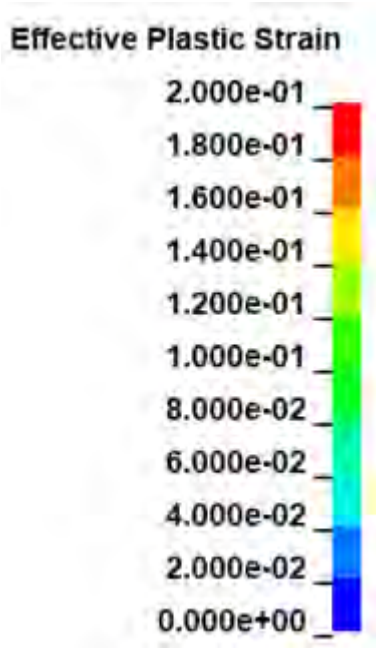
- There was significant damage to the posts and base plates at Post 6, 7 and 8, including:
  - Effective true plastic strain
    - Post 6 = 0.29
    - Post 7 = 0.33
    - Post 8 = 0.28
- These values indicate *possible* material failure at the outside edges of the post flanges at weld.

Images at Final Deformation

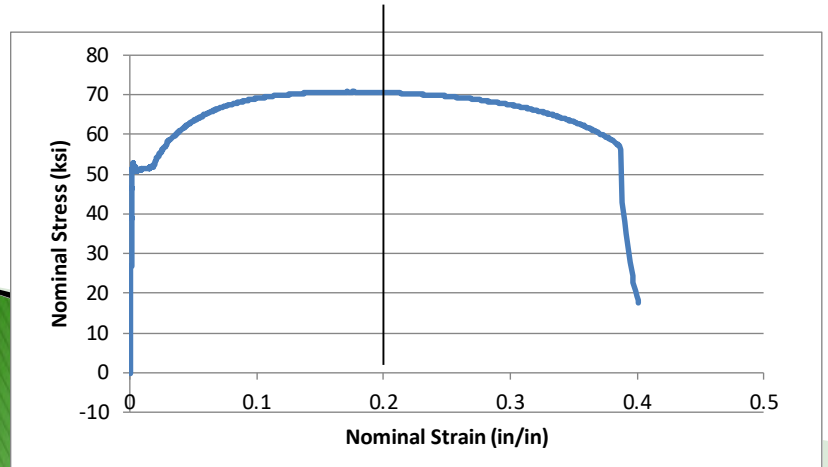








True Plastic Strain at Necking = 0.179



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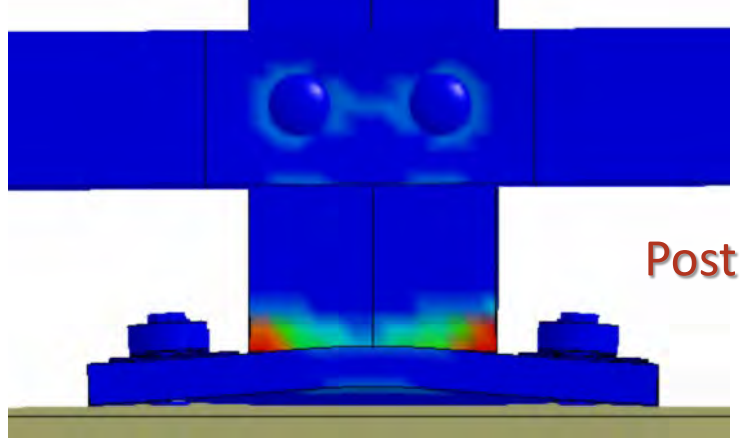
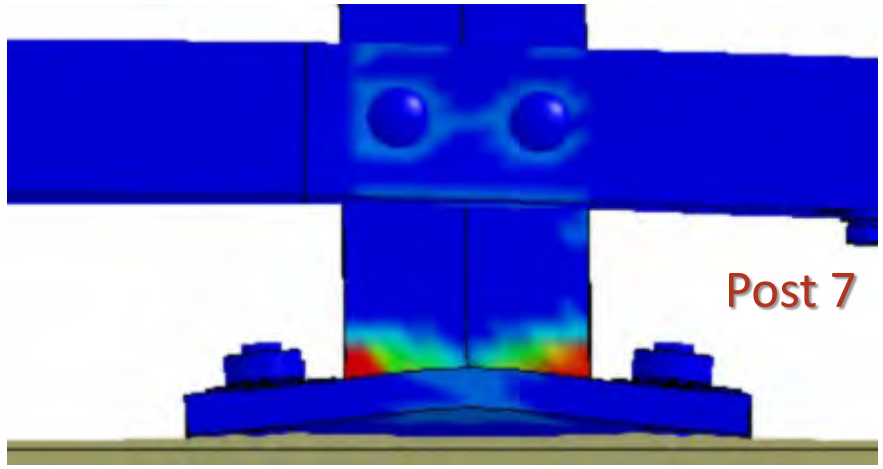
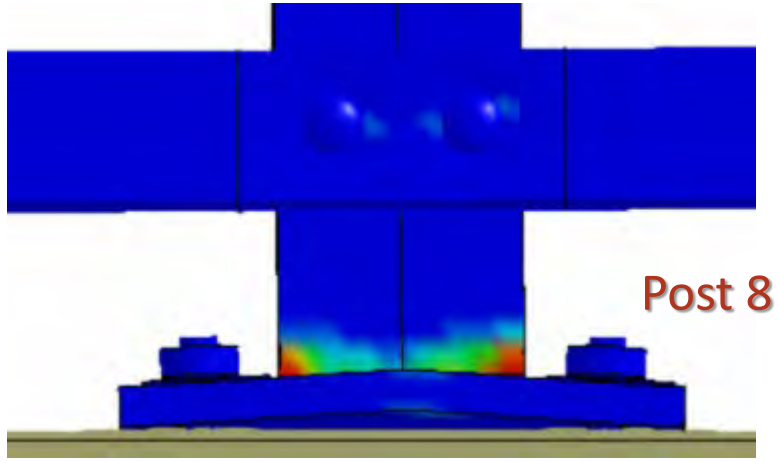
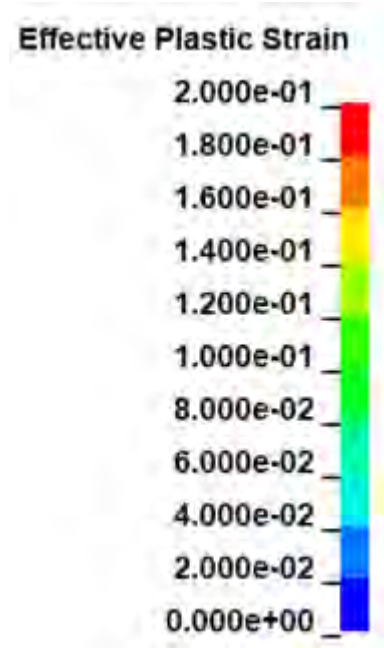
Damage to Base Plates

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





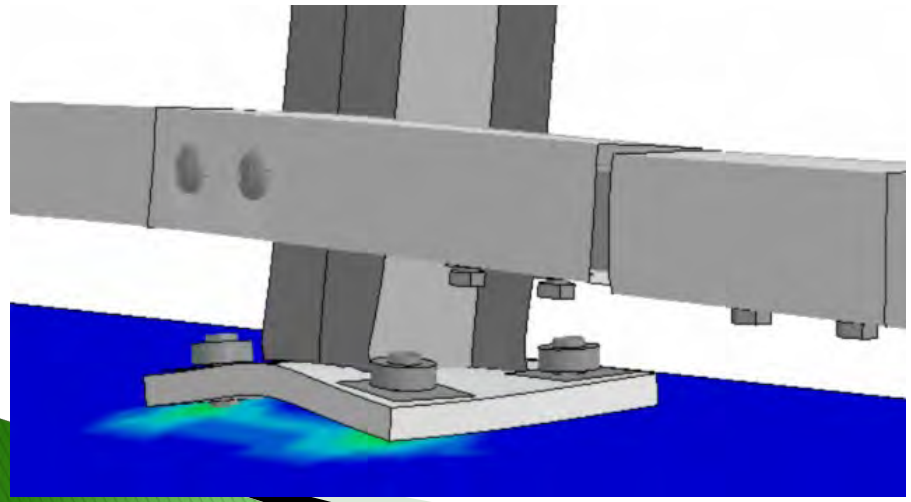




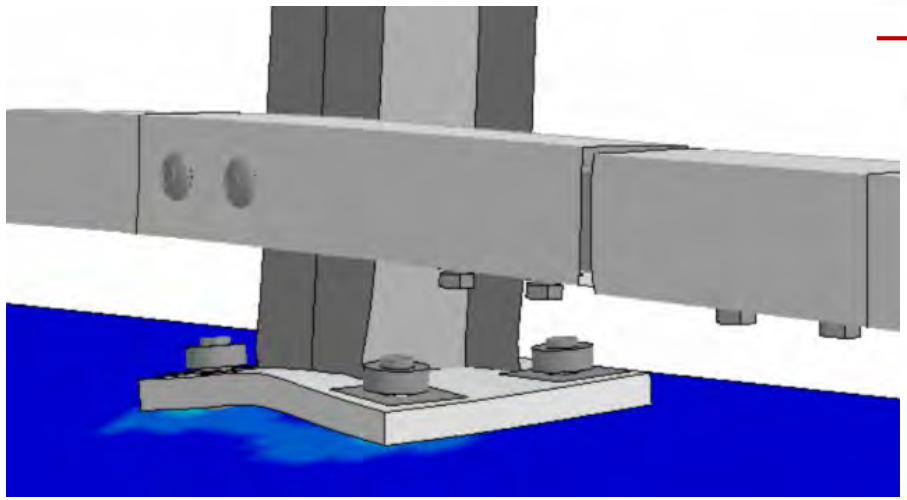
Barrier Damage

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

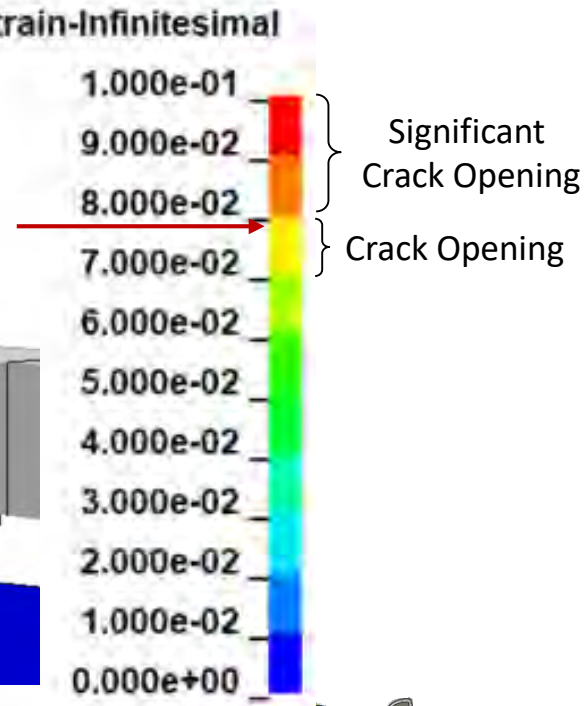
Anchor tensile forces will increase as post strength increases



Dynamic at t = 0.515 seconds



Final Static



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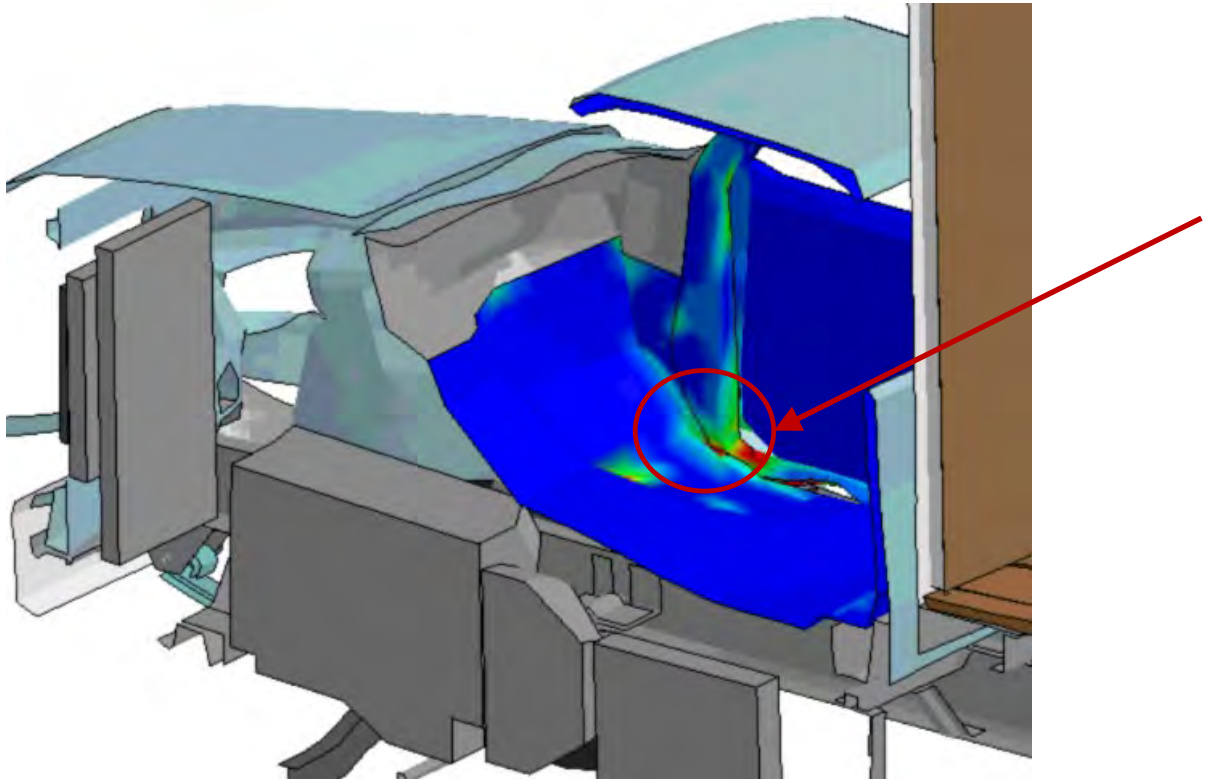
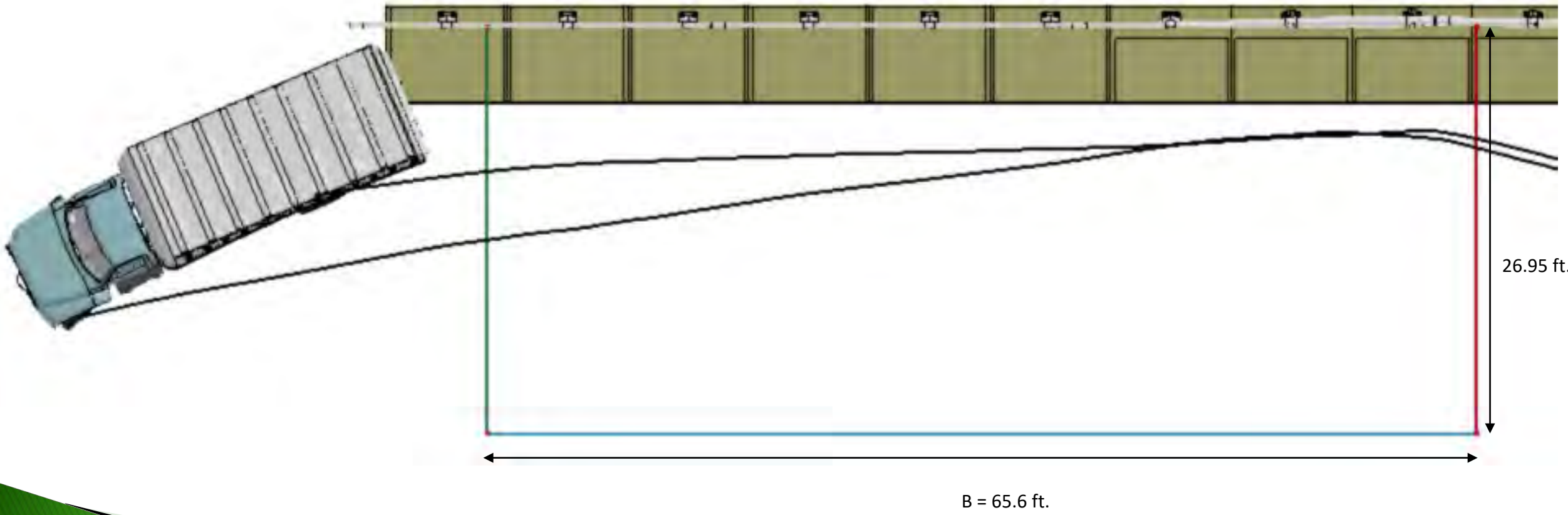
Occupant Compartment Intrusion (OCI)



Maximum OCI was ≈ 1 inch (23 mm) and occurred at the lower right-front corner of the top-pan at the wheel well.

Exit Box – Bed Height = 47.5” – Test 4-12

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.”



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

- The analysis showed that barrier adequately contained and redirected the 10,000S vehicle.
- Occupant compartment intrusion was minimal.
- The **maximum roll angle** of the vehicle:
  - Cabin= 18.8 degrees.
  - Cargo Box = 21.3 degrees.
- The **maximum pitch angle** of the vehicle:
  - Cabin = 5.6 degrees.
  - Cargo Box = 3.5 degrees.
- *The damage to the barrier was relatively extensive and included:*
  - *Damage to curb around the front anchor bolts.*
  - *Plastic deformation of posts and base plates.*
  - *Maximum dynamic barrier deflection of 8.2 inches.*
  - *Maximum permanent barrier deflection of 5.8 inches.*

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

Conclusions for Overall Barrier Performance

- MASH Requirements:
  - Structural Adequacy: (**PASS**)
    - The barrier successfully contained and redirected the vehicle in all test cases, but with significant barrier deflections for Test 4-12.
  - Occupant Risk (**PASS**)
    - Occupant compartment intrusion was well below allowable limits for all cases
    - OIV and ORA
      - Small Car : OIV (within critical limits); ORA (within preferred limits) (*values highly dependent on time of occupant impact*)
      - Pickup: OIV (within preferred limits); ORA (within critical)
  - Vehicle Trajectory (**PASS**)
    - Vehicle remained upright and stable through impact and redirection, with relatively low angular displacements for all cases.

Conclusions for Overall Barrier Performance

- Barrier Damages:
  - The barrier experienced moderate plastic deformations of the posts, rails and baseplates for Test 4-11 (Pickup), but more significant damage for Test 4-12 (SUT).
  - Lateral deflections were relatively high for 4-12 (e.g., 8.2”)
  - Concrete curb damage at Post 7 was likely for Test 4-12.
    - The damages corresponded to potential cracks around the front anchor bolts and/or pryout damage.
- Crash Performance:
  - The analysis indicates that:
    - The barrier system meets MASH TL4 criteria; however, relatively high barrier damages are likely under these conditions.
    - The barrier system meets MASH TL3 criteria with only moderate barrier damages.