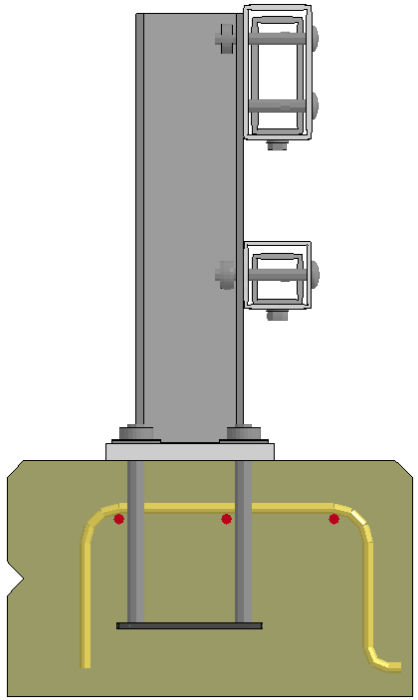
Development of MASH Computer Simulated Steel Bridge Rail and Transition Details



Task 7 – NETC 2-Bar MASH TL4

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

Chuck A. Plaxico
Malcolm H. Ray
Roadsafe LLC

June 3, 2019

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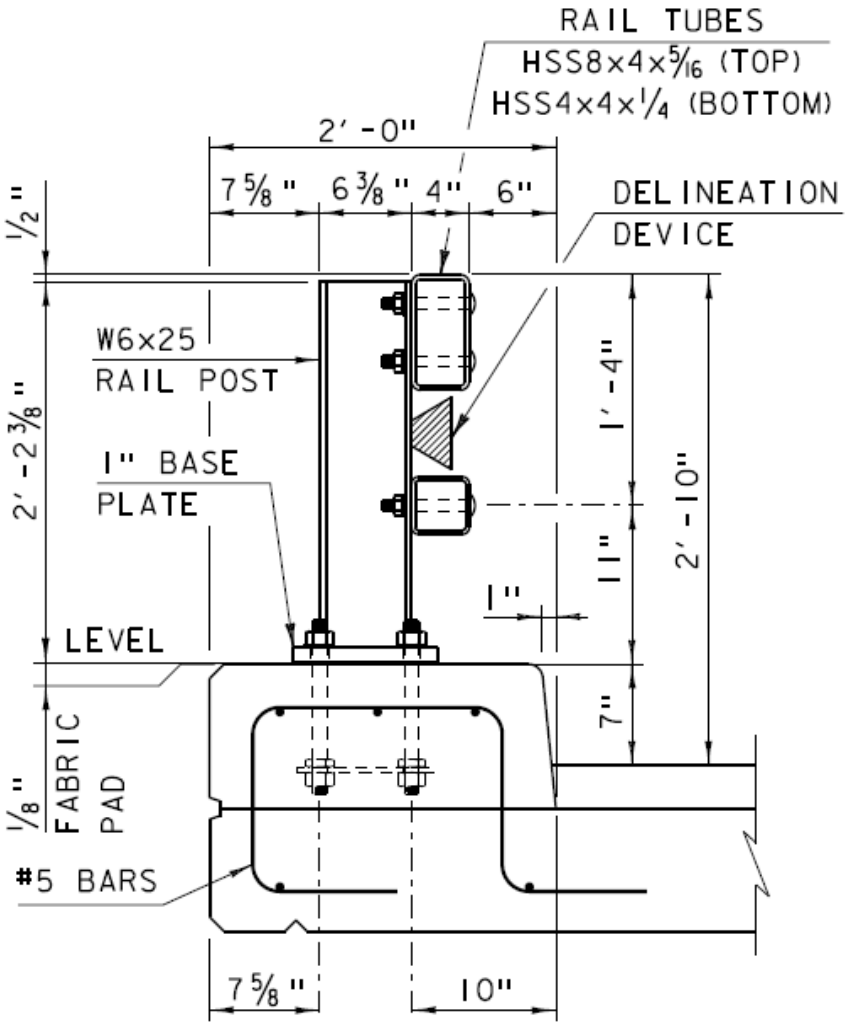
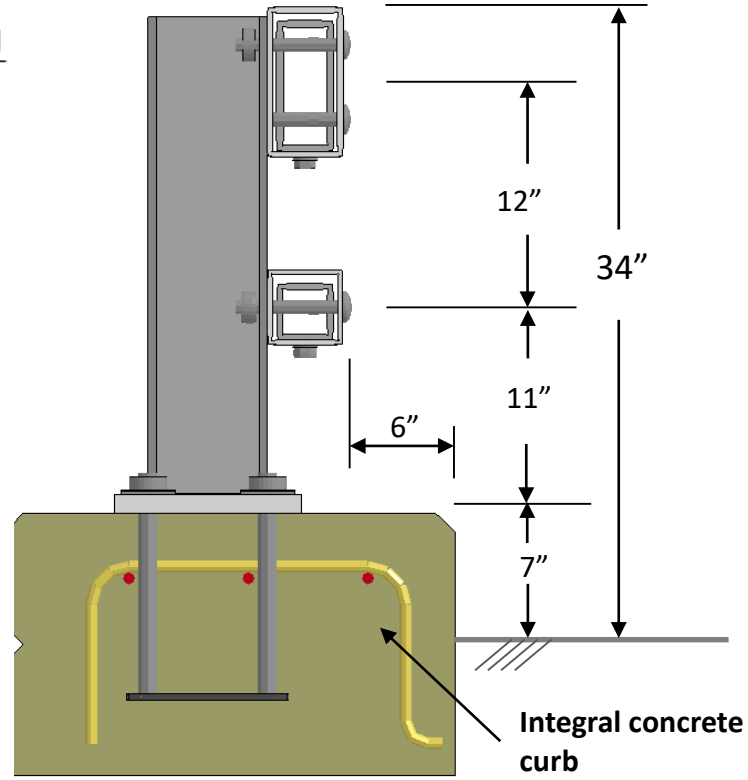
Task 7 – MASH TL-3 Evaluation of NETC 2-Bar Bridge Rail

- The finite element model of the NETC 3-Bar bridge rail was developed in Tasks 3.
- That model was used as a baseline for developing the NETC 2-Bar bridge rail.
- In the 3-Bar model, the deck and granite curb extension were modeled based on RIDOT design as shown with:
  - A contact interface between the concrete deck and granite curb
  - And hoop steel with vertical leg near to front anchor rods.
- Other states use an integral concrete curb extension.
- Based on RIDOT recommendation, 2-Bar bridge rail was modeled with the integral curb (consistent with other states).



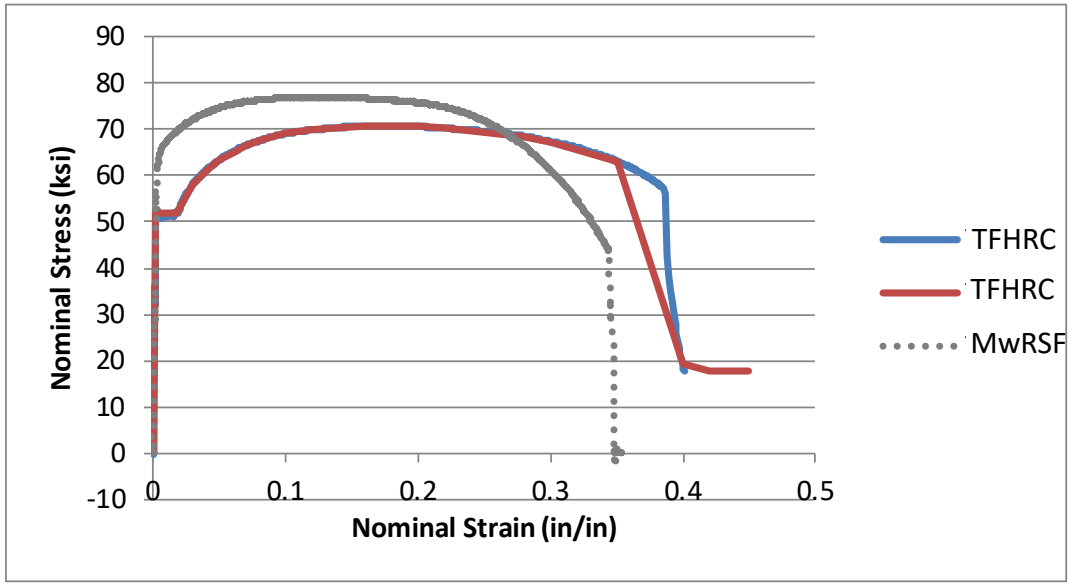


NETC 2-Bar BR

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.

Material Strength Range for ASTM 572-50



- The plot shown here includes:
  - Test 1 and 2 from coupons cut from a W6x25 post from one manufacturer
  - Test 3 from coupons cut from another manufacturer.
- Both strengths are possible for posts installed in the field and in full-scale test installations.
- The weaker strength post was used in the analyses to achieve maximum post plasticity
- The stronger post strength was not evaluated but would result in higher loading on the anchor and concrete.

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MASH Test Level 3

- *MASH* specifies three (2) tests for assessing TL-3 crash performance for bridge rails:
  - ***Test 3-10*:** Involves a 2425-lb passenger car (1100C vehicle) impacting the critical impact point at a nominal speed and angle of 62 mph and 25 degrees. Test optional for transitions.
  - ***Test 3-11:*** 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.

1100C

2270P

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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:

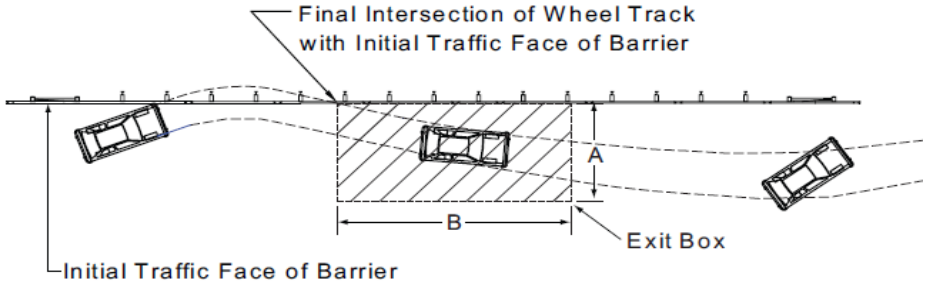
- Although not required by *MASH*, post vehicle trajectory was examined for completeness of the evaluations.
- *MASH* uses the concept of the "exit box" which was adopted directly from CEN standards.
- It is defined by the initial traffic face of the barrier and a line parallel to the initial traffic 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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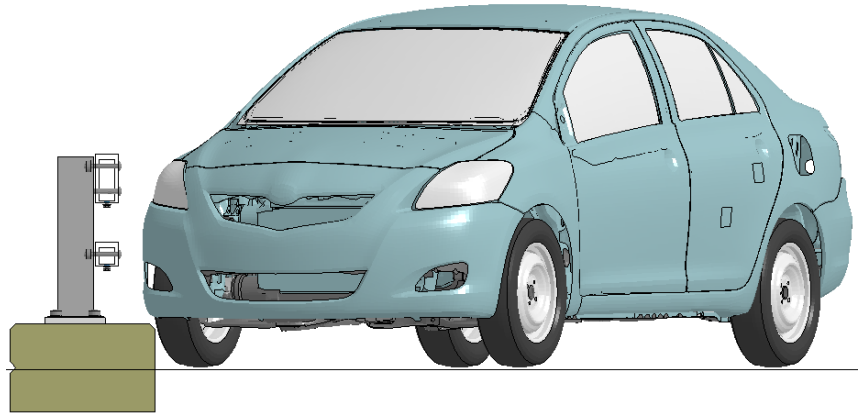
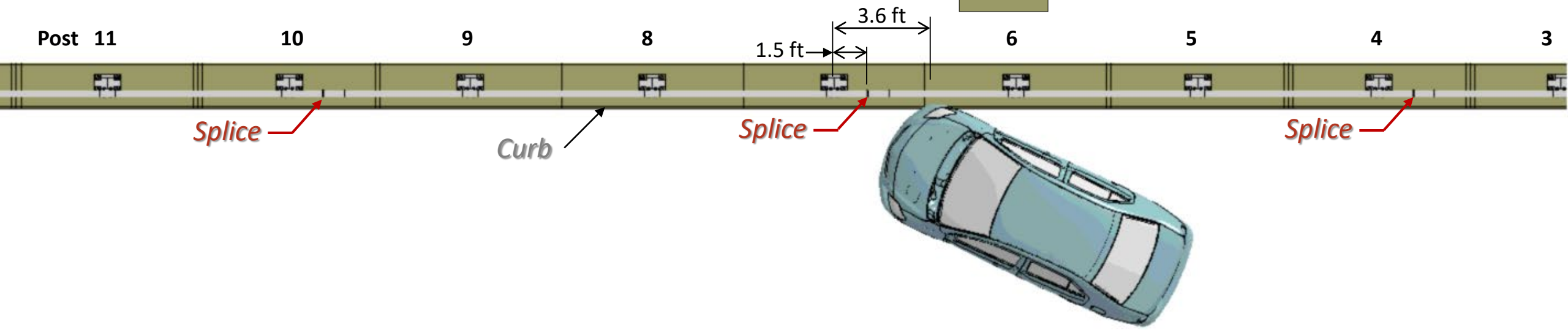
MASH Test 3-10 Simulation on the NETC 2-Bar

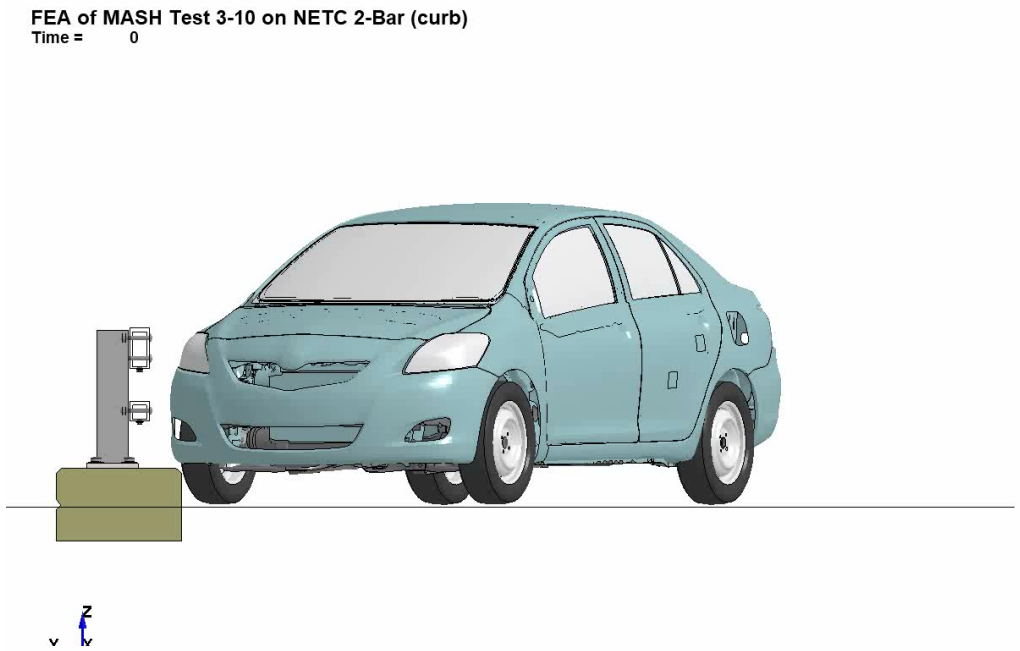
- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point = 3.6 ft upstream from critical post and 2.1 ft upstream of splice.
    - *MASH 2016 suggested CIPs*
      - 3.6 ft upstream from critical Post
      - 3.6 ft upstream from splice

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



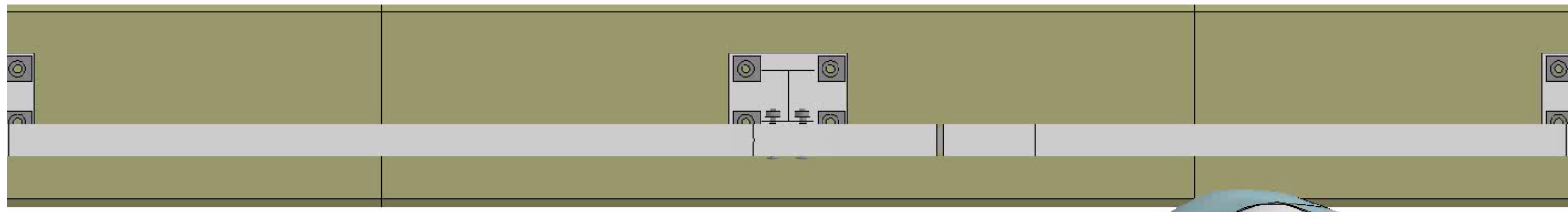


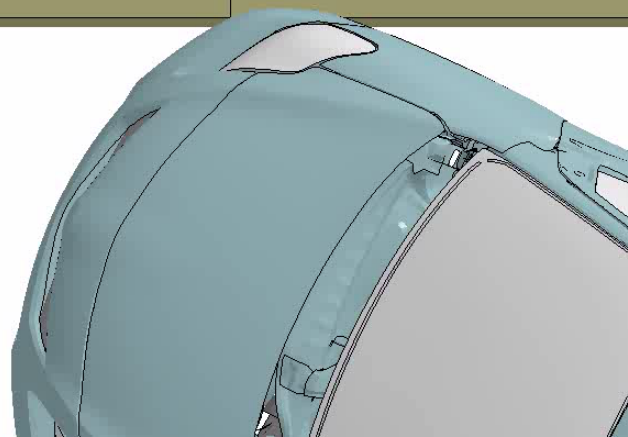
Movies


FEA of MASH Test 3-10 on NETC 2-Bar (curb)
Time = 0
Z
Y
FEA of MASH Test 3-10 on NETC 2-Bar (curb)
Time = 0
Z
X
Y

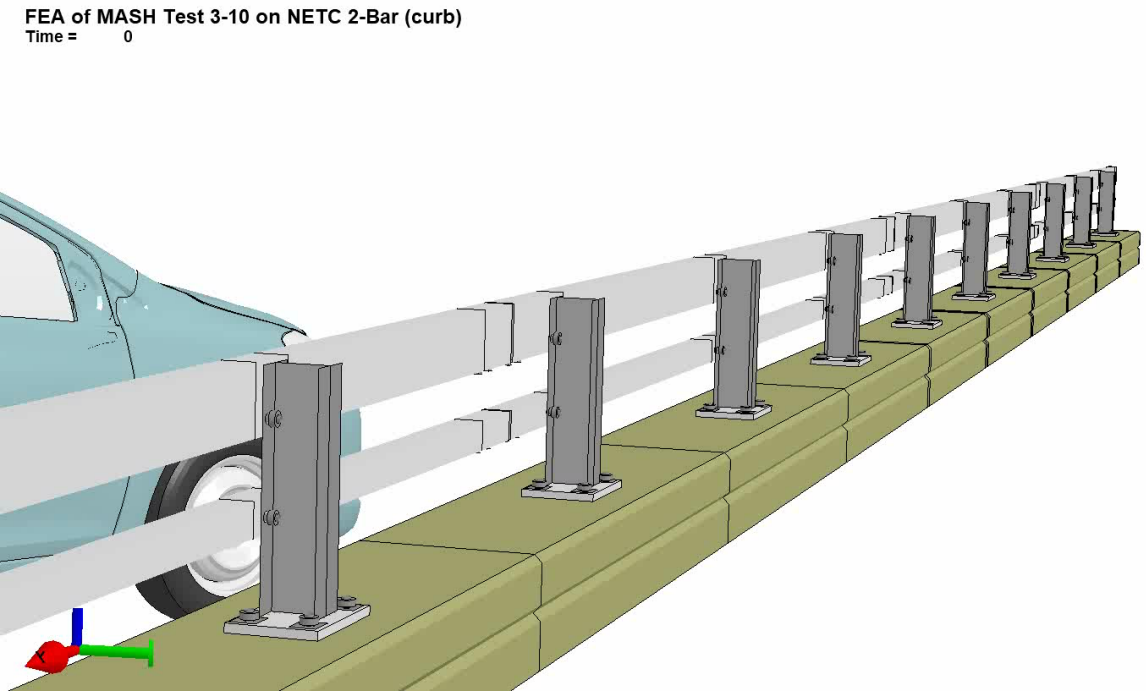
FEA of MASH Test 3-10 on NETC 2-Bar (curb)

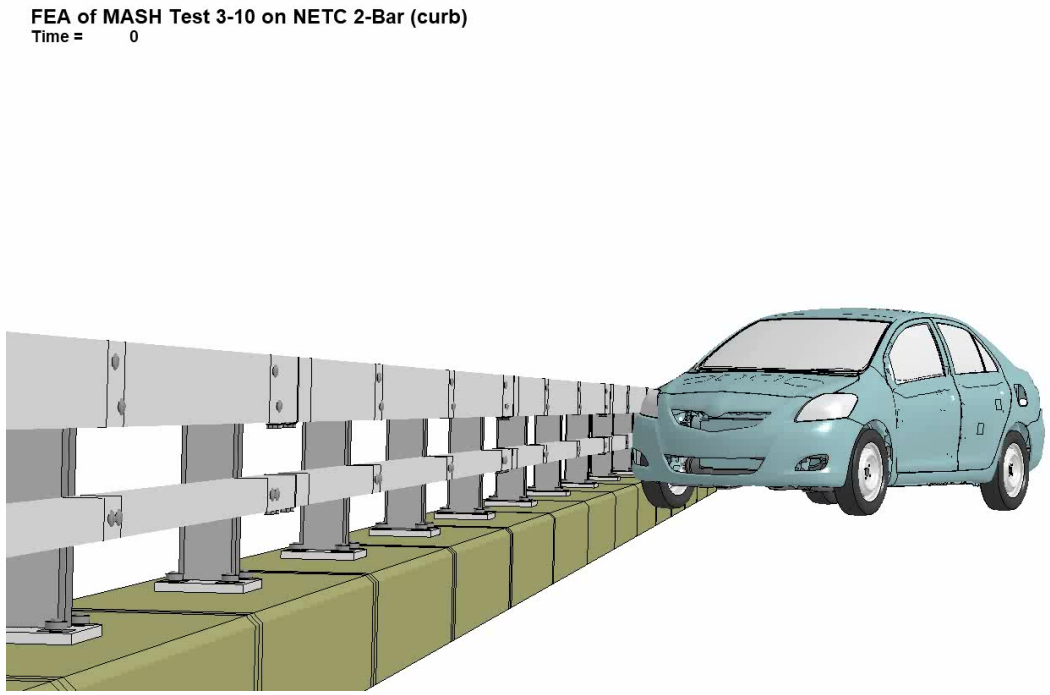
Time = 0





Movies





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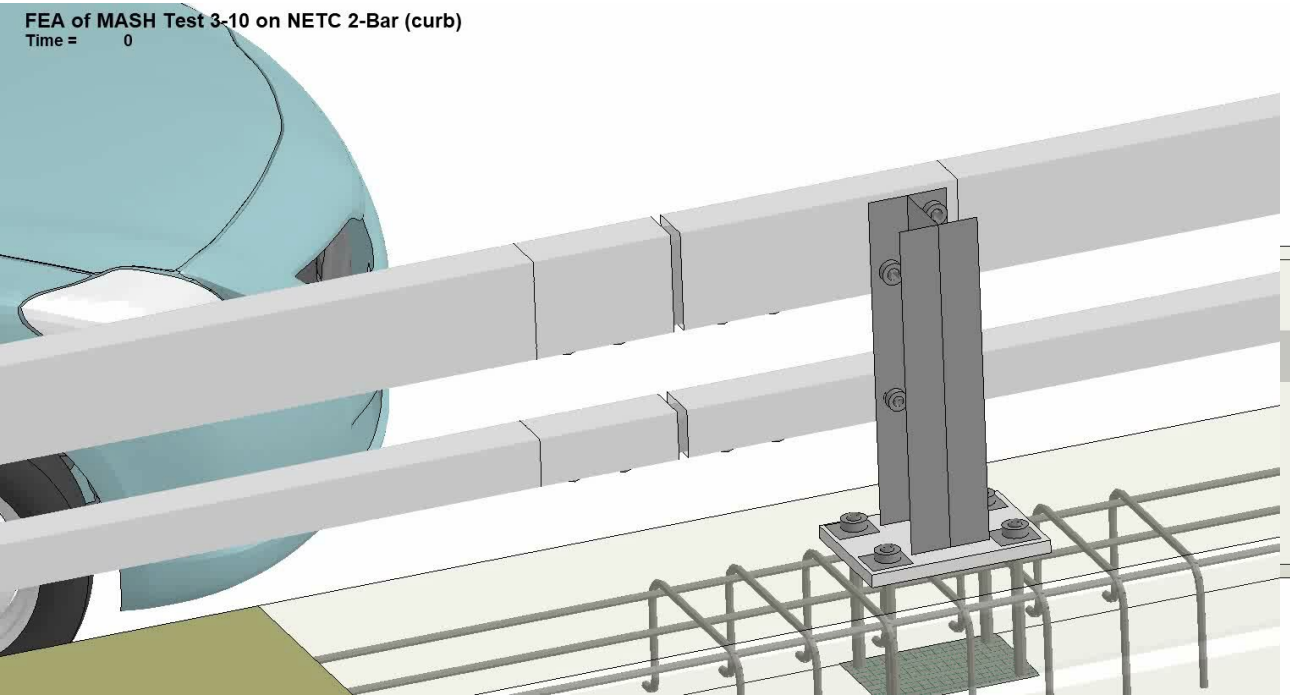
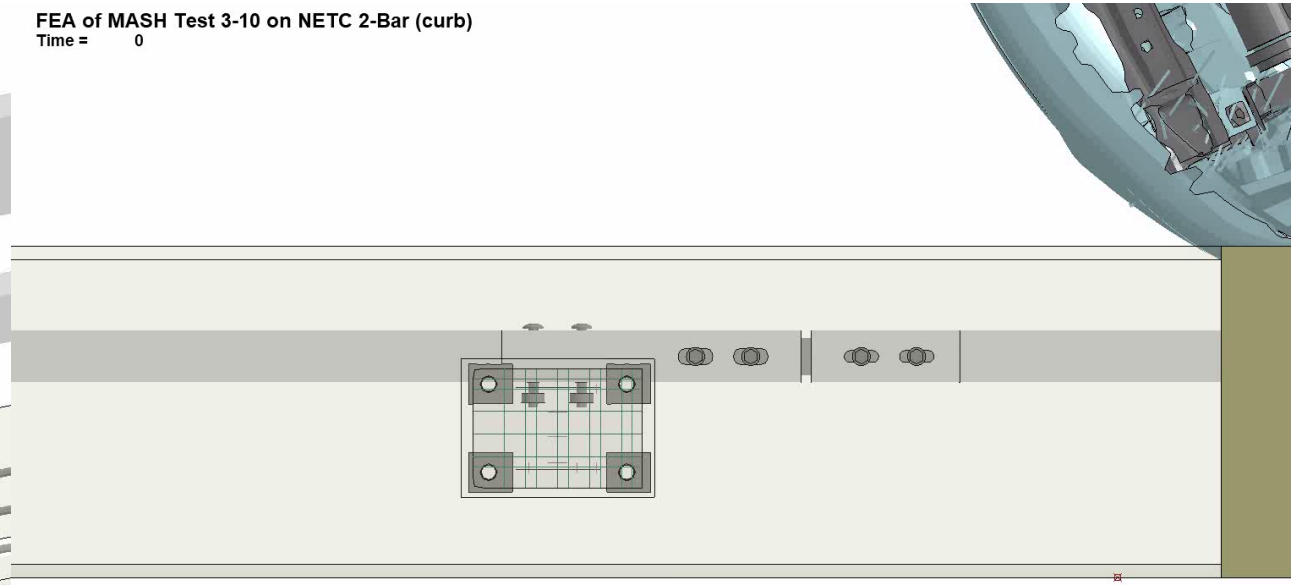
Movies





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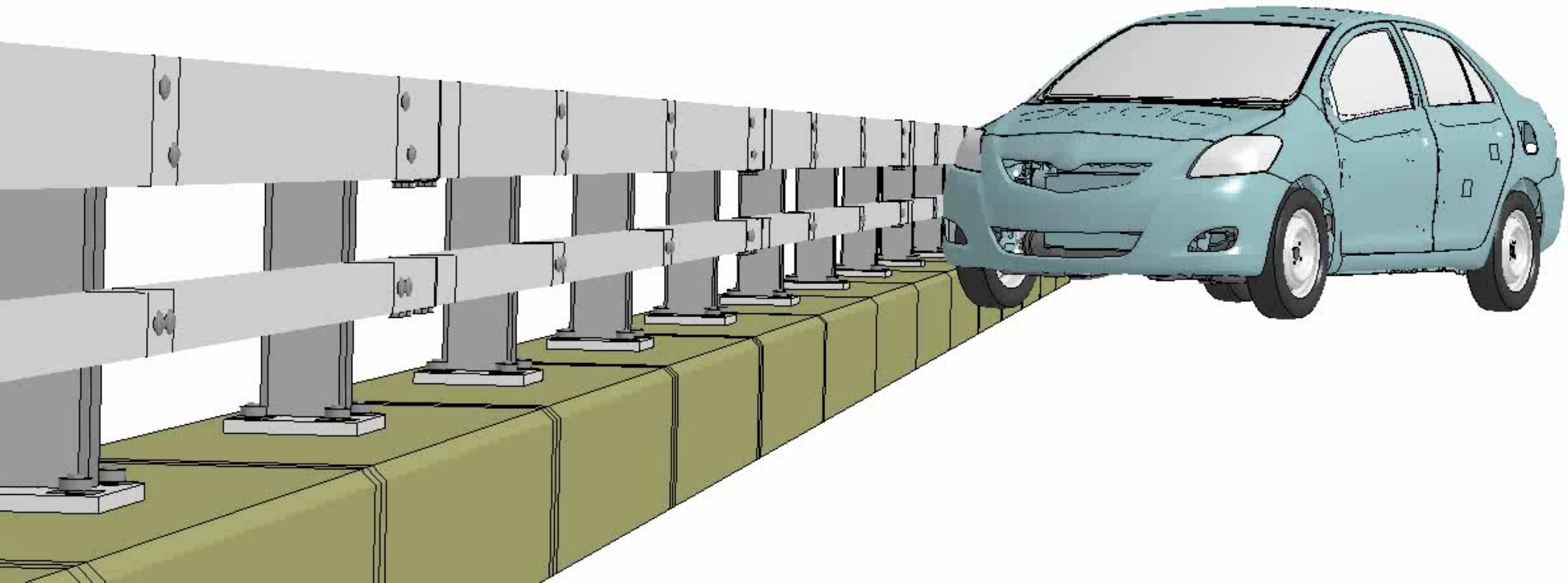
FEA of MASH Test 3-10 on NETC 2-Bar (curb)
Time = 0



TRAP – Summary Table

Occupant Risk Factors		MASH Test 3-10
Occupant Impact Velocity (ft/s)	x-direction	26.2
	y-direction	33.1
	at time	at 0.0793 seconds on right side of interior
THIV (ft/s)		42.0
		at 0.0793 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-5.5 (0.0812 - 0.0912 seconds)
	y-direction	-6.4 (0.2169 - 0.2269 seconds)
PHD (g's)		6.4 (0.2169 - 0.2269 seconds)
ASI		2.51 (0.0257 - 0.0757 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-14.8 (0.0241 - 0.0741 seconds)
	y-direction	-19.8 (0.0263 - 0.0763 seconds)
	z-direction	-3.2 (0.0603 - 0.1103 seconds)
Maximum Angular Disp. (deg)	Roll	7 (0.5291 seconds)
	Pitch	-5.4 (0.3745 seconds)
	Yaw	-39.8 (0.4896 seconds)

MASH Criteria

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

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

< 75 deg ✓

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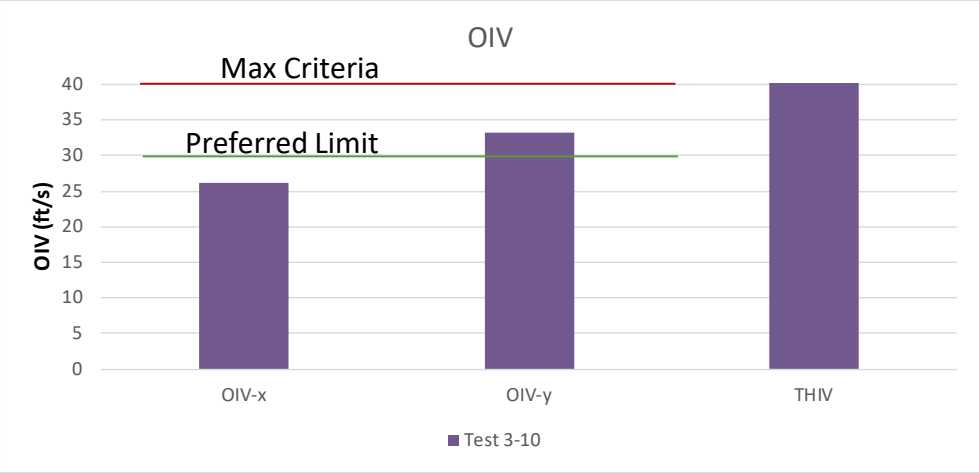
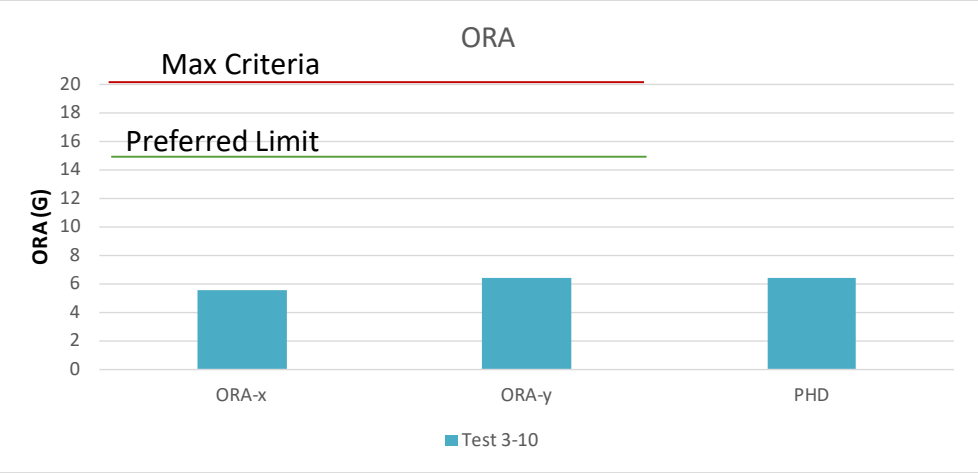
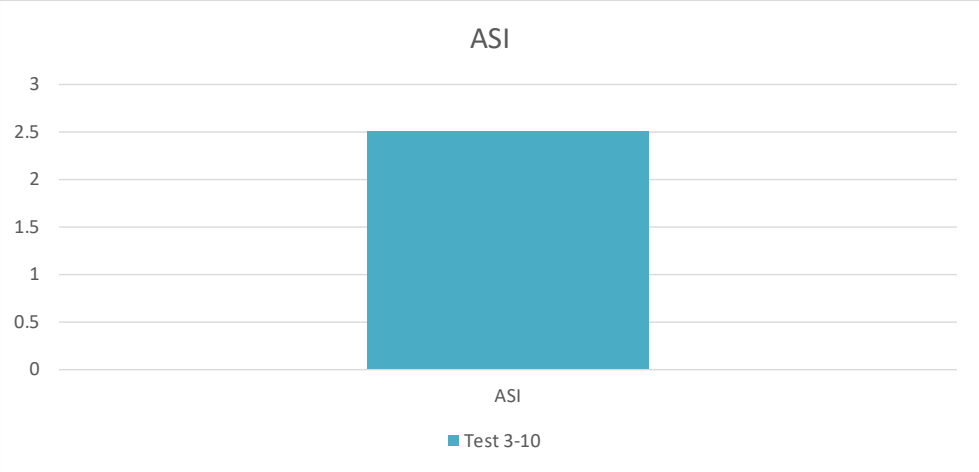
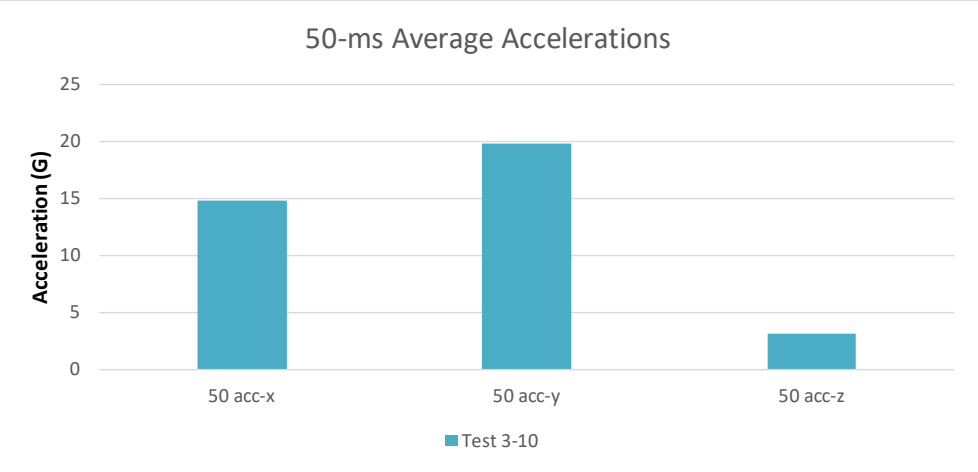
TRAP









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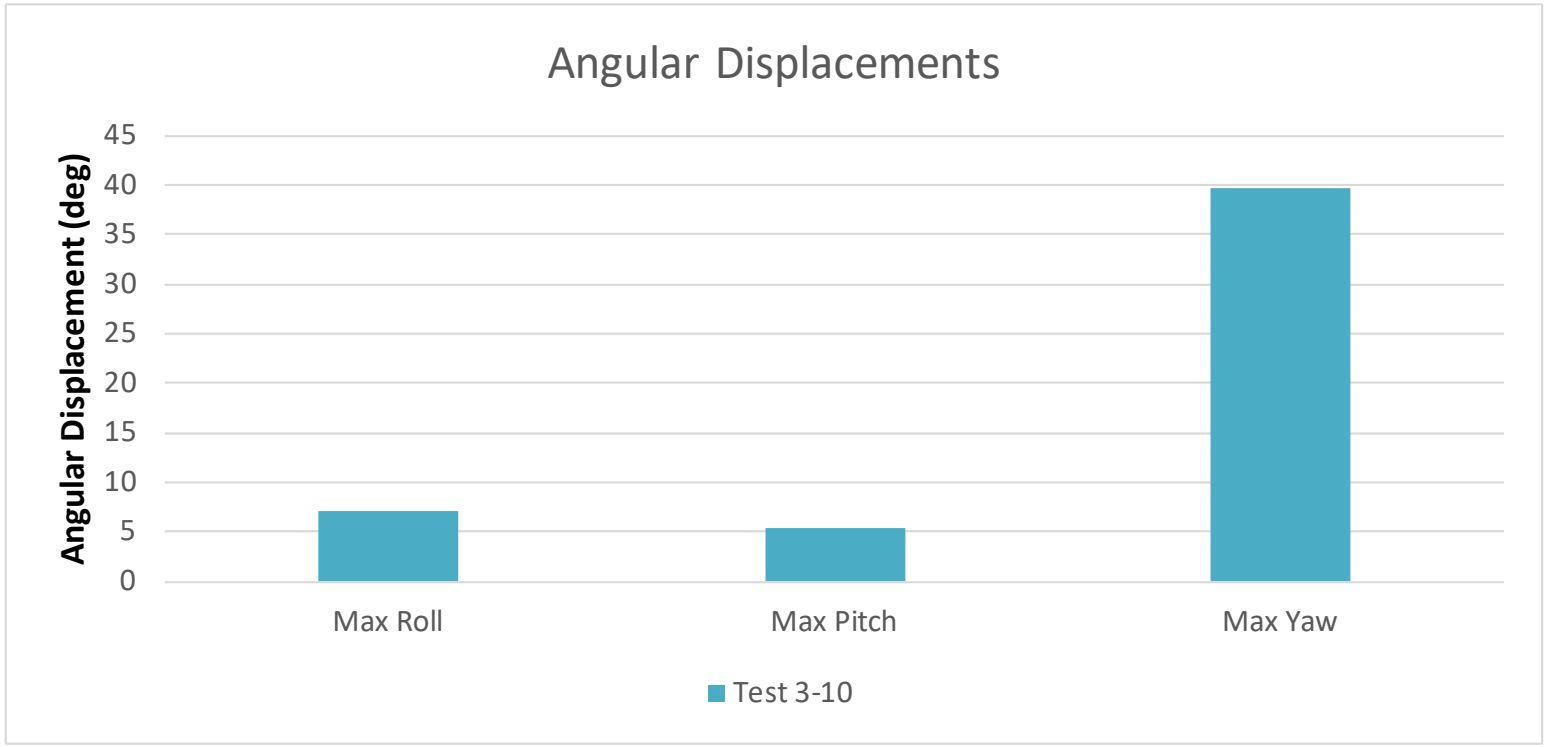
TRAP



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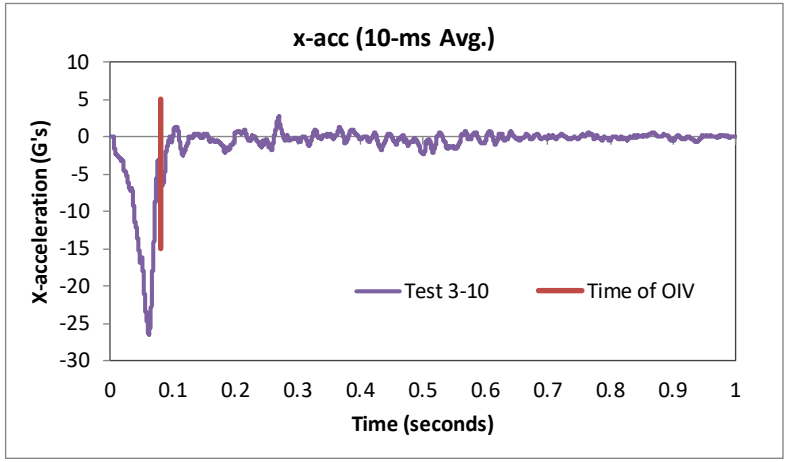
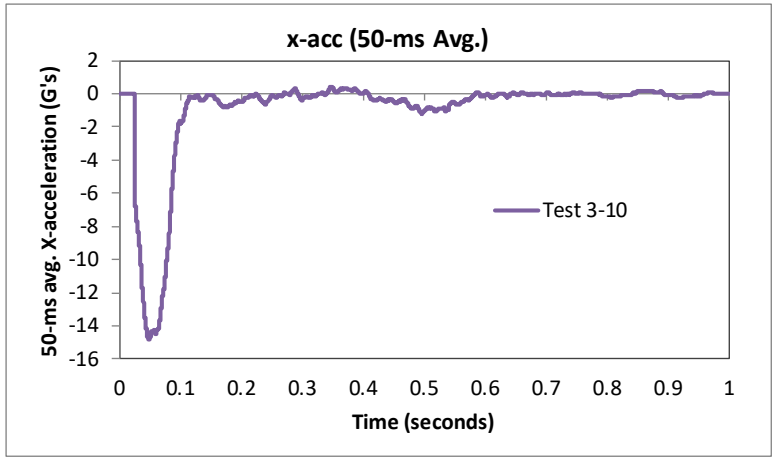
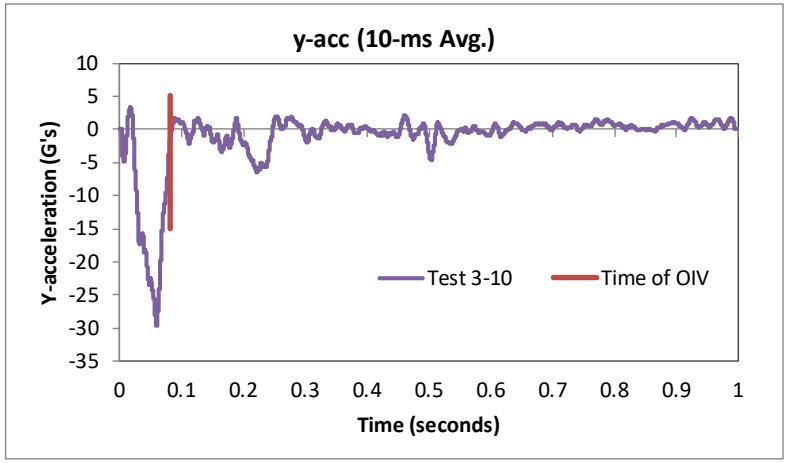
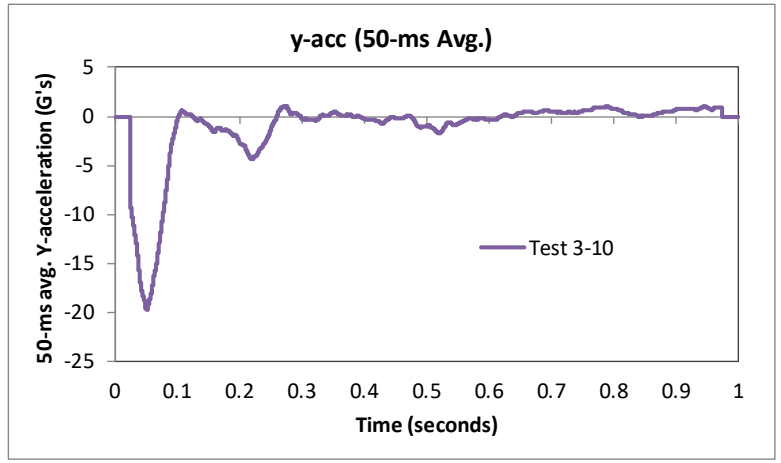
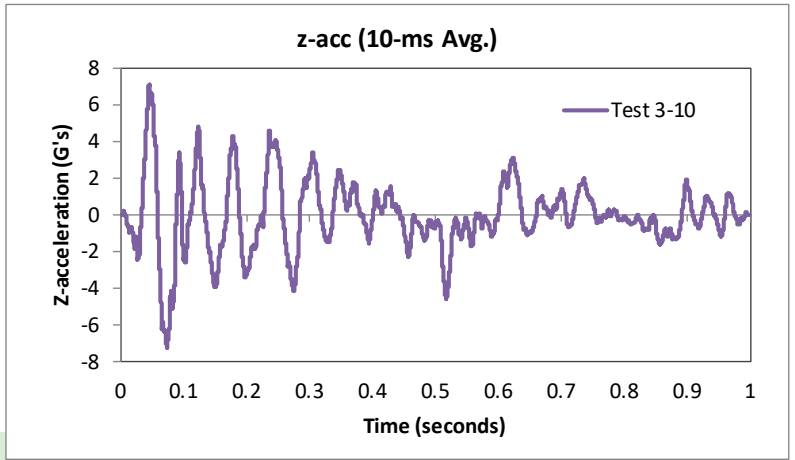
Acceleration Plots

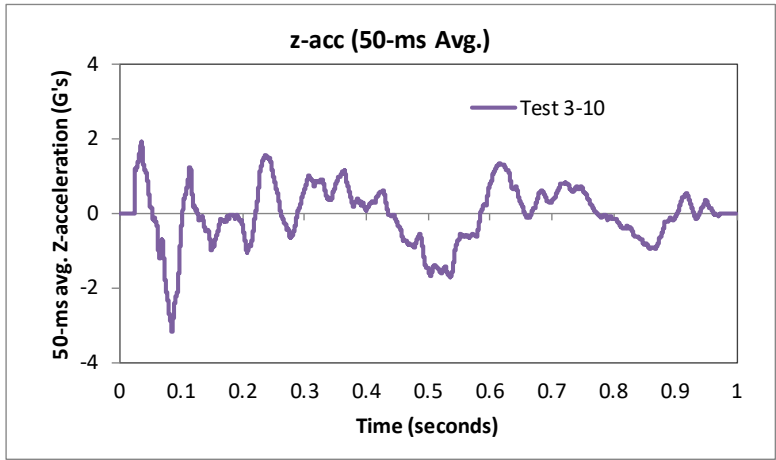




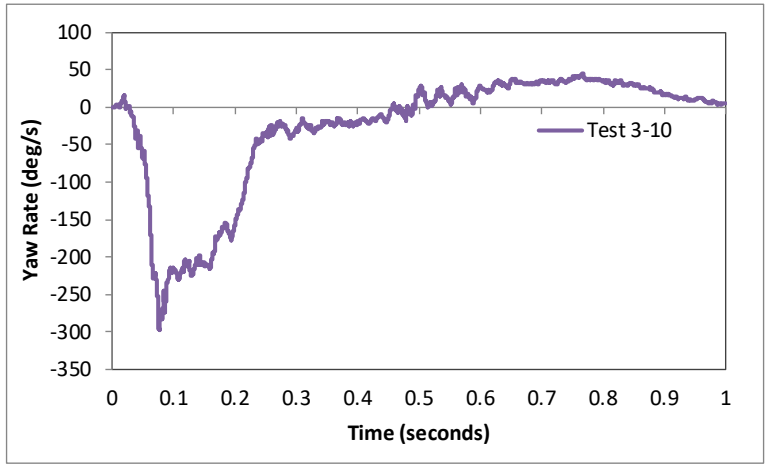


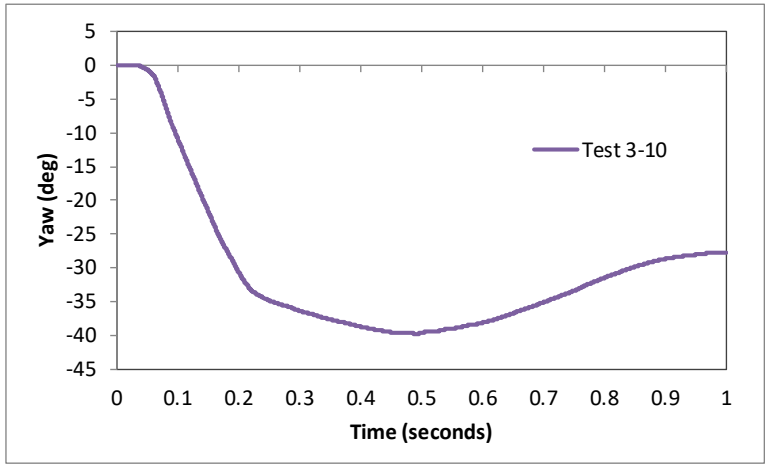


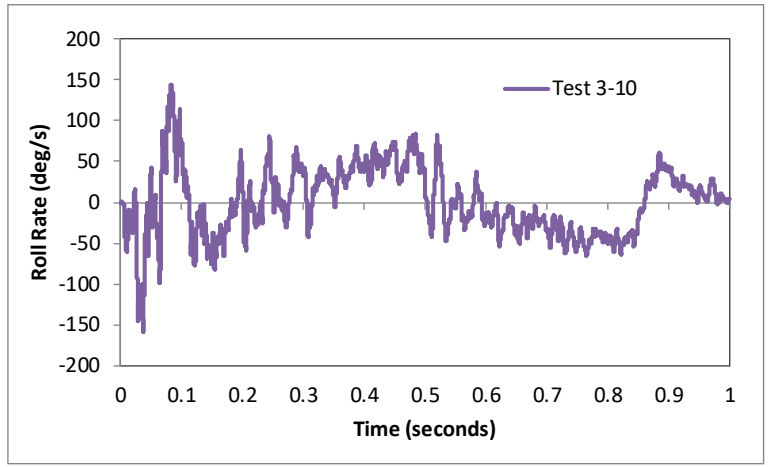


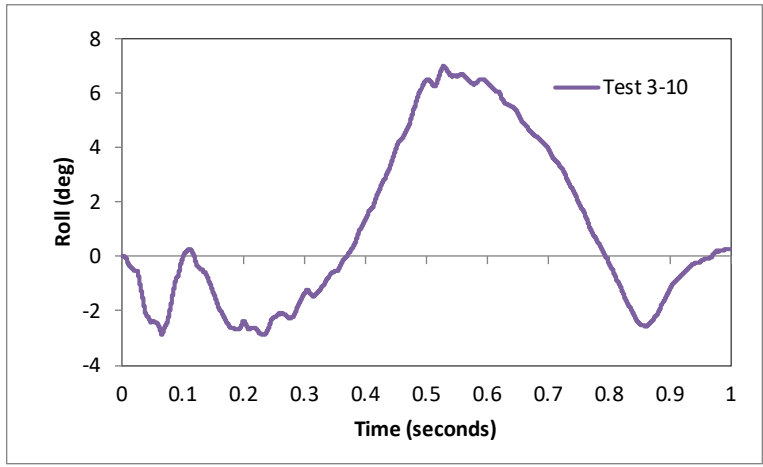


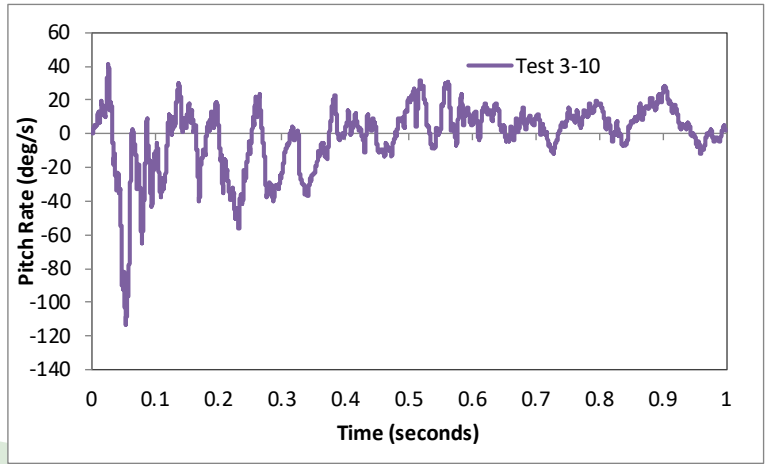
Angular Rate and Displacement Plots

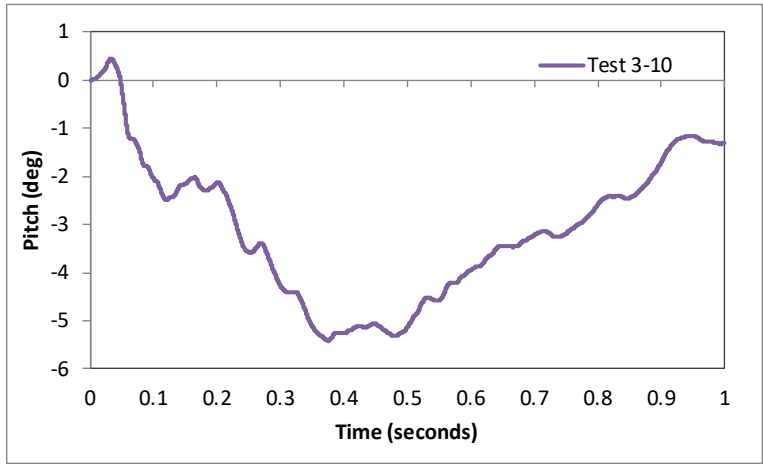






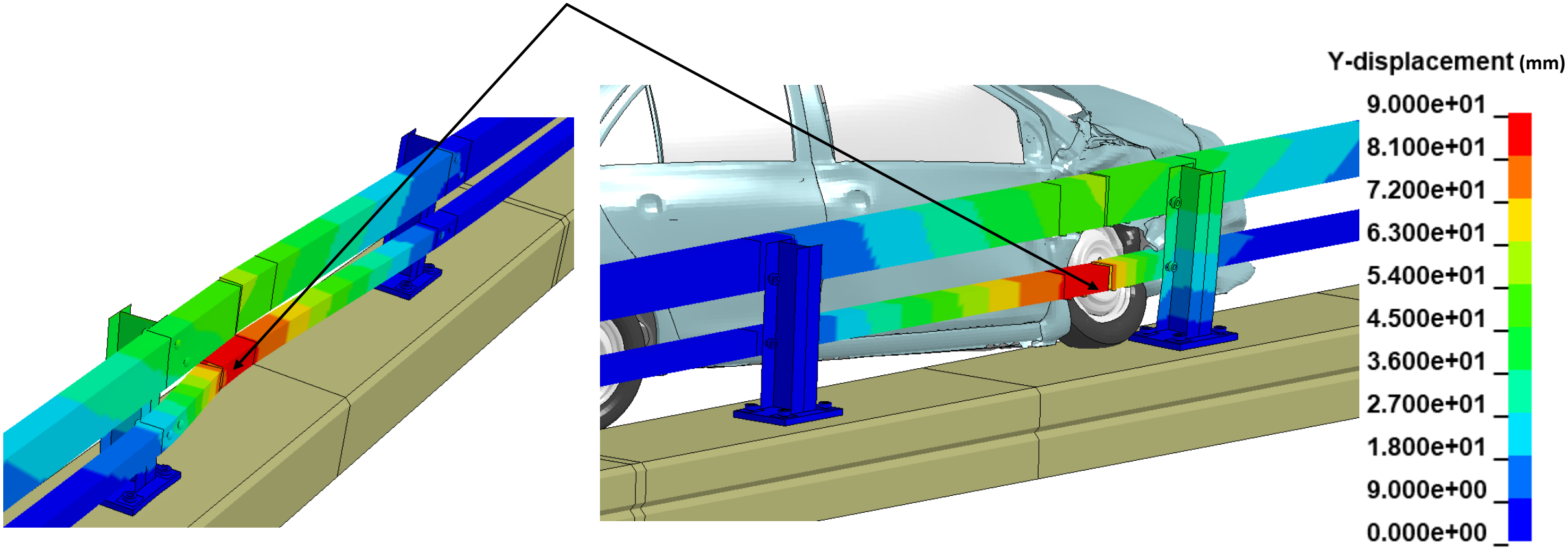






Lateral Dynamic Deflection

Maximum dynamic deflection = 3.6 in (91.9 mm) at 0.06 seconds



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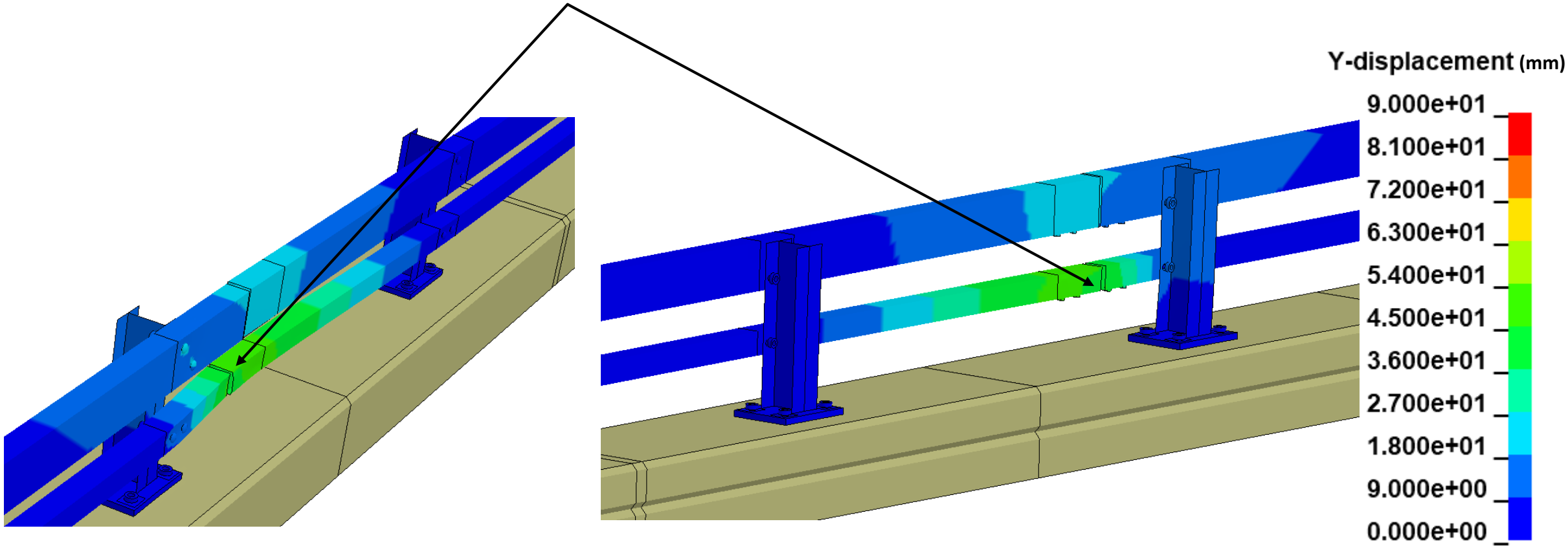
Lateral Permanent Deflection

Maximum permanent deflection = 2.03 in (51.5 mm)



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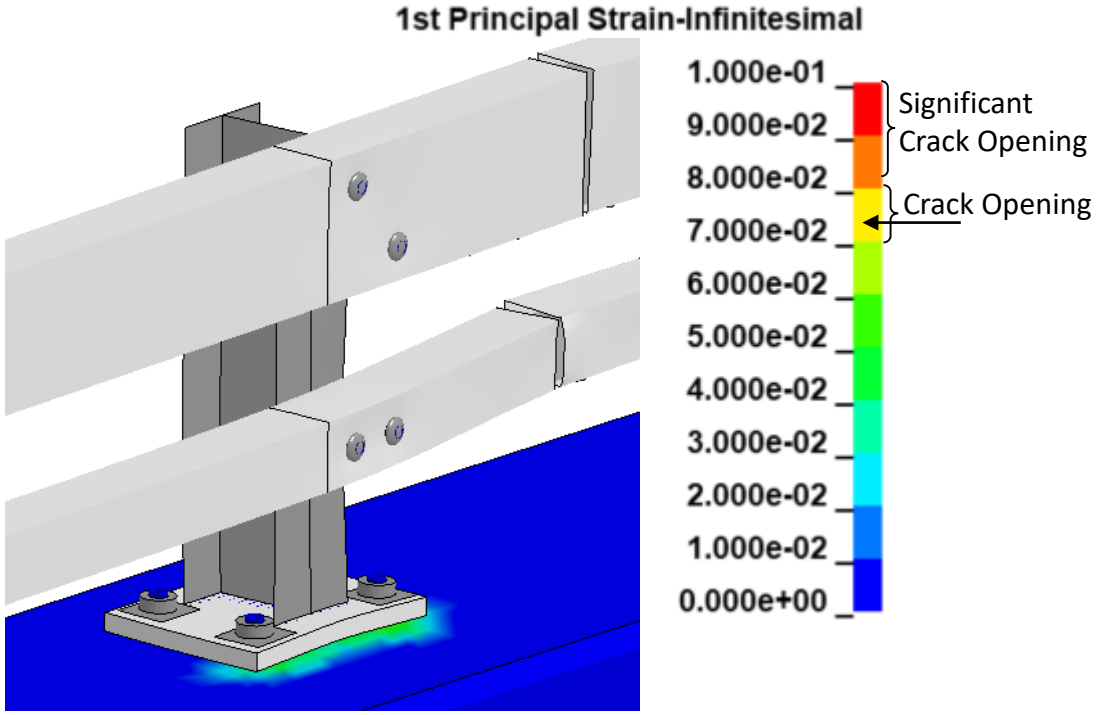
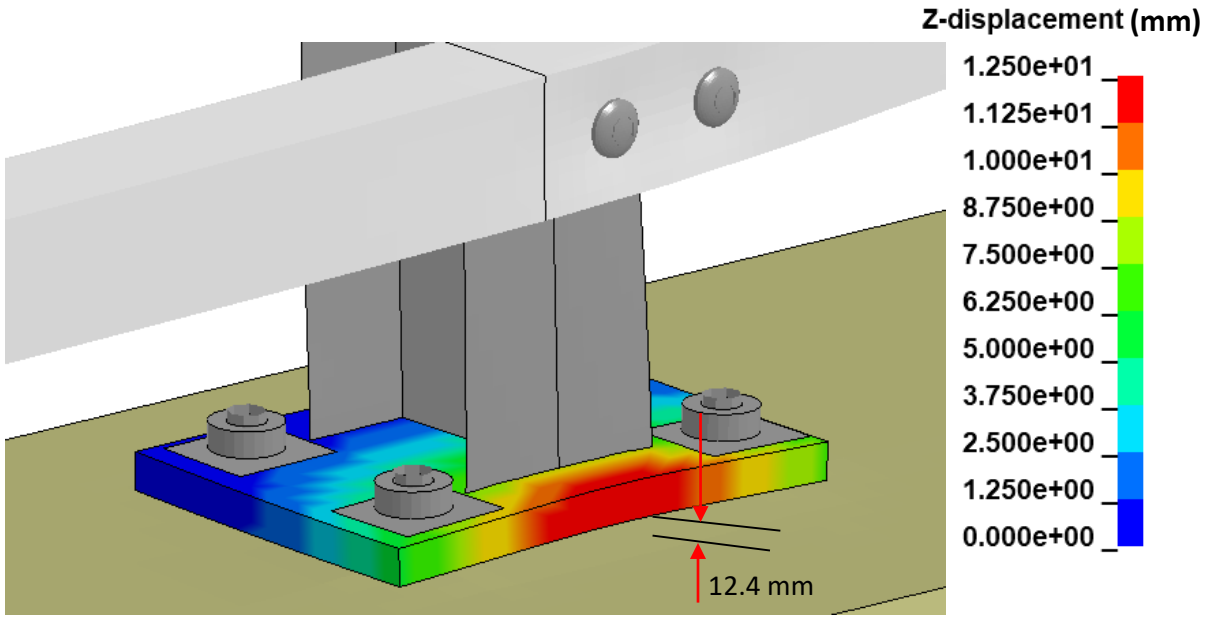
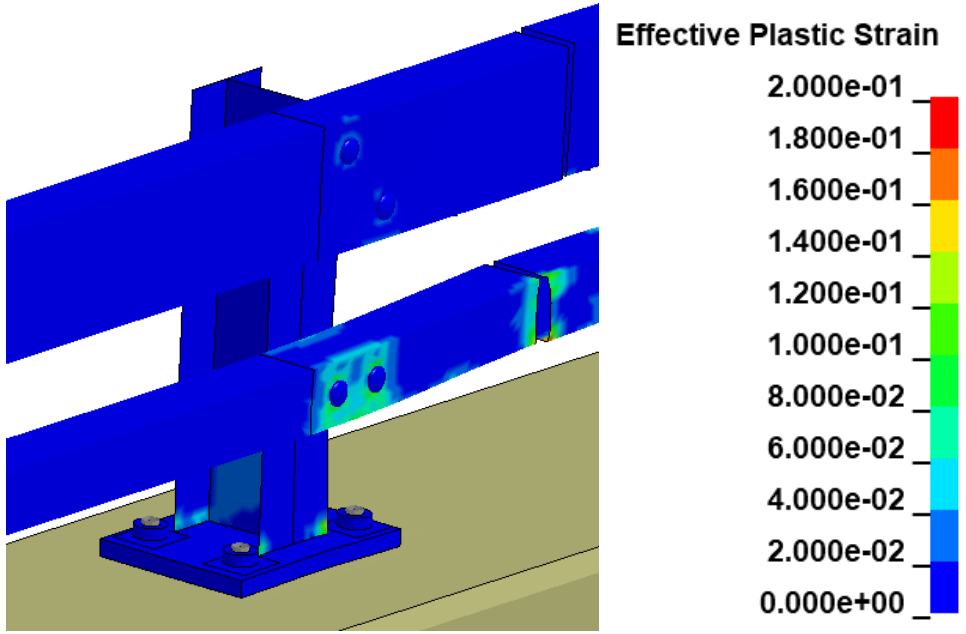
Barrier Damage

- Analysis indicated possible cracks in concrete curb near surface at front anchor bolts
  - Max dynamic 1st Prin. Strain = 0.073
- There was minimal damage to the post and base plates at the critical post location.
  - Plastic strain = 0.14
- Vertical deflection of the base plate:
  - Dynamic = 0.49 in (12.4 mm) at 0.06 seconds
  - Permanent = 0.16 in (4.1 mm)

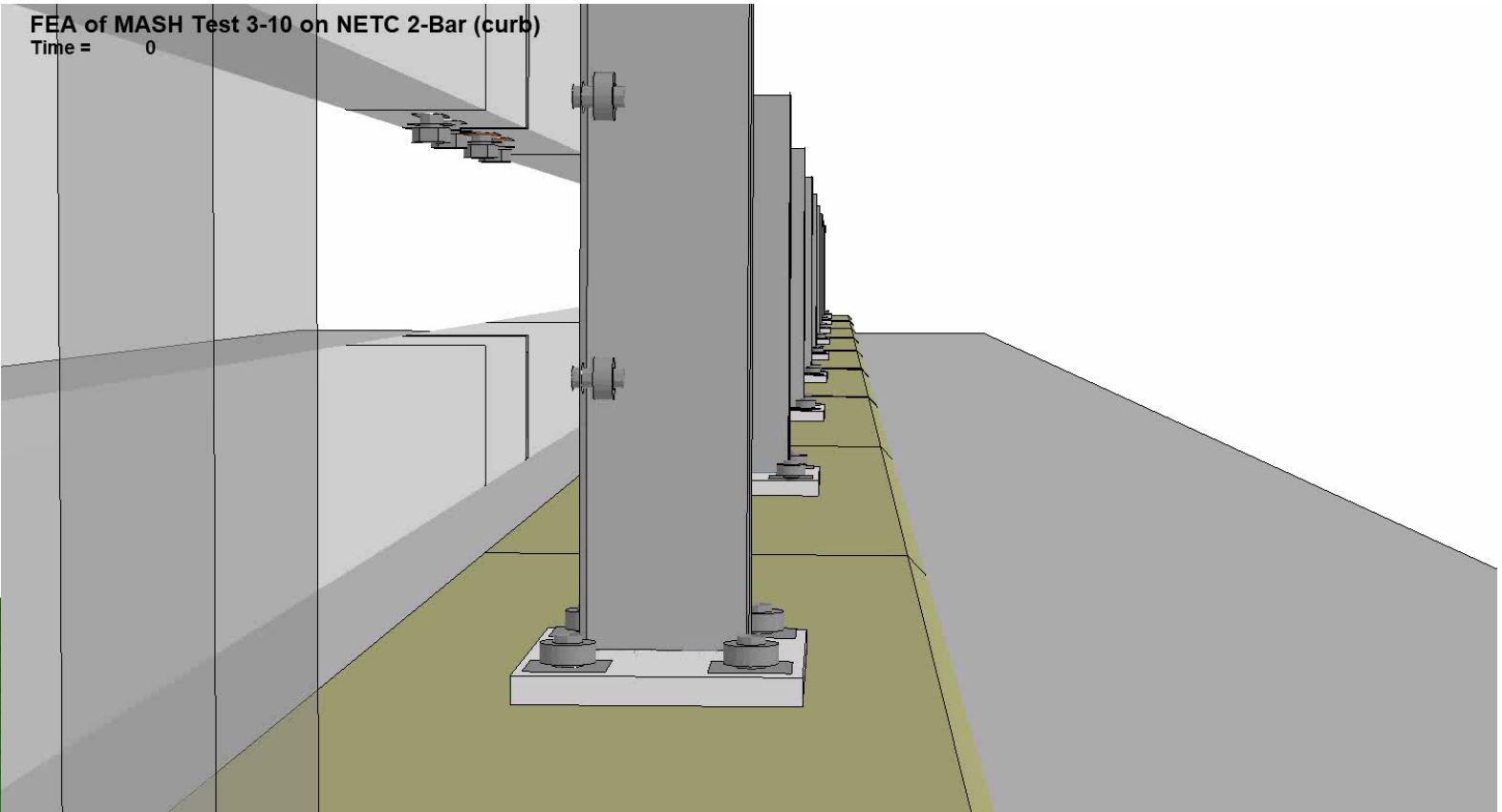


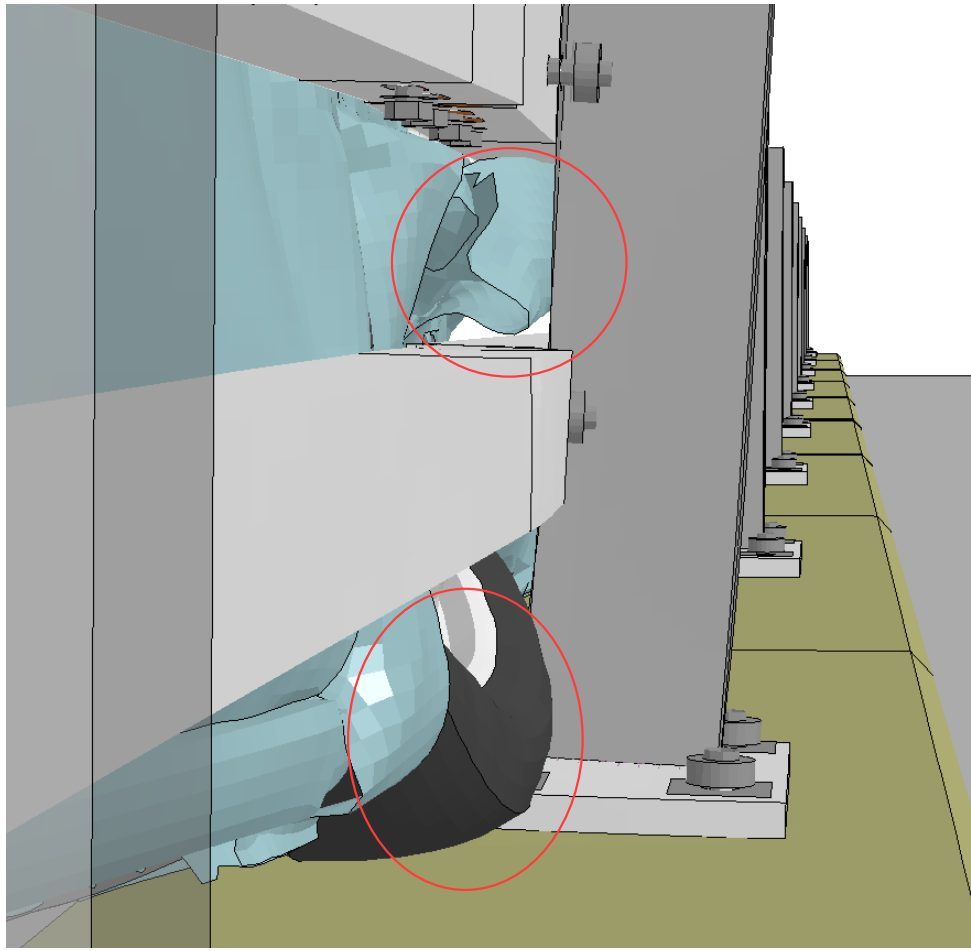




Assessment of Potential Vehicle Contact with Post

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





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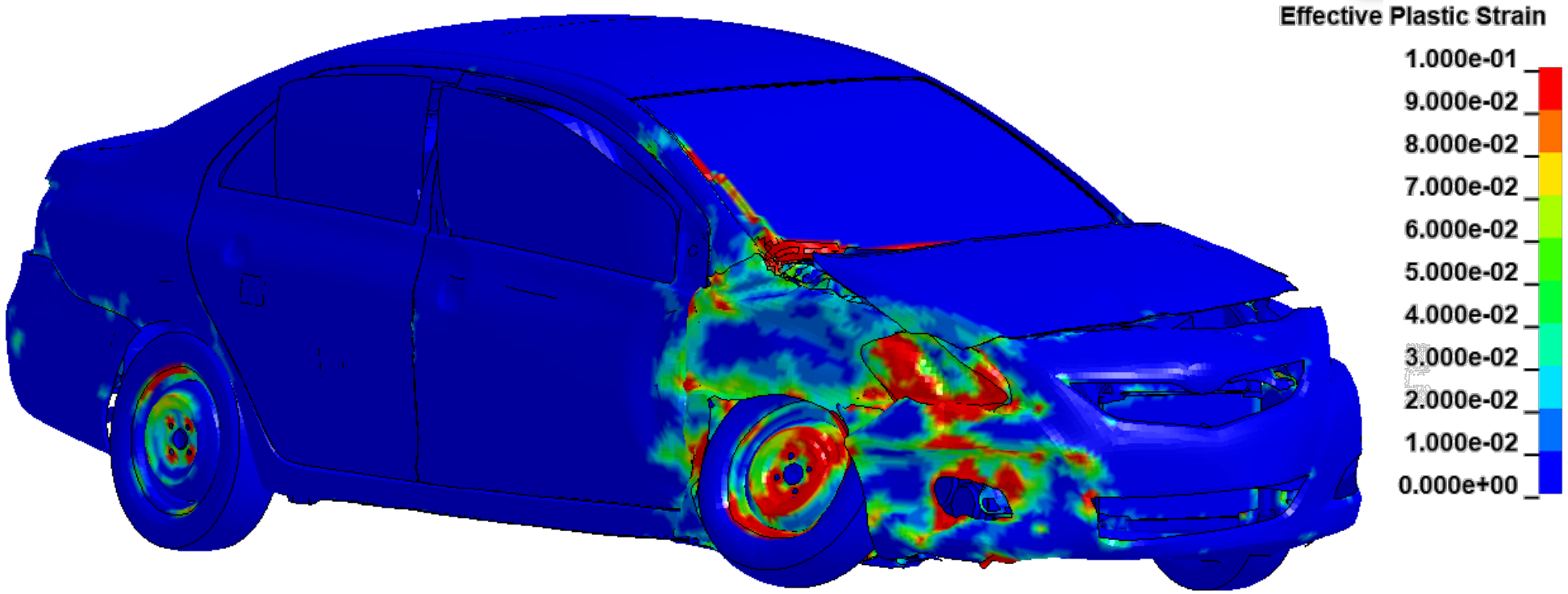
Effective Plastic Strain for Small Car Test



- 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.
- The impact-side windows were broken.
- The windshield was fractured on the impact side (from vehicle deformation).
- The rear-left wheel was deformed.

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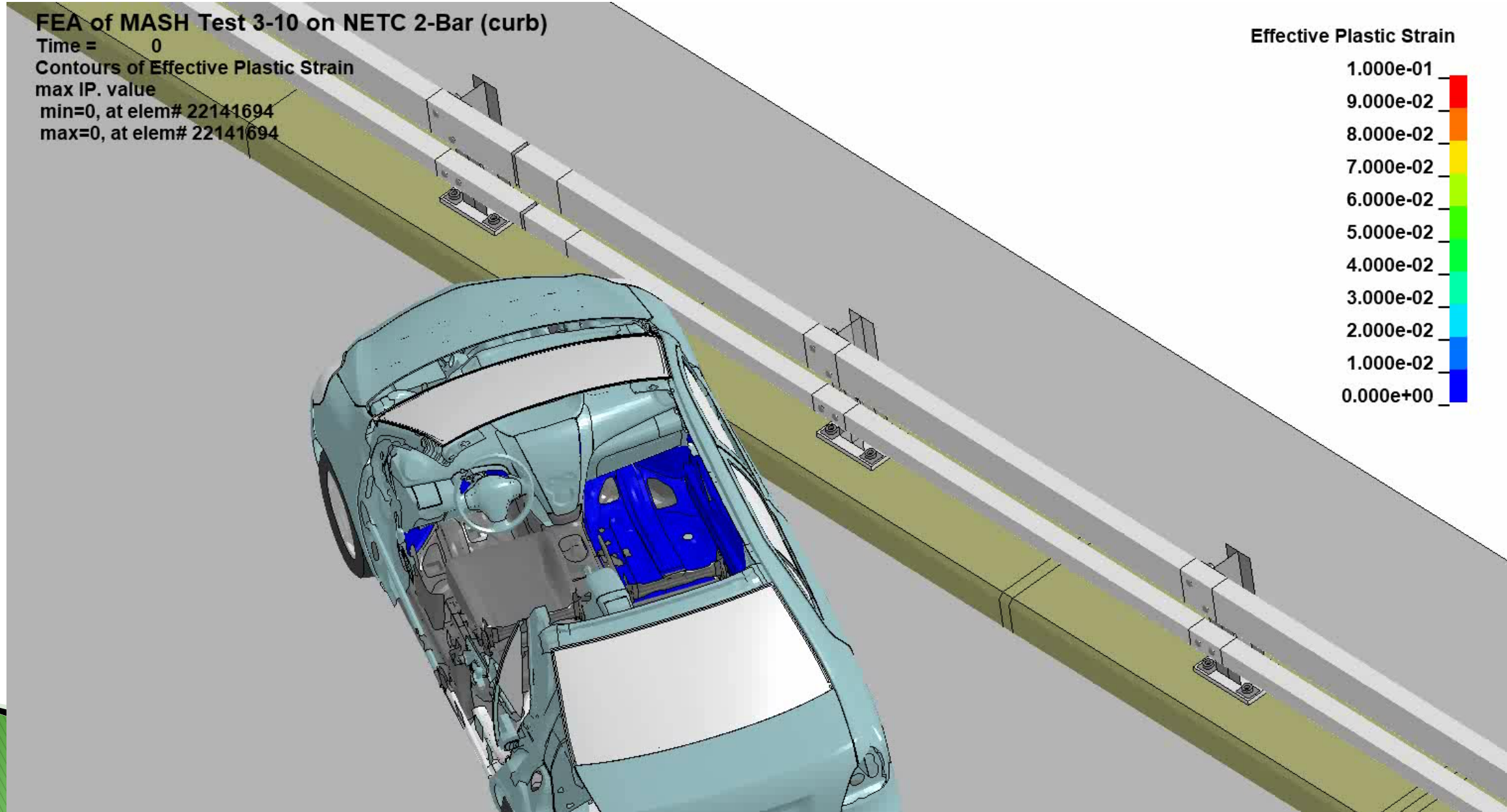
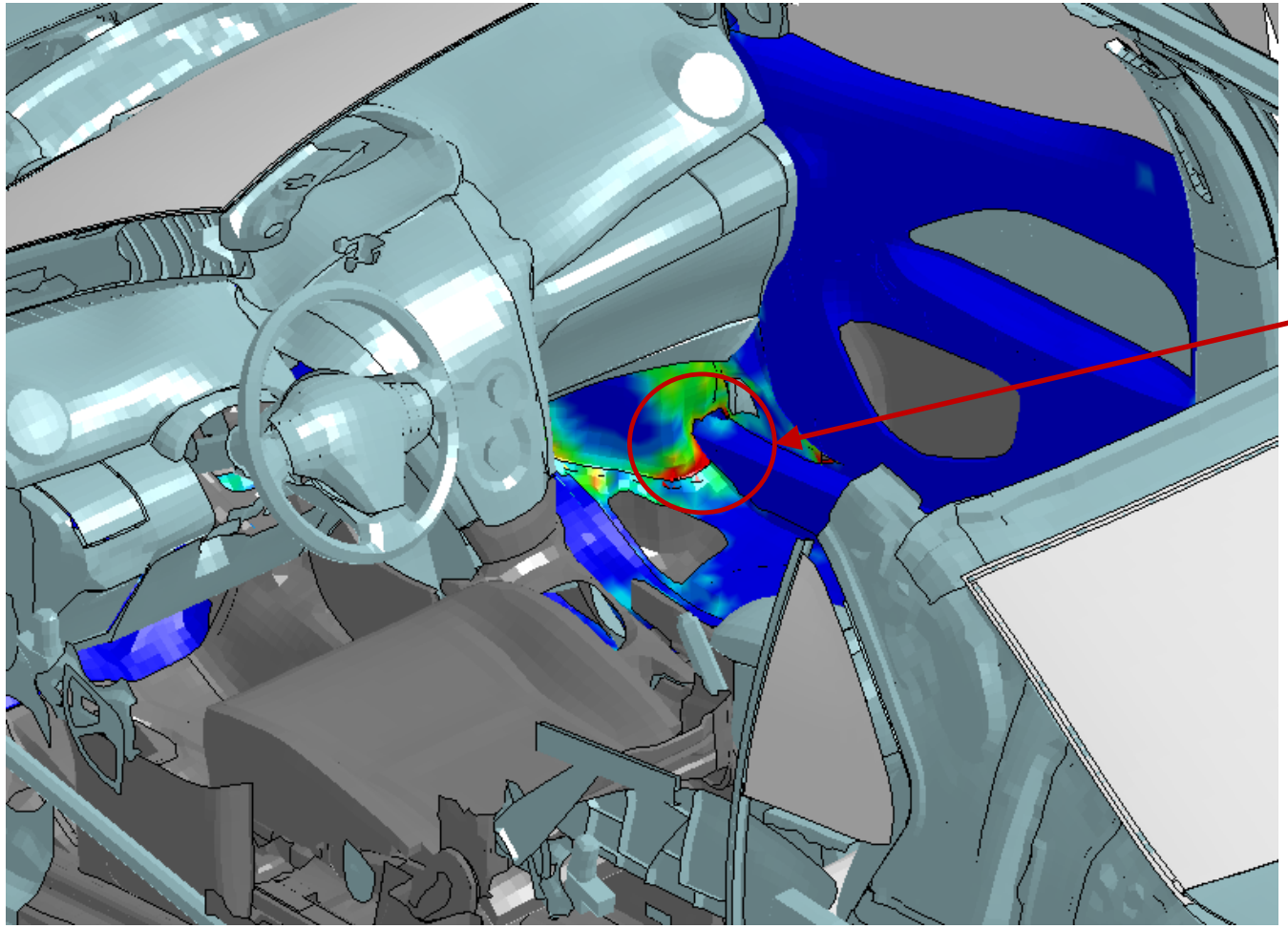
Occupant Compartment Intrusion (OCI) Video



Occupant Compartment Intrusion (OCI)

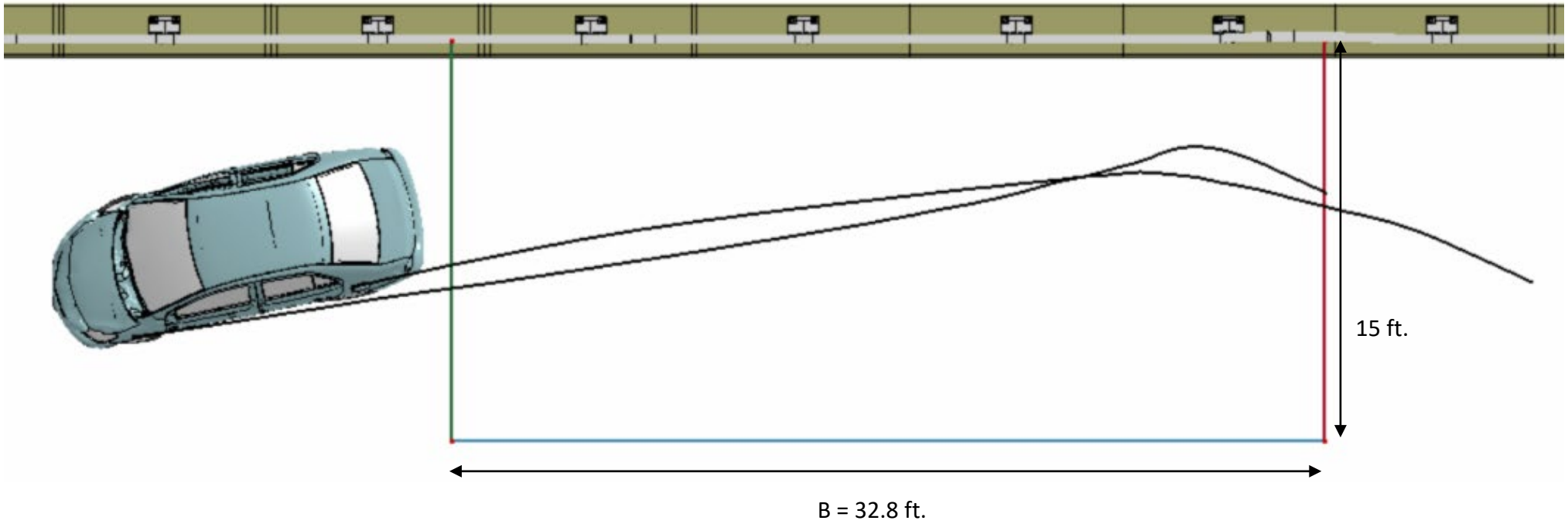


Maximum OCI of the floor, doors, and side panels was ≈**3.3 inches** (85 mm) and occurred at the right-front toe-pan at the wheel well.

Maximum allowable is 9".

Exit Box – NETC 2-Bar – Test 3-10

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 3-10 on the NETC 2-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 = **7 degrees** and Max Pitch = **5.4 degrees**.
- The OIV was within critical limits and the maximum ORA was within preferred limits specified in MASH.
  - OIV_x = **26.2 ft/s** and OIV_y = **33.1 ft/s**
  - ORA_x = **5.5 G** and ORA_y = **6.4 G** (*values strongly dependent on time of occupant impact*)
- The maximum **occupant compartment deformation** was approximately **3.3 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 lower railing at the splice connection upstream of critical post.
- The greatest deformation of the barrier was:
  - Max Dynamic = **3.6 inches**; Max Permanent = **2.03 inches**

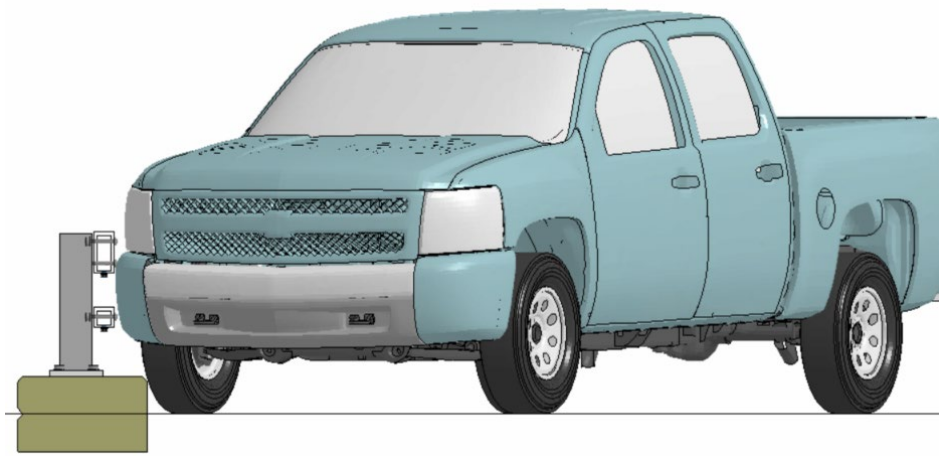
Conclusions for Test 3-10 on the NETC 2-BAR Bridge Rail

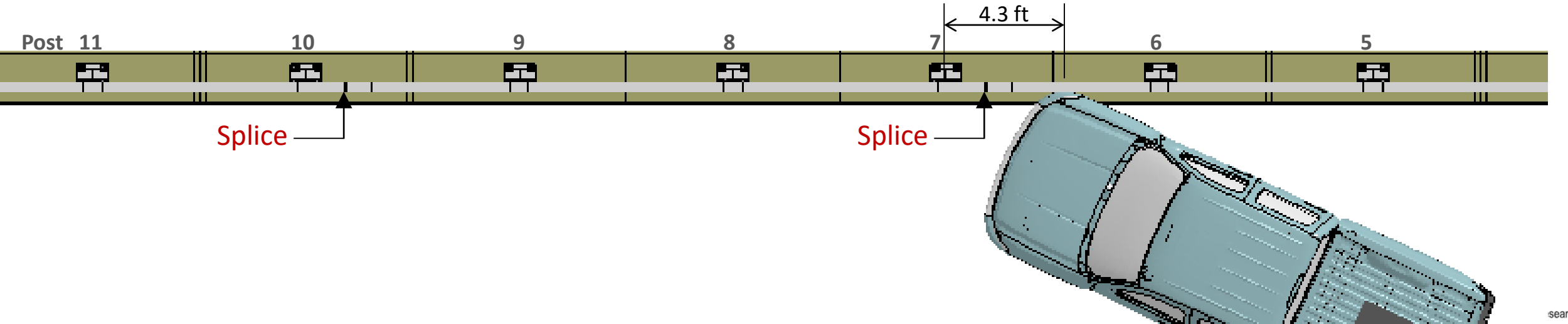
Evaluation Factors		Evaluation Criteria	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is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

MASH Test 3-11 Simulation on the NETC 2-Bar

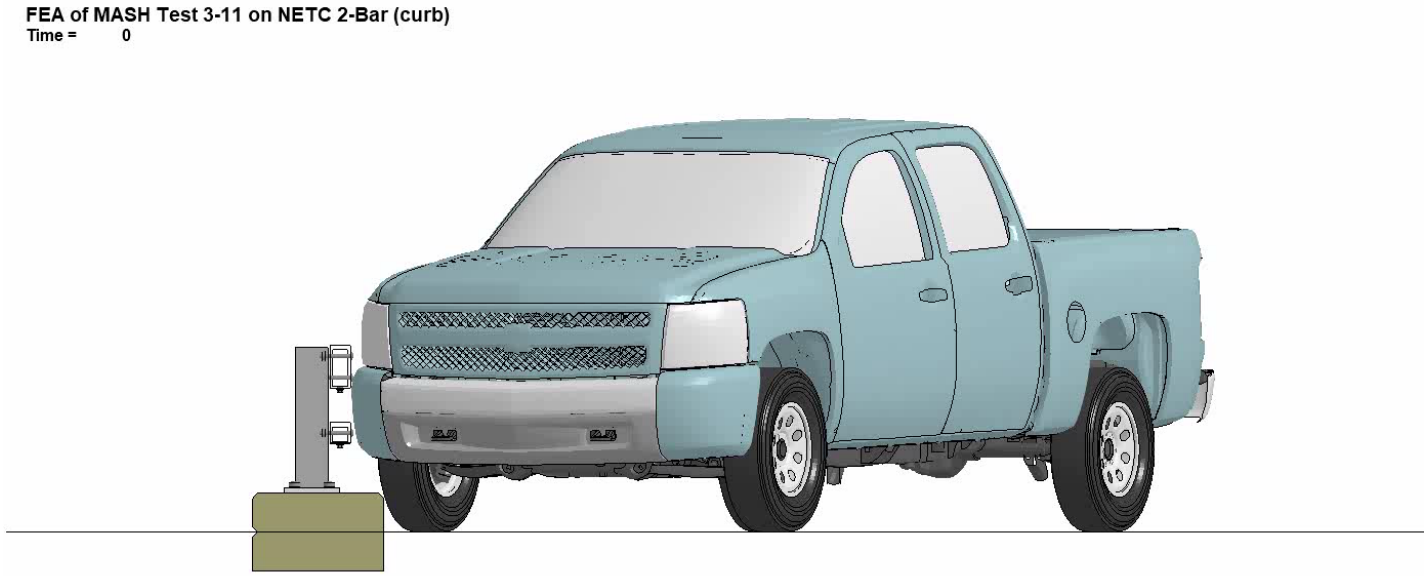
- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point = 4.3 ft upstream from Post 7
    - (*MASH 2016 suggested CIP for rigid barriers)*

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





Movies


FEA of MASH Test 3-11 on NETC 2-Bar (curb)
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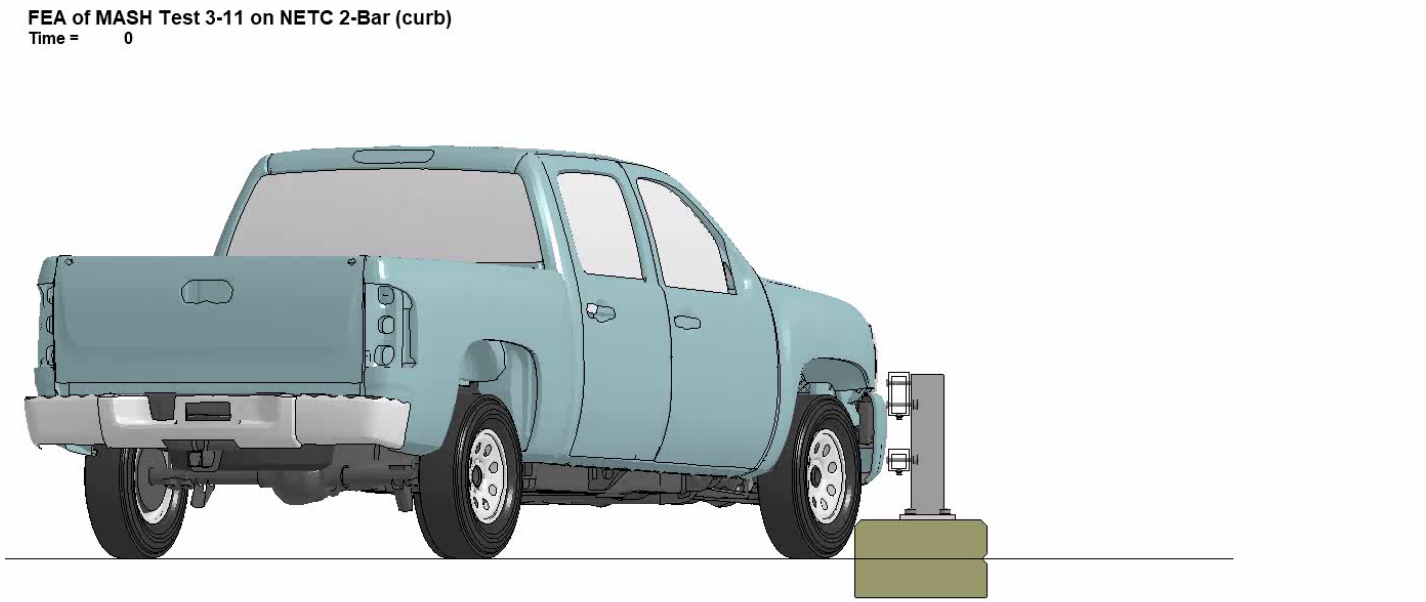
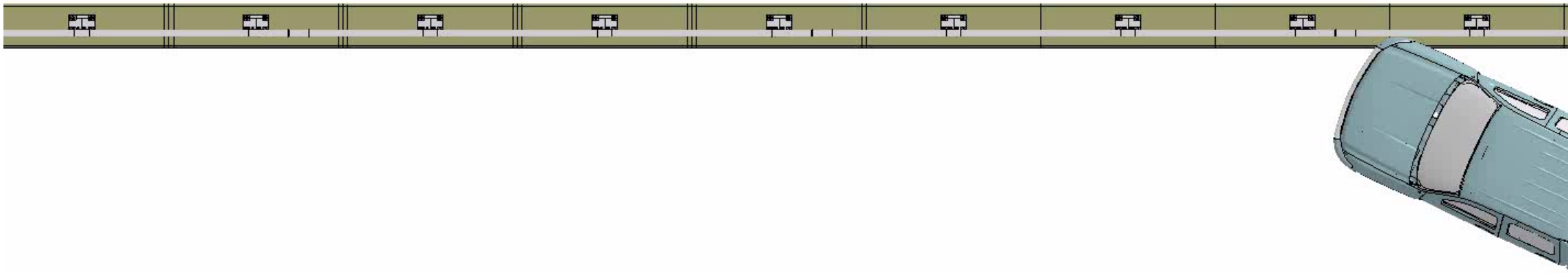

FEA of MASH Test 3-11 on NETC 2-Bar (curb)
Time = 0

FEA of MASH Test 3-11 on NETC 2-Bar (curb)
Time = 0



FEA of MASH Test 3-11 on NETC 2-Bar (curb)
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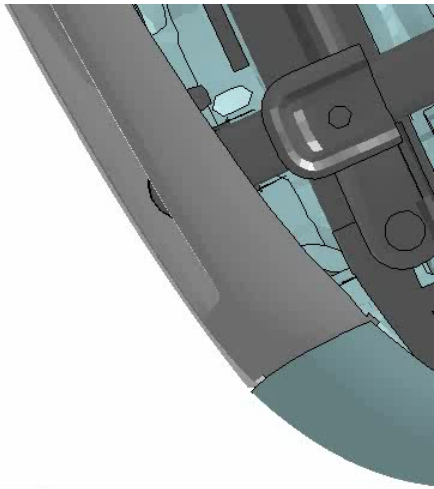

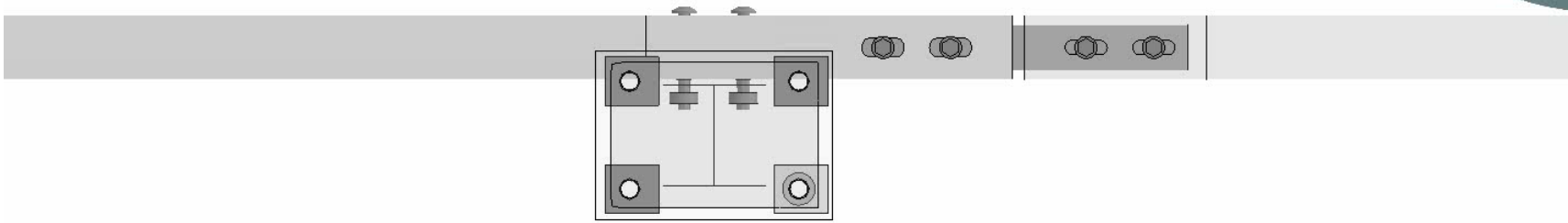

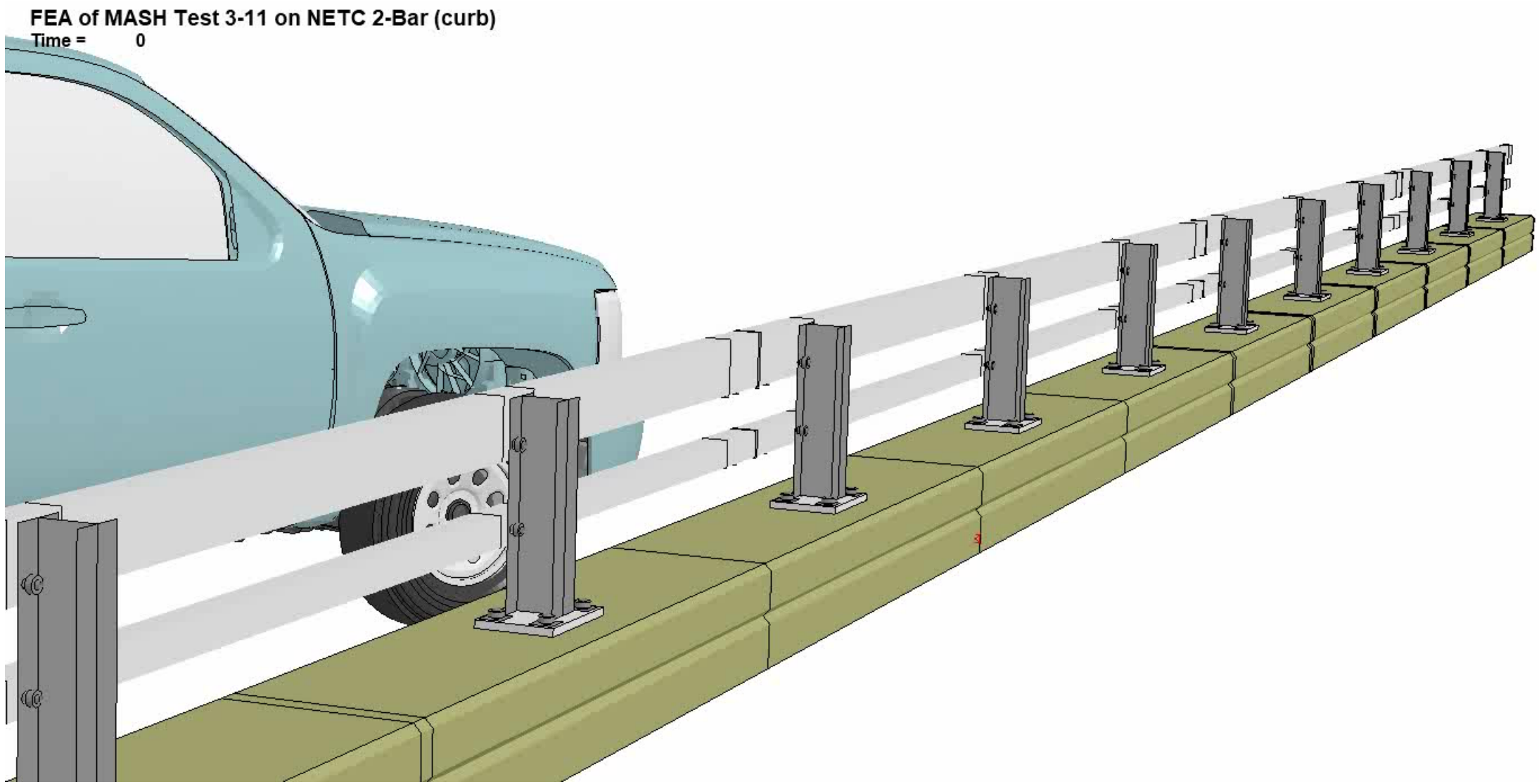

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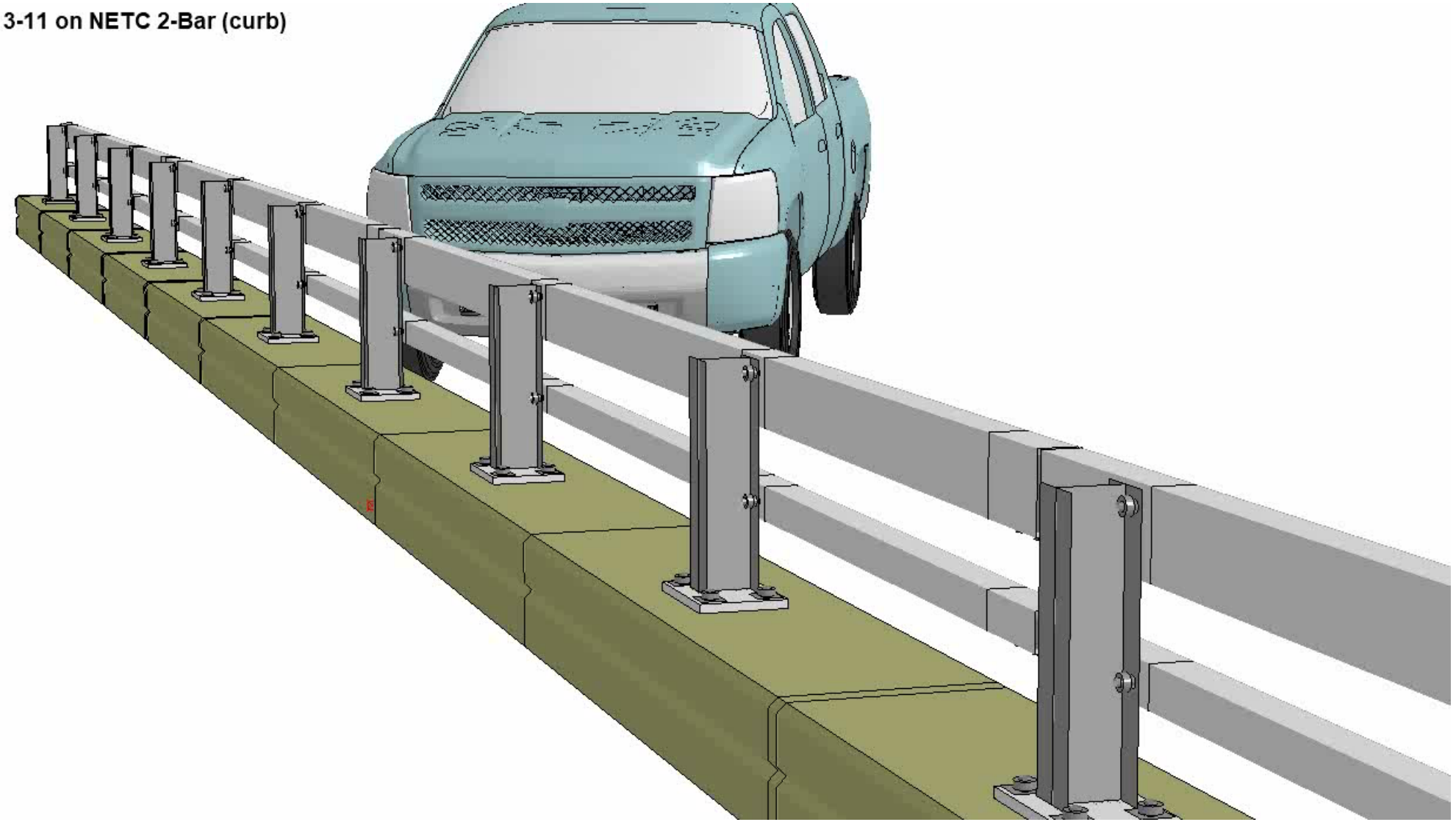
FEA of MASH Test 3-11 on NETC 2-Bar (curb)
Time = 0



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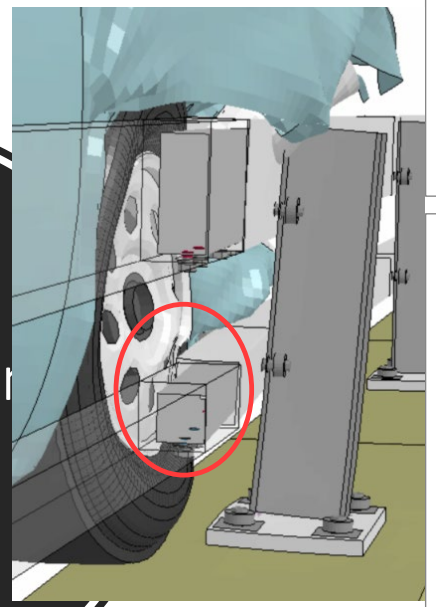
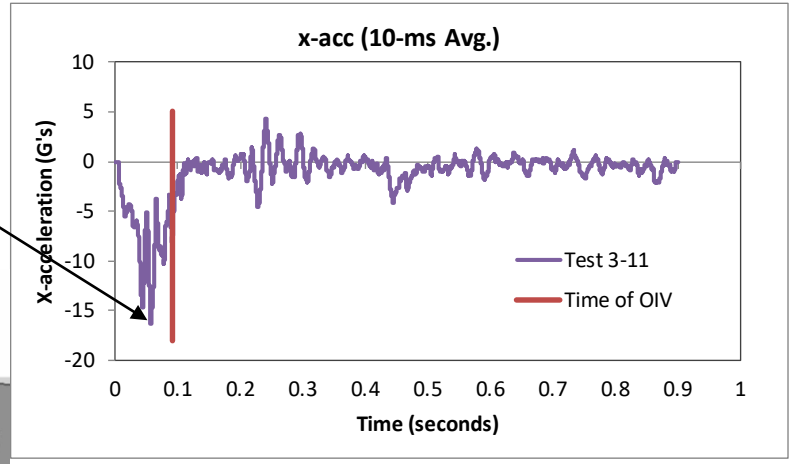
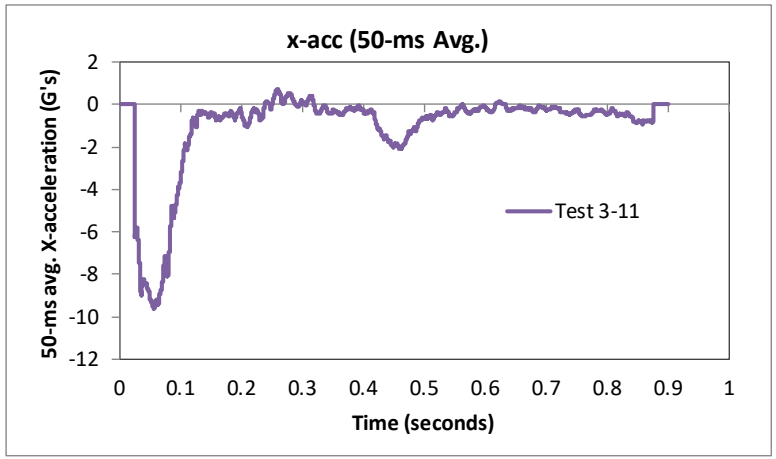
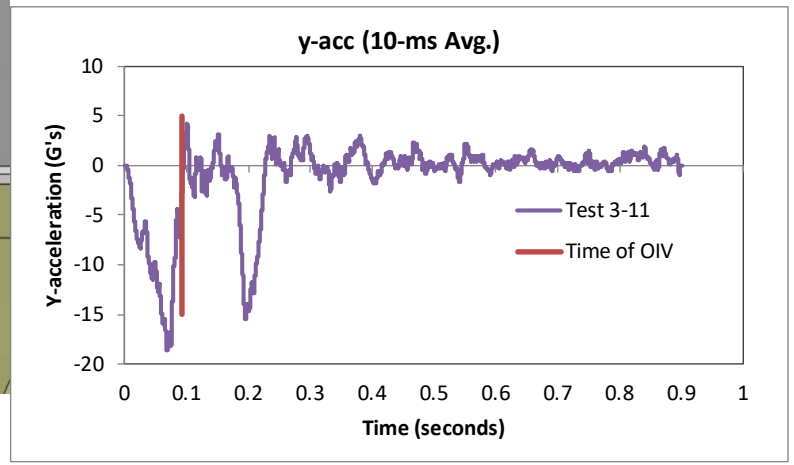
Acceleration Plots

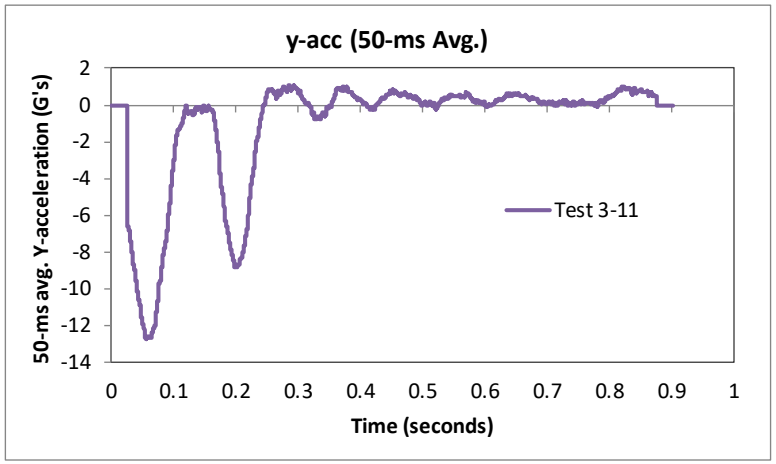
Front wheel snag on splice

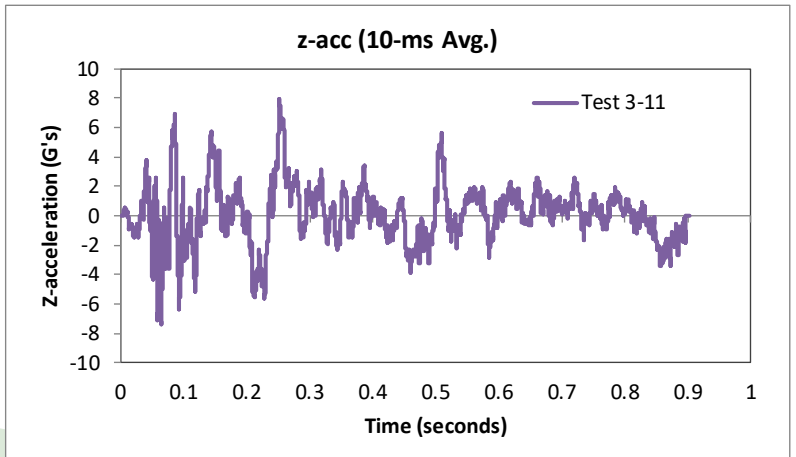


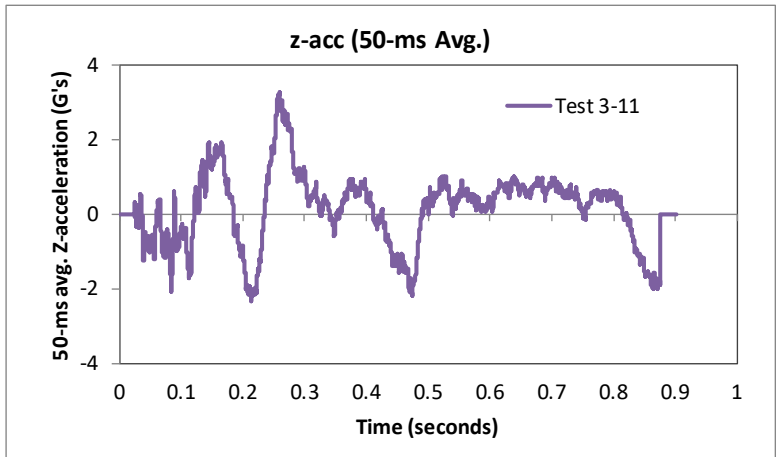












TRAP – Summary Table

Occupant Risk Factors		MASH Test 3-11
Occupant Impact Velocity (ft/s)	x-direction	20.7
	y-direction	26.9
	at time	at 0.0919 seconds on right side of interior
THIV (ft/s)		33.5 at 0.0893 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-4.6 (0.2233 - 0.2333 seconds)
	y-direction	-15.4 (0.1905 - 0.2005 seconds)
PHD (g's)		15.4 (0.1905 - 0.2005 seconds)
ASI		1.63 (0.0308 - 0.0808 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-9.6 (0.0320 - 0.0820 seconds)
	y-direction	-12.7 (0.0303 - 0.0803 seconds)
	z-direction	3.3 (0.2342 - 0.2842 seconds)
Maximum Angular Disp. (deg)	Roll	9 (0.7864 seconds)
	Pitch	-10.1 (0.4644 seconds)
	Yaw	-28.8 (0.3265 seconds)

MASH Criteria

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

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

< 75 deg ✓

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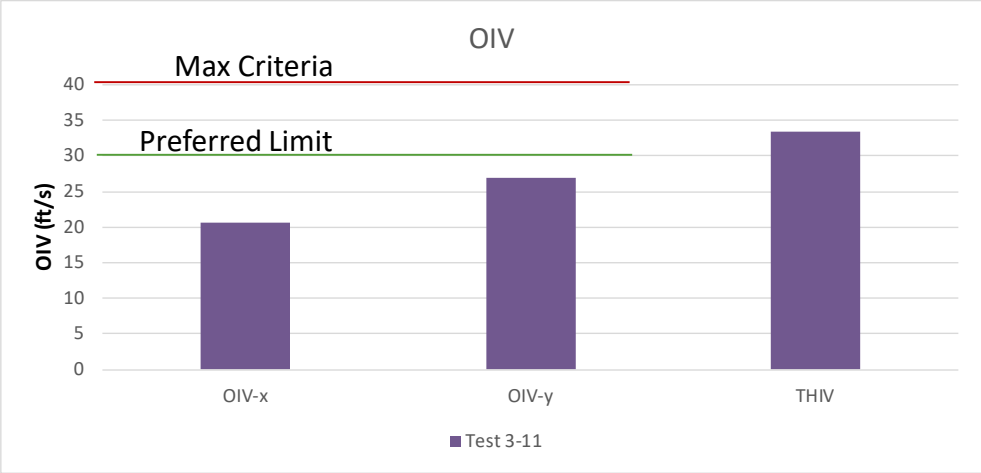
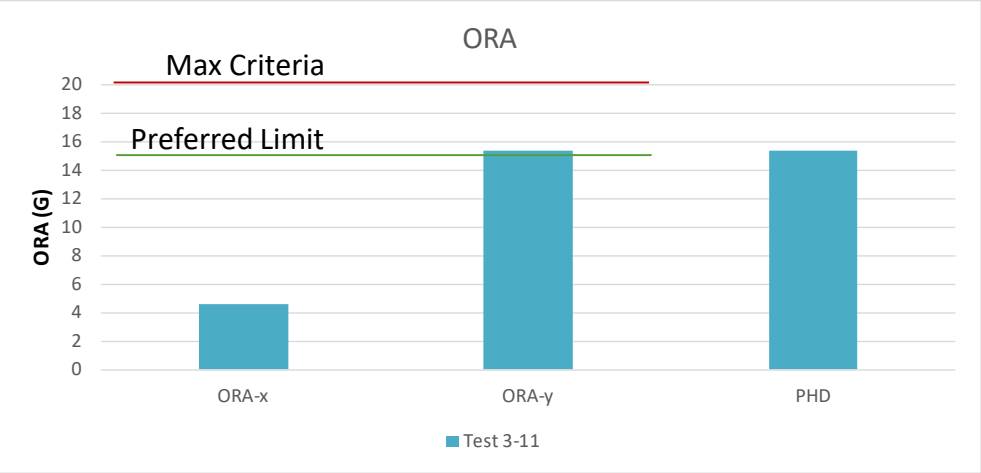
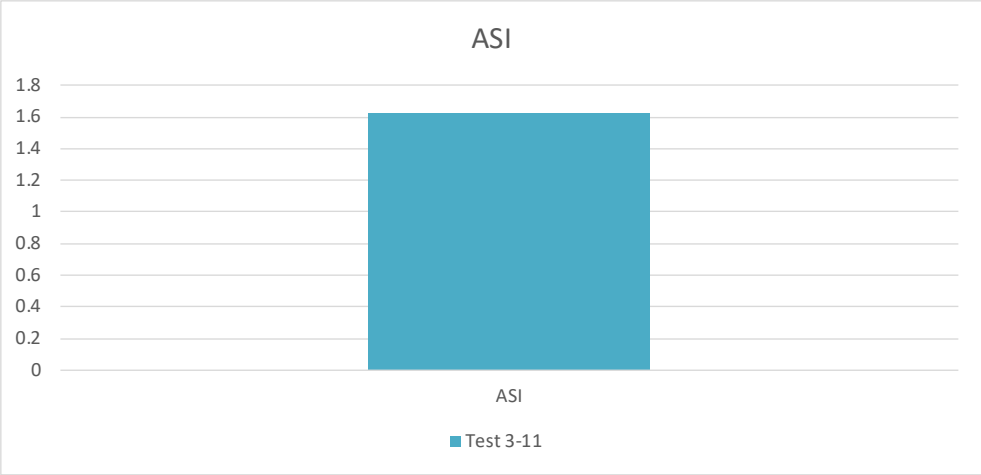
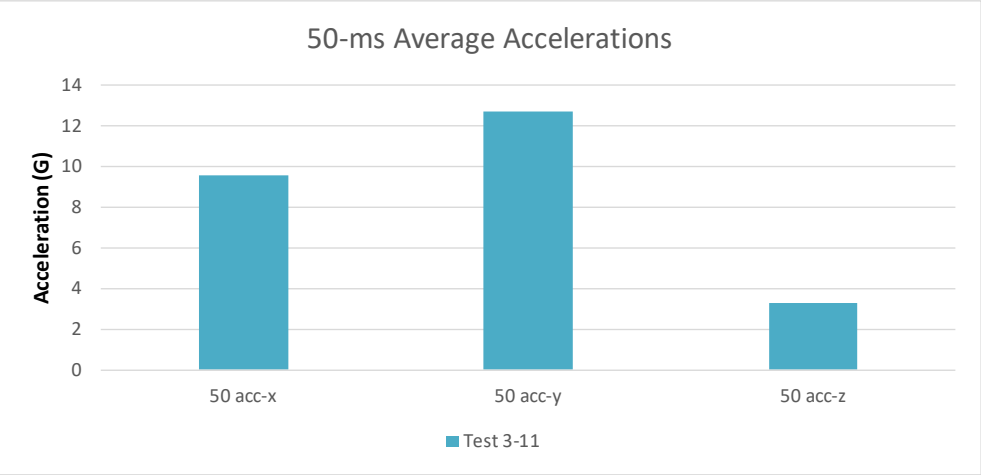
TRAP









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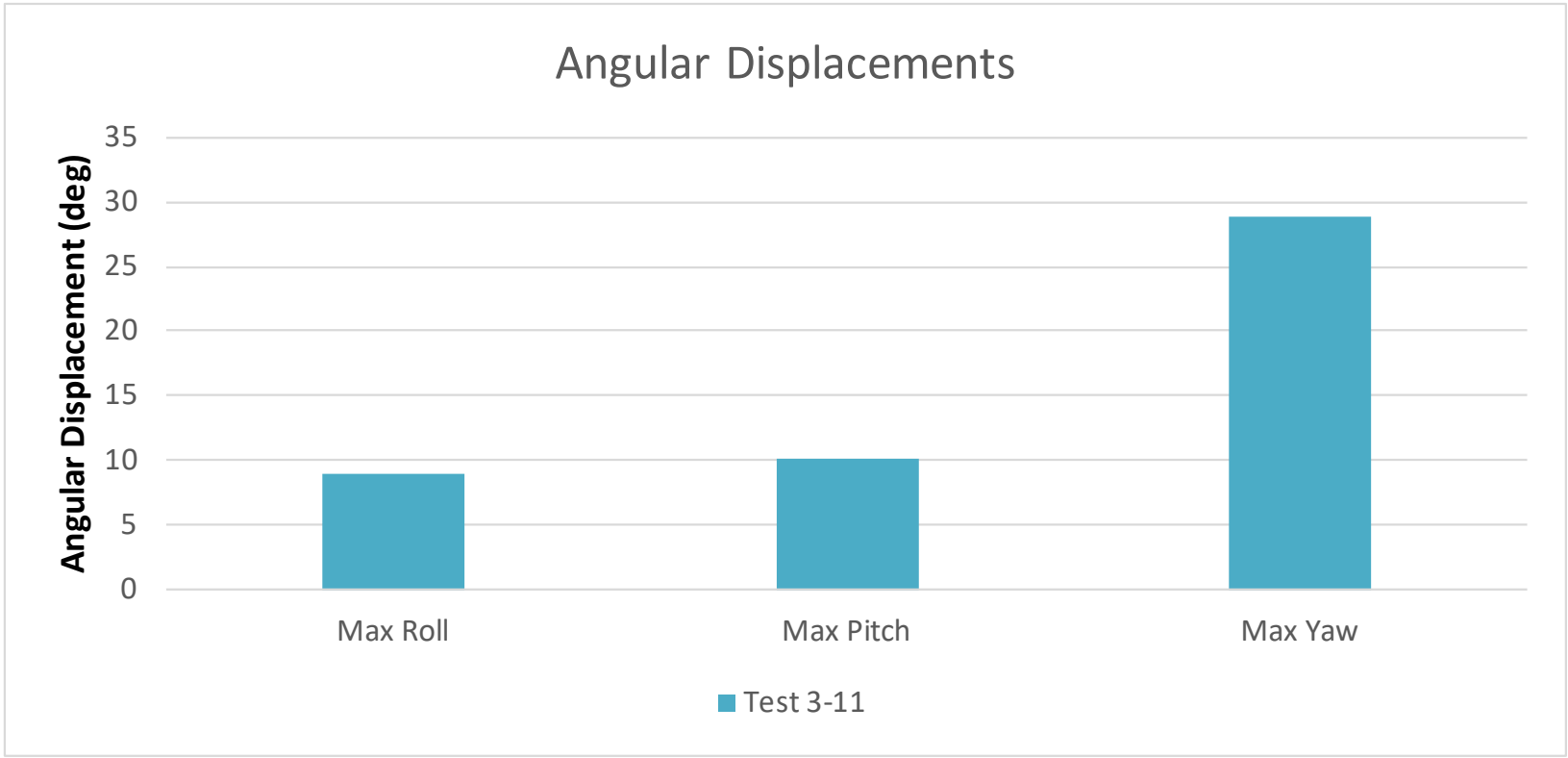
TRAP



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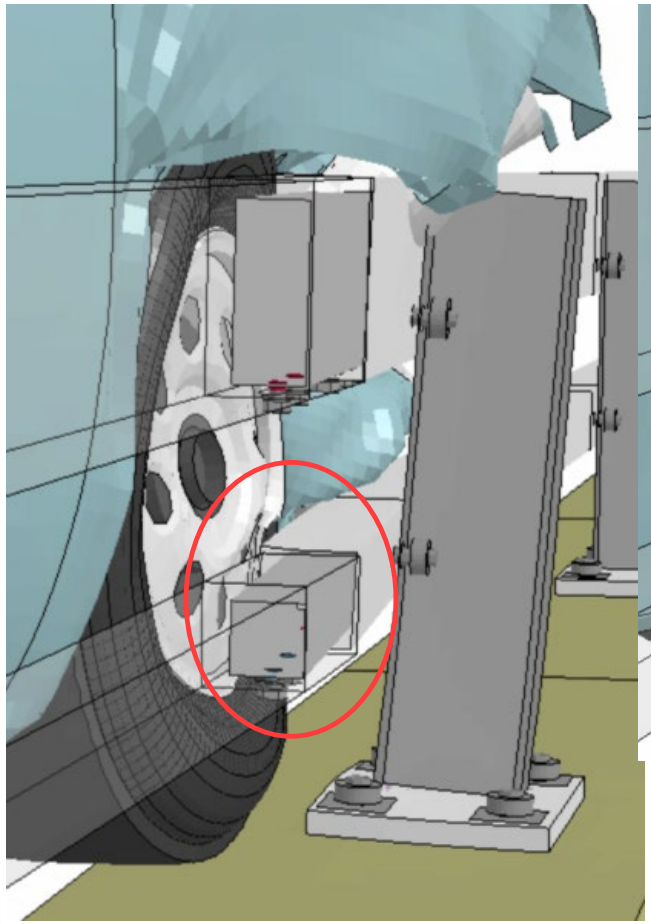
Assessment of Potential Vehicle Snag

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

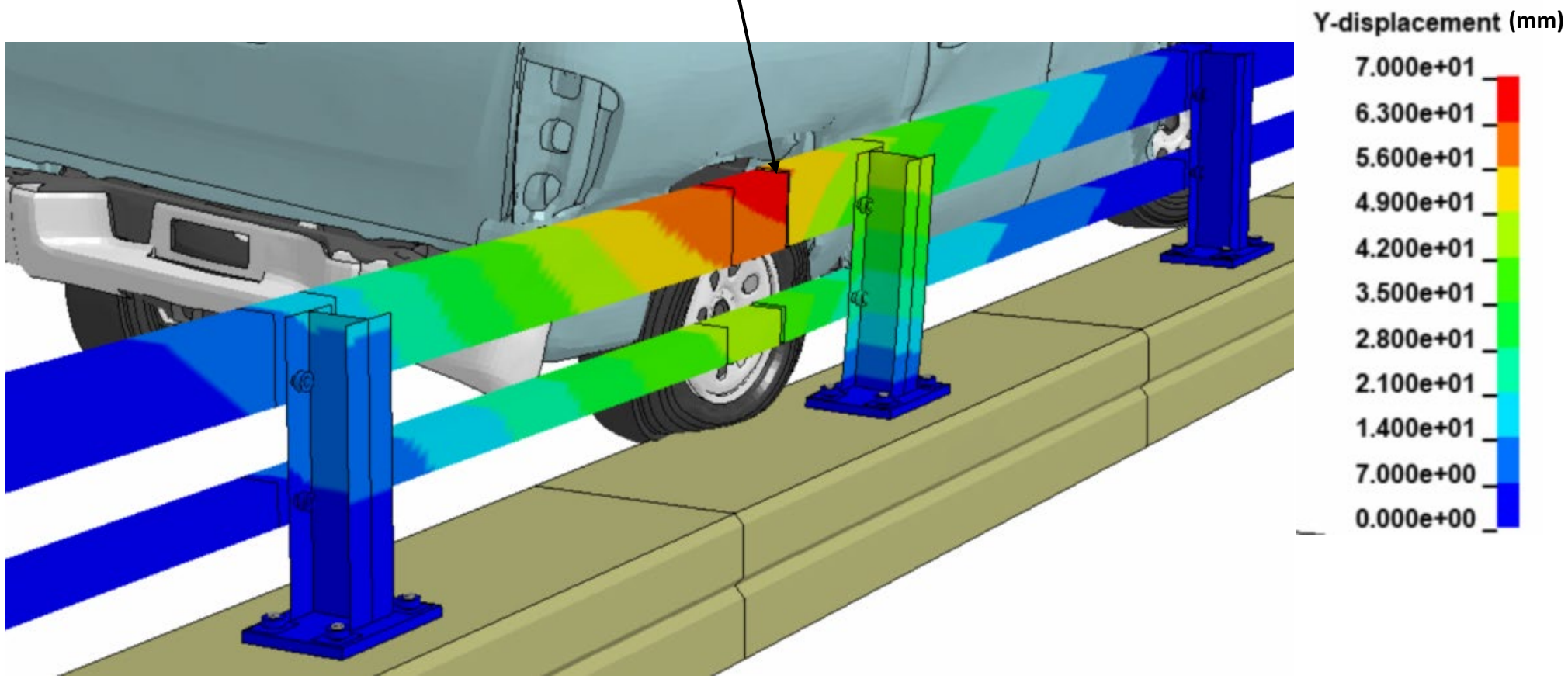
Front Wheel Snag



Door Snag

Lateral Dynamic Deflection

Maximum dynamic deflection = 2.7 in (68.7 mm) @ 0.2 seconds



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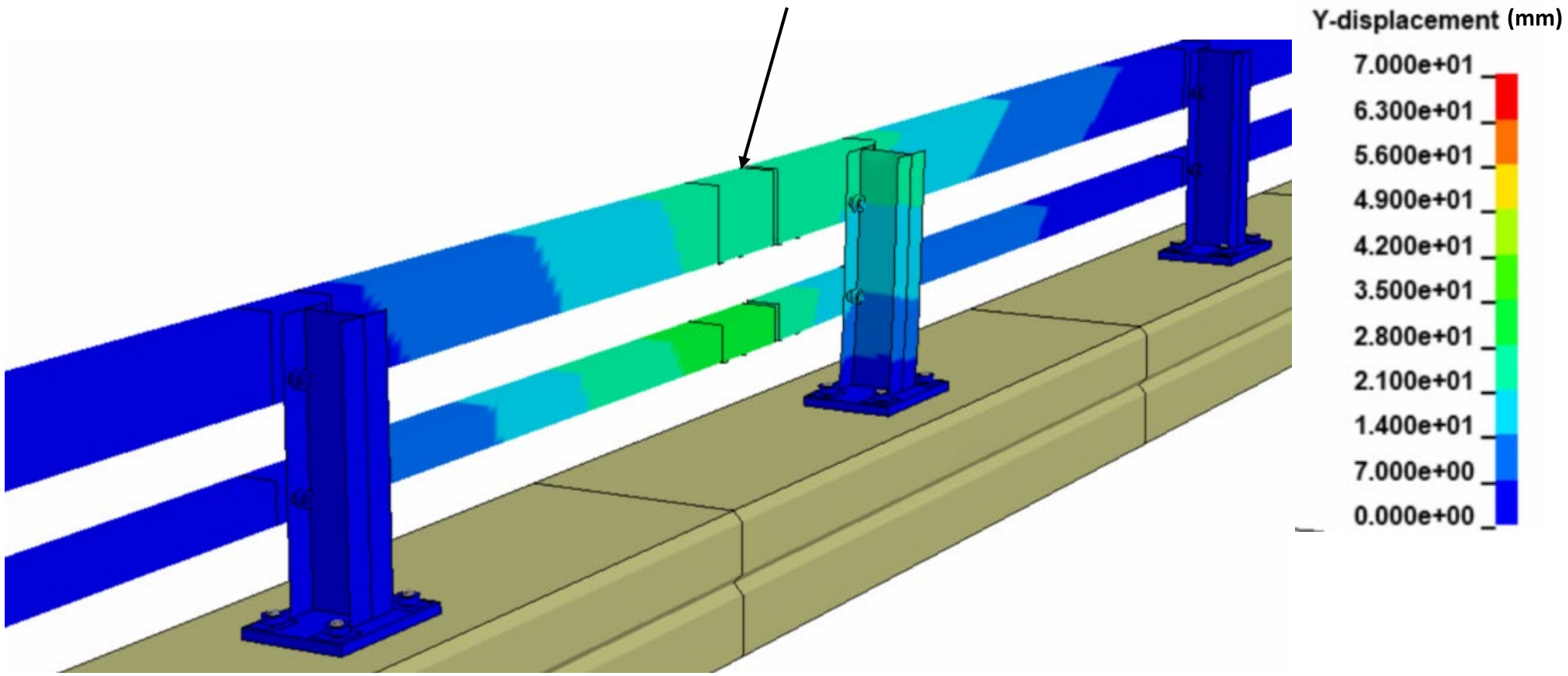
Lateral Permanent Deflection

Maximum permanent deflection = 1.27 in (32.3 mm)



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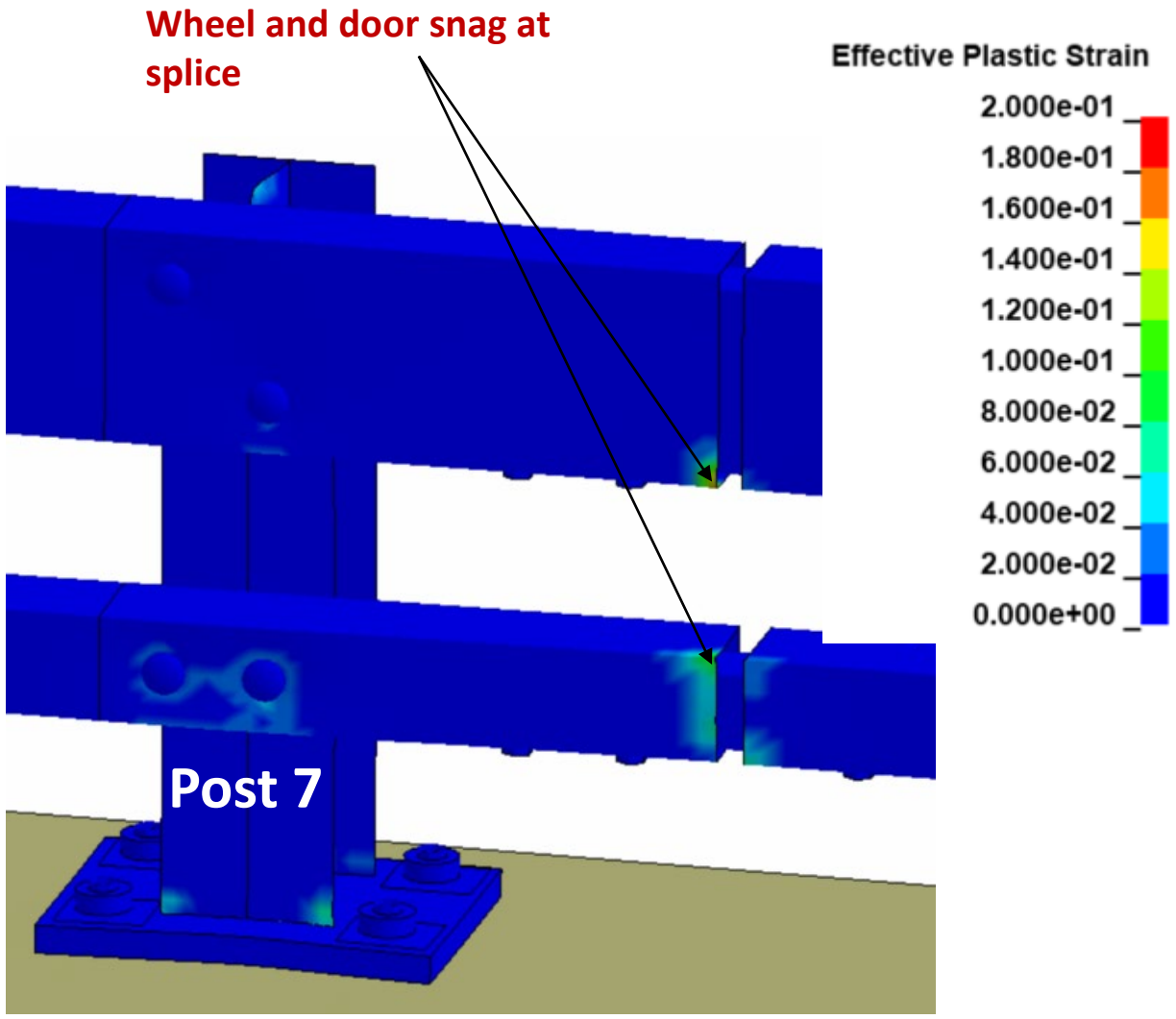
Barrier Damage

- There was moderate damage to the rail tubes between Post 6 and 7, with additional damage at the end of the rails at the splice.
- There was moderate damage to Post 6 and 7 and their base plates.
  - There was plastic deformation of at the lower part of the posts and to the base plates.
  - True plastic strain = 0.1 at outer edge of post flange at the weld.
  - Vertical deflection of base plate (Post 6):
    - Dynamic = 0.14 inches (3.5 mm)
    - Permanent = 0.04 inches (1 mm)
  - Vertical deflection of base plate (Post 7):
    - Dynamic = 0.62 inches (15.7 mm)
    - Permanent = 0.24 inches (6.2 mm)



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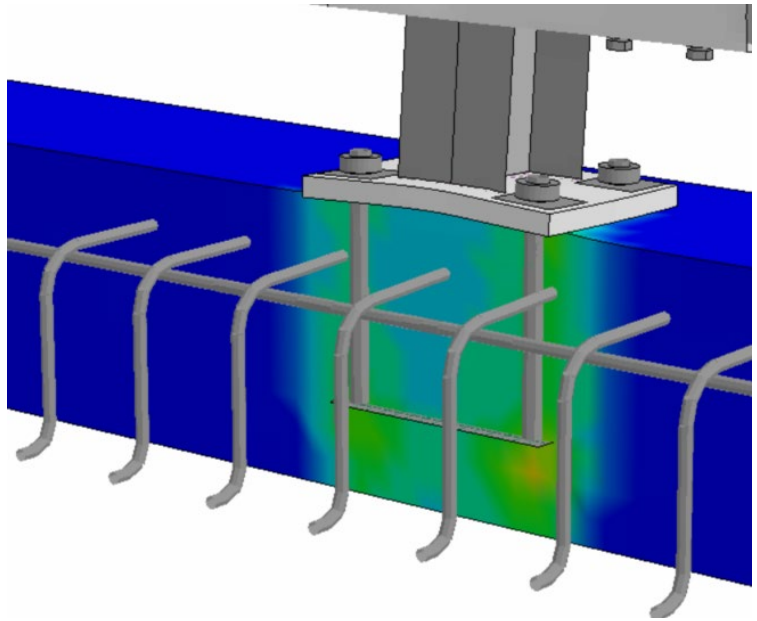
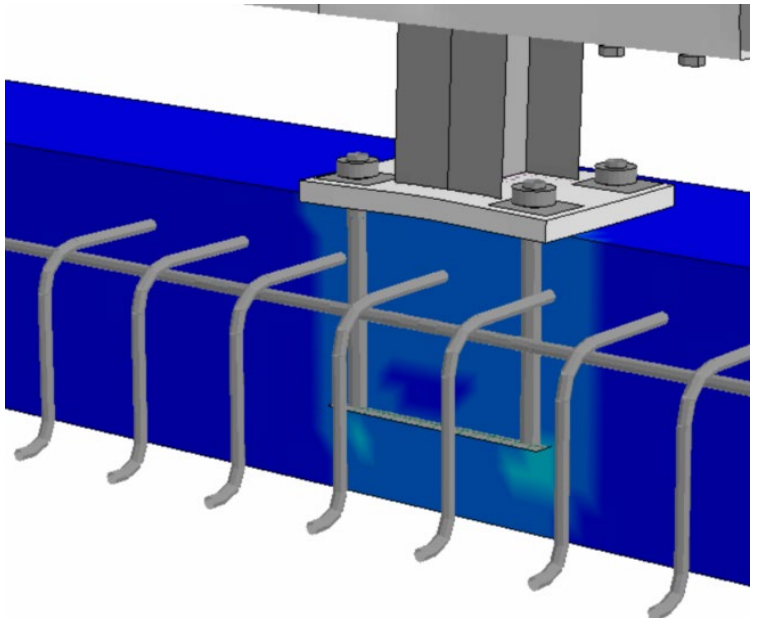
Barrier Damage

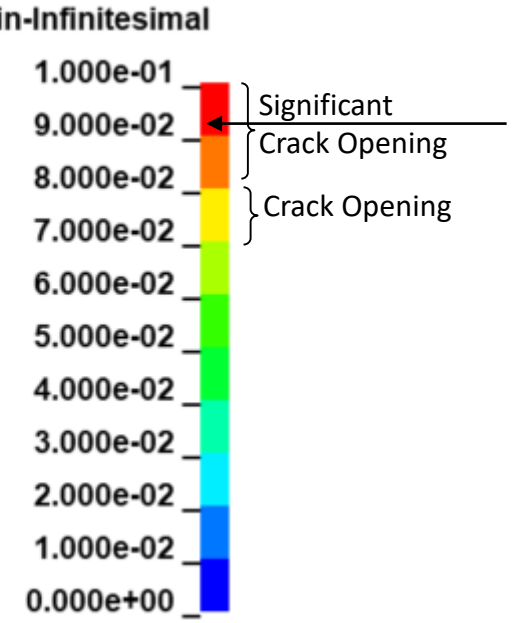
- Analysis indicated potential for significant crack opening in concrete due to anchor pryout around front anchor bolts.
  - Max dynamic 1st Prin. Strain = 0.092
  - Final 1st Prin. Strain = 0.076



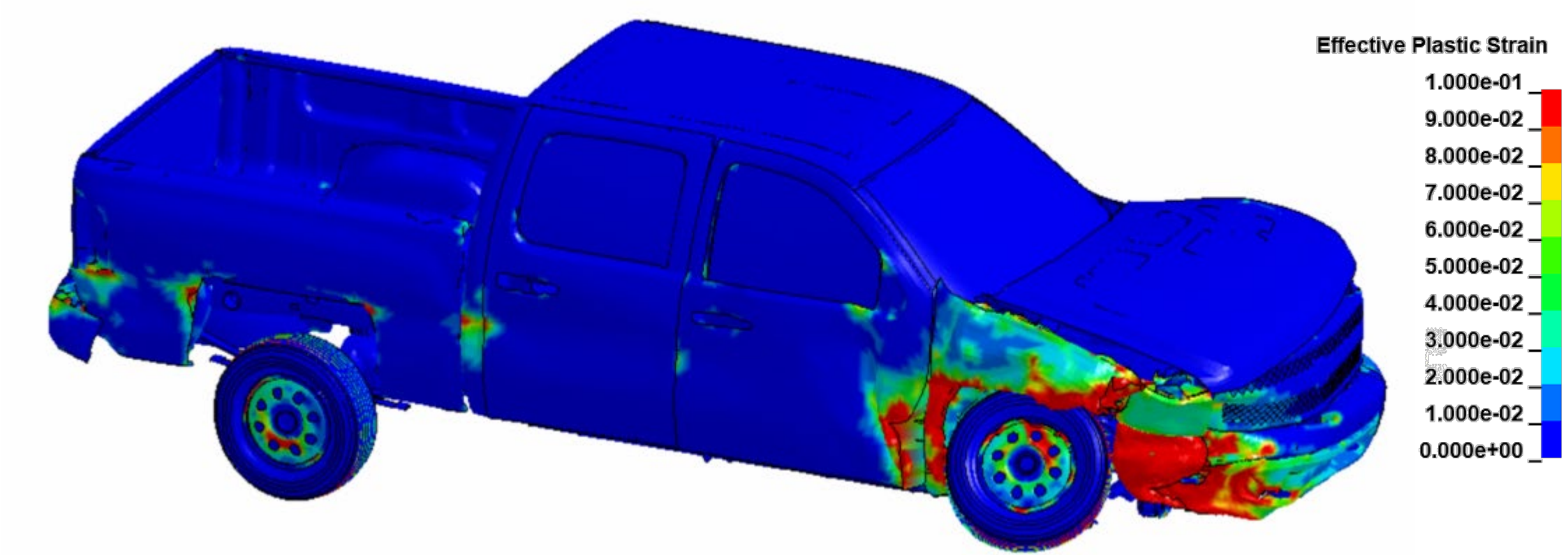
Dynamic at time = 0.075 seconds



Final Static



Effective Plastic Strain for Pickup Test



The most severe damages were to the front bumper, front fender, passenger front door, the upper and lower control arm of front suspension, front wheel, rear wheel, and the rear quarter panel of the vehicle on the impact side.

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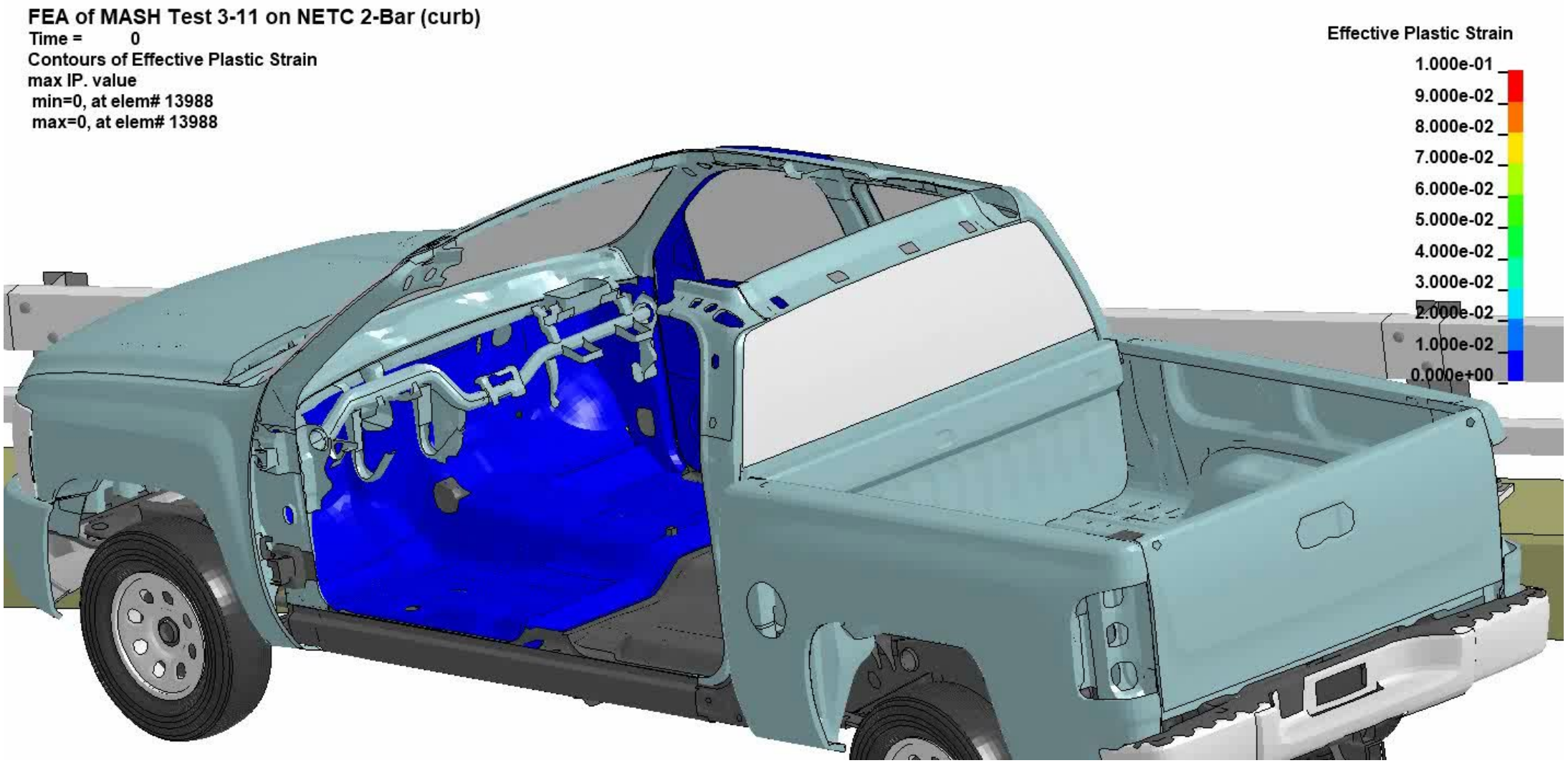
Occupant Compartment Intrusion



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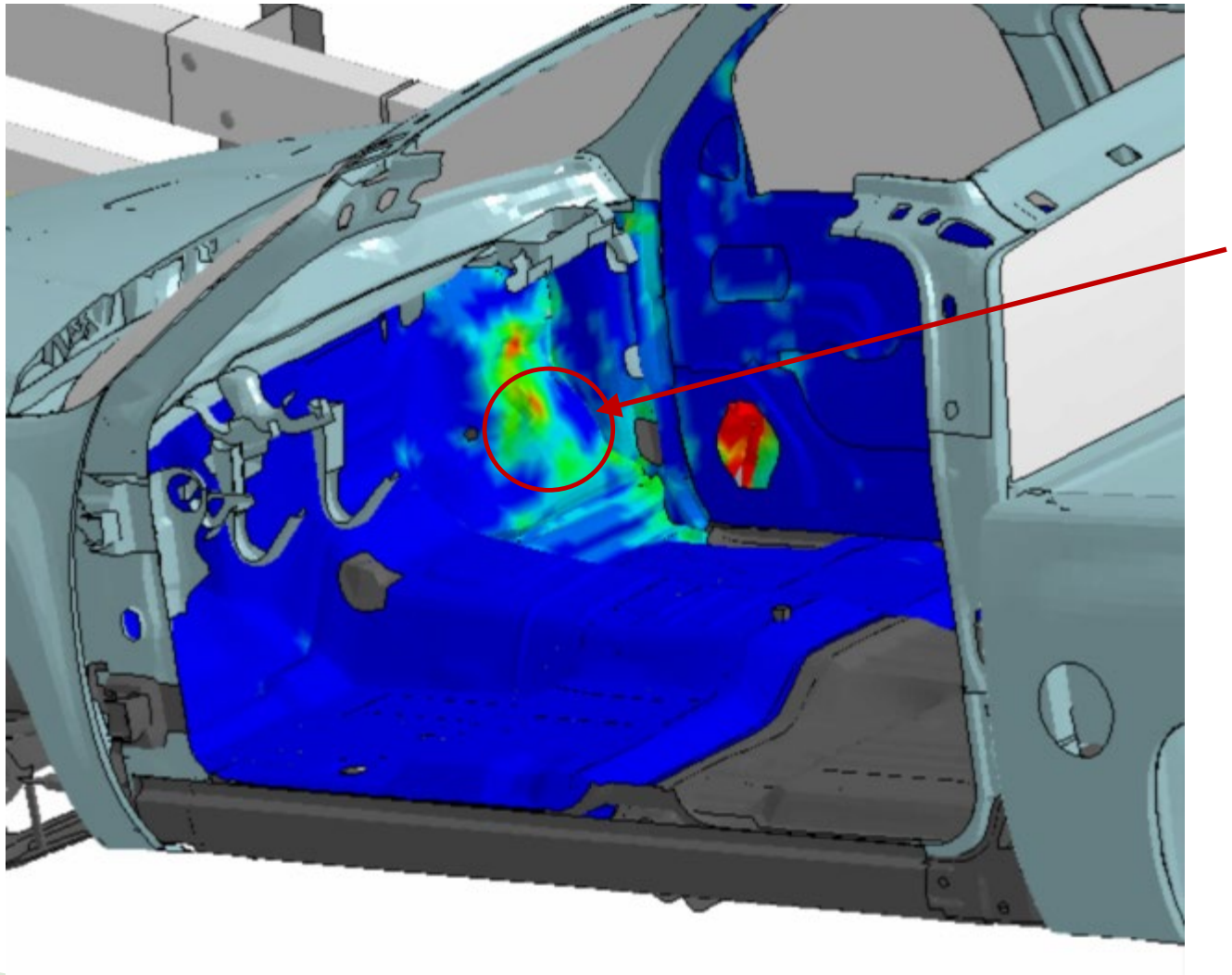
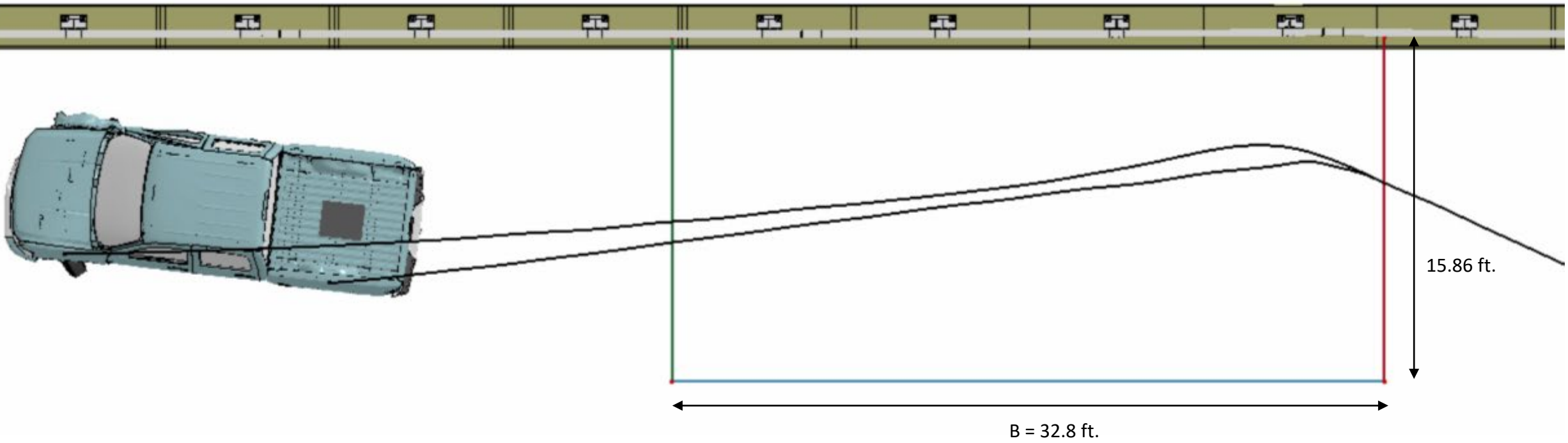
Occupant Compartment Intrusion (OCI)



Maximum OCI was ≈5.4 inches (138 mm) and occurred at the right-front toe-pan at the wheel well.

Exit Box – NETC 2-Bar – Test 3-11

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 3-11 on the NETC 2-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 = **9 degrees** and Max Pitch = **10.1 degrees**.
- The OIV was within preferred limits and the maximum ORA was within critical limits specified in MASH.
  - OIV_x = **20.7 ft/s** and OIV_y = **26.9 ft/s**
  - ORA_x = **4.6 G** and ORA_y = **15.4 G**
- The maximum occupant compartment deformation was approximately **5.4 inches** and occurred at the lower right-front toe pan. This value is well within acceptable limit of 9 inches.
- The vehicle also **remained well within the "exit box"** limits and showed no sign of entering back into travel lanes at aggressive angle.
- Barrier damage was moderate and barrier deflections were considered low to moderate..
- The greatest deformation of the barrier occurred at the top rail splice connection and was:
  - Max Dynamic = **2.7 inches**; Max Permanent = **1.27 inches**

Conclusions for Test 3-11 on the NETC 3-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

Conclusions for Overall Barrier Performance

- MASH Requirements:
  - Structural Adequacy: (**PASS**)
    - The barrier successfully contained and redirected the vehicle in all test cases.
  - Occupant Risk (**PASS**)
    - Occupant compartment intrusion was 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 3-11 (Pickup).
  - Concrete curb damage at Post 7 was likely for Test 3-11.
    - 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 TL3 criteria with only moderate barrier damages.