Development of MASH Computer Simulated Steel Bridge Rail and Transition Details

Task 3 – NETC 3-Bar MASH TL4

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

Chuck A. Plaxico

Archie Ray

Roadsafe LLC

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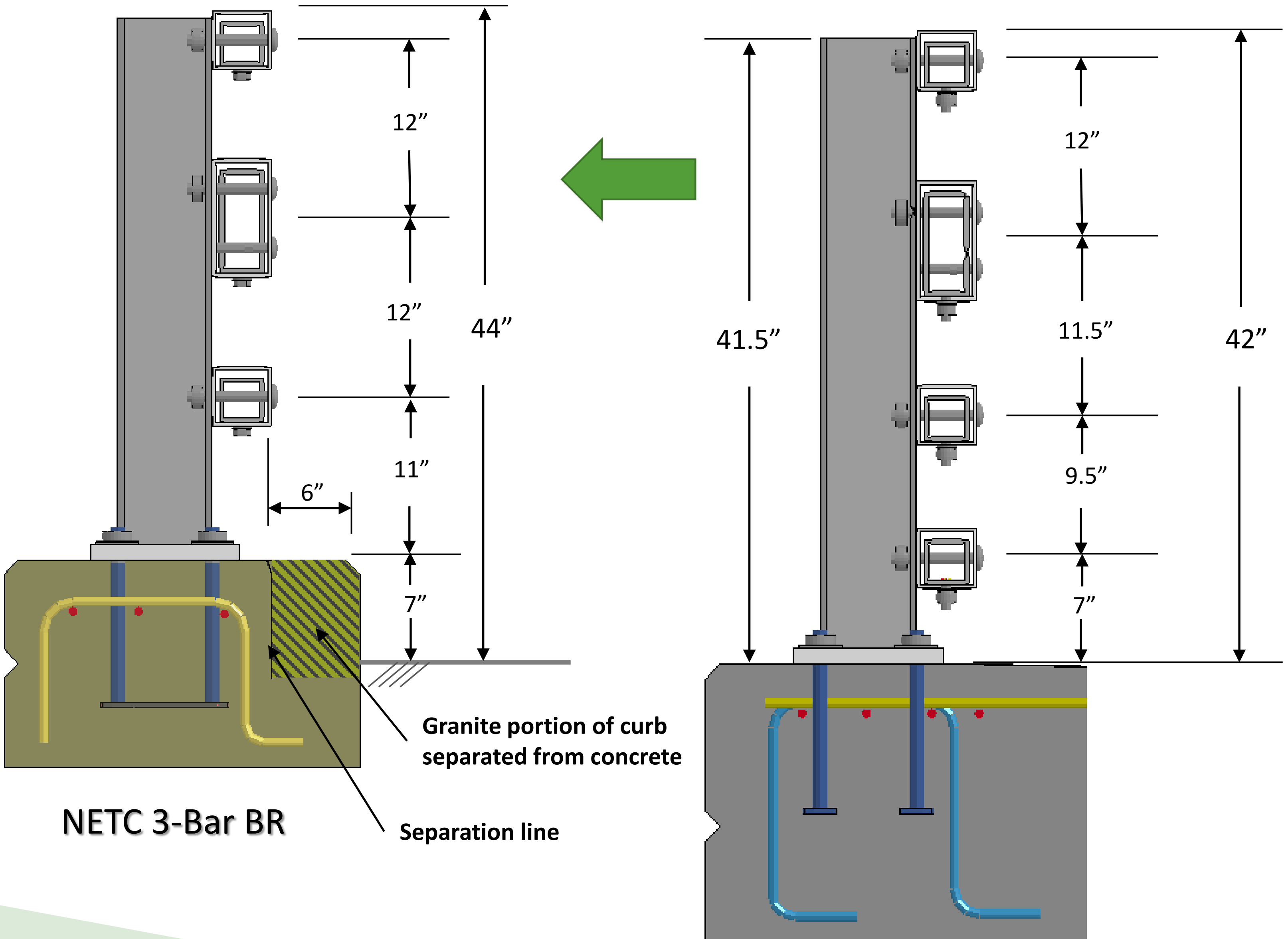
Revisions to Report

- Tests 4-10 and 4-11 were re-evaluated with updated splice and impact conditions.
  - The splice connection was revised to include correct geometry for the cap screws and to include the bushing-spacers for the cap screws.
  - The splice was moved to the opposite side of the post so that the critical impact point for the splice could be achieved without running a "reverse direction" impact.

Task 3 – MASH TL-4 Evaluation of NETC 3-Bar Bridge Rail

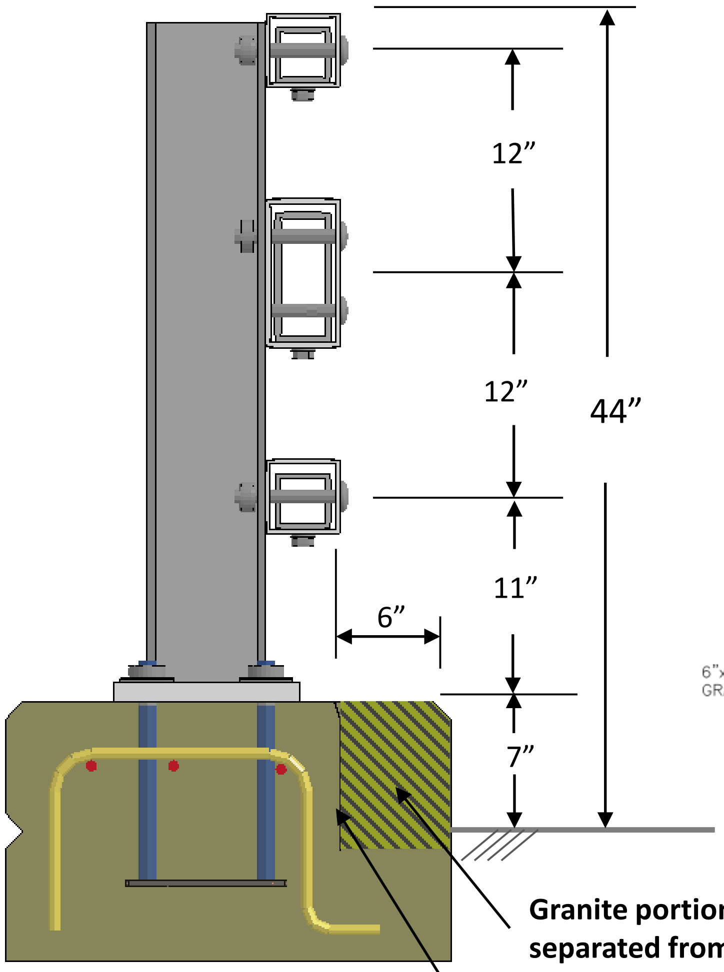
- The finite element model of the NETC 4-Bar system was developed in Task 2.
- That model was used as a baseline for developing the NETC 3-Bar bridge rail.



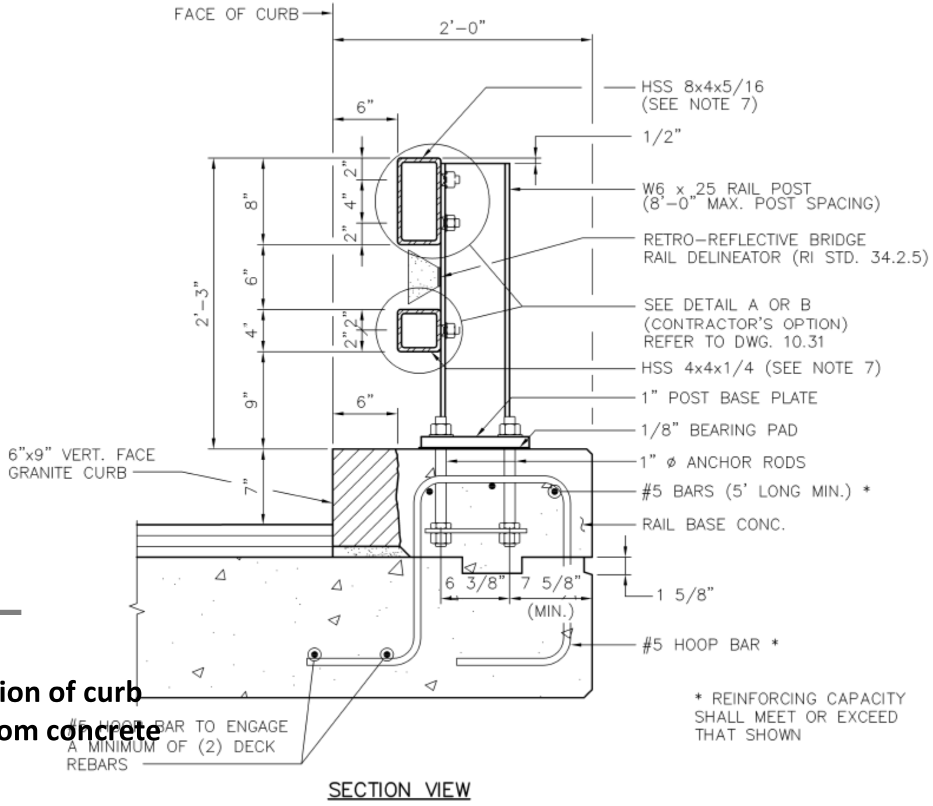
NETC 3-Bar BR

Task 3 – MASH TL-4 Evaluation of NETC 3-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 for developing the NETC 3-Bar bridge rail.
- The curb dimensions and reinforcing was modeled based on the RIDOT drawings.



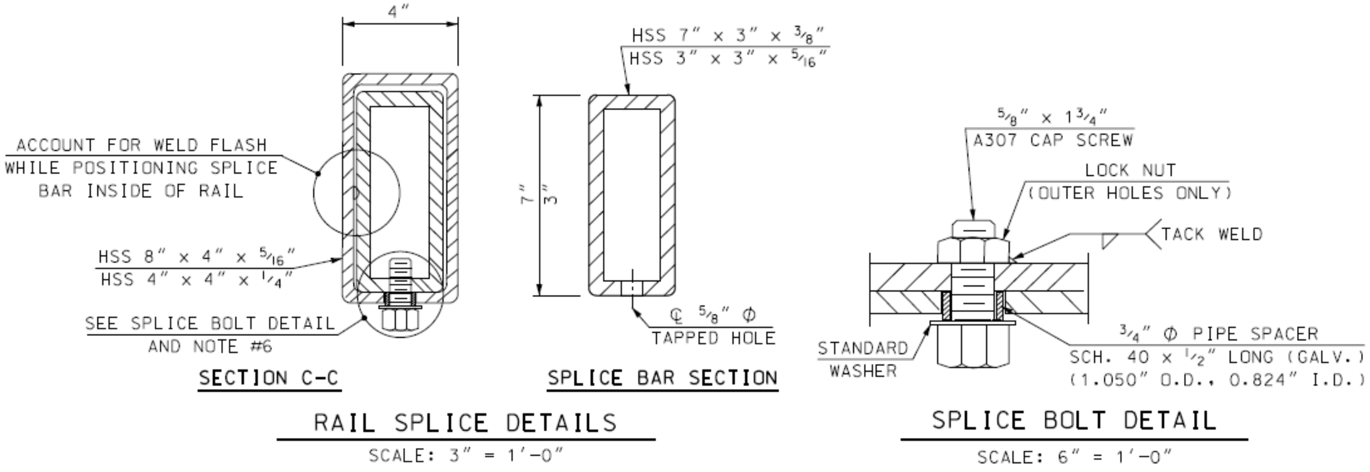
NETC 3-Bar BR

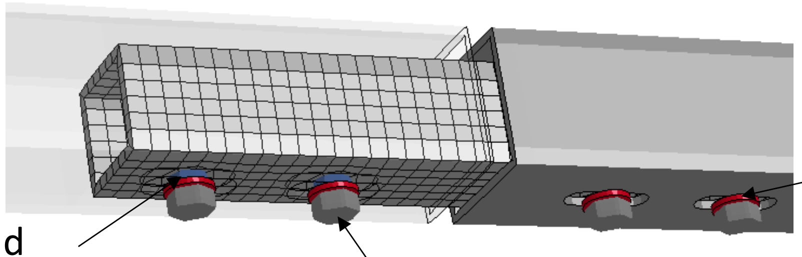


RIDOT Drawing

Splice Model

- The model was updated to include
  - Correct cap-screw dimensions,
  - Bushing-spacers for the cap screws on one side of the splice, and
  - Proper clamping force for the cap screws on the opposite side of the splice.
- The updated model was used for all subsequent *MASH* evaluations of the NETC bridge rails.

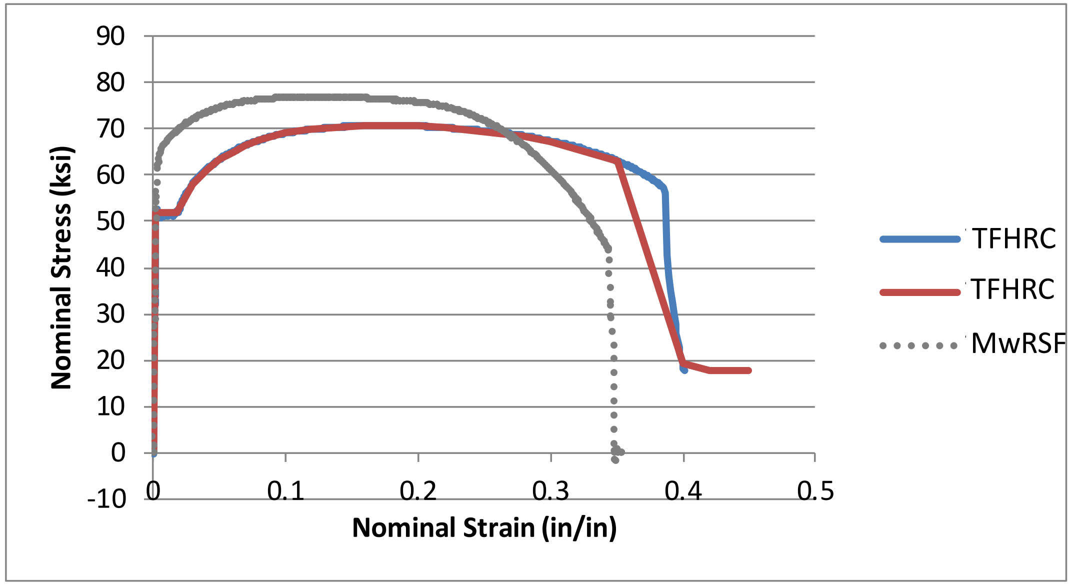




Materials

- **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 <u>**46 ksi**</u> and <u>**58 ksi**</u>, 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 <u>**50.6 ksi**</u> and <u>**70 ksi**</u>**,** 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 <u>**rigid**</u> 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.

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

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

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Evaluation Criteria

<u>Post Impact Vehicle Behavior:</u>

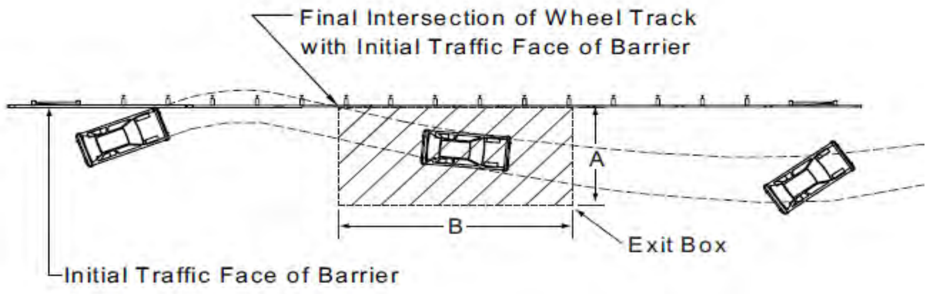
- Although not required by *MASH*, post vehicle trajectory was examined for completeness of the evaluations.
- *MASH* uses the concept of the "exit box" which was adopted directly from CEN standards.
- It is defined by the initial traffic face of the barrier and a line parallel to the initial traffic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



FEA vs. Test MASH Vehicle Models

1100C

Test Vehicle: Kia Rio

2270P

Test Vehicle: Dodge Ram

10000S

Test Vehicle: Varies

FEA Vehicle: 2010 Toyota Yaris

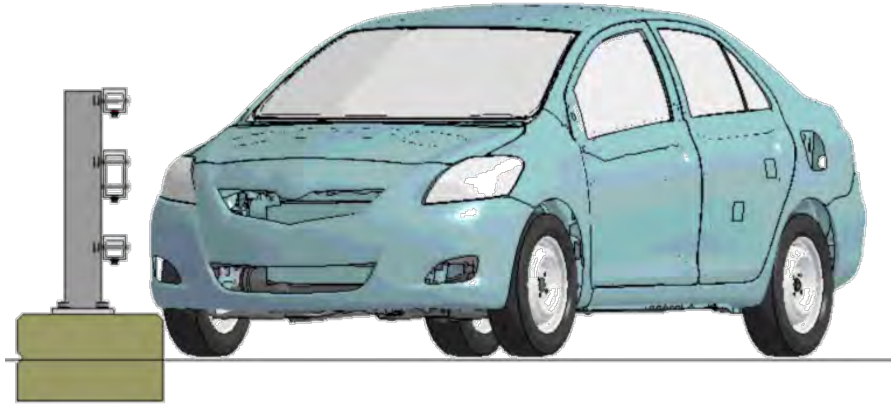
FEA Vehicle: 2007 Chevrolet Silverado

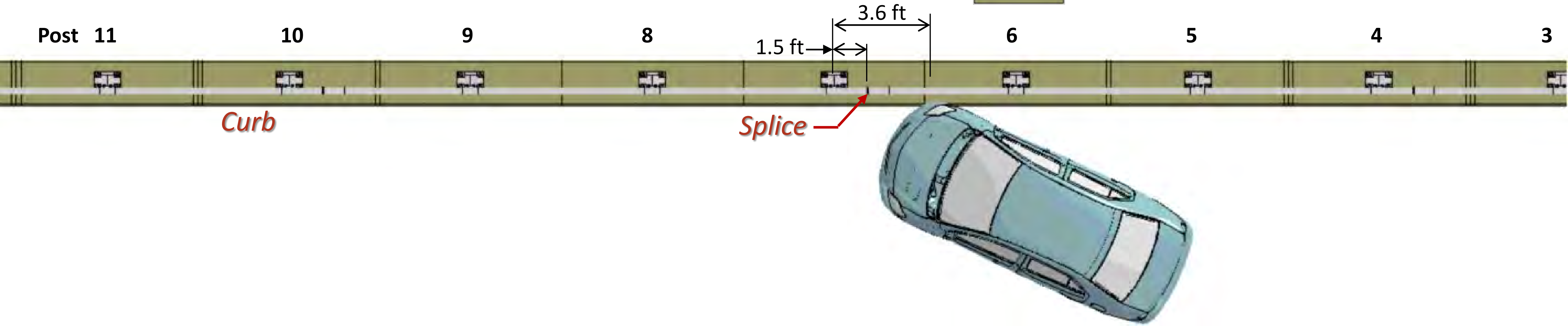
FEA Vehicle: 1996 Ford F800

Analyses included two model versions where … 47.5” (Ford) / 50.0” (GMC)

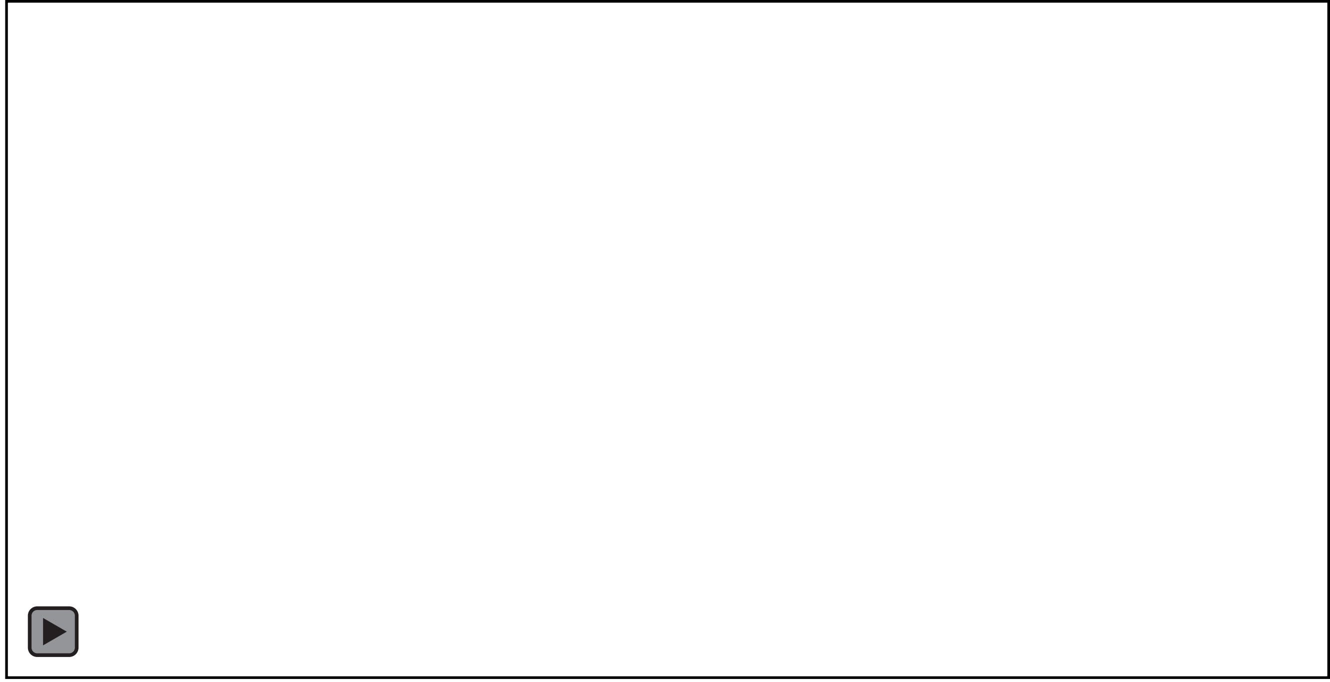
MASH Test 4-10 Simulation on the NETC 3-Bar

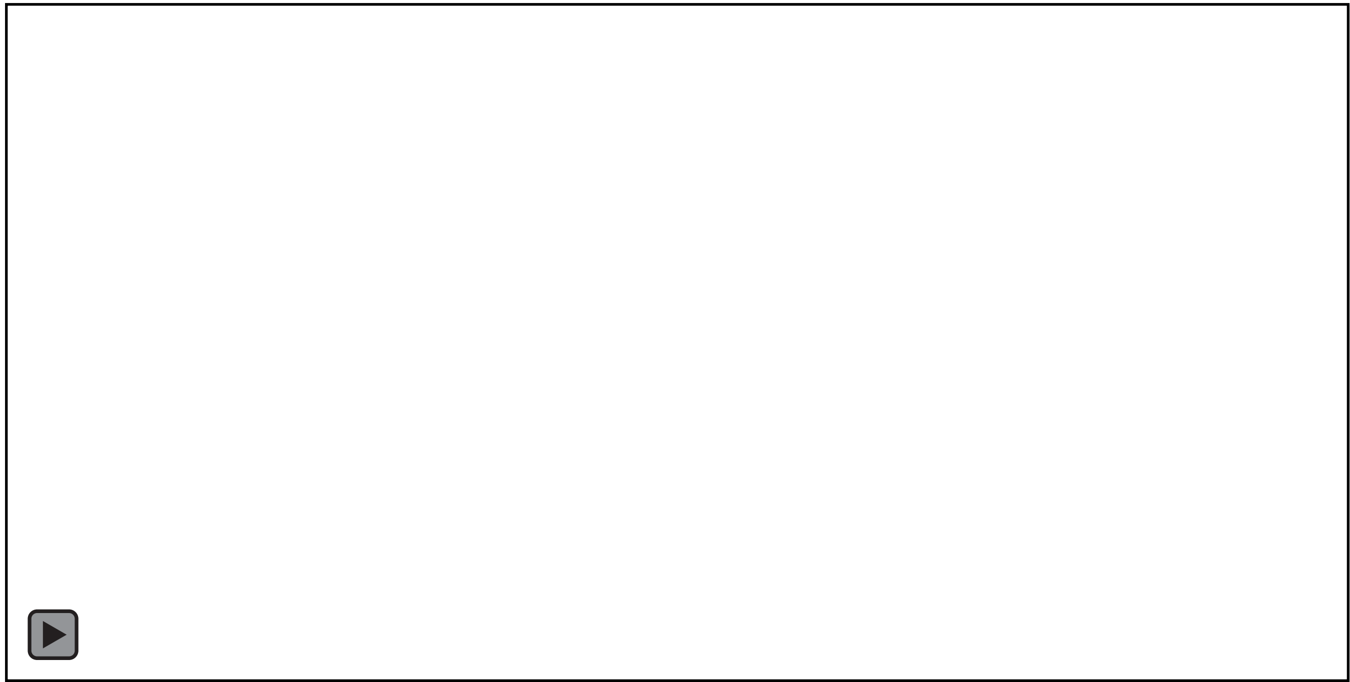
- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point (*MASH 2016 suggested CIP*)
    - IP01 = 3.6 ft upstream from critical Post
    - IP02 = 3.6 ft upstream from splice
- Vehicle Model
  - YarisC_V1l_R160407.k
  - Vehicle Mass = 1,177 kg (2,595 lb)





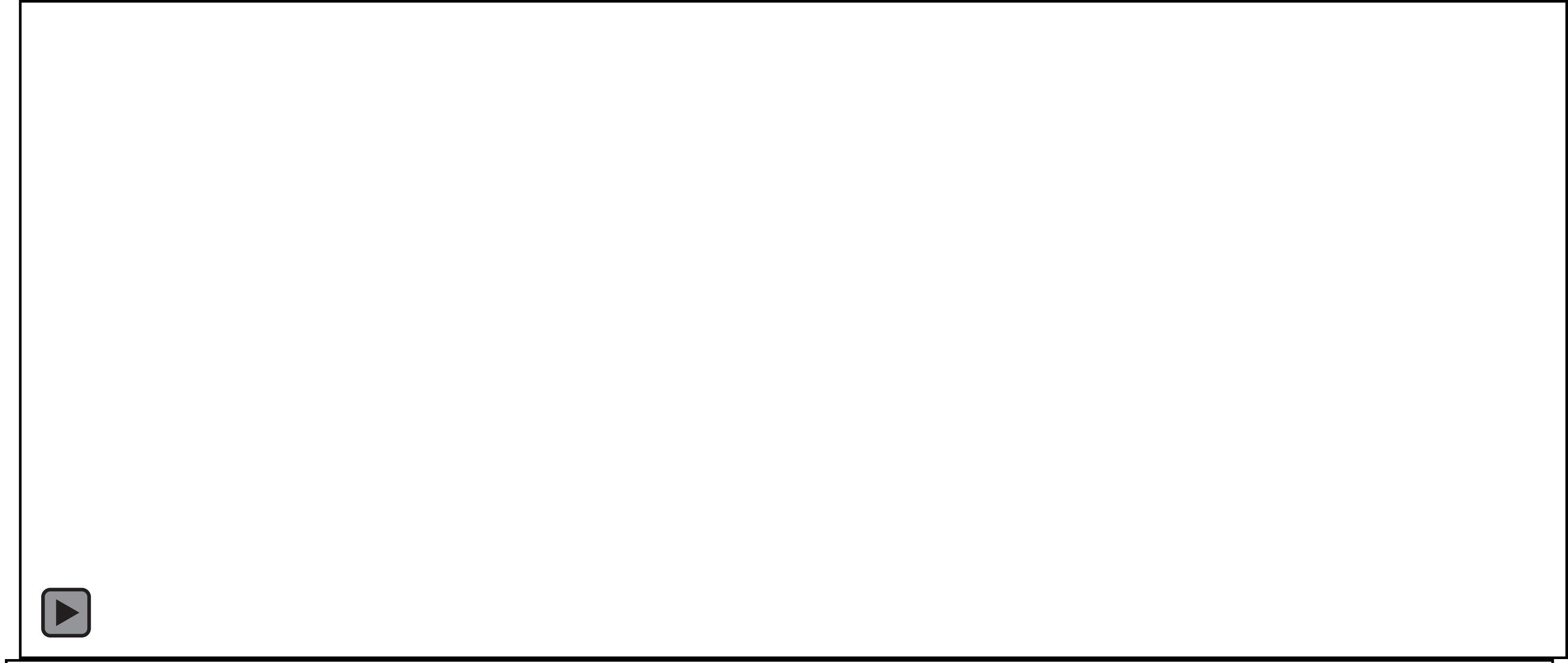
Movies

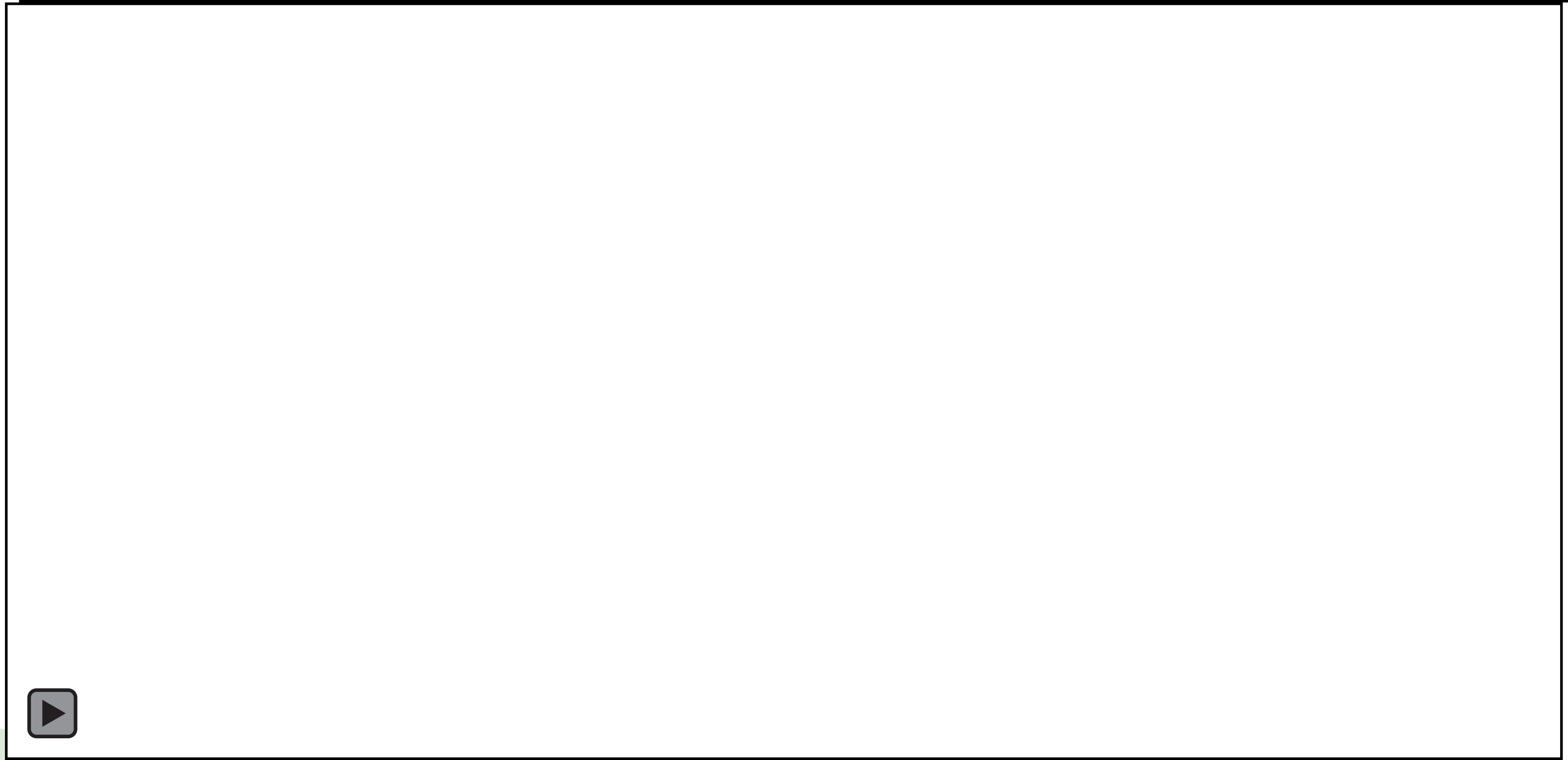




Movies

Windshield Cracked when lower part of A-Pillar / upper part of fender contacted top rail





Movies

Movies

TRAP – Summary Table

Occupant Risk Factors		MASH T4-10 Test 4-10
Occupant Impact Velocity (ft/s)	x-direction	25.6
	y-direction	32.5
	at time	at 0.0792 seconds on right side of interior
THIV (ft/s)		41.3 at 0.0792 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-6.7 (0.0811 - 0.0911 seconds)
	y-direction	-6 (0.2306 - 0.2406 seconds)
PHD (g's)		7.1 (0.0800 - 0.0900 seconds)
ASI		2.49 (0.0253 - 0.0753 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-14.8 (0.0241 - 0.0741 seconds)
	y-direction	-19.6 (0.0262 - 0.0762 seconds)
	z-direction	-3.1 (0.0602 - 0.1102 seconds)
Maximum Angular Disp. (deg)	Roll	7.3 (0.5359 seconds)
	Pitch	-5.2 (0.4892 seconds)
	Yaw	-40.3 (0.4954 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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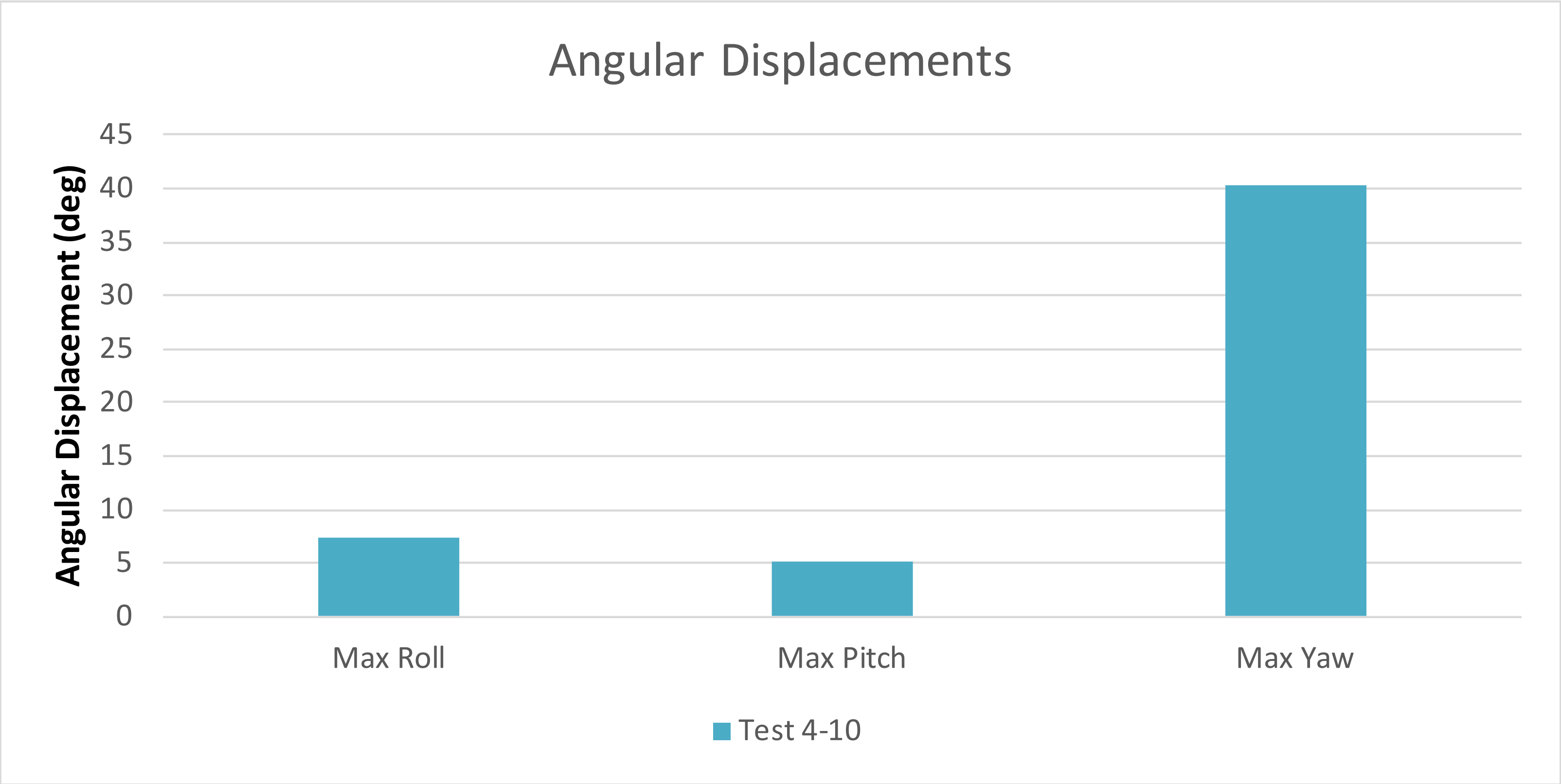
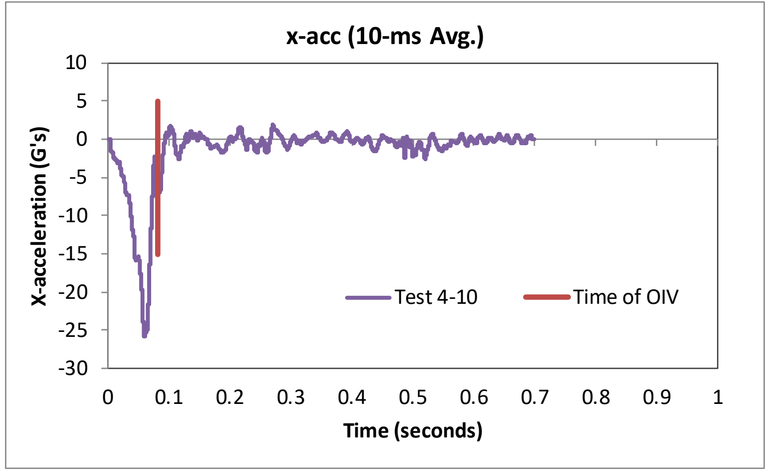
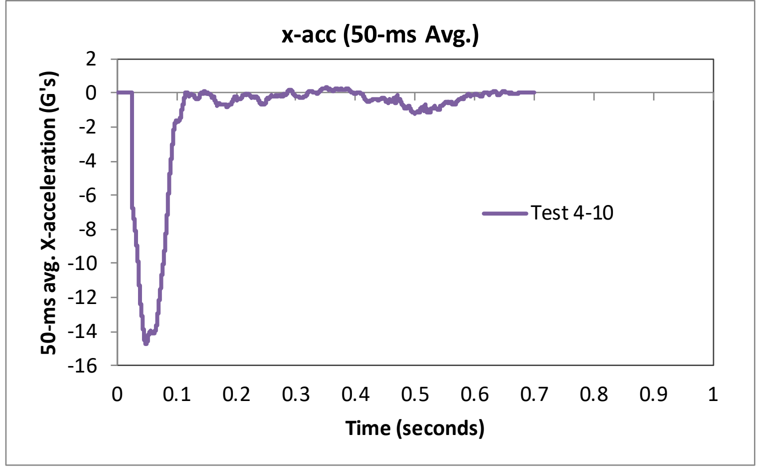
TRAP

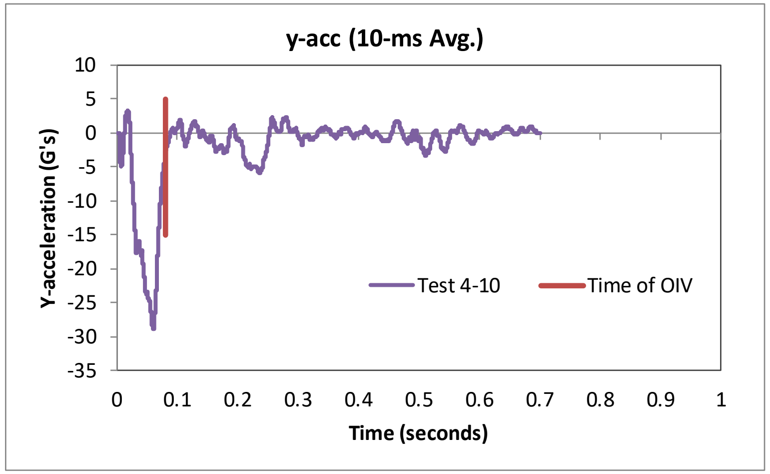


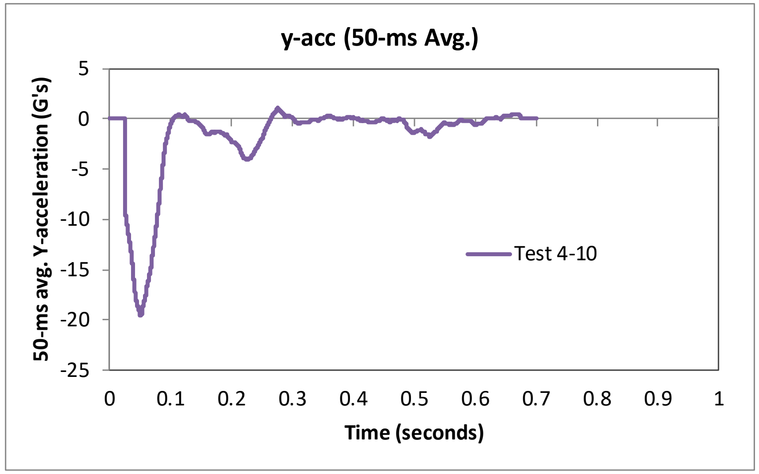
Angular Displacements
Angular Displacement (deg)
45
40
35
30
25
20
15
10
5
0
Max Roll
Max Pitch
Max Yaw
Test 4-10

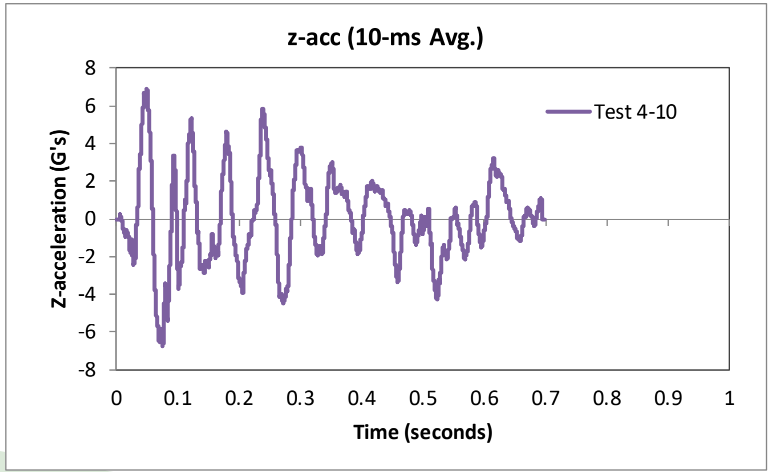
Acceleration Plots

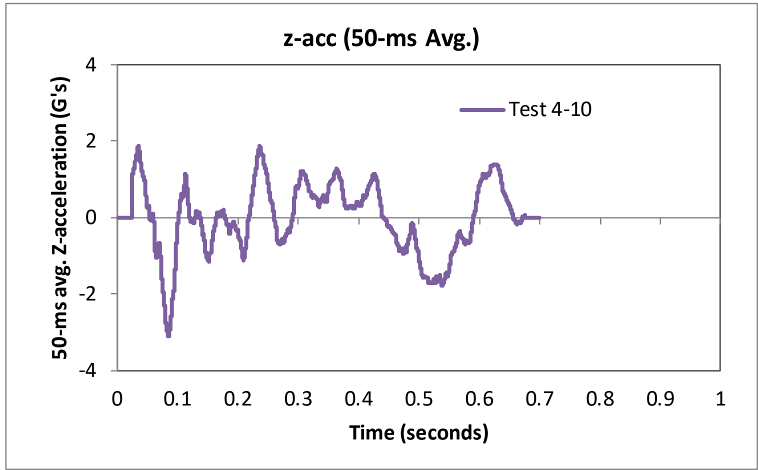




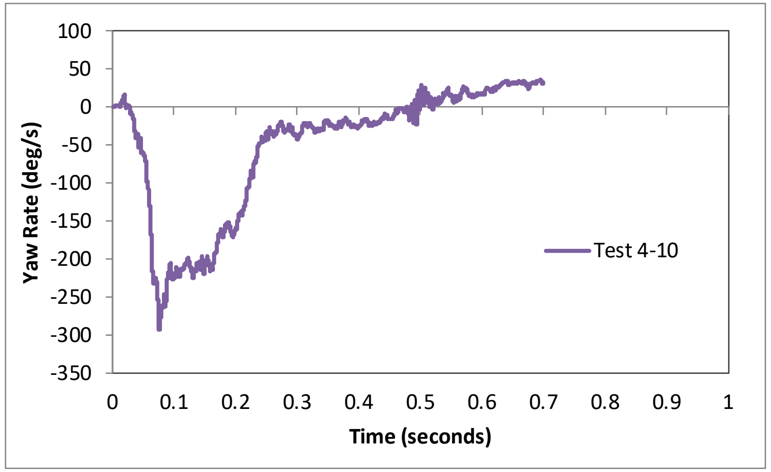


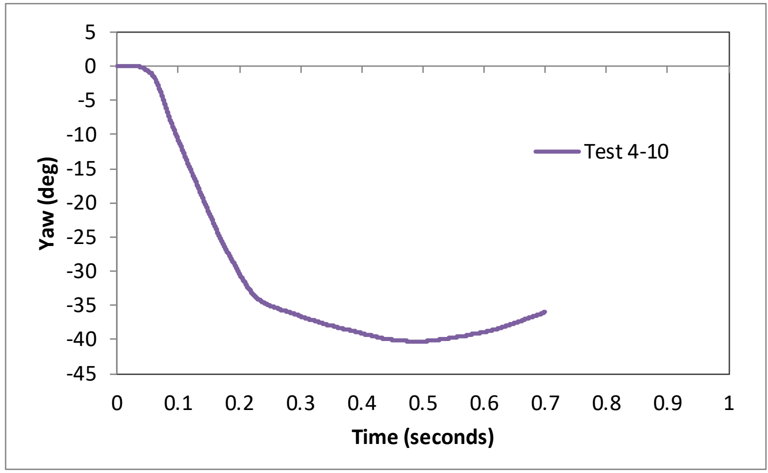


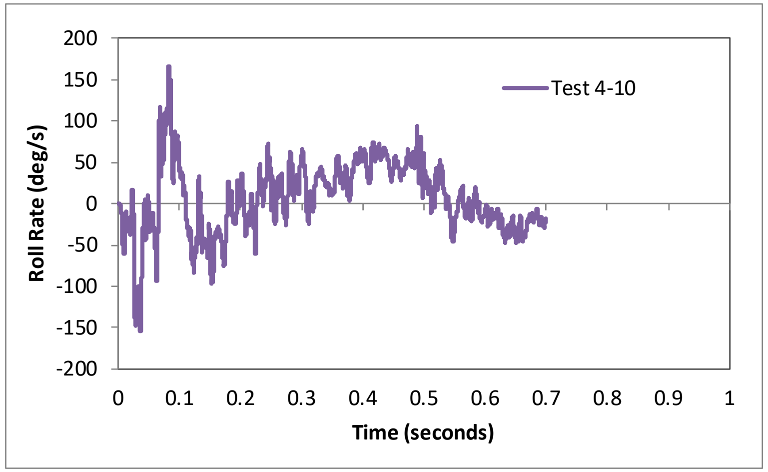


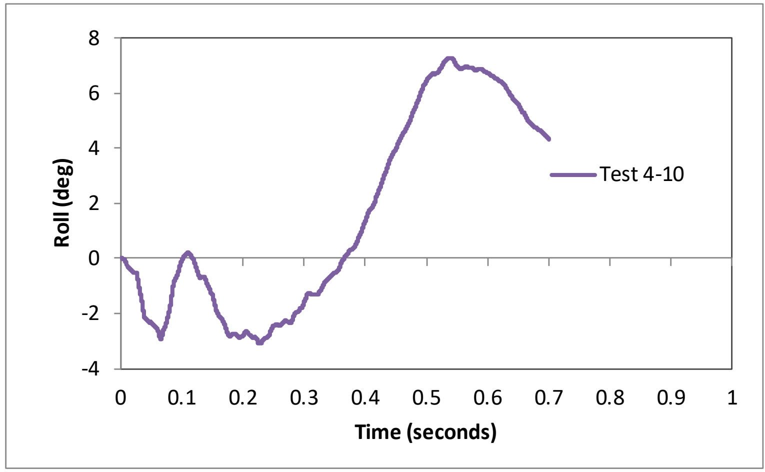


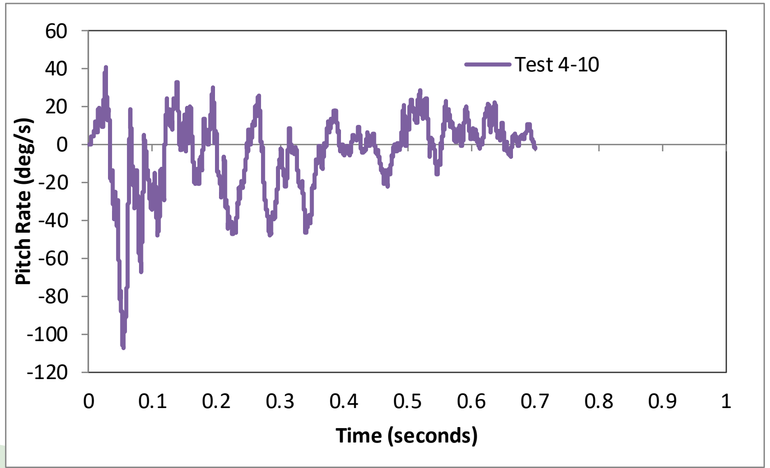
Angular Rate and Displacement Plots

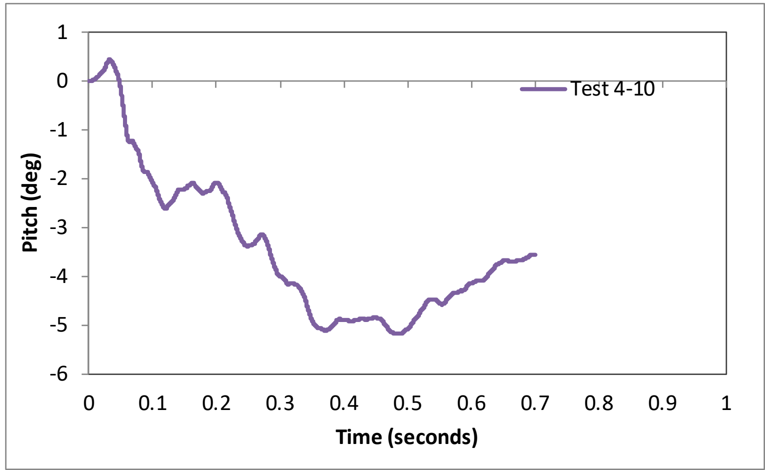




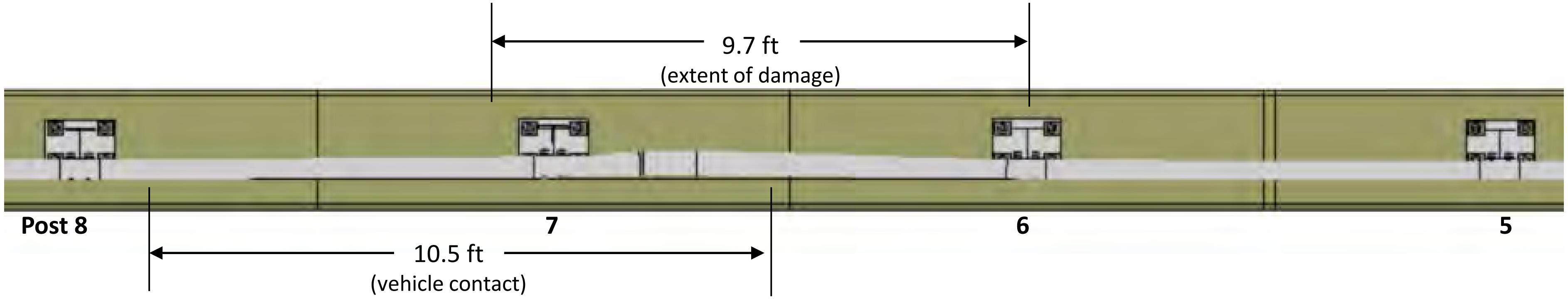






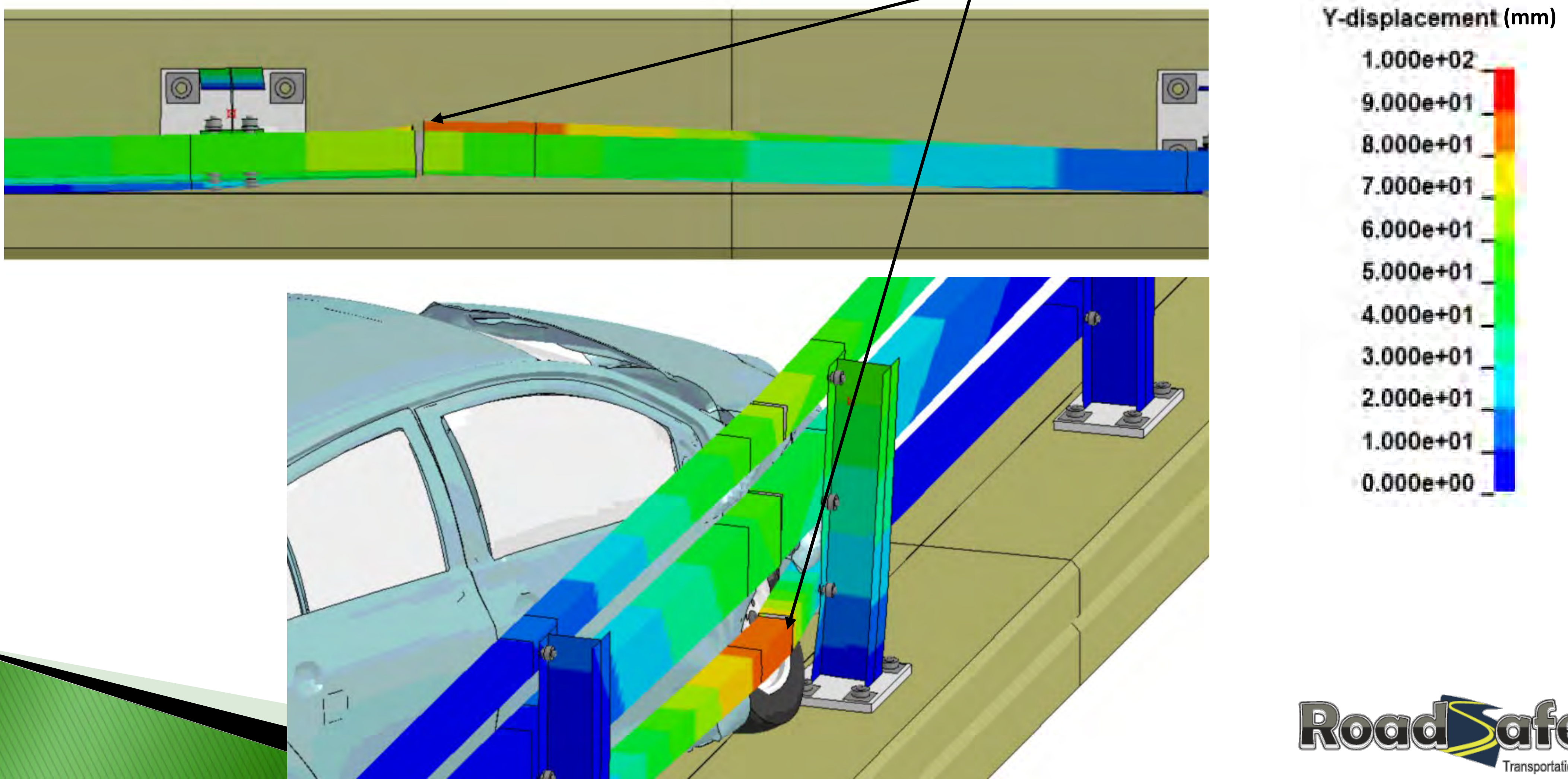


Extent of Damage



Lateral Dynamic Deflection

Maximum dynamic deflection = 3.35 in (85 mm)



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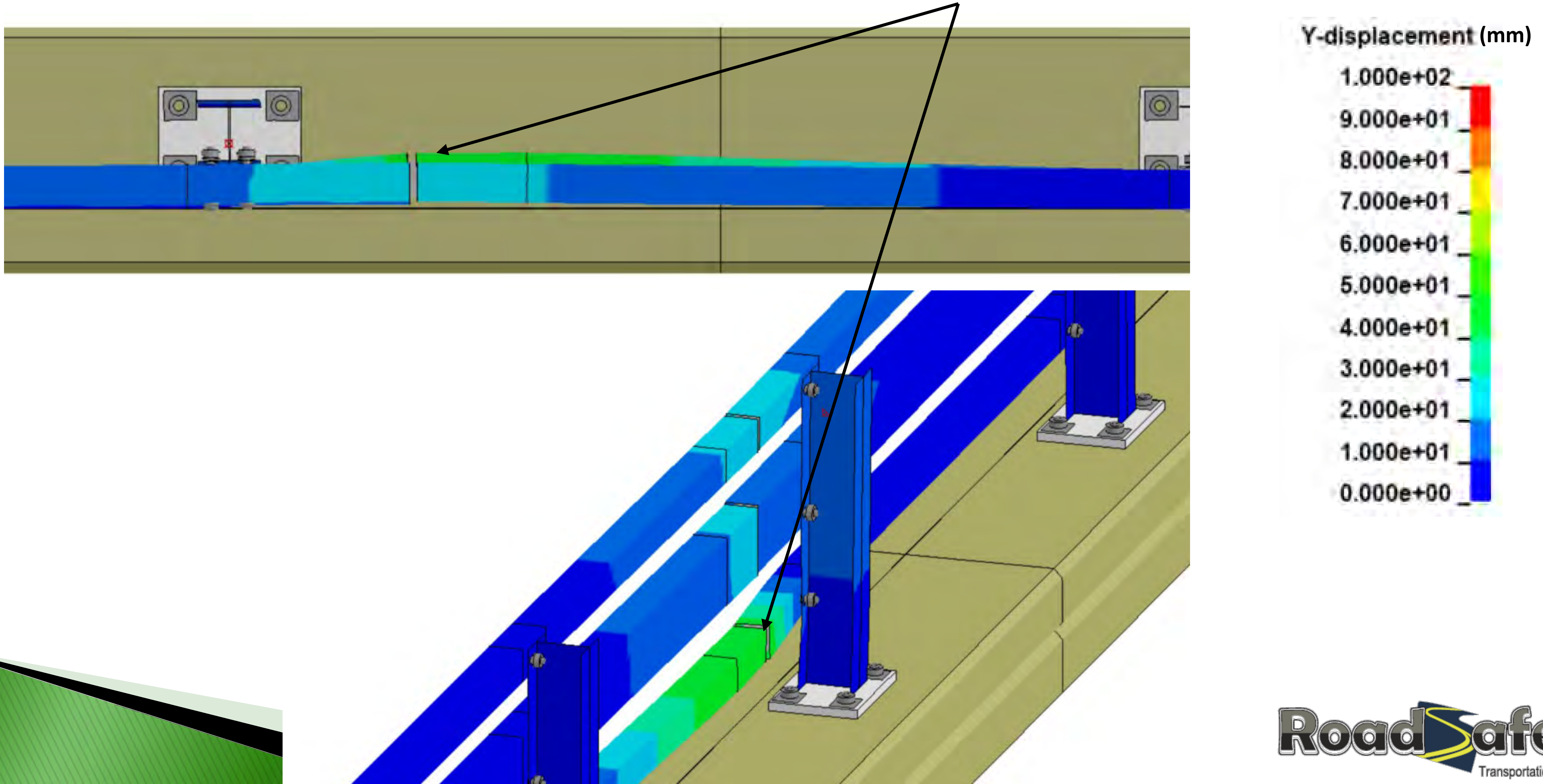
Lateral Permanent Deflection

Maximum permanent deflection = 1.85 in (47 mm)



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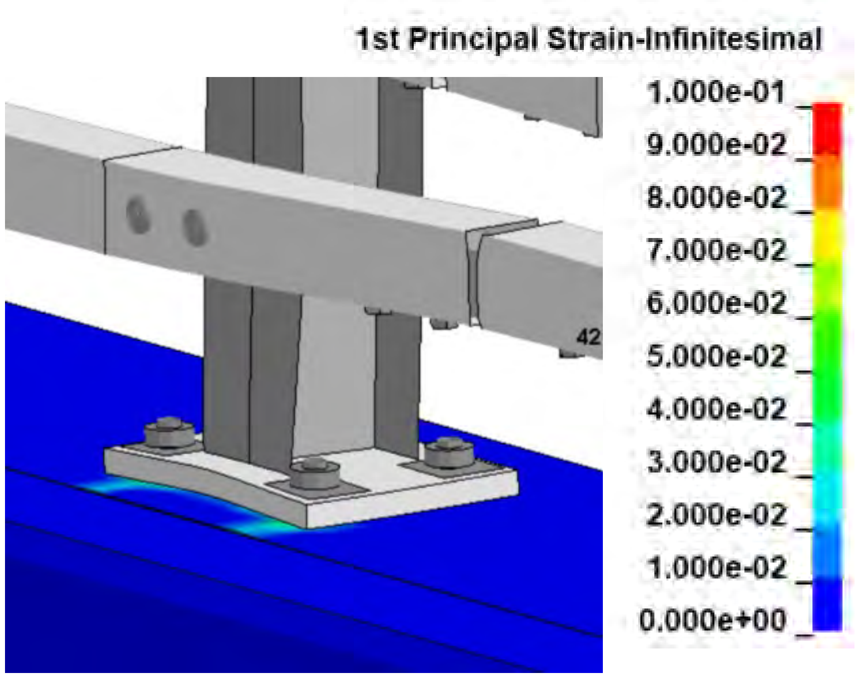
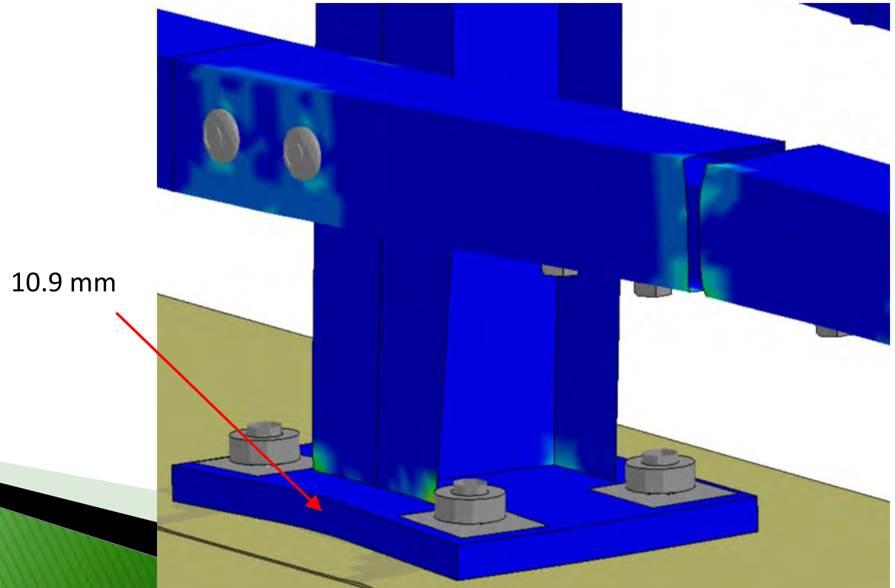
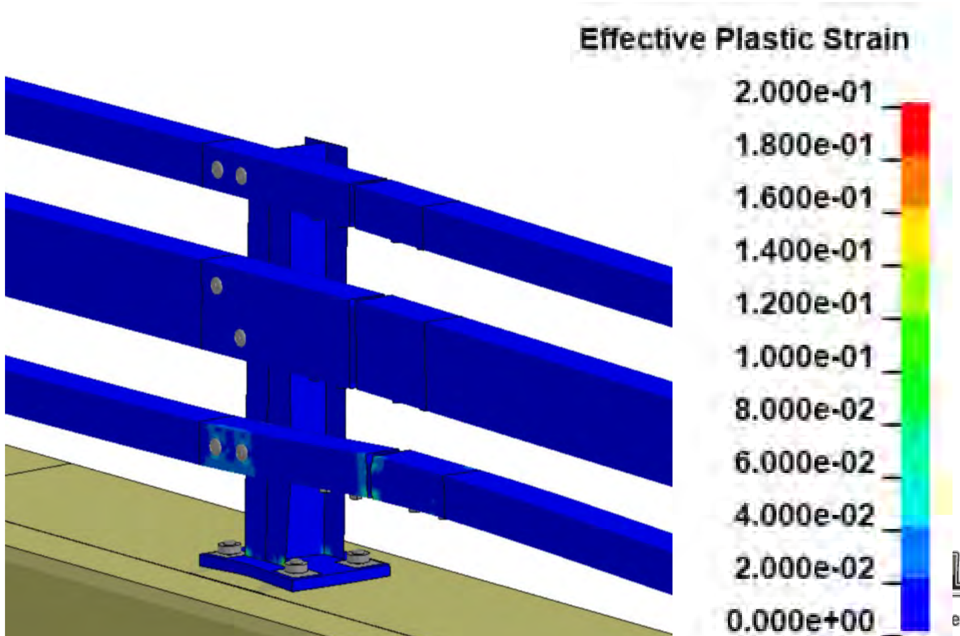
Barrier Damage

- Analysis indicated minimal damage to the concrete curb/deck.
    - Max dynamic 1st Prin. Strain = 0.06
    - Final 1st Prin. Strain = 0.017
- There was low to moderate damage to the post and base plates at the critical post location.
- Vertical deflection of the base plate:
    - Dynamic = 0.429 in (10.9 mm) at 0.06 seconds
    - Permanent = 0.14 in (3.6 mm)
- Moderate damage to the lower rail.

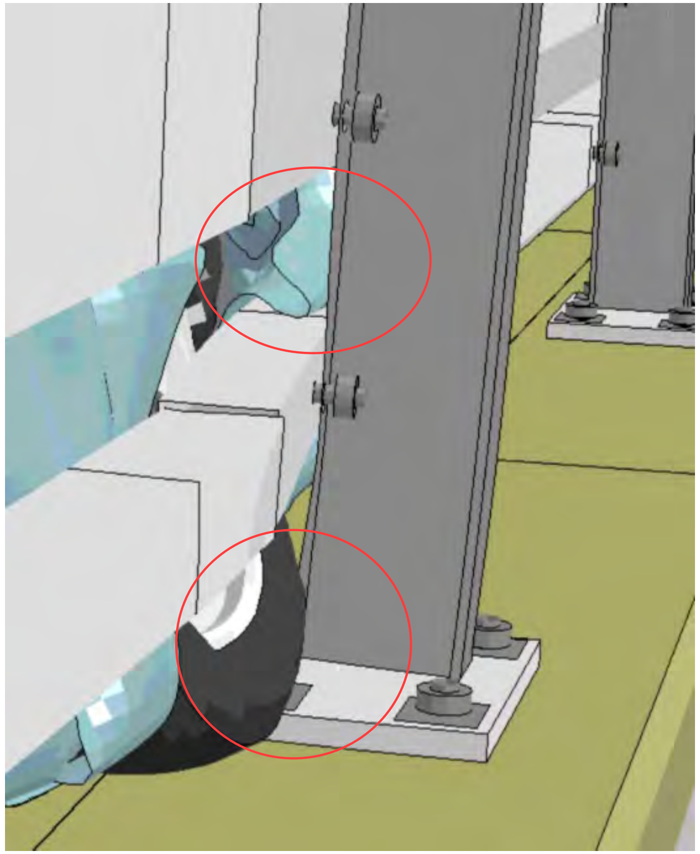






Assessment of Potential Vehicle Contact with Post

- The front fender made slight contact with the post.
- The contact between the front tire and post was more notable.
  - 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, such a snag is considered possible.



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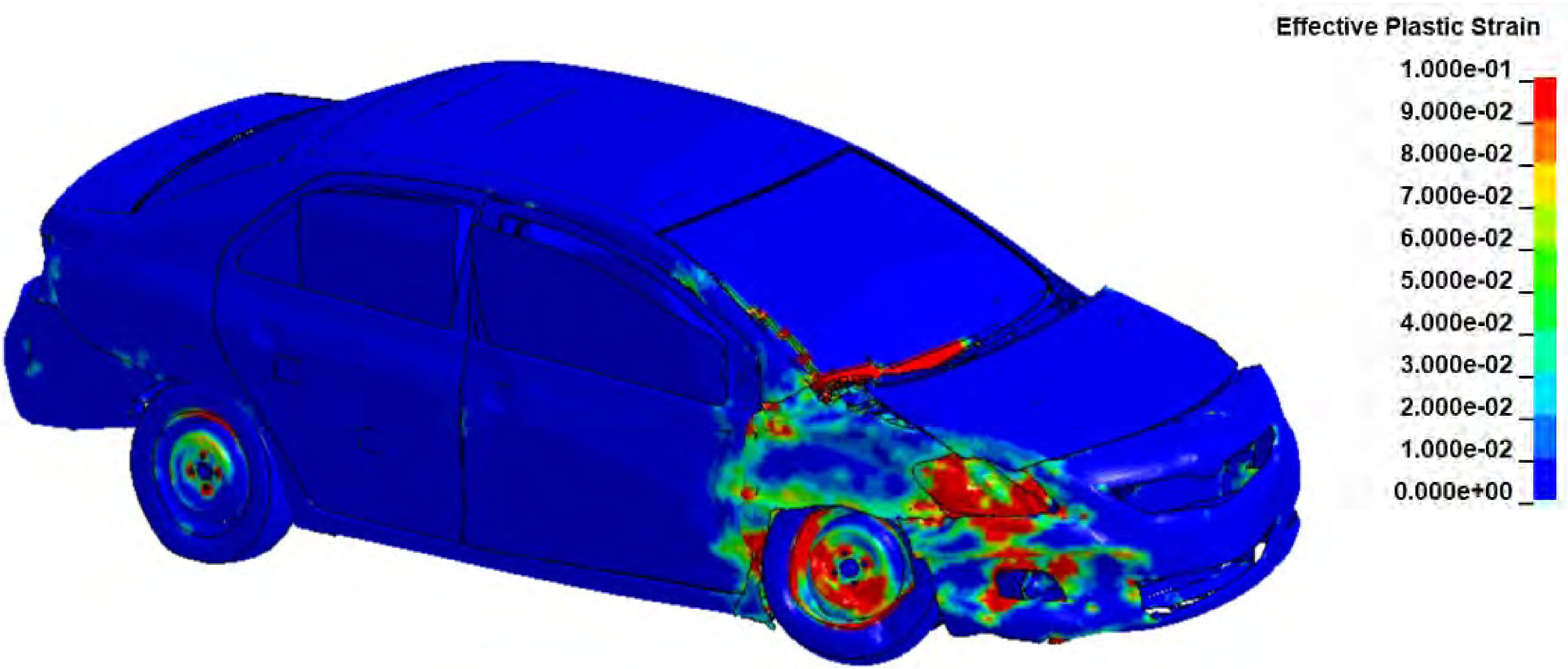
Effective Plastic Strain for Small Car Test



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

Occupant Compartment Intrusion (OCI) Video

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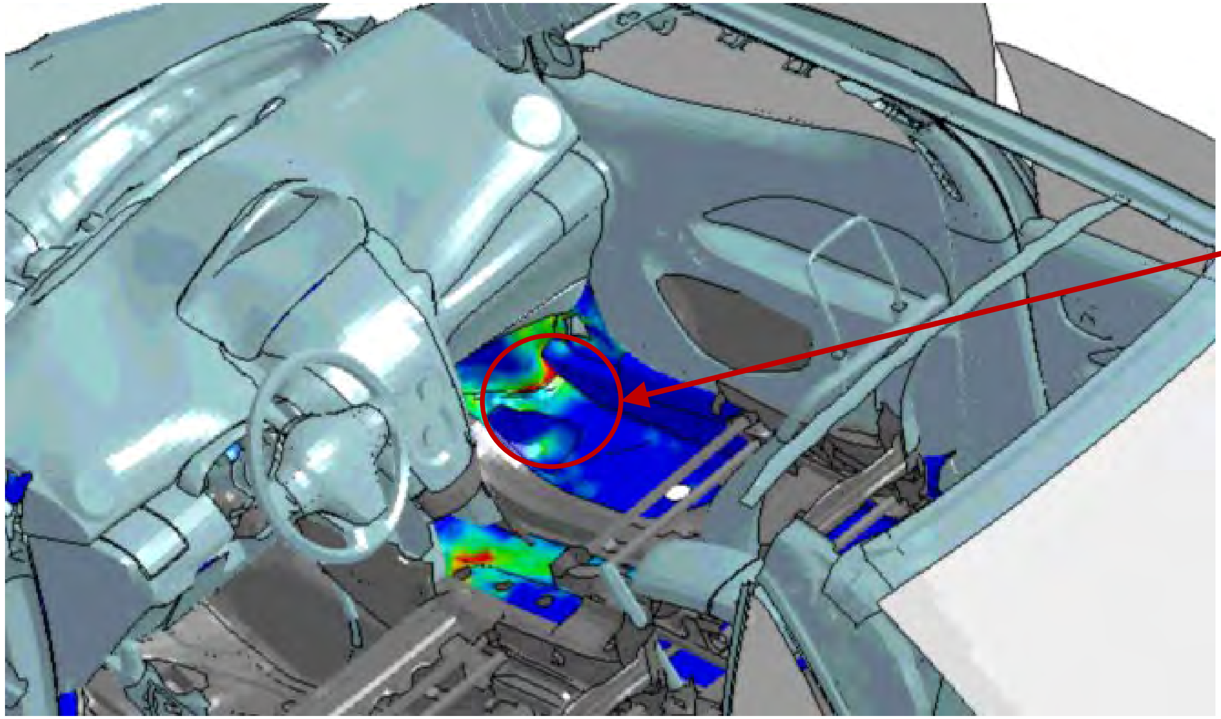
Occupant Compartment Intrusion (OCI)



Maximum OCI of the floor, doors, and side panels was ≈**2.76 inches** (70 mm) and occurred at the right-front toe-pan at the wheel well.

Maximum allowable is 9".

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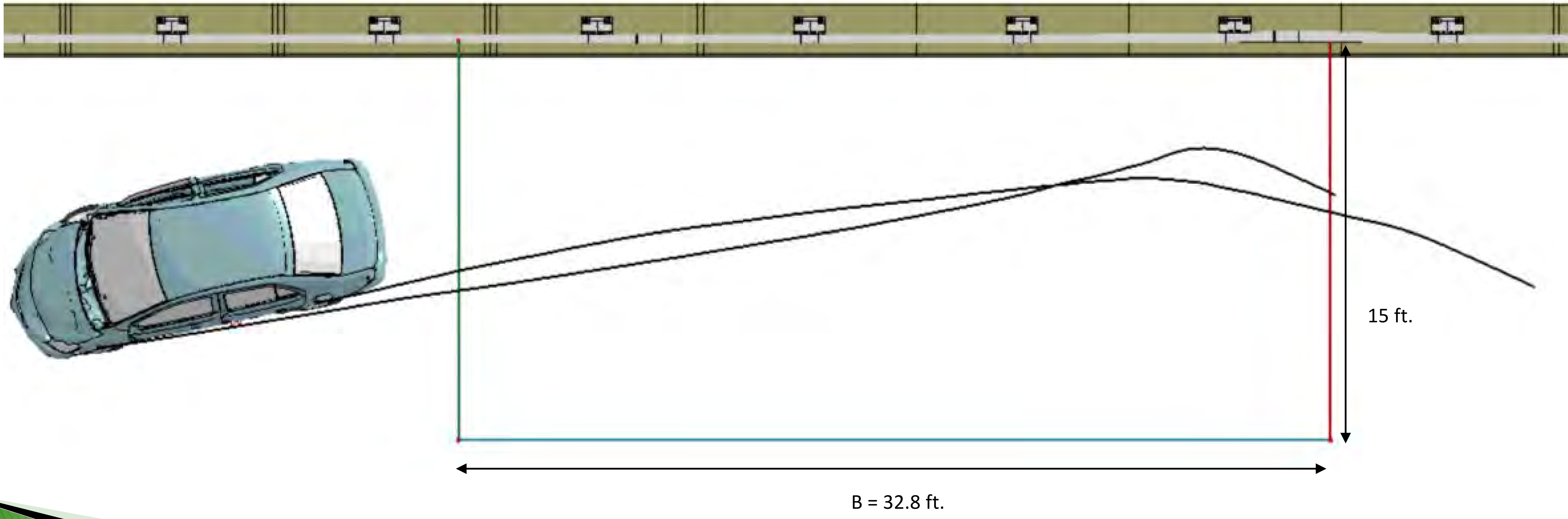
Exit Box – NETC 3-Bar – Test 4-11

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 Regarding Test 4-10 on the NETC 3-Bar

- 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 = **7.3 degrees** and Max Pitch = **5.2 degrees**.
- The OIV was within critical limits and the maximum ORA was within preferred limits specified in MASH.
  - OIV_x = **25.6 ft/s** and OIV_y = **32.5 ft/s**
  - ORA_x = **6.7 G** and ORA_y = **6.0 G** (*values strongly dependent on time of occupant impact*)
- The maximum **occupant compartment deformation** was approximately **2.76 inches** and occurred at the lower right-front toe pan. This value is well within acceptable limit of 9 inches.
- The **windshield cracked** during contact between the A-Pillar and top railing.
- The side windows on the passenger side failed, but the failure was not due to direct impact from the railing on the glass. Thus the **head-slap criteria passed**.
- 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.
- The greatest deformation of the barrier was:
  - Max Dynamic = **3.35 inches**; Max Permanent = **1.85 inches**

Conclusions on Test 4-10 on the NETC 3-Bar

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

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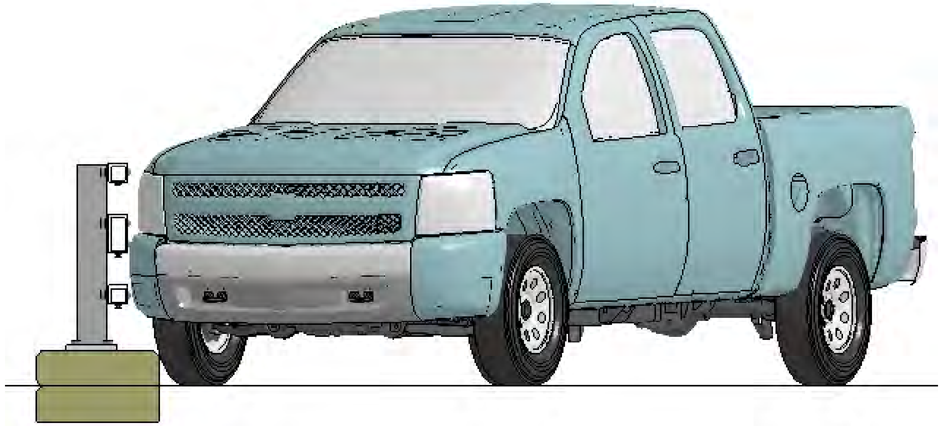
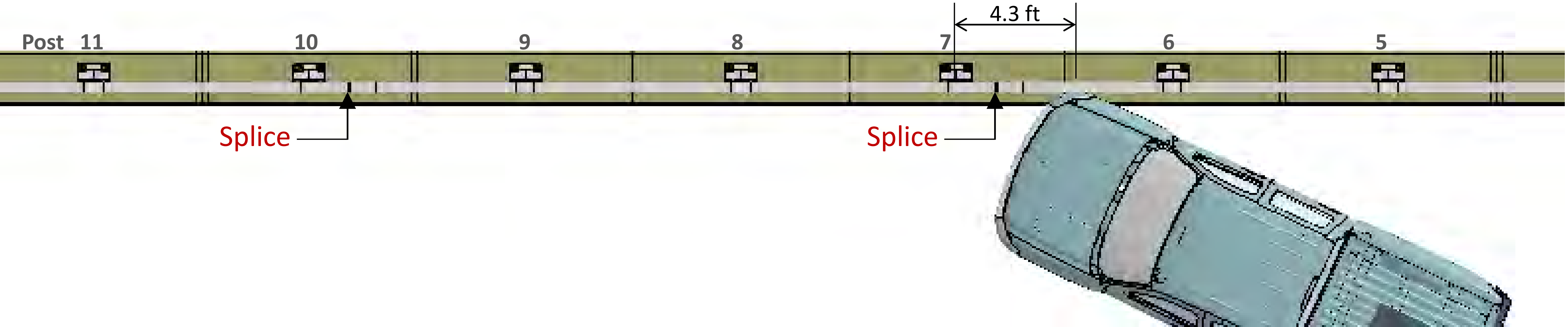
MASH Test 4-11 Simulation on the NETC 3-Bar

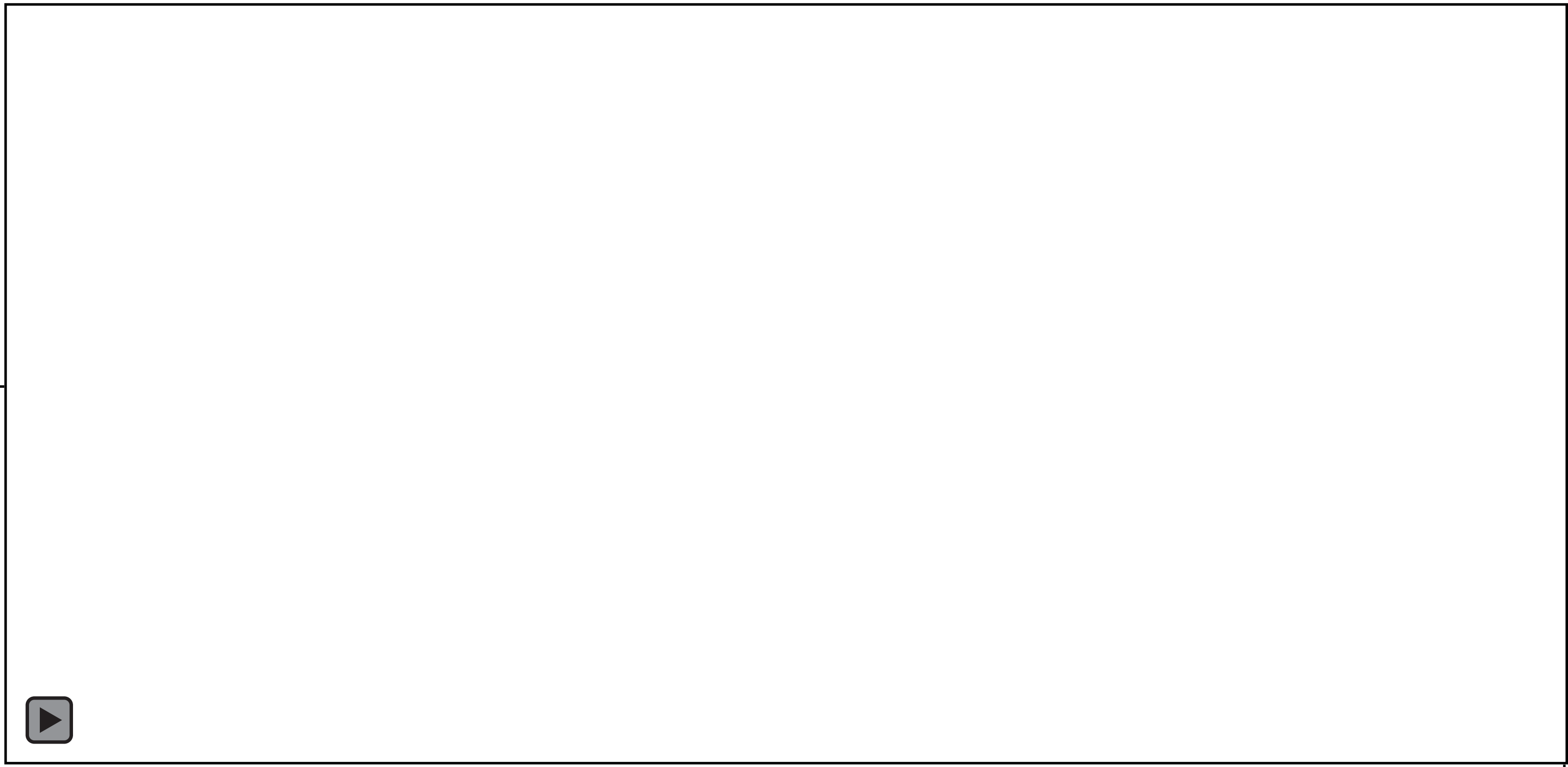
- Impact Conditions
  - Impact Speed = 62.1 mph (100 km/hr)
  - Impact Angle = 25 degrees
  - Impact Point = 4.3 ft upstream from Post 7
    - (*MASH 2016 suggested CIP for rigid barriers)*
- Vehicle Model
  - SilveradoC_V3a_V180201_TireRS_35psi.k
  - Vehicle Mass = 2,268 kg (5,001 lb)

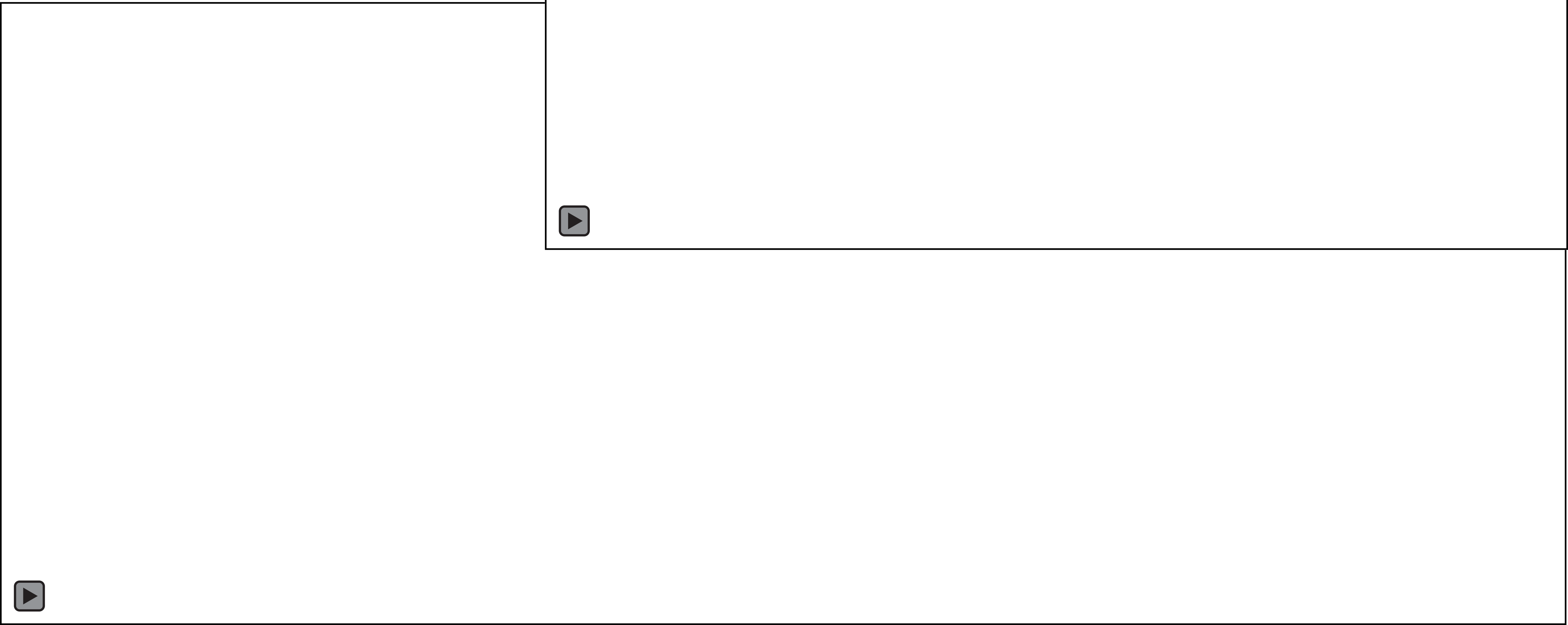




Movies

Movies





Movies

Movies

TRAP – Summary Table

Occupant Risk Factors		MASH Test 4-11
Occupant Impact Velocity (ft/s)	x-direction	22.0
	y-direction	26.6
	at time	at 0.0912 seconds on right side of interior
THIV (ft/s)		34.1 at 0.0884 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-4.7 (0.0945 - 0.1045 seconds)
	y-direction	-15.4 (0.2019 - 0.2119 seconds)
PHD (g's)		15.4 (0.2018 - 0.2118 seconds)
ASI		1.6 (0.0389 - 0.0889 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-10.5 (0.0381 - 0.0881 seconds)
	y-direction	-12 (0.0392 - 0.0892 seconds)
	z-direction	2.6 (0.1245 - 0.1745 seconds)
Maximum Angular Disp. (deg)	Roll	9.9 (0.6491 seconds)
	Pitch	-7.5 (0.4551 seconds)
	Yaw	-29.7 (0.2255 seconds)

MASH Criteria

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

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

< 75 deg ✓

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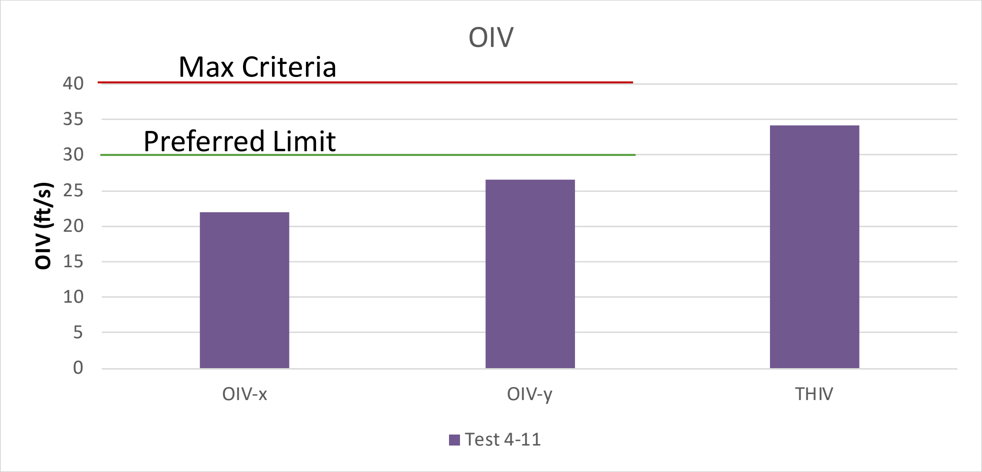
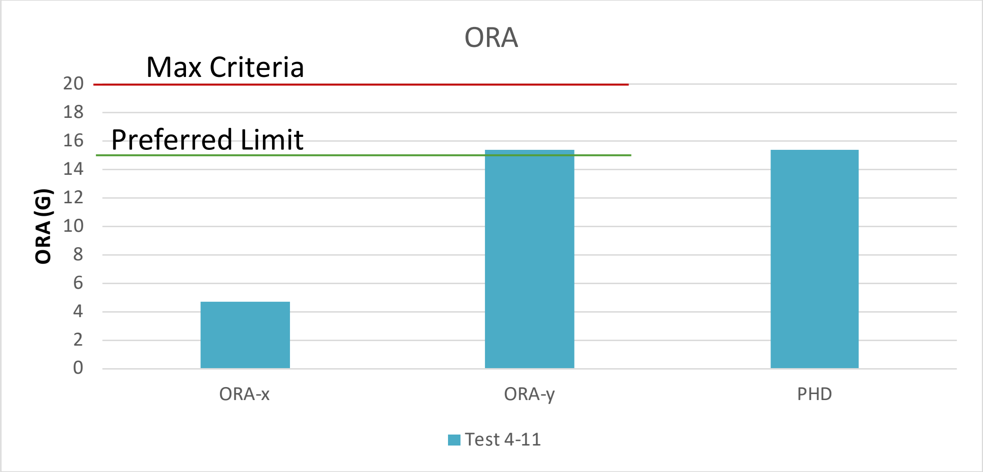
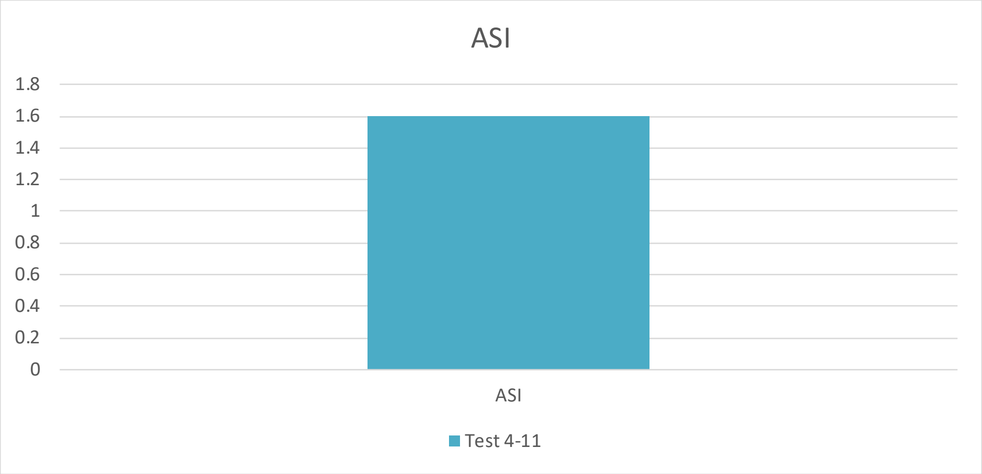
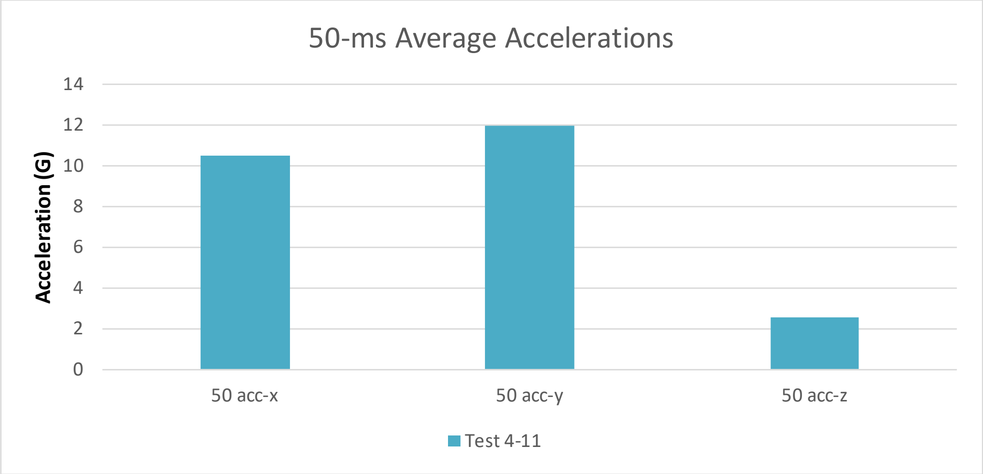
TRAP









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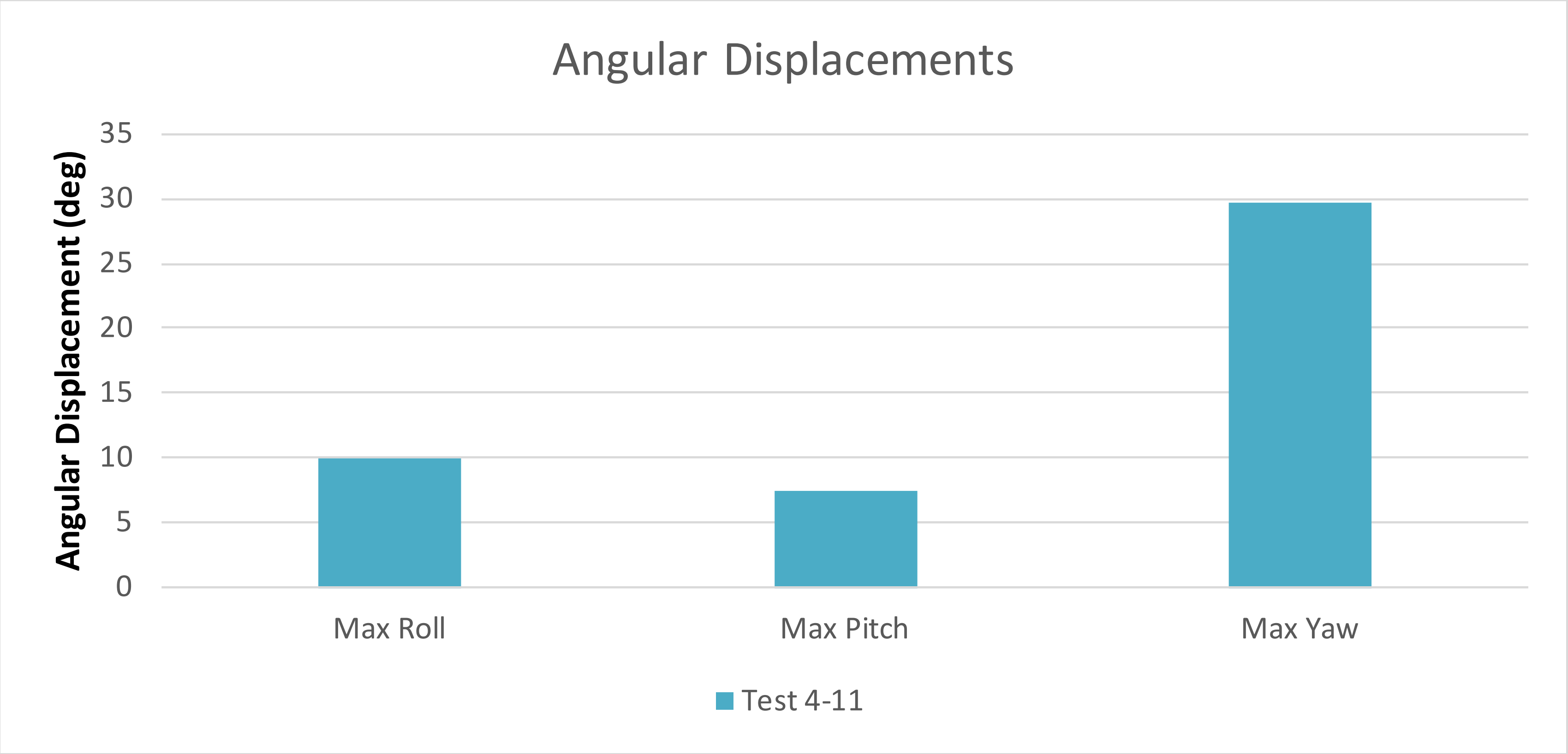
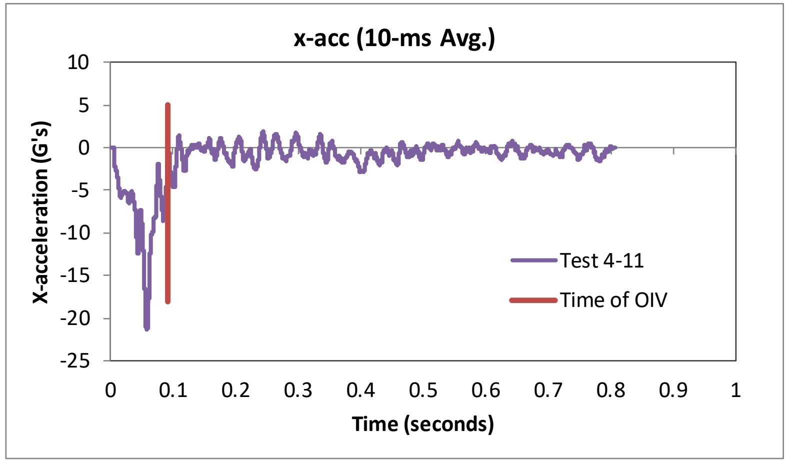
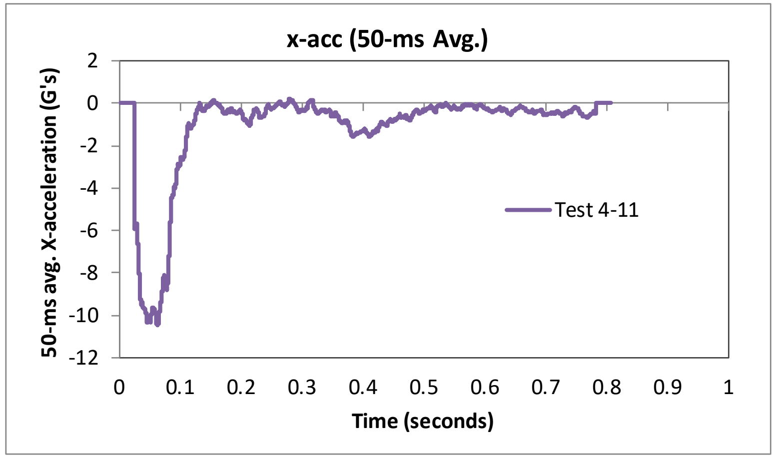
TRAP

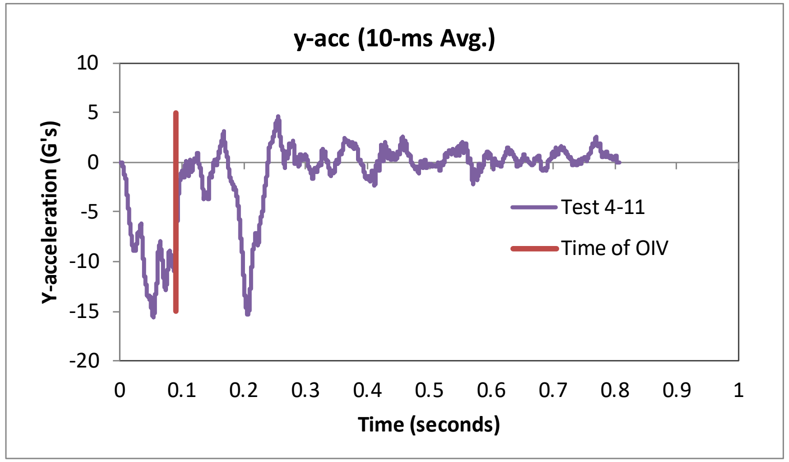


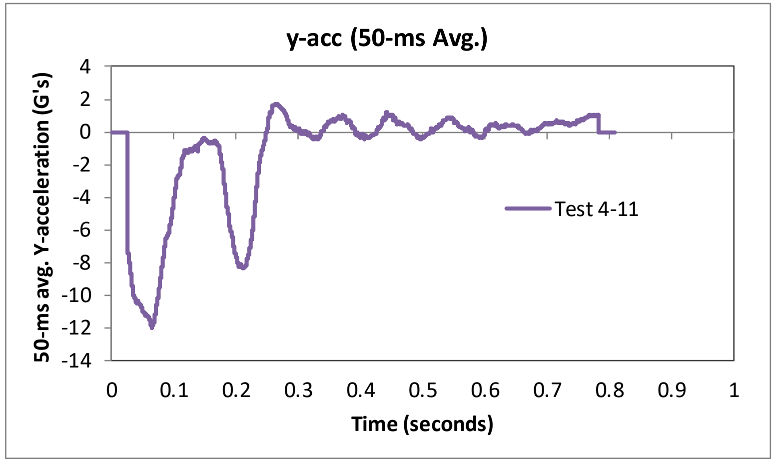
Angular Displacements
Angular Displacement (deg)
35
30
25
20
15
10
5
0
Max Roll
Max Pitch
Max Yaw
Test 4-11

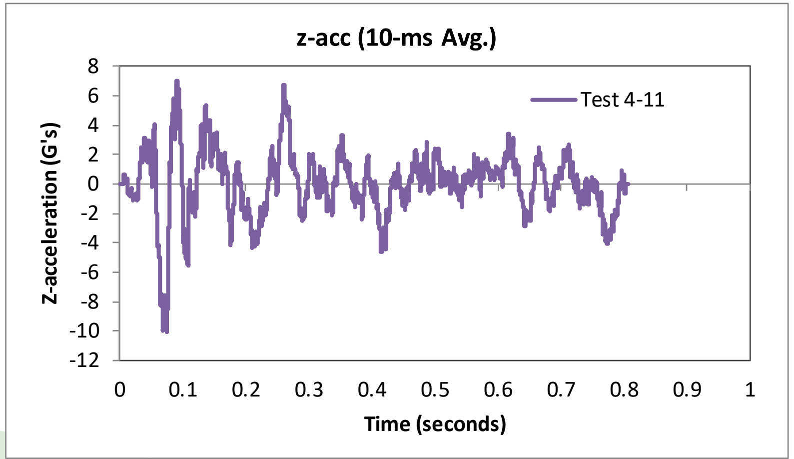
Acceleration Plots

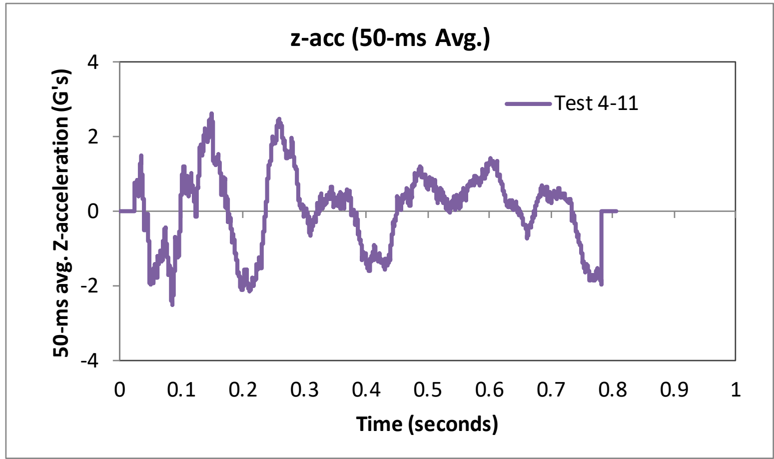




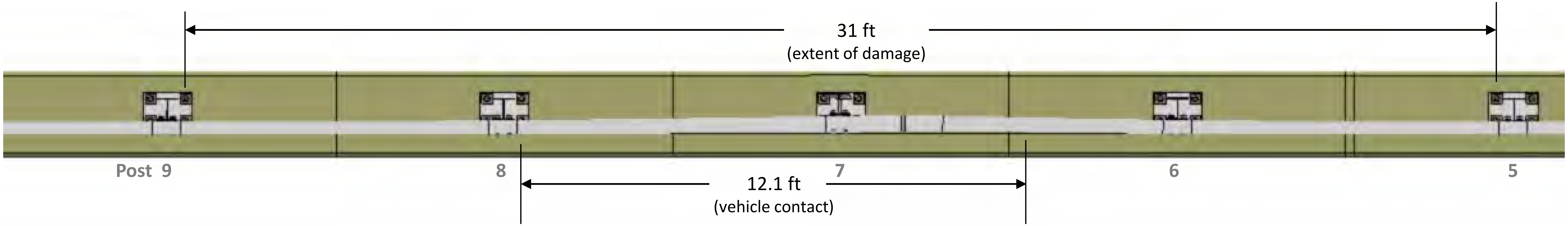






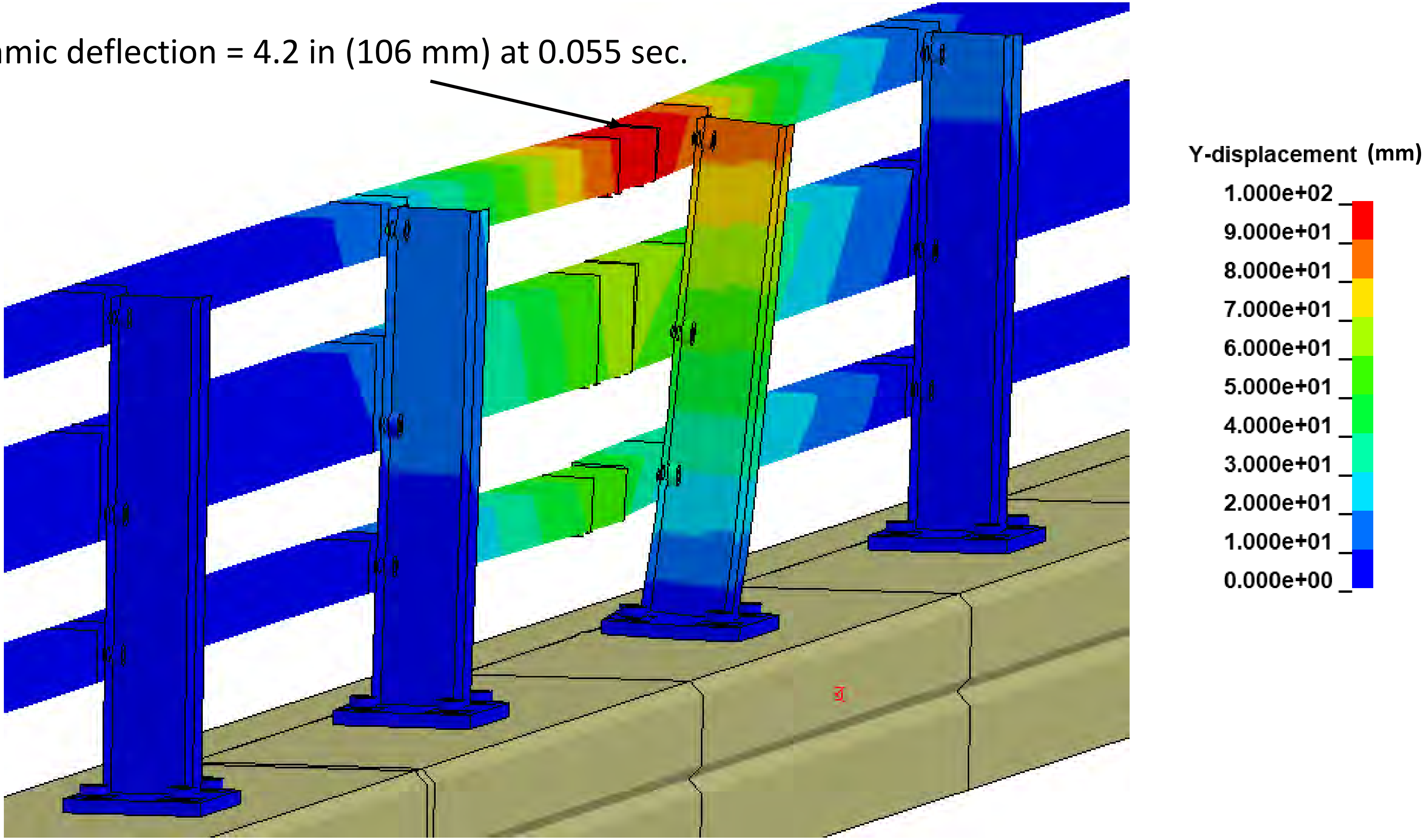


Extent of Damage



Lateral Dynamic Deflection

Maximum dynamic deflection = 4.2 in (106 mm) at 0.055 sec.



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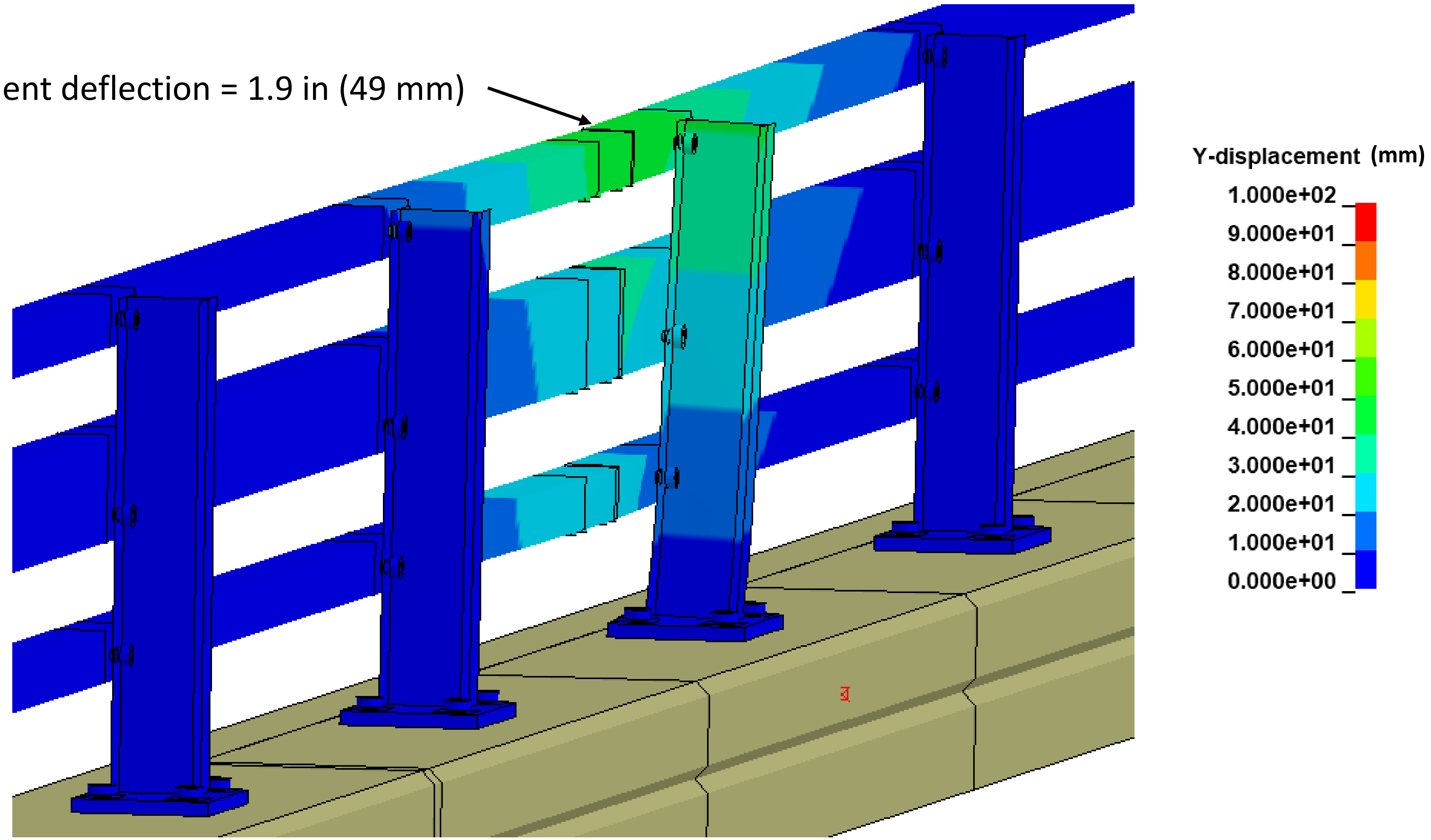
Lateral Permanent Deflection

Maximum permanent deflection = 1.9 in (49 mm)



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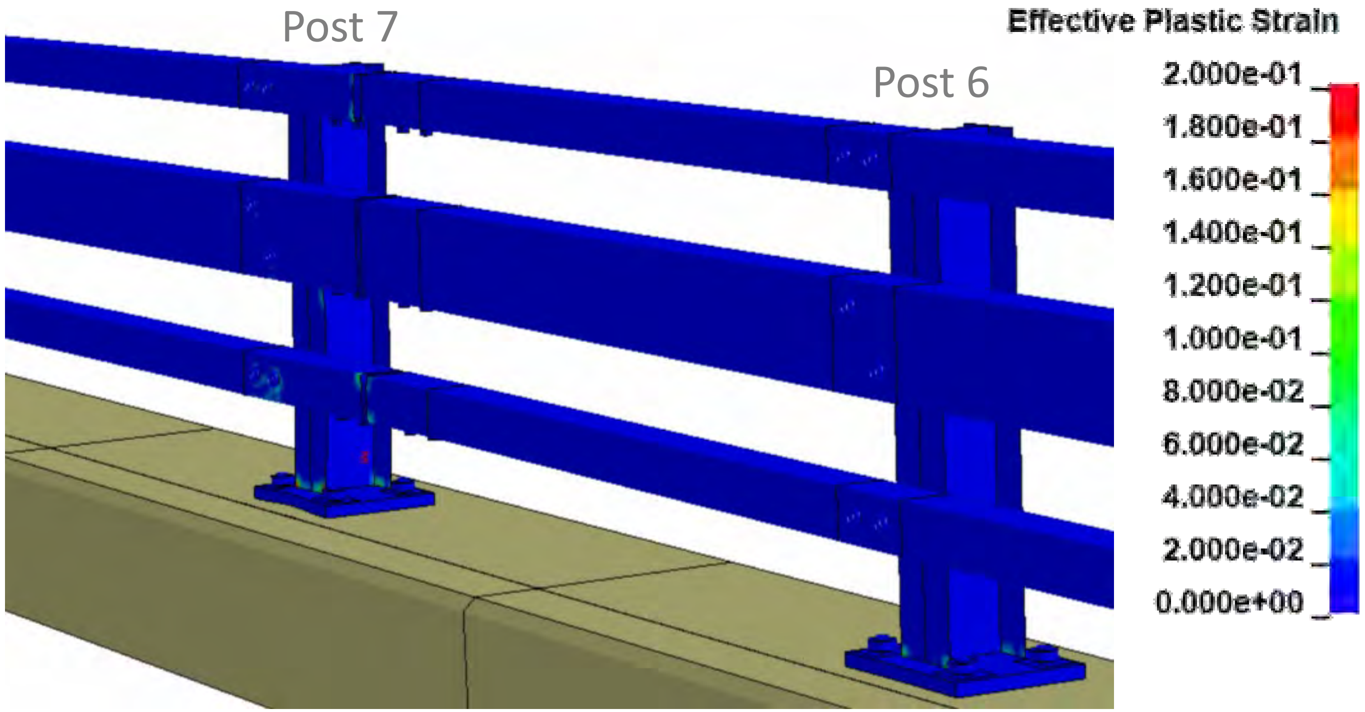
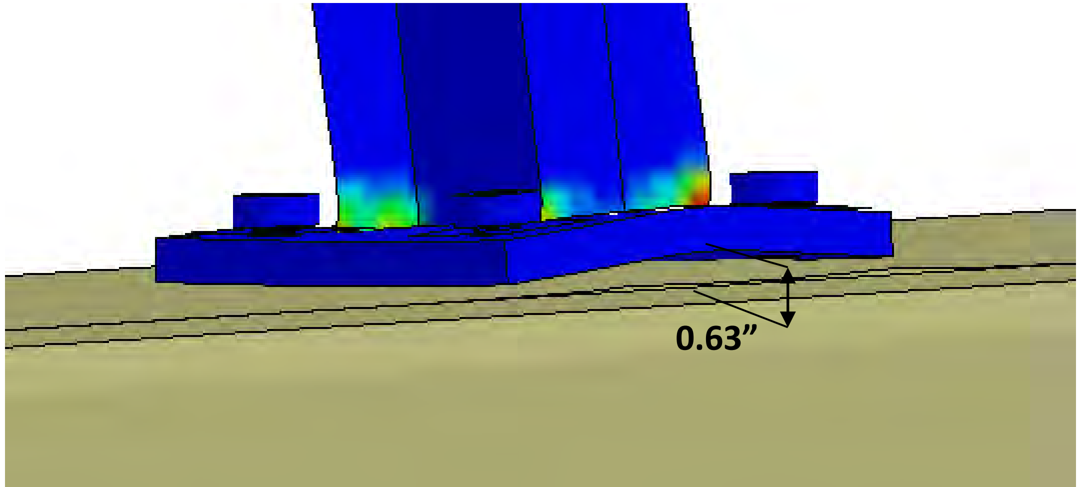
Barrier Damage

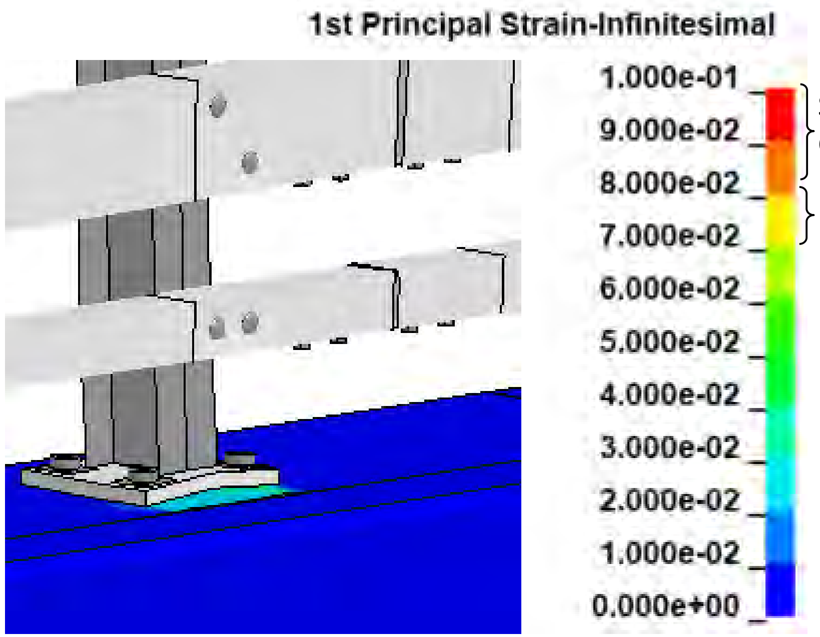
- There was moderate damage to Post 7 and its base plate.
  - There was plastic deformation of at the lower part of the post and to the base plate.
  - Vertical deflection of base plate:
    - Dynamic = 0.63 inches (16 mm)
    - Permanent = 0.29 inches (7.4 mm)
- There was minimal damage to Post 6 and its base plate.
- There was moderate damage to the rails between these two posts.





Concrete Damage

- Analysis resulted in possible concrete damage at post 7, but failure was not considered likely.
  - Max dynamic 1st Prin. Strain = 0.07
  - Final 1st Prin. Strain = 0.0



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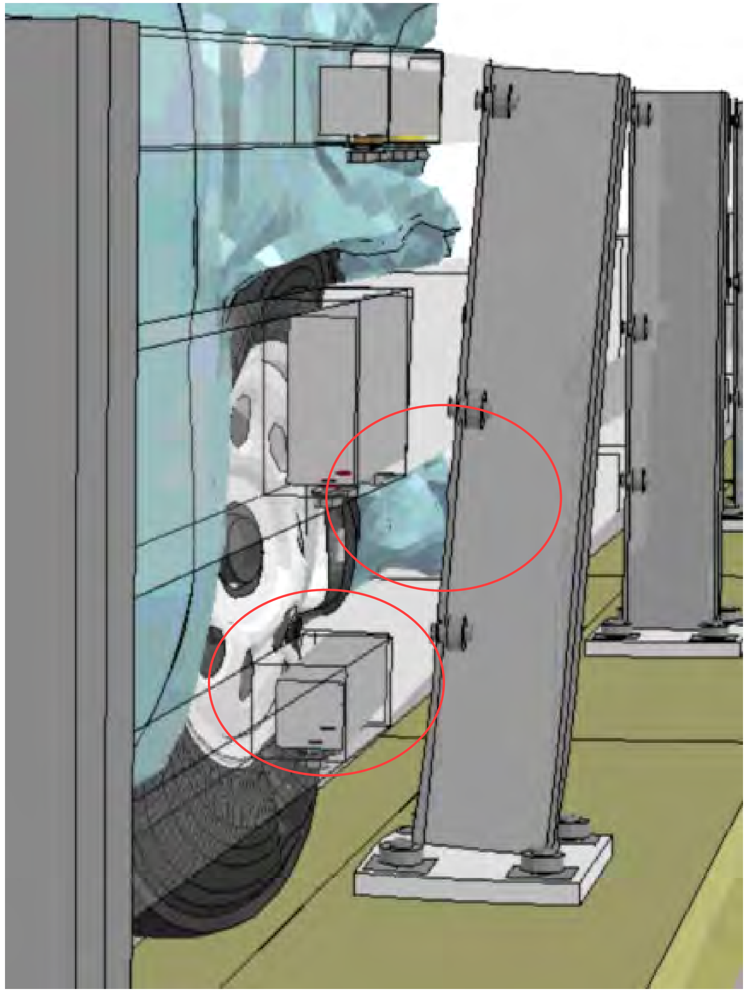
Assessment of Vehicle Snag Points

- The front fender and bumper made slight contact with the post, but the contact force was negligible.
- The tire rim snagged on the splice, which resulted in peak longitudinal acceleration of 15 G.
- Tires did <u>not</u> contact post.



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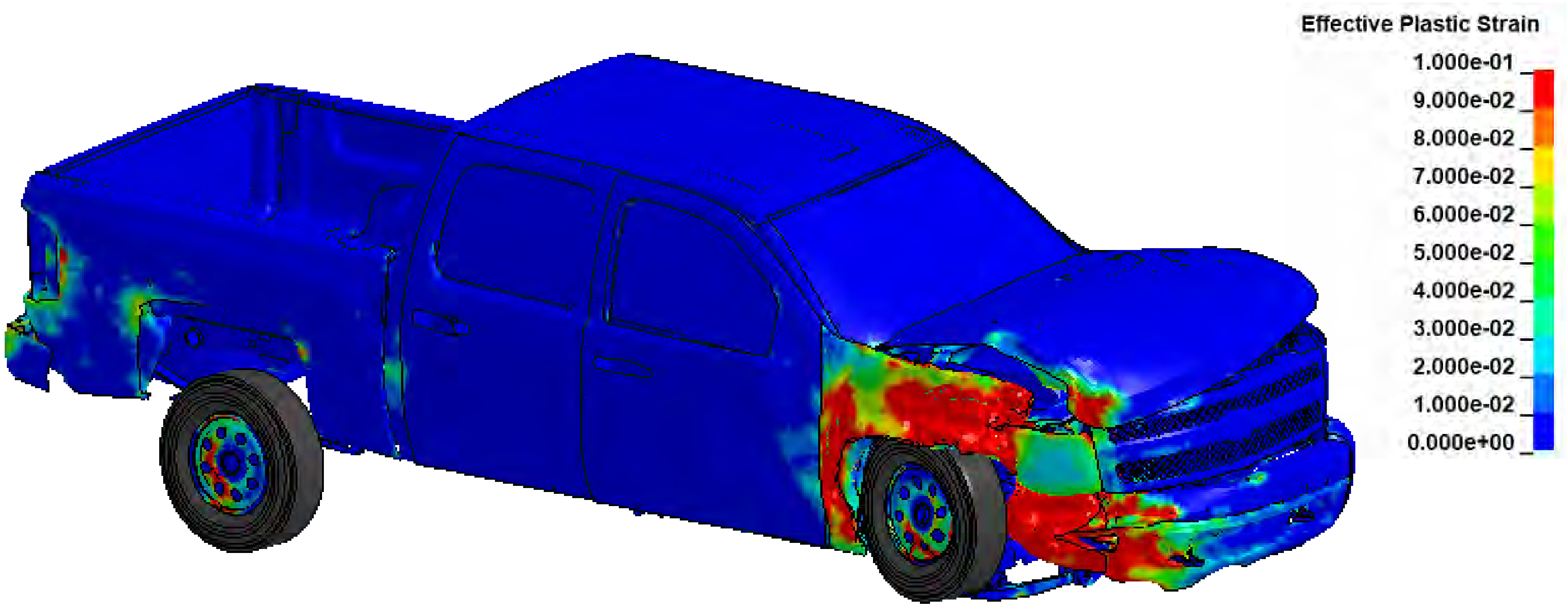
Effective Plastic Strain for Pickup Test



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

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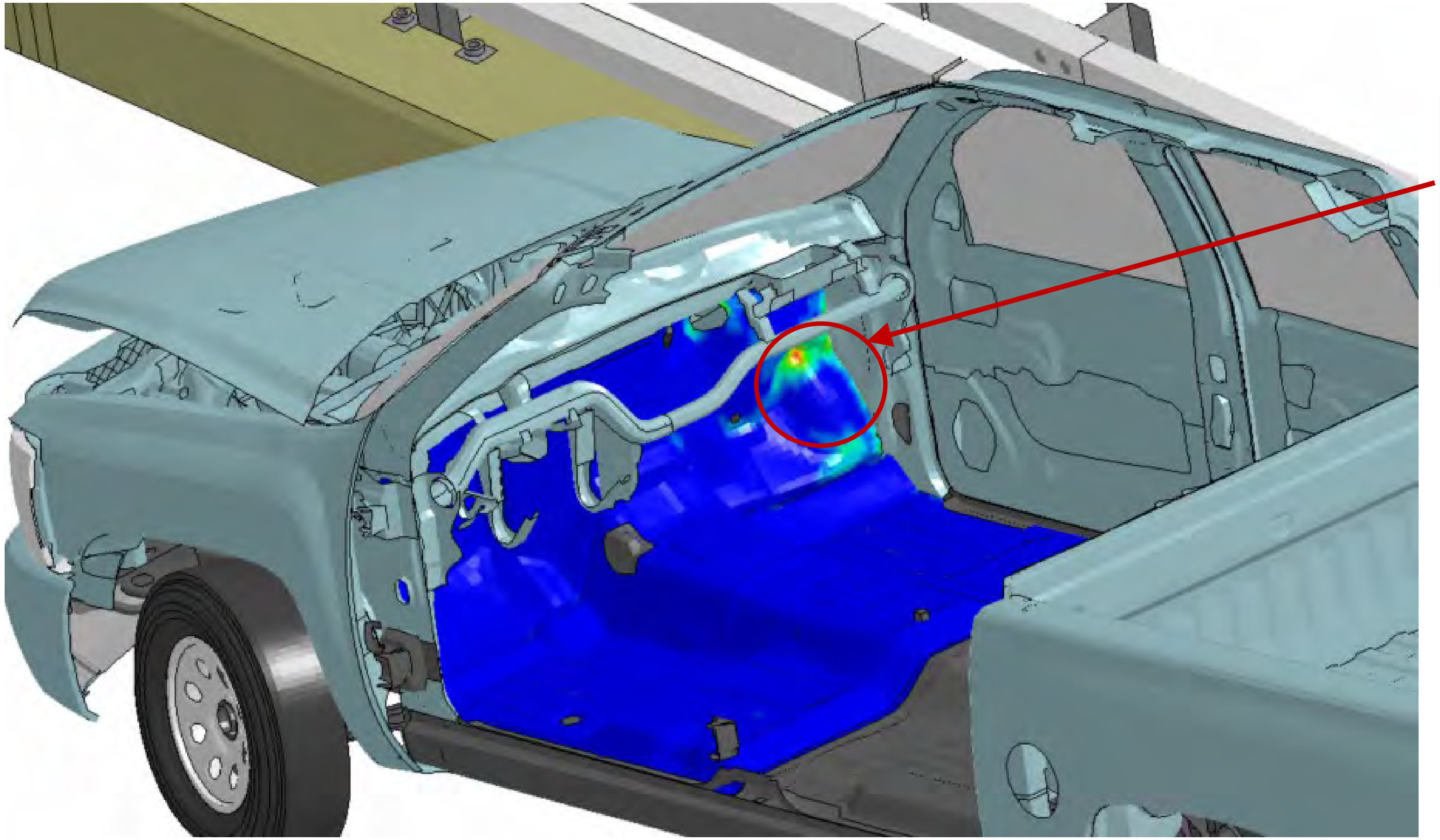
Occupant Compartment Intrusion

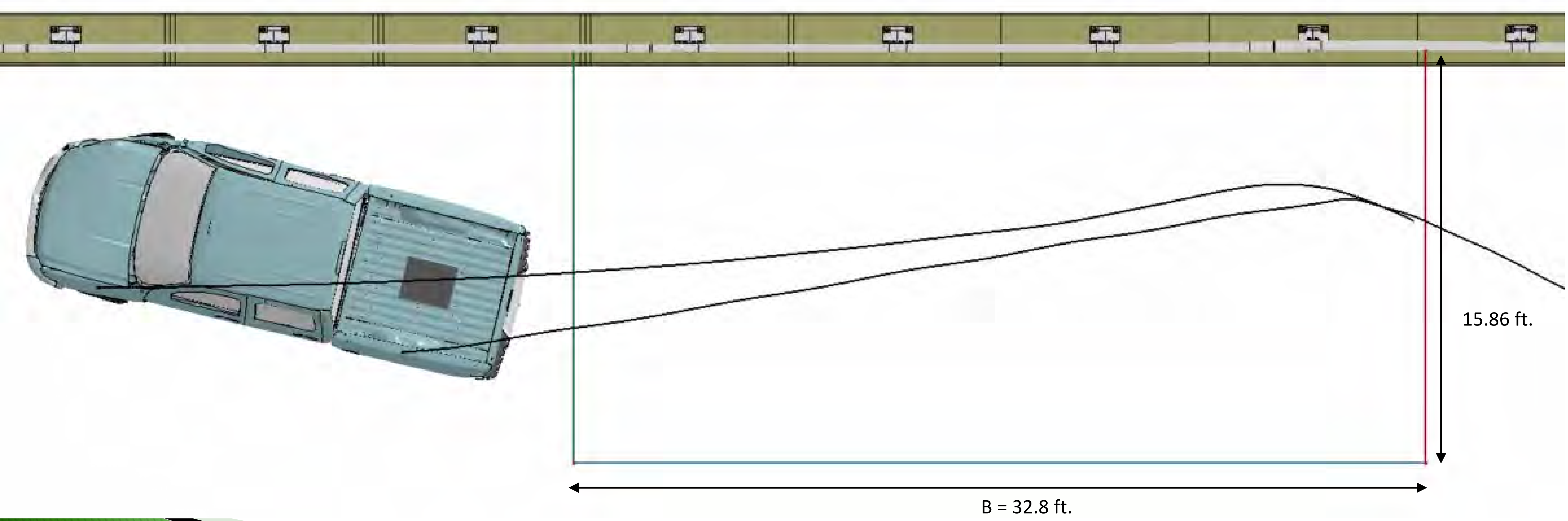
Occupant Compartment Intrusion (OCI)



Maximum OCI was ≈3.3 inches (85 mm) and occurred at the right-front toe-pan at the wheel well.

Exit Box – NETC 3-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."



Conclusions Regarding Test 4-11 on the MDOT S3-TL4

- 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 =**9.9 degrees** and Max Pitch = **7.5 degrees**.
- The OIV was within critical limits and the maximum ORA was within recommended limits specified in MASH.
  - OIV_x = **22.0 ft/s** and OIV_y = **26.6 ft/s**
  - ORA_x = **4.7 G** and ORA_y = **15.4 G**
- 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 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 splice connection and was:
  - Max Dynamic = **4.2 inches**; Max Permanent = **1.9 inche**s

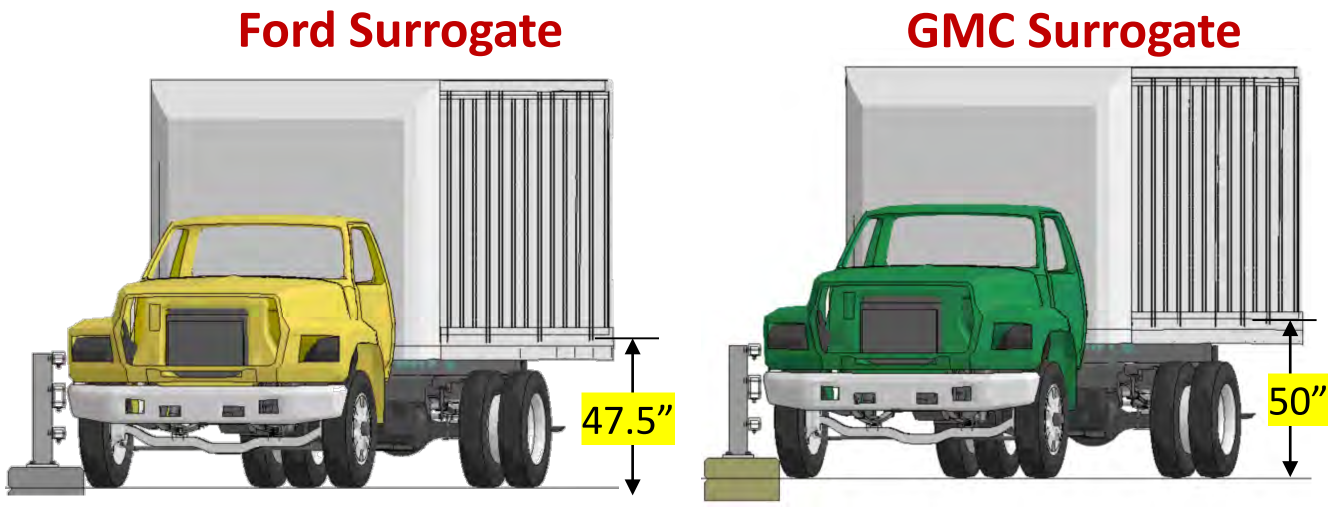
Conclusions on Test 4-11 on the NETC 3-Bar

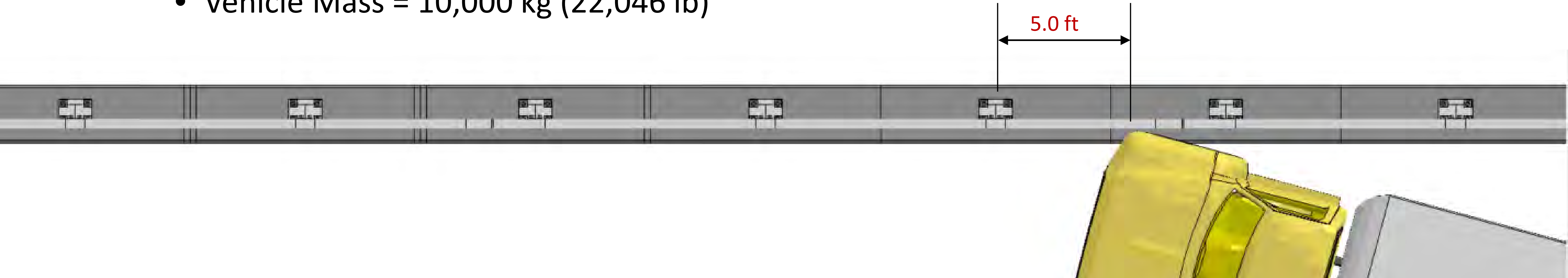
Evaluation Factors		Evaluation Criteria	Results
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is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

MASH Test 4-12 Simulation

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

Two Analysis Cases
(varying bed height)





Movies

Bed Height = 47.5 inches

Bed Height = 50 inches

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Movies

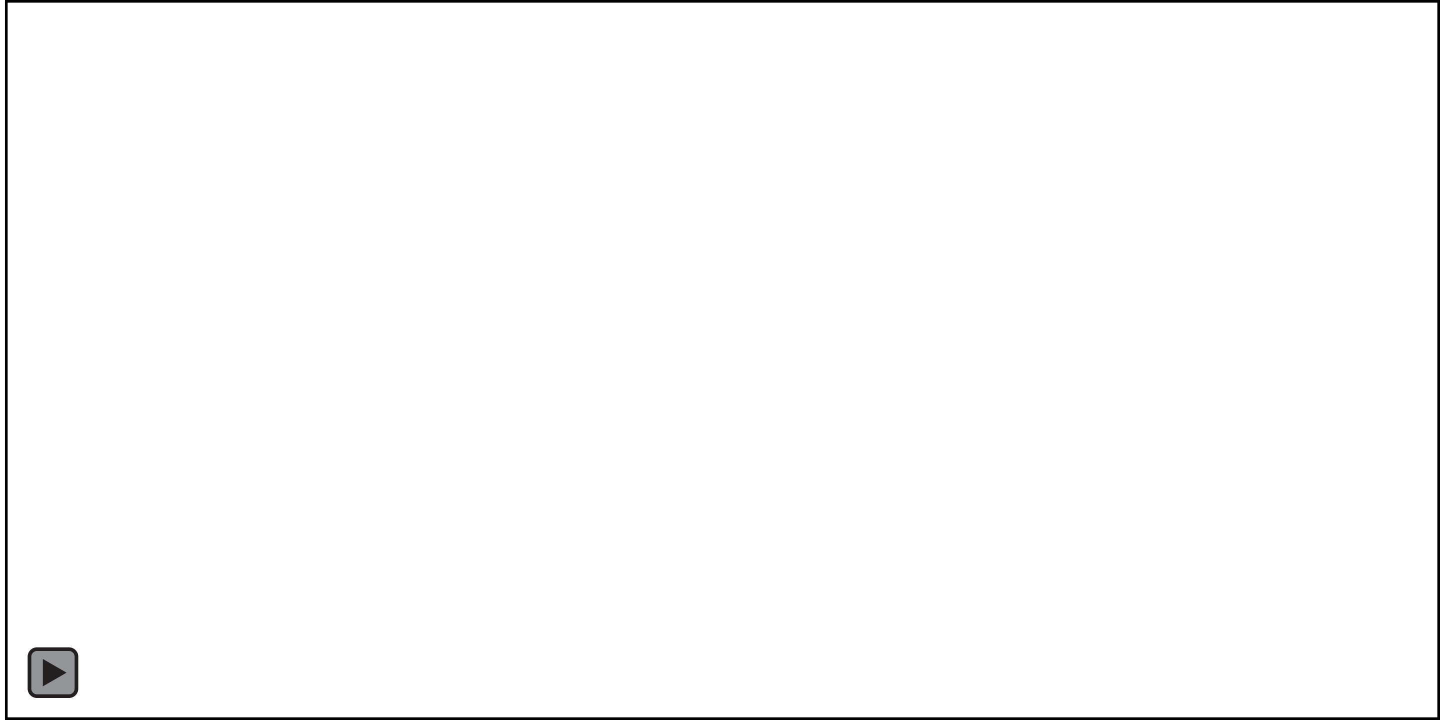
Bed Height = 47.5 inches

Bed Height = 50 inches

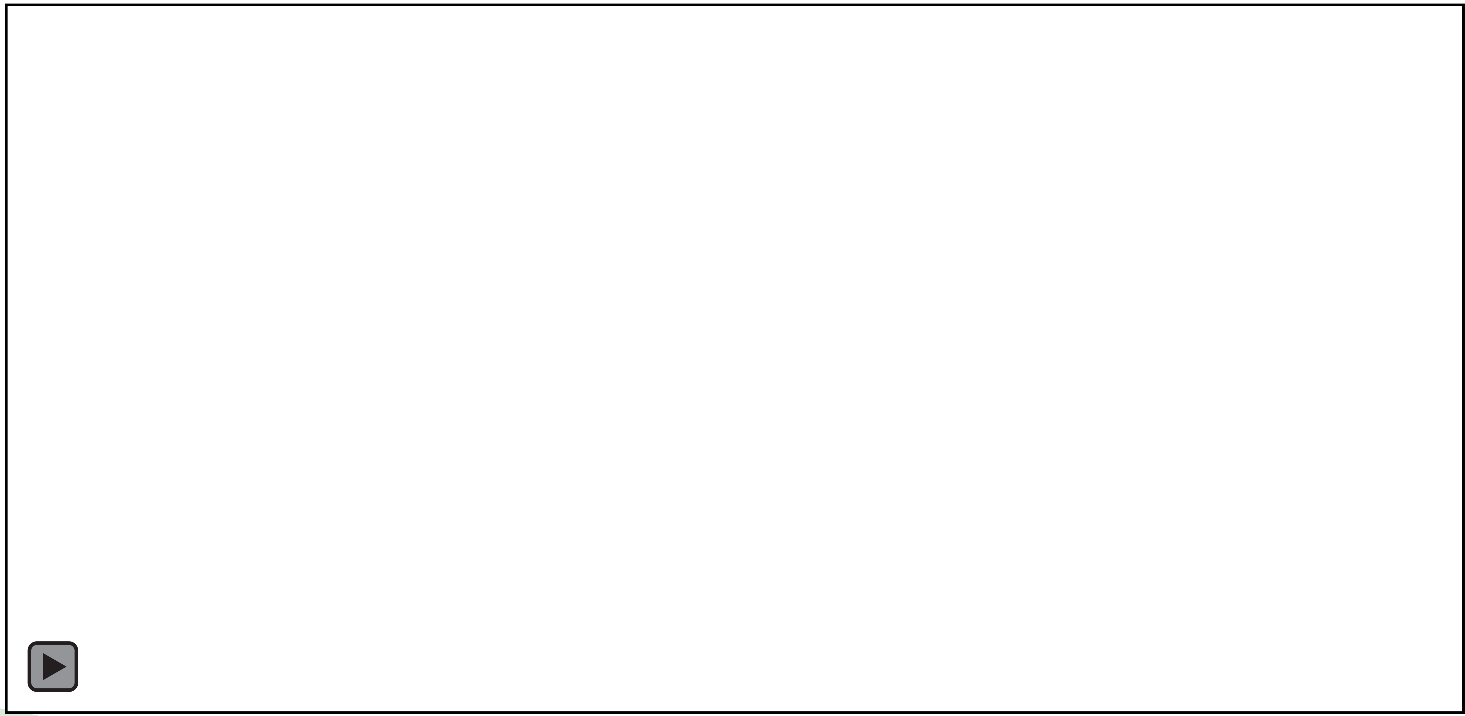
Bed Height = 47.5 inches

Bed Height = 50 inches

Bed Height = 47.5 inches



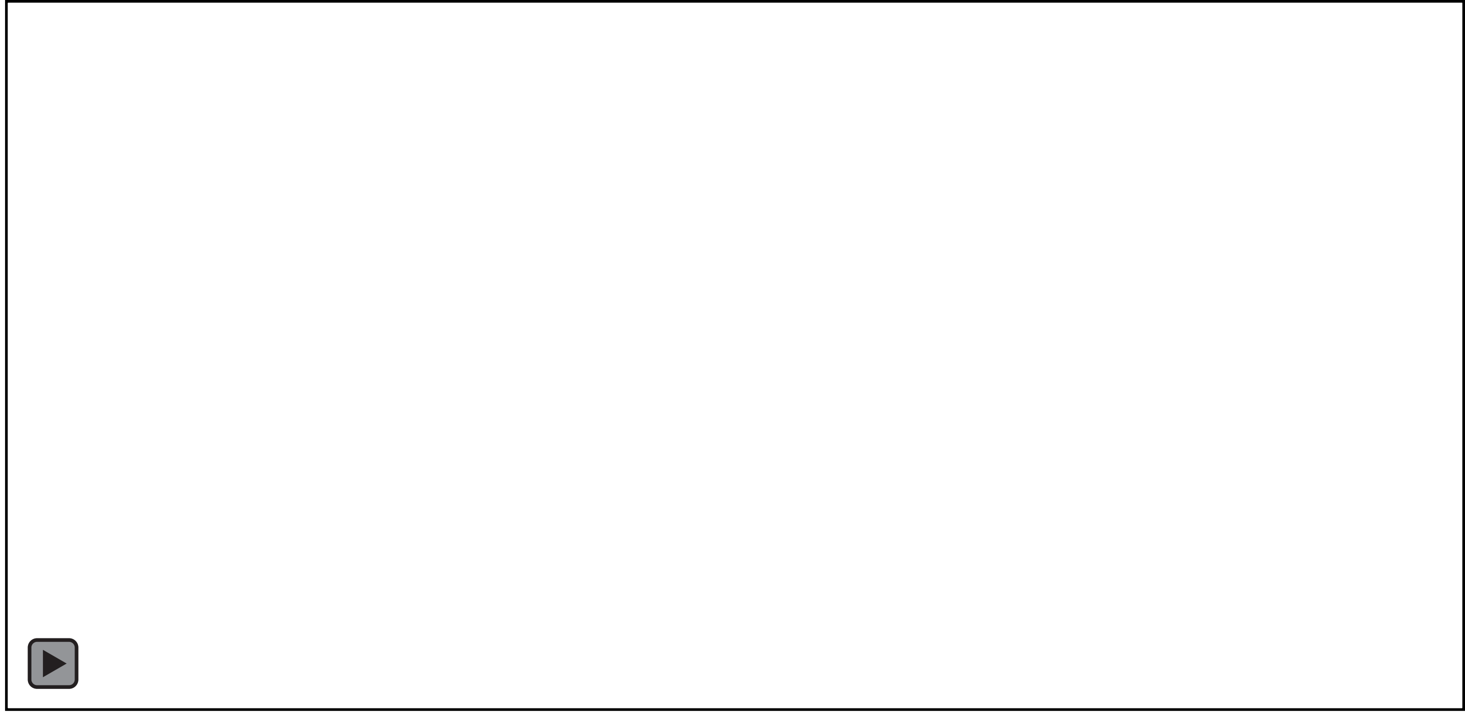
Bed Height = 50 inches



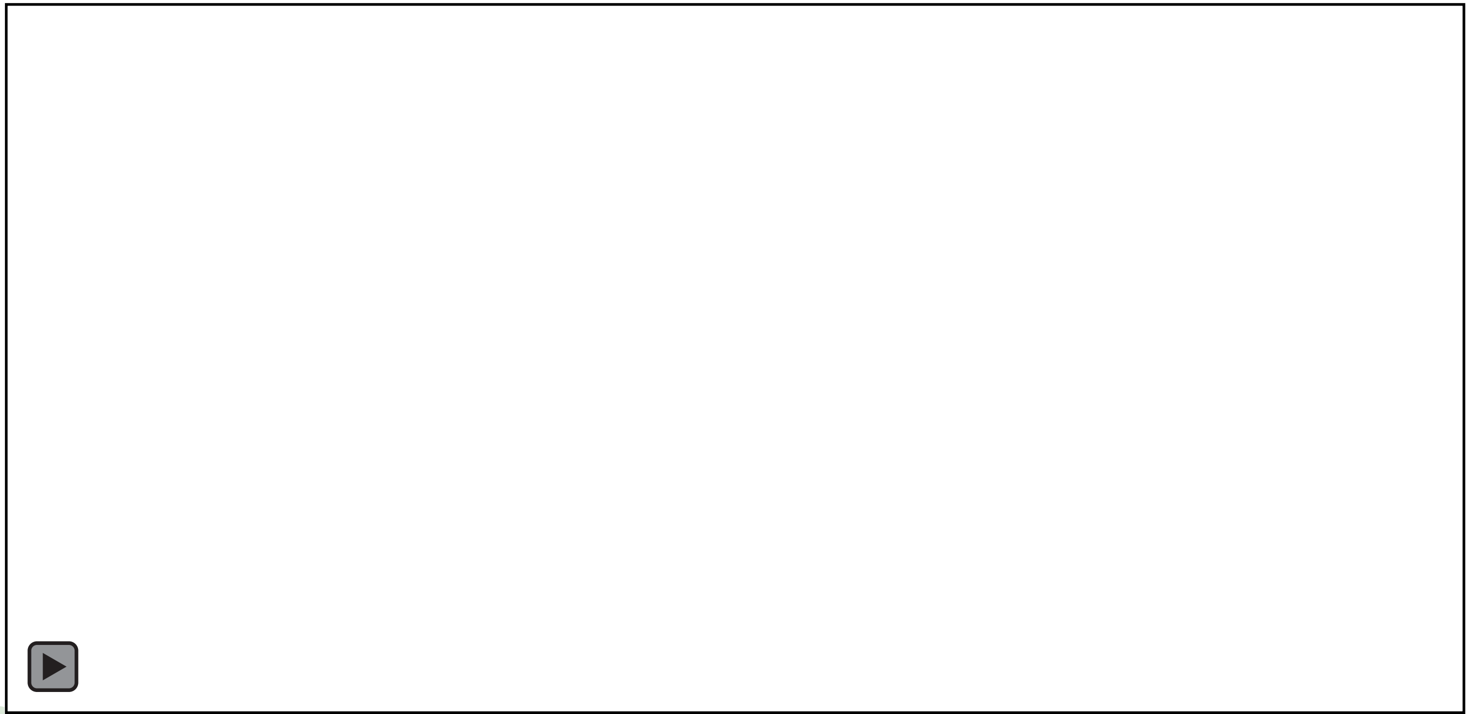
Bed Height = 47.5 inches

Bed Height = 50 inches

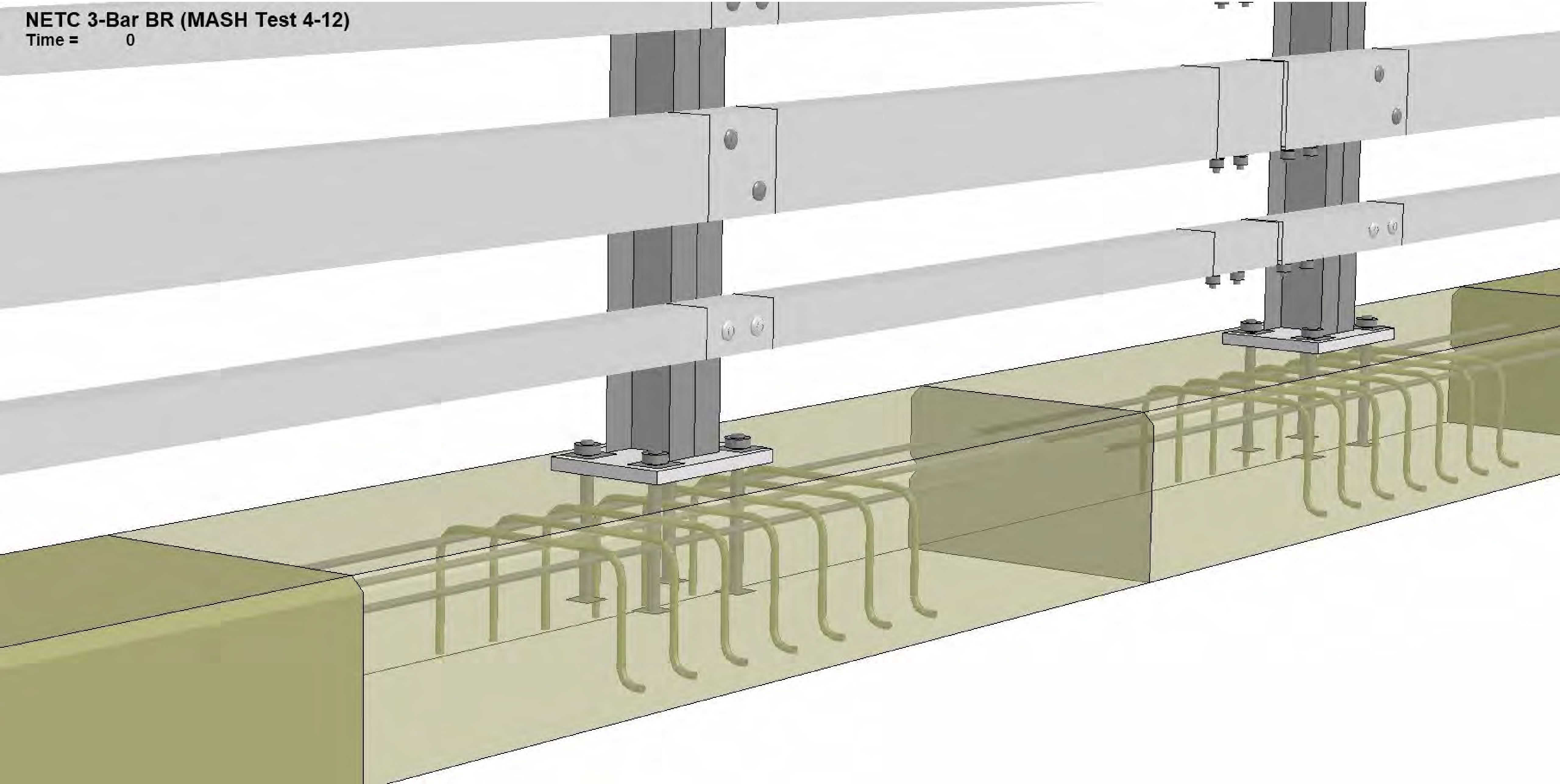
Bed Height = 47.5 inches



Bed Height = 50 inches



Bed Height = 47.5 inches



TRAP – Summary Table

Occupant Risk Factors		MASH T4-12	
		Case 1 (47.5")	Case 2 (50")
Occupant Impact Velocity (ft/s)	x-direction	2.0	3.0
	y-direction	-14.8	-14.1
	at time	at 0.1407 seconds on left side of interior	at 0.1464 seconds on left side of interior
THIV (ft/s)		15.4 at 0.1407 seconds on left side of interior	14.4 at 0.1464 seconds on left side of interior
Ridedown Acceleration (g's)	x-direction	-7 (0.2038 - 0.2138 seconds)	-5.7 (0.1784 - 0.1884 seconds)
	y-direction	5.3 (0.1491 - 0.1591 seconds)	5.9 (0.1559 - 0.1659 seconds)
PHD (g's)		7 (0.2038 - 0.2138 seconds)	7.4 (0.1571 - 0.1671 seconds)
ASI		0.76 (0.0532 - 0.1032 seconds)	0.66 (0.0557 - 0.1057 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-2.8 (0.1651 - 0.2151 seconds)	-2.3 (0.1447 - 0.1947 seconds)
	y-direction	6.4 (0.0549 - 0.1049 seconds)	5.7 (0.0556 - 0.1056 seconds)
	z-direction	3.5 (0.3327 - 0.3827 seconds)	2.4 (0.3262 - 0.3762 seconds)
Maximum Angular Disp. (deg)	Roll	-20.8 (0.9596 seconds)	-70.8 (1.4987 seconds)
	Pitch	-7.8 (0.7127 seconds)	-6.9 (0.6292 seconds)
	Yaw	20.7 (1.0333 seconds)	38 (1.4969 seconds)

MASH Criteria

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

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

< 75 deg ✓

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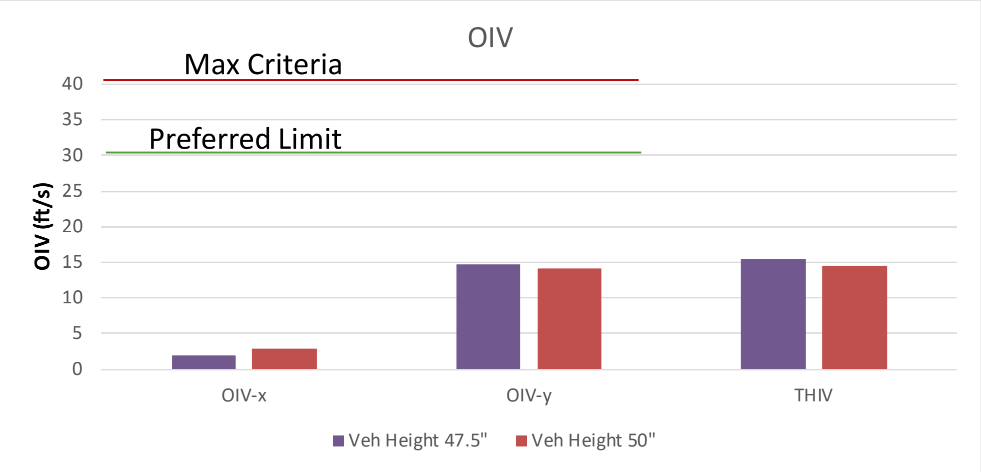
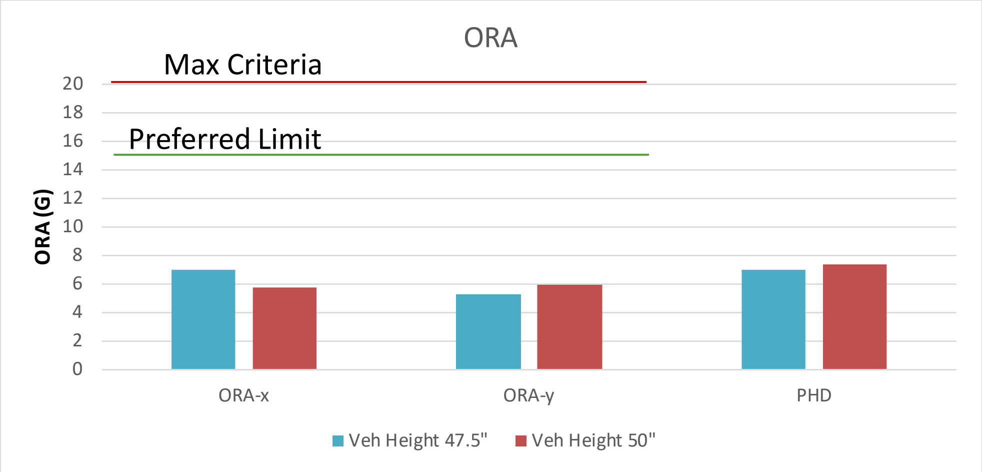
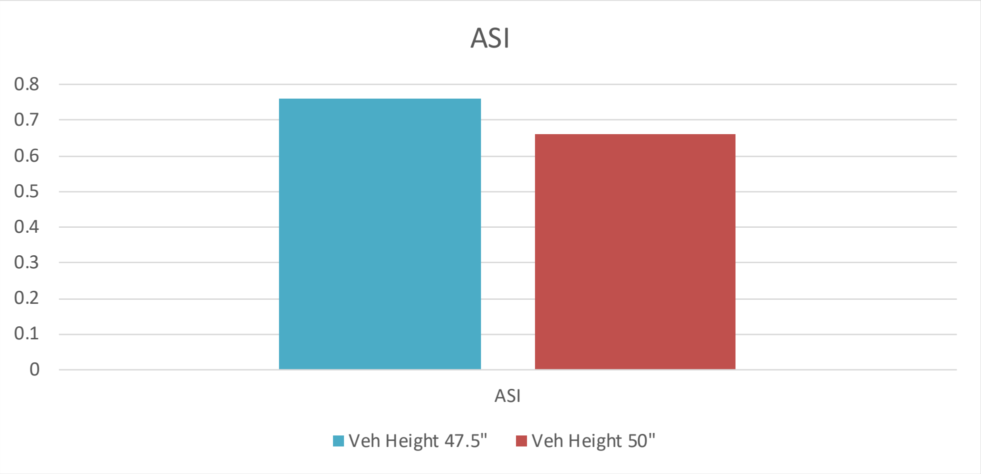
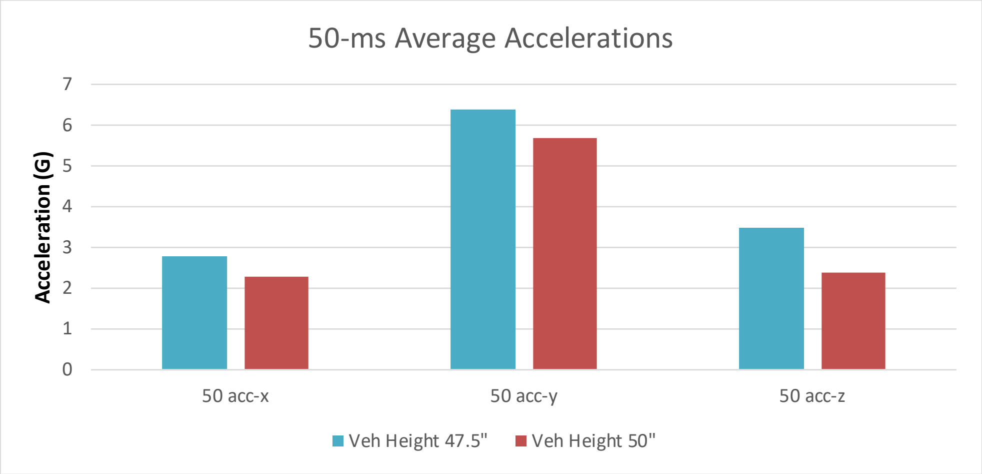
TRAP









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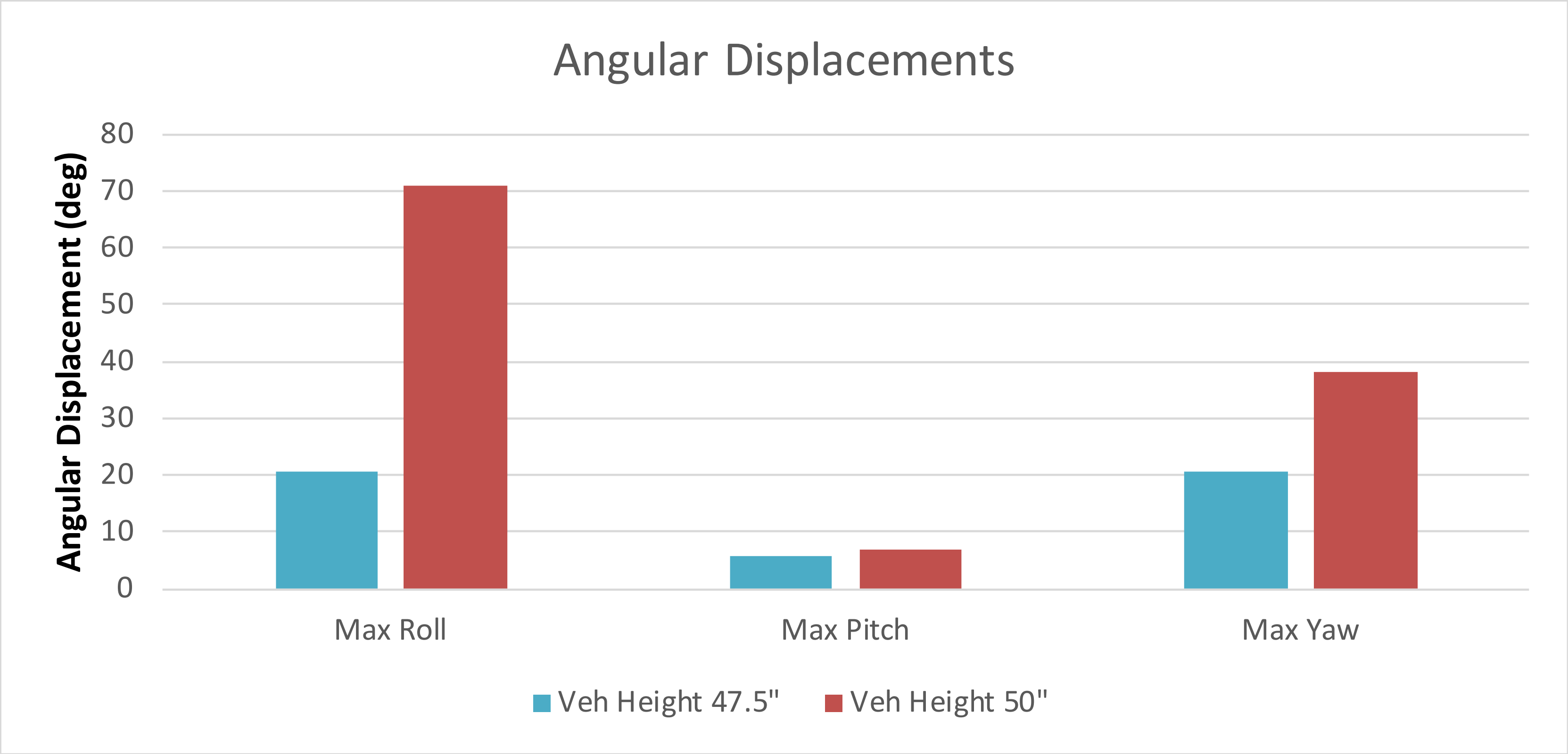
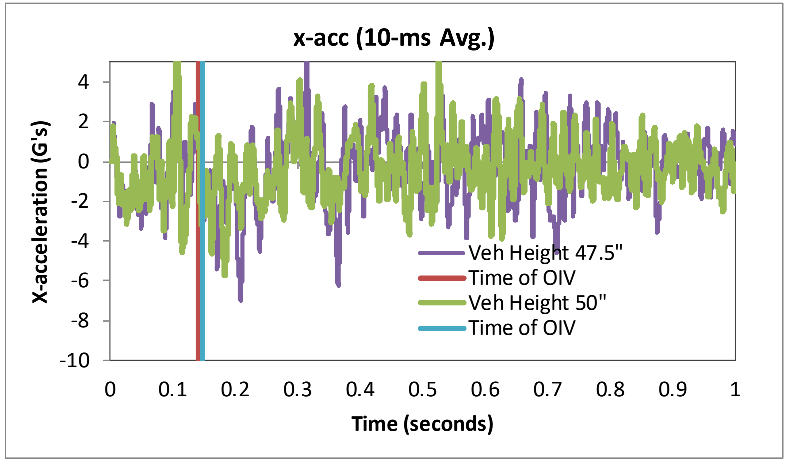
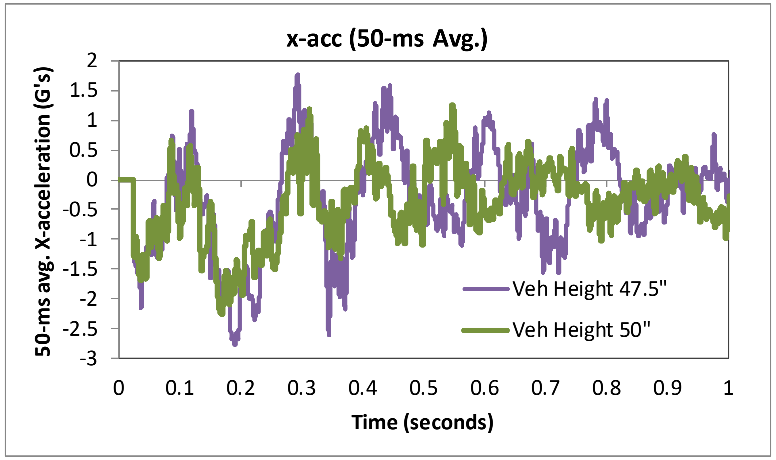
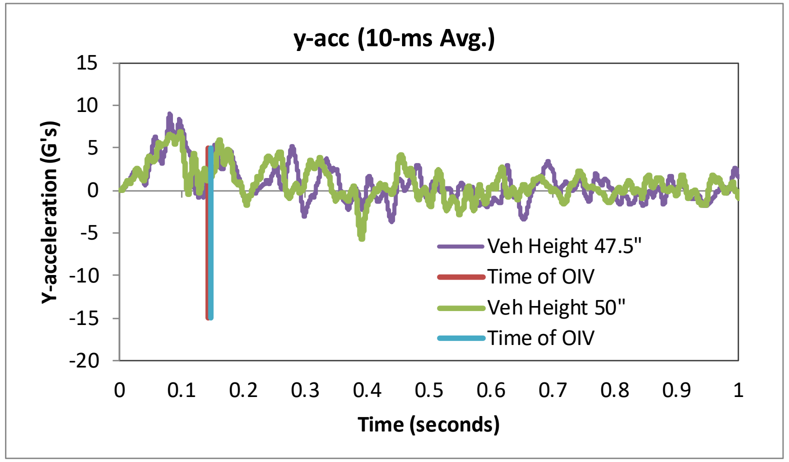
TRAP

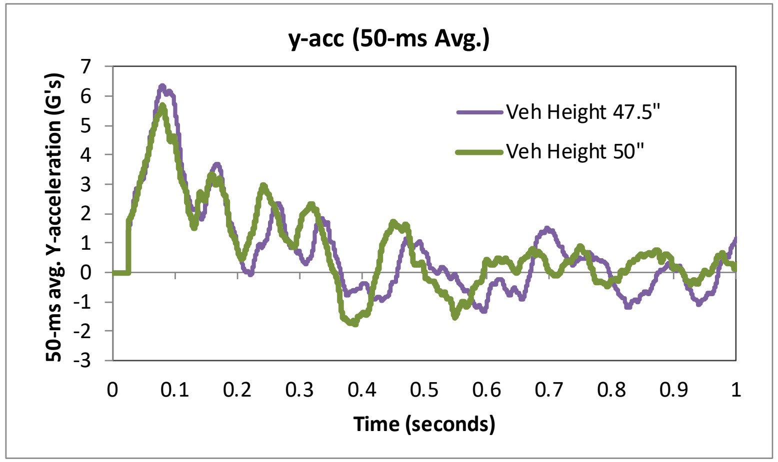

Angular Displacements
Angular Displacement (deg)
80
70
60
50
40
30
20
10
0
Max Roll
Max Pitch
Max Yaw
Veh Height 47.5"
Veh Height 50"

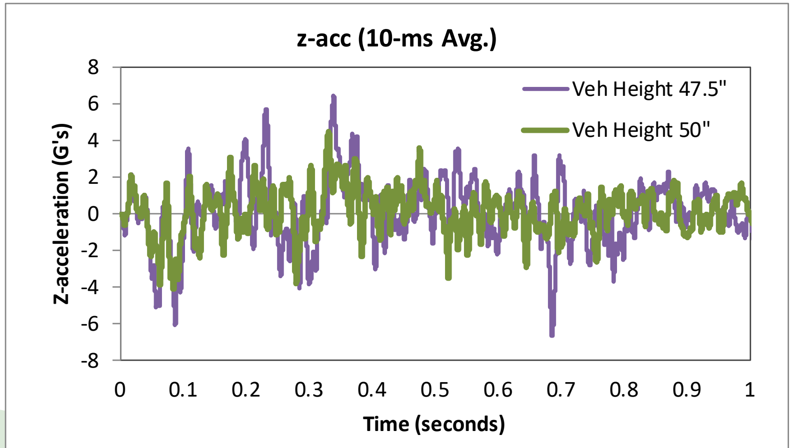
Acceleration Plots

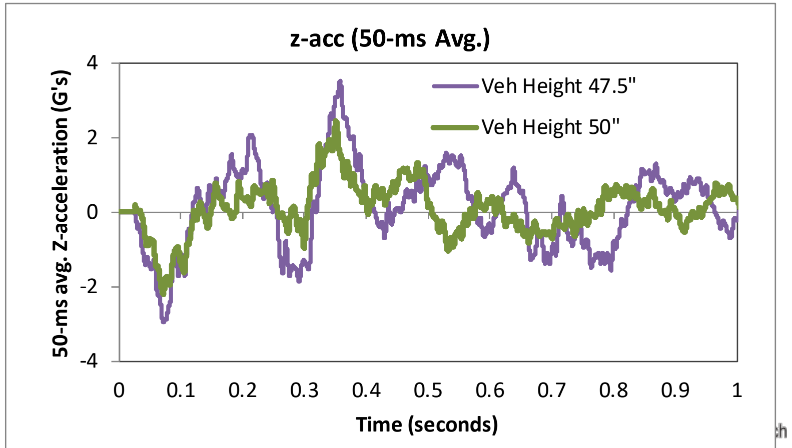




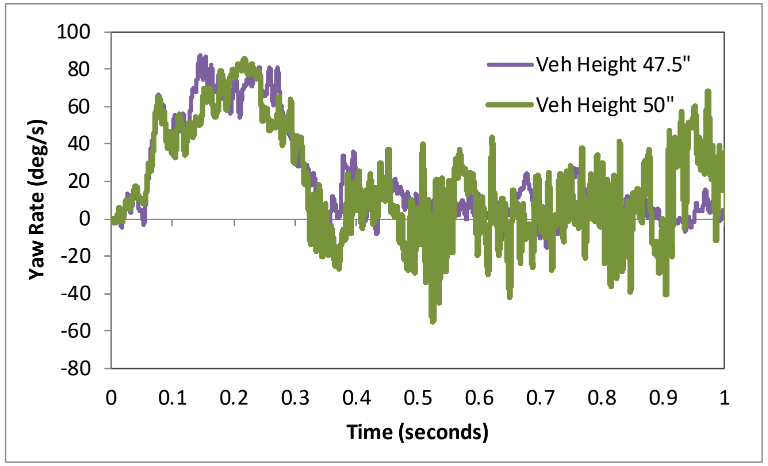


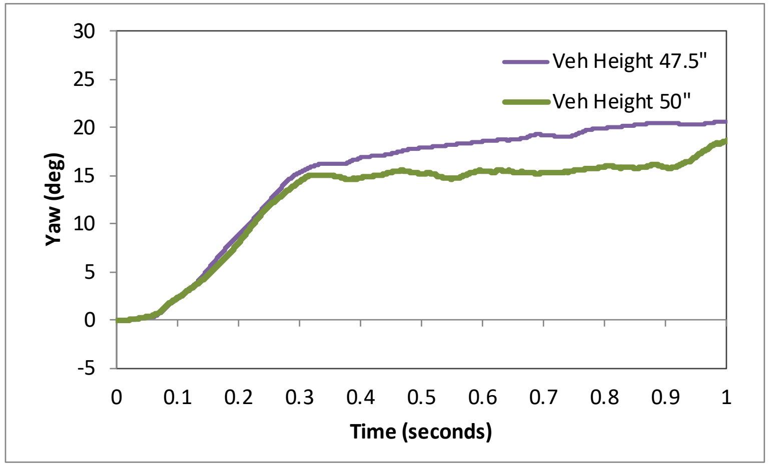


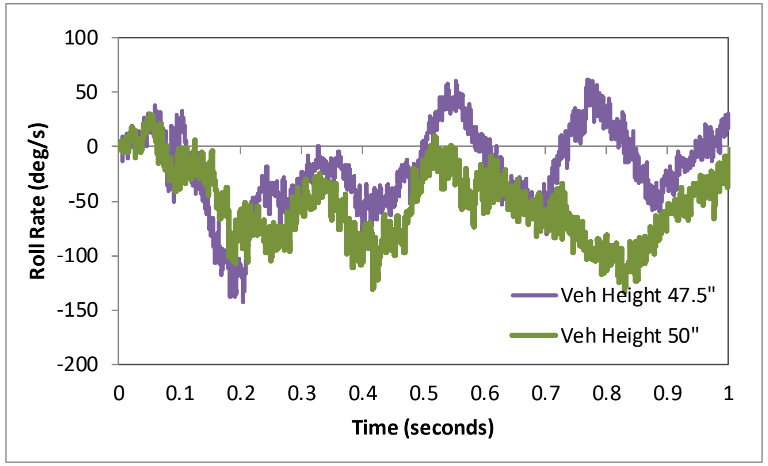


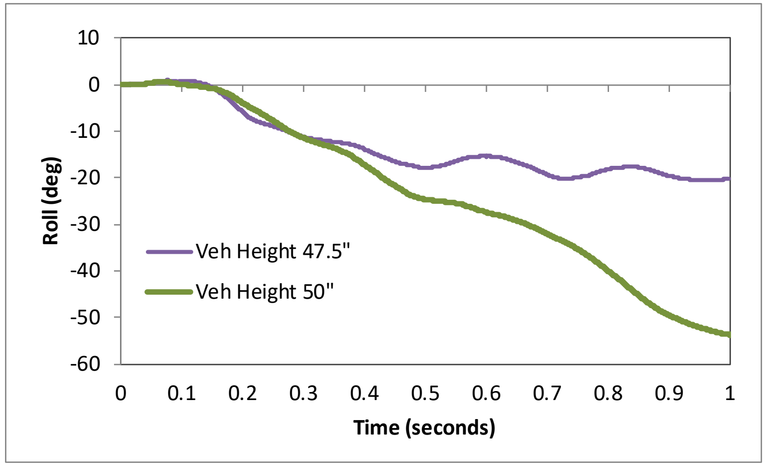


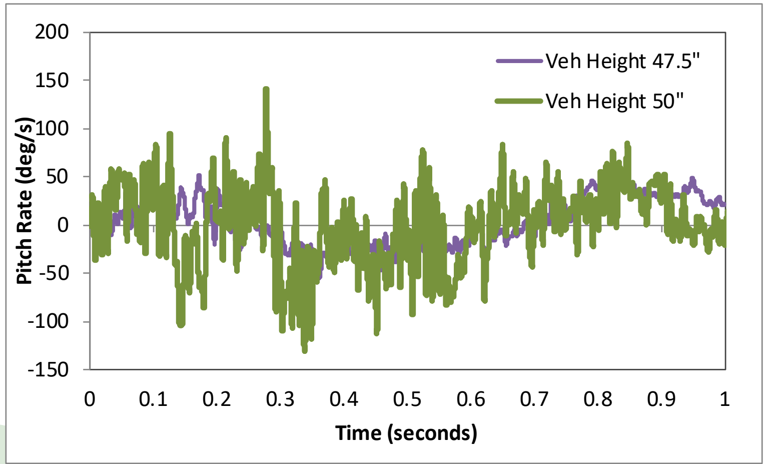
Angular Rate and Displacement Plots

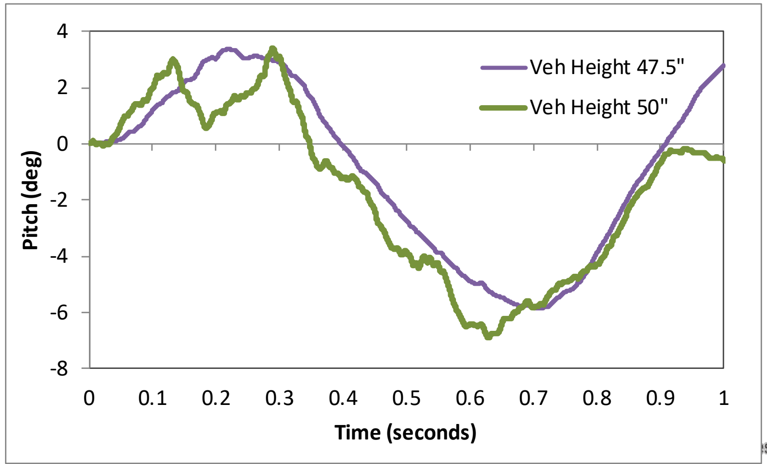




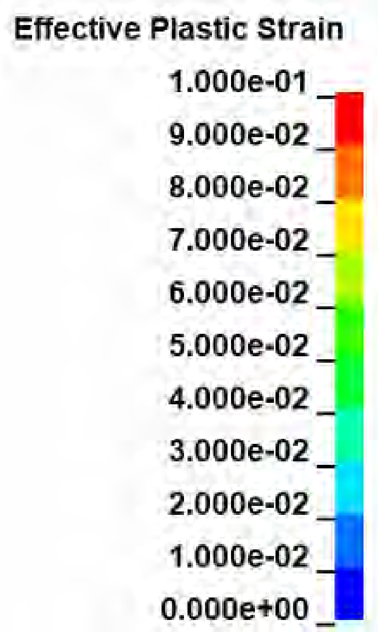








Effective Plastic Strain for SUT Tests



Case 1 (47.5”)

Case 2 (50”)

Analysis terminated prior to complete overturn

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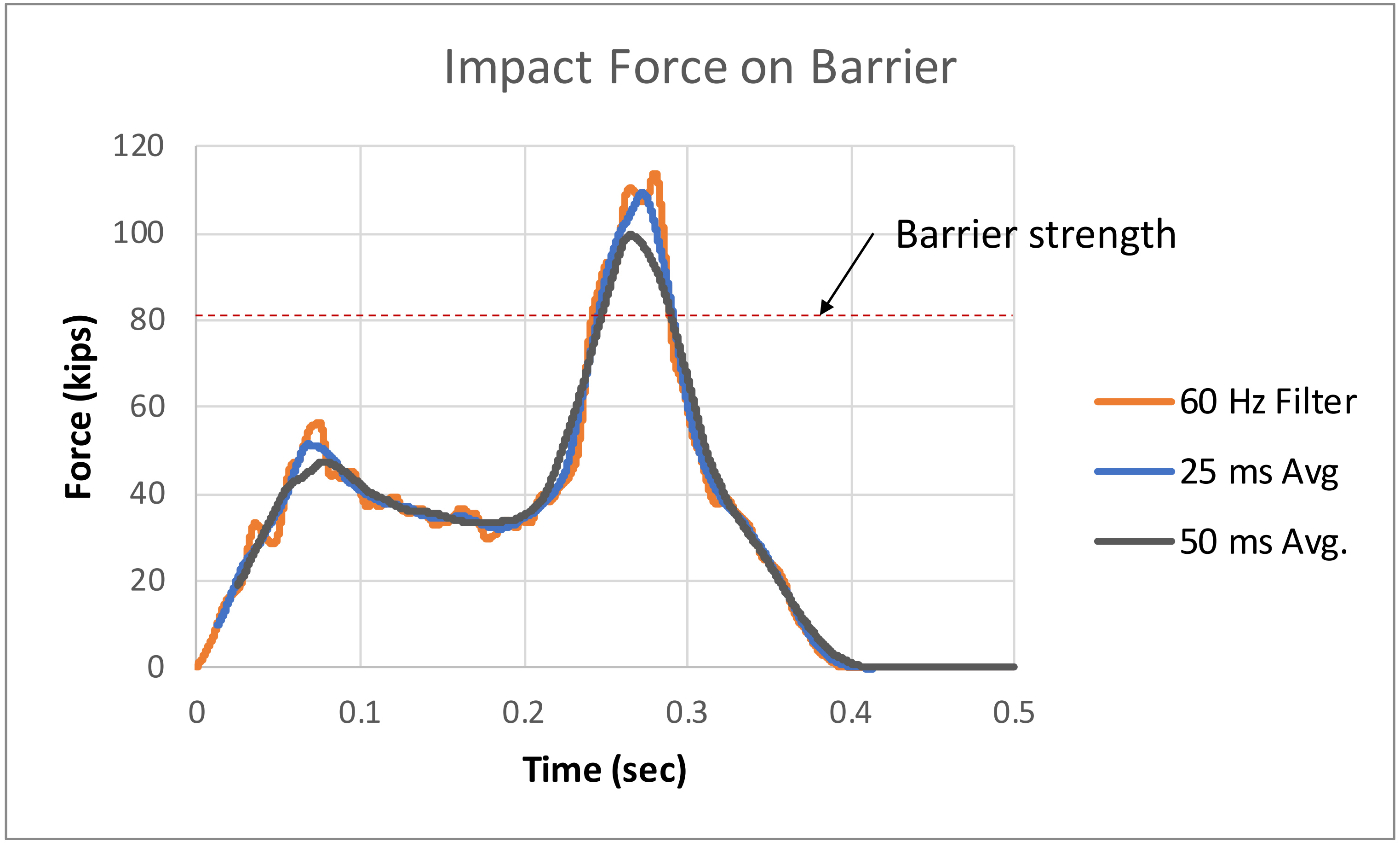
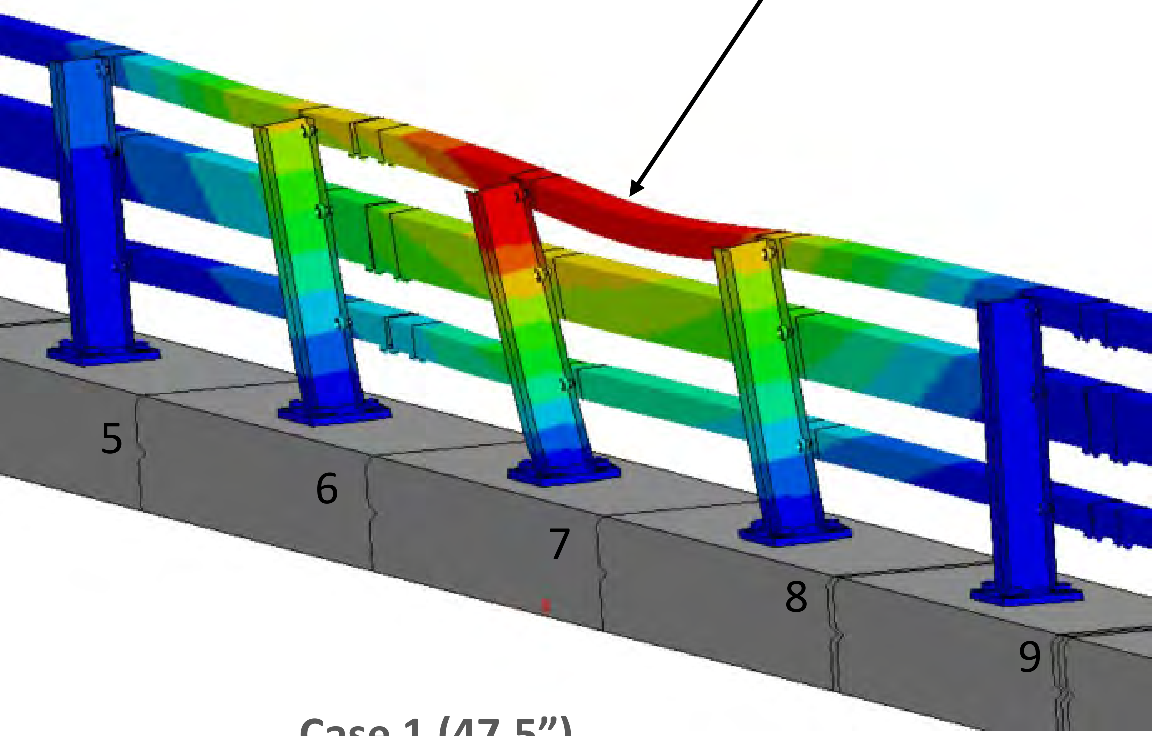
- Note that the peak lateral loads result from the “tail slap” not the front of the vehicle.
- This is important regarding containment, because the vehicle would already be passing (or passed) the damaged section if failure did occur.

Impact Forces on Bridge Rail from FEA



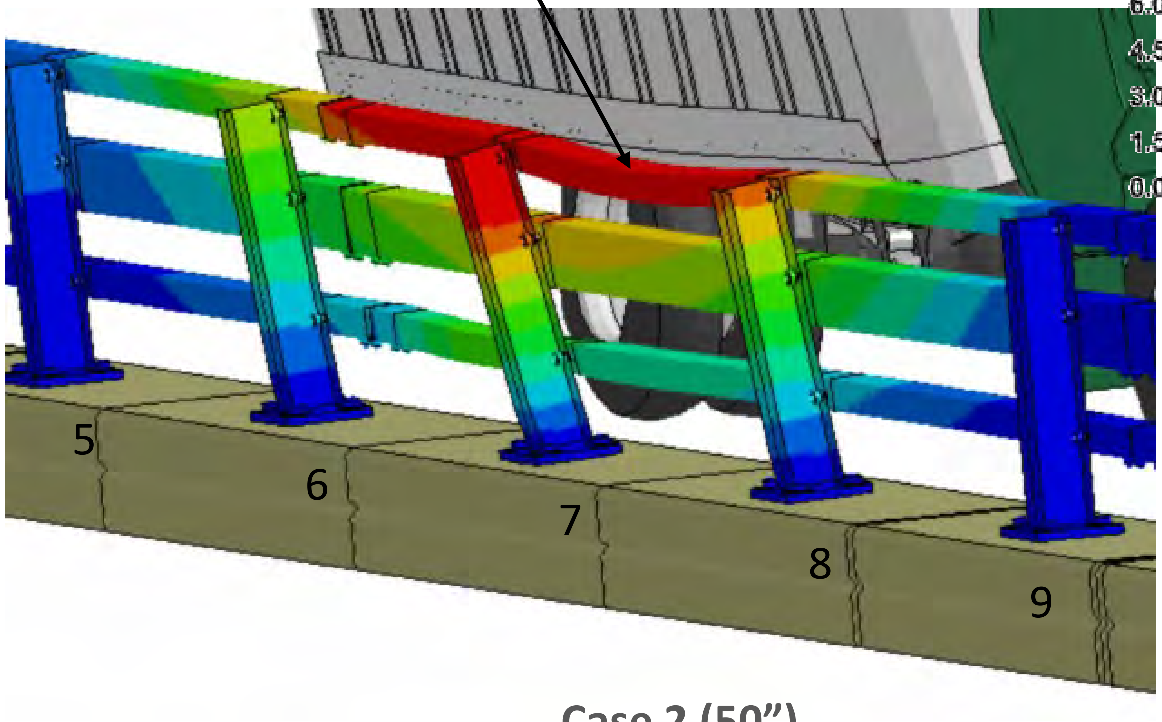
Lateral Dynamic Deflection

Maximum dynamic deflection = 7.64 in (194 mm)

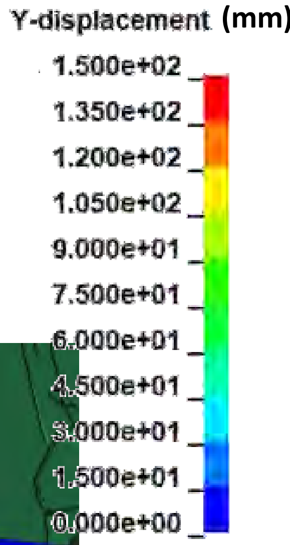


Case 1 (47.5”)

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



Case 2 (50”)



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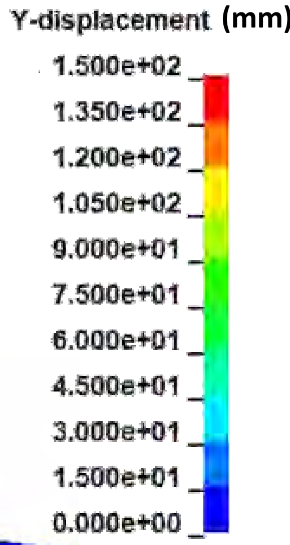
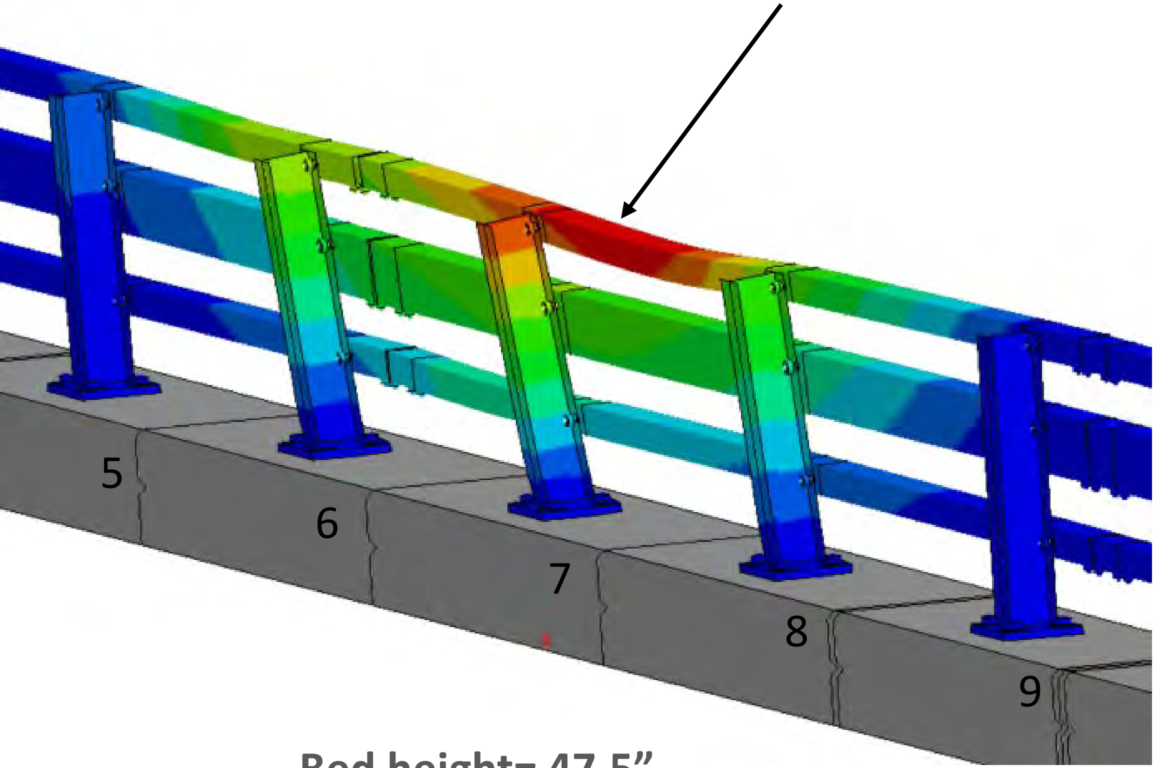
Lateral Permanent Deflection



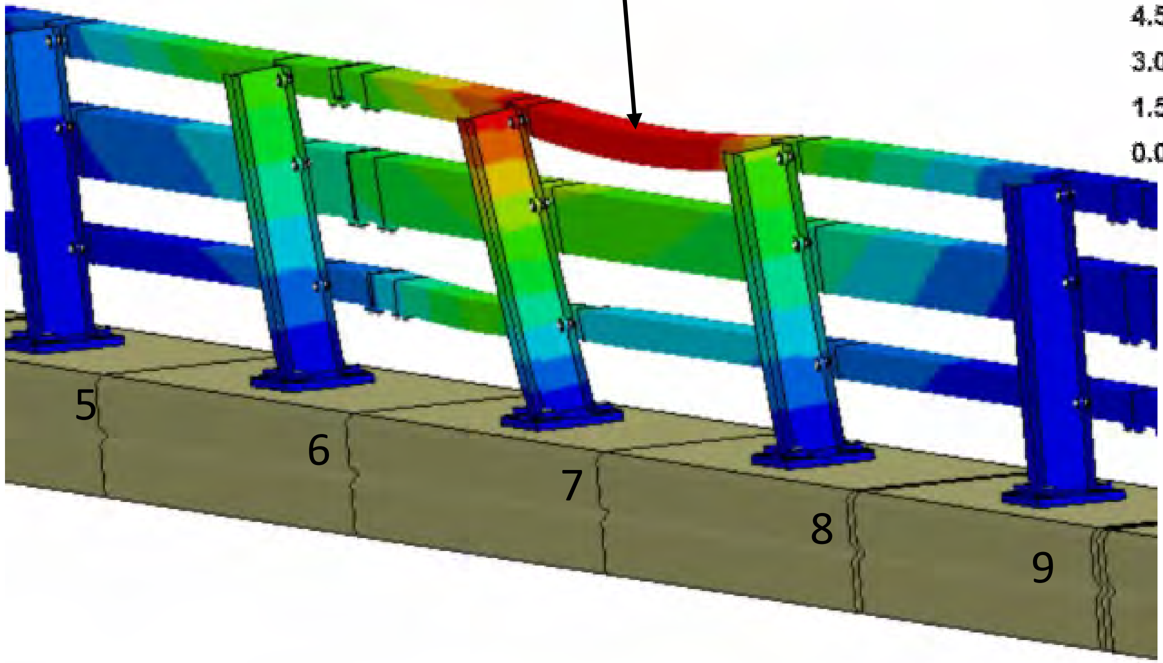
Maximum permanent deflection = 5.7 in (146 mm)



Bed height= 47.5”

Maximum permanent deflection

- Lateral = 6.6 in (168 mm)
- Vertical = 0.79 in (20 mm)

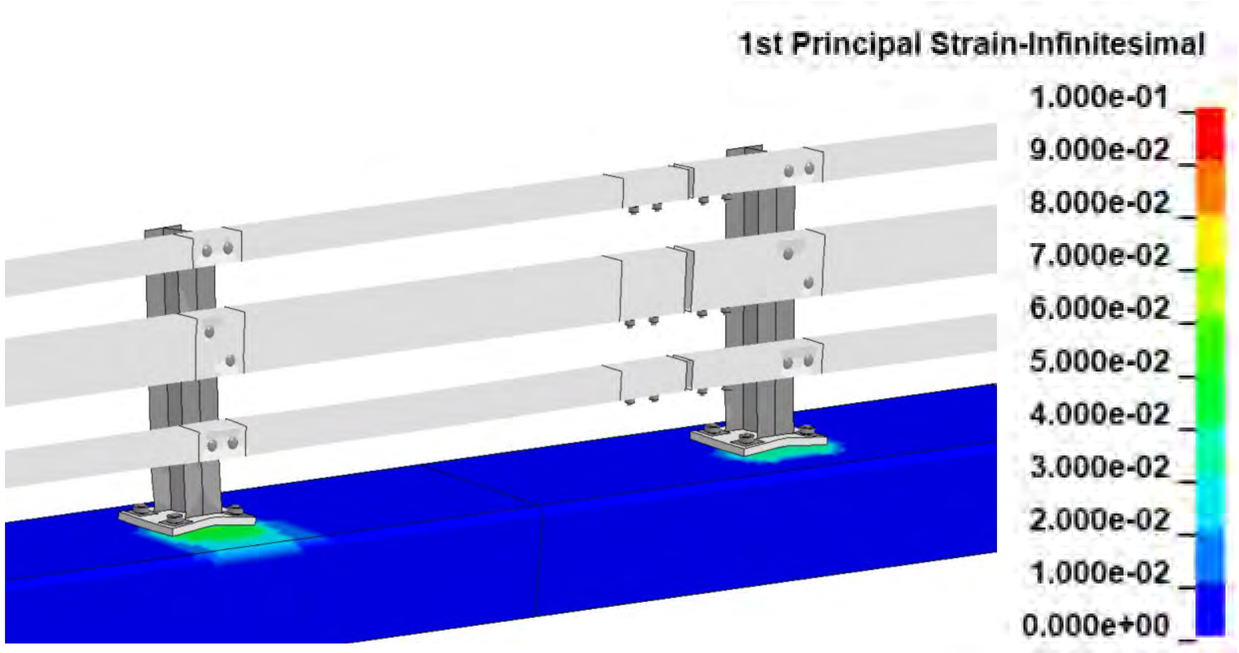


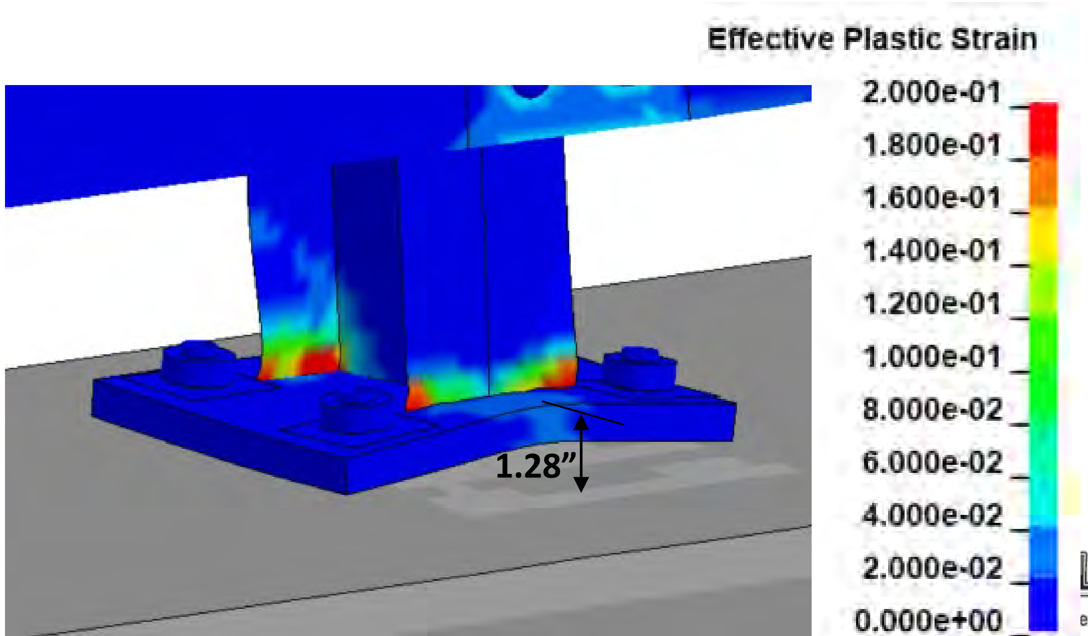
Bed height= 50”

Barrier Damage

<u>Case 1 – Bed Height = 47.5”:</u>

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





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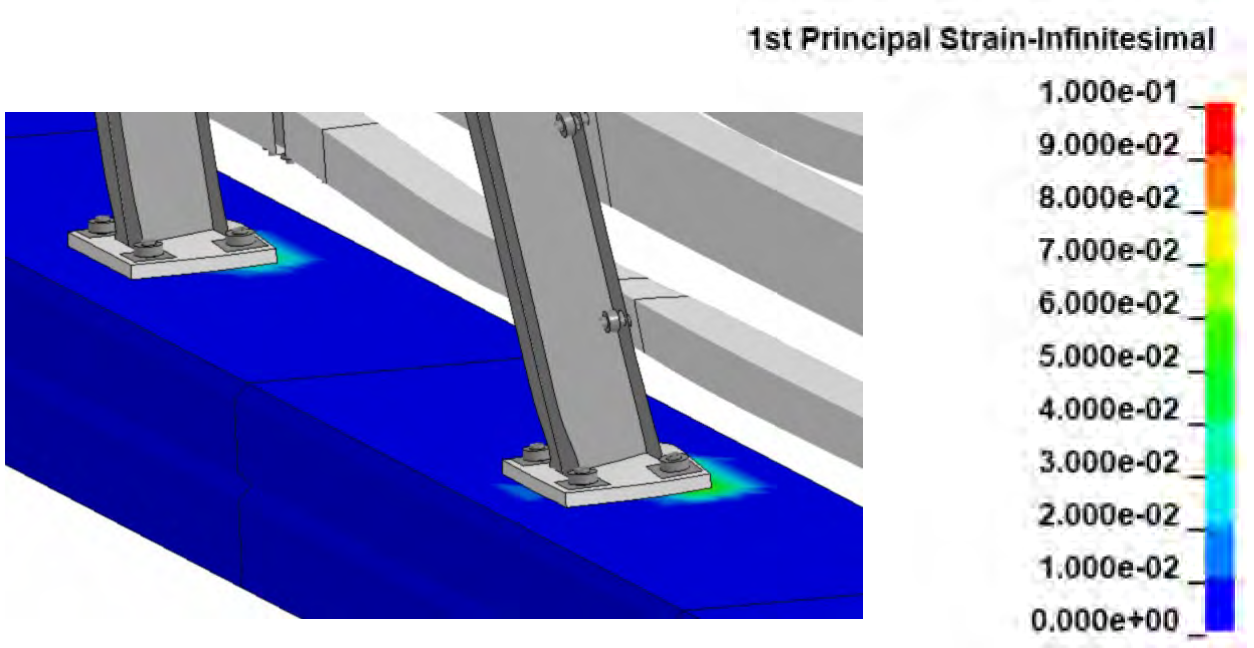
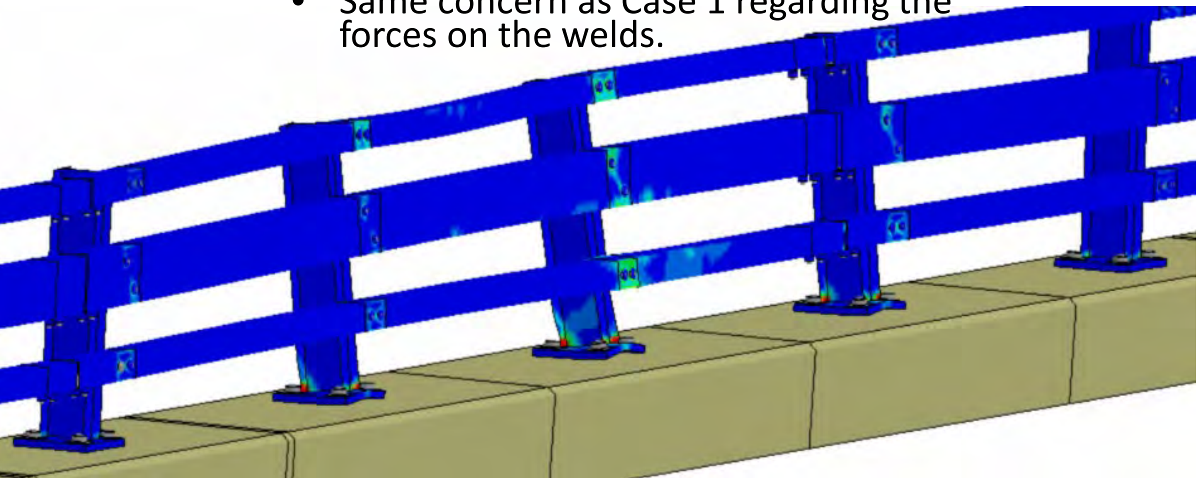
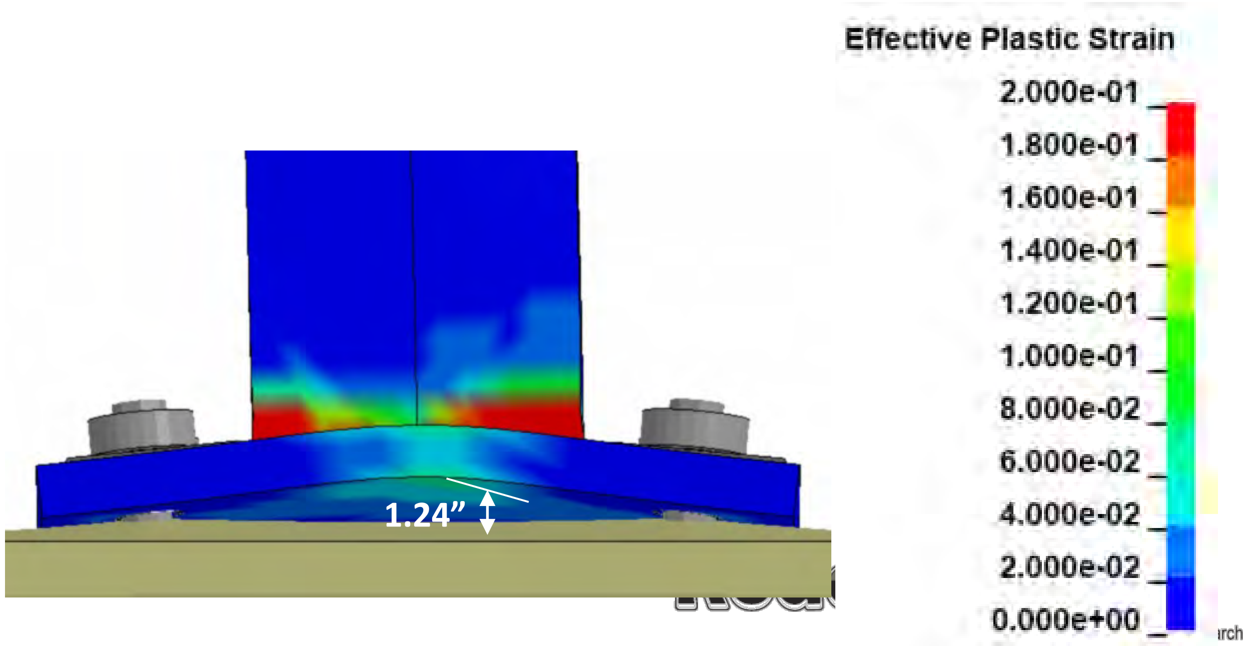
Barrier Damage

Case 2 – Bed Height = 50”:

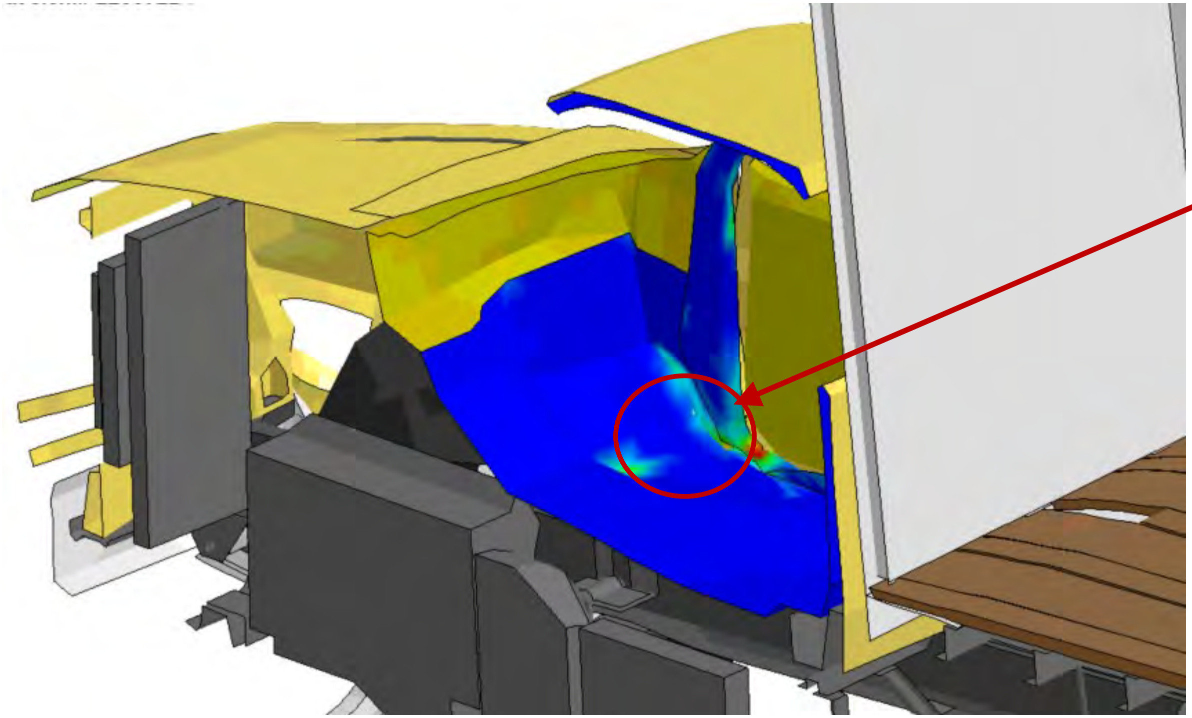
- Analysis resulted in notable concrete damage at two posts.
  - Potential cracks at front anchor bolts and/or anchor pullout.
- There was also significant damage to the posts and base plates at three post locations.
  - The post flanges buckled at the welded connection to the base plate.
  - Vertical deflection of base plate:
    - Dynamic = 1.24 inches
    - Permanent = 0.91 inches
  - Same concern as Case 1 regarding the forces on the welds.







Occupant Compartment Intrusion (OCI)

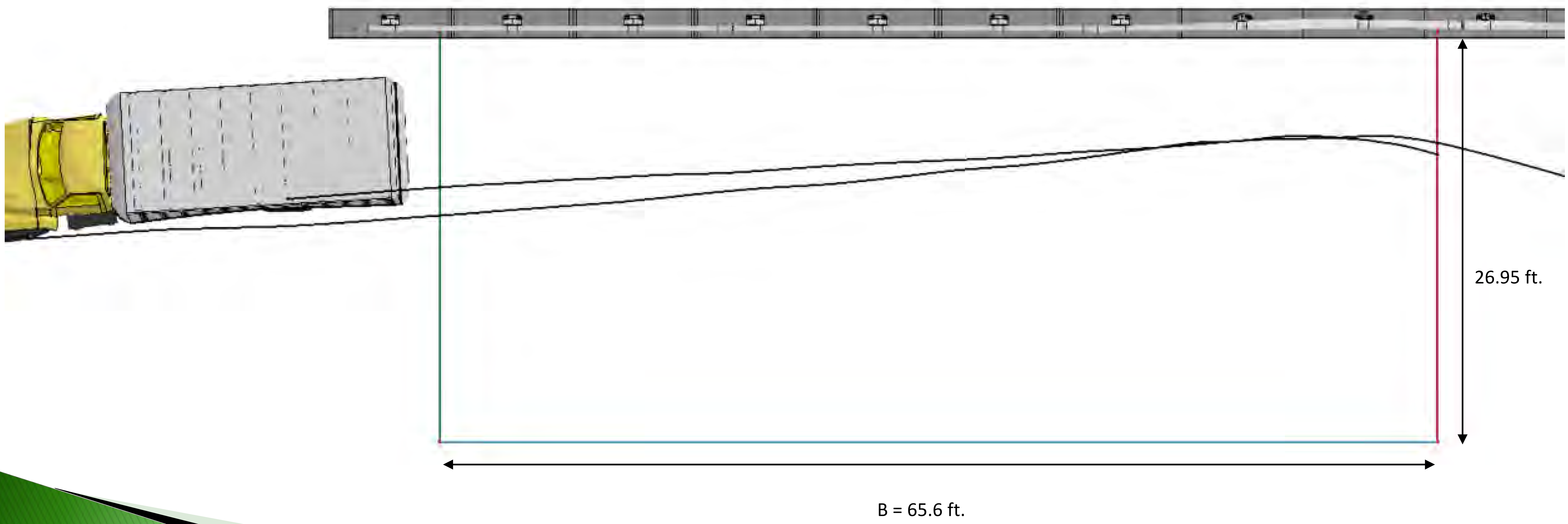


<u>Case 1 (47.5”):</u>
Maximum OCI was ≈ 1 inch (27 mm) and occurred at the lower right-front corner of the top-pan at the wheel well.

<u>Case 2 (50”)</u>:
Maximum OCI was 3.27” (83 mm) and occurred at the floor pan near the lower-front edge of the door.

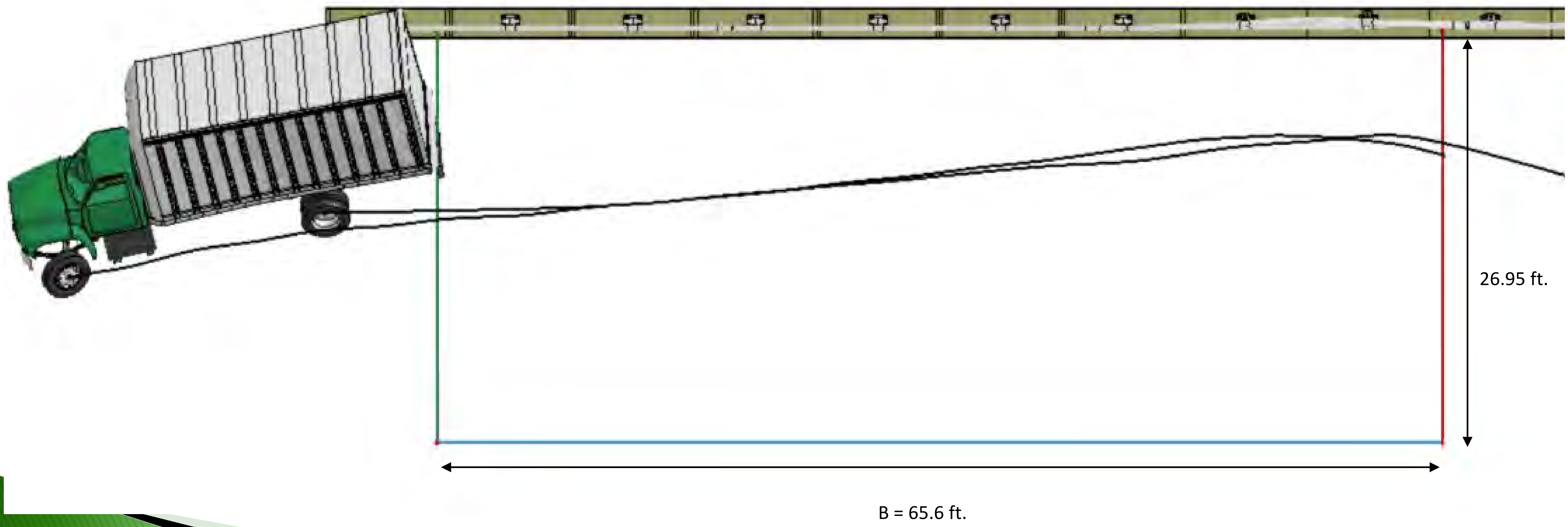
Exit Box – Bed Height = 47.5” – Test 4-12

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.”



Exit Box – Bed Height = 50” – 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 3-Bar

- The analysis showed that barrier adequately contained and redirected the 10,000S vehicle.
- Occupant compartment intrusion was negligible.
- The **maximum roll angle** of the vehicle:
  - Case 1 (Bed Height = 47.5”) = 20.5 degrees.
  - Case 2 (Bed Height = 50.0”) = 90 degrees.
- The **maximum pitch angle** of the vehicle:
  - Case 1 (Bed Height = 47.5”) = 5.9 degrees.
  - Case 2 (Bed Height = 50.0”) = 6.9 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 8.1 inches.*
  - *Maximum permanent barrier deflection of 6.6 inches.*

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

Evaluation Factors		Evaluation Criteria – MASH Test 4-12	Results Case 1/ Case 2
Structural Adequacy	A	Test article should contain and redirect the vehicle or bring the vehicle to a controlled stop; the vehicle should not penetrate, underride, or override the installation although controlled lateral deflection of the test article is acceptable.	Pass/Pass
Occupant Risk	D	Detached elements, fragments, or other debris from the test article should not penetrate or show potential for penetrating the occupant compartment, or present undue hazard to other traffic, pedestrians, or personnel in a work zone. Deformations of, or intrusions into, to occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.	Pass/Pass
	G	It is preferable, although not essential, that the vehicle remain upright during and after collision.	Pass/Fail

Conclusions for Overall Barrier Performance

- MASH Requirements:
  - Structural Adequacy: (PASS)
    - The barrier successfully contained and redirected the vehicle in all test cases, with controlled lateral deflections for the pickup and SUT tests.
  - Occupant Risk (PASS)
    - Occupant compartment intrusion was well below allowable limits
    - OIV and ORA
      - Small Car : OIV (within critical limits); ORA (within preferred limits) (*<u>values highly dependent on time of occupant impact</u>*)
      - Pickup: OIV (within preferred limits); ORA (within preferred limits)
  - Vehicle Trajectory (PASS)
    - Small car: Vehicle remained upright and stable through impact and redirection, with relatively low angular displacements.
    - Pickup: Vehicle remained upright and stable through impact and redirection, with relatively low angular displacements.
    - SUT: Vehicle remained upright and relatively stable for Case 1 (47.5” bed height) but rolled onto its side for Case 2 (50” bed height). MASH “prefers that the vehicle remain upright, but it is not required.

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Conclusions for Overall Barrier Performance

- Barrier Damages:
  - The barrier experienced relatively high plastic deformations of the posts, rails and baseplates for the Pickup and SUT tests.
  - Lateral deflections were relatively high for the SUT case (e.g., 8.1 inches)
  - Concrete curb damage at two post locations was considered likely for the SUT test case (based on the 1st principle strain values in the concrete).
    - The damages corresponded to potential cracks around the front anchor bolts and/or anchor pullout.
- 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.

Considerations for Design Revisions

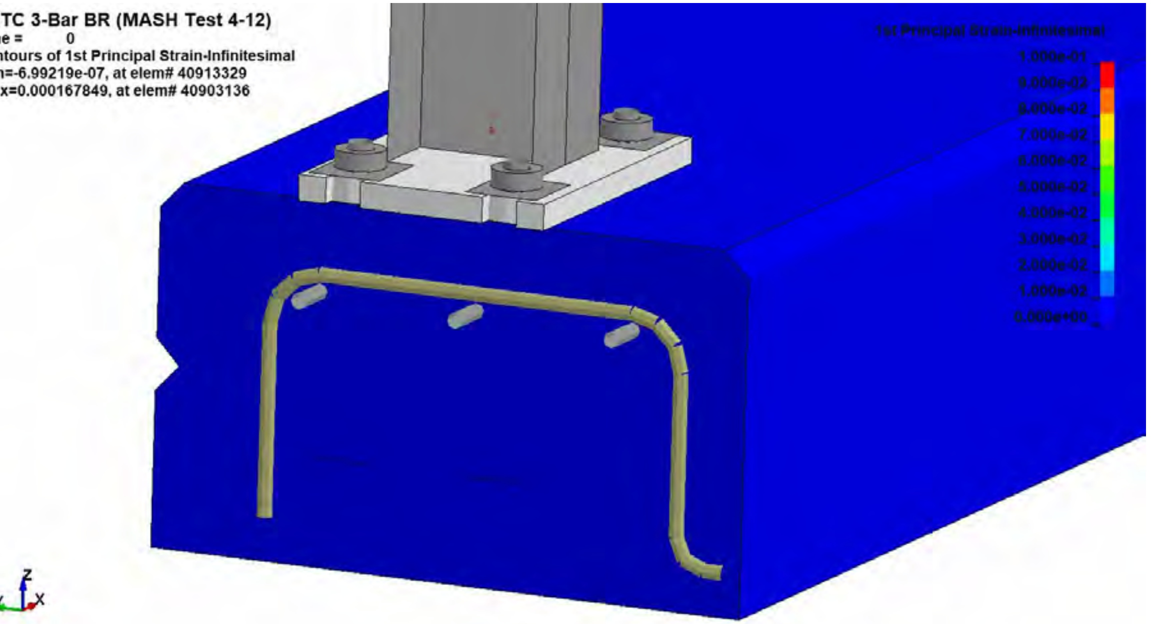
- **Baseplate**: Consider increasing thickness (e.g., 1.25 inches)
- **Anchor bolts**: Increase number to 5 with 3 on traffic side / Increase length
- **Post Spacing**: Decrease post spacing (e.g., 6.5 ft)
- **Tube rails:** Increase rail tube size to increase both the stiffness of the rail and the standoff distance from the post.
- **Concrete strength:** Increase from 4000 psi (e.g., 5000 or 5500 psi)
- **Curb/deck steel reinforcement:** Increase at the post locations and add longitudinal steel nearer to the anchor plates.

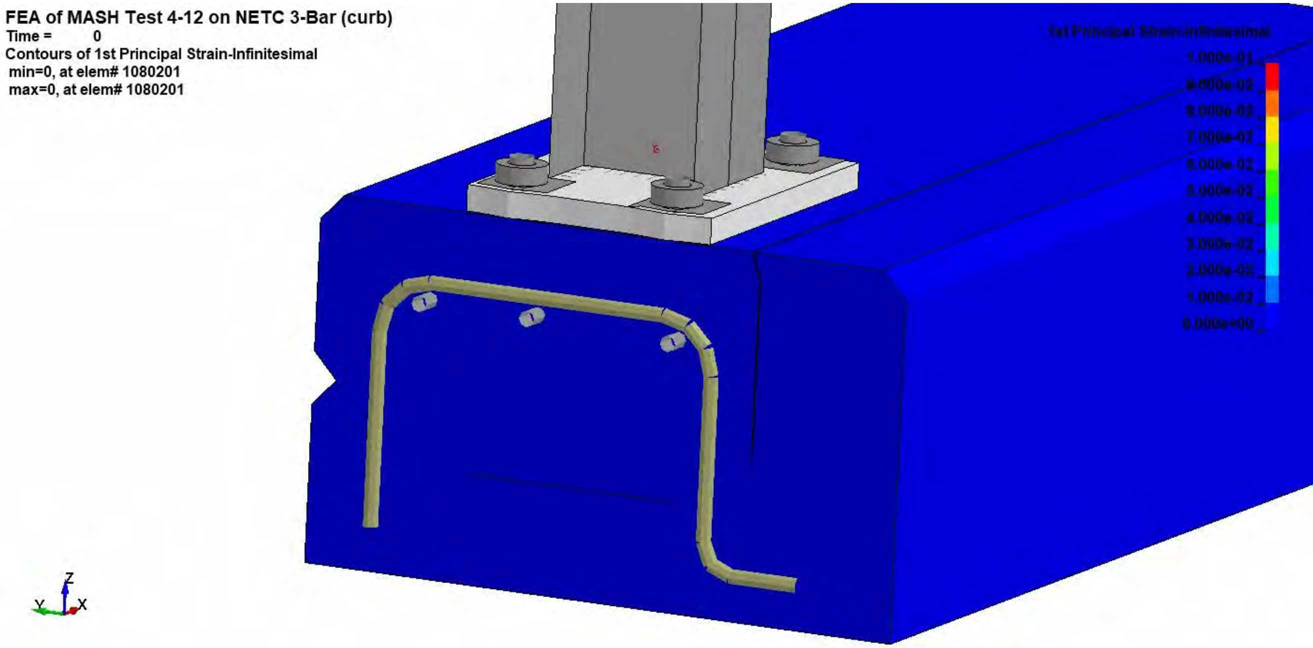
Supplemental Slides

Supplemental Analysis

With Weld Correction for Post-to-Base Plate

- Weld constraint was corrected.
- Strains on back flange were reduced.
- Strains on front flange essentially the same.
- Overall lateral deflections reduced by 0.5 inches (8%)
- Strains in concrete increased approximately 25% (Peak Strain = 0.1)





Revisiting the Strength Calculations

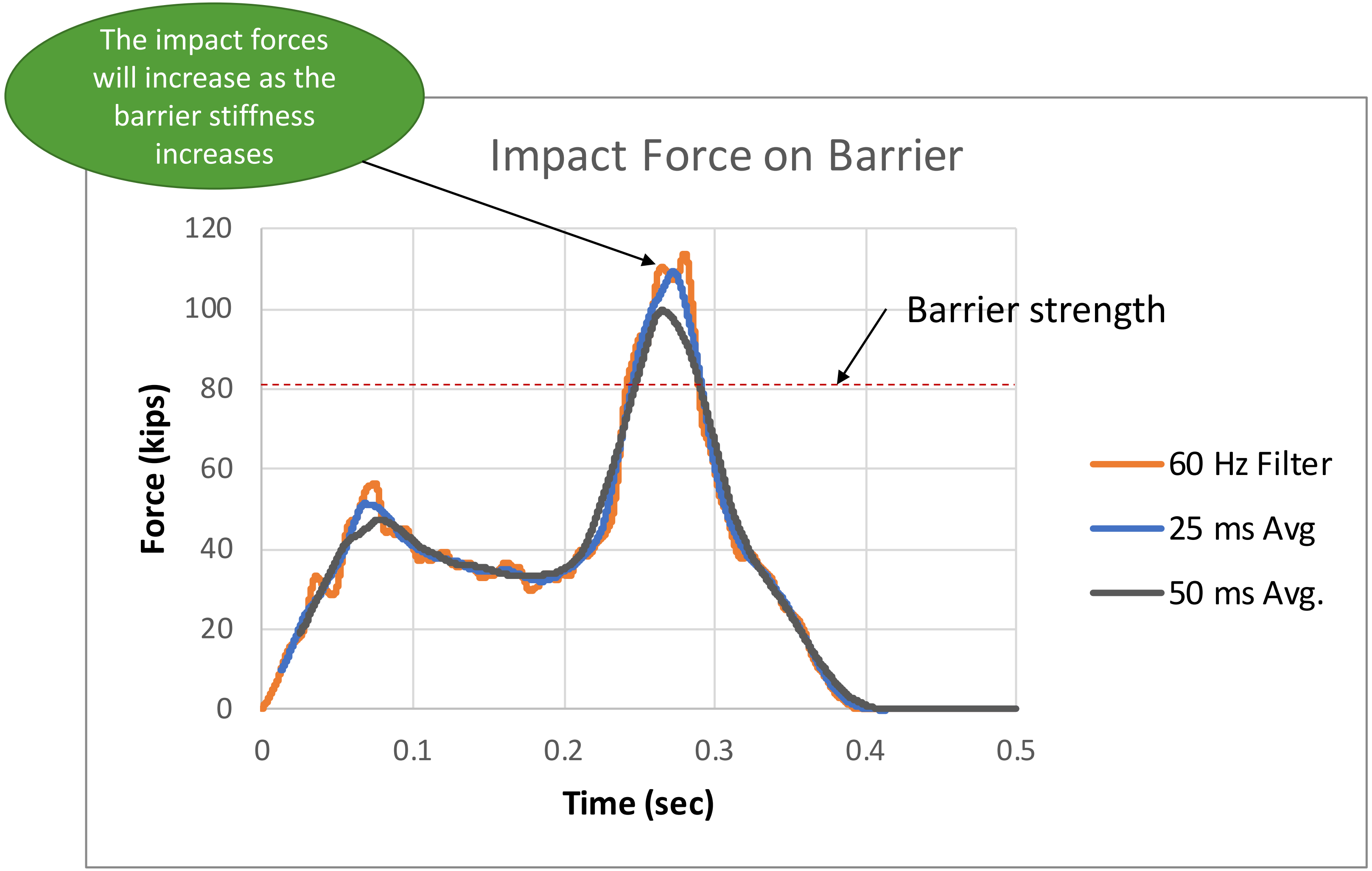
- The MASH TL4 strength calculations for this barrier was based on recommended design loads for a 42" tall barrier.
- These conditions assume that the bed of the SUT does not impact the side of the railing.
- The analysis, however, indicated that the vehicle would impact the side of the railing for both the 45.5" and 50" cargo-bed height cases
  - *(although the 50" bed height was close to passing over the top of the railing)*
- The strength calculations of the barrier assuming that the bed impacts the side of the top rail (as occurred in the FEA) requires <u>using "Tall" barrier design loads:</u>
  - Design Load = 93 kip
  - L_t = 14 ft
  - H_e = 40 in (i.e., height to mid-point of top rail)
- Yields a barrier strength of 80.4 kips which is less than the 93 kip design load.

Design Forces and Designations	Test Level 3			Test Level 4				
	Report 350[1]	Report 350[2]	MASH[3]	Report 350[1]	MASH[3]			
	Barrier Height (in)			Barrier Height (in)				
	all	all	all	all	36	39	42	Tall
F_t Transverse (kip)	54	61	71	54	67.2	72.3	79.1	93.3
F_L Longitudinal (kip)	18			18	21.6	23.6	26.8	27.5
F_v Vertical (kip)	4.5			18	37.8	32.7	22	N/A
L_t and L_L (ft)	4			3.5	4	5	5	14
H_e (in)	24	18	19.5	32	25.1	28.7	30.2	45.5

(1) *[AASHTO12]*
(2) *[Dolbrolvony17]*
(3) *[Sheikh11]*
N/A Not applicable

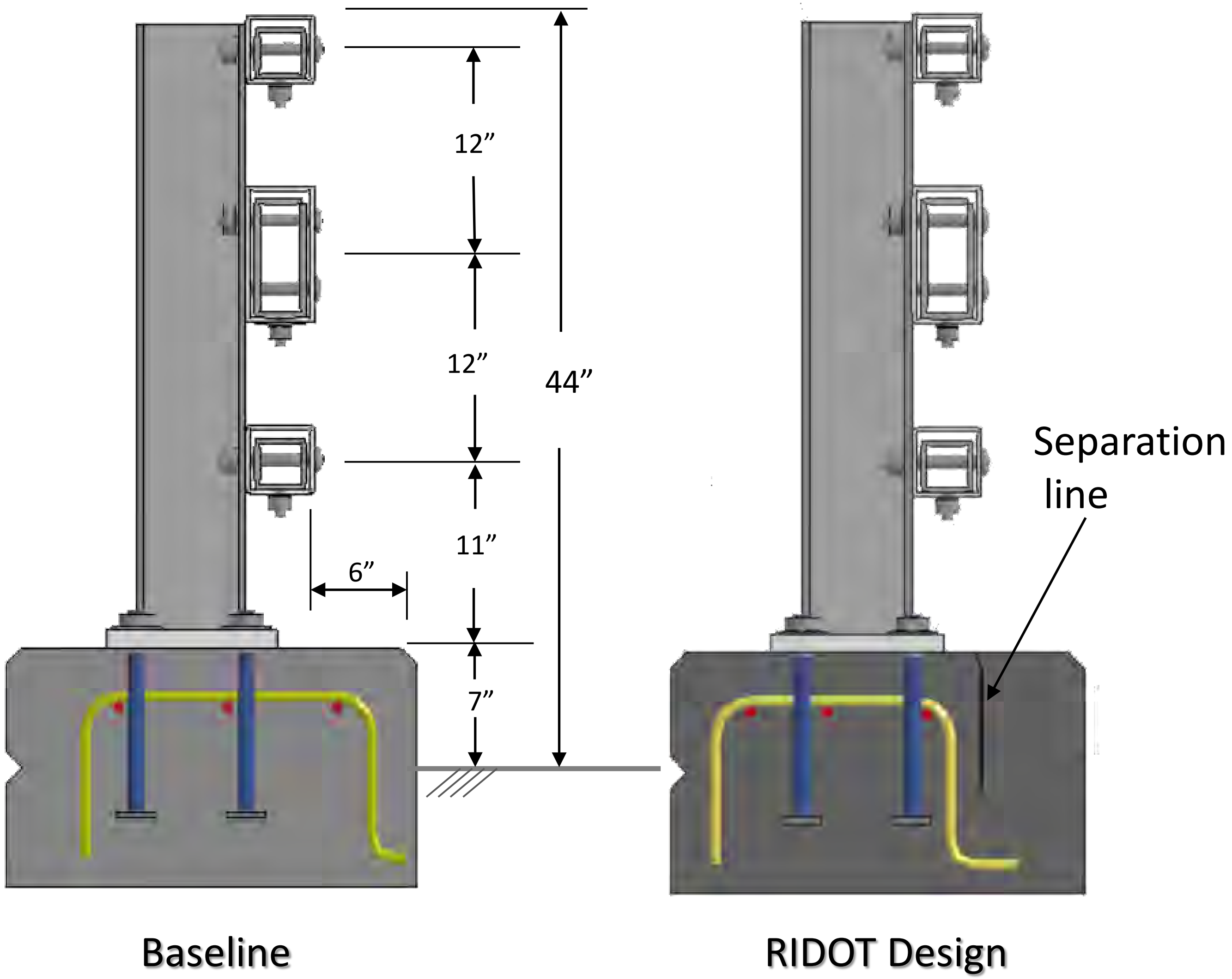
		Description	Variable	Units	3-Bar Bridge Rail (Design Loads for Tall Barrier)	
					NHDOT 3 Bar Curb Mounted	MaineDOT 3 Bar Curb Mounted
					Summary	Summary
	Summary of Strength by Component	Post Strength Based on Plastic Strength of Post	P_{p1}	kips	42.95	52.15
		Post Strength Based on Anchor Bolt Tension	P_{p2}	kips	49.54	62.64
		Post Strength based on Weld Strength	P_{p3}	kips	47.86	58.11
		Post Strength based on Pryout Shear Cone	P_{p4}	kips	38.46	39.77
		Post Strength based on Pushout Shear	P_{p5}	kips	50.09	52.20
		Post Strength based on Punching Shear	P_{p6}	kips	42.33	50.31
		Critical Plastic Strength of Post	P_p	**kips**	**38.46**	**39.77**
Bridge Railing Strength	Aussumed Multi-Span Failure Modes	Rail Strength based on failure of 1 rail span	$R'_{1\text{-Span}}$	kips	591.56	591.56
		Rail Strength based on failure of 2 rail spans	$R'_{2\text{-Span}}$	kips	134.11	136.44
		Rail Strength based on failure of 3 rail spans	$R'_{3\text{-Span}}$	kips	107.20	109.67
		Rail Strength based on failure of 4 rail spans	$R'_{4\text{-Span}}$	kips	122.13	125.48
		Rail Strength based on failure of 5 rail spans	$R'_{5\text{-Span}}$	kips	129.82	133.63
		Rail Strength based on failure of 6 rail spans	$R'_{6\text{-Span}}$	kips	149.52	154.12
		Crtitical Bridge Rail Strength at y_{bar} :	R'	kips	107.20	109.67
		Critical Bridge Rail Strength at H_e :	**R**	**kips**	**80.40**	**77.10**
		Strength Assessment for MASH TL-4			**FAIL**	**FAIL**

Impact Forces on Bridge Rail from FEA

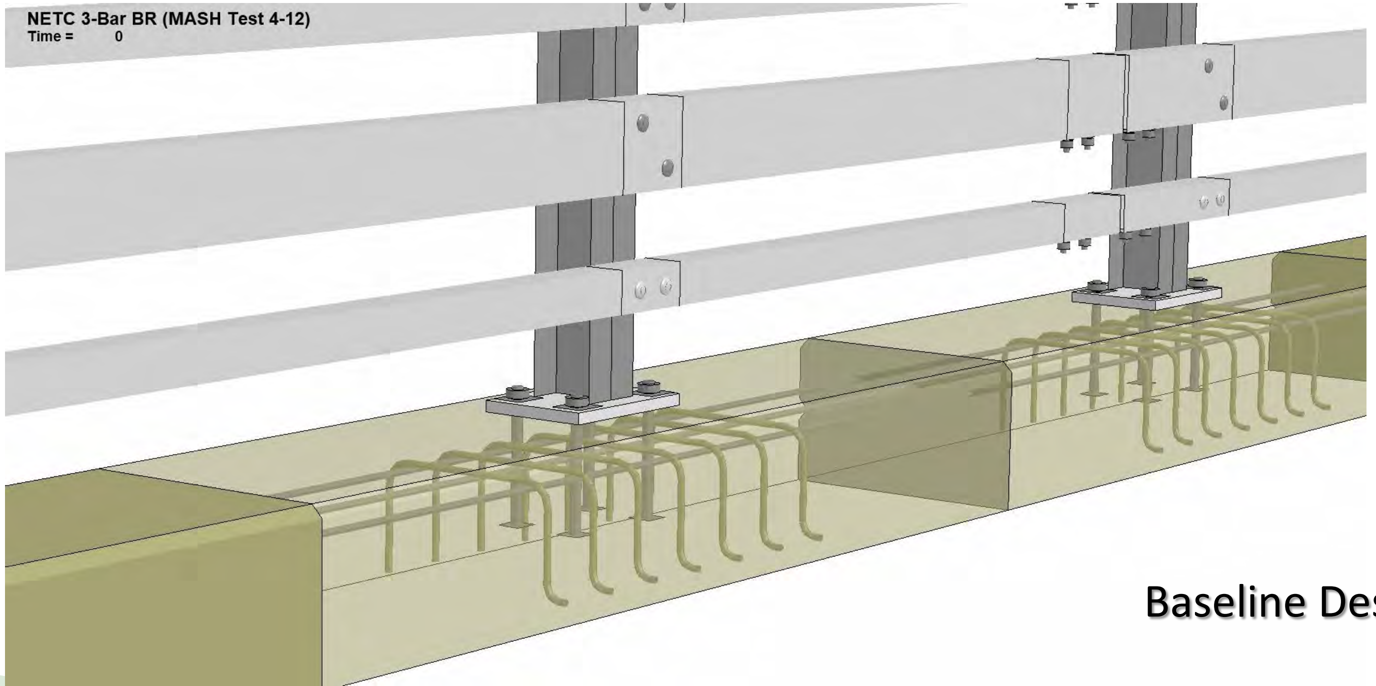


Assessment of Design with Stirrups Positioned Closer to Anchor Rods

- The design used in the analysis included stirrups that were extended relative to the width of the integral curb.
- The tested design included a 6” wide granite curb similar to the RIDOT design, in which the vertical portion of the stirrups was closer to the anchor rods.
- The RIDOT design was modeled and evaluated for Test 4-12 to assess concrete and anchor response.



Assessment of Design with Stirrups Positioned Closer to Anchor Rods



Baseline Design

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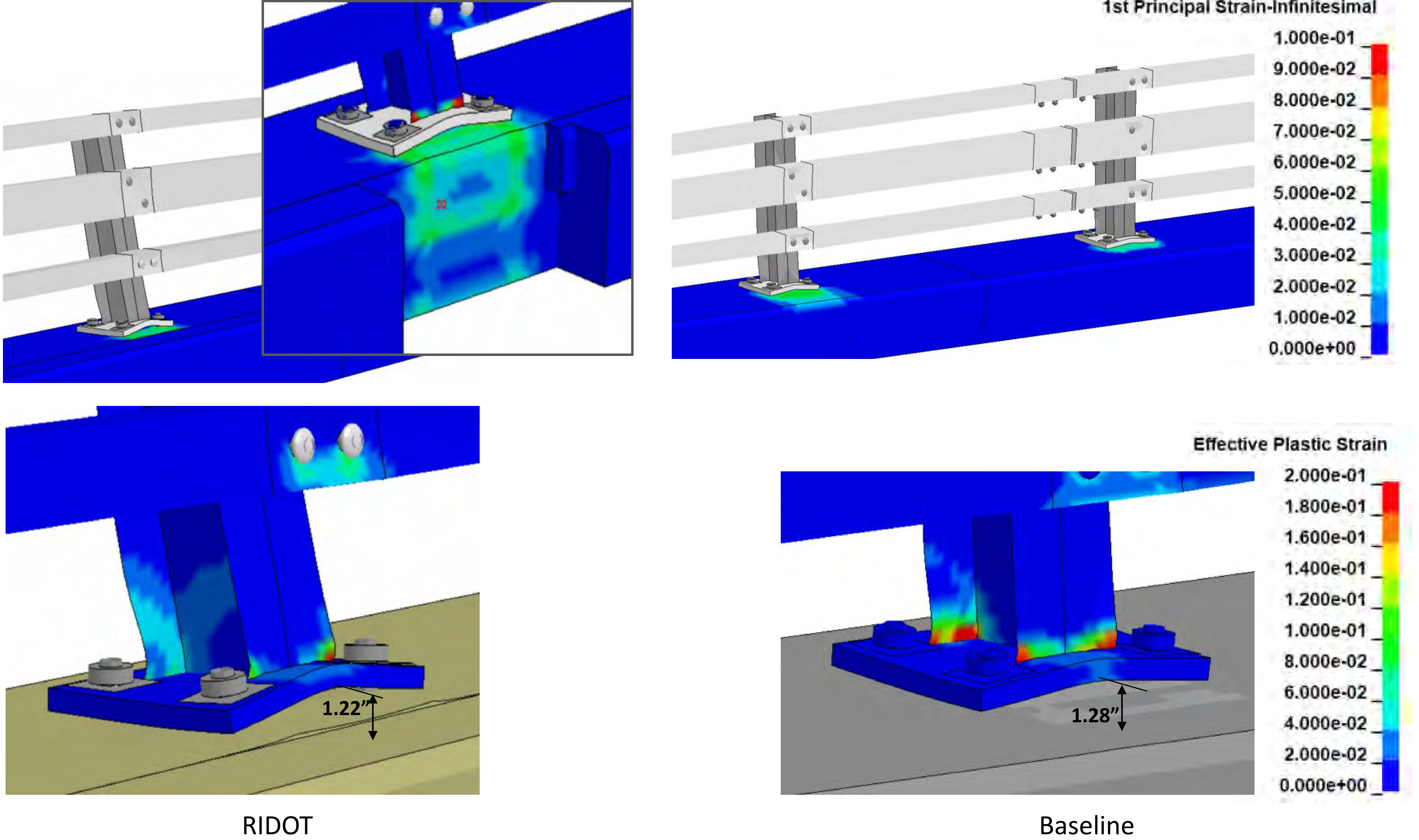

1st Principal Strain-Infinitesimal
1.000e-01
9.000e-02
8.000e-02
7.000e-02
6.000e-02
5.000e-02
4.000e-02
3.000e-02
2.000e-02
1.000e-02
0.000e+00
Effective Plastic Strain
2.000e-01
1.800e-01
1.600e-01
1.400e-01
1.200e-01
1.000e-01
8.000e-02
6.000e-02
4.000e-02
2.000e-02
0.000e+00
1.22”
1.28”
RIDOT
Baseline

Conclusions

- Shortening the stirrups so that the vertical leg of the stirrup on the traffic side of the curb is nearer to the anchor bolts resulted in decreasing total vertical deflection of the base plate approximately 5 percent.
- The lower deflections of the baseplate decreased the stress concentrations at the outside edges of the front flange (e.g., reduced weld stresses).