RUTGERS
THE STATE UNIVERSITY OF NEW JERSEY

More than a Pretty Face(ade): Meeting Safety & Historic Requirements in Concrete Barriers

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Outline

1. ***Background and Objectives***
2. ***Finite Element Modeling***
3. ***Experimental Setup***
4. ***Full-Scale Testing***
5. ***Model Validation***
6. ***Conclusions***

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RUTGERS Introduction and Problem Statement

- ❑ ***Many bridges built in the 1930's and 1940's are reaching the end of their design service lives, and need to be replaced or rehabilitated.***
  - ***Some of these bridges have historical significance, and must be preserved***
- ❑ ***The Pulaski Skyway in Jersey City, Hudson County, was built in 1932 and has been undergoing rehabilitation since April, 2014***
  - ***As a part of Pulaski Skyway Contract 2, the concrete balustrade must be replaced with a new, solid crash tested barrier***
  - ***The balustrade is crumbling and has not been tested to today's standards***

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RUTGERS Introduction and Problem Statement

- ***Current Balustrade Condition (NJDOT)***

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RUTGERS Introduction and Problem Statement

- *The Historical Preservation Office (HPO) mandated that the aesthetics of the original barrier be retained.*
  - *The original barrier would be retained, and a solid crash-tested barrier would be placed in front of it*
  - *This solution is not desirable because the view of the balustrade would be obstructed*
- *The optimal solution is to use an open-faced balustrade that has been crash tested*
  - *There are currently no open-faced balustrade designs that have been crash tested to the most current safety standards*
  - *The design must meet AASHTO Section 13 load requirements and NJDOT specifications*
  - *The new barrier design must pass a TL-4 collision specified in the AASHTO Manual for Assessing Safety Hardware (MASH)*

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RUTGERS Research Objectives

- ***Research Objectives***
  - *Provide an open balustrade design that would meet the requirements from both the Historic Preservation Office (HPO) (Aesthetics) and the Federal Highway Administration (FHWA) (Safety).*
  - *Develop a finite element (FE) model using LS-DYNA for crash test simulation, and conduct a parametric study to optimize the open balustrade design.*
  - *Calibrate and Validate the Finite Element Model using LS-DYNA in accordance with NCHRP Report W179: Procedures for Verification and Validation of Computer Simulations Used for Roadside Safety Applications*

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Introduction and Problem Statement

➢ *Crash Testing Criteria*

- ❑ *NCHRP Report 350 (1993) and NCHRP Project 22-14 (2002)*
- ❑ *On January 1, 2011 AASHTO MASH was adopted by the FHWA*
- ❑ *Below is a table of the 6 AASHTO MASH test levels and a comparison of NCHRP Report 350 and MASH TL-4 test parameters*
- ❑ *The SUT impact severity has a large increase between NCHRP 350 and MASH*
- ❑ *The small car and pickup truck collisions do not change much*

Test Level	Vehicle	Velocity	Angle
TL-1	1100C (passenger car) 2270P (pickup truck)	31 mi/hr [50 km/hr] 31 mi/hr [50 km/hr]	25° 25°
TL-2	1100C (passenger car) 2270P (pickup truck)	44 mi/hr [70 km/hr] 44 mi/hr [70 km/hr]	25° 25°
TL-3	1100C (passenger car) 2270P (pickup truck)	62 mi/hr [100 km/hr] 62 mi/hr [100 km/hr]	25° 25°
TL-4	1100C (passenger car) 2270P (pickup truck) 10000S (single-unit truck)	62 mi/hr [100 km/hr] 62 mi/hr [100 km/hr] 56 mi/hr [90 km/hr]	25° 25° 15°
TL-5	1100C (passenger car) 2270P (pickup truck) 36000V (tractor-van trailer)	62 mi/hr [100 km/hr] 62 mi/hr [100 km/hr] 50 mi/hr [80 km/hr]	25° 25° 15°
TL-6	1100C (passenger car) 2270P (pickup truck) 36000T (tractor-tanker trailer)	62 mi/hr [100 km/hr] 62 mi/hr [100 km/hr] 50 mi/hr [80 km/hr]	20° 25° 15°

	Parameter	NCHRP 350	AASHTO MASH
SUT	Vehicle Mass	8,000 kg	10,000 kg
	Impact Velocity	50 mph	56 mph
	Impact Angle	15°	15°
	CG height of ballast	63 in	67 in
Pickup	Vehicle Mass	2,000 kg	2,270 kg
	Impact Velocity	62 mph	62 mph
	Impact Angle	25°	25°
Small Car	Vehicle Mass	820 kg	1,100 kg
	Impact Velocity	62 mph	62 mph
	Impact Angle	20°	25°

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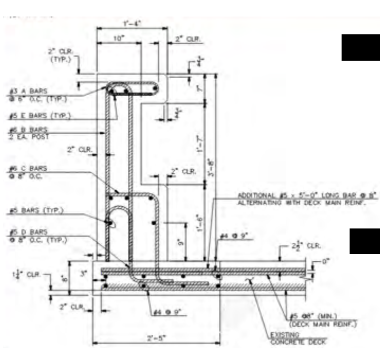
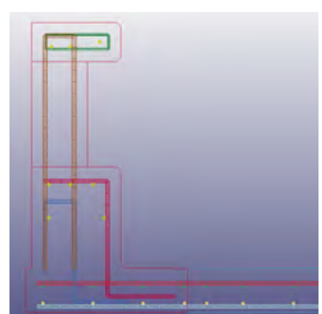
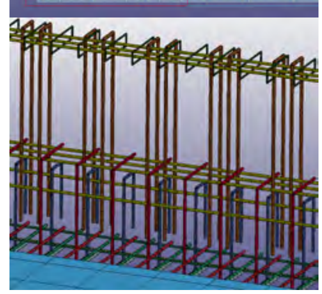
Finite Element Modeling

➢ *Modeling the Barrier - LS-DYNA*

- ❑ *After the materials are defined, the rebar is placed in the correct locations, and the barrier and deck concrete is modeled*







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Finite Element Modeling

➢ *Parametric Study*

- *A parametric study was performed to optimize performance and aesthetics of the balustrade design*
- *The first parameter evaluated was balustrade height*
  - *Heights tested include 42 inches, 43 inches, and 44 inches*
- *After height is decided, different post width and window opening combinations were evaluated*
- *The controlling case for barrier damage is the single unit truck collision, so this is the first vehicle to be tested and evaluated*
- *The baseline model for the parametric study has a total height of 44 inches, post width of 8 inches, and a window opening width of 6 inches*

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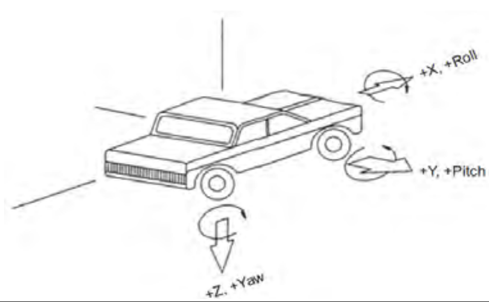
Finite Element Modeling

➢ *Parametric Study: Data Collection*

- *The time-history data is extracted from LS-PrePost then processed using the Test Risk Assessment Program (TRAP)*
  - *The accelerations are filtered using SAE Class 180 filter*
  - *Rotational rates are integrated to calculate the angle of rotation at different points in time*
- *Other criteria are checked visually or measured using LS-PrePost*
- *Below is the recommended vehicle coordinate sign convention and directions set forth in AASHTO MASH*



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Finite Element Modeling

- ***Parametric Study: SUT Height Comparison Results***
  - *The rolling in the 44 inch barrier was contained on the traffic side of the barrier and did not lean over like the other two*
  - *Because it did not lean, it was deflected back into the lane faster*
  - *In the 42 and 43 inch cases, the rear tires hit the barrier and begin the rolling "tripping" motion, but when the height is increased to 44 inches, the box hits and the vehicle is better contained*

Result: 44 inches

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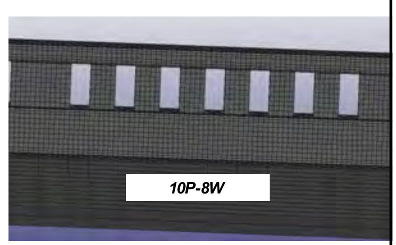
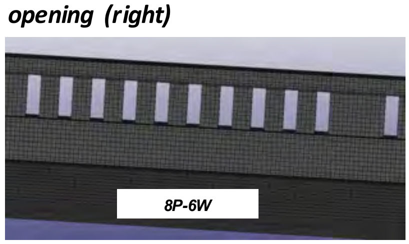
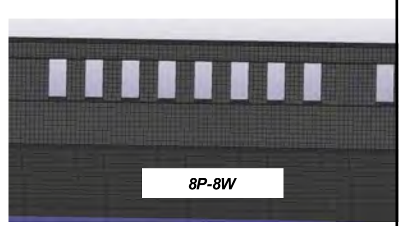
Finite Element Modeling

- ***Parametric Study: SUT Post Width and Window Opening Comparisons***
  - *Because the 10 inch post width is larger than the 8 inch one, and the better looking 8 inch post already delivers the required capacity, there is no need to simulate the 10 inch post barriers.*
  - *Two post width and barrier combinations will be tested with the 44 inch high barrier:*
    - *8 inch post width with a 6 inch window opening (left)*
    - *8 inch post width with an 8 inch window opening (right)*







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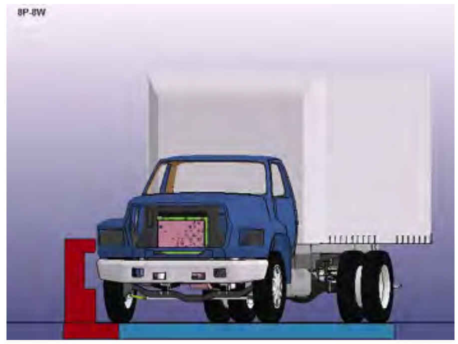
Finite Element Modeling

- *Parametric Study: SUT Post Width and Window Opening Comparisons*



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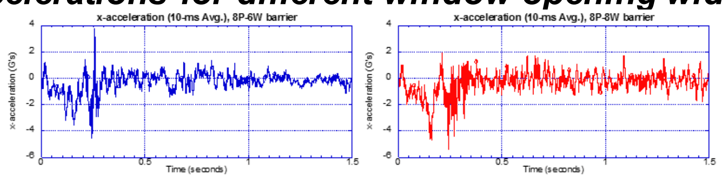
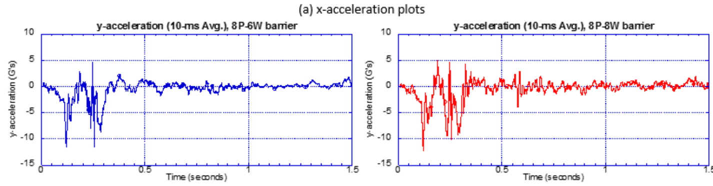
Finite Element Modeling

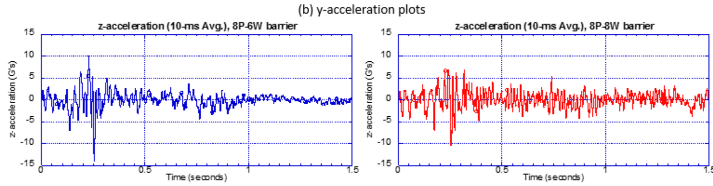
- *Parametric Study: SUT Time-History comparison of accelerations for different window opening widths*



(a) x-acceleration plots



(b) y-acceleration plots



(c) z-acceleration plots

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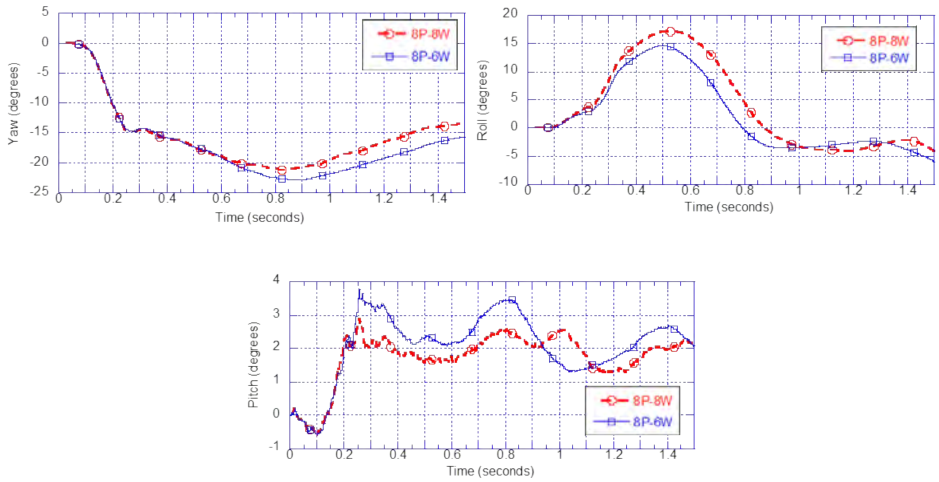
RUTGERS — Finite Element Modeling

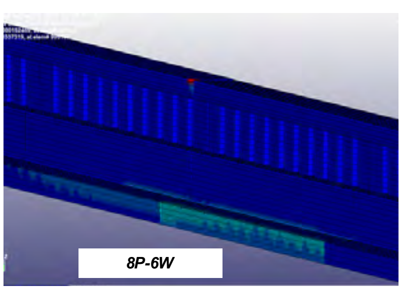
➢ ***Parametric Study: SUT Time-History comparison of Rotations for different window opening widths***

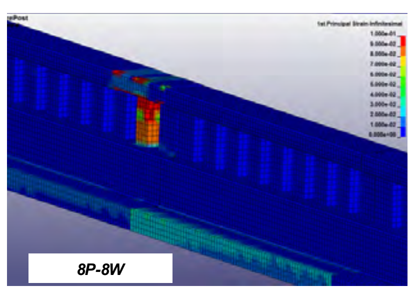


RUTGERS — Finite Element Modeling

➢ ***Parametric Study: SUT Window Opening Comparison Results***

- ❑ *Vehicle behavior was relatively unchanged*
- ❑ *The controlling factor when comparing window openings is damage*
- ❑ *The pictures below show the damage to each barrier after the single unit truck collision*





RUTGERS — Finite Element Modeling

- **_Parametric Study: All Vehicles_**
  - **_Single Unit Truck:_**
    - **_Barrier Chosen: 44 inch height, 8 inch post width, 6 inch window_**
  - **_Pickup Truck:_**
    - **_Barrier Chosen: 44 inch height, 8 inch post width, 6 inch window_**
  - **_Small Car:_**
    - **_Barrier Chosen: Any Height, 8 inch post width, 6 inch window_**

Final Design:

- **_Height = 44 inches_**
- **_Post Width = 8 inches_**
- **_Window Opening Width = 6 inches_**

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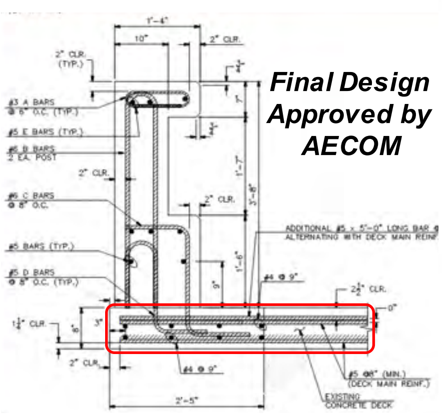
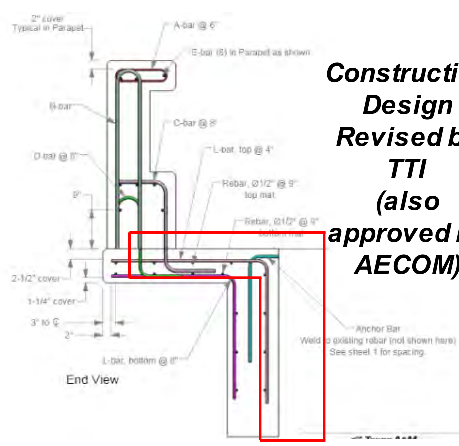
RUTGERS — Experimental Setup

- **_Design Changes_**
  - **_Design and rebar details inside the barrier did not change_**
  - **_Anchorage of the barrier at the testing facility changed_**
    - **_Barrier was secured to a rigid concrete apron and a bridge cantilever was simulated_**



Final Design Approved by AECOM



Construction Design Revised by TTI (also approved by AECOM)

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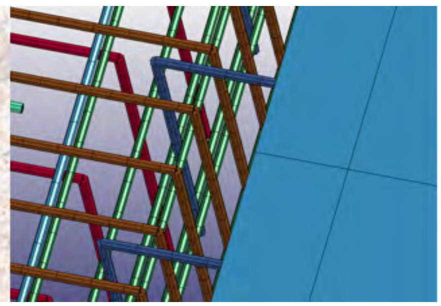
Experimental Setup

- ***Testing Setup***
  - ***Anchor bars were welded to dowels sticking out of the rigid concrete apron***
  - ***Deck bars were placed and bent downward to be developed in the wall***

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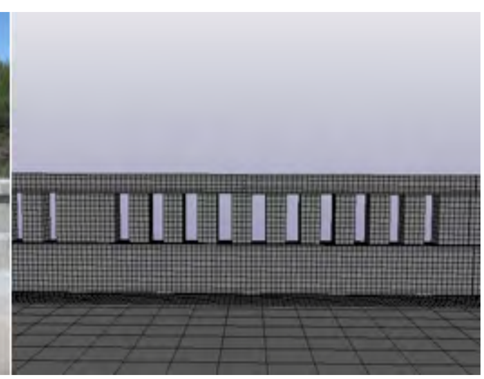
Experimental Setup

- ***Final Product***
  - ***Below shows the fully constructed barrier and its Finite Element Model Representation***

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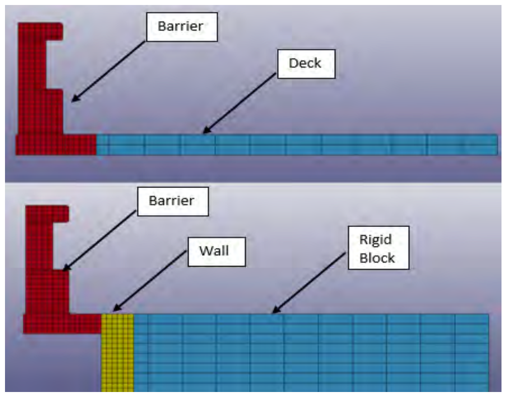
Experimental Setup

➢ *Final Product*

- ❑ ***Below shows the original and updated setup***
- ❑ ***Reinforcing steel material properties did not change***
- ❑ ***Concrete strength was updated to match field conditions***



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Construction of Barrier

During Construction ***Completion of Construction***

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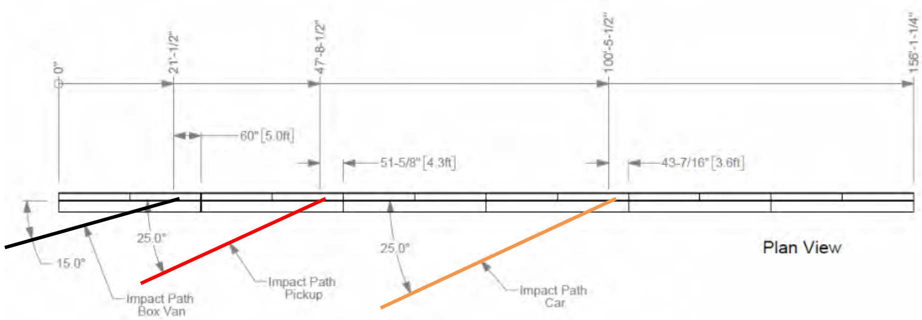
Testing Setup

Test Installation



SUT 12/16/16 **Pickup 12/20/16** **Car 12/21/16**

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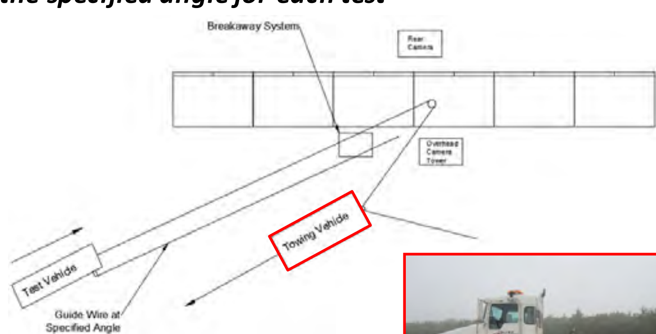
Experimental Setup

➢ ***Experimental Setup: Vehicle Propulsion and Guidance***

❑ ***The vehicle was towed toward the barrier using a 2:1 cable pulley system***

❑ ***The correct collision angle was achieved by the use of a guide wire set at the specified angle for each test***



RUTGERS — Full-Scale Crash Testing

- ***Vehicles: SUT***
- ***Vehicle Used: 2006 International 4200 Single Unit Box Truck***
- ***Vehicle Modeled: Report 350 Vehicle model modified to fulfill MASH Criteria***
- ***Modifications Performed:***
  - ***Shift ballast to the correct location***
  - ***Add more rigid constraints to the ballast for stability, and more were added to the accelerometer to reduce noise recorded***
  - ***Strengthen U-bolts attaching front axle to suspension leafs***
  - ***Contact friction coefficients were modified***

Model	Tires to Rail	Tires to Deck	Vehicle to Rail
Original	0.300	0.600	0.25
Modified	0.900	0.800	0.15

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RUTGERS — Full-Scale Crash Testing

- ***MASH Test 4-12***
  - Collided 5 ft upstream of first open-joint
  - Speed = 57.4 MPH (MASH 56 MPH)
  - Angle = 15.3 degrees (MASH 15 degrees)
  - Vehicle was successfully contained and redirected

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Full-Scale Crash Testing

- ***MASH Test 4-12***

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Full-Scale Crash Testing

- ***MASH Test 4-12: Damage***

Final Result: PASS

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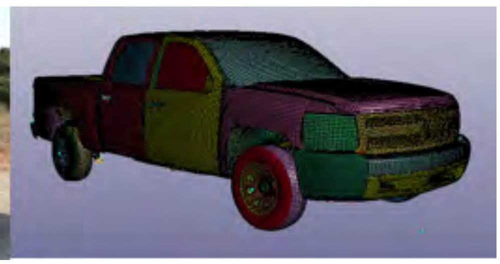
RUTGERS Full-Scale Crash Testing

- ***Vehicles: Pickup Truck***

- ❑ *Vehicle Used: 2011 Dodge Ram 1500 Quad-Cab*
- ❑ *Vehicle Modeled: 2007 Chevy Silverado*
- ❑ *Modifications Performed:*
  - *Add more rigid constraints to the accelerometer to reduce noise recorded*
  - *Contact friction coefficients were modified*

Model	Tires to Rail	Tires to Deck	Vehicle to Rail (static)	Vehicle to Rail (dynamic)
Original	0.400	0.600	0.200	0.100
Modified	0.160	0.800	0.110	0.110



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RUTGERS Full-Scale Crash Testing

- ***MASH Test 4-11***

- Collided 4.3 ft upstream of the second open-joint
- Speed = 62.5 MPH (<u>MASH 62 MPH</u>)
- Angle = 24.0 degrees (<u>MASH 25 degrees</u>)
- Vehicle was successfully contained and redirected

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Full-Scale Crash Testing

- ***MASH Test 4-11***

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Full-Scale Crash Testing

- ***MASH Test 4-11: Damage & Test Result***

Final Result: PASS

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Full-Scale Crash Testing

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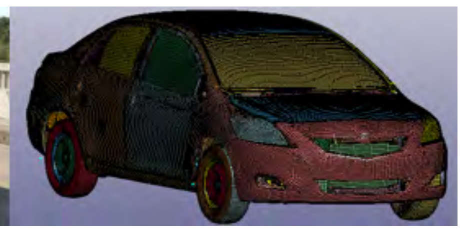
- **Vehicles: Small Car**
- *Vehicle Used: 2010 Kia Rio*
- *Vehicle Modeled: 2010 Toyota Yaris*
- *Modifications Performed:*
  - *Add more rigid constraints to the accelerometer to reduce noise recorded*
  - *Contact friction coefficients were modified*

Model	Tires to Rail	Tires to Deck	Vehicle to Rail (static)	Vehicle to Rail (dynamic)
Original	0.400	0.400	0.200	0.100
Modified	0.200	0.700	0.100	0.100



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Full-Scale Crash Testing

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- **MASH Test 4-10**

- Collided 3.6 ft upstream of the fourth open-joint
- Speed = 62.5 MPH (MASH 62 MPH)
- Angle = 25.0 degrees (MASH 25 degrees)
- Vehicle was successfully contained and redirected

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Full-Scale Crash Testing

- *MASH Test 4-10*

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Full-Scale Crash Testing

- *MASH Test 4-10: Damage*

Final Result: PASS

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Full-Scale Crash Testing

- ***MASH TL-4 Results***
  - *All three crash tests at TL-4 were successful and met the criteria set forth in MASH.*
  - *The barrier can now be used anywhere in the state of New Jersey where containment of a single unit truck is necessary.*
  - *The barrier will eventually be approved by the FHWA which means it could be adopted by other states*
  - *The FHWA announced that validated models for tested hardware can be used to evaluate retrofits*
    - *Re-testing hardware with retrofits is not necessary*

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Model Validation

- ***Validation Procedure***
- *There are three steps to perform when validating a crash scenario:*
  1. *Solution Verification*
     a) *Ensures the model is stable*
     b) *Verifies that all laws of physics are upheld*
  2. *Validating Time-History curves according to NCHRP Report w179*
     a) *Compares curves based on Sprague-Geers magnitude, phase, and comprehensive (MPC) metrics*
     b) *Compares curves using ANOVA metrics*
     c) *Calculations are performed using the Roadside Safety Verification and Validation Program (RSVVP)*
  3. *Phenomena Importance Ranking Tables (PIRT)*
     a) *Ensures the peak values for occupant risk criteria and vehicle behavior are in good agreement*
- *After all steps return an affirmative result, the model is considered validated*

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Model Validation

- ***Validation of SUT***

Time = 0.0 seconds | *Time = 0.1 seconds* | *Time = 0.2 seconds* | *Time = 0.3 seconds* | *Time = 0.4 seconds*

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Model Validation

- ***Validation of Pickup Truck – PASSED***

Time = 0.0 seconds | *Time = 0.1 seconds* | *Time = 0.2 seconds* | *Time = 0.3 seconds*

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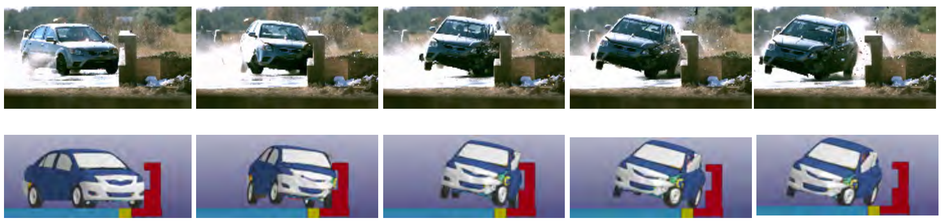
Model Validation

➢ ***Validation of Small Car – PASSED***



Time = 0.0 seconds *Time = 0.1 seconds* *Time = 0.2 seconds* *Time = 0.3 seconds* *Time = 0.4 seconds*

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Summary of Deliverables

➢ ***Summary***

- ***All three crash tests at TL-4 were successfully performed and met the criteria set forth in MASH.***
- ***The team has modified the truck models as well as the barrier model to reflect the actual test setup.***
- ***The team has finished the validation of crash scenarios with test data for all three crash tests.***
- ***The team submitted a request to FHWA for barrier approval (expected soon)***

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Conclusions

- **Conclusions**
  - ***As barrier height increases, stability of impacting vehicles also increases***
  - ***Dynamic finite element modeling is a good tool for predicting the nature of real-world situations***
  - ***Although models are good at predicting behavior in a crash test, they are still not a substitute for full-scale tests***
  - ***A computer simulation validated with full-scale test data CAN replace a full-scale test***

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Future Tasks

- **Future Tasks**
  - ***Designing a guardrail transition terminal***
    - *A Thrie beam rail transition is needed to redirect vehicles away from the concrete rail end*
    - *Impacts with rail ends are very severe and in a lot of cases, deadly*
    - *The unique shape of our barrier profile makes a new design necessary*

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Future Tasks

- ***Future Tasks***
  - ***Check Barrier with MASH TL-5 using LS-DYNA Model***
  - ***Crash Test at MASH TL-5 , if Model provides Acceptable Results***
  - ***Model and Validate Temporary Steel Barriers that are not crash-tested to validate their applicability***

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Acknowledgements

The RIME Group would like to thank the New Jersey Department of Transportation (NJDOT) for their support on this project. Their financial support and the technical assistance of NJDOT staff, Giri Venkiteela, Paul Thomas, David Mudge, and Lynn Middleton, are gratefully acknowledged. The team also acknowledge the help of AECOM and their staff, Geroge Sholy and Jitesh Shah.

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Questions?

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