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Route 139 Rehabilitation: Pulaski Skyway Contract 2

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16. Abstract

After being outside and exposed to the elements during many years of service, concrete and the reinforcement within begins to deteriorate and corrode, which affects the performance of concrete bridge balustrades, especially those built in the 1930's and 1940's. Many of these old concrete balustrades are approaching the end of their design service lives. The Historic Preservation Office is trying to replace an important historical concrete balustrade on NJ Route 139/Hoboken Viaduct in Jersey City, Hudson County while retaining the historic appearance. At the same time, the new design must also satisfy the requirements of the target level crash test of AASHTO MASH TL-4 which was adopted by the FHWA on January 1, 2011.

In this study, the research team provides the open-faced balustrade design that will meet the aesthetic and safety requirements of both HPO and FHWA. The team incorporated the following four components: (1) Work/Coordinate with NJDOT and HPO to further develop the initial design alternative along with plans, specifications, and other appropriate documents. (2) Develop a detailed Finite Element (FE) model using LS-DYNA Software for crash test simulation. (3) Conduct a parametric study using the developed FE model to optimize the initial design alternative and evaluate the effects of various parameters on the overall performance of the concrete balustrade. Based on the simulation results, the team modified, enhanced, and optimized the initial design alternative and is attempting to obtain FHWA's approval of the optimized design alternative. The team has coordinated with the crash testing facility, Texas A&M Transportation Institute (TTI) for the actual crash testing at test level 4 (TL-4) in accordance with AASHTO MASH.

The barrier has been successfully crash tested, and the computer simulations have been validated. The outcome of this research is an optimized open balustrade design that meets the design safety and aesthetic criteria for AASHTO and HPO, respectively, as well as the crash test requirements for FHWA. The optimized deign will not only enable the New Jersey Department of Transportation (NJDOT) to use the HPO approved design in the Route 139 Rehabilitation project, but also enable NJDOT to replace other similar historic barriers while avoiding, or at least mitigating, the adverse effects to similar historic bridges.

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EXECUTIVE SUMMARY

During many years of service, the deterioration of concrete and embedded reinforcement would affect the performance of concrete balustrades, especially those that were built during the decades of the 1930's and 40's. Many old concrete balustrades are approaching the end of their design service life and need to be replaced with new balustrade. However, the new design of the balustrade needs to retain its historic appearance and aesthetics to be approved by the Historic Preservation Office (HPO) before construction. Moreover, the new balustrade design also needs to satisfy the requirements of a target level of crash tests in accordance with the American Association of State Highway Transportation Officials (AASHTO) Manual for Assessing Safety Hardware (MASH) adopted by the Federal Highway Administration (FHWA) on January 1, 2011.

The Hoboken Viaduct (Rt. 139) located in Jersey City Hudson County was constructed in 1932 as part of the Rt. 1/1&9 Historic Corridor with an open concrete balustrade along the length of the roadway. It was originally proposed to replace the existing balustrade with a solid crash-tested bridge railing during the Pulaski Contract 2 (formerly Rt. 139, Contract 3 Project). The HPO has previously approved the new bridge railing design with similar aesthetical appearance as the existing balustrade. Currently the existing balustrade is being replaced and the solid balustrade is being manufactured using a form liner to replicate the look of the existing open balustrade; however, the newly designed balustrade is also required to meet the current MASH crash test criteria for TL-4. Therefore, the Rutgers Infrastructure Monitoring and Evaluation (RIME) Team aimed at providing a balustrade design that would meet the aesthetics and safety requirements from both HPO and FHWA, respectively.

The scope of this project incorporates the components listed below:

- Coordinate with NJDOT and HPO to further develop the initial design alternatives along with plans, specifications, and other appropriate documents.
- Develop a detailed Finite Element (FE) model using LS-DYNA Software for crash test simulation.
- Conduct a parametric study using the developed FE model to optimize the initial design and evaluate the effects of various parameters on the overall performance of the concrete balustrade.
- Develop a final design alternative that meets aesthetic requirements of HPO and that also has a high probability of success under MASH TL-4 compliance testing.
- Submit the final design details to an outside consultant (AECOM) for review/modification.
- Coordinate with the crash test facility, Texas A&M Transportation Institute (TTI), to have the barrier constructed, perform full-scale crash tests per MASH TL-4 requirements to verify crash performance.

- Modify the FE analysis model as needed to replicate field conditions (e.g., actual filed boundary conditions, test vehicle geometric and mass properties, and impact speed and angle).
- Validate the FE models for use in future projects.

The research group conducted a detailed literature review about historic rehabilitation, preexisting open-faced balustrade designs, finite element crash test simulation, and full scale crash testing. A finite element model of the barrier was then developed and used to perform a parametric study to assess crash performance of the various aesthetic open-faced balustrade design options. The study resulted in an aesthetic design which was ultimately successfully full-scale crash tested at TTI according to MASH TL-4 criteria; the design is therefore eligible for use on federal-aid reimbursement projects as a MASH TL-4 system. Future work is needed to further evaluate the crashworthiness of the balustrade under higher severity impact conditions, (i.e., MASH TL-5 tractor-trailer test) and to develop a crashworthy rail terminal design for the system.

BACKGROUND

Many bridges in the United States were built in the 1930's and 1940's and are reaching the end of their design service lives. Since they have been built and operated, there have been many changes in the vehicles in terms of configurations, weights, and types of vehicles on the road. Average daily truck traffic has also increased greatly, and because of this the way bridges are designed and built have changed drastically. Accordingly, the AASHTO bridge design specifications has been updating to accommodate these changes and to increase the longevity and safety of the bridges economically. Because highway safety is a paramount concern, Section 13 of the AASHTO code deals specifically with railings used to bring vehicles to a safe controlled stop and to prevent vehicles from being driven off of the bridge.

Roadside safety barriers intended for use on the National Highway System (NHS) are required to be tested according to FHWA approved procedures and must meet all safety and capacity criteria. The first procedures document was published by the Highway Research Board in 1962. *[HRC 482, 1962]* These procedures have been revised three times, based on the ever evolving vehicle fleet, updates in vehicle and crash statistics, as well as advancements in roadside safety technology. The first two revisions were made by the National Cooperative Highway Research Program (NCHRP) starting in 1981 with NCHRP Report 230 and then in 1993 with NCHRP Report 350. The most recent update to the testing procedures is detailed in the AASHTO document *Manual for Assessing Safety Hardware (MASH)*, which was officially adopted by the FHWA in 2011.

Performing full-scale tests is expensive and time consuming. Therefore, to help ensure that the testing will be successful, finite element analysis is widely used in the industry to simulate crash test conditions and predict the response of the system so that the design can be improved and optimized prior to conducting the full-scale tests.

In recent years, many bridges are getting rehabilitated or replaced, and they need to have the old balustrades replaced to meet the modern day crashworthiness criteria. Some bridges being rehabilitated are classified as historic and have certain aesthetic features which make them sentimental to a specific city or town. The aesthetics make it more difficult to replace components of the bridge because typical specifications cannot be employed in some situations and the historical barriers do not comply with MASH requirement. In situations where this is the case, new components must be designed to maintain the original historical and aesthetic shape, while still complying with safety standards.

The Historic Preservation Office (HPO) has approved the Pulaski Skyway Contract 2 project that will replace the existing balustrade with a solid crash-tested parapet for use on the Hoboken Viaduct (Rt. 139) located in Jersey City in Hudson County. The New Jersey Department of Transportation (NJDOT), in response to providing context sensitive design alternatives, initiated a project to develop additional aesthetically pleasing bridge rail alternatives. The alternative balustrade design is based on the existing historic bridge with slight modifications. The proposed balustrade design was modeled and analyzed using finite element (FE) simulation and then constructed and crash-tested to MASH TL-4. This test requires both containment and stability, and non-overturning. Therefore, there was a need to develop a bridge balustrade that incorporates the following five major aspects:

1) Develop an open balustrade design with similar modern design options to fit the historic bridge aesthetics.

2) Avoid or mitigate the adverse effects to historic bridges in terms of structural, functional, historical, and environmental considerations.

3) Using the FE model developed in the overall framework, perform computer-based simulation of the proposed TL-4 design to ensure potentially positive outcome from the actual crash test.

4) Pass the crash test TL-4 in accordance with MASH.

5) The improved bridge railing could potentially be adopted by other states that face similar issues.

OBJECTIVES

The objective is to fulfill the commitment to the HPO, as part of the approval of the Pulaski Contract 2 (Rt. 139 Contract 3) Project, requiring the design and crash testing of an open faced balustrade that closely replicates the original open faced balustrade on Rt. 139/Hoboken Viaduct. Although this balustrade is being designed for Rt. 139/Hoboken Viaduct, if it is approved, it can become a standard design for NJDOT. Once it becomes a standard approved design detail, it can be used to replace similar historic looking balustrades anywhere in the state of New Jersey, and it may be adopted by other states as well. The research methodology can be broadly classified into the following key scopes:

- **Review designs of open-faced balustrades that other states have tested.** The research team has reviewed designs of balustrades other state agencies have developed, and chose one to investigate further.

- **Develop an initial design to model and test.** The research team, in coordination with NJDOT, modified an existing balustrade design from TXDOT and developed a spreadsheet to check that the initial design meets AASHTO capacity requirements. This design was used as the baseline.

- **Develop a detailed finite element model.** The research team has developed a detailed FE model of the initial design using LS-DYNA.

- **Conduct a parametric study by FE simulation.** The research team conducted a parametric study of the baseline model using LS-DYNA and studied the behavior of different balustrade shapes.

- **Select the final design for the HPO approval in terms of aesthetics appearance.** The HPO has approved the aesthetics of the balustrade design.

- **Perform a full scale crash test.** The research team has coordinated with Texas Transportation Institute (TTI) to perform the full scale test. A comprehensive report was provided.

- **Have the design certified by NJDOT and AECOM.** The balustrade design and crash testing results were reviewed, and the professional engineers at NJDOT and AECOM approved the final design.

LITERATURE REVIEW

The RIME Team has searched and found the most relevant literature as the first step in the development process to assemble and review current practice, technical literature, research findings of recently completed and ongoing projects, and procedures from domestic and foreign sources. Moreover, a complete literature search of all related research work done by FHWA, NCHRP, SHRP, and other DOT's regarding open faced concrete balustrade historic bridges has been completed.

Historic Bridge Rehabilitation

The preliminary literature search revealed that very little has been published that addresses specific evaluation criteria or guidelines for historic bridge rehabilitation or replacement. Rather, much of the existing body of literature describes particular rehabilitation projects or general approaches and considerations for historic bridge rehabilitation. Harshbarger et al. (2007) presents a literature search and findings of a survey on the current state of historic bridge rehabilitation or replacement decision-making by state and local transportation agencies, and nationally applicable decision-making guidelines for historic bridges.(1) The author proposed a decision-making process that considers the following factors:

1) Factors adversely affecting historical significance, such as aesthetic changes
2) Structural and functional considerations. The new components must meet AASHTO and FHWA requirements
3) Historical and environmental considerations
4) Decision-making thresholds considerations

Demond (1996) provides six alternative solutions to rehabilitate bridges when replacing a bridge is not desirable. (2) The six alternatives are listed and briefly described below:

1) **Rehabilitation (widening)** – Widening the existing structure (usually an overdesigned truss) to accommodate larger traffic volume.
2) **Rehabilitation (complimentary)** – Making traffic on the existing structure one way and building a similar bridge next to the original to handle traffic in the other direction.
3) **Twinning** – Similar to complimentary rehabilitation, but the new bridge as identical as possible to the original.
4) **Adaptive reuse** – Using the original bridge for something besides transportation.
5) **National landmark rehabilitation** – Maintaining the original appearance with minimal alterations to accommodate current highway standards.
6) **Removal and replacement with mitigation** – Salvaging components from the old bridge for use on a new bridge. This is done when functional requirements are too unreasonable to attain.

Open-Faced Balustrade Design

There are many kinds of rail designs that are practically used all over the U.S. The materials used vary from wood, concrete, steel W-beam, steel tube, aluminum, or a combination. The bridge railings using cast-in-place concrete, usually with higher level of crash resistance, are listed in Table 1 which is excerpted from the AASHTO-ARTBA-AGC Task Force 13 (TF13) Bridge Railing Guide website. In general, all the bridge rail systems shown in the 1993 AASHTO-ARTBA-AGC Guide to Standardized Barrier Hardware and the 2003 FHWA-CALTRANS Bridge Guide are included in the TF31 on-line guide along with all the materials from the earlier publications.

Table 1 - Bridge railings using cast-in-place concrete [http://guides.roadsafellc.com]

Name/Designator	Image	Mounting Type	Aesthetic	See Through	Test Spec./ Test Level
SBC04d TL-4 F Shape		Deck	No	No	R350/TL4
SBC04e TL-5 F Shape		Deck	No	No	R350/TL5
SBC05d TL-4 Safety Shape		Deck	No	No	R350/TL4
SBC05e TL-5 Safety Shape		Parapet	No	No	R350/TL5
SBC07b TX T411		Parapet	Yes	Yes	R350/TL3
SBC07c Natchez Trace Bridge Rail		Parapet	Yes	Yes	R350/TL3
SBC07d TX F411		Deck	Yes	Yes	R350/TL4
SBC12b CA Type 80 SW		Parapet	Yes	Yes	R350/TL2
SBC12d CA Type 80		Parapet	No	Yes	R350/TL4
SBC13d CA Type 732		Parapet	No	No	R350/TL4

Finite-Element Crash Test Simulation

As early as 1990's, the advances in crashworthiness and dynamic finite element analysis have allowed considerable modeling and simulation of vehicle impacts with roadside hardware. Eskandarian et al. (1997) described in detail the finite element models and the validation of a bogie test vehicle and its honeycomb material in impacts with an instrumented rigid pole. This model can be exercised in various simulations of crash scenarios for design optimization of roadside hardware. This validation also allows the use of the model for impacts with narrow objects, which is a critical aspect of crashes with roadside safety devices.(3)

Consolazio et al (2002) carried out several cycles of concept refinement for a portable concrete barrier system using non-linear dynamic finite element impact simulation (LS-DYNA) rather than expensive full scale crash testing. Issues such as ensuring stable vehicle redirection during impact, properly accounting for frictional effects (and associated energy dissipation), and monitoring system energy parameters are discussed together with corresponding example simulations. As shown in Figure 1, the simulation validated using results obtained from full-scale crash testing of the barrier demonstrate successful barrier performance.(4) Additionally, Consolazio and Nassif (2002) used computer-based simulations to finalize pioneering work on simulating 3D-4D that was used for the proper design of highway sign support systems by simulating driver's vision and perception of the sight distance and vision.

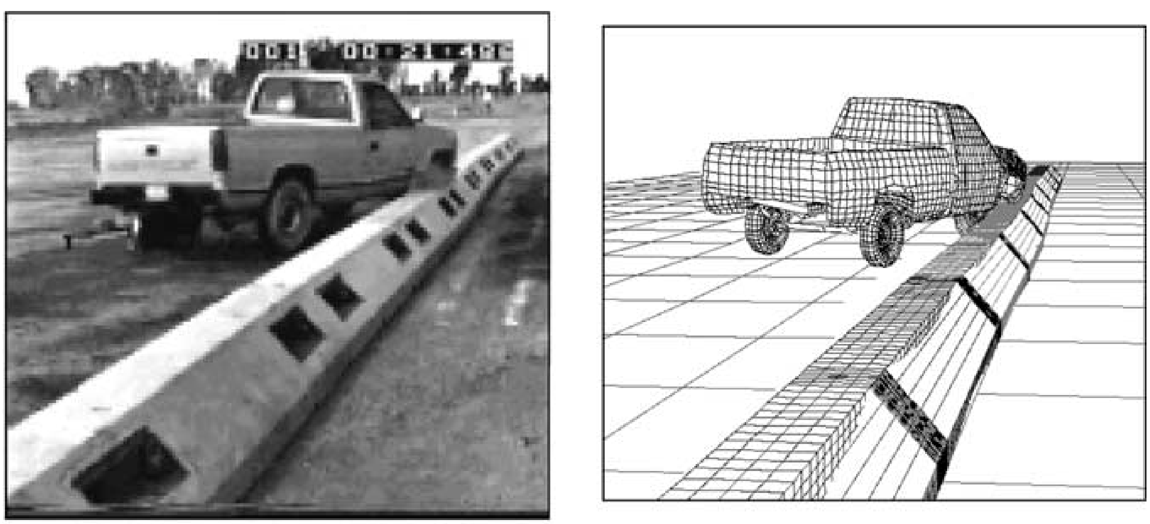


Figure 1. Comparison of crash test results and simulation results for 2000P vehicle.

Atahan (2006) developed a finite-element representation of the crash-tested barrier with a special fillet weld with failure model and subjected to crash testing using the nonlinear finite-element code LS-DYNA. This baseline model simulation was intended to replicate the failed crash test and validate the fidelity of the finite-element models. Qualitative and quantitative comparisons show that the baseline model simulation was successful in replicating the failed crash test. Upon validation, an improved NYPCB model was developed by using proper welding details and subjected to full-scale impact simulation to determine whether this design would satisfy the crash testing requirements. Results of the simulation were encouraging. It was predicted that the barrier would successfully contain and redirect the impacting vehicle in a stable manner.[5] Subsequent full-scale crash testing on the NYPCB with proper welding details passed the NCHRP Report 350 requirements and substantiated the LS-DYNA predictions (see Figure 2).

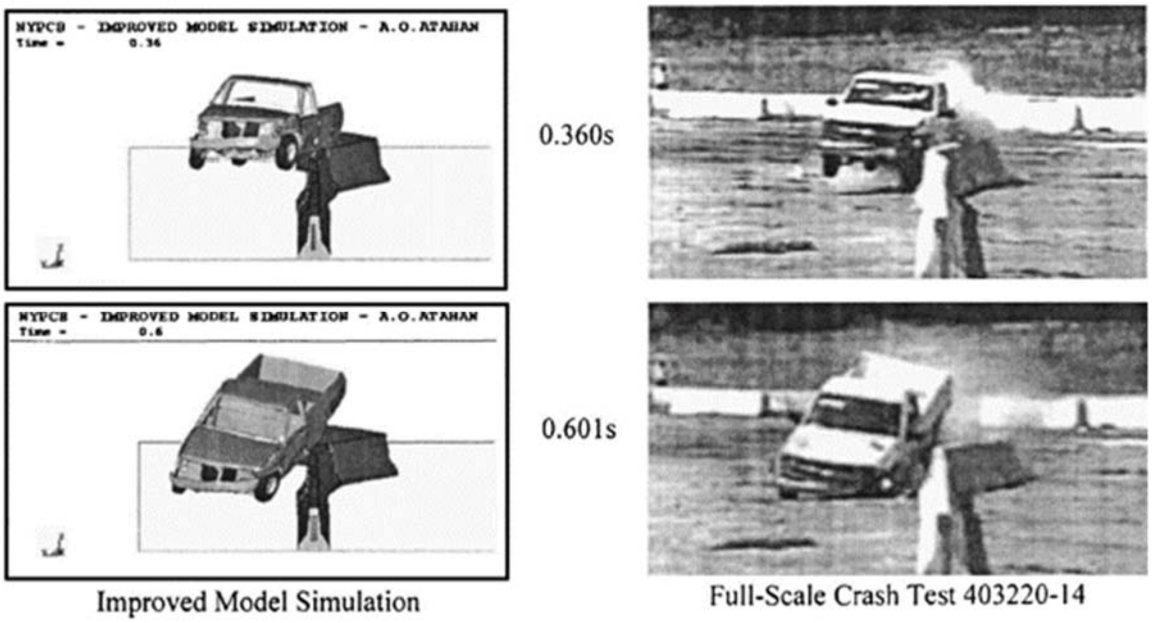


Figure 2. Comparison of improved model simulation versus crash test

Ray et al. (2009) conducted a study regarding the design and analysis of Annisquam River Bridge Railing in Minnesota. The authors developed a baseline finite element (FE) model of Annisquam River Bridge railing based on a previous approved Minnesota Test Level 3 bridge railing using LS-DYNA. The baseline FE model was validated with the full-scale crash test results. Furthermore, in order to evaluate the crashworthiness of various design alternatives, a series of six FE models were developed and FE analysis was performed. In addition, the resistance analysis based on procedure specified in AASHTO LRFD Bridge Design Specifications was also performed to verify the railing design. Overall, the analysis results from both FE simulation and AASHTO resistance analysis confirmed that the Annisquam Bridge satisfied the crash test requirement at TL-3 level in accordance with NCHRP Report 350.[6]

Ray et al (2010) developed guidelines for verification and validation of detailed finite element models used for crash simulations of roadside safety features. Crash simulations using finite element (FE) analysis have been used by different researchers and provided help to evaluate the safety performance of roadside safety hardware and features. In this study, the authors conducted a detailed literature review on comparison of metrics and repeatability of full-scale crash tests, hierarchical modeling, validation in the roadside safety literature, and verification process. The authors also conducted a survey with practitioners to collect the related information. Furthermore, the authors developed verification and validation procedures and investigated the uncertainties in measured test data and simulation responses. The concept of the recommended verification and validation guidelines was developed and calibrated with several selected crash simulations of roadside hardware designs. Moreover, the recommendations for implementation of hardware modification acceptance were provided.

Borovinsek et al (2007) evaluated the use of computer simulations to evaluate barrier designs according to European standard EN 1317. EN 1317 criteria defines safety in terms of containment level, impact severity, and deformation of the barrier after impact. Two vehicles are used to evaluate the barrier, a 900 kg personal car and a high mass vehicle such as a heavy goods vehicle or a bus. The heavy weight vehicle properties depend on the containment level being evaluated. Accelerometers were defined at the center of gravity of the vehicle and the barriers were modeled using mainly shell elements. Bolted connections were modeled with beam elements. Soil conditions are difficult to accurately model because they are always changing and hard to predict. Soil conditions were modeled with spring elements in different directions where the barrier was secured to the ground, and is shown in Figure 3. Contacts were defined where applicable and different reinforcements were evaluated. The reinforcements evaluated included a longitudinally placed tension belt, wheel guidance profile, and a single wire rope, which are shown in Figure 4.

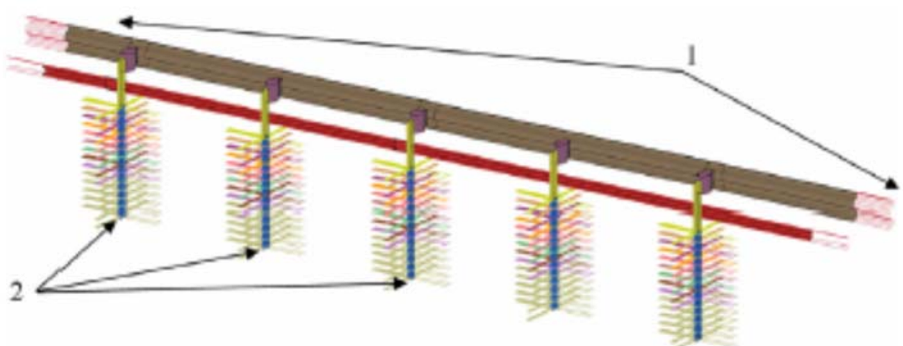


Figure 3. Spring elements used to simulate soil conditions

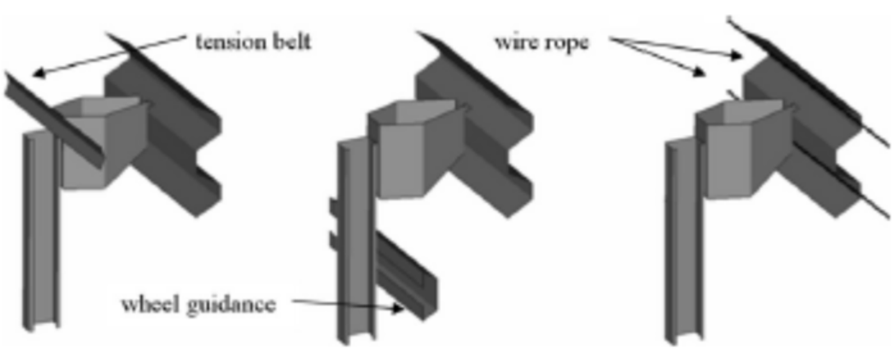


Figure 4. Guardrail reinforcement options evaluated

The wheel guidance system was chosen as the best option for containment level H1 and was certified later with a large scale test. The barrier performed acceptably and safely redirected the truck without any major parts separating from the barrier. The finite element models were compared to the experimental results and that the Acceleration severity index (ASI) time dependencies were in fairly good agreement and the values differed by less than the acceptable 10% margin. It was concluded that the computer simulations can be used to evaluate the experimental parameters with reasonable accuracy, and the use of simulations reduces the development and testing costs of new barrier designs.(7)

Ren and Vesenjak (2005) compared results of an LS-DYNA simulation and full scale crash test of a metal barrier according to European Standard EN 1317. The rail evaluated was composed of a W-shaped guardrail, distance spacers, and posts with 2/3 of their height rammed into the soil. Each section of the guard rail is 4.2 m long with a 0.2 m splice at each section. The material was defined using tensile test results of S 235 steel and an effective plastic strain of 0.28. When the effective plastic strain reaches this level, the load carrying capability of the element becomes zero, effectively removing it from the model. Viscoelastic springs were defined on the posts to simulate soil, and linear springs were defined at the ends of the guardrail to simulate the continuation of the rail. The vehicle evaluated and tested was a Fiat Uno impacting at 100 km/h at 20 degrees. When the full scale test and simulation were compared, there was very good agreement in the results and the model and it was determined that the model could be used for computational evaluation of other road safety barriers in the place of performing full scale tests.(8)

Itoh et al. (2006) performed a simulation and full scale crash test for a 1.1 meter high F-shaped barrier. As per Japanese testing standards, the vehicle to be used is a 25,000 kg truck impacting at 100 km/h at 15 degrees to produce 650 kJ of energy. However, due to limited pulling power available, the truck used was only 20,000 kg and the angle was changed to 17 degrees to produce 660 kJ of energy. In the model, the subgrade of the barrier was modeled with springs, and the simulation was run. The barrier showed satisfactory performance in the model, and when tested full-scale, the barrier was shown to meet all safety requirements.(9) The results from the models and experimental results were in good agreement, as shown in Figure 5.

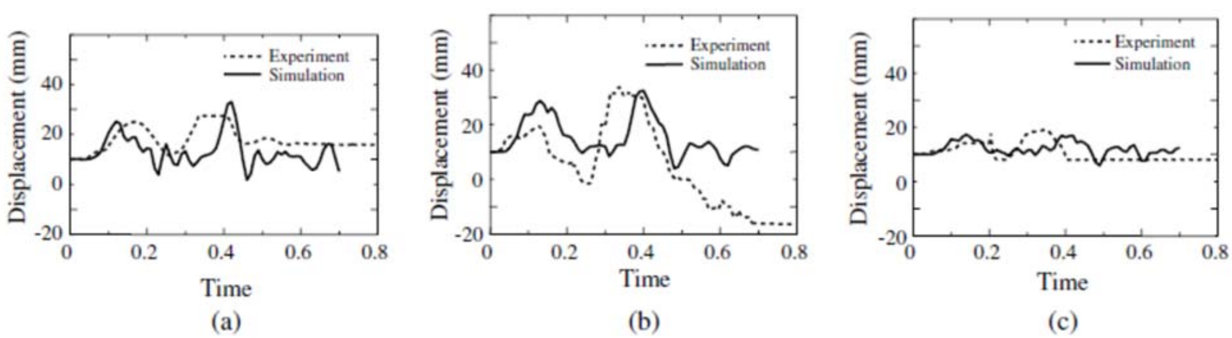


Figure 5. Comparison of experimental and simulation results

Marzougui et al (2012) evaluated the practicality of using finite element models to evaluate barrier retrofits. During NCHRP project 22-14(3), seven barriers previously accepted under NCHRP Report 350 were tested under MASH conditions, and three of them failed the pickup truck collision (Test 3-11). These collisions were then modeled using LS-DYNA and validated. Different retrofit options were then evaluated using these models to find a functional retrofit option. The FHWA recently announced that crash simulation results would be considered acceptable for evaluating improvements to previously tested barriers, which means there would be no need for another crash test.(10) Barrier models were made in LS-DYNA using the exact geometry and connection details as the barriers tested. The finite element model of the Chevy Silverado was tested and was accepted as an acceptable surrogate for the 2270P vehicle previously used. Two of the barriers that were investigated for retrofits include the G9 Thrie-beam barrier and the G4 median barrier. The G4 median barrier failed because the truck overrode the installation and the Thrie-beam barrier failed because the wheel snagged on the bottom of the barrier and caused the truck to roll 360 degrees. A comparison of between the models and tests is shown in Figure 6.

The visual comparison shown in Figure 6 is only the first step in validating the models and showing that they are successfully able to replicate the full-scale collisions. The second step to validation was to compare the graphs of the accelerations, and the roll, pitch, and yaw of the vehicle. The third step is to statistically compare the models with the experimental results by the use of Phenomena Importance Rating Tables (PIRT's). PIRT tables look at a variety of parameters measured to evaluate whether the values in the model fall close enough to the experimental values to be deemed valid. After evaluating different retrofit options, it was shown that the Thrie-beam rail could be retrofitted with a half-blockout to reduce roll, and the G4(1S) median barrier could be improved by increasing the height 3-in to prevent the truck from overriding the barrier.

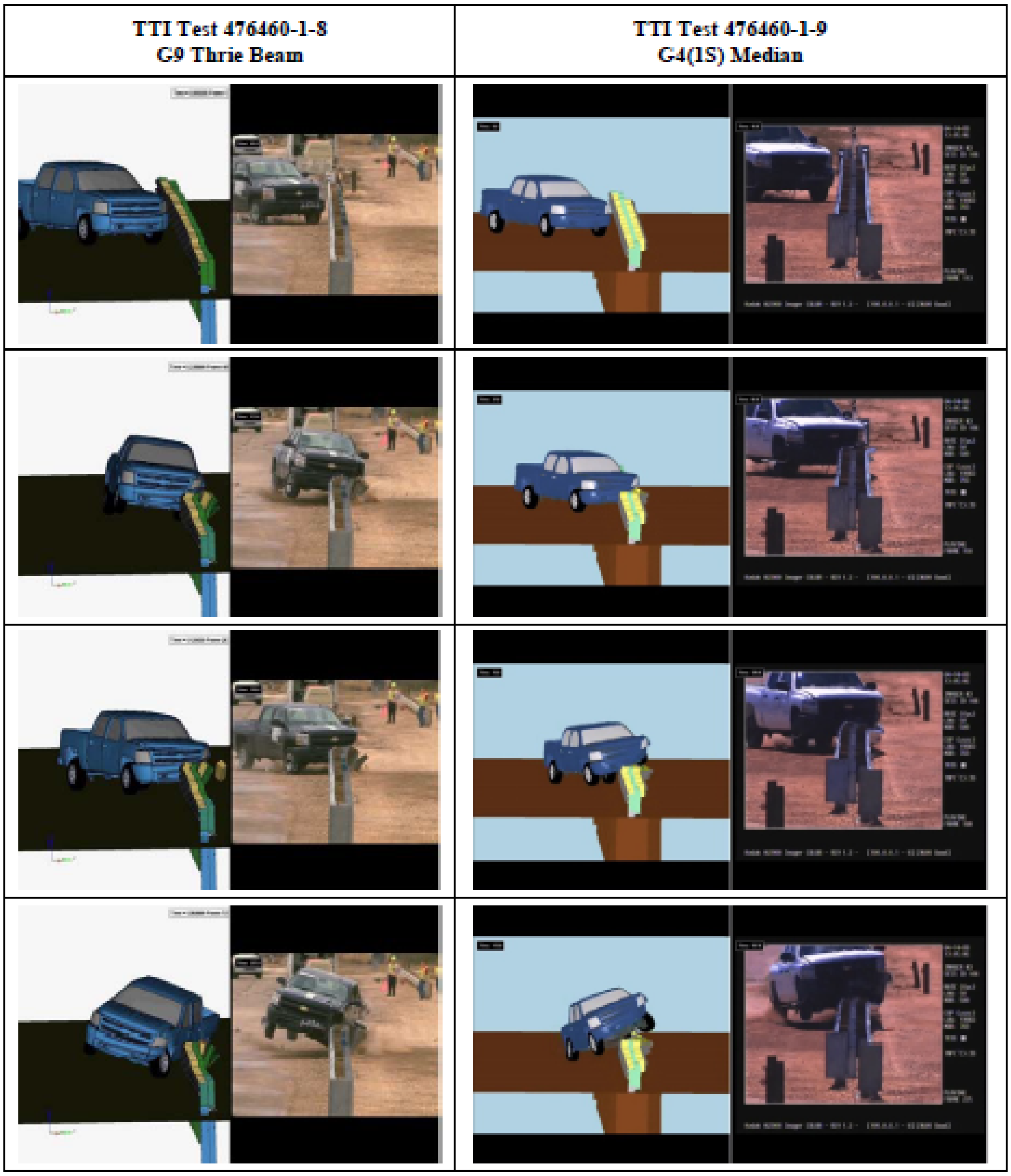


Figure 6. Comparison between models and full scale tests for G9 Thrie Beam and G4(1S) barriers

Marzougui et al (2014) evaluated the crashworthiness of roadside barriers previously accepted under NCHRP Report 350. The adoption of the new MASH requirements raises the question of whether this hardware still fulfills the safety requirements of the new standard. Because many of these previously accepted barriers are already in use, finite element models were used to investigate the crashworthiness under the new conditions. The 32-in New Jersey shaped barriers were evaluated under the MASH conditions. Tests 3-10 and 3-11 using a small car and pickup truck, respectively, were modeled in LS-DYNA, and compared to full-scale results. The barrier was modeled using rigid shell material because the deformation is very small when these vehicles are used, and the barrier was fixed at the bottom. Rigorous validation efforts were not undertaken for the research because the New Jersey shaped barriers were extensively used in other simulation studies.[11] The models were compared using visual comparisons, traditional metric comparison, and analytical comparisons using procedures outlined in NCHRP Project 22-24. The simulations for both tests were stable, showed no unusual behavior, and traditional and analytical validation efforts showed good agreement between the models and experimental results. The conclusion of this study was that finite element simulations provide a good representation of experimental setups, and that the New Jersey shaped barrier in question still passes the new MASH requirements.

Abu-Odeh (2008) conducted a study regarding how different concrete material models behaved in a bridge rail subjected to a bogie impact. In the past, concrete barriers were modeled using a rigid or elastic material characterization because it would reduce the computing time needed, and because there were no models that could accurately predict the behavior of the concrete that were not difficult to use. The author developed a finite element model of the TxDOT type T501 bridge rail and simulated a 5000 lb. bogie vehicle impacting it at 20 miles per hour using LS-DYNA. Three material models for concrete were simulated to investigate the accuracy of the predicted behavior. Each of these models required varying input to simulate. Some only required the unconfined compressive strength and density, while others required additional information. The conclusion of this study was that the models all predict, with reasonable accuracy, the behavior and deformation of the concrete after the impact with the bogie. The crack pattern each model predicted is very approximate, and none of them correctly mapped it, but the overall damage predicted was accurate.[12]

Borrvall et al (2011) investigated and evaluated the RHT concrete model that is available in LS-DYNA. They conducted a study to compare how the RHT model performed when a reinforced concrete plate was modeled and subjected to a blast load. The findings of this experiment were that the experimental results and model were in good agreement. When the damage is displayed in the simulation, there is good qualitative agreement between it and the experimental results. The pressure measured at the center of the block was higher than what the simulation displayed, but it was still in close enough agreement to be deemed acceptable. It was noted that this model could still be developed further to more accurately predict spalling, scabbing and crack prediction, but as far as showing overall damage and failed sections, this model is good.[13]

When modeling rebar, there are two methods that can be used: smeared and explicit. Schwer (2014) discussed these two methods in great detail and how they are input into models. Schwer provided a breakdown of the different methods of reinforcement shown in Figure 7.

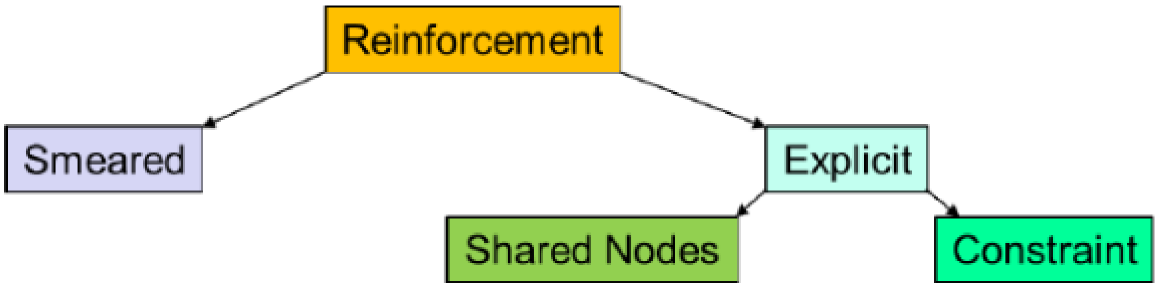


Figure 7. Breakdown of reinforcement modeling methods

Smeared reinforcement works well when the stress does not go too far beyond the yield stress. The reinforcement is modeled within the mesh of the concrete, and elements of concrete are given different material properties to act as steel. The concept of smeared reinforcement is that elements are given volume fraction average of material properties, e.g. yield strength, shear modulus, bulk modulus, etc. One material model used to model smeared reinforcement is *MAT_PSEUDO_TENSOR. The property averaging for this material is calculated via the relation

$$K = (1 - f_R)K_c + f_R K_R$$

Where K is the averaged volume bulk modulus, K_c is the concrete bulk modulus, K_R is the reinforcement bulk modulus, and f_R is the volume fraction of the reinforcement. The same format of averaging is used for all other material properties. Using this volume fraction average for the elements containing reinforcement treats these elements as a composite material. This method of averaging is accurate until yield occurs, and homogenization is lost.

The second method of including reinforcement is explicit reinforcement. To explicitly model reinforcement, section properties must be defined, and this section can then be used to model the rebar as either truss elements or beam elements. It can be modeled by using shared nodes or constraint methods. When using shared nodes, the meshing effort can become overwhelming, especially when there are multiple layers of reinforcement. When using this method, all nodes of the rebar must be coincident with nodes of concrete to be combined with them. This requires a lot of time and is very tedious.

The other method of explicitly modeling rebar is by the use of constraint methods. When using this method, the meshes of the concrete and reinforcement are completely independent of one another, and there is no need to have any coincident nodes. This makes the meshing very easy and fast. After the meshes are defined, the rebar is simply placed at the right location inside the concrete, and constrained. LS-DYNA provides the *ALE_COUPLING_NODAL_CONSTRAINT which locks the acceleration and velocity of the reinforcement nodes to the concrete nodes. In doing this, the relative motion of both materials is the same and this allows the concrete and steel to act as one unit, as they do in real life.

The author found that using a constraint method was the easiest and fastest method of modeling. Because the mesh refinement of the steel and concrete were performed independently of one another, it is accomplished faster than the smeared models, and the rebar placement is easier to accurately perform.(14)

Crash Testing

Since 1993, bridge railings have been crash tested and classified according the guidelines shown in NCHRP Report 350. Prior to 1993, bridge balustrades was evaluated using a somewhat different AASHTO testing criteria. The use of Report 350, however, standardized the testing of all roadside hardware such that the same basic test and evaluation criteria are used for all roadside hardware systems. Report 350 classifies bridge railings, as well as all other roadside hardware, according to six test levels. The test levels are based on a matrix of required crash tests involving different types of vehicles impacting the bridge railings at different speeds and angles.

The AASHTO Manual for Assessing Safety Hardware (MASH) is the standard guidelines for crash testing of permanent and temporary highway safety features as the replacement of NCHRP Report 350. Since January 1, 2011, FHWA adopted the AASHTO MASH as the standard for the crash testing for highway safety hardware. MASH was developed through National Cooperative Highway Research Program (NCHRP) Project 22-14(02), “Improvement of Procedures for the Safety-Performance Evaluation of Roadside Features,” It covers the evaluation of impact performance for various highway safety features. Regarding the TL-4 test that will be conducted in this study, the speed for the single unit truck test is increased from 80 km/h to 90 km/h. In addition, the small car impact angle is also increased from 20 to 25 degrees.

A summary of the six test levels as they apply to bridge railings is shown in Table 2. Prior to 1993, bridge railings were tested according to the AASHTO Guidelines for testing bridge railings, Report 230 or NCHRP Report 239. In 1997 the FHWA issued a memorandum describing equivalences between the earlier crash testing criteria and Report 350. Many of the bridge railing systems in the TF13 on-line guide were first tested and accepted for use under these earlier guide test guidelines.

Table 2 - A summary of crash test levels for bridge railings from MASH

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

Bullard et al. (2002) developed two aesthetically pleasing and crashworthy bridge rails for TXDOT. Researchers performed full-scale crash tests in accordance with NCHRP Report 350. The bridge rail, the Texas F411, has successfully passed TL3 and acceptably passed TL-4, and is ready for implementation (See Figure 8).[23]

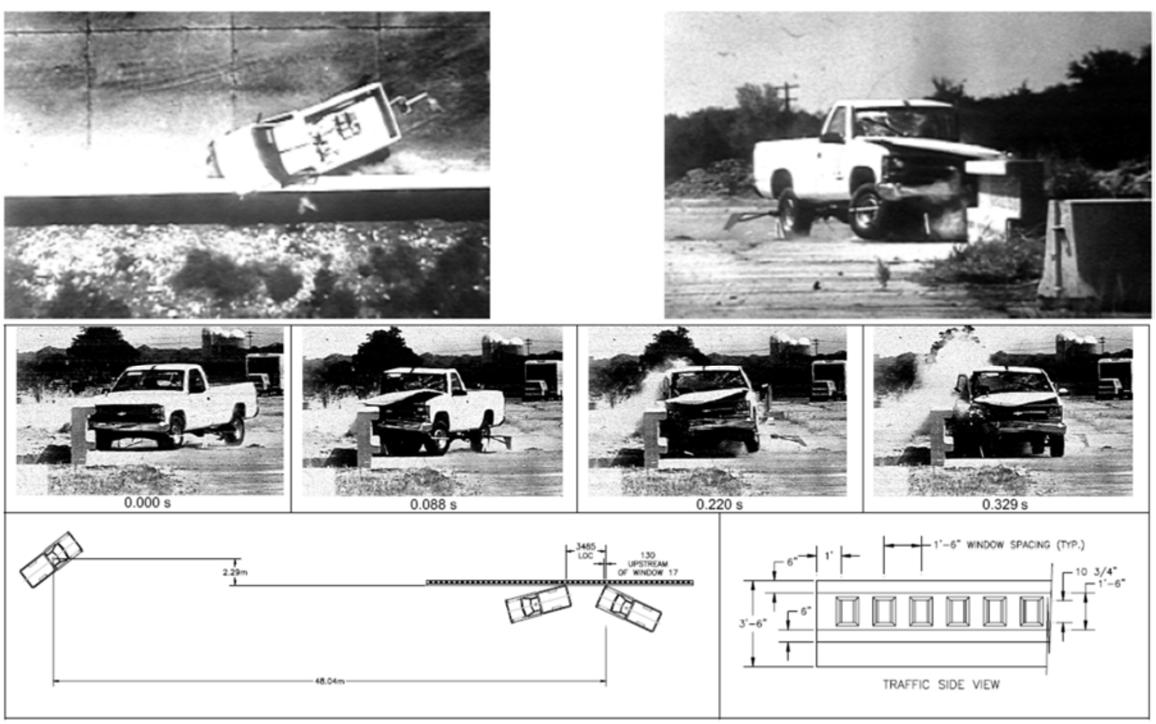


Figure 8. Test photos for NCHRP Report 350 Test 3-11[23]

Alberson et al. (2004) conducted the full-scale crash test and evaluation of the bridge balustrade TX F411 to Test Level 4 in accordance with R350, which is higher than those conducted by Bullard et al. in 2002. The TL-4 vehicle utilized was a single-unit box-van truck impacting the railing at 15 degrees and 49.7 mi/h (80 km/h). As a result, the F411 bridge balustrade performed acceptably for NCHRP Report 350 Test 4-12. Based on the performance, the F411 was suggested for use where containment of 18,000 lb. single-unit trucks is desired (see Figure 9). Figure 10 shows the constructed Texas F411 bridge rail that was tested. [24]

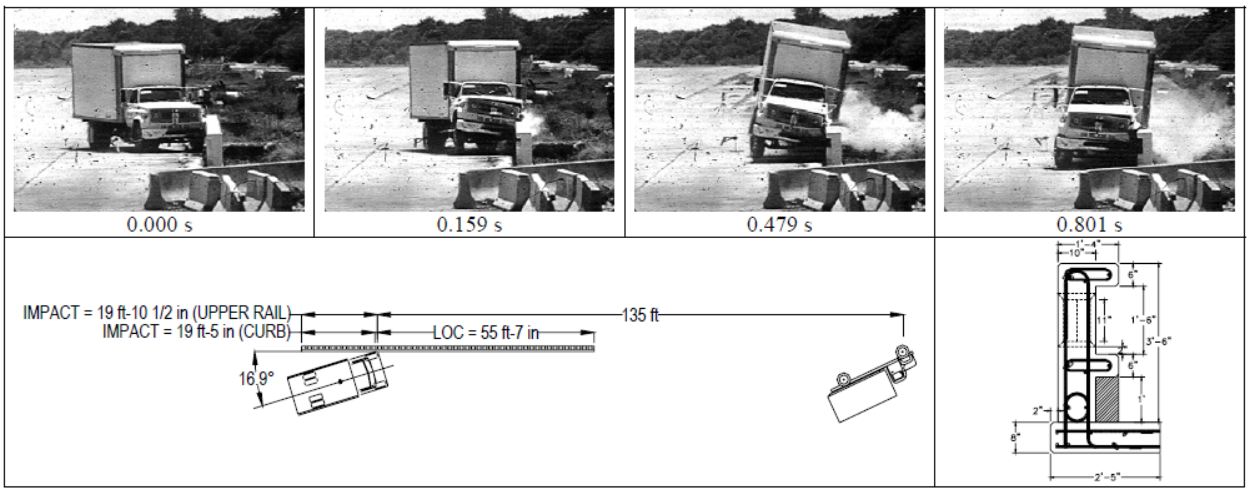


Figure 9. Test photos for NCHRP Report 350 Test 4-12[24]

Figure 10. Texas F411 bridge rail [24]

Bullard et al. (2011) performed a MASH 4-12 test with a 32 in NJ barrier. This was previously tested under NCHRP Report 350 TL-4 conditions and passed marginally, but when tested again under the more severe MASH TL-4 conditions, the single unit truck rolled over that same barrier and failed.(17) Figure 11 shows the failed MASH 4-12 test of the 32 in high Jersey barrier.

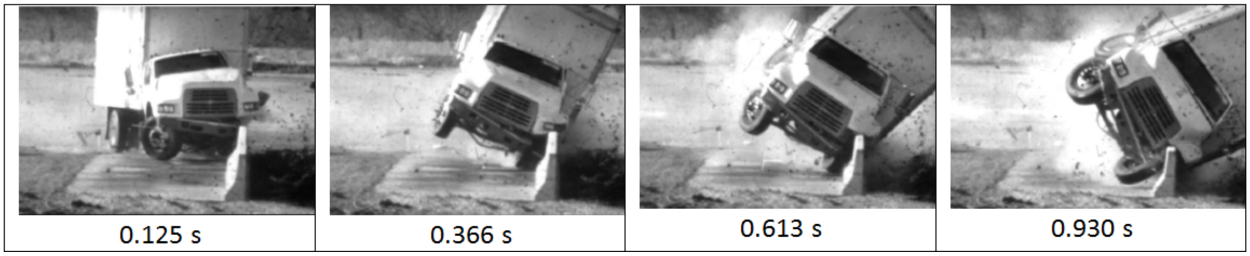


Figure 11. Test photos for failed MASH 4-12 test for 32 in barrier

In response to this failed test, Sheikh et al. (2011) investigated and found that the minimum required rail height for longitudinal barriers in TL-4 impact conditions for AASHTO MASH is different from NCHRP Report 350. The impact conditions that were changed include the vehicle mass, velocity at impact, and center of gravity of the single unit truck. A comparison of the test conditions is shown in Table 3.

The minimum height specified in the AASHTO design specifications for TL-4 impact conditions is 32 in, but with the increased impact severity, this height may not be sufficient. Finite element models were used to simulate collisions for barriers of the following heights: 42, 39, 38, 37, and 36-in. The barrier was modeled using a rigid shell material because the deformation of the test article is very small. As expected, the 42 in barrier provided the most stability because it was the tallest. As the height decreased, so did the stability of the vehicle. The 36 in rail was marginally stable and passed the MASH TL-4 collision and the truck did not roll over. It was determined that any further reduction in height from 36 in would allow the rear axle to pass over the barrier, and allow the truck to roll over. For this reason, 36 in was chosen as the minimum allowed height for TL-4 barriers.(18)

Table 3 - Comparison of NCHRP report 350 and MASH TL-4 impact conditions for Single Unit Truck

Parameter	**NCHRP Report 350**	**AASHTO MASH**
Vehicle Mass	17,640 lb.	22,050 lb.
Impact Velocity	50 mi/h	56 mi/h
Impact Angle	15°	15°
CG Height of Vehicle Ballast	67-in	63-in

Pfeifer et al. (1996) evaluated the Minnesota Combination Bridge Rail subjected to TL-4 conditions according to NCHRP Report 350. This rail was initially meant to be used on low service level roadways, but it was determined that with modifications, the rail would be able to withstand R350 TL-4 conditions. The first iteration of the redesign process included increasing the size of the weld at the base of the post to increase the post capacity, and changing anchor bolt details. The full-scale test of this first design failed due to snagging, so a second iteration of the design was necessary. The second iteration of modifications included extending the tubular rail and concrete barrier 4 in toward the roadway. These modifications were retrofitted to the existing system. The parapet was extended by dowelling into the existing parapet, and the tube was extended by welding an additional steel tube to the original top rail. Because the tube used for the retrofit was not readily available from steel suppliers, the final iteration replaced the two tubes welded together with one larger tube to accomplish the same 4 in clearance. The most notable changes in the design from the original to the iteration are the width of the concrete portion increasing from 1'-0" to 1'-4" and the width of the steel tube increasing from 6-in to 10-in.(21)

Buth et al. (1998) tested a Texas T411 to NCHRP R350 TL-3. Previously tested under NCHRP R230, it needed to be tested again under NCHRP R350 to ensure the structural adequacy for the new standards. Under R230, TL-3 tests included an 820 kg passenger car traveling at 96.9 km/h at 21.2 degrees, and a 2043 kg passenger car traveling at 100.1 km/h at 26 degrees. Under NCHRP R350, the 820 kg passenger car did not change, the 2043 kg passenger car was replaced with a 2000 kg pickup truck traveling at 100 km/h at 25 degrees. The vehicle used for the test was a 1993 Chevrolet 2500 pickup truck. All strength and containment requirements were met; however, there was extensive occupant compartment deformation which indicate high risk of serious injury to vehicle occupants.(22) Figure 12 shows images of the failed test due to excessive deformations.

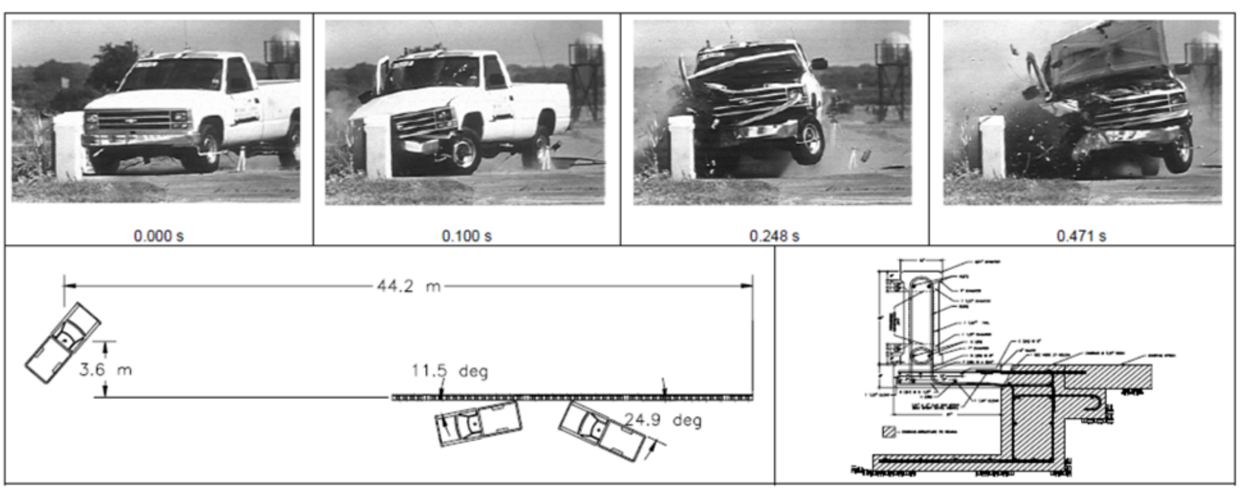


Figure 12. Failed pickup truck test of the Texas T411 bridge rail (22)

DEVELOPMENT OF FINITE ELEMENT MODEL OF NEW BALUSTRADE DESIGN

Open-Faced Balustrade Design

The Rt. 139/Hoboken Viaduct located in Jersey City Hudson County was constructed in 1932 as part of the Rt. 1/1&9 Historic Corridor with an open concrete balustrade along the length of the roadway. Figure 13 shows photos of existing balustrade on Rt. 139/Hoboken Viaduct. The original design features an open-faced balustrade with column to opening ratio of 1:1, approximately. NJDOT developed the preliminary design with only slight changes from original design (Figure 14(a)). The HPO approved the new concrete balustrade design but the new designed balustrade must also be shown to meet current crash test criteria of MASH TL-4.

Figure 13. Existing open-faced balustrade on Route 139/Hoboken Viaduct

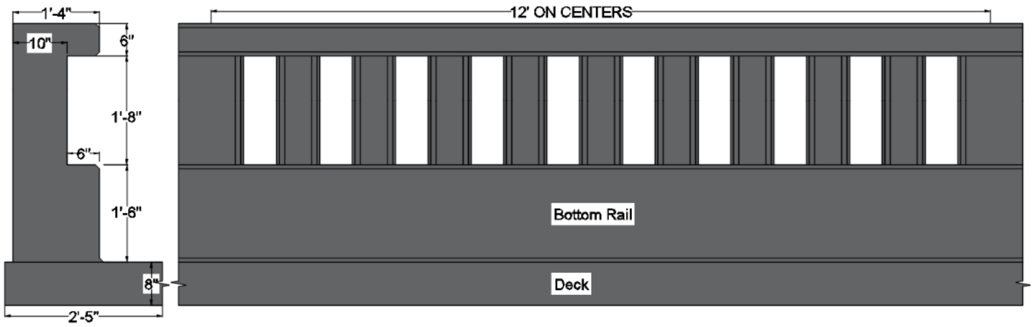
The new concrete balustrade design section, geometries, and reinforcement were verified in accordance with AASTHO Bridge Design Specifications. Through structural analysis, the existing balustrade design was refined regarding parameters such as reinforcement details, material properties, opening ratios, etc. The structural performance of the refined design was compared with other designs that are close in shape that have been modeled using FEA and passed the simulation and crash tests, such as Texas F411.

This design, although very similar to the Texas F411, required further modifications to meet all of the specifications set forth in the NJDOT bridge design manual. The design consultant, AECOM, validated the preliminary design, and made changes and improvements to it to ensure the bridge rail fulfills all requirements set forth by NJDOT. The specifications that force design changes are sections 20.8 in the deck slab design manual, that specify that a 2½-in top deck cover is preferred, and a minimum 2-in cover for all rebar. [26] The deck slab specification does not change any of the aesthetics, it only moves the rebar ½-in down in the deck, but the 2-in cover does change the aesthetics of the barrier. A lot of the design changes are inside the concrete and not seen, such as the change in shape of some rebars, but the only visible change in the design is the increase in top-rail height, from 6-in to 7-in. This in turn makes the height of the posts 1-in shorter to maintain the same total height of 44-in. The rebar details that were changed by AECOM are as follows:

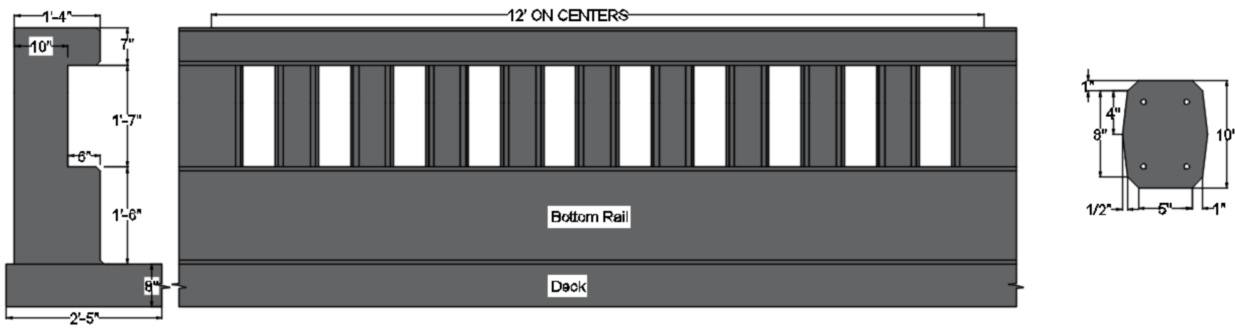
1) Vertical bars in the posts were increased from #5's to #6's, their length was increased to develop a stronger bond, and the radius at the hoop was decreased to maintain the 2-in. cover requirement.
2) The three #5 U-bars at 9-in. were replaced with a #6 C-bar and #5 D-bar at 8-in. This change reduces the labor needed to tie the rebar because there is only two bars instead of three sticking up from the deck.
3) M-bars were eliminated.
4) W-bars in the bottom rail were eliminated.
5) An extra 5-ft deck bar was added at 8 in on the top alternating with the deck reinforcement.
6) Deck bar spacing was decreased from 9-in to 8-in.
7) Top deck rebar was moved down ½-in.

All of these changes increase the capacity of the barrier, while also reducing the labor required to assemble it because there are less total bars to bend and tie. Figure 16 shows the old and new rebar details.

When designing the balustrade, it is important to ensure that it satisfies all of the strength requirements set forth in Section 13 of the AASHTO LRFD bridge design specifications. This section specifies the design forces and strength requirements for bridge rails based on the desired test level and provides a specific procedure for their calculation.. This procedure is required for checking the capacity of the rail, and for checking if the rail will remain stable when it is subjected to impact. Before the parametric study was performed using finite element analysis, all of the designs to be considered were first checked using the criteria set forth in section 13. This was done because the final design must conform to these specifications to ensure the structural integrity of the rail. After AECOM made changes to the proposed design in Figure 14(b), it was found that the rail does have the capacity to handle the collision, and was set as the baseline for the parametric study. Figure 14 shows the aesthetic appearance of the new design and Figure 15 and Figure 16 shows a comparison of the details for the design before and after AECOM modified it.

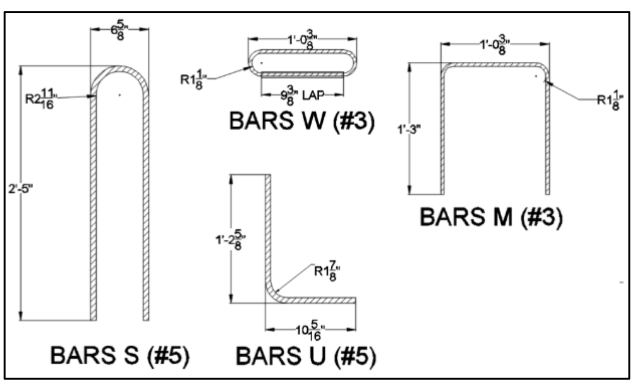


(a)

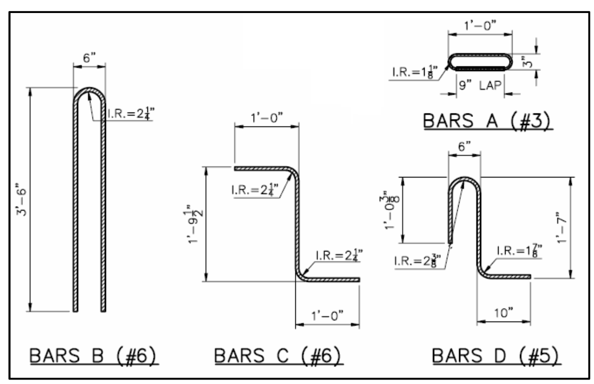


(b)

Figure 14. Open-faced balustrade design (plan); (a) proposed and (b) modified by AECOM

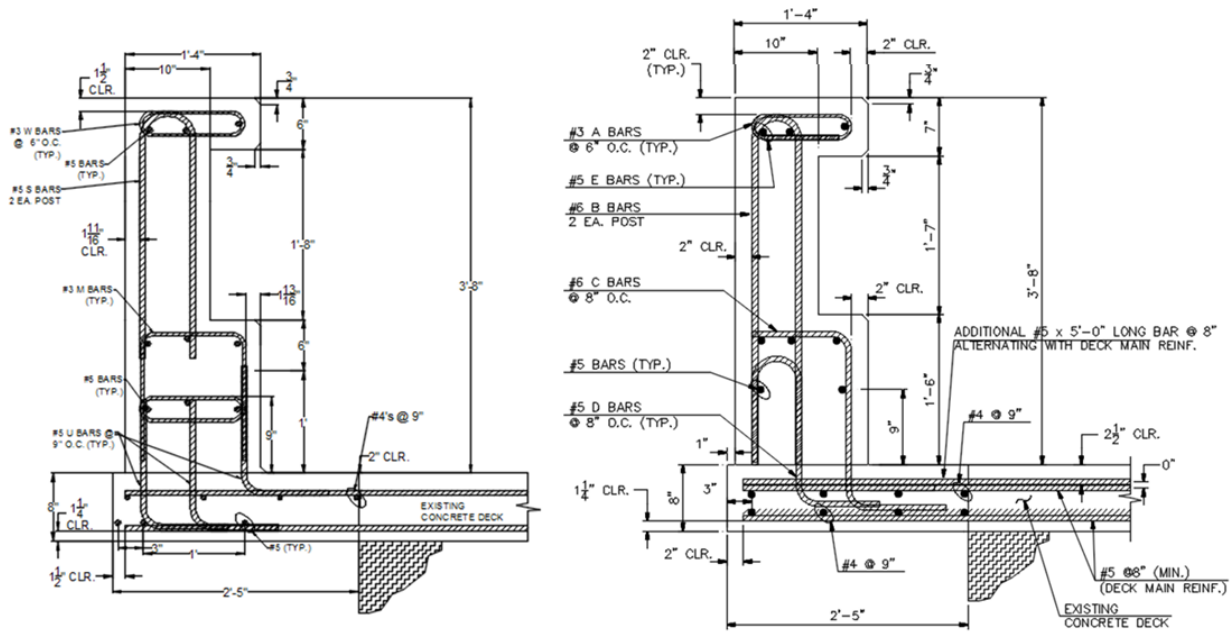


(a)



(b)

Figure 15. Details of reinforcement design; (a) original design and (b) modified design



(a) (b)

Figure 16. Details for open-faced balustrade design; (a) original design and (b) modified design

Finite Element Analysis Using LS-DYNA Software

Before performing the full-scale crash tests to check if the new balustrade satisfies the requirements of AASHTO MASH TL-4, the RIME Team performed a parametric study to compare the behavior and performance of different barrier shapes. By performing these simulations, the RIME Team was able to change different parameters of the balustrade to optimize the design and make it look as historic as possible while still fulfilling all required FHWA requirements. Utilizing FEA also allows many different designs to be analyzed without needing to physically test them, which saves time and money.

<u>LS-DYNA Software</u>

LS-DYNA is a commercial finite element software that is being utilized for the analysis of the balustrade on Rt. 139/Hoboken Viaduct. LS-DYNA is the dynamic non-linear explicit FE code which is very practical for simulating real-world situations. This program is very popular in the automotive industry for simulating vehicle crashes which include large deformations of the chassis, and failure of several components within the vehicle and on whatever the vehicle is impacting. [(28)] LS-DYNA also has features such as accelerometers that can measure translational and rotational accelerations in the three principal axis directions, which can be defined in either a local (e.g., fixed to the vehicle) or global coordinate system. This software was used to carry out the parametric study of the balustrade to optimize the design. The team prepared the input for the analysis using the preprocessor provided with the LS-DYNA software package called LS-PrePost.

Modeling

When modeling the balustrade, there are many things that need to be taken into consideration. Because both steel and concrete are present in the barrier, they need to be modeled together to create an accurate model. The two materials are very different from each other by nature, and need to be modeled accordingly. Steel is an isotropic material that can handle tension, compression, and bending, while concrete is only good in compression, but not bending or tension.

Because of the long and narrow shape of rebar and the modes by which it is able to carry load, the RT modeled all of the rebar as beam elements. Because steel is an isotropic material, it was not difficult to define the parameters in LS-DYNA. The only parameters needed to model it is the stress-strain relationship curve, density, and yield strength.

Concrete was modeled as solid elements because more detail in the model can be created easier and more detailed information about deformation and stresses can be obtained. The material model *MAT_RHT was used in the models and parametric study. This material model is more desirable to use because it has been validated, it can predict behavior of concrete very well, the input needed is very limited, and it has shown to be the most reliable out of all the concrete models that have been used by the research team. The only parameters needed for this model are density and compressive strength, unlike other material models that require much more input data.

The concrete and steel occupy the same space, so the two need to be joined to one another. The research group decided to use a nodal constraint method because it is faster, easier, and more accurate than using shared nodes or smeared reinforcement. The rebar was originally constrained to the concrete by the use of the *ALE_COUPLING _NODAL_CONSTRAINT which locks the acceleration and velocity at the nodes of the concrete and steel together in order to act as one unit when strain occurs. (14) When creating this constraint, the concrete is set as the master, and the steel bars are set as the slave coupled to the concrete. This constraint method works well, but there were a few bugs that came along with it. For example, in some model cases, some of the deck rebar did not couple correctly, and fell out of the deck and barrier for no apparent reason. Not having a portion of the rebar act in the concrete causes problems because the capacity of the barrier would be lowered. In order for the calculations to be accurate, all rebar must be present and acting to give the correct solution. To solve this issue, *ALE_COUPLING_NODAL_CONSTRAINT was replaced with *CONSTRAINED_ BEAM_IN_SOLID which did not have any noticeable issues. This constraint method accomplishes the same task as the ale coupling constraint, but none of the rebar falls out when this one is used. The *CONSTRAINED_BEAM_IN_SOLID card is an overhauled constraint method that is more attractive than *CONSTRAINED_LANGRANGE_IN_SOLID, or *ALE_COUPLING_NODAL_CONSTRAINT. (27, 28)

Data Collection

When collecting data about the vehicle accelerations and rotations, accelerometers are defined in the model at the center of gravity of each vehicle. The center of gravity of each vehicle is where the accelerometers will be placed during the full-scale test to collect the data. The accelerometer was connected to the vehicle model using *Nodal-Rigid-Body-Constraint. The time-history data was collected from the accelerometer in a local reference coordinate system that was fixed to the vehicle with the x-direction coincident with the forward direction of the vehicle, the local y-direction is fixed toward the right side of the vehicle and the local z-direction is fixed downward; which was consistent with the way the test data was collected from physical accelerometers. These accelerometers record data directions shown in Table 4. A graphical representation of the directions for each vehicle is shown in Figure 17.

Table 4 - Accelerometer data collected

Axis	Data Collected	Data Collected
Longitudinal (x-axis)	x-acceleration	Roll Rate
Transverse (y-axis)	y-acceleration	Pitch Rate
Vertical (z-axis)	z-acceleration	Yaw Rate

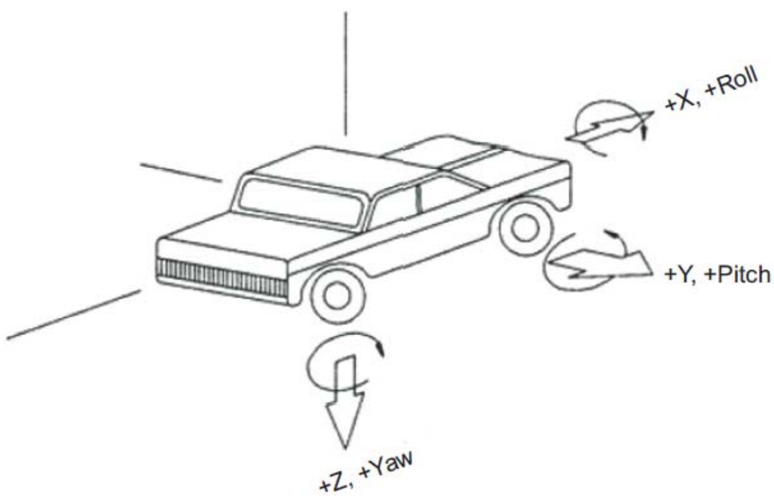


Figure 17. Recommended vehicle coordinate system (AASHTO, 2016)

The data was collected at a frequency of 50 kHz which was determined to be sufficient to avoid aliasing of the data. The acceleration and angular rotation data was filtered using an SAE-180 Hz filter before it was further processed using the Test Risk Assessment Program (TRAP) developed by TTI. TRAP calculates standardized occupant risk factors from vehicle crash data in accordance with the MASH guidelines and the European Committee for Standardization (CEN). The input required for the TRAP program includes:

1) x, y, and z- accelerations at the center of gravity of the vehicle
2) Roll, pitch, and yaw angular rates at the center of gravity of the vehicle
3) Vehicle mass, speed immediately before impact, angle of impact

After all of these parameters are input, the angular rates are integrated to calculate the rotational angles at different times. Plots are then generated using Excel and Kaleidagraph.

Parametric Study

The Rt. 139/Hoboken Viaduct has a balustrade with a unique appearance. It is an aesthetic open-faced design with window openings shown in Figure 13. In order to keep the appearance of the barrier as close as possible to the original one while still fulfilling the safety requirements of AASHTO MASH TL-4, a parametric study was performed changing the following 3 parameters:

1) Total Barrier Height
2) Post Width
3) Window Opening Width

The Texas F411 has a height of 42 in, a post width of 12 in, and a window opening of 6-in. This post width to window opening ratio is 1:2, which is not acceptable for the historical appearance of the barrier. To make the design acceptable, the research team started with a design with a height of 42 in, a post width of 8 in, and a window opening of 6 in for the parametric study. This resulted in a post width to window opening ratio of 4:3, which was close enough to the original Pulaski barrier's ratio of 1:1 for the Historical Preservation Office to approve the aesthetic design. Table 5 shows the study matrix and the specific parameter values investigated.

Table 5 - List of parameters and values to be simulated

Test Level	Value 1	Value 2	Value 3
Barrier Height (in)	42	43	44
Post Width (in)	8	10	12
Window Opening (in)	6	8	10

Height Adjustment

The first parameter the RIME Team changed was the total barrier height. The height will be adjusted by changing the height of the posts in the barrier. The height of the previously tested Texas F411 barrier is 42-in, but in the full-scale crash test, the truck appeared to start tipping over the barrier. The truck never fully rolled over the barrier, but there was a noticeable risk of overturning. The range of heights investigated in the parametric study included 42-in, 43-in, and 44-in.

The distance from the ground to the bottom of the box on the truck is approximately 43.5 in, which is higher than the top of the 42-in barrier. As a result, the truck tires strike the barrier when the back of the truck is swinging towards it, causing the truck to “trip” over the barrier and begin the rollover motion. Figure 18 shows the gap between the SUT box and the top of the 42” barrier and that the tires are the first part in the rear of the vehicle to make contact with the barrier.

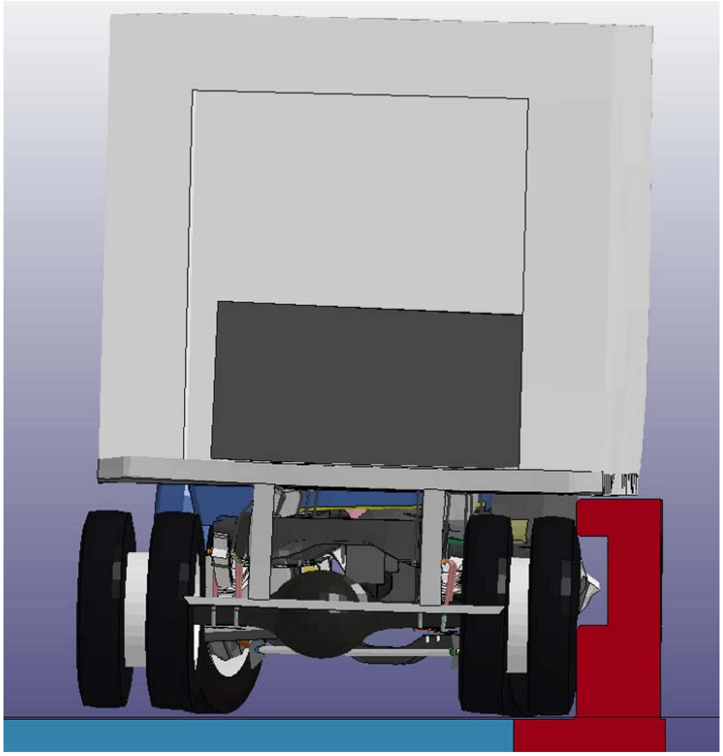


Figure 18. Rear view of SUT tires contacting the 42 in barrier

This gap, although small, has a notable effect on the kinematics of the truck during and after the collision. The height of the barrier determines which part of the truck in the rear will hit first, and ultimately determines how the truck will behave. If the barrier height is below the cargo box, the tires will hit the barrier and the box will ride on it for a longer time. On the other hand, if the barrier is high, the cargo box will hit the barrier first and more effectively keep the SUT on the correct side. When the box hits the barrier first, the roll angle of the truck is reduced and the truck is also deflected away from the barrier faster, which results in significantly less extension of the vehicle behind the barrier (e.g., top of cargo box leaning over the barrier). This is shown in the collision with the 44-in barrier. Figure 19 shows a comparison of SUT collisions with different barrier heights. As seen in the 44-in barrier case, the box hits the barrier instead of the tires, and this causes all of the rolling motion to occur on the correct side of the barrier.

As shown in Figure 19, the 42-in and 43-in barrier cases resulted in the truck leaning over and extending behind the barrier; whereas, the 44-in barrier contained all of the rolling on the traffic side of the barrier. Figure 20 shows graphs comparing acceleration values for all three axes and how they change for each barrier height. In general, the height does not significantly affect the acceleration in the x- or z-directions, but does affect the acceleration in the y-direction. The y-axis is normal to the inside face of the barrier, and is affected when the height increases from 43-in to 44-in. The 1-in height increase causes the box to hit the barrier instead of the tires, and when this occurs, the truck is quickly deflected away from the barrier instead of tilting over it. This sudden change in direction causes a significantly higher acceleration in the y-direction. This spike in acceleration is seen at a time of about 0.25 s after the collision.

The height of the barrier also has very significant effect on the kinematics of the truck. The roll, pitch, and yaw of the truck change drastically when the height of the barrier is changed. The roll angle in the 44-in barrier case was about the same as that for the 42-in case, but what is not evident on the graph is that although the roll angle is about the same, all of the rolling in the 44-in barrier case is contained on the traffic side of the barrier. For example, in the 42-in barrier case the bottom of the cargo box rests on top of the barrier and truck box rolls over and behind the barrier. Further, because the truck is not in sustained contact with the top of the barrier in the 44-in case, the pitch of the vehicle is also affected. Figure 21 shows the graphs comparing the yaw, roll, and pitch for each collision.

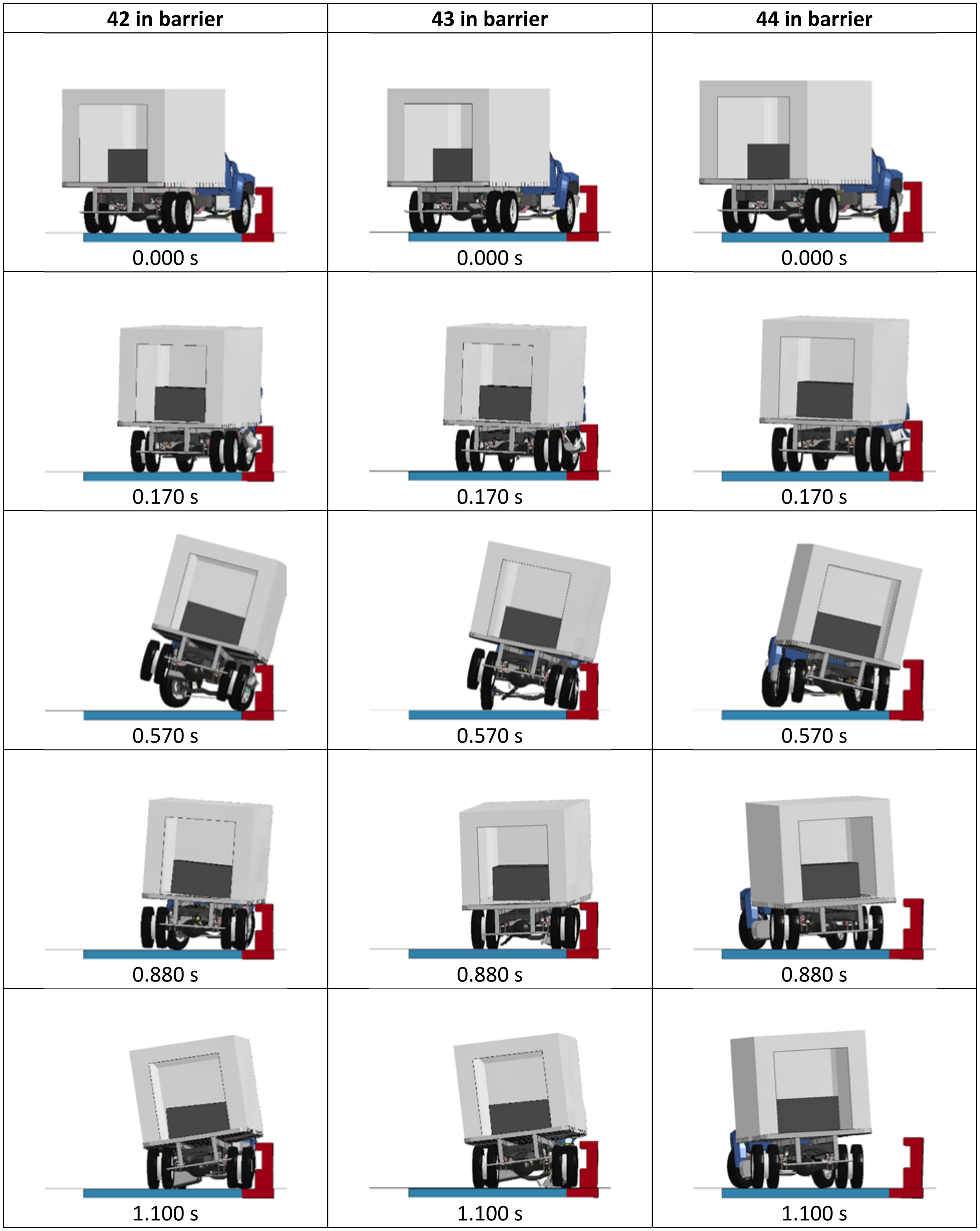
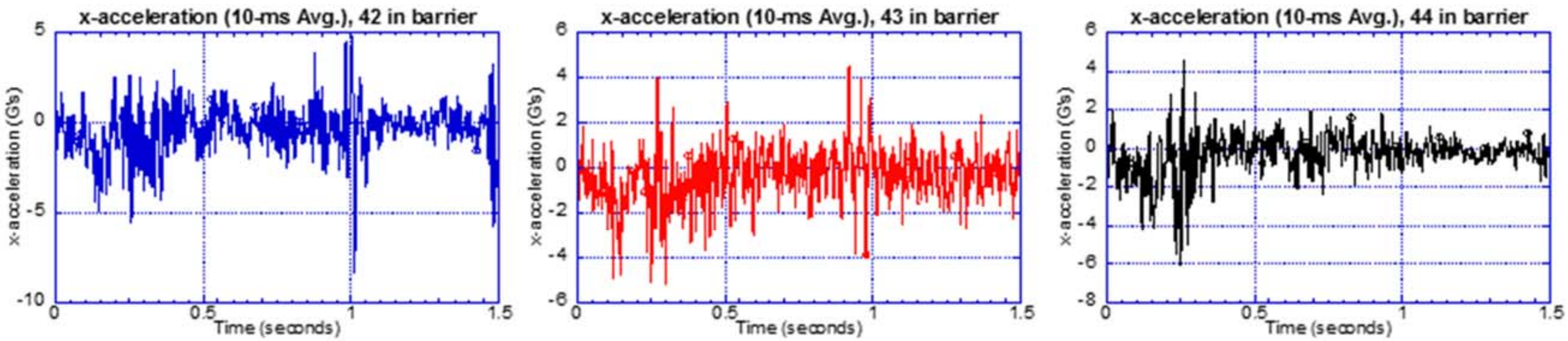
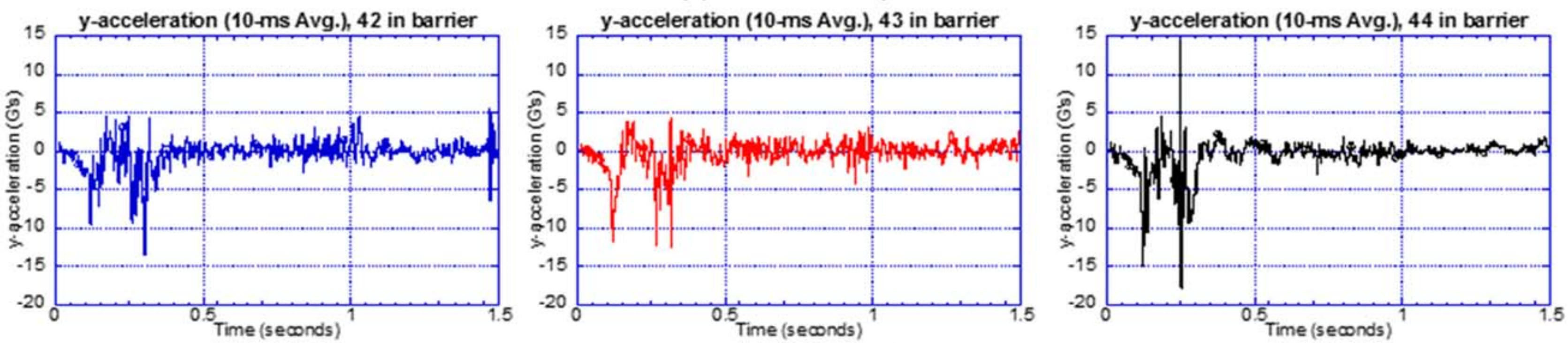


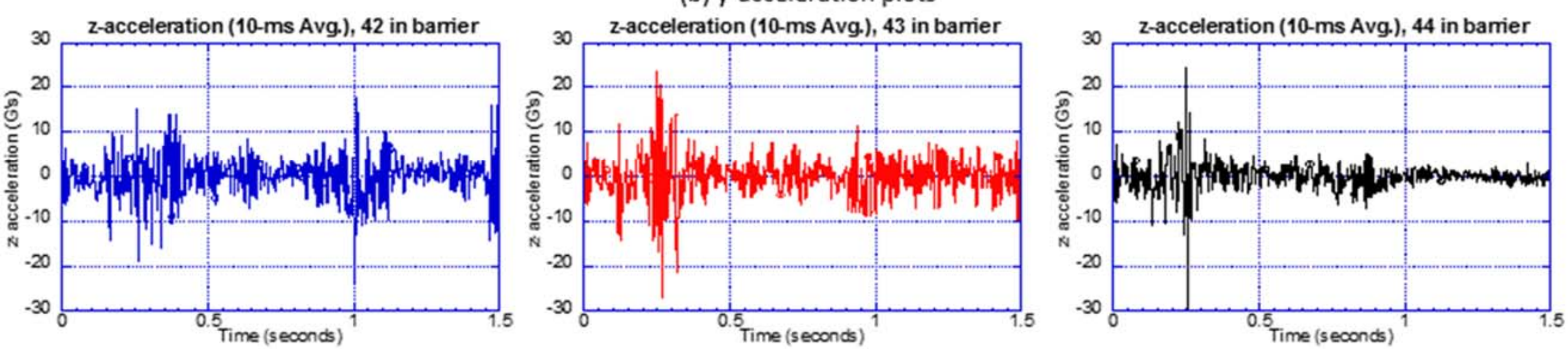
Figure 19. SUT collisions with different height barriers



(a) x-acceleration plots



(b) y-acceleration plots



(c) z-acceleration plots

Figure 20. SUT collision comparison of accelerations for different height barriers

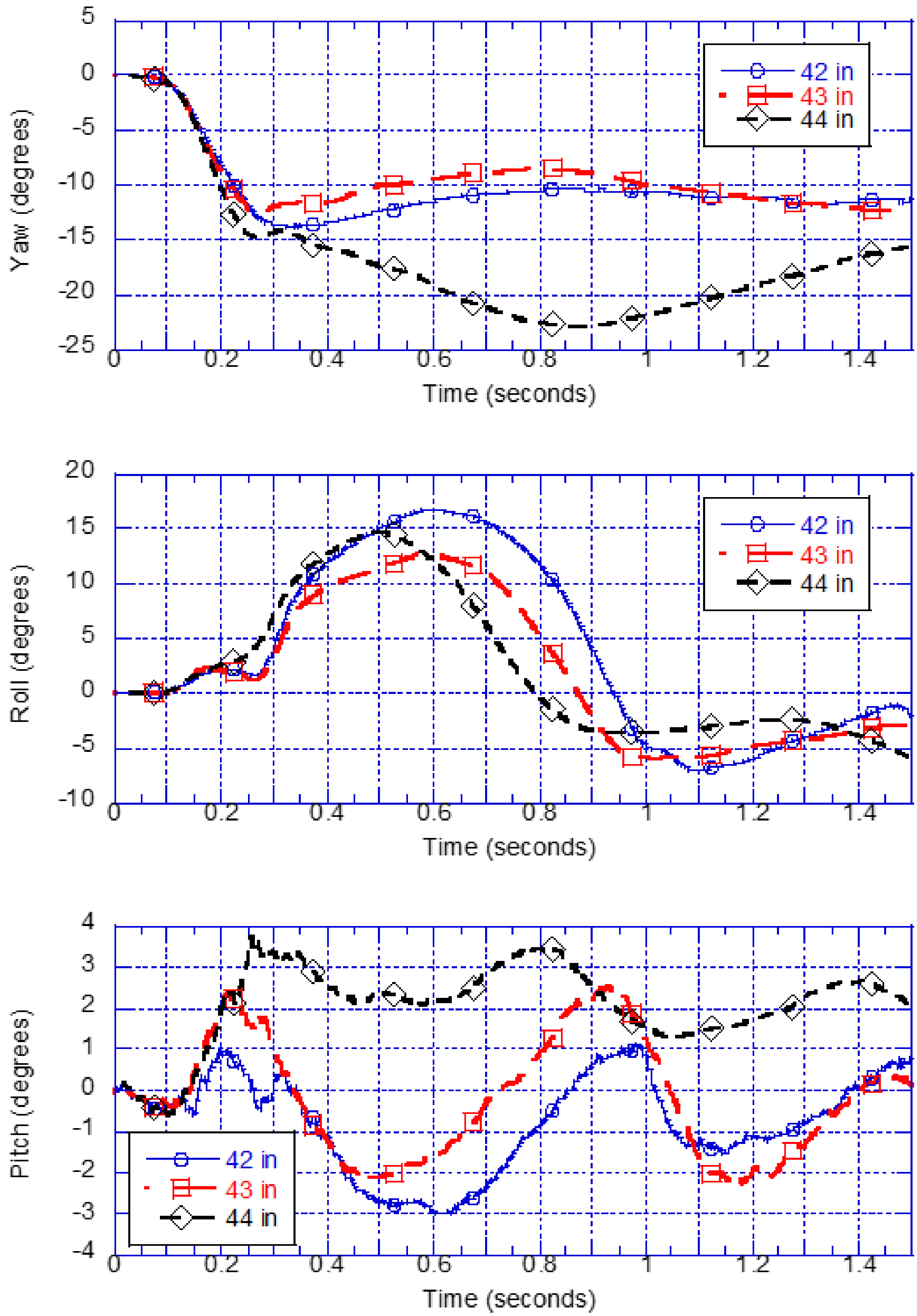


Figure 21. SUT collision comparison of axial rotations for different height barriers

Post Width / Window Opening Adjustment

When adjusting the post width and window opening, it is very important to keep in mind that the ratio of post width to window opening must stay close to 1-to-1. Keeping this in mind, it must be noted that not all combinations in the parameter matrix can be used. For example, a post width of 12-in cannot be combined with a window opening of 6-in or 8-in. The only combinations of post width and window openings that can be considered for use are shown in Table 6.

Table 6 - Compatible post and window combinations

Compatible Combinations	Post Width (in)	Window Opening (in)
1	8	6 or 8
2	10	8 or 10
3	12	10 or 12

These combinations represent the ones that have an acceptable ratio close enough to 1-to-1 to satisfy the Historical Preservation Office's requirements. Some of these still must be eliminated though. The combinations in Row 3 in Table 6 are all unsuitable because a post width of 12-in is too large and does not look like the balustrade we are trying to replicate. The 10-in post width is large, but is not too large to completely rule out. Although a 10-in window opening would make the ratio 1-to-1, this wide of an opening would look too wide for the appearance of the barrier. After eliminating those cases, only three acceptable combinations remain and are shown in Table 7.

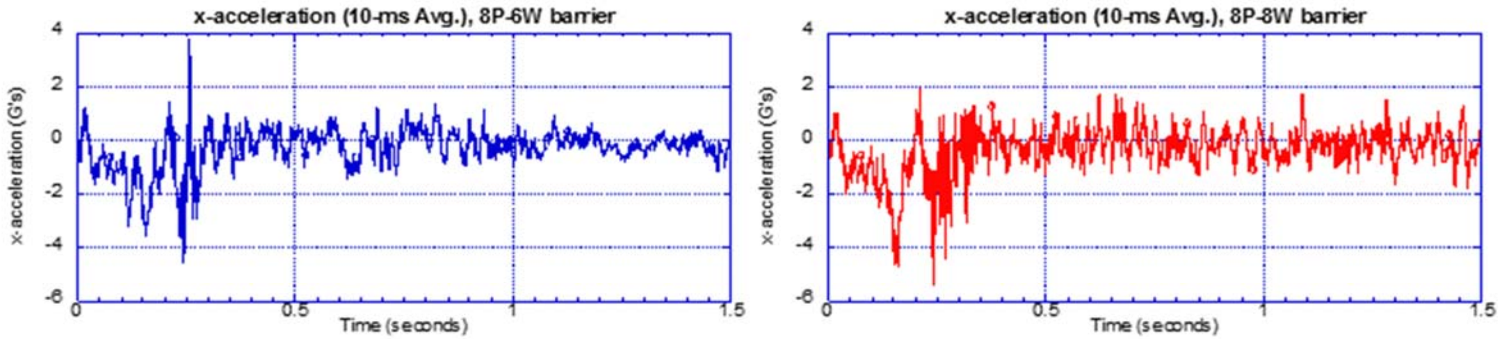
Table 7 - Acceptable post and window combinations

Combination	Post Width (in)	Window Opening (in)
1	8	6
2	8	8
3	10	8

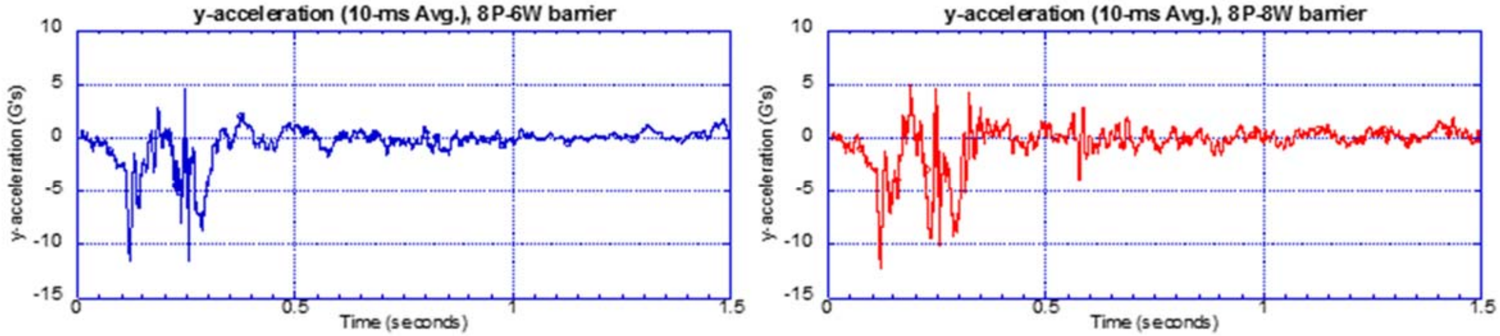
Although combination number three in Table 7 is still viewed as acceptable, it is still not considered very desirable because the thinner post width of 8 in is better aesthetically. The RIME Team simulated all three combinations with a height of 44-in. It was found through analyzing results that the post and window-opening widths did not have much of an effect on how the truck behaved during collisions, so after the height of 44-in was decided on, combinations one and two from Table 7 were compared to see which one is preferable. The results indicated that both options performed very similarly. Figure 22 shows the comparison of the collisions between the two combinations.

As seen in Figure 22, the window opening width had virtually no effect on the behavior of the truck during or after the collision. With this being said, it can be seen in Figure 23 and Figure 24 that the accelerations in every direction and the rotations about every axis do not vary by a significant margin

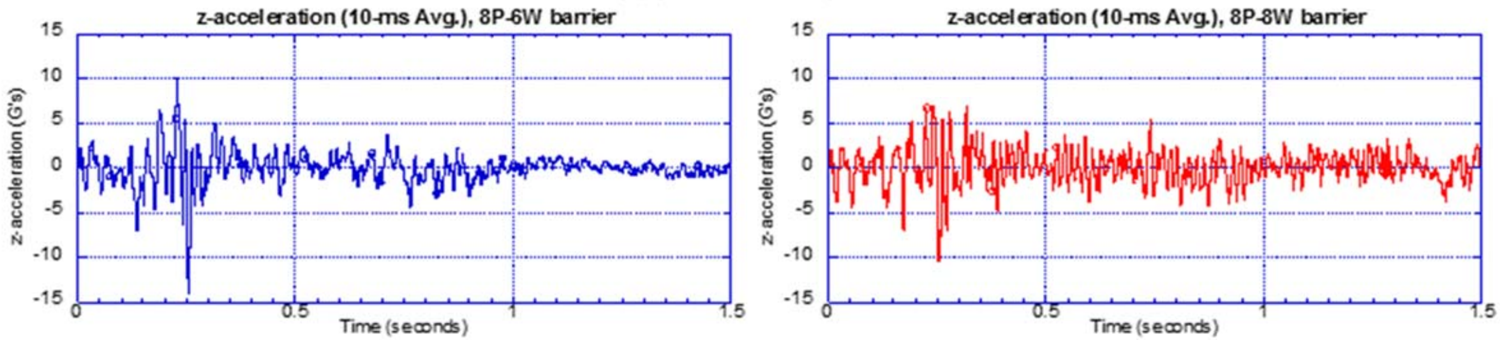
Figure 22. Comparison of 44 in high barrier with 6 in window and 8 in window



(a) x-acceleration plots



(b) y-acceleration plots



(c) z-acceleration plots

Figure 23. SUT collision comparison of accelerations with 6 in window and 8 in window for different post and window widths

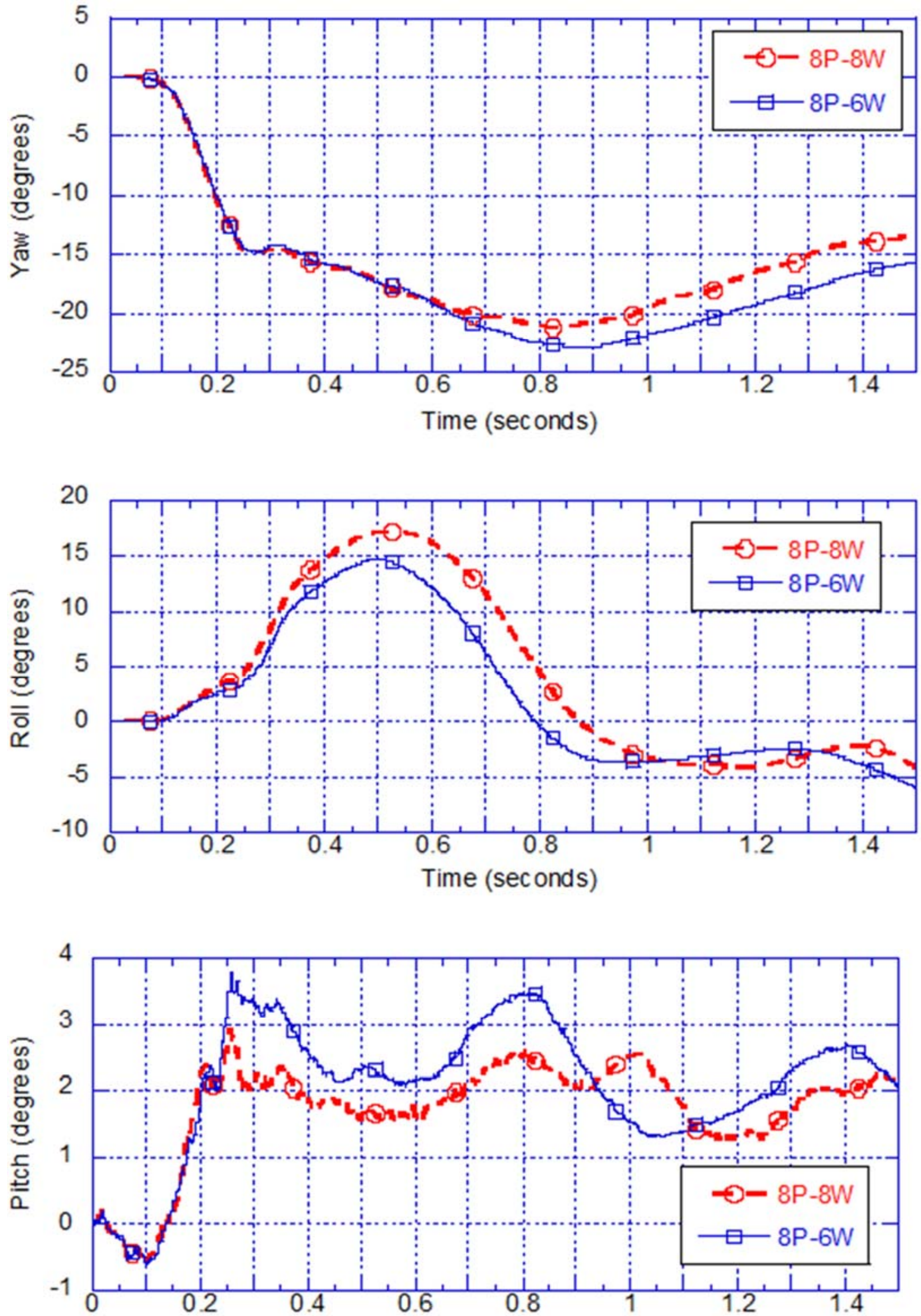


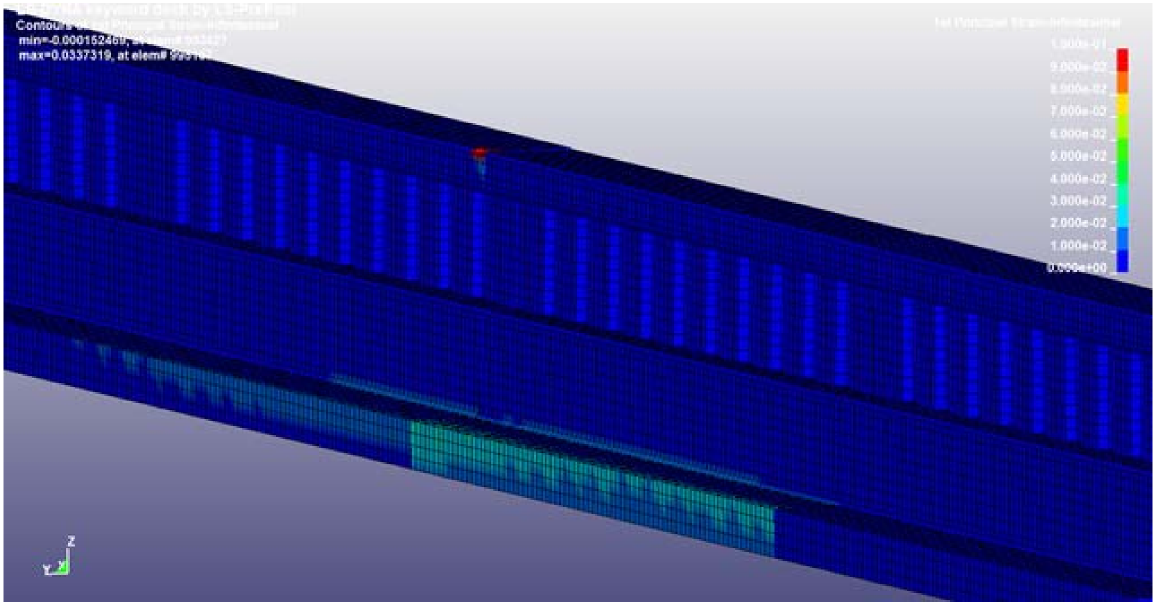
Figure 24. SUT collision comparison of axial rotations with 6 in window and 8 in window

As shown from the graphs, the change in values for all of the data was small, and the behavior of the truck was not changed significantly. The strength of the barrier however is affected by the width of the window opening. When the posts are spaced further apart, the amount of resistance per linear foot of barrier decreases because there is less reinforcing steel per linear of foot. This, in turn, makes the barrier more susceptible to damage than it otherwise would be. This decrease in steel per unit length means the concrete of the posts will crack more easily, and the steel bars may also fail if the collision is severe enough. Figure 25 shows a comparison of the damage incurred on the barrier for both cases.

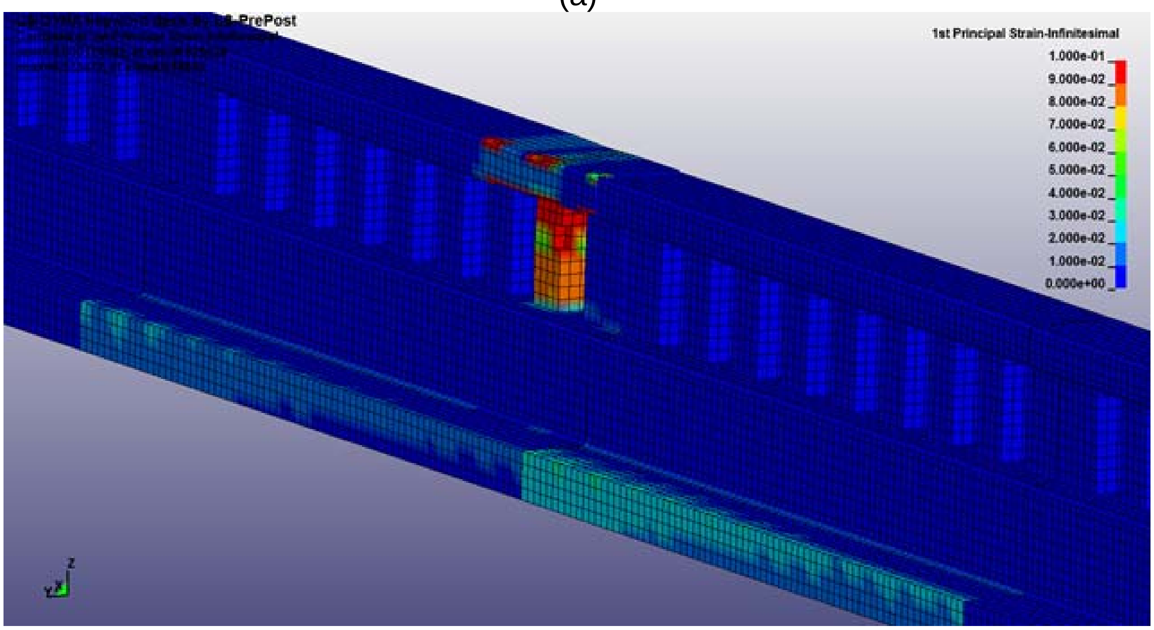
As shown in Figure 25, the post directly in the line of the collision with the truck in the 8-in window case (on the bottom) is completely destroyed, while that same post in the in the 6-in window case (on the top) is virtually unharmed. This is due to the fact that the rebar in this post was over stressed and yielded because there was not enough contribution from other posts which were too far away to share the load of the impact. This permanent deformation of the steel bars caused cracking and failing of concrete in that post. Further, the wider opening makes it more likely for vehicle components to pass through the opening and make direct contact with the posts.

After reviewing the results for all barriers, it was decided that the final design would have a height of 44-in, post width of 8-in, and a window opening of 6-in. Even though the ratio of post width to window opening is not exactly 1-to-1, it is close enough to the original Pulaski barrier to satisfy the aesthetic requirements of the Historic Preservation Office, and is more durable than the 8-in window opening.

The collisions of the pickup truck and the passenger car are both much less severe than the SUT collision because these vehicles are much lighter. This means that in this parametric study, the damage incurred on the barrier is only a concern for the SUT collisions.



(a)



(b)

Figure 25. Damage comparison; (a) 6-in window (top) and (b) 8-in window.

Pickup Truck Collision

The AASHTO MASH TL-4 criteria calls for a pickup truck impacting at 62 miles per hour at an angle of 25 degrees. The parametric study for the pickup truck was identical to the single unit truck, with the only differences being the vehicle, impact speed, and angle. Because this vehicle is much smaller and not as tall as the single unit truck, the results do not change throughout the parametric study the same way they did for the single unit truck. Because the bottom of the pickup truck bed is much lower than the top of the barrier (regardless of which height is being tested), the behavior of the truck will not change much when the height is changed in 1-in increments. When the back of the truck swings around and hits the barrier, the body will always hit first, and there is virtually no risk of the tires hitting first because unlike the SUT, the bed of the truck is not completely above the tires. Side views of the SUT and pickup truck are shown in Figure 26. This is different from the single unit truck where the tires might hit first if the barrier height is lower, causing the rolling “tripping” motion over the barrier. Figure 27 shows a comparison of pickup truck collisions with different height barriers. As shown in the figure, the height of the barrier has almost no effect on the behavior of the vehicle during and after collision. This is largely due to the fact that the part of the truck hitting the barrier during the backswing is not dependent on the height difference of 2-in. The wall of the truck bed will always be hitting first.

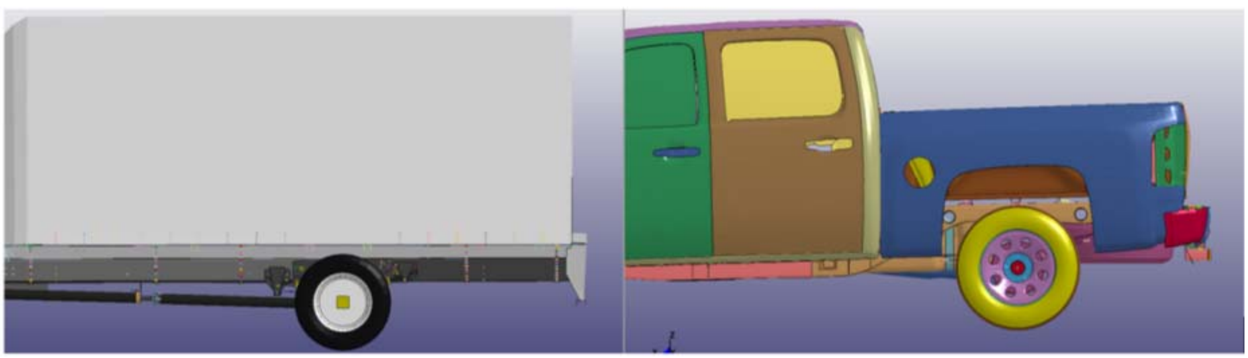


Figure 26. Wheel locations relative to bottom plane of cargo areas for SUT and pickup truck

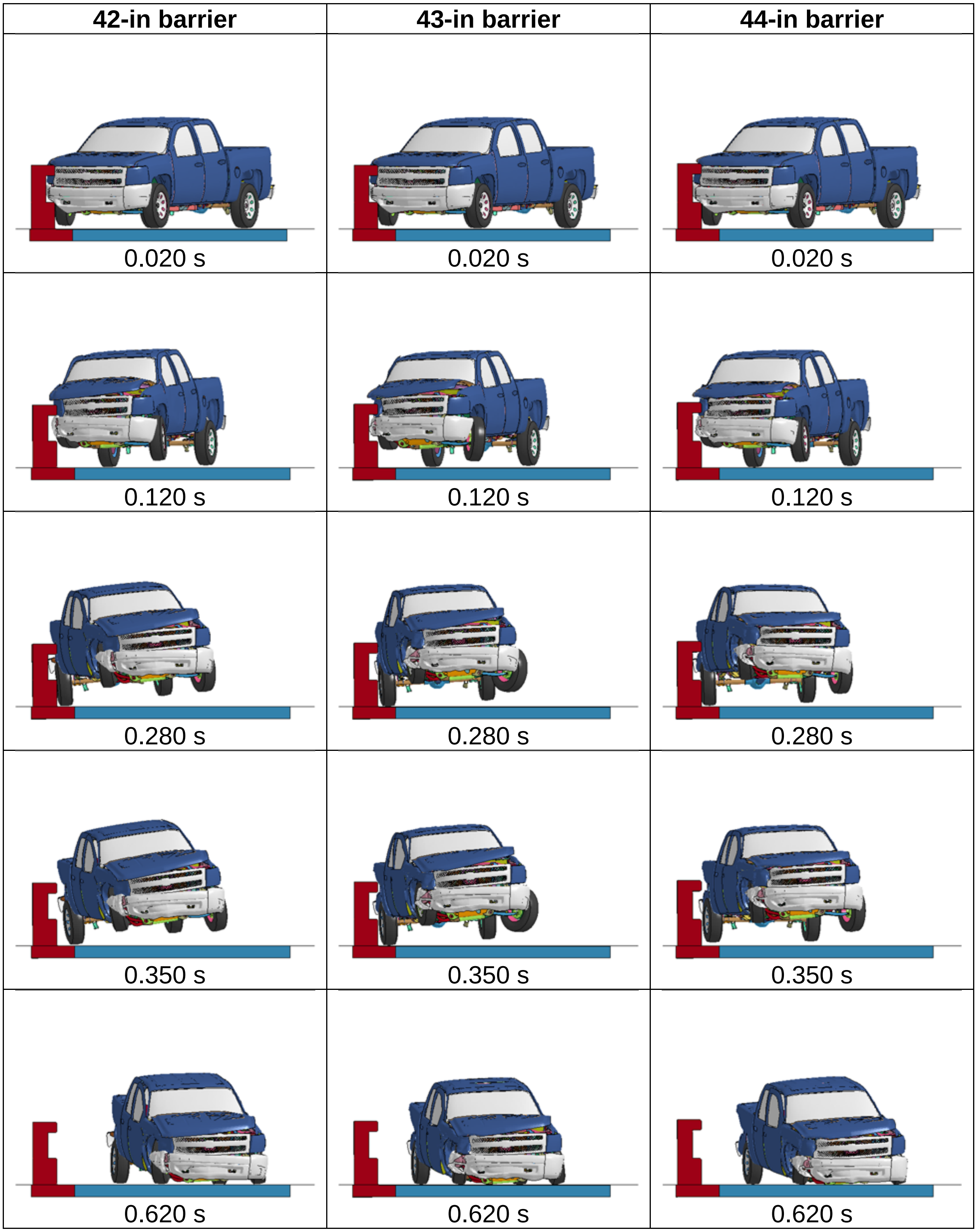


Figure 27. Pickup truck collisions with the 42, 43, and 44-in barriers

Figure 28 shows graphs comparing the accelerations in the x, y, and z-axes for different height barriers. As seen in the graphs, the accelerations in every direction are almost identical. Because the tires are not hitting the barrier first, the truck bounces back towards the traffic side rapidly (like in the 44-in single unit truck collision). This is what the large spike in the y-acceleration is at 0.05 s. The accelerations for each analysis cases are almost identical because every collision is very similar.

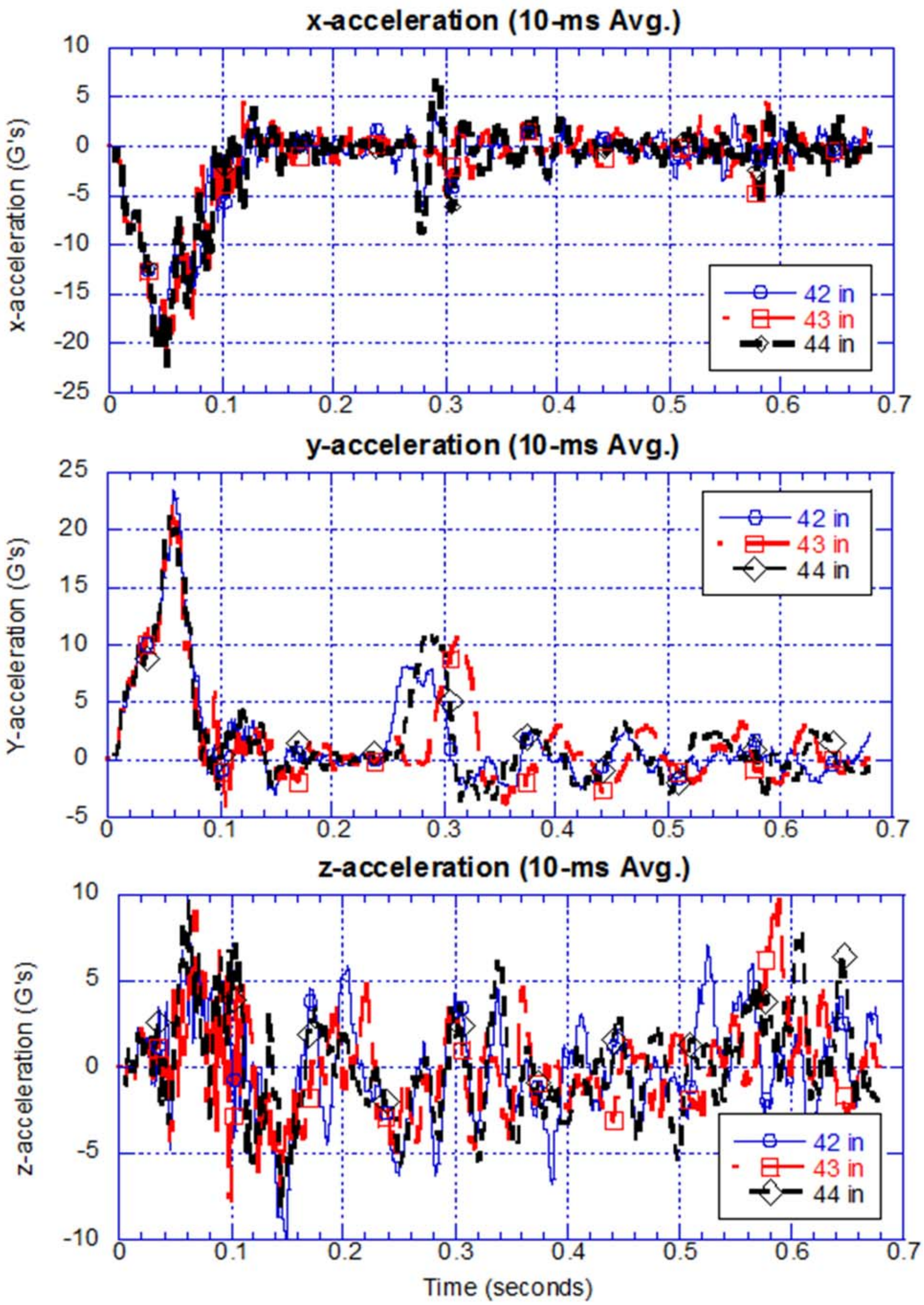


Figure 28. Pickup truck collision comparison for different height barriers

As seen in Figure 29, the yaw is also very close for all cases. As far as rotations, the parameters with the highest variation is seen in the graphs for roll and pitch. The roll is slightly lower as the height increases because the center of rotation (top point of contact between vehicle and barrier) which makes the rotation about the truck's x-axis lower. This in turn affects the pitch because pitch depends on how long the rear tires stay in the air. The longer the rear tires spend off of the ground, the longer the pitch values are away from the zero degree mark.

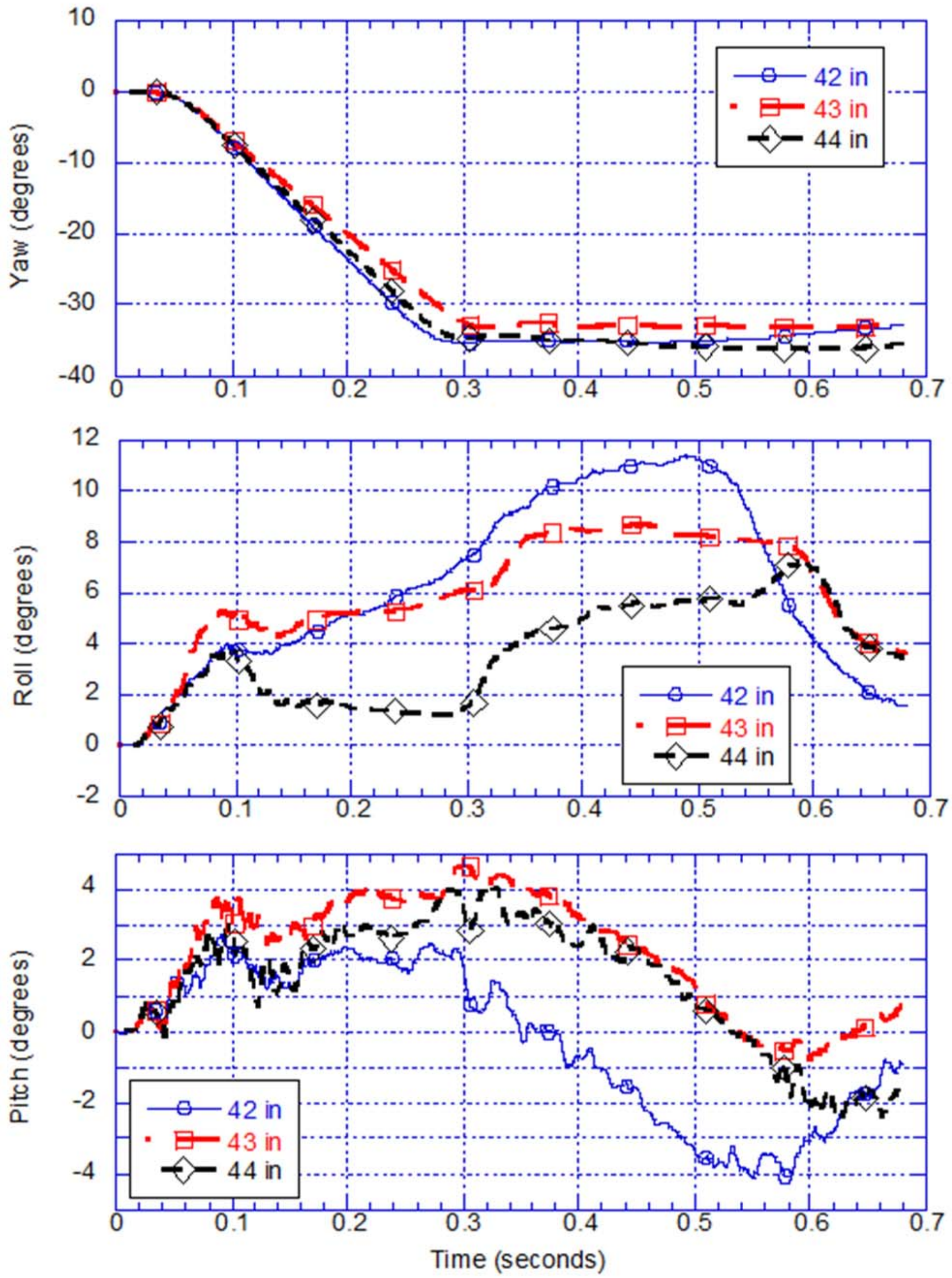


Figure 29. Pickup truck collision comparison of axial rotations for different height barriers

Figure 28 and Figure 29 show very little variation in the accelerations and rotations when the height of the barrier is changed. Also, the damage to the barrier for all three heights is very minimal and not a concern for collisions with this vehicle. The only visible damage incurred on the barrier is seen on the top of the bottom rail. Other than at this location, there doesn't seem to be a high risk of cracking or damage. The damage for all three height cases was almost identical, and Figure 30 shows the damage that is incurred on the 44-in barrier when the pickup truck collides.

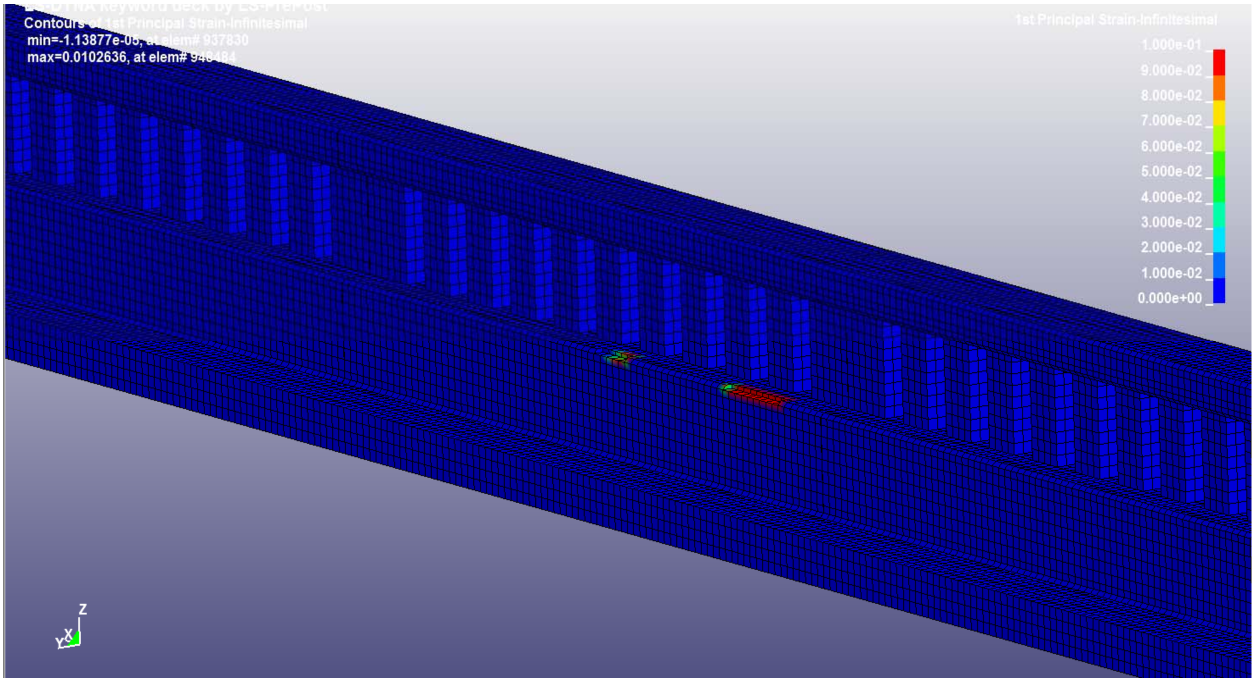


Figure 30. Damage incurred on 44-in barrier after pickup truck collision

The barrier tested with the pickup truck had a window opening of 6-in. The barrier with an 8-in window opening which was evaluated with the single unit truck would have probably performed very well in the pickup truck collision, and most likely would not have been severely damaged. The reason we did not test this barrier with the pickup truck is because it was severely damaged in the SUT collision, which is more severe and controls in this parametric study. Because it was already eliminated in the SUT collision, a successful performance with this vehicle would not matter.

Passenger Car Collision

The AASHTO MASH TL-4 criteria calls for a passenger car impacting at 62 miles per hour at an angle of 25 degrees. The parametric study for the passenger car was identical to the pickup truck and single unit truck, with the only difference being the vehicle. Figure 31 shows a comparison of passenger car collisions with different height barriers. Every analysis case with this vehicle yielded almost identical results. When the vehicle impacted the barrier, it bounced back almost immediately and the rear of the vehicle barely contacted the barrier during redirection. As shown in the figure, the height of the barrier has almost no effect on the behavior of the vehicle during and after collision.

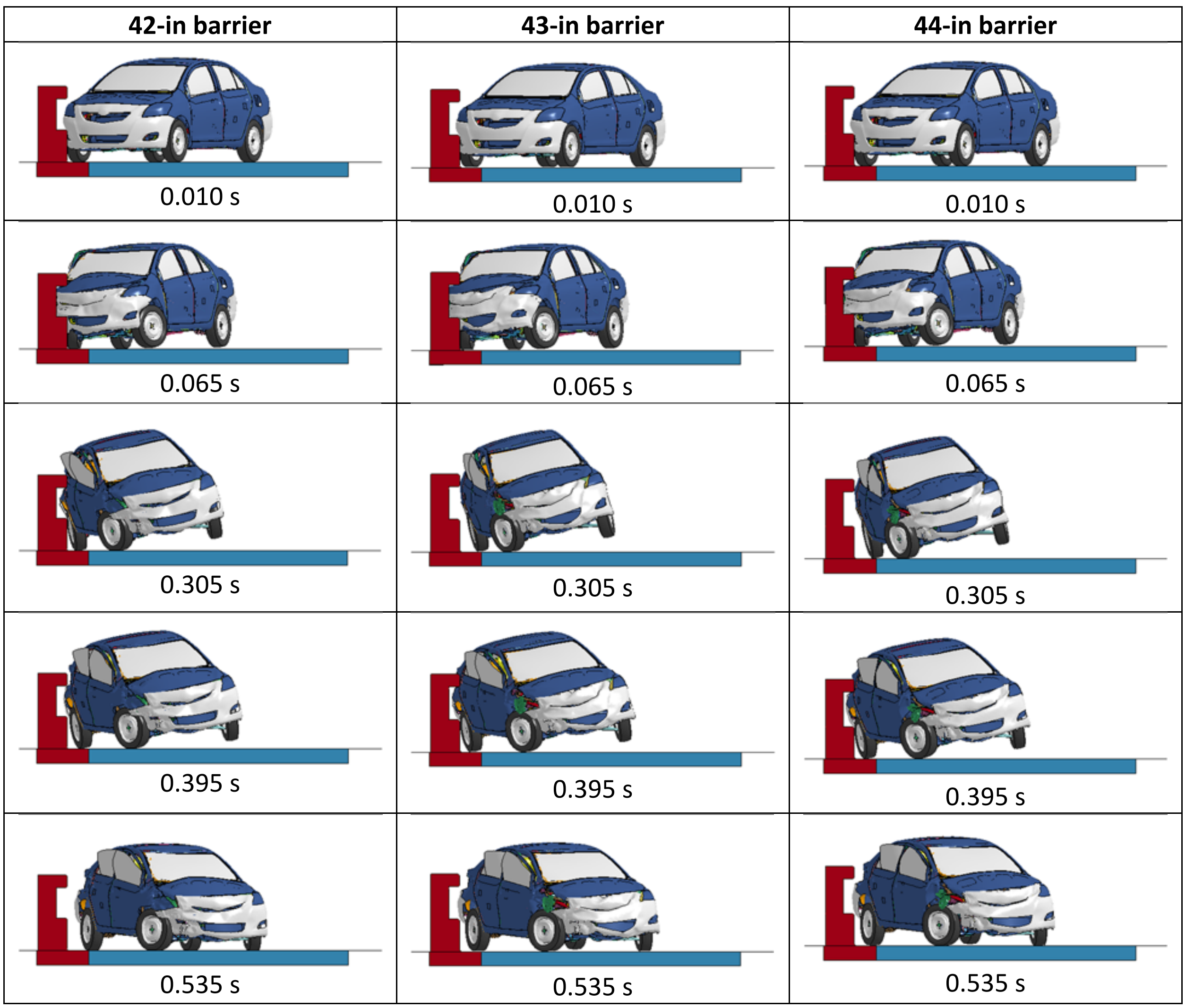


Figure 31. Passenger car collisions with the 42, 43, and 44-in barriers

Figure 32 shows graphs comparing the accelerations in the x, y, and z-axes for different height barriers. As seen in the graphs, the accelerations for each analysis case are essentially identical; thus the barrier height parameter does not affect the behavior of the vehicle during or after the collision. Since height difference did not change which part of the vehicle was hit, the vehicle's trajectory remained consistent for each analysis case.

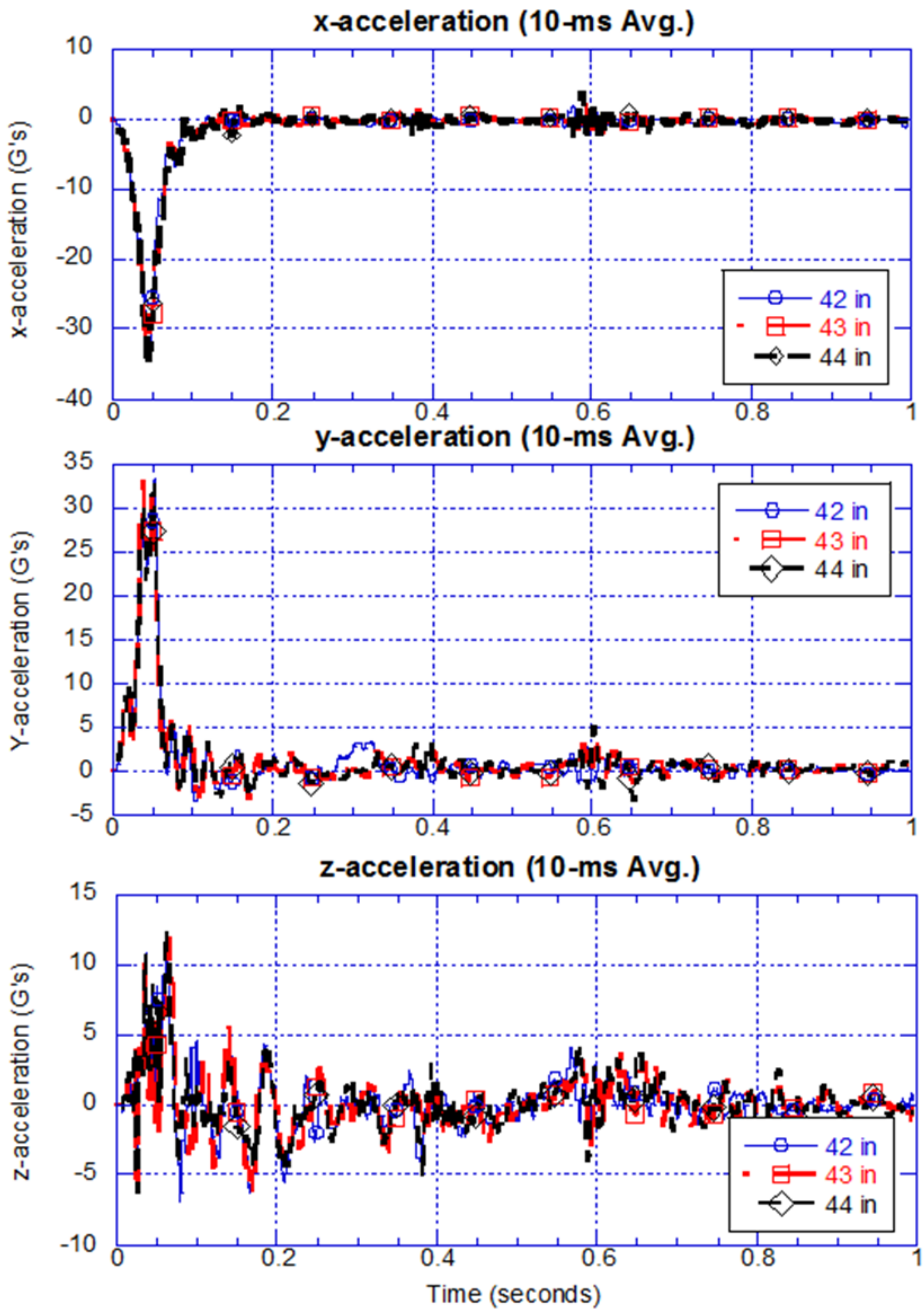


Figure 32. Passenger car collision comparison for different height barriers

As seen in Figure 33, the yaw, roll, and pitch was also very similar for all cases. Because the same part of the vehicle is hitting in each collision, the rotations about every axis have very little variation. Because the passenger car is very short and the center of gravity is well-below the top of the barrier, the collisions are minimally effected by the change in height.

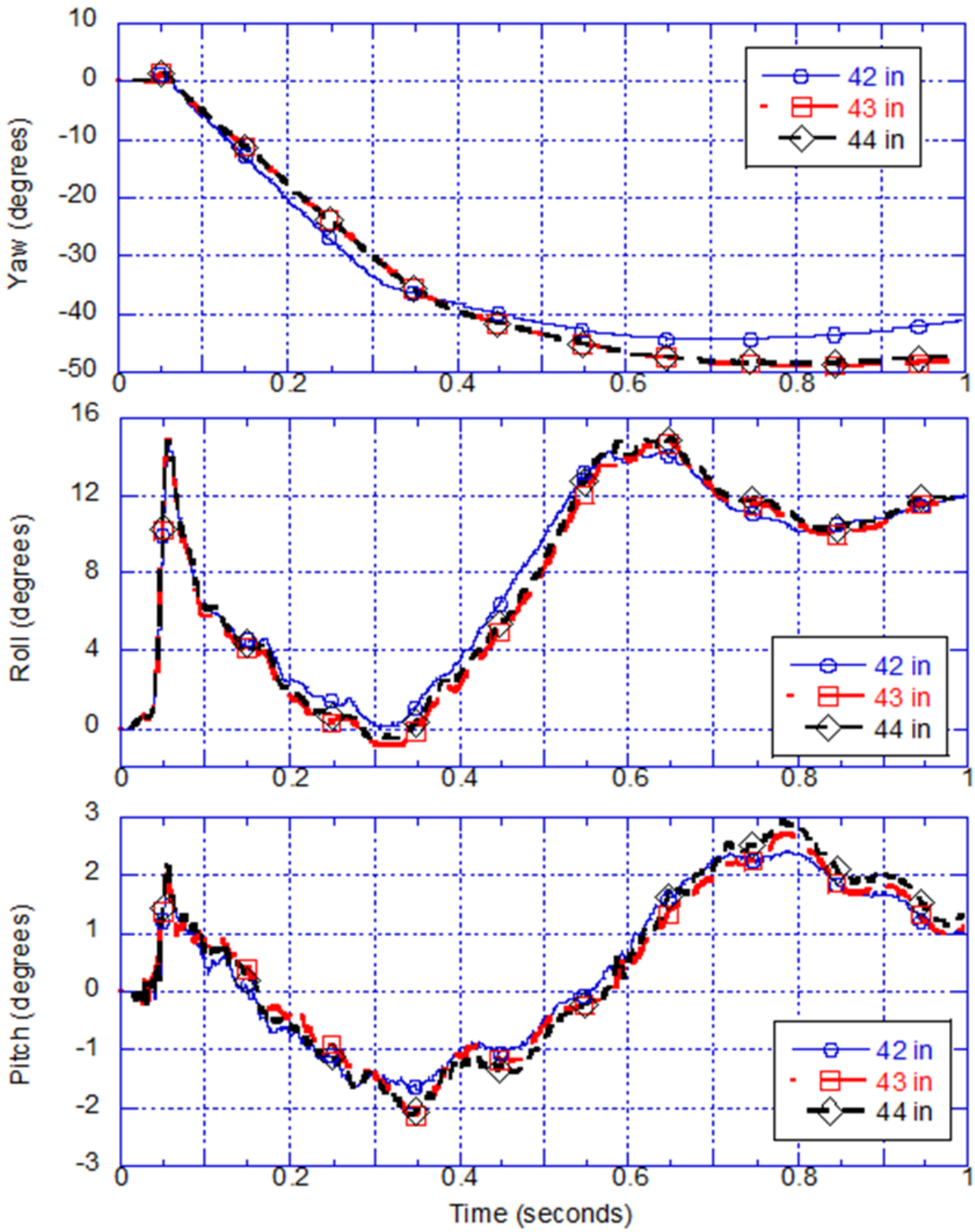


Figure 33. Passenger car collision comparison for different height barriers

Figure 32 and Figure 33 shows very little variation in the collision data when the height of the barrier is changed. Also, the damage to the barrier for all three heights is non-existent and not a concern for collisions with this vehicle. There doesn't seem to be a high risk of noticeable cracking or damage when this vehicle collides with the barrier. Figure 34 shows the damage (or lack thereof) that is incurred on the 44-in barrier when the passenger car collides.

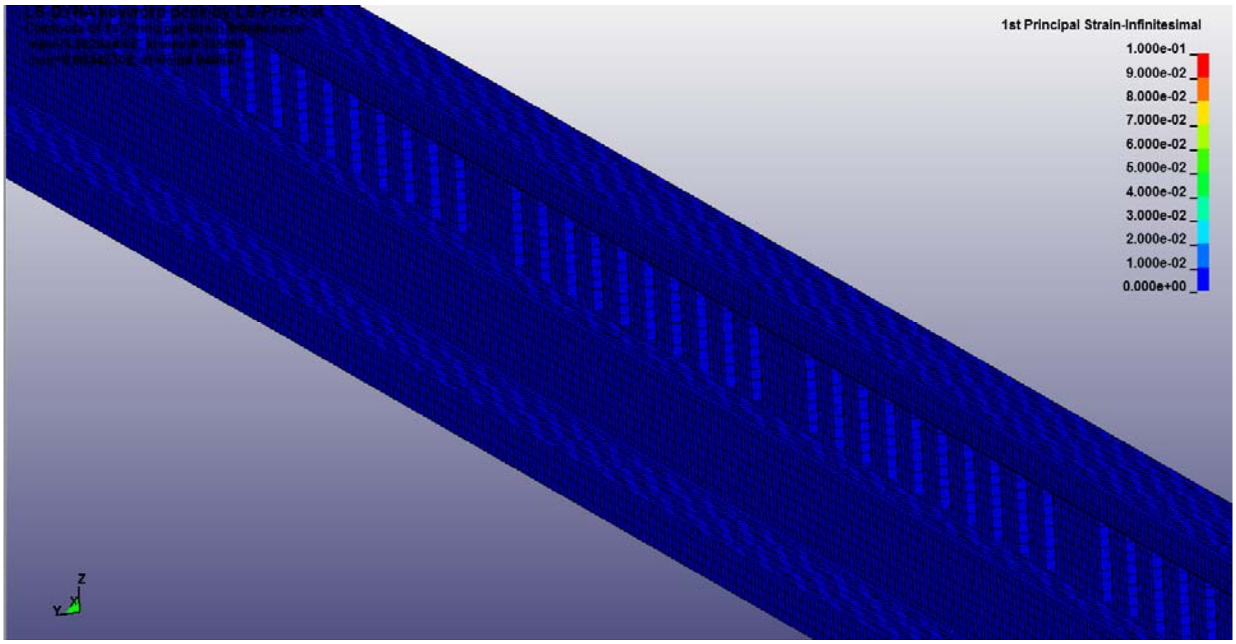


Figure 34. Damage incurred on 44-in barrier after passenger car collision

Final Design

After conducting the parametric study, it was found that each of the design options evaluated met the requirements of MASH for TL-4. The occupant risk metrics were below the maximum permissible values for each case. Table 14 shows the maximum permissible values for acceleration, roll, pitch, and yaw. The single unit truck does not have any required limits. The only requirement in MASH for the single unit truck collision is that the barrier contains and redirects the vehicle in a controlled manner. It is preferred, although not essential, that the vehicle remains upright during and after the collision.

After analyzing all of the results and seeing the behavior of the vehicle, the final design was chosen for testing. The modified design shown in Figure 14 and Figure 16 was chosen to be tested under MASH TL-4 impact conditions.

FULL SCALE TESTING

Testing Facility

The full-scale tests were performed at Texas A&M Transportation Institute (TTI). Founded in 1950, TTI has become a world leader in roadway safety studies, and since 1965 has conducted over 2,000 full scale crash tests. Their test facility is a 2,000-acre complex where they perform a variety of crash tests, ranging from small passenger cars to large tractor-trailers and tanker trucks, into a variety of roadside hardware such as bridge rails, and signs. Their vast experience and knowledge in the field of roadside safety hardware is what led the research team to pick them as the facility to perform these tests. After sharing the details of the barrier with them, their engineers generated their own construction drawings and renderings, and experimental setup. They also handle all construction, vehicle data collection and processing, and photography and videography.

Construction and Finite Element Model Representation

To construct the barrier, conditions of being on a bridge must be simulated. TTI performs many of these tests at their facilities, and they are all built using the same method. There is a rigid concrete block that all concrete bridge barriers to be tested are attached too. Figure 35 shows a Solidworks rendering view from the end of the barrier to show how it will be laid out.

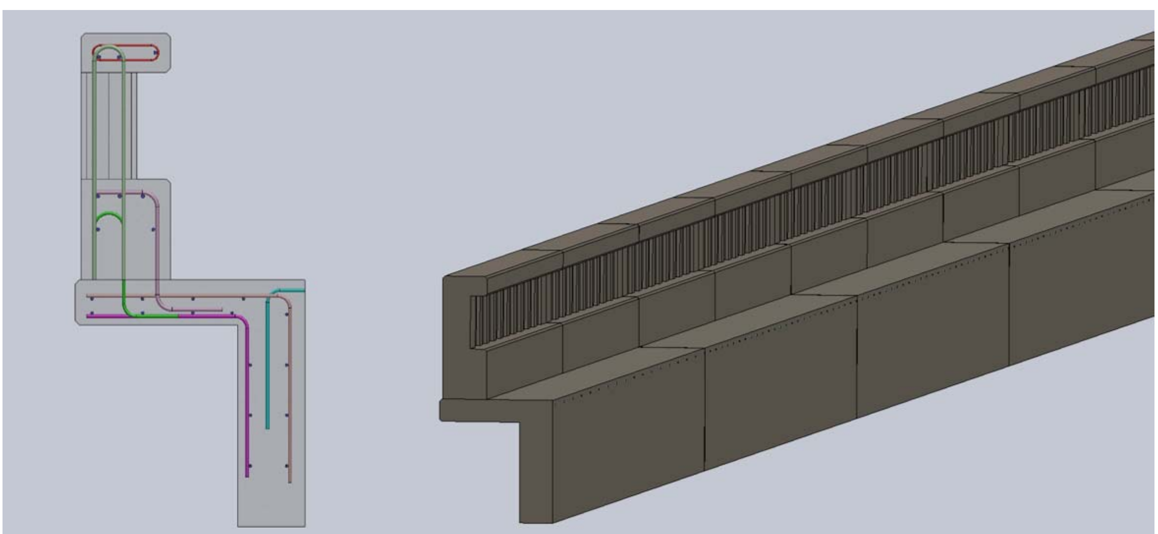


Figure 35. Solidworks rendering of barrier-rebar layout and isometric view of barrier attachment (Provided by TTI)

On the edge of this rigid block, there are dowels sticking out at 18-in along the length of the barrier, and 15-ft upstream and downstream of the impact locations, they are located every 12-in. Anchor bars are welded to each of these dowels and are developed in the concrete wall to secure it to the rigid block. Figure 36 shows these anchor bars welded to the dowels.

Figure 36 shows the deck bars. Because the rigid block concrete is preexisting, the deck bars are bent and developed in the wall portion of the setup. The bottom deck bars are placed at 8-in, and the top deck bars are placed at 4-in. They are placed at 4-in because in the barrier specifications, there is a 5-ft bar alternating with the regular deck reinforcement to provide additional strength to the connection with the deck. All of the longitudinal #4 bars are tied to the deck bars. After this part of the rebar assembly is finished, the vertical wall portion is then poured. This is shown in Figure 37.

Figure 36. Anchor bars welded to dowels and epoxy coated deck bars (TTI) and FEM representation

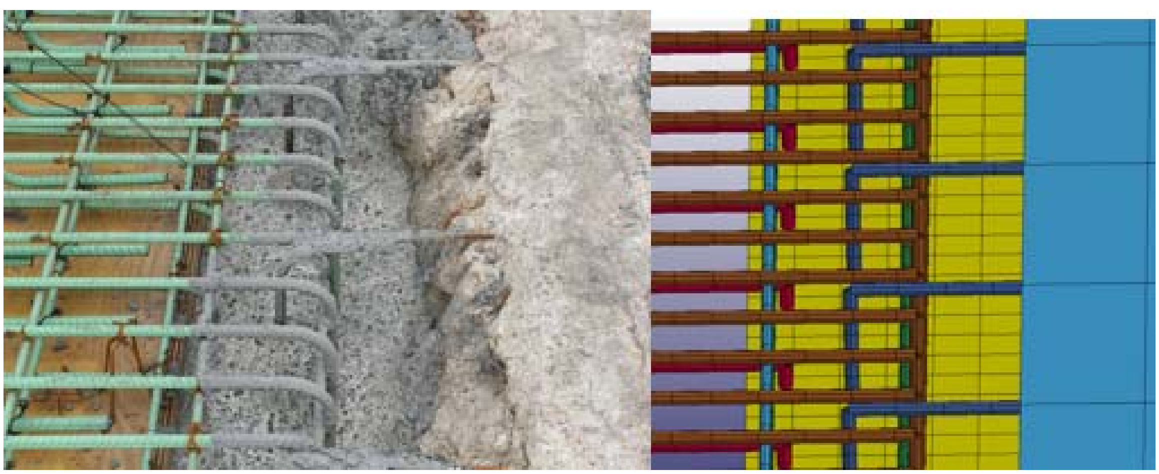


Figure 37. Filled wall portion of barrier setup (TTI) and FEM representation

The C-bars and D-bars (see Figure 15) that attach the barrier to the deck can be tied to the deck bars before or after the pouring of the wall because they do not come in contact with it. After they are tied to the deck bars, the longitudinal bars in the bottom portion of the barrier can also be tied to them. Figure 38 shows these bars tied in the assembly. When this part of the assembly is completed, the remaining portion of the deck is poured, leaving only the C-bars and D-bars protruding up from the concrete. This is shown in Figure 39.

Figure 38. C and D-bars tied to deck bars (picture from TTI)

Figure 39. C and D-bars protruding up from finished deck (picture from TTI)

After the deck is poured, the formwork for the barrier is assembled and set into place. The vertical b-bars, the a-bars in the top rail, and the longitudinal e-bars are then tied into place and secured to the formwork to ensure proper placement. This setup is shown in Figure 40. To create the openings needed between the posts, foam blocks are cut and then glued into the appropriate position on the formwork. When the concrete for the barrier is poured, it will flow around the blocks leaving behind the iconic openings required for this historic looking barrier.

Figure 40. Vertical bars and top rail reinforcement secured to formwork (TTI)

The other side of the formwork and the ends are set into place and the concrete is then poured. After the concrete is hard enough, the formwork is removed and the foam blocks can be removed easily. Once the foam blocks are removed, the barrier construction is complete. Figure 41 shows the finished product and its FEM counterpart.

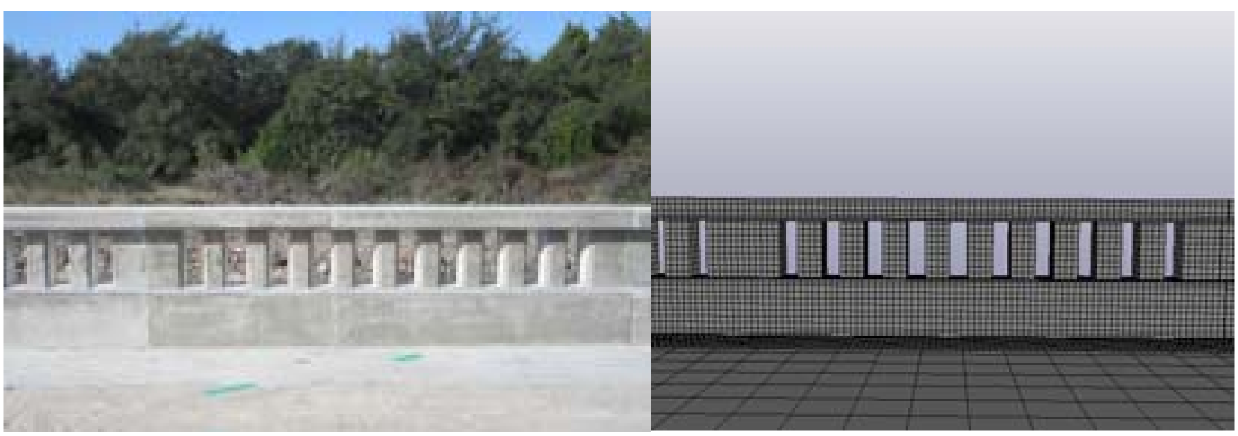


Figure 41. Fully constructed barrier (TTI) and FEM representation

Because the concrete for many components was poured at different times, there were many cold joints that needed to be simulated. This included the portions of barrier that were touching at their ends forming contraction joints, and at the interface of the deck and barrier. Figure 42 displays the location of the cold joint created when the barrier is poured after the deck. This cold joint was modeled by unmerging the nodes of these elements that were coincident such that the barrier does not act as if it was all poured at the same time. Figure 43 shows the original and updated barrier model setup.

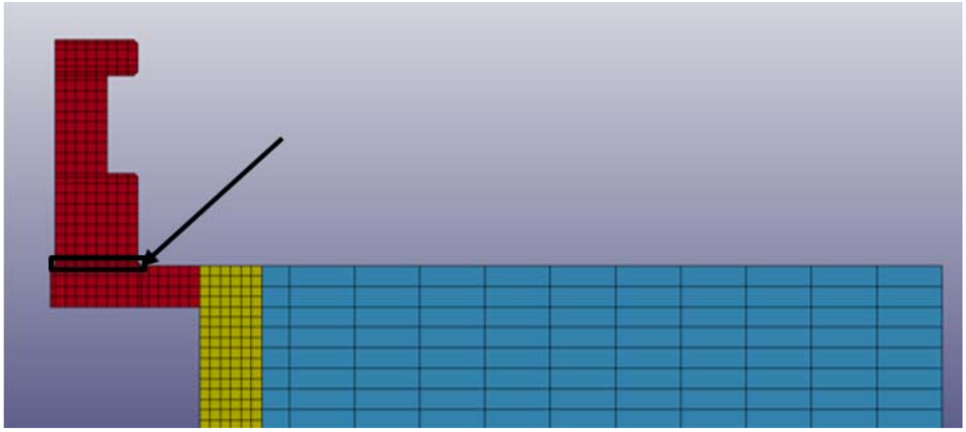


Figure 42. Location of cold joint interface between deck and barrier

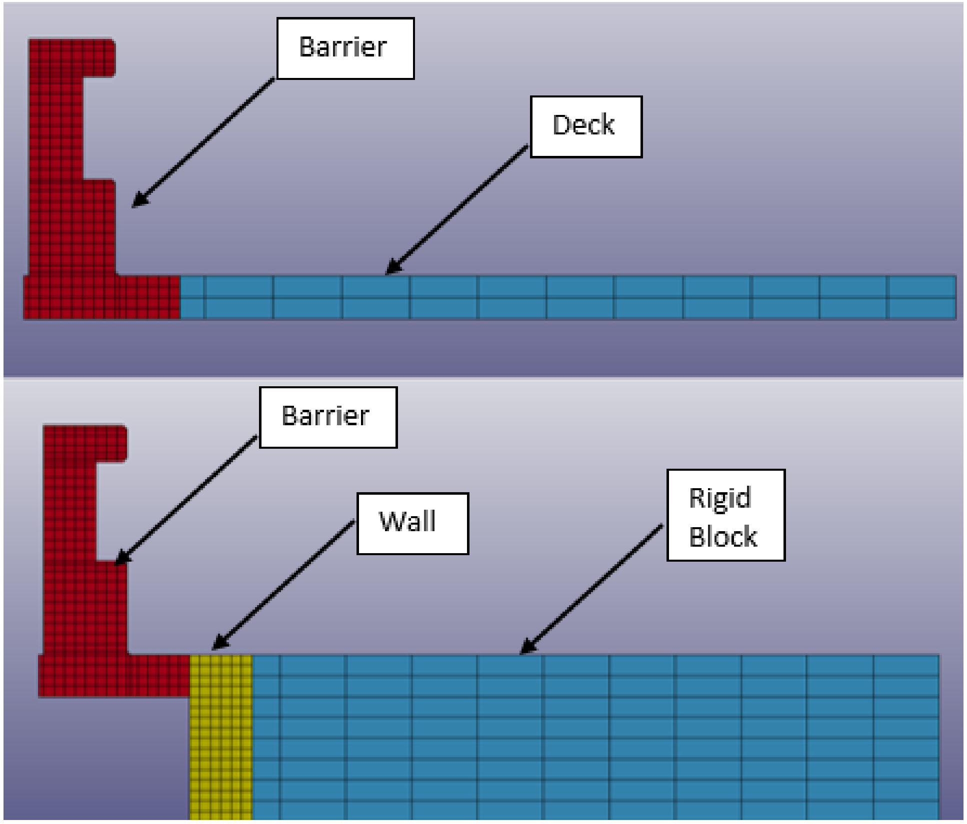


Figure 43. Original (top) and final (bottom) barrier model assembly

Material Specifications
For this barrier design, the only material specifications listed are the concrete axial compressive strength, steel rebar grade and yield strength, and steel rebar corrosion protection. All of these minimum design requirements must be met to give the designed resistance and meet all NJDOT specifications in order to be implemented.

Concrete Specifications

The concrete used for the barrier was supplied by Martin Marietta, and was a P gravel mix containing Type C fly ash. The required minimum concrete compressive strength for this barrier design is 4,000 psi. The first pour of the deck took place on November 10, 2016 and the last occurred on December 9, 2016. Table 8 and Figure 44 summarizes the concrete strength of barrier and the impact location. The majority of concrete pours exceeded 4000 psi when the 1st crash test for SUT was performed. The Parapet (C) and (E) where the vehicles crashed as well as wall and deck obtained more than 4000 psi. However, some pours on Parapet (D) did not fulfill with the minimum strength of 4000 psi when the crash tests were performed.

Table 8 - Concrete Strength of Barrier

Section	Pour Date	Break Date	Age at Break	Strength	Age at 1st Crash Test	Impact Section
Wall (A)	11/10/16	12/14/16	34 days	5848 psi	36 days	No
Deck (B)	11/16/16	12/14/16	28 days	5773 psi	30 days	No
Parapet (C)	11/30/16	12/14/16	14 days	5350 psi	16 days	Yes (SUT)
Parapet (D)*	12/1/16	12/21/16	20 days	2530 psi	15 days	No
Parapet (D)*	12/1/16	12/21/16	20 days	3077 psi	15 days	No
Parapet (D)	12/1/16	12/21/16	20 days	5660 psi	15 days	No
Parapet (E)	12/9/16	12/14/16	5 days	5110 psi	7 days	Yes (Pickup)
Parapet (E)	12/9/16	12/14/16	5 days	4630 psi	7 days	Yes (Small)
* Less than 4000 psi at crash testing						

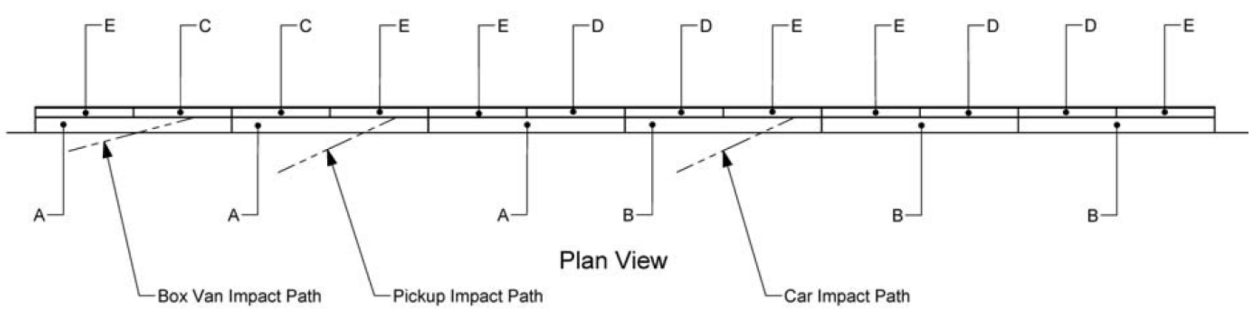


Figure 44. Concrete pour and impact location

Reinforcing Steel Specifications

The reinforcement specified for this barrier is grade 60 epoxy coated steel bars. As per NJDOT specifications, the bars are all corrosion protected with a protective layer of epoxy, and the tensile yield strength is 60,000 psi. The steel supplier for this barrier was CMC Steel in Allen, TX. The bars were delivered coated with epoxy, and were then cut and bent by the construction team at TTI.[34]

Vehicles

As per AASHTO MASH TL-4 requirements, three vehicles must be tested to determine the crashworthiness of the longitudinal barrier. The first vehicle to be tested is a 10,000 kg single unit truck. Next is a 2,270 kg pickup truck, and finally a 1,100 kg passenger car. After these vehicles were received by TTI, the inside of the vehicles were stripped down leaving only the necessities. Usually the back seats are removed and a data acquisition system and accelerometers are put in the place of them, and the front seats remain in order to place a crash test dummy. Under MASH, the crash test dummy does not play a role in determining whether the barrier passes or fails, but is there for the research purposes of TTI. The only vehicle that is required to have a crash test dummy under MASH is the passenger car. It is required because the vehicle is very light, and the 165 lb. dummy in the driver's seat makes up a significant portion of the total system mass, about 6.5 %. The vehicles used are described in this section.

Single Unit Truck (10000S)

The first vehicle crash tested was the 2006 International 4200 single unit box truck, shown in Figure 45. In order to achieve the required 10,000 kg and center of mass height a concrete block ballast was cast and mounted in the middle of the box of the truck. Accelerometers were mounted in the box of the truck in front of the concrete block, and in the cab of the truck on the floor between the driver and passenger seats.

Figure 45. 10000S single unit truck tested (TTI)

Pickup Truck (2270P)
The second vehicle used for crash testing was a 2011 Dodge Ram 1500 quad-cab pickup truck shown in Figure 46. The rear seats of this vehicle were removed and data collection hardware, including accelerometers, were mounted on the floor in their place. A crash test dummy was also placed in this vehicle in the driver's seat. Unlike the single unit truck, there was no need to add weight in the back to achieve the required 2,270 kg required for the test.

Figure 46. 2270P pickup truck tested (TTI)

Small Car (1100C)

The third and final vehicle used to test the barrier was a 2010 Kia Rio shown in Figure 47. The rear seats of the vehicle were removed and data collection hardware, including accelerometers, were mounted to the floor in their place. A required crash test dummy was placed in the driver's seat for the test. There was no need to add additional weight to this vehicle to achieve the required 1,100 kg required for the test.

Figure 47. 1100C small passenger car tested (TTI)

Experimental Setup

Vehicle Propulsion and Guidance

After the test vehicle is prepared and accelerometers are installed, it is placed at a set distance far from the barrier, and at the specified angle for the specific test. A two-to-one reverse tow cable pulley system was used to propel the vehicle and a steel guide wire was anchored to the ground and tensioned along the distance that the vehicle was being towed for. The system was oriented such that the towing truck drives away from the impact location to pull the test vehicle towards it. The front wheel of the test vehicle was attached to the guide wire using TTI's proprietary vehicle guidance system, and the vehicle was towed using a cable attached to the front of the vehicle. Both of these systems are detached just before impact resulting in a free-moving vehicle colliding with the barrier. After the collision, the vehicle's breaks are applied remotely to bring it to a controlled stop. Figure 48 shows a schematic of how the system was laid out.

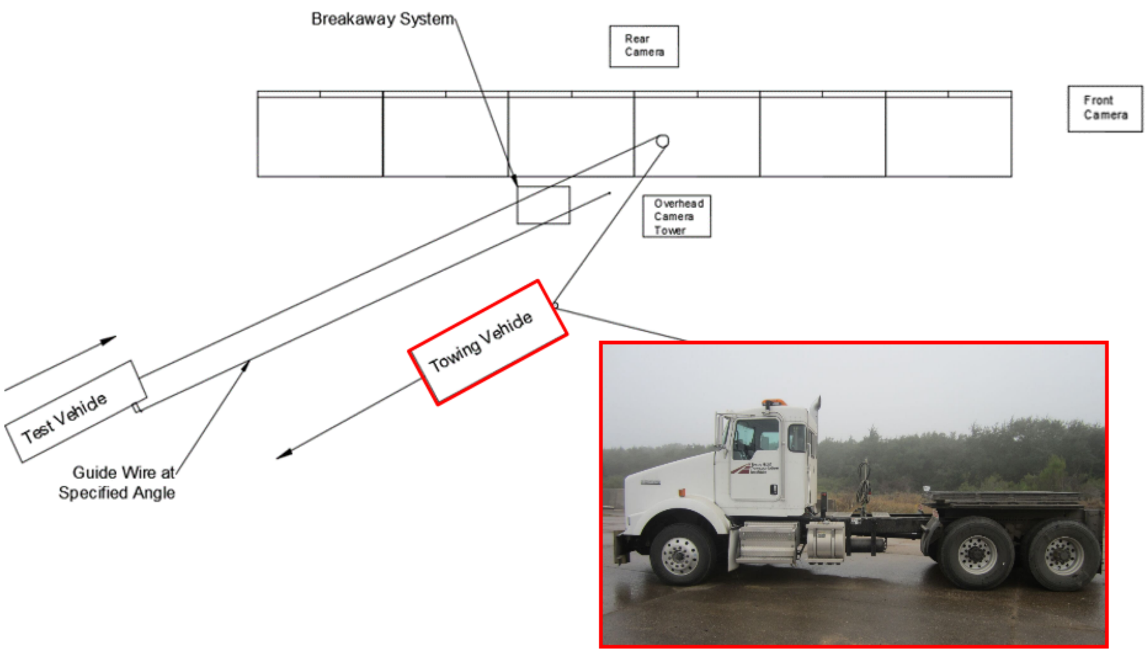


Figure 48. Cable-tow and vehicle guidance system

Data Collection

The system used to collect data from each collision was the Tiny Data Acquisition System Pro by Diversified Technical Systems, Inc. This system contained accelerometers that recorded acceleration in the x, y, and z directions, and angular rate transducers along each axis recorded the roll, pitch and yaw rates. Data was collected at a rate of 10,000 Hz.(34) After the data is collected, the procedure for processing it is identical to the one when data from a simulation is used. The accelerometer and rotational rate data is then input into the Test Risk Assessment Program (TRAP) which filters the acceleration data and integrates the rotational rates to calculate the angular displacement.

Test Results

The three vehicles were all tested according to MASH TL-4 standards and the results of the tests are that the barrier satisfactorily met all requirements. Full scale crash tests are typically the last step in proving the crashworthiness of a barrier. The barrier is now on its way to getting FHWA approval, and validating the finite element models is an important last step of the process. A barrier does not need to be modeled and validated to get approval and be implemented, but having validated models makes the process of retrofitting easier than ever. The FHWA recently announced that crash simulation results would be considered acceptable for evaluating improvements to previously tested barriers, which means there would be no need for another crash test.(10)

When validating a finite element model of a vehicle crash using testing data, there are three main steps: (1) solution verification, (2) time-history validation, and (3) Phenomena Importance Verification (PIRT's) (Ray et al., 2010). It was shown that all criteria were fulfilled and the finite element collision scenarios are valid. The time interval being evaluated is from the moment of impact to 0.6 s for the single unit truck, and 0.5 s for the other vehicles. All three crash tests were successful, and the results of the simulations were in very good agreement. The details of the model validation are shown in the appendix.

Damage to the Installation

During the severe impact with the single unit truck, the barrier sustained some damage. Most of it is superficial (tire marks, paint marks, other marks from metal contacting it), but some of it can compromise the integrity of the barrier after the fact. The damage to be worried about includes large cracks, broken pieces of concrete, and permanent deformation of the barrier, all of which occurred during this test. During the initial collision of the cabin with the barrier, the barrier did not experience any notable deflection, but when the box swung around for the secondary impact, the barrier experienced a large deflection that caused permanent deformation. The barrier at the time of maximum deflection and the permanent deformation left after the box impact are shown in Figure 49 and Figure 50. The top rail of the barrier was permanently deflected backwards about 2.1-in after the secondary impact.

Figure 49. Maximum barrier deflection and permanent damage.

Figure 50. Permanent deflection of barrier after single unit truck test.

The barrier and the portion of the deck that is cantilevered were poured at different times, so a crack formed at the interface between the bottom rail of the barrier and the top of the deck after the secondary impact. In addition to this crack, there were also fragments of concrete missing from rail that were detached during the collision. This crack, along with the superficial damage shown from the tires rubbing against the barrier is shown in Figure 51.

Figure 51. Barrier damage and crack at deck-barrier interface.

A crack also formed in the deck at the contraction joint of the barrier sections. Because only one of the two sections of the barrier was pushed out from the impact, and because the deck is continuous along every two sections of barrier, a large shear force was generated causing the deck to crack. This damage can be seen in Figure 52.

Figure 52. Crack in deck on non-impact side of barrier.

The small car and pickup truck collisions were much less severe, and the damage incurred on the barrier is very minimal. The only collision that produced notable damage was the single unit truck.

Occupant Risk Data and Testing Conditions

All three crash tests were successful, and therefore the barrier will be approved for use on roadways. All occupant risk criteria regarding ridedown accelerations, and rotational angles were within the specified allowances in MASH, and the barrier is safe for containment of single unit trucks.

Single Unit Truck (10000S)

MASH Test 4-12 of the 10000S single unit truck was performed on December 16, 2016. The only requirement for this test to be deemed a pass is that the truck must stay on the correct side of the barrier and not overturn to the other side, or show potential for overturning to the other side. The vehicle must be safely contained and redirected from the barrier and not show any signs of ending on the other side. It is preferable, although not essential, that the vehicle remains upright during and after the test, but is not a requirement for the pass/fail grade.(16) The truck was successfully contained and redirected on the correct side of the barrier, remained upright, also stayed very close to the barrier for the duration of the collision, and was very stable throughout the whole event. The actual impact conditions and the results for the crash test are shown in Figure 53.

General Information

- Test Agency: Texas A&M Transportation Institute (TTI)
- Test Standard Test No.: MASH Test 4-12
- TTI Test No.: 607451-1
- Test Date: 2016-12-16

Test Article

- Type: Bridge Rail
- Name: Pulaski Skyway Bridge Parapet
- Installation Length: 156 ft-1¼ inches
- Material or Key Elements: Twelve 13 ft long sections w/16-inch wide × 44 inch tall rail with 7-inch tall × 16-inch wide rail atop 19-inch tall concrete posts 8 inches wide × 10 inches deep spaced on 14-inch centers, atop 18-inch tall × 16-inch wide curb

Soil Type and Condition: Concrete Bridge Deck, Dry

Test Vehicle

- Type/Designation: 10000S
- Make and Model: 2006 International 4200
- Curb: 12,180 lb
- Test Inertial: 22,030 lb
- Dummy: 165 lb
- Gross Static: 22,195 lb

Impact Conditions

- Speed: 57.4 mi/h
- Angle: 15.3 degrees
- Location/Orientation: 5.1 ft upstream of open joint

Impact Severity: 169 kip-ft

Exit Conditions

- Speed: Remained in
- Angle: contact to end

Occupant Risk Values

- Longitudinal OIV: 13.1 ft/s
- Lateral OIV: 6.9 ft/s
- Longitudinal Ridedown: 2.4 g
- Lateral Ridedown: 4.1 g
- THIV: 16.9 km/h
- PHD: 4.3 g
- ASI: 0.95
- Max. 0.050-s Average
  - Longitudinal: −3.4 g
  - Lateral: 2.9 g
  - Vertical: 7.4 g

Post-Impact Trajectory

- Stopping Distance: 248 ft dwnstrm; 25 ft twd field side

Vehicle Stability

- Maximum Yaw Angle: 16 degrees
- Maximum Pitch Angle: 8 degrees
- Maximum Roll Angle: 12 degrees
- Vehicle Snagging: No
- Vehicle Pocketing: No

Test Article Deflections

- Dynamic: 4.4 inches
- Permanent: 2.1 inches
- Working Width: 20.1 inches

Vehicle Damage

- VDS: 11LFQ5
- CDC: 11FLEW4
- Max. Exterior Deformation: 14.0 inches
- OCDI: LF0000000
- Max. Occupant Compartment Deformation: 8.0 inches

Figure 53. Summary of results for MASH test 4-12

Pickup Truck (2270P)

MASH Test 4-11 of the 2270P pickup truck was performed on December 20, 2016. All of the requirements of this test were satisfactorily met, and they are listed in Table 9. The pickup truck was successfully contained and redirected, and remained upright during and after the collision. Other than non-structural fragments (front grill, pieces of metal from the body, front passenger window) getting taken off of the car, the main damage incurred on the vehicle included the front axle bending and locking the front drivers-side wheel and the tire detaching from the rear driver's side rim, and body damage on the impact side of the vehicle. The intrusions into the occupant compartment were minimal, and did exceed any of the limits specified in MASH. The actual impact conditions and the results for the crash test are shown in Figure 54 The occupant risk requirements for rotational angles, ridedown accelerations, and occupant impact velocities are listed in Table 14.

General Information

Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	MASH Test 4-11
TTI Test No.	607451-2
Test Date	2016-12-20

Test Article

Type	Bridge Rail
Name	Pulaski Skyway Bridge Parapet
Installation Length	156 ft-1¼ inches
Material or Key Elements	Twelve 13 ft long sections w/16-inch wide × 44 inch tall rail with 7-inch tall × 16-inch wide rail atop 19-inch tall concrete posts 8 inches wide × 10 inches deep spaced on 14-inch centers, atop 18-inch tall × 16-inch wide curb
Soil Type and Condition	Concrete Bridge Deck, Dry

Test Vehicle

Type/Designation	2270P
Make and Model	2011 Dodge RAM 1500
Curb	4936 lb
Test Inertial	5037 lb
Dummy	165 lb
Gross Static	5202

Impact Conditions

Speed	62.5 mi/h
Angle	24.0 degrees
Location/Orientation	4.2 ft upstream of joint
Impact Severity	109 kip-ft

Exit Conditions

Speed	51.1 mi/h
Angle	9.1 degrees

Occupant Risk Values

Longitudinal OIV	18.0 ft/s
Lateral OIV	28.9 ft/s
Longitudinal Ridedown	4.4 g
Lateral Ridedown	8.9 g
THIV	37.8 km/h
PHD	9.0 g
ASI	2.05
Max. 0.050-s Average	
Longitudinal	−9.5 g
Lateral	15.9 g
Vertical	−2.9 g

Post-Impact Trajectory

Stopping Distance	233 ft dwnstrm 95 ft twd traffic

Vehicle Stability

Maximum Yaw Angle	32 degrees
Maximum Pitch Angle	6 degrees
Maximum Roll Angle	24 degrees
Vehicle Snagging	No
Vehicle Pocketing	No

Test Article Deflections

Dynamic	1.0 inch
Permanent	0.25 inch
Working Width	17.0 inches

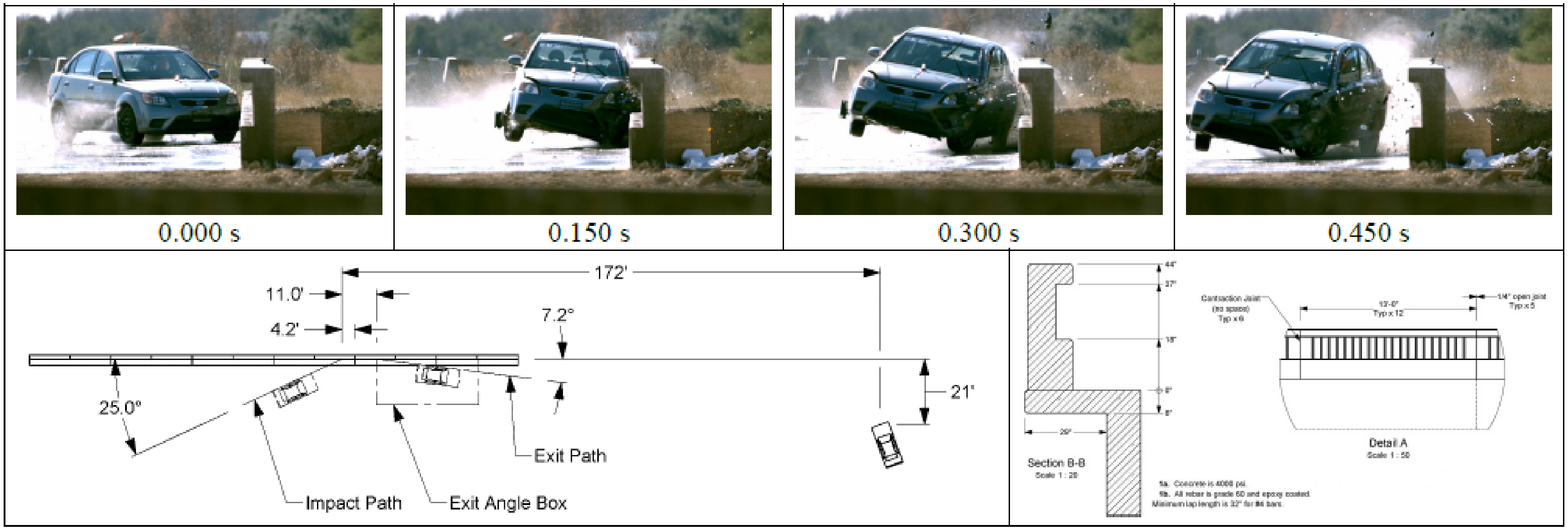
Vehicle Damage

VDS	11LFQ5
CDC	11FLEW4
Max. Exterior Deformation	14.0 inches
OCDI	LF0000000
Max. Occupant Compartment Deformation	2.0 inches

Figure 54. Summary of results from MASH Test 4-11

Small Car (1100C)

MASH Test 4-10 of the 1100C passenger car was performed on December 21, 2016. All of the requirements of this test were satisfactorily met, and they are listed in Table 9. The car was successfully contained and redirected, and remained upright during and after the collision. The intrusions into the occupant compartment were minimal, and did exceed any of the limits specified in MASH. The actual impact conditions and the results for the crash test are shown in Figure 55. The occupant risk requirements for rotational angles, ridedown accelerations, and occupant impact velocities are listed in Table 14.



General Information

Test Agency	Texas A&M Transportation Institute (TTI)
Test Standard Test No.	MASH Test 4-10
TTI Test No.	607451-3
Test Date	2016-12-21

Test Article

Type	Bridge Rail
Name	Pulaski Skyway Bridge Parapet
Installation Length	156 ft-1¼ inches
Material or Key Elements	Twelve 13 ft long sections w/16-inch wide × 44 inch tall rail with 7-inch tall × 16-inch wide rail atop 19-inch tall concrete posts 8 inches wide × 10 inches deep spaced on 14-inch centers, atop 18-inch tall × 16-inch wide curb

Soil Type and Condition	Concrete Bridge Deck, Dry

Test Vehicle

Type/Designation	1100C
Make and Model	2010 Kia Rio
Curb	2518 lb
Test Inertial	2429 lb
Dummy	165 lb
Gross Static	2594 lb

Impact Conditions

Speed	62.5 mi/h
Angle	25.0 degrees
Location/Orientation	4.2 ft upstream of open joint
Impact Severity	57 kip-ft

Exit Conditions

Speed	50.4 mi/h
Angle	7.2 degrees

Occupant Risk Values

Longitudinal OIV	23.0 ft/s
Lateral OIV	31.5 ft/s
Longitudinal Ridedown	4.2 g
Lateral Ridedown	11.0 g
THIV	42.5 km/h
PHD	11.3 g
ASI	2.79
Max. 0.050-s Average	
Longitudinal	−13.3 g
Lateral	20.2 g
Vertical	−4.0 g

Post-Impact Trajectory

Stopping Distance	172 ft dwnstrm 21 ft twd traffic

Vehicle Stability

Maximum Yaw Angle	44 degrees
Maximum Pitch Angle	4 degrees
Maximum Roll Angle	11 degrees
Vehicle Snagging	No
Vehicle Pocketing	No

Test Article Deflections

Dynamic	0.5 inch
Permanent	Negligible
Working Width	16.5 inches

Vehicle Damage

VDS	11LFQ4
CDC	11FLEW4
Max. Exterior Deformation	9.0 inches
OCDI	LF0003000
Max. Occupant Compartment Deformation	3.5 inches

Figure 55. Summary of results from MASH test 4-10

Validation Process

The first step in validating the model is checking the solution verification criteria to ensure the model is stable and all laws of physics are upheld. The solution verification tables for each vehicle are shown in the appendix, and all criteria passes.

The next step in validating the model is validating the time-history curves. All accelerations and rotations about the three axes were compared using RSVVP and the theory described in the beginning of this section. Although the Sprague-Geers metrics did not pass for some single-channel comparisons, the multi-channel comparison passed, and therefore the time-histories pass and are validated. The scores for the time-history validation for the individual channels, as well as the multi-channel comparisons, are shown in the appendix.

The third and final step of the validation process is checking that all criteria in the Phenomena Importance Ranking Table (PIRT) is fulfilled. The criteria that needs to be fulfilled in order for the model to be considered fully validated is shown in the appendix.

Table 9 - List of requirements for passing MASH tests 4-10 and 4-11(16)

- 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
- 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, the occupant compartment should not exceed limits set forth in Section 5.2.2 and Appendix E.
- The vehicle should remain upright during and after collision. The maximum roll and pitch angles are not to exceed 75 degrees.
- Occupant impact velocities (OIV) should satisfy the following limits:
    - Preferred: 30 ft/s and Maximum: 40 ft/s
- The occupant ridedown acceleration should satisfy the following limits:
    - Preferred: 15.0 G and Maximum: 20.49 G

Deformations and intrusions should be limited as follows:

- Roof ≤ 4 in
- Windshield—no tear of plastic liner and maximum deformation of 3-in.
- 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. 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. Lateral deformation should be limited to 3-in.
    - Wheel/foot well and toe pan areas ≤ 9-in.
    - Side front panel (forward of A-pillar) ≤ 12-in.
    - Front side door area (above seat) ≤ 9-in.
    - Front side door area (below seat) ≤ 12-in.
    - Floor pan and transmission tunnel areas ≤ 12-in.

CONCLUSIONS

This purpose of this project was to provide an open-faced concrete balustrade design as mitigation for the Pulaski Skyway Contract 2 (Rt. 139 Contract 3) Project. A preliminary design was developed based on AASHTO design procedures and was then approved by the Historic Preservation Office. The preliminary design was used as the basis for a parametric study to investigate the effects of (1) total barrier height, (2) post width, and (3) window opening width on the crash performance of the barrier. The parametric study was carried out using finite element analysis to simulate impact conditions consistent with MASH Test Level 4.

Based on the results of the parametric study, the following conclusions were made: (1) as the total height of the barrier increases, the likelihood of a truck overturning is decreased, (2) the closer the posts are to each other the more capacity the barrier will have, and (3) finite element models can be a very useful tool in predicting the behavior of vehicles during a collision. Because barrier height decides which part of the vehicle comes in contact with the barrier, if the height is increased the parts impacting the barrier will be higher and more easily keep the vehicle upright. This is especially true for the box truck test because if the box impacts the barrier instead of the tires, the truck will not start the tripping motion that causes leaning over the barrier. For smaller vehicles such as the pickup truck and passenger car, the height does not affect the overturning potential nearly as much because the center of gravity is below the total height of the barrier. If the post openings are too wide, components of the vehicles may get caught in these openings and cause more damage to the barrier or vehicles. It was found that changing the spacing of the posts did not have a large effect on the kinematics of the truck, and that height was the main factor that affected how the truck responded. The final design of the barrier had a total height of 44-in, a post width of 8-in, and a window opening of 6-in.

The design was developed according to the AASHTO bridge design specifications to ensure proper strength and capacity of the barrier for TL-4 loading conditions. Using the design loads and procedures set forth in these specifications simplifies the design process and ensures the design will have a very low probability of failure while staying economical.

While finite element models are a useful tool in predicting how a vehicle will react in a collision, they are not suitable to completely replace full scale crash tests. While they can predict behavior with reasonable accuracy, there is no way to know exactly how a vehicle or barrier system will act until the collision is performed in real life. The vehicle behavior exhibited in the model did not exactly match the real life behavior, and the model needed to be calibrated after the full-scale tests. Once these models are calibrated and validated, they can be used to simulate new barriers more accurately because variables like friction and contact definitions will already be adjusted to match real-life conditions.

The barrier has been designed, constructed, and successfully crash tested to AASHTO MASH TL-4. Because these tests were successful, the barrier is now on its way to becoming a standard NJDOT specification and will be able to be used anywhere in the state where similar open-faced balustrades need replacement. This barrier may also be adopted by other state DOT's and used on highways all over the country that need to meet the TL-4 standard.

Scope for Future Work

This project focused on designing, modeling, and crash testing an aesthetic concrete barrier to meet AASHTO MASH TL-4 standards. This barrier provides crashworthy protection for vehicles as big and heavy as a 10,000 kilogram single unit truck. Having the ability to resist this vehicle fulfills the requirement of this project, but there are still many vehicles on the road that are bigger, heavier, and may not be contained properly by this barrier. In areas where tractor trailers make up a significant portion of the traffic on the road, a barrier passing MASH TL-5 collision conditions is necessary. TL-5 barriers are required to have a minimum height of 42 in and because the barrier discussed in this project is 44 in tall, the shape could be retained and only rebar details would need be changed to accommodate the tractor-trailer impact loading. If the original shape is retained, the only vehicle that would need to be tested is the tractor-trailer because the other two vehicles in the TL-5 requirements (small car and pickup truck) were already tested for the TL-4 crash tests. Refining the design and testing the barrier to a higher test level would not only increase the capacity of the barrier, but would also allow it to be used on many more bridges than a TL-4 barrier.

Whenever a bridge rail is placed on a bridge, there is the risk of a car losing control before reaching the bridge and hitting the barrier at the end causing extensive vehicle damage and severe injury to the occupants. To avoid this kind of disaster there is always a terminal guard rail placed before the concrete barrier to prevent the vehicle from impacting the end. This metal guide rail gradually increases from flexible to rigid in order to redirect the vehicle away from the rail end. Because this barrier is new, there are no terminals designed especially for this specific shape. In order for this rail to be as safe as possible, a terminal to compliment this rail must be designed, crash tested, and approved to be used wherever this barrier is constructed. Because barriers are tested by impacting the vehicle in the middle of the section, there is no way of knowing how a vehicle would react at the end. Constructing and testing this component ensures that a collision at the beginning of the barrier would also yield a safe vehicle response. Therefore, in order to implement the new balustrade, an appropriate end treatment must also be developed.

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APPENDIX A: PARAMETRIC STUDY DATA

Table 10 - SUT collision data for different height barriers (parametric study)

Occupant Risk Factors		42 in parapet	43 in parapet	44 in parapet
		FEA	FEA	FEA
Occupant Impact Velocity (m/s)	x-direction	2.1	1.9	2.3
	y-direction	2.4	2.5	3.6
	at time	at 0.2226 seconds on right side of interior	at 0.2095 seconds on right side of interior	at 0.1966 seconds on right side of interior
THIV (m/s)		3.2 at 0.2226 seconds on right side of interior	3.1 at 0.2095 seconds on right side of interior	4.3 at 0.1966 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-4.7 (1.0077 - 1.0177 seconds)	-3.7 (0.2460 - 0.2560 seconds)	-4.6 (0.2372 - 0.2472 seconds)
	y-direction	-10 (0.2930 - 0.3030 seconds)	-9.3 (0.2581 - 0.2681 seconds)	-11.5 (0.2501 - 0.2601 seconds)
PHD (g's)		10.3 (0.2929 - 0.3029 seconds)	9.4 (0.2580 - 0.2680 seconds)	11.5 (0.2501 - 0.2601 seconds)
ASI		0.64 (0.2531 - 0.3031 seconds)	0.63 (0.0921 - 0.1421 seconds)	0.8 (0.2503 - 0.3003 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-2.3 (0.1250 - 0.1750 seconds)	-2.3 (0.1171 - 0.1671 seconds)	-2.2 (0.1131 - 0.1631 seconds)
	y-direction	-5.6 (0.2531 - 0.3031 seconds)	-5.1 (0.0920 - 0.1420 seconds)	-6.5 (0.2500 - 0.3000 seconds)
	z-direction	-5.1 (0.9800 - 1.0300 seconds)	-3.1 (0.1222 - 0.1722 seconds)	-3.8 (0.2518 - 0.3018 seconds)
Maximum Angular Disp. (deg)	Roll	16.8 (0.6067 seconds)	12.9 (0.5854 seconds)	14.7 (0.4934 seconds)
	Pitch	-3 (0.6148 seconds)	2.5 (0.9293 seconds)	3.8 (0.2572 seconds)
	Yaw	-13.7 (0.3294 seconds)	-12.7 (0.2698 seconds)	-22.9 (0.8766 seconds)

Table 11 - SUT collision data for different window openings (parametric study)

Occupant Risk Factors		8P-6W	8P-8W
		FEA	FEA
Occupant Impact Velocity (m/s)	x-direction	2.3	2.6
	y-direction	3.6	3.4
	at time	at 0.1966 seconds on right side of interior	at 0.1927 seconds on right side of interior
THIV (m/s)		4.3 at 0.1966 seconds on right side of interior	4.3 at 0.1927 seconds on right side of interior
Ridedown Acceleration (g's)	x-direction	-4.6 (0.2372 - 0.2472 seconds)	-5.4 (0.2363 - 0.2463 seconds)
	y-direction	-11.5 (0.2501 - 0.2601 seconds)	-10.1 (0.2499 - 0.2599 seconds)
PHD (g's)		11.5 (0.2501 - 0.2601 seconds)	10.5 (0.2500 - 0.2600 seconds)
ASI		0.8 (0.2503 - 0.3003 seconds)	0.72 (0.2500 - 0.3000 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-2.2 (0.1131 - 0.1631 seconds)	-2.9 (0.1161 - 0.1661 seconds)
	y-direction	-6.5 (0.2500 - 0.3000 seconds)	-6.2 (0.2500 - 0.3000 seconds)
	z-direction	-3.8 (0.2518 - 0.3018 seconds)	-2.3 (0.2547 - 0.3047 seconds)
Maximum Angular Disp. (deg)	Roll	14.7 (0.4934 seconds)	17.2 (0.5171 seconds)
	Pitch	3.8 (0.2572 seconds)	2.9 (0.2573 seconds)
	Yaw	-22.9 (0.8766 seconds)	-21.2 (0.8245 seconds)

Table 12 - Pickup Truck collision data for different height barriers (parametric study)

Occupant Risk Factors		42 in parapet FEA	43 in parapet FEA	44 in parapet FEA
Occupant Impact Velocity (m/s)	x-direction	8.8	9.2	9.3
	y-direction	-8.3	-7.8	-8
	at time	at 0.0851 seconds on left side of interior	at 0.0857 seconds on left side of interior	at 0.0855 seconds on left side of interior
THIV (m/s)		12.1 at 0.0851 seconds on left side of interior	12 at 0.0857 seconds on left side of interior	11.8 at 0.0855 seconds on left side of interior
Ridedown Acceleration (g's)	x-direction	-9.5 (0.0959 - 0.1059 seconds)	-6.1 (0.0924 - 0.1024 seconds)	-8.7 (0.2738 - 0.2838 seconds)
	y-direction	8.1 (0.2619 - 0.2719 seconds)	10.6 (0.3070 - 0.3170 seconds)	11.1 (0.2821 - 0.2921 seconds)
PHD (g's)		9.5 (0.0959 - 0.1059 seconds)	10.7 (0.3070 - 0.3170 seconds)	12.9 (0.2746 - 0.2846 seconds)
ASI		1.97 (0.0270 - 0.0770 seconds)	2.02 (0.0272 - 0.0772 seconds)	2 (0.0288 - 0.0788 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-14.2 (0.0337 - 0.0837 seconds)	-15.7 (0.0272 - 0.0772 seconds)	-14.8 (0.0255 - 0.0755 seconds)
	y-direction	14.2 (0.0272 - 0.0772 seconds)	13.8 (0.0271 - 0.0771 seconds)	14.1 (0.0287 - 0.0787 seconds)
	z-direction	-4.1 (0.1170 - 0.1670 seconds)	-4.3 (0.1209 - 0.1709 seconds)	4.5 (0.0586 - 0.1086 seconds)
Maximum Angular Disp. (deg)	Roll	11.4 (0.4891 seconds)	8.7 (0.4534 seconds)	9 (0.9206 seconds)
	Pitch	4.1 (0.5502 seconds)	-4.7 (0.2985 seconds)	-4.1 (0.3240 seconds)
	Yaw	35.2 (0.4664 seconds)	33.3 (0.3198 seconds)	36.3 (0.6071 seconds)

Table 13 - Small Car collision data for different height barriers (parametric study)

Occupant Risk Factors		42 in parapet	43 in parapet	44 in parapet
		FEA	FEA	FEA
Occupant Impact Velocity (m/s)	x-direction	8.9	9.9	9.9
	y-direction	-8.8	-8.9	-8.9
	at time	at 0.0749 seconds on left side of interior	at 0.0751 seconds on left side of interior	at 0.0754 seconds on left side of interior
THIV (m/s)		12.5 at 0.0749 seconds on left side of interior	13.3 at 0.0751 seconds on left side of interior	13.2 at 0.0754 seconds on left side of interior
Ridedown Acceleration (g's)	x-direction	-5.1 (0.0763 - 0.0863 seconds)	-5.3 (0.0776 - 0.0876 seconds)	-6.5 (0.0767 - 0.0867 seconds)
	y-direction	4.7 (0.0874 - 0.0974 seconds)	5.5 (0.0906 - 0.1006 seconds)	4.9 (0.5985 - 0.6085 seconds)
PHD (g's)		6.3 (0.0749 - 0.0849 seconds)	5.8 (0.0785 - 0.0885 seconds)	6.7 (0.0759 - 0.0859 seconds)
ASI		2.43 (0.0148 - 0.0648 seconds)	2.46 (0.0165 - 0.0665 seconds)	2.5 (0.0165 - 0.0665 seconds)
Max 50-ms moving avg. acc. (g's)	x-direction	-17 (0.0189 - 0.0689 seconds)	-19 (0.0196 - 0.0696 seconds)	-18.8 (0.0176 - 0.0676 seconds)
	y-direction	17.4 (0.0112 - 0.0612 seconds)	17.1 (0.0110 - 0.0610 seconds)	17.2 (0.0139 - 0.0639 seconds)
	z-direction	5.4 (0.0303 - 0.0803 seconds)	5.8 (0.0304 - 0.0804 seconds)	5.6 (0.0303 - 0.0803 seconds)
Maximum Angular Disp. (deg)	Roll	-14.6 (0.0569 seconds)	-14.9 (0.0566 seconds)	-15 (0.6501 seconds)
	Pitch	-2.4 (0.7864 seconds)	-2.7 (0.7834 seconds)	-2.9 (0.7840 seconds)
	Yaw	44.3 (0.7064 seconds)	48.8 (0.8274 seconds)	48.4 (0.8064 seconds)

APPENDIX B: GENERAL INFORMATION

Table 14 - Preferred and maximum permissible acceleration values [16]

Acceleration Parameter		MASH Test 4-10		MASH Test 4-11		MASH Test 4-12	
		Small Car		Pickup Truck		Single Unit Truck	
		Pref.	Max	Pref.	Max	Pref.	Max
Occupant Impact Velocity (m/s)	x-direction	9.1	12.2	9.1	12.2	n/a	n/a
	y-direction	9.1	12.2	9.1	12.2	n/a	n/a
Ridedown Acceleration (g's)	x-direction	15	20.49	15	20.49	n/a	n/a
	y-direction	15	20.49	15	20.49	n/a	n/a
Maximum Angular Disp. (deg)	Roll	n/a	75	n/a	75	n/a	n/a
	Pitch	n/a	75	n/a	75	n/a	n/a
	Yaw	n/a	n/a	n/a	n/a	n/a	n/a

APPENDIX C: MODEL VALIDATION

Validation Procedure

The first step of validating a computer model is the analysis solution verification. Checking the solution verification criteria is a way to determine that the model is stable, and that all laws of physics are being upheld. These checks ensure that energy is conserved, that hourglass energy is not excessive, and that the amount of mass added to the model during analysis does not affect the accuracy of the solution.
The second step in validating a computer model is the time-history validation, which compares parameters such as accelerations and rotational velocities using single-channel comparisons, and a multi-channel weighted comparison. This is accomplished by the use of the Roadside Safety Verification and Validation Program (RSVVP). The comparison method described in NCHRP w179 involves using the Sprague-Geers magnitude-phase-composite (MPC) comparison metrics. In MPC metrics the phase and magnitude components should not be dependent on each other, and should be compared separately. (30) This allows the person analyzing the curves to identify the aspects that do not agree. For all three parameters (magnitude, phase, and comprehensive), a value of 40% or lower indicates a pass, and a value greater than 40% indicates a failure.(29,30) Although the comprehensive metric comparison is not used to determine if the model is validated or not, it is still calculated by RSVVP.
In addition to the MPC metric comparisons, Analysis of Variance (ANOVA) metrics are also compared. ANOVA comparisons are based on the assumption that the true curves measured in the field and test curves extracted from the model represent the same event in such a way that any differences between the curves must be attributable to random experimental error only.(29,30) These comparisons assess whether the variance between the two curves can be attributed to random error. Two ANOVA metrics are compared: average residual error normalized by the peak response (e^{-r}), and the standard deviation of the normalized residuals (σ^{r}).

When dealing with vehicle crashes, it is acceptable for some comparison channels in the model to fail, while the overall model can still be considered valid. In order for this to be accounted for, each channel is given a weighting factor that corresponds to the importance, or “weight” each parameter has on the behavior of the vehicle during the collision. The most accurate method for calculating the weighting factors is the Inertial Method that uses a proportion of momentum in each channel to calculate the factor. In order to perform the calculation using this method, the vehicle mass and three angular inertial properties must be known. These exact quantities are not always known for the test vehicles, and calculating these properties is a very time consuming process that includes a series of very involved calculations.

Because of this, the default method used in RSVVP for calculating the weighting factors is the Area Method, which is a pseudo momentum approach. The weighting factors calculated using the Area Method produce similar factors to those calculated using the Inertia Method, making it acceptable to use in validating collision models. The factors are calculated using only measured information from the full-scale crash tests. The factors for linear and rotational momentum are calculated separately from one another

because of the unit difference, and each one is assigned an “index” value. This value gauges how important the parameter is relative to other ones. Once each channel’s index value is calculated, the weighting factors are calculated by simply dividing the index value by the summation of all index values. These factors are then used to compute the multi-channel comparison metrics for the model. If all metrics satisfy the criteria listed above, the time-histories for the vehicle can be considered verified.
The third and final step in validating a computer model is comparing various parameters using a Phenomena Importance Ranking Table (PIRT). The items set forth in the Phenomena Importance Ranking Table include information about structural adequacy, occupant risk, and vehicle trajectory. Each item in the table describes very important events that occur during a vehicle collision, and it is very important that every event occurs in the model and during testing, and that measured values, such as rotations and accelerations, are close enough to one another such that the difference between the model and collision is insignificant.

Once all three steps of the validation process are completed and all criteria is affirmative, then the model is considered validated, and can be accepted as an accurate representation of what occurs during full scale testing.

Single Unit Truck (10000S)

Before the crash scenario was modeled, the vehicle needed modifications. The first vehicle crash tested was the 2006 International 4200 single unit box truck, shown in Figure 56, and the vehicle model used was downloaded from the Center for Collision Safety and Analysis (CCSA) George Mason University. It was a truck that fulfilled the requirements of a TL-4 vehicle under NCHRP Report 350. To make this vehicle usable, dimensions and the mass were modified to fulfill the requirements of MASH. In order to achieve the required 10,000 kg and center of mass height, a concrete block ballast was cast and mounted in the middle of the truck box. Accelerometers were mounted in the box of the truck in front of the concrete ballast, and in the cab of the truck on the floor between the driver and passenger seats.

Figure 56. 10000S single unit truck and FEM representation

There were very small differences in some dimensions of the vehicle, but none of them were large enough to warrant making any major modifications. One modification that

was made includes the fuel tank location. It was originally on the impact side in the model, but on the outside in the full-scale test. The truck model was reflected in order to match the full-scale test. Another simple modification that was made was the ballast location. Additional rigid constraints were added to the ballast to attach it more firmly to the cargo box. Additional rigid constraints were also added to the accelerometer to better simulate the actual mounting scheme used in the full-scale test vehicle.
When running the simulations, the axle was detaching from the suspension leafs, which did not occur in the full-scale test. Upon further investigation, it was found that the U-bolts connecting the axle to the suspension leafs were failing in the simulation. To correct this problem, the U-bolts were strengthened to ensure this failure and detaching would not occur. After these modifications were performed, the vehicle model was ready to be simulated.

The final changes to the simulation were modifications to the contact frictions. The friction between surfaces plays an integral role in determining how the vehicle will interact with the barrier during and after impact. They were iteratively modified until the behavior was as representative of the full-scale test as possible. The original and modified friction values are listed in Table 15.

Table 15 - Original and modified friction coefficients for 10000S simulation

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

MASH Test 4-12 of the 10000S single unit truck was performed on December 16, 2016. The only requirement for this test to be deemed successful is that the barrier must contain and redirect the vehicle and not show potential for the vehicle to penetrate, vault or roll over the top of the barrier. It is preferable, although not required, that the vehicle remains upright during and after the test. [(16)] The truck was successfully contained and redirected on the correct side of the barrier, remained upright, also stayed very close to the barrier for the duration of the collision, and was very stable throughout the crash event. Figure 57 shows sequential views from the full-scale crash test and the finite element analysis. The kinematics of the vehicle in test and the FEA were very similar to each other. The accelerations and rotations were also in very good agreement, as shown in Figure 58 and Figure 59.

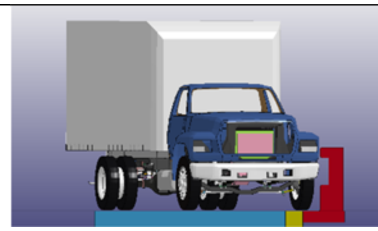
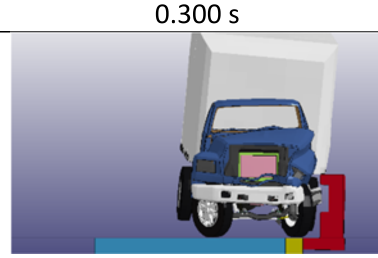
Test	Simulation
 0.000 s	 0.000 s
 0.100 s	 0.100 s
 0.200 s	 0.200 s
 0.300 s	 0.300 s
 0.400	 0.400

Figure 57. Sequential views of MASH Test 4-12 and FEA

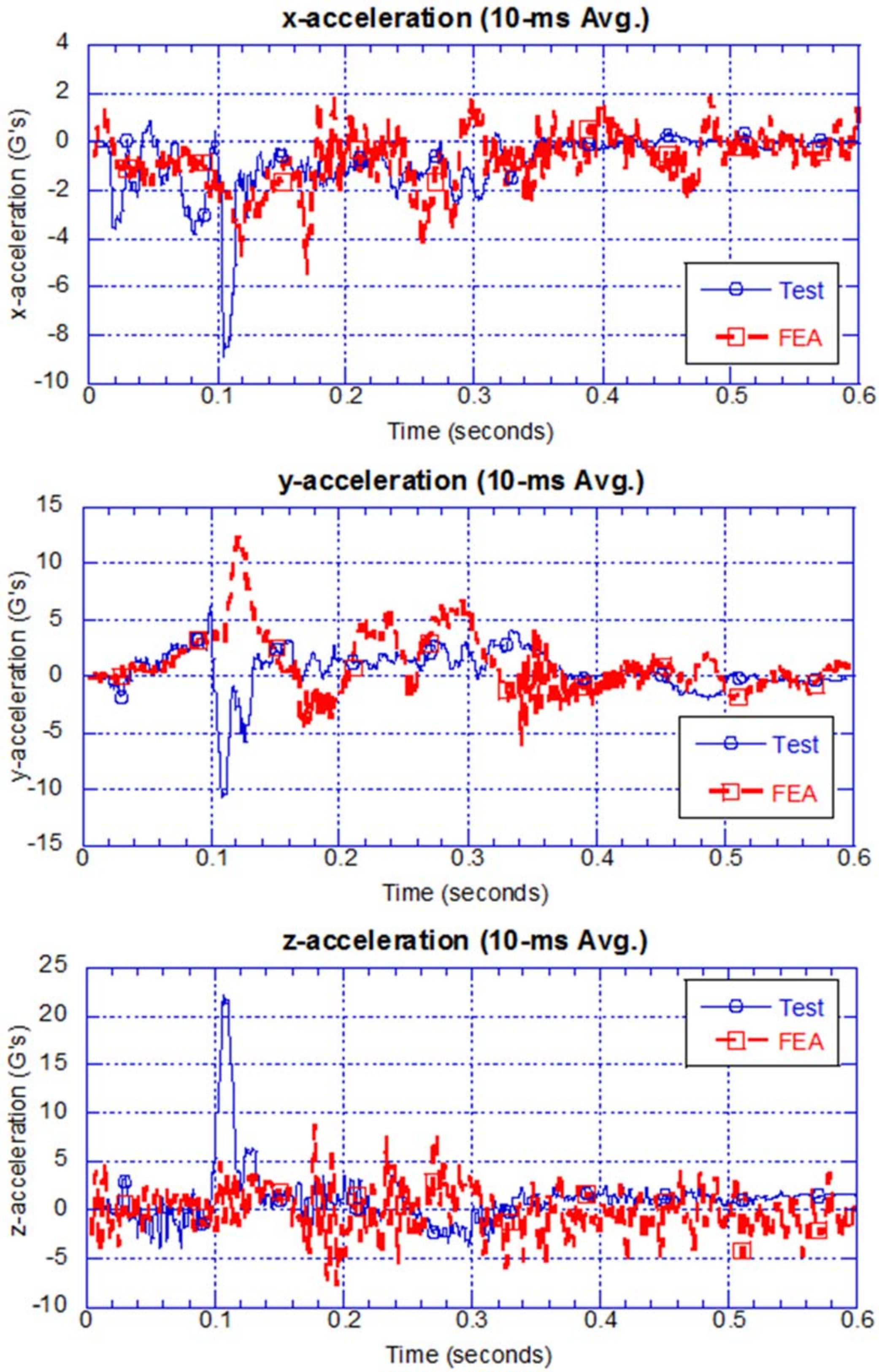


Figure 58. Acceleration comparison between MASH Test 4-12 and FEA

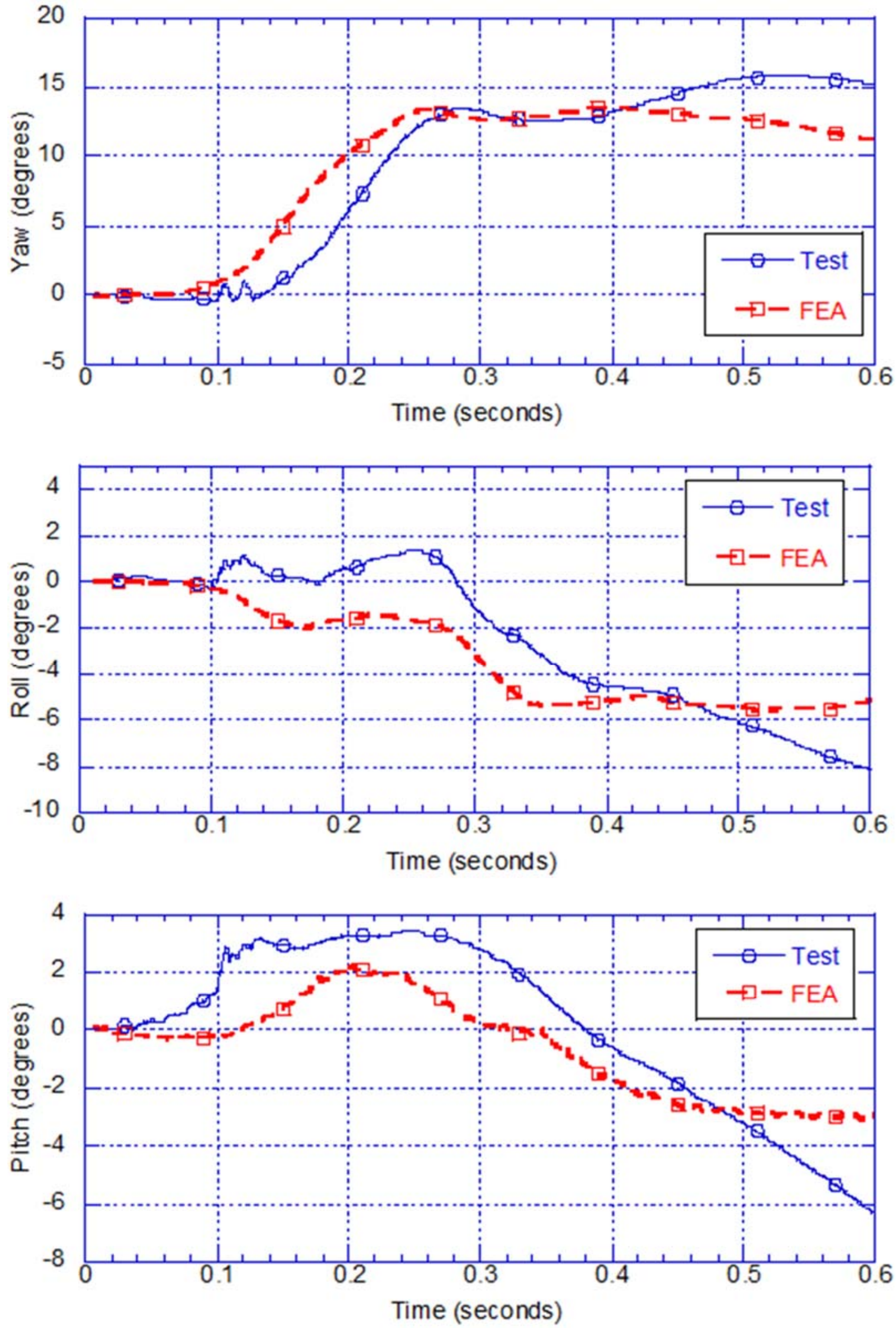


Figure 59. Rotational Angle comparison between MASH Test 4-12 and FEA

Table 16 - SUT model solution verification criteria.

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	<1	YES
Hourglass Energy of the analysis solution at the end of the run is less than 5% of the total initial energy at the beginning of the run.	<1	YES
The part/material with the highest amount of hourglass energy at any time during the run is less than 5% of the total initial energy at the beginning of the run.	<1	YES
Mass added to the total model is less than 5% the total model mass at the start of the run.	<1	YES
The part/material with the most mass added had less than 10% of its initial mass added.	<1	YES
The moving parts/materials in the model have less than 5% of mass added to the initial moving mass of the model.	<1	YES
There are no shooting nodes in the solution?	YES	YES
There are no solid elements with negative volumes?	YES	YES

Table 17 - SUT time-history comparison.

Single Channel Time History Comparison Results			**Time interval [0 sec - 0.6 sec]**		
O	***Sprague-Geer Metrics***		**M**	**P**	**Pass?**
	X acceleration		6.5	40.6	Fail
	Y acceleration		20.4	50.4	Fail
	Z acceleration		50.4	48.8	Fail
	Yaw rate		27.9	24.1	Pass
	Roll rate		32.4	35.2	Pass
	Pitch rate		20.7	43.2	Fail
P	***ANOVA Metrics***		**Mean**	**SD**	**Pass?**
	X acceleration/Peak		0.47	13.51	Pass
	Y acceleration/Peak		2.28	19.4	Pass
	Z acceleration/Peak		-4.45	22.51	Pass
	Yaw rate		-1.95	14.67	Pass
	Roll rate		6	19.7	Fail
	Pitch rate		4.33	16.26	Pass
Multi-Channel Weighting Factors			**Time interval [0 sec - 0.6 sec]**		
Multi-Channel Weighting Method Peaks Area I Area II Inertial		**X Channel**	0.16059642		
		Y Channel	0.106453842		
		Z Channel	0.232949738		
		Yaw Channel	0.222019916		
		Roll Channel	0.155941409		
		Pitch Channel	0.122038675		
Sprague-Geer Metrics			**M**	**P**	**Pass?**
	All Channels (weighted)		28.7	39.4	Pass
ANOVA Metrics			**Mean**	**SD**	**Pass?**
	All Channels (weighted)		0.3	17.8	Pass

Table 18 - SUT Phenomena Importance Ranking Table (PIRT)

Evaluation Criteria				Known Result	Analysis Result	Agree?
Structural Adequacy	A	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	YES	YES	YES
		A2	The relative difference in the maximum dynamic deflection is less than 20 percent.	4.4	0.62	YES
		A3	The relative difference in the time of vehicle-barrier contact is less than 20 percent.	0.6	0.6	YES
		A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	n/a	n/a	0
		A5	Barrier did not fail (answer Yes or No).	YES	YES	YES
		A6	There were no failures of connector elements (Answer Yes or No).	n/a	n/a	0
		A7	There was no significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	YES	YES	YES
		A8	There was no significant snagging between vehicle body components and barrier elements (Answer Yes or No).	YES	YES	YES
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 (Answer Yes or No).	YES	YES	YES
	F	F1	The vehicle should remain upright during and after the collision. The maximum pitch & roll angles are not to exceed 75 degrees.	YES	YES	YES
		F2	Maximum Vehicle roll - relative difference is less than 20% or absolute difference is less than 5 degrees.	8	5.6	YES
		F3	Maximum Vehicle pitch - relative difference is less than 20% or absolute difference is less than 5 degrees.	6.3	3.1	YES
		F4	Maximum Vehicle yaw - relative difference is less than 20% or absolute difference is less than 5 degrees.	15.8	13.5	YES
	H	H1	Longitudinal & lateral occupant impact velocities (OIV) should fall below the preferred value of 30 ft/s (9.1 m/s), or at least below the maximum allowed value of 40 ft/s (12.2 m/s)	YES	YES	YES
		H2	Longitudinal OIV (m/s) - Relative difference is less than 20% or absolute difference is less than 2 m/s	4	2.6	YES
		H3	Lateral OIV (m/s - Relative difference is less than 20% or absolute difference is less than 2 m/s)	2.1	3.5	YES
	I	I1	Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.	YES	YES	YES
		I2	Longitudinal ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	2.4	4.4	YES
		I3	Lateral ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	4.1	6.7	YES
Trajectory	L		The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant ride-down acceleration in the longitudinal direction should not exceed 20 G's.	YES	YES	YES
	M		The exit angle from the test article preferable should be less than 60 percent of the test impact angle, measured at the time of vehicle loss of contact with test device.	YES	YES	YES

Table 19 - SUT composite validation table

Composite Test Comparison		
Table 1 - Analysis Solution Verification	Did all solution verification criteria in table pass?	YES
Table 2 - RSVVP Results	Do all the time history evaluation scores from the single channel factors result in a satisfactory comparison (i.e., The comparison passes the criterion)?	NO
	If all the values for Single Channel comparison did not pass, did the weighted procedure result in an acceptable comparison?	YES
Table 3 - Roadside Safety Phenomena Importance Ranking Table	Did all the critical criteria in the PIRT Table pass? Note: Tire deflation was observed in the test but not in the simulation. This was due to the fact that tire deflation was not incorporated into the model. This is considered not to have a critical effect on the outcome of the test.	YES
Overall	Are the results of Steps I through III all affirmative (i.e., YES)? If all three steps result in a "YES" answer, the comparison can be considered validated or verified. If one of the steps results in a negative response, the result cannot be considered validated or verified.	YES

*A "YES" for the weighted procedure but not single channels is acceptable.

Pickup Truck (2270P)

The second vehicle used for crash testing was a 2011 Dodge Ram 1500 quad-cab pickup truck shown in Figure 60. The rear seats of this vehicle were removed and data collection hardware, including accelerometers, were mounted on the floor in their place. A crash test dummy was also placed in this vehicle in the driver's seat. Unlike the single unit truck, there was no need to add a ballast in the back to achieve the required 2,270 kg required for the test. The model used to simulate this collision was a 2007 Chevy Silverado. The dimensions of the Chevy Silverado pickup truck model and the Dodge Ram 1500 used in the test are very similar, and therefore no dimensional changes were needed. The only modification made to this vehicle was the accelerometer mounting. The number of rigid constraints between the accelerometer and the floor of the cab was increased to reduce the noise collected by the accelerometer and to give a more accurate reading.

Figure 60. 2270P vehicle used and Chevy Silverado modeled

The final changes to the simulation were modifications to the contact frictions. They were iteratively modified until the behavior was as representative of the full-scale test as possible. The original and modified friction values are listed in Table 20.

Table 20 - Original and modified friction coefficients for 2270P simulation

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

MASH Test 4-11 of the 2270P pickup truck was performed on December 20, 2016. All of the requirements of this test were satisfactorily met, and they are listed in Table 9. The pickup truck was successfully contained and redirected, and remained upright during and after the collision. Other than non-structural fragments (front grill, pieces of metal from the body, front passenger window) getting taken off of the car, the main damage incurred on the vehicle included the front axle bending and locking the front drivers-side wheel and the tire detaching from the rear drivers side rim, and body damage on the impact side of the vehicle. The intrusions into the occupant compartment were minimal, and did exceed any of the limits specified in MASH. Figure

61 shows a visual comparison between the full scale crash test and the finite element model. The kinematics of the test and model were very similar to each other, and were in good agreement. The accelerations and rotations were also in very good agreement, as shown in Figure 62 and Figure 63.

Figure 61. Visual comparison between MASH Test 4-11 and FEA

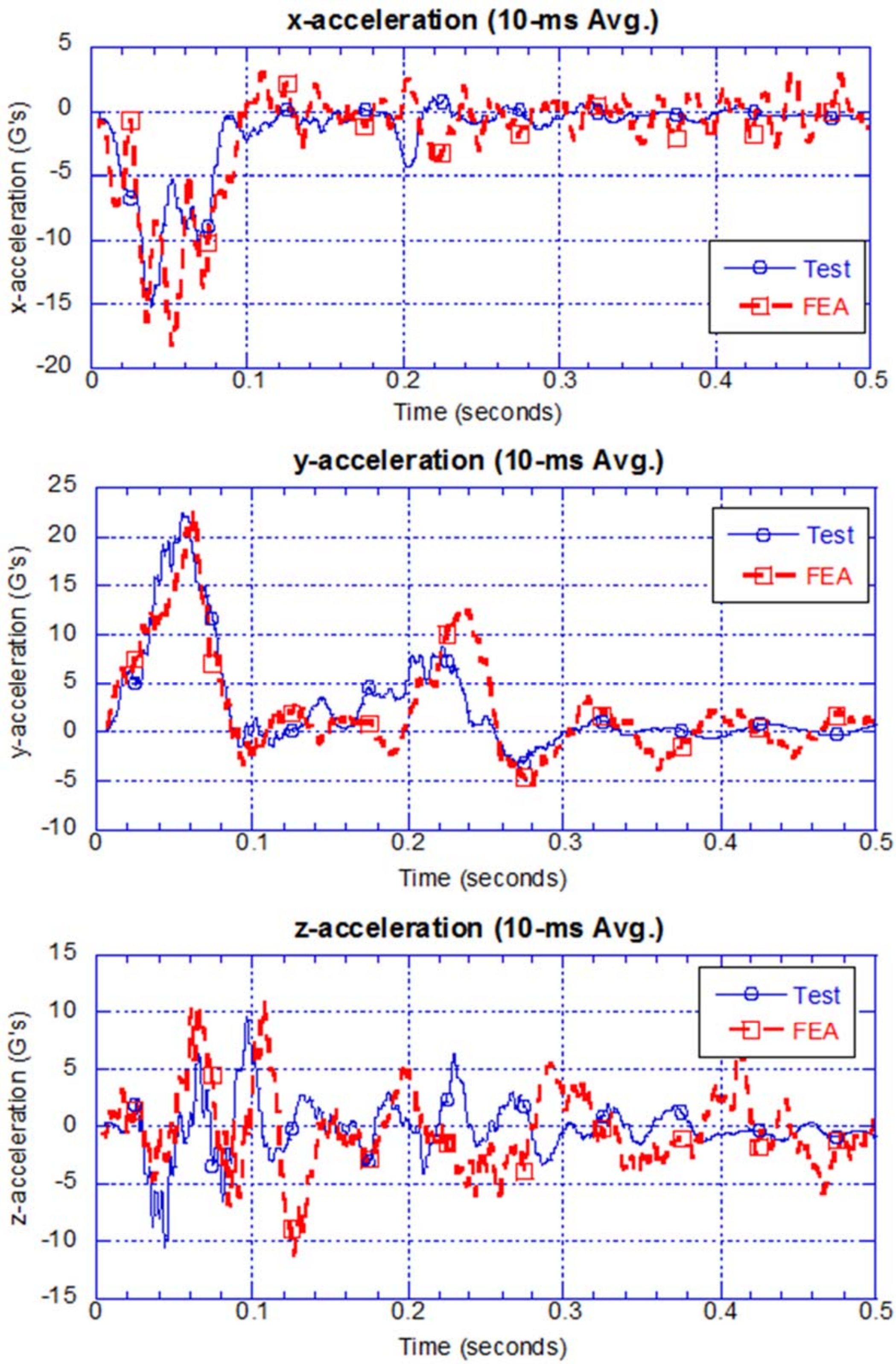


Figure 62. Acceleration comparison between MASH test 4-11 and FEA

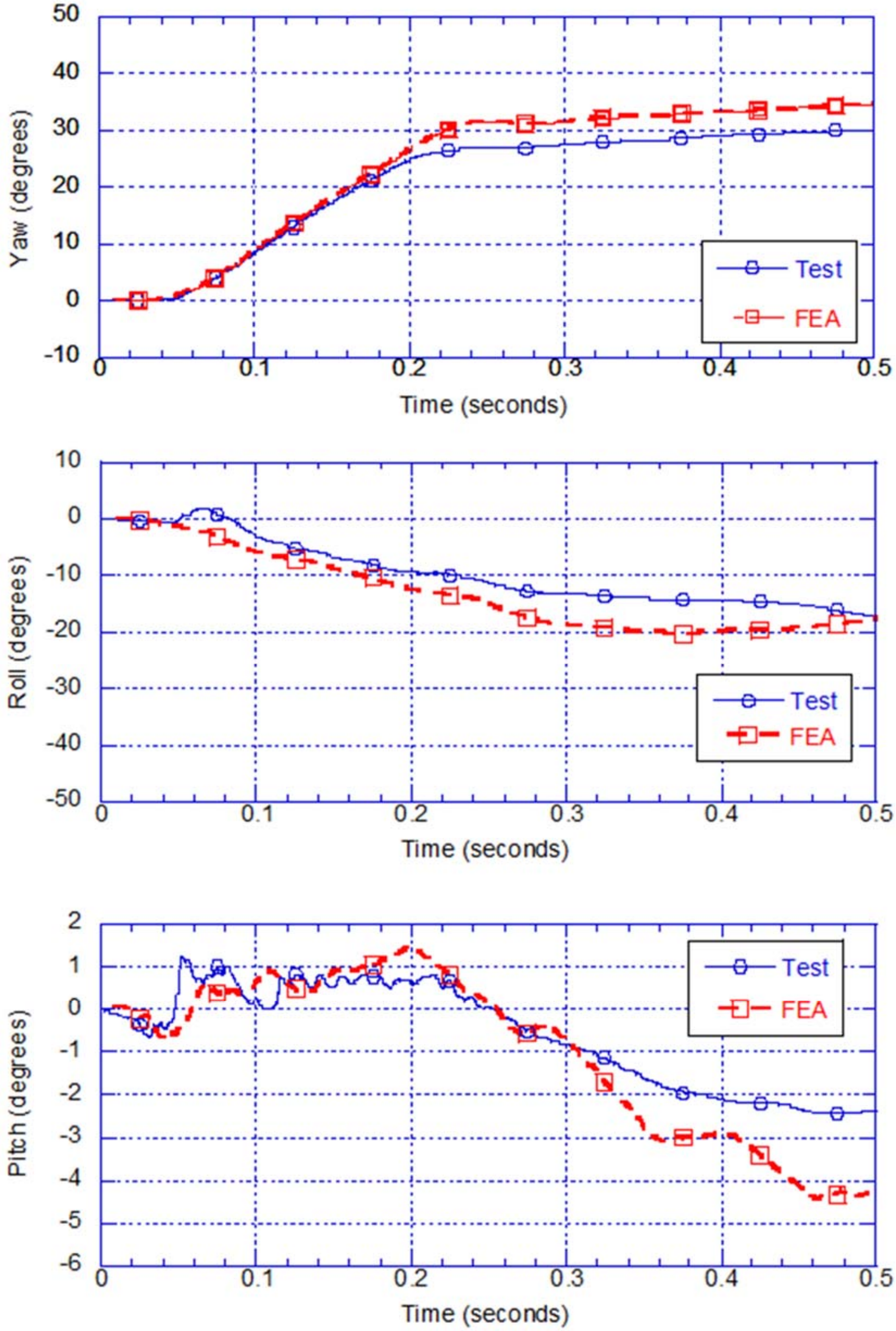


Figure 63. Rotational angle comparison between MASH test 4-11 and FEA

Table 21 - Pickup Truck model solution verification criteria.

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	<1	YES
Hourglass Energy of the analysis solution at the end of the run is less than 5% of the total initial energy at the beginning of the run.	<1	YES
The part/material with the highest amount of hourglass energy at any time during the run is less than 5% of the total initial energy at the beginning of the run.	<1	YES
Mass added to the total model is less than 5% the total model mass at the start of the run.	<1	YES
The part/material with the most mass added had less than 10% of its initial mass added.	<1	YES
The moving parts/materials in the model have less than 5% of mass added to the initial moving mass of the model.	<1	YES
There are no shooting nodes in the solution?	YES	YES
There are no solid elements with negative volumes?	YES	YES

Table 22 - Pickup Truck time-history comparison.

Single Channel Time History Comparison Results			Time interval [0 sec - 0.5 sec]		
	Sprague-Geer Metrics		**M**	**P**	**Pass?**
O	X acceleration		37.7	26.4	Fail
	Y acceleration		0.1	19.4	Pass
	Z acceleration		47.2	46.7	Fail
	Yaw rate		9.8	7.6	Pass
	Roll rate		0.7	49.9	Fail
	Pitch rate		13.9	48.8	Fail
	ANOVA Metrics		**Mean**	**SD**	**Pass?**
P	X acceleration/Peak		-0.59	17.39	Pass
	Y acceleration/Peak		-1.06	11.99	Pass
	Z acceleration/Peak		-1.55	34.16	Pass
	Yaw rate		2.03	9.56	Pass
	Roll rate		2.06	24.83	Pass
	Pitch rate		-5.47	13.14	Pass
Multi-Channel Weighting Factors			**Time interval [0 sec - 0.5 sec]**		
Multi-Channel Weighting Method Peaks Area I Area II Inertial		**X Channel**	0.17521272		
		Y Channel	0.302934251		
		Z Channel	0.021853028		
		Yaw Channel	0.363504853		
		Roll Channel	0.118629509		
		Pitch Channel	0.017865638		
Sprague-Geer Metrics			**M**	**P**	**Pass?**
	All Channels (weighted)		11.6	21.2	Pass
ANOVA Metrics			**Mean**	**SD**	**Pass?**
	All Channels (weighted)		-1.2	13.7	Pass

Table 23 - Pickup Truck Phenomena Importance Ranking Table (PIRT)

Evaluation Criteria				Known Result	Analysis Result	Agree?
Structural Adequacy	A	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	YES	YES	YES
		A2	The relative difference in the maximum dynamic deflection is less than 20 percent.	1	0.58	YES
		A3	The relative difference in the time of vehicle-barrier contact is less than 20 percent.	0.33	0.27	YES
		A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	n/a	n/a	0
		A5	Barrier did not fail (answer Yes or No).	YES	YES	YES
		A6	There were no failures of connector elements (Answer Yes or No).	n/a	n/a	0
		A7	There was no significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	YES	YES	YES
		A8	There was no significant snagging between vehicle body components and barrier elements (Answer Yes or No).	YES	YES	YES
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 (Answer Yes or No).	YES	YES	YES
	F	F1	The vehicle should remain upright during and after the collision. The maximum pitch & roll angles are not to exceed 75 degrees.	YES	YES	YES
		F2	Maximum Vehicle roll - relative difference is less than 20% or absolute difference is less than 5 degrees.	24	20.2	YES
		F3	Maximum Vehicle pitch - relative difference is less than 20% or absolute difference is less than 5 degrees.	6	4.4	YES
		F4	Maximum Vehicle yaw - relative difference is less than 20% or absolute difference is less than 5 degrees.	32	36	YES
	H	H1	Longitudinal & lateral occupant impact velocities (OIV) should fall below the preferred value of 30 ft/s (9.1 m/s), or at least below the maximum allowed value of 40 ft/s (12.2 m/s)	YES	YES	YES
		H2	Longitudinal OIV (m/s) - Relative difference is less than 20% or absolute difference is less than 2 m/s	5.5	7.2	YES
		H3	Lateral OIV (m/s - Relative difference is less than 20% or absolute difference is less than 2 m/s)	8.8	8.1	YES
	I	I1	Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.	YES	YES	YES
		I2	Longitudinal ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	4.4	4.2	YES
		I3	Lateral ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	8.9	12.5	YES
Trajectory	L		The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant ride-down acceleration in the longitudinal direction should not exceed 20 G's.	YES	YES	YES
	M		The exit angle from the test article preferable should be less than 60 percent of the test impact angle, measured at the time of vehicle loss of contact with test device.	YES	YES	YES

Table 24 - Pickup Truck composite validation table

Composite Test Comparison		
Table 1 - Analysis Solution Verification	Did all solution verification criteria in table pass?	YES
Table 2 - RSVVP Results	Do all the time history evaluation scores from the single channel factors result in a satisfactory comparison (i.e., The comparison passes the criterion)?	NO
	If all the values for Single Channel comparison did not pass, did the weighted procedure result in an acceptable comparison?	YES
Table 3 - Roadside Safety Phenomena Importance Ranking Table	Did all the critical criteria in the PIRT Table pass? Note: Tire deflation was observed in the test but not in the simulation. This was due to the fact that tire deflation was not incorporated into the model. This is considered not to have a critical effect on the outcome of the test.	YES
Overall	Are the results of Steps I through III all affirmative (i.e., YES)? If all three steps result in a "YES" answer, the comparison can be considered validated or verified. If one of the steps results in a negative response, the result cannot be considered validated or verified.	YES

*A "YES" for the weighted procedure but not single channels is acceptable.

Small Car (1100C)

The third and final vehicle used to test the barrier was a 2010 Kia Rio shown in Figure 64. The rear seats of the vehicle were removed and data collection hardware, including accelerometers, were mounted to the floor in their place. A required crash test dummy was placed in the driver's seat for the test. There was no need to add additional weight to this vehicle to achieve the required 1,100 kg required for the test. The model used to simulate this collision was a 2010 Toyota Yaris. The dimensions of the Toyota Yaris model and Kia Rio used in the test are very similar, and therefore no dimensional changes were needed. The only modification made to this vehicle was the accelerometer mounting. The number of rigid constraints between the accelerometer and the floor of the cab was increased to reduce the noise collected by the accelerometer and to give a more accurate reading. The final changes to the simulation were modifications to the contact frictions. The friction between surfaces plays an integral role in determining how the vehicle will behave during and after impact. They were iteratively modified until the behavior was as representative of the full-scale test as possible. The original and modified friction values are listed in Table 25.

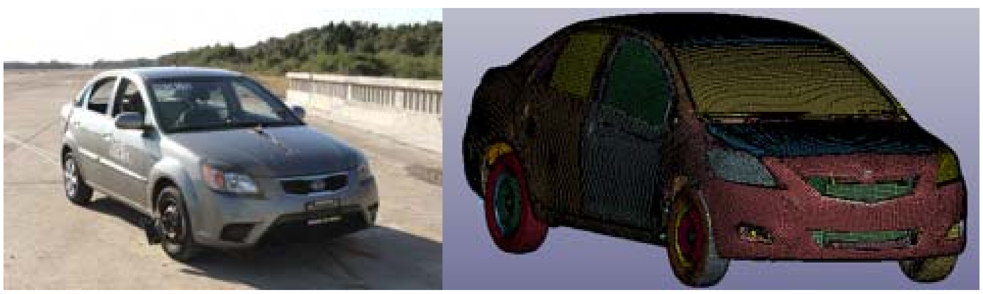


Figure 64. 1100C vehicle used (TTI) and Toyota Yaris modeled

Table 25 - Original and modified friction coefficients for the 1100C simulation.

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

MASH Test 4-10 of the 1100C passenger car was performed on December 21, 2016. All of the requirements of this test were satisfactorily met, and they are listed in Table 9. The car was successfully contained and redirected, and remained upright during and after the collision. The intrusions into the occupant compartment were minimal, and did exceed any of the limits specified in MASH. Figure 65 shows a visual comparison between the full-scale crash test and the finite element model. The kinematics of the test and model were very similar to each other, and were in good agreement. The accelerations and rotations were also in very good agreement, as shown in Figure 66 and Figure 67.

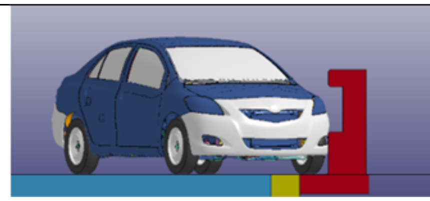
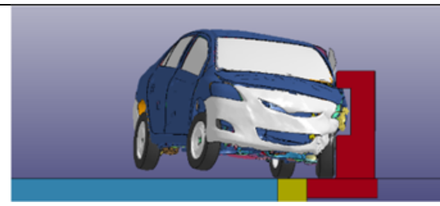
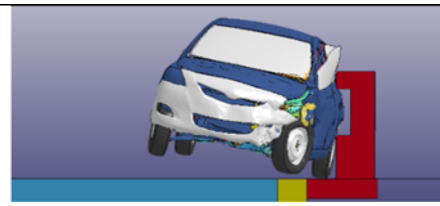
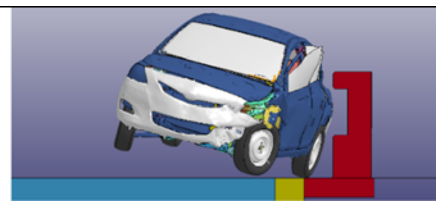
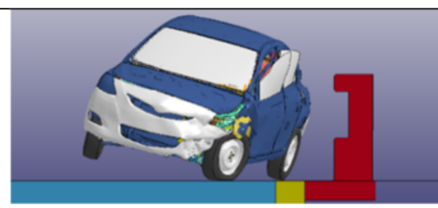
Test	Simulation
 0.000 s	 0.000 s
 0.100 s	 0.100 s
 0.200 s	 0.200 s
 0.300 s	 0.300 s
 0.400	 0.400

Figure 65. Visual comparison between MASH test 4-10 and FEA

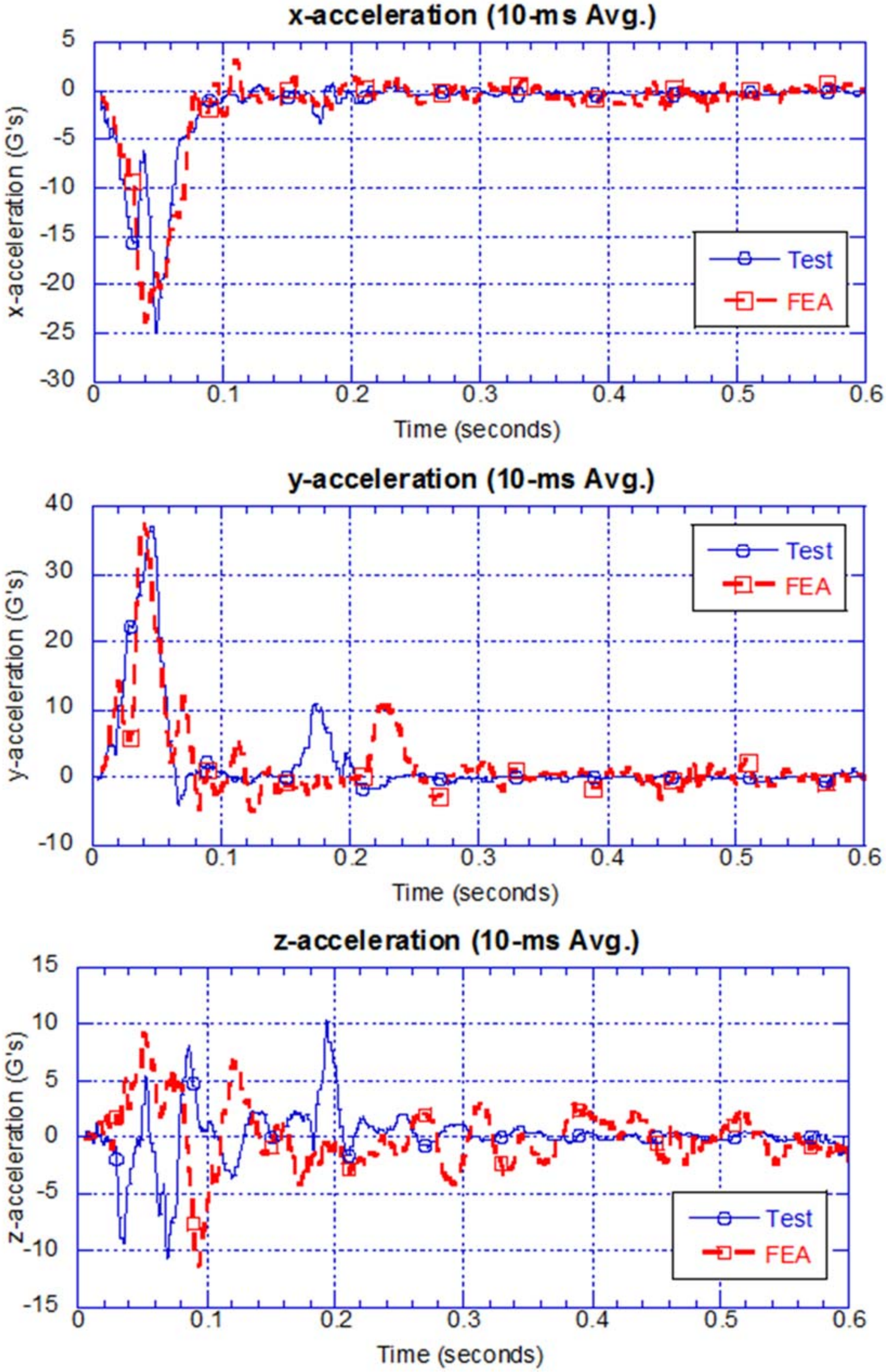


Figure 66. Acceleration comparison between MASH test 4-10 and FEA

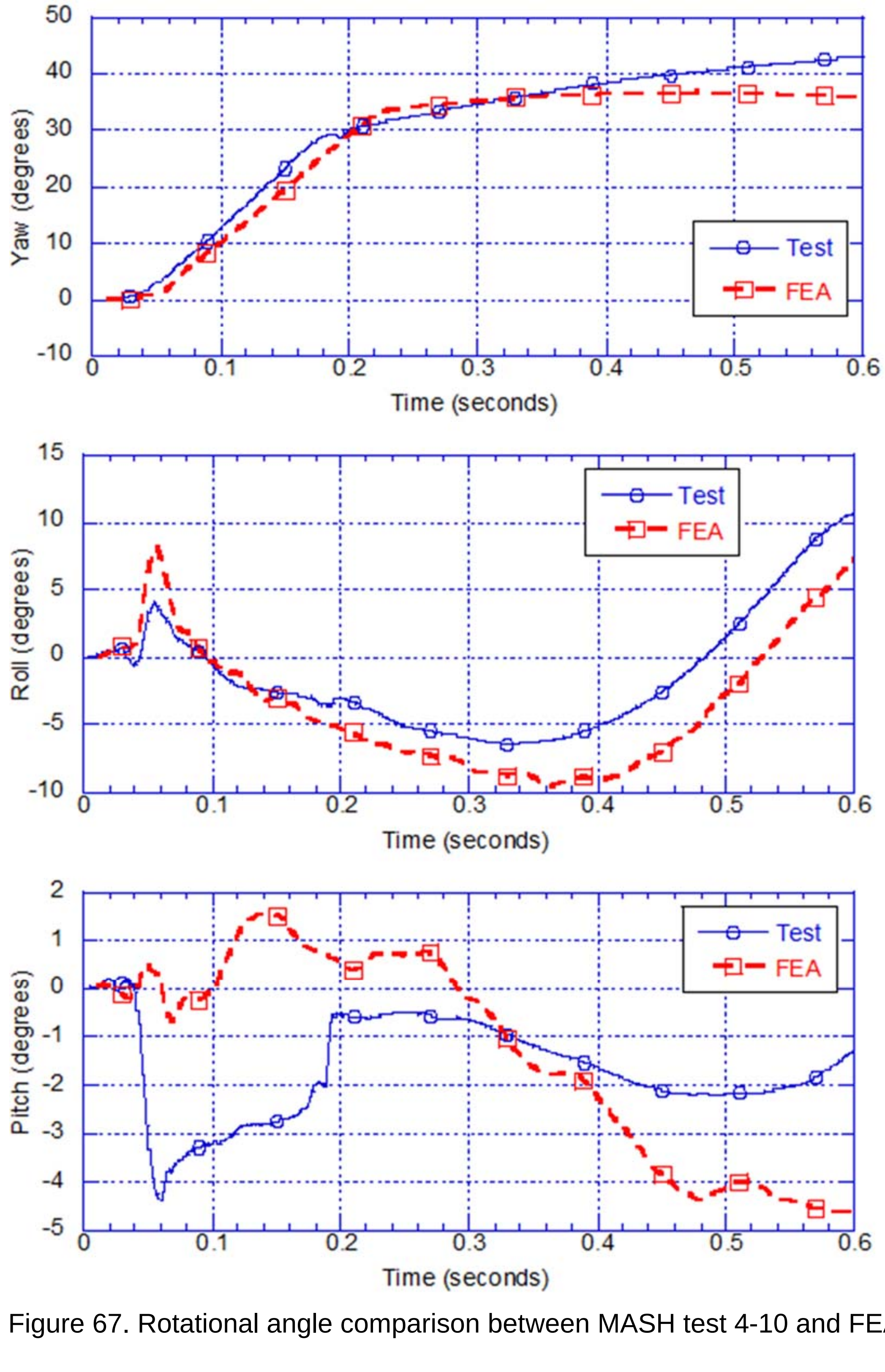


Figure 67. Rotational angle comparison between MASH test 4-10 and FEA

Table 26 - Small Car model solution verification criteria.

Verification Evaluation Criteria	Change (%)	Pass?
Total energy of the analysis solution (i.e., kinetic, potential, contact, etc.) must not vary more than 10 percent from the beginning of the run to the end of the run.	5.39	YES
Hourglass Energy of the analysis solution at the end of the run is less than 5% of the total initial energy at the beginning of the run.	<1	YES
The part/material with the highest amount of hourglass energy at any time during the run is less than 5% of the total initial energy at the beginning of the run.	<1	YES
Mass added to the total model is less than 5% the total model mass at the start of the run.	<1	YES
The part/material with the most mass added had less than 10% of its initial mass added.	<1	YES
The moving parts/materials in the model have less than 5% of mass added to the initial moving mass of the model.	3.8	YES
There are no shooting nodes in the solution?	YES	YES
There are no solid elements with negative volumes?	YES	YES

Table 27 - Small Car time-history comparison.

Single Channel Time History Comparison Results			Time interval [0 sec - 0.5 sec]		
O	***Sprague-Geer Metrics***		**M**	**P**	**Pass?**
	X acceleration		10.2	23.4	Pass
	Y acceleration		1.2	24.8	Pass
	Z acceleration		1.6	42.4	Fail
	Yaw rate		3.1	15.2	Pass
	Roll rate		42.1	18.8	Fail
	Pitch rate		40.7	53.6	Fail
P	***ANOVA Metrics***		**Mean**	**SD**	**Pass?**
	X acceleration/Peak		-0.34	9.63	Pass
	Y acceleration/Peak		-0.37	10.29	Pass
	Z acceleration/Peak		-0.38	18.37	Pass
	Yaw rate		-4.26	13.25	Pass
	Roll rate		-0.7	13.13	Pass
	Pitch rate		-0.86	16.74	Pass
Multi-Channel Weighting Factors			**Time interval [0 sec - 0.5 sec]**		
Multi-Channel Weighting Method Peaks Area I Area II Inertial		**X Channel**	0.219987577		
		Y Channel	0.273368452		
		Z Channel	0.006643971		
		Yaw Channel	0.428663933		
		Roll Channel	0.066102883		
		Pitch Channel	0.005233184		
Sprague-Geer Metrics			**M**	**P**	**Pass?**
	All Channels (weighted)		6.9	20.3	Pass
ANOVA Metrics			**Mean**	**SD**	**Pass?**
	All Channels (weighted)		-2.1	11.7	Pass

Table 28 - Small Car Phenomena Importance Ranking Table (PIRT)

Evaluation Criteria				Known Result	Analysis Result	Agree?
Structural Adequacy	A	A1	Test article should contain and redirect the vehicle; the vehicle should not penetrate, under-ride, or override the installation although controlled lateral deflection of the test article is acceptable.	YES	YES	YES
		A2	The relative difference in the maximum dynamic deflection is less than 20 percent.	0.5	0.22	YES
		A3	The relative difference in the time of vehicle-barrier contact is less than 20 percent.	0.23	0.255	YES
		A4	The relative difference in the number of broken or significantly bent posts is less than 20 percent.	n/a	n/a	0
		A5	Barrier did not fail (answer Yes or No).	YES	YES	YES
		A6	There were no failures of connector elements (Answer Yes or No).	n/a	n/a	0
		A7	There was no significant snagging between the vehicle wheels and barrier elements (Answer Yes or No).	YES	YES	YES
		A8	There was no significant snagging between vehicle body components and barrier elements (Answer Yes or No).	YES	YES	YES
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 (Answer Yes or No).	YES	YES	YES
	F	F1	The vehicle should remain upright during and after the collision. The maximum pitch & roll angles are not to exceed 75 degrees.	YES	YES	YES
		F2	Maximum Vehicle roll - relative difference is less than 20% or absolute difference is less than 5 degrees.	11	10.8	YES
		F3	Maximum Vehicle pitch - relative difference is less than 20% or absolute difference is less than 5 degrees.	4	4.6	YES
		F4	Maximum Vehicle yaw - relative difference is less than 20% or absolute difference is less than 5 degrees.	44	36	YES
	H	H1	Longitudinal & lateral occupant impact velocities (OIV) should fall below the preferred value of 30 ft/s (9.1 m/s), or at least below the maximum allowed value of 40 ft/s (12.2 m/s)	YES	YES	YES
		H2	Longitudinal OIV (m/s) - Relative difference is less than 20% or absolute difference is less than 2 m/s	7	8.4	YES
		H3	Lateral OIV (m/s - Relative difference is less than 20% or absolute difference is less than 2 m/s)	11	11.4	YES
	I	I1	Longitudinal & lateral occupant ridedown accelerations (ORA) should fall below the preferred value of 15.0 g, or at least below the maximum allowed value of 20.49 g.	YES	YES	YES
		I2	Longitudinal ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	2.4	4.4	YES
		I3	Lateral ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's	4.1	6.7	YES
Trajectory	L		The occupant impact velocity in the longitudinal direction should not exceed 40 ft/sec and the occupant ride-down acceleration in the longitudinal direction should not exceed 20 G's.	YES	YES	YES
	M		The exit angle from the test article preferable should be less than 60 percent of the test impact angle, measured at the time of vehicle loss of contact with test device.	YES	YES	YES

Table 29 - Small Car composite validation table

Composite Test Comparison		
Table 1 - Analysis Solution Verification	Did all solution verification criteria in table pass?	YES
Table 2 - RSVVP Results	Do all the time history evaluation scores from the single channel factors result in a satisfactory comparison (i.e., The comparison passes the criterion)?	NO
	If all the values for Single Channel comparison did not pass, did the weighted procedure result in an acceptable comparison?	YES
Table 3 - Roadside Safety Phenomena Importance Ranking Table	Did all the critical criteria in the PIRT Table pass? Note: Tire deflation was observed in the test but not in the simulation. This was due to the fact that tire deflation was not incorporated into the model. This is considered not to have a critical effect on the outcome of the test.	YES
Overall	Are the results of Steps I through III all affirmative (i.e., YES)? If all three steps result in a "YES" answer, the comparison can be considered validated or verified. If one of the steps results in a negative response, the result cannot be considered validated or verified.	YES

*A "YES" for the weighted procedure but not single channels is acceptable.

APPENDIX D: TTI TECHNICAL MOMORANDUM

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Texas A&M Transportation Institute
Proving Ground

Texas A&M Transportation Institute
3135 TAMU
College Station, TX 77843-3135

979-845-6375
Fax: 979-845-6107
http://tti.tamu.edu/crashtesting

December 21, 2016

Mr. Hani Nassif
Rutgers, The State University of New Jersey
Civil & Environmental Engineering
96 Frelinghuysen Road
Piscataway, NJ 08854-8014

RE: TO309, Route 139 Rehabilitation: Pulaski Skyway Contract 2
Rutgers PO S2394504
Subaward Agreement No. 5994

Dear Mr. Nassif,

Thank you for the opportunity to perform full-scale crash tests on the Rutgers Bridge Parapet to the Test Level 4 (TL-4) specifications of American Association of State Highway and Transportation Officials (AASHTO) *Manual for Assessing Safety Hardware* (*MASH*). *MASH* Tests 4-12, 4-11, and 4-10 were performed on the Rutgers Bridge Parapet.

Preliminary results indicate that the Rutgers Bridge Parapet satisfactorily met all the requirements for all three *MASH* tests specified for TL-4 longitudinal barriers. I have attached a draft summary assessment for your convenience. If you or others require additional information before the final report is issued, please contact me at 979-458-3541 or m-robinson@tti.tamu.edu, or William Williams at 979-862-2297 or w-williams@tti.tamu.edu.

Regards,

DocuSigned by:
Matt Robinson
EAA226FA58FD417...

Matthew N. Robinson
Test Facility Manager/Research Specialist IV

cc: File

A better job done safer and sooner.

TTI Proving Ground
3100 SH 47, Bldg. 7091
Bryan, TX 77807

Table 8.4. Assessment Summary for *MASH* TL-4 Tests on Rutgers Bridge Parapet.

Evaluation Factors	Evaluation Criteria	Test No. 607451-1	Test No. 607451-2	Test No. 607451-3
Structural Adequacy	C	S*	S	S
Occupant Risk	D	S	S	S
	F	N/A	S	S
	G	S	N/A	N/A
	H	N/A	S	S
	I	N/A	S	S
	Test No.	*MASH* Test 4-12	*MASH* Test 4-11	*MASH* Test 4-10
	Pass/Fail	Pass	Pass	Pass

* S = Satisfactory
U = Unsatisfactory
N/A = Not Applicable

APPENDIX E: FHWA APPROVAL LETTER FOR HIGHWAY SAFETY HARDWARE

The request for federal aid reimbursement eligibility of highway safety hardware was submitted on 5/10/2017 to Michael S. Griffith, Director of Office of Safety Technology at Federal Highway Administration (FHWA). The NJDOT Balustrade Pulaski Skyway Bridge Parapet was approved on 7/7/2017.

The FHWA approval letter is assigned FHWA control number **B-285**. This will be available online at the following FHWA link.

https://safety.fhwa.dot.gov/roadway_dept/countermeasures/reduce_crash_severity/listing.cfm?code=long

U.S. Department
of Transportation
Federal Highway
Administration

1200 New Jersey Ave., SE
Washington, D.C. 20590

July 7, 2017

In Reply Refer To:
HSST-1/ B-285

Mr. Hani Nassif
RIME Laboratory
Rutgers, The State University of New Jersey
96 Frelinghuysen Rd,
Piscataway, NJ 08854

Dear Mr. Nassif:

This letter is in response to your May 10, 2017 request for the Federal Highway Administration (FHWA) to review a roadside safety device, hardware, or system for eligibility for reimbursement under the Federal-aid highway program. This FHWA letter of eligibility is assigned FHWA control number B-285 and is valid until a subsequent letter is issued by FHWA that expressly references this device.

Decision

The following devices are eligible, with details provided in the form which is attached as an integral part of this letter:

- NJDOT Balustrade Pulaski Skyway Bridge Parapet

Scope of this Letter

To be found eligible for Federal-aid funding, new roadside safety devices should meet the crash test and evaluation criteria contained in the American Association of State Highway and Transportation Officials'(AASHTO) Manual for Assessing Safety Hardware (MASH). However, the FHWA, the Department of Transportation, and the United States Government do not regulate the manufacture of roadside safety devices. Eligibility for reimbursement under the Federal-aid highway program does not establish approval, certification or endorsement of the device for any particular purpose or use.

This letter is not a determination by the FHWA, the Department of Transportation, or the United States Government that a vehicle crash involving the device will result in any particular outcome, nor is it a guarantee of the in-service performance of this device. Proper manufacturing, installation, and maintenance are required in order for this device to function as tested.

This finding of eligibility is limited to the crashworthiness of the system and does not cover other structural features, nor conformity with the Manual on Uniform Traffic Control Devices.

Eligibility for Reimbursement

Based solely on a review of crash test results and certifications submitted by the manufacturer, and the crash test laboratory, FHWA agrees that the device described herein meets the crash test and evaluation criteria of the American Association of State Highway and Transportation Officials' Manual for Assessing Safety Hardware (MASH). Therefore, the device is eligible for reimbursement under the Federal-aid highway program if installed under the range of tested conditions.

Name of system: NJDOT Balustrade Pulaski Skyway Bridge Parapet
Type of system: Bridge Barrier
Test Level: MASH Test Level 4 (TL4)
Testing conducted by: Texas AM Transportation Institute
Date of request: May 10, 2017
Date initially acknowledged: June 22, 2017

FHWA concurs with the recommendation of the accredited crash testing laboratory as stated within the attached form.

Full Description of the Eligible Device

The device and supporting documentation, including reports of the crash tests or other testing done, videos of any crash testing, and/or drawings of the device, are described in the attached form.

Notice

This eligibility letter is issued for the subject device as tested. Modifications made to the device are not covered by this letter and will need to be tested in accordance with all recommended tests in AASHTO's MASH as part of a new and separate submittal.

You are expected to supply potential users with sufficient information on design, installation and maintenance requirements to ensure proper performance.

You are expected to certify to potential users that the hardware furnished has the same chemistry, mechanical properties, and geometry as that submitted for review, and that it will meet the test and evaluation criteria of AASHTO's MASH.

Issuance of this letter does not convey property rights of any sort or any exclusive privilege. This letter is based on the premise that information and reports submitted by you are accurate and correct. We reserve the right to modify or revoke this letter if: (1) there are any inaccuracies in the information submitted in support of your request for this letter, (2) the qualification testing was flawed, (3) in-service performance or other information reveals safety problems, (4) the system is significantly different from the version that was crash tested, or (5) any other information indicates that the letter was issued in error or otherwise does not reflect full and complete information about the crashworthiness of the system.

Standard Provisions

- To prevent misunderstanding by others, this letter of eligibility designated as FHWA control number B-285 shall not be reproduced except in full. This letter and the test documentation upon which it is based are public information. All such letters and documentation may be reviewed upon request.
- This letter shall not be construed as authorization or consent by the FHWA to use, manufacture, or sell any patented system for which the applicant is not the patent holder.
- If the subject device is a patented product it may be considered to be proprietary. If proprietary systems are specified by a highway agency for use on Federal-aid projects: (a) they must be supplied through competitive bidding with equally suitable unpatented items; (b) the highway agency must certify that they are essential for synchronization with the existing highway facilities or that no equally suitable alternative exists; or (c) they must be used for research or for a distinctive type of construction on relatively short sections of road for experimental purposes. Our regulations concerning proprietary products are contained in Title 23, Code of Federal Regulations, Section 635.411.

Sincerely,

Robert Ritter
Acting Director, Office of Safety
Technologies
Office of Safety

Enclosures

Request for Federal Aid Reimbursement Eligibility of Highway Safety Hardware

Submitter			
	Date of Request:	May 10, 2017	(●) New ( ) Resubmission
	Name:	Hani Nassif	
	Company:	RIME Laboratory - Rutgers, The State University of New Jersey	
	Address:	96 Frelinghuysen Rd, Piscataway, NJ 08854	
	Country:	U.S.A.	
	To:	Michael S. Griffith, Director FHWA, Office of Safety Technologies	

I request the following devices be considered eligible for reimbursement under the Federal-aid highway program.

Device & Testing Criterion - Enter from right to left starting with Test Level

! - ! - !

System Type	Submission Type	Device Name / Variant	Testing Criterion	Test Level
'B': Rigid/Semi-Rigid Barriers (Roadside, Median, Bridge Railings)	(●) Physical Crash Testing ( ) Engineering Analysis	NJDOT Balustrade/ Pulaski Skyway Bridge Parapet	AASHTO MASH	TL4

By submitting this request for review and evaluation by the Federal Highway Administration, I certify that the product(s) was (were) tested in conformity with the AASHTO Manual for Assessing Safety Hardware and that the evaluation results meet the appropriate evaluation criteria in the MASH.

Individual or Organization responsible for the product:

Contact Name:	Lynn Middleton	Same as Submitter ☐
Company Name:	New Jersey Department of Transportation	Same as Submitter ☐
Address:	Office of Legislative, Administrative & Regulatory Actions, 1035 Parkway Ave, Trenton, NJ 08625	Same as Submitter ☐
Country:	U.S.A.	Same as Submitter ☐

Enter below all disclosures of financial interests as required by the FHWA `Federal-Aid Reimbursement Eligibility Process for Safety Hardware Devices' document.

The RIME Team at Rutgers University was awarded a research funding contract in 2013 in response to a Request For Proposal (RFP) announced by the NJDOT Research Bureau to conduct research, design and evaluate a New Jersey historic bridge balustrade. The design is non-proprietary and Rutgers RIME Team has no further financial interest in the marketing or use of this design.

PRODUCT DESCRIPTION

(●) New Hardware or Significant Modification ( ) Modification to Existing Hardware

This balustrade is an open-faced concrete barrier with top rail, curb, and post columns. The test installation is a 156 ft. and 1-1/4 in. long steel reinforced concrete bridge parapet, and deck comprises of six 26-ft. long segments. Each 26-ft. long segment of this 44-in. tall system is comprised of two 13-ft. long sections. The top rail is 7-in. tall and 16-in. deep, and the bottom of the top rail measures 37-in. above the bridge deck. The rail is integral to, and sat atop, eleven 19-in. tall reinforced concrete posts per section. The nine interior posts are each 8-in. wide x 10-in. deep, and the end posts are each 12-in. wide x 10-in. deep, and all posts are integral to an 18-in. tall x 16-in. deep curb. The window spacing between posts is 6-in. The bridge parapet contains 1/4-in. wide expansion control joints along the length of the parapet between 26-ft long segment. Furthermore, the bridge parapet contains cold contraction joints (with no space) located between 13-ft. long section at the halfway point of each 26-ft. long segment. Longitudinal reinforcement does not extend across the cold contraction joints in the barrier. All exposed edges have a 3/4-in. chamfer.

CRASH TESTING

By signature below, the Engineer affiliated with the testing laboratory, agrees in support of this submission that all of the critical and relevant crash tests for this device listed above were conducted to meet the MASH test criteria. The Engineer has determined that no other crash tests are necessary to determine the device meets the MASH criteria.

Engineer Name:	William F. Williams	
Engineer Signature:	William Willams Digitally signed by William Willams DN: cn=William Willams, o=Texas Transportation Insitue, ou=CEF, email=w-williams@tti.tamu.edu, c=US Date: 2017.04.25 15:16:35 -05'00'	
Address:	3135 TAMU, College Station, TX 77843-3135	Same as Submitter ☐
Country:	U.S.A.	Same as Submitter ☐

A brief description of each crash test and its result:

Required Test Number	Narrative Description	Evaluation Results
4-10 (1100C)	Test 607451-3; 2016-12-21; Report TTI 607451-1-3; 2,429 lb small passenger car (2010 Kia Rio) impacting at 62.5 mph and 25.0 degrees; The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection during the test was 0.5 in. No detached elements, fragments, or other debris were present to penetrate or show potential for penetrating the occupant compartment or to present hazard to others in the area. Maximum occupant compartment deformation was 3.5 in. in the left toe pan area. The vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 11 degrees and 4 degrees, respectively. Occupant risk factors were within the limits specified in MASH.	PASS

Required Test Number	Narrative Description	Evaluation Results
4-11 (2270P)	Test 607451-2; 2016-12-20; Report TTI 607451-1-3; 5,037 lb pick up truck (2011 Dodge RAM 1500) impacting at 62.5 mph and 24.0 degrees; The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection of the bridge parapet during the test was 1.0 in. No detached elements, fragments, or other debris were present to penetrate or show potential for penetrating the occupant compartment or to present hazard to others in the area. Maximum occupant compartment deformation was 2.0 in. in the left kick panel/toe pan area. The vehicle remained upright during and after the collision event. Maximum roll and pitch angles were 24 degrees and 6 degrees, respectively. Occupant risk factors were within the preferred limits specified in MASH.	PASS
4-12 (10000S)	Test 607451-1; 2016-12-16; Report TTI 607451-1-3; 22,030 lb single unit truck (2006 International 4200) impacting at 57.4 mph and 15.3 degrees; The vehicle did not penetrate, underride, or override the installation. Maximum dynamic deflection of the bridge parapet during the test was 4.4 in. No detached elements, fragments, or other debris were present to penetrate or show potential for penetrating the occupant compartment or to present hazard to others in the area. Maximum occupant compartment deformation was 8.0 in. in the left kick panel/toe pan area.	PASS
4-20 (1100C)		Non-Relevant Test, not conducted
4-21 (2270P)		Non-Relevant Test, not conducted
4-22 (10000S)		Non-Relevant Test, not conducted

Full Scale Crash Testing was done in compliance with MASH by the following accredited crash test laboratory (cite the laboratory's accreditation status as noted in the crash test reports.):

Laboratory Name:	Texas AM Transportation Institute	
Laboratory Signature:	Darrell L. Kuhn — Darrell L. Kuhn 2017.04.25 15:34:27 -05'00'	
Address:	Roadside Safety & Physical Security, Texas A&M University System, 3135 TAMU, College Station, TX 77843-3135	Same as Submitter ☐
Country:	U.S.A.	Same as Submitter ☐
Accreditation Certificate Number and Dates of current Accreditation period :	ISO 17025 Laboratory, Testing Certificate # 2821.01 Expires April 30, 2019	

Submitter Signature*: Digitally signed by Hani Nassif
DN: cn=Hani Nassif, o=Rutgers, The State University of NJ, ou=Dept. of Civil & Env. Eng., email=nassif@soe.rutgers.edu, c=US
Date: 2017.05.09 22:10:31 -05'00'

Submit Form

ATTACHMENTS

Attach to this form:

1) Additional disclosures of related financial interest as indicated above.
2) A copy of the full test report, video, and a Test Data Summary Sheet for each test conducted in support of this request.
3) A drawing or drawings of the device(s) that conform to the Task Force-13 Drawing Specifications [Hardware Guide Drawing Standards]. For proprietary products, a single isometric line drawing is usually acceptable to illustrate the product, with detailed specifications, intended use, and contact information provided on the reverse. Additional drawings (not in TF-13 format) showing details that are relevant to understanding the dimensions and performance of the device should also be submitted to facilitate our review.

FHWA Official Business Only:

Eligibility Letter		
Number	Date	Key Words