# Assessing Options for Improving Roadside Barrier Crashworthiness

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## Abstract

*The introduction of new crash test requirements raises questions about the efficacy of commonly used barriers that had been accepted under earlier test requirements. Seven commonly-used barriers were crash tested under the new MASH requirements in a recent NCHRP project. Three of the barriers tested did not meet the new requirements for the test with the 2270 kg vehicle. While the implementation of the MASH standards does not require hardware that passed the previous NCHRP 350 requirements to be re-evaluated, there is an interest in knowing whether these devices can be modified to meet the more stringent MASH requirements by DOTs.*

*In another effort, these seven NCHRP crash tests were successfully simulated to provide an extended validation of the new finite element model of a Chevrolet Silverado pick-up truck as a surrogate for the 2270 kg test vehicle. This provided the opportunity to, among other things, evaluate the potential of various retrofit options for improving two of the three barriers that failed. An analyses of six modifications for the G9 Thrie-beam barrier and three variations of the G4(1S) guardrail median barrier was undertaken.*

*A summary of the testing and simulation modeling of the two tests is presented as the basis for the simulation of modified versions of the barriers. The evaluation results are presented for each of the retrofit options and recommendations offered.*

## Introduction

### Background

Highway engineers design roadways and their immediate environments to allow safe operation of a variety of vehicles, in varying numbers, and under different conditions across the country. Roadside barriers are deployed to assure safety by preventing vehicles from leaving the road and/or protecting an errant vehicle from objects along the road. In the interests of safety, roadside barriers are designed and tested to meet specific crashworthiness requirements. Since the 1960's, protocols and procedures for crashworthiness evaluation of roadside hardware have evolved with current requirements outlined in the Manual for Assessing of Safety Hardware (MASH) which was adopted by American Association of State Highway and Transportation Officials (AASHTO) in October 2009 [1].

The barrier crashworthiness requirements in MASH and its predecessors have served as the benchmark for the development of new and improvements to roadside safety hardware. Crash testing has been the predominant means to demonstrate the crashworthiness of new hardware, but it is costly and time consuming. Simulation, however, has increasingly played an important role in crashworthiness evaluations for more than a decade. Most new designs originate and are refined in simulation studies that replicate the required crashworthiness tests. Improved modeling and crash simulation software capabilities and growing confidence in the detailed performance results have recently provided further impetus for increased use of simulation approaches to assess barrier improvements. In addition, recently the FHWA announced that crash simulation results would be considered acceptable for evaluating improvements to previously tested barriers for eligibility.

For more than 20 years, the Federal Highway Administration (FHWA) has promoted the use of crash simulations based upon finite element models as a means to develop innovative designs and to evaluate their performance. To do so, requires finite element (FE) models of vehicles and the hardware. FE models have been developed to describe the vehicle and test articles as a collection of elements that reflect the geometry of the items, the nature of connections between adjacent elements, the characteristics of the element materials, and properties associated with the relationships between elements (e.g., joints, fracture mechanics). The models have been subjected to the traditional validation efforts, as well as a series of extended comparisons aimed at providing additional confidence in them. The ultimate validation for roadside purposes is comparison to actual crash tests using the same vehicle.

The adoption of the new MASH crashworthiness criteria raised questions about the viability of commonly-used barriers that were approved under the earlier NCHRP Report 350 requirements [2]. In another effort, some barriers were tested under the MASH requirements using the Chevy Silverado as the 2270P vehicle. It was found through the testing that three of seven commonly-used barriers that met the NCHRP 350 requirements did not meet the MASH requirements. In an effort aimed at demonstrating the viability of the new Silverado Pick-up FE model (intended to be the surrogate 2270 kg test vehicle) these tests were successfully simulated. The resulting vehicle-to-barrier models became the basis for efforts to assess retrofit options for the barriers that failed. The efforts described in this paper focus on the simulation of MASH test 3-11, namely the impact of a 2270 kg test vehicle into a barrier at 100 km/h (62.2 mph) at an angle of 25 degrees. The simulation results demonstrated that models and crash simulation tools can effectively be used to evaluate retrofits, updates, or improvements to roadside hardware.

## Objectives

The objectives of this effort were to 1) consider various design improvement options for two of the barriers that failed the MASH requirements for impacts with the 2270 kg test vehicle, and 2) recommend retrofit options that showed improved performance for further evaluations. The barriers that were studied included the G9 thrie-beam barrier and the G4(1S) median barrier. A secondary objective was to demonstrate the potential usefulness of crash simulations in the development of improved barriers.

## Approach

This research effort used the newly developed FE model of the 2007 Chevrolet Silverado pick-up truck to simulate the MASH 3-11 crash test of that vehicle into the two barriers. Data and video from the crash test provided the usual test metrics. Simulations replicating MASH Test 3-11 were set up to generate the equivalent metrics for comparison. The comparisons between the crash test data and simulation results were made using traditional methods as well as recently developed analytical methods [3]. Reports were generated to document the crash test and simulation comparisons for the G9 Thrie-beam barrier and the G4(1S) guardrail median barrier. This paper provides background on 1) the barrier crashworthiness evaluation process, 2) the role of modeling and simulation, 3) validation efforts, and 4) the model features and analyses of improvement options. This process was supported by full-scale crash tests that allowed the validity of the models to be ascertained.

### Crash Test Results

Full-scale crash tests of a 2007 Chevrolet Silverado quad-cab pick-up truck into commonly-used, NCHRP 350 approved barriers were conducted that the Texas Transportation Institute under NCHRP Project 22-14(3) "Evaluation of Existing Roadside Hardware Using Updated Criteria" [4]. Two of the barriers tested are:

- G-9 Thrie Beam (Test 476460-1-8: 2/26/2009)
- G4(1S) Median Barrier (Test 476460-1-9; 4/14/2009)

In the first test, a 2007 Chevrolet Silverado 4-door pickup truck traveling at a speed of 63.3 mph impacting a Thrie-beam barrier at an impact angle of 26.4 degrees. Thrie beam guardrail contained and redirected the vehicle but did not meet the testing criteria because the Silverado pickup rolled 360 degrees after impact. The maximum dynamic deflection of the Thrie-beam barrier during the test was 33.2 inches and maximum occupant compartment deformation was 3.56 inches in the right rear passenger area. In the second test, a similar vehicle traveling at a speed of 64.0 mph impacted a G4(1S) W-beam median barrier at an angle of 25.1 degrees. The vehicle in this test overrode the barrier did not meet the testing criteria.

## Simulation Analyses

The simulations of MASH Test 3-11 for the two barriers incrementally replicated the movement of the vehicle into the barrier and monitored the condition of each element during the impact event. The follow paragraphs provide a brief background on the vehicle and barrier models used and the analyses that were undertaken to ascertain that the models and simulations could effectively replicate the impact event.

### Vehicle Model

In 2009, The NCAC released a detailed finite element (FE) model of a 2007 Chevy Silverado pick-up truck. The Chevy Silverado model was developed jointly by FHWA and NHTSA to serve multiple purposes for studying and advancing vehicle and highway safety research. Reverse engineering methods were employed to build the FE model and the attention to detail was critical to making it suitable for application for different crash conditions. The model consists of over 950,000 elements representing the vehicle, including the components of the steering & suspensions systems [5].

This model was initially validated following traditional protocols of comparison the full frontal impact with a vertical wall required under the New Car Assessment Program (NCAP) administered by the National Highway Traffic Safety Administration (NHTSA) and the simulated results. In addition, validation efforts included comparison of the inertial properties of the vehicle (before tear-down) and in its simulated form, component response tests for the front & rear suspension, and non-destructive bump & terrain tests. These validation tests indicated that the model could provide a viable representation of the real vehicle in various dynamic loading situations [8]. An extended validation of the Silverado FE model was also undertaken for NHTSA to further demonstrate the soundness of the model. In these efforts, the model was used to simulate a variety of other NCAP and IIHS impacts. In these comparisons the model performed well for vary types of impacts (e.g., offset, pole, side) and at varying speeds [6, 7].

## Barrier Hardware Models

Finite element models for the G9 Thrie-beam barrier and the G4(1S) median barrier were developed by the National Crash Analysis Center by translating the exact geometry of every piece of the barriers into elements. The properties of the materials that comprised each part were defined and each connection detailed. The components for these barriers have been used in many simulations and the staff had refined the associated models over several years. Material parameters were obtained from standard sources (e.g., manufacturer's specifications) and/or verified with lab testing. The features of these models are documented in detail in the references cited earlier [8, 9].

## Model Validation

Model validation is critical to having confidence in the results of the simulations. A model is considered validated when comparisons between the models results compare favorably to test data. Data from full-scale crash tests involving a Silverado pick-up and the G-9 Thrie Beam barrier and the G4(1S) barriers for MASH Test 3-11 which requires an impact at 100 k/hr (62.2 m/h) at an angle of 25 degrees was compared to data generated by simulation of the test. The following comparisons were undertaken for the validation:

- Visual Comparisons - Sequential images compared the simulation and test results at various increments of time during the crash event. Figure 1 shows some of these sequential visual comparisons. The comparisons showed similar interactions between the vehicle and barrier, the degree of penetration, and changes in vehicle stability (e.g. roll, pitch, and yaw).
- Graphical Comparisons – The comparison of accelerations (i.e. x, y, and z axis) and vehicle orientation parameters (i.e. roll, pitch, and yaw rates) were made for the recorded duration of the crash event. The data for all factors was considered similar and it was consider an indication that the model provides representative results. (Not shown)
- Verification and Validation Procedures - More detailed comparisons are provided by applying the newly developed verification and validation (V&V) procedures that compare test-oriented Phenomena Importance Rating Table (PIRT) factors and Statistical Evaluation of basic testing parameters [3]. Table 1 summarizes the PIRT factors associated with the MASH testing criteria for Test 3-11 for the three failed tests. These cover structural adequacy, occupant risk, and vehicle trajectory in accordance with MASH criteria. For each of the three tests, with the first column (labeled "Test') gives the crash test values (truth) and the second column (labeled "Sim") provides the corresponding simulated values. In this table, it can be seen that the crash test and simulated values for the PIRT factors are similar or within acceptable bounds, thereby indicating that the simulations are acceptable representations of the crash test. Last, a statistical evaluation under the V&V procedure compares single and multi-channel analyses of the test and simulation metrics. The multi-channel results for the two barriers are provided in Table 2. The Sprague-Geers statistical comparison of the six typical crash test metrics (e.g., x-, y-, & x- accelerations and roll, pitch and yaw rates) for the magnitude, phase, and combined measures is provided. It can be noted by the "Yes" values indicate that test and simulation are statistically the same using either

approach. The simultaneous multi-channel statistics all pass allowing it to be concluded that the test and model results compare within the criteria established. A more rigorous discussion of these results is provided in the previous cited documents.

| TTI Test 476460-1-8<br>G9 Thrie Beam | TTI Test 476460-1-9<br>G4(1S) Median |
|---|---|

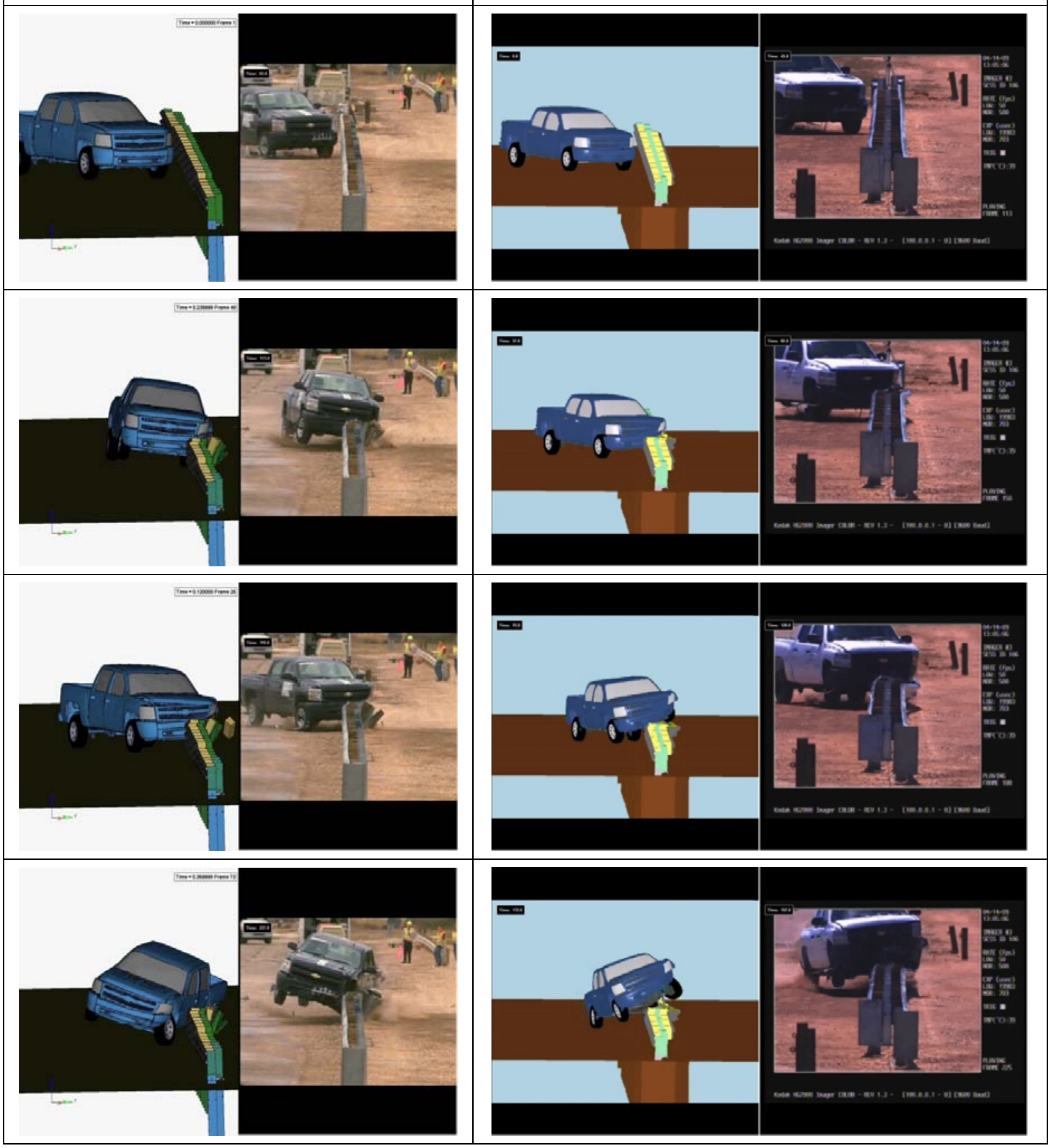


**Figure 1 – Side by Side Comparisons of Test and Simulation for the two Barriers Analyzed**

**Table 1 – Summary of MASH-based PIRT Evaluation Criteria for the two Barriers Analyzed**

| **Test Conditions** | | **Test Reference:** | TTI 476460-1-8 | | TTI 476460-1-9 | |
|---|---|---|---|---|---|---|
| | | **Barrier:** | G9 Thrie Beam | | G4(1S) Median | |
| | | **Vehicle:** | Silverado 2270 | | Silverado 2270 | |
| | | **Impact:** | 100kmh/25$^o$ | | 100kmh/25$^o$ | |
| | | | **Test** | **Sim** | **Test** | **Sim** |
| **Structural Adequacy Criteria** | | | | | | |
| 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 | No | No |
| A2 | The relative difference in the maximum dynamic deflection is less than 20 percent. | | 0.84 m | 0.77 m | 0.7 m | 0.5 m |
| A3 | The relative difference in the length of vehicle-barrier contact is less than 20 percent. | | 6.8 m | 6.1 m | --- | --- |
| A4 | The relative difference in the number of broken or significantly bent posts is less than 20 percent. | | 3 | 3 | 4 | 4 |
| A5 | Barrier did not fail | | Yes | Yes | No | No |
| A6 | There were no failures of connector elements (Answer Yes or No). | | No | No | No | No |
| A7 | There was no significant snagging between the vehicle wheels and barrier elements | | No | No | No | No |
| A8 | There was no significant snagging between vehicle body components and barrier elements | | Yes | Yes | Yes | Yes |
| **Occupant Risk Criteria** | | | | | | |
| 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. | | Yes | Yes | No | No |
| F1 | The vehicle should remain upright during and after the collision. The maximum pitch & roll angles are not to exceed 75 degrees. | | No | No | No | No |
| F2 | Maximum vehicle roll – relative difference is less than 20% or absolute difference is less than 5 degrees. | | 38 | 34 | 5 | 5 |
| F3 | Maximum vehicle pitch – relative difference is less than 20% or absolute difference is less than 5 deg. | | 9 | 13 | -6 | -1 |
| F4 | Maximum vehicle yaw – relative difference is less than 20% or absolute difference is less than 5 deg. | | 42 | 45 | 26 | 22 |
| 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 | Yes |
| H2 | Longitudinal OIV (m/s) - Relative difference is less than 20%t or absolute difference is less than 2 m/s | | 5.2 | 6.4 | 6.5 | 8.3 |
| H3 | Lateral OIV (m/s - Relative difference is less than 20% or absolute difference is less than 2 m/s | | 5.3 | 5.8 | 4.3 | 3.3 |
| 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 | Yes |
| I2 | Longitudinal ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's | | 6.9 | 9.8 | 10.2 | 13.1 |
| I3 | Lateral ORA (g) - Relative difference is less than 20% or absolute difference is less than 4 g's | | 7.7 | 6.7 | 9.6 | 7.1 |
| **Vehicle Trajectory** | | | | | | |
| | Vehicle trajectory went behind the test article (Answer Yes or No) | | Yes | Yes | No | No |

**Table 2 – V&V Statistical Comparisons for the Three Failed Longitudinal Barriers**

| | | | | | |
|---|---|---|---|---|---|
| **Test Conditions** | **Test Reference:** | TTI 476460-1-8 | | TTI 476460-1-9 | |
| | **Barrier:** | G9 Thrie Beam | | G4(1s) Median | |
| | **Vehicle:** | Silverado 2270 | | Silverado 2270 | |
| | **Impact:** | 63.4 mph - 26.4$^o$ | | 64.0mph - 25.1$^o$ | |
| **Multi-Channel Comparisons** | | | Pass? | | Pass? |
| **Sprauge-Geer Metrics** | Magnitude | 25.5 | Yes | 21.8 | Yes |
| | Phase | 22.7 | | 24.1 | |
| **ANOVA Metrics** | Mean Residual | 0.02 | Yes | -1.4 | Yes |
| | SD Residual | 0.21 | | 34.0 | |

Based upon the visual, graphical, PIRT factor, and statistical comparisons, it was concluded that the models for impacts with both barriers are valid. Therefore, the models are considered viable for use in analyzing retrofit options for these three barriers within the range of conditions simulated.

## Retrofit Analyses

Design improvement options were suggested by practitioners for the G9 thrie-beam and G4(1S) median barriers. These suggestions were based upon their familiarity with barrier design and past impact performance results. Since there is a need for options to "improve" deployed barriers of these types, the emphasis focused on retrofit design options. All options were simulated and their performance assessed by visual and the roll, pitch, and yaw metric comparisons. The following paragraphs describe the retrofit options that were analyzed using computer simulation for the G9 thrie-beam and the G4(1S) median barriers.

### G9 Thire Beam Retrofit Options

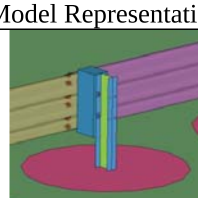
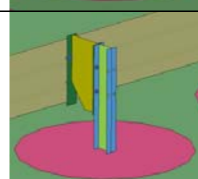
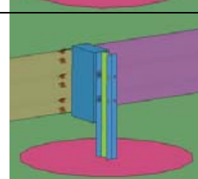
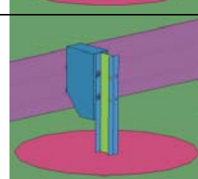
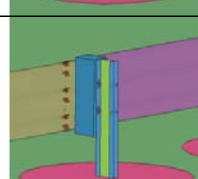
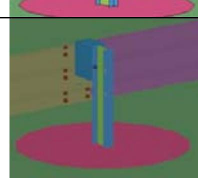
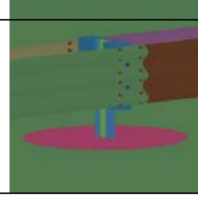
The G9 thrie-beam impact with the Silverado pickup truck at 62 mph and 25 degrees redirected the vehicle, but the roll effects of the impact contributed to the vehicle rolling onto its side shortly after leaving contact with the barrier. This result was noted in the simulations and reflected in the similarity of the various accelerations and roll, pitch, and yaw rates in comparing the actual data. It was hypothesized that the vehicle's wheel became snagged with the lower part of the thrie beam which induced a roll reaction that led to the rollover. Therefore measures to mitigate that effect were considered as retrofit options.

The G-9 thrie-beam got the most attention in the search for retrofit alternatives. Table 3 shows the current design and the six options that were considered. The table also provides data describing the features of the retrofit options. These features reflect concepts that were intended to reduce the roll induced on the vehicle by the deformation of the thrie-beam rail. The wider thrie rail seems to induce a strong roll moment by catching the vehicle tire when it deflects. A weakening of the lower portion of the rail to reduce that tendency is reflected in the alternatives that involve notching the blockout or using a half block out. Another concept is to keep the wheel further from the post to prevent the snagging that induces a roll moment by using a deeper blockout.

Six options were analyzed by altering the basic barrier model and running the crash simulation (Table 3). These included:

- Using the modified thrie-beam design which has a notch at the lower edge of the blockout to allow the lower part of the thrie-rail to bend upward on impact.
- Use deeper blockouts to reduce interaction with the rail as the impact forces push the rails back.
- Use a notched wood blockout for the same reason as cited for the modified thrie beam.
- Increase the height of the top of rail to provide more clearance for the tire on impact.
- Use a blockout with half the depth to allow less interaction with the rail as the impact forces push the rail system back.
- Add a rail to the backside of the barrier (as in a median installation) to stiffen the system.

**Table 3 – G9 Thrie Beam Retrofit Options Summary**

| Alternative: | Model Representation | Features: |
|---|---|---|
| Original Design |  | Rail Top Height – 31.5 inches<br>Blockout<br>Depth –8”<br>Material – Wood<br>Design - |
| Option 1- Notched Steel Blockout |  | Rail Top Height – 31.5 inches<br>Blockout<br>Depth – 9”<br>Material – Steel W 6x9<br>Design – 4 inch notch |
| Option 2 - Deeper Blockout |  | Rail Top Height – 31.5 inches<br>Blockout<br>Depth – 14”<br>Material – Wood<br>Design - |
| Option 3 - Deeper Notched Blockout |  | Rail Top Height – 31.5 inches<br>Blockout<br>Depth – 14”<br>Material – wood<br>Design – 6” notch at bottom |
| Option 4 - Increased Rail Height |  | Rail Top Height – 32.5 inches<br>Blockout<br>Depth – 8”<br>Material – Wood<br>Design - |
| Option 5 - Half Blockout |  | Rail Top Height – 31.5 inches<br>Blockout<br>Depth –8”<br>Material – Wood<br>Design – half length |
| Option 6 - Median Version (Dual Rails) |  | Rail Top Height – 31.5 inches<br>Blockout<br>Depth – 8” each side<br>Material – Wood<br>Design – rails both sides of post |

These retrofit options were translated to changes in the thrie-beam barrier model for crash simulation analyses. The results of the impact simulations for these retrofit options showed that in most of the cases, the roll, pitch, and yaw metrics are similar for the retrofit option in comparison to the baseline simulation with the original design. The only exception occurs for the half blockout option (Option 5). Figure 2 shows the roll, pitch, and yaw angles from the Option 5 simulation compared to the original design. It can be noted by the blue lines that roll metric decreases by 25 degrees over the crash event. Since the ultimate test failure was caused by the rollover of the vehicle, this may represent the most viable option (subject to other considerations and possibly validation by crash testing). The difference in vehicle behavior in the impact can be noted in Figure 3 which provides side-by-side views of the relative variations in vehicle behavior.

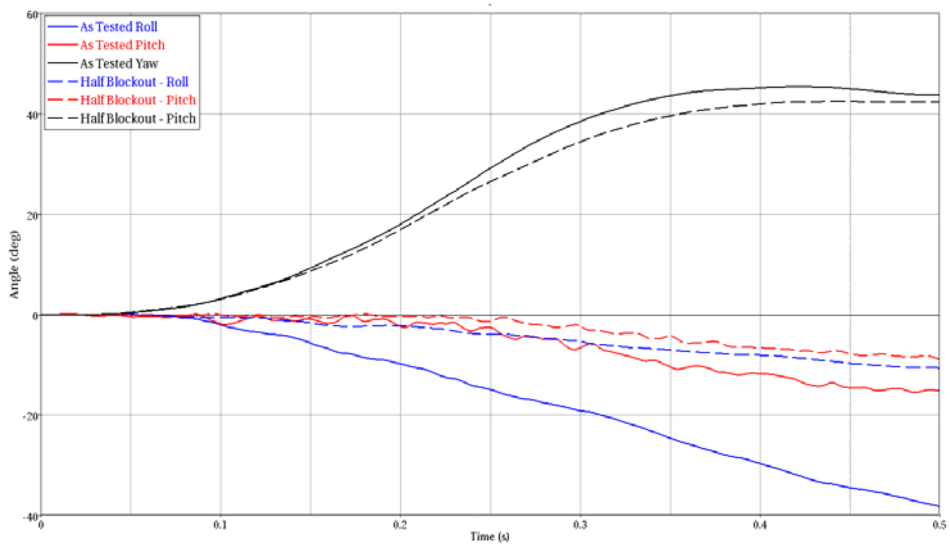



**Figure 2 – Roll, Pitch, & Roll Comparisons of Original Design & Half Blockout Thrie-Beam Option**

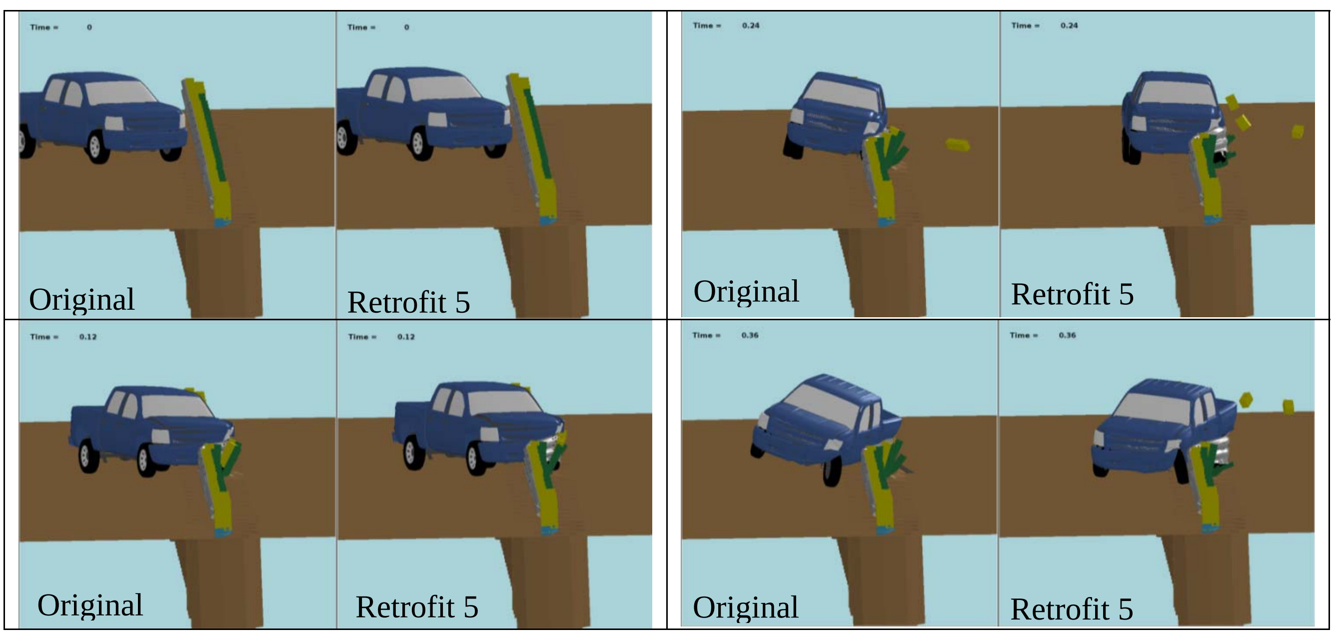
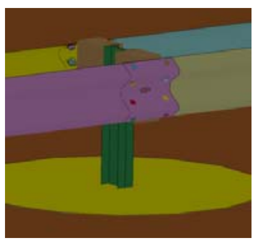
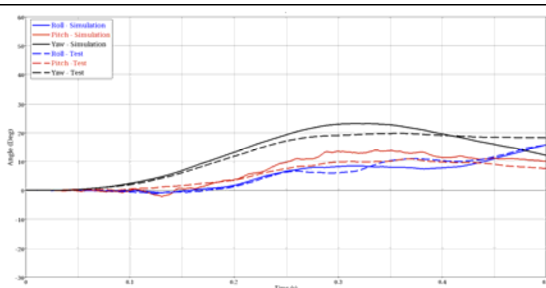
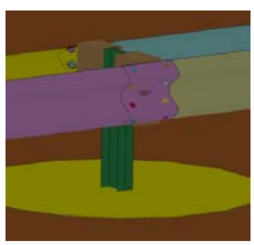
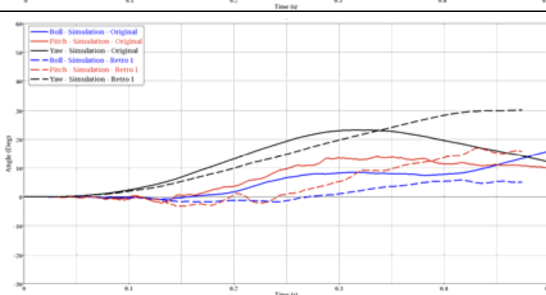
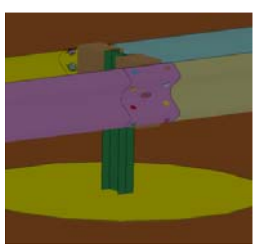
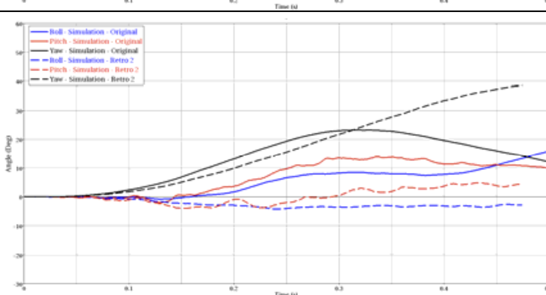
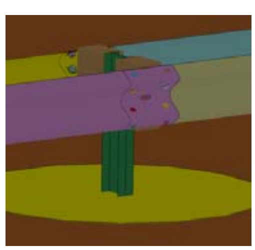
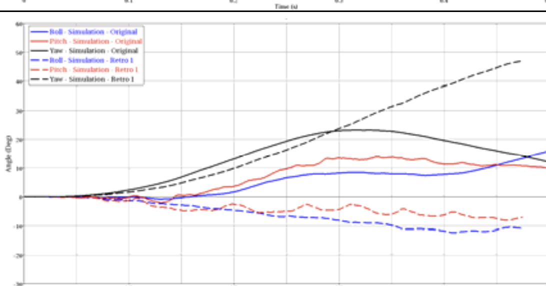



**Figure 3 - Simulation Comparisons of the Original Design & Half Blockout Thrie-Beam Option**

## G4(1S) Median Barrier Retrofit Options

Three variations of the G4(1S) median barrier were analyzed as retrofit options. These were similar in that they only varied by the heights of the top of the rail. There was a one inch increase in height for each case. The corresponding results are shown in Table 4. Recalling that the barrier failed because the vehicle vaulted over the standard height version, as was shown in Figure 1, the need exists to control the pitch and roll of the vehicle after impact. It can be noted that there is incrementally greater variations between the simulated changes in pitch when the original design is compared to the versions with the increased height. The greatest change occurs for the three inch increase. It can be noted that the pitch angle changes from a positive 10 degrees (mean barrier climbing) to a negative 10 degrees downward suggesting a solid interaction with the barrier. There were changes in the roll metric that were probably a function of the nature of the interface with the barrier, but roll angles did not come close to the maximum allowable. Figure 4 shows side-by-side views of the simulation results from the three inch increased high case and the original case.

**Table 4 – Simulation Results for G4-1S Median Barrier Retrofit Options**

| | | |
|---|---|---|
| **Current Design**<br><br>Rail Top Height – 27.5 inches |  |  |
| **Option 1- Rail Raised One Inch**<br><br>Rail Top Height – 28.5 inches |  |  |
| **Option 2 – Rail Raised Two Inches**<br><br>Rail Top Height – 29.5 inches |  |  |
| **Option 3 – Rail Raised Three Inches**<br><br>Rail Top Height – 31.5 inches |  |  |

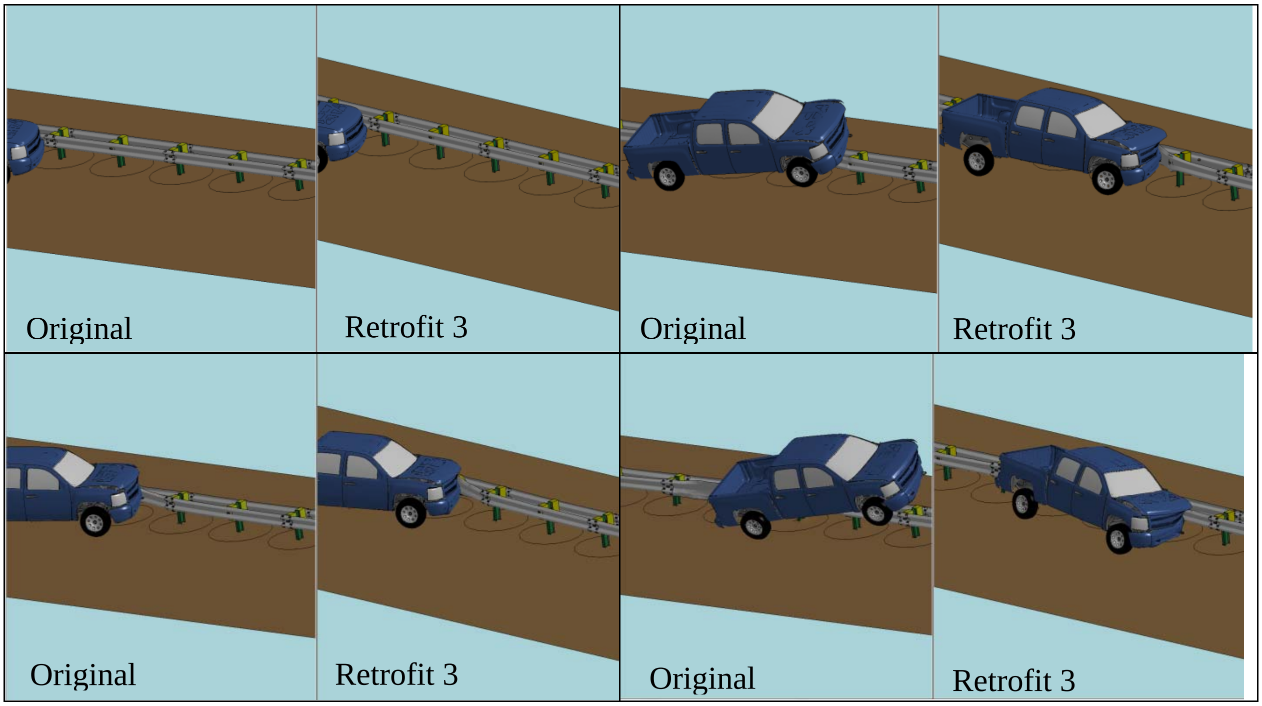



**Figure 4 - Simulation Comparisons of the Original Design & the Three Inch Increased Height.**

## Summary & Conclusions

Previous efforts, originally conducted to further validate the Silverado FE model, provided a basis for simulating impacts with the two barriers that did not meet full-scale crash testing criteria. This document provides a summary of the two crash tests and provides a brief overview of the analyses that were conducted to demonstrate the validity of the models. This included passing the newly developed verification and validations requirements. For both cases it was noted that:

- The detailed Chevrolet Silverado FE model was stable and displayed no unusual behavior.
- The detailed barrier models indicated variations in results reflecting the design changes that were considered.
- Visual comparison of test and the simulation results generated by the software provided useful representations of the effects of various changes.
- The traditional comparison of graphs of roll, pitch, and yaw measures provided a more detailed indication of retrofit option effectiveness.

The retrofit analyses assessed various modifications of the tested barrier designs for two-commonly-used, previously approved to determine if they could pass the new MASH requirements for oblique, high-speed impacts. The findings included:

- For the G9 Thrie Beam barrier, six options were considered in an attempt to mitigate the rollover observed in the crash test. These included:
    - Using a notched steel blockout, deeper blockouts, deeper-notched blockouts, increased rail height, half blockouts, and dual rails (median barrier style).

- The analyses of roll, pitch, and yaw metrics indicated that the half blockout offered a large drop in roll which would address the rollover problem noted in the crash test.
- The visual comparisons also indicated that there would be more vehicle stability.

- For the G4(1S) median barrier three options were considered in an attempt to mitigate the vaulting observed in the crash test. These included:
  - Raising the top of rail one inch, two inches, and three inches.
  - It was noted that the pitch metric decreased with each incremental increase in barrier height. This was believed to reduce the risk of vaulting.
  - Reduced pitching improved the interface with the barrier which contributed to the reduced the propensity to vault.
  - The visual comparisons showed greater vehicle stability.
- Further consideration of other factors is needed to determine that the retrofit options are fully viable. Crash testing for the most promising retrofit option would be prudent.

Further efforts might be considered useful to:

- Increased focus on the metrics compared. There may be metrics unique to a type of impact that should get more attention.
- Consideration of the other applicable MASH tests for the viable retrofit options.

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