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16. Abstract

Crash test results have shown that vehicles that receive good ratings in existing co-linear consumer information tests still may require structural modifications for good performance in NHTSA's frontal oblique test procedure. The purpose of this study is to determine incremental vehicle structural change requirements and their associated mass and cost to significantly reduce occupant compartment intrusion.

An available finite element model of a mid-size sedan was updated and validated using test data from a 2015 Toyota Camry. The generated baseline model correlates well with the New Car Assessment Program (NCAP) full overlap test, NHTSA's left and right oblique impact tests, and with the IIHS small and moderate overlap crash tests. The developed baseline model was used to evaluate necessary countermeasures to reduce occupant compartment intrusion according to defined design goals for the left and right oblique impact configuration.

As a result, three optimized models were created. The accomplished reduction of occupant compartment intrusion ranges from 52 percent to 77 percent. The associated added mass ranges from 7 kg to 17 kg and the associated cost ranges from $21 to $39. The significant reduction in occupant compartment intrusion was achieved without unintended consequences, i.e. no considerable increase of vehicle pulse for oblique and co-linear load cases was observed.

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1. Background

Consumer information crash tests, such as the National Highway Traffic Safety Administration's New Car Assessment Program (NCAP) full overlap frontal impact and the Insurance Institute for Highway Safety (IIHS) small and moderate overlap frontal impacts, have contributed to advance vehicle safety and reduce injury risk in the past. Recent studies have indicated that oblique crashes represent common real-world accident patterns related to belted occupant fatalities.[1] When comparing the number of injuries by body region for oblique and co-linear frontal impacts, it was observed that drivers in left oblique impacts experienced more Maximum Abbreviated Injury Scale (MAIS) 3+ injuries in almost every body region than drivers in co-linear crashes.[2]

The Center for Collision Safety and Analysis at George Mason University has analyzed 16 left oblique tests conducted by NHTSA regarding intrusion patterns and related injury risk. It was found that passengers in vehicles with higher occupant compartment intrusion values in the longitudinal vehicle direction tended to have higher loads to the tibia and associated higher risk of lower extremity injury. While occupant compartment intrusion is not the only cause for lower extremity injuries, it can be concluded that the risk of injury generally increases as the maximum intrusion from the floor or toe pan increases.[3]

IIHS compared the performance of 25 vehicles in NHTSA's frontal oblique condition and the IIHS small overlap configuration. The selected cars represent a wide range of vehicle sizes. With respect to lower extremity injuries, it was found that 36 percent (9 cars) of the vehicles exceeded preliminary Injury Assessment Reference Values (IARVs) in the oblique impact, while only 8 percent (2 cars) exceeded the IARVs for the small overlap configuration.[4]

The oblique impact test captures the deformations of a significant number of real world accidents that occur today, and the development of additional countermeasures for restraints and vehicle structure may have the potential to further improve vehicle safety and reduce injury risk in the future.

The developed laboratory test procedure is conducted in combination with a more biofidelic dummy, the Test device for Human Occupant Restraints (THOR).[5] An oblique moving deformable barrier (OMDB) was optimized to produce target vehicle crush patterns similar to real world cases.[6] It has a weight of 2,486 kilograms (kg) and impacts a stationary vehicle at a speed of 90 kilometers per hour (km/h). The vehicle is placed at a 15-degree angle and a 35-percent overlap occurs between the OMDB and the front end of the struck vehicle, as shown in Figure 1.

[1] Bean, J., Kahane, C., Mynatt, M., Rudd, R., Rush, C., Wiacek, C. (2009). *Fatalities in frontal crashes despite seat belts and air bags: Review of all CDS cases – Model and calendar years 2000-2007 – 122 Fatalities*," (Report No. DOT HS 811 202). Washington, DC: National Highway Traffic Safety Administration. Available at https://crashstats.nhtsa.dot.gov/Api/Public/Publication/811102

[2] Federal Register Vol. 80 No. 241, New Car Assessment Program (NCAP), Request for comments, December 2015, page 24

[3] Zhang, R., Reichert, R., Kan, C.-D., & Cao, L. (2015). Evaluation of driver lower extremity injuries in 16 oblique crashes with THOR," *International Journal of Crashworthiness*, *21*:2, 120-134. doi: 10.1080/13588265.2015.1120983

[4] Mueller, R. (2017, January 26). Comparison of frontal crash modes: IIHS small overlap and NHTSA oblique.," (Presentation). SAE 2017 Government/Industry Meeting, Washington, DC, January 25-27, 2017.

[5] NHTSA. (2015, December 5). Laboratory Test Procedure for Oblique Offset Moving Deformable Barrier Impact Test In Docket NHTSA-2015-0119-0017. Available at https://www.regulations.gov/contentStreamer?documentId=NHTSA-2015-0119-0017&attachmentNumber=1&contentType=pdf

[6] Saunders, J., Craig, M.J., & Suway, J. (2011). NHTSA's Test Procedure Evaluations for Small Overlap/Oblique Crashes. (Paper No. 11-0343). 22nd International Technical Conference for the Enhanced Safety of Vehicles, , Washington, DC, June 13-16, 2011.

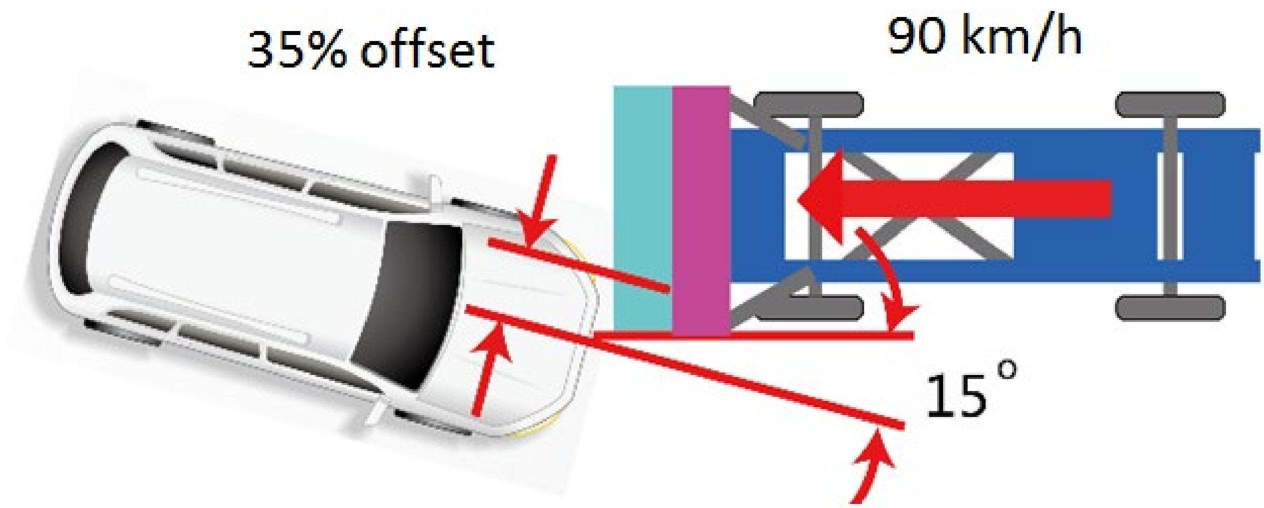


Figure 1 - Frontal Oblique Test Configuration

In its evaluation of the oblique impact configuration, NHTSA contracted the CCSA to develop structural countermeasures to reduce occupant compartment intrusion for the oblique impact condition and to determine associated incremental changes in mass and cost for a vehicle that performs well in co-linear impact configurations. Development of respective restraint system countermeasures and associated occupant injury risk is not part of this research.

The project was conducted by the CCSA at GMU. DYNAmore, an engineering service firm, supported the efforts by providing expertise with respect to state of the art modeling techniques used in industry. The steel manufacturer Big River Steel (BRS) conducted the incremental cost analysis for the developed structural countermeasures. BRS produces a broad range of steel products, especially the steels requiring the highest strength and lightest weight for automotive industries.

2. Objective

The objective of the structural countermeasure research was to demonstrate necessary changes to a passenger vehicle's structure to significantly reduce occupant compartment intrusion in NHTSA's oblique frontal crash test condition. Structural countermeasures of both the driver's and passenger's sides of the vehicle for left- and right-side oblique impacts were developed.

The studied vehicle had to meet the structural intrusion requirements for a “Good” or “Acceptable” structural rating in the IIHS small overlap, “Good” rating in the IIHS moderate overlap, and 5-Star rating in the NCAP full frontal test.

In the IIHS moderate overlap configuration, the tested vehicle travels at a speed of 64 km/h with a 40 percent overlap co-linear into a fixed deformable barrier. The vehicle is equipped with a 50th percentile male Hybrid III dummy in the driver seat. The initial structural rating is based on comparison of intrusion measurements with rating guidelines for the upper and lower occupant compartment, as outlined in Chapter 3.3.1. For example, intrusions of 15 centimeter or less at the driver’s toe-pan, would be rated “Good.”

In the IIHS small overlap configuration, the tested vehicle travels at a speed of 64 km/h with a 25 percent overlap co-linear into a fixed rigid barrier. The vehicle is equipped with a 50th percentile male Hybrid III dummy in the driver seat. The initial structural rating is based on comparison of intrusion measurements with rating guidelines for the upper and lower occupant compartment, as outlined in Chapter 3.3.1. For example, intrusions of 15 centimeter or less at the driver’s toe-pan, would be rated “Good.”

In the NCAP full frontal configuration, the tested vehicle travels at a speed of 56 km/h with full overlap co-linear into a rigid wall. The vehicle is equipped with a 50th percentile male Hybrid III dummy in the driver seat and with a 5th percentile female Hybrid III dummy in the passenger seat. The current NCAP rating is based on injury risk assessment rather than occupant compartment intrusion.

A finite element model for an appropriate passenger vehicle that fulfills the above requirements was selected and validated to match the acceleration and intrusion measurements in NCAP frontal full overlap, IIHS moderate and small overlap test procedures. The simulation results were compared to available crash test results using an objective rating methodology. Similarly, baseline simulations for oblique frontal test configurations were conducted and compared to respective test data.

The simulation results were used to establish design goals to minimize occupant compartment intrusion in left- and right-side oblique frontal crashes. Structural countermeasures were developed according to the previously defined design goals. The associated incremental differences in vehicle mass, material, and manufacturing cost between the baseline model and the model with implemented countermeasures were determined.

The effects of implemented structural design changes were evaluated with respect to vehicle pulse and intrusion characteristics in existing co-linear impact configurations.

The period of performance for this project was from August 2016 to March 2017.

3. Methods

3.1 Vehicle Selection

Several criteria were used to determine an appropriate vehicle on which to conduct this research. These included analysis of the number of vehicle sales as a measure of how well it represents mid-size sedans in the United States, performance in existing consumer information tests, and availability of an adequate finite element simulation baseline model. A FE model of a 2012 Toyota Camry, which has been developed in a previous project, was used as a starting point, as outlined in Chapter 3.2.1.

3.1.1 Sales Numbers

Table 1 shows the U.S. sales of popular mid-size moderately priced vehicles in 2012.[7]

Table 1 - 2012 U.S. Sales Numbers for Mid-Size Vehicles

Make and Model	US Sales
Toyota Camry	404,886
Honda Accord	331,872
Nissan Altima	302,934
Ford Fusion	241,263
Hyundai Sonata	230,605
Chevy Malibu	210,951
VW Jetta	170,424
Kia Optima	152,399
Chrysler 200	125,476
Subaru Legacy	47,127
Mazda 6	33,756

The Toyota Camry has sale numbers that are higher than any other of the cars in its segment. It adequately represents the mid-size vehicle segment and is a good candidate for the intended structural countermeasure research.

3.1.2 Full-Scale Test Results

Toyota introduced structural design changes in January 2014. Test results with vehicles that were built before January 2014 did not include these changes and are called Model Year (MY) 2012 Toyota Camry and test results with vehicles that were built after this date are called MY 2015 vehicles in this report. Table 2 outlines the available full-scale test results.

The NCAP rating is based on occupant injury criteria. The MY 2012 vehicle received 5 stars for the driver and 4 stars for the passenger. The MY 2015 vehicle received 4 stars for the driver and 5 stars for the passenger. Occupant risk depends on vehicle structure and restraint system performance. Occupant compartment intrusion was small and the vehicle pulse was judged good for both vehicles. According to the defined project task, the vehicle to be studied "should meet the structural intrusion requirements for a 5-Star rating in NCAP frontal." It

[7] 2012 Year End Top 25 Best-selling Cars in America," www.goodcarbadcar.net/p/sales-stats.html, accessed February 2017

can be stated that the MY 2012 as well as MY 2015 Toyota Camry vehicles represent vehicles with structural intrusion characteristics that allow them to receive a 5-Star NCAP rating.

The Toyota Camry received an overall Good rating in the 64 km/h IIHS moderate overlap impact with a Good sub-rating for the structure and safety cage. This applies to 2012-2016 models. Therefore, MY 2012 as well as MY 2015 vehicles meet the structural intrusion requirements for a Good rating in the IIHS moderate overlap impact.

Table 2 - Full-Scale Test Results

	MY 2012	MY 2015
NCAP	4/5-Star	4/5-Star
IIHS Moderate Overlap	Good (Structure)	Good (Structure)
IIHS Small Overlap	Poor (Structure)	Acceptable (Structure)
Left Oblique	Test data available	Test data available
Right Oblique	Test data available	No test data available

Beginning with 2014 models (built after December 2013) the front structure of the Toyota Camry was modified specifically to improve performance in the 64 km/h small overlap frontal crash test. The MY 2012 received a Poor rating with a Poor sub-rating for structure and safety cage. The MY 2015 received a Good overall rating with an Acceptable sub-rating for structure and safety cage. The MY 2015 meets the structural intrusion requirements for an Acceptable structural rating in the IIHS small overlap impact.

In addition, left oblique frontal impact tests were conducted with a 2012 Toyota Camry (NHTSA test # 9124) and a 2015 Toyota Camry (# 8790). A right oblique frontal impact test was conducted with a 2012 Toyota Camry (# 9121).

3.2 Baseline Model Generation

3.2.1 2012 Toyota Camry

In a previous project, a 2012 Toyota Camry (VIN 4T1BF1FK2CU079329), as shown in Figure 2, was purchased and a detailed finite element (FE) model was built using a reverse engineering process.

In the previous project, a digitizing device was used to scan all relevant components including their internal structure. Accurate computer aided design (CAD) surfaces were generated and used for FE mesh generation. All components were positioned using a defined reference coordinate system and checked for penetrations. Spot-welds, bead welds, bolts, and joints were used for respective part connections. Material thicknesses and mass distribution were assigned to the individual parts and components. Mass, measured center of gravity (CG) location and inertial properties of the entire vehicle were verified. Material property data for many structural parts was obtained by cutting specimens from the actual vehicle components and conducting material coupon tests.

Figure 2 - 2012 Toyota Camry (a) Physical Vehicle and (b) FE Model

Most components were modeled using shell elements with an average element size of 6 millimeters (mm). The model was evaluated and validated using the nonlinear, explicit FE code LS-DYNA[8] with a minimum time-step of 0.7 microseconds using 16 central processing units (cpu's) on a Hewlett-Packard high-performance computer system. Additional details regarding the modeling approach and validation process can be found in "Validation of a Toyota Camry Finite Element Model for Multiple Impact Configurations."[9] The FE model contains relevant structural and interior components, such as body in white, engine, drivetrain, steering, suspension, seats, trims, etc., which are represented by more than 1,000 parts and approximately 2.25 million nodes and elements.

3.2.2 2015 Toyota Camry

Nondestructive analysis of a physical 2015 Toyota Camry, including additional available and provided information, was used to determine differences between the MY 2012 and MY 2015 mid-size sedans. Figure 3(a) illustrates relevant structural differences between MY 2012 and MY 2015. To improve performance in the IIHS small overlap test from Poor to Acceptable, a spacer (2) was added beyond the bumper reinforcement (1) to the front side member (3), to direct crash energy through the side member into the reinforced A-pillar (4), which diffuses it through the roof rail, rocker panel, and floor pan. These changes were phased in as a MY 2014.5 package during December 2013.[10] Full-scale crash tests with vehicles that included these changes will be called "2015 Toyota Camry" tests in the remainder of this report.

Figure 3(b) shows (from right to left) a bottom view of the finite element model with an enlarged view of the added bumper reinforcement extension and "spacer" for the simulation model and the physical vehicle.

[8] Hallquist, J. O. (2013, February). LS-DYNA Keyword User Manual. Livermore, CA: Livermore Software Technology Corporation.
[9] Reichert, R., Mohan, P., Marzougui, D., Kan, C., & Brown, D. Validation of a Toyota Camry Finite Element Model for Multiple Impact Configurations," (SAE Technical Paper 2016-01-1534). SAE 2016 World Congress and Exhibition, Detroit, April 12-14, 2016. doi:10.4271/2016-01-1534.
[10] SAE International (2016, September 7). Camry's mid-cycle 'refresh' more than just front and rear panels." Retrieved from the SAE website at www.articles.sae.org/13135/

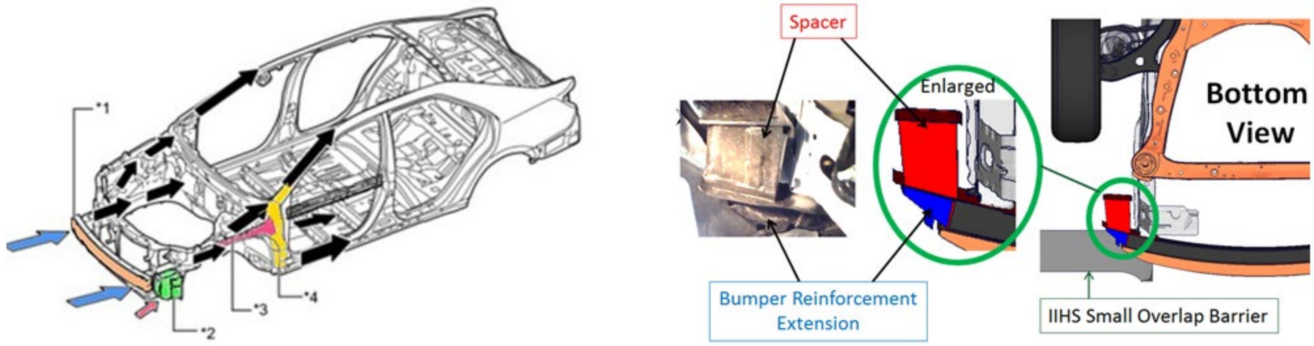


Figure 3 - 2015 Toyota Camry Design Changes (a) Overall Schematic, (b) "Spacer"

The available 2012 Toyota Camry FE model was updated accordingly. Available full-scale test results show that the design changes mainly affected performance in the IIHS small overlap impact, while other crash configurations, such as NCAP full overlap and NHTSA left oblique impact, showed similar results for the 2012 and 2015 models. Figure 4(a) depicts the updated FE model with added bumper reinforcement and spacer (1). Material thickness for parts of the rocker pillar, A-pillar, and side-member (2) was increased by 10 percent as a result of the conducted baseline simulations, as outlined in Chapter 4. It was known that these parts were reinforced in the physical vehicle, but no information about the exact thickness increase was available. In addition, advanced modeling techniques for the wheel connection (3) were implemented to better represent the failure mechanisms and wheel kinematics seen in the IIHS small overlap impact.

Figure 4(b) shows the effect of the bumper reinforcement and spacer in the IIHS small overlap impact. Due to the minor overlap of 25 percent with the vehicle, the longitudinal rail is not activated when no spacer exists. The frontal rail remains undeformed and no crash energy is absorbed. The effect of the added bumper reinforcement extension and spacer can be seen in Figure 4(b) on the right. The added components interact with the IIHS small overlap barrier and activate the frontal rail on the driver side. The deformation of the longitudinal rail contributes to the structural crash energy absorption.

All updates were implemented to the driver and passenger side of the FE model. The associated added vehicle mass is equivalent to 9.7 kg and is similar to the difference in vehicle mass from NHTSA's left oblique test of a 2015 Toyota Camry (test #8790, 1450 kg as delivered, 1734 kg as tested) and a 2012 vehicle (test #9124, 1443 kg as delivered, 1759 kg as tested).

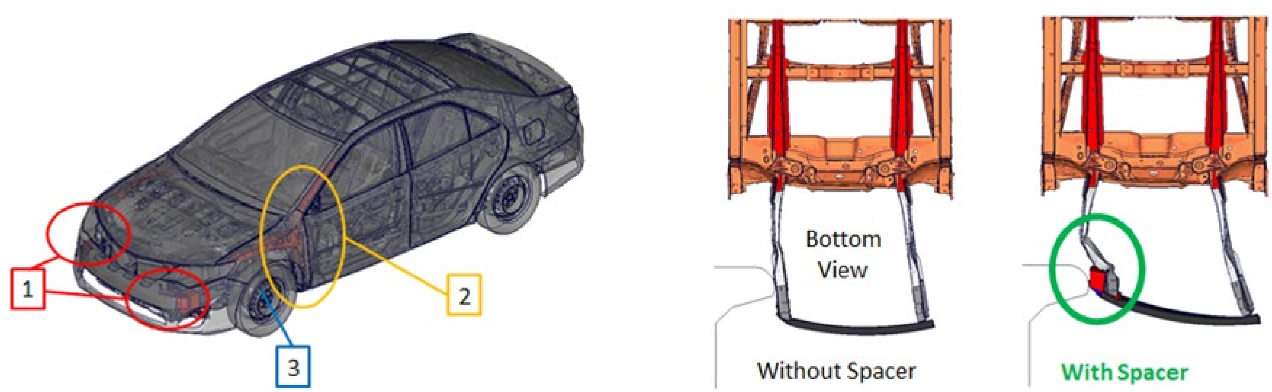


Figure 4 - (a) 2015 Toyota Camry FE model (b) Effect of spacer in IIHS small overlap

Available test data from the 2015 Toyota Camry was used to evaluate the updated FE model, as outlined in Chapter 4. Despite the fact that complete information for all the detailed design changes from MY 2012 to MY 2015 was not available, it was determined that the updated FE model does a good job of simulating the performance of a 2015 Toyota Camry in the respective crash configurations. It will be called the “2015 Toyota Camry baseline model” in the remainder of this report.

All baseline simulations were conducted using this model. Developed structural countermeasures to significantly reduce occupant compartment intrusion were evaluated with respect to the 2015 Toyota Camry baseline model.

3.3 Validation Procedure

3.3.1 Intrusion Measurements

Baseline simulations were compared against established occupant compartment intrusion criteria and measurement definitions from respective crash test results, as shown in Figure 5.

Figure 5(a) illustrates the rating chart used by IIHS for its structural rating in the moderate overlap impact. Figure 5(b) shows the respective measurement points.[11]

For the IIHS small overlap, i.e. 25 percent overlap, and moderate overlap, i.e. 40 percent overlap, test protocols, the lower and upper occupant compartment each receive a sub-rating. Lower or upper intrusion measures all falling in the area labeled Good receive a Good structural sub-rating if no additional observations lead to a downgraded rating. Similarly, vehicles with all intrusion measures falling into one of the other three zones shown in Figure 5(a) receive an Acceptable, MARGINAL, or Poor sub-rating. When intrusion measurements fall in different rating bands, the sub-rating generally reflects the band with the most measures. However, the sub-rating will not be more than one rating level better than the worst measurement.

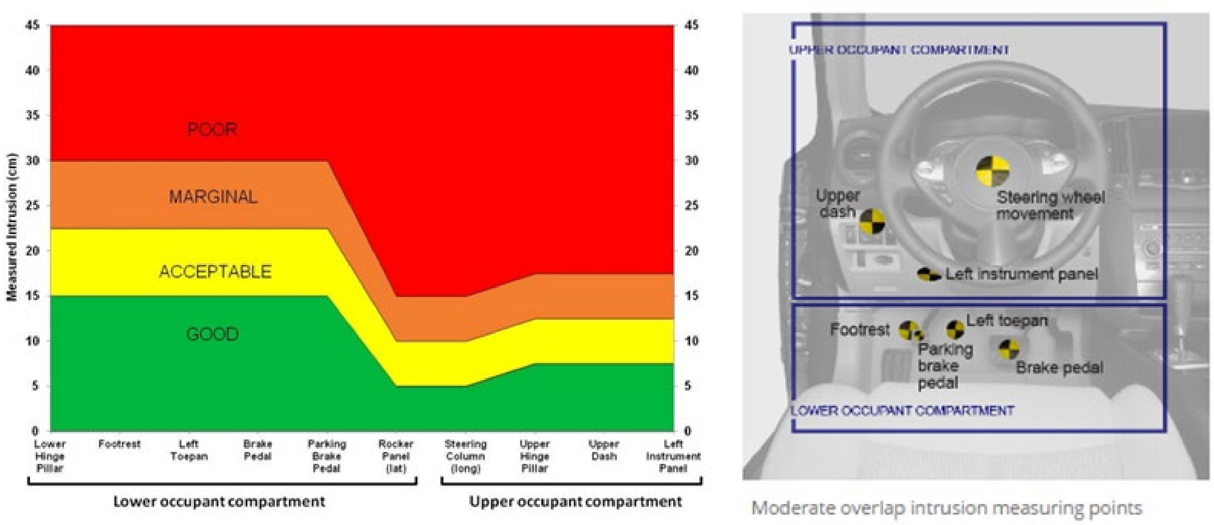


Figure 5 - (a) IIHS MO Rating Chart, (b) MO Points

[11] IIHS (2011). Moderate overlap, Guidelines for rating structural performance. Arlington, VA: Author.

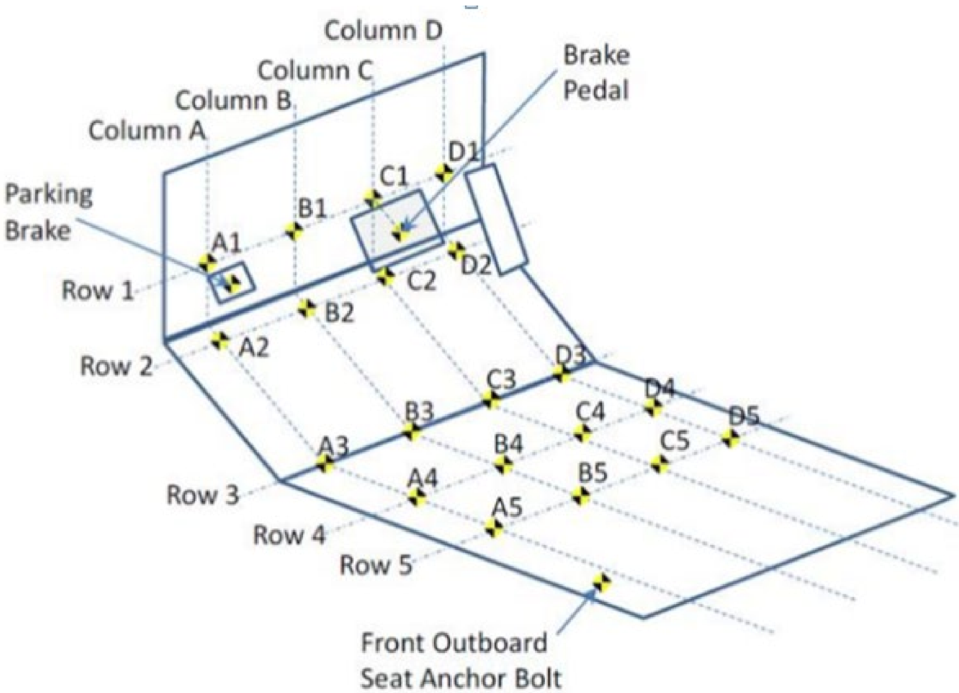


Figure 5 - (c) Oblique Toe-Pan Intrusion Measurement Points

Figure 5(c) shows the measurement points used in NHTSA's oblique impact configuration.[12] Measurements are taken with respect to the rear of the vehicle. It was observed that measurements other than those in the longitudinal vehicle direction are sensitive to the overall vehicle deformation and reference system. To develop structural countermeasures for NHTSA's oblique impact configuration, measurements in the longitudinal vehicle direction are compared for test and simulation, as well as baseline and countermeasure models.

In addition to lower and upper occupant compartment intrusion measurements, door sill deformation data is used to compare baseline simulations with available test data, and to compare simulations with and without countermeasures.

3.3.2 Vehicle Pulse

Time history data is used to compare the vehicle acceleration pulse of the simulations with available test data from the respective impact configurations. The software tool CORrelation and Analysis (CORA)[13] is used to objectively evaluate the correlation between test and simulation results. Figure 6 illustrates how CORA compares and rates two curves.

CORA was developed by the Partnership for Dummy technology and Biomechanics (PDB) and takes into account phase shift, size, and shape, as well as the comparison of values at each time increment. Using these criteria, an objective rating is given that indicates how well a curve (e.g., simulation) compares to a reference curve (e.g., test). Rating results range between 0 and 1, where 0 means no correlation and 1 means (close to) perfect correlation.

[12] NHTSA, 2015.

[13] Thunert, C. (2012). CORA Release 3.6 User's Manual, Version 3.6. Braunschweig, Germany: GNS mbH, and Partnership for Dummy Technology and Biomechanics.

Two general examples of curve comparisons using CORA are shown in Figure 6 on the bottom. Inner and outer corridors are depicted in green and blue, respectively. The example on the right shows a test result in black and a simulation curve in red. A correlation rating of 0.26 was given by CORA, and therefore the correlation is judged as poor. The example on the left shows where the test in black and simulation in red correlate very closely and a near-perfect rating of 0.96 was given.

Applying default parameters within CORA used in the automotive industry,[14] such as 5 percent for inner corridor and 50 percent for outer corridor, the following evaluation scheme is used when comparing vehicle time history data in test and simulation.

- CORA rating between 0.8 and 1 — Good
- CORA rating between 0.6 and 0.8 — Acceptable
- CORA rating between 0.4 and 0.6 — Marginal
- CORA rating between below 0.4 — Poor

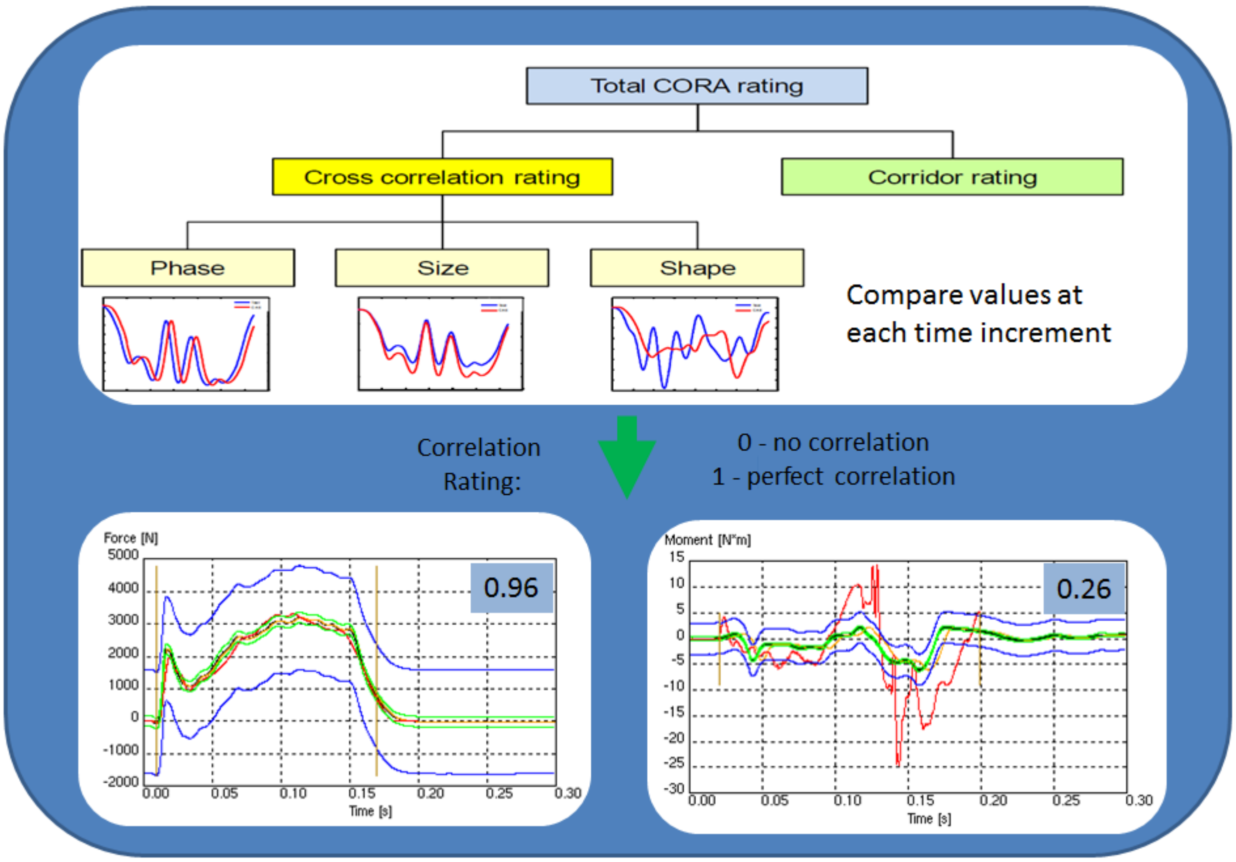


Figure 6 - CORA: Objective Correlation Rating Methodology

3.4 Mass and Cost Analysis

3.4.1 Incremental Mass Analysis

Using the baseline model (BM), which represents a 2015 Toyota Camry, as a reference, structural countermeasures were developed to significantly reduce occupant compartment intrusion in the left and right oblique impact condition. The model with implemented design changes is called the “countermeasure model” (CM). Added and modified components were evaluated with respect to incremental change in mass. The overall associated incremental difference in vehicle mass between the BM and the CM was determined.

3.4.2 Incremental Cost Analysis

Using the BM that represents a 2015 Toyota Camry as a reference, structural countermeasures were developed to significantly reduce occupant compartment intrusion in the left and right oblique impact conditions. As in the incremental mass analysis, the model with implemented design changes is called the “countermeasure model”. Added and modified components were evaluated with respect to incremental change in material and manufacturing cost. The overall associated difference in cost between the BM and the CM was determined.

Incremental cost analysis was conducted in cooperation with BRS. BRS operates the world’s first Flex Steel Mill, located in Arkansas, with over $1.3 billion invested in property, plant, and equipment. Over the past 25 years, the BRS management team has gained broad experience working with automotive and other industries.

The assumption for the cost analysis is that components with changed material thickness and changed steel strength, but the same geometry, will undergo the same manufacturing process. Cost of labor, energy, equipment, building, maintenance, and overhead will remain the same and are a second order effects. Tooling cost can increase with increasing material strength by 10 percent, however a 10 percent tool cost increase will affect part cost by less than 2 percent and is also considered a second order effect. Material is a first order effect on cost in both material price and quantity of material purchased, as shown in Figure 7(a).

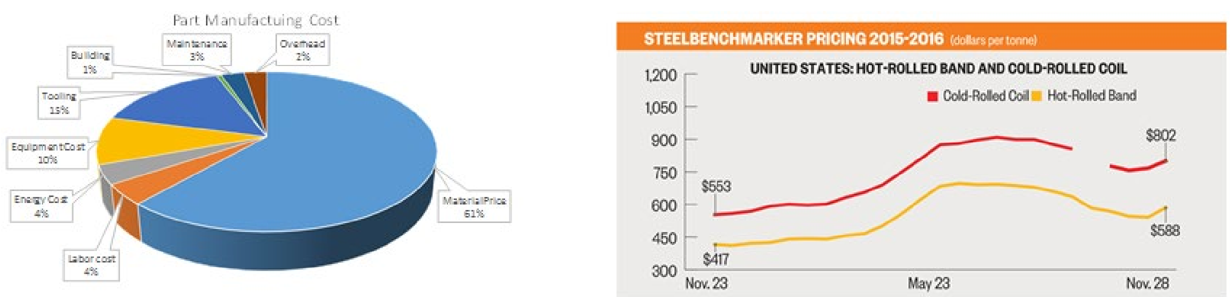


Figure 7 - (a) Manufacturing Cost and (b) Steel Benchmark Pricing

Material price is obtained from steel material pricing commonly used in the automotive industry. Cost extras of gauge and width are second order effects and not considered as part of this estimate. Material grade and coating extras are first order effects. Base price is relatively dynamic, and is based on market supply and demand. At time of writing, market price for cold-rolled (CR) mild steel is $0.80/kg according to the American Metal Market, as shown in Figure 7(b). Grade extras are relatively static.

Material cost depends on the amount of material purchased, which is more than merely part weight as a result of trimming of the stamping blank as it is formed into the final part, as shown in Figure 8. Stamping yield varies from part to part, but on average is 65 percent, which is the assumed value in this cost estimate. This ensures that cost estimates will be on the conservative side.

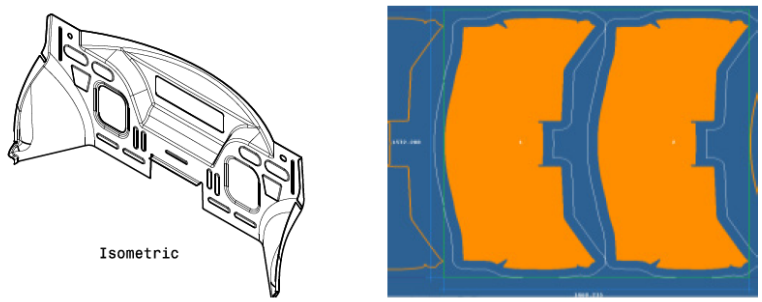


Figure 8 - Example Part (a) CAD Design and (b) Untrimmed Blank

The cost estimate is based on associated yield strength of the materials used in the baseline and countermeasure simulations. Steel grades that are common in the automotive industry and enable the yield strength for these applications were assumed. When developing structural countermeasures, material thicknesses of respective parts were changed only within the commercially available gauge range.

Stamping and manufacturing processes were considered when developing design changes. The steel grade that can be used for respective components depends on its shape. Generally, components with geometries that require a large amount of deep drawing and have "sharp" corners cannot be made out of steel grades that exceed a certain amount of strength, when the same stamping process may be used. Other stamping processes, such as hot stamping, would be required, resulting in a significant amount of additional cost. Higher strength steels for modified and added components were therefore limited to steel grades that allow for production of the respective part using the same stamping and joining process.

3.4.3 Effect on Fuel Economy

A general rule of thumb is that for every 10 percent reduction in vehicle weight, the fuel consumption of vehicles is reduced by 5-7 percent.[14] Using this rule of thumb, for a 1700 kg vehicle, an increase of vehicle mass by 17 kg would increase fuel consumption by about 0.6 percent.

[14] Cheah, L. (2010). Cars on a Diet: The Material and Energy Impacts of Passenger Vehicle Weight Reduction in the U.S.," (Doctoral thesis). Cambridge, MA: Massachusetts Institute of Technology.

4. Baseline Simulations

The results of the conducted baseline simulations using the 2015 Toyota Camry BM are outlined in this chapter. Simulation results are compared to available full-scale crash test results for NHTSA's left and right oblique impact, NCAP full overlap, IIHS small overlap, and IIHS moderate overlap configurations.

4.1 Left Oblique – Baseline Simulation

NHTSA's left oblique full-scale impact test #8790,[15] consisting of an OMDB traveling at a speed of 90 km/h into the front driver side of a stationary 2015 Toyota Camry, was used to evaluate the developed BM. The Toyota Camry was positioned with a 15-degree angle relative to the OMDB and impacted with a 35 percent overlap.

In addition, NHTSA's left oblique full-scale impact test #9124[16] of a 2012 Toyota Camry was used to evaluate the difference between a MY 2012 vehicle and a MY 2015 vehicle in this crash configuration.

4.1.1 Comparison of 2012 and 2015 Left Oblique Impact Test Results

Figure 9 compares two available full-scale crash tests. Figure 9(a) shows the overall post-crash vehicle deformation for the 2015 Toyota Camry on the left and the 2012 Toyota Camry on the right. Both model years show a similar overall vehicle deformation pattern.

Figure 9 (a) - 2012 & 2015 Left Oblique Test Results - Overall

[15] Walsh, V. (2015, February 19). Moving Barrier to Vehicle Crash Test in Support of NHTSA's Frontal Oblique Offset Program Research Moving Deformable Barrier Into Left Front of a 2014 Toyota Camry, 90.1kph, 15 Degree Angle, 35% Overlap (NHTSA Test Report No. R20144143, PDF no. v08790R002, also known as Test 8790). Washington, DC: National Highway Traffic Safety Administration. Available at www-nrd.nhtsa.dot.gov/database/VSR/SearchMedia.aspx?database=v&tstno=8790&mediatype=r&r_tstno=8790 [Click on Report-2]

[16] Walsh, V., & Dutton, E. (2015, March 4). Moving Barrier to Vehicle Crash Test in Support of NHTSA's Frontal Oblique Offset Program Research Moving Deformable Barrier Into Left Front of a 2012 Toyota Camry, 90.1kph, 15 Degree Angle, 35% Overlap (NHTSA Test Report No. RC5141, PDF no. v09124R001, also known as Test 9124). Washington, DC: National Highway Traffic Safety Administration. Available at www-nrd.nhtsa.dot.gov/database/VSR/SearchMedia.aspx?database=v&tstno=9124&mediatype=r&r_tstno=9124

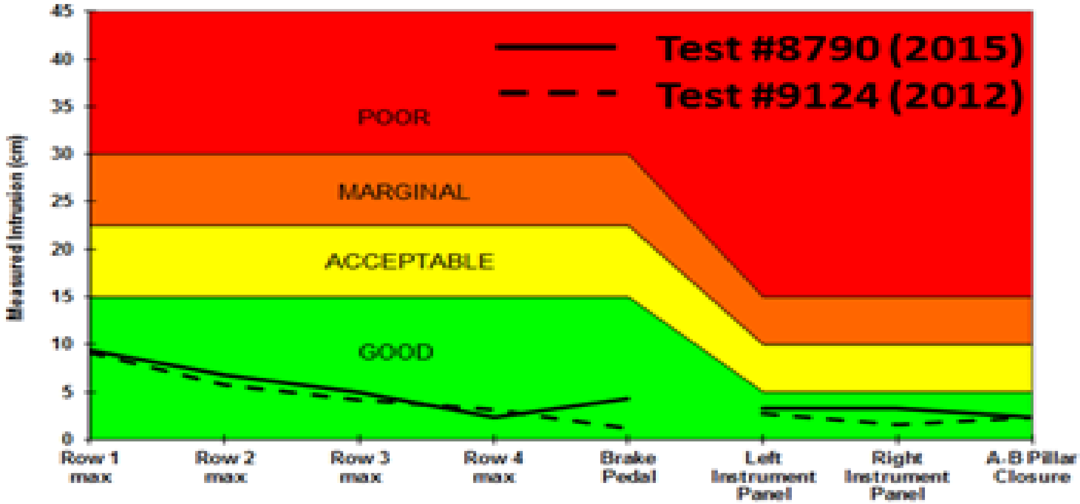


Figure 9 (b)- 2012 & 2015 Left Oblique Test Results – Intrusion

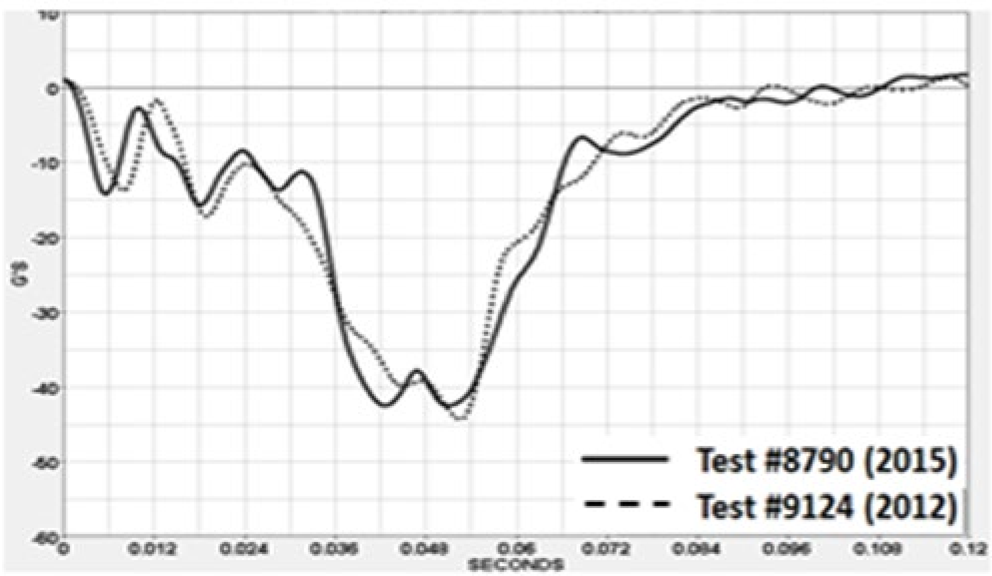


Figure 9 (c) - 2012 & 2015 Left Oblique Test Results - Vehicle Pulse

Toe-pan intrusion was recorded in both tests for measurement points in 5 rows, consisting of 4 points each, as shown in Figure 5(c). The maximum intrusion values for each row are represented in the adapted structural rating chart, derived from IIHS moderate overlap structural evaluation.

Figure 9(b) shows the maximum intrusion for row 1 to row 4, brake-pedal, left and right instrument panel, and A- to B-pillar closure. The 2015 Toyota Camry test results are shown as a black solid line and 2012 Toyota Camry test results are shown as a black dashed line. The highest values occur in row 1, which is the most forward and upward location at the toe-pan. Values decrease for more rearward locations in both tests. Comparable results, with a maximum intrusion of 94 mm in the 2015 model and 91 mm in the 2012 model, were observed.

Similarly, no significant differences in door sill deformation were detected. The 2015 vehicle had a maximum value of 39 mm, while the 2015 Toyota Camry had a maximum value of 40 mm.

Figure 9(c) illustrates the vehicle pulse from both full-scale tests. Again, similar characteristics, with a maximum peak acceleration of 45g for the 2012 and 43g for the 2015 vehicle, can be observed.

NHTSA's left oblique impact full-scale test results for a 2012 and 2015 Toyota Camry show similar characteristics with respect to vehicle deformation, occupant compartment intrusion, and vehicle pulse.

4.1.2 Left Oblique - Occupant Compartment Intrusion

Figure 10 compares overall vehicle deformation and specific occupant compartment intrusion values for a 2015 Toyota Camry in test and simulation. Figure 10(a) shows the overall vehicle deformation in the baseline simulation on the left and in the full-scale crash test on the right. Similar deformation of the frontal structure, door frame, and roof are observed. The A-pillar shows minor buckling in both test and simulation.

Figure 10(b) depicts the door sill deformation. Pre-crash measurement points are shown in green. These points were chosen to be the same in test and simulation. Post-crash measurement points for the simulation are illustrated in blue. Respective post-crash points for the 2015 full-scale crash test are depicted in black with markers. The maximum deformation values are 40 mm for the test and 25 mm for the simulation. It is noted that there is no significant door sill deformation in either test or simulation. Intrusion along the rocker pillar and minor bending of the A-pillar area are well captured in the simulation model.

Toe-pan intrusion was recorded for measurement points in 5 rows, consisting of 4 points each, in test and simulation, as shown in Figure 5(c). The maximum intrusion values for each row are shown in the adapted structural rating chart, derived from the IIHS moderate overlap structural evaluation protocol.

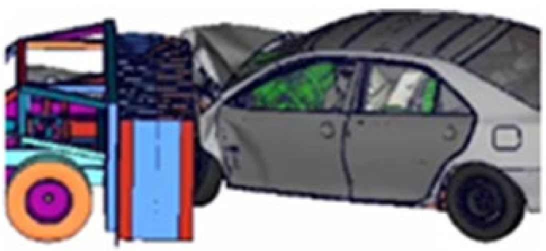


Figure 10 (a) - 2015 Left Oblique Test Versus Simulation - Overall

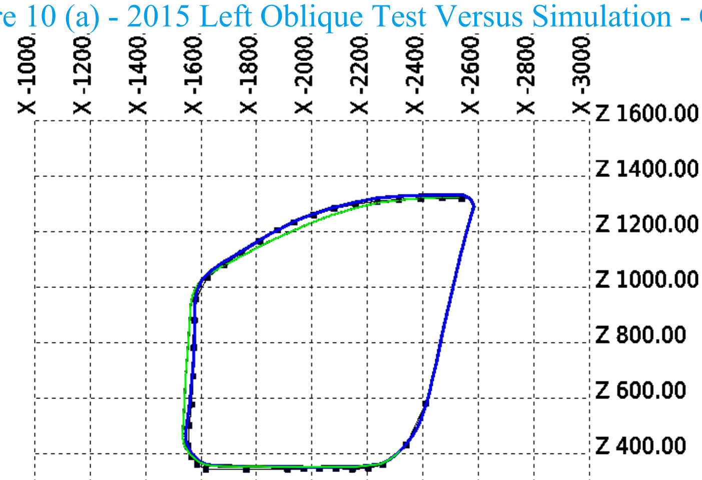


Figure 10 (b) - 2015 Left Oblique Test Versus Simulation – Door Sill

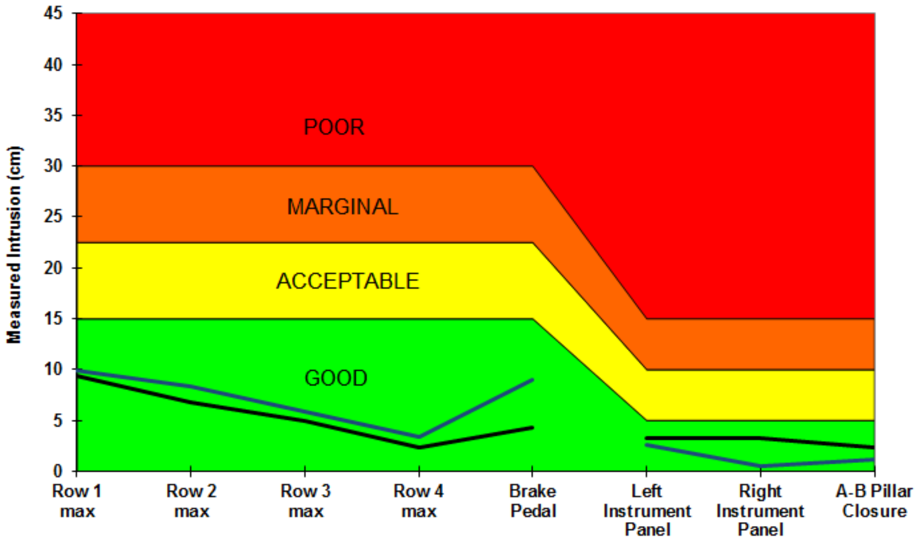


Figure 10 (c) - 2015 Left Oblique Test Versus Simulation - Intrusion

Figure 10(c) visualizes the maximum intrusion for row 1 to row 4, brake-pedal, left and right instrument panel, and A- to B-pillar closure. The 2015 Toyota Camry test results are shown in black and BM simulation results are shown in blue. The highest values occur in row 1, which is the most forward and upward location at the toe-pan. Values decrease for more rearward locations in test and simulation. A maximum intrusion of 94 mm is observed in the test, versus 99 mm in the simulation. Lower and upper occupant compartment intrusion, including toe-pan deformation from the full-scale crash test, is well captured in the simulation model.

The BM simulates well the structural intrusion characteristics of a 2015 Toyota Camry in the left oblique impact configuration.

4.1.3 Left Oblique - Vehicle Pulse

Figure 11(a) compares acceleration pulse on the top and velocity pulse on the bottom for a 2015 Toyota Camry in test and BM simulation in the left oblique impact configuration. Test results are depicted using a black solid line and simulation results are depicted using a blue dashed line. Good overall correlation for both acceleration and velocity time history data can be observed. Values for maximum peak acceleration (a_{max}), maximum peak acceleration that lasted 5 milliseconds (a_{5ms}), maximum peak acceleration that lasted 15 milliseconds (a_{15ms}), and change in velocity (Δv) correlate well. The characteristic values a_{5ms} and a_{15ms} were evaluated in addition to a_{max} to describe the correlation between test and simulation for different time intervals. Objective CORA rating values of 0.94 for acceleration and 0.96 for velocity document the good correlation between test and simulation.

Figure 11(b) shows the OMDB acceleration pulse on the top and velocity time history for the left oblique impact configuration on the bottom. Test data is depicted as a black solid line and simulation data as a blue dashed line. Good correlation between test and BM simulation can be observed. The objective CORA rating values are 0.95 for the acceleration and 0.98 for the velocity.

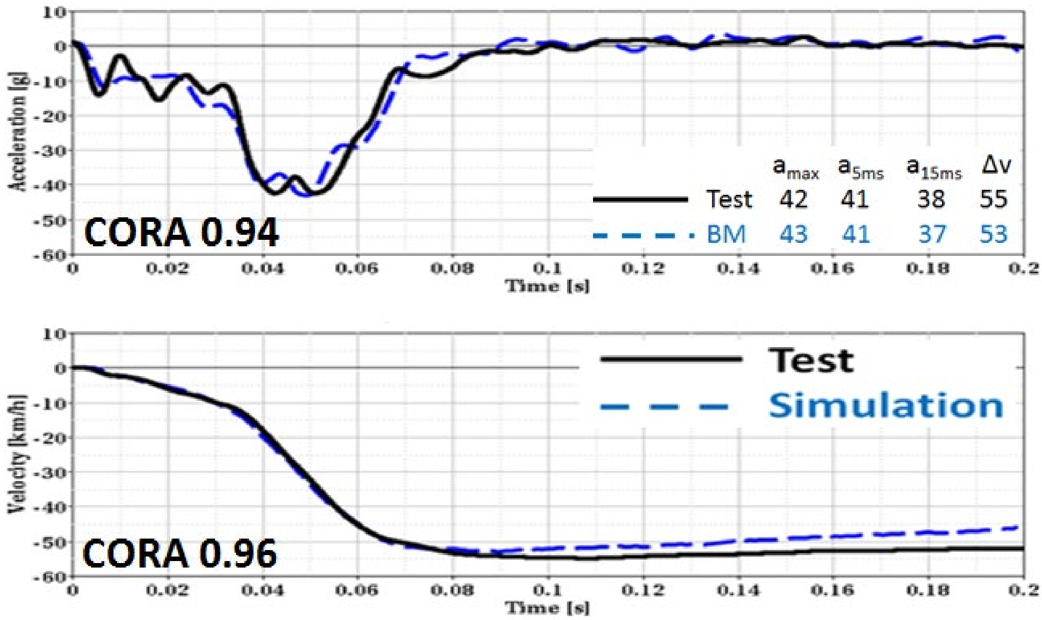


Figure 11(a) - 2015 Left Oblique Test Versus Simulation - Vehicle Pulse

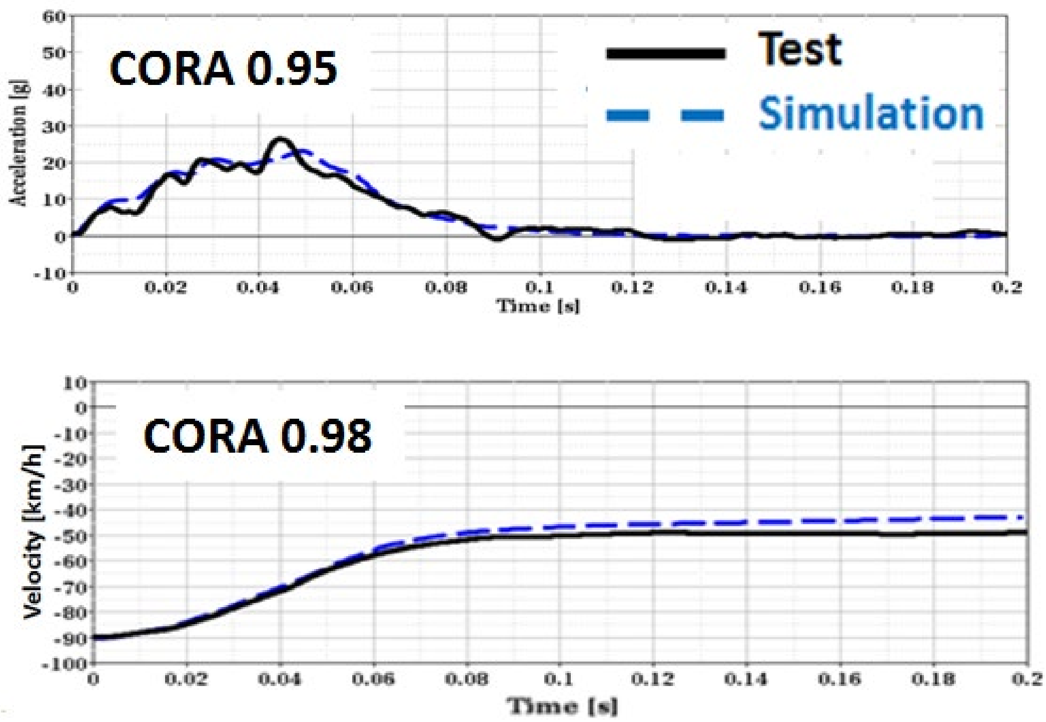


Figure 11(b) - 2015 Left Oblique Test Versus Simulation - Barrier Pulse

It was found that the BM well represents the vehicle and barrier pulse characteristics of a 2015 Toyota Camry in the left oblique impact configuration.

4.2 Right Oblique – Baseline Simulation

NHTSA's right oblique impact test #9121,[17] consisting of a RMBD traveling at a speed of 90 km/h into the front passenger side of a stationary 2012 Toyota Camry, was used to evaluate the developed baseline simulation model. The Toyota Camry was positioned with a 15-degree angle relative to the OMDB and impacted with a 35 percent overlap.

No full-scale right oblique crash test data of a 2015 Toyota Camry was available. Test results for the left oblique impact configuration show similar vehicle deformation, intrusion, and vehicle pulse characteristics for the 2012 and 2015 models, as outlined in Chapter 4.1.1. Therefore, it was assumed, that the 2015 test results for the right oblique configuration are similar to the available data from a 2012 Toyota Camry. The available test data was therefore used to compare the right oblique baseline simulations.

4.2.1 Right Oblique - Occupant Compartment Intrusion

Figure 12 compares overall vehicle deformation and specific occupant compartment intrusion values in test and simulation. Figure 12(a) shows the overall vehicle deformation in the baseline simulation on the left and in the full-scale crash test on the right. Similar deformation of the frontal structure, door frame, and roof were observed. The A-pillar showed minor buckling in test and simulation.

Figure 12(b) depicts the door sill deformation. Pre-crash measurement points are shown in green. These points were chosen to be the same in test and simulation. Post-crash measurement points for the simulation are illustrated in blue. Respective post-crash points for the 2012 full-scale crash test are depicted in black with markers. The maximum deformation values were 38 mm for the test and 35 mm for the simulation. Door sill deformation was considered moderate in test and simulation. Intrusion along the rocker pillar and minor bending of the A-Pillar area were well captured in the simulation model.

Toe-pan intrusion was recorded for measurement points in 5 rows, consisting of 3 points each, in test and simulation. The maximum intrusion values for each row are visualized in the adapted chart, derived from the IIHS moderate overlap structural evaluation rating.

Figure 12(a) - Right Oblique Test Versus Simulation - Overall

[17] Walsh, V., & Martino, A. (2015, March 3). Moving Barrier to Vehicle Crash Test in Support of NHTSA's Frontal Oblique Offset Program Research Moving Deformable Barrier Into Right Front of a 2012 Toyota Camry 90.1kph, 15 Degree Angle, 35% Overlap (NHTSA Test Report No. RC5142; PDF No. v09121R001, also known as Test 9121). Washington, DC: National Highway Traffic Safety Administration. Available at www-nrd.nhtsa.dot.gov/database/VSR/SearchMedia.aspx?database=v&tstno=9121&mediatype=r&r_tstno=9121

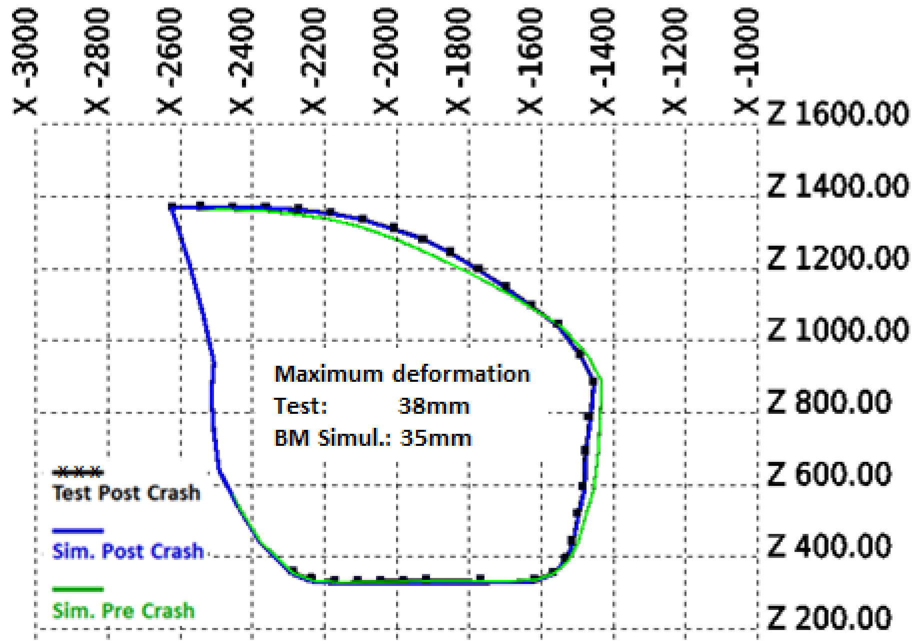


Figure 12(b) - Right Oblique Test Versus Simulation - Door Sill Deformation

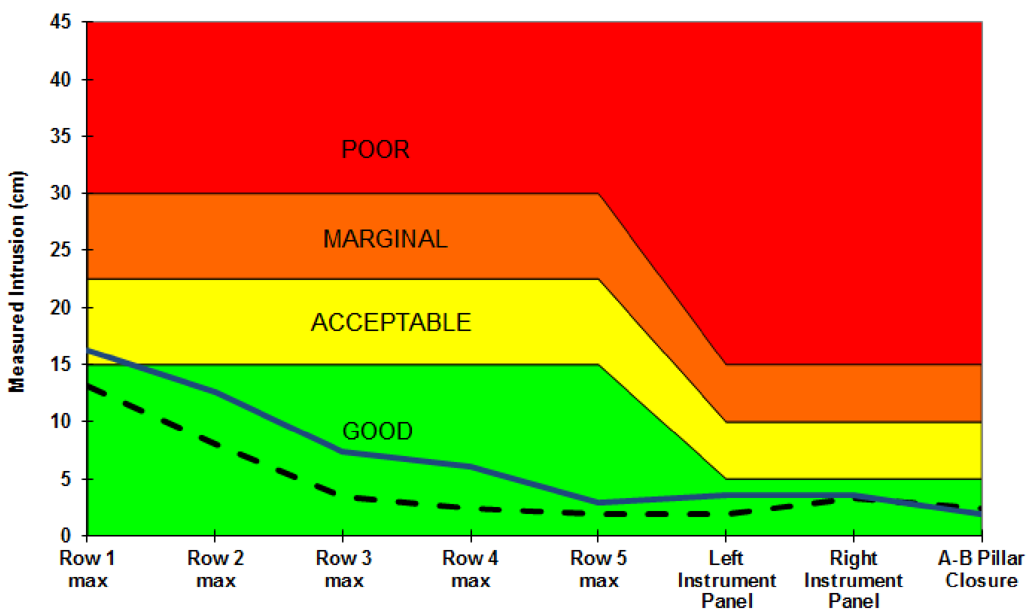


Figure 12(a) - Right Oblique Test Versus Simulation - Intrusion

Figure 12(c) shows the maximum intrusion for row 1 to row 4, brake-pedal, left and right instrument panel, and A- to B-pillar closure. The 2012 Toyota Camry test results are shown using black dashed line and 2015 Toyota Camry baseline simulation results are shown using blue solid line. The highest values occur in row 1, which is the most forward and upward location at the toe-pan. Values decrease for more rearward locations in both test and simulation. A maximum intrusion of 163 mm in row 1 is observed in the simulation and 131 mm in the test.

No full-scale crash test results exist for the right oblique configuration with a MY 2015 Toyota Camry. As described in Chapter 4.1.1, MY 2012 and MY 2015 test results were similar for the left oblique impact. Therefore, it was assumed, that test results are similar for the right oblique configuration as well and that the BM represents reasonably well the structural intrusion characteristics of a 2015 Toyota Camry in the right oblique impact configuration.

4.2.2 Right Oblique - Vehicle Pulse

Figure 13(a) compares vehicle acceleration pulse on the top and velocity pulse on the bottom in test and BM simulation for the right oblique impact configuration. As before, test results are depicted as a black solid line and simulation results are depicted as a blue dashed line. Good overall correlation for acceleration and velocity time history data can be observed. Values for maximum peak acceleration (a_{max}), maximum peak acceleration that lasts 5 milliseconds (a_{5ms}), maximum peak acceleration that lasts 15 milliseconds (a_{15ms}), and Δv compare well. Objective CORA rating values of 0.93 for the vehicle acceleration and 0.96 for the vehicle velocity document the good correlation between test and simulation.

Figure 13(b) shows the OMDB barrier acceleration pulse on the top and velocity time history for the right oblique impact configuration on the bottom. Here again, test data is depicted by a black solid line and simulation data by a blue dashed line. Good correlation between test and BM simulation can be observed. The CORA rating values were 0.95 for the acceleration data and 0.99 for the velocity data.

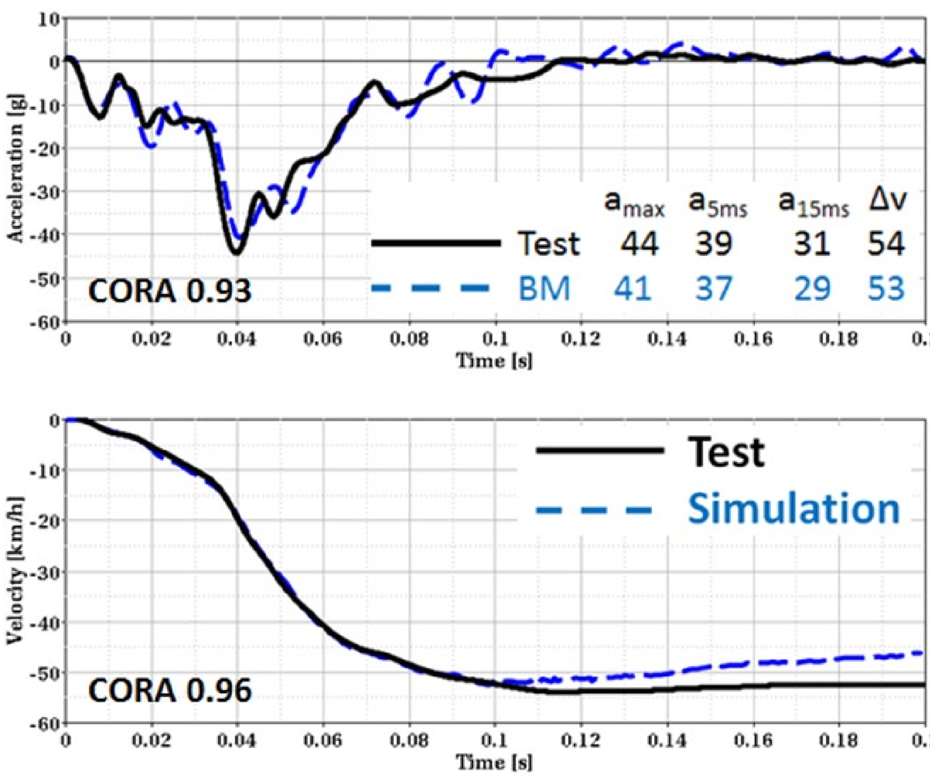


Figure 13(a) - Right Oblique Test Versus Simulation - Vehicle Pulse

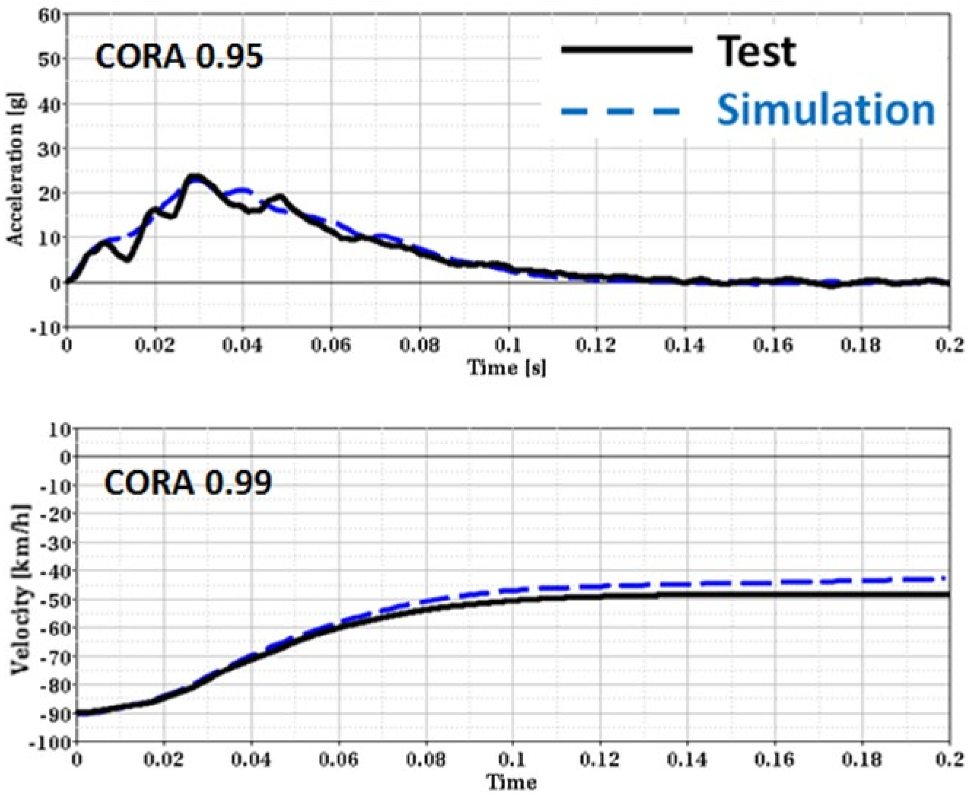


Figure 13(b) - Right Oblique Test Versus Simulation - Barrier Pulse

Assuming similar pulse characteristics for a 2015 and 2012 model for the right oblique configuration, as seen for the left oblique impact, the BM represents well the vehicle and barrier pulse characteristics of a 2015 Toyota Camry in the right oblique impact configuration.

4.3 IIHS Small Overlap – Baseline Simulation

IIHS Small Overlap test CEN1349[18] of a 2015 Toyota Camry traveling at 64 km/h into a fixed rigid barrier with a 25 percent overlap was used to evaluate the developed baseline simulation model.

4.3.1 IIHS SO - Occupant Compartment Intrusion

Figure 14 compares overall vehicle deformation and specific occupant compartment intrusion values in test and simulation. Figure 14(a) shows the overall vehicle deformation in the baseline simulation and in the full-scale crash test. Similar deformation of the frontal structure, door frame, and roof were observed. The A-pillar shows noticeable buckling in both test and simulation. The failure mechanism of the wheel to control-arm connection and overall wheel kinematics are well captured. In the later stages of the impact, after maximum intrusion and occupant injury values have occurred, additional material failure of various components in the rocker pillar, door

[18] Insurance Institute for Highway Safety, Highway Loss Data Institute. (undated). 2015 Toyota Camry (Web page report appears to reference CEN1349 and Small Overlap Frontal Test). Arlington, VA: Author Available at www.iihs.org/iihs/ratings/vehicle/v/toyota/camry-4-door-sedan/2015

hinge, door, and sill area were observed in the test which are not completely captured in the simulation. Consequently, some differences in the rebound phase were observed.

Figure 14(b) depicts the door sill deformation in test and simulation. Pre-crash measurement points are shown in green. These points were chosen to be the same in the BM and the physical vehicle. Post-crash measurement points for the BM are illustrated in blue. Respective post-crash points for the 2015 Toyota Camry full-scale crash test are depicted in black. A similar deformation pattern was observed with significant bending of the A-pillar and deformation of the rocker pillar. The absolute deformation is larger in the test than in the simulation. The qualitative characteristics of the door sill deformation are reasonably well captured in the simulation.

Figure 14(a) - IIHS SO - Overall Test and Simulation

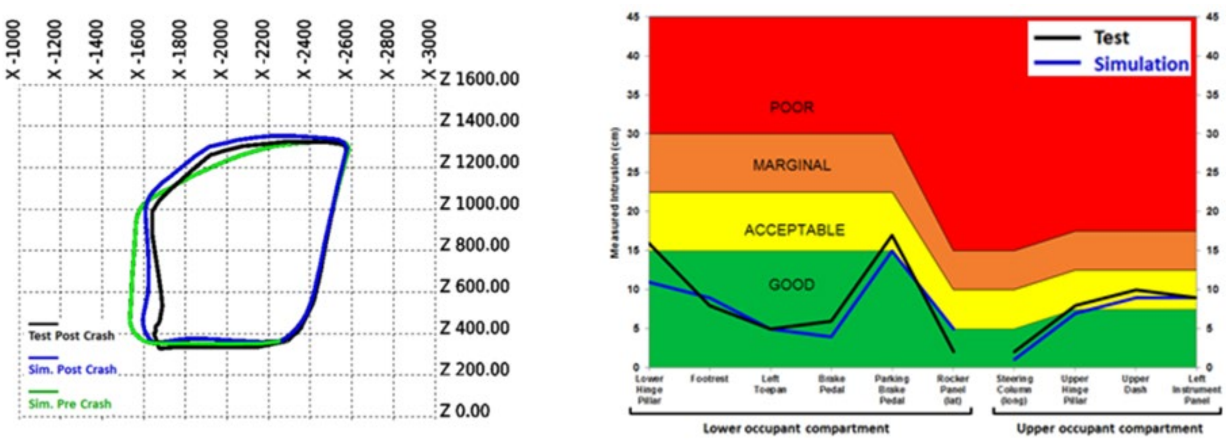


Figure 14 - IIHS SO - (b) Door Sill (c) Intrusion

Intrusion for the lower and upper occupant compartment according to the IIHS SO rating protocol is shown in Figure 14(c). The 2015 Toyota Camry test results are shown using black solid line and 2015 Toyota Camry BM simulation results are shown using a blue line. Test and simulation results correlate well, resulting in an Acceptable structural rating for both test and BM simulation.

It can be stated that the BM captures the overall and door sill deformation seen in the 2015 Toyota Camry full-scale crash test reasonably well. Occupant compartment intrusion characteristics are well captured in the simulation.

4.3.2 IIHS SO - Vehicle Pulse

Figure 15(a) shows the body-in-white (BIW) of the 2015 Toyota Camry baseline simulation with significant deformation of the longitudinal rails, shown in red. Bumper reinforcement extension and "spacer," which interacted with the IIHS SO barrier, are depicted in blue.

Figure 15(b) compares vehicle acceleration pulse on the top and velocity pulse on the bottom in test and BM simulation for the IIHS small overlap configuration. Test results are depicted using a black solid line and simulation results are depicted using a blue dashed line. Acceptable overall correlation for acceleration and velocity time history plots were observed. Values for maximum peak acceleration (a_{max}), maximum peak acceleration that lasted 5 milliseconds (a_{5ms}), and maximum peak acceleration that lasted 15 milliseconds (a_{15ms}), correlate well between test and simulation. The Δv shows differences in the rebound phase caused by material failure of various components in the rocker pillar, door hinge, door, and sill area in the test that are not completely captured in the simulation. The Δv compares well for the early time period, which is mainly relevant for occupant compartment intrusion and occupant injury risk. CORA rating values of 0.69 for acceleration and 0.75 for velocity time history data document the acceptable correlation between test and simulation.

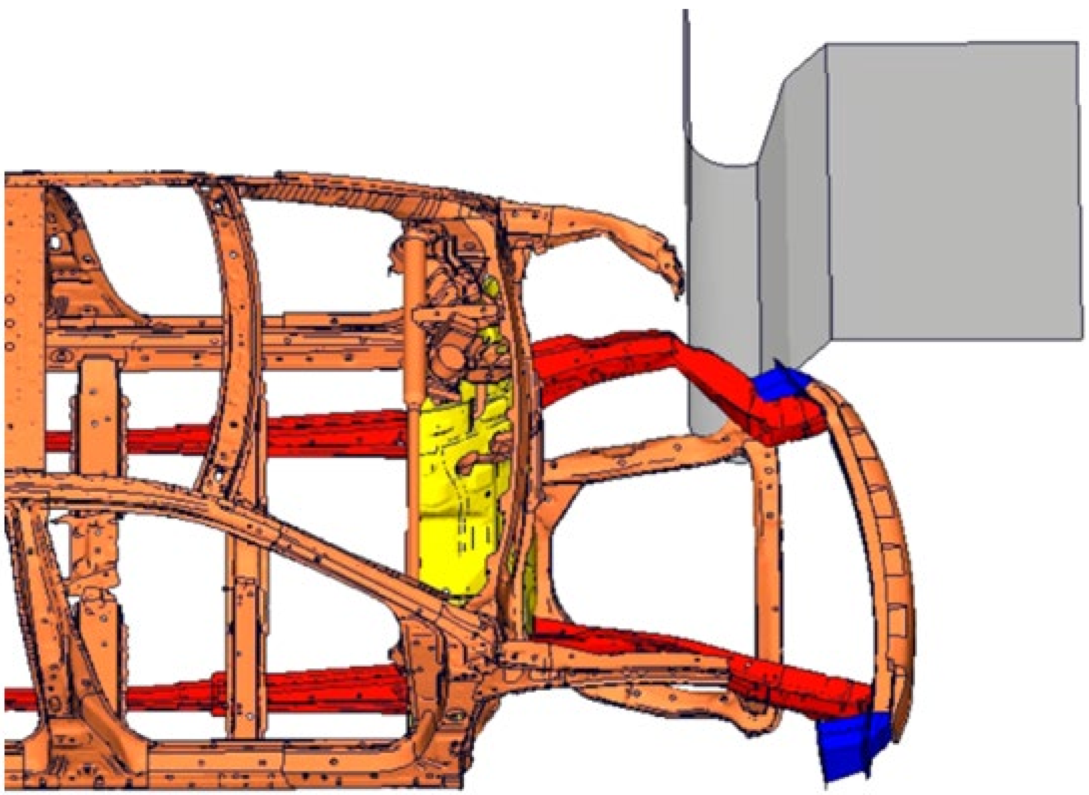


Figure 15(a) - IIHS SO Test Versus Simulation - FE Model BIW

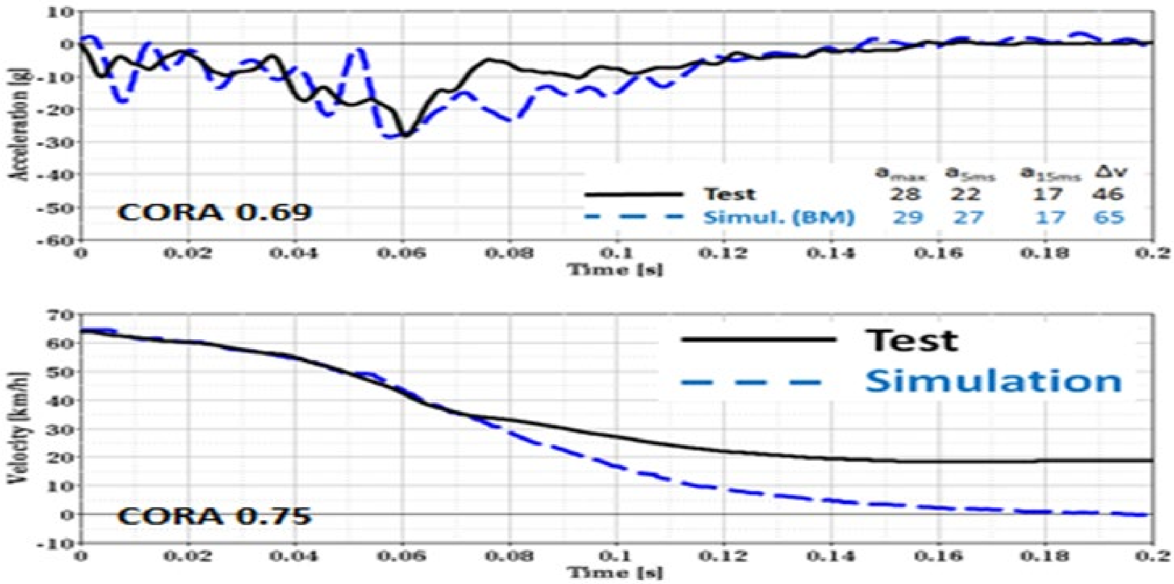


Figure 15(b) - IIHS SO Test Versus Simulation – Vehicle Pulse

The BM provides a reasonably acceptable representation of the vehicle kinematics of a 2015 Toyota Camry in the IIHS small overlap impact configuration. Specifically, it satisfactorily captures the early stage of the impact until the time when maximum occupant loads and maximum occupant compartment intrusions have occurred.

4.4 IIHS Moderate Overlap – Baseline Simulation

IIHS test #1109[19] of a 2012 Toyota Camry was used to evaluate the developed BM simulation. The moderate overlap frontal test, where the vehicle travels at 64 km/h into a barrier with a deformable aluminum honeycomb face with a moderate overlap of 40 percent, was conducted by Toyota as part of the frontal crash test verification. Some occupant injury criteria and vehicle intrusion measurements were available from the conducted test, but no video or technical time history data was accessible. According to the IIHS website, this result represents both MY 2012 and MY 2015. Therefore, it is assumed that 2015 and 2012 Toyota Camry models show similar results.

4.4.1 IIHS MO - Occupant Compartment Intrusion

Figure 16(a) shows the overall vehicle deformation from the BM simulation. Roof, A-pillar and door sill remain practically undeformed. No data from the full-scale crash test was available.

Figure 16(b) compares specific available occupant compartment intrusion values for the test, illustrated by a black dashed line, and for the simulation, depicted as a blue solid line. Intrusion values for the lower occupant compartment are higher for the simulation and are well matched for the upper occupant compartment measurement points. An overall Good structural rating according to the IIHS moderate overlap structural rating protocol was observed for the test and simulation.

[19] Ibid.

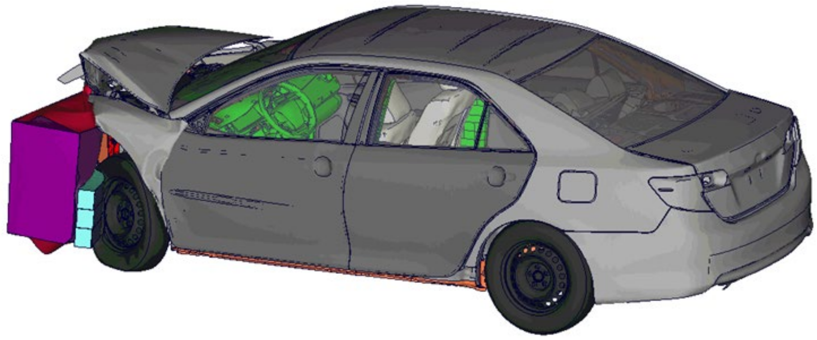


Figure 16(a) – MO Overall Simulation

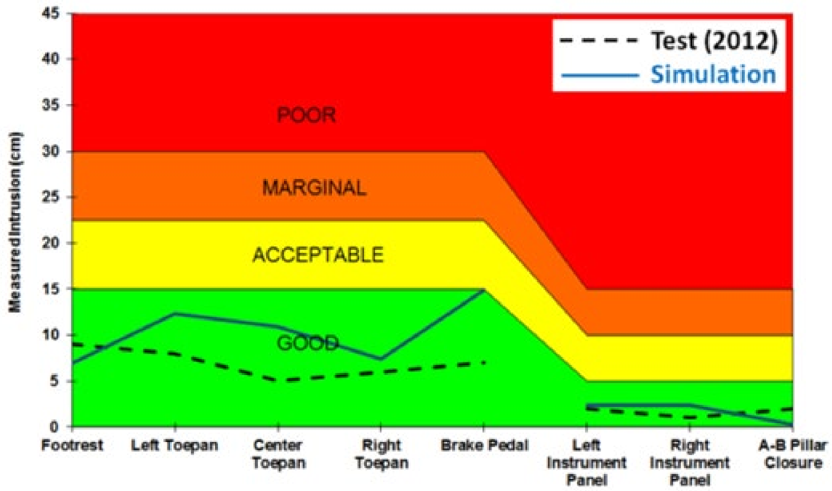


Figure 16(b) – MO Intrusion

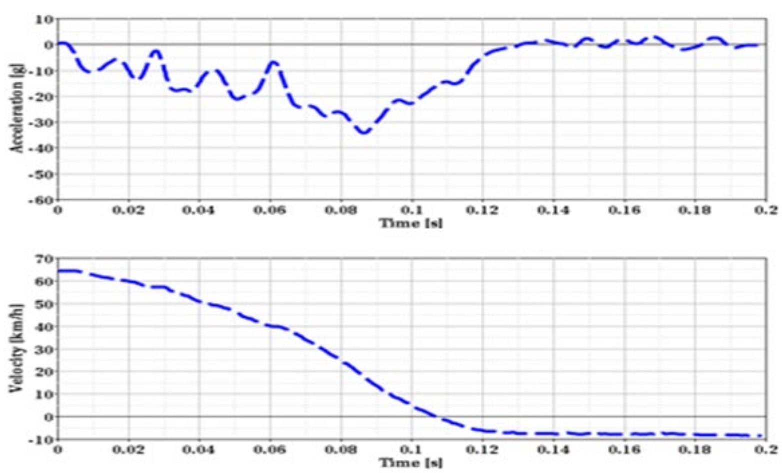


Figure 16(c) – MO Vehicle Pulse

It can be assumed that the BM represents reasonably well the structural intrusion characteristics of a 2015 Toyota Camry in the IIHS MO impact configuration.

4.4.2 IIHS MO - Vehicle Pulse

Figure 16(c) shows the 2015 Toyota Camry BM simulation vehicle acceleration pulse at the top and velocity pulse at the bottom in the IIHS MO configuration. No respective test data was available.

4.5 NCAP Full Overlap – Baseline Simulation

NHTSA test #8545[20] of a 2015 Toyota Camry was used to evaluate the BM simulation in the 56 km/h NCAP full overlap impact into a rigid barrier.

4.5.1 NCAP - Occupant Compartment Intrusion

Figure 17 compares overall vehicle deformation and specific occupant compartment intrusion values in test and simulation. Figure 17(a) shows the overall vehicle deformation in the BM simulation on the right and in the full-scale crash test on the left. Similar deformation of the frontal structure, door frame, and roof were observed. No significant deformation of the roof, A-pillar, or door sill occurs in either test or simulation.

The same measurement points used for the IIHS moderate overlap configuration were evaluated for the BM simulation and are illustrated using the respective structural intrusion rating chart.

Figure 17(b) shows the maximum intrusion for the lower and upper occupant compartment in the BM simulation using a blue solid line. Available test results are depicted by a black solid line. Respective points that were not recorded in the test were interpolated from existing test measurements and are illustrated using a black dashed line. Intrusion values are small when compared to previously analyzed impact configurations in test and simulation.

Figure 17(a) - NCAP Test Versus Simulation - Overall

[20] Walsh, V., & Dutton, E. (2014, March 31). New Car Assessment Program Frontal Barrier Impact Test, 2014.5 Toyota Camry Four Door Sedan (NHTSA Test No: M20145109, PDF no. v08545R001, also called NCAP-CAL-14-009). Washington, DC: National Highway Traffic Safety Administration. Available at www-nrd.nhtsa.dot.gov/-database/VSR/SearchMedia.aspx?database=v&tstno=8545&mediatype=r&r_tstno=8545

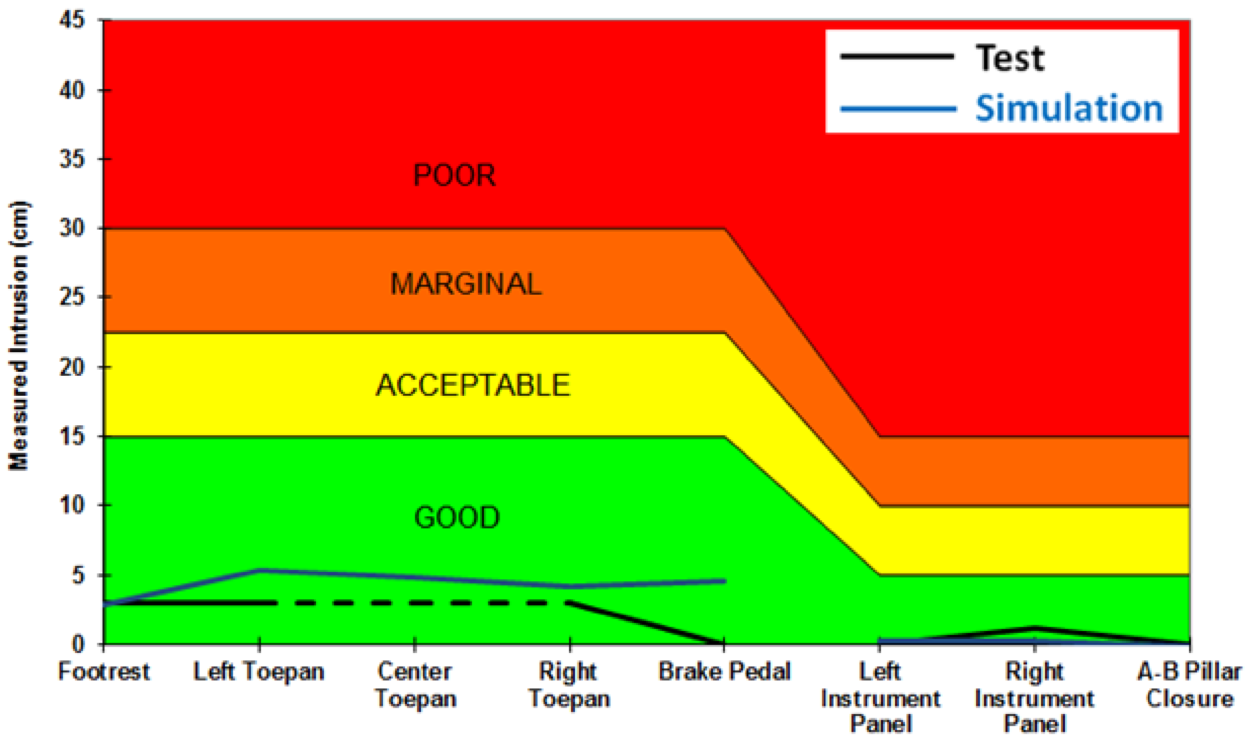


Figure 17(b) - NCAP Test Versus Simulation - Intrusion Chart

The BM is well representative of the structural intrusion characteristics of a 2015 Toyota Camry in the NCAP full overlap configuration.

4.5.2 NCAP - Vehicle Pulse

Figure 18(a) compares vehicle acceleration pulse in test and BM simulation in the NCAP full overlap configuration. Figure 18(b) compares the respective vehicle velocity time history data. Test results are depicted using black solid line and simulation results are depicted using a blue dashed line. Good overall correlation was observed. Values for relevant maximum peak acceleration (a_{max}), maximum peak acceleration that lasted 5 milliseconds (a_{5ms}), maximum peak acceleration that lasted 15 milliseconds (a_{15ms}), and Δv compared well between test and simulation. CORA rating values of 0.86 for the acceleration and 0.98 for the velocity document the good correlation between test and simulation.

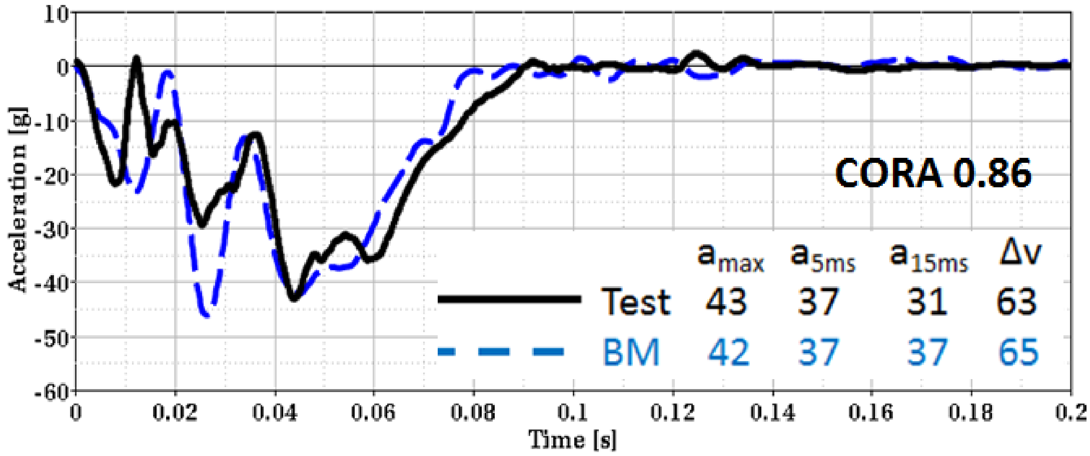


Figure 18(a) - 2015 NCAP Test Versus Simulation - Acceleration Pulse

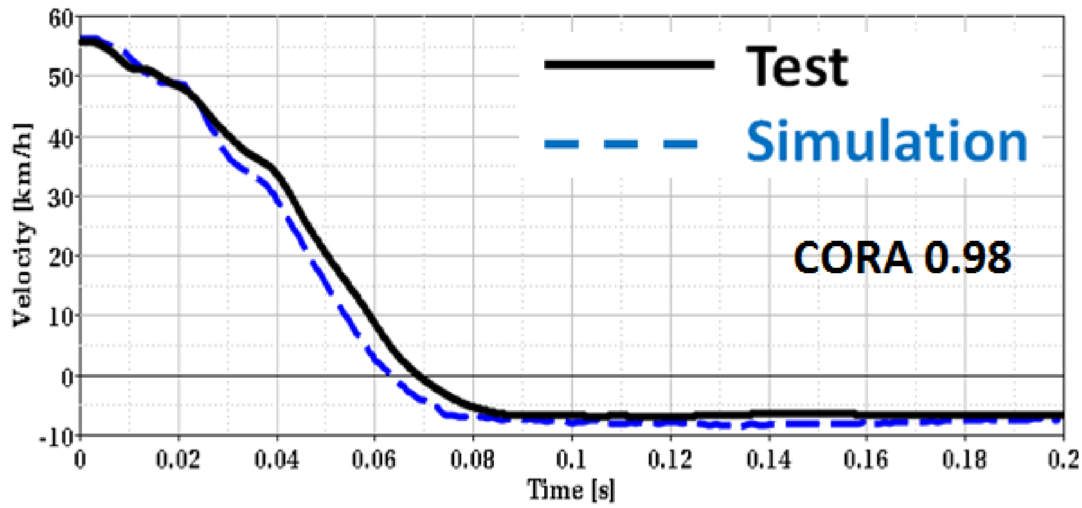


Figure 18(b) - 2015 NCAP Test Versus Simulation - Velocity Pulse

The BM well represents the vehicle characteristics of a 2015 Toyota Camry in the NCAP full overlap configuration.

4.6 Summary – Baseline Simulations

A 2015 Toyota Camry was chosen to serve as a BM to conduct the structural countermeasure research program to significantly reduce occupant compartment intrusion for NHTSA's left and right oblique impact configurations. It was selected because of how well it represents the mid-size sedan vehicle class and because it achieved high safety ratings in existing test configurations. Specifically, it received an Acceptable rating in the IIHS SO, a Good rating in the IIHS MO, and a 5-Star rating in the NCAP full frontal overlap impact.

A FE model of a 2012 Toyota Camry was developed using a reverse engineering process in a previous project. The available FE model was updated with known structural changes that were implemented for the 2015 Toyota Camry. The structural changes were specifically introduced to improve the performance in the IIHS SO configuration, for which the previous model year received a Poor rating.

The resulting updated FE BM was then evaluated using available full-scale test results of a 2015 Toyota Camry with respect to structural intrusion and vehicle crash pulse characteristics. Occupant risk analysis was not included in this research. Table 3 summarizes the results for the analyzed crash configurations.

The 2015 Toyota Camry received an Acceptable rating according to the IIHS small overlap protocol for its structural crash performance. Using the same evaluation criteria, the BM simulation captures the occupant compartment characteristics well, resulting in the same Acceptable rating with respect to intrusion measurements. Comparison of acceleration and velocity time history data in the test and simulation show an acceptable correlation, with CORA rating values of 0.68 for the acceleration pulse and 0.75 for the velocity pulse. The BM, therefore, satisfactorily represents the structural crash characteristics of a 2015 Toyota Camry in the IIHS SO.

Table 3 – Summary of Baseline Simulations

	Test (Intrusion)	Simulation (Intrusion)	Acceleration Pulse (CORA rating)	Velocity Pulse (CORA rating)
IIHS Small Overlap	Acceptable	Acceptable	0.69 (acceptable)	0.75 (acceptable)
IIHS Moderate Overlap	Good	Good	No test data	No test data
NCAP Full Overlap	4/5-Star	4/5-Star	0.86 (good)	0.98 (good)
Left Oblique (Driver Side)	Good correlation		0.94 (good)	0.96 (good)
Right Oblique (Pass. Side)	Good correlation		0.93 (good)	0.96 (good)

The 2015 Toyota Camry received a Good rating according the IIHS MO test protocol. Only limited test data was available for this test, since it was conducted by Toyota as part of the frontal crash test verification. Using the same evaluation criteria, the BM simulation captures the occupant compartment characteristics reasonably well, resulting in a Good rating with respect to intrusion measurements. The BM simulation therefore represents reasonably well the structural crash characteristics of a 2015 Toyota Camry in the IIHS MO impact.

The NCAP rating is based on occupant injury criteria. The MY 2012 vehicle received 5 stars for the driver and 4 stars for the passenger. The MY 2015 vehicle received 4 stars for the driver and 5 stars for the passenger. Occupant risk depends on vehicle structure and restraint system performance. Occupant compartment intrusion was small and the vehicle pulse was judged good for both vehicles. According, to the defined project task, the vehicle to be studied "should meet the structural intrusion requirements for a 5-Star rating in NCAP frontal." It can be stated that the MY 2012, as well as MY 2015 Toyota Camry vehicles represent vehicles with structural intrusion characteristics that allow them to receive 5-Star NCAP ratings. Using a rating chart adapted from the IIHS MO overlap configuration, good correlation between test and simulation was observed with respect to occupant compartment intrusion. Comparison of acceleration and velocity time history data in test and simulation show good correlation, with CORA rating values of 0.86 for the acceleration pulse and 0.98 for the velocity pulse. The BM, therefore well represents the structural crash characteristics of a 2015 Toyota Camry in the NCAP full overlap impact.

In addition to existing safety rating impact configurations, test results for NHTSA's left and right oblique load cases were used to evaluate the BM simulation. Using a rating chart adapted from the IIHS MO configuration, good correlation between test and simulation was observed with respect to occupant compartment intrusion for the left and right oblique impact situations. Comparison of acceleration and velocity time history data in test and simulation show good correlation, with CORA rating values of 0.94 for the acceleration pulse and 0.96 for the velocity pulse in the left oblique impact. Similarly, good correlation of test and simulation, with CORA rating values of 0.93 for the acceleration pulse and 0.96 for the velocity pulse, in the right oblique impact could be observed. The BM, therefore, well represents the structural crash characteristics of a 2015 Toyota Camry in NHTSA's left and right oblique impact conditions.

The updated FE model well represents the structural performance of a 2015 Toyota Camry in existing crash configurations, as well as in NHTSA's left and right oblique impact tests. It represents a good BM that can be used as reference to develop structural countermeasures to significantly reduce occupant compartment intrusion for left and right oblique crash configurations. The developed model with respective structural countermeasures will be called the "Countermeasure Model." In addition to comparing BM and CM in left and right oblique impact conditions, it will also be used to analyze how introduced countermeasures affect vehicle crash characteristics in existing co-linear impact configurations, i.e. IIHS SO, MO, and NCAP full overlap.

5. Design Goals

Conducted BM simulations show good correlation with structural crash characteristics of a 2015 Toyota Camry in co-linear and oblique crash configurations. The results were used to determine design goals to significantly reduce occupant compartment intrusion in NHTSA's left and right oblique impact condition. Developed performance targets include significant reduction of maximum absolute occupant compartment intrusion, significant reduction of relative intrusion values of adjacent points on the toe-pan, maintaining or reducing moderate door sill deformation, and maintaining moderate vehicle crash pulses.

5.1 Maximum Intrusion

Significant occupant compartment intrusion was observed in the toe-pan area for the left and right oblique crash conditions. Therefore, the first design goal was to reduce maximum occupant compartment intrusion by at least 50 percent. This was used as the main design goal for the structural countermeasure development.

Figure 19(a) illustrates locations and respective maximum intrusions in the toe-pan area for the left oblique impact BM simulation. It was found that the maximum intrusion of 99 mm occurred in row 1 at point C1. According to the first design goal defined, the aim is to develop structural countermeasures that limit the maximum intrusion to 50 mm.

Figure 19(b) shows locations and respective maximum intrusions in the toe-pan area for the right oblique impact BM simulation. The maximum intrusion of 163 mm occurred in row 1 at point B1. According to the first design goal defined, the aim is to develop structural countermeasures to limit the maximum intrusion to 82 mm.

Since the absolute intrusion values are larger for the right oblique condition, there is an additional objective to develop another set of countermeasures that would reduce the maximum toe-pan intrusion to 50 mm on the right side, which is the defined absolute performance target for the left oblique configuration.

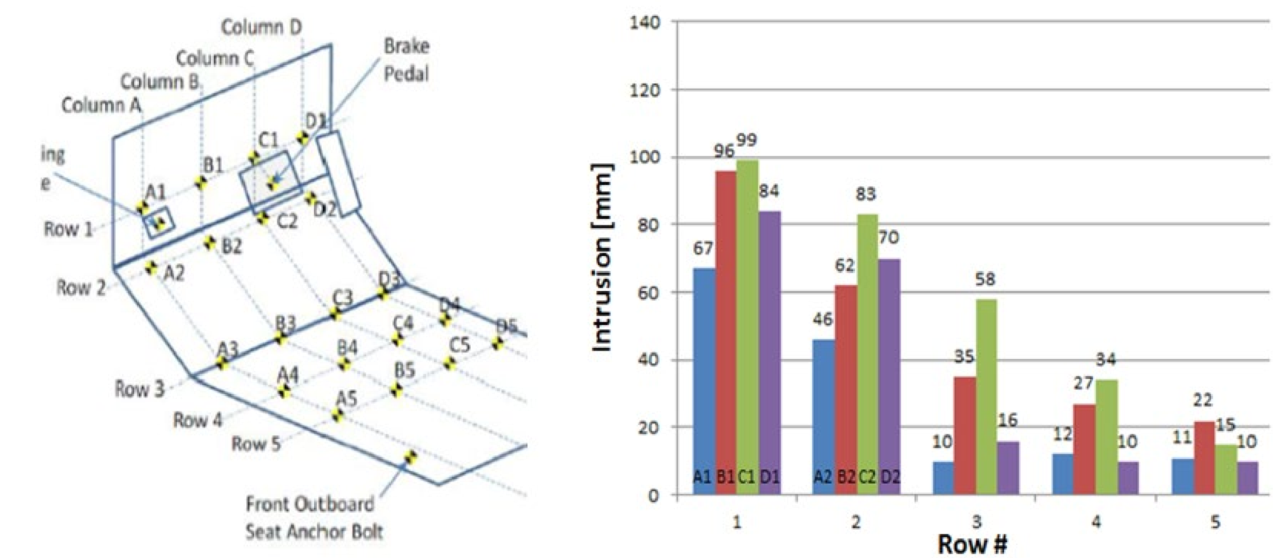


Figure 19(a) - BM Toe-Pan Intrusion Measurements for Left Oblique Impact

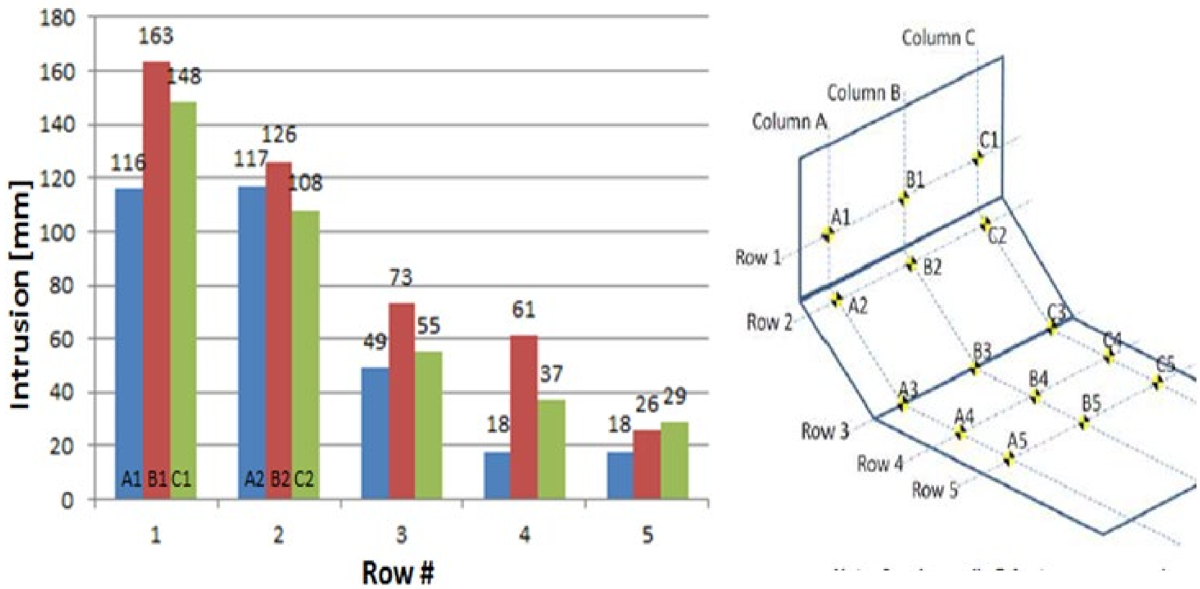


Figure 19(b) - BM Toe-Pan Intrusion Measurements for Right Oblique Impact

5.2 Relative Intrusion

While occupant risk analysis was not part of this research, it is known that local buckling of the toe-pan can contribute to lower extremity injuries. Therefore, relative intrusion of adjacent points was evaluated to investigate the deformed shape of the toe-pan. A maximum relative intrusion of 54 mm between point D2 and C2 for the left oblique configuration and a maximum relative intrusion of 68 mm between point A2 and A3 for the right oblique impact were observed in the baseline simulations, as shown in Figure 19.

Figure 20 illustrates the biomechanical range of foot motion. Taking initial foot position and initial distances between measurement points into account, a maximum value of 34 mm was determined to be critical for both foot dorsiflexion as well as foot eversion.

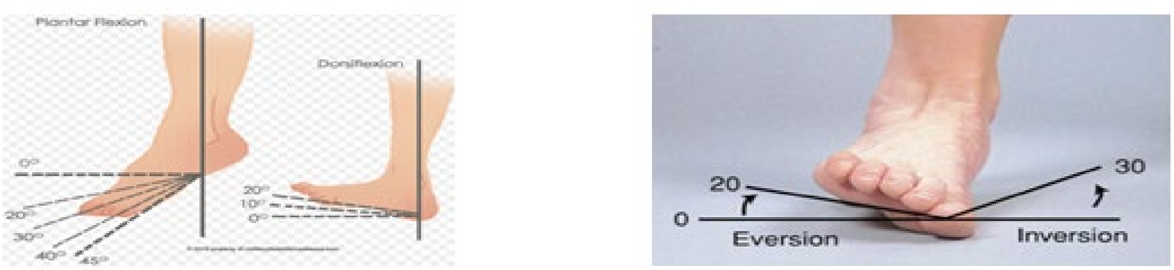


Figure 20 - Range of Foot Motion for (a) Dorsiflexion, (b) Eversion

The second design goal defined is to reduce relative intrusion of adjacent points of the toe-pan by at least 50 percent.

5.3 Door Sill Deformation

Moderate door sill deformation was observed in the baseline simulations for the oblique impact condition. Figure 21(a) shows the measurement points for the driver side and Figure 21(b) depicts the measurement points for the passenger side. Maximum deformations of 25 mm in the left oblique and 35 mm in the right oblique impact baseline simulation were recorded.

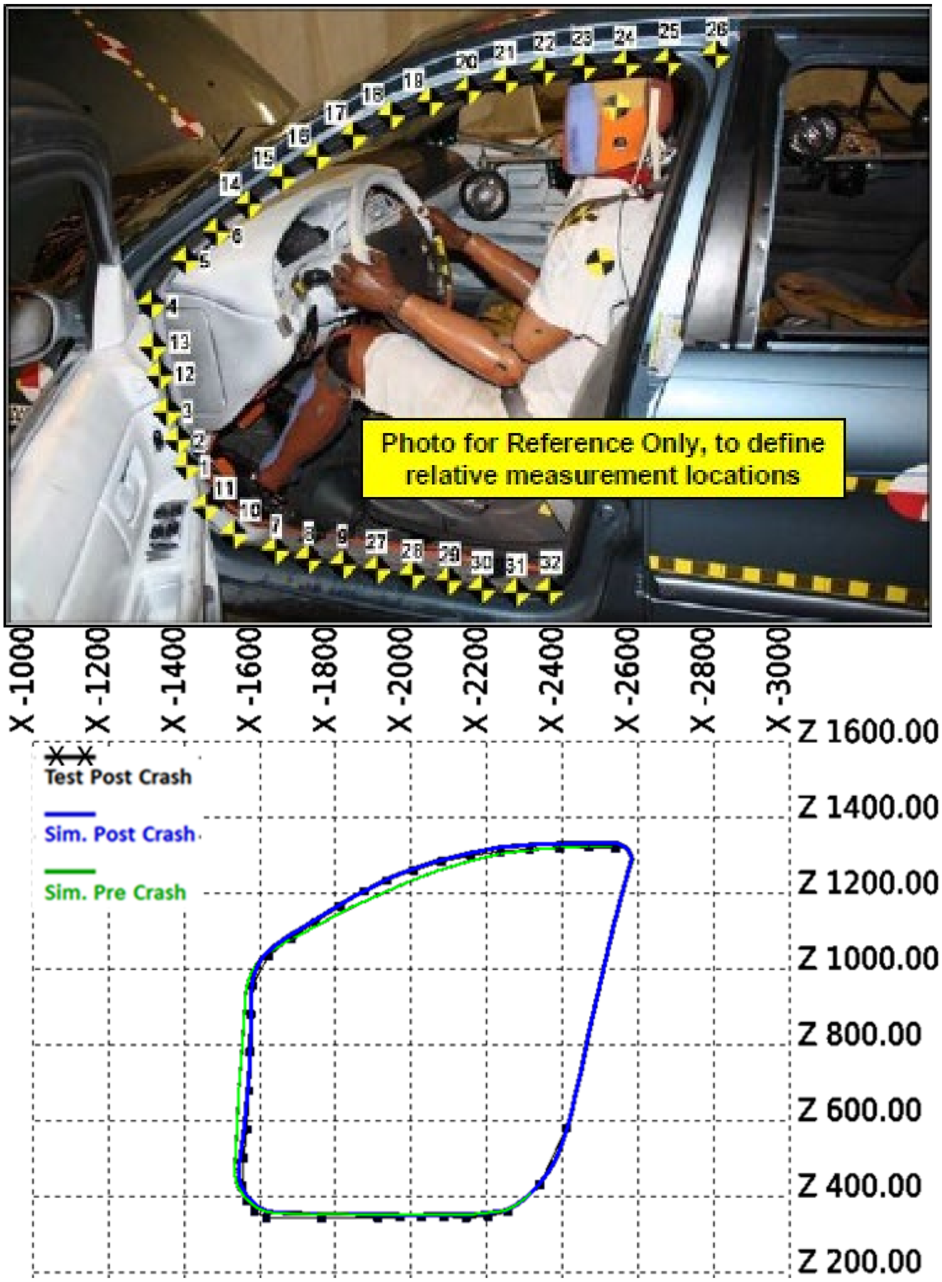


Figure 21(a) - Door Sill Deformation for Driver Side

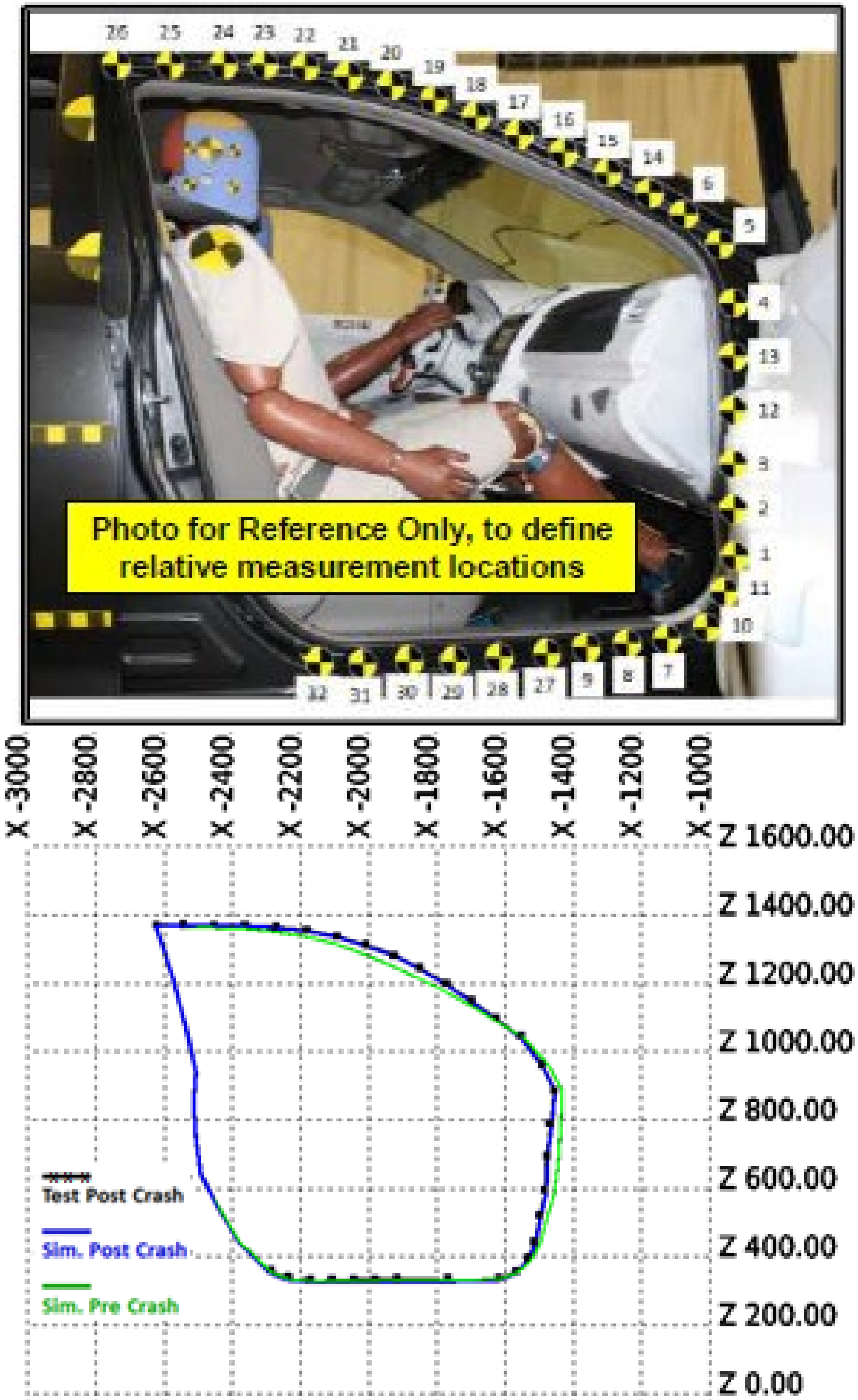


Figure 21(b) - Door Sill Deformation for Passenger Side

The third design goal used to significantly reduce occupant compartment intrusion is to maintain or further reduce moderate door sill deformation.

5.4 Vehicle Pulse

Structural countermeasures can influence the vehicle acceleration pulse and consequently occupant injury risk and restraint system performance. A significant increase in vehicle pulse would be considered an unintended consequence and will be monitored. The 2015 Toyota Camry received good ratings in existing consumer information tests. Respective vehicle pulses in full-scale crash tests and baseline simulations can therefore be considered moderate. When implementing structural countermeasures, an increase of no more than 5g for characteristic peak acceleration values (a_{5ms} and a_{15ms}) will be considered Good conservation of the moderate vehicle pulse for the respective crash configurations.

6. Crash Mechanism Analysis

To develop structural countermeasures to significantly reduce occupant compartment intrusion in NHTSA's oblique impact condition, the conducted baseline simulations were analyzed with respect to crash mechanisms that specifically contribute to the observed toe-pan intrusion in left and right oblique impacts.

6.1 Firewall

Local buckling of the firewall was found to be a major factor contributing to the observed occupant compartment intrusion. Figure 22(a) shows the driver-side firewall pre- and post-crash in the left oblique impact. Figure 22(b) depicts a pre-test and post-test picture of the passenger side firewall from the right oblique impact. Areas with significant collapsing are marked with black arrows.

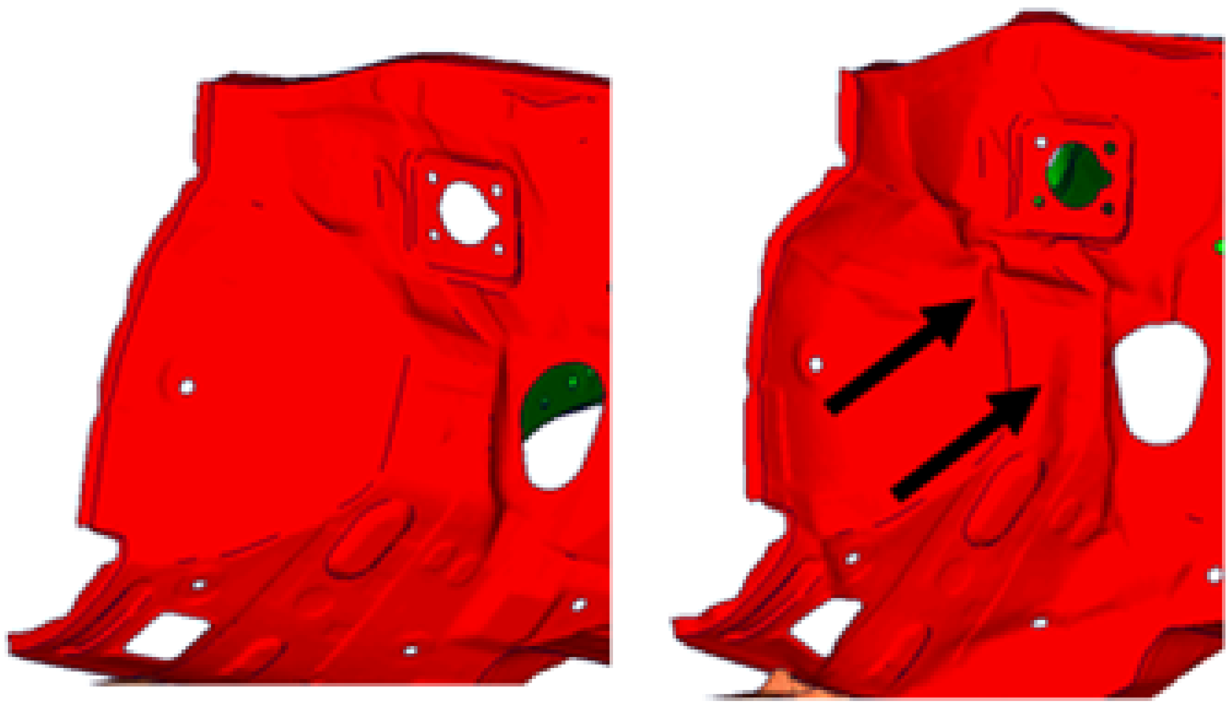


Figure 22(a) - Firewall in Driver-Side Oblique Impact

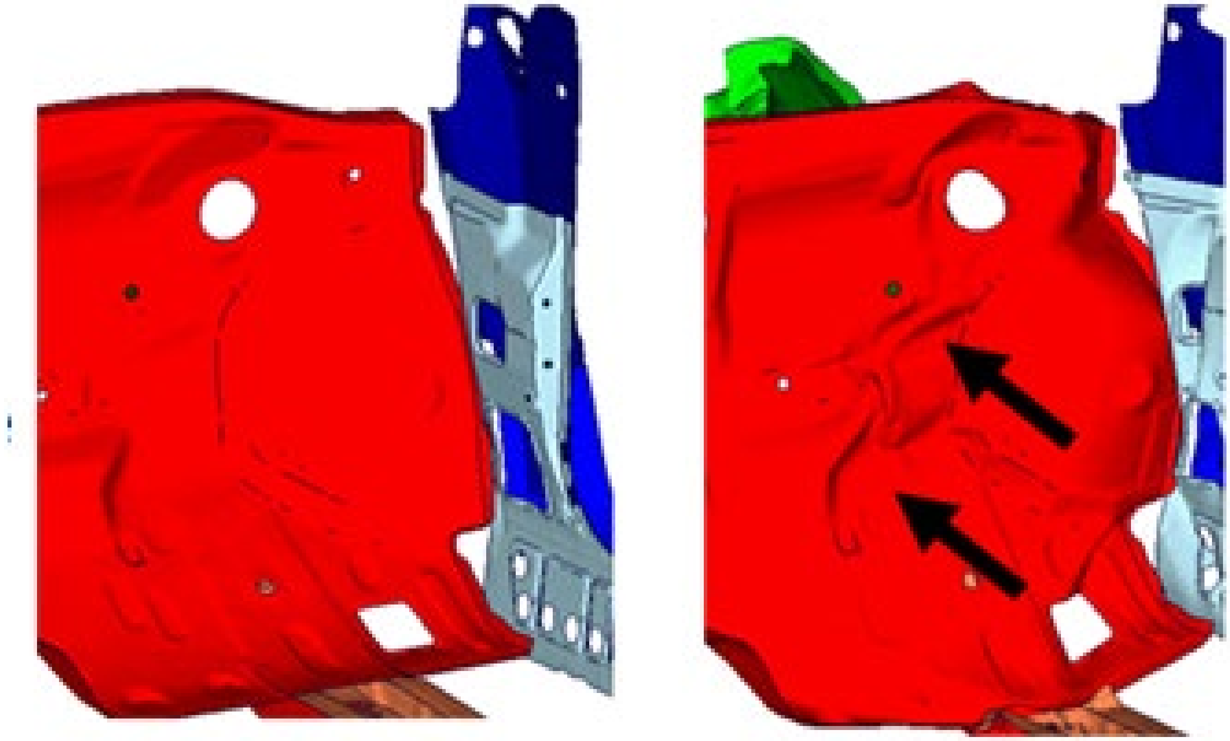


Figure 22(b) – Firewall in Passenger Side Oblique Impact

Local buckling of the firewall contributes to maximum occupant compartment intrusion in the left and right oblique impact configurations. It also contributes to relative intrusion of adjacent points.

6.2 Front Rails

Highest intrusion values were observed for toe-pan measurement points in row 1, which represent the most forward and upward measurement locations, as shown in Figure 19. It was found that the load transferred through the longitudinal rail contributed to the maximum intrusion values. Figure 23(a) shows relevant components pre-crash and Figure 23(b) depicts the same components post-crash for the baseline simulation in the left oblique impact configuration. The firewall is depicted in pink and the two rearmost components of the frontal rail are shown in green. The load transferred into the occupant compartment due to the impact is represented by a yellow arrow. It can be noted that the load introduced through the frontal rails is being leveraged through the difference in height between the frontal rail and the bottom of the mid-rails, shown in red.

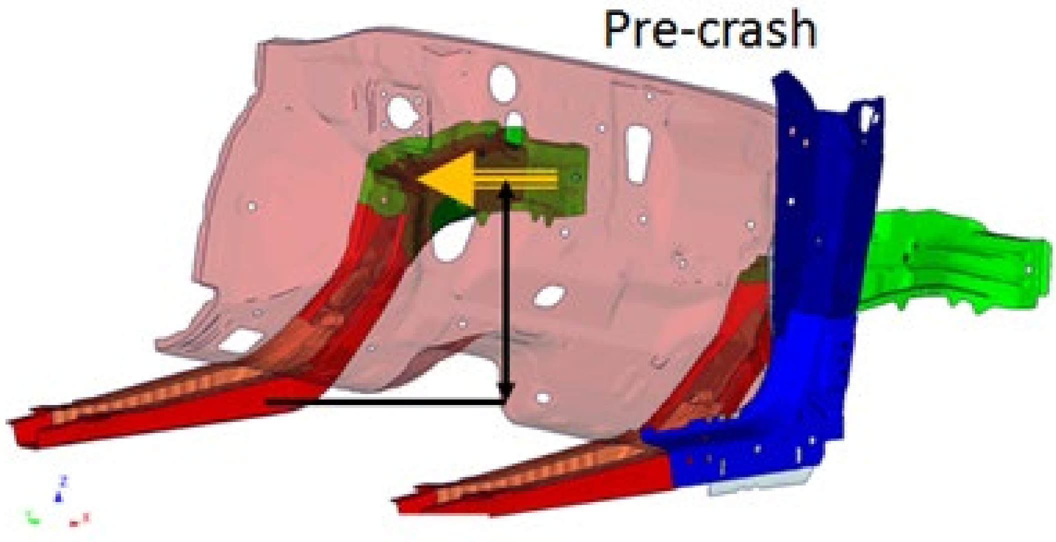


Figure 23(a) - Firewall in Left Oblique Impact Pre-Crash

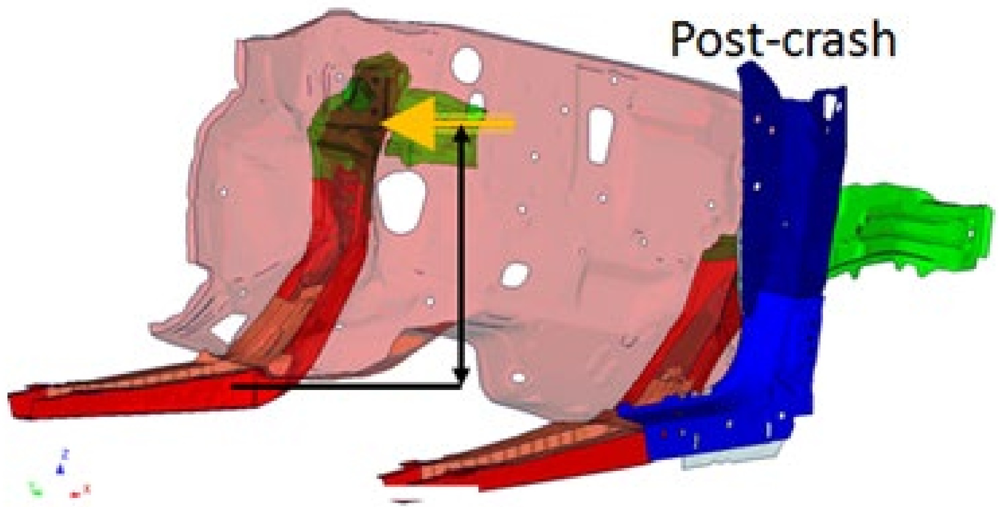


Figure 23(b) - Firewall in Left Oblique Impact Post-Crash

The load introduced through the frontal rail contributes to the maximum intrusion values and local buckling of the toe-pan.

6.3 Mid-Rails

Local buckling of the mid-rails also contributed to the observed occupant compartment intrusion. Figure 24(a) shows the relevant components pre-crash and Figure 24(b) depicts the same components post-crash for the baseline simulation of the right oblique impact configuration. The firewall is depicted in pink and the mid-rails are shown in red. It was found that there is a significant amount of deformation occurring in the right mid-rail in the areas marked with a black arrow.

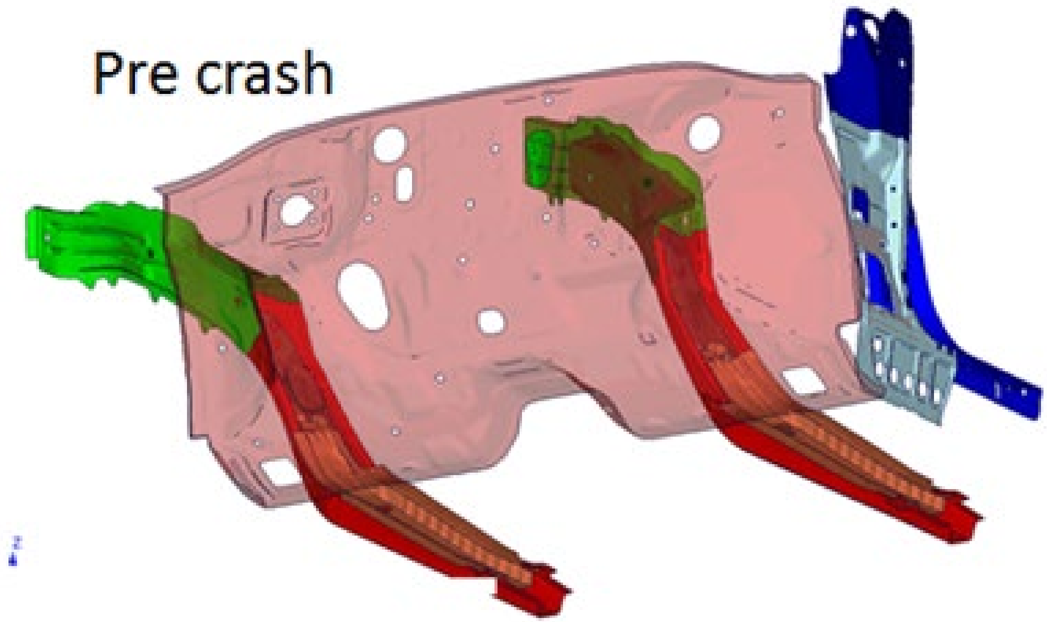


Figure 24(a) - Firewall and Mid-Rail in Right Oblique Impact Pre-Crash

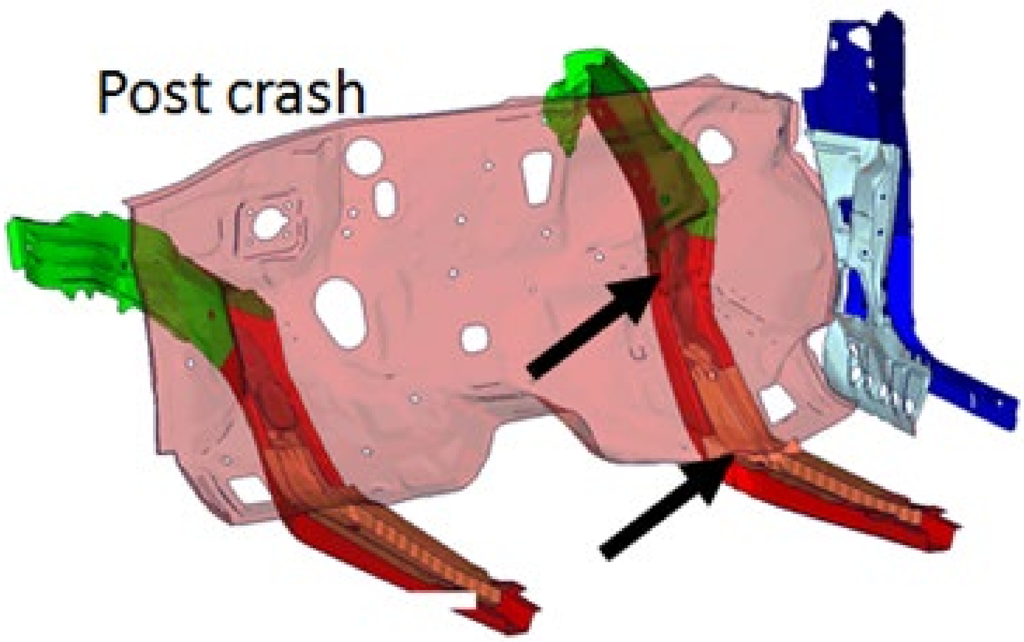


Figure 24(b) - Firewall and Mid-Rail in Right Oblique Impact Post-Crash

Local buckling of the mid-rails contributed to the maximum occupant compartment intrusion.

6.4 Rocker Pillar

The parking brake on the driver side, shown in dark blue, in Figure 25(a) is connected to the rocker pillar and the toe-pan area. It acts as a reinforcement of the rocker pillar area on the driver side. Since there is no equivalent component on the passenger side, a significant amount of deformation of the right rocker pillar components was observed in the right oblique impact configuration. Figure 25(b) shows the relevant passenger side components pre- and post-crash. The black arrow marks the deformation of the rocker pillar components, shown in light and dark blue.

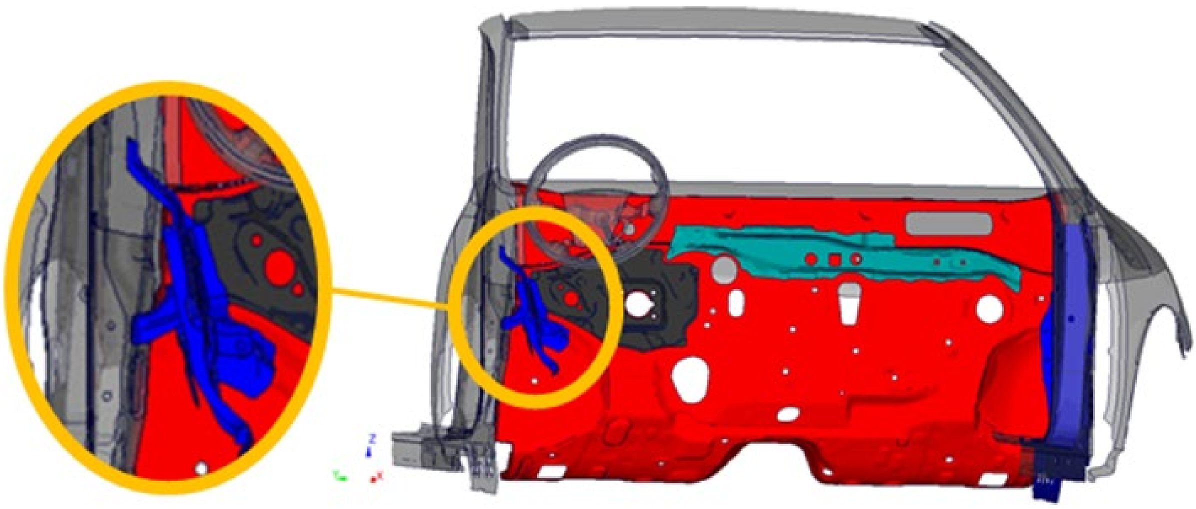


Figure 25(a) - Parking Brake Pre- and Post-Crash

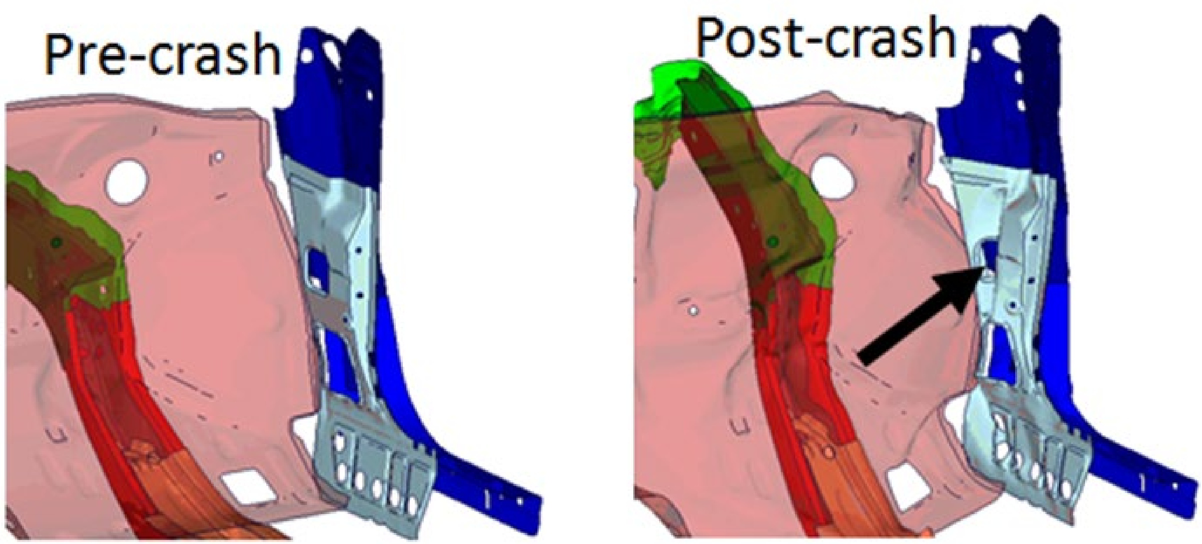


Figure 25(b) - Right Rocker Pillar Pre- and Post-Crash

Deformation of the rocker pillar components on the passenger side contributes to the maximum occupant compartment intrusion in the right oblique impact. It also contributes to relative intrusion of adjacent points.

6.5 Firewall Support

Figure 26(a) shows the enlarged firewall support on the driver side and Figure 26(b) depicts the complete firewall with attached reinforcements. It can be noted that no equivalent firewall support exists on the passenger side.

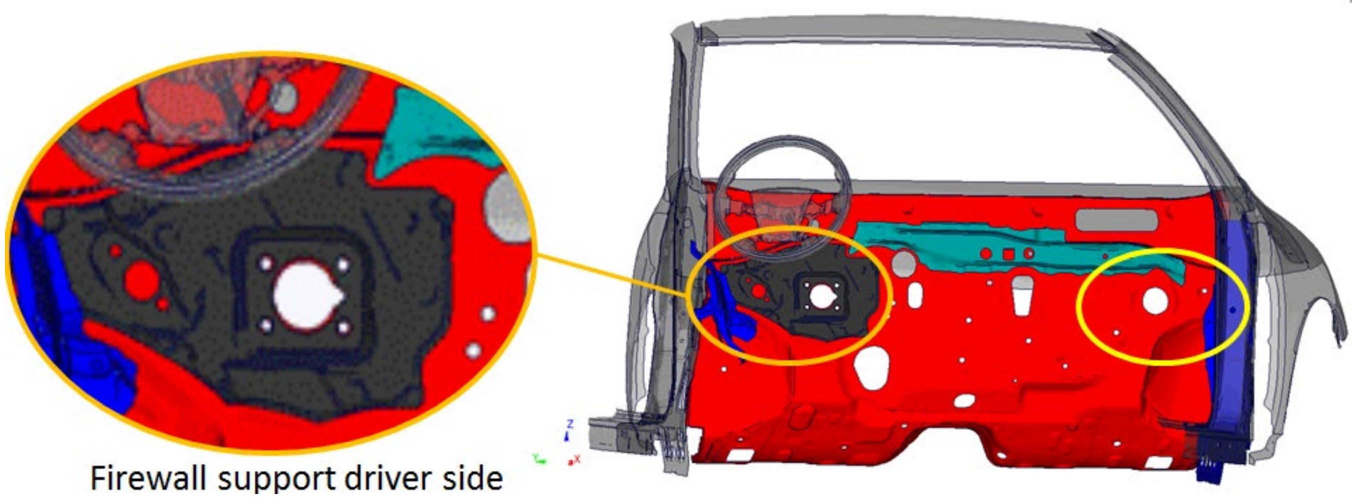


Figure 26 - Left Firewall Support (a) Enlarged, (b) Entire Firewall

The absence of an equivalent firewall support component on the passenger side contributes to the maximum occupant compartment intrusion in the right oblique impact. It also contributes to relative intrusion of adjacent points.

7. Countermeasure Model 1

The first Countermeasure Model (CM1) was developed to define minimal structural changes to meet the design goals outlined in Chapter 5 for the left and right frontal oblique configurations.

Figure 27(a) presents an overview of the implemented modifications. Firewall, three components of the right hinge pillar, and two parts of the left and right frontal rails were optimized.

To reduce maximum toe-pan intrusion and local buckling, material thickness and material strength were increased for the firewall, shown in pink. Material thickness was also increased for three components of the right hinge pillar, shown in blue in Figure 27(b). For the inner hinge pillar (a) and the middle hinge pillar (b) material strength was also increased. The material strength for the outer hinge pillar (c) was not changed to allow the same manufacturing stamping process as for the BM. Optimization of the right hinge pillar contributed to reduced intrusion and reduced local buckling, specifically in the right oblique impact. The parking brake on the driver side acts as a reinforcement of the hinge pillar area on the driver side. Therefore, the left hinge pillar components were not changed.

Figure 27(c) shows an exploded view of two parts of the frontal rails. To reduce the load induced into the firewall, material thickness for these parts of the left and right frontal rails, shown in green, were marginally reduced. This contributed to reduction in maximum toe-pan intrusion and local buckling.

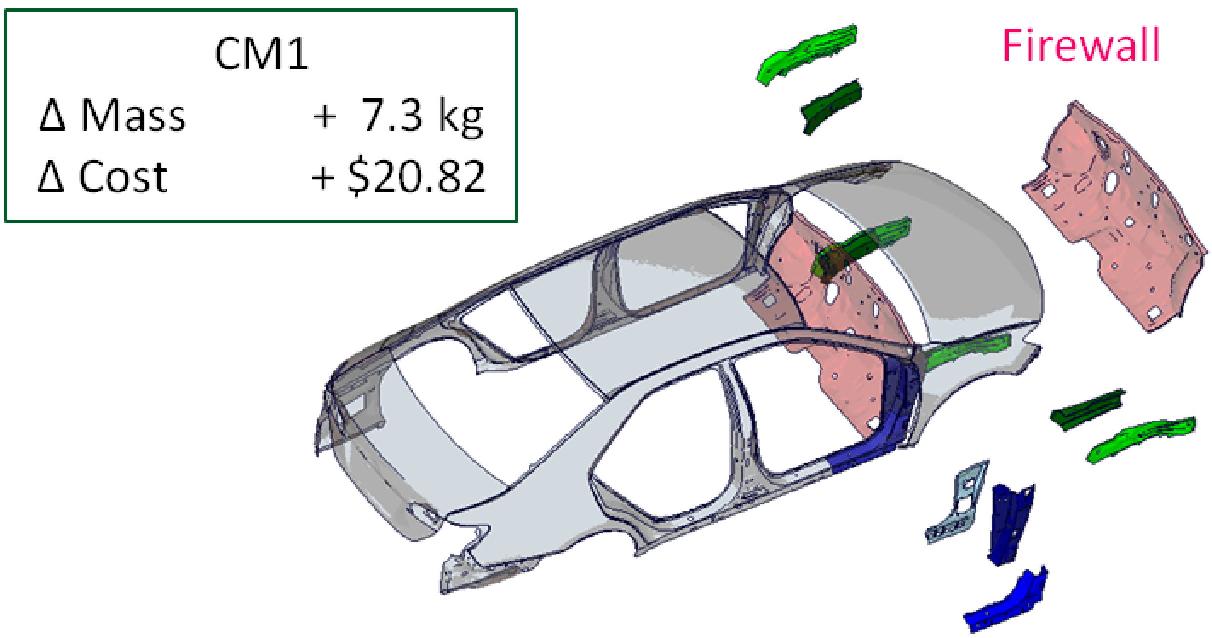


Figure 27(a) - CM1 Exploded View Overall, (b) Right Hinge Pillar, (c) Frontal Rail Parts

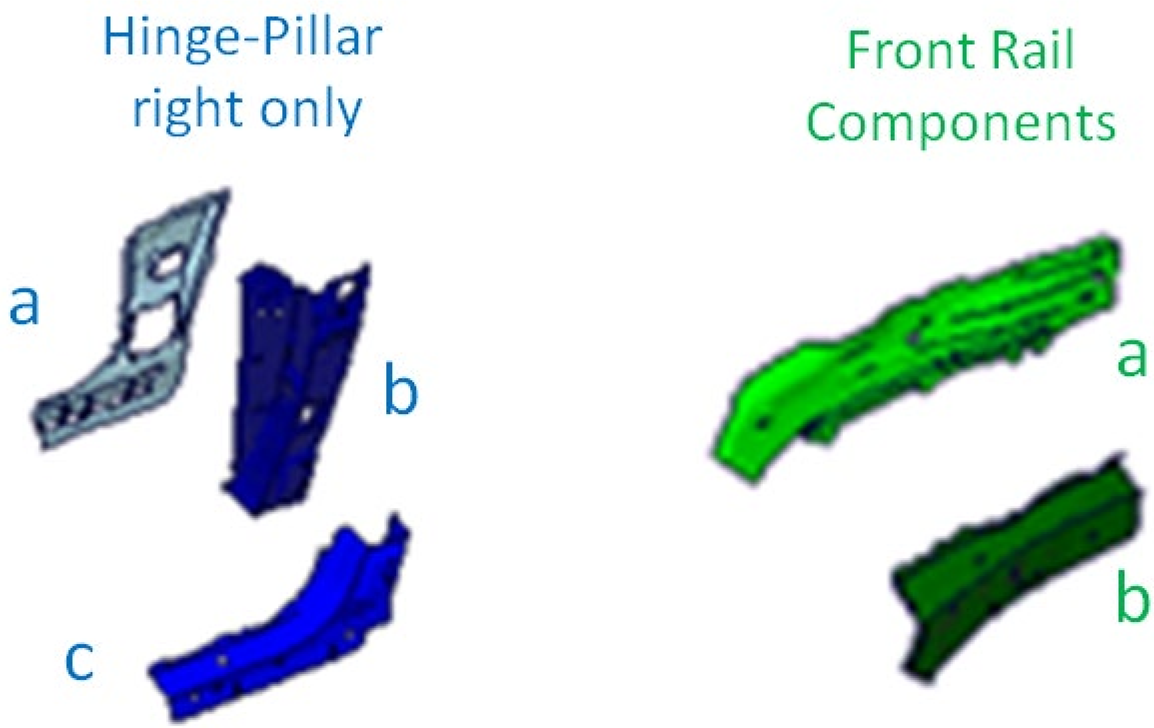


Figure 27 - (b) CM1 Right Hinge Pillar, (c) CM1 Frontal Rail Parts

7.1 CM1 - Mass and Cost Analysis

Table 4 lists the material grade, material gauge, mass, and cost for the different components in the BM and CM1.

For example, row 4 outlines the modification for the inner hinge pillar (a). In the BM, a steel material with 360 megapascal (MPa) yield strength and a thickness of 0.9 mm was used. The respective commercially available steel grade is DP 350/600. The associated mass is 0.9 kg and the associated cost is \$1.61. Material cost is the amount of material purchased, which is more than part weight as a result of trimming of the stamping blank as it is formed into the final part, as shown in Figure 8. Stamping yield varies from part to part but on average is 65 percent and is the assumed value in this cost estimate.

In CM1, a steel material with 450 MPa yield strength and a thickness of 1.3 mm was used. The respective commercially available steel grade is DP 500/800.The associated mass is 1.3 kg and the associated cost is \$2.42. Hence, the associated change in cost for the hinge pillar (a) is \$0.81 and the associated change in mass is 0.4 kg. Mass and cost analysis is combined for left and right side frontal rail components.

Most of the added mass can be attributed to the firewall component. Adding local reinforcements on the driver and passenger side would be an alternative approach to reduce occupant compartment intrusion.

Table 4 - CM1 - Cost and Mass Analysis

	Baseline Model (BM)					
Part	**Yield Strength {Mpa]**	**Assumed Grade**	**Gauge [mm]**	**Mass [kg]**	**Price [$/kg]**	**Cost [$] Based on 65%**
Firewall	250	BH 260/370	2.1	19.6	0.91	27.44
Hinge Pillar (a)	360	DP 350/600	0.9	0.9	1.16	1.61
Hinge Pillar (b)	360	DP 350/600	1.1	1.5	1.16	2.68
Hinge Pillar (c)	360	DP 350/600	1.3	1.2	1.16	2.14
Front Rail (a)*	360	DP 350/600	2.8	4.3	1.16	7.67
Front Rail (b)*	360	DP 350/600	2.1	4.2	1.16	7.5
* left and right side combined						

	Countermeasure Model 1 (CM1)						Delta	
Part	**Yield Strength {Mpa]**	**Assumed Grade**	**Gauge [mm]**	**Mass [kg]**	**Price [$/kg]**	**Cost [$] Based on 65%**	**Δ Cost [$]**	**Δ Mass [kg]**
Firewall	360	DP 350/600	2.9	27	1.16	48.18	20.74	7.4
Hinge Pillar (a)	450	DP 500/800	1.3	1.3	1.21	2.42	0.81	0.4
Hinge Pillar (b)	450	DP 500/800	1.5	2.1	1.21	3.91	1.23	0.6
Hinge Pillar (c)	360	DP 350/600	1.7	1.6	1.16	2.86	0.72	0.4
Front Rail (a)*	360	DP 350/600	2.1	3.6	1.16	6.42	-1.25	-0.7
Front Rail (b)*	360	DP 350/600	1.8	3.4	1.16	6.07	-1.43	-0.8
* left and right side combined						**Total**	**20.82**	**7.3**

The total change in mass for CM1 is +7.3 kg. The total change in cost for CM1 is +$20.82.

7.2 CM1 - Left Oblique (Driver Side)

NHTSA's left oblique impact configuration was used to evaluate the stationary Toyota Camry CM1 when impacted by an Oblique Moving Deformable Barrier (OMDB) traveling at a speed of 90 km/h into the front driver side. CM1 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 5. The Toyota Camry was positioned with a 15-degree angle relative to the OMDB and impacted with a 35 percent overlap.

Figure 28(a) illustrates the toe-pan measurement points. Figure 28(b) depicts the intrusion values for each point in the baseline simulation. The maximum intrusion was recorded for point C1 and the maximum relative intrusion for adjacent points was recorded between point D2 and D3. Figure 28(c) depicts the intrusion values for each point in the simulation using CM1. The maximum intrusion was recorded for point B1 and the maximum relative intrusion for adjacent points was recorded between points B1 and B2. The maximum relative intrusion of adjacent points was reduced from 54 mm to 19 mm, which is equivalent to a 67 percent reduction.

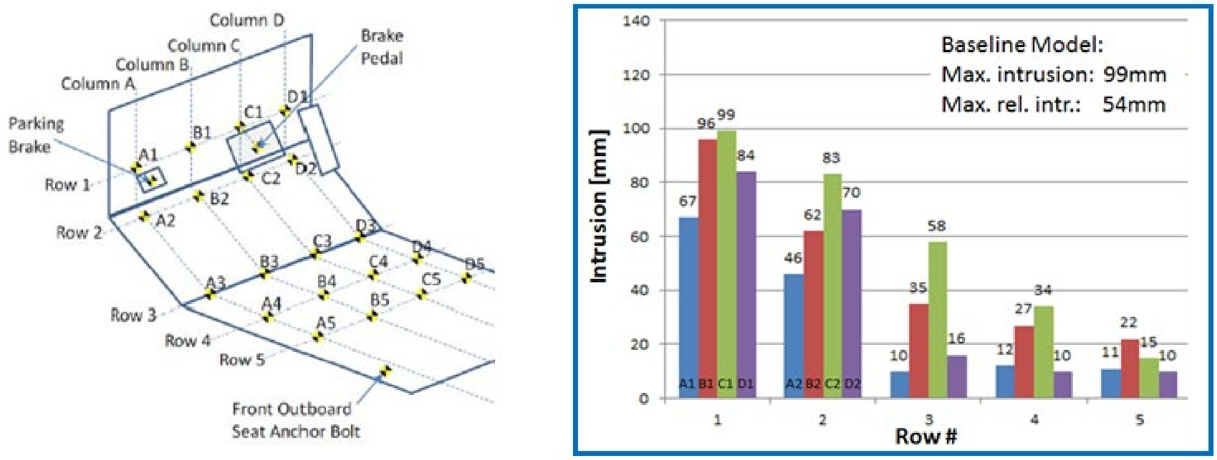


Figure 28 - Left Oblique Toe Pan Intrusion (a) Measurement Points (b) BM

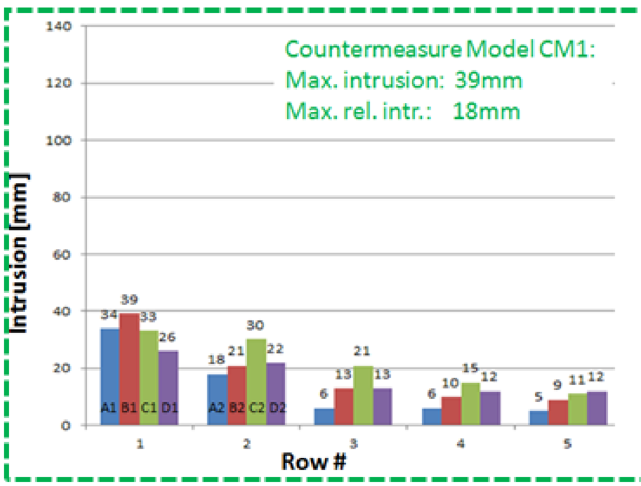


Figure 28(c) - Left Oblique Toe Pan Intrusion CM1

Figure 29(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM1 simulation using a green dashed line in the adapted IIHS moderate overlap chart. The maximum toe-pan intrusion in the left oblique impact was reduced from 99 mm to 39 mm, which is equivalent to a 61 percent reduction.

Figure 29(b) depicts the door sill deformation for the BM simulation in blue and the CM1 simulation in dark green. The maximum door sill deformation was reduced from 25 mm to 14 mm. Both values are considered moderate.

Figure 29(c) shows the comparison of the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM1 simulation is shown using a green dotted line. The maximum peak acceleration a_{max} increased from 43g to 46g. The maximum peak acceleration that lasted 5 milliseconds (a_{5ms}) increased from 41g to 43g. The maximum peak acceleration that lasted 15 milliseconds (a_{15ms}) increased from 37g to 38g. The Δv was 53km/h for both models. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes is therefore predicted.

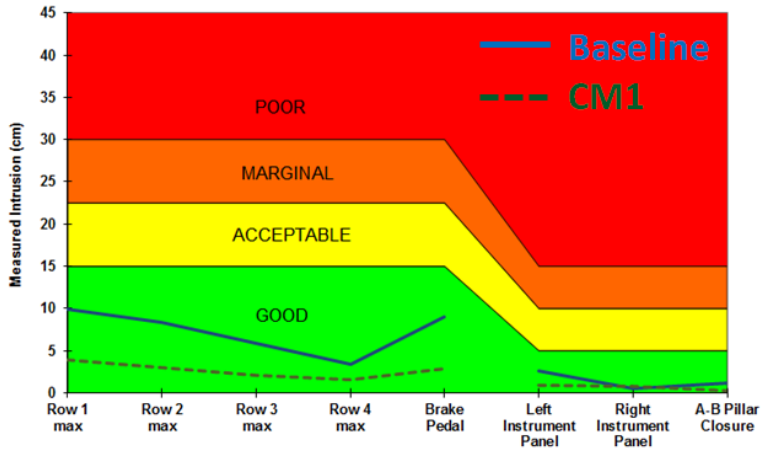


Figure 29(a) - CM1 Left Oblique Intrusion

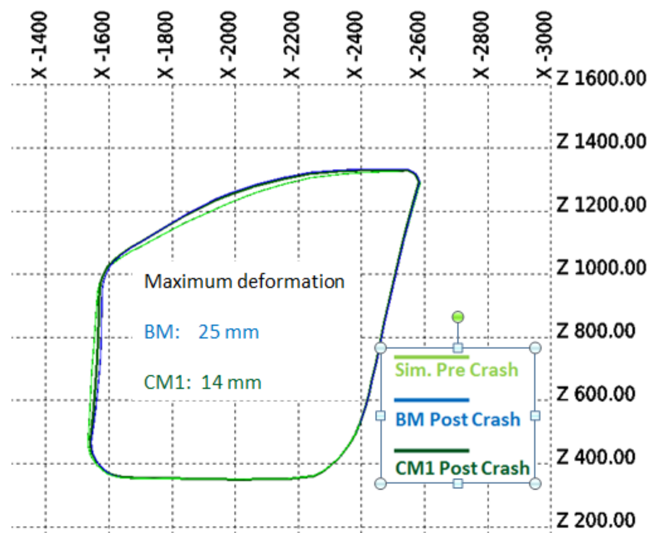


Figure 29(b) - CM1 Left Oblique Door Sill

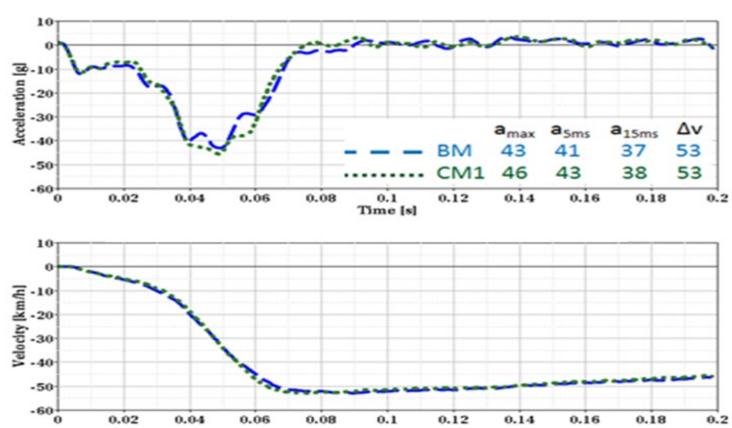


Figure 29(c) - CM1 Left Oblique Vehicle Pulse

Thus, CM1 fulfills all design goals defined in Chapter 5 for the left oblique impact configuration. The absolute maximum intrusion was reduced from 99 mm to 39 mm, which is equivalent to a 61 percent reduction.

7.3 CM1 - Right Oblique (Passenger Side)

NHTSA's right oblique impact configuration was utilized to evaluate the stationary Toyota Camry CM1 when impacted by an OMDB traveling at a speed of 90 km/h into the front passenger side. CM1 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 5. The Toyota Camry was positioned with a 15-degree angle relative to the OMDB and impacted with a 35 percent overlap.

Figure 30(a) schematically illustrates the toe-pan measurement points. Figure 30(b) depicts the intrusion values for each point in the baseline simulation. The maximum intrusion was recorded for point B1 and the maximum relative intrusion for adjacent points was recorded between points A2 and A3. Figure 30(c) depicts the intrusion values for each point in the simulation using CM1. The maximum intrusion was recorded for point C1 and the maximum relative intrusion for adjacent points was recorded between points C1 and C2. The maximum relative intrusion of adjacent points was reduced from 68 mm to 32 mm, which is equivalent to a 53 percent reduction.

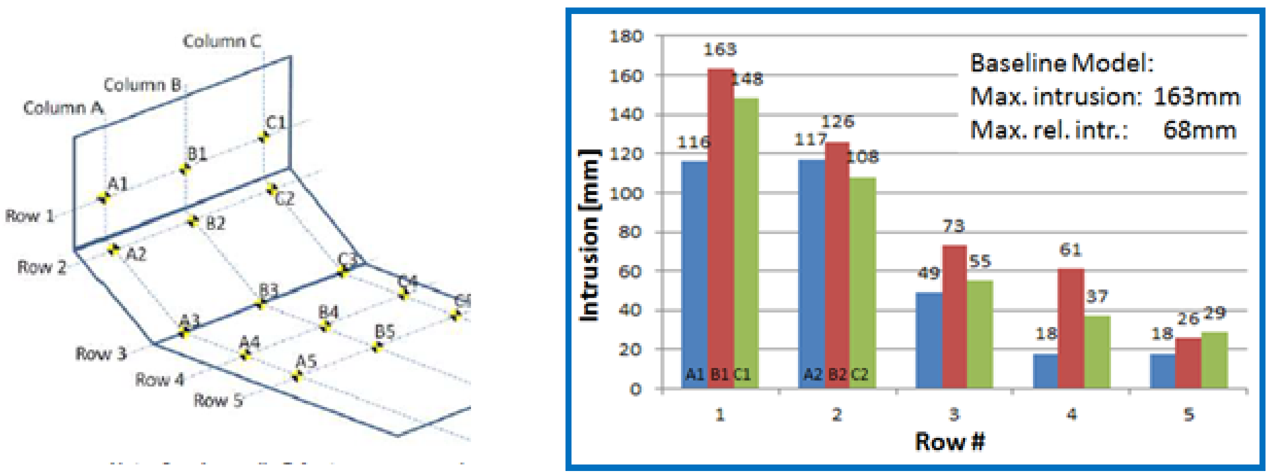


Figure 30 - Right Oblique Toe Pan Intrusion (a) Measurement Points, (b) BM

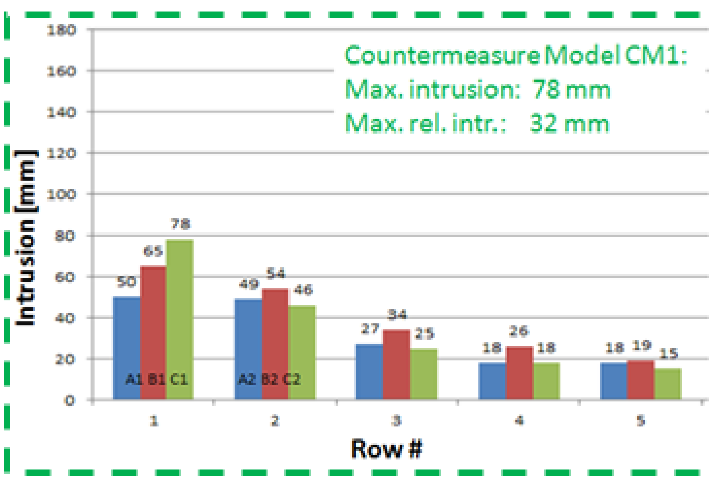


Figure 30(c) - Right Oblique Toe Pan Intrusion CM1

Figure 31(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM1 simulation using a green dashed line in the adapted IIHS moderate overlap chart. The maximum toe-pan intrusion in the right oblique impact was reduced from 163 mm to 78 mm, which is equivalent to a 52 percent reduction.

Figure 31(b) depicts the door sill deformation for the BM simulation in blue and the CM1 simulation in dark green. The maximum door sill deformation was reduced from 35 mm to 15 mm. Both values are considered moderate.

Figure 31(c) shows the comparison of the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM1 simulation is shown using a green dotted line. The maximum peak acceleration a_{max} increased from 41g to 44g. The maximum peak acceleration that lasted 5 milliseconds (a_{5ms}) increased from 37g to 39g. The maximum peak acceleration that lasted 15 milliseconds (a_{15ms}) increased from 29g to 33g. The Δv decreased from 53 km/h to 52 km/h. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM1 is therefore predicted.

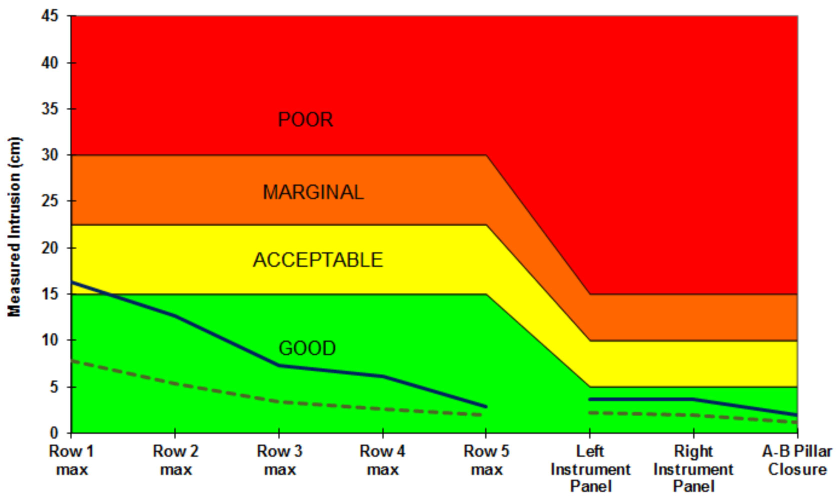


Figure 31(a) - CM1- Right Oblique Intrusion

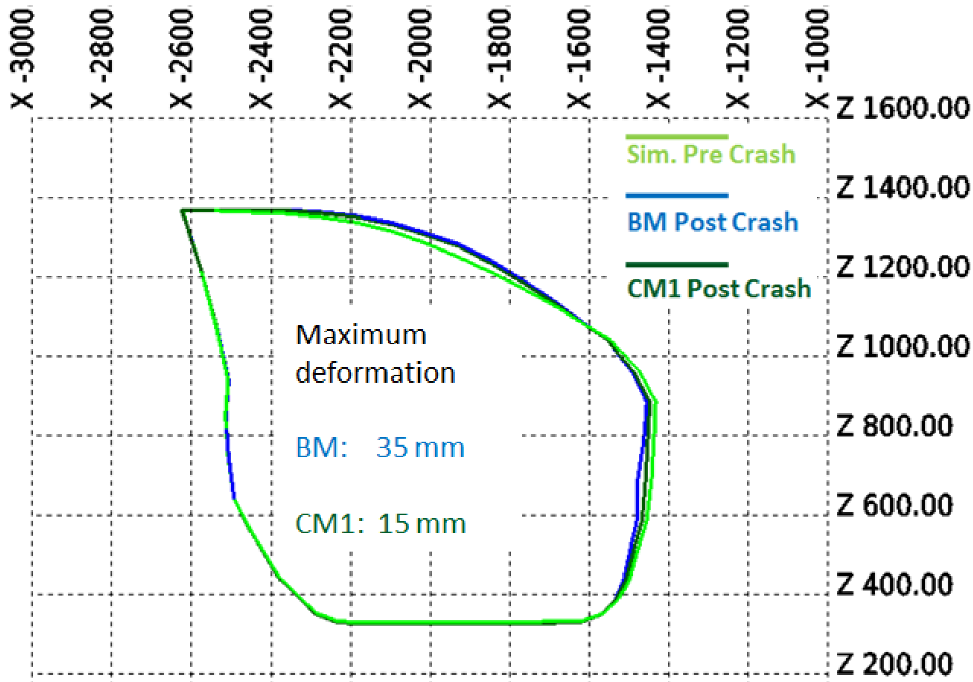


Figure 31(b) - CM1- Right Oblique Door Sill

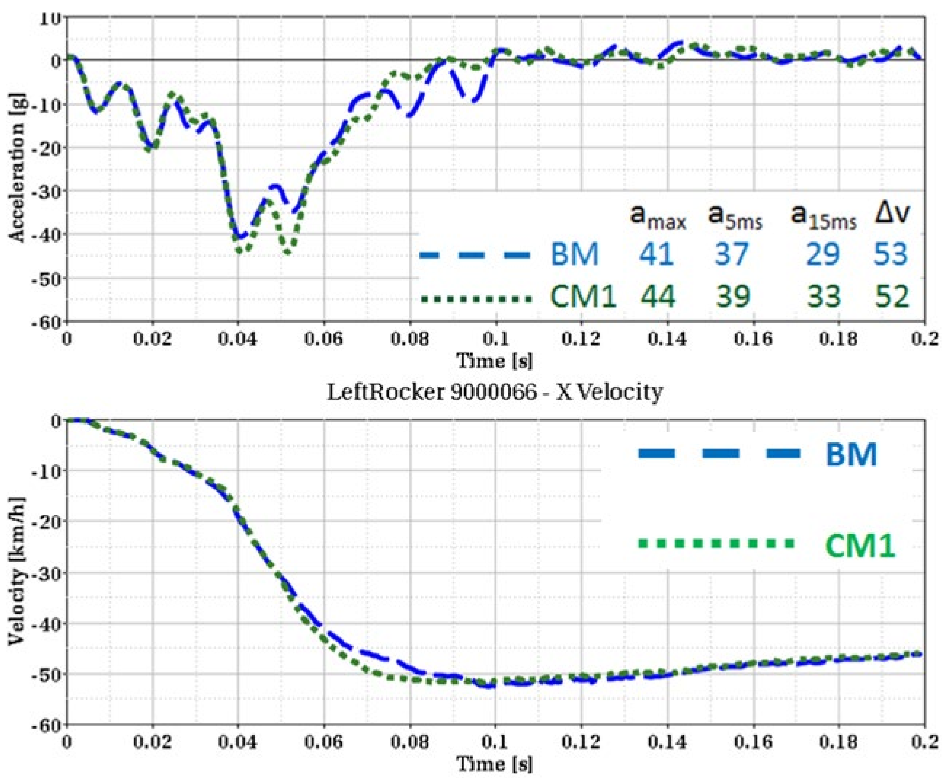


Figure 31(c) - CM1- Right Oblique Vehicle Pulse

Thus, CM1 fulfills all design goals defined in Chapter 5 for the right oblique impact configuration. The absolute maximum intrusion was reduced from 163 mm to 78 mm, which is equivalent to a 52 percent reduction.

7.4 CM1 - IIHS Small Overlap

The IIHS small overlap test configuration was utilized to evaluate the developed Toyota Camry CM1 traveling at 64 km/h into a fixed rigid barrier with a 25 percent overlap. CM1 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 4.

Figure 32(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM1 simulation using a green dashed line. Similar maximum intrusion values result in an Acceptable rating according to the IIHS structural rating protocol for both models.

Figure 32(b) depicts the door sill deformation for the BM simulation in blue and the CM1 simulation in dark green. Similar maximum values with respect to the undeformed shape, shown in light green, were observed.

Figure 32(c) shows the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM1 simulation is shown using a green dotted line. The maximum relevant peak accelerations increased by no more than 3g. The Δv increased by 1 km/h. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM1 is therefore predicted.

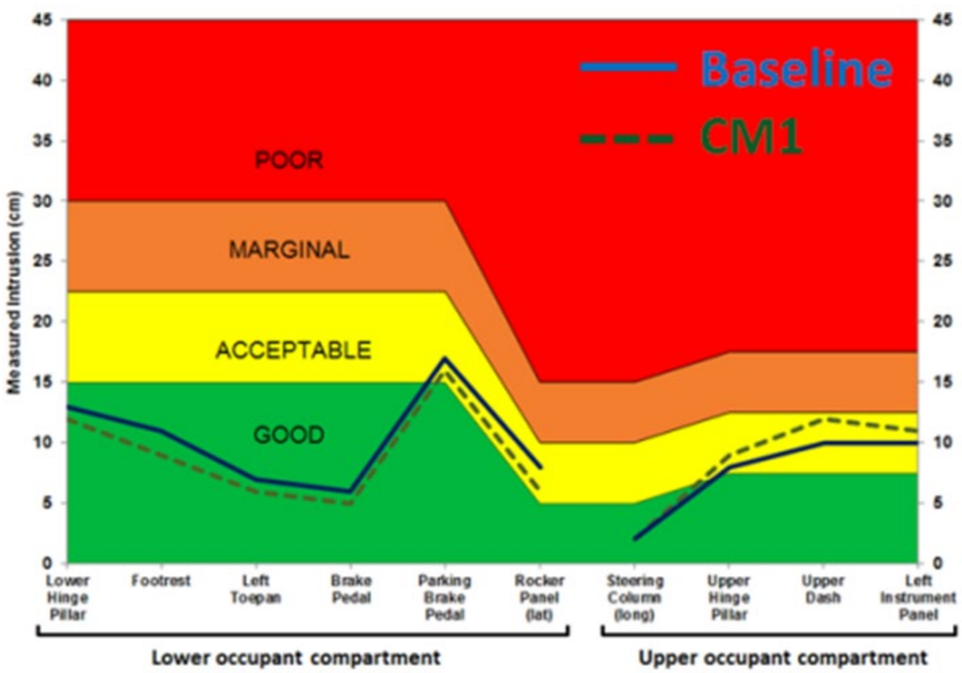


Figure 32(a) - CM1- IIHS SO Intrusion

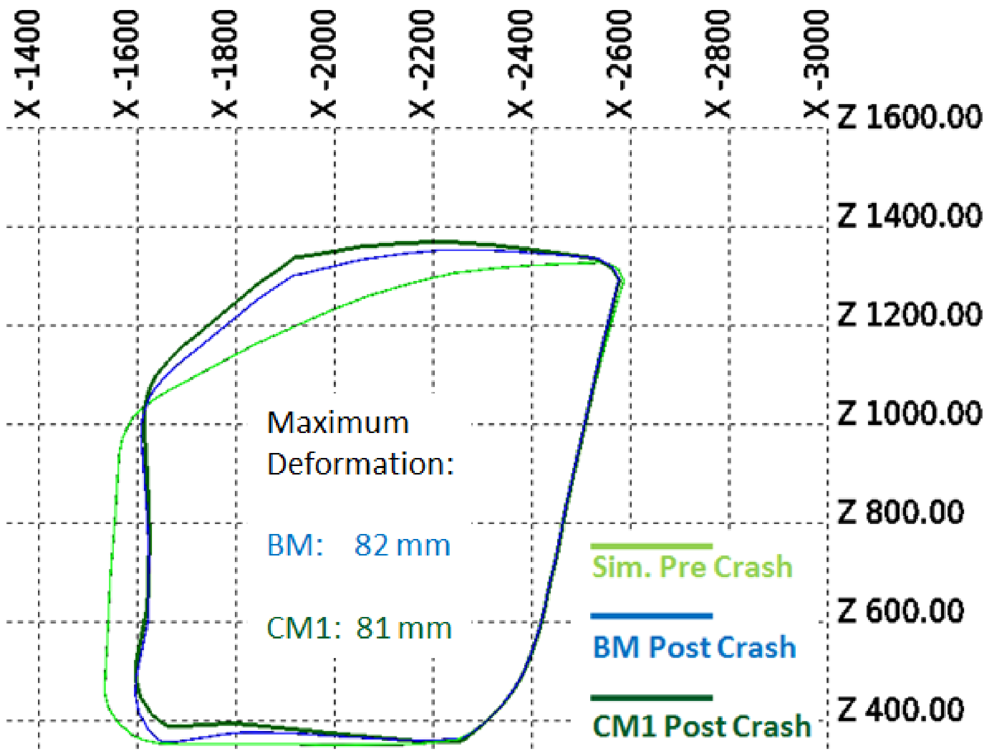


Figure 32(b) - CM1- IIHS SO Door Sill

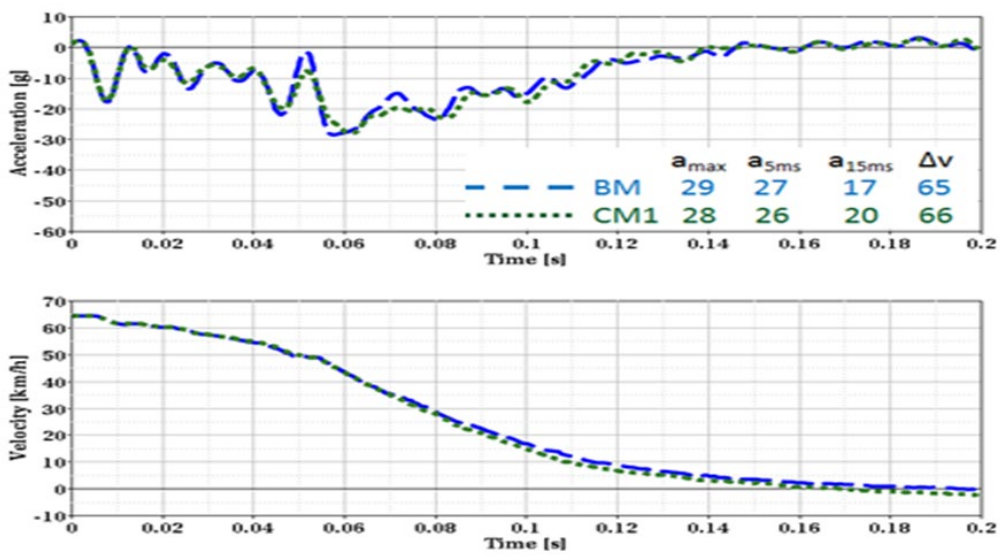


Figure 32(c) - CM1- IIHS SO Vehicle Pulse

Thus, CM1 shows similar occupant compartment intrusion and vehicle pulse characteristics to the BM. No unintended consequences are anticipated for the IIHS small overlap impact due to the implemented structural changes. Additional local design changes and reinforcements would allow further improvement in the IIHS SO structural rating.

7.5 CM1 - IIHS Moderate Overlap

The IIHS moderate overlap configuration was exercised to evaluate the developed Toyota Camry CM1 traveling at 64 km/h into a fixed deformable aluminum honeycomb barrier with an overlap of 40 percent. CM1 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 4.

Figure 33(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM1 simulation using a green dashed line. The implemented structural design changes resulted in a significant reduction in occupant compartment intrusion for the IIHS moderate overlap configuration within the “Good” rating range, according to the IIHS structural rating protocol.

Figure 33(b) depicts the door sill deformation for the BM simulation in blue and the CM1 simulation in dark green. No relevant deformation with respect to the undeformed shape, shown in light green, was observed for either BM or CM1.

Figure 33(c) shows the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM1 simulation is shown using a green dotted line. The maximum relevant peak accelerations changed by no more than 1g. The Δv is the same for both simulations. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM1 is therefore predicted.

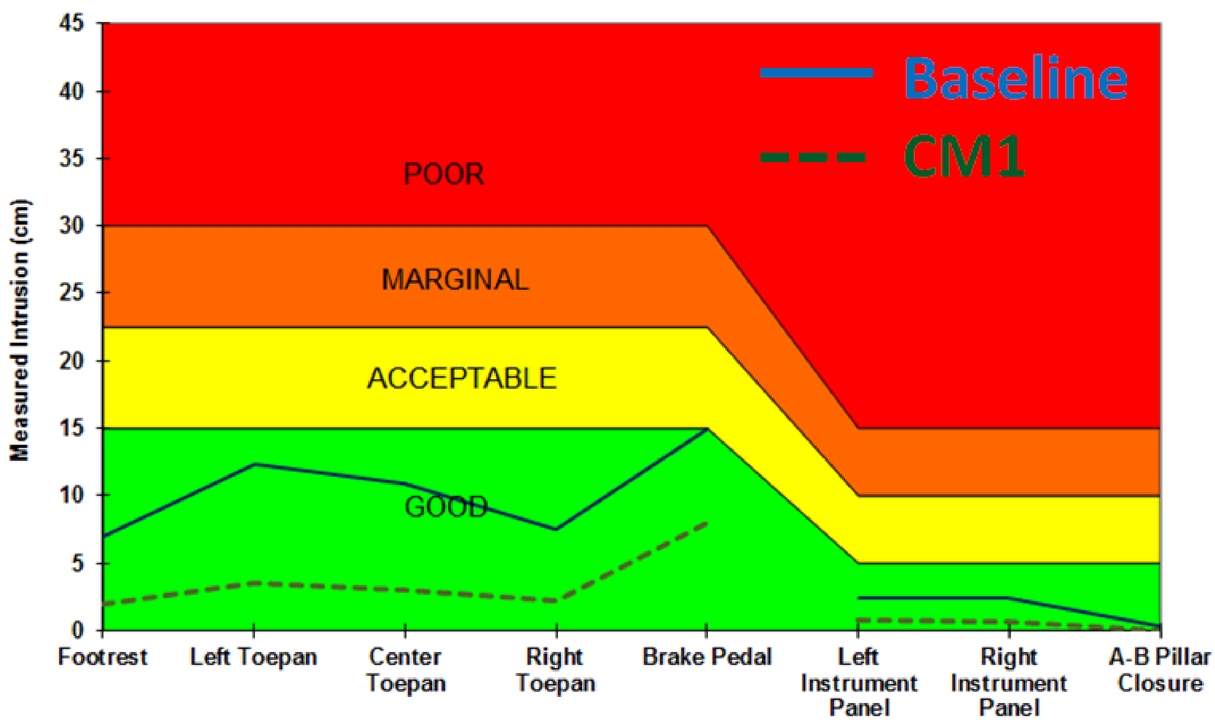


Figure 33(a) - CM1- IIHS MO (a) Intrusion

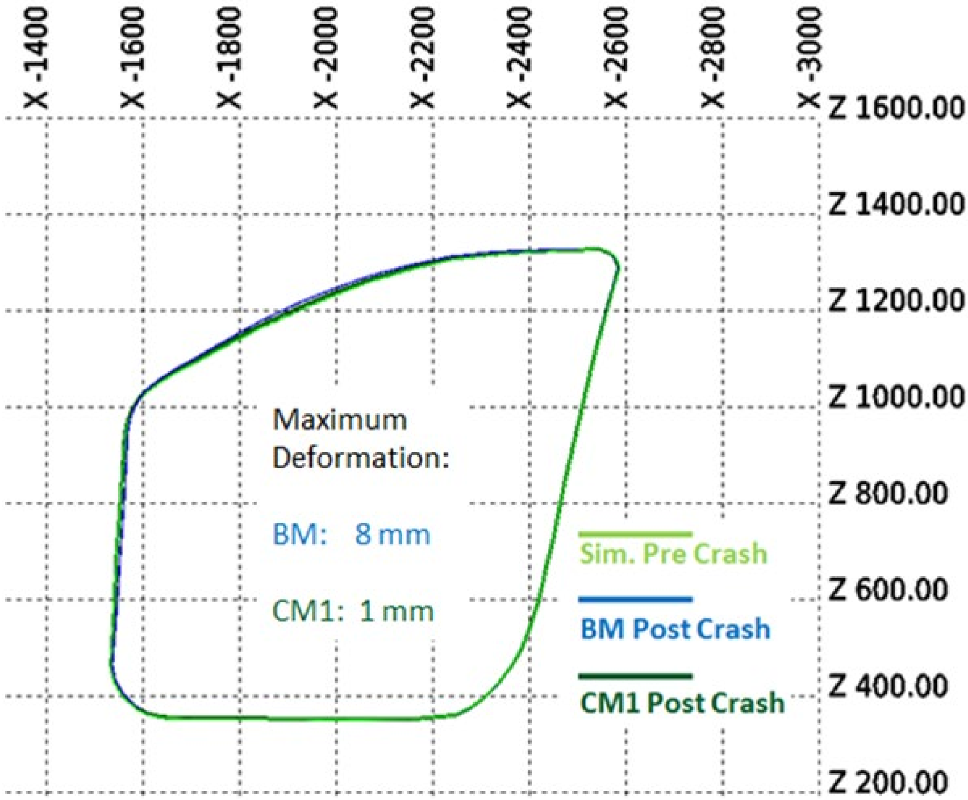


Figure 33(b) - CM1- IIHS MO Door Sill

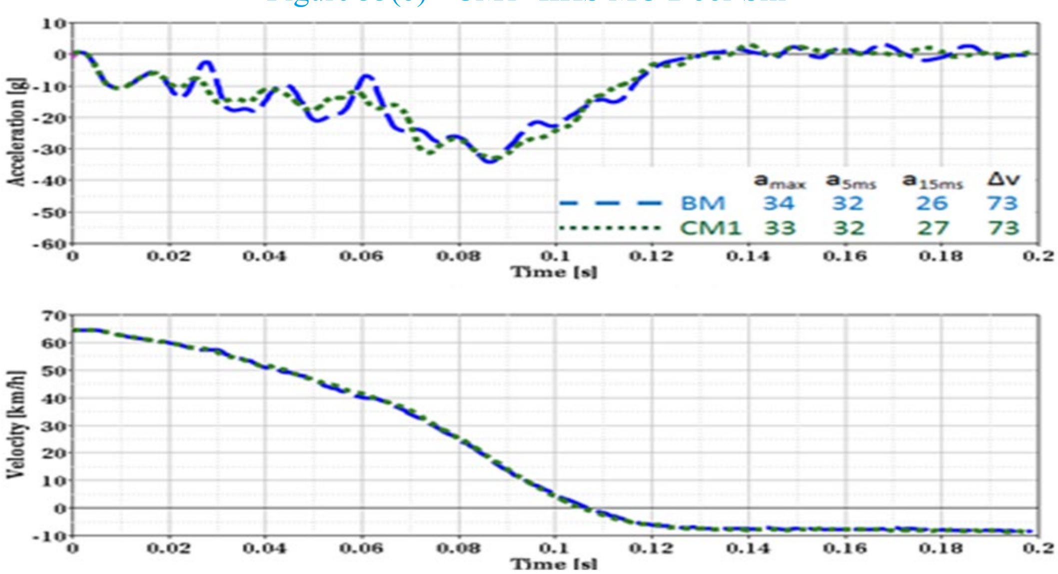


Figure 33(c) - CM1- IIHS MO Vehicle Pulse

Thus, CM1 shows reduced occupant compartment intrusion and similar vehicle pulse characteristics compared to the BM. No unintended consequences are anticipated for the IIHS moderate overlap impact due to the implemented design changes.

7.6 CM1 - NCAP Full Overlap

NHTSA's frontal NCAP full overlap configuration was exercised to evaluate the developed Toyota Camry CM1 traveling at 56 km/h into a fixed rigid barrier. CM1 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 4.

Figure 34(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM1 simulation using a green dashed line. The implemented structural design changes resulted in a significant reduction in occupant compartment intrusion for the NCAP full overlap configuration.

Figure 34(b) depicts the door sill deformation for the BM simulation in blue and the CM1 simulation in dark green. No relevant deformation with respect to the undeformed shape, shown in light green, was observed for either BM or CM1.

Figure 34(c) shows the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM1 simulation is shown using a green dotted line. The maximum relevant peak accelerations changed by no more than 3g. The Δv is the same for both simulations. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM1 is therefore predicted.

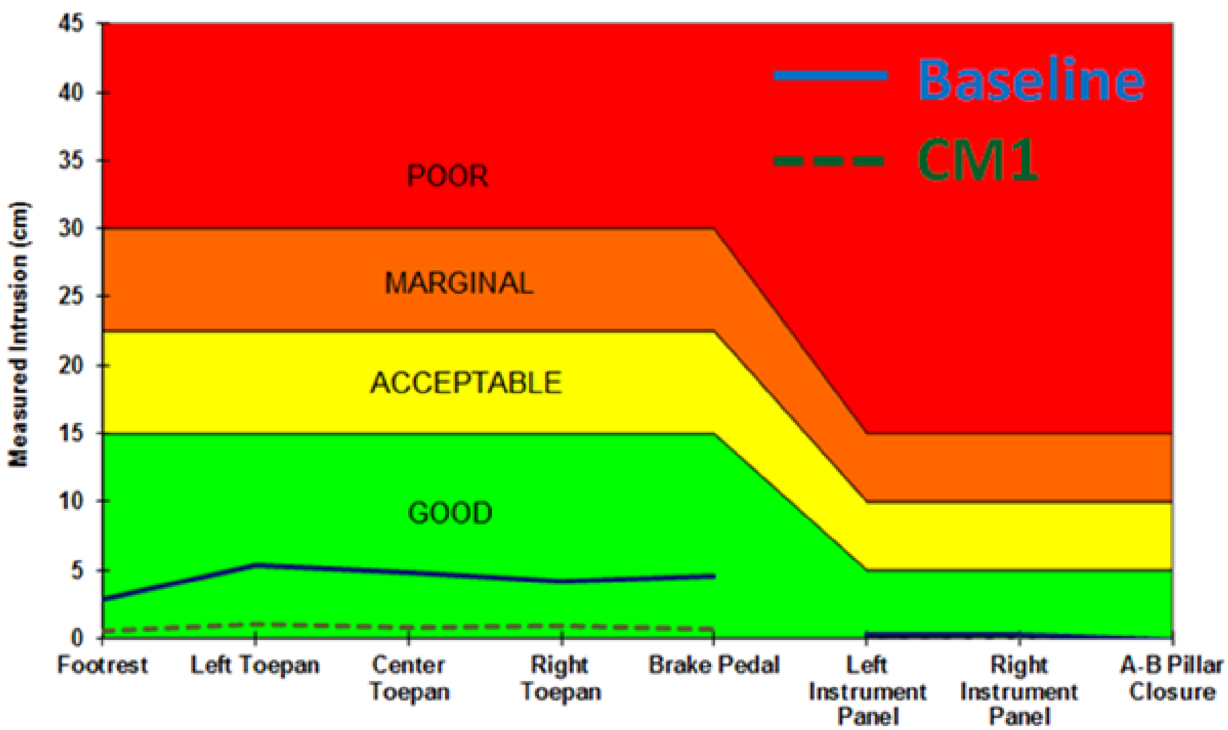


Figure 34(a) - CM1- NCAP Intrusion

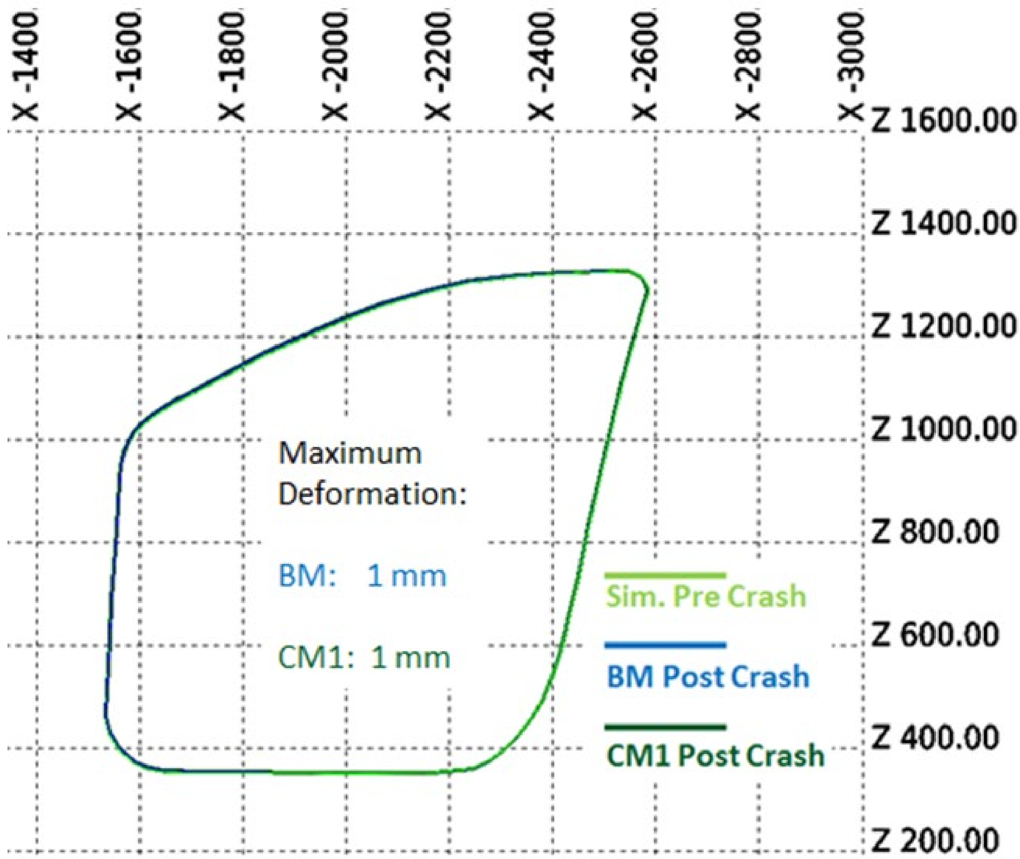


Figure 34(b) - CM1- NCAP Door Sill

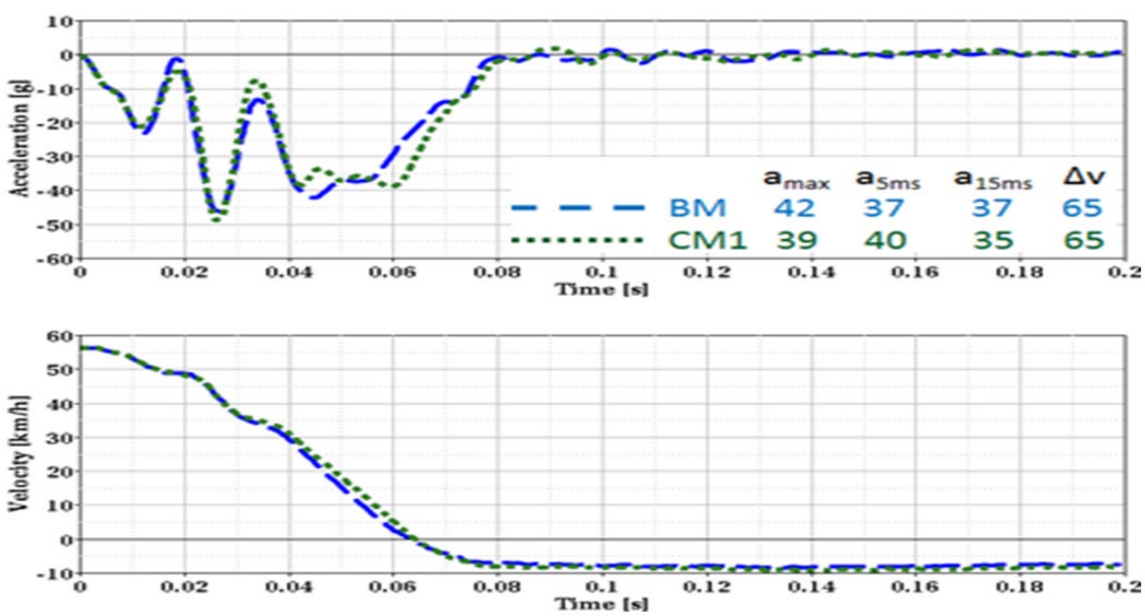


Figure 34(c) - CM1- NCAP Vehicle Pulse

8. Countermeasure Model 2

The second Countermeasure Model (CM2) was developed to define structural changes to meet the design goals outlined in Chapter 5 for the left and right frontal oblique configurations. In addition, it aimed to reduce the maximum occupant compartment intrusion to no more than 50 mm, which is equivalent to a 50 percent reduction for the left oblique configuration and a 69 percent reduction for the right oblique impact condition.

Figure 35(a) presents an overview of the implemented structural changes. Firewall, three components of the right hinge pillar, two parts of the left and right frontal rails, and three parts of the left and right mid-rails were optimized.

To reduce maximum toe-pan intrusion and local buckling, material thickness and material strength were increased for the firewall, shown in pink. Material thickness was also increased for three components of the right hinge pillar, shown in blue. For the inner hinge pillar (a) and the middle hinge pillar (b) material strength was also increased. The material strength for the outer hinge pillar (c) was not changed to allow the same manufacturing stamping process used for the BM. Optimization of the right hinge pillar contributed to reduced intrusion and reduced local buckling, specifically in the right oblique impact. The parking brake on the driver side acts as a reinforcement of the hinge pillar area on the driver side. Therefore, the left hinge pillar components were not changed.

To reduce the load induced into the firewall, material thickness for two parts of the left and right frontal rails, shown in green, were marginally reduced. This contributed to reduction in maximum toe-pan intrusion and local buckling.

Figure 35(b) illustrates the exploded view of the optimized mid-rail components. Material thickness was increased for all three parts on the left and right side. For the mid-rail top (a) and the mid-rail inner (b) material strength was increased as well. The material strength for the mid-rail bottom (c) was not changed to allow the same manufacturing stamping process used for the BM. These measures reduced local buckling of the mid-rail and resulted in reduced occupant compartment intrusion.

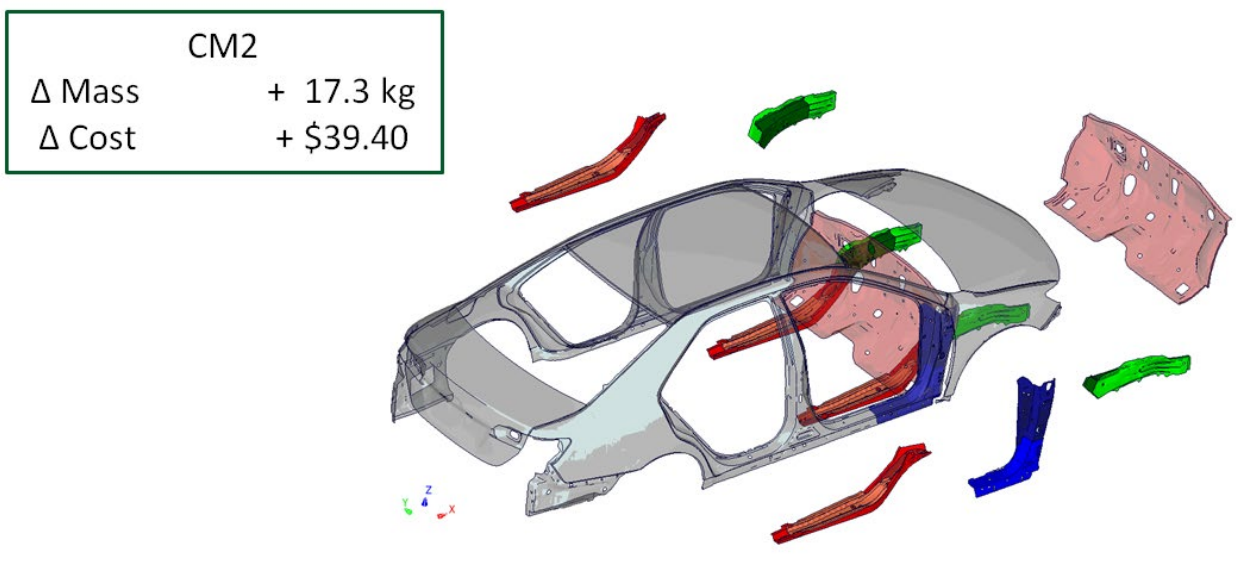


Figure 35(a) - CM2 Exploded View Overall

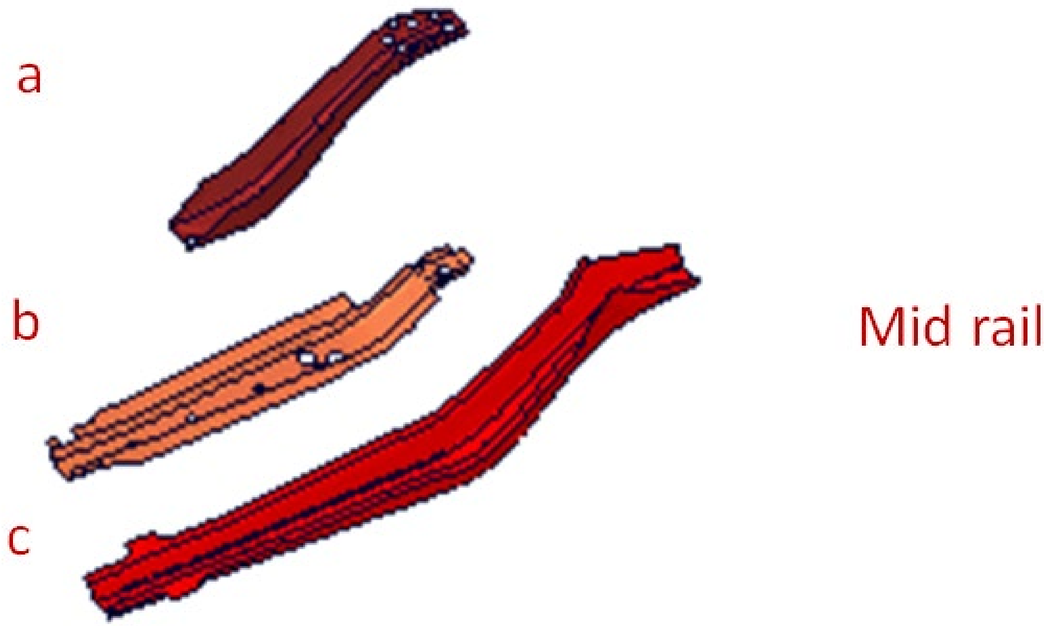


Figure 35(b) - CM2 Exploded View Mid-Rail Components

8.1 CM2 - Mass and Cost Analysis

Table 5 lists the material grade, material gauge, mass, and cost for the different components in the BM and CM2.

For example, row 4 outlines the modification for the inner hinge pillar (a). In the BM, a steel material with 360 MPa yield strength and a thickness of 0.9 mm was used. The respective commercially available steel grade is DP 350/600. The associated mass is 0.9 kg and the associated cost is \$1.61. Material cost is the amount of material purchased, which is more than part weight as a result of trimming of the stamping blank as it is formed into the final part, as shown in Figure 8. Stamping yield varies from part to part, but on average is 65 percent and is the assumed value in this cost estimate.

In CM2, a steel material with 450 MPa yield strength and a thickness of 1.4 mm is used. The respective commercially available steel grade is a DP 500/800. The associated mass is 1.4 kg and the associated cost is \$2.61. Hence, the associated change in cost for the hinge pillar (a) is \$1.00 and the associated change in mass is 0.5 kg. Mass and cost analysis is combined for left and right side frontal and mid-rail components.

Table 5 - CM2 - Cost and Mass Analysis

		Baseline Model (BM)					
Part		Yield Strength {Mpa]	Assumed Grade	Gauge [mm]	Mass [kg]	Price [$/kg]	Cost [$] Based on 65%
Firewall		250	BH 260/370	2.1	19.6	0.91	27.44
Hinge Pillar (a)		360	DP 350/600	0.9	0.9	1.16	1.61
Hinge Pillar (b)		360	DP 350/600	1.1	1.5	1.16	2.68
Hinge Pillar (c)		360	DP 350/600	1.3	1.2	1.16	2.14
Front Rail (a)*		360	DP 350/600	2.8	4.3	1.16	7.67
Front Rail (b)*		360	DP 350/600	2.1	4.2	1.16	7.5
Mid-Rail (a)*		360	DP 350/600	1.6	3.7	1.16	6.6
Mid-Rail (b)*		360	DP 350/600	1.4	2.4	1.16	4.28
Mid-Rail (c)*		360	DP 350/600	2	9.4	1.16	16.78
* left and right side combined							

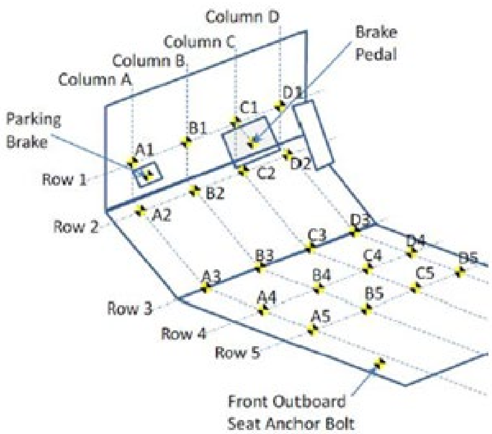
		Countermeasure Model 2 (CM2)							Delta	
Part		Yield Strength {Mpa]	Assumed Grade	Gauge [mm]	Mass [kg]	Price [$/kg]	Cost [$] Based on 65%		Δ Cost [$]	Δ Mass [kg]
Firewall		360	DP 350/600	3.2	29.8	1.16	53.18		25.74	10.2
Hinge Pillar (a)		450	DP 500/800	1.4	1.4	1.21	2.61		1	0.5
Hinge Pillar (b)		450	DP 500/800	1.6	2.2	1.21	4.1		1.42	0.7
Hinge Pillar (c)		360	DP 350/600	1.8	1.7	1.16	3.03		0.89	0.5
Front Rail (a)*		360	DP 350/600	2.1	3.6	1.16	6.42		-1.25	-0.7
Front Rail (b)*		360	DP 350/600	1.8	3.4	1.16	6.07		-1.43	-0.8
Mid-Rail (a)*		450	DP 500/800	2.4	5.5	1.21	10.24		3.64	1.8
Mid-Rail (b)*		450	DP 500/800	2.2	3.7	1.21	6.89		2.61	1.3
Mid-Rail (c)*		360	DP 350/600	2.8	13.2	1.16	23.56		6.78	3.8
* left and right side combined							**Total**		**39.4**	**17.3**

The total change in mass for CM2 is +17.3 kg. The total change in cost for CM2 is +$39.40.

8.2 CM2 - Left Oblique (Driver Side)

NHTSA's left oblique impact configuration was used to evaluate the stationary Toyota Camry CM2 when impacted by an OMDB traveling at a speed of 90 km/h into the front driver side. CM2 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 4. The Toyota Camry was positioned with a 15-degree angle relative to the OMDB and impacted with a 35 percent overlap.

Figure 36(a) illustrates the toe-pan measurement points on the driver side. Figure 36(b) depicts the intrusion values for each point in the baseline simulation. The maximum intrusion was recorded for point C1 and the maximum relative intrusion for adjacent points was recorded between point D2 and D3. Figure 36(c) shows the intrusion values for each point in the CM2. The maximum intrusion was recorded for point B1 and the maximum relative intrusion for adjacent points was recorded between points B1 and B2. The maximum relative intrusion of adjacent points was reduced from 54 mm to 12 mm, which is equivalent to a 78 percent reduction.



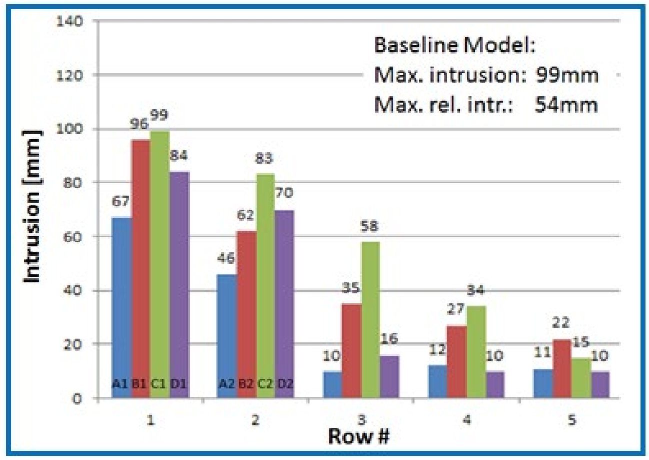


Figure 36 - Left Oblique Toe-Pan Intrusion (a) Measurement Points, (b) BM

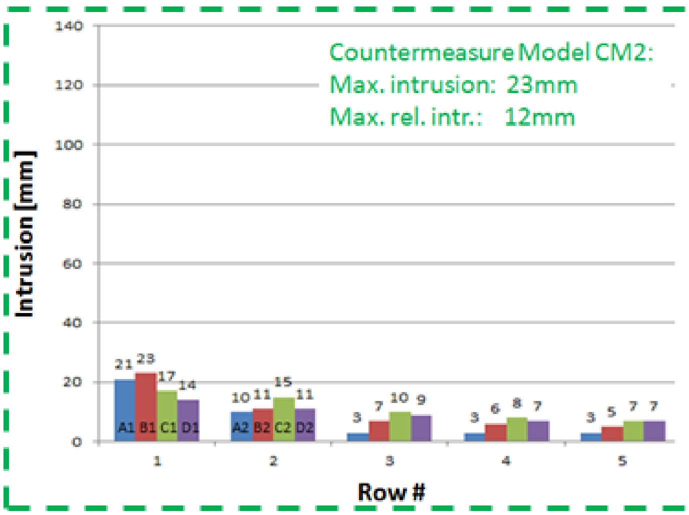


Figure 36(c) - Left Oblique Toe-Pan Intrusion CM2

Figure 37(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM2 simulation using a green dashed line in the adapted IIHS moderate overlap chart. The maximum toe-pan intrusion in the left oblique impact was reduced from 99 mm to 23 mm, which is equivalent to a 77 percent reduction.

Figure 37(b) depicts the door sill deformation for the BM simulation in blue and the CM2 simulation in dark green. The maximum door sill deformation was reduced from 25 mm to 10 mm. Both values are considered moderate.

Figure 37(c) shows the comparison of the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM2 is shown using a green dotted line. The maximum peak acceleration a_{max} increased from 43g to 46g. The maximum peak acceleration that lasted 5 milliseconds (a_{5ms}) increased from 41g to 44g. The maximum peak acceleration that lasted 15 milliseconds (a_{15ms}) increased from 37g to 41g. The Δv was 53km/h for both models. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes is therefore predicted.

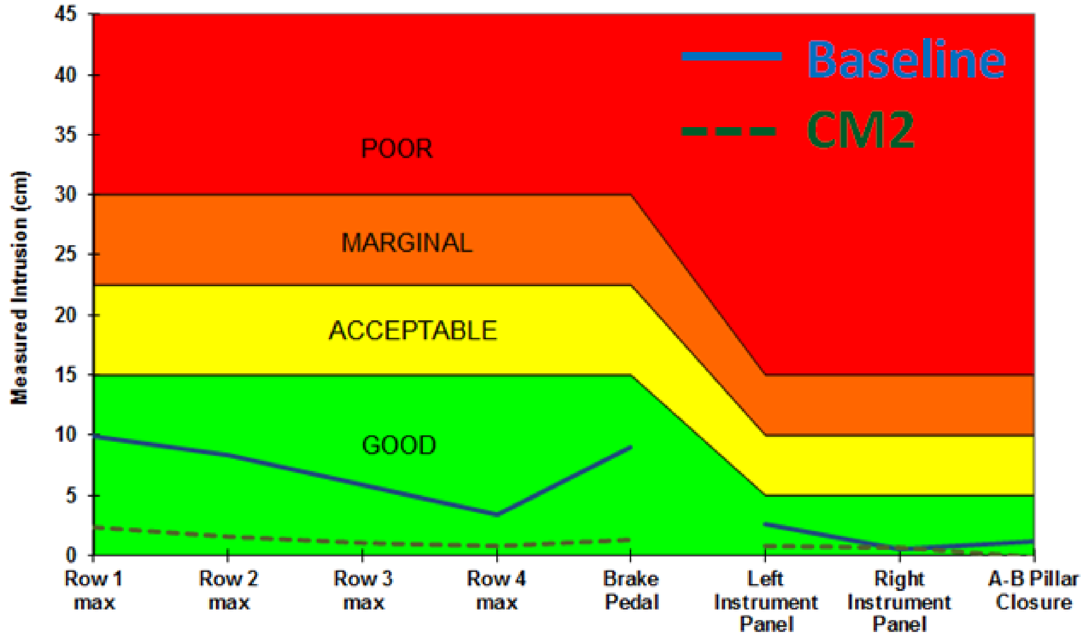


Figure 37(a) - CM2 Left Oblique Intrusion

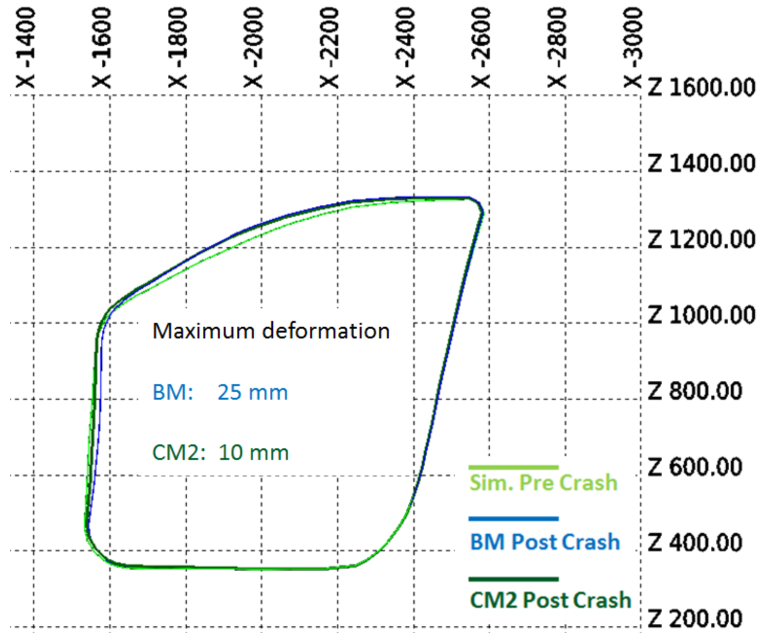


Figure 37(b) - CM2 Left Oblique Door Sill

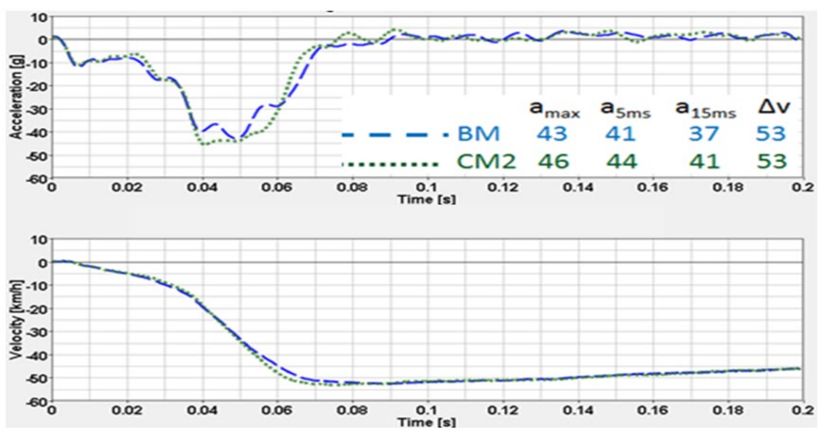


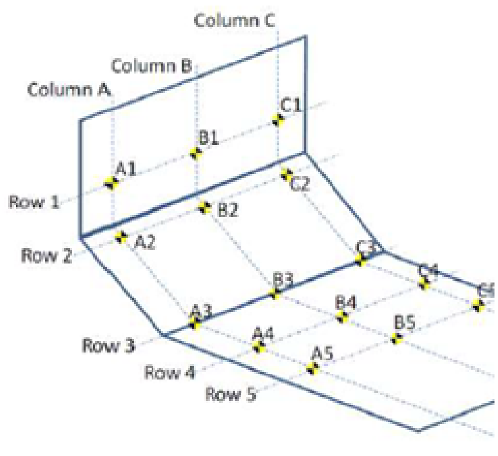
Figure 37(c) - CM2 Left Oblique Vehicle Pulse

Thus, CM2 fulfills all design goals defined in Chapter 5 for the left oblique impact configuration. The absolute maximum intrusion was reduced from 99 mm to 23 mm, which is equivalent to a 77 percent reduction.

8.3 CM2 - Right Oblique (Passenger Side)

NHTSA's right oblique impact configuration was exercised to evaluate the stationary Toyota Camry CM2 when impacted by an OMDB traveling at a speed of 90 km/h into the front passenger side. CM2 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 4. The Toyota Camry was positioned with a 15-degree angle relative to the OMDB and impacted with a 35 percent overlap.

Figure 38(a) schematically illustrates the toe-pan measurement points. Figure 38(b) depicts the intrusion values for each point in the BM simulation. The maximum intrusion was recorded for point B1 and the maximum relative intrusion for adjacent points was recorded between points A2 and A3. Figure 38(c) depicts the intrusion values for each point in the CM2 simulation. The maximum intrusion was recorded for point C1 and the maximum relative intrusion for adjacent points was recorded between points C1 and C2. The maximum relative intrusion of adjacent points was reduced from 68 mm to 25 mm, which is equivalent to a 63 percent reduction.



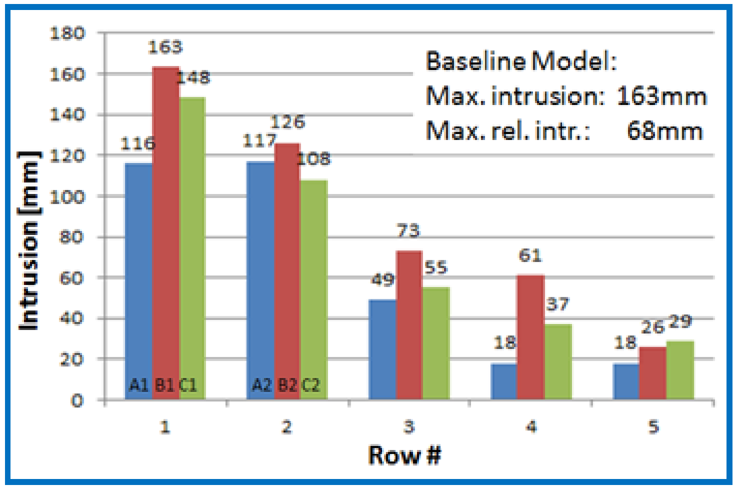


Figure 38 - CM2 Right Oblique Toe Pan Intrusion (a) Measurement Points, (b) BM

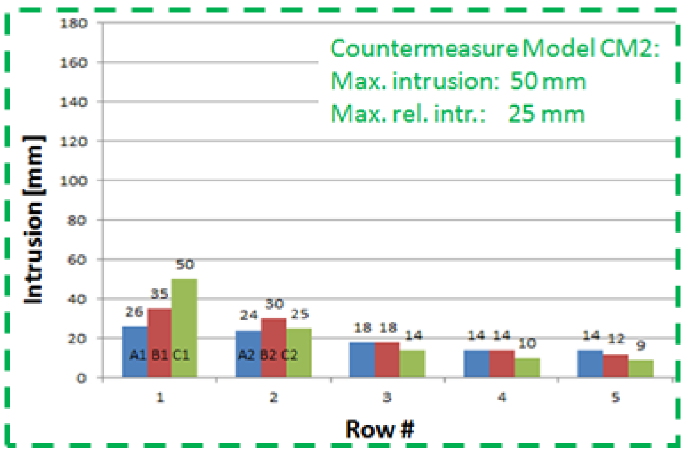


Figure 38(c) - CM2 Right Oblique Toe Pan Intrusion CM2

Figure 39(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM2 simulation using a green dashed line in the adapted IIHS moderate overlap chart. The maximum toe-pan intrusion in the right oblique impact was reduced from 163 mm to 50 mm, which is equivalent to a 69 percent reduction.

Figure 39(b) depicts the door sill deformation for the BM simulation in blue and the CM2 simulation in dark green. The maximum door sill deformation was reduced from 35 mm to 12 mm. Both values are considered moderate.

Figure 39(c) shows the comparison of the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM2 simulation is shown using a green dotted line. The maximum peak acceleration a_{max} increased from 41g to 47g. The maximum peak acceleration that lasted 5 milliseconds (a_{5ms}) increased from 37g to 40g. The maximum peak acceleration that lasted 15 milliseconds (a_{15ms}) increased from 29g to 32g. The Δv decreased from 53 km/h to 52 km/h. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM2 is therefore predicted.

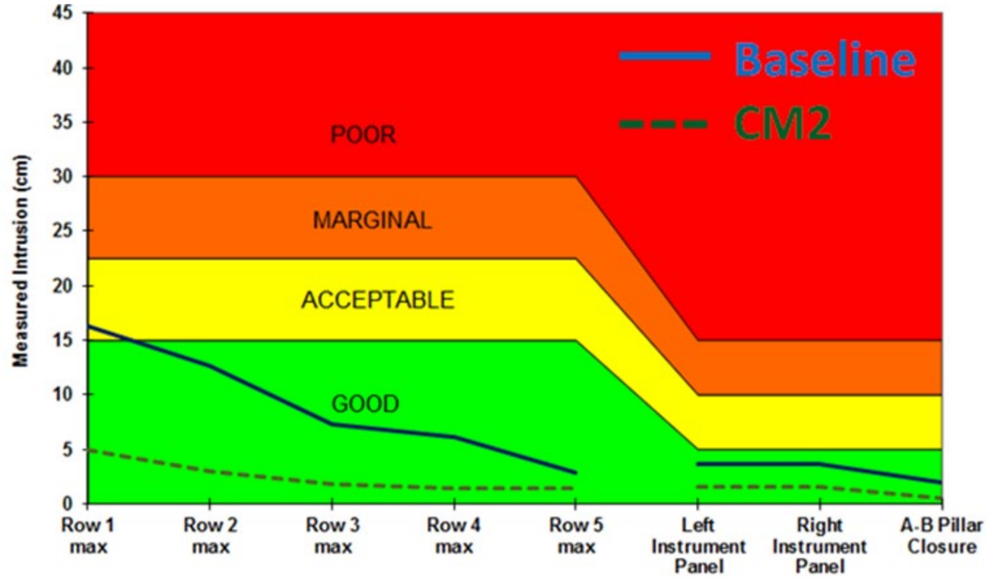


Figure 39(a) - CM2 Right Oblique Intrusion

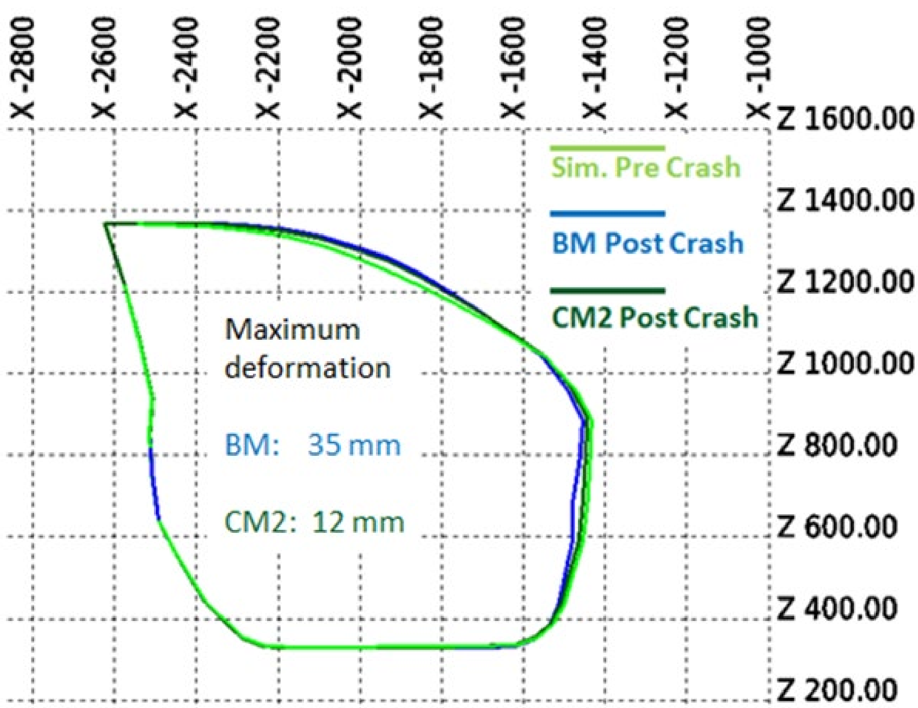


Figure 39(b) - CM2 Right Oblique Door Sill

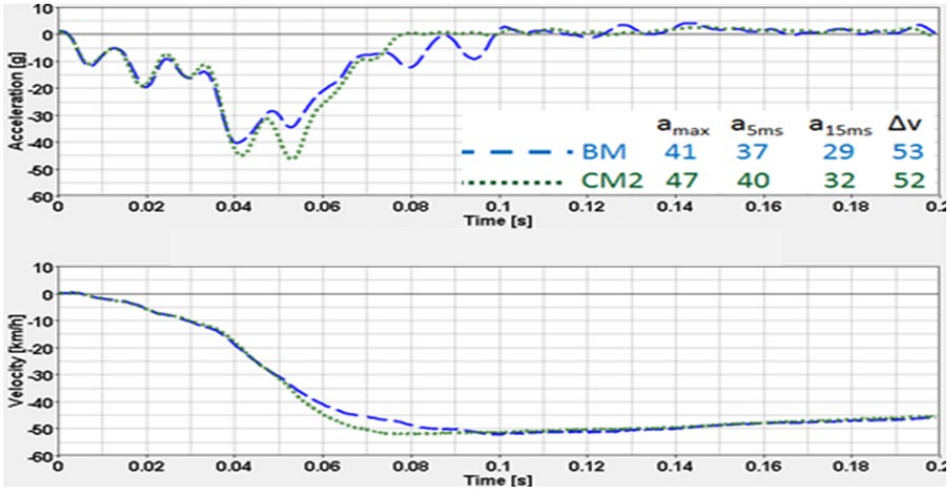


Figure 39(c) - CM2 Right Oblique Vehicle Pulse

Thus, CM2 fulfills all design goals defined in Chapter 5 for the right oblique impact configuration. The absolute maximum intrusion was reduced from 163 mm to 50 mm, which is equivalent to a 69 percent reduction.

8.4 CM2 - IIHS Small Overlap

The IIHS small overlap test configuration was utilized to evaluate the developed Toyota Camry CM2 traveling at 64 km/h into a fixed rigid barrier with a 25 percent overlap. CM2 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 4.

Figure 40(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM2 simulation using a green dashed line. Similar maximum intrusion values specifically for the lower occupant compartment result in an Acceptable rating according to the IIHS structural rating protocol for both models.

Figure 40(b) depicts the door sill deformation for the BM simulation in blue and for the CM2 simulation in dark green. Similar maximum values with respect to the undeformed shape, shown in light green, were observed.

Figure 40(c) shows the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM2 simulation is shown using a green dotted line. The maximum relevant peak accelerations increased by no more than 3g. The Δv increased by 2 km/h. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM2 is therefore predicted.

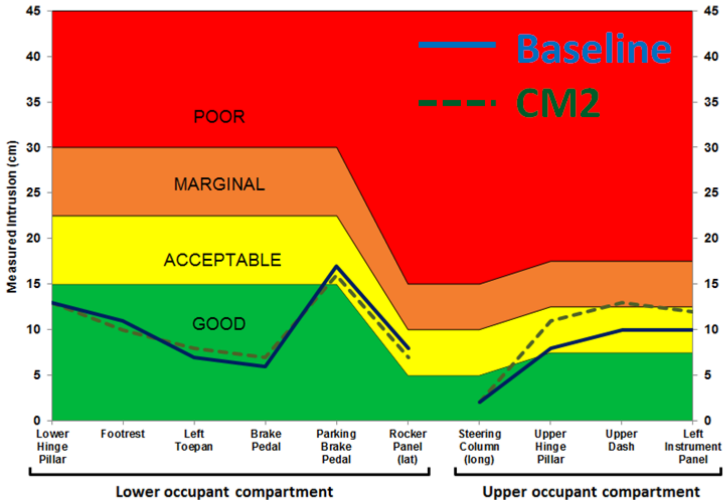


Figure 40(a) - CM2 IIHS SO Intrusion

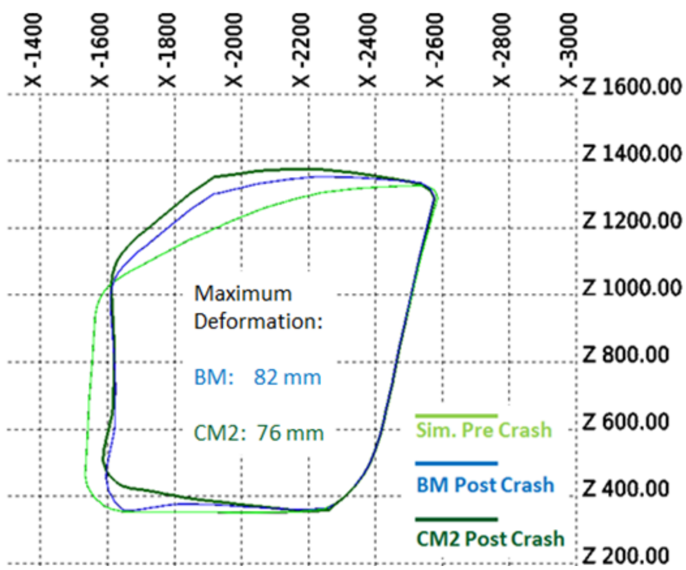


Figure 40(b) - CM2 IIHS SO Door Sill

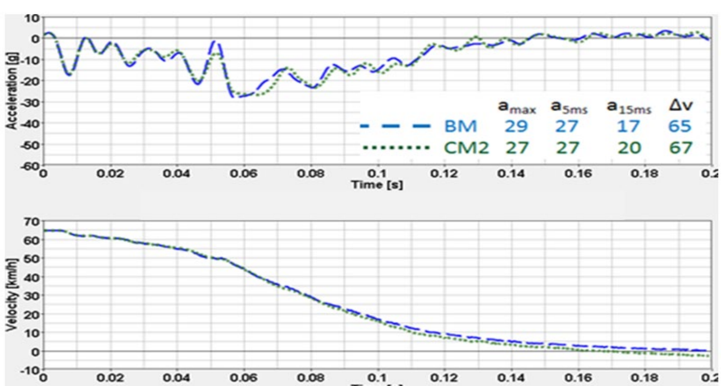


Figure 40(c) - CM2 IIHS SO Vehicle Pulse

Thus, CM2 shows similar occupant compartment intrusion and vehicle pulse characteristics as the BM. No unintended consequences are anticipated for the IIHS small overlap impact due to the implemented design changes.

8.5 CM2 - IIHS Moderate Overlap

The IIHS moderate overlap configuration was used to evaluate the developed Toyota Camry CM2 traveling at 64 km/h into a fixed deformable aluminum honeycomb barrier with an overlap of 40 percent. CM2 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 5.

Figure 41(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM2 simulation using a green dashed line. The implemented structural design changes resulted in a significant reduction in occupant compartment intrusion for the IIHS moderate overlap configuration within the "Good" rating range, according to the IIHS structural rating protocol.

Figure 41(b) depicts the door sill deformation for the BM simulation in blue and the CM2 simulation in dark green. No relevant deformation with respect to the undeformed shape, shown in light green, was observed for BM and CM2.

Figure 41(c) shows the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM2 simulation is shown using a green dotted line. The maximum relevant peak accelerations changed by no more than 1g. The Δv is the same for both simulations. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM2 is therefore predicted.

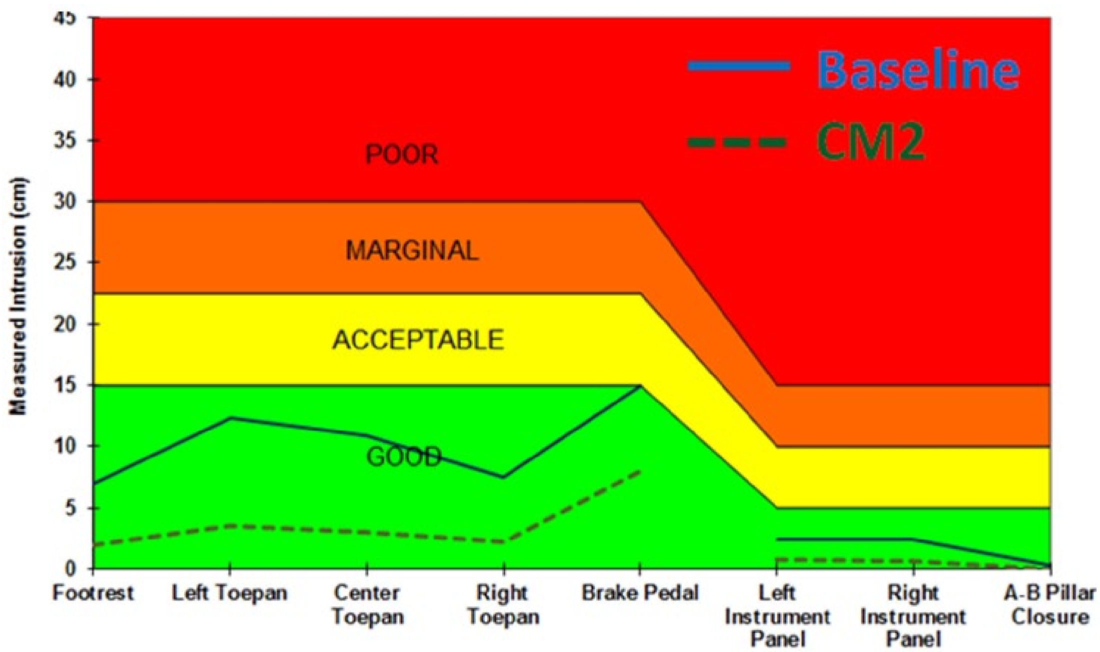


Figure 41(a) - CM2 IIHS MO Intrusion

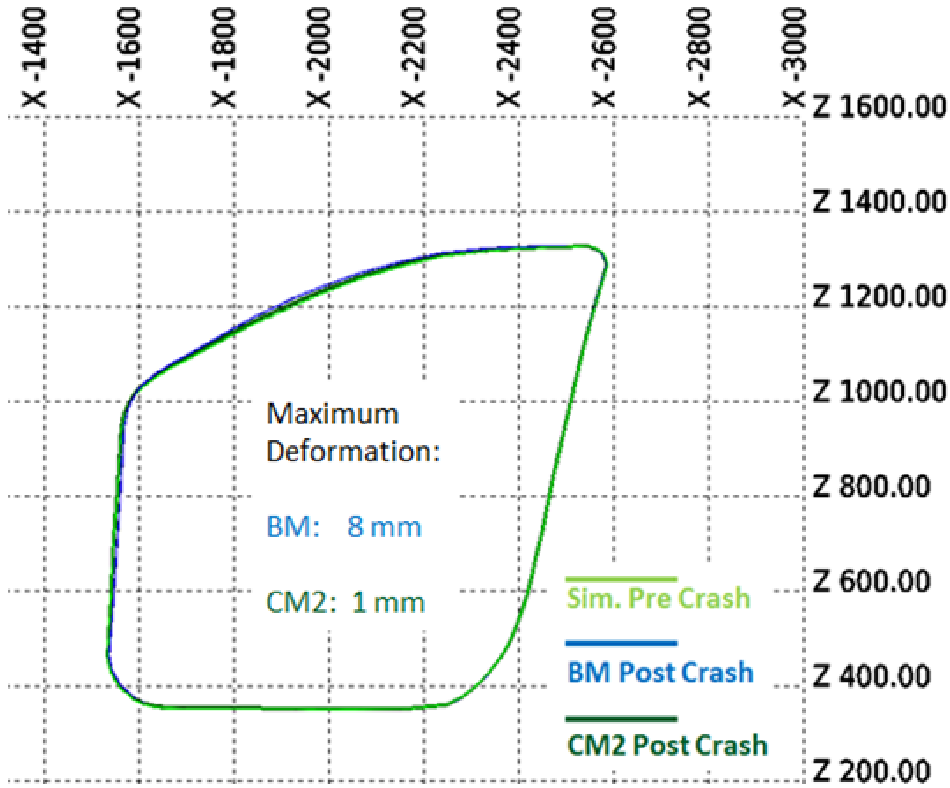


Figure 41(b) - CM2 IIHS MO Door Sill

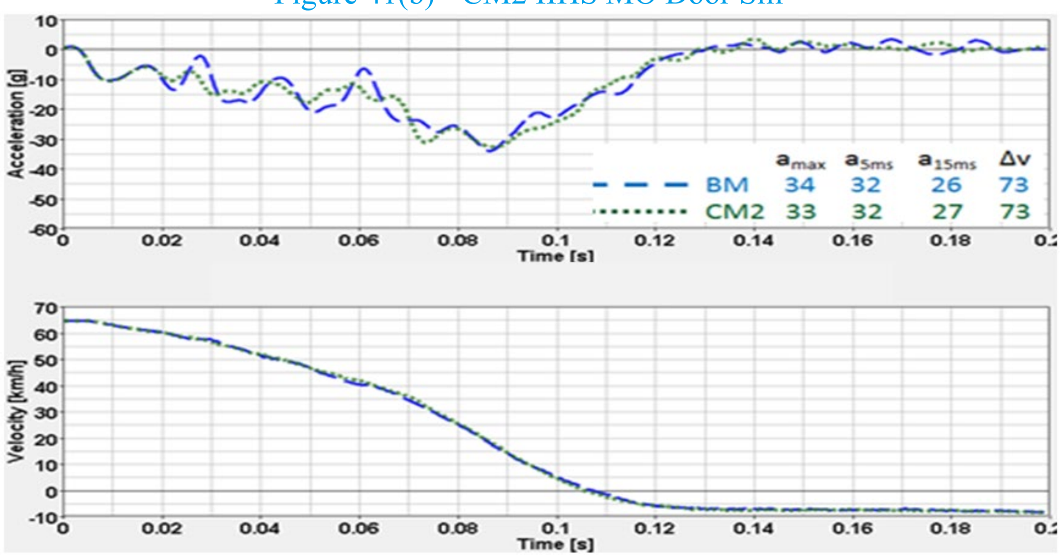


Figure 41(c) - CM2 IIHS MO Vehicle Pulse

Thus, CM2 shows similar occupant compartment intrusion and vehicle pulse characteristics as the BM. No unintended consequences are anticipated for the IIHS moderate overlap impact due to the implemented design changes.

8.6 CM2 - NCAP Full Overlap

NHTSA's NCAP frontal full overlap configuration was exercised to evaluate the developed Toyota Camry CM2 traveling at 56 km/h into a fixed rigid barrier. CM2 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 5.

Figure 42(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM2 simulation using a green dashed line. The implemented structural design changes resulted in a significant reduction in occupant compartment intrusion for the NCAP full overlap configuration.

Figure 42(b) depicts the door sill deformation for the BM simulation in blue and CM2 simulation in dark green. No relevant deformation with respect to the undeformed shape, shown in light green, were observed for BM and CM2.

Figure 42(c) shows the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM2 simulation is shown using a green dotted line. The maximum relevant peak accelerations changed by no more than 3g. The Δv increased by 1 km/h. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM2 is therefore predicted.

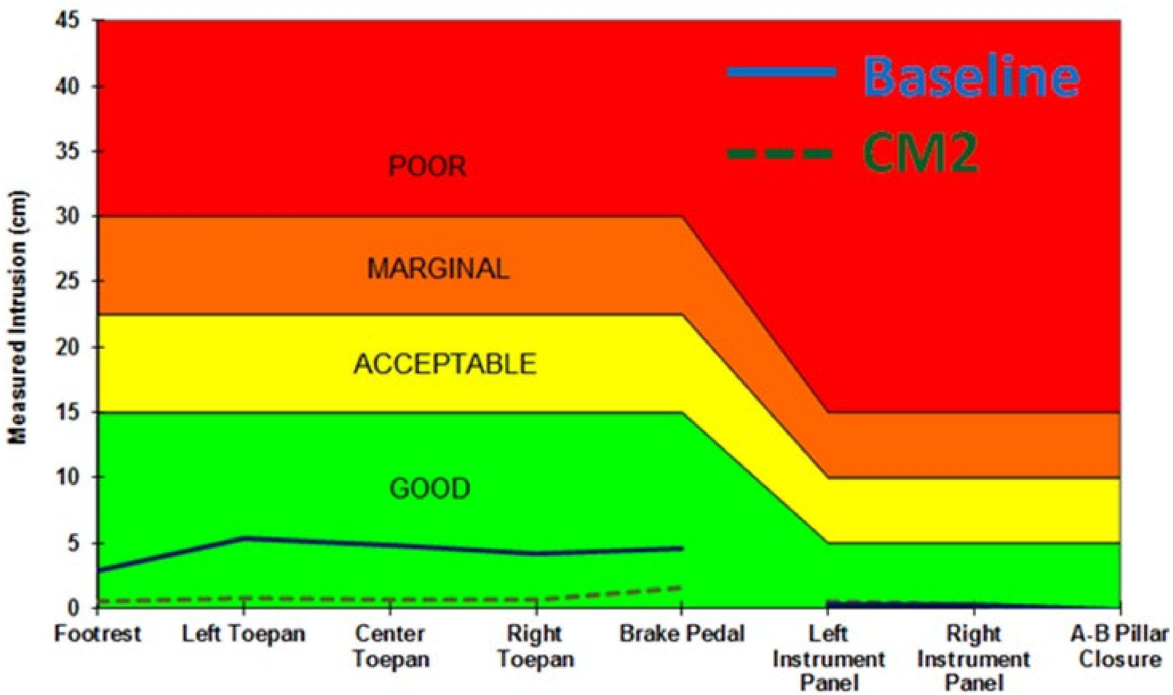


Figure 42(a) - CM2 NCAP (a) Intrusion

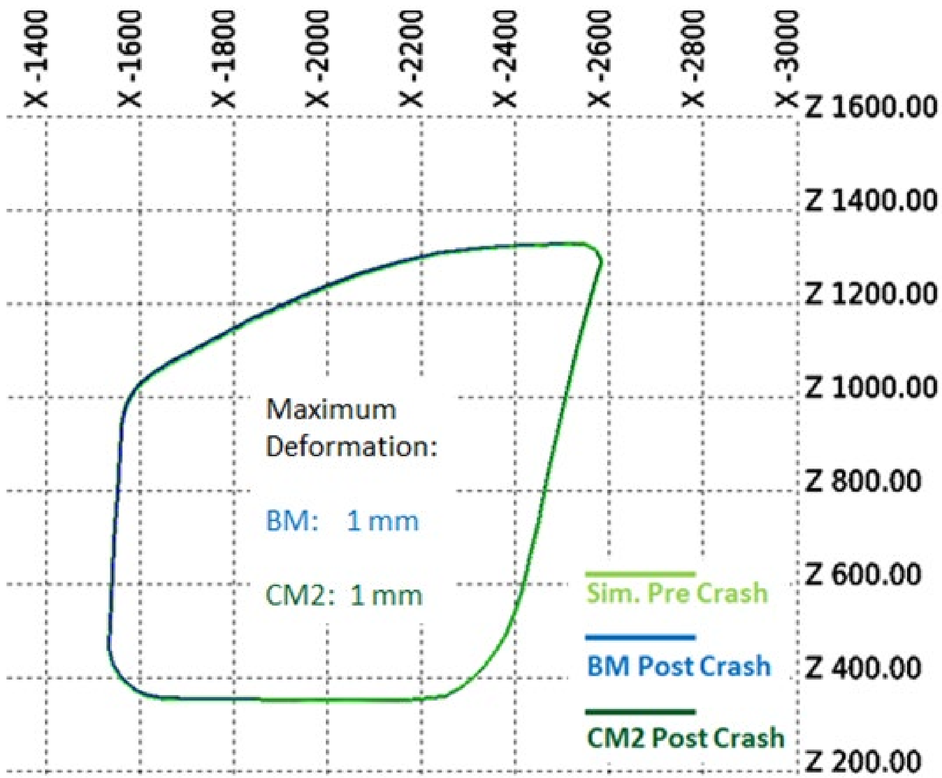


Figure 42(b) - CM2 NCAP Door Sill

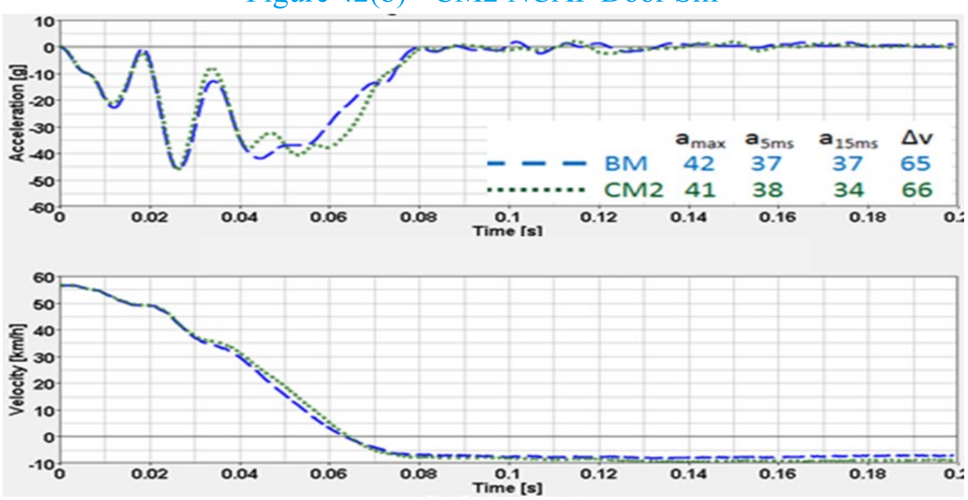


Figure 42(c) - CM2 NCAP Vehicle Pulse

Thus, CM2 shows reduced occupant compartment intrusion and similar vehicle pulse characteristics compared to the BM. No unintended consequences are anticipated for the NCAP full overlap impact due to the implemented design changes.

9. Countermeasure Model 3

The third Countermeasure Model (CM3) was developed to define structural changes to meet the design goals outlined in Chapter 5. Since the right oblique impact showed higher occupant compartment intrusion than the left oblique impact in test and simulation, it was specifically targeting design changes to balance performance for the driver and passenger side.

Figure 43(a) presents an overview of the implemented modifications. Firewall, three components of the right hinge pillar, two parts of the left and right frontal rails, and three parts of the right mid-rail were optimized. Additionally, a firewall support component for the passenger side was created.

To reduce maximum toe-pan intrusion and local buckling, material thickness and material strength were increased for the firewall, shown in pink. Material thickness was also increased for three components of the right hinge pillar, shown in blue. For the inner and middle hinge pillar, material strength was also increased. The material strength for the outer hinge pillar was not changed to allow the same manufacturing stamping process used for the BM. These changes contributed to reduced intrusion and reduced local buckling, specifically in the right oblique impact. The parking brake on the driver side acts as a reinforcement of the hinge pillar area. Therefore, the left hinge pillar components were not changed.

To reduce the load induced into the firewall, material thickness for two parts of the left and right frontal rails, shown in green, were marginally reduced. This contributed to reduction in maximum toe-pan intrusion and local buckling.

Material thickness was increased for all three parts of the right mid-rail. For the mid-rail top and inner, material strength was increased as well. The material strength for the mid-rail bottom was not changed to allow the same manufacturing stamping process as for the BM. These measures reduced local buckling of the mid-rail and resulted in reduced occupant compartment intrusion, specifically for the passenger side

Figure 43(b) illustrates the additional firewall support component on the passenger side. It is shown both in the vehicle environment and enlarged, and was designed to reduce local buckling. The firewall support on the passenger side is similar to the existing firewall support on the driver side. The additional component further reduces occupant compartment intrusion on the passenger side, as compared to the previously analyzed models CM1 and CM2.

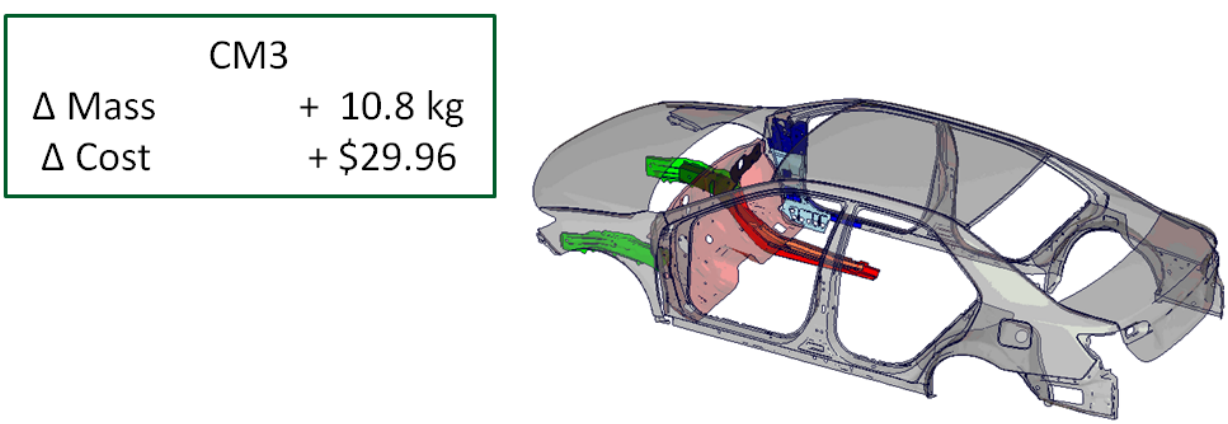


Figure 43(a) - CM3 Overview

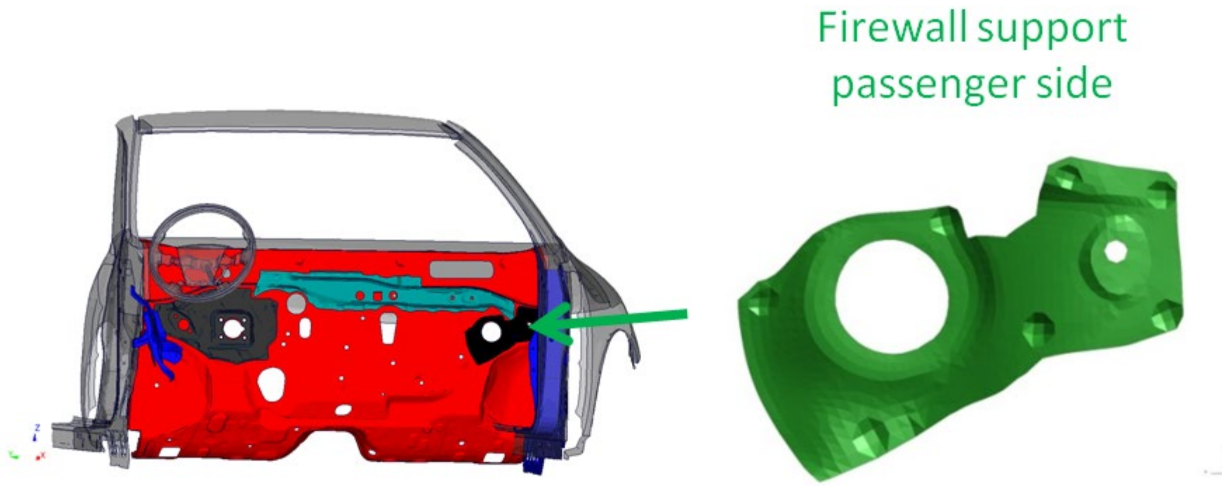


Figure 43(b) - CM3 Firewall Support Passenger Side

9.1 CM3 - Mass and Cost Analysis

Table 6 lists the material grade, material thickness, mass, and cost for the different components in the BM and CM3. The associated incremental change in mass and cost are shown in the last two columns.

For example, row 4 outlines the modification for the inner hinge pillar (a). In the BM, a steel material with 360 MPa yield strength and a thickness of 0.9 mm was used. The respective commercially available steel grade is DP 350/600. The associated mass is 0.9 kg and the associated cost is $1.61. Material cost is the amount of material purchased, which is more than part weight as a result of trimming of the stamping blank as it is formed into the final part, as shown in Figure 8. Stamping yield varies from part to part but on average is 65 percent and is the assumed value in this cost estimate.

In CM3, a steel material with 450 MPa yield strength and a thickness of 1.3 mm is used. The respective commercially available steel grade is DP 500/800. The associated mass is 1.3 kg and the associated cost is $2.42. Hence, the associated change in cost for the hinge pillar (a) is $0.81 and the associated change in mass is 0.4 kg. Mass and cost analysis is combined for left and right side frontal rail components.

Table 6 - CM3: Incremental Cost and Mass Analysis

Part		Baseline Model (BM)					
		Yield Strength {Mpa]	Assumed Grade	Gauge [mm]	Mass [kg]	Price [$/kg]	Cost [$] Based on 65%
Firewall		250	BH 260/370	2.1	19.6	0.91	27.44
Hinge Pillar (a)		360	DP 350/600	0.9	0.9	1.16	1.61
Hinge Pillar (b)		360	DP 350/600	1.1	1.5	1.16	2.68
Hinge Pillar (c)		360	DP 350/600	1.3	1.2	1.16	2.14
Front Rail (a)*		360	DP 350/600	2.8	4.3	1.16	7.67
Front Rail (b)*		360	DP 350/600	2.1	4.2	1.16	7.5
Mid-Rail (a)		360	DP 350/600	1.6	1.9	1.16	3.39
Mid-Rail (b)		360	DP 350/600	1.4	1.2	1.16	2.14
Mid-Rail (c)		360	DP 350/600	2	4.7	1.16	8.39
Firewall Support		-	-	-	0	-	0
* left and right side combined							

Part		Countermeasure Model 3 (CM3)							Delta	
		Yield Strength {Mpa]	Assumed Grade	Gauge [mm]	Mass [kg]	Price [$/kg]	Cost [$] Based on 65%		Δ Cost [$]	Δ Mass [kg]
Firewall		360	DP 350/600	2.9	27	1.16	48.18		20.74	7.4
Hinge Pillar (a)		450	DP 500/800	1.3	1.3	1.21	2.42		0.81	0.4
Hinge Pillar (b)		450	DP 500/800	1.5	2.1	1.21	3.91		1.23	0.6
Hinge Pillar (c)		360	DP 350/600	1.7	1.6	1.16	2.86		0.72	0.4
Front Rail (a)*		360	DP 350/600	2.1	3.6	1.16	6.42		-1.25	-0.7
Front Rail (b)*		360	DP 350/600	1.8	3.4	1.16	6.07		-1.43	-0.8
Mid-Rail (a)		450	DP 500/800	2.1	2.4	1.21	4.47		1.08	0.5
Mid-Rail (b)		450	DP 500/800	1.9	1.6	1.21	2.98		0.84	0.4
Mid-Rail (c)		360	DP 350/600	2.5	5.9	1.16	10.53		2.14	1.2
Firewall Support		450	DP 500/800	2.5	1.4	1.21	5.08		5.08	1.4
* left and right side combined							**Total**		**29.96**	**10.8**

The total change in mass for CM3 is +10.8 kg. The total change in cost for CM3 is +$29.96.

9.2 CM3 - Left Oblique (Driver Side)

NHTSA's left oblique impact configuration was used to evaluate the stationary Toyota Camry CM3 when impacted by an OMDB traveling at a speed of 90 km/h into the front driver side. CM3 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 4. The Toyota Camry was positioned with a 15-degree angle relative to the OMDB and impacted with a 35 percent overlap.

Figure 44(a) illustrates the toe-pan measurement points on the driver side. Figure 44(b) depicts the intrusion values for each point in the BM simulation. The maximum intrusion was recorded for point C1 and the maximum relative intrusion for adjacent points was recorded between points D2 and D3. Figure 44(c) depicts the intrusion values for each point in the CM3 simulation. The maximum intrusion was recorded for point B1 and the maximum relative intrusion for adjacent points was recorded between points B1 and B2. The maximum relative intrusion of adjacent points was reduced from 54 mm to 19 mm, which is equivalent to a 65 percent reduction.

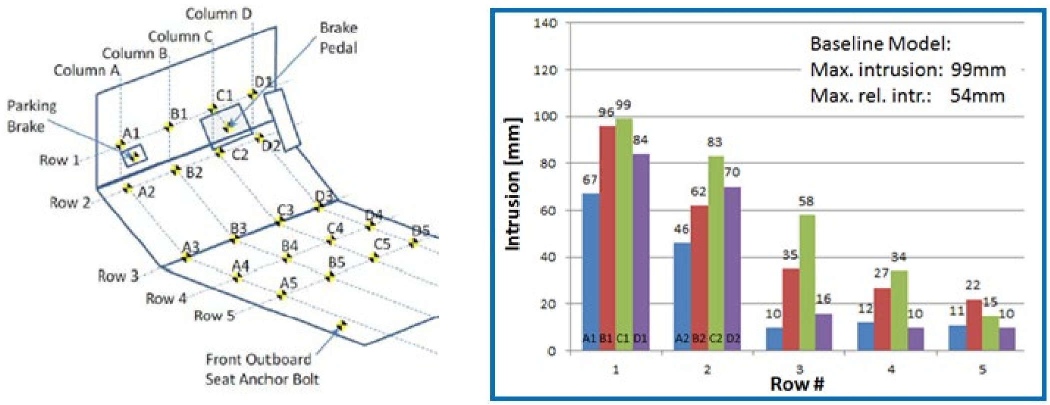


Figure 44 - Left Oblique Toe-Pan Intrusion (a) Measurement Points (b) BM

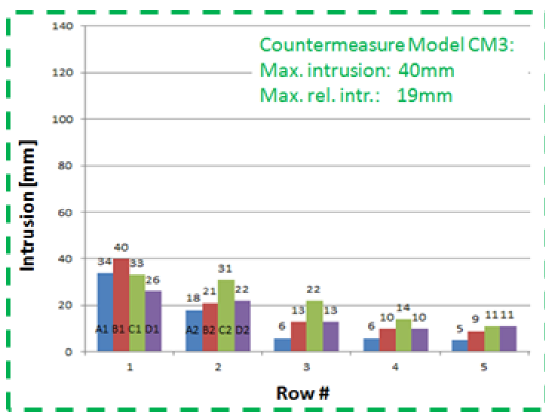


Figure 44(c) - Left Oblique Toe-Pan Intrusion CM3

Figure 45(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM3 simulation using a green dashed line in the adapted IIHS moderate overlap chart. The maximum toe-pan intrusion in the left oblique impact was reduced from 99 mm to 40 mm, which is equivalent to a 60 percent reduction.

Figure 45(b) depicts the door sill deformation for the BM simulation in blue and the CM3 simulation in dark green. The maximum door sill deformation was reduced from 25 mm to 14 mm. Both values are considered moderate.

Figure 45(c) shows the comparison of the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM3 simulation is shown using a green dotted line. The maximum peak acceleration a_{max} increased from 43g to 44g. The maximum peak acceleration that lasted 5 milliseconds (a_{5ms}) increased from 41g to 43g. The maximum peak acceleration that lasted 15 milliseconds (a_{15ms}) increased from 37g to 39g. No difference with respect to Δv was observed. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes is therefore predicted.

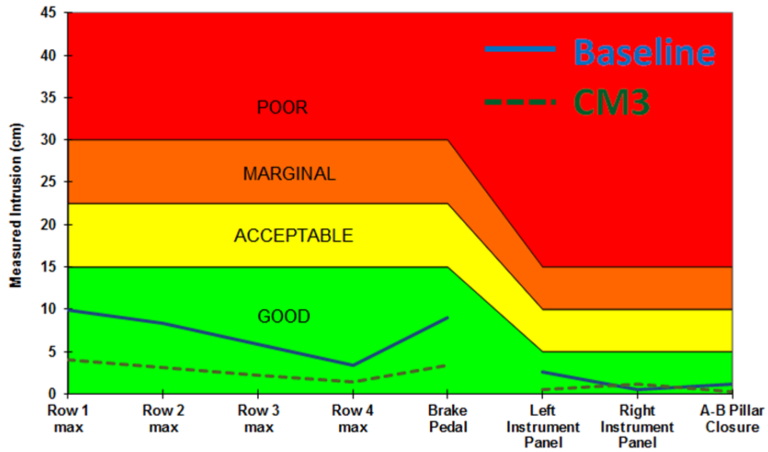


Figure 45 - CM3 Left Oblique (a) Intrusion (b) Door Sill (c) Vehicle Pulse

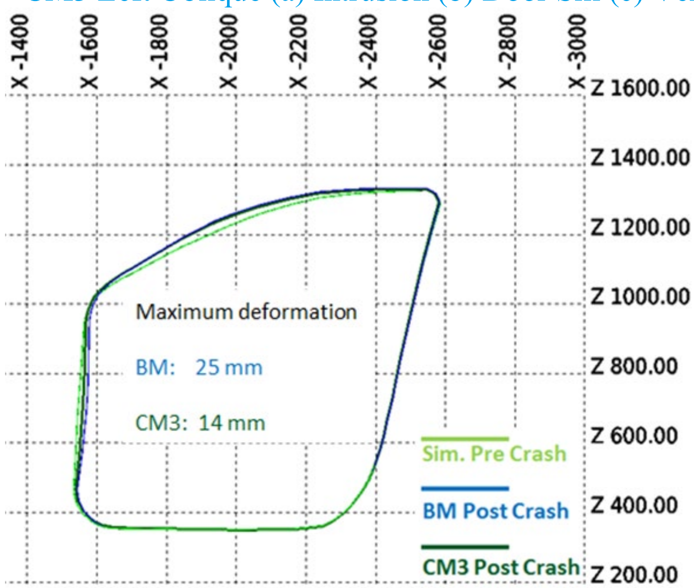


Figure 45 - CM3 Left Oblique (a) Intrusion (b) Door Sill (c) Vehicle Pulse

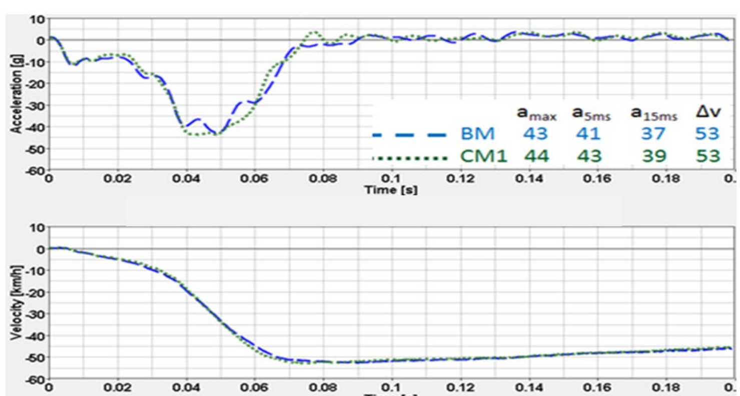


Figure 45 - CM3 Left Oblique (a) Intrusion (b) Door Sill (c) Vehicle Pulse

Thus, CM3 fulfills all design goals defined in Chapter 5 for the left oblique impact configuration. The absolute maximum intrusion was reduced from 99 mm to 40 mm, which is equivalent to a 60 percent reduction.

9.3 CM3 - Right Oblique (Passenger Side)

NHTSA's right oblique impact configuration was exercised to evaluate the stationary Toyota Camry CM3 when impacted by an OMDB traveling at a speed of 90 km/h into the front passenger side. CM3 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 4. The model was positioned with a 15-degree angle relative to the OMDB and impacted with a 35 percent overlap.

Figure 46(a) illustrates the toe-pan measurement points on the passenger side. Figure 46(b) depicts the intrusion values for each point in the BM simulation. The maximum intrusion was recorded for point B1 and the maximum relative intrusion for adjacent points was recorded between points A2 and A3. Figure 46(c) depicts the intrusion values for each point in the CM3 simulation. The maximum intrusion was recorded for point C1 and the maximum relative intrusion for adjacent points was recorded between points C1 and C2. The maximum relative intrusion of adjacent points was reduced from 68 mm to 30 mm, which is equivalent to a 56 percent reduction.

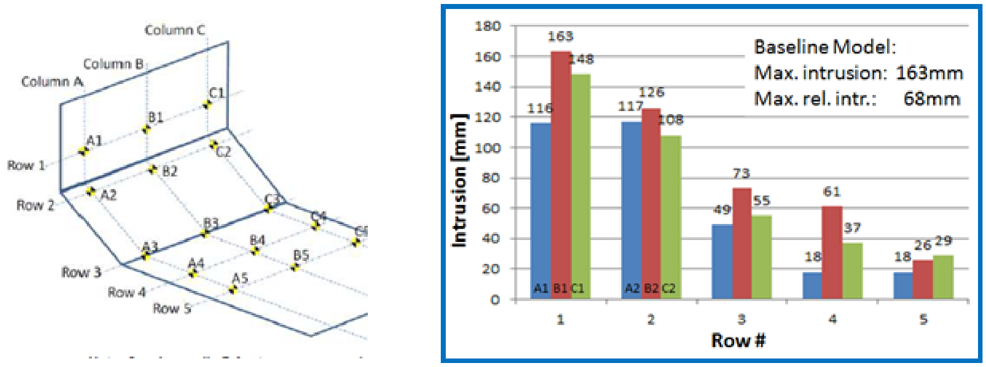


Figure 46 - Right Oblique Toe Pan Intrusion (a) Measurement Points, (b) BM

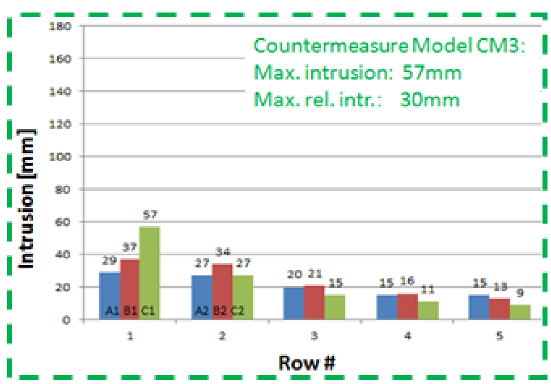


Figure 46(c) - Right Oblique Toe Pan Intrusion CM3

Figure 47(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM3 simulation using a green dashed line in the adapted IIHS moderate overlap chart. The maximum toe-pan intrusion in the right oblique impact was reduced from 163 mm to 57 mm, which is equivalent to a 65 percent reduction.

Figure 47(b) depicts the door sill deformation for the BM simulation in blue and the CM3 simulation in dark green. The maximum door sill deformation was reduced from 35 mm to 8 mm. Both values are considered moderate.

Figure 47(c) shows the comparison of the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM3 simulation is shown using a green dotted line. The maximum peak acceleration a_{max} increased from 41g to 47g. The maximum peak acceleration that lasted 5 milliseconds (a_{5ms}) increased from 37g to 40g. The maximum peak acceleration that lasted 15 milliseconds (a_{15ms}) remained unchanged at 29g. The Δv decreased from 53 km/h to 52 km/h. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM3 is therefore predicted.

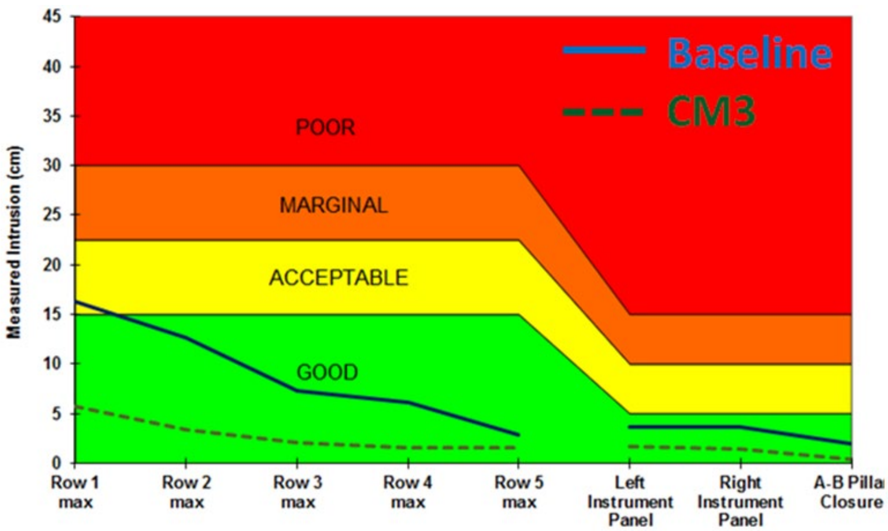


Figure 47 - Right Oblique (a) Intrusion, (b) Door Sill

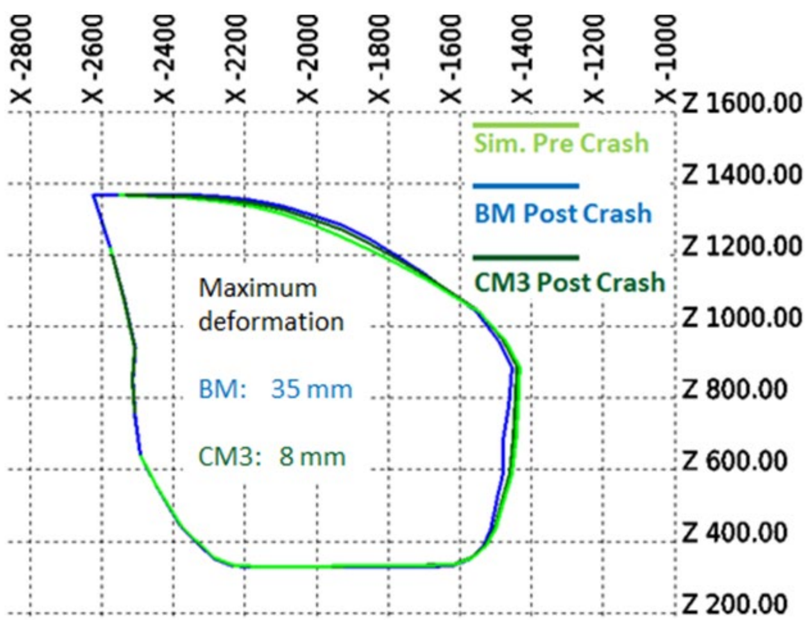


Figure 47(b) - Right Oblique Intrusion

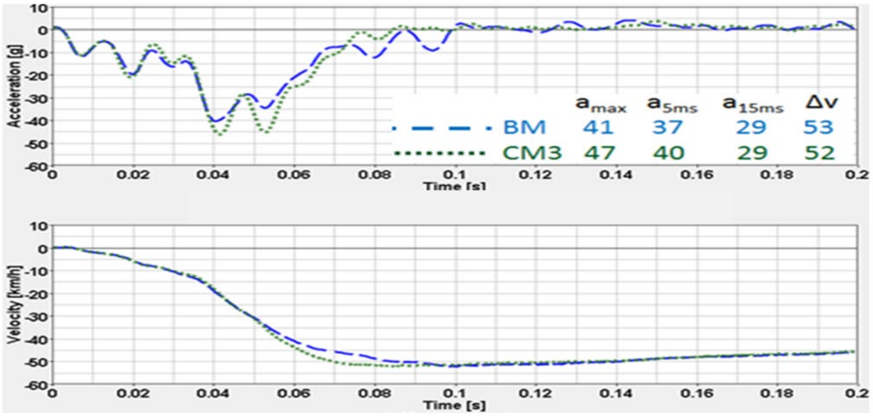


Figure 47(c) - Right Oblique Vehicle Pulse

Thus, CM3 fulfills all design goals defined in Chapter 5 for the right oblique impact configuration. The absolute maximum intrusion was reduced from 163 mm to 57 mm, which is equivalent to a 65 percent reduction.

9.4 CM3 - IIHS Small Overlap

The IIHS small overlap test configuration was used to evaluate the developed Toyota Camry CM3 traveling at 64 km/h into a fixed rigid barrier with a 25 percent overlap. CM3 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 4.

Figure 48(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM3 simulation using a green dashed line. Similar maximum intrusion values result in an Acceptable rating according to the IIHS structural rating protocol for both models.

Figure 48(b) depicts the door sill deformation for the BM simulation in blue and the CM3 simulation in dark green. Similar maximum values with respect to the undeformed shape, shown in light green, was observed.

Figure 48(c) shows the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM3 simulation is shown using a green dotted line. The maximum relevant peak accelerations changed by no more than 2g. No difference with respect to Δv was observed. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM3 is therefore predicted.

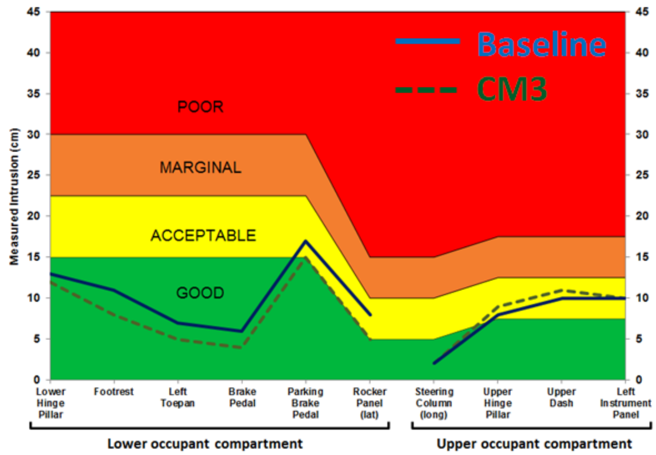


Figure 48 - CM3 IIHS SO (a) Intrusion (b) Door Sill (c) Vehicle Pulse

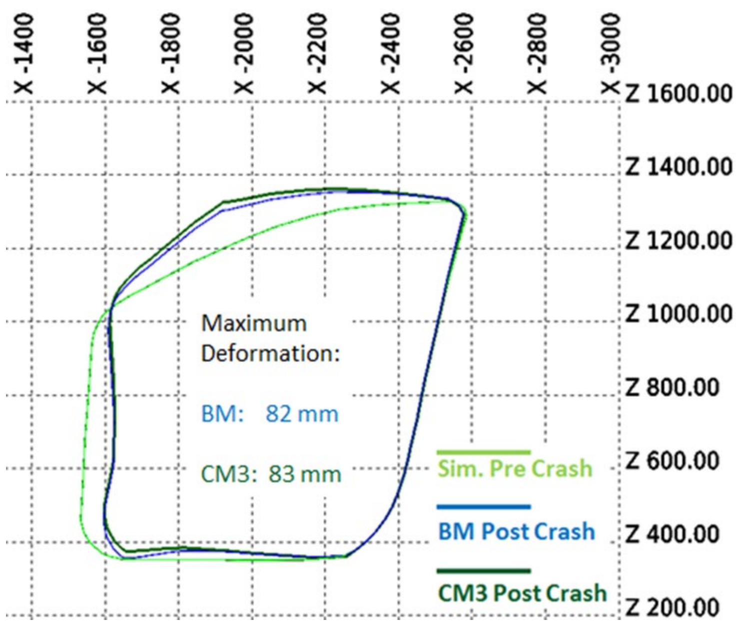


Figure 48 - CM3 IIHS SO (a) Intrusion (b) Door Sill (c) Vehicle Pulse

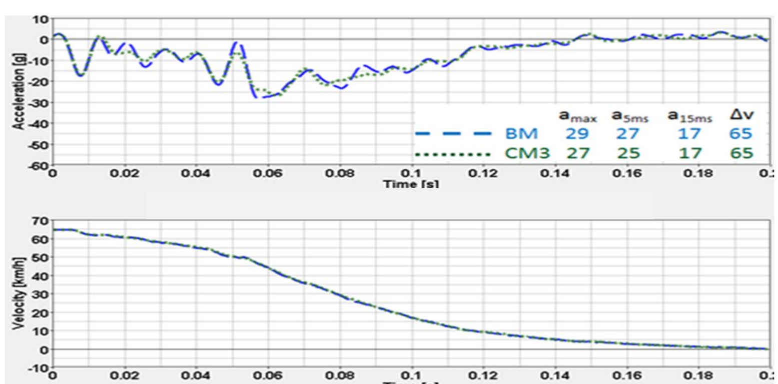


Figure 48 - CM3 IIHS SO (a) Intrusion (b) Door Sill (c) Vehicle Pulse

Thus, CM3 shows similar occupant compartment intrusion and vehicle pulse characteristics as the BM. No unintended consequences are anticipated for the IIHS small overlap impact due to the implemented design changes.

9.5 CM3 - IIHS Moderate Overlap

The IIHS moderate overlap configuration was exercised to evaluate the developed Toyota Camry CM3 traveling at 64 km/h into a fixed deformable aluminum honeycomb barrier with an overlap of 40 percent. CM3 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 5.

Figure 49(a) illustrates the intrusion characteristics for the BM simulation using a blue solid line and for the CM3 simulation using a green dashed line. The implemented structural design changes resulted in a significant reduction in occupant compartment intrusion for the IIHS moderate overlap configuration within the "Good" rating range, according to the IIHS structural rating protocol.

Figure 49(b) depicts the door sill deformation for the BM simulation in blue and the CM3 simulation in dark green. No relevant deformation with respect to the undeformed shape, shown in light green, was observed for BM and CM3.

Figure 49(c) shows the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM3 simulation is shown using a green dotted line. The maximum relevant peak accelerations increased by no more than 1g. The Δv increased by 1 km/h. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM3 is therefore predicted.

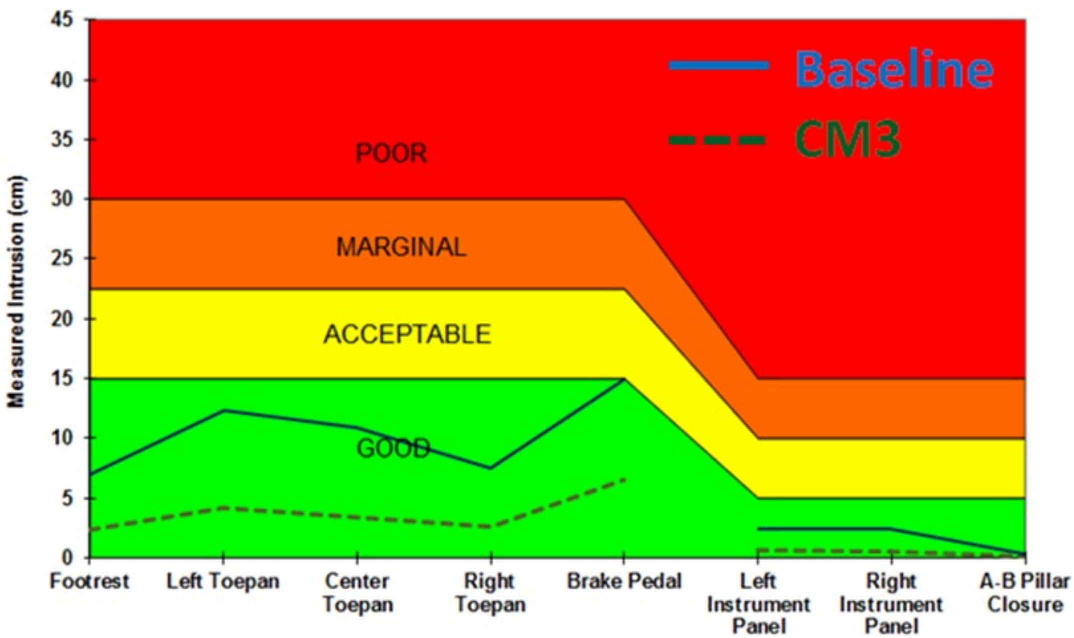


Figure 49(a) - CM3 IIHS MO Intrusion

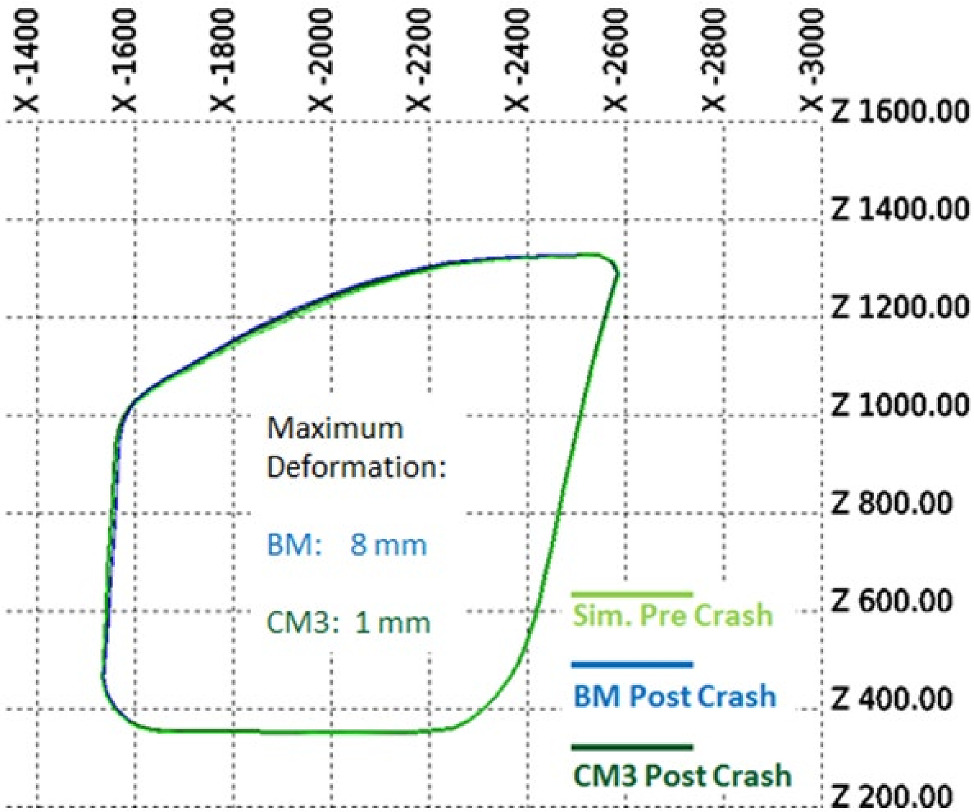


Figure 49(b) - CM3 IIHS MO Door Sill

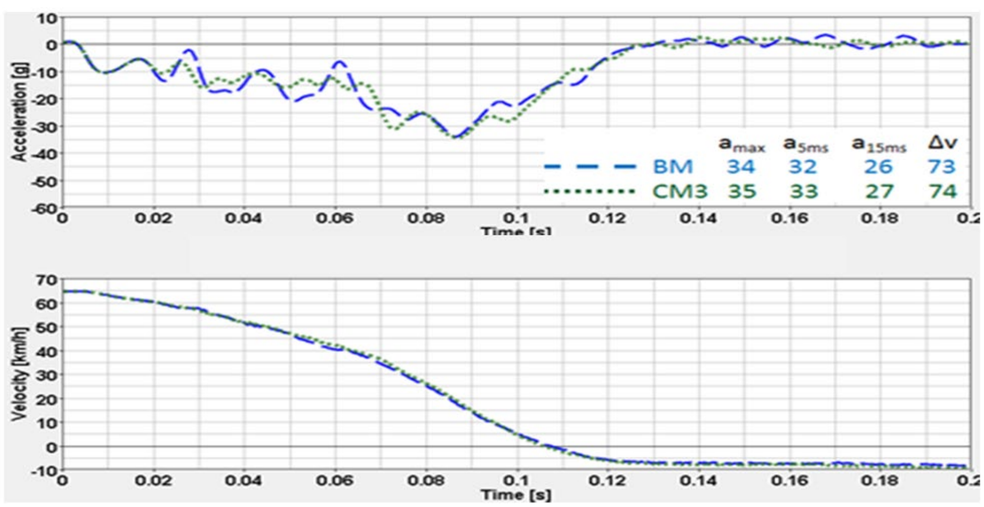


Figure 49(c) - CM3 IIHS MO Vehicle Pulse

Thus, CM3 shows reduced occupant compartment intrusion and similar vehicle pulse characteristics compared to the BM. No unintended consequences are anticipated for the IIHS moderate overlap impact due to the implemented design changes.

9.6 CM3 - NCAP Full Overlap

NHTSA's NCAP frontal full overlap configuration was used to evaluate the developed Toyota Camry CM3 traveling at 56 km/h into a fixed rigid barrier. CM3 simulation results are compared against the respective BM simulation. The BM showed good correlation with respect to various test results of a 2015 Toyota Camry, as outlined in Chapter 5.

Figure 50(a) illustrates the intrusion characteristics for the BM using a blue solid line and for the CM3 using a green dashed line. The implemented structural design changes resulted in a significant reduction in occupant compartment intrusion for the NCAP full overlap configuration.

Figure 50(b) depicts the door sill deformation for the BM simulation in blue and the CM3 simulation in dark green. No relevant deformation with respect to the undeformed shape, shown in light green, was observed for BM and CM3.

Figure 50(c) shows the vehicle acceleration pulse on the top and vehicle velocity pulse on the bottom. The BM simulation is shown using a blue dashed line and the CM3 simulation is shown using a green dotted line. The maximum relevant peak accelerations increased by no more than 1g. No difference with respect to Δv was observed. The change in vehicle pulse is considered moderate. No significant effect with respect to restraint system performance and occupant injury risk due to the introduced structural changes for CM3 is therefore predicted.

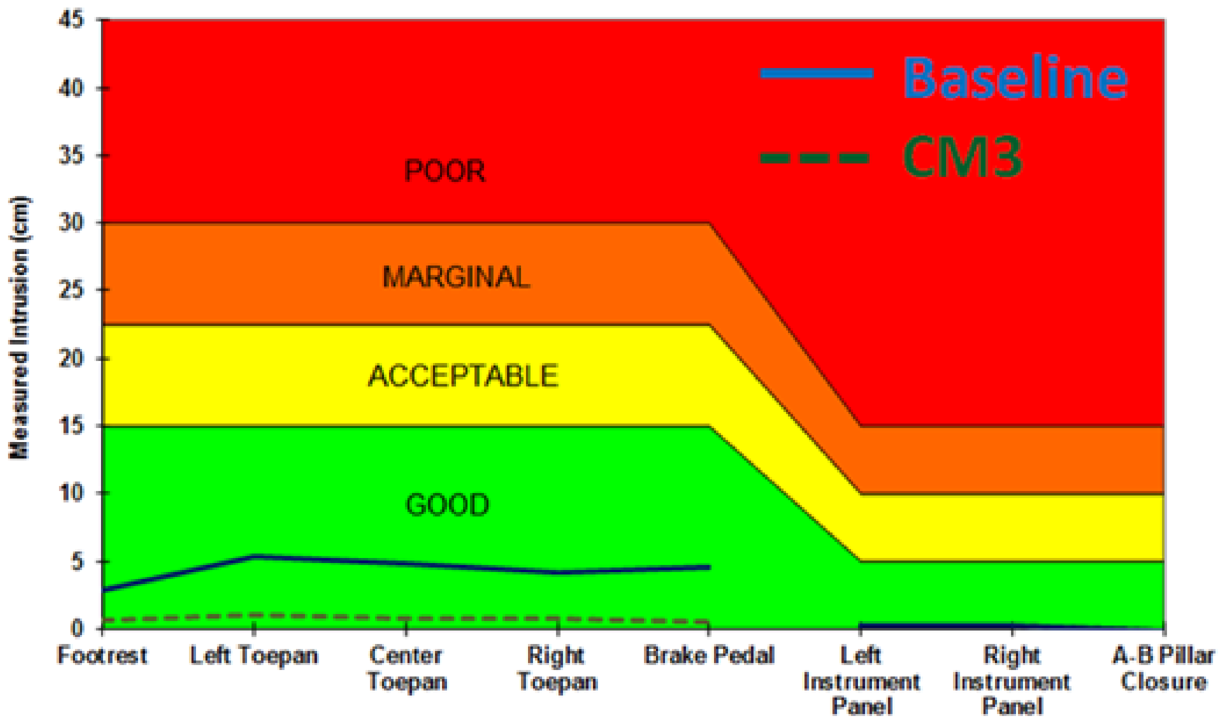


Figure 50(a) - CM3 NCAP Intrusion

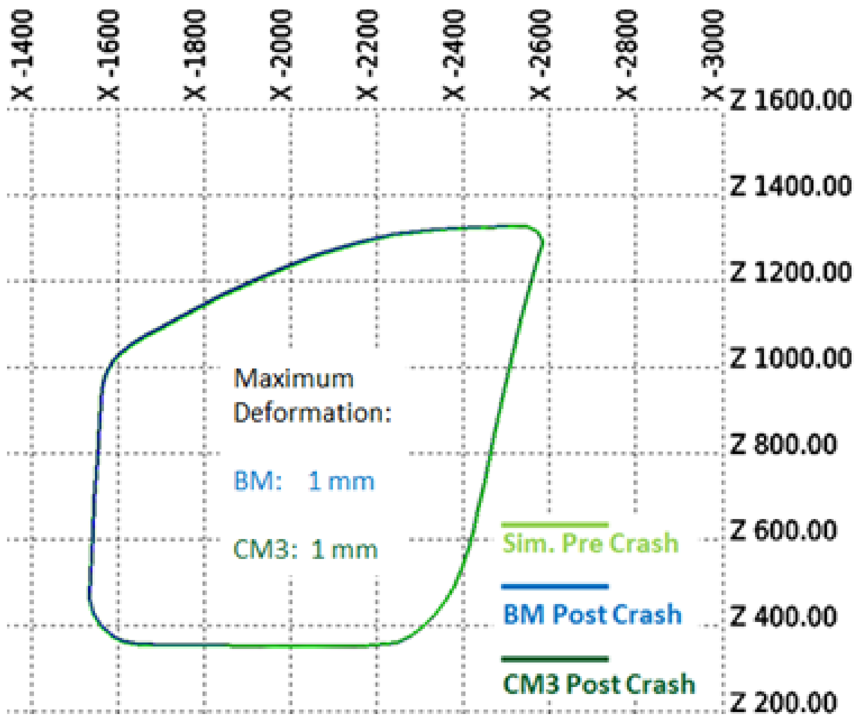


Figure 50(b) - CM3 NCAP Door Sill

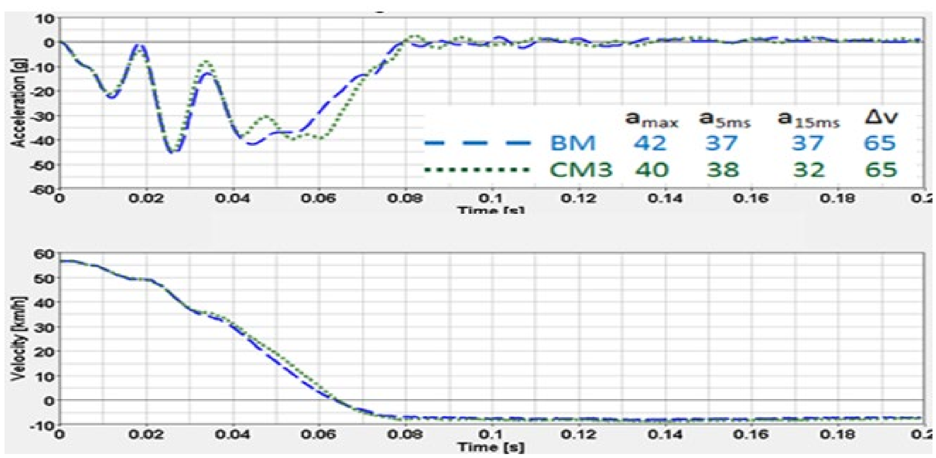


Figure 50(c) - CM3 NCAP Vehicle Pulse

Thus, CM3 shows reduced occupant compartment intrusion and similar vehicle pulse characteristics compared to the BM. No unintended consequences are anticipated for the NCAP full overlap impact due to the implemented design changes.

Occupant risk analysis, vehicle durability, and fatigue performance were not part of this study. Additional research in concert with restraint systems and occupants would ensure that the optimized structure does not adversely affect the measured occupant injury predictions.

10. Conclusion

Recent studies with respect to oblique crashes and related injury risk were evaluated, as referenced in Chapter 1. NHTSA found that oblique crashes represent common real-world accident patterns. The risk of injury is often higher than in co-linear crashes.

CCSA analyzed left oblique tests regarding intrusion patterns and related injury risk. It was concluded that vehicles with higher occupant compartment intrusion tended to have higher risk of lower extremity injury.

IIHS compared the performance of 25 vehicles in the left oblique and IIHS small overlap impact configurations. It was found that the risk of lower extremity injury, applying respective metrics for the different dummies used, was higher in the oblique impact condition.

The development of countermeasures for both restraints and vehicle structure will therefore potentially improve vehicle safety and reduce injury risk in the future.

NHTSA has contracted the CCSA to evaluate structural countermeasures, including associated mass and cost, to reduce occupant compartment intrusion in the oblique impact condition.

A vehicle that performs well in the IIHS small overlap, the IIHS moderate overlap, and in the NCAP full overlap test was selected.

A finite element model of an appropriate mid-sized passenger vehicle was developed and validated to match the acceleration and intrusion measurements available from full-scale crash tests. Baseline simulations were conducted for frontal NCAP full overlap, IIHS moderate overlap, IIHS small overlap, left and right oblique impact configurations. The simulation results were compared to available crash test data and rated using the objective correlation evaluation tool CORA.

Baseline simulations using the developed finite element model show that it suitably represents the structural crash characteristics of a 2015 Toyota Camry, as summarized in Table 7.

Table 7 - Baseline Simulations Summary

	Test (Intrusion)	Simulation (Intrusion)	Acceleration Pulse (CORA rating)	Velocity Pulse (CORA rating)
IIHS Small Overlap	Acceptable	Acceptable	0.69 (acceptable)	0.75 (acceptable)
IIHS Moderate Overlap	Good	Good	No test data	No test data
NCAP Full Overlap	4/5-Star	4/5-Star	0.86 (good)	0.98 (good)
Left Oblique (Driver Side)	Good correlation		0.94 (good)	0.96 (good)
Right Oblique (Pass. Side)	Good correlation		0.93 (good)	0.96 (good)

Crash mechanisms that specifically contribute to high toe-pan intrusion in the oblique impact condition were analyzed. Local deformation and buckling of the toe-pan, a high load introduced by the longitudinal rails, and local buckling of the mid-rails were found to be mainly responsible for producing high intrusions for both left-side and right-side oblique configurations. Deformation of the right rocker-pillar and upper firewall area at the passenger side were found to produce additional occupant compartment intrusion, specifically for the right-side oblique impact. The parking brake and left firewall support, which only exist on the driver side, stabilize these areas for the left-side oblique impact.

Baseline simulation results were used to establish design goals to minimize occupant compartment intrusion. A 50 percent reduction of the maximum intrusion was defined as the main design goal. To reduce local buckling and maintain a more continuous shape of the deformed toe-pan, a second design goal was to reduce intrusion of adjacent measurement points by at least 50 percent as well. Maintaining moderate door sill deformation was defined as a third design goal. Lastly, a fourth design goal was to maintain moderate vehicle pulses in all impact configurations as a prerequisite for good restraint system performance and low injury risk in current and future rating tests.

Structural countermeasures to significantly reduce occupant compartment intrusion in the oblique impact condition were developed according to the previously defined design goals. Three countermeasure models with different specific foci were developed. CM1 represents minimum requirements to fulfill the defined design goals. CM2 aims to reduce the maximum intrusion for the left and right oblique condition to 50 mm or less, which is equivalent to a 66 percent reduction for the passenger side configuration. CM3 was developed to balance occupant compartment intrusion for left and right side. Therefore, some countermeasures were developed specifically for the passenger side.

As an example, Figure 51 is a visualization of the occupant compartment intrusion for CM2. Results for the driver side in the left oblique impact are shown on the left and for the passenger side in the right oblique impact are shown on the right. On the top cross section view, intrusions for the BM are shown in blue and for the CM2 in green. In the middle, intrusions for the BM are represented using a color code where a darker color means a higher intrusion. The same color code is used on the bottom for CM2, showing a significant reduction of occupant compartment intrusion.

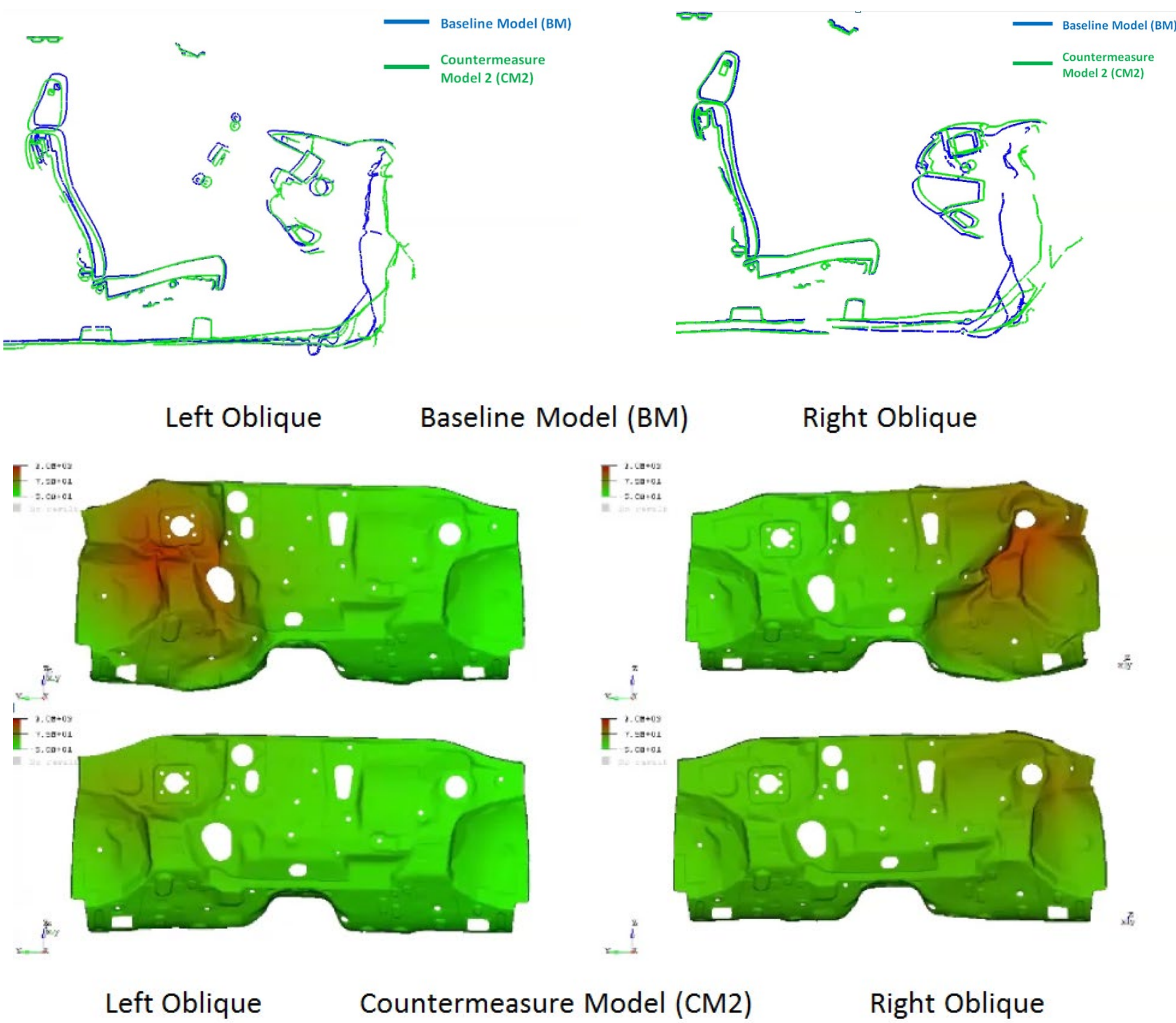


Figure 51 – Left and Right Oblique BM Versus CM2

Table 8 summarizes the design changes for the countermeasure models CM1, CM2, and CM3.

Table 8 - Countermeasure Models Overview

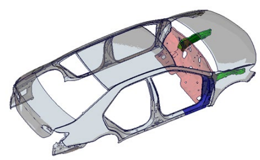
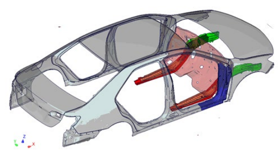
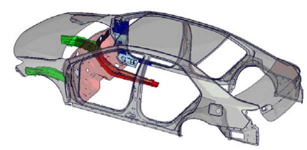
	CM1	CM2	CM3
			
Firewall with increased thickness and strength	✓	✓	✓
Left and right front rail parts with reduced thickness	✓	✓	✓
Left mid-rail with increased thickness and strength		✓	
Right mid-rail with increased thickness and strength		✓	✓
Right rocker pillar with increased thickness and strength	✓	✓	✓
Additional firewall support on passenger side			✓
	Minimum Design Changes	Max. Intrusion $\leq$ 50mm for left & right oblique	Balanced crash performance for left & right oblique

Table 9 summarizes the associated incremental change in mass and cost, as well as the percentage amount of occupant compartment intrusion reduction for the developed countermeasure models CM1, CM2, and CM3 with respect to the baseline model.

CM1 fulfills all design goals defined in Chapter 5 for the left and right oblique impact configurations. The maximum intrusion was reduced from 99 mm to 39 mm (61 percent) for the left and from 163 mm to 78 mm (52 percent) for the right oblique impact.

CM2 fulfills all design goals for the left and right oblique impact configurations. The maximum intrusion was reduced from 99 mm to 23 mm (77 percent) for the left and from 163 mm to 50 mm (69%) for the right oblique impact.

CM3 fulfills all design goals for the left and right oblique impact configurations. The maximum intrusion was reduced from 99 mm to 40 mm (60%) for the left and from 163 mm to 56 mm (65%) for the right oblique impact.

The structural countermeasures developed for the oblique impact condition had no substantial effect on the IIHS small overlap test and resulted in a significant reduction in occupant compartment intrusion for the NCAP full overlap and IIHS moderate overlap configurations. Moderate vehicle pulses, which allow a 5-Star NCAP, Good IIHS MO, and Acceptable IIHS SO rating results, were conserved for all three countermeasure models.

Table 9 - Summary of Results

	Δ Mass [kg]	Δ Cost [$]	Left Oblique: Max. Intrusion Reduction	Right Oblique: Max. Intrusion Reduction	All Design Goals Fulfilled	No Unintended Consequences for NCAP, IIHS MO & SO
CM1	7.3	20.83	61%	52%	✓	✓
CM2	17.3	39.04	77%	69%	✓	✓
CM3	10.8	29.96	60%	65%	✓	✓

In summary, structural countermeasures were developed that reduce the maximum occupant compartment intrusion in the oblique impact condition between 52 percent and 77 percent. The associated added mass ranges from 7 kg to 17 kg and the associated cost ranges from almost $21 to $39. The associated impact on fuel economy is considered small. The significant reduction in occupant compartment intrusion was accomplished without unintended consequences, such as considerable increase of vehicle pulse for oblique and co-linear load cases.

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