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April 2018

Structural Countermeasure/ Research Program:

Mass and Cost Increase Due to Oblique Offset Moving Deformable Barrier Impact Test

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16. Abstract

NHTSA awarded a contract to EDAG, Inc., to identify changes to a vehicle’s structure in order to reduce the occupant compartment intrusions from NHTSA’s oblique offset frontal crash condition.

Review of test results and literature indicated that for the four passenger car segments, sub-compact, compact, mid-size and large car, the sub-compacts structural performance have higher structural intrusions and higher passenger compartment decelerations from the other three and would require more significant changes. Vehicles studied were:

1. Mid-Size sedan structure – 2014 Honda Accord, representing passenger cars; and
2. Light Duty pickup structure – 2014 Chevrolet Silverado 1500.

Additional structural reinforcements required to reduce the passenger compartment intrusions added a mass of 4.3 kg to the 2014 Accord costing $24.37. Changes to the 2014 Silverado to improve performance in the IIHS small overlap test add 9.0 kg costing $17.35.

The study considered structural reinforcement of both the driver and passenger sides of the vehicle for left- and right-side oblique offset impacts.

17. Key Word
mass and cost increase, oblique offset moving deformable barrier impact test

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Executive Summary

The National Highway Traffic Safety Administration awarded a contract to an automotive design and engineering company, EDAG, Inc., to identify necessary changes to a vehicle's structure in order to reduce the occupant compartment intrusions from NHTSA's oblique offset frontal[1] crash condition. The vehicles to be studied should meet the structural intrusion requirements for a "Good" or "Acceptable" structural rating in the Insurance Institute of Highway Safety (IIHS) small overlap test, a "Good" rating in the IIHS moderate overlap test, and a 5-star rating in the New Car Assessment Program (NCAP) frontal impact test.

Review of NHTSA's oblique test results and published literature indicated that for the four passenger car segments, sub-compact, compact, midsize, and large car, the sub-compact's structural performance is significantly different (higher structural intrusions, higher passenger compartment decelerations) from the other three segments. The necessary design changes to the vehicle's structure to reduce the occupant compartment intrusions will be significantly different for each of these categories. The sub-compact car structure would require more significant changes compared to the other passenger car segments. The least amount of change would be required for the pickup truck vehicles. In order to obtain the most accurate assessment of mass and cost for the structural changes for the passenger car segment and for the pickup truck segment, the following studies were completed under Contract DTNH22-15-D-00006.

3. Midsize sedan structure – A 2014 model year (MY) Honda Accord was analyzed to represent passenger cars. The results from this can be scaled to compact and large-car segments, and possibly also to unibody-structure-based mini-van and SUV segments

4. Light-duty pickup structure – A 2014 MY Chevrolet Silverado 1500 was analyzed to represent pickup trucks. The results from this can be scaled to cab-on-frame-based SUV segments.

Additional structural reinforcements required to reduce the passenger compartment intrusions added a mass of 4.3 kg to the Honda Accord body structure at cost of $24.37. The changes to the Silverado 1500 structure are predominantly required to improve the performance for the IIHS small overlap test, to bring the vehicle to the "Acceptable" IIHS rating. These changes add 9.0 kg to the Silverado 1500 at a cost of $17.35 and are also beneficial to the NHTSA offset oblique test.

The study considered structural reinforcement of both the driver and passenger sides of the vehicle for left- and right-side oblique offset impacts. The recommended designs verified through CAE modeling that all relevant crash tests performance requirements were met. All modeled test results were comparable to the actual crash tests performed on the Honda Accord and Silverado 1500. The LS-DYNA finite element software used by the EDAG team is an

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[1] National Highway Traffic Safety Administration. (2015, December 5). Laboratory test procedure for oblique offset moving deformable barrier impact test (Memorandum/Report. Docket No. NHTSA-2015-0119-0017). Washington, DC: Author. Available at www.regulations.gov/contentStreamer?documentId=NHTSA-2015-0119-0017&attachmentNumber=1&contentType=pdf

industry standard for crash simulation and modeling. The generated LS-DYNA models may also be helpful for conducting future vehicle to vehicle crash analysis and other safety studies. These CAE models are also suitable for updating to include vehicle interiors for assessment of restraint systems with the use of crash test dummies and human body models.

1 Introduction and Scope of Work

1.1 Purpose

The objective of this task order was to demonstrate necessary changes to a vehicle's structure in order to reduce the occupant compartment intrusion from NHTSA's oblique offset frontal crash condition. The vehicle to be studied was to meet the structural intrusion requirements for a "Good" or "Acceptable" structural rating in the IIHS small overlap test. The "Good" rating in IIHS moderate overlap test and the 5-star NCAP frontal test rating.

This task order was expected to define the incremental vehicle design change requirements and their associated costs in order to reduce significant occupant intrusion from the NHTSA oblique offset frontal crash condition. It considers structural reinforcement of both the driver and passenger sides of the vehicle for left- and right-side oblique offset impacts.

This task order was conducted using finite element simulation vehicle models that have demonstrated good performance in NCAP frontal, IIHS moderate offset, and IIHS small overlap test conditions. This task order did not require modeling of the crash test dummy. More specifically, the objectives as stated in the task order were to:

- Identify and validate a finite element model for a passenger vehicle to match the acceleration and intrusion measurements in NCAP frontal, IIHS moderate overlap, and IIHS small overlap test procedures. The simulation results should be compared to available crash test results using an objective rating methodology.

- Conduct simulations for the NHTSA oblique offset frontal test configuration. Use the baseline simulation models to develop and evaluate left- and right-side oblique offset crash environments. Compare the simulation results to oblique offset test data, where available, using the previously identified objective rating method.

- The simulation results should be used to establish design goals to minimize occupant compartment intrusion in left- and right-side oblique offset frontal crashes. While there are no established structural performance targets for oblique testing, the design goals should meet the occupant compartment intrusion requirements for a "Good" or "Acceptable" rating in the IIHS small overlap and overall "Good" rating in the IIHS moderate overlap tests. The contractor shall recommend any appropriate additional intrusion limits.

- Develop design changes for the vehicle finite element model to improve the structural performance in left- and right-side oblique offset frontal crash tests. Once an acceptable design has been established, develop an estimate for the change in mass for the final design.

- Develop incremental material and manufacturing costs for the design changes for the vehicle.

1.3 Technical Approach

This section discusses the technical approach the EDAG team used to meet the task order objectives. Our approach incorporated all the NHTSA requirements, milestones, and deliverables specified in this solicitation as discussed in Section 2.1 of this proposal.

Review of the test results and published literature indicate that for the four passenger car segments, sub-compact, compact, midsize and large car, the sub-compacts structural performance is significantly different (higher structural intrusions, higher passenger compartment decelerations) from the other three segments. Saunders, Craig, and Parent[2] also highlight this as shown in Figure 1. The sub-compact vehicle identified as PC1 in Figure 1 shows results that are considerably different from the other categories identified as PC2 to PC6. The pickup truck (PU1) segment shows the most favorable results.

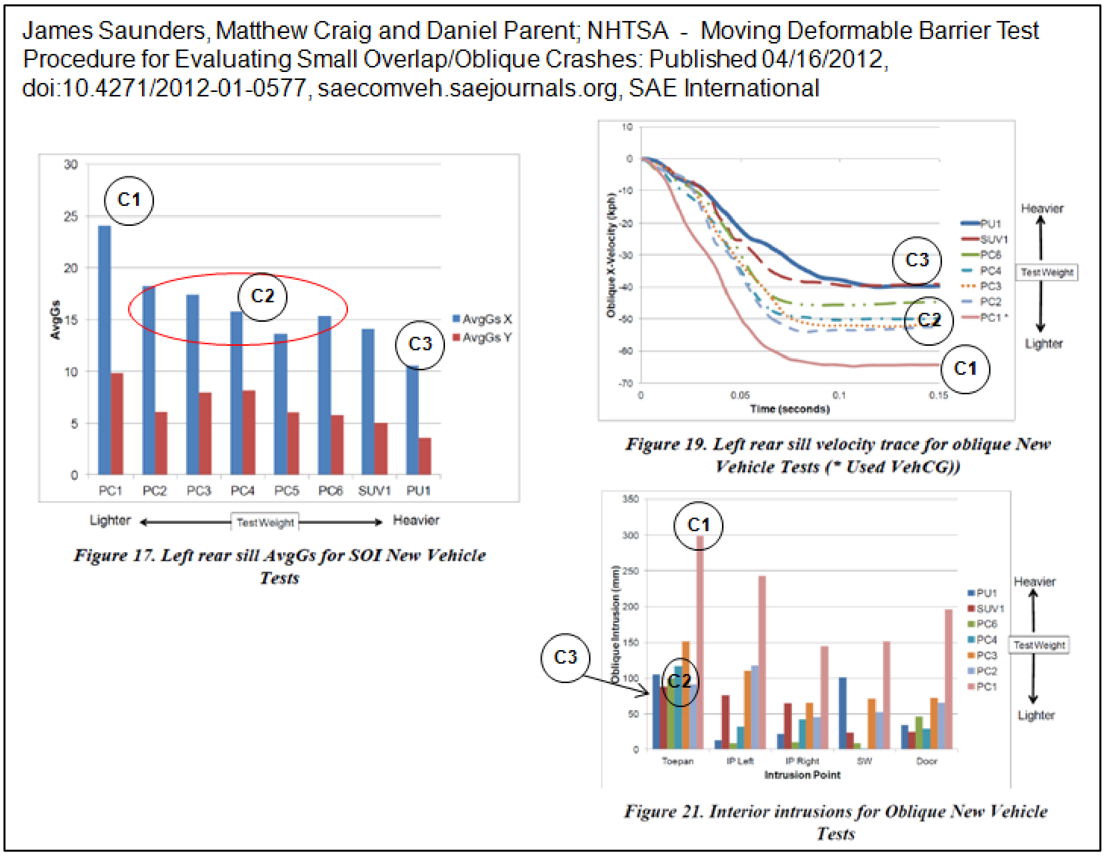
James Saunders, Matthew Craig and Daniel Parent; NHTSA - Moving Deformable Barrier Test Procedure for Evaluating Small Overlap/Oblique Crashes: Published 04/16/2012, doi:10.4271/2012-01-0577, saecomveh.saejournals.org, SAE International

Figure 17. Left rear sill AvgGs for SOI New Vehicle Tests

Figure 19. Left rear sill velocity trace for oblique New Vehicle Tests (Used VehCG))*

Figure 21. Interior intrusions for Oblique New Vehicle Tests

Figure 1: Vehicle Passenger Compartment Acceleration, Velocity and Interior Intrusions[3] (Categories C1 to C3 Marked by EDAG)

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[2] Saunders, J., Parent, D., & Craig, M. (2012, April 16). Moving Deformable Barrier Test Procedure for Evaluating Small Overlap/Oblique Crashes. (SAE Report No. 2012-01-0577). *SAE Int. Journal of Commercial Vehicles.* *5*(1):2012, doi:10.4271/2012-01-0577. doi:10.4271/2012-01-0577 Available at https://one.nhtsa.gov/DOT/NHTSA/NVS/Crashworthiness/Small%20Overlap%20and%20Oblique%20Research/2012-01-0577.pdf

[3] Saunders, Parent, & Craig, 2012.

As highlighted in Figure 1, the test results can be split into three structural categories, C1> sub-compact (PC1), C2> compact, mid-size and large car (PC2 to PC6), C3> Cab on frame based pickup trucks (PU1). The necessary design changes to the vehicle's structure to reduce the occupant compartment intrusions will be significantly different for each of these categories. The sub-compact car structure requires the most drastic changes compared with the other passenger car segments. The least amount of changes will be required to the pickup segment of vehicles. It was determined that in order to obtain the most accurate assessment of mass and cost for the structural changes, this study should include three different vehicle structures, one for each of these categories.

1. Mids-size sedan structure – 2014 Honda Accord to represent Category C2; the results from this can be scaled to compact and large-car segments, possibly also to unibody-structure-based minivan and SUV segments

2. Light-duty pickup structure – The 2014 Chevrolet Silverado 1500 represents Category C3; the results from this can be scaled to body-on-frame-based SUV segments.

3. Sub-compact structure – to represent Category C1. An up-to-date suitable CAE model is not available for the sub-compact segment. For this option, a CAE model would have to be created from vehicle tear-down and geometry scanning; the timing for such an effort is beyond the scope of this task order. The test results for the sub-compact (C1 - Figure 1) show significantly higher deceleration G values and intrusion values compared with the mid-size sedan (C2 - Figure 1). Therefore, the countermeasure results from the mid-size sedan cannot be scaled to the sub-compact structure.

1.4 Model Selection and Methodology

The vehicle models chosen for this study were based on the following criteria.

1. Availability of NHTSA oblique test results
2. Availability of a good correlated CAE model that can be modified with minimum effort to represent the vehicle for the NHTSA oblique test simulation
3. Latest possible production year vehicle that meets NHTSA's 5-star rating as well as "Good" or "Acceptable" rating for the IIHS small overlap and "Good" rating for the IIHS moderate overlap

1.4.1 Passenger Cars: Compact, Midsize and Large Cars

For passenger cars classed as compact, mid-size and large cars the oblique test results range from MY 2007 to MY 2014. For this category, detailed CAE models are available for the MY 2001 Ford Taurus, 2012 Toyota Camry, and 2012 Honda Accord. The 2012 Toyota Camry achieved a "Marginal" rating for the IIHS small overlap test.

The recommended vehicle for this category is the 2014 Honda Accord with "Good" IIHS ratings, 5-star NHTSA rating, and results from two NHTSA oblique tests. The CAE model of the 2012 Honda Accord was created and correlated for the NHTSA study DTNH22-13-C-00320.[4] Initial simulations run using this CAE model to simulate the NHTSA oblique test show very promising results as shown in Figure 2. The 2012 model was created from detailed vehicle tear-down and scanned geometry data by EDAG and George Washington University. The following steps were completed starting with the 2012 Accord CAE model.

1. Updated 2012 Honda Accord CAE model to MY 2014 to include the following major structural changes.
    - New front suspension changed from double wish-bone to McPherson strut
    - New engine cradle design (aluminum and steel friction-welded assembly)
    - Reinforced body side structure with laser-welded hot stamping
2. Update CAE model to include spot-weld and joint adhesive failures
3. Correlate CAE with the following crash load cases:
    - Frontal NCAP Test
    - Lateral NCAP Moving Deformable Barrier Test
    - Lateral NCAP Pole Test
    - IIHS Roof Crush Test
    - IIHS Lateral Moving Deformable Barrier Test
    - IIHS Moderate Frontal Offset Test
    - IIHS Small Overlap Front Test
    - NHTSA Oblique Test (simulating left- and right-side frontal oblique offset)
4. Study results for the NHTSA oblique test simulations to identify suitable design changes (new loads paths, reinforce existing load paths, optimize for grades and gauges of parts, etc.)
5. Update CAE model from Step 4 with design changes to reduce passenger compartment intrusions and rerun all the crash load cases specified in Step 3. The recommended changes were fine-tuned in such a way that vehicle crash performance was not jeopardized and design packaging space for other vehicle systems is not violated.
6. Cost modeling of incremental manufacturing and assembly costs of the added/subtracted components.

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[4] Singh, H., Kan, C-D., Marzougui, D., & Quong, S. (2016, February). Update to future midsize lightweight vehicle findings in response to manufacturer review and IIHS small-overlap testing (Report No. DOT HS 812 237). Washington, DC: National Highway Traffic Safety Administration. Available at www.nhtsa.gov/staticfiles/rulemaking/pdf/cafe/812237_LightWeightVehicleReport.pdf

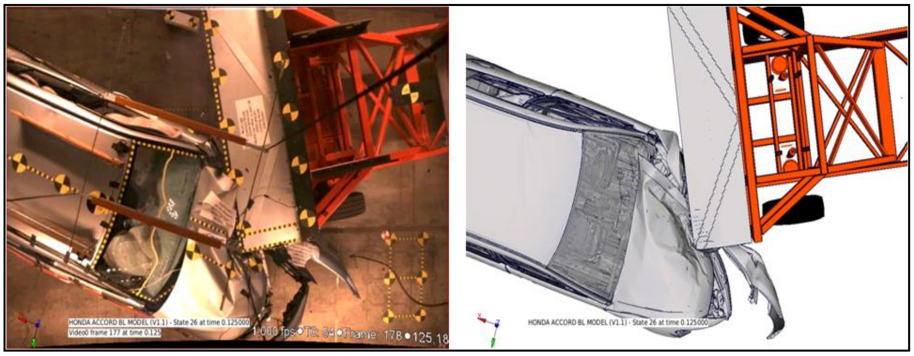

Figure 2: NHTSA Oblique Test (2014 Honda Accord) Versus EDAG CAE Model (2012 Honda Accord)

1.4.2 Light-Duty Pickup Truck

Oblique test results for the light-duty pickup segment are available for the 2011 Dodge Ram 1500 and 2012 Chevrolet Silverado 1500. For this segment, detailed CAE models are available for MY 2007, MY2011, and 2014 Chevrolet Silverado 1500. At the time this part of the study was being performed, the IIHS small overlap test had not been conducted for these vehicles. However, IIHS was to conduct two small overlap tests on the 2016 Silverado on January 26 and 28, 2016, so the results were available for this study. The recommended vehicle for this category is the 2014 Silverado 1500 with 5-star NHTSA ratings.

A detailed CAE model of the 2014 Silverado 1500 was created and correlated for the NHTSA light-weighting study DTNH22-13-C-00329.[5] It was created from detailed vehicle tear-down and scanned geometry data by EDAG. A CAE model of the light-weighted vehicle design for year 2025 based on the 2014 Silverado 1500 baseline vehicle is also available. The 2014 Silverado 1500 CAE is built with spot-weld and adhesive failures. An initial simulation run to simulate the NHTSA oblique test showed very promising results as shown in Figure 3. This model was refined and used to determine the design changes to reduce passenger compartment intrusion when subjected to the NHTSA oblique test on both sides of the vehicle.

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[5] Singh, H., Davies, J., Kramer, D., Fisher, A., Paramasuwom, M., Mogal, V., ... and Ganesan, V. (in press). *Mass reduction for light-duty vehicles for model years 2017-2025* (Report No. DOT HS to be determined at publication). Washington, DC: National Highway Traffic Safety Administration. See also Singh, Kan, Marzougui& Quong, 2016.

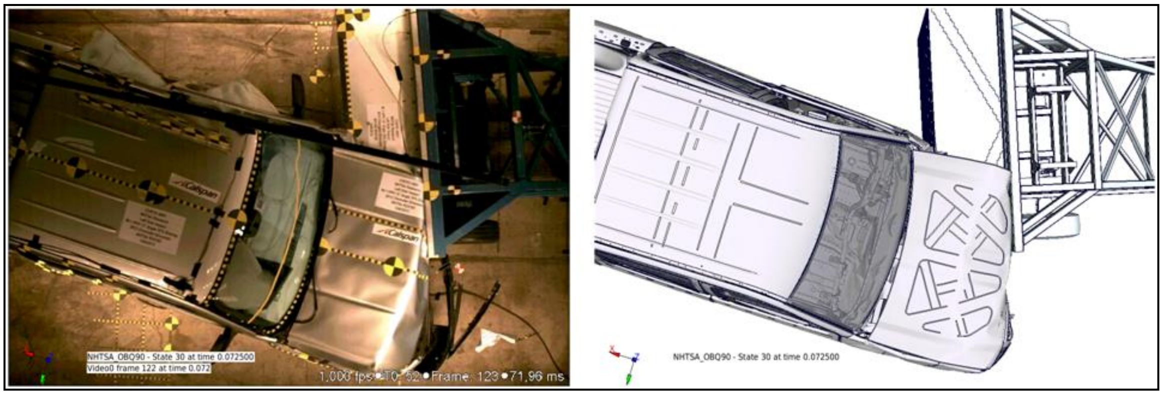

Figure 3: NHTSA Oblique Test (2012 Silverado 1500) Versus EDAG CAE Model (2014 Silverado 1500)

1.5 Design Strategy for Limiting Compartment Intrusion

The structure of a modern light-duty vehicle is split into several zones. Each zone has significantly different performance requirements. For example, the front end of the vehicle is subjected to impacts over a large speed range and impacts with objects with large mass or effective mass, such as fixed objects as well as relatively small mass such as pedestrians. A vehicle manufacturer may design the front end of a vehicle to be compliant in order to reduce injury potential for pedestrians. For lower speed impacts (below 20 kph) the emphasis is to minimize damage to vehicles safety systems and low repair costs.

For high-speed impacts, the emphasis is to absorb energy to achieve a controlled deceleration pulse and minimize structural damage/ intrusions into the passenger compartment. To satisfy these conflicting requirements within a very confined package space imposes very stringent requirements on material properties and suitable design of load paths. The structural load paths must be designed to absorb the maximum amount of energy, not just in straight head-on collisions, but also in oblique and offset impacts as shown in Figure 4.

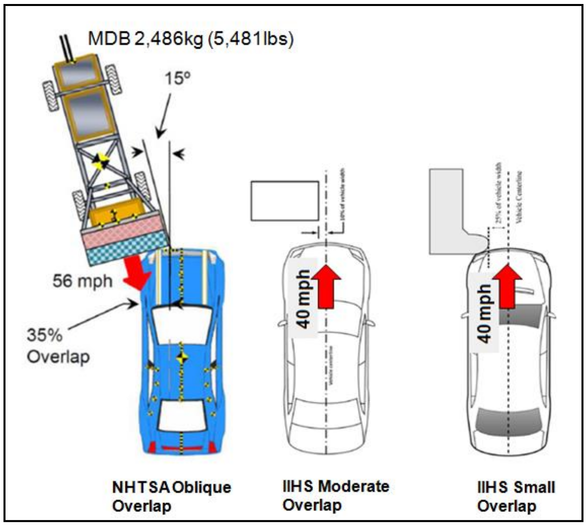

Figure 4: Vehicle frontal offset crash tests

In these crash events, the intrusions into the toe pan and dash panel are generally caused by hard contact between the intruding wheel and/or the engine/transmission assembly. The following three methods are generally applied to reduce the offending intrusions.

1. Absorb as much energy as possible by the sacrificial structure in front of the toe-pan/dash panel (front rail, shot gun rail, engine cradle, etc.). This could require additional structure and/or controlled crush initiators at key locations. The front structure is very finely tuned to produce a controlled deceleration. Any change in this area has to be fully assessed for the unintended consequences and making the vehicle pulse too aggressive.
2. Introduce failure points at key locations to deflect the offending surfaces away from the critical zones on toe-pan/dash panel. On some vehicles, the rear engine cradle mount is designed to fail to deflect the engine downward just prior to hard contact with the dash panel. For the IIHS small overlap requirement to reduce the wheel intrusion into the toe-pan, failure points can be introduced on suspension joints to deflect the wheel sideways.
3. As a last resort, the passenger compartment is suitably reinforced by using high-0strength materials with optimized designed load paths. For frontal impacts, the reinforcements are generally confined to toe-pan, central tunnel structure, front hinge pillar and A-pillar structures.

The detailed design of reinforcing components will also consider manufacturability, joining, and assembly into the vehicle design. On all design programs at EDAG a bill of material (BOM) is maintained to track changes to existing components and all additional components, by component name, material grade, material thickness, manufacturing process, and incremental mass. These parameters are also reflected in the on-going CAE models. The BOM also provides important input to the cost model.

1.6 Incremental Manufacturing and Material Costs

EDAG uses the technical cost modeling (TCM) approach developed by Massachusetts Institute of Technology's Materials Systems Laboratory research.[6] The basis of the model was established in the WorldAutoSteel ULSAB project and expanded by EDAG during the WorldAutoSteel Future Steel Vehicle program. This method was also used for the mass estimates for the NHTSA lightweight vehicle midsize sedan and light duty truck programs. The results from this costing method have been peer reviewed. The TCM facilitates the understanding of the cost consequences of an engineering decision. Therefore, TCM offers a clear metric for the decision between engineering solutions leading to a product with similar characteristics.

In general, the total cost will be broken down into each of the operations involved in the manufacturing process, e.g. for a sheet metal part produced by starting from blanking the steel coil, until the final operation to fabricate the component. The sequence of the different operations involved in a manufacturing process establishes the final cost estimate. The application of the TCM will allow consideration of the whole production process, from part production, assembly, logistics and overhead cost. It does not consider non-manufacturing costs, for example; profit margins, marketing and sales, etc., since these costs depend not only on the product itself, but also the corporate strategies and policies of specific OEMs.

In the TCM the costs are categorized into fixed costs, such as tooling, equipment, and facilities; and variable costs such as labor, material, energy, and maintenance. These costs are assessed through an interactive process between the product designers, manufacturing engineers and costs analysts. The most important step in the cost assessment process is the determination of production related inputs such as pre-product characteristics (e.g., blank size), cycle time and tooling costs. These inputs are evaluated on an individual part by part basis depending on the design data and the related manufacturing operations for each of the components and assemblies. Production site specific program parameters, including annual production volume, product life cycle; and plant parameters including annual working days, building unit cost, average wage; and part independent process parameters including space requirements, reject rate, maintenance rate are parameterized in the TCM to allow for parameter influence analyses in a later project stage.

Figure 5 provides an example of the TCM approach to estimate the cost for a stamped part. Independent process, plant, and production-site-specific parameters together with part-specific material and process data define the input for the TCM analysis. As a result, the model provides the material, labor, equipment, tooling, energy, building, and maintenance costs per part. These costs can be used to put the different process options for the part production in perspective and to decide the optimal production method.

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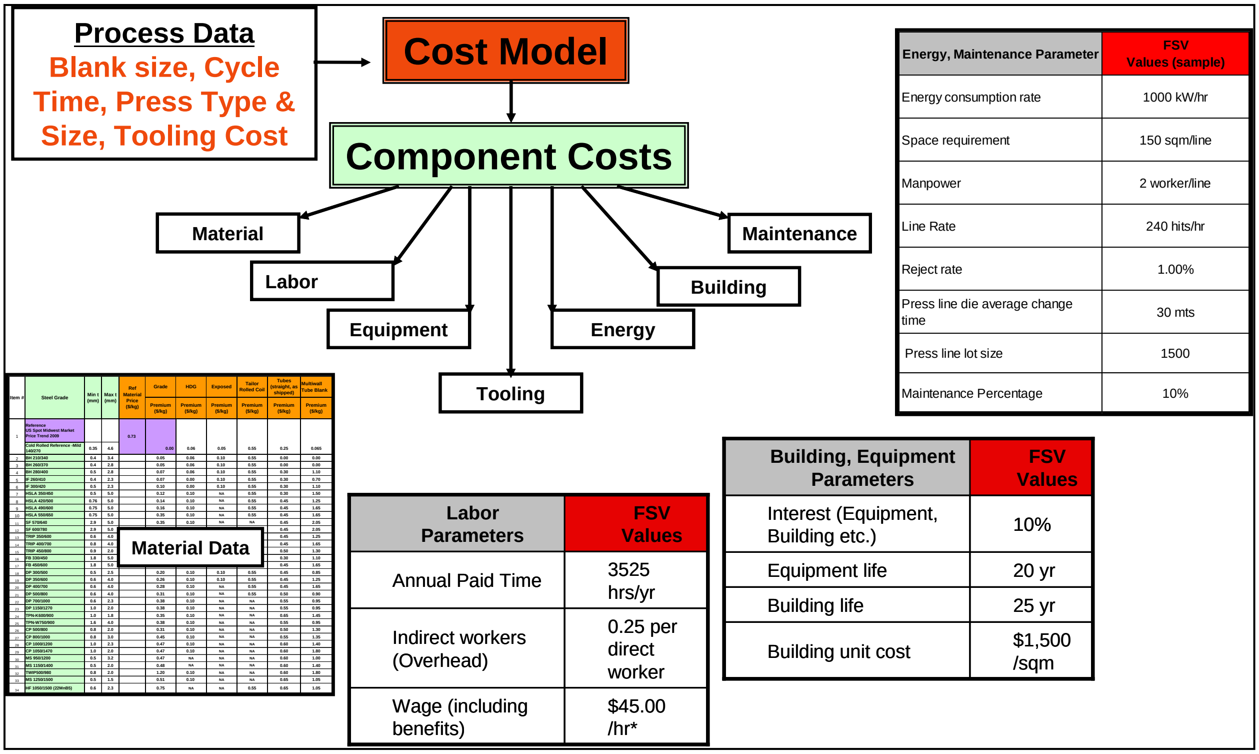
[6] Field, F., Kirchain, R., & Roth, R. (2007, October). Process cost modeling: Strategic engineering and economic evaluation of materials technologies. *Journal of the Minerals, Metals and Materials Society, 59*(10), 21-32.



Energy, Maintenance Parameter	FSV Values (sample)
Energy consumption rate	1000 kW/hr
Space requirement	150 sqm/line
Manpower	2 worker/line
Line Rate	240 hits/hr
Reject rate	1.00%
Press line die average change time	30 mts
Press line lot size	1500
Maintenance Percentage	10%

Labor Parameters	FSV Values
Annual Paid Time	3525 hrs/yr
Indirect workers (Overhead)	0.25 per direct worker
Wage (including benefits)	$45.00 /hr*

Building, Equipment Parameters	FSV Values
Interest (Equipment, Building etc.)	10%
Equipment life	20 yr
Building life	25 yr
Building unit cost	$1,500 /sqm

Figure 5: Technical Cost Model of a Stamping Process

1.6.1 Steel Prices

The fluctuation of the cold-rolled steel coil base prices from 2010 to 2014 are shown Figure 6 including the nominal prices and the prices adjusted to 2014 dollars. The team used the 2010 to 2014 average steel price for the cost assessment, $0.82/ kg adjusted to 2014 dollars.[7]

Using this figure as the base price for mild steel cold-rolled coils, the prices of the higher steel grades were established by applying the appropriate grade premiums to the base price. Similarly, the appropriate process premium was added to the base price to attain the prices of steel in other finished forms such as hot-dip galvanized, tailor-rolled coils, and tubes.

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[7] FRED Economic Data. (n.a.) Gross Domestic Product. Table 1.1.9, Implicit Price Deflators for GDP. (Web page). St. Louis: Federal Reserve Bank of St. Louis. Retrieved from the FREDD web site at https://fred.stlouisfed.org/release/tables?rid=53&eid=13116

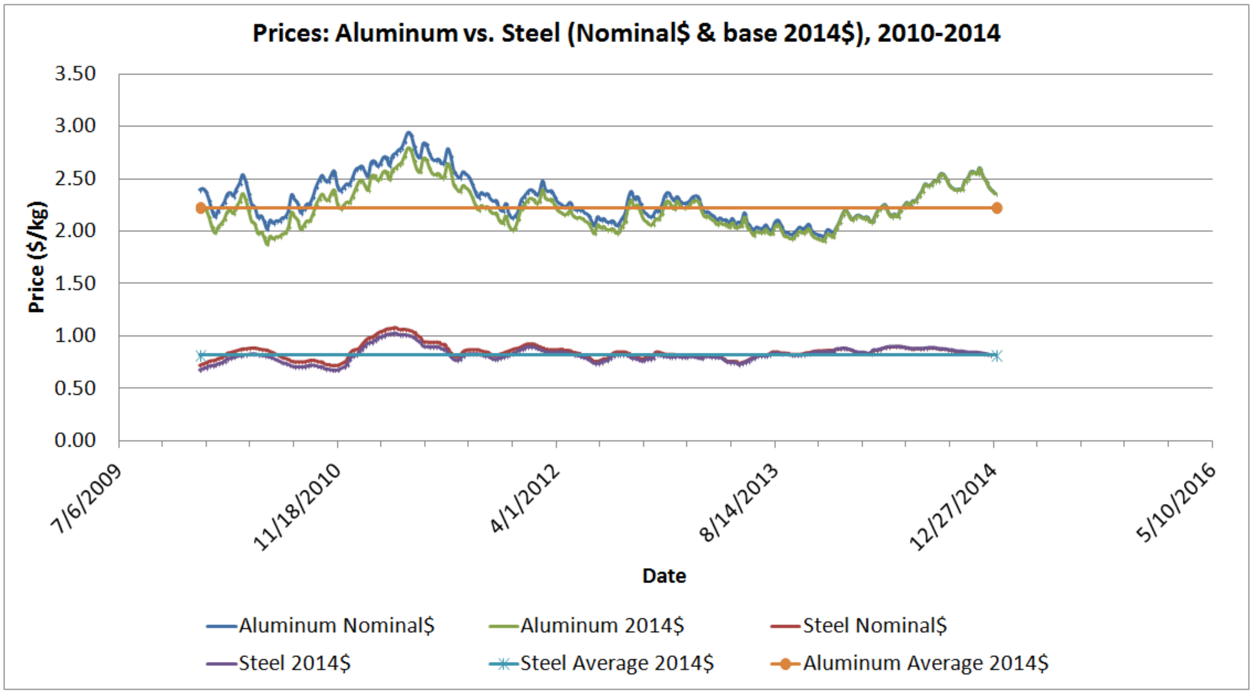

Figure 6: 2010 to 2014 Prices of kg Cost per Kilogram Adjusted to 2014 Dollars[8] [9]

The different grade and process premiums were estimated by EDAG based on inputs received from WorldAutoSteel. The different grades of steel and the respective premiums are shown in Table 1. For example, if DP 700/1000 is the specified material for a part, a grade premium of $0.38 is added to $0.82 to get the material price of $1.20/ kg. If the material price is required for the DP 700/1000 grade steel in the form of tubes, an additional process premium of $0.55 is added to get the material price of $1.75/ kg.

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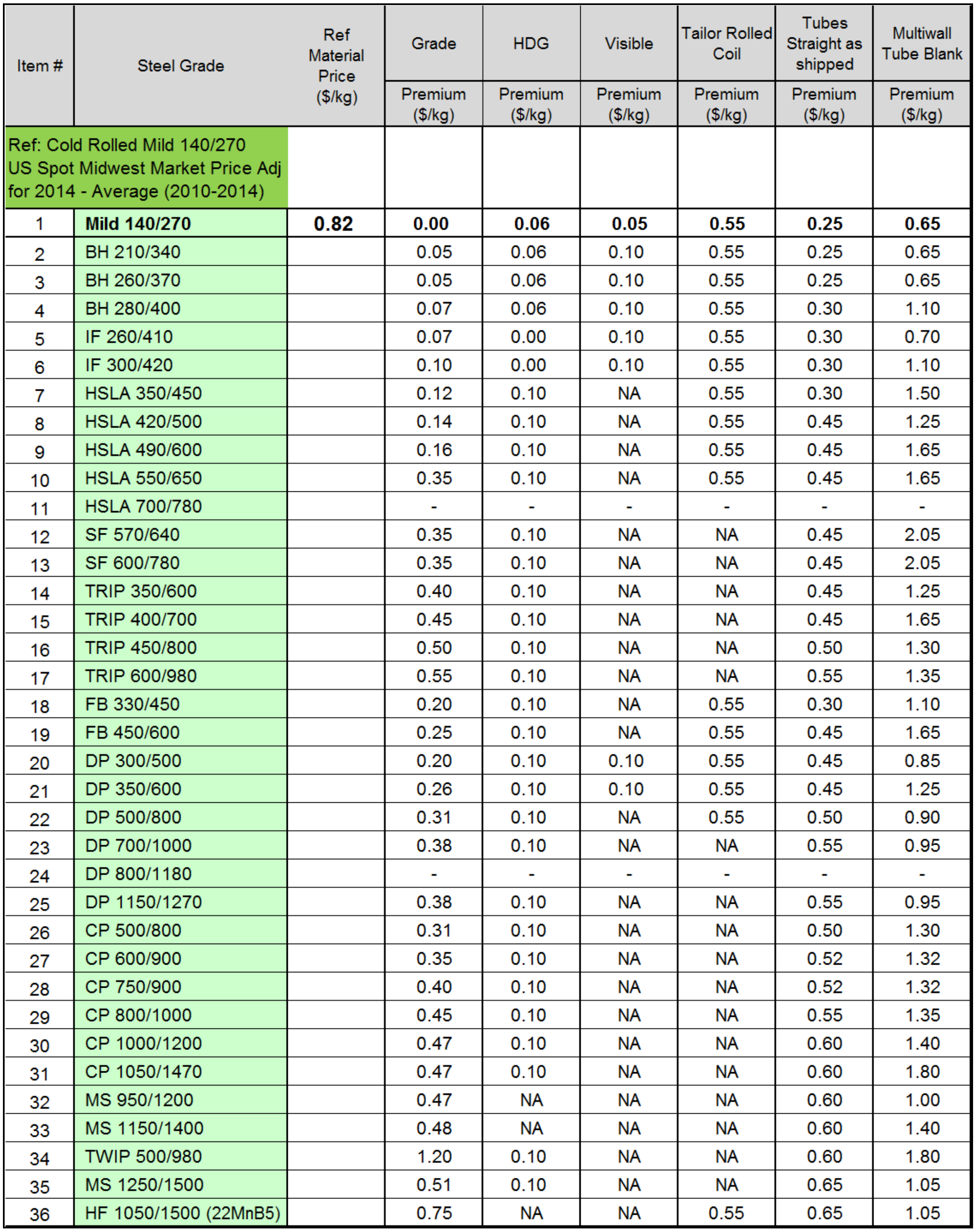
[8] Nominal prices are based on data received from Platts' Steel Cold Rolled Coil Ex-works Indiana; adjusted prices take into account the GDP deflator in 2010, 2011, 2012, and 2014.

[9] FRED Econimic Data (n.a.), Table 1.1.9.



Item #	Steel Grade	Ref Material Price ($/kg)	Grade	HDG	Visible	Tailor Rolled Coil	Tubes Straight as shipped	Multiwall Tube Blank
			Premium ($/kg)	Premium ($/kg)	Premium ($/kg)	Premium ($/kg)	Premium ($/kg)	Premium ($/kg)
Ref: Cold Rolled Mild 140/270 US Spot Midwest Market Price Adj for 2014 - Average (2010-2014)								
1	**Mild 140/270**	**0.82**	**0.00**	**0.06**	**0.05**	**0.55**	**0.25**	**0.65**
2	BH 210/340		0.05	0.06	0.10	0.55	0.25	0.65
3	BH 260/370		0.05	0.06	0.10	0.55	0.25	0.65
4	BH 280/400		0.07	0.06	0.10	0.55	0.30	1.10
5	IF 260/410		0.07	0.00	0.10	0.55	0.30	0.70
6	IF 300/420		0.10	0.00	0.10	0.55	0.30	1.10
7	HSLA 350/450		0.12	0.10	NA	0.55	0.30	1.50
8	HSLA 420/500		0.14	0.10	NA	0.55	0.45	1.25
9	HSLA 490/600		0.16	0.10	NA	0.55	0.45	1.65
10	HSLA 550/650		0.35	0.10	NA	0.55	0.45	1.65
11	HSLA 700/780		-	-	-	-	-	-
12	SF 570/640		0.35	0.10	NA	NA	0.45	2.05
13	SF 600/780		0.35	0.10	NA	NA	0.45	2.05
14	TRIP 350/600		0.40	0.10	NA	NA	0.45	1.25
15	TRIP 400/700		0.45	0.10	NA	NA	0.45	1.65
16	TRIP 450/800		0.50	0.10	NA	NA	0.50	1.30
17	TRIP 600/980		0.55	0.10	NA	NA	0.55	1.35
18	FB 330/450		0.20	0.10	NA	0.55	0.30	1.10
19	FB 450/600		0.25	0.10	NA	0.55	0.45	1.65
20	DP 300/500		0.20	0.10	0.10	0.55	0.45	0.85
21	DP 350/600		0.26	0.10	0.10	0.55	0.45	1.25
22	DP 500/800		0.31	0.10	NA	0.55	0.50	0.90
23	DP 700/1000		0.38	0.10	NA	NA	0.55	0.95
24	DP 800/1180		-	-	-	-	-	-
25	DP 1150/1270		0.38	0.10	NA	NA	0.55	0.95
26	CP 500/800		0.31	0.10	NA	NA	0.50	1.30
27	CP 600/900		0.35	0.10	NA	NA	0.52	1.32
28	CP 750/900		0.40	0.10	NA	NA	0.52	1.32
29	CP 800/1000		0.45	0.10	NA	NA	0.55	1.35
30	CP 1000/1200		0.47	0.10	NA	NA	0.60	1.40
31	CP 1050/1470		0.47	0.10	NA	NA	0.60	1.80
32	MS 950/1200		0.47	NA	NA	NA	0.60	1.00
33	MS 1150/1400		0.48	NA	NA	NA	0.60	1.40
34	TWIP 500/980		1.20	0.10	NA	NA	0.60	1.80
35	MS 1250/1500		0.51	0.10	NA	NA	0.65	1.05
36	HF 1050/1500 (22MnB5)		0.75	NA	NA	0.55	0.65	1.05

Table 1: Price for different grades and finished forms of steel[10]

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[10] www.worldautosteel.org accessed Sept. 11, 2017

1.7 Project Team

This project was completed by EDAG, Inc. The EDAG team has extensive experience in the areas of automotive engineering, development, and vehicle crash test modeling and analysis. EDAG was the prime contractor and technical lead on optimizing the lightweight vehicle design, performed the cost modeling, and examined advanced manufacturing techniques as well as vehicle crash modelling, correlation, and analysis.

2 Passenger Cars: MY 2014 Honda Accord Study - Summary

2.1 CAE Model Creation and Correlation

The CAE model of the 2012 Honda Accord that was created and correlated for NHTSA's study (Singh et al., in press) was updated to represent the 2014 MY Honda Accord. The front suspension was changed from double wish-bone to McPherson struts as shown in Figure **7**. The engine cradle structure on the 2014 MY, shown in Figure **7**, is a novel multi-material construction made from steel stampings that were friction-stir-welded to an aluminum casting. The geometry of the engine cradle was laser-scanned, converted to a finite element mesh, and integrated into the CAE model. Major changes to the body structure, front rails, dash panel, and body side structures were updated with the 2014 MY geometry and material properties. The updated panels are shown in Figure **8**. The CAE model was further updated to include spot-weld and joint-adhesive failures. The adhesive properties to predict the adhesive failure were provided by Dow Automotive and are proprietary data. In the released CAE model the Dow Automotive data is encrypted.

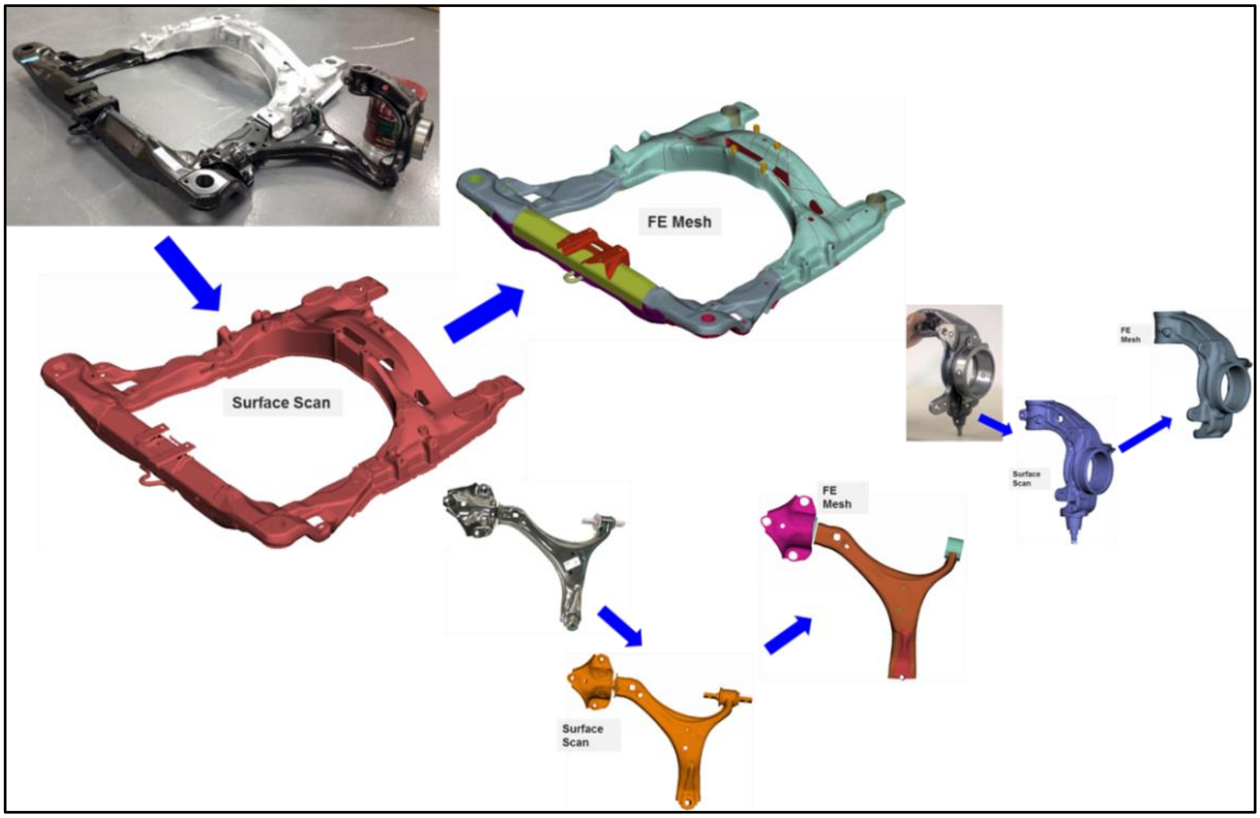


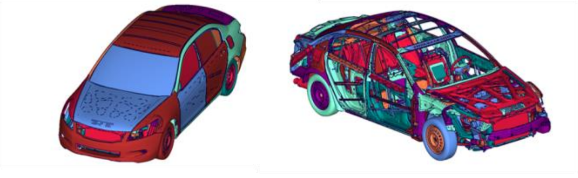
Figure 7: 2014 Honda Accord Engine Cradle and Front Suspension

Figure 8: 2014 Honda Accord Body Structure Panels

The CAE model for the 2014 Honda Accord shown in Figure 9 was correlated with the following crash load cases prior to using it for countermeasure study for the oblique impact.

- NHTSA Oblique Test (simulating left- and right-side frontal oblique offset)
- Frontal NCAP Test
- IIHS Moderate (40%) Frontal Offset Test
- IIHS Small (25%) Overlap Front Test
- Lateral NCAP Moving Deformable Barrier Test
- Lateral NCAP Pole Test
- IIHS Roof Crush Test
- IIHS Lateral Moving Deformable Barrier Test

The results of the correlation with test results and reduction in the occupant compartment intrusions with the addition of the countermeasures are shown in Section 0 .

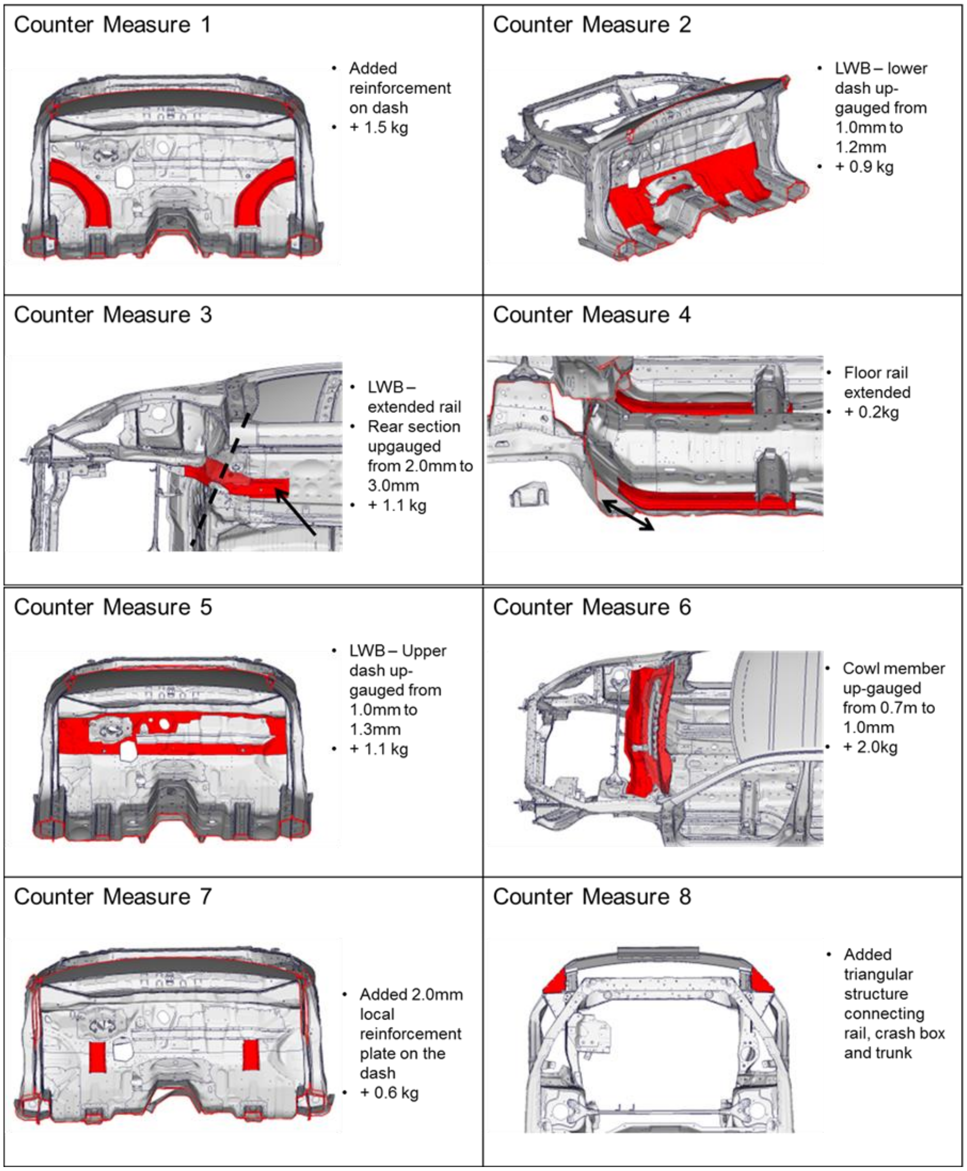


Number of Parts	1207
Number of nodes	2,124,917
Number of Shells	1,847,155
Number of Beams	659
Number of Solids	243,237
Total number of elements	2,091,327

Figure 9: 2014 Honda Accord CAE Model

2.2 Mass of Structural Design Changes to Reduce Passenger Compartment Intrusions

The correlated CAE model from the previous step was used to identify suitable design countermeasures to reduce the occupant compartment intrusions. The countermeasures were based on observed body structure deformations when subjected to oblique impact on the driver and passenger side. High intrusion values were mainly observed in the mid to lower section of the dash panel. The dash mid to lower area is impacted by battery and brake booster assemblies on the driver side and by the transmission and engine block on the passenger side of the dash panel. These areas were selectively reinforced as illustrated in Figure **10** countermeasures 1 to 8. The mass increase and efficiency of each countermeasure were assessed for their effectiveness to reduce the intrusion values.



Counter Measure 1
- Added reinforcement on dash
- + 1.5 kg

Counter Measure 2
- LWB – lower dash up-gauged from 1.0mm to 1.2mm
- + 0.9 kg

Counter Measure 3
- LWB – extended rail
- Rear section upgauged from 2.0mm to 3.0mm
- + 1.1 kg

Counter Measure 4
- Floor rail extended
- + 0.2kg

Counter Measure 5
- LWB – Upper dash up-gauged from 1.0mm to 1.3mm
- + 1.1 kg

Counter Measure 6
- Cowl member up-gauged from 0.7m to 1.0mm
- + 2.0kg

Counter Measure 7
- Added 2.0mm local reinforcement plate on the dash
- + 0.6 kg

Counter Measure 8
- Added triangular structure connecting rail, crash box and trunk

Figure 10: Body Structural Countermeasures 1 to 8

The most effective countermeasures were combined to determine the most efficient final set of recommendations as illustrated in Figure **11** and Figure **12**. Several CAE simulation iterations were completed to find the optimal set of structural changes. The recommended changes have to be fine-tuned in such a way that vehicle crash performance is not jeopardized for all other crash requirements, and also to make sure the design-packaging space for other vehicle systems is not violated.

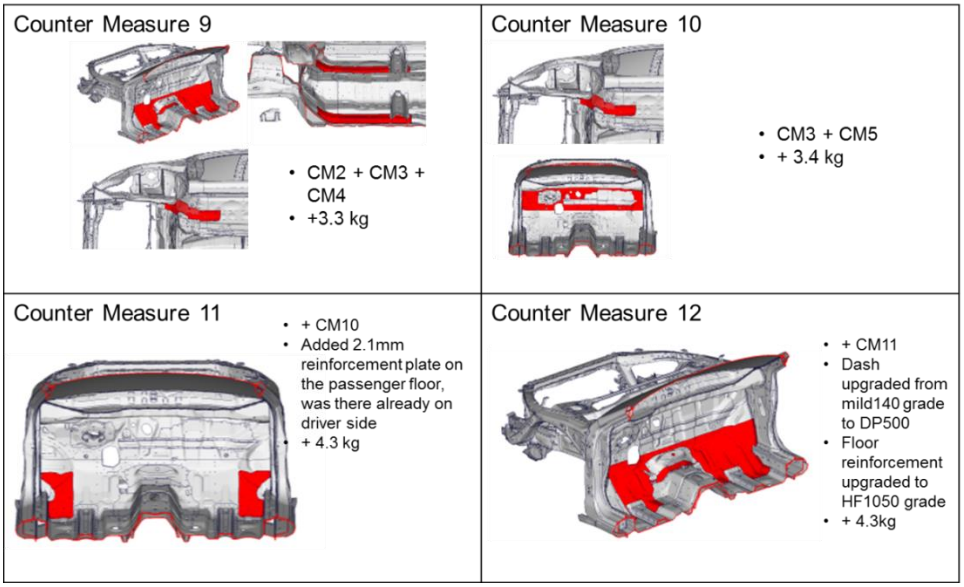


Figure 11: Body Structural Countermeasures 9 to 12

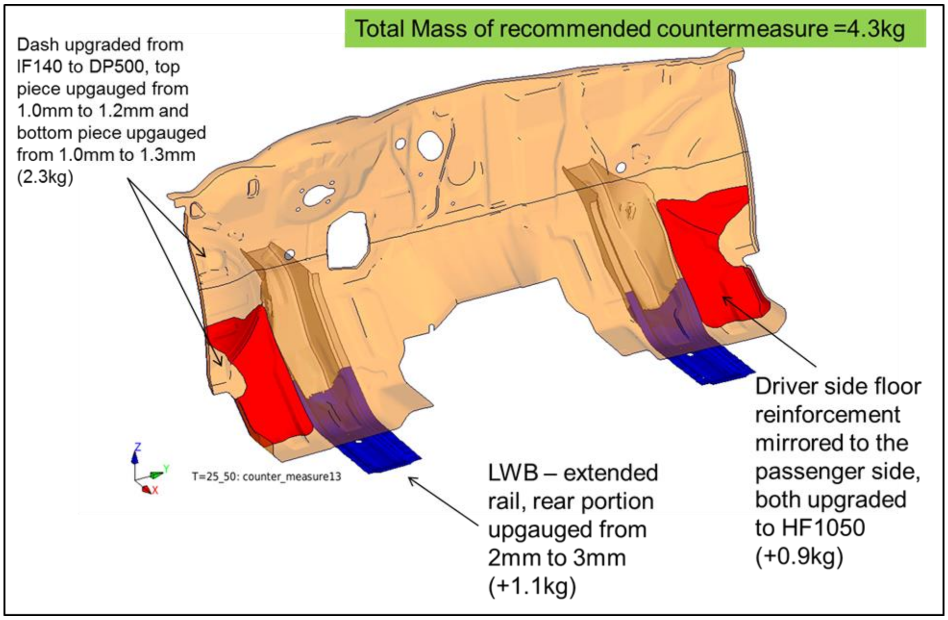


Figure 12: Structural Countermeasures to Reduce Occupant Compartment Intrusions

The recommended changes shown in Figure 12 add up to an additional mass increase of 4.3 kg for the entire body structure. These changes are as follows.:

1. The dash panel is changed to a laser-welded blank stamping, with increases in thickness from 1.00 mm to 1.20 mm upper segment and to 1.3 mm lower segment, incurring a mass penalty of 2.3 kg. Its material steel grade is also changed from low-strength steel to higher strength duel phase DP500. The dash panel using the higher grade can still be successfully formed. The DP500 grade is a good formable grade with over 20 percent elongation.
2. The front rail extensions (left and right) stamped parts that are positioned under the lower dash panel and front floor panels are converted into laser-welded blank (LWB) stampings with two thicknesses. The thickness of the rear of this part is increased from 2.00mm to 3.00mm, incurring a mass penalty of 1.1 kg for both parts.
3. The driver side front floor reinforcement panel (shown in red in Figure 12) is duplicated (mirror image) on to the passenger at an additional mass of 0.90 kg. The grade of steel is also changed to advanced high-strength steel HF1050/1500 suitable only for hot-stamping.

The results of the correlation with test results and reduction in the occupant compartment intrusions with the addition of the countermeasures are shown in Section 0 .

2.3 Cost of Recommended Changes to Reduce Passenger Compartment Intrusions

Costs are calculated using the EDAG in-house, TCM-based cost model (Section 2.5). Incremental manufacturing and assembly costs of the added/subtracted components are summarized in Table 2 and Table 3. The total cost increase for the countermeasures is $24.37 ($59.91 - $35.54). Total mass increase for the countermeasures is 4.3 kg (19.0 kg – 14.7 kg).

2014 Honda Accord - Baseline Parts						
Item #	Part Name	Qty per Veh	Steel Grade	Mass (kg)	Manufacturing Process	Part Piece Cost
1	Dash Panel	1	Mild 140/270	8.300	Stamping Single Thickness	$14.64
2	Dash Panel Bracket Lh	1	DP 500/800	0.900	Stamping Single Thickness	$3.68
3	Reinforcement Dash Panel Longitudinal Lh	1	Mild 140/270	2.765	Stamping Single Thickness	$8.61
4	Reinforcement Dash Panel Longitudinal Rh	1	Mild 140/270	2.765	Stamping Single Thickness	$8.61
			Total Mass	**14.73**	Total Part Piece Cost	**$35.54**

Table 2: 2014 Honda Accord Baseline Model – Subtracted Parts

2014 Honda Accord - Counter-Measure Parts						
Item #	Part Name	Qty per Veh	Steel Grade	Mass (kg)	Manufacturing Process	Part Piece Cost
1	Dash Panel	1	DP 500/800	10.600	Laser Welded Blank	$26.76
2	Dash Panel Bracket Lh	1	HF 1050/1500	0.900	Hot Stamped Single Thickness	$5.66
3	Dash Panel Bracket Rh	1	HF 1050/1500	0.900	Hot Stamped Single Thickness	$5.66
4	Reinforcement Dash Panel Longitudinal Lh	1	DP 500/800	3.300	Laser Welded Blank	$10.15
5	Reinforcement Dash Panel Longitudinal Rh	1	DP 500/800	3.300	Laser Welded Blank	$10.15
	Additional Assembly Cost					$1.53
			Total Mass	**19.000**	Total Part Piece Cost	**$59.91**

Table 3: 2014 Honda Accord With Countermeasures Model – Added Parts

3 Light-Duty Pickup Truck: MY 2014 Silverado 1500 Study - Summary

3.1 CAE Model 2014 Silverado 1500

A very detailed CAE model of the 2014 Silverado 1500 was created and correlated for NHTSA's lightweighting study (Singh et al., in press). It was created from detailed vehicle tear-down and scanned geometry data by EDAG. The 2014 Silverado 1500 CAE is built with spot-weld and adhesive failures. The adhesive properties to predict the adhesive failure were provided by Dow Automotive and are proprietary data. In the released CAE model the Dow Automotive data is encrypted. For this study, the CAE model was further modified from four-wheel-drive to rear-wheel–drive to represent the power train similar to NHTSA oblique-tested vehicles. The front drive differential, front drive shafts and power transfer unit were removed from the CAE model as shown in Figure 13. Comparison of the tested vehicles versus the CAE model is shown Table 4.

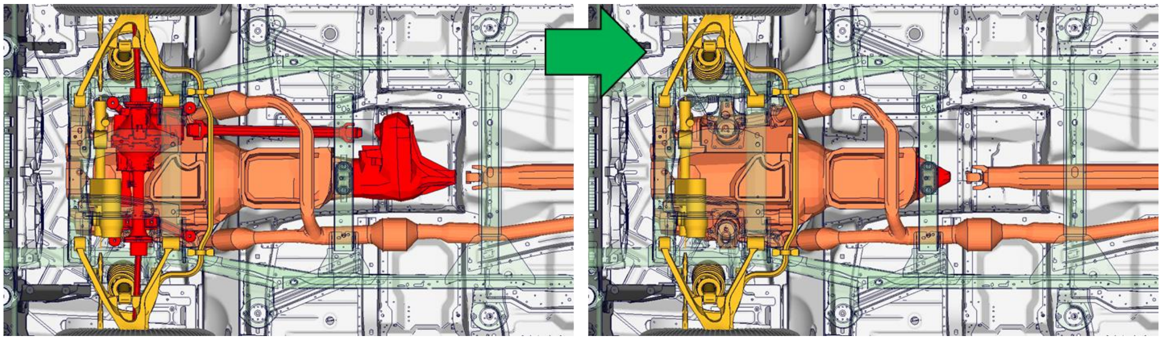
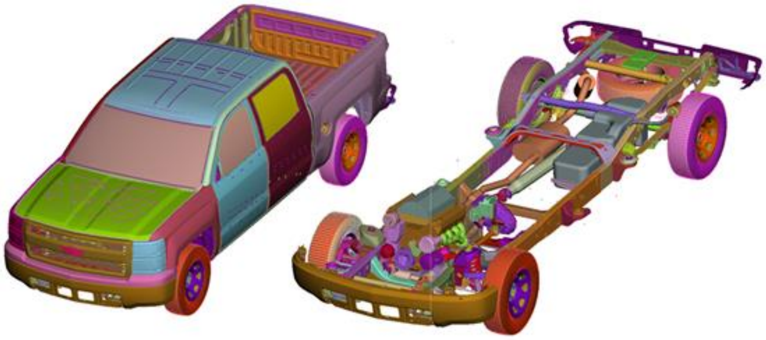


Figure 13: 2014 Silverado 1500 With the Front Wheel Drive Components Shown in Red

Description	Tahoe (Test)	Silverado 1500 (Test)	CAE Model Silverado 1500
Model Year	2016	2012	2014
Drive	RWD	RWD	RWD
Engine Size (L)	5.3	4.8	5.3
Tested Weight (kg)	2722	2624	2582
Body Style	SUV	Crew-Cab	Crew-Cab

Table 4: Oblique Test Vehicles Versus CAE Model



	2014 Silverado 1500 LS-DYNA Model
Number of Parts	1,476
Number of Nodes	2,741,848
Number of Shells	2,577,274
Number of Beams	15,534
Number of Solids	277,588
Total Number of Elements	2,870,507

Figure 14: 2014 Silverado 1500 CAE Model

The CAE model for the 2014 Silverado 1500 used in this study, shown in Figure 14, was correlated with the following crash load cases prior to using it for countermeasure study for the Oblique Impact.

- NHTSA Oblique Test (simulating left-side frontal oblique offset)
- IIHS Small (25%) Overlap Front Test

The results of the correlation with test results and reduction in the occupant compartment intrusions with the addition of the countermeasures are shown in Section 6. This CAE model was originally created and correlated for NHTSA's lightweighting study, (Singh et al., in press). The results of correlation of all other crash and NVH loads cases are fully discussed in the NHTSA report in Singh et al. (in press).[5]

3.2 Mass of Structural Design Changes to Reduce Passenger Compartment Intrusions

The correlated CAE model from the previous step was used to identify suitable design countermeasures to reduce the occupant compartment intrusions. The countermeasures were based on observed structure deformations when subjected to IIHS small offset and NHTSA oblique impact tests on the driver and passenger sides.

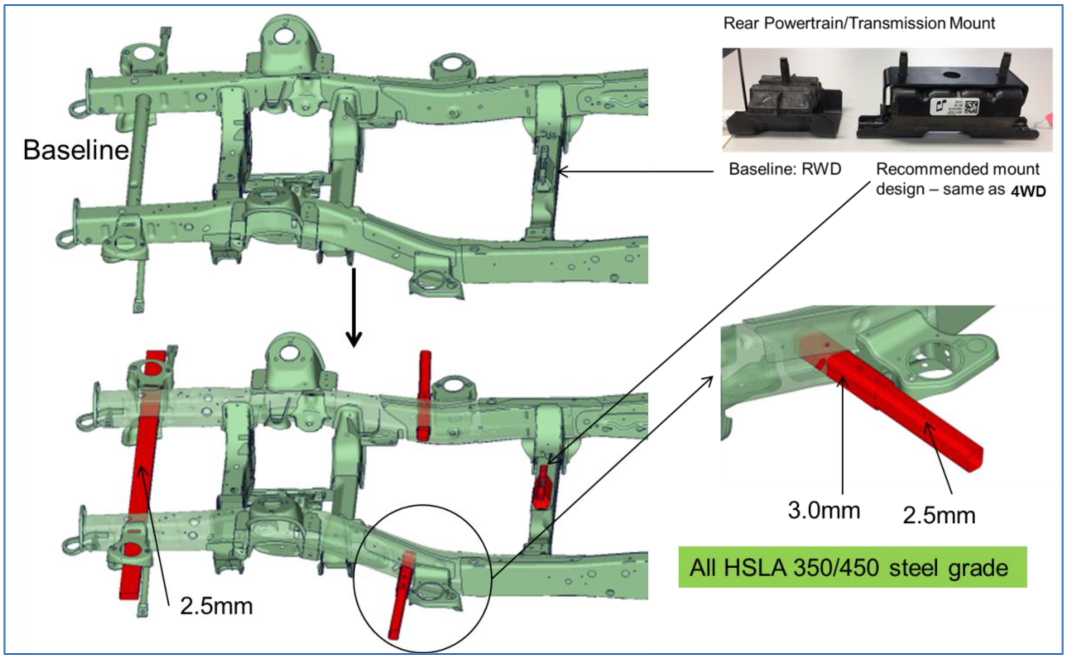


Figure 15: Structural Countermeasures to Reduce Occupant Compartment Intrusions

High intrusion values were observed mainly in the mid to lower section of the dash panel. The dash mid to lower area is impacted by the left front wheel and by the transmission on the passenger side. The rearward wheel intrusions are reduced by adding additional structure to the frame structure as shown in Figure 16.

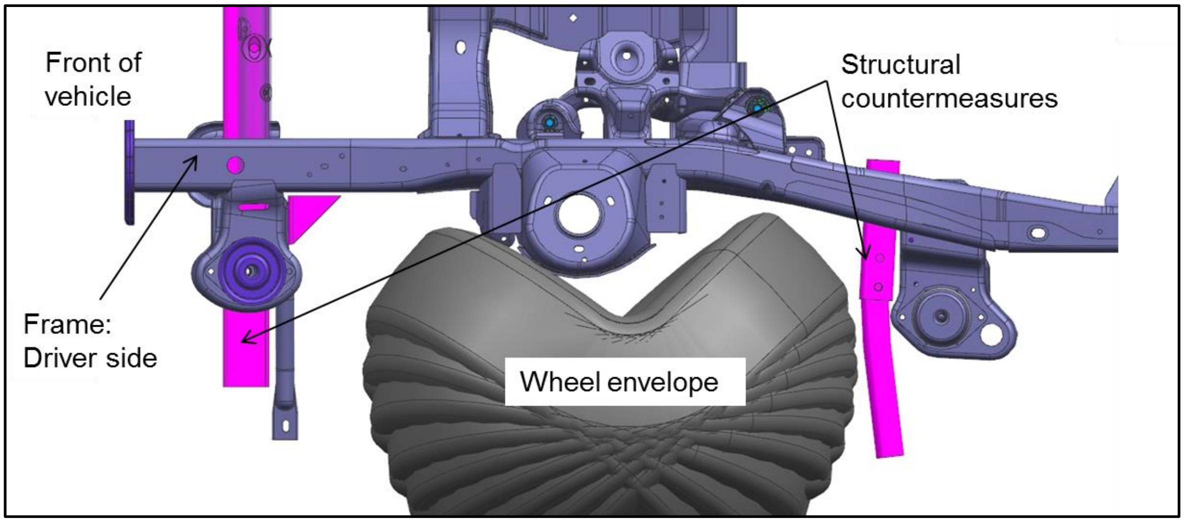
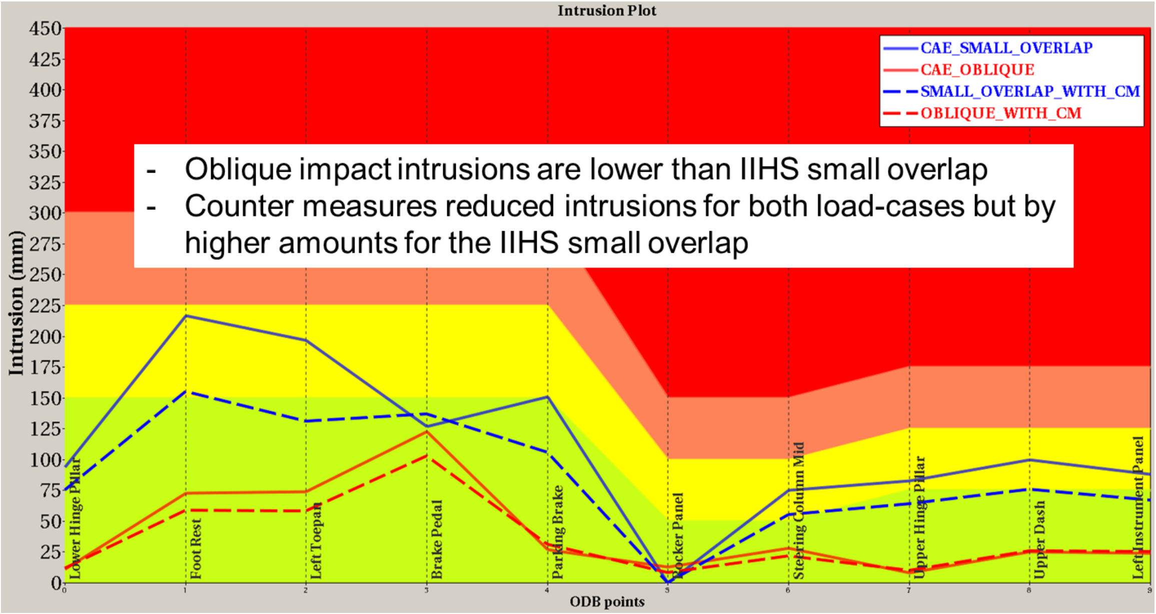


Figure 16: Structural Countermeasures to Reduce Occupant Compartment Intrusions



- Oblique impact intrusions are lower than IIHS small overlap
- Counter measures reduced intrusions for both load-cases but by higher amounts for the IIHS small overlap

Figure 17: Structural Countermeasures: Reduce Occupant Compartment Intrusions for Oblique and IIHS Small Overlap

Higher deformations were also observed for the IIHS small overlap results as shown in Figure 17. The proposed countermeasures reduce the intrusion values for both load cases but by higher amounts for the IIHS small overlap. The recommended changes shown in Figure 15 add up to an additional mass increase of 9.0 kg. These changes are symmetrical on the left and right sides of the vehicle and are made up of:

1. Modified front cross member to extend beyond frame rails, to be positioned in front of the front wheel/tires;
2. Front wheel blocker bar positioned in front of the cab front mount; and
3. The rear powertrain/transmission mount: change from the baseline design to the more robust design that is used on the 4WD options of the Silverado 1500. The recommended mount is 1.0 kg heavier than the baseline.

3.3 Cost of Recommended Changes to Reduce Passenger Compartment Intrusions

Costs are calculated using EDAG in-house TCM-based cost model (Section 2.5). Incremental manufacturing and assembly costs of the added/subtracted components are summarized in Table 5 to Table 8. The total cost increase for the countermeasures is $17.35. Total mass increase for the countermeasures is 9.0 kg.

Silverado Chassis Frame Baseline Manufacturing Costs						
Item #	Part Name	Qty per Veh	Material	Mass (kg)	Manufacturing Process	Part Piece Cost
1	Tube Front Crossmember	1	Mild 140/270	3.29	Hydoform Single Thickness	$5.08
2	Transmission Rear Mount	1	Various	0.65	Various	$2.77
			Total Mass	**3.94**	Total Parts Cost	**$7.85**

Table 5: 2014 Silverado Baseline Model – Subtracted Parts

Silverado Chassis Frame Countermeasures Manufacturing Costs						
Item #	Part Name	Qty per Veh	Material	Mass (kg)	Manufacturing Process	Part Piece Cost
1	Tube Front Crossmember	1	HLSA 350/450	6.50	Roll Form Closed Profile	$7.40
2	Side Frame Tube Inner Upper	2	HLSA 350/450	1.00	Roll Form Open Profile	$1.82
3	Side Frame Tube Inner Lower	2	HLSA 350/450	1.20	Roll Form Open Profile	$2.14
4	Side Frame Tube Outer	2	HLSA 350/450	2.60	Roll Form Closed Profile	$6.08
5	Transmission Rear Mount	1	Various	1.66	Various	$8.12
			Total Mass	**12.96**	Total Part Cost	**$25.56**

Table 6: 2014 Silverado With Countermeasures Model – Added Parts

Silverado Chassis Frame Baseline and Countermeasure Assembly Costs				
Item #	Part Name	Number of Fasteners or MIG Weld Length (mm)	Assembly Process	Cost
1	Chassis Frame Baseline	600 mm	MIG Weld	-$0.98
2	Chassis Frame Assembly Counter-Measure	1400 mm (additional assembly steps and fixtures cost)	MIG Weld	$3.78
		4 (washers, step bolts and nuts)	Mechanical Fasteners	$1.86
		Chassis Frame Assembly Cost Increase for the additional Countermeasures		**$4.66**

Table 7: 2014 Silverado With Countermeasures Model – Assembly Costs

Silverado Chassis Frame Baseline Versus. Countermeasure Costs				
Item #	Part Name	Process	Cost	Mass (kg)
1	Chassis Frame (Baseline)	Manufacture	-$7.85	3.94
		Assembly	-$0.98	
		Total	-$8.83	
2	Chassis Frame (Counter-Measure)	Manufacture	$20.54	12.96
		Assembly	$5.64	
		Total	$26.18	
		Δ Cost / Mass	**$17.35**	**9.02**

Table 8: 2014 Silverado With Countermeasures Model – Summary Cost and Mass Increase

4 CAE Modeling

4.1 Vehicle Finite Element Analysis Modeling Introduction

Finite element analysis models are used extensively in the automotive industry to support the design and engineering process to create safe and mass efficient vehicles. For this program, detailed FEA models for the baseline vehicle were constructed and correlated with the available test results. The CAE LS-DYNA models are constructed to be compatible with available FEA models from NHTSA[11] and suitable for frontal vehicle-to-vehicle crash simulation.

4.1.1 Crash Simulation Software using LS-DYNA

Finite element analysis methods are used extensively by automotive industry researchers and engineers to both simulate and analyze automotive crashes and also design and develop safety systems for passenger vehicles in high-speed impacts. LS-DYNA finite element software is the industry standard software for crash simulation and modeling. LS-DYNA software is based on computer programs originally developed by Lawrence Livermore National Laboratory for impact and defense applications. This software is based on non-linear explicit FE formulations, and is suited for large deformation applications, which is typical of the crashed structures seen in the automobile industry (single vehicles, vehicle-to-vehicle, vehicle-to-barrier, etc.). Other desirable features of LS-DYNA include an extensive library of material models, handling of large material deformation and material fracture, computational efficiency in explicit formulation, and domain decomposition by parallel processing for large simulations.

With the advent of high-speed, high-memory-capacity computers in the early 1990’s, computer technology reached the point where vehicle crashes could be accurately visualized (simulated) using the computer. Enhanced visualization from computer simulations also permits a better understanding of the crash event than using only high-speed videos of an actual crash. In addition, the simulation solvers like LS-DYNA calculate the accelerations, forces, deflections, stresses, and strains on every part of the vehicle and structure throughout the collision event. This vast amount of data collection is not possible for crash tests that rely on electronic sensors as the sole source of obtaining engineering data. Thus, impact simulations utilizing nonlinear FE analysis and rigid body dynamics have become effective tools in optimizing and evaluating vehicle safety systems.

4.1.2 Crash Simulation LS-DYNA FEA Models

The automotive companies use finite element models for crash simulation ranging in size of 2 to 10 million elements. For competitive reasons, these finite element models are not distributed outside the automotive companies. In terms of publicly available, open-source finite element

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[11] NHTSA. (n.a.). Crash Simulation Vehicle Models (Web page). Washington, DC: Author. Available at www.nhtsa.gov/crash-simulation-vehicle-models

models of automobiles, the largest models are approaching about 2 million elements in size. For this study, the LS-DYNA models constructed for the baseline 2014 Honda Accord and the 2014 Silverado 1500 are approximately 3 million elements in size. These finite element models are quite extensive in detail in order to accurately predict crashworthiness behavior of the vehicle in question.

For this study, LS-DYNA version 8.0 is used for simulation. Pre- and post-processing is done using a system that has 64-bit Windows 7 as the operating system with 24 GB RAM. The vehicle models are constructed to be compatible with available FEA models from George Washington University and suitable for frontal vehicle-to-vehicle crash simulation.
There are many aspects of FE modeling that affect the accuracy of the simulation. A partial list of the factors that were considered is given below.

1. Element Type

   The element formulation in CAE model is used with LS-DYNA Type 16 fully integrated Bathe-Dvorkin shell element for major load path parts.

2. Element Formulation

   For more accurate material stress strain behavior, the option of the material formulation for strain rate effect, visco plastic VP=1.0 is used.[12]

3. Integration Points

   The integration point through the thickness of the sheet metal in the model is used with 5-point integration option for major load path parts.

4. Modeling of Spot Welds, Self-Piercing Rivets, and Adhesive Bonding

   The spot welds on the structure are modeled with mesh-independent hexa solid weld element[13] of LS-DYNA. The mechanical properties of the spot welds are dependent on the thickness and yield strength of the joining panels. Spot-weld failure based on tensile and shear force properties[14] is represented on the MAT_100 (*MAT_SPOTWELD-DAMAGE-FAILURE)[15] LS-DYNA material representation card. The data for the failure

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[12] Livermore Software Technology Corporation. (2012, March 26, 2012) LSDYNA keyword user's manual, volume II: Material models (Revision 1275, Version 971). Livermore, CA: Author. Available at www.dynamore.de/en/downloads/manuals/ls-dyna-manuals/ls-dyna-971-manual-vol-ii-material-models/at_download/file

[13] Malcolm, S., & Nutwell, E. (2007). Spotweld Failure Prediction Using Solid Element Assemblies. (Paper presented at 6th European LS-DYNA Users' Conference, Gothenburg, Sweden, May 29-30, 2007).

[14] Chao, Y. J. (2003). Ultimate strength and failure mechanism of resistance spot weld subjected to tensile, shear, or combined tensile/shear loads. *Journal of Engineering Materials and Technology, Vol. 23*.

[15] Livermore Software Technology Corporation, 2012

forces is taken from several technical publications[16] and scaled based on spot-weld nugget diameter, material yield strength, and the thickness of the thinner of the two panels. The calculated failure forces are further scaled to account for the dynamic effects[17]. Self-piercing rivets are also represented using MAT_100 cards, with failure forces calculated based on test data.

The adhesive bonding of panels is modeled using strips of hexa elements to represent the adhesive thickness layer. The LS-DYNA material MAT 240[18] cohesive material model is used. The adhesive material properties were provided by Dow Automotive and are based on test results that were correlated to failure prediction models. The data provided by Dow Automotive is confidential. In the LS-DYNA model, the adhesive material properties are encrypted.

5. Material Failure Criteria

   When considering the sheet material fracture/failure behavior, the failure option "major in plane strain at failure" (EPSMAJ) of LS-DYNA MAT_123 *MODIFIED_ PIECEWISE_LINEAR_PLASTICITY[19] is used for the materials that are considered to have lower elongation and are prone to fail under extreme impact conditions. LS-DYNA computes the “major in plane strain” in all elements at each time step. When the plastic strain exceeds the failure criterion in an element, that element is eroded (i.e., removed from the finite element model).

4.1.3 Material Properties and Modeling

The following sections discuss how steel and aluminum were modeled in this study.

4.1.3.1 Steel

Table 9 lists the common material properties of the steels used in the LS-DYNA model. Figure 18 and Figure 19 show data used to define the static and dynamic stress versus strain for the various types of steel used in the finite element baseline and LWT models. The steel properties for the various grades were provided by WorldAutoSteel, the automotive group of the World Steel Association. The comprehensive data including strain rate dependent stress strain curves were developed through testing by WorldAutoSteel member companies.

For these projects the part material data was obtained first by conducting material tensile tests on the corresponding part samples. From the tensile test data, the yield strength, ultimate tensile

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[16] Radakovic, D. J., & Tumuluru, M. (2008). Predicting resistance spot weld failure modes in shear tension tests of advanced high-strength automotive steels. *Welding Journal, Vol. 87.*

[17] Wang, K., Chao, Y. J., Zhu, X., & Miller, K. W. (2010, December) Dynamic separation of resistance spot welded joints: Part II—Analysis of test results and a model *Experimental Mechanics, Vol. 50* Issue 7. DOI: 10.1007/s11340-009-9277-y.

[18] Livermore Software Technology Corporation, 2012

[19] Ibid.

strength, and elongation were compared with known grades of steel in the WorldAutoSteel database and the most suitable grade of steel was identified for each part.

Steel Grade	Density (kg/m^3)	Poisson's ratio	Modulus of Elasticity (MPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Failure Elongation (%)
Mild 140/270	7,850	0.3	21.0×10^4	140	270	No Failure
BH 210/340	7,850	0.3	21.0×10^4	210	340	No Failure
BH 260/370	7,850	0.3	21.0×10^4	260	370	No Failure
BH 280/400	7,850	0.3	21.0×10^4	280	400	No Failure
HSLA 350/450	7,850	0.3	21.0×10^4	350	450	No Failure
HSLA 420/500	7,850	0.3	21.0×10^4	420	500	No Failure
HSLA 550/650	7,850	0.3	21.0×10^4	550	675	No Failure
DP 700/1000	7,850	0.3	21.0×10^4	700	1000	29
HF 1050/1500	7,850	0.3	21.0×10^4	1050	1600	18
DP 1150/1270	7,850	0.3	21.0×10^4	1150	1270	24
MS 1250/1500	7,850	0.3	21.0×10^4	1250	1500	13.5

Table 9: Table of Common Engineering Properties of Steels Used in CAE Models

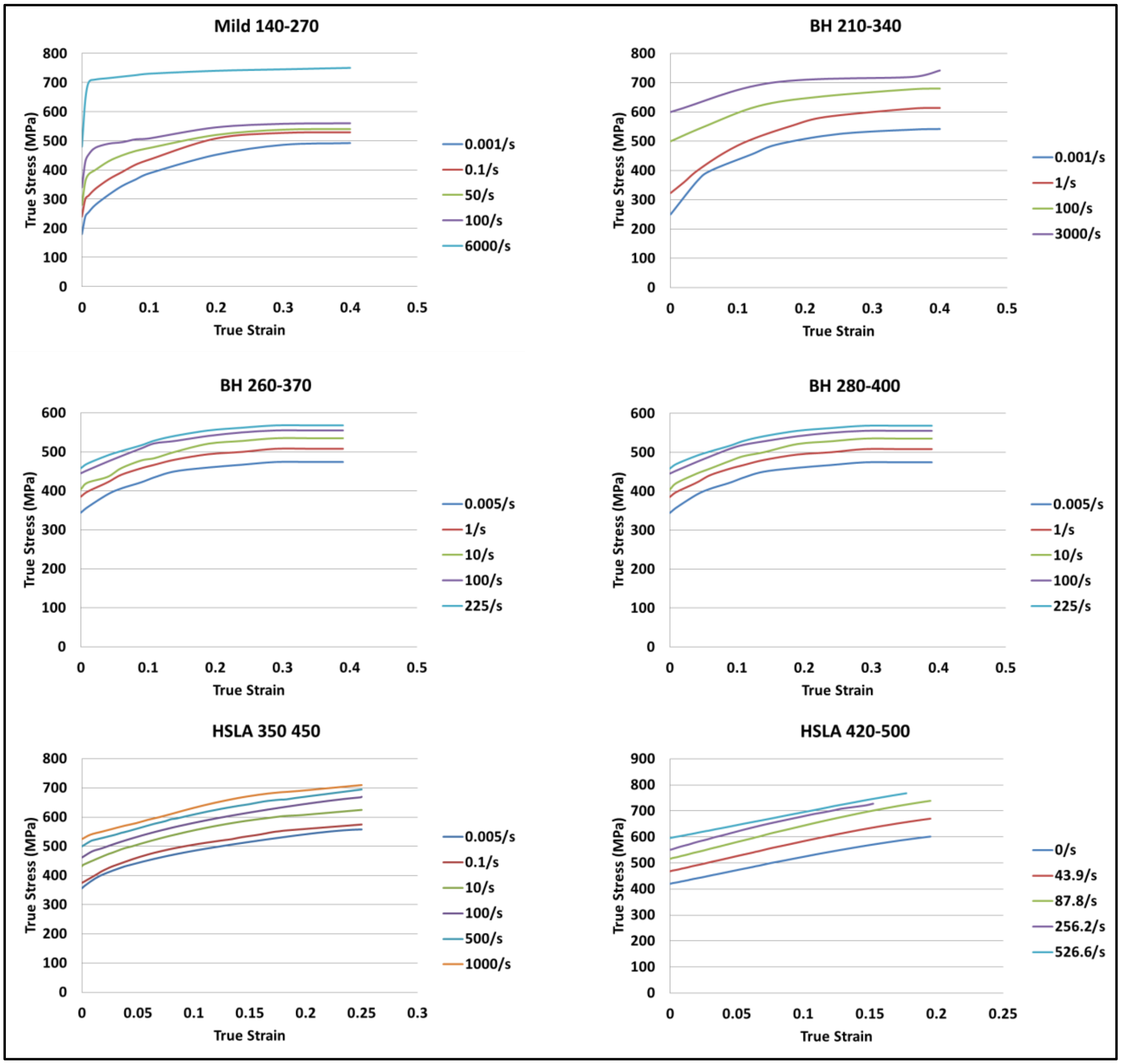
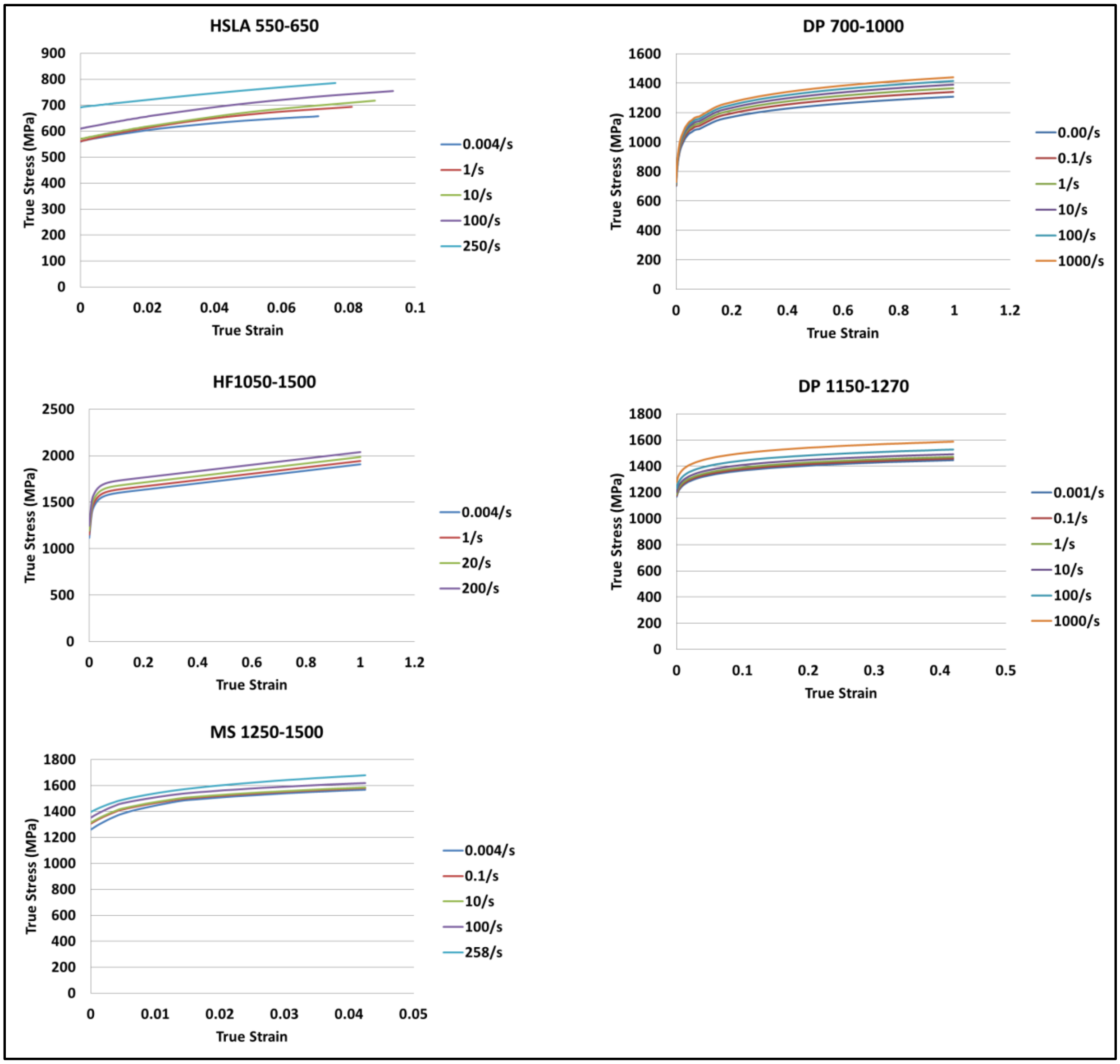


Figure 18: Material Curves of Stress Versus Strain Used for Steel in Model – Part I



HSLA 550-650

DP 700-1000

HF1050-1500

DP 1150-1270

MS 1250-1500

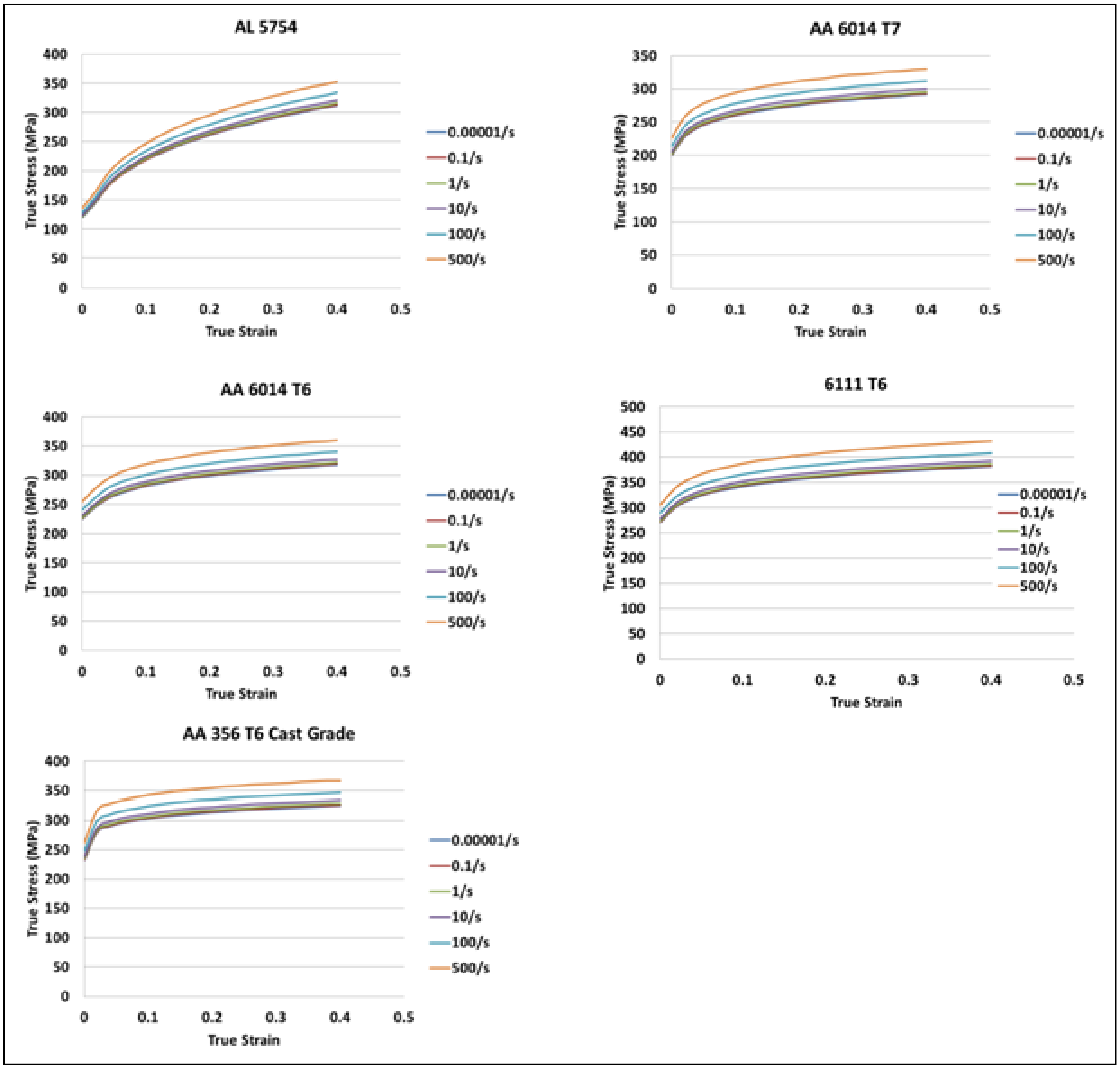
Figure 19: Material Curves of Stress Versus Strain Used for Steel in Model – Part II

4.1.3.2 Aluminum

Aluminum is mainly used for the upper structure sheet metal of the LWT design. The modeling approach for aluminum is well understood as the automotive industry has been modeling this material satisfactorily for many years. The material properties of the aluminum grades used for this study are shown in Table 2. The stress-strain curves for aluminum alloys used in the LS-DYNA model are presented in Figure 20. The material properties for aluminum grades were derived with input from Aluminum Associations' ATG (Aluminum Transportation Group) and EDAG's in-house database.

Aluminum Alloy Grade	Density (kg/m3)	Poisson's ratio	Modulus of Elasticity (MPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Failure Elongation (%)
AL 5754	2,700	0.33	7.1×10^4	120	250	16
AA 6014-T7	2,700	0.33	7.1×10^4	200	270	17
AA 6014-T6	2,700	0.33	7.1×10^4	225	294	18
AA 356-T6 CAST	2,700	0.33	7.1×10^4	232	302	10
AA 6111-T6	2,700	0.33	7.1×10^4	270	355	16

Table 10: Table of Common Engineering Properties of Aluminum Used in CAE Models



AL 5754

AA 6014 T7

AA 6014 T6

6111 T6

AA 356 T6 Cast Grade

Figure 20: Material Curves of Stress Versus Strain Used for Aluminum in LS-DYNA Model

5 CAE and Test Performance Results for 2014 Honda Accord

In this section, the test results are compared with the predicted CAE results for the baseline CAE model to show quality and accuracy of the correlation, and also with the CAE model that include the countermeasures to reduce the occupant compartment intrusion from NHTSA’s oblique offset frontal crash condition. The recommended countermeasures are shown in Figure 12.

For the load cases that did not have real vehicle test data to correlate to, the results are compared with other similar reference vehicles.

5.1 NHTSA Oblique Test Driver Side

This test is used to determine the crashworthiness of the vehicle to protect occupants in offset frontal impact crash cases. The test consists of an oblique moving deformable barrier that weighs 2,490.2 kg travels at a target speed of 90.12 km/h into a stationary vehicle. The struck vehicle’s longitudinal centerline is positioned 15 degrees clockwise from the moving barrier’s centerline for right impacts. The test vehicle is struck at 35percent of the left or right side of the vehicle as shown in Figure 21.

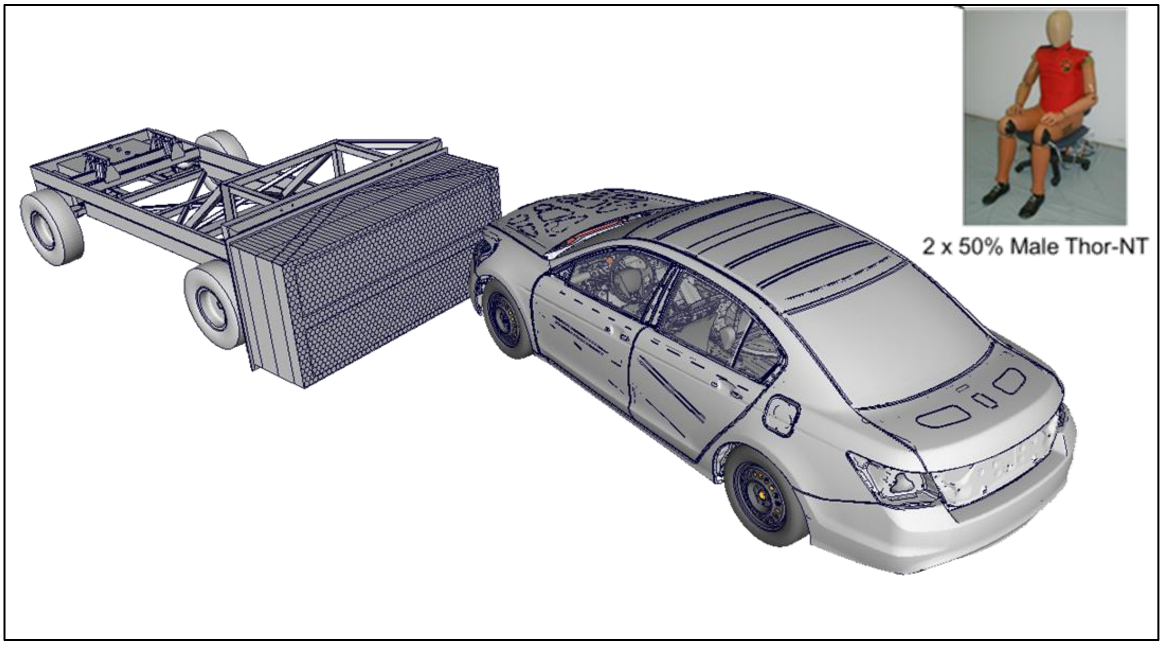


Figure 21: NHTSA Oblique Test Left

The test vehicle is equipped with two 50th percentile male THOR-NT dummies with combined mass of 197.8 kg and a cargo mass of 44.8 kg. These masses were accounted for in the CAE model. The test vehicle and CAE set up for the oblique crash test is shown in Table 11.

	Test Baseline	**EDAG CAE Baseline**
	2014 Honda Accord	2012 CAE model updated to represent 2014 Honda Accord
Engine Disp (L)	2.4	2.4
Tested Weight (kg)	1,708	1,720

Table 11: Test Versus CAE Vehicle Specification

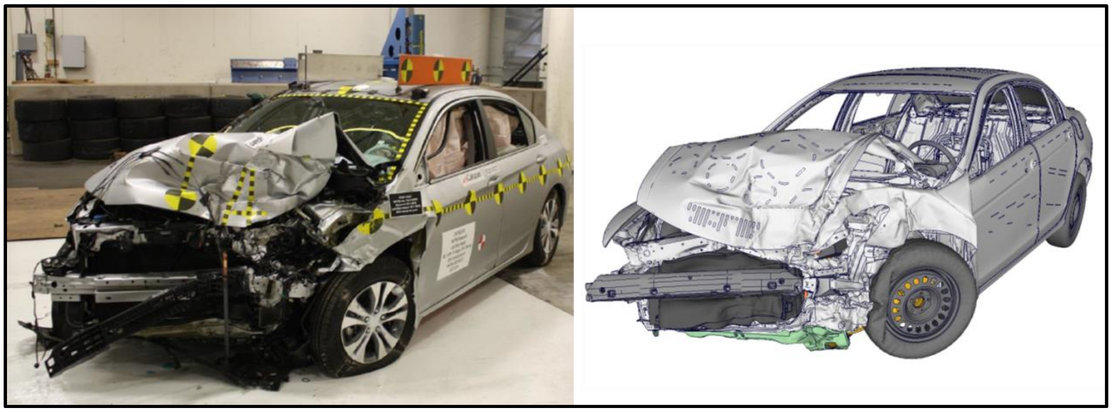


Figure 22: NHTSA Oblique Test Left – Post-Crash Comparison Test Versus CAE Baseline

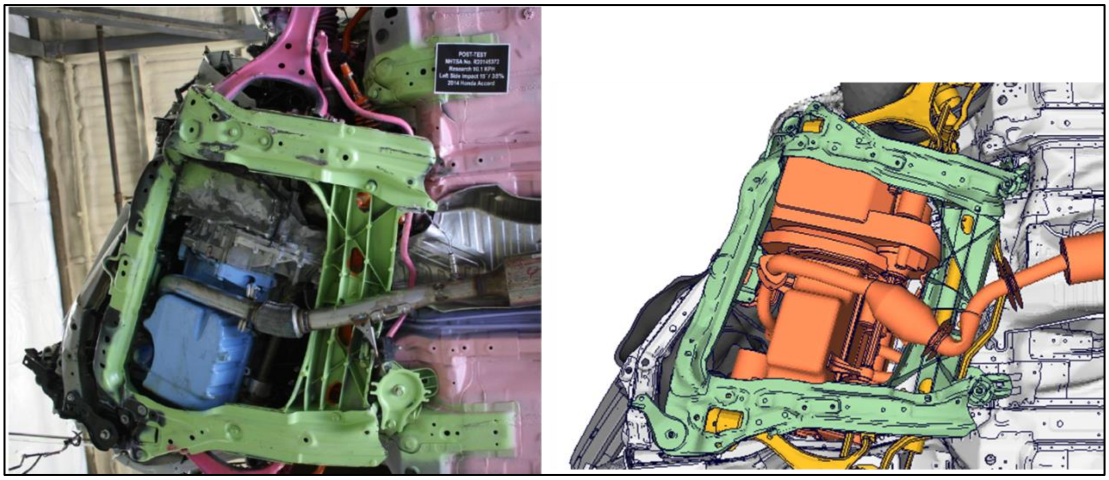


Figure 23: NHTSA Oblique Test Left – Post-Crash Comparison Test Versus CAE Baseline

Figure 22 and Figure 23 show the post-crash comparison of both test and CAE simulations. The overall kinematics, deformation shape, and the material failures, especially in the sub-frame on the simulation structure, correlate well with test. The EDAG team visited CALSPAN proving ground to inspect and take additional measurements of the crash-tested vehicle. The additional collected information increased the team's knowledge to improve the correlation between the test and the CAE model.

The acceleration in X and Y of the vehicle is shown in Figure 24; the data is taken from accelerometers attached under the B-pillar sill section of the vehicle. The CAE model shows good overall agreement in terms of pulse shape, width and magnitude compared with the test pulse. The average pulse difference between test and CAE model for both components are less than 5 percent. The average pulse is measured between 0ms to the time acceleration reaches 10Gs after peak. Velocity of both vehicles also showed very good correlation with a CORA[20] score higher than 90 percent for both velocity components as shown in Figure 25.

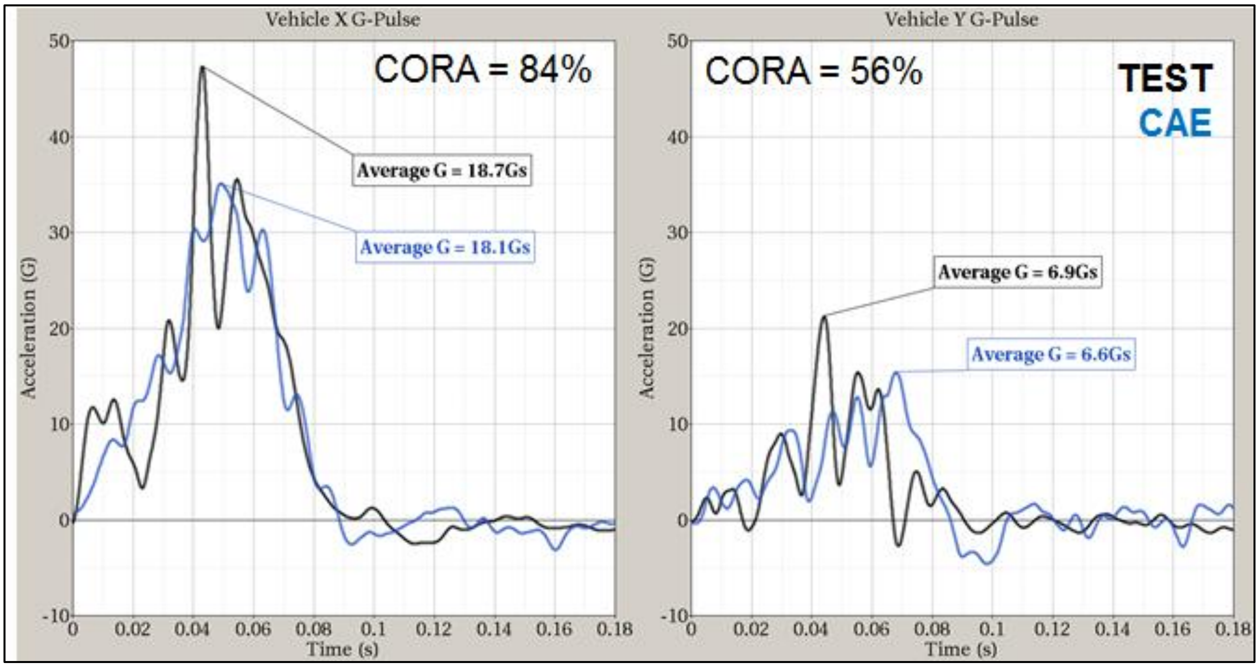


Figure 24: Test Versus CAE X and Y Acceleration Pulse

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[20] According to its web site, the CORA (CORrelation and Analysis) software "provides an objective evaluation of time-history signals, e.g., derived from test and simulation." See www.pdb-org.com/en/information/18-cora-download.html

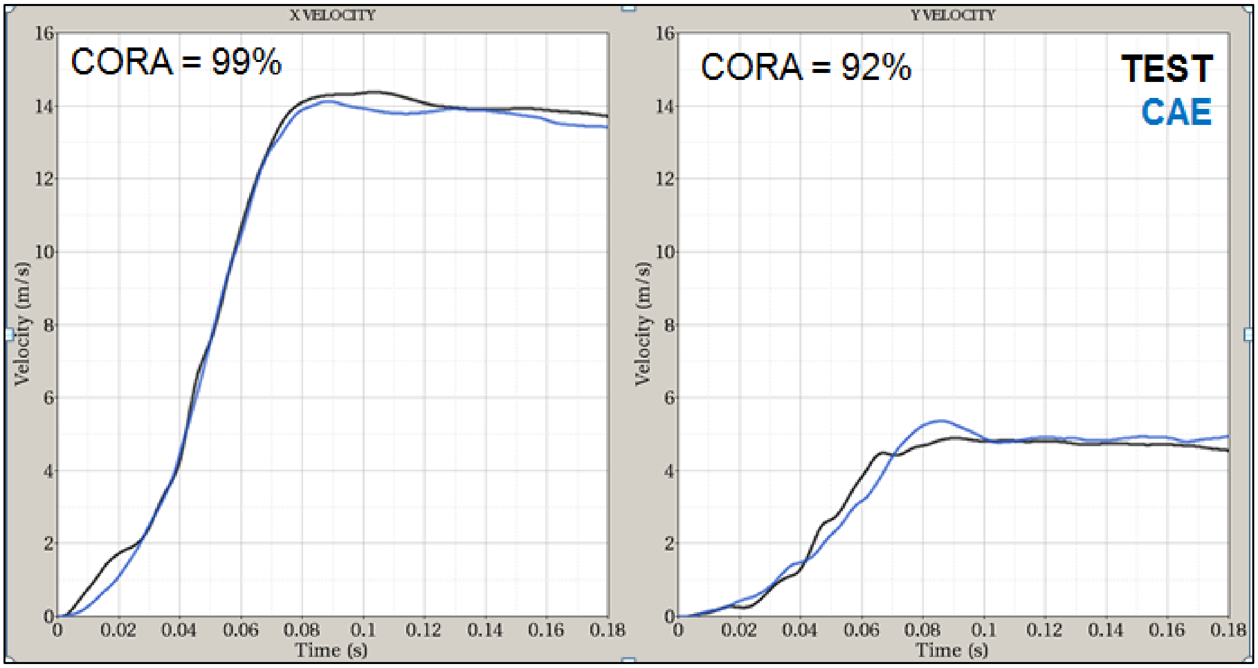


Figure 25: Test Versus CAE X and Y Velocity

For intrusion comparison, the standard NCAP driver compartment intrusion is measured along with the deformation of the floor for the driver as per the oblique test protocol. The passenger side intrusion is not included in the report as the intrusions are very small. The driver compartment and floor pan intrusion are shown in Figure **26** and Figure 27 respectively. For evaluation purpose, we used IIHS intrusion ratings methodology to evaluate the floor pan intrusion. The rating is divided into four categories classed as Good (< 150mm), Acceptable (< 225mm), Moderate (< 300mm) and Poor (> 300mm). The CAE simulation correlates very well with the test intrusion numbers, all within 15mm as shown in Figure 27.

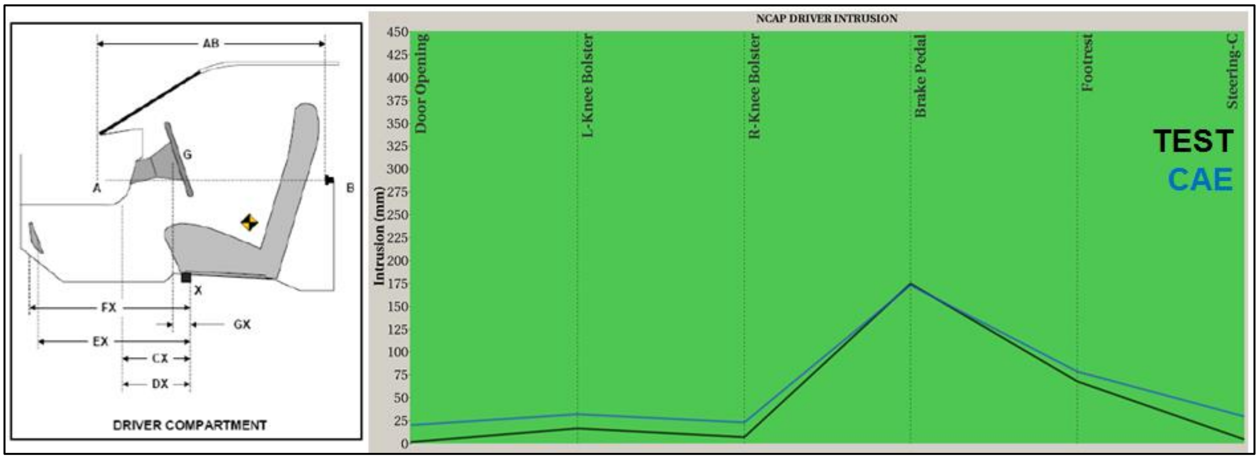


Figure 26: Test Versus CAE NCAP Driver Compartment Intrusion

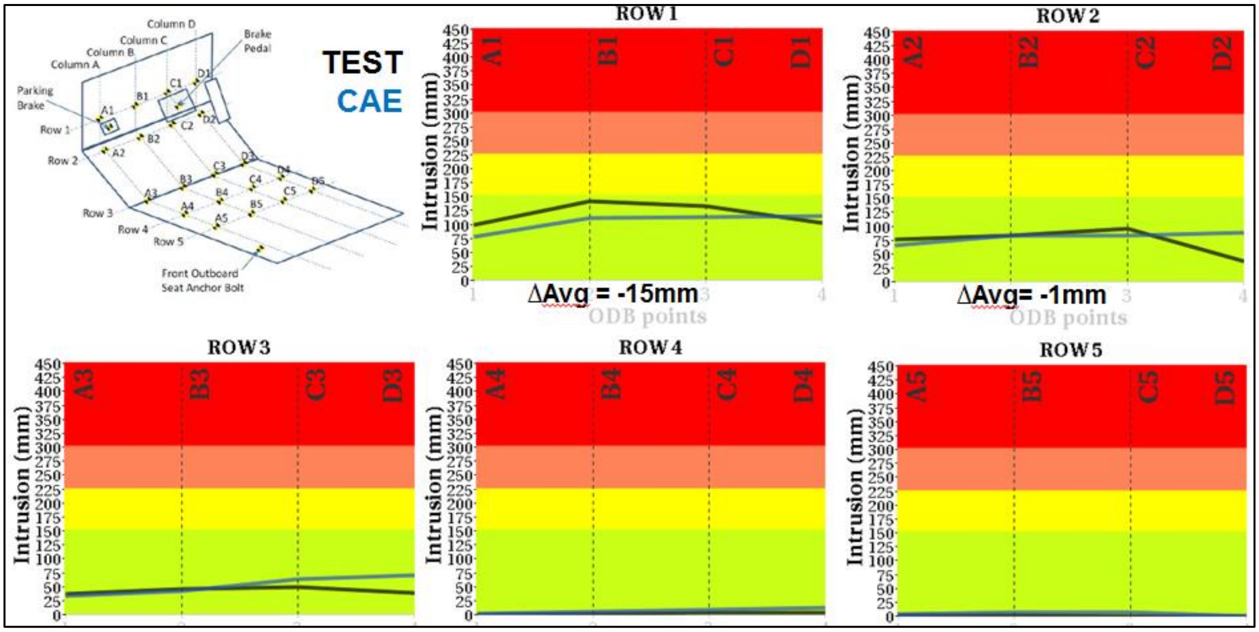


Figure 27: Test Versus CAE NCAP Driver Floor Pan Intrusion

Overall, the CAE simulation for the oblique impact correlates well with the test in both vehicle kinematics and intrusion. Using this correlated model, the countermeasures are applied as discussed in Section 2.2 to improve the intrusion numbers shown in the baseline model.

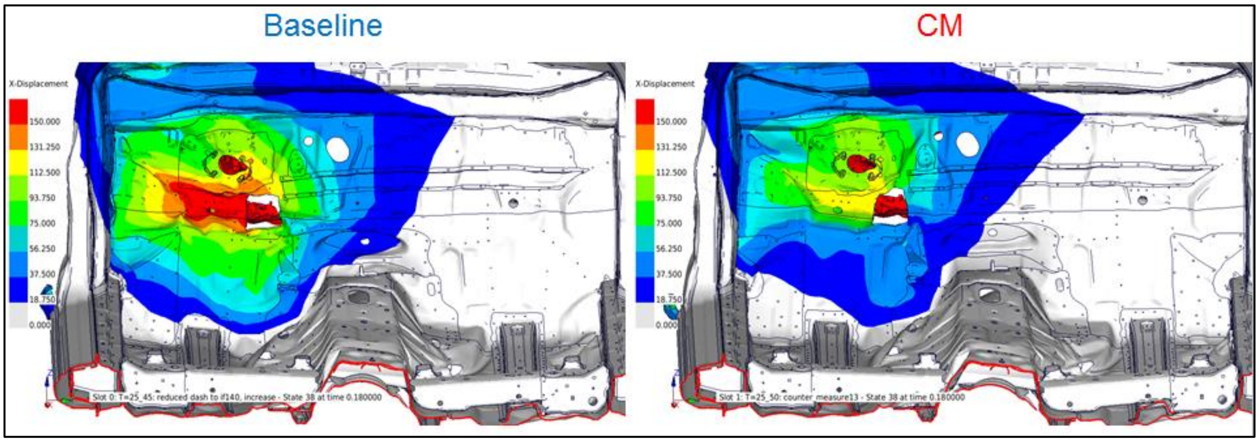


Figure 28: Base CAE Versus Countermeasure CAE – Dash view

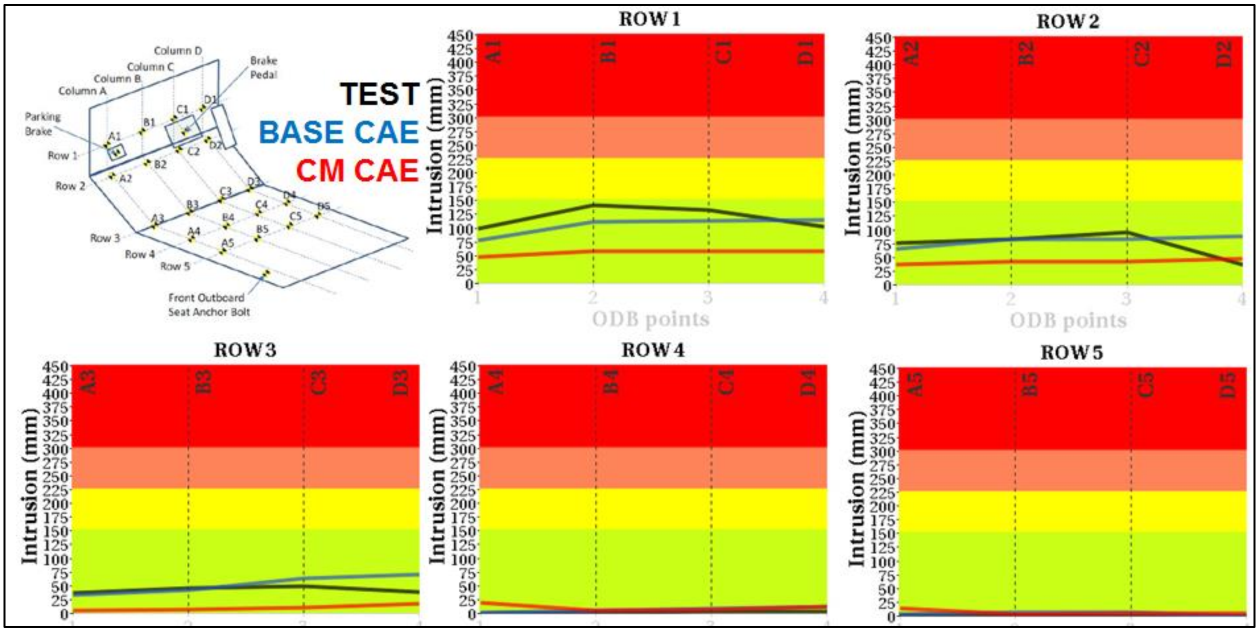


Figure 29: Base CAE Versus Countermeasure CAE – Floor Pan Intrusion

Figure 28 and Figure 29 show the intrusion on the dash and the floor pan. The countermeasure has significantly reduced the intrusion on the dash and the floor pan. The countermeasure has increased the vehicle average acceleration pulse by less than 1G in both X and Y directions that show the occupants will experience similar G levels as compared to the base model. The acceleration pulse of the countermeasure model is shown in Figure 30.

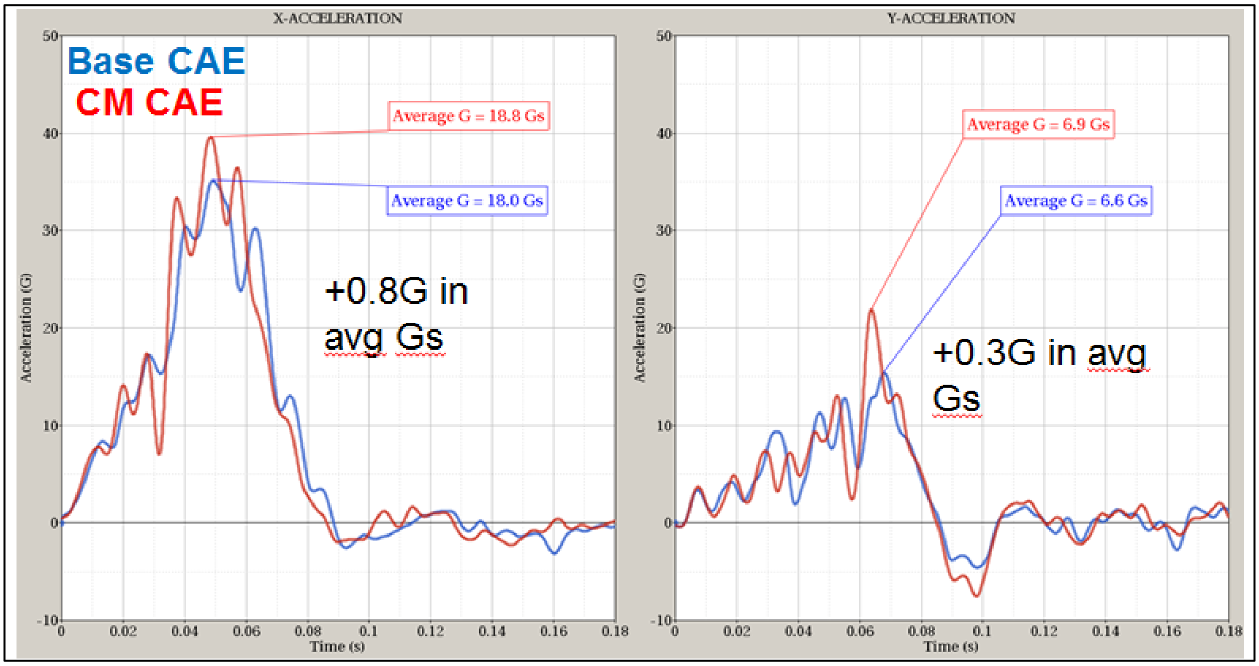


Figure 30: Base CAE Versus Countermeasure CAE – X and Y Acceleration Pulse

5.2 NHTSA Oblique Test Passenger Side

Similar to the driver side, the base model was also compared to the oblique test that impacts the vehicle on the passenger side. The setup of the test/model is the same but the barrier is positioned on the right side, symmetrical as it was in the left side impact. The setup of the model and test vehicle/CAE model specification is shown in Figure 31 and Table 12.

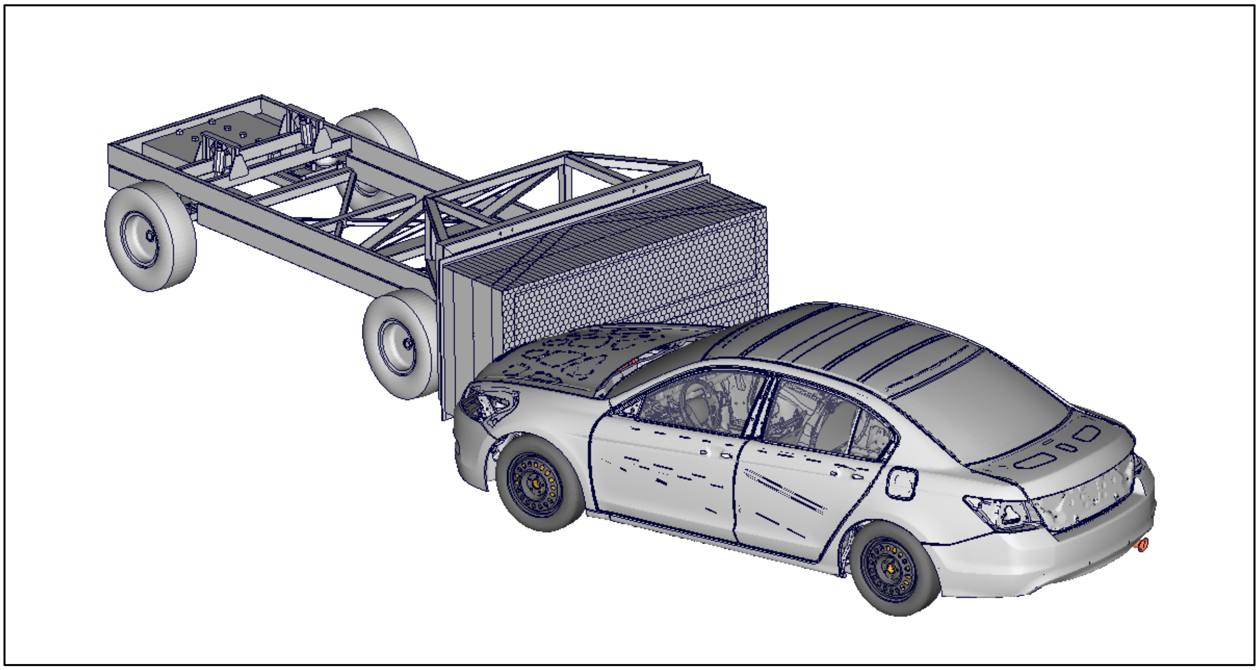


Figure 31: NHTSA Oblique Test Right

	Test Baseline	EDAG CAE Baseline
	2014 Honda Accord	2012 CAE model updated to represent 2014 Honda Accord
Engine Disp (L)	2.4	2.4
Tested Weight (kg)	1,722	1,720

Table 12: Test Versus CAE Vehicle Specification

Post-Crash images of both Test and CAE simulation of the NHTSA oblique test passenger side are shown in Figure 32 and Figure 33. The overall kinematics, deformation shape, and the material failures, especially in the sub-frame on the simulation structure, correlate well with the test.

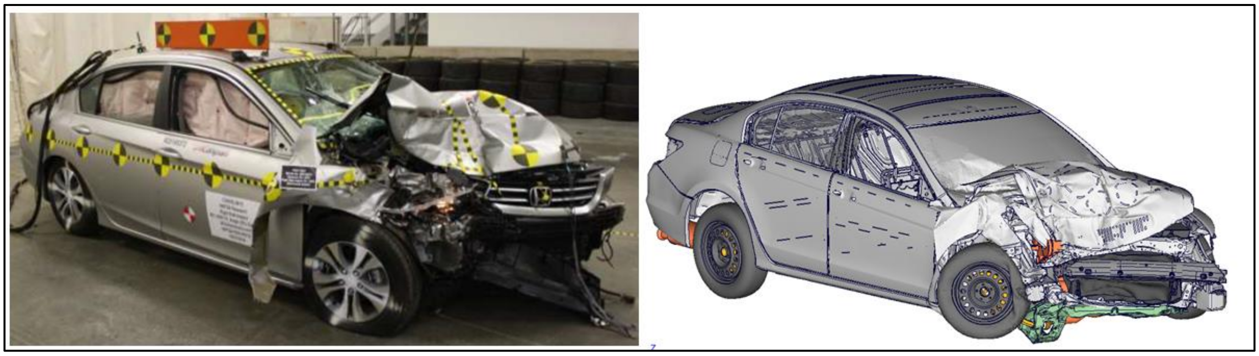


Figure 32: Test Versus CAE – Post-Crash Comparison

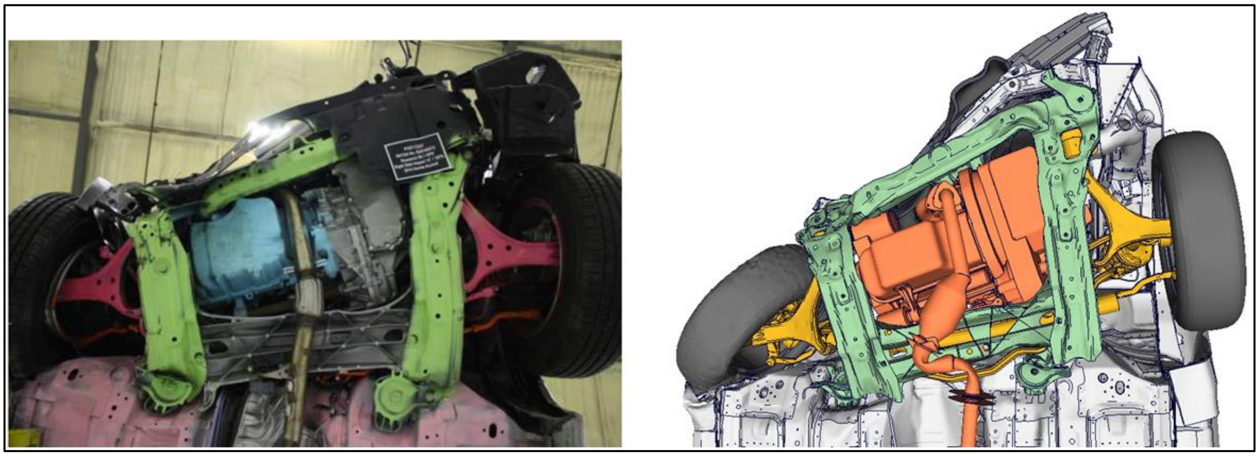


Figure 33: Test Versus CAE – Post-Crash Comparison

The acceleration in X and Y of the vehicle is shown in Figure 24 and the data is taken from accelerometers attached under the B-pillar sill section, similar to the driver side impact. The CAE model shows good overall agreement in terms of pulse shape, width and magnitude compared with the test pulse for the X component and the average pulse difference is less than 2 percent. The Y-acceleration pulse comparison shows average CORA score of 58 percent.

X and Y –Velocity between test and CAE prediction show good correlation with a CORA score of 98 percent and 81 percent as shown in Figure 35.

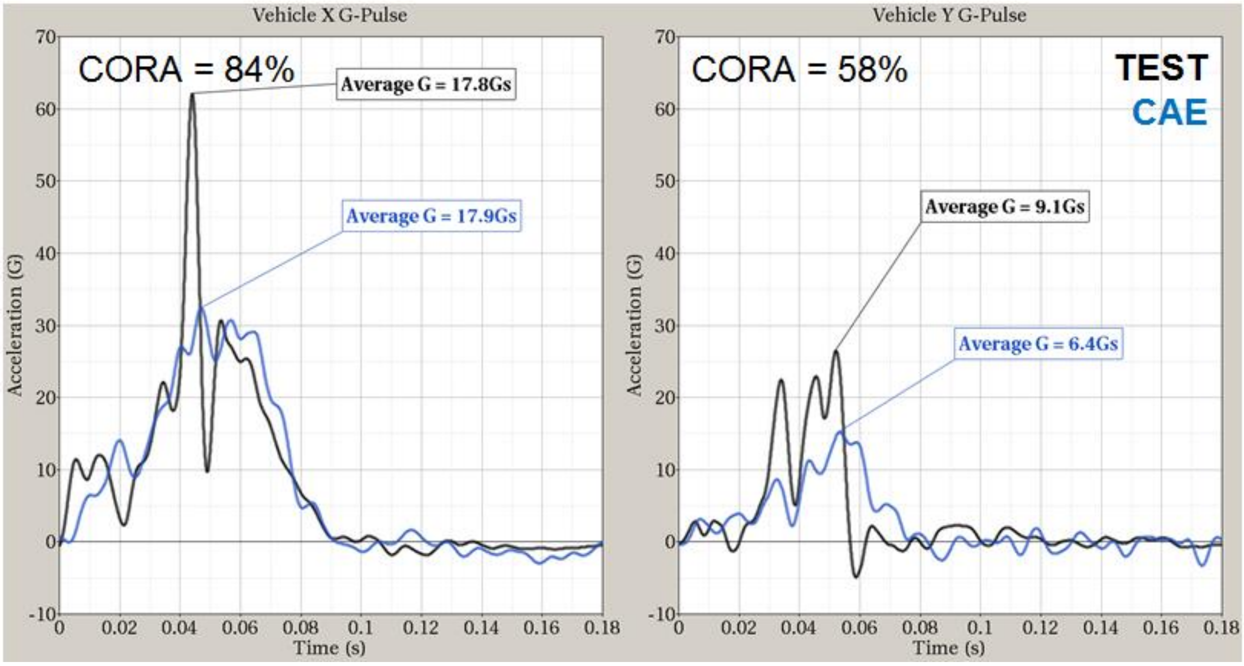


Figure 34: Test Versus CAE – X and Y Vehicle Acceleration Pulse

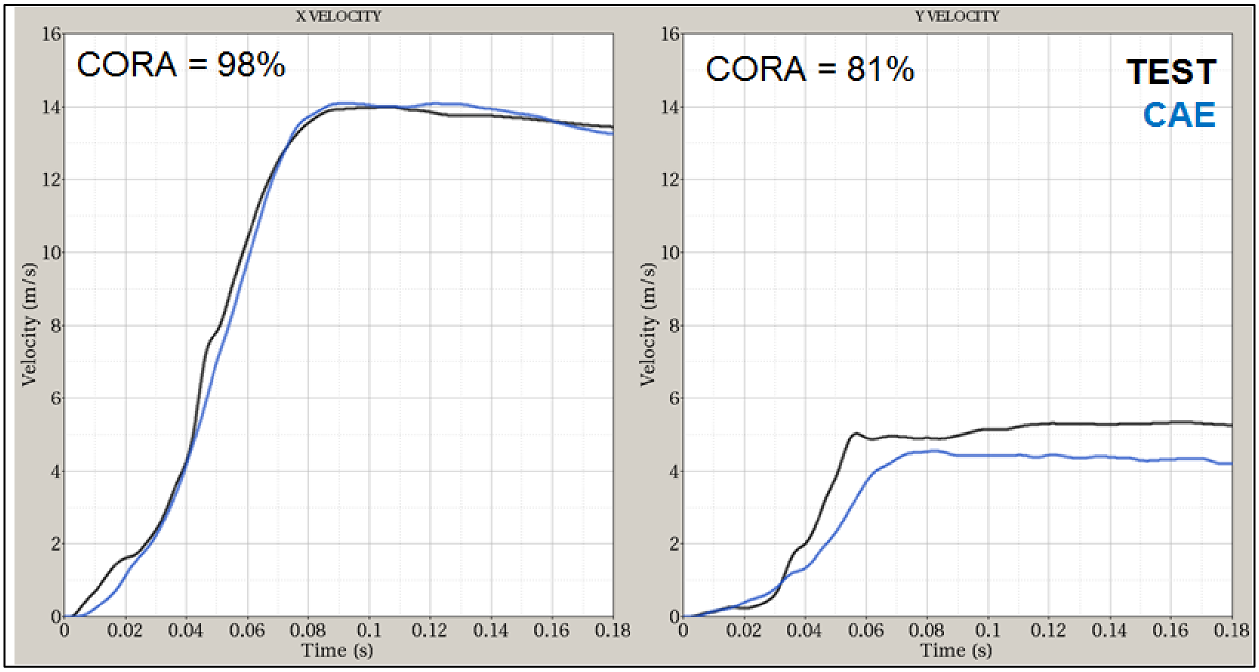


Figure 35: Test Versus CAE – X and Y Vehicle Velocity

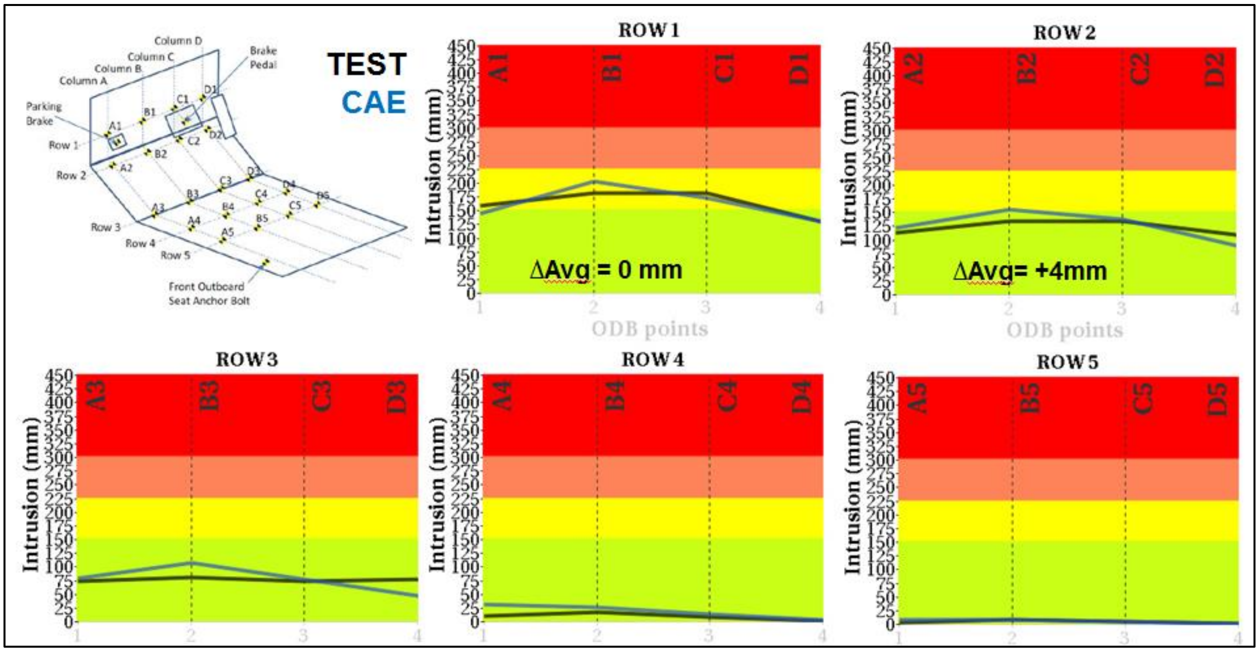


Figure 36: Test Versus CAE - Passenger Floor Pan Intrusion

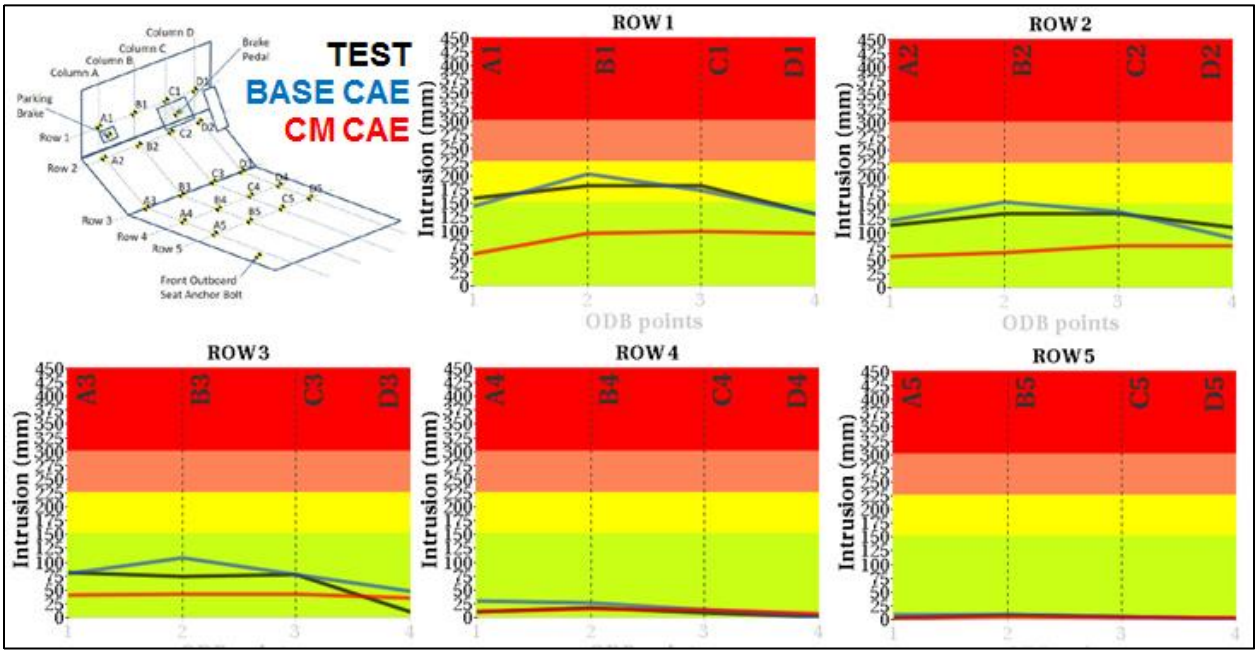


Figure 37: Base CAE Versus Countermeasure CAE Floor Plan Intrusion

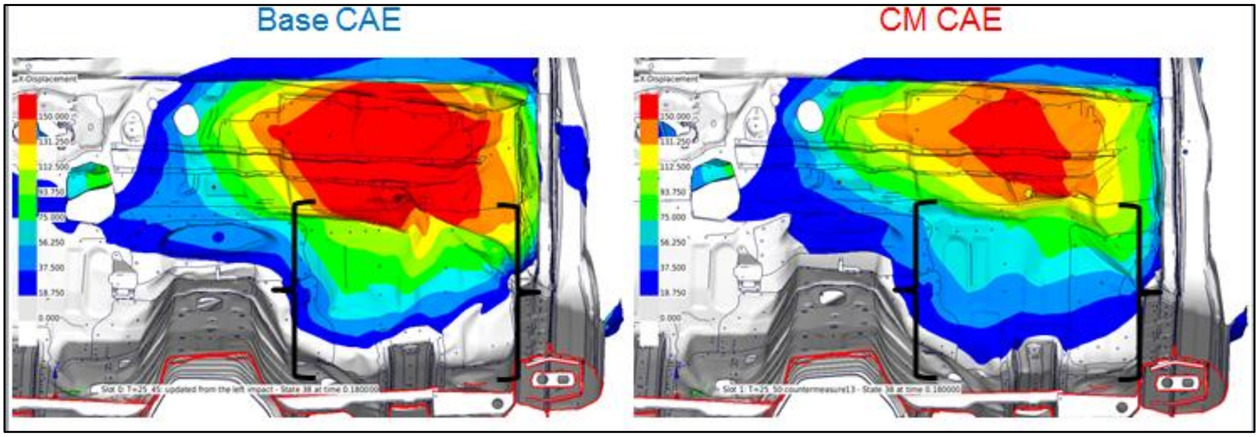


Figure 38: Base CAE Versus CM CAE – Dash Intrusion View

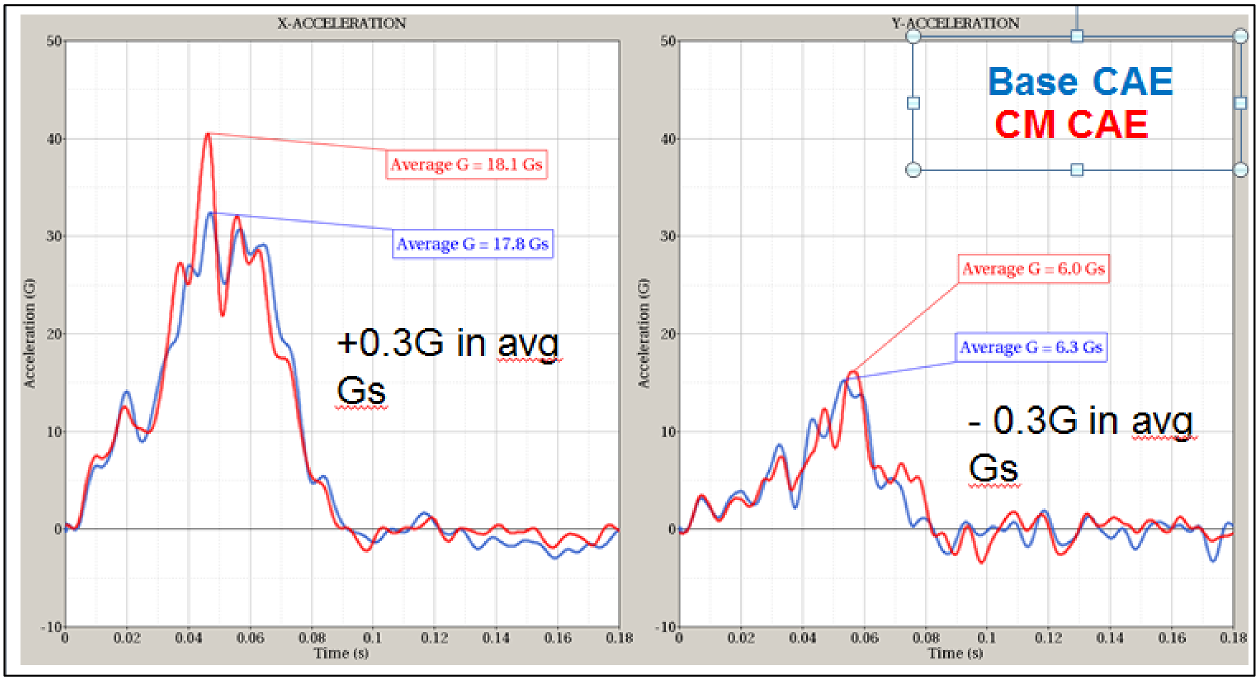


Figure 39: Base CAE Versus Countermeasure CAE – X and Y Acceleration Pulse

Figure 36 shows the comparison of passenger floor pan between test and CAE model. The CAE model correlates well with the test intrusion numbers with very small difference between them. The passenger side oblique impact seems to be slightly more severe than the driver side as the intrusion numbers for the top row (row1) on the lower dash foot well are above the 150 mm rating line.

Countermeasure that was discussed in section 2.2 is applied to the CAE model to reduce the intrusion number below the 150mm rating line.

Figure **37** and Figure 38 shows the improvement in intrusion on the passenger floor pan after the countermeasure design is applied. The intrusions are reduced by approximately 50 percent, especially for the first 3 rows (rows 1, 2 and 3) of measurements and the numbers are well below the 150mm line. The countermeasure model has X and Y acceleration pulse similar to the base model as shown in Figure 39.

In summary, the CAE model correlates well with both test setups in terms of kinematic, deformation, and intrusion. The recommended countermeasures reduce the intrusion values to well below 150mm, eventually reducing injury risk to the occupants.

5.3 NCAP Frontal Full Barrier – 56 km/h (35 mph)

This test is used to determine the crashworthiness of the vehicle to protect occupants in frontal impact crash cases. The NCAP frontal impact test undertaken by NHTSA is a full-frontal barrier test at a vehicle speed of 56 km/h (35 mph). The LS-DYNA models for the baseline 2014 Honda Accord were created to represent the test setup, such as vehicle velocity of 56 km/h against a flat rigid wall barrier. The test vehicles are equipped with a hybrid III 50th percentile male dummy on the driver seat and a hybrid III 5th percentile female dummy on passenger seat; with combined occupant mass of 141 kg and cargo mass of 44.8 kg. These masses were also accounted for in the CAE models. Although the structural countermeasures were meant for the oblique impact test, the CAE model with the CM was also analyzed for this load case. A comparison of the test vehicle and the CAE models is shown in Table 13.

Description	Test	Baseline CAE	CM CAE
Model	2014	2014 (updated 2011)	2014 (updated 2011)
Engine Disp (L)	2.4	2.4	2.4
Tested Weight (kg)	1,722	1,720	1,724

Table 13: Test Versus CAE Models – Vehicle Specifications

The test vehicle and LS-DYNA set up for the frontal crash test of the baseline model into a rigid barrier is shown in Figure 40.

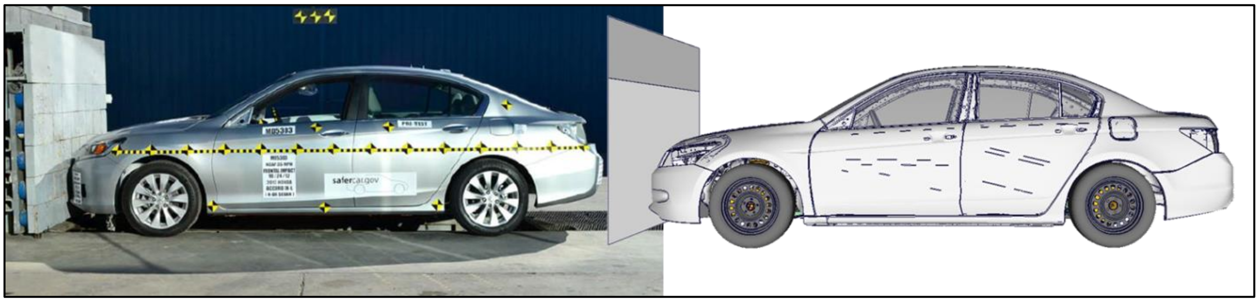


Figure 40: Test Versus CAE Model – NCAP Frontal Test Setup

Images of the post-crash vehicles for the actual laboratory crash test and the simulation are shown in Figure 41 and
Figure **42**. The overall predicted vehicle kinematics and the crushed shapes from the front side and from underneath the vehicle correlate very well with the test vehicles.

Figure 41: Test Versus CAE Model – Post-Crash Comparison

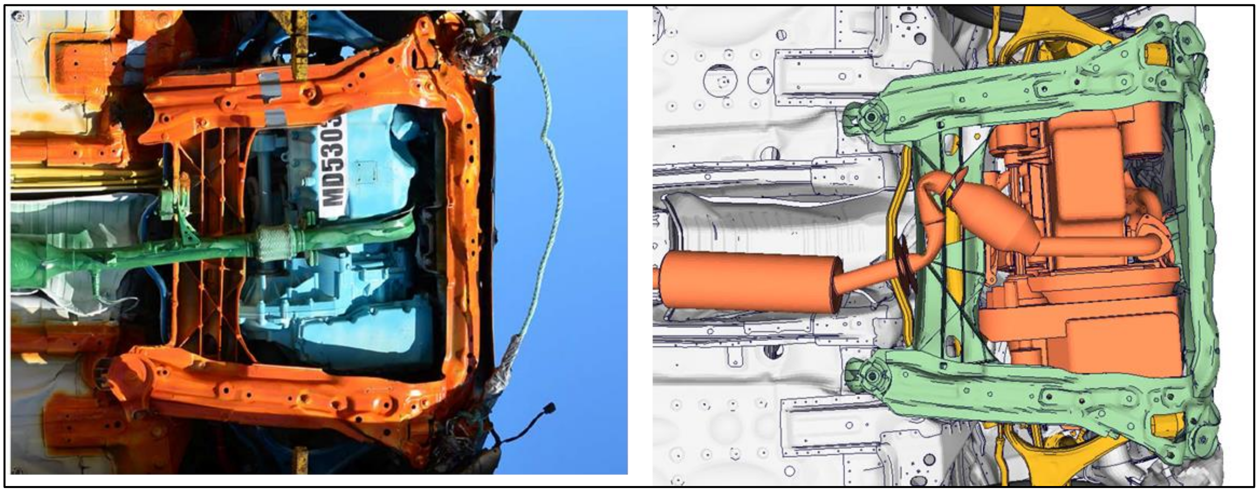
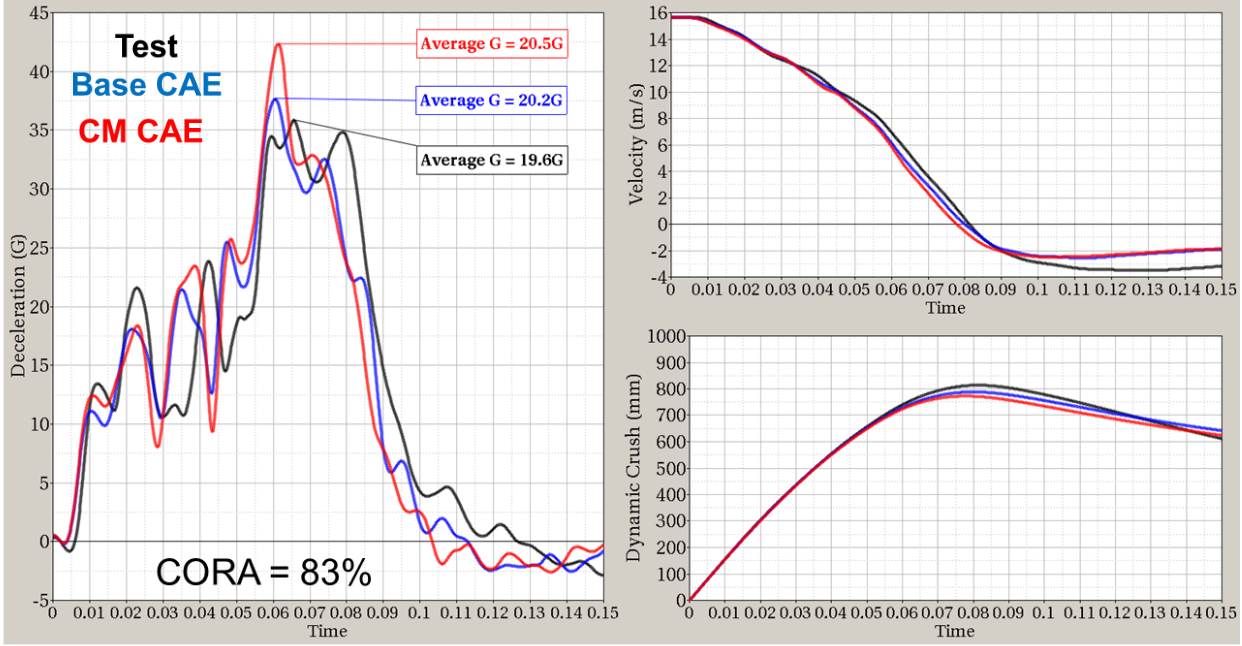


Figure 42: Test Versus CAE Model – Post-Crash Comparison

The vehicle acceleration pulse, time to zero velocity and the dynamic crush of the vehicle comparison is shown in Figure 43. Test and baseline CAE models correlate well on all 3 parameters with CORA score of 83 percent for the acceleration pulse and the difference between average G-pulse is only 3 percent. With the included countermeasures, as expected the model will experience slightly higher G-pulse due to the increase in structural strength of the occupant compartment. The CAE model with countermeasure experienced additional Gs of 0.3G (1%) compared to the baseline model.



	TEST	Base CAE	CM CAE
Avg G	19.6	20.2	20.5
Time to Zero (ms)	81	79	78
Dynamic Crush (mm)	814	785	773

Figure 43: Test Versus Baseline Versus Countermeasure – Vehicle Motion Comparison

In terms of vehicle velocity to zero, the baseline model correlates well with the test as its reaches zero velocity only 2ms earlier than the test. For the model with countermeasure, it reaches zero velocity 1ms earlier than the baseline model.

The dynamic crush of the baseline model also correlates well with the test having 29mm less crush than the baseline. After countermeasure, the CAE model has dynamic crush of 773mm that is 12mm less than the baseline due to increase in thickness of the rail extension.

The NCAP standard driver compartment intrusion was measure in all three vehicles as shown in Figure **44**. The baseline model correlates well on every point versus the test except for the steering wheel. In the test, the steering wheel experience interaction with the air bag and dummy, both of these interactions are not in the CAE model.

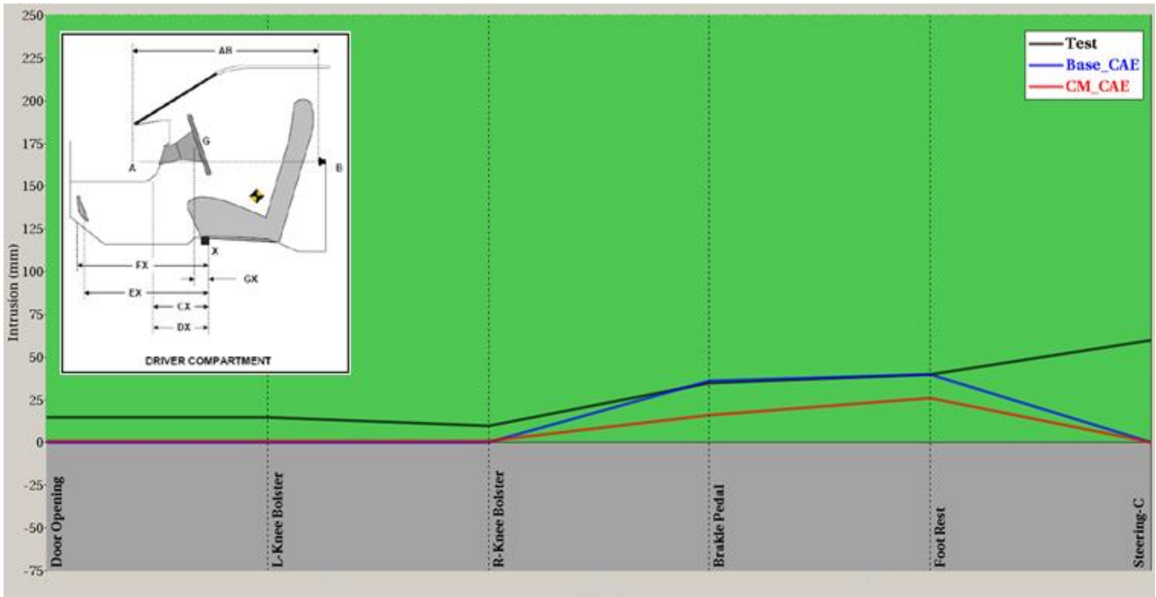


Figure 44: NCAP Driver Compartment Intrusion

In summary, the CAE model correlates well with both test setups in terms of kinematic, deformation, and intrusion. The countermeasure model performance did not vary

5.4 IIHS Moderate Overlap Frontal Crash Test

The IIHS moderate overlap frontal crash test subjects the test vehicle to a partial frontal impact into a stationary deformable barrier. The test vehicle is aligned such that the right edge of the barrier is offset from the horizontal centerline of the vehicle by 10±1 percent of the vehicle width (defined in SAE J1100 – Motor Vehicle Dimensions) as shown in this way 40 percent of the test vehicle's front face is impacted in the crash.

The LS-DYNA models for the baseline 2014 Accord and countermeasure model were created to represent the test setup, such as vehicle velocity of 64 km/h against a deformable barrier. The test vehicles are equipped with a hybrid III 50th percentile male dummy on the driver seat. The mass of the test dummy was accounted for in the CAE models. Comparisons of vehicle parameters are shown in Table 14.

Description	Test	Baseline CAE	CM CAE
Model	2013	2014 (updated 2011)	2014 (updated 2011)
Engine Disp (L)	2.4	2.4	2.4
Tested Weight (kg)	1,478	1,548	1,552

Table 14: IIHS Frontal Moderate - Test Vehicles and CAE Models Parameters

The LS-DYNA model set up for the IIHS Frontal Moderate crash test of the baseline model is shown in
Figure **45**.

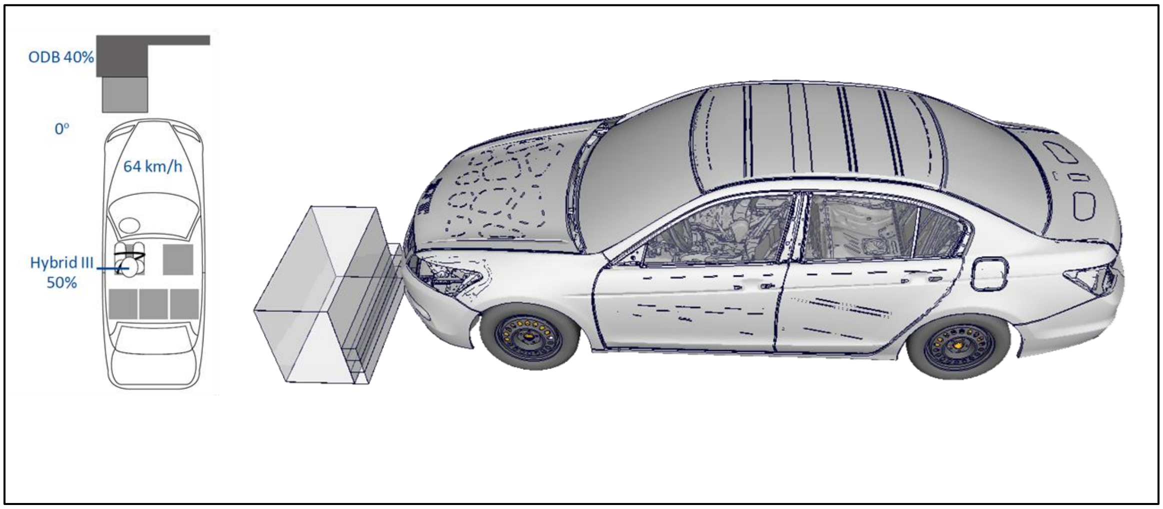


Figure 45: IIHS Frontal Moderate - Test and LS-DYNA Model Setup

The only available data from IIHS regarding this test is the intrusion number; therefore there will be no comparison with test in terms structural deformation and kinematics.

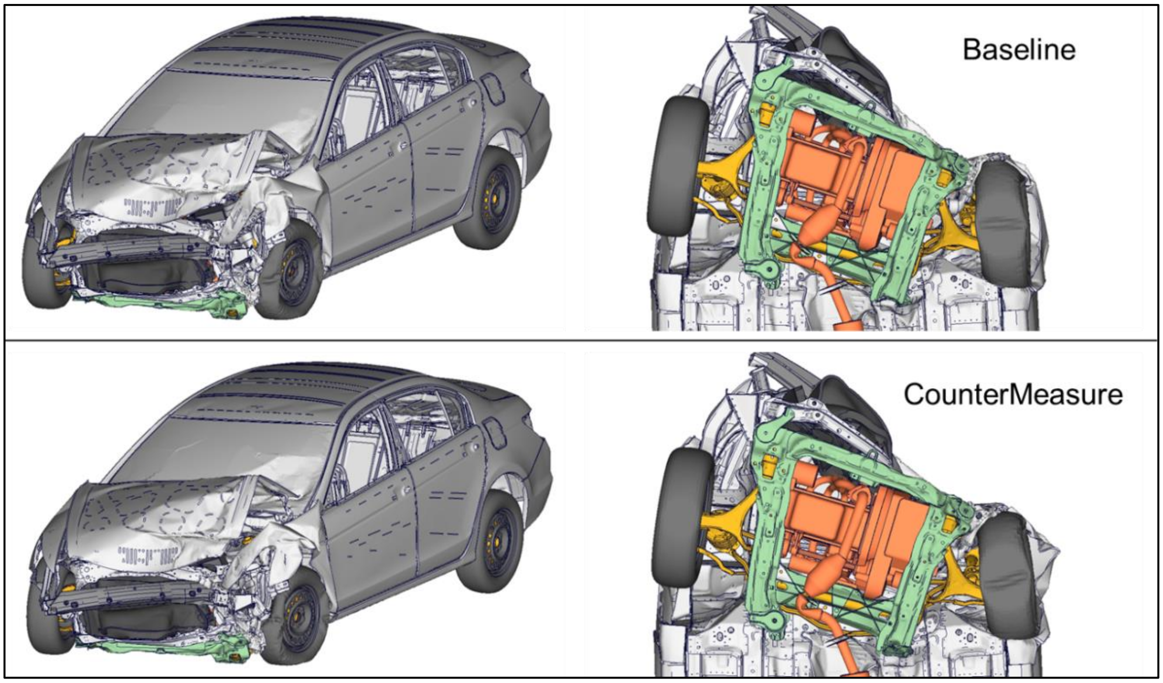


Figure 46: IIHS Frontal Offset - Post-Crash Comparison CAE results for Baseline and Countermeasure

Post-crash images of the simulation results shown in Figure 46 compares the overall predicted vehicle crushed shapes from the front, side and from underneath the vehicle. The baseline CAE model and the countermeasure CAE model show similar crash performance.

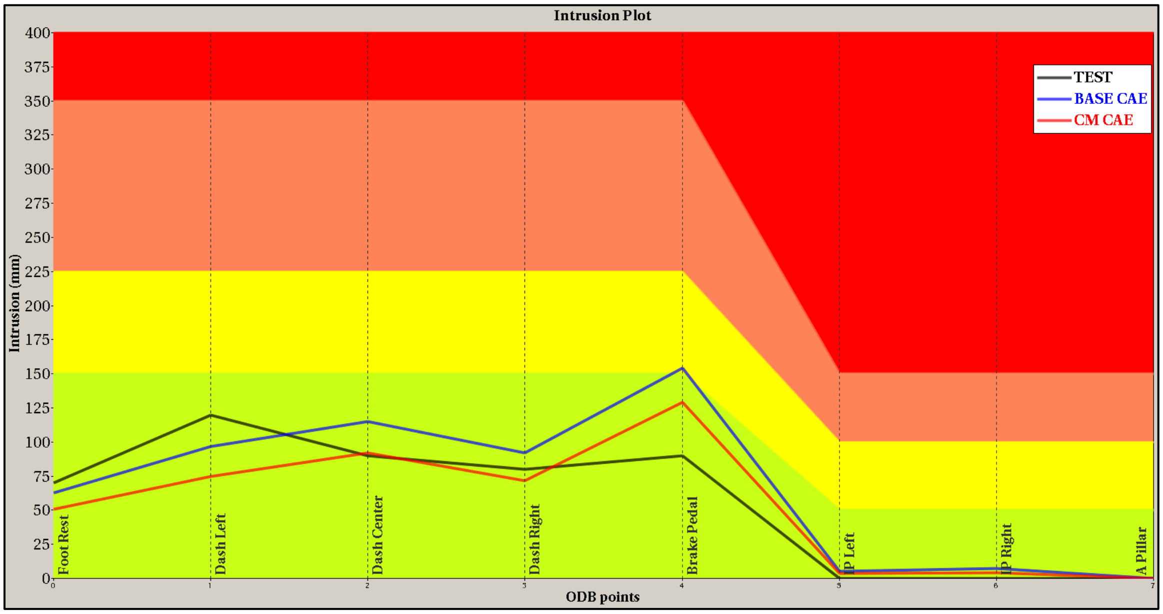


Figure 47: IIHS Frontal Moderate – Intrusion Values Comparison Test versus CAE results for Baseline and LWT

The IIHS intrusion results for the CAE baseline correlates well with the test in every point except for the brake pedal as shown in Figure 47. The full test report is not available for this test to study further. However, as expected, the countermeasures have reduced the baseline intrusion due to those reinforcements to the dash panels.

5.5 IIHS Small Overlap Frontal Barrier Test

The IIHS small overlap frontal barrier test is designed to reproduce what happens when the front corner of a vehicle hits another vehicle or an object like a tree or utility pole. Because occupants move both forward and toward the side of the vehicle, the small overlap test is also a trial for some safety belt and air bag designs.

In this test, a vehicle travels at 40 mph toward a 5-foot tall rigid steel barrier. A hybrid III 50th percentile male representing an average-size man is positioned in the driver seat. Twenty-five percent of the total width of the vehicle strikes the barrier on the driver side as shown in Figure 48. On most vehicles, the barrier is outboard of the main longitudinal members of the vehicle structure.

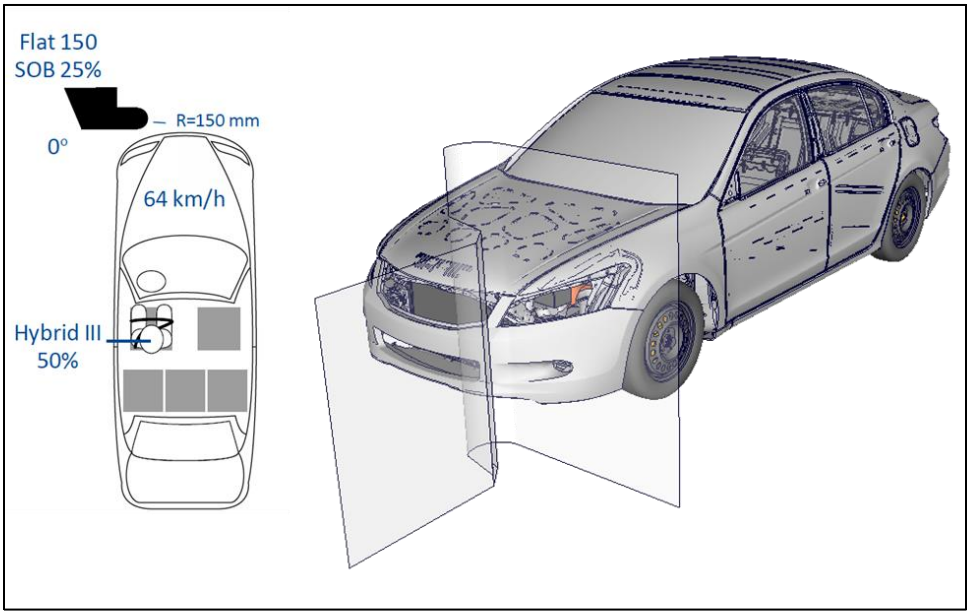


Figure 48: IIHS Small Overlap Test – Test Setup

Post-Crash images of the simulation results shown in Figure 49 and Figure 50 compare well the overall predicted vehicle crushed shapes from the front, side, and underneath the vehicle.

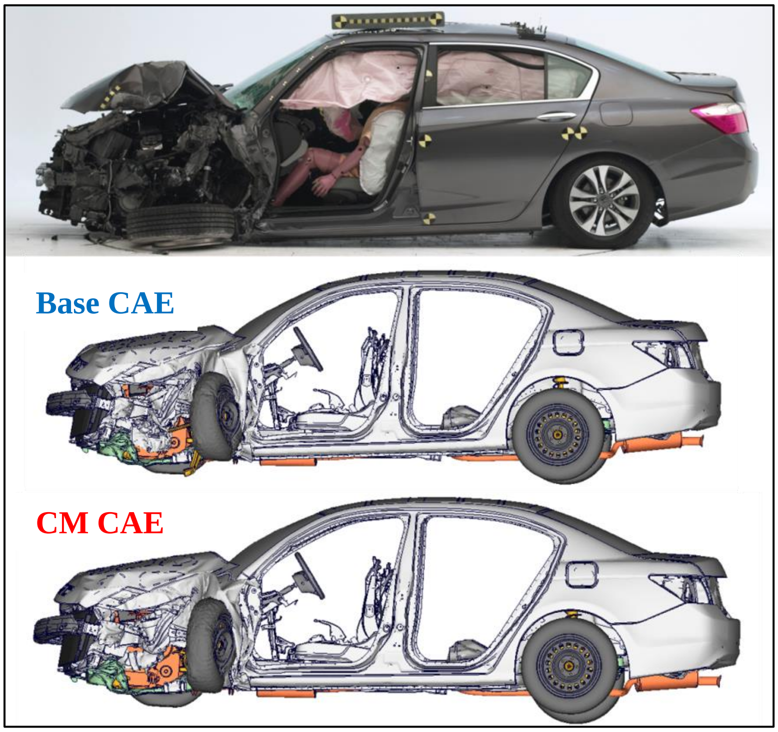


Figure 49: IIHS Small Overlap Test Versus Base CAE Versus CM CAE

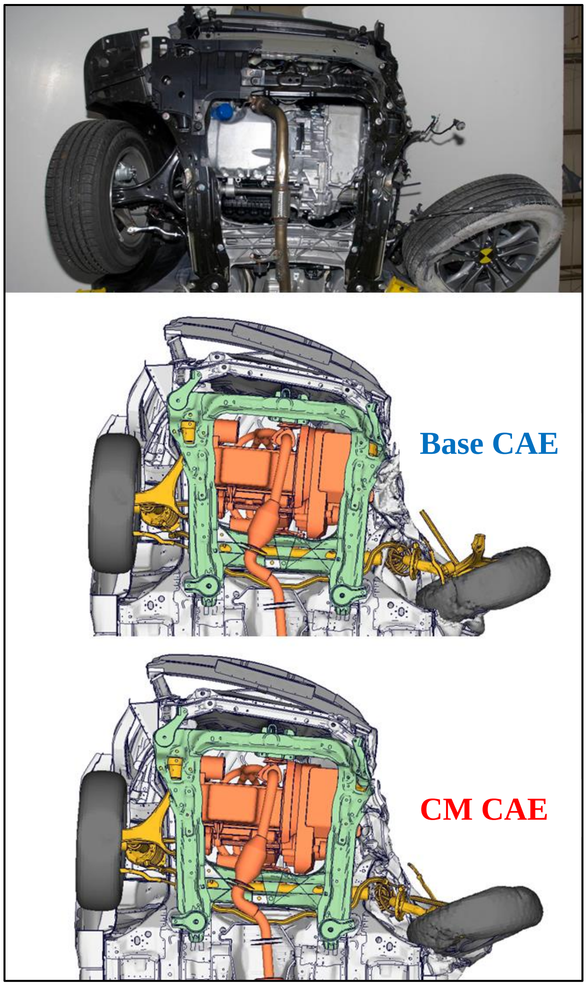


Figure 50: IIHS Small Overlap Test Versus Base CAE Versus CM CAE

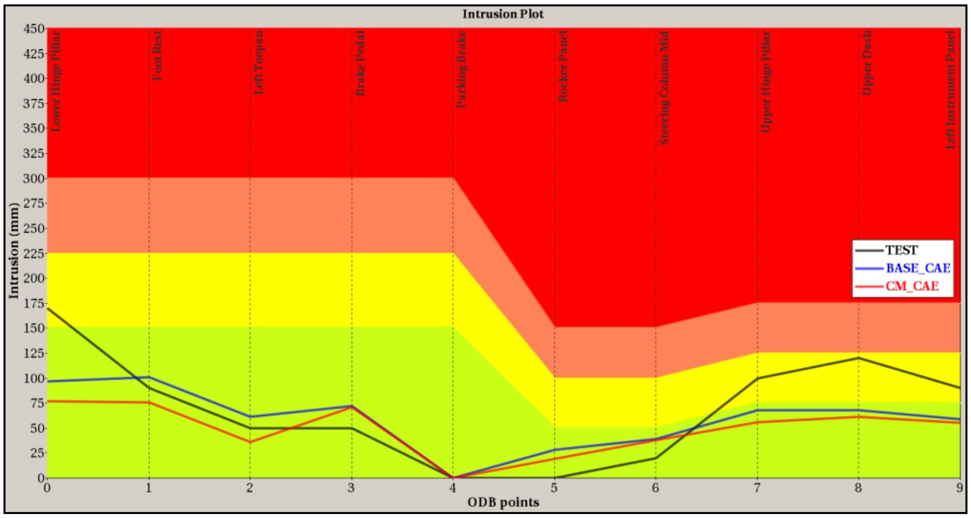


Figure 51: IIHS Small Overlap Intrusion - Test Versus Base CAE Versus CM CAE

The results for the baseline CAE model in Figure 51 show good overall correlation with the test results. As expected, the countermeasure CAE model has improved intrusion numbers due to the reinforcement added to the structure.

5.6 IIHS Roof Strength Test

The IIHS roof strength test evaluates the crashworthiness of the vehicle structure in rollover crashes. This test is conducted by loading the roof structure of the vehicle with a rigid plate (platen) until 5 inches of crush is achieved. The maximum force sustained by the roof before 5 inches of platen displacement is compared to the vehicle's curb weight to find the strength-to-weight ratio. In addition to the voluntary IIHS roof strength test, there is also a Federal requirement for roof strength. Federal Motor Vehicle Safety Standard No. 216 specifies that roof structure must sustain a load three times the vehicle curb weight. For vehicles with a GVWR from 6,001 to 10,000 lbs, the SWR requirements are 1.5 time the CVW. The IIHS roof crush test is a consumer information test, and rates the tested vehicle for safety. The roof structure must sustain loading of four times the curb weight for a good rating. There is no rating associated with FMVSS No. 216, which requires sequential loading on both sides of the roof. The IIHS tests just one side of the roof.

The LS-DYNA set up for the IIHS roof crush test of the baseline CAE model is shown in Figure 52. The CAE model is held rigidly with clamps about the rocker section.

Figure 52: IIHS Roof Strength Test - LS-DYNA Model Setup

Figure 53 shows the results for the test and both CAE model simulations. The SWR for the test is 4.9 compared to the predictions for the baseline that is at 4.6. Although the roof crush force is very close, the SWR difference is due to the fact that the weight of the CAE model is at 1,548 kg but the test vehicle is at 1,470 kg. The CAE model was built based on the NCAP frontal test where the vehicle curb weight is 1,539 kg. The countermeasure model should not see any difference in terms of roof crush strength as major parts related to the load case were untouched, therefore the result is similar to the baseline shown in Figure 54.

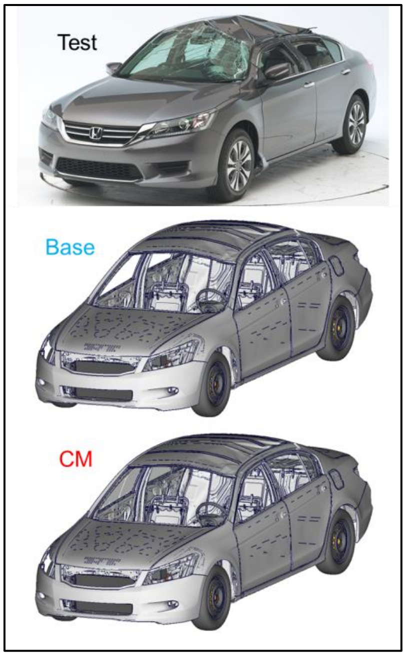


Figure 53: IIHS Roof Strength Test - Comparison Test Versus Baseline and CM

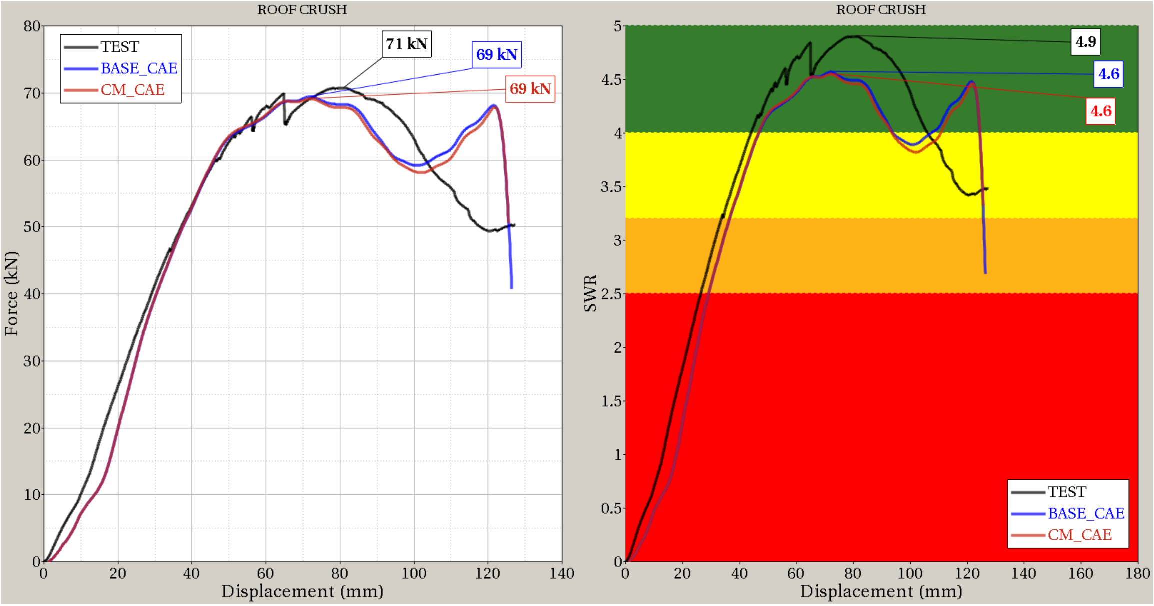


Figure 54: IIHS Roof Strength Test - Comparison F150 Test Versus CAE for Baseline and CM

5.7 NCAP Side MDB Test

In this crash test, a moveable deformable barrier, with a mass of 1,370 kg impacts the vehicle on the driver’s side with velocity of 61.9 km/h ± 0.8 km/h. The LS-DYNA models for the baseline 2014 Accord and countermeasure model were created to represent the test setup. Mass for a hybrid III 50th percentile male on the driver seat and a 5th percentile female dummy on the rear passenger seat behind the driver position, with a combined occupant mass of 141 kg kg and cargo mass of 45 kg in the rear was included in the CAE models. The CAE model set up for the NCAP side impact MDB crash test of the 2014 Accord model with a moving deformable barrier is shown in Figure 55.

Comparisons of other vehicle test parameters are shown in Table 15. The test vehicle is 69 kg lighter than the baseline due to different trim level is being tested. Dimensionally the test vehicle is similar to the baseline vehicle. The differences will introduce some differences to the dynamic crush behavior, but it should not be significant enough to alter the safety crashworthiness ratings or conclusions.

Description	Test	Base CAE	CM CAE
Model	2013	2014 (updated 2011)	2014 (updated 2011)
Engine Disp (L)	2.4	2.4	2.4
Tested Weight (kg)	1,652	1,721	1,725

Table 15: NCAP Side MDB - Test Vehicles and CAE Models Parameters

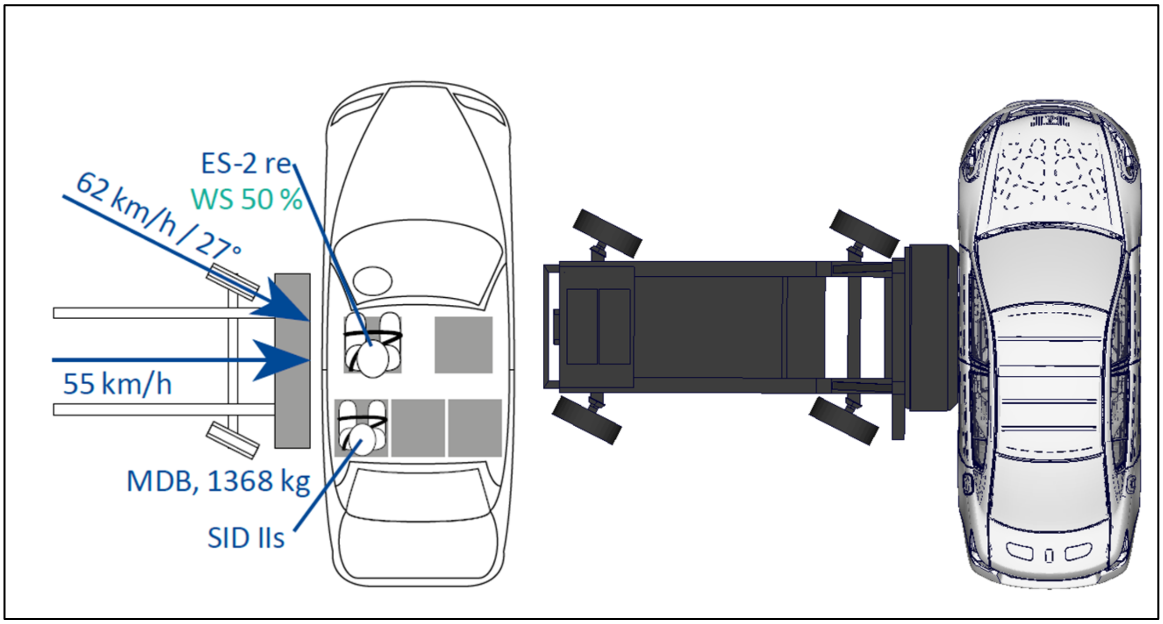


Figure 55: NCAP Side MDB - Test and CAE Model Setup

Images of the post-crash vehicles for the crash test and the simulation results are shown in Figure 56 and
Figure **57**. The overall predicted vehicle kinematics and the crushed shapes from the side and from underneath the vehicle correlate very well with the test vehicles.

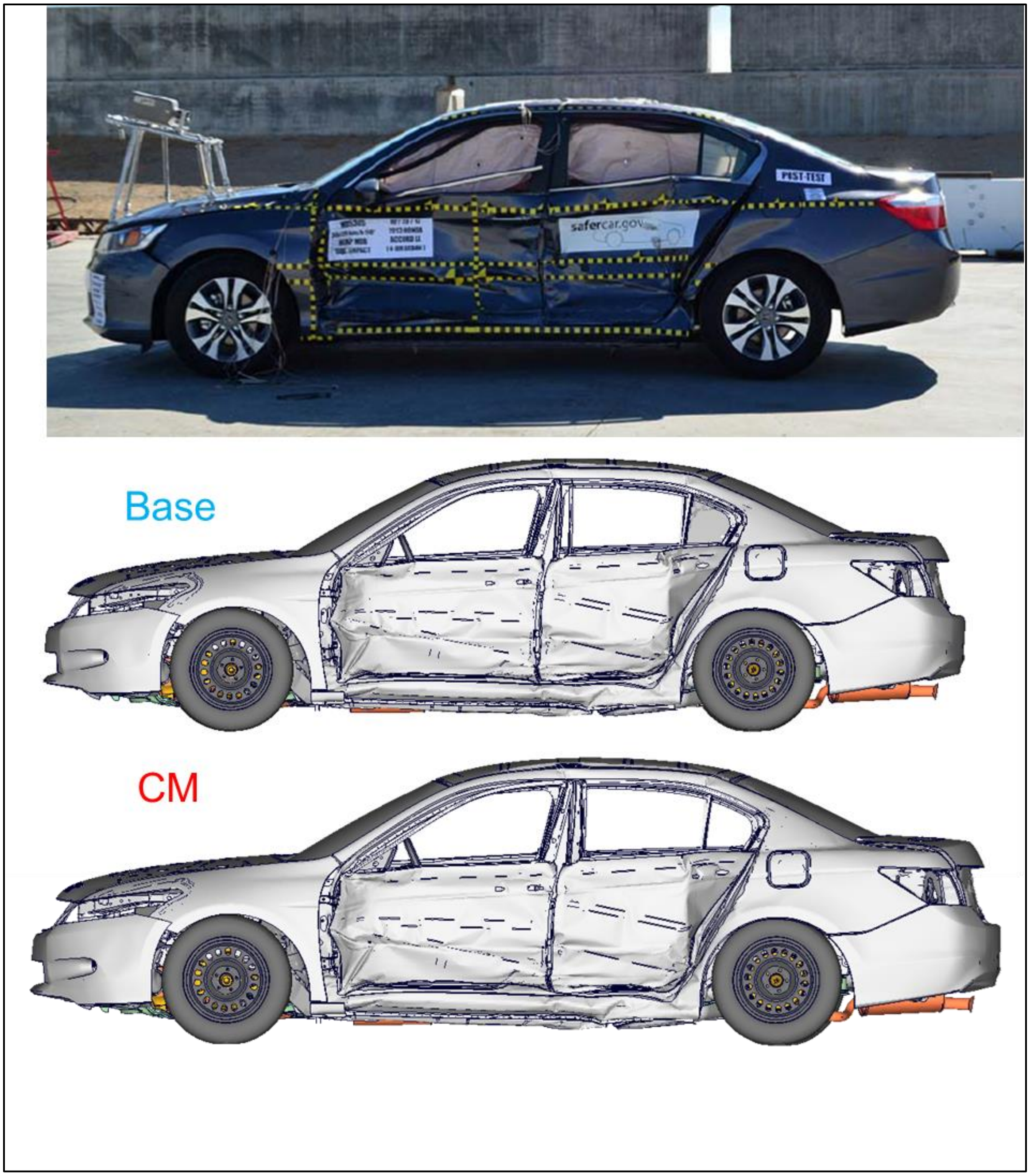


Figure 56: NCAP Side MDB - Post-Crash Comparison Test Versus CAE for Baseline and LWT

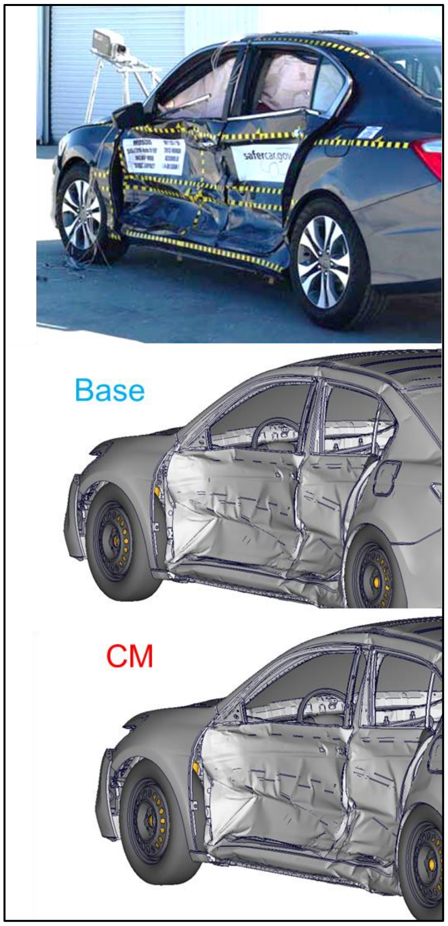


Figure 57: NCAP Side MDB - Post-Crash Comparison Test Versus CAE for Baseline and LWT

The NHTSA crash test provides measurement of the struck side profile deformation at 6 levels. Levels 2 and 3, which are near the mid door level, were measured in the model and compared with the crash test. An overlay of the Level 2 and 3 intrusion profile amounts for the model and test is shown in Figure 58.

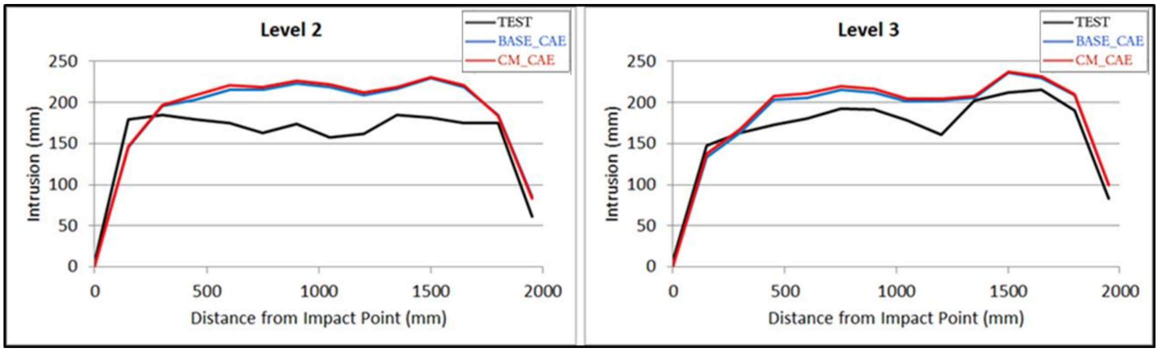


Figure 58: NCAP Side MDB Level 2 and 3 Struck Side Intrusion Profile

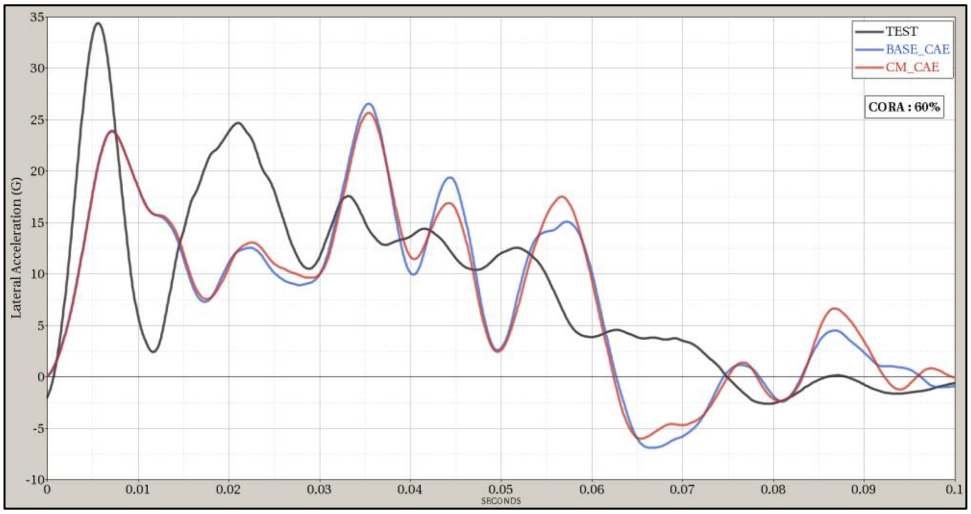


Figure 59: NCAP Side MDB – Vehicle CG Acceleration Test Versus Base CAE Versus CM CAE

Vehicle lateral Center of gravity acceleration in Y direction is compared with test vehicle as shown in Figure 59. CAE models correlate reasonably well with test results and have a CORA score of 60 percent. The countermeasures did not affect the results of this load case for both intrusions and vehicle acceleration.

5.8 NCAP Side Rigid Pole Test

The NCAP side impact rigid pole test subjects the test vehicle to a side door impact with a fixed, rigid pole 254 mm (10 inches) in diameter, at a speed of 32.2 km/h (20 mph). The test vehicle is towed into the pole at a 75° angle. Figure 60 shows the baseline CAE model and test set-up. The only ATD used in this test is a fully instrumented 5th percentile female, positioned in the driver's seat. The CAE models fully account for the ATD and additional cargo mass required for this test. Table 16 lists the test and baseline vehicle parameters.

Description	Test	Base CAE	CM CAE
Model	2013	2014 (updated 2011)	2014 (updated 2011)
Engine Disp (L)	2.4	2.4	2.4
Tested Weight (kg)	1,615	1,721	1,725

Table 16: NCAP Side Rigid Pole - Test Vehicles and CAE Models Parameters

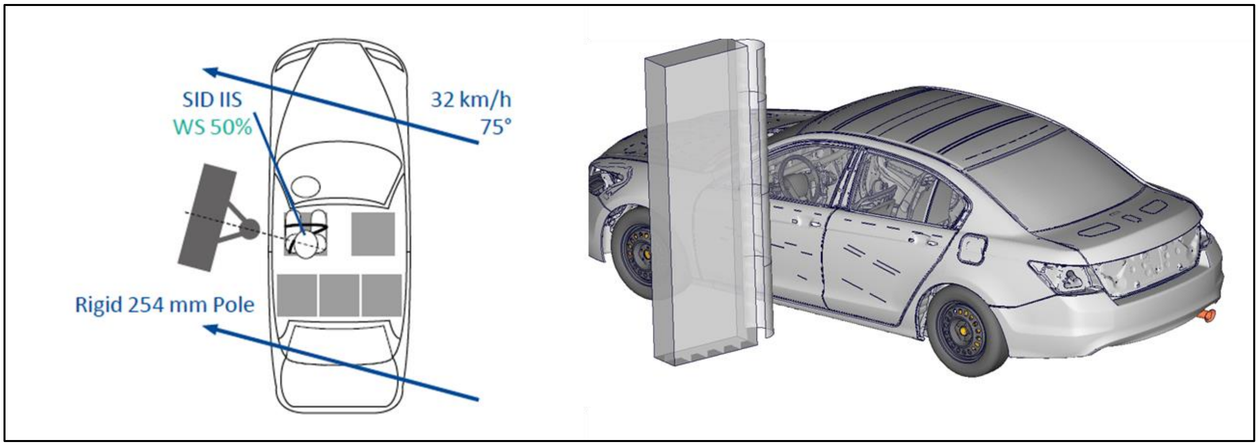


Figure 60: NCAP Side Rigid Pole - Test and CAE Model Setup

Side-structure deformation and vehicle crash behaviors were analyzed and compared to the test vehicle as shown in Figure 61, Figure 62 and Figure 63. By comparing the deformations, it can be observed the CAE baseline model and CAE countermeasure model show similar deformation modes as the tested vehicle.

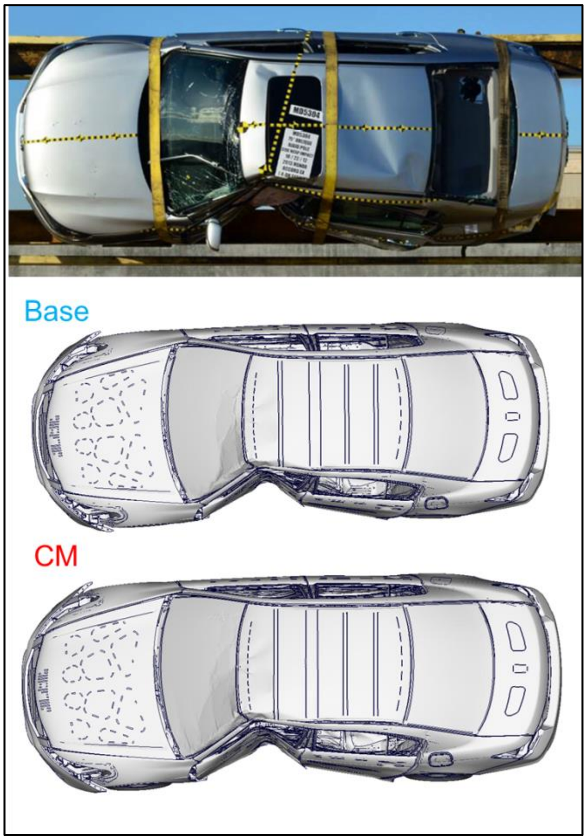


Figure 61: NCAP Side Rigid Pole – Test Versus Base CAE Versus CM CAE

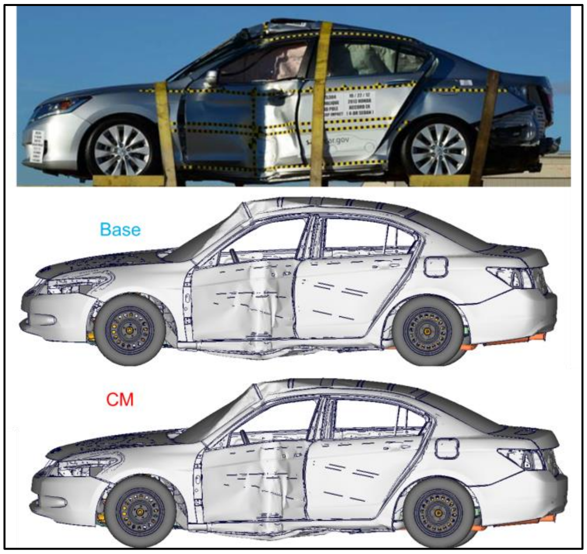


Figure 62: NCAP Side Rigid Pole – Test Versus Base CAE Versus CM CAE

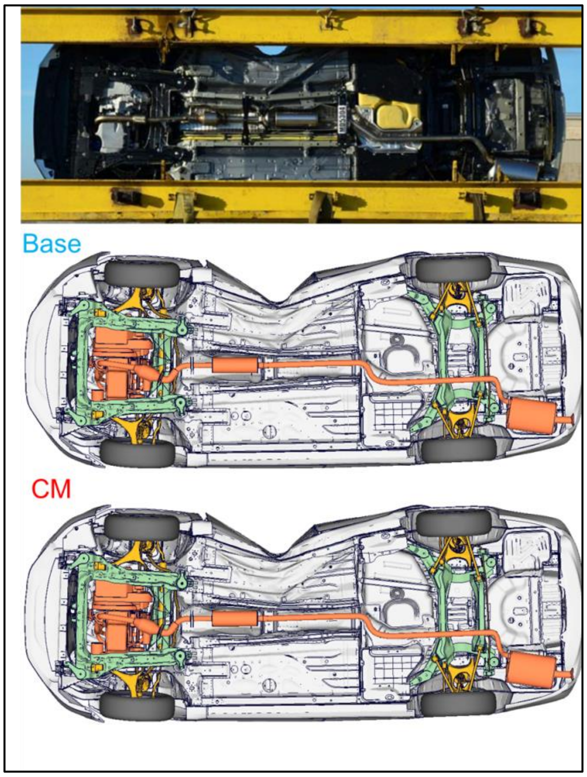


Figure 63: NCAP Side Rigid Pole – Test Versus Base CAE Versus CM CAE

Vehicle center of gravity acceleration measured in lateral Y direction and compared with test vehicle as shown in Figure 64. The baseline CAE model has average correlation with the test with a CORA score of 57 percent. The pulse oscillation in the CAE model is due to the accelerometer attached on the floor structure experience deformation.

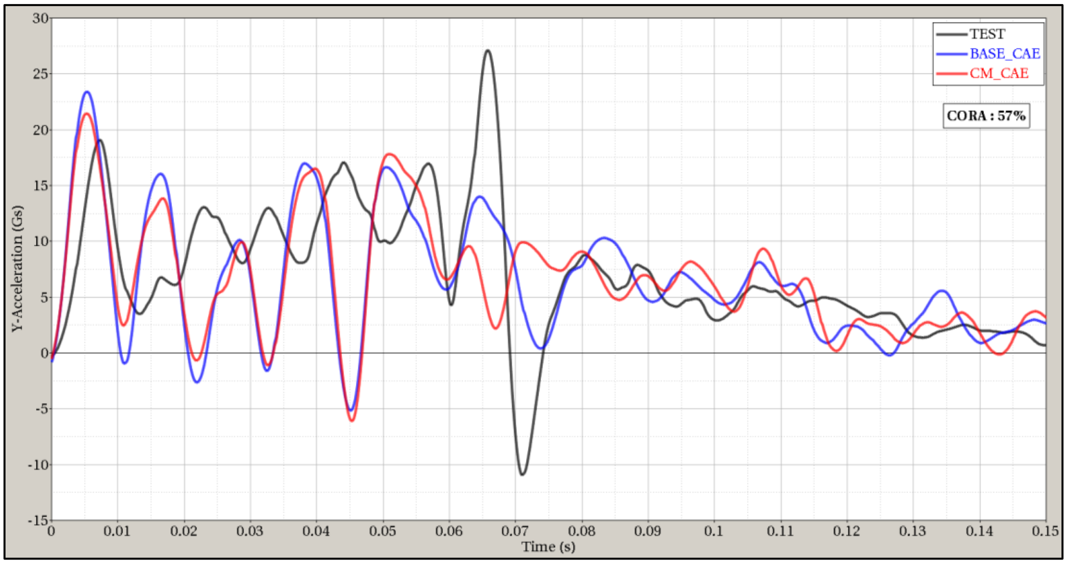
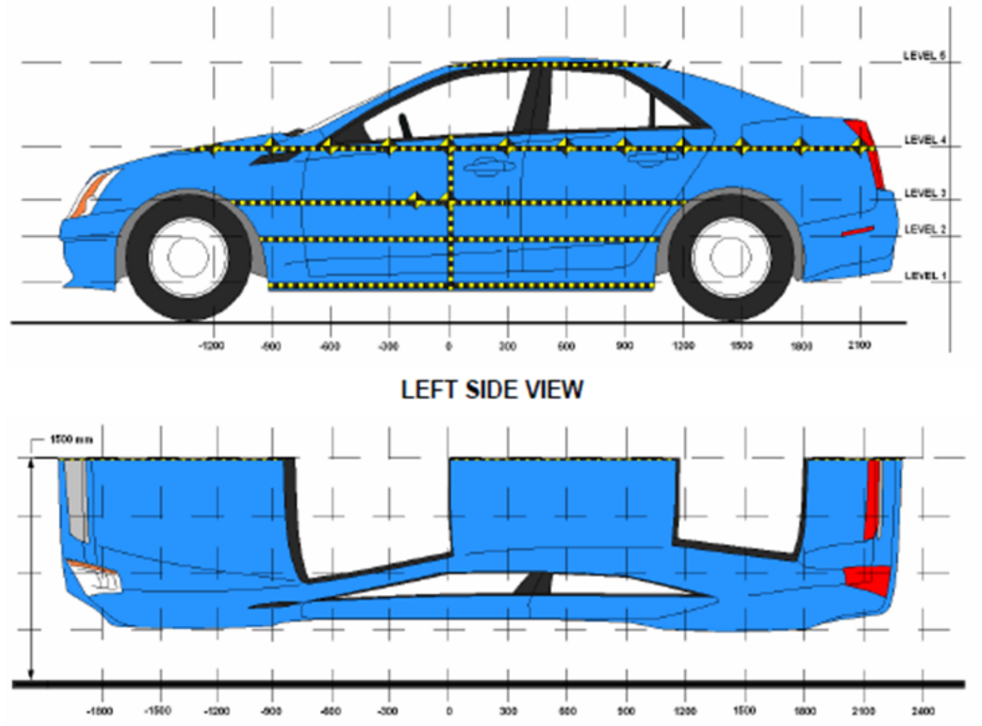


Figure 64: NCAP Rigid Side Pole – Vehicle CG Acceleration Comparison Tests Versus Base CAE and CM CAE

Figure 65 shows maximum exterior crush for 5 levels. It can be seen that the maximum static crush for each level for the baseline CAE model correlates well with the test. The countermeasure model result is also close to the baseline CAE model. The intrusions along the length of the vehicle for levels 1 to 4 are shown in Figure 66, located at sill top, door midpoint, driver H-point, and at the windowsill. As can be seen the exterior crush profiles at levels 1 to 4 for the test vehicle are in good agreement with the CAE baseline and CAE countermeasure model results.



			Max Exterior Static Crush		
Level	**Description**	**Distance from ground**	**Test**	**Base**	**CM**
1	Sill Top	241	348	348	344
2	Occupant	559	405	386	380
3	Mid-Door	620	413	393	386
4	Window Sill	902	389	378	368
5	Window Top	1395	203	156	142

Figure 65: NCAP Side Rigid Pole – Post-Crash Comparison Test Versus Base CAE and Countermeasure CAE

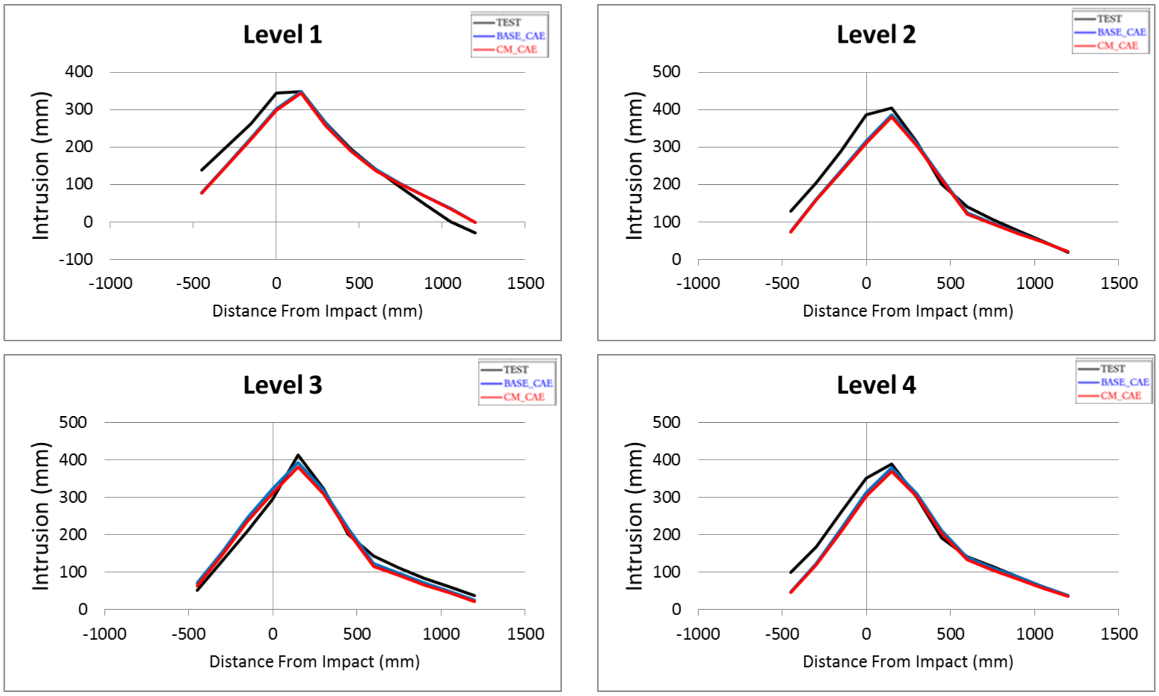


Figure 66: NCAP Side Rigid Pole - Post-Crash Comparison Test Versus Base CAE Versus Countermeasure CAE

5.9 IIHS Side Impact Crash Test

The IIHS side impact crash test consists of a stationary test vehicle struck on the driver's side by a moving deformable barrier, a crash cart fitted with an IIHS deformable aluminum barrier element. The model was setup to include 1,500 kg MDB traveling at a speed 50 km/h. The CAE model setup with the positioned MDB is shown in Figure 67. IIHS has only tested a two-door version of the 2013 Honda Accord; hence the results will not be comparable to baseline CAE model.

According to the IIHS side impact test protocol, the test weight of the vehicle, which includes the vehicle instrumentation, three cameras, and two SID–IIs dummies, is 150 to 225 kg greater than the measured curb weight of the vehicle. If the vehicle test weight needs to be increased to fall within the range, ballast weight is distributed in a manner that comes closest to replicating the original front/rear and left/right weight distribution of the vehicle. Test and model setup are shown in Figure 67.

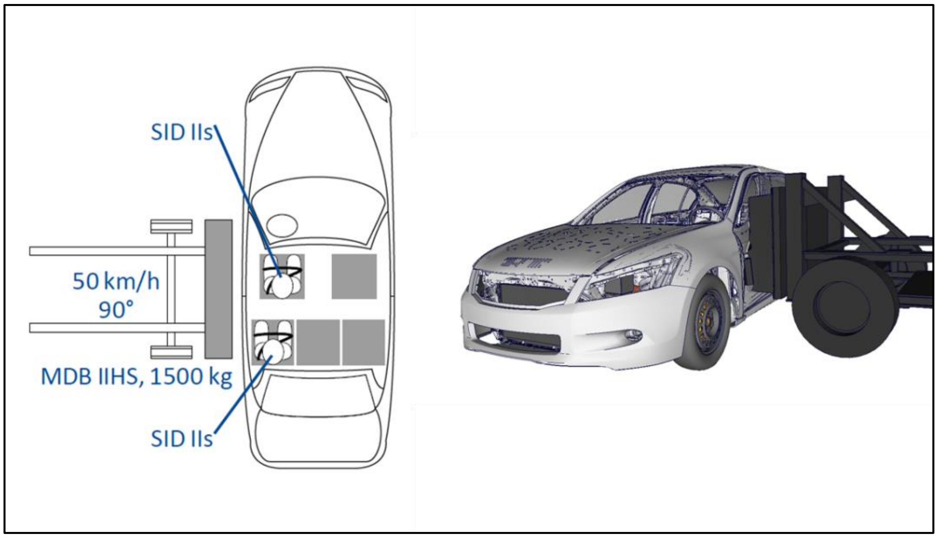


Figure 67: IIHS Side Impact Test – Base CAE Model Setup

Post-crash comparison between Base CAE and CM CAE is shown in Figure 68 and Figure 69.

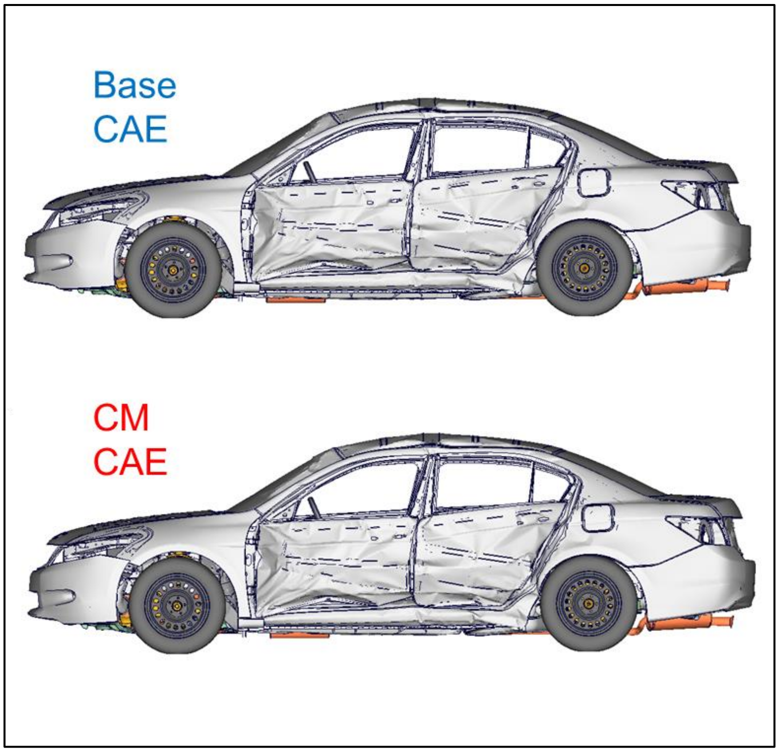


Figure 68: IIHS Side Impact - Comparison CAE Model Base Versus CM

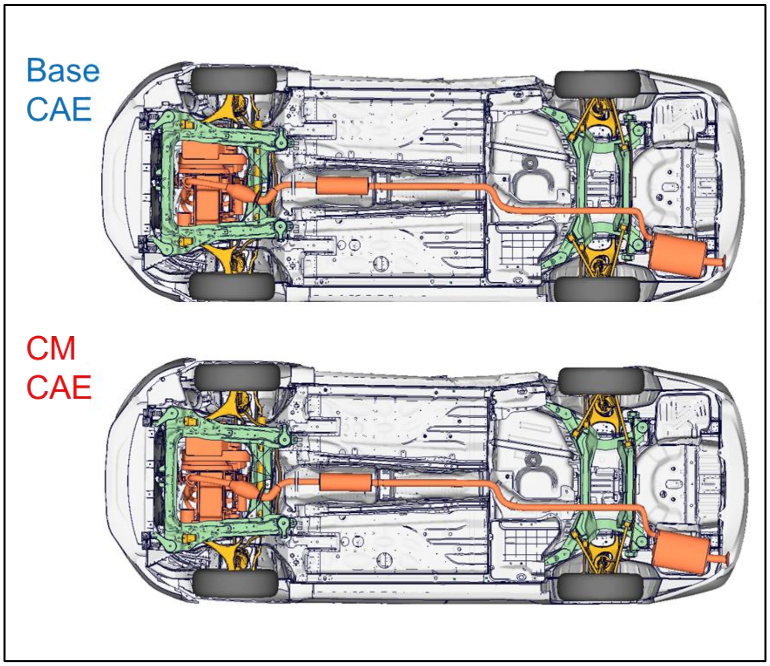


Figure 69: IIHS Side Impact - Comparison CAE Model Base Versus CM

Overall the comparison shows very little difference in terms of structural deformation as the countermeasure, mainly focused on the frontal structures. Figure 70 shows the IIHS intrusions for this crash impact; for both CAE models the max intrusions are in the good region.

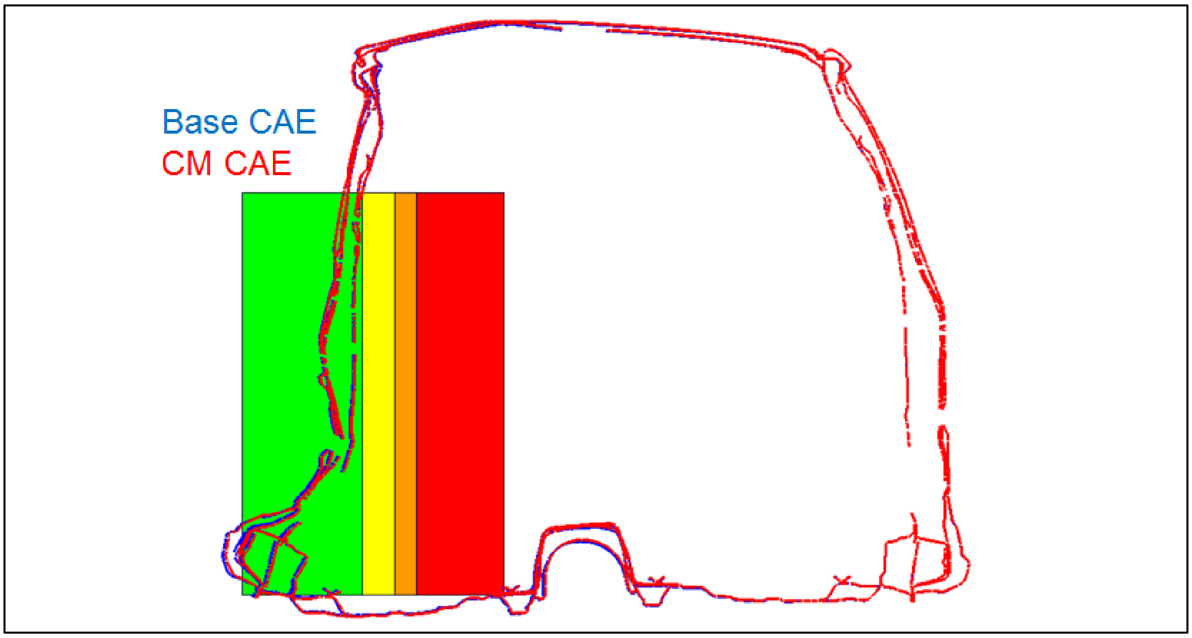


Figure 70: IIHS Intrusion - Comparison CAE Model Base Versus CM

6 CAE and Test Performance Results for the 2014 Silverado 1500

In this section the test results are compared with the predicted CAE results for the baseline CAE model to show quality and accuracy of the correlation, and also with the CAE model that include the countermeasures to reduce the occupant compartment intrusions for the NHTSA's oblique offset frontal crash condition. The recommended countermeasures are shown in Figure 15.

For the load cases that did not have real vehicle test data to which to correlate to, the results are compared with other similar reference vehicles.

6.1 NHTSA Oblique Test Driver Side

This test is used to determine the crashworthiness of the vehicle to protect occupants in offset frontal impact crash cases. The test consists of an Oblique Moving Deformable Barrier (OMDB) traveling at a target speed of 90.12 km/h into a stationary vehicle. The struck vehicle is positioned 15 degrees relative to the moving barrier and impacted 35 percent of the left or right side of the vehicle as shown in Figure **71**.

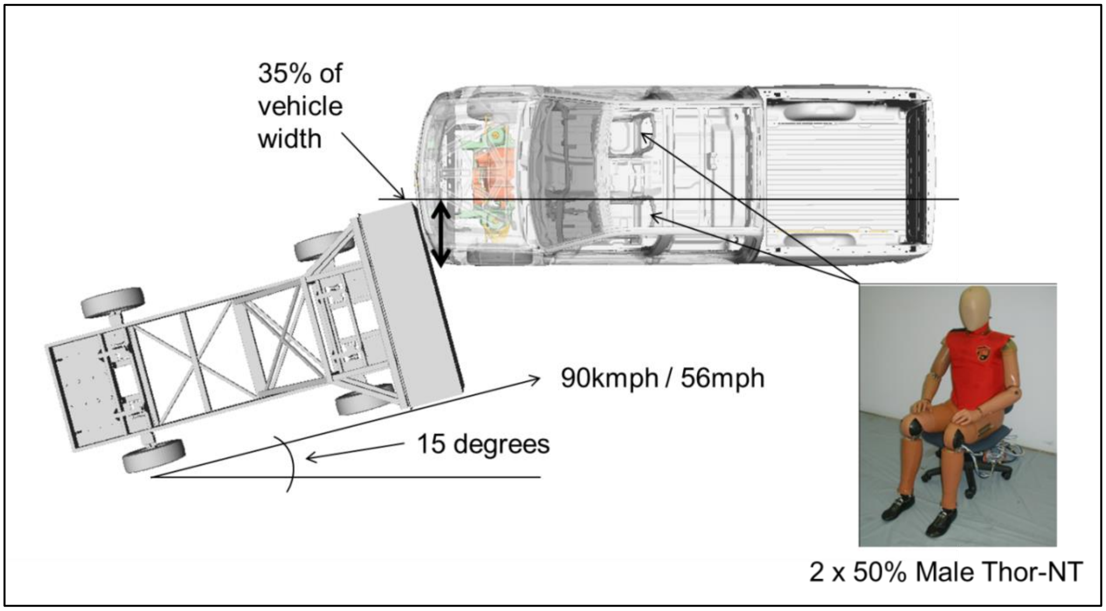


Figure 71 : NHTSA Oblique Impact Setup

The CAE baseline model used in this project is the model used in the NTHSA light-duty truck program that represents a 2014 Chevy Silverado and has a curb weight of 2,432 kg and AWD driveline. There is no test data available for the 2014 Silverado on the NHTSA oblique test; therefore the 2012 Silverado and 2016 Tahoe were chosen to compare with the CAE Model. The CAE model's driveline had to be modified to RWD as both the test were RWD vehicles. The modification is shown in Figure **72**. The test and modified CAE vehicle specification is shown in Figure **73**.

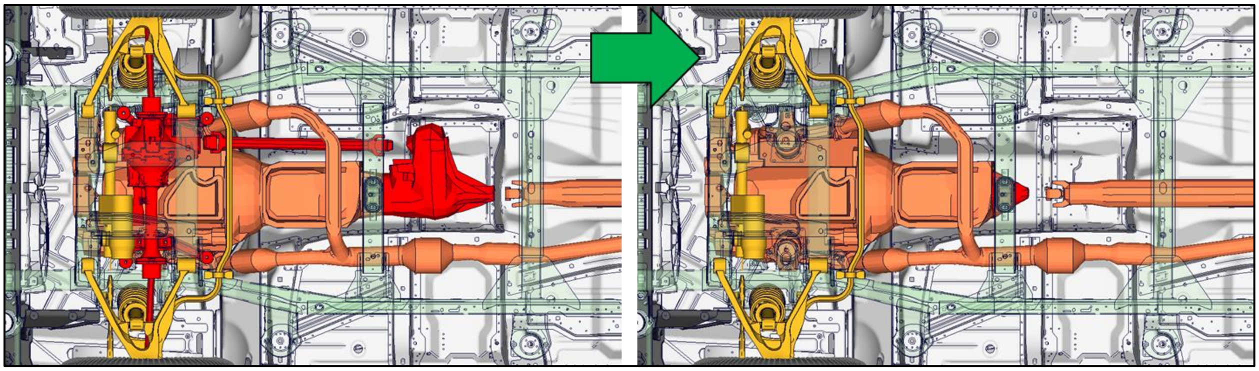


Figure 72: CAE Model Modification From AWD to RWD

Description	Tahoe	Silverado	FE
Model	2016	2012	2014
Final Driver	RWD	RWD	RWD
Engine Disp (L)	5.3	4.8	5.3
Tested Weight (kg)	2722	2624	2582
Body Style	SUV	CrewCab	CrewCab

Figure 73: Test Versus CAE Model Test Specification

Figure **74** and Figure **75** show the post-oblique impact image comparing the 2012 Silverado test versus the 2014 Silverado CAE model. Overall deformation mode from the front and bottom look identical except for the wheels in the test seems to have intruded more in the driver floor area. Both front rails in the test and CAE seem to have engaged well with the barrier for good crash energy absorption.

Figure 74: NHTSA Oblique Impact Post-Crash – 2012 Silverado Versus CAE Baseline

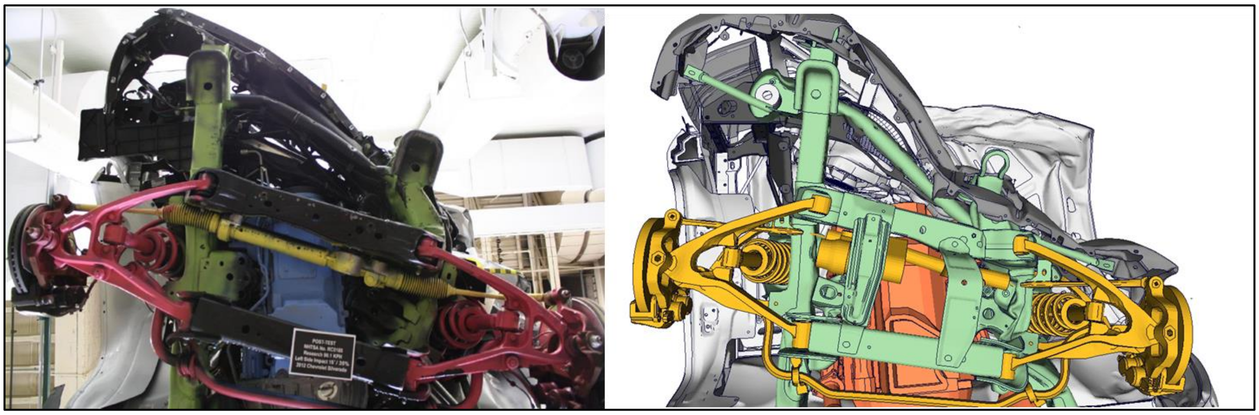


Figure 75: NHTSA Oblique Impact Post-Crash – 2012 Silverado Versus CAE Baseline

Figure **76** and Figure **77** show the post-oblique impact image comparing the 2016 Tahoe test vehicle versus the 2014 Silverado CAE model. The front deformation mode looks similar on both but from the bottom view, the Tahoe's front rail does not seem to have engaged efficiently with the barrier causing more load to be transferred to the suspension and wheel. This explained the shear failure in the lower control arm of the Tahoe. This scenario did not happen in the 2012 Silverado although the vehicle is 4 years older and based on the previous generation frame design.


No. 008 Post-Test Left Front 3-4 View of Test Vehicle

Figure 76: NHTSA Oblique Impact Post-Crash – 2016 Tahoe Versus CAE Baseline

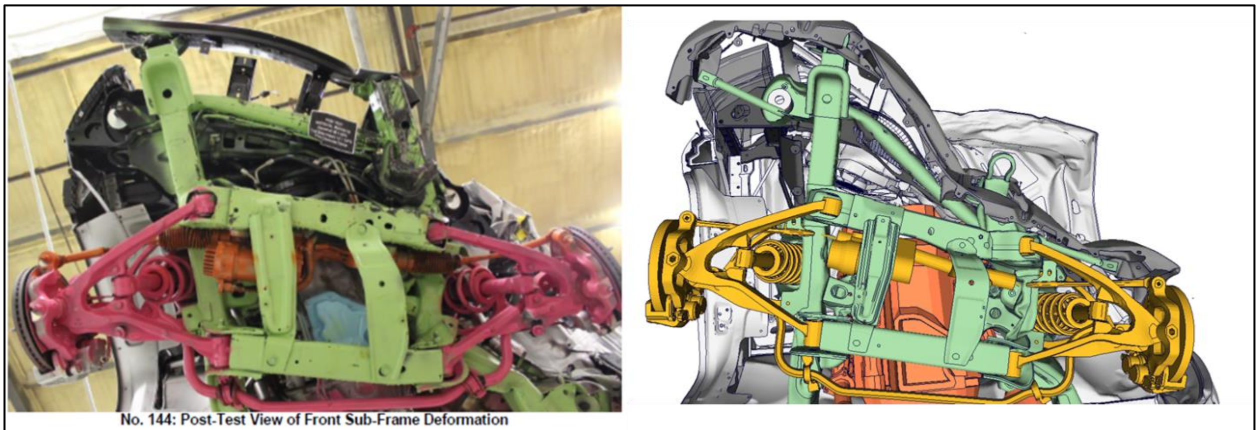
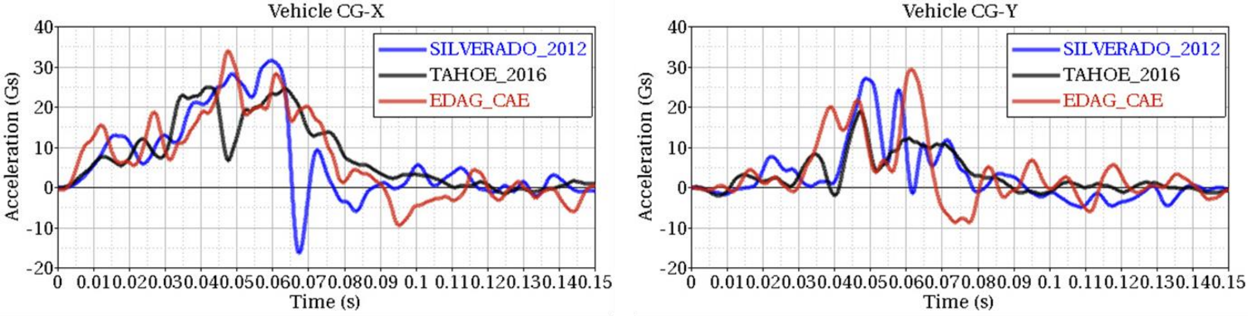

No. 144: Post-Test View of Front Sub-Frame Deformation

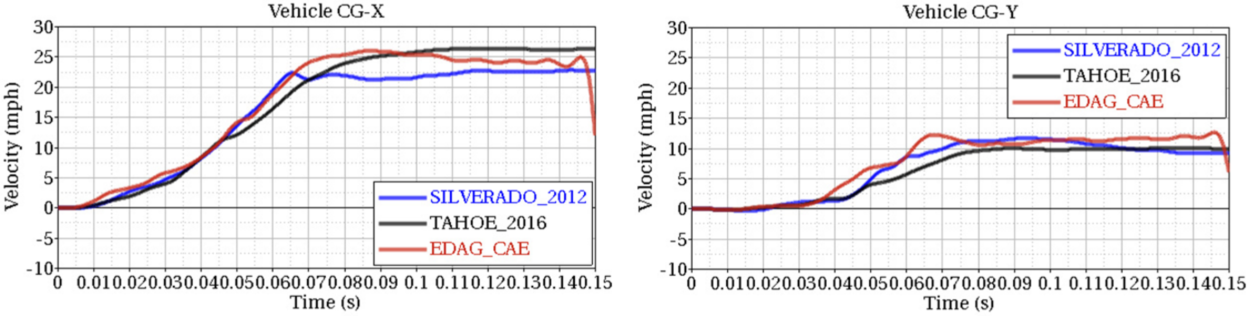
Figure 77: NHTSA Oblique Impact Post-Crash – 2016 Tahoe Versus CAE Baseline

Figure **78** and Figure **79** show the vehicle kinematic comparison in terms of acceleration and velocity between the 2016 Tahoe, 2012 Silverado, and CAE Model. The CORA score for acceleration between the two test vehicles shows less than 70 percent. The CAE model results compare well to both test vehicles result.



CORA	EDAG CAE Model	
	x	y
Silverado 2012	0.64	0.54
Tahoe 2016	0.66	0.52
	Silverado 2012	
Tahoe 2016	0.67	0.63

Figure 78: NHTSA Oblique Impact Acceleration – Test Versus CAE Baseline



CORA	EDAG CAE Model	
	x	y
Silverado 2012	0.89	0.88
Tahoe 2016	0.94	0.75
	Silverado 2012	
Tahoe 2016	0.88	0.88

Figure 79: NHTSA Oblique Impact Velocity – Test Versus CAE Baseline

In terms of vehicle velocity in the X and Y direction, the CAE model correlates well with both test results with CORA score close to 90 percent. Figure **80** and Figure **81** shows the intrusion in the driver compartment and driver floor area comparing both the test and the CAE model. For the 2016 Tahoe, the result was only available for first row of the floor intrusion points.

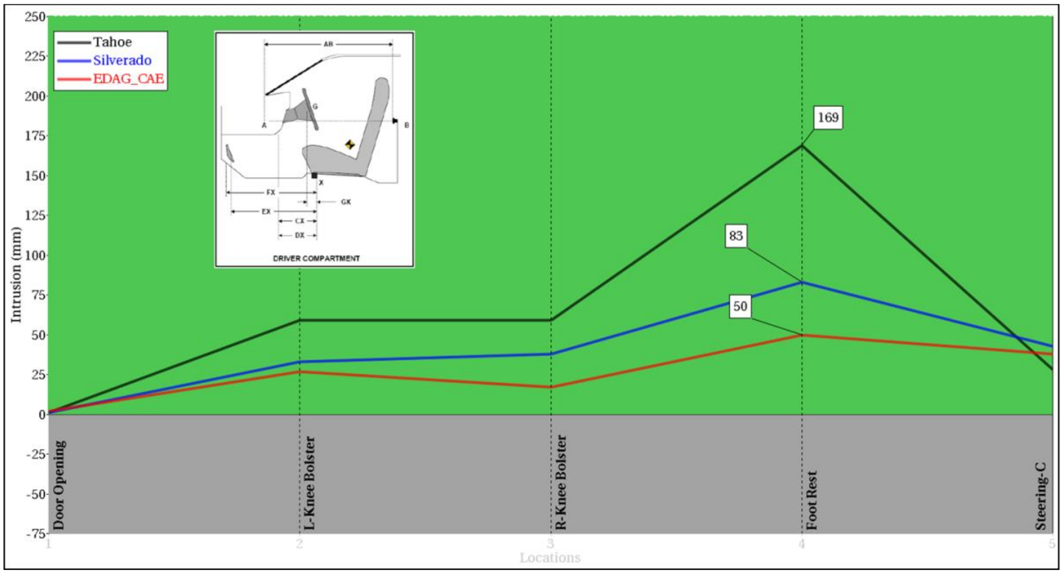


Figure 80: NHTSA Oblique Impact Driver Compartment Intrusion – Test Versus CAE Baseline

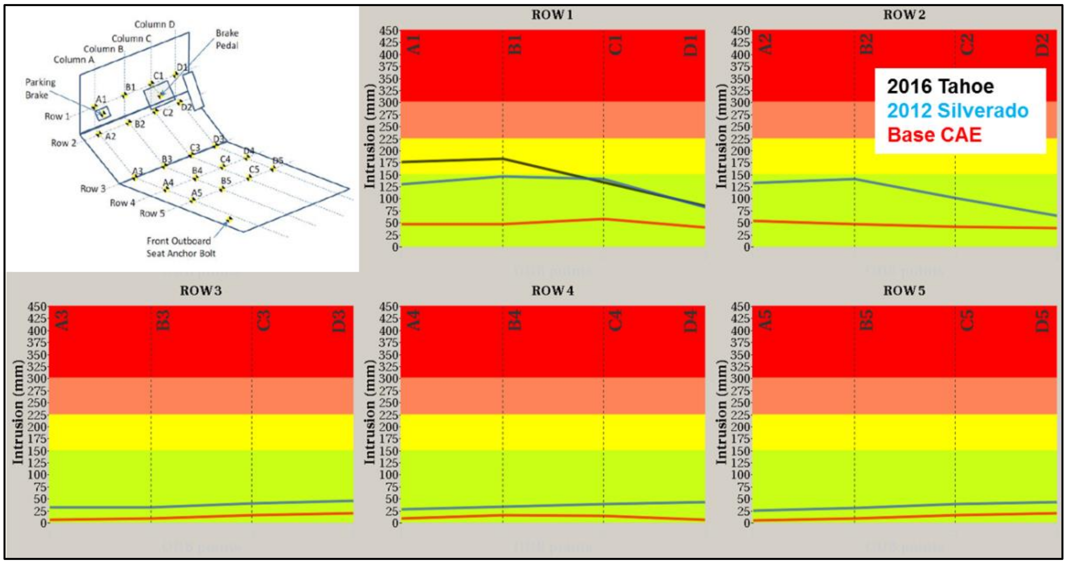


Figure 81: NHTSA Oblique Impact Driver Floor Intrusion – Test Versus CAE Baseline

The 2016 Tahoe recorded very high intrusion around the footrest area compared to the 2012 Silverado and the CAE model. This can be explained by the post-crash image shown in Figure **77** where the front rail of the Tahoe did not connect well with the barrier and all the load were transferred to the suspension and wheel. This caused the failure on the lower control arm and the wheel to intrude hard in the driver footrest area. The CAE model intrusion performance is better than the 2012 Silverado as the CAE model represents 2014 Silverado that has improved design and strength in the frame and cabin structure.

The CAE model crash kinematics shows good correlation with the two tests vehicle although the intrusion numbers are lower for the 2014 Silverado CAE model.

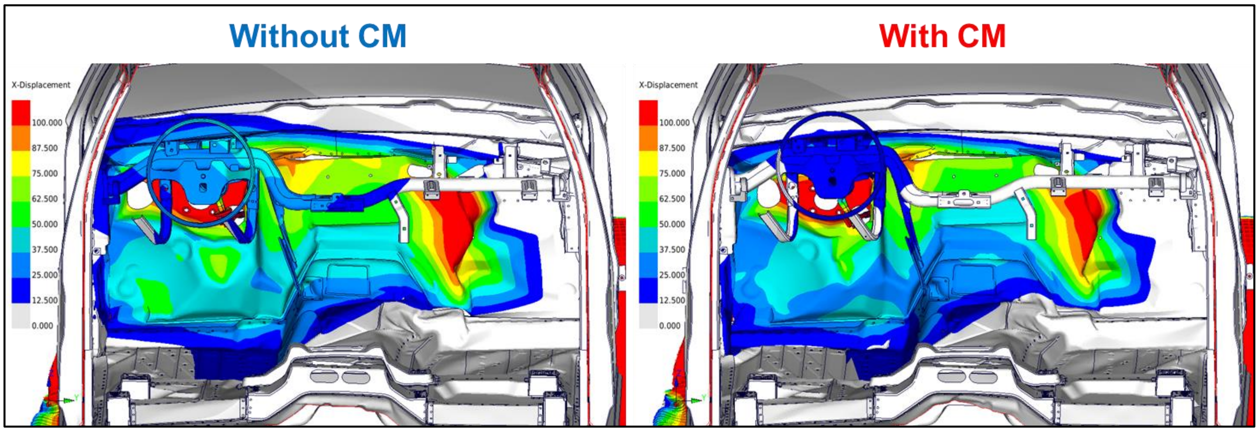


Figure 82: NHTSA Oblique Impact Driver Floor Intrusion – Base CAE Versus CM CAE

Figure **82** and Figure **83** show comparison of the CAE model with and without the countermeasures. The intrusion plot in Figure **82** shows overall reduction in intrusion across the occupant compartment. The floor intrusions are well below the 150 mm line that is used in IIHS as an intrusion target for good rating in the footrest areas. Although the intrusion has improved with the countermeasures, the amount of improvement is not significant.

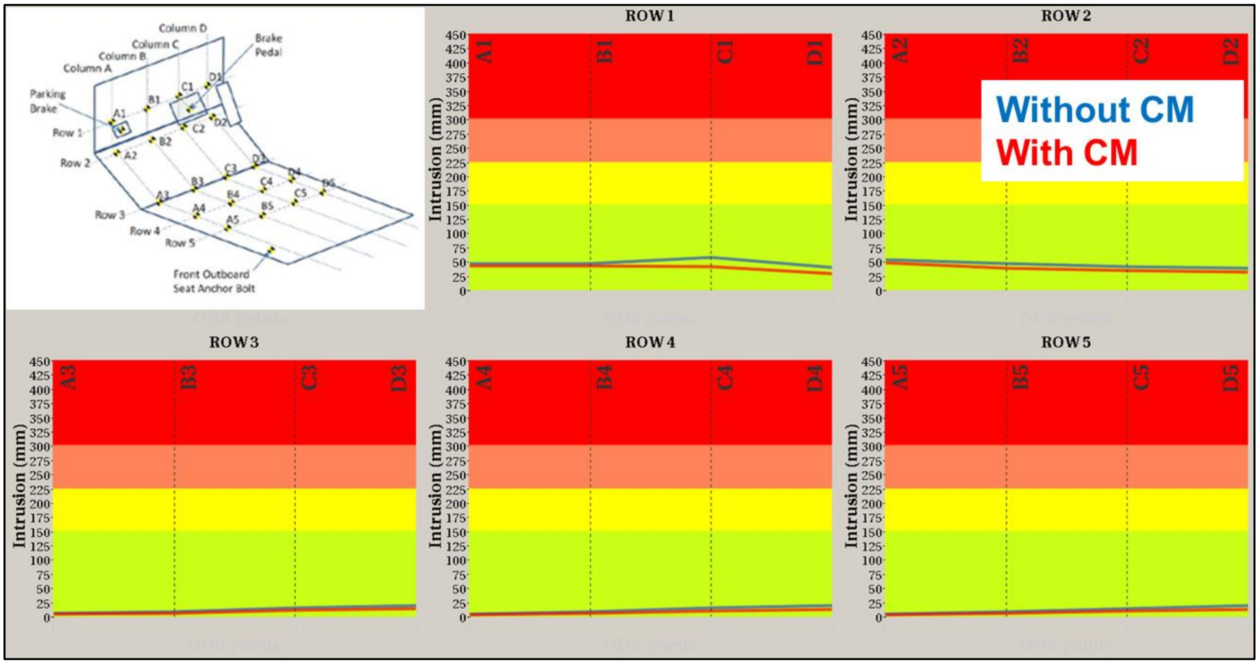


Figure 83: NHTSA Oblique Impact Driver Floor Intrusion – Base CAE Versus CM CAE

6.2 NHTSA Oblique Test Passenger Side

The oblique impact simulation was also conducted for the passenger side impact. No test was conducted for this condition; hence there is no test data to compare with. The setup is shown in Figure 84.

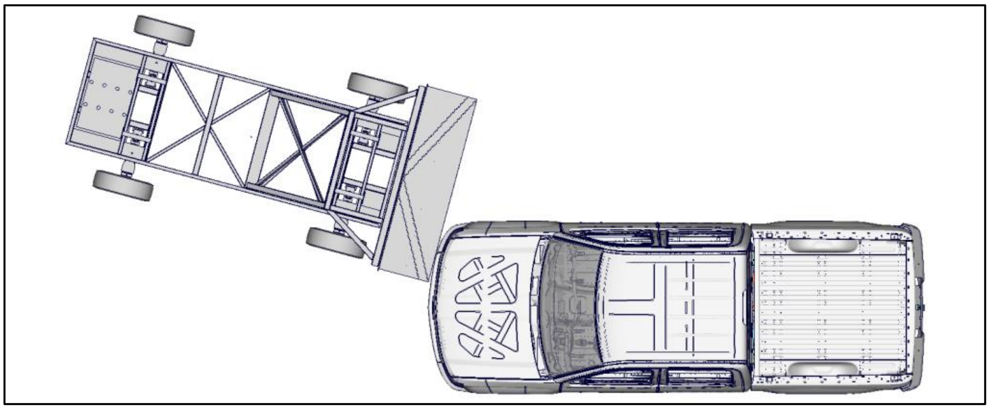


Figure 84: NHTSA Oblique Impact Right Side (Passenger) – CAE model Setup

The countermeasures were also included in this model and the comparison in term of the floor intrusion is shown in Figure 85.

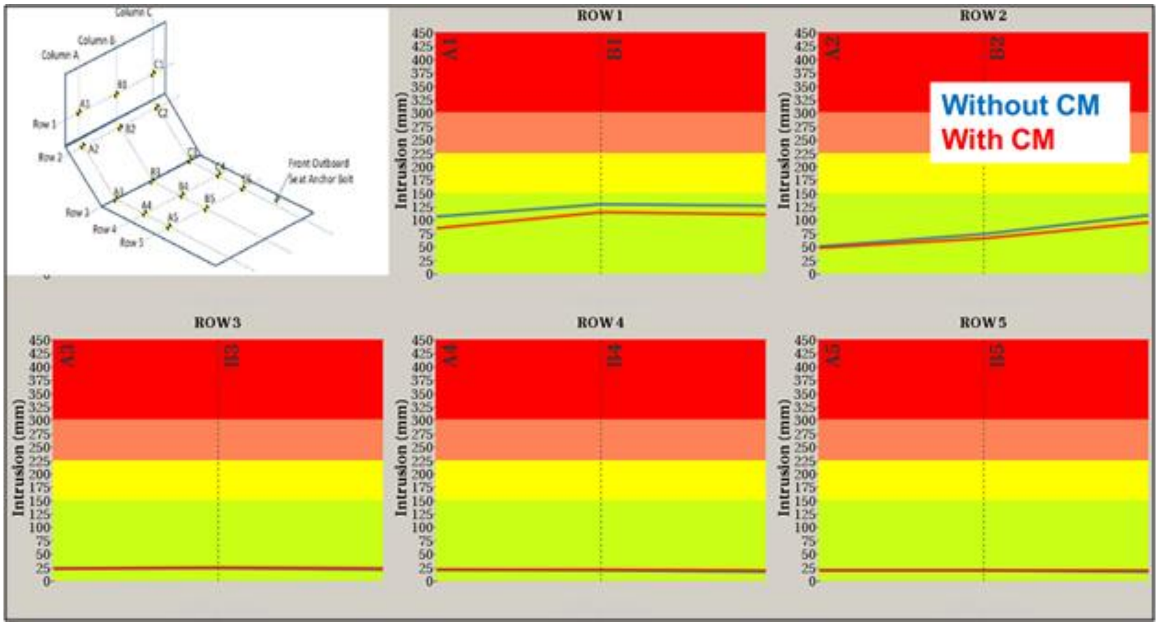


Figure 85: NHTSA Oblique Impact Passenger Side - Passenger Floor Intrusions

Similarly, to the left side impact, the countermeasures show some improvement in terms of floor intrusion and the intrusions are below 150 mm.

6.3 IIHS Small Overlap Frontal Barrier Test

The IIHS small overlap frontal barrier test is designed to reproduce what happens when the front corner of a vehicle hits another vehicle or an object like a tree or utility pole.

In this test a vehicle travels at 40 mph toward a 5-foot tall rigid steel barrier. A hybrid III 50th percentile male dummy representing an average-size man is positioned in the driver seat. Twenty-five percent of the total width of the vehicle strikes the barrier on the driver side as shown in Figure 86. On most vehicles, the barrier is outboard of the main longitudinal members of the vehicle structure. The CAE model was built for the previous NHTSA lightweighting program when IIHS had not conducted this test on the baseline vehicle 2014 Silverado 1500. At that time, CAE results for the baseline were compared with the IIHS test conducted on the 2015 Ford F-150.[21] By the start of this program, IIHS had conducted this test on two different 2016 Silverado variants, the crew cab and the double cab. These variants are shown in Figure 87.

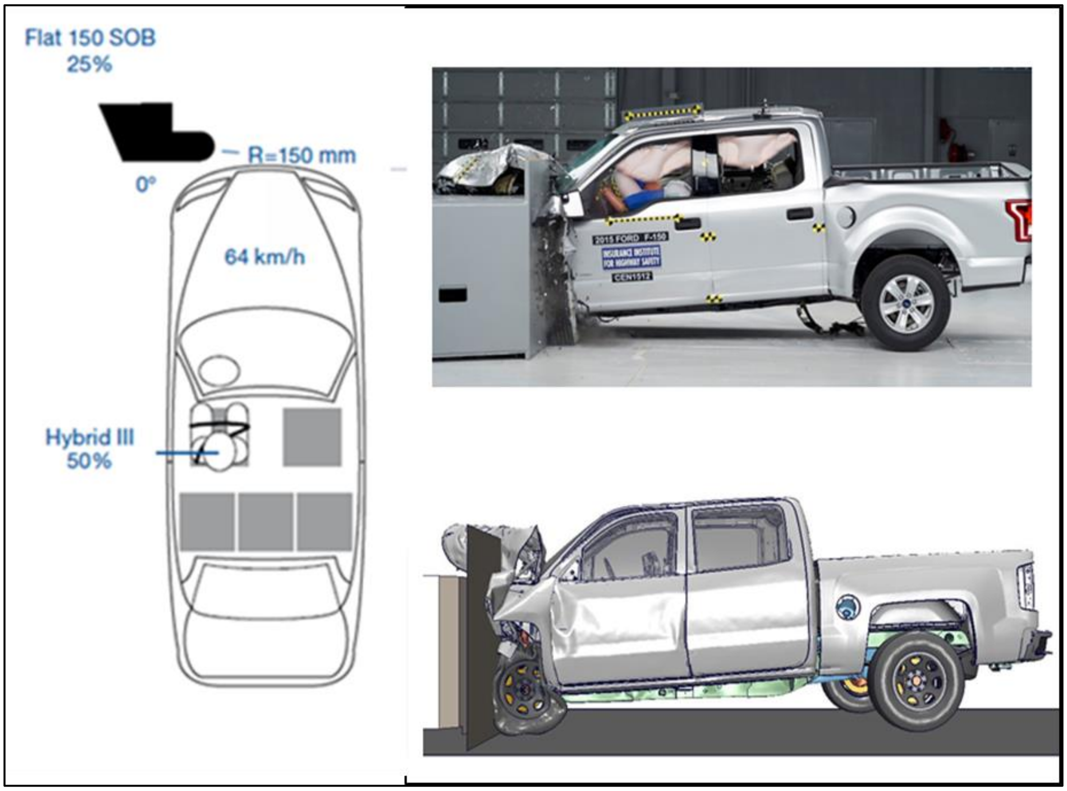


Figure 86: IIHS Small Overlap Test – Test Setup

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[21] IIHS Crashworthiness Evaluation; 2015 Ford F-150 (CEN1512) Small Overlap Front


Model : 2016 Chevy Silverado 1500 Crew
Engine : 5.3L RWD
Weight : 2347 kg

Model : 2016 Chevy Silverado 1500 Ext
Engine : 5.3L RWD
Weight : 2337 kg

Model : 2014 Chevy Silverado 1500 Crew
Engine : 5.3L RWD
Weight : 2318 kg

Figure 87: Test Versus CAE - Vehicle Specifications

Post-Crash comparison of the two tests versus the CAE Baseline is shown in Figure 88. The Crew Cab seems to have performed worst compared to the extended cab as the A-pillar collapsed causing more intrusion the driver foot area. CAE model seems to be more aligned with the extended cab from this view. All three vehicles show the wheel intruding in the driver's footrest region.

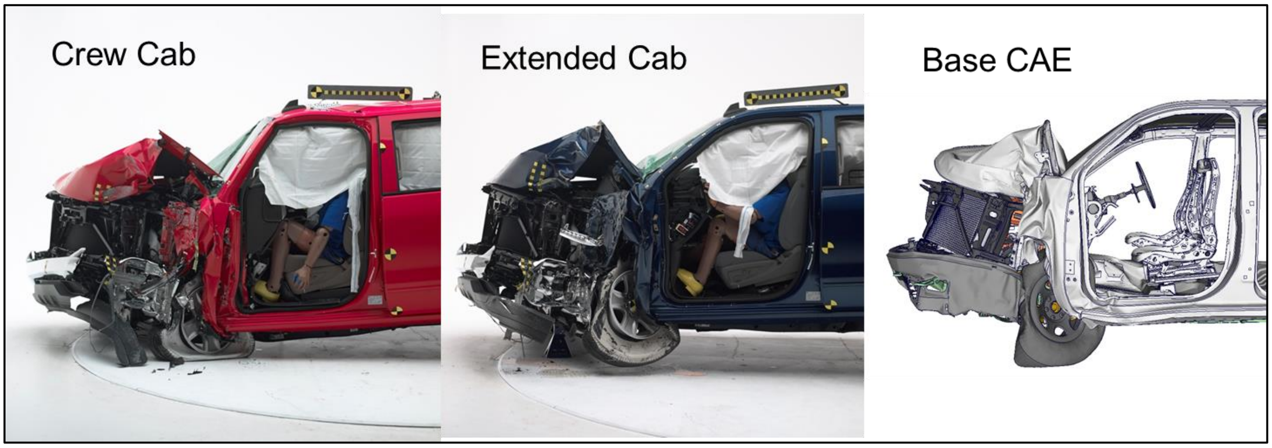

Figure 88: Test Versus CAE Base - Post-Crash Comparison

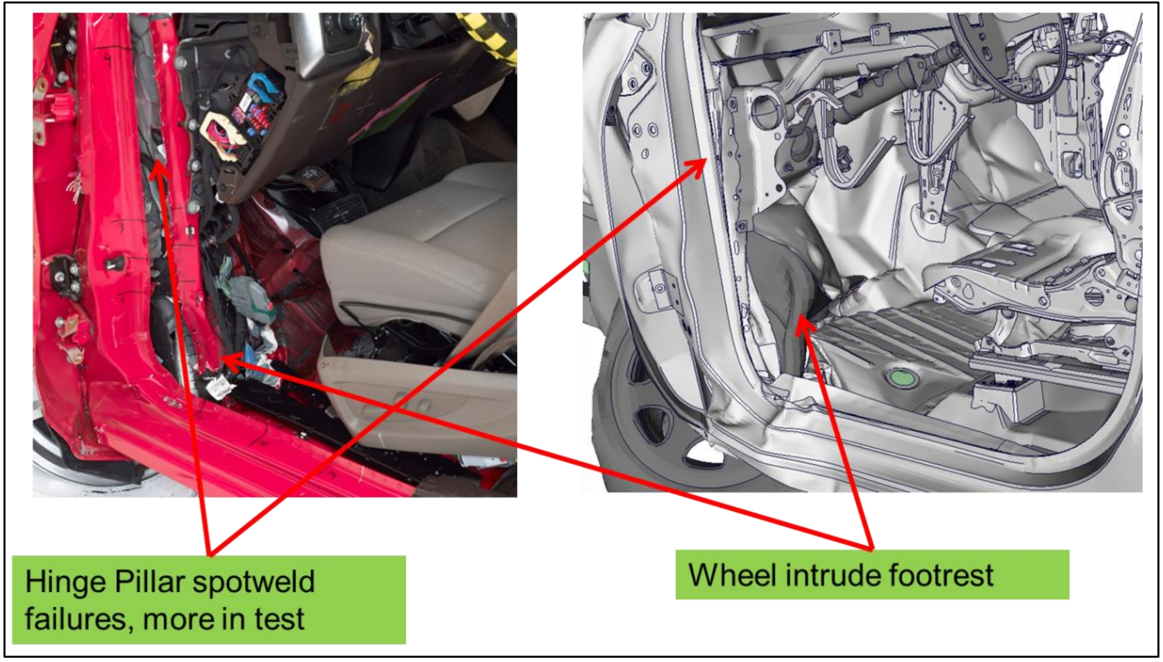

Figure 89: Crew Cab Test Versus CAE Base – Post-Crash Comparison

Figure 89 shows the footrest area for the crew cab vehicle versus CAE. Both images show the wheel intruding through the dash and floor, causing a lot of spot-weld failures within the region. The test also shows spot-weld failures along the hinge pillar, as also seen in the CAE model.

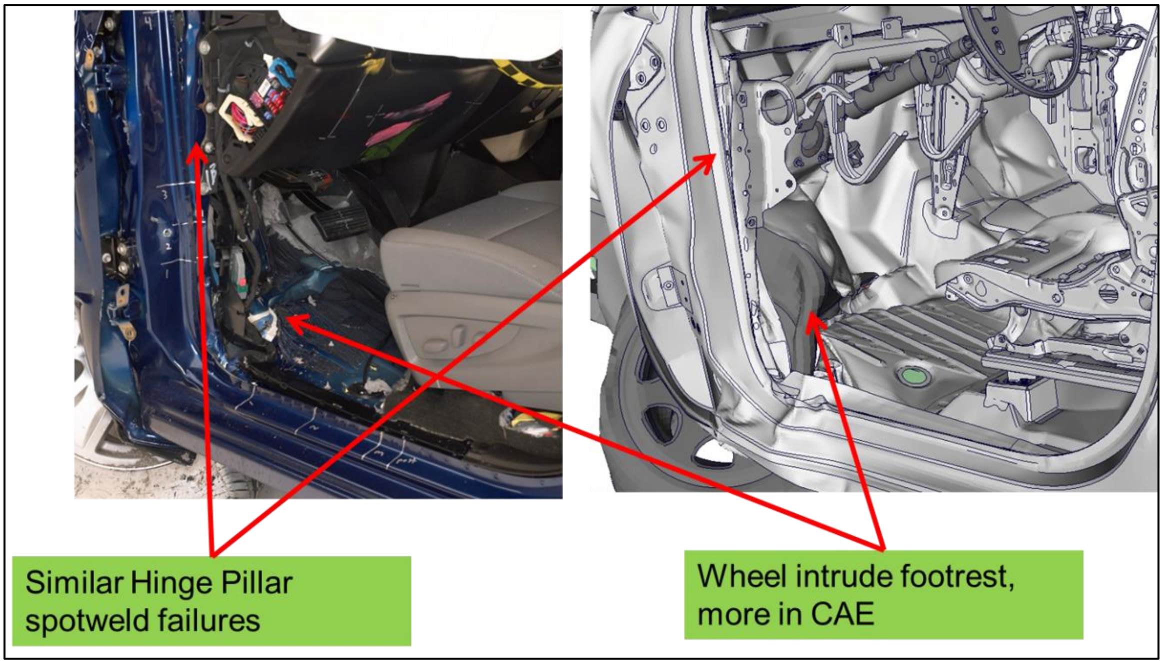

Figure 90: Extended Cab Test Versus CAE Base – Post-Crash Comparison

On the other hand, comparing the extended cab test versus the CAE baseline, the extended cab vehicle has less intrusion from the wheel compared to the CAE model but has similar spot-weld failures on the hinge pillars as shown in Figure **90**. Figure **91** shows IIHS intrusion plot of all three models, confirming the observations made on the vehicle deformations.

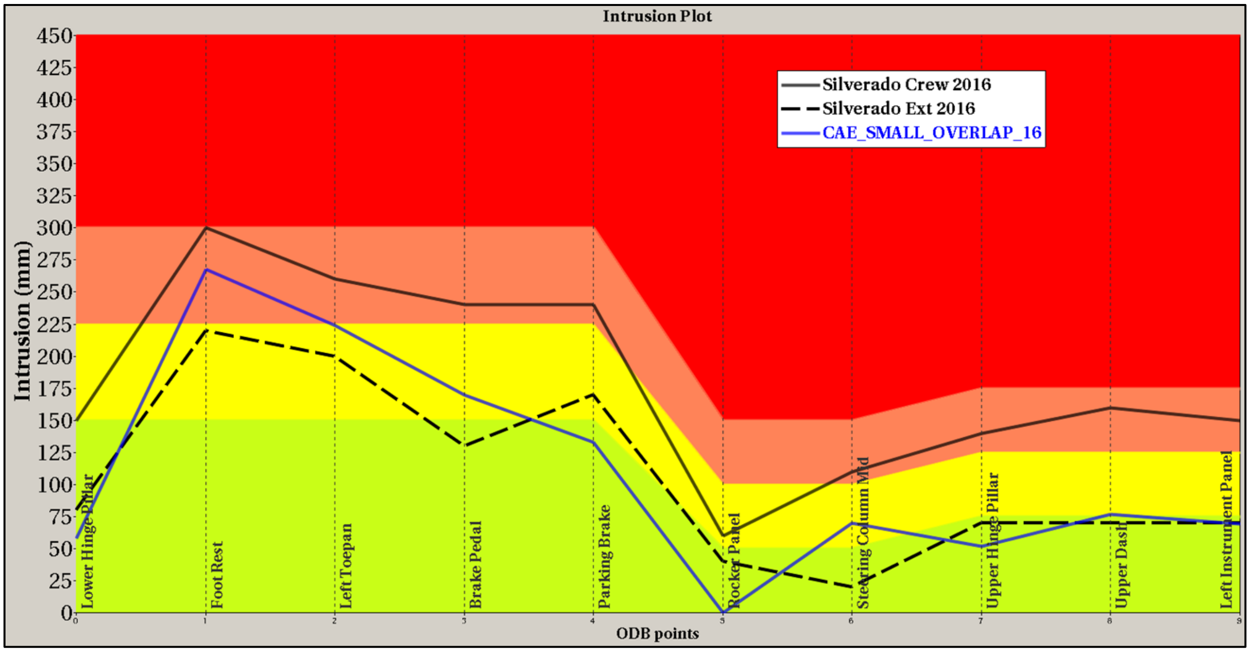

Figure 91: Test Versus CAE Baseline – IIHS Intrusion Plot

The CAE model has similar intrusion level in the upper area (i.e., upper dash, upper hinge pillar, and left instrument panel) and has intrusion in between both the test in the driver foot area. As mentioned previously, the CAE model was built before the IIHS Silverado test data was available. Some minor changes were made to the CAE model to achieve this correlation.

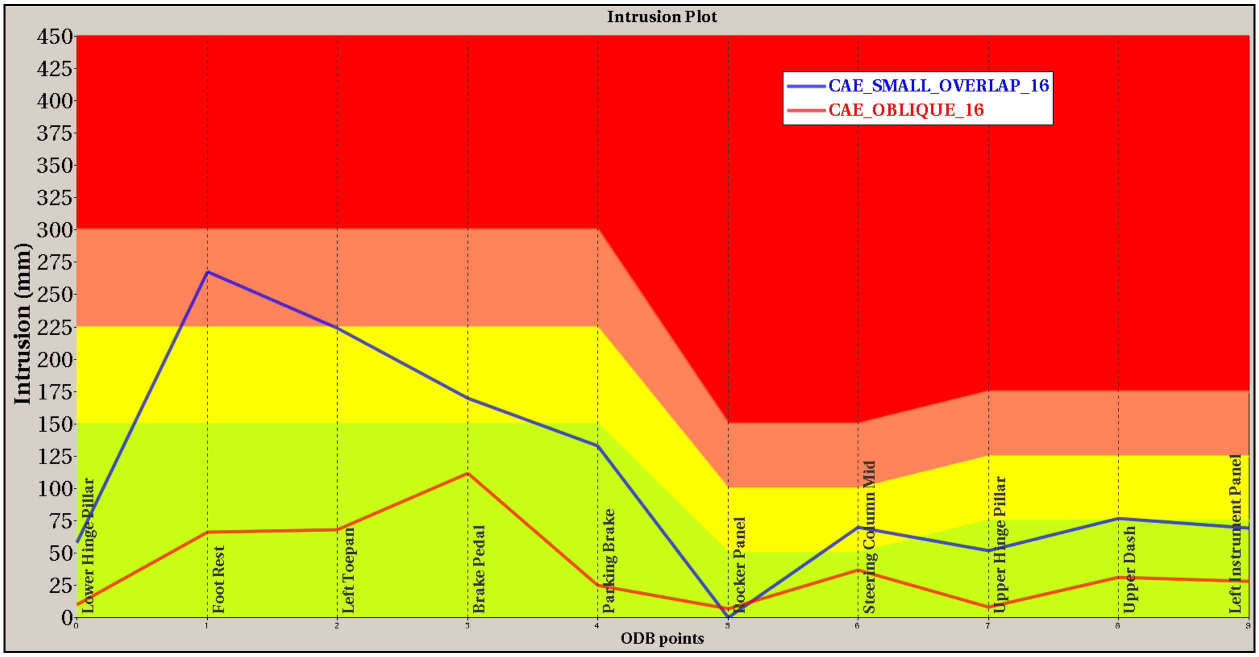

Figure 92: CAE Baseline Comparison – Small Overlap Versus Oblique Impact

Another interesting comparison made in this project is the IIHS intrusion measurement method that was used on the CAE oblique impact model to compare with the CAE small overlap model. This comparison as shown in Figure 92 shows that the predicted intrusion values are lower for the NHTSA oblique compared to IIHS small overlap test.

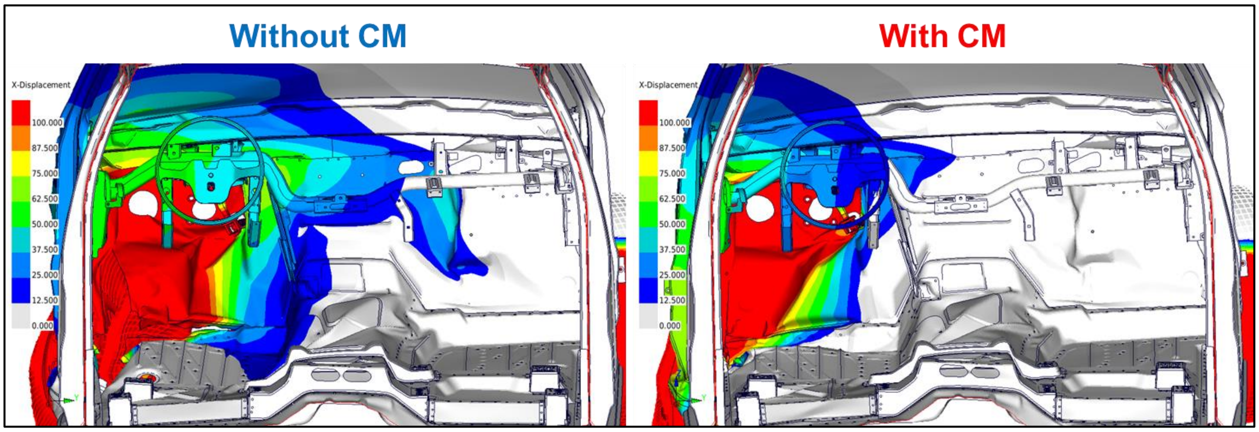

Figure 93: Without Versus With Countermeasure – Dash Panel Intrusion

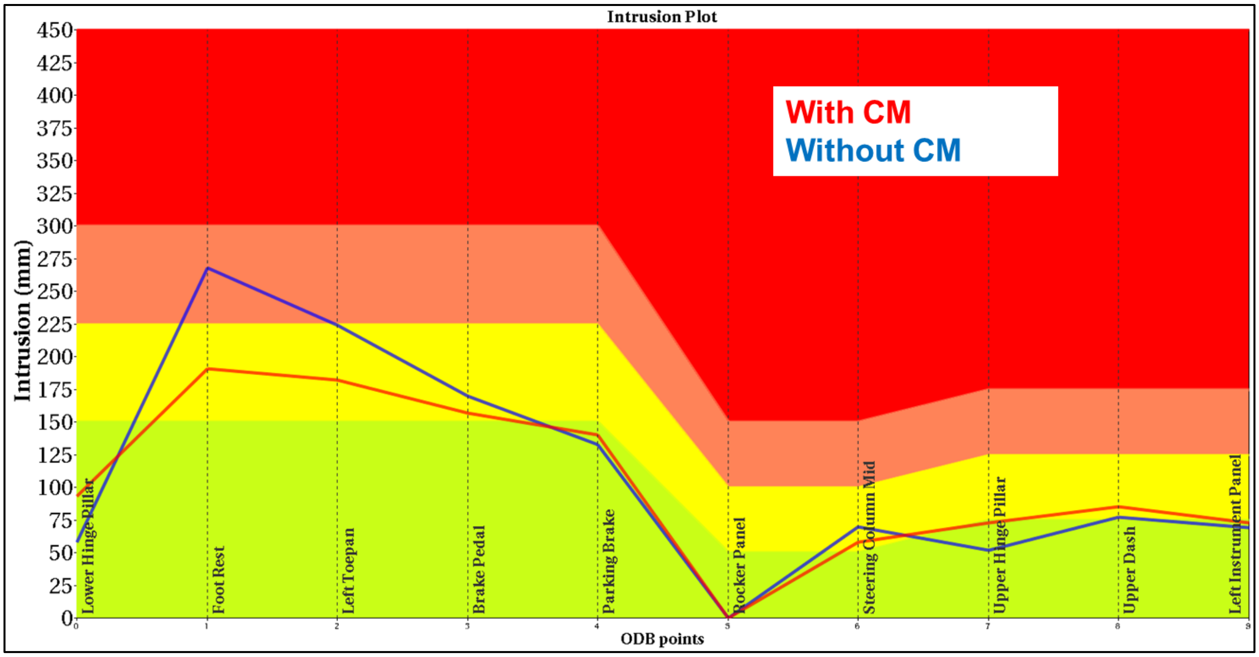

Figure 94: Without Versus With Countermeasure – IIHS Intrusion

In the IIHS small overlap study, the countermeasures were assigned to the CAE model. In the dash panel intrusion image shown in Figure 93, the wheel intrusion is not visible anymore in the model with countermeasure and the overall intrusions are reduced. This observation can be confirmed by the IIHS Intrusion plot shown in Figure 94 where the intrusion in the footrest area (footrest, toe-pan, brake pedal) are reduced as the countermeasure designs were focused to reduce wheel intrusion into the cab footrest region.

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