Working Paper

NCAC 2012-W-005 July 2012

Extended Validation of the Finite Element Model for the 2010 Toyota Yaris Passenger Sedan

Dhafer Marzougui
Randa Radwan Samaha
Chongzhen Cui
Cing-Dao (Steve) Kan
The National Crash Analysis Center
The George Washington University
45085 University Drive, Ashburn, VA 20147 USA
Email: dmarzoug@ncac.gwu.edu
Email: rrsamaha@ncac.gwu.edu
Email: cdkan@ncac.gwu.edu

Kenneth S. Opiela
Turner Fairbank Highway Research Center
Federal Highway Administration, USDOT
6300 Georgetown Pike, McLean VA 22101 USA
Email: kenneth.opiela@dot.gov

ABSTRACT
A finite element (FE) model based on a 2010 Toyota Yaris passenger sedan was developed through the process of reverse engineering at the National Crash Analysis Center (NCAC) of The George Washington University (GWU). This detailed FE model was constructed to include full functional capabilities of the suspension and steering subsystems. This model was validated by comparing the simulation of the NCAP frontal wall impact with actual data from NHTSA tests for comparable vehicles. Acceptable results of the initial validation led to the release of the FE model. Subsequently, validation efforts continued with comparisons to data from other full frontal wall and offset deformable barrier impacts. Simulation results compared well to data from these tests. Finally, model robustness was demonstrated by additional simulations of centerline pole impacts, full frontal and offset impacts into a Chevrolet Silverado, and damage comparisons for impacts at varying speeds. The simulations executed without error in these runs and the results reflected the expected responses and consistency with varying parameters. These results led to the conclusion that the model was robust across various impact scenarios.

Extended Validation of the Finite Element Model for the 2010 Toyota Yaris Passenger Sedan

BACKGROUND

A finite element (FE) model based on a 2010 Toyota Yaris passenger sedan was developed through the process of reverse engineering at the National Crash Analysis Center (NCAC) of The George Washington University (GWU). These efforts were conducted under a contract with the Federal Highway Administration (FHWA). This model will become part of the array of FE models developed to support crash simulation. The model was validated against the National Highway Traffic Safety Administration (NHTSA) frontal New Car Assessment Program (NCAP) test for the corresponding vehicle. This vehicle was selected for modeling to reflect current automotive designs and technology advancements for an important segment of the vehicle fleet. This model is expected to support current and future NHTSA research related to occupant risk and vehicle compatibility as well as FHWA barrier crash evaluation, research, and development efforts. This vehicle conforms to the Manual for the Assessment of Safety Hardware (MASH) requirements for an 1100C test vehicle [1].

MODELING SUMMARY

A production 2010 Toyota Yaris four-door passenger sedan was purchased as the basis for the model [VIN JTDBT4K37A4067025]. The reverse engineering process systematically disassembled the vehicle part by part. Each part was cataloged, scanned to define its geometry, measured for thicknesses, and classified by material type. All data was entered into a computer file and then each part was meshed to create a computer representation for finite element modeling that reflected all of the structural and mechanical features in digital form.

Parts were broken down into elements such that critical features were represented consistent with the implications of element size on simulation processing times. Material data for the major structural components was obtained through coupon testing from samples taken from vehicle parts. From the material testing, appropriate stress and strain values were determined to include in the model for the analysis of crush behavior in crash simulation.

A representation of the resulting FE model in comparison to the actual vehicle is shown in Figure 1. This detailed FE model was constructed to include full functional capabilities of the suspension and steering subsystems (Figure 2), details of the inner door components (Figure 3), and coarse representations of the interior components (Figure 4). Table 1 summarizes the final FE model properties.

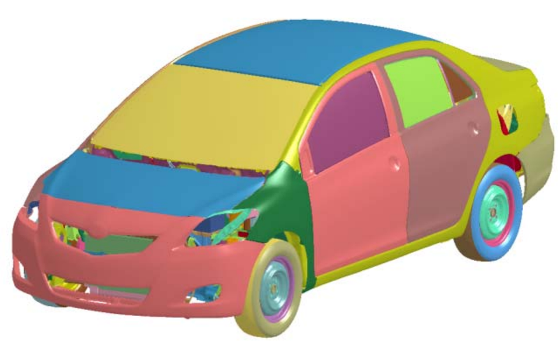



Figure 1 – Actual and FE model of a 2010 Toyota Yaris sedan

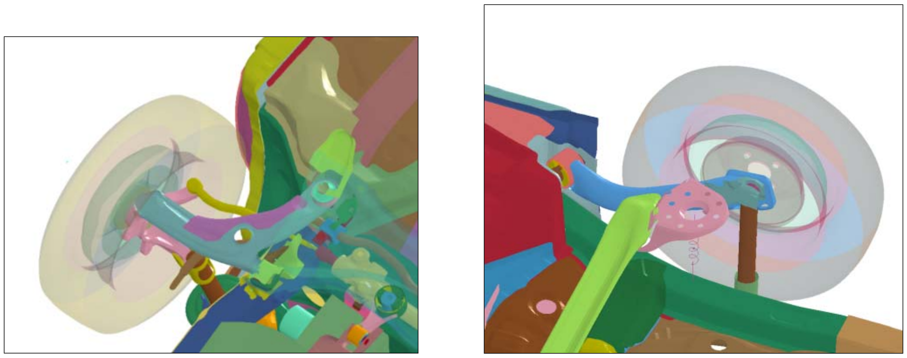


Figure 2 – Details of the front (left) and rear (right) steering and suspension subsystems

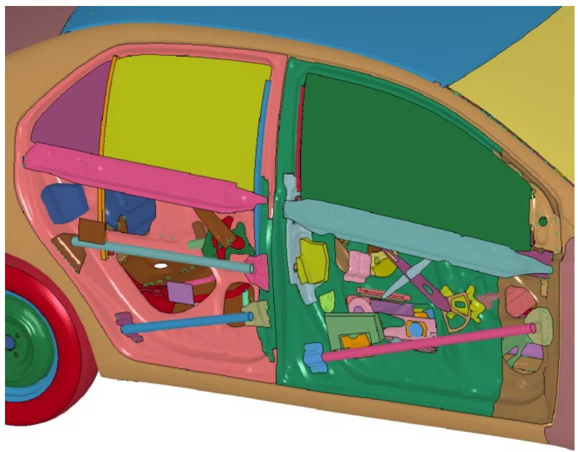


Figure 3 – Details of the inner door components

Figure 4 – Coarse representations of structural interior components

Table 1 – Toyota Yaris FE model summary

Number of Parts	917	Beam Element Connections	4,425
Number of Nodes	1,480,422	Nodal Rigid Body Connections	727
Number of Shells	1,250,424	Extra Node Set Connections	20
Number of Beams	4,738	Rigid Body Connections	2
Number of Solids	258,887	Spotweld Connections	4,107
Total Number of Elements	1,514,068	Joint Connections	39

Details about the model and the outcome of the initial validation efforts are documented in "Development and Validation of a Finite Element Model for a 2010 Toyota Yaris Sedan" NCAC 2011-T-001 [2]. This document describes the additional validation efforts that were undertaken to assess the robustness of the Yaris FE model for various types of impacts. These efforts were conducted by NCAC in support of the National Highway Traffic Safety Administration (NHTSA) study "Investigate Self and Partner Protection of New Vehicle Designs Using Structural Modeling," TOPR No. 16 under DTFH61-09-D-00001.

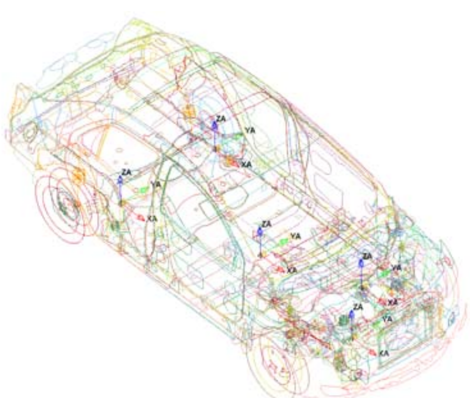
INITIAL MODEL VALIDATION

The FE model was initially verified and validated in several ways to assure that it was an accurate representation of the actual vehicle. These efforts included checks for completeness of elements and adequacy of connection details. The mass, moments of inertia, and center of gravity (CG) locations of the actual vehicle, as measured at the SEAS, Inc. lab, and FE model were compared. The results are shown in Table 2. The weight; pitch, roll, and yaw inertias; and x, y, and z coordinates for the CG were found to be similar and within acceptable limits.

Table 2 – Actual vehicle and FE model mass, inertia, and CG comparisons based upon data from testing at SEAS, Inc.

	Actual Vehicle	FE Model
Weight, kg	1078	1100
Pitch inertia, kg-m^2	1498	1566
Yaw inertia, kg-m^2	1647	1739
Roll inertia, kg-m^2	388	395
Vehicle CG X, mm	1022	1004
Vehicle CG Y, mm	-8.3	-4.4
Vehicle CG Z, mm	558	569

The focus of the initial validation was the comparison of the simulation of the NCAP frontal wall impact with actual data from NHTSA Tests 5677 and 6221 for a comparable vehicle [3, 4]. For this simulation, accelerometers were positioned in the same locations as the NCAP test (Figure 5). The most commonly benchmarked accelerometers for NCAP performance are the left rear seat, right rear seat, and engine top and bottom. The left rear seat and right rear seat accelerometers are used to measure the deceleration response and velocity of the vehicle cabin in the wall impact.



Location	Node ID
Left Seat	319812
Right Seat	319820
Engine Top	319828
Engine Bottom	319836

Figure 5 – Accelerometer locations in FE model

Table 3 provides specific data for key parameters of the FE model and the vehicle used in the NCAP tests. It is easily noted that all were very similar. More information on the NCAP test vehicle, like vehicle weight distribution, vehicle attitude, center of gravity (CG) location, and fuel tank capacity, are published in the NHTSA test reports.

Table 3 – Comparison of vehicle characteristics for FE model and two NCAP test vehicles

	FE Model	**Test 5677**	**Test 6221**
Weight (kg)	1263	1271	1245
Engine Type	1.5L V4	1.5L V4	1.5L V4
Tire size	P185/60R15	P185/60R15	P185/60R15
Attitude (mm) (As delivered)	F – 668	F – 673	F – 675
	R – 673	R – 680	R – 673
Wheelbase (mm)	2538	2551	2463
CG (mm) Rear of front wheel C/L	1035	999	976
Body Style	4 Door Sedan	4 Door Sedan	3 Door Liftback

The overall global deformation pattern of the FE model was very similar to that of the NCAP test, as shown in Figure 6. Figure 7 compares the left and right rear seat accelerations of the test and simulation, also indicating similar vehicle behavior between the test and simulation. The Roadside Safety Verification and Validation Program (RSVVP) was used to generate objective measures of how well the simulation follows the test data [5]. The Sprague-Geers MPC metrics were used to quantify the similarity of the test and simulation curve shapes and the ANOVA metric was used to evaluate the residual error. The acceptance criteria for the Sprague-Geers metrics are a difference of less than 40% in magnitude, phase, or comprehensive (the square root of the sum of the squares of M and P). The acceptance criteria for the ANOVA metric are an average residual error of less than 5% and a standard deviation of the residual errors of less than 20%. When the values fall under these acceptance criteria, the simulation can be said to have good correlation with the test, with any deviations in the data attributable to random experimental error. These objective rating metrics for the left and right rear seat accelerations compared to Test 5677 are summarized in Table 4. It is worth noting that the acceptance criteria in RSVVP were developed for roadside safety applications where tests typically involve longer duration complex impact sequences with more variability than the NHTSA vehicle crash tests being considered for the FE model validation. In the future, developing acceptance criteria for NHTSA type crash test would be more pertinent and applicable to vehicle FE model validation efforts.

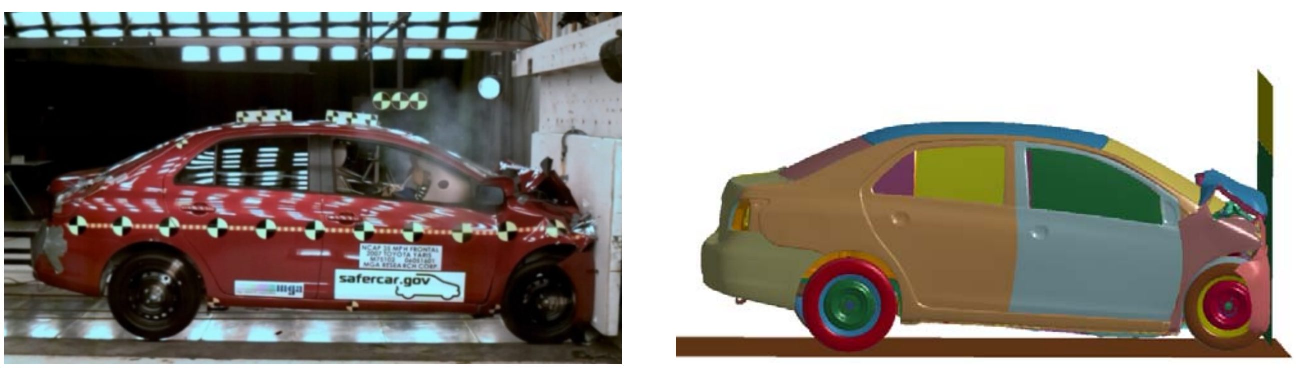


Figure 6 – Comparison of the global deformation for Yaris in NCAP Test 5677 and simulation

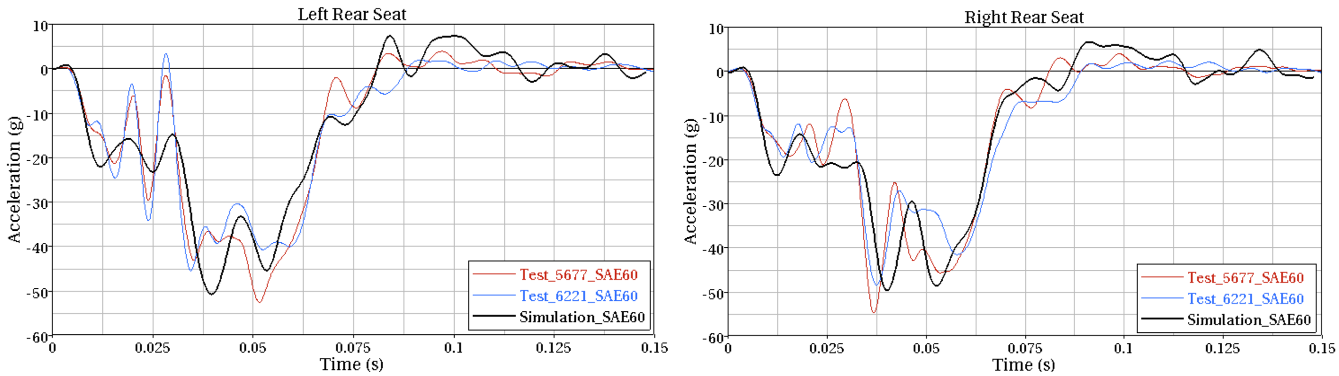


Figure 7 – Comparison of left and right rear seat X accelerations for tests and simulation

Table 4 – Objective rating criteria for left and right rear seat accelerations

		Left Rear Seat Acceleration		Right Rear Seat Acceleration	
		Value (%)	Pass?	Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	-2.7	Y	0.7	Y
	Phase	8.4	Y	9.3	Y
	Comprehensive	8.8	Y	9.3	Y
ANOVA Metric	Average	0.6	Y	0.1	Y
	Standard Deviation	10.1	Y	10.6	Y

The response of the engine during the crash event was captured through two accelerometers. Both the engine top and bottom accelerations in the simulation closely tracked the engine response in the two tests, as shown in Figure 8. The objective rating metrics for the engine top acceleration compared to Test 5677 are shown in Table 5.

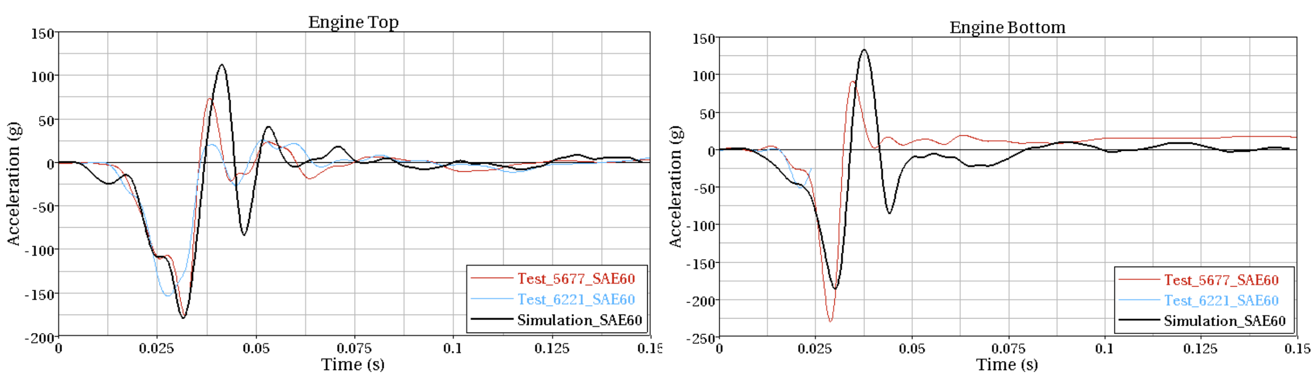


Figure 8 – Comparison of engine top and bottom accelerations for tests and simulation

Table 5 – Objective rating criteria for engine top acceleration

		Engine Top Acceleration	
		Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	17.7	Y
	Phase	16	Y
	Comprehensive	23.9	Y
ANOVA Metric	Average	-0.2	Y
	Standard Deviation	12.6	Y

Lastly, the simulation and test forces were compared (Figure 9). The total wall force in the simulation closely matched that of the two tests. The simulation showed slightly higher maximum force, but also showed similar peak timing and impact duration. The similarity of the simulation and Test 5677 wall force curves is quantified in Table 6. Additionally, similar stiffness was observed in the FE model and test vehicles, as shown in the force-displacement plot.

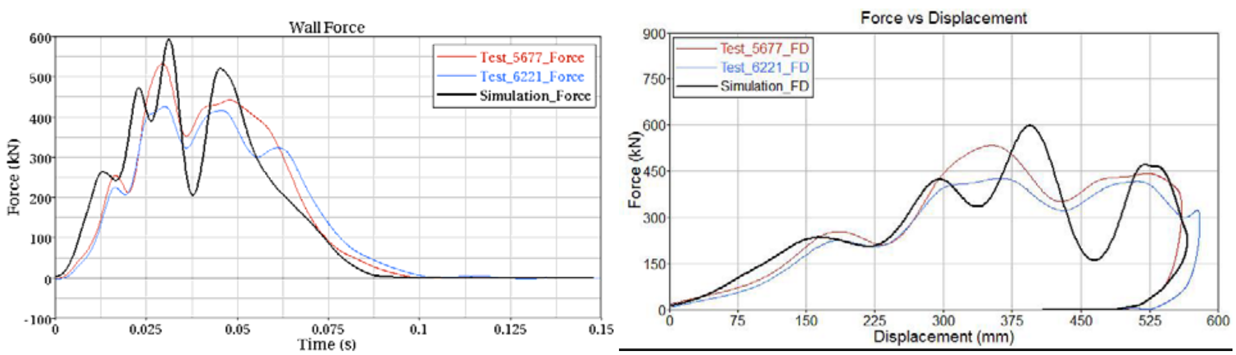


Figure 9 – Total wall force (left) and force-displacement (right) plots for the tests versus simulation

Table 6 – Objective rating criteria for total wall force

		Total Wall Force	
		Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	-1.2	Y
	Phase	8.2	Y
	Comprehensive	8.3	Y
ANOVA Metric	Average	-0.7	Y
	Standard Deviation	11.2	Y

All of the data presented above validates the FE model of the Toyota Yaris as a good representation of the physical vehicle. More information on the NCAP validation can be found in NCAP Report 2011-T-001 [2].

ADDITIONAL MODEL VALIDATIONS

The Yaris FE model was further validated by comparisons to additional tests where crash data was available. These comparisons included a 25 mph full frontal and offset deformable barrier impact. These impacts were simulated to determine if the model would yield similar results as the physical test. The results of these additional comparisons are described in the following sections.

Full Frontal Impact at 25 mph

The model was verified against a full frontal impact into a rigid wall at 25 mph (NHTSA Test 6069) [6]. A comparison of the test and simulation vehicles is shown in Table 7.

The overall global deformation pattern of the FE model was very similar to that of the NHTSA test, as shown in Figure 10. Figure 11 compares the left and right rear seat accelerations of the test and simulation, also indicating similar vehicle behavior between the test and simulation. Table 8 summarizes the statistical comparison of the data from the simulation and the test, noting that it passed the objective criteria.

Table 7 – Comparison of vehicle characteristics for FE model and NHTSA Test 6069 vehicle

	FE Model	Test 6069
Weight (kg)	1211	1212
Engine Type	1.5L V4	1.5L V4
Tire size	P185/60R15	P185/60R15
Attitude (mm) (As delivered)	F – 668	F – 673
	R – 673	R – 672
Wheelbase (mm)	2538	2550
Body Style	4 Door Sedan	4 Door Sedan

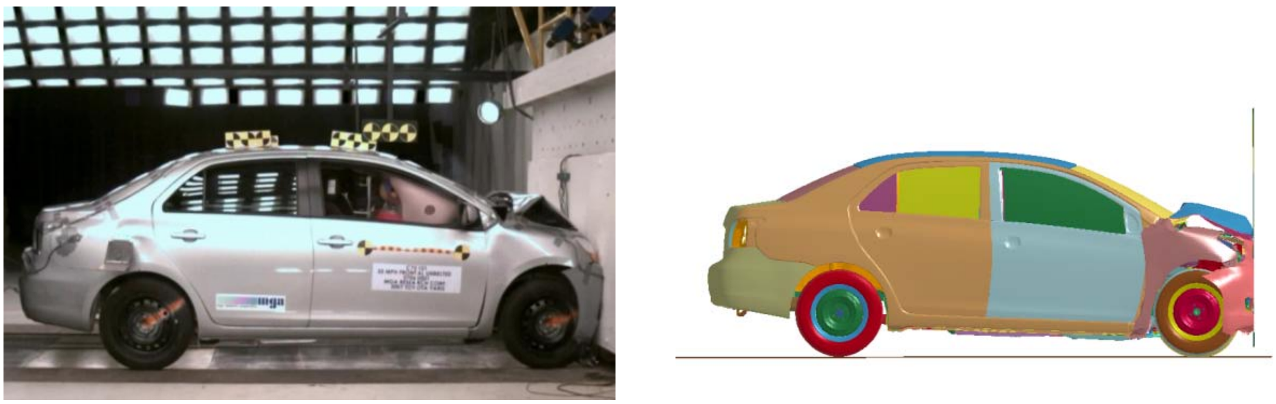


Figure 10 – Comparison of the global deformation for Yaris in NHTSA test no. 6069 and simulation

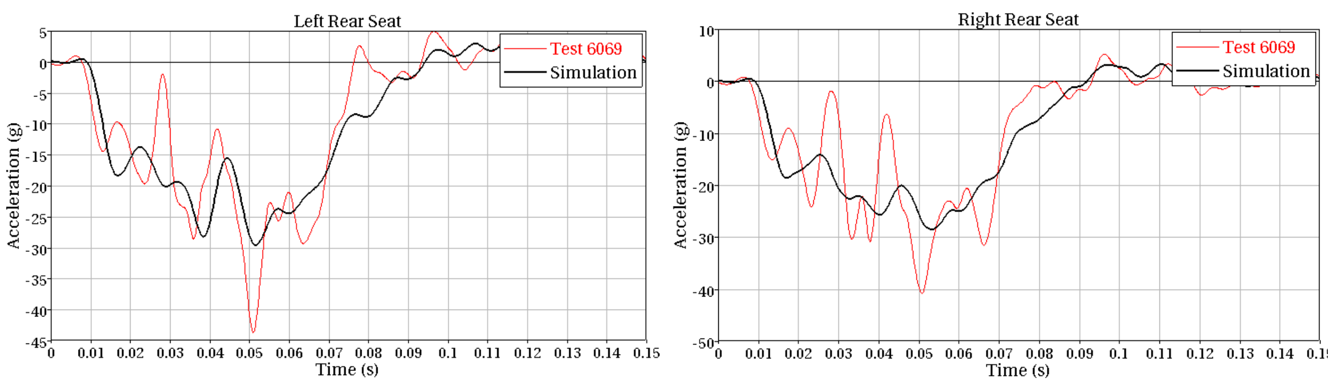


Figure 11 – Comparison of left and right rear seat X accelerations for NHTSA Test 6069 and simulation

Table 8 – Objective rating criteria for left and right rear seat accelerations for 25 mph full frontal impact

		Left Rear Seat Acceleration		Right Rear Seat Acceleration	
		Value (%)	Pass?	Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	-4	Y	-4.5	Y
	Phase	11.4	Y	12.4	Y
	Comprehensive	12	Y	13.2	Y
ANOVA Metric	Average	-0.7	Y	-0.4	Y
	Standard Deviation	11.3	Y	13.5	Y

The simulation and test forces were compared (Figure 12). The total wall force in the simulation closely matched that of the two tests (Table 9). The simulation showed slightly higher maximum force, but also showed similar peak timing and impact duration. Similar stiffness was observed in the FE model and test vehicles, as shown in the force-displacement plot.

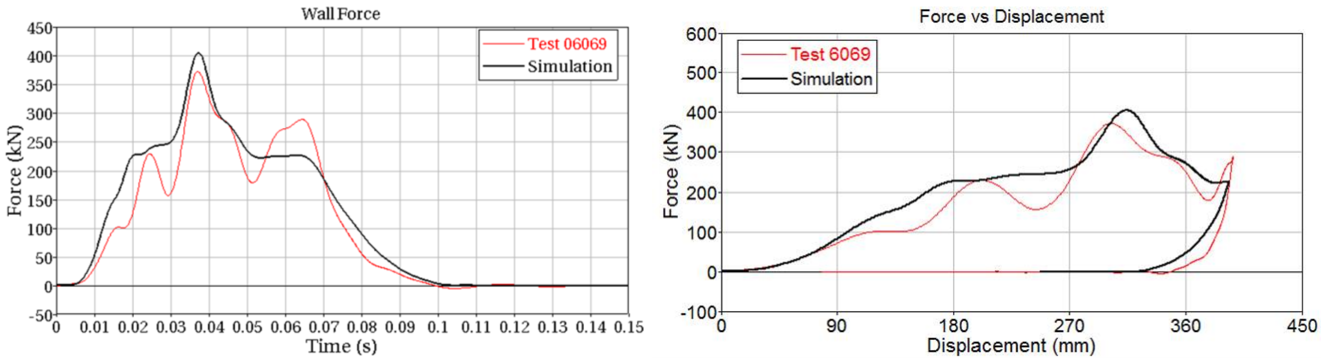


Figure 12 – Total wall force (left) and force-displacement (right) plots for NHTSA Test 6069 versus simulation

Table 9 – Objective rating criteria for total wall force for 25 mph full frontal impact

		Total Wall Force	
		Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	7.5	Y
	Phase	6.1	Y
	Comprehensive	9.7	Y
ANOVA Metric	Average	3.3	Y
	Standard Deviation	8.1	Y

All of the data presented above further indicated that the FE model of the Toyota Yaris is a good representation of the physical vehicle.

IIHS Offset Deformable Barrier

The model was run under the IIHS offset deformable barrier (ODB) crash test protocol, in which the vehicle strikes a deformable barrier at 40 mph with a 40% overlap on the driver side. The simulation results were compared to IIHS Test CEF0610 [7]. The overall vehicle deformation and pulse were similar between the test and simulation (Figure 13 and Figure 14). Table 10 summarizes the objective rating criteria for the simulation data compared to the test data.

Figure 13 – Comparison of post-impact deformation of IIHS ODB test

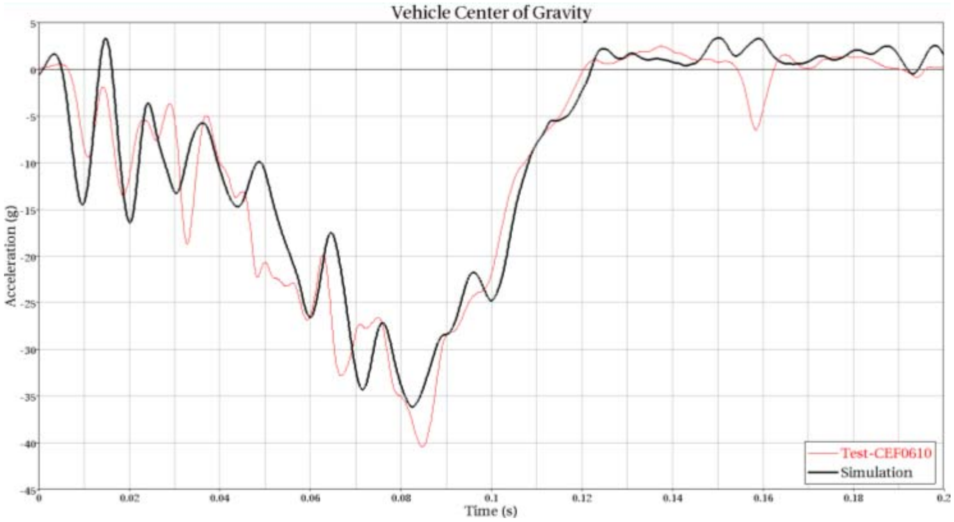


Figure 14 – Acceleration at the vehicle CG for the IIHS ODB test and simulation

Table 10 – Objective rating criteria for vehicle CG acceleration in the IIHS ODB simulation

		CG Acceleration	
		Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	-5.4	Y
	Phase	7.7	Y
	Comprehensive	9.4	Y
ANOVA Metric	Average	2	Y
	Standard Deviation	9.2	Y

The intrusion was also compared between the test and simulation. The intrusion was measured at four places on the footwell, as shown in Figure 15. The comparison of the intrusion is shown in Table 11.

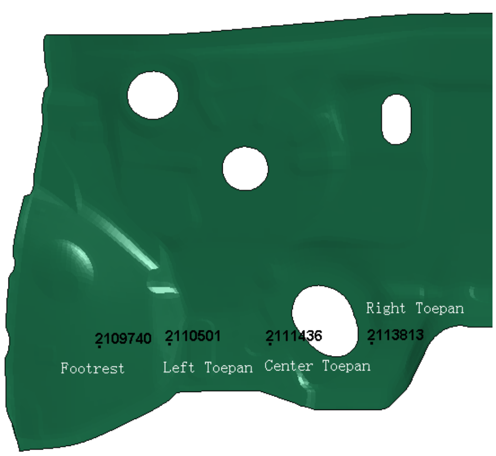


Figure 15 – Footwell intrusion measurement locations

Table 11 – Comparison of footwell intrusion between IIHS test and simulation

Location	IIHS test(mm)	Simulation(mm)
Footrest	-20	-85
Left toepan	-100	-118
Center toepan	-50	-101
Right toepan	-40	-75

MODEL ROBUSTNESS

As further tests of the robustness of the FE model of the Toyota Yaris, several different crash configurations were run to confirm that the simulations would run to completion with no computational errors. These included centerline pole, full frontal and offset into the Silverado, and varying speed rigid wall impacts. Data for actual crashes of these types did not exist, so analytical comparisons were not possible. The results are presented in the following sections.

Centerline Pole Impact at 35 mph

The centerline pole impact at 35 mph was selected for one of the robustness runs, as it is a severe, high speed crash with large, localized deformation. This crash condition would test the robustness of the FE model. The centerline pole simulation was run with the Toyota Yaris at an impact speed of 35 mph. The model was proven to be robust, as no errors were encountered and the simulation ran to completion. The pre- and post-crash images showing the severity of the deformation is shown in Figure 16 and the vehicle acceleration is shown in Figure 17. These are consistent with expected results for this type of impact.

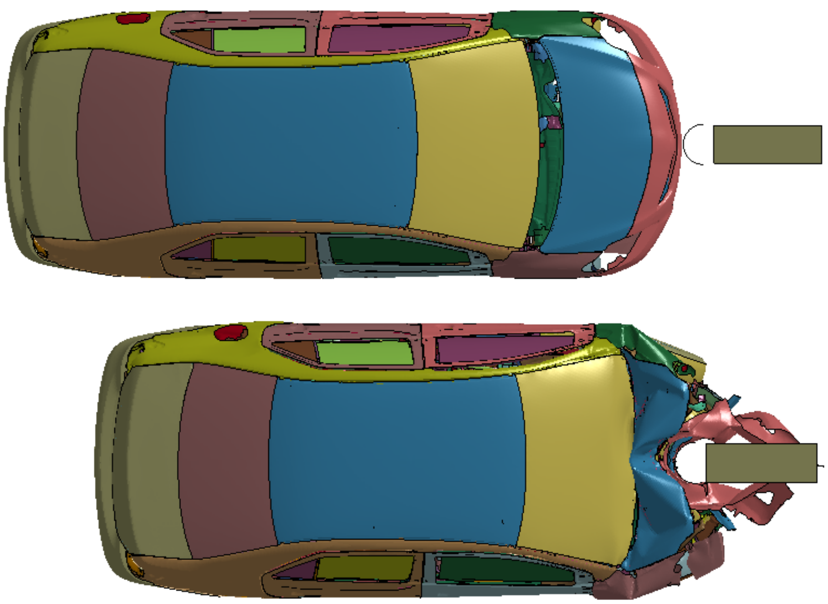


Figure 16 – Pre- and post-crash images of the Yaris for the centerline pole robustness simulation

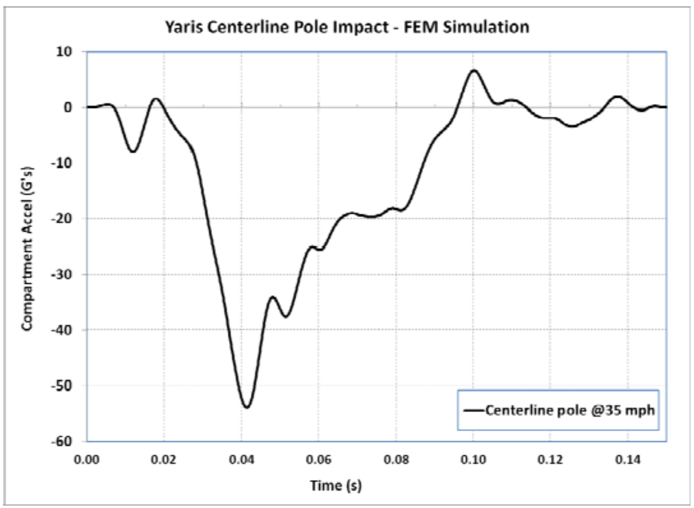


Figure 17 – Compartment acceleration of Yaris in centerline pole impact at 35 mph

Full Frontal Impact into Silverado

Additionally, the Yaris model was tested for robustness in a head-on, full frontal impact with the 2007 Chevrolet Silverado FE model at 35 mph. This simulation ran to completion with no errors. The extent of the deformation is shown in Figure 18 and the vehicle pulse is shown in Figure 19. The accelerations for the right rear seat and left rear seat are similar, showing a symmetrical impact expected of a full frontal crash.

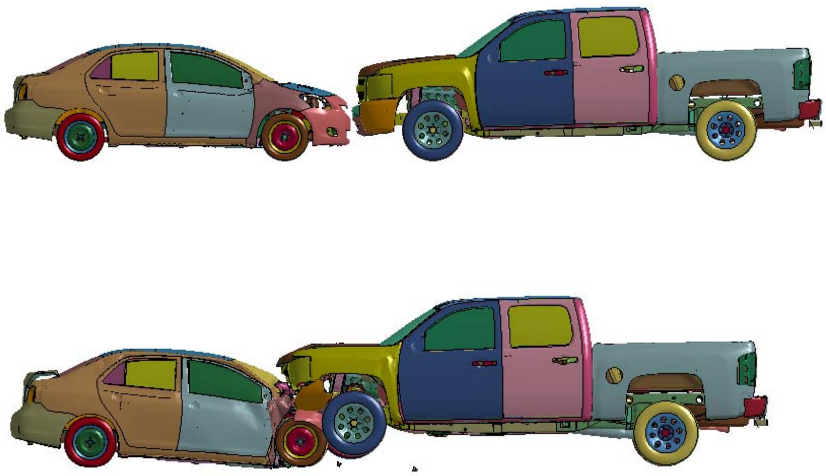


Figure 18 – Pre- and post-crash images of the Yaris striking the Silverado with 100% overlap

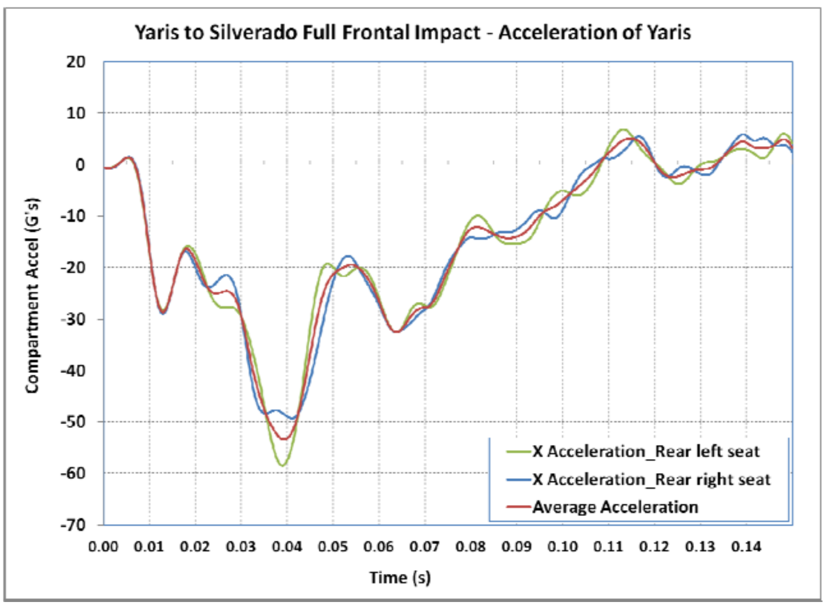


Figure 19 – Compartment acceleration of Yaris in full frontal impact with Silverado

Offset Impact into Silverado

The Yaris model was run into the Silverado model at 35 mph with a 40% overlap. This simulation ran to completion with no errors, showing the robustness of the Yaris FE model. The deformation of the Yaris is shown in Figure 20 and the vehicle pulse is shown in Figure 21. The acceleration of the left rear seat was greater than that of the right rear seat, as expected in an offset crash on the driver side.

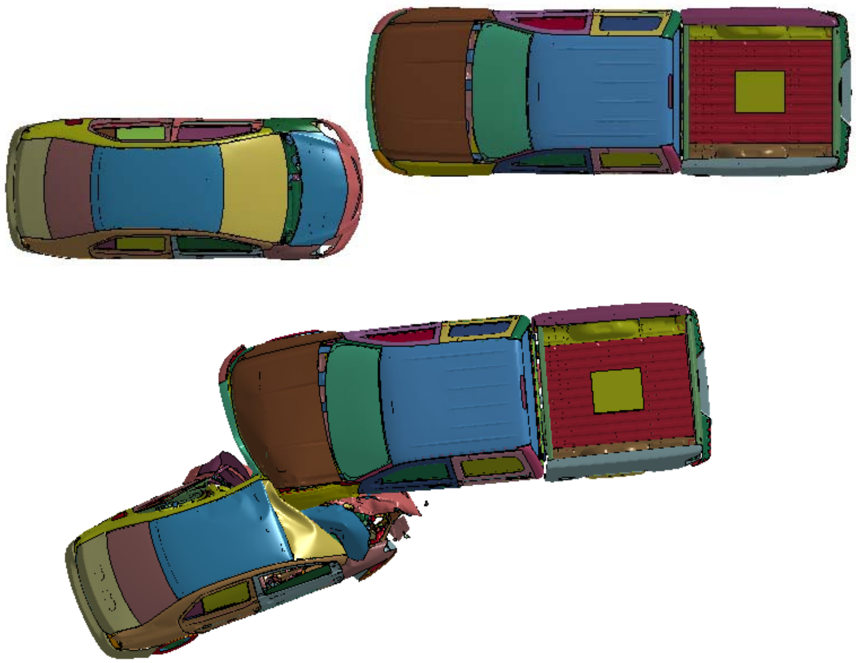


Figure 20 – Pre- and post-crash images of the Yaris striking the Silverado with 40% overlap

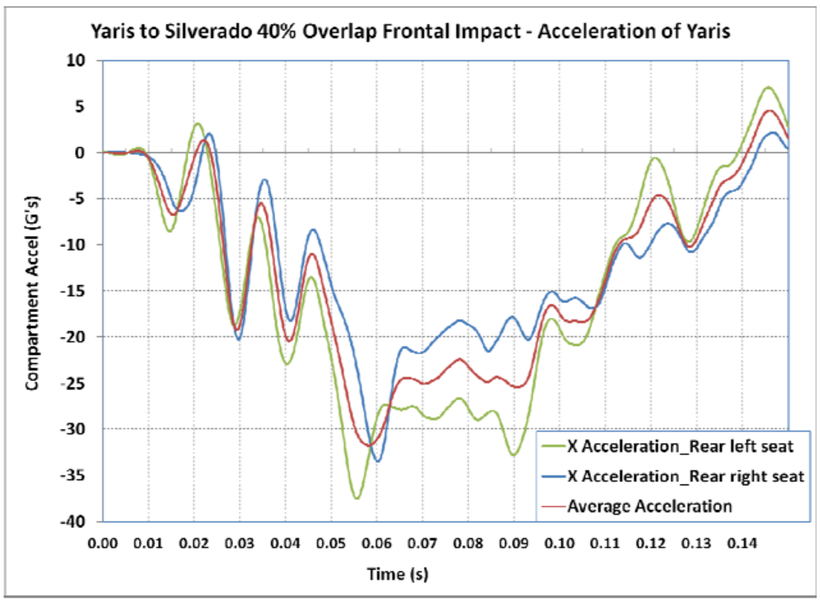


Figure 21 – Compartment acceleration of Yaris in 40% offset impact with Silverado

VARYING SPEED TREND ANALYSIS

Additional simulations were run with the Toyota Yaris FE model to verify that the model would show consistent deformations for rigid wall, offset deformable barrier, and centerline pole impacts at varying speeds. The results were compared between low and high speeds within the same crash configuration to confirm that the vehicle responses were valid in the physical realm.

NCAP Rigid Wall

The NCAP rigid wall simulation was run at 25 mph and 35 mph. The pre- and post-crash images and resulting compartment accelerations are shown in Figure 22 and Figure 23. These runs verified that the higher speed impact yielded a more severe crash pulse than the lower speed impact.

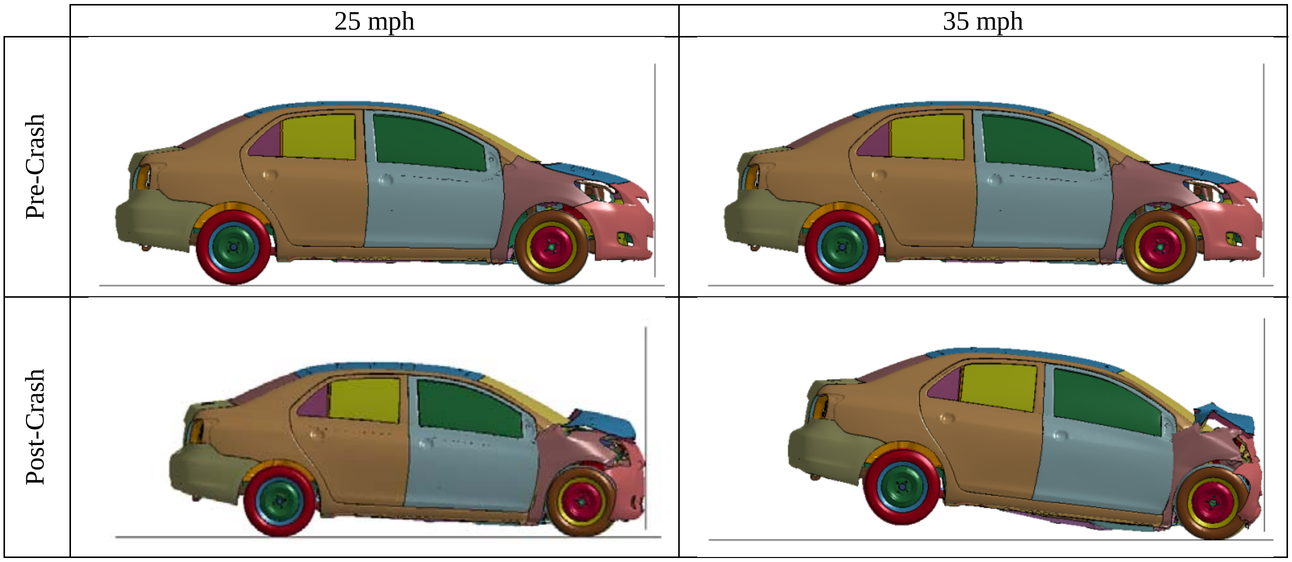


Figure 22 – Pre- and post-crash images of the Yaris for the full frontal impact at 25 mph and 35 mph

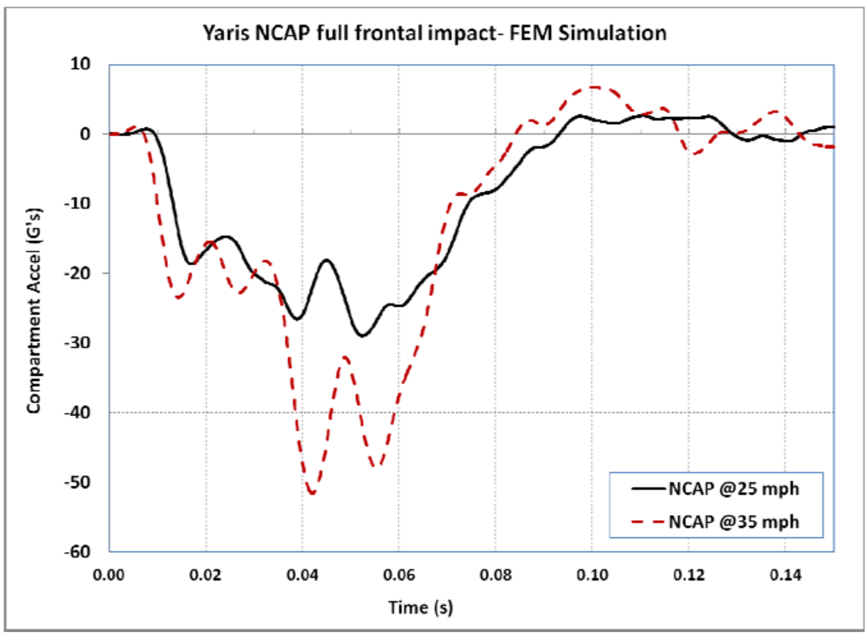


Figure 23 – Yaris compartment accelerations for NCAP frontal verification simulations

IIHS Offset Deformable Barrier

The IIHS ODB simulation was run at 25 mph and 40 mph. The pre- and post-crash images and resulting CG and left rear accelerometer outputs are shown in Figure 24 and Figure 25. These runs verified that the higher speed impact yielded higher compartment accelerations than the lower speed impact.

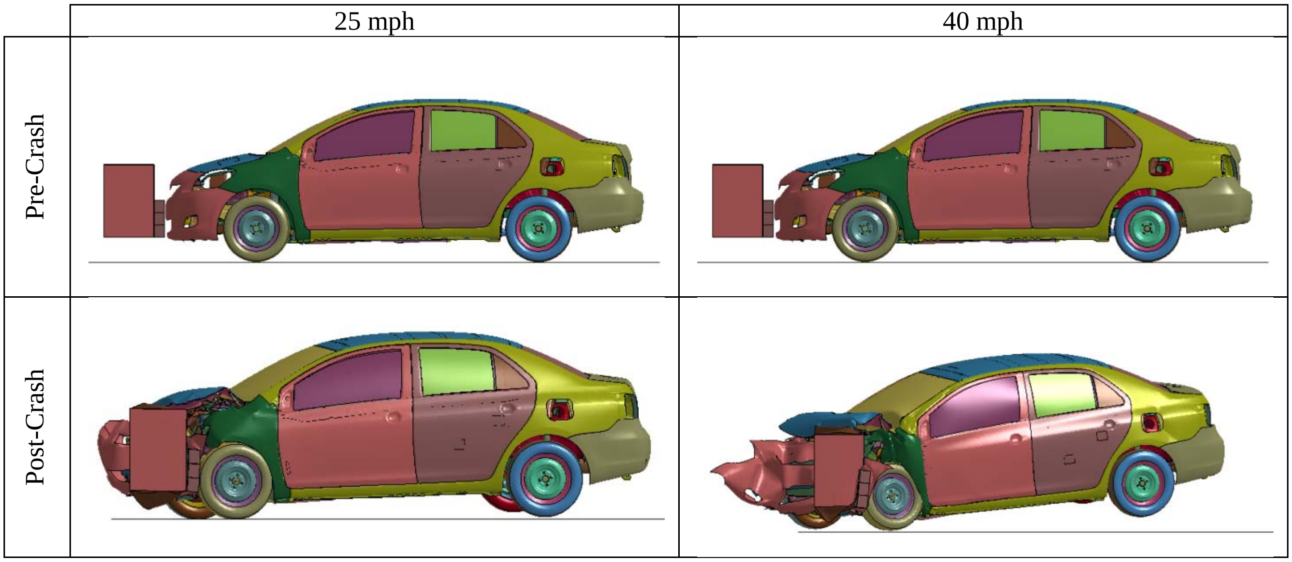


Figure 24 – Pre- and post-crash images of the Yaris for the IIHS ODB impact at 25 mph and 40 mph

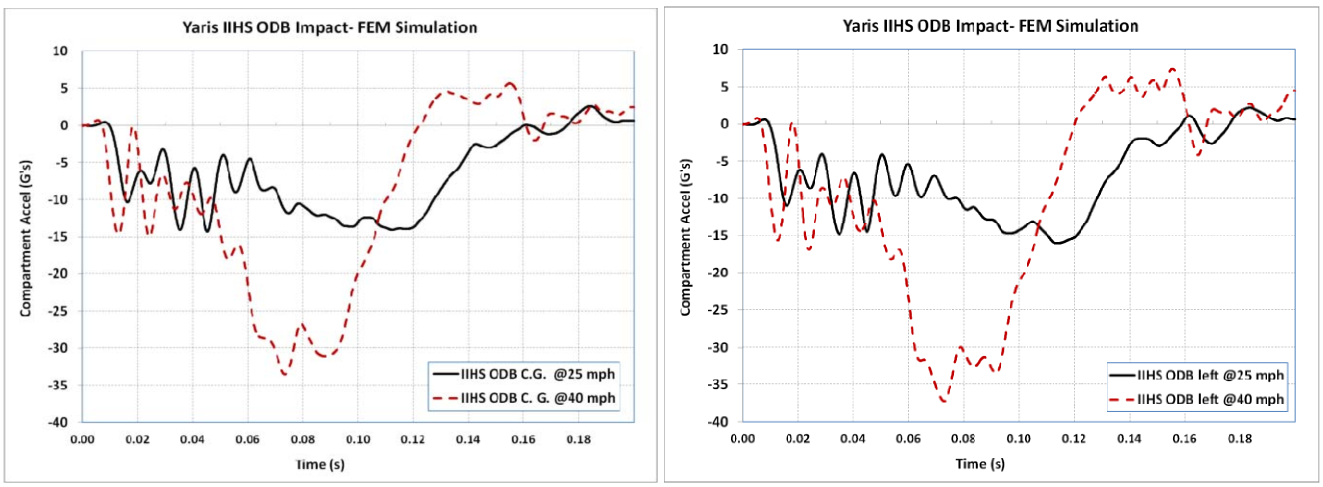


Figure 25 – Yaris CG (left) and left rear (right) accelerometer outputs for IIHS ODB verification simulations

Centerline Pole

The centerline pole simulation was run at 25 mph and 35 mph. The pre- and post-crash images and resulting compartment accelerations are shown in Figure 26 and Figure 27. These runs verified that the higher speed impact yielded a more severe crash pulse than the lower speed impact.

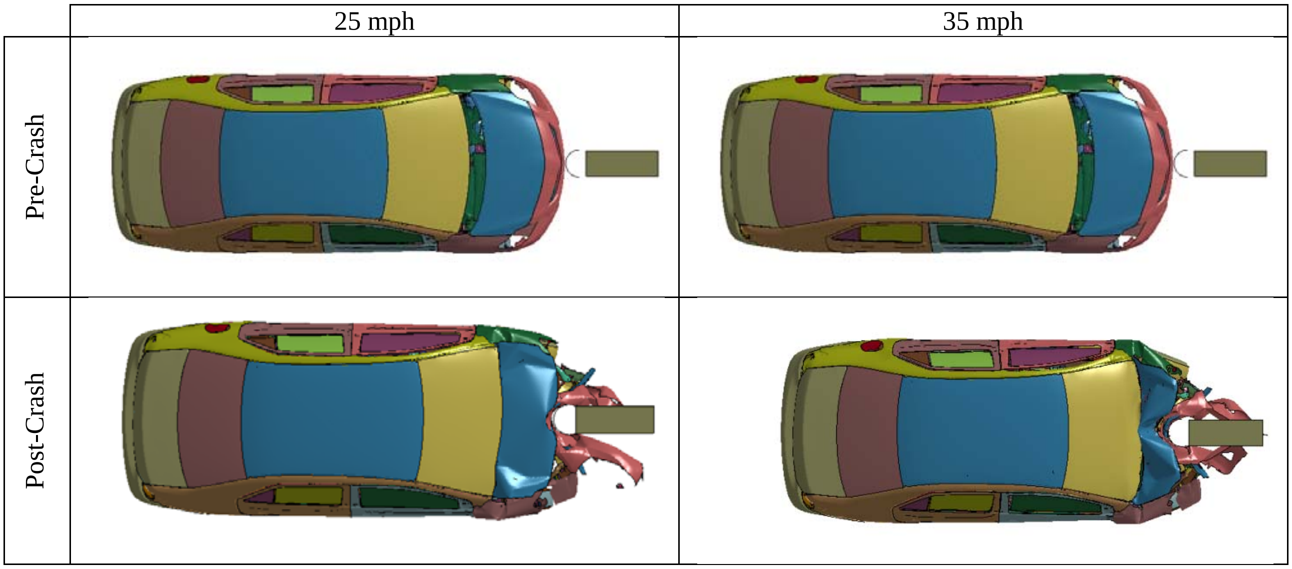


Figure 26 – Pre- and post-crash images of the Yaris for the centerline pole impact at 25 mph and 35 mph

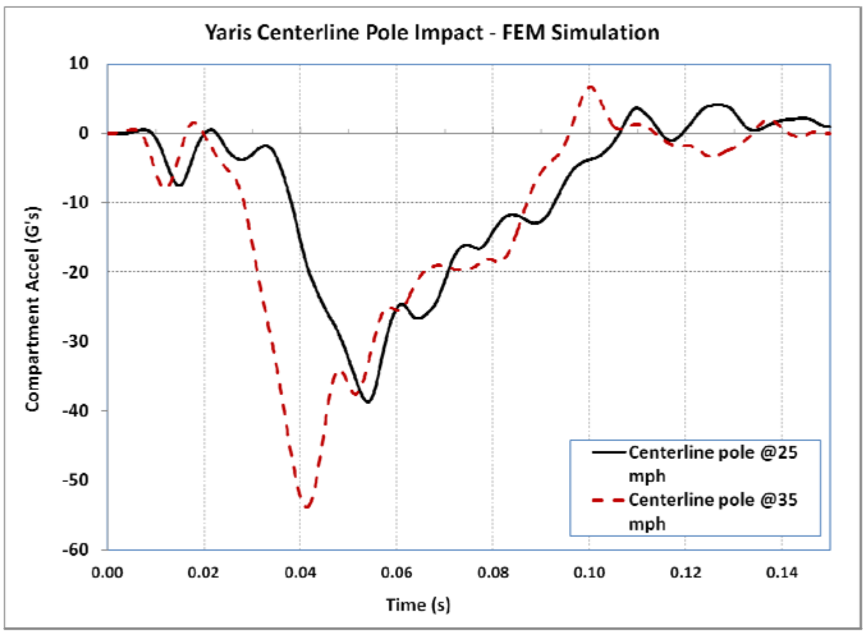


Figure 27 – Yaris compartment accelerations for centerline pole verification tests

SUMMARY AND CONCLUSIONS

A finite element model of the 2010 Toyota Yaris passenger sedan was created using a reverse engineering process by the NCAC under contract to the FHWA. This vehicle was modeled to support current and future NHTSA and FHWA research efforts. The modeling effort led to a detailed model that:

- Consisted of 1,514,068 elements,
- Represented the functions of the steering and suspension components,
- Included all interior door components, and
- Included partial vehicle interior components.

The model was initially validated by comparison to images and data derived from the NHTSA NCAP tests, which involved frontal impact into a rigid wall at 35 mph. Comparisons of data from the tests and the model included:

- View of side deformations,
- Acceleration and velocity changes for the rear seat cross member,
- Accelerations of the top and bottom of the engine,
- Total forces over time, and
- Force displacement plots.

Vehicle kinematics and the accelerometer output data were compared and the simulation results showed overall good correlation with the physical test results.

Extended validation efforts continued with comparisons to data from other full frontal wall and offset deformable barrier impacts. The simulation results compared well to data from these tests, further demonstrating the validity of the Yaris model. Finally, model robustness was demonstrated by additional simulations of centerline pole impacts, full frontal and offset impacts into a Chevrolet Silverado, and damage comparisons for impacts at varying speeds. The simulations executed without error in these runs and the results reflected the expected responses and consistency with varying parameters. The robustness study confirmed that the model was stable under several different crash configurations and speeds, including those where severe vehicle deformation occurs.

This model development process has proven the FE model of the Toyota Yaris to be robust and applicable for the study of a variety of crash scenarios.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the Federal Highway Administration (FHWA) and National Highway Traffic Safety Administration (NHTSA) of the U.S. Department of Transportation for supporting these modeling and simulation efforts.

REFERENCES

[1] AASHTO, Manual for Assessment of Safety Hardware, published by the American Associations of State Highway & Transportation Officials, Washington, DC, 2009.
[2] NCAC, “Development and Validation of a Finite Element Model for a 2010 Toyota Yaris Sedan” NCAC 2011-T-001, prepared for FHWA, Dec 2011.
[3] MGA Research Corporation, “Final Report of New Car Assessment Program Testing of a 2007 Toyota Yaris,” NHTSA Test No. 5677, June 2006.
[4] MGA Research Corporation, “Final Report of a New Car Assessment Program Testing of a 2008 Toyota Yaris 3-Door Liftback,” NHTSA Test No. 6221, November 2007.
[5] Ray, M.L., et al; “Guidelines for Verification and Validation of Crash Simulations Used in Roadside Safety Applications,” Report from NCHRP Project 22-24, TRB, Washington, DC, 2010.
[6] MGA Research Corporation, “Final Report of FMVSS 208 Compliance Testing of a 2007 Toyota Yaris,” NHTSA Test No. 6069, August 2007.
[7] Insurance Institute for Highway Safety, “Crash Test Report: 2007 Toyota Yaris,” IIHS Test CEF0610, December 2006.

FOR MORE INFORMATION

See the NCAC website (www.ncac.gwu.edu) for more information, or contact:

- FHWA Office of Safety R&D
  - Dr. Kenneth Opiela, PE
    202-493-3371
    kenneth.opiela@dot.gov
- NCAC Staff
  - Dr. Steve Kan (Director, NCAC)
    703-726-8511
    cdkan@ncac.gwu.edu
  - Dr. Dhafer Marzougui (Director, Highway Safety and Infrastructure Research, NCAC)
    703-726-8532
    dmarzoug@ncac.gwu.edu
  - Randa Radwan Samaha (Director, Advanced Research, NCAC)
    703-726-8271
    rrsamaha@ncac.gwu.edu

This Working Paper was produced under FHWA Contract DTFH61-09-D-00001 "Advanced Crash Analyses to Improve Safety & Security" with the National Crash Analysis Center of The George Washington University, Ashburn, Virginia.