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Extended Validation of the Finite Element Model for the 2002 Ford Explorer Sport Utility Vehicle

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ABSTRACT

A finite element (FE) model based on a 2002 Ford Explorer sport utility vehicle was developed through the process of reverse engineering at the National Crash Analysis Center (NCAC) of The George Washington University (GWU). 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 another full frontal wall, side impact, 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 and checks of damage consistency for wall, offset deformable barrier, and centerline pole impacts at varying speeds. The simulations executed without error in these runs and the results reflected the expected responses and consistency with varying parameters. This led to the conclusion that the model was robust across various impact scenarios.

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INTRODUCTION

A finite element (FE) model of a 2002 Ford Explorer was developed by the National Crash Analysis Center (NCAC) at The George Washington University (GWU) under contract with the Federal Highway Administration (FHWA). This model was developed through reverse engineering and was intended for use in a variety of impact scenarios to support FHWA and National Highway Traffic Safety Administration (NHTSA) research.

MODEL BUILDING

A 2002 Ford Explorer (VIN: 1FMDU72KX3UA60597) was disassembled and each part was scanned to define its geometry, measured for thickness, and classified by material type. Material data was obtained through coupon testing, when possible. Standard material types were assigned for any parts for which no test data were available. The exterior and interior of the final vehicle model are shown in Figure 1 and a summary of the FE model components is provided in Table 1. The vehicle interior includes the instrument panel, full front row seats, and rear seat structure. The steering wheel, door trim, and rear seat cushions are not included in the model.

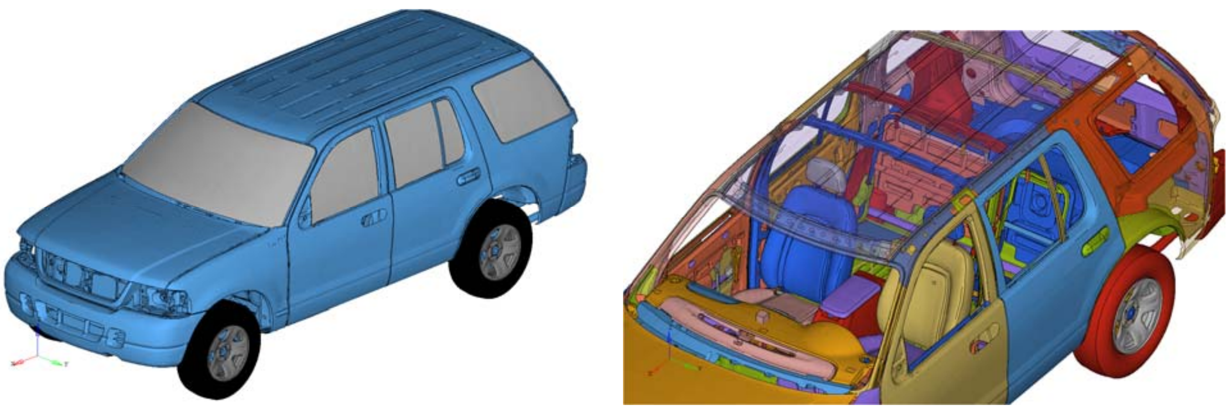


Figure 1 – Ford Explorer FE model exterior and interior views

Table 1 – Ford Explorer FE model summary

Number of Parts	923	Beam Element Connections	
Number of Nodes	724,628	Nodal Rigid Body Connections	2,102
Number of Shells	680,288	Extra Node Set Connections	132
Number of Beams	185	Rigid Body Connections	7
Number of Solids	33,690	Spotweld Connections	6,842
Total Number of Elements	714,205	Joint Connections	54

Accelerometers were included in the model to compare simulation results with test data. Figure 2 shows the locations of some of the most commonly used accelerometers for model validation.

Figure 2 – Accelerometer locations in FE model

Details about the modeling and the outcome of the initial validation efforts are documented in "Development and Validation of a Finite Element Model for the 2002 Ford Explorer" NCAC 2008-T-004 [1]. This document describes the additional validation efforts that were undertaken to enhance the Explorer FE model and assess its robustness for various types of impacts. These efforts were conducted by the 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 to assure that it was a complete and accurate representation of the actual vehicle. The focus of the initial validation was the comparison of the simulation of the NCAP frontal test with actual data from NHTSA Tests 3730 and 5034 for a comparable vehicle [2,3]. A comparison of the vehicles used for the simulation and two NCAP tests is shown in Table 2. In addition to these comparisons, it is notable that the Explorer for Test 5034 was a used vehicle and had accumulated 70,974 miles.

Table 2 – Comparison of vehicle characteristics for FE model and two NCAP test vehicles

	FE Simulation	NCAP Test 3730	NCAP Test 5034
Unloaded Vehicle Weight (UVW)	2024.6 kg	2040 kg	2010.5 kg
Dummy Weight (2 per test)	151 kg (2x75.5 kg)	152 kg (2x76 kg)	129 kg (76+53 kg)
Cargo Weight	71 kg	131 kg	123.8 kg
As Tested Weight (ATW)	2246.6 kg	2323 kg	2263.3 kg
Model Year	2003	2002	2002
Drive Train	4WD	4WD	4WD
Engine Type	4.0 L V6	4.0 L V6	4.0 L V8
Testing Agency	NCAC	KARCO (CA)	TRC (OH)

The post-crash images show the extent of the deformation (Figure 3). The simulation and two tests exhibited similar vehicle kinematics. These similarities can also be observed in the vehicle acceleration, measured at the left and right rear seat cross-members (Figure 4). The Roadside Safety Verification and Validation Program (RSVVP) was used to generate objective measures of how well the simulation follows the test data [4]. 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 3730 are summarized in Table 3. 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.

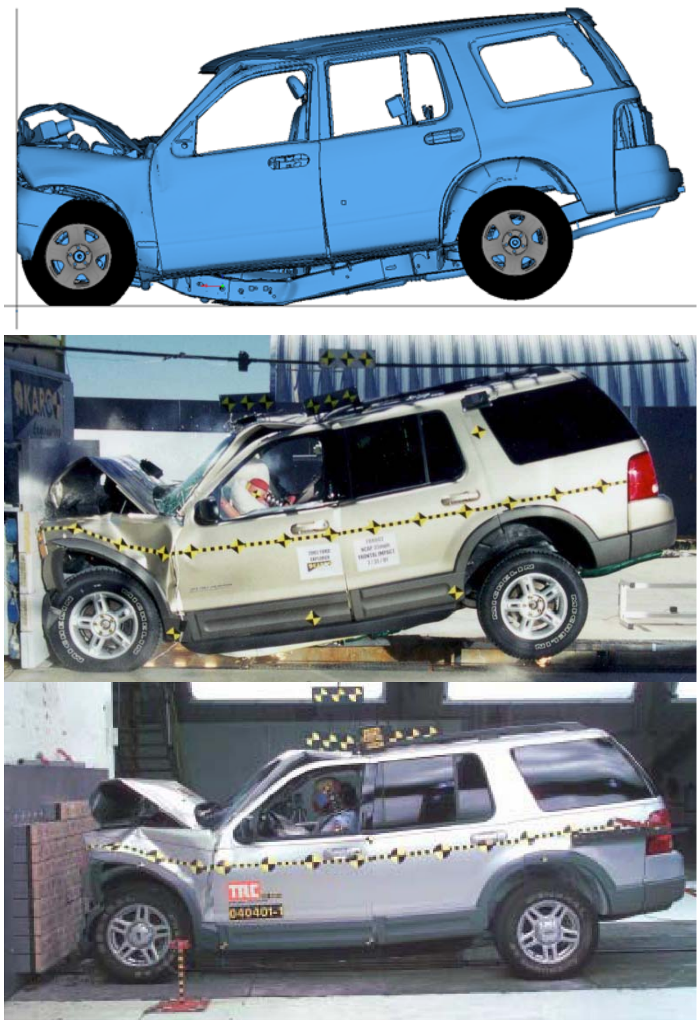


Figure 3 – Comparison of global deformation for Explorer in NCAP frontal simulation (top), Test 3730 (middle), and Test 5034 (bottom)

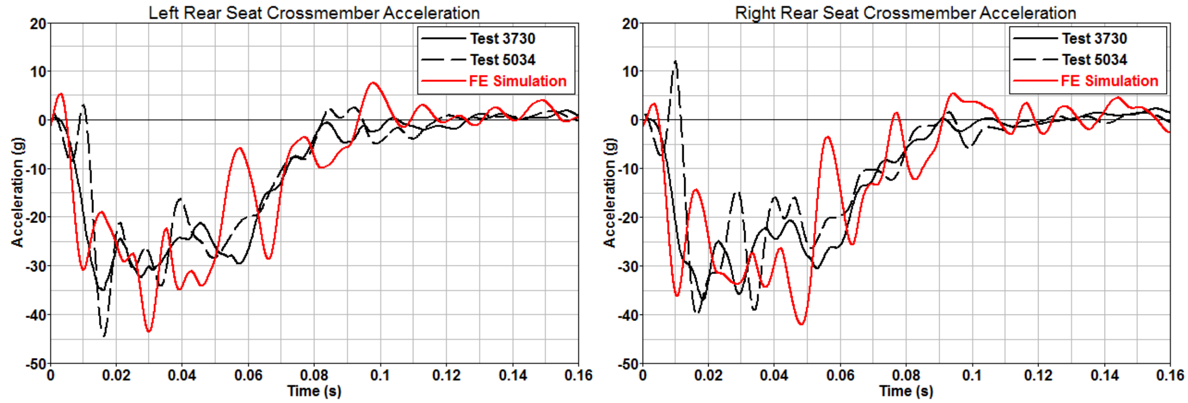


Figure 4 – Comparison of left and right rear seat crossmember accelerations for tests and simulation

Table 3 – 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	4.7	Y	4.4	Y
	Phase	13.9	Y	13.4	Y
	Comprehensive	14.6	Y	14.1	Y
ANOVA Metric	Average	1	Y	0.4	Y
	Standard Deviation	18.6	Y	17.2	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 5 and quantified in Table 4.

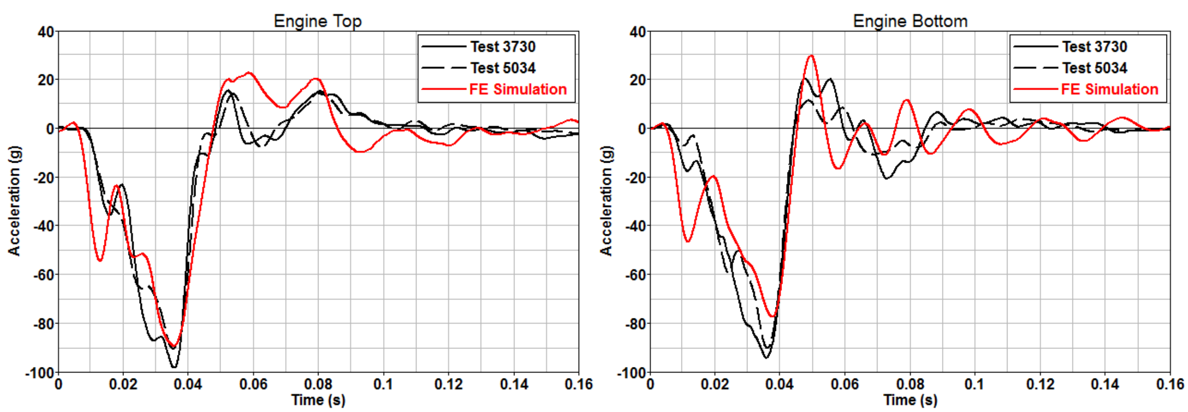


Figure 5 – Comparison of engine top and bottom accelerations for tests and simulation

Table 4 – Objective rating criteria for engine top and bottom accelerations

		Engine Top Acceleration		**Engine Bottom Acceleration**	
		Value (%)	Pass?	Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	1.1	Y	-14.3	Y
	Phase	13.7	Y	14.4	Y
	Comprehensive	13.7	Y	20.3	Y
ANOVA Metric	Average	0.5	Y	0.5	Y
	Standard Deviation	11.2	Y	11.8	Y

The simulation and test forces were compared, again showing that the simulation results were very similar to the test results (Figure 6 and Table 5). The peak timing and values for the total force were closely matched, and force-displacement curves showed that the simulated and test vehicles were of similar stiffness.

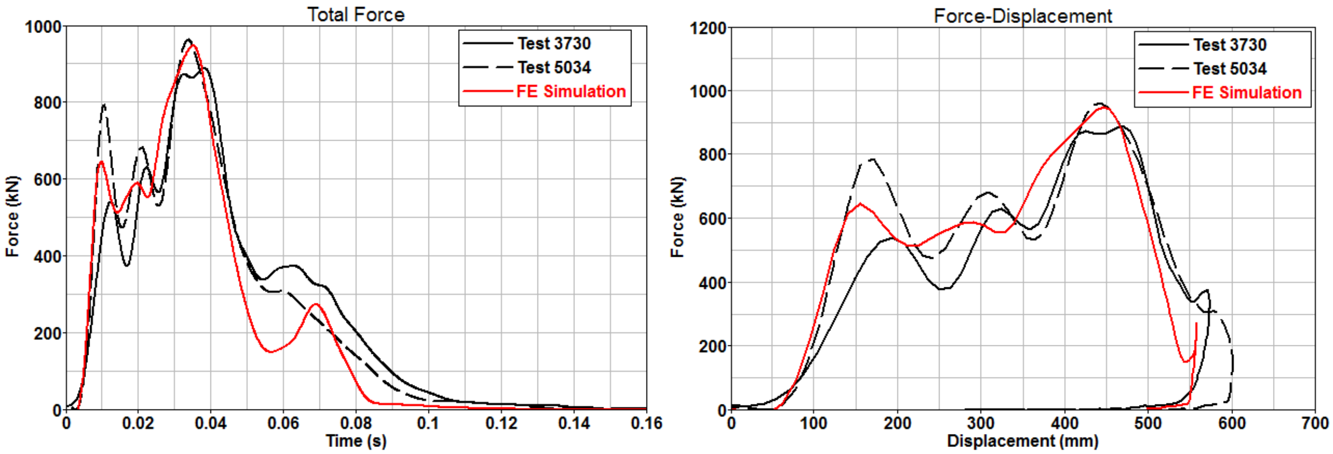
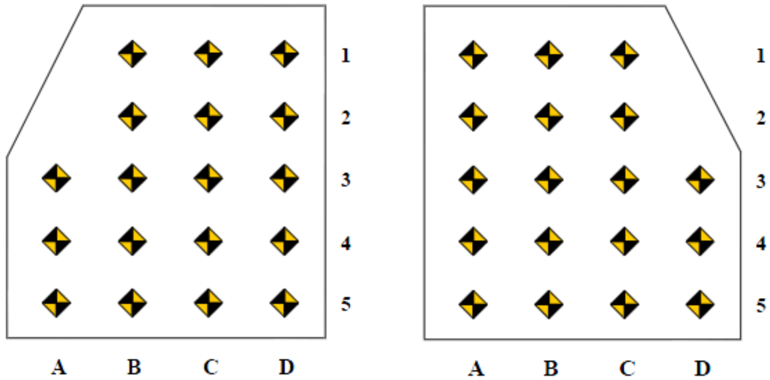


Figure 6 – Comparison of total wall force (left) and force-displacement (right) for tests and simulation

Table 5 – Objective rating criteria for total wall force

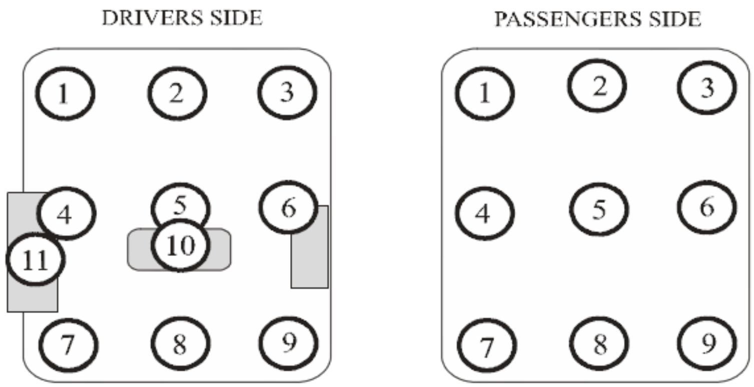
		Total Wall Force	
		Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	-1.8	Y
	Phase	8.2	Y
	Comprehensive	8.4	Y
ANOVA Metric	Average	-2.9	Y
	Standard Deviation	8.9	Y

Lastly, intrusion data was compared. Matching the vehicle pulse was the most important factor in the validation, so the intrusion comparison was performed primarily for informational purposes and did not result in any changes to the FE model in order to better match the test data. Comparisons of the intrusion measurements for each test to the simulation, as well as diagrams showing the intrusion measurement locations, are provided in Figure 7 and Figure 8. The reference line for the FE simulation intrusion measurements was selected to be forward of the rear bumper at the cargo area floor pan. The additional intrusion observed on the passenger side of the FE vehicle compared to the driver side was caused by the difference in the buckling modes between the two sides of the vehicle. This vehicle was not previously validated to the compartment intrusions and no further changes were made to this model following the intrusion data analysis.



	Driver			Passenger	
	Test # 3730	FE Simulation		Test # 3730	FE Simulation
Measurement Location	X-Axis Values	X-Axis Values	Measurement Location	X-Axis Values	X-Axis Values
	mm	mm		mm	mm
A3	-13	-22.5	A1	-3	-80.9
B1	-59	-44.4	B1	3	-84.2
C1	-66	-58.4	C1	6	-72.7
D1	-86	-57.4	D3	-1	-19.4

Figure 7 – Intrusion comparison between Test 3730 and simulation for driver side and passenger side



	Driver			Passenger	
	Test # 5034	FE Simulation		Test # 5034	FE Simulation
Measurement Location	X-Axis Values	X-Axis Values	Measurement Location	X-Axis Values	X-Axis Values
	mm	mm		mm	mm
1	-27	-44.4	1	-57	-80.9
2	-54	-58.4	2	-48	-84.2
3	-54	-57.4	3	-27	-72.7
4	-11	-23.8	4	-35	-21.6
5	-11	-25.3	5	-12	-20.1
6	-45	-27.8	6	-5	-20

Figure 8 – Intrusion comparison between Test 5034 and simulation for driver side and passenger side

All of the above comparisons led to the conclusion that the FE model of the Ford Explorer is a valid representation of the physical vehicle. More information on the NCAP validation can be found in NCAP Report 2008-T-004 [1].

ADDITIONAL MODEL VALIDATIONS

The Explorer FE model was further validated by comparisons to additional tests where crash data was available. These comparisons included a Canadian rigid wall impact, a side impact test, and an offset deformable barrier test. 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. The primary validation was done with the NCAP frontal test and no further changes were made to the model as a result of these additional comparisons.

CMVSS 212/301

The Ford Explorer model was simulated in a full frontal impact with a rigid wall at 30 mph and the results were compared to Canada Motor Vehicle Safety Standard (CMVSS) 212/301 Test 4690 [5]. A comparison of the vehicles used in the FE simulation and physical tests is presented in Table 6.

Similar deformation was observed in the test and simulation (Figure 9). The accelerations for the left and right rear seat crossmembers were found to be within an acceptable deviation from the test responses (Figure 10 and Table 7).

Table 6 – Comparison of vehicle characteristics for FE model and CMVSS Test 4690

	FE Simulation	**CMVSS 212/301 Test 4690**
Unloaded Vehicle Weight (UVW)	2024.6 kg	2044.3 kg
Dummy Weight	151 kg (2 x 75.5 kg)	(2 x HIII 5%, 2 x HIII 6y.o., 1 x HIII 3 y.o.)
Cargo Weight	71 kg	-
As Tested Weight (ATW)	2246.6 kg	2389.1 kg
Model Year	2003	2003
Drive Train	4WD	4WD
Engine Type	4.0 L V6	4.0 L V6
Testing Agency	NCAC	PMG (Canada)

Figure 9 – Post-crash images of Explorer after CMVSS 212/301 impact in test and simulation

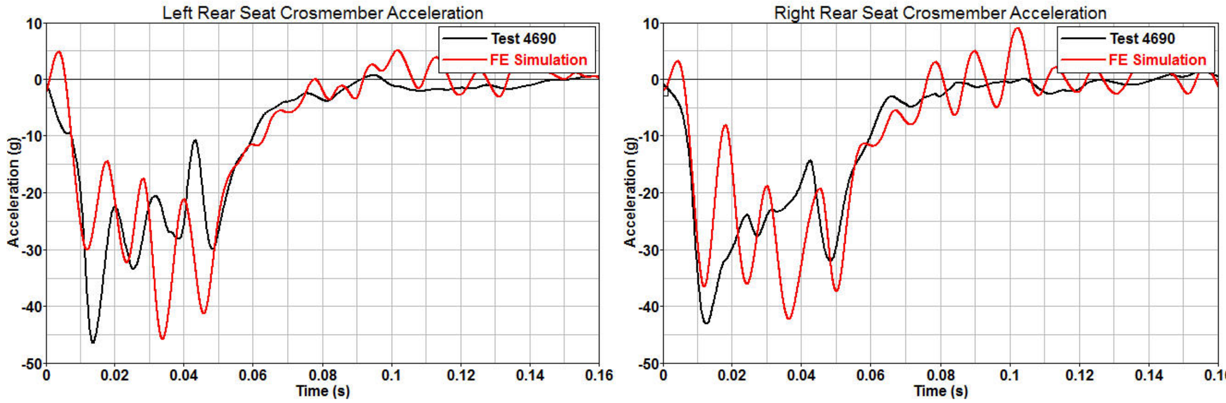


Figure 10 – Left and right rear seat crossmember accelerations for CMVSS 212/301 test and simulation

Table 7 – 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	5.6	Y	5.6	Y
	Phase	14.8	Y	14.2	Y
	Comprehensive	15.8	Y	15.2	Y
ANOVA Metric	Average	1.5	Y	1.2	Y
	Standard Deviation	13.7	Y	14.4	Y

The engine top and bottom accelerations were also compared between the test and simulation. Figure 11 shows acceptable correlation between the test and simulation data. This acceptability of the simulation data compared to the test data is quantified in Table 8.

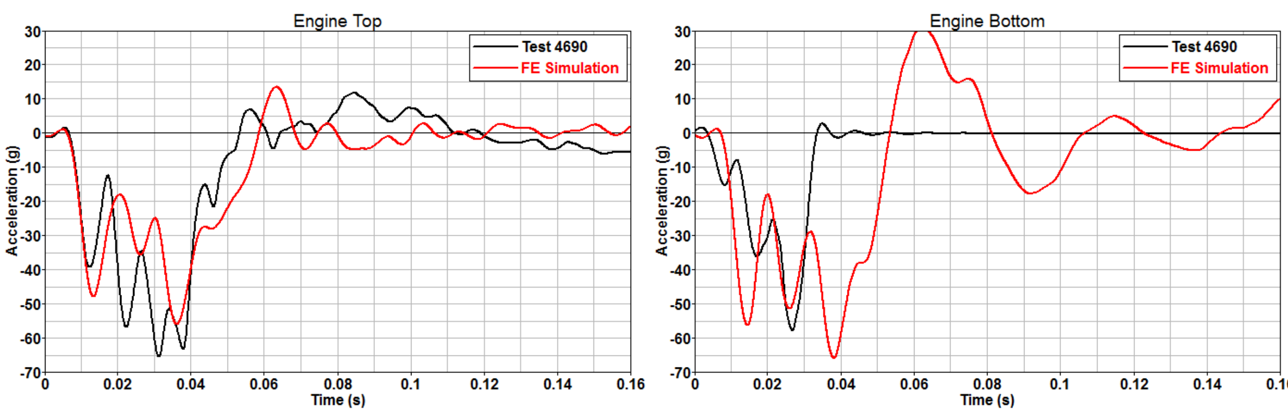


Figure 11 – Engine top and bottom accelerations for CMVSS 212/301 test and simulation

Table 8 – Objective rating criteria for engine top and bottom accelerations

		Engine Top Acceleration		Engine Bottom Acceleration	
		Value (%)	Pass?	Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	-13.2	Y	83.5	N
	Phase	17.8	Y	30.6	Y
	Comprehensive	22.1	Y	89	N
ANOVA Metric	Average	0.9	Y	-6.2	N
	Standard Deviation	15.3	Y	31.5	Y

NCAP Side Impact

The Explorer model was run under NCAP side impact conditions and the results were compared to NCAP Test 4087 [6]. A comparison of the vehicle characteristics for the test and simulation is presented in Table 9. The struck side acceleration measured at the left B-pillar is shown in Figure 12. Table 10 shows that the simulation passed the objective rating criteria for the left B-pillar acceleration data.

Table 9 – Comparison of vehicle characteristics for FE model and side NCAP test no. 4087

	FE Simulation	**SNCAP Test 4087**
Unloaded Vehicle Weight (UVW)	2024.6 kg	2009.5 kg
Dummy Weight	151 kg (2 x 75.5 kg)	161.5 kg (2 x 80.75 kg)
Cargo Weight	71 kg	126.9 kg
As Tested Weight (ATW)	2246.6 kg	2297.9 kg
Model Year	2003	2002
Drive Train	4WD	4WD
Engine Type	4.0 L V6	4.0 L V6
Testing Agency	NCAC	MGA (WI)

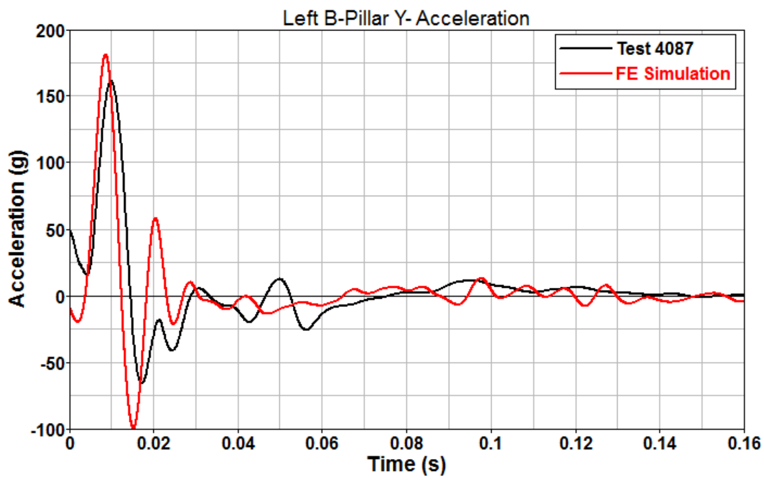


Figure 12 – Left B-pillar Y acceleration for side NCAP test and simulation

Table 10 – Objective rating criteria for left B-pillar Y acceleration

		Left B-pillar Acceleration	
		Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	3.1	Y
	Phase	25.2	Y
	Comprehensive	25.4	Y
ANOVA Metric	Average	-0.6	Y
	Standard Deviation	13.7	Y

The post-test deformation is shown in Figure 13. The discrepancy in the deformation profiles can be better observed through the intrusion profiles shown in Figure 14. This difference was due to the way the door latch was modeled in the simulation. In the physical test, the front door on the struck side of the vehicle did not separate from the body at the hinges, but the door opened at the latch during the crash event. The rear door on the struck side did not separate from the body at either the hinges or latches. The doors on the far side did not open either during the event. The FE model, however, does not incorporate failure for the latches and did not capture the observed front door behavior.

Figure 13 – Comparison of post-crash deformation between the side NCAP test and simulation

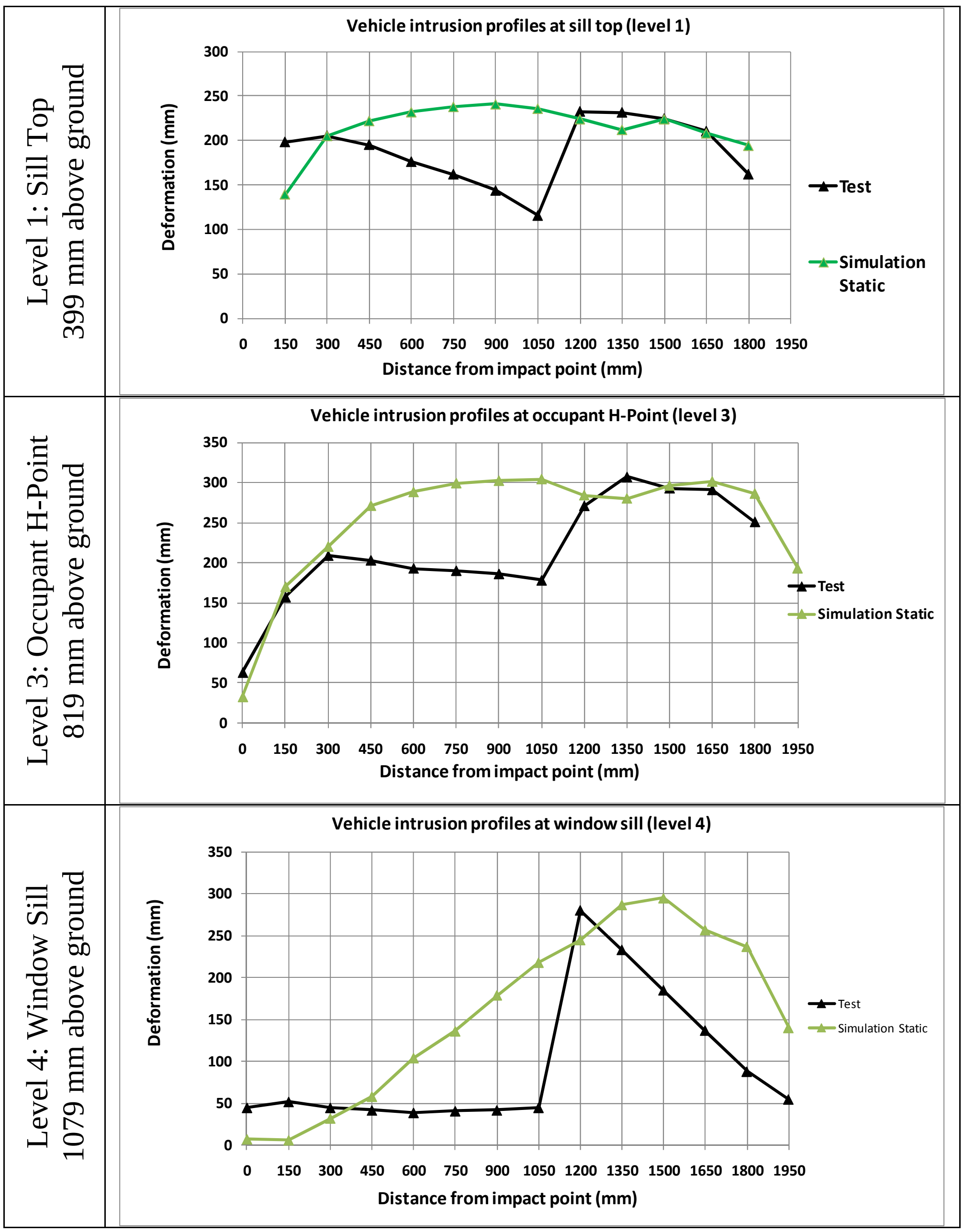


Figure 14 – Intrusion on levels 1, 3, and 4 after NCAP side impact

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, and compared to data from IIHS Test CEF0125 [7]. A comparison of the test and simulation vehicle characteristics and deformation is shown in Table 11 and Figure 15. The acceleration and velocity plots for the simulation closely matched those of the test (Figure 16 and Table 12).

Table 11 – Comparison of vehicle characteristics for FE model and IIHS Test CEF0125

	FE Simulation	**IIHS Test CEF 0125**
Unloaded Vehicle Weight (UVW)	2024.6 kg	2046 kg
Dummy Weight	151 kg (2 x 75.5 kg)	~ 76 kg
Cargo Weight	71 kg	~ 26 kg
As Tested Weight (ATW)	2246.6 kg	2148 kg
Model Year	2003	2002
Drive Train	4WD	4WD
Engine Type	4.0 L V6	4.0 L V6
Testing Agency	NCAC	IIHS (VA)

Figure 15 – Comparison of post-impact deformation for IIHS ODB test

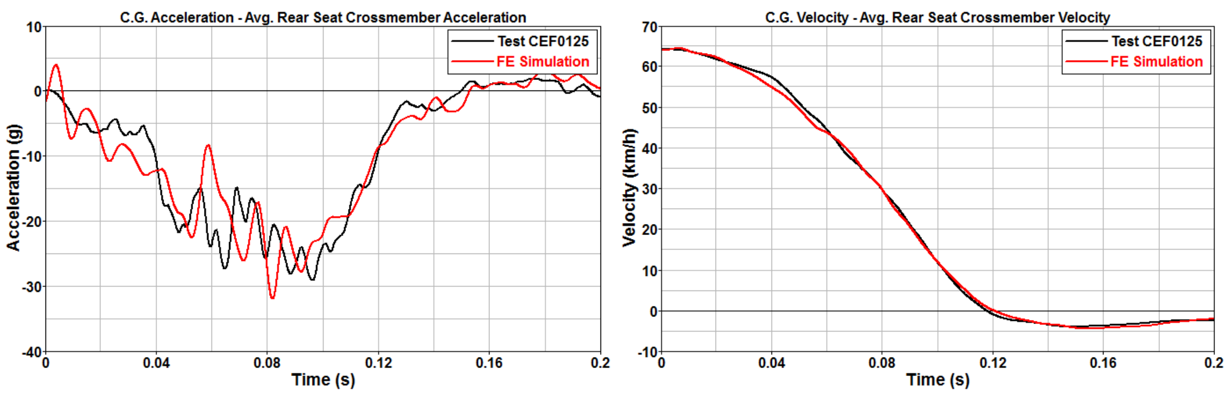


Figure 16 – Vehicle acceleration (left) and velocity (right) profiles of the test and simulation for the IIHS ODB test

Table 12 – Objective rating criteria for vehicle CG acceleration

		Vehicle CG Acceleration	
		Value (%)	Pass?
Sprague-Geers MPC Metric	Magnitude	-2.1	Y
	Phase	9	Y
	Comprehensive	9.2	Y
ANOVA Metric	Average	0.2	Y
	Standard Deviation	13.1	Y

MODEL ROBUSTNESS

The FE model was checked for robustness by running the model through a severe crash simulation with large deformation. The centerline pole simulation at 35 mph was selected for the robustness check. When the model was run under these crash conditions, a negative volume error occurred and the simulation was unable to complete. To correct this error, the model was updated, including changing the radiator fan axle material property from elastic to elasto-plastic and adding a contact interior for the bumper foam. The updated model was run again in the centerline pole impact condition and the results are shown in Figure 17 and Figure 18.

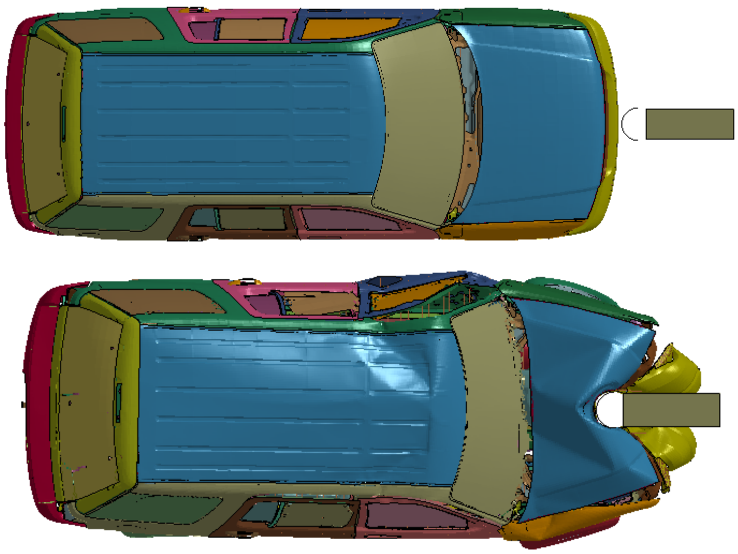


Figure 17 – Pre- and post-crash images of the Explorer for the centerline pole robustness simulation

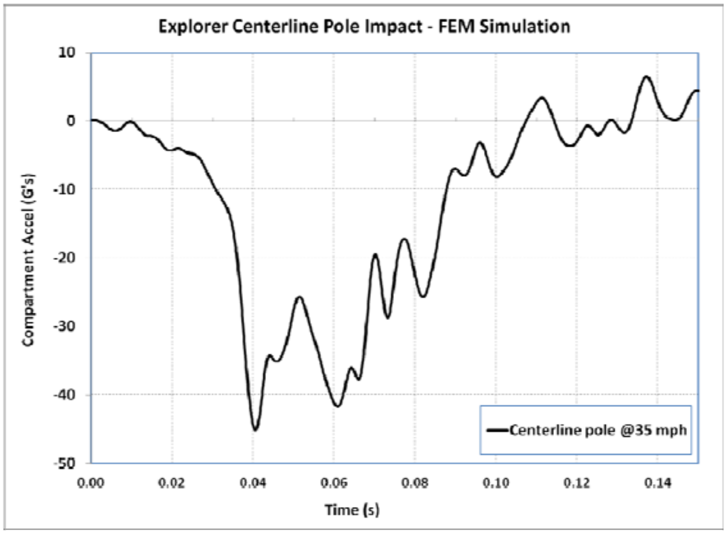


Figure 18 – Explorer compartment acceleration for the centerline pole robustness simulation

VARYING SPEED TREND ANALYSIS

Several more simulations were run with the Ford Explorer FE model to verify that the model was providing consistent trends for different crash scenarios. The NCAP rigid wall, IIHS offset deformable barrier, and centerline pole simulations were run and 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 19 and Figure 20. These runs verified that the higher speed impact yielded a slightly more severe crash pulse than the lower speed impact.

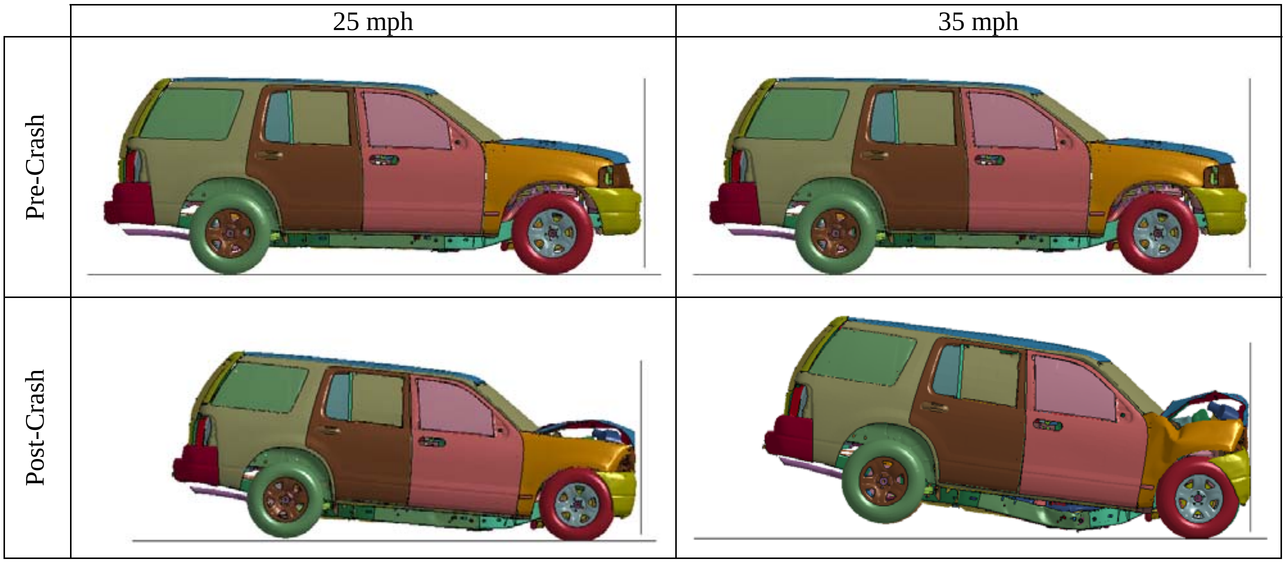


Figure 19 – Pre- and post-crash images of the Explorer for the full frontal impact at 25 mph and 35 mph

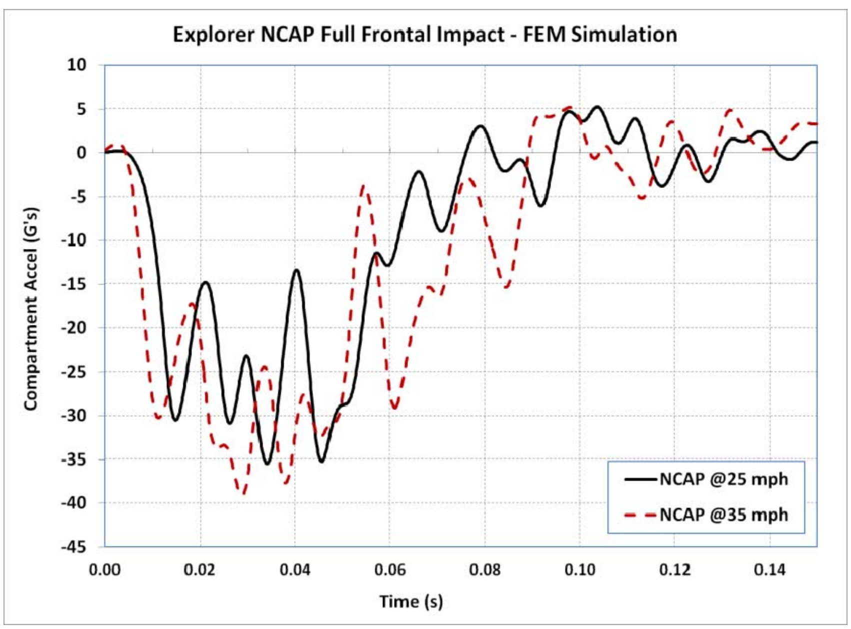


Figure 20 – Explorer compartment accelerations for NCAP frontal verification simulations

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 21 and Figure 22. These runs verified that the higher speed impact yielded higher compartment accelerations than the lower speed impact.

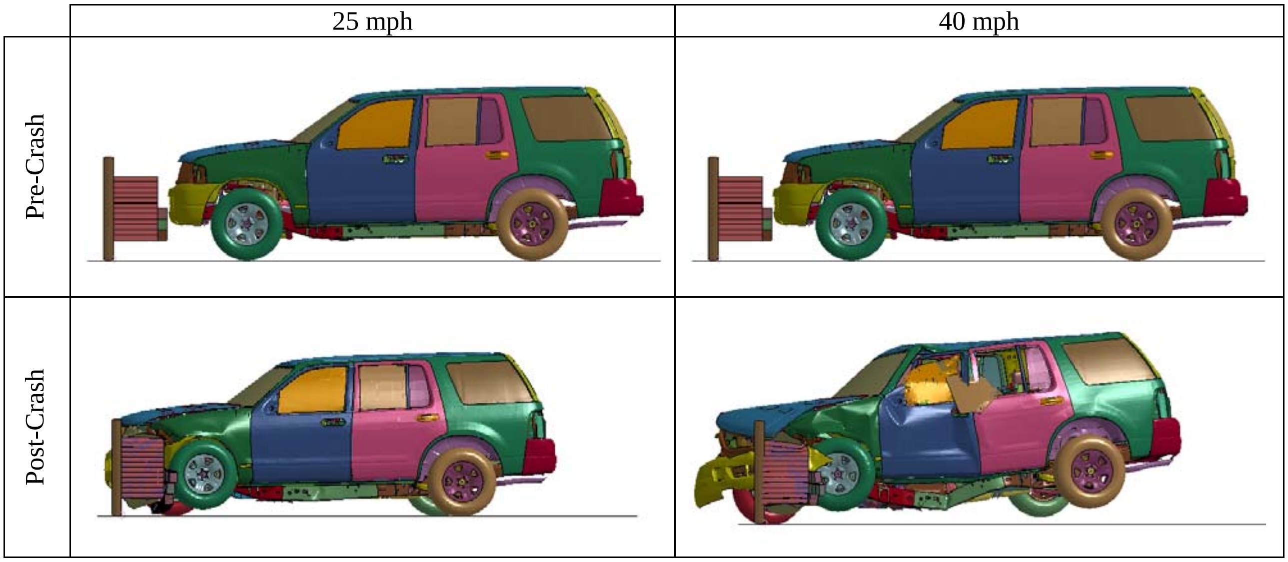


Figure 21 – Pre- and post-crash images of the Explorer for the IIHS ODB impact at 25 mph and 40 mph

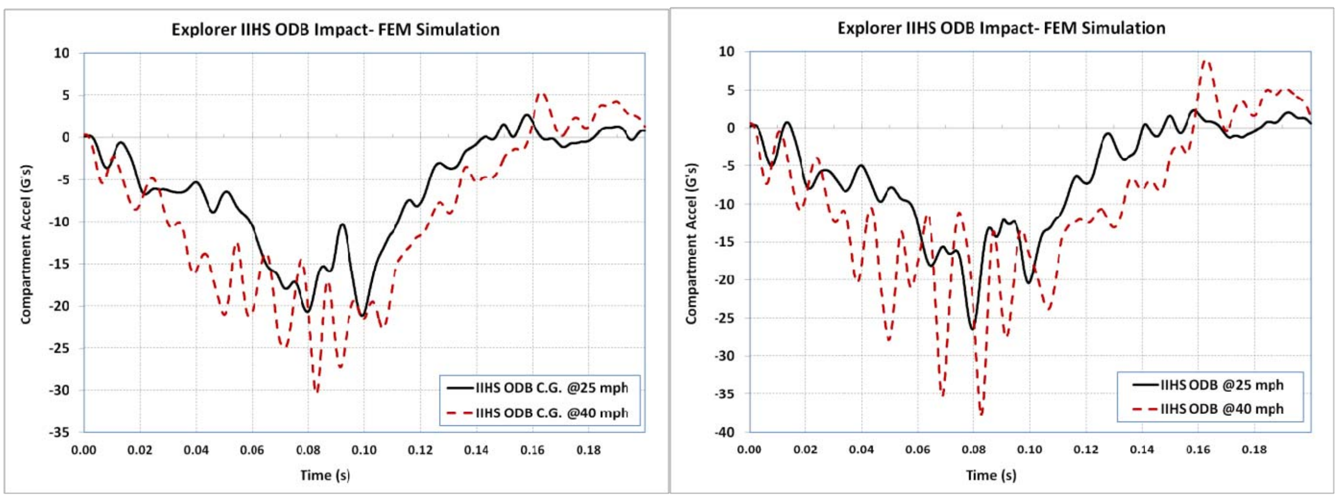


Figure 22 – Explorer CG (left) and left rear (right) accelerometer outputs for IIHS ODB verification simulations

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 23 and Figure 24. These runs verified that the higher speed impact yielded a more severe crash pulse than the lower speed impact.

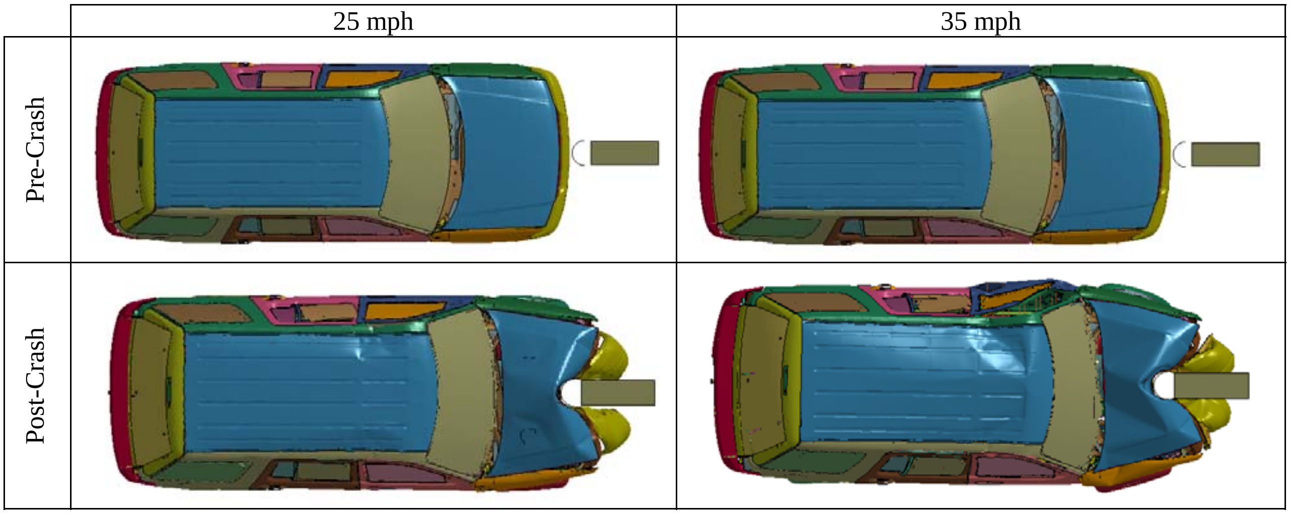


Figure 23 – Pre- and post-crash images of the Explorer for the centerline pole impact at 25 mph and 35 mph

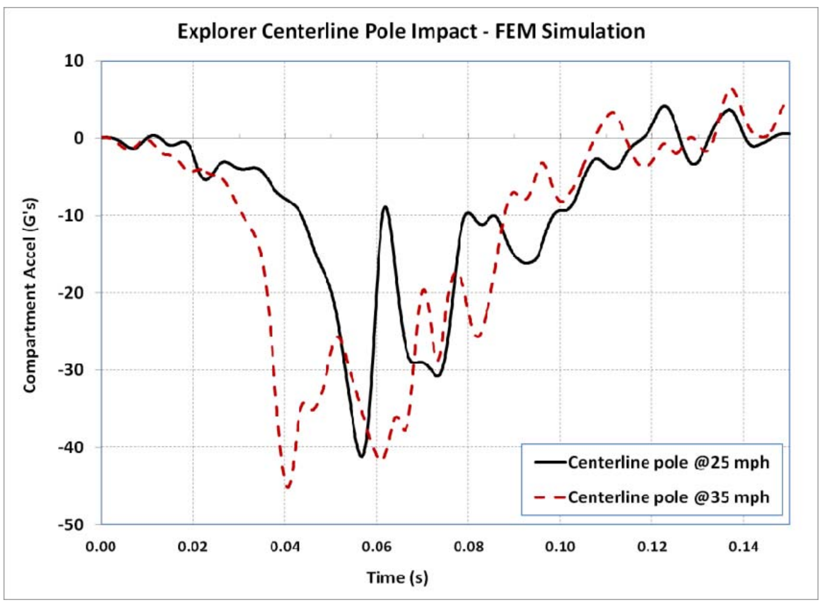


Figure 24 – Explorer compartment accelerations for centerline pole verification tests

SUMMARY AND CONCLUSIONS

A finite element model of the 2002 Ford Explorer sport utility vehicle was created using a reverse engineering process by the NCAC under contract to the FHWA. This vehicle was modeled to support NHTSA and FHWA research efforts.

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 crossmember,
- Accelerations of the top and bottom of the engine,
- Total forces over time,
- Force displacement plots, and
- Driver and passenger side intrusion.

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

This model was further verified against CMVSS 212/301 frontal impact, NCAP side impact, and IIHS offset deformable barrier frontal test configurations. The simulation results compared well to data from these tests, further demonstrating the validity of the Explorer model.

A robustness study was conducted to confirm that the model would be stable under crash conditions with severe deformation as in centerline pole impacts. This study revealed that the model was unstable, so several changes were made to the model to improve its robustness.

A consistency study confirmed that the model would yield reasonable results between high and low speed tests for rigid wall, offset deformable barriers, and centerline pole crash configurations. As expected, the high speed impacts resulted in greater vehicle deformation and higher compartment accelerations.

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

ACKNOWLEDGEMENTS

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REFERENCES

[1] NCAC, "Development and Validation of a Finite Element Model for a 2002 Ford Explorer" NCAC 2008-T-004, prepared for FHWA, Dec 2008.
[2] KARCO Engineering, "Final Report of New Car Assessment Program Testing of a 2002 Ford Explorer XLT 4WD SUV," NHTSA Test No. 3730, August 2001.
[3] Transportation Research Center Inc., "2002 Ford Explorer MPV into a Frontal Load Cell Barrier," NHTSA Test No. 5034, April 2004.
[4] 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.
[5] PMG Technologies, "Compliance Frontal Impact CMVSS 212/301: Ford Explorer 2003," NHTSA Test No. 4690, February 2003.
[6] MGA Research Corporation, "Final Report of FMVSS 214D Indicant Compliance Side Impact Test of a 2002/Ford/Explorer/SUV," NHTSA Test No. 4087, February 2002.
[7] Insurance Institute for Highway Safety, "Crash Test Report: 2002 Ford Explorer," IIHS Test CEF0125, November 2001.

FOR MORE INFORMATION

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