On Rollover Simulations of a Full-sized Sedan

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Abstract

Rollover crashes are responsible for many occupant injuries and fatalities. Rollover crash fatalities account for 36 percent of total fatalities for passenger cars and light trucks. Front seat occupants are vulnerable to head, neck and thoracic injuries resulting from impact with the collapsing roof structure. Modeling and simulation on parallel computing platforms using state-of-the-art software – such as LS-DYNA® – is an attractive and economical approach for studying the structural responses of the vehicle and occupant to rollover events.

This paper presents simulations of rollover events of a full-sized sedan subjected to several initial vehicle orientations and front occupant positions. The National Crash Analysis Center database provided the finite element model for the full-size sedan. The front-seat occupant model is the Hybrid III finite element model developed by Livermore Software Technology Corporation, which represents the 50% male anthropomorphic test device (ATD). Thus, this study makes use of a single software platform for analyses of both the vehicle and occupant – leading to efficient computations.

The current work focused on Single Event Single Rollovers (SESR). Several case studies are presented, and one case simulated a previously performed test using the Controlled Rollover Impact System (CRIS). The first case (far side impact) matched the CRIS Test 51502 initial release conditions, and the numerical simulations match the kinetic conditions when the vehicle contacted the ground – as calculated by rigid body dynamics. The second case looked at near side impact, and the third case looked at far side impact but with a 10 degree pitch angle. Results show that the largest neck forces occur for near side impact. Comparison of the first case simulation results with CRIS Test 51502 is examined for suitability of validating the finite element models to rollovers.

Introduction

Rollover crashes are responsible for many occupant injuries and fatalities. Rollover crash fatalities account for 36 percent of total fatalities for passenger cars and light trucks. Front seat occupants are vulnerable to head, neck and thoracic injuries resulting from impact with the collapsing roof structure. Modeling and simulation on parallel computing platforms using state-of-the-art software – such as LS-DYNA – is an attractive and economical approach for studying the structural responses of the vehicle and occupant to rollover events.

The National Highway Transportation Administration (NHTSA) [1] of the US Department of Transportation is interested in validating occupant motion using finite element modeling of a previously performed rollover tests. NHTSA had experiments performed in which a vehicle was rotating about its roll axis and dropped onto the ground. The test was performed using a Controlled Rollover Impact System (CRIS) developed by Exponent® Engineering and Scientific

Consulting (formerly Failure Analysis Associates) [2] and Ford Motor Company [3]. NHTSA is interested in using a single code to model both the vehicle and anthropomorphic test device (ATD), and this paper presents findings using LS-DYNA [4] and their ATD models.

Rollover test were performed on several 1999 Ford Crown Victoria. NHTSA has performed a preliminary analysis of one test. However, because an adequate finite element (FE) model for the Crown Vic was not available, a FE element model for a 2000 Ford Taurus was used as a surrogate vehicle in the numerical simulations. The Taurus FE model was obtained from the National Crash Analysis Center [5]. Both vehicles are considered full-size sedans, but there are differences in their inertia properties, dimensions and shapes. These differences and potential effects on simulation results are addressed in this paper.

A simulation with the Taurus FE model of CRIS test 51502 [6], which used a Crown Victoria, was performed using the given test initial conditions – this is a far side impact. The results show significant differences between experimental and simulation results. Additional simulations were performed for near side impact and far side impact with a pitch a 10 degree pitch.

Controlled Rollover Impact System (CRIS)

Exponent® Engineering and Scientific Consulting (formerly Failure Analysis Associates) and Ford Motor Company developed the CRIS dynamic test to study roof-to-ground behavior during a vehicle rollover. The main advantage of the CRIS test is controllability of roll, pitch and yaw angles, roll rate, translational velocity, and drop height for the first roof-to-ground impact. The system uses a moving support-fixture that supports a rotating full-size car that is dropped onto the pavement at predetermined orientation and velocity. The support fixture attaches to the back end of a flatbed semi-trailer. The system is well suited to study roof strength issues, occupant protection systems and occupant response.

Figure 1 is a schematic of the test rig used to conduct the CRIS dynamic test for an automobile impacting the pavement during a rollover [6]. The automobile is attached to a support structure on a moving semi-trailer.

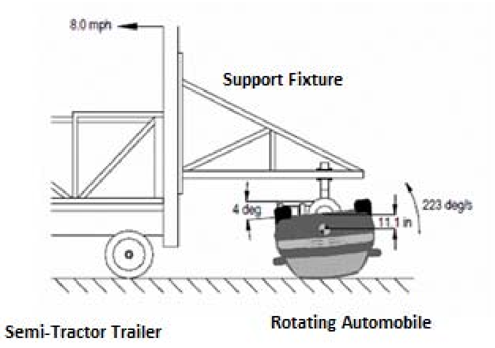

Figure 1: Schematic of the Controlled Rollover Impact System (CRIS).

During the CRIS test, the vehicle response divides into three phases. In the first phase (prerelease phase), the vehicle rotates as a rigid body about the roll-axis (center of mass) under the control of the CRIS rig and translates horizontally at the speed of the semi-tractor trailer. The second phase is the free-fall phase during which the vehicle falls through the air toward the ground as a rigid rotating body and continues moving horizontally. The third phase starts when the vehicle contacts the ground and begins to undergo severe deformation. Note, the first two phases are essentially rigid body motions, and they can be analyzed as such. This implies no finite element analysis is needed for Phase 1 and 2. However, here the finite element simulations begin with the initial conditions and orientation given in Table 1.

Table 1: Initial Conditions and Orientation

Translational Velocity	8 mph
Vertical Velocity	0 mph
Translational Velocity	8 mph
Rotational Speed	223 deg/sec
Release Angle	49.2 deg
Roof-to-Ground Angle at Impact	4 deg

In order to achieve a 4 degree roof-to-ground angle at impact, rigid body calculations show that the release angle is 49.2 degrees. The orientation of the Taurus at the release angle of 49.2 degrees is shown in Figure 2. The far-side impact occurs just above the drivers head.

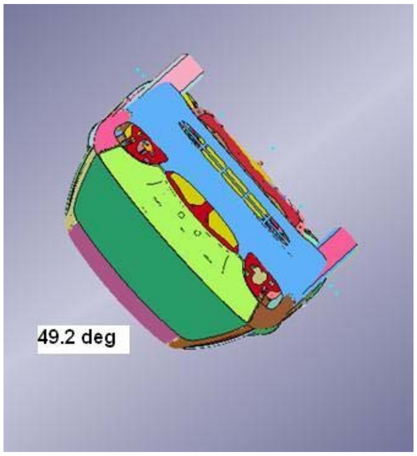

Figure 2: Release orientation of 49.2 degrees with the ground.

Differences between a Crown Victoria and a Taurus

A rollover test (CRIS Test 51502, [6]) was performed on a 1999 Ford Crown Victoria. NHTSA has performed a preliminary analysis of this test. However, because a finite element (FE) model for the Crown Vic was not available, a FE element model for a 2000 Ford Taurus used as a surrogate vehicle in the numerical simulations. The Taurus FE model was obtained from the National Crash Analysis Center. Both vehicles are considered full-size sedans, but there are differences in their inertia properties, dimensions and shapes. This section addresses these differences and potential effects on simulation results.

First, a discussion of inertial properties is presented. The inertia properties of the vehicle play an important role in the vehicle's rollover dynamics, roof crush and dummy response. Several sets of properties for the Ford Crown Victoria and Taurus were obtained from various sources [7-11]. An examination of the properties from these sources shows there are variations among the sources. Table 2 shows the Crown Victoria data from [7], the Taurus data from [11] and the modified Taurus data from [12]. It should be noted that a cradle weighing approximately 1000 lb_f was used to attach the Crown Victoria to the test rig and, thus, this inertia was added to the modified Taurus model [12]. Table 1 also shows variations in the moments of inertia for yaw, pitch and roll.

Table 2: Inertial Properties for Ford 1999 Crown Victoria and Ford 2001 Taurus.

	Curb Weight	Yaw Moment of Inertia	Pitch Moment of Inertia	Roll Moment of Inertia
Crown Victoria^{PP}[7]	4,020 lb_f 1,824 kg	2,935 lb_f-ft-sec^2 3,978.20 kg-m^2	2,831 lb_f-ft-sec^2 3,837.49 kg-m^2	574 lb_f-ft-sec^2 777.58 kg-m^2
Taurus FE Model (NCAC as received)[11]	3,845 lb_f 1,744 kg	2,480 lb_f-ft-sec^2 3,370 kg-m^2	2,245 lb_f-ft-sec2 3,050 kg-m^2	411 lb_f-ft-sec^2 558 kg-m^2
Taurus FE Model (TRACC modified) [12]	4,020 lb_f 1,823 kg	2,929 lb_f-ft-sec^2 3,980 kg-m^2	2,819 lb_f-ft-sec^2 3,830 kg-m^2	567 lb_f-ft-sec^2 771 kg-m^2

Note: PP = Police Package

Second, since the two vehicles are different, a look at the dimensional differences is warranted. The dimensional differences between the Crown Vic and Taurus are given in Table 3, and it is seen that overall the Crown Victoria is the larger of the two, but the Taurus has slightly more headroom.

Table 3: Comparison of dimensions for a Crown Victoria and Taurus.

Dimension	Crown Victoria	Taurus
Length	212 inches	197.6 inches
Wheelbase	115 inches	108.5 inches
Width	78.2 inches	73 inches
Height	56.8 inches	56.1 inches
Front Head Room	39.4 inches	40.0 inches

Third, since the shapes of the cars are obviously different, an examination of the consequences in a rollover event is presented. A look at the front views of the Crown Vic (Figure 3) and the Taurus (Figure 4) shows that the roof profiles are quite different. Recently, I have observed this difference when driving and it is fairly apparent when viewing approaching and passing cars.

Overall, the Crown Vic appears to be a more rectilinear vehicle, and the Taurus appears to be more elliptic-like. Other automobiles seem to fall into these categories; however, from my observations, the Taurus seems to be one of the most elliptic

Figure 3: Front view of 1999 Ford Crown Victoria showing a flat-like roof.

Figure 4: Front view of 2000 Ford Taurus showing an elliptic-like roof.

When simulating impact between objects, the shape of the contacting surfaces is important, and the CRIS test is no different. The CRIS test data showed contact took place when the roof of the Crown Vic made an angle of 4 degrees with the ground. This would be a 184 degree rotation of the car from its resting position on the ground. Figure 5 and Figure 6 are schematics representing the roofs (in an upside-down position) of the Crown Vic and the Taurus, respectively. Figure 7 and Figure 8 schematically show the positions of the Crown Vic and Taurus roofs contacting the ground. The roof of the Crown Vic is represented by a flat line to illustrate the physics. It is easily seen that when the flat-like roof contacts the ground – other than horizontal contact – the point of contact/impact will be the corner. In contrast, when the elliptic-like roof makes contact, it is dependent on the angle that the roof makes with the ground.

Figure 5. Flat-like roof horizontal to ground.

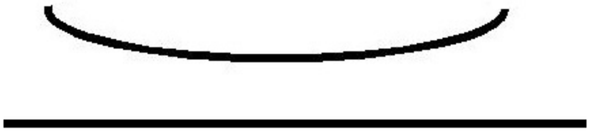

Figure 6: Elliptic-like roof horizontal to ground.

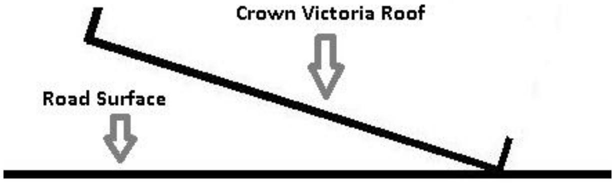

Figure 7: Elliptic-like roof horizontal to ground.

Figure 8: Elliptic-like roof impacting the ground.

Translating the above to the CRIS test results, it is seen that at ground contact the reported roll angle of 4 degrees occurs closer to the driver's side edge of the roof for the Crown Vic. This affects the structural response of the roof and the roof's interaction with the head of the ATD. It seems reasonable that for the Taurus to have the same point of contact/impact relative to the head of the ATD, the contact point would have to be closer to the side edge of the roof.

Finite Element Models

Finite element models for the 2001 Ford Taurus and the Hybrid III 50th male ATD were obtained for this study. At the time this work was being performed, the National Crash Analysis Center was developing Version 4 of the 2001 Ford Taurus model, and they provided an advanced copy [11]. The model contains 921,793 elements and is shown in Figure 9: Finite element model for the 2001 Ford Taurus shown at the release orientation from the CRIS rig. It was pointed out that the model was developed primarily for frontal crash events.

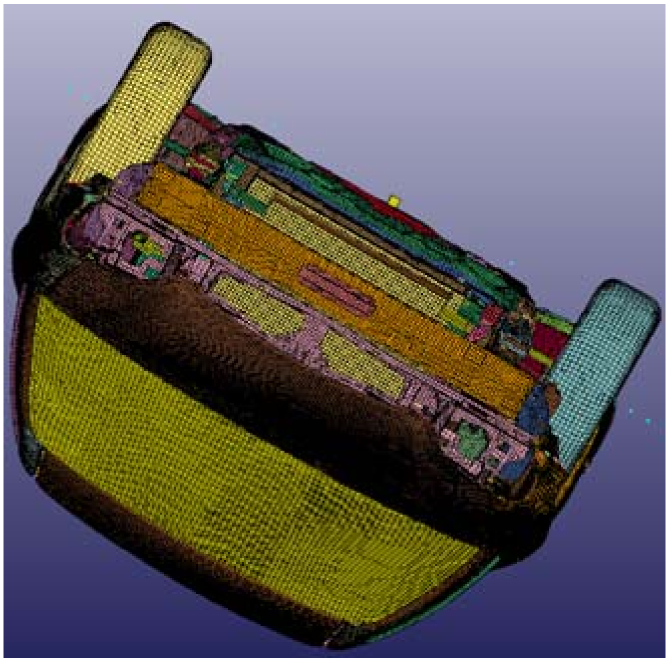

Figure 9: Finite element model for the 2001 Ford Taurus shown at the release orientation from the CRIS rig.

The driver-side front occupant in CRIS Test 51502 was a Hybrid III 50th male ATD. For these exploratory simulations, one of LSTCs version of the Hybrid III was used (LSTC.H3_50TH_ FAST.111130_V2.0). The H III ATD was specifically developed for frontal impact simulations and, thus, the model parameters were calibrated for frontal crash events. Figure 10 and Figure 11 show the side and front views of the ATD, respectively.

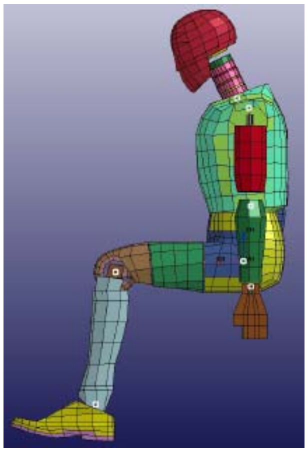

Figure 10: Side view of H3_50TH_ FAST.

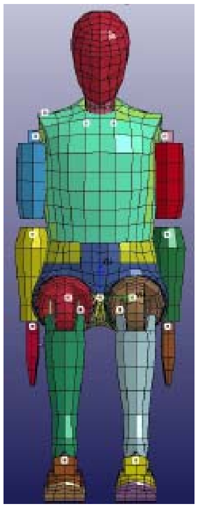

Figure 11: Front view of H3_50TH_ FAST.

Table 4 shows that a total of 4,310 elements are used and the minimum computational time step was 1.0 µs.

Table 4: H3 Model and computational statistics.

Number of Nodes	**7,402**
Number of Solid Elements	2,644
Number of Shell Elements	1,624
Number of Beam Elements	3
Number of Spring Elements	7
Number of Concentrated Masses	32
Total Number of Elements	4,310
Number of Materials	103
Computational Time Step	1.0 µs

Comparison of Simulations with CRIS Test

Two metrics were considered for comparing simulations to test results: upper neck force (F_z) and upper neck moment (M_y). Results from experiments showed that neck moments were extremely sensitive to contact orientations whereas neck forces were less sensitive. Therefore in this work, the neck force was chosen as the comparative metric.

CRIS Test 51502 was a far side impact with a drop height of 11 inches (27.94 cm), translational velocity of 8 mph (13 kph) and a roll angular velocity of 223 deg/s. Figure 12 shows the 49.2 degree release orientation; This is to say, the Taurus is rotated 130.8 degrees from it position when the tires are resting on the ground. Figure 13 shows the simulation result at the approximate time the roof of the Taurus initially makes contact with the ground. Note the head of the ATD is between the door and the initial contact point on the roof.

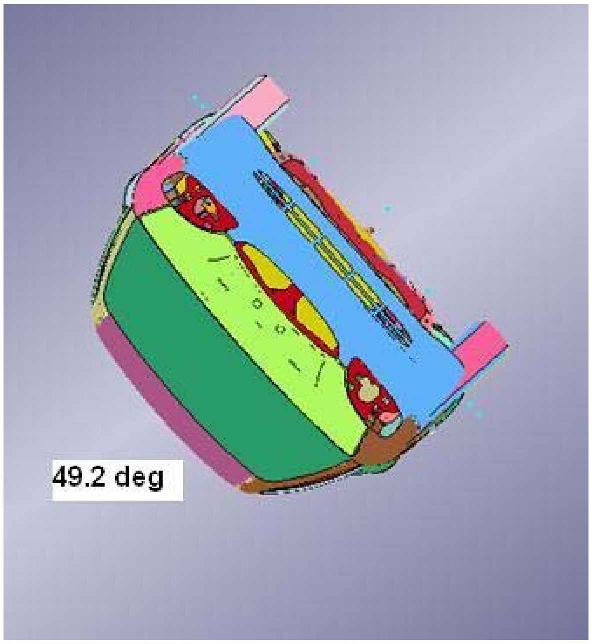

Figure 12: Taurus orientation at beginning of simulation.

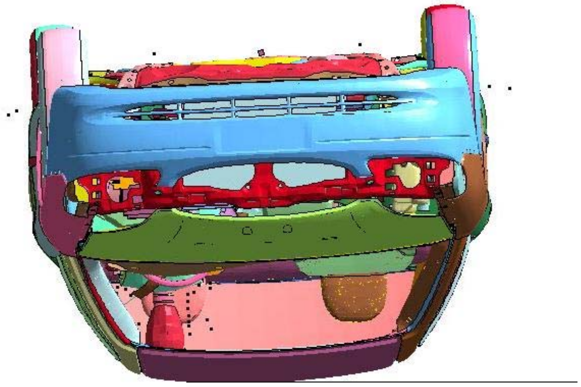

Figure 13: Taurus orientation at initial impact with pavement.

Figure 10 shows the head position at the simulation time of 0.265 sec where it is seen that the head is slightly misaligned with the neck and the roof's light-gauge sheet metal has started to move away from the pavement and into the cabin. The localized impulse delivered to the initial contact area causes the sheet metal to undergo extensive plastic deformation. The impulse appears to be large enough to substantially drive the sheet metal into contact with the head and potentially anchor the head – perhaps temporarily.

Figure 14: Head position at 0.265 sec showing roof sheet metal being driven into the cabin by the initial contact impulse. This neck position is very near the orientation at which the maximum neck force Fz occurs

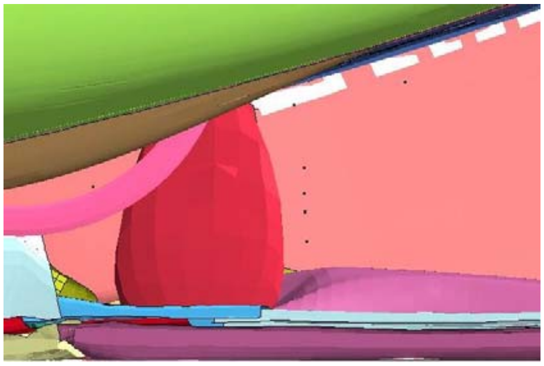

Figure 15: Head and roof sheet metal configuration at 0.320 sec.

The experimentally measured neck forces from CRIS Test 51502 are shown in Figure 17 where the maximum force was 11 kN. Figure 17shows the history of the normal (A joints-39) and shear (B joints-39) neck forces. The peak value of 20 kN occurred when the neck is very close to the position shown in Figure 14 and the second peak of 5 kN occurred at about the position shown in Figure 15.

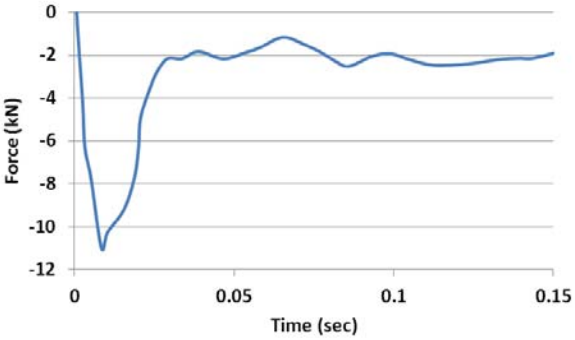

Figure 16: Neck forces from CRIS Test 51502.

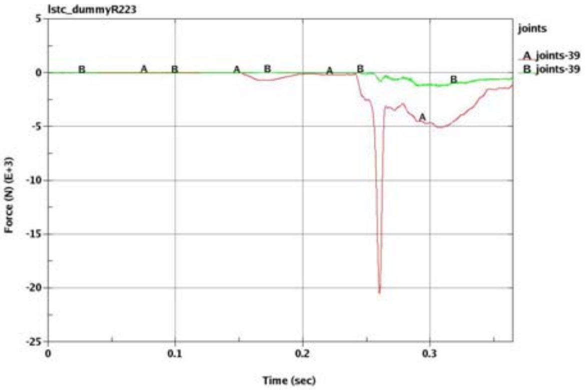

Figure 17: Neck forces from LS-DYNA simulation of CRIS Test51502.

Effect of Initial Conditions and Orientations

From the above study, it was observed that the initial contact point has an effect on the behavior of the ATD as well as the car's response. It was decided to make another simulation in which ground contact occurs at 176 degrees (near-side contact), which is 8 degrees earlier than the previous case. The initial contact point is shown in Figure 18 where it is over and behind the front seat passenger. This point would be a mirror image about the vertical longitudinal center plane of the car of the previous case.

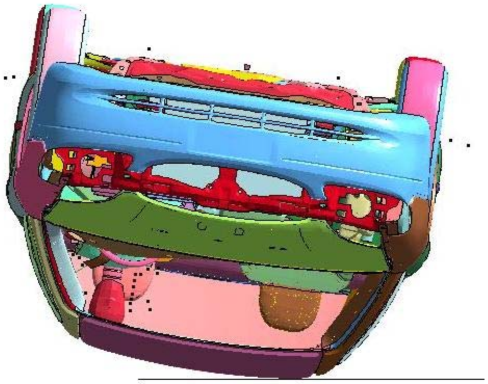

Figure 18: Initial contact at 0.22 seconds after near side impact.

Figure 19: Deformed roof configuration at 0.35 sections showing continued roof and pillar deformations. Note, minimal roof deformation near initial contact point.

As the rollover event evolves (Figure 19), pillar deformation continues to push on the torso of the ATD, which is potentially restrained by the seat belts, and roof deformation continues its contact with the head. The normal neck force and shear force are shown in Figure 20; the peak value is almost 35 kN whereas the shear force is less than 2.5 kN.

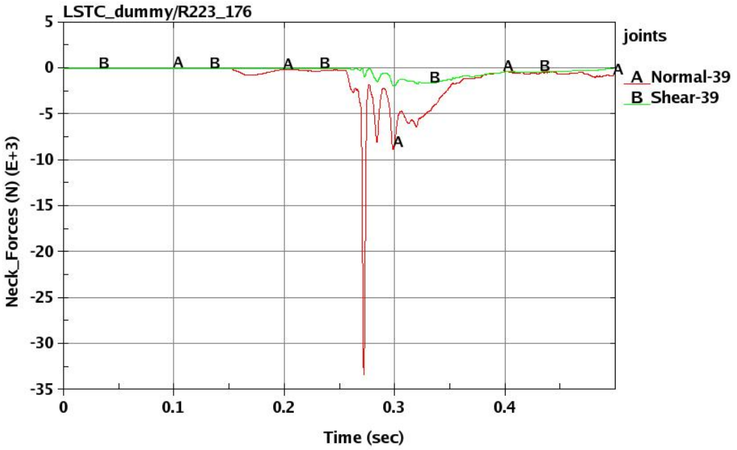

Figure 20: Temporal evolution of the normal neck force, Fn, and the shear neck force, Fs, during near side impact.

The final case considered was a far side impact with a 10 degree pitch. To illustrate this and its effect on rollover impact dynamics, the Taurus was initially oriented at release with a roll angle of 190 degrees, and a pitch of 10 degree angle with the ground. Figure 21Figure 24 shows the side view at ground contact and Figure 22 shows the side view at the end of the simulation. Note the back of the Taurus continues to move toward the ground.

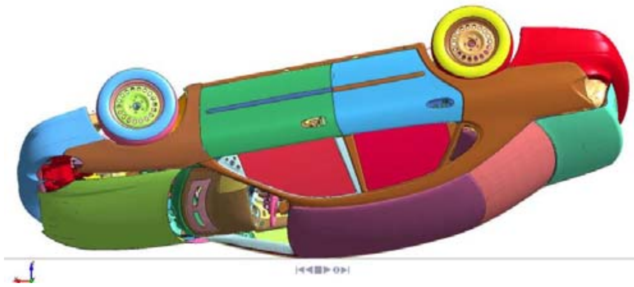

Figure 21: Side view at time of contact with the ground (0.36 seconds). Contact occurs near roof edge.

Figure 22: Side view at the end of the simulation 0.50 sec). The back of the Taurus continued moving toward the ground.

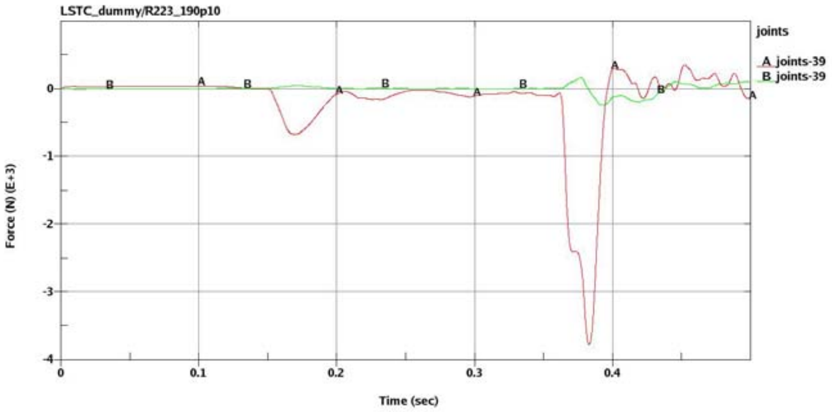

Figure 23: Time history of the neck's normal force (A joints-39) and shear force (B joints-39).

Figure 23 shows the temporal evolution of the neck force, which was slightly less than 4kN.

A comparison of the results for maximum neck force between the CRIS 51502 experiment and three simulation cases is given in Table 5: Comparison of experimental and simulation results.

Table 5: Comparison of experimental and simulation results.

Case	Maximum Neck Force (kN)
CRIS 51502 Test – Far Side Impact	11
CRIS 51502 Simulation – Far Side Impact	20
Near Side Impact	34
Far Side Impact with 10 degree Pitch	4

Summary and Conclusions

The initial simulation of CRIS Test 51502 using a 2001 Taurus as a surrogate for the 1999 Crown Victoria test vehicle and using the initial test conditions showed noticable difference in ATD neck forces occurred. This difference was explainable by examining the physical differences between the two vehicles -- in particular the difference in roof geometry, which controls the point of vehicle impact with the ground. Note, prior to running simulations, inertia differences between the two vehicles were minimized by adding inertia to the Taurus.
Several case studies were performed. The first case studied matched the CRIS Test 51502 initial release conditions, and the numerical simulations match the kinetic conditions when the vehicle contacted the ground – as calculated by rigid body dynamics. The second case looked at near side impact, and the third case looked at far side impact but included an initial pitch angle of 10 degrees.

Using the exact CRIS initial conditions, the results for simulating the CRIS test overestimated the value of the neck force: 20 kN (simulation) vs. 10 kN (experimental). This is due primarily to the difference in roof shapes: ellipitic (Taurus) vs. flat (Crown Victoria). The near side impact had the highest neck force (34 kN), and the far side impact with a 10 degree pitch had the lowest (4 kN). The trend from near side-to-far side (34 kN to 20 kN) impact shows decreasing peak values of the neck normal force, thus, indicating lower forces are expected as the impact occurs nearer the outside edge of the roof. Recall because of roof shape, the impact of the Crown Victoria was near the outside edge of the roof.

It was observed in the simulations that when large deformation of the B-pillar occur, the shoulder part of the seat belt loses tension and the ATD is free to move. This may not be adverse – since it allows the occupant to move laterally – but needs further investigation. During this study it was noted that the deforming roof panel presents varying contact topology to the head of the ATD. In some cases, the deforming roof appears to cradle the head of the ATD.

The suitability of using this approach with different test and simulation vehicles for validation is not clear cut because of the difference in the roof shapes of the test and surrogate vehicle. When the answer is known *a priori*, one can always make adjustments to reach it. However, this approach using identical test and simulation vehicles would be valid for evaluating rollover events under various initial conditions and orientations.

The vintage of the vehicles used in this study were fairly old (1999 and 2001), and the roof deformations during the rollover event were large. In the auto industry's quest for continuous safety improvement for rollover events, research is focused on increasing the strength of the A-pillar and B-pillar, which are the main structural components controlling roof crush. This is primarily being accomplished by the use of, for example, higher strength materials, tailored-welded blanks and hot forming gradient composites. Note the B-pillar must be optimized for side impact and rollover events. The vehicle models used by non-automaker crash researchers will have to incorporate the newer manufactured pillars. This most likely can be accomplished by reverse manufacturing the pillars to capture residual stresses and strength gradients.

Finally the Hybrid III ATD finite element model was used because the physical ATD was a Hybrid III. Future work should use models with higher bio-fidelity (for example, finite element models being developed by the Global Human Body Models Consortium (GHBMC) or the Total Human Model for Safety (THUMS).

Acknowledgement

This work was performed for Argonne's Transportation Research and Analysis Computing Center (TRACC), which is funded by the U.S. Department of Transportation. Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC. RFK Engineering Mechanics Consultants wishes to acknowledge Dawn Tucker-Thomas of the U.S. DOT Research and Innovative Technology Administration (RITA) for supporting this work along with the support from TRACC's Director, Dr. Hubert Ley and TRACC staff members, C. Bojanowski, M. Balcerzak, for assembling the final model. The simulations were performed on TRACCs High Performance Computing Cluster.

Thanks are due to Stephen Ridella of the National Highway Traffic Safety Administration (NHTSA) who proposed this research and Dhafer Marzougui of the National Crash Analysis Center who provided valuable information on features of the Taurus finite element model.

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