Argonne NATIONAL LABORATORY

Energy Systems Division

ANL/ESD/12-11

Computational Mechanics Support to National Highway Traffic Safety Administration (NHTSA)

Progress Report, August 2012

About Argonne National Laboratory

Availability of This Report

This report is available, at no cost, at http://www.osti.gov/bridge. It is also available on paper to the U.S. Department of Energy and its contractors, for a processing fee, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

Disclaimer

Computational Mechanics Support to National Highway Traffic Safety Administration (NHTSA), Progress Report, August 2012

By:
C. Bojanowski[1], M. Balcerzak[1], R. Kulak[2],
and H. Ley[1] – Principal Investigator
[1] Transportation Research and Analysis Computing Center (TRACC)
Energy Systems Division, Argonne National Laboratory
[2] RFK Engineering Mechanics Consultants

Submitted to:
Stephen Ridella[1]
[1] National Highway Traffic Safety Administration (NHTSA)

August 2012

Table of Contents

List of Figures

List of Tables

1. Introduction and Objectives

The Transportation Research and Analysis Computing Center (TRACC) with the National Highway Safety Administration (NHTSA) Vehicle Safety Research has established an interagency agreement between the U.S. Department of Transportation and the U.S Department of Energy to provide assistance to NHTSA's ongoing projects. The work will be performed in FY 2013 by the Transportation Research and Analysis Computing Center at Argonne National Laboratory. The project will be performed under the "Work for Others" (WFO) clause of the prime contract between the operator of Argonne National Laboratory (UChicago Argonne LLC) and the U.S Department of Energy.

For the past five years, NHTSA has been using TRACC's HPC computer and participating in computational structural mechanics training classes. NHTSA mainly used the LS-DYNA software package including: LS-DYNA (multiphysics solvers), LS-OPT (optimization tool) and LS-PrePost (pre- and post-processing tool). NHTSA crash analysis researchers were early users of the TRACC cluster and have become the most active users of TRACC's 500 core LS-DYNA software license. The large core-license-pool allows NHTSA to minimize the time needed to obtain simulation results and, thus, expand modeling variations that must be considered to ensure credible treatment of crash events while meeting critical project deadlines. The purposes of this project are (1) to enhance future cooperation between NHTSA and TRACC and (2) to secure NHTSA's access to TRACC's high performance cluster, LS-DYNA and TRACC's staff expertise.

The CRIS dynamic test was developed by Exponent® Engineering and Scientific Consulting and Ford Motor Company to study roof-to-ground behavior during a vehicle rollover. NHTSA had performed simulations of the CRIS Test 51502 using a coupled code approach in which LS-DYNA® (Livermore Software Technology Corporation/LSTC) was coupled to MADYMO®(TASS Engineering). The physical test was performed using a 1999 Ford Crown Victoria and Hybrid III 50th dummy. However, because there was no finite element model available for the Crown Victoria, the NHTSA numerical simulations used a finite element model for a 2000 Ford Taurus as a surrogate and a MADYMO Hybrid III 50^{th} dummy. Because of issues associated with code couplings and dealing with two software vendors, NHTSA has tasked TRACC with performing simulations that use dummy models that are directly attainable from LSTC. LSTC has two Hybrid III 50^{th} models available: a coarse model and a fine model.

The first task that TRACC has been asked to work on is to use LSTC Hybrid III 50^{th} dummy models in the finite element model of the 2001 Ford Taurus and to compare the response of the dummy (as measured by neck forces and neck moments) to the response obtained by NHTSAs simulations that used the MADYMO Hybrid 50^{th} dummy model. This is the main focus of this report. All models developed will be available to NHTSA.

2. Description of Initial Models

2.1. Taurus Model

The 2001 Ford Taurus finite element model version 4 developed by the National Crash Analysis Center (NCAC) was obtained directly from the NCAC. This model is not yet available in the NCAC Finite Element Archive, but it is an updated development model. The model contains 921,793 elements. Figure 2.1 shows the front view of the model repositioned to the orientation used in the CRIS test just prior to release and impact with the ground. Figure 2.2 is the side view of the model positioned to the pre-release state.

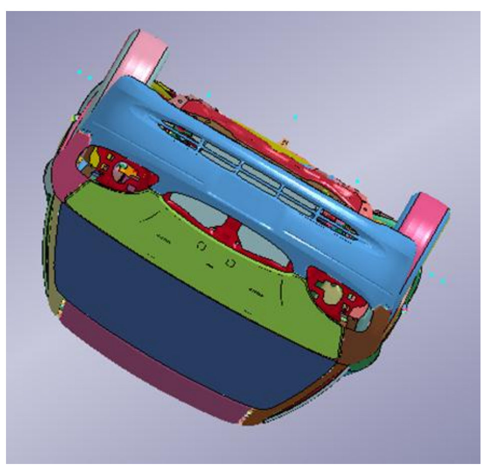


Figure 2.1: Front view of the finite element model for a 2001 Ford Taurus just prior to release from the CRIS system.

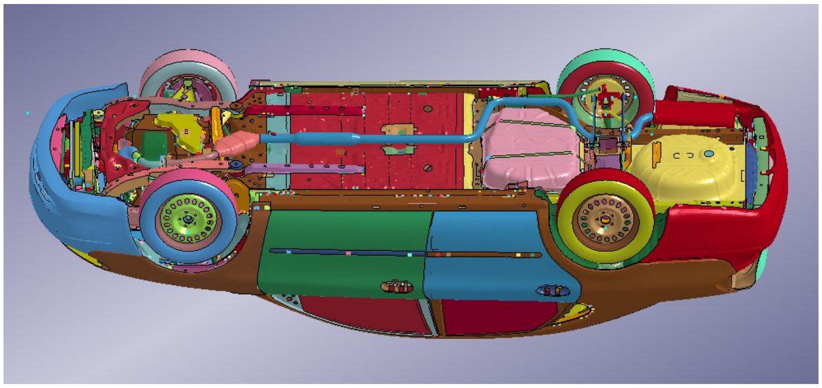


Figure 2.2: Side view of the finite element model of a 2001 Ford Taurus just prior to release from the CRIS system.

2.2. LSTC Dummy Model

The anthropomorphic test device (ATD) used in CRIS Test 51502 was the Hybrid III 50th male, and finite element models of this ATD were used in the simulations reported here. The Hybrid III ATD was developed for use in frontal impact tests and, thus, was "tuned" for this type of response. Recently, Livermore Software Technology Corporation (LSTC) has improved their suite of dummies to reduce difficulties in positioning, injury/response extraction, and overall performance. LSTC.H3_50TH_FAST.111130_V2.0 was used in the initial CRIS simulations. Figure 2.3 and Figure 2.4 show, respectively, front and side views of the dummy model. The statistics for the FAST Hybrid III model are given in Table 2.1. The model contains 4,310 elements, 7,402 nodes, 103 materials and requires a maximum computational time step of 1 μs. The original units for the Hybrid III (mm-ms-kg-kN) have been converted to the units of Ford Taurus FE model - mm-s-tonne-N.

Table 2.1: Statistics for LSTC.H3_50TH_FAST.111130_V2.0.

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

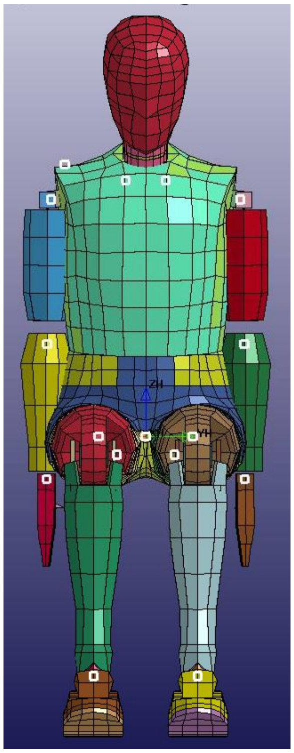


Figure 2.3: Front view of the LSTC Hybrid III 50th Fast Dummy.

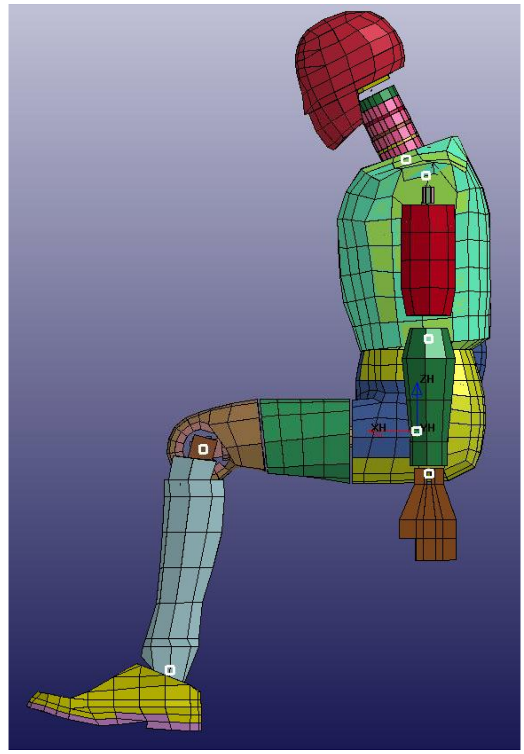


Figure 2.4: Side view of the LSTC Hybrid III 50th Fast Dummy.

2.3. NCAC Hybrid III Dummy

The National Crash Analysis Center (NCAC) has recently developed a new detailed finite element model of the Hybrid III 50th percentile dummy used for frontal crash simulations. The dummy model is presented in Figure 2.5 and Figure 2.6, while the statistics for this model are presented in Table 2.2. The model consists of 397,491 elements, 228,650 nodes and 365 material models. The computational time step is fixed at 0.5 μs.

Table 2.2: Statistics for NCAC Hybrid III 50TH Detailed Dummy model.

Item	Value
Nodes	228,650
Solid Elements	186,808
Shell Elements	210,440
Beam Elements	242
Rigid Elements	14,014
Nodal Rigid Bodies	185
Total Number of Elements	397,491
Number of Material	365
Computational Time Step	0.5 μs

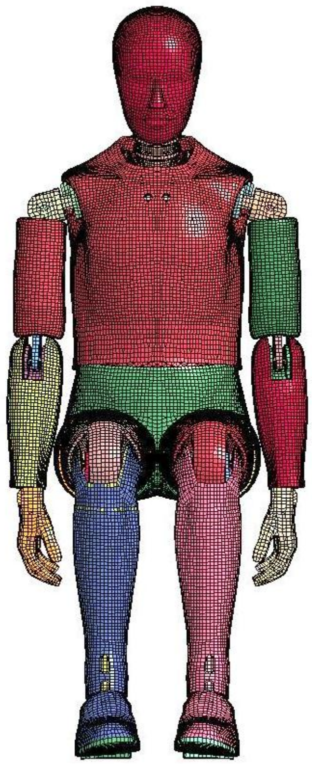


Figure 2.5: Front view of the NCAC Hybrid III 50th Detailed Dummy model.

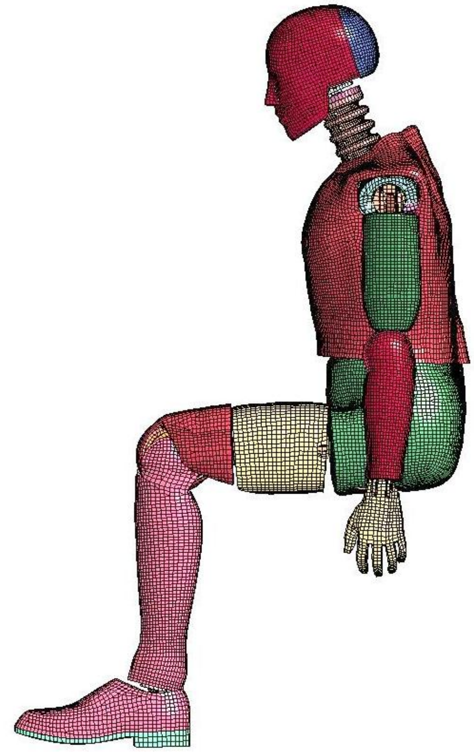


Figure 2.6: Side view of the NCAC Hybrid III 50th Detailed Dummy model.

3. Comparison of CRIS Test Vehicle and Simulation Vehicle

The CRIS dynamic test was developed by Exponent® Engineering and Scientific Consulting and Ford Motor Company 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 is attached to the back end of a flatbed semi-trailer. The system is well suited to study roof strength issues and occupant protection systems [1].

Figure 3.1 is a schematic of the test rig used to conduct the CRIS dynamic test for an automobile impacting the pavement during a rollover. The automobile is attached to a support structure that in turn is attached to a moving semi-trailer. Table 3.1 gives the impact conditions for CRIS test 51502.

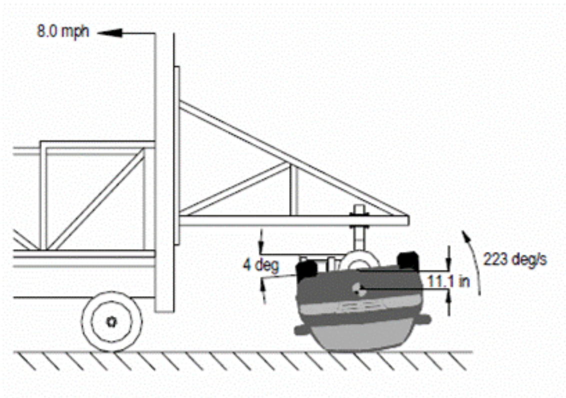


Figure 3.1: Schematic of the Controlled Rollover Impact System (CRIS) [1].

Table 3.1: Impact Conditions

Lateral Velocity	**8 mph (13 kph)**
Vertical Drop Height	11.1 in (282 mm)
Roll Rate	37.2 rpm (223 deg/sec)

Physical testing was conducted using a 1999 Ford Crown Victoria with a body-on-frame construction, but the numerical simulations were performed using a finite element model for a 2001 Ford Taurus. The reason for this is that the Taurus finite element model was the closest available FE model to the Crown Victoria. The numerical simulation results were compared by NHTSA with CRIS test 51502 [1]. In order to mount the Crown Victoria in the CRIS rig (Section 2), a special cradle was designed. At the moment of writing this report the exact weight and inertia properties of the cradle is unknown to TRACC. Figure 3.2 shows some of the details of the cradle. The assumed inertia properties [2] for a Crown Victoria and calculated properties of the Taurus model are given in Table 3.2. The inertia properties of the Taurus model were modified to match the Crown Victoria properties.

Figure 3.2: CRIS cradle mounted on the Crown Victoria's (a) front (b) back.

Table 3.2: Inertial Properties for Ford 1999 Crown Victoria [2] and Ford 2001 Taurus.

	Curb Weight	Yaw Moment of Inertia	Pitch Moment of Inertia	Roll Moment of Inertia
Crown Victoria^{PP} [2]	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	3,337.8 lb_f 1,514 kg	2,167.5 lb_f-ft-sec^2 2,936.92 kg-m^2	1,950.0 lb_f-ft-sec2 2,642.31 kg-m^2	388.8 lb_f-ft-sec^2 526.83 kg-m^2

Note: PP = Police Package

A comparison of the static roof-crush between the Ford Crown Victoria and Taurus was presented in [1]. The comparison of the test results (Figure 3.3) shows relatively close agreement between the two vehicles. Assuming that the Crown Vic and the Taurus are manufactured using the same steel for the A-, B- and C-pillars, then the dynamic roof-crush behavior should be similar. Thus from a roof-crush-resistance aspect, the Taurus appears to be a good surrogate for the Crown Victoria.

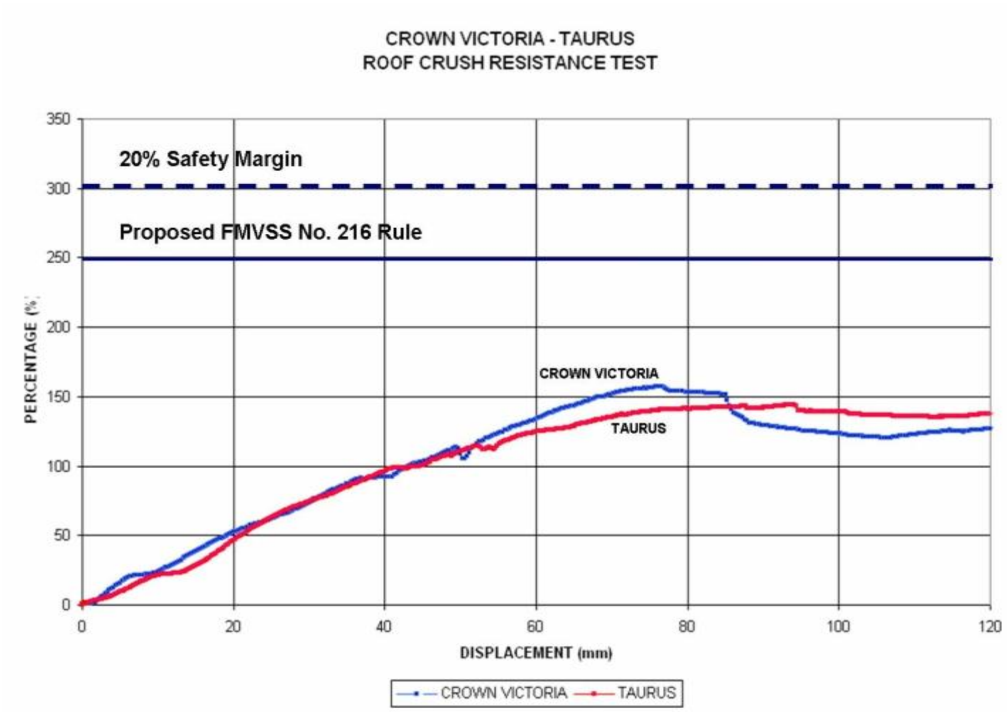


Figure 3.3: Static Resistance Force versus Roof Crush for Ford Taurus and Crown Victoria [1].

4. Model Development

4.1. Vehicle Model Updates

4.1.1. Initial Conditions Adjustment

In order to compare the behavior of different dummy models, the kinematics of the vehicle model should be assumed to be the same, although some differences were found between the data given in the draft of the paper [1] describing CRIS test 51502 and the previous results from MADYMO coupled simulations (details revealed in Chapter 7 of this report). As the comparison of different dummy models was the primary goal of this study, it was assumed that the kinematics given in the results with the MADYMO dummy will be extracted and used for further study. Figure 4.1 presents snapshots of the model's motion. Larger deformations in the vehicle roof were noticed in the new simulation. Figure 4.2 presents post-test deformation of the Taurus model in comparison to the post test Ford Crown Victoria. The deformation pattern in the model closely resembles the deformations of the Crown Victoria.

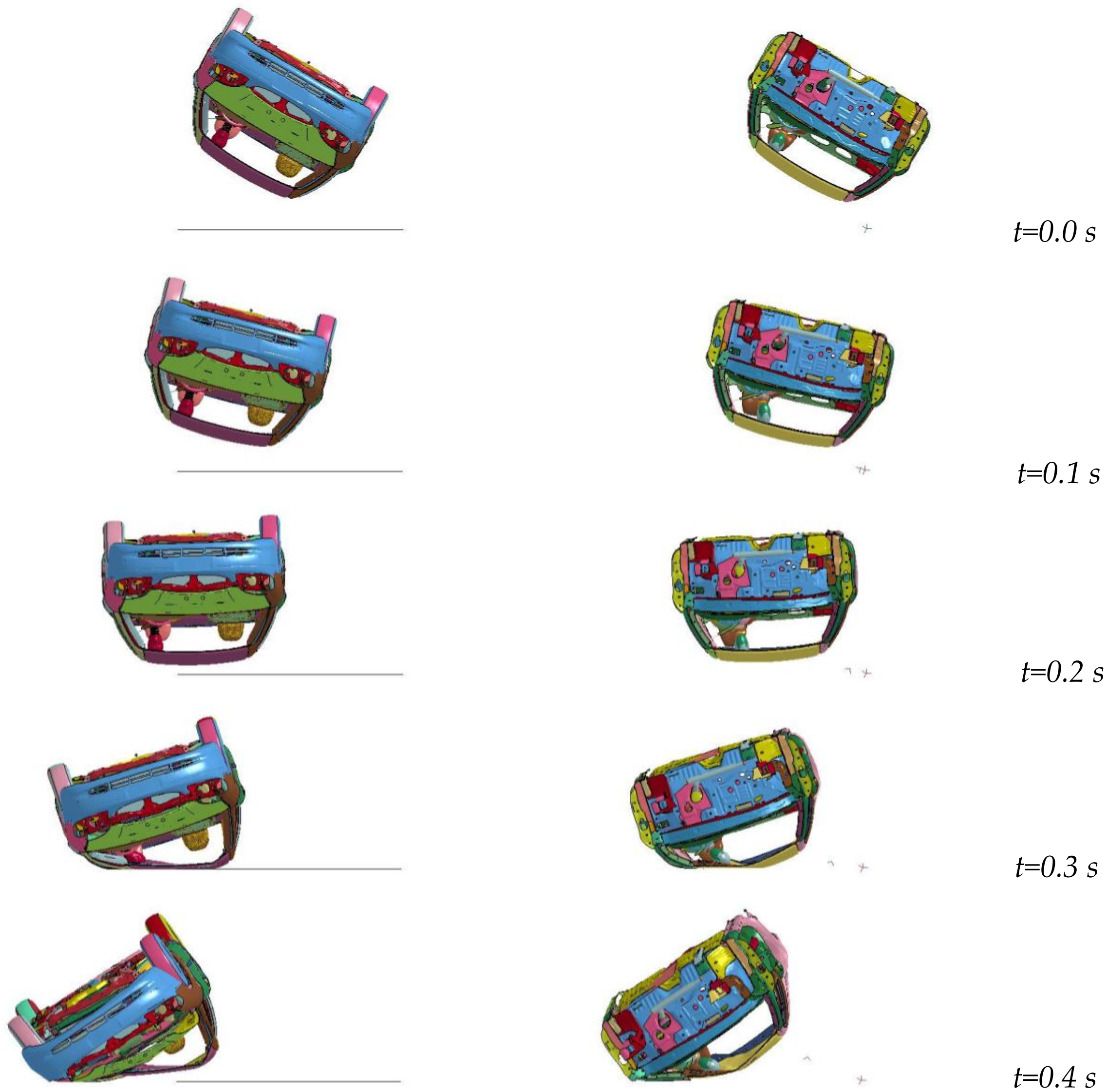


Figure 4.1: Comparison of vehicle kinematics and deformations in (left) TRACC simulation with NCAC dummy (right) NHTSA simulation with MADYMO dummy.

Figure 4.2: CRIS post-test vehicle front and rear view damage comparison.

4.1.2. Mass and Inertia Properties Adjustment

The vehicle model used in the CRIS test was a 1999 Ford Crown Victoria, but the numerical model used a 2001 Ford Taurus FE model developed by NCAC. Even though these cars have similar roof structure, the Ford Crown Victoria is over 300 kg heavier. In order to obtain comparable behavior, the mass and inertia properties of the Taurus FE model were adjusted to match the characteristics of the Crown Victoria (based on properties from [2]). To match the mass and location of the center of gravity (CG), additional masses were added in the engine and rear chassis areas. To match the inertia characteristics, an inertia part was used at the CG of the model and rigidly attached to the floor of the model. The 2001 Ford Crown Victoria model data was used as a reference, which is based on the same design as used in the CRIS experiment with the 1999 Crown Victoria. Confirmation of these properties is needed. Additionally, in the 2001 Ford Taurus NCAC model, the mass of two occupants and luggage was hardcoded, resulting in almost 200 kg of extra mass. It was removed from the FE model before the simulations were performed. Table 4.1 presents mass and inertia properties of original Taurus model (without hardcoded mass of passengers and luggage) and the model after modifications to match the Crown Victoria characteristics. The CG location for the two vehicles was almost the same. The moments of inertia and the mass were subject to change.

Table 4.1: Comparison of mass and inertia properties of original Taurus model to the model with adjusted mass and inertia characteristics. (CG location for the vehicle standing on the ground with a default location of origin of the coordinate system)

	Ford Taurus	Adjusted Ford Taurus
mass	1,514.49 kg	1,823.42 kg
CG location X	-1,999.91 mm	-1,999.91 mm
CG location Y	-5.802 mm	-5.80198 mm
CG location Z	550.7 mm	568.202 mm
Ixx	526.834 kg-m^2	770.907 kg-m^2
Iyy	2,642.31 kg-m^2	3,831.25 kg-m^2
Izz	2,936.92 kg-m^2	3,978.75 kg-m^2

4.1.3. Strain-rate effect

Two models of the new Taurus were provided by NCAC – with and without strain rate effects. The model without strain-rates was used previously for roof crush validation. For simulations of CRIS test, the strain rate effects were included in the model. All steel parts in the vehicle were modeled using LS-DYNA material model MAT_024 (*MAT_PIECEWISE_LINEAR_ PLASTICITY). The strain rate effect in material model MAT_024 is described using Cowper Symonds model, which scales the yield stress with the factor:

$$1+\left(\frac{\dot{\varepsilon}}{C}\right)^{1/p}$$

Where $\dot{\varepsilon}$ - strain rate; C, p – experimentally estimated strain rate parameters,

The strain rate parameters for all material models of steel used in the Taurus model were defined as $C = 8000$ and $p = 8$.

4.2. Restraint System Modeling

Following standard LS-DYNA modeling procedure, the seatbelt model consists of 2D shell and 1D seatbelt elements (see Figure 4.3 for details). The shell element part of the seatbelt model is used in the area where it can contact the dummy, and the 1D element part is used in the areas that pass through the sliprings (D-rings) or into the retractors. The three-point restraint system has two sliprings with an assumed friction coefficient of 0.05 (see Figure 4.3).

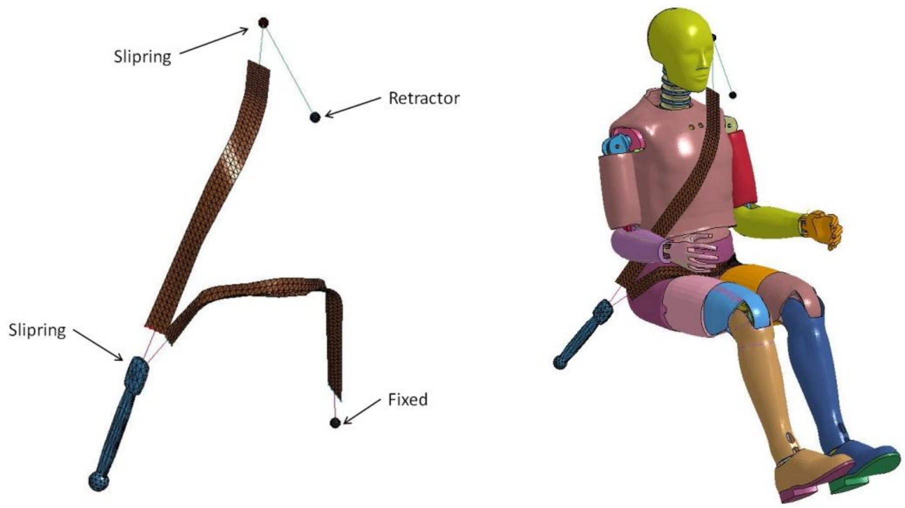


Figure 4.3: Improved seatbelt model.

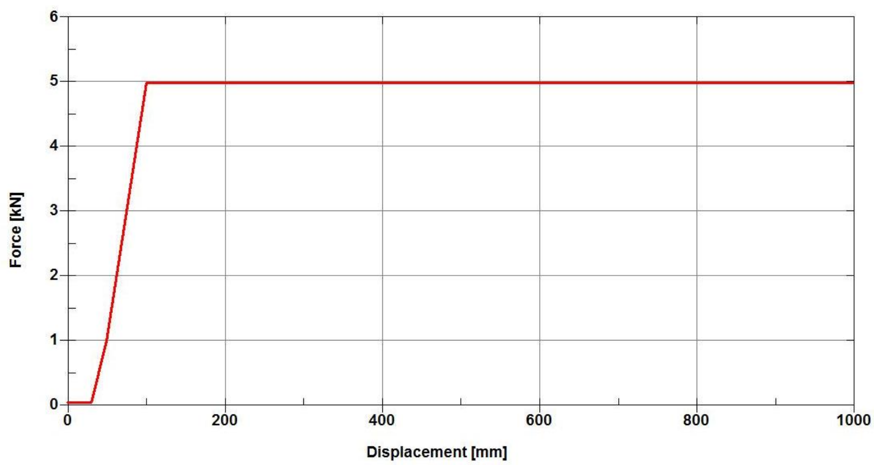


Figure 4.4: Function used in retractor modeling.

The force-displacement characteristics for the retractor are presented in Figure 4.4. The initial tension force in the retractor equals 50 N, and the maximum tension force reaches 5,000 N when the displacement is equal to 100 mm and remains constant after that. This curve is a modification of the relationship used by NHTSA in their coupled MADYMO – LS-DYNA model.

4.3. Occupant Setup

4.3.1. LSTC Dummy Model Positioning

To correctly position the LSTC fast dummy in the NCAC 2001 Taurus model, the driver's seat was moved 150 mm backwards and then the following dummy operations were performed:

- H – point operations:
  - Translation dx = -2,360.0 mm, dy = 371.0 mm, dz = 580 mm,

- Rotation rx = 0 deg, ry = -17.00 deg, rz = 0 deg,
- Limb operations:
  - Lower leg rotation (left + right) -17.00 deg,
  - Lower arm rotation (left + right) -75.00 deg,
  - Feet rotation (left + right) -5.00 deg,
- Lumbar operations:
  - Rotation -6.00 deg,

Figure 4.5 presents the properly positioned LSTC dummy with the Taurus driver's seat and fitted seatbelts. The inclination angle of the seat was not subject to adjustment in this study. However, it can be an important parameter in the sensitivity analysis.

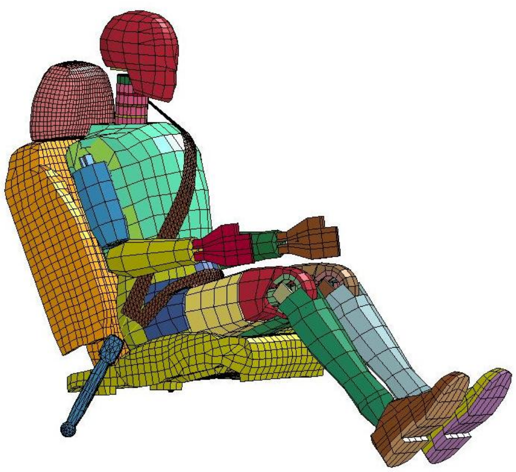


Figure 4.5: LSTC detailed dummy positioned for the Taurus seat.

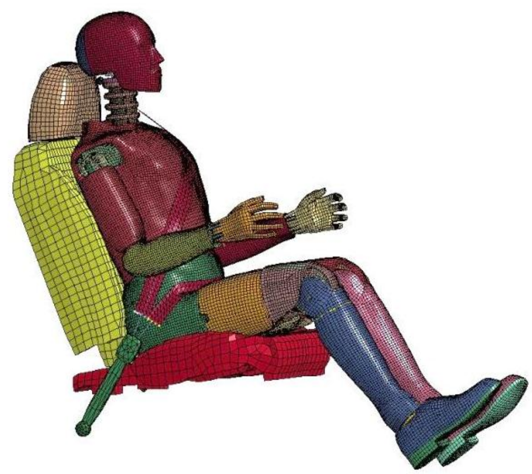


Figure 4.6: NCAC detailed dummy positioned for the Taurus seat.

4.3.2. NCAC Dummy Model Positioning

To correctly position the NCAC dummy in the Taurus model, the driver's seat was also moved 150mm backwards and then the following dummy operations were performed:

- H – point operations:
  - Translation dx = -2,358.2 mm, dy = 372.5 mm, dz = 580 mm,
  - Rotation rx = 0 deg, ry = -17.87 deg, rz = 0 deg,
- Limb operations:
  - Lower leg rotation (left + right) -17.00 deg,
  - Lower arm rotation (left + right) -75.00 deg,
  - Feet rotation (left + right) -5.00 deg,
  - Shoulder rotation (left + right) -2.00 deg,

- Lumbar operations:
    - Rotation -11.50 deg,

Figure 4.6 shows the properly positioned NCAC detailed dummy with the driver's seat and fitted seatbelts. For both dummies, similar segment sets for contact with the car interior and the seatbelts were defined. The components of the models were kept in separate files i.e. vehicle, dummy, restraint system, cross-system definitions, and a global file with include commands to join all the components into a single input file. That way easy substitution of the components is possible.

5. Evaluation of LSTC Dummy Model Performance

It is important to note again that the following simulations are matching the simulation results obtained from NHTSA in terms of initial configuration and initial velocities of the vehicle. These were different from the initial conditions specified for the experiment. Further in Chapter 7.2 results are shown for the initial conditions matching the experimental input. However, the results for these simulations are quite different from the results obtained by NHTSA coupled model and this TRACC adjusted model. Comments of NHTSA on unresolved issues listed in Chapter 7.1 are aiming to help match the experimental data more precisely in the future efforts.

5.1. Kinematics

Figure 5.1 presents side-by-side snapshots comparing the behavior of LSTC FAST dummy and MADYMO dummy. Even though both dummy models are supposed to have the same initial velocity, there is a visible difference in their motion before the dummy hits the ground. Motion of the limbs is smaller in the LSTC FAST dummy than in the MADYMO dummy, possibly due to the higher stiffness of the joints, though it does not have a significant effect on the obtained results. However, this statement was not cross-checked between the models.

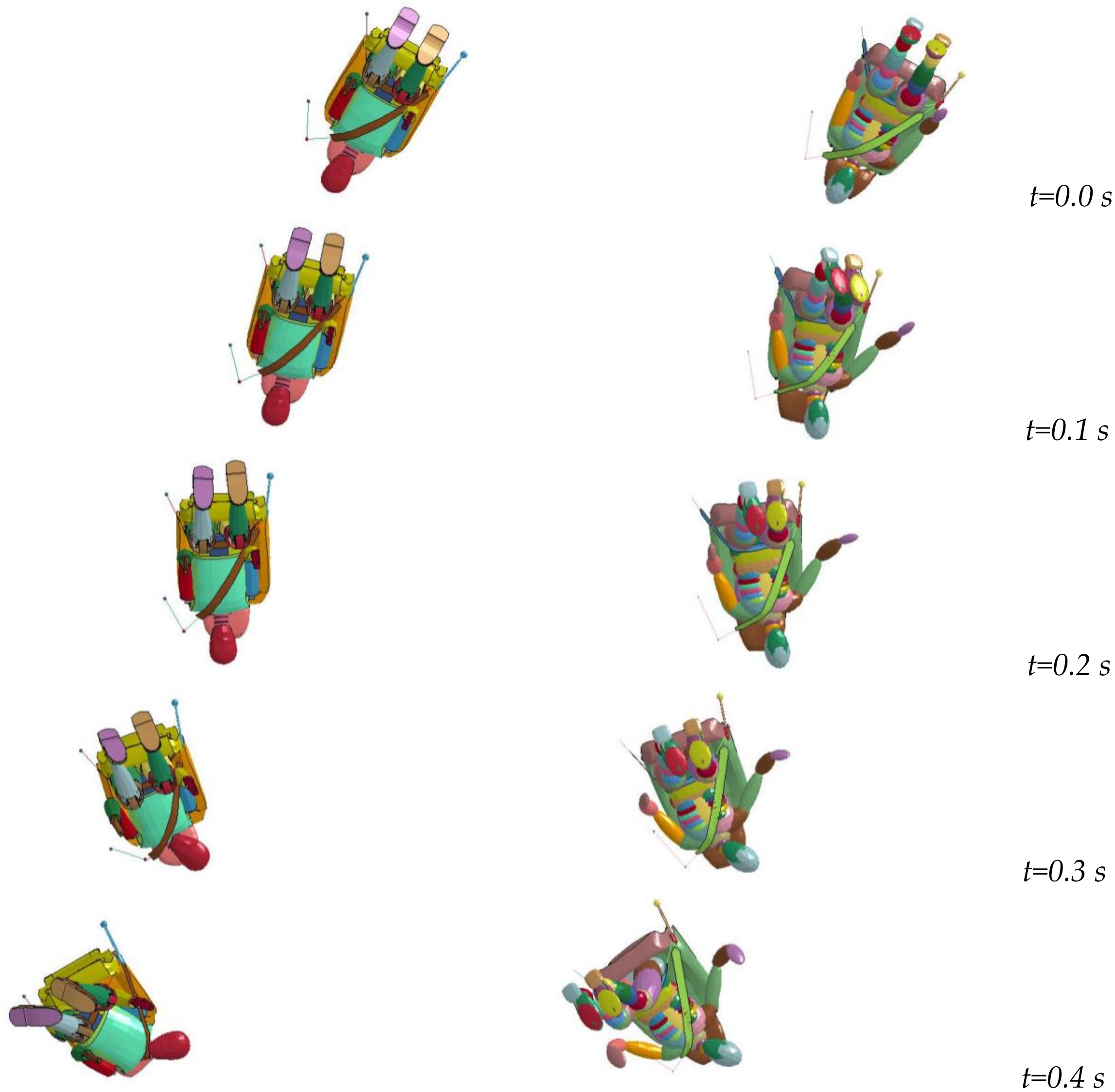


Figure 5.1: Comparison of the motion of (left) LSTC dummy and (right) MADYMO dummy models.

5.2. Upper Neck Force and Moment

Figure 5.2 presents comparisons of neck force and moment histories from (1) the experimental CRIS test, (2) the simulation using the MADYMO dummy and (3) the simulation using the LSTC FAST dummy. The neck force history for both models has similar behavior, but there is a difference in the amplitudes. For the neck moment histories, the amplitude is different, and the overall behavior does not correspond to the results from the coupled LS-DYNA-MADYMO simulation or the experimental test. The results obtained, especially neck moment history, can be strongly affected by neck position of the dummy model (more in Chapter 7.1.4).

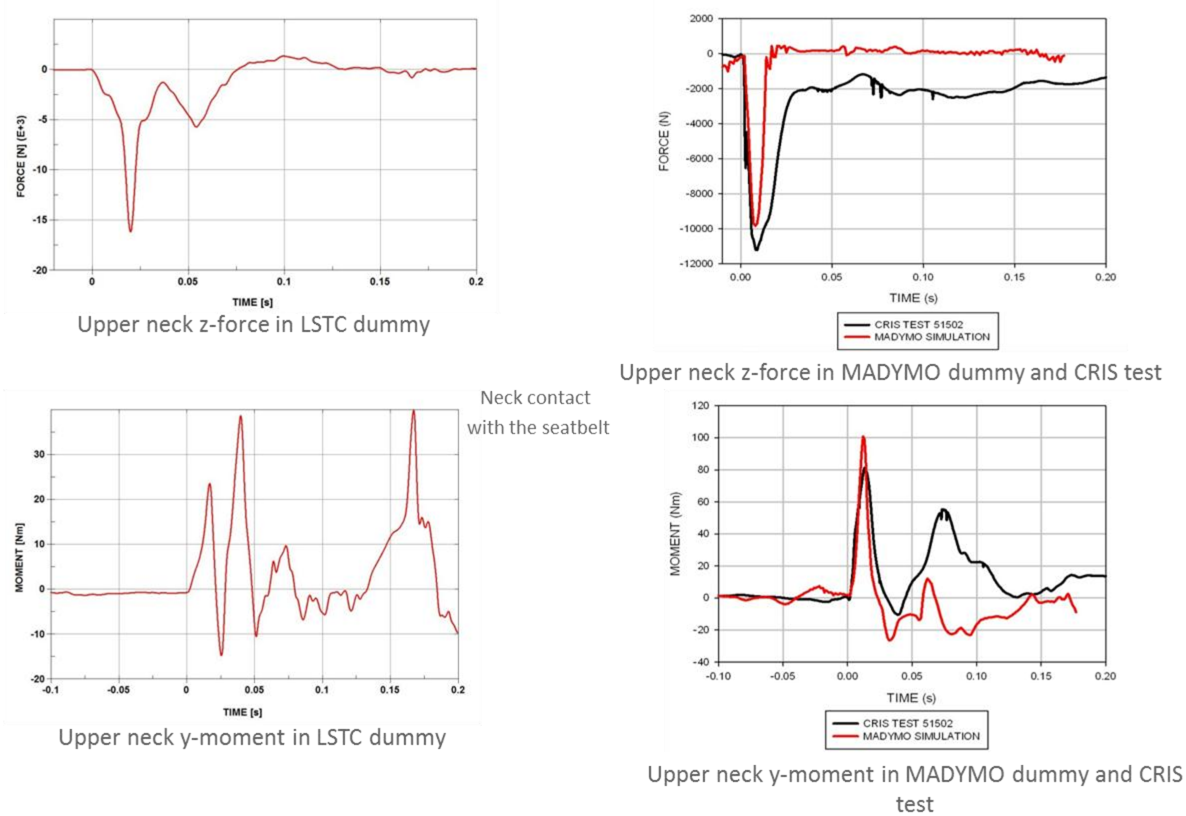


Figure 5.2: Comparison of neck forces and moments for LSTC dummy model, MADYMO dummy model and experimental results.

6. Evaluation of NCAC Dummy Model Performance

6.1. Kinematics

Figure 6.1 presents side-by-side snapshots comparing the behaviors of the NCAC detailed dummy and the MADYMO dummy. Similar to the LSTC fast dummy response, despite the assumed identical initial velocity of both dummies, there are visible differences in the motion of the two dummies before they hit the ground. Joints in the NCAC detailed dummy may also have a higher stiffness than in the MADYMO model, but it is not a crucial parameter affecting the results for neck forces and moments. This statement was not cross-checked between the models and can’t be assumed as the definite cause of the discrepancy.

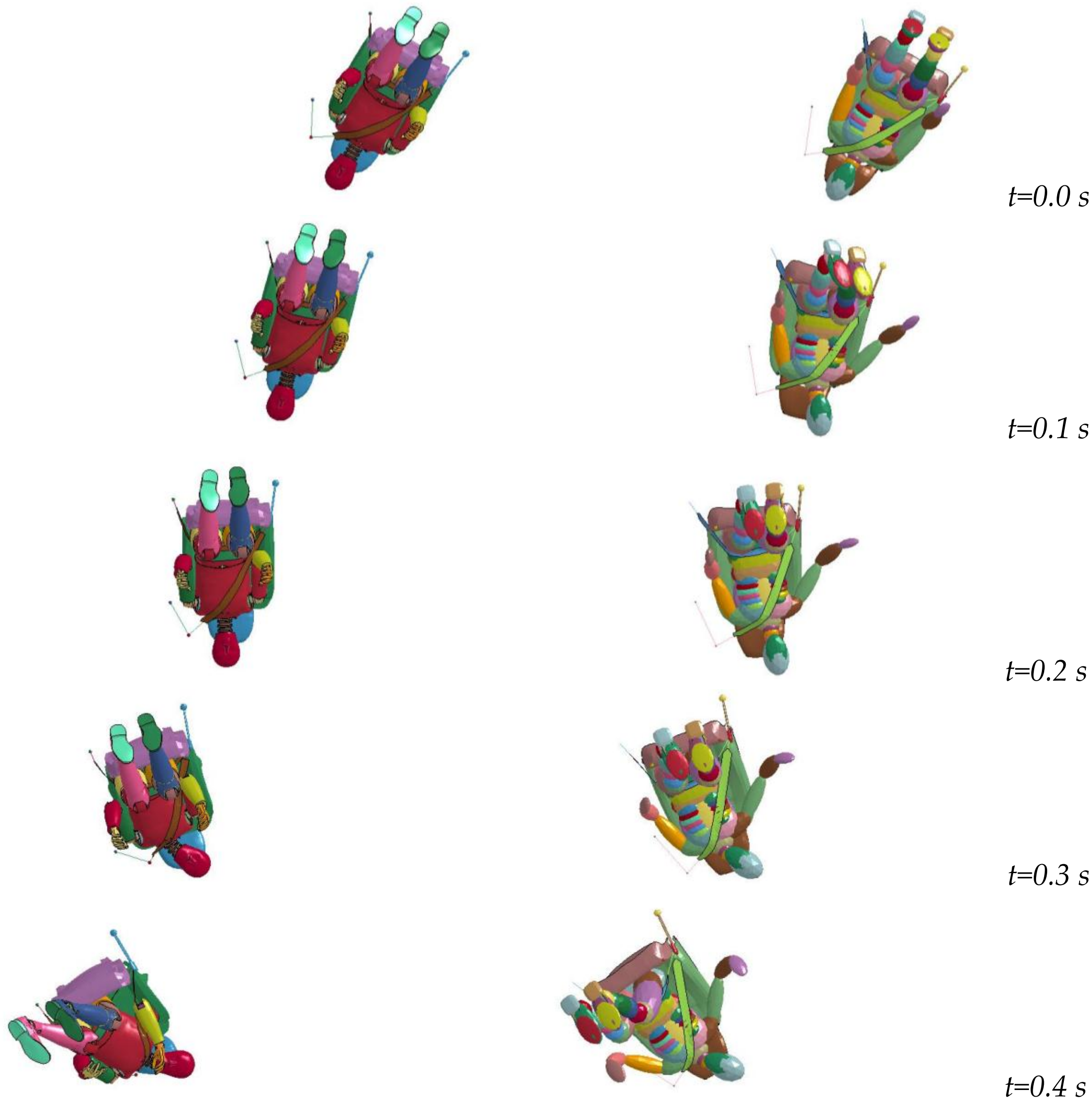
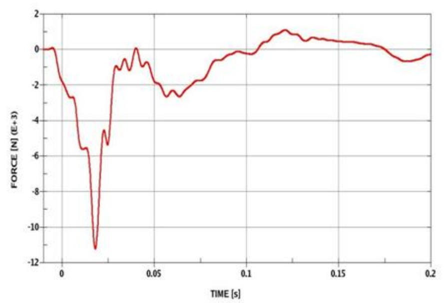


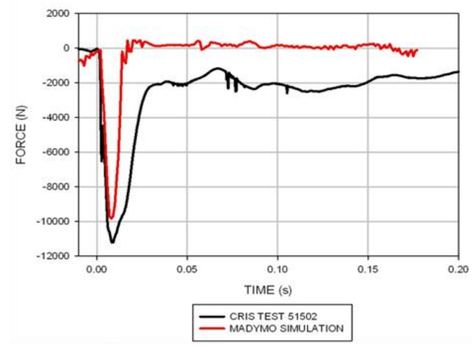
Figure 6.1: Comparison of the motion of (left) NCAC dummy and (right) MADYMO dummy models.

6.2. Upper Neck Force and Moment

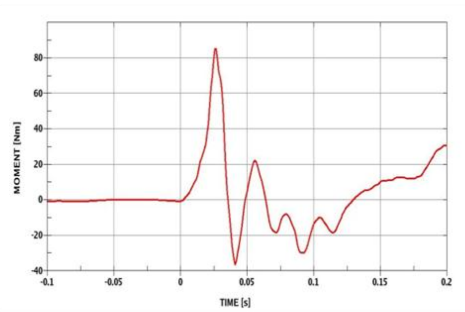
Figure 6.2 presents comparison of the neck force and moment histories for the NCAC detailed dummy, MADYMO dummy and the experimental test results. The comparison shows that the NCAC detailed dummy gives results that are very close to the results obtained using the MADYMO dummy, though the results obtained might be affected by dummy initial position (more in chapter 7.1.4).



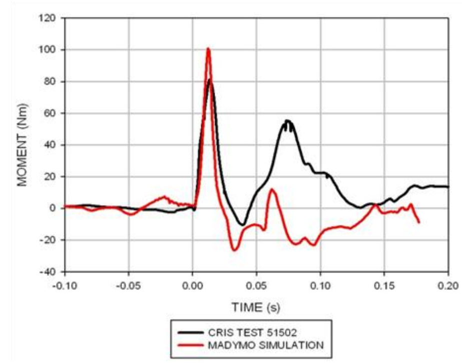
Upper neck z-force in NCAC dummy



Upper neck z-force in MADYMO dummy and CRIS test



Upper neck y-moment in NCAC dummy



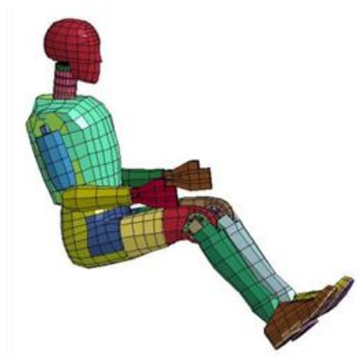
Upper neck y-moment in MADYMO dummy and CRIS test

Figure 6.2: Comparison of neck forces and moments for LSTC dummy model, MADYMO dummy model and experimental results.

6.3. Timing Comparison for Both Models

The study shows that the NCAC detailed dummy gives results that are closer to the LS-DYNA - MADYMO coupled analysis. On the other hand, the detailed dummy has almost 100 times more elements than the LSTC FAST dummy, and the time step is limited to a fixed value of 0.5 microseconds (in comparison to 1 microsecond for the FAST dummy model). Table 6.1 presents comparison of calculation time of 0.5 s simulation on TRACC computational cluster using 8 nodes (64 cores). For the LSTC dummy simulation, the total calculation time was 9h 28m, and for the NCAC detailed dummy simulation, the total calculation time was 28h 58m – over three times more.

Table 6.1: Comparison of two models of Hybrid III 50th dummy.

	 **LSTC Fast Dummy**	 **NCAC Detailed Dummy**
No of elements	4,278	397,491
Timestep	1 microsecond	0.5 microsecond
Termination time	0.5 s	0.5 s
Resources	8 nodes (64cores)	8 nodes (64 cores)
Total calculation time	9h 28m	28h 58m

7. Unresolved Issues

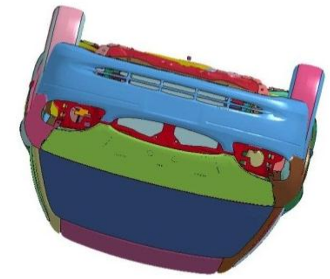
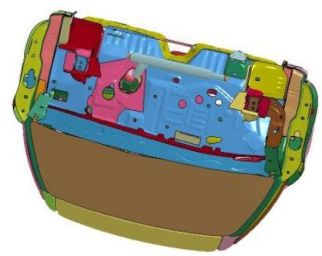
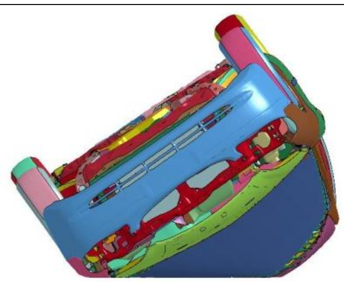
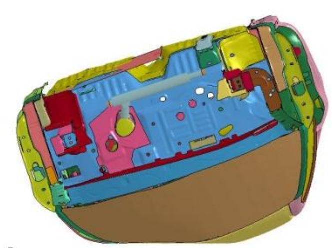
The work presented above pertains to matching the simulated results read from *d3plot* files obtained from NHTSA. However, in this process it was discovered that the initial conditions in the simulation do not match the initial conditions determined based on the experiment i.e. drop height, rotation rate, initial angle, mass etc. The parameters that do not match or are missing are listed in this Chapter. Additional data on these parameters needs to be obtained before matching to the experimental results can be done. An initial attempt to match the experimental test setup was made in Chapter 7.2.

7.1. Input Parameters for Experiment

7.1.1. Initial Rotational Velocity

In the paper by Ridella and Barsan-Anelli [1] describing the CRIS Test 51502, the initial rotational velocity was 223 deg/s. In the simulations described above, the angular velocity was taken to be 165 deg/s, and this value was reversed engineered from animations made from *d3plots* that were provided by NHTSA. Initial angle of the vehicle plane vs. ground was set to 30 deg following these *d3plots* and description in [1]. Table 7.1 presents comparison of vehicle motion for the following models: TRACC at 223 deg/s (TRACC223); TRACC at 165 deg/s and NHTSA at 165 deg/s. The impact angle is defined as the angle that a line tangent to the roof makes with the ground (see Figure 7.4 below). Different initial roll rate results in a different impact angle. The TRACC223 impact angle was 12.7 degrees (with experimental value of 4 degrees). As expected, this resulted in a different deformed configuration for the Taurus model. To obtain 4 deg angle between the roof and the ground at the moment of impact the initial angle of 30 deg has to be modified (see Chapter 7.2). Figure 7.1 compares the neck forces, and Figure 7.2 compares the neck moments. The NCAC detailed dummy model was used for both cases.

Table 7.1: Comparison of vehicle models motion. TRACC model with 226deg/s (left), TRACC model with 165deg/s (middle) and NHTSA model (right).

t=0.1s			
t=0.2s			
t=0.3s			
	TRACC (223 deg/s)	TRACC (165 deg/s)	NHTSA model

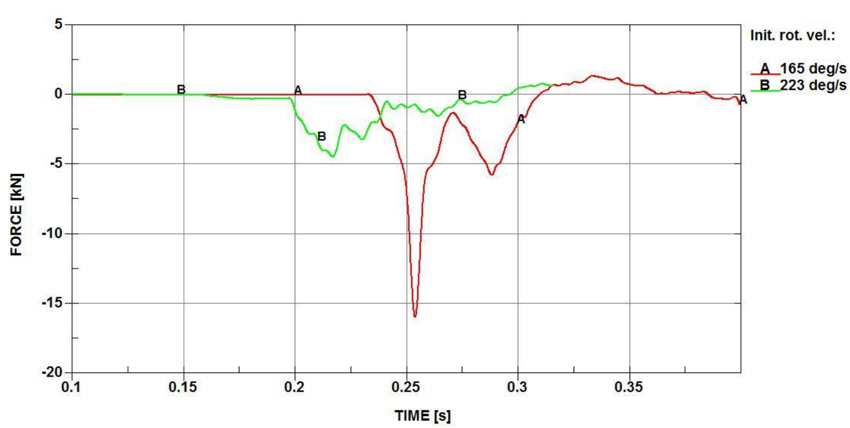


Figure 7.1: Comparison of neck forces from the NCAC detailed model with different initial rotational velocity.

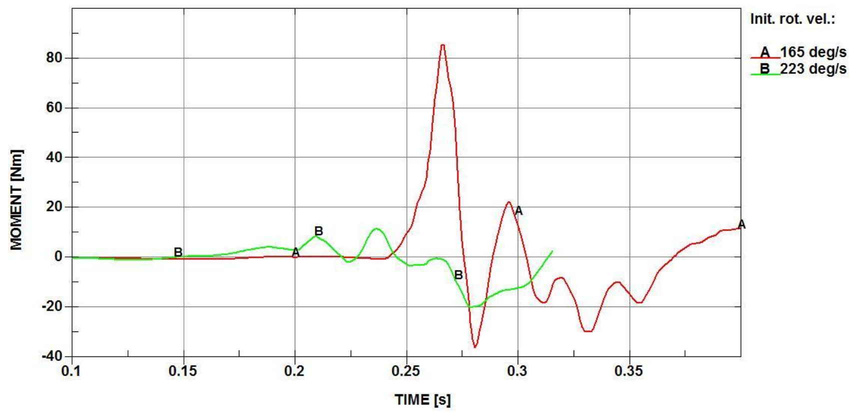


Figure 7.2: Comparison of neck moments for NCAC detailed dummy model with different initial velocity.

7.1.2. Drop Height

Figure 7.3 shows the initial configuration of the vehicle with the ground as obtained from *d3plot* files [3] for NHTSAs LS-DYNA/MADYMO simulation. In these files the drop height was not set to 11.1 inches as described as an initial configuration for the experimental CRIS test [1]. In the numerical results from NHTSA the height from the roof lower corner to the ground was set to (11.1 in), what is presented in Figure 7.3. Vertical displacement of CG in this case equals 15.9 in. This discrepancy requires clarification.

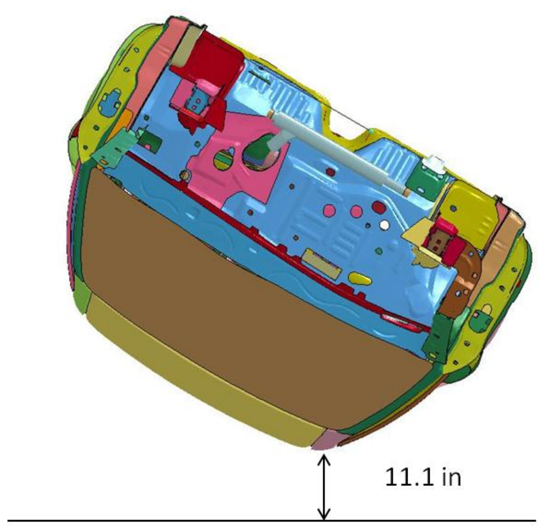


Figure 7.3: Initial position of the vehicle model in relation to the ground.

7.1.3. Impact Configuration of the Vehicle

Another difference between the paper [1] and the LS-DYNA/MADYMO simulation results is the impact configuration of the vehicle. According to the data given in the paper, the impact angle should be 4 degrees (Figure 3.1). However, viewing the animation made from the *d3plot* files shows that the impact angle is 9 degrees (see Figure 7.4). It indicates that the initial position of the Taurus needs to be modified to achieve the 4 deg angle.

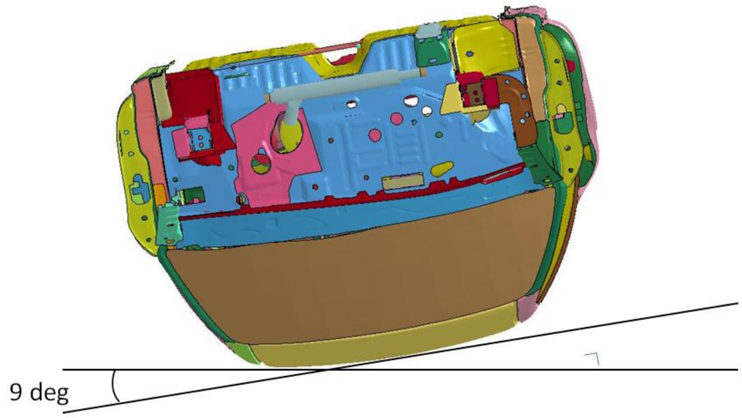


Figure 7.4: Impact configuration of the model.

7.1.4. Dummy's Neck Position

Dummies can be positioned inside the car in many different ways, including different neck and lumbar position. That results in a different head location with respect to the roof, and this can have a significant effect on the results. Figure 7.5 presents comparison of dummies' in their neutral configurations. To study the effect of neck position, a series of numerical tests were carried out for three positions of the dummy's neck: maximum allowed backwards, neutral and maximum allowed forwards. The force time histories for FAST LSTC dummy are presented in Figure 7.6 and neck moment histories in Figure 7.7. While neck force histories are similar, having only different amplitude, the neck moments behave in a totally different way. Comparing the maximum backwards and maximum forwards position, it is noted that the neck moment changes its sign.

Figure 7.5: Neutral position of the MADYMO dummy (left), the LSTC Fast dummy (middle) and the NCAC detailed dummy (right).

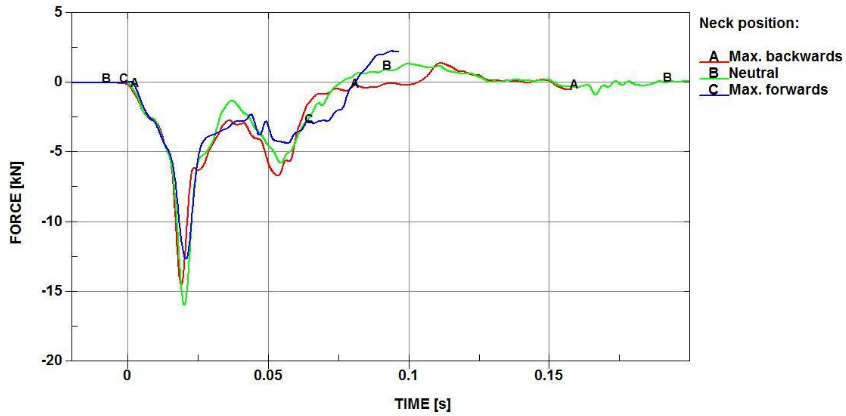


Figure 7.6: Comparison of neck forces for LSTC FAST dummy and variable neck position.

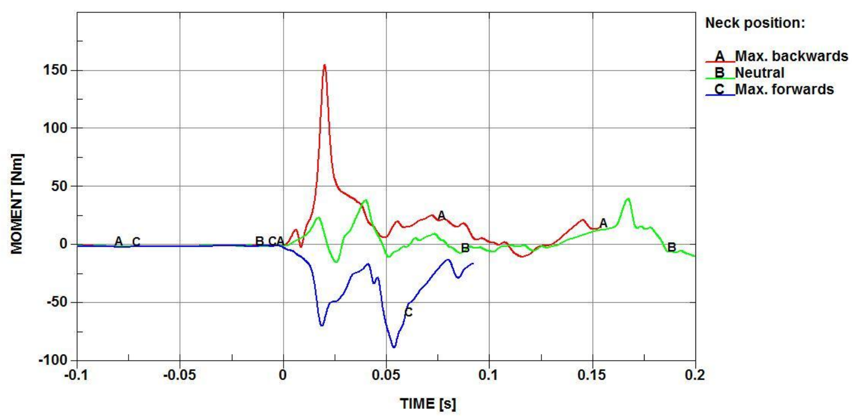


Figure 7.7: Comparison of neck moment for LSTC FAST dummy and variable neck position.

Figure 7.8 presents neck force histories for the detailed NCAC dummy, and Figure 7.9 presents moment histories. Similar to the results for the LSTC FAST dummy model, the neck forces do not differ much; however, there are big differences in the neck moment histories. This comparison may suggest that both dummy models can be positioned inside the vehicle in such a way that neck force and neck moment would be closer to the experimental data. The NCAC detailed dummy model is less sensitive to the neck position change than the LSTC FAST dummy model.

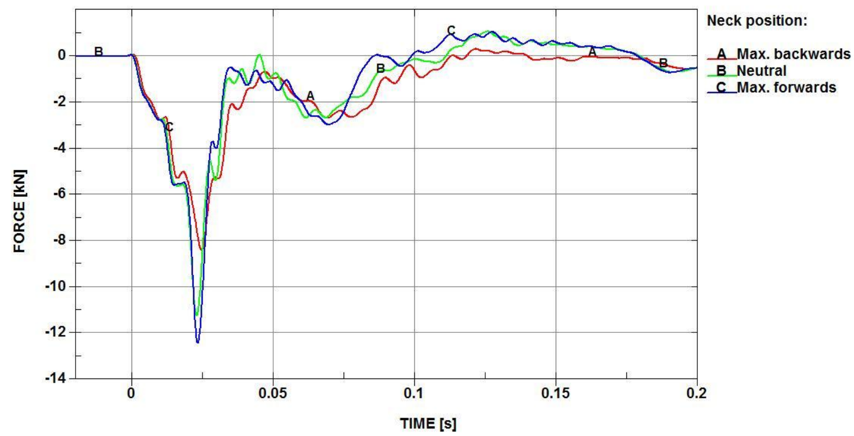


Figure 7.8: Comparison of neck forces for NCAC detailed dummy and variable neck position.

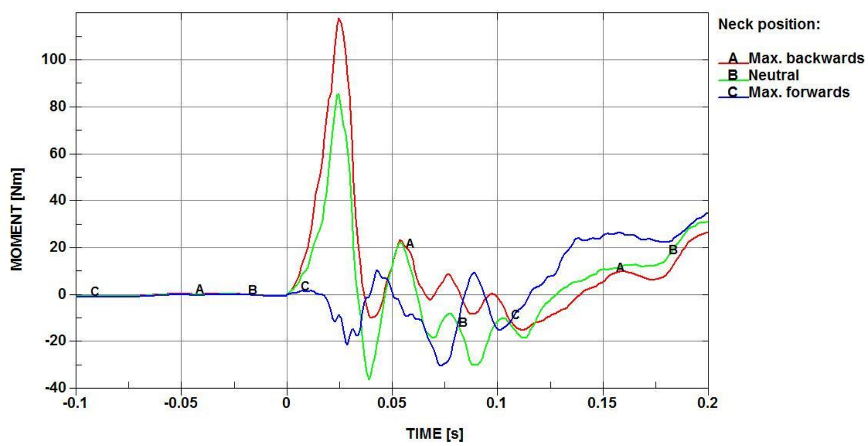


Figure 7.9: Comparison of neck moment for NCAC detailed dummy and variable neck position.

7.1.5. Weight of CRIS Mount

The additional weight of the CRIS equipment used in the physical test was not included in the numerical model of the vehicle. In [1] not enough details on the CRIS test equipment were given. To properly model this additional equipment, the following information should be provided:

- What is the weight of the equipment
- What is the effect of the additional weight on the CG of the car
- How does it influence the overall stiffness of the car

7.1.6. Crown Victoria Inertial Properties

In order to compare simulation dummy response metrics to CRIS Test 51502, the Taurus must have the same inertial properties as the Crown Victoria. In the current study a data from the web [2] was used. For the simulation model to represent the physical model, the exact Crown Victoria inertial properties need to be obtained from the CRIS test report.

7.1.7. Restraint System at Release Time

Prior to releasing the Crown Victoria in the CRIS test, the Crown Victoria rotates about the roll axis. The numerical simulations, on the other hand, start during the last half of the final rotation. In the CRIS test, the restraint system had several rotations to get to its pre-impact state. That is to say, the inertia forces will have pushed the dummy into the seat cushion and sideways toward the window, and the restraint system will have taken out all the slack and probably locked into position. In the numerical simulations this was not the case. An initial velocity was specified for the vehicle and the dummy and the dummy model was not exerting any pressure on the chair in this initial state. Also the photos from the report indicate that the dummy's hands could have been strapped to the steering wheel.

7.2. Matching the Experiment

To present the effect of differences in the initial conditions between the coupled LS-DYNA-MADYMO model and the experimental test described in the CRIS technical paper [1] a number of numerical simulations were carried out, with a different drop height and initial rotational velocity. The detailed values for both cases are presented in Table 1. *Case 1* corresponds to the initial conditions given in [1] while *Case 2* corresponds to the LS-DYNA-MADYMO coupled analysis.

Table 7.2: Initial conditions from CRIS test technical paper [1] and coupled DYNA-MADYMO analysis.

	Drop height [in]	Initial angle [deg]	Impact angle [deg]	Initial angular velocity [deg/s]
Case 1 (CRIS technical paper [1])	11.1	49 (back calculated)	4	223
Case 2 (coupled DYNA-MADYMO results)	15.9	30 (given)	9	165

Figure 7.10 and Figure 7.11 present respectively the neck force and moment history comparison for the LSTC FAST dummy model. In case of the neck force history, the main difference is in the amplitude of the force, though there are bigger differences between the neck moment histories. Figure 7.12 and Figure 7.13 presents the neck force and moment comparison for the NCAC detailed dummy model. In case of the model with the NCAC detailed dummy, there is also a

significant difference between the neck force amplitude for two numerical models, but the neck moment histories are more similar than in case of the LSTC fast dummy.

The simulations were carried out with the default neck position, though as presented in chapter 7.1.4 the dummy's neck position has a significant effect on the obtained results. The neck position influences both the neck force as well as the neck moment, so it probably could be positioned in such a way to better fit the experimental data. This operation should be performed once additional data about the CRIS test are obtained.

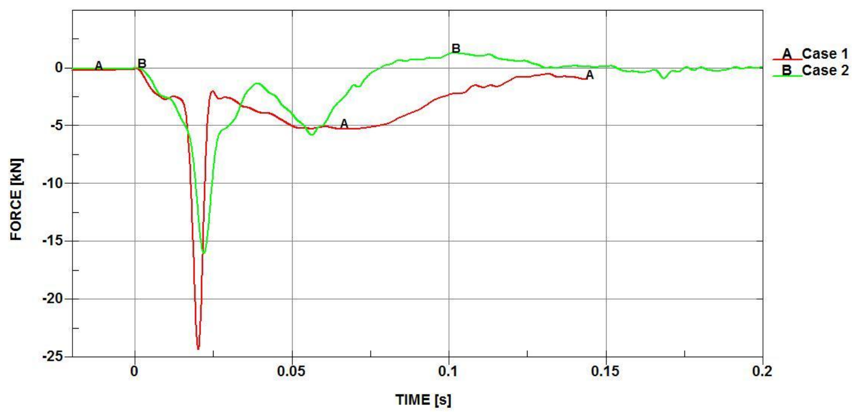


Figure 7.10: Comparison of the neck force histories for LSTC fast dummy and variable initial conditions.

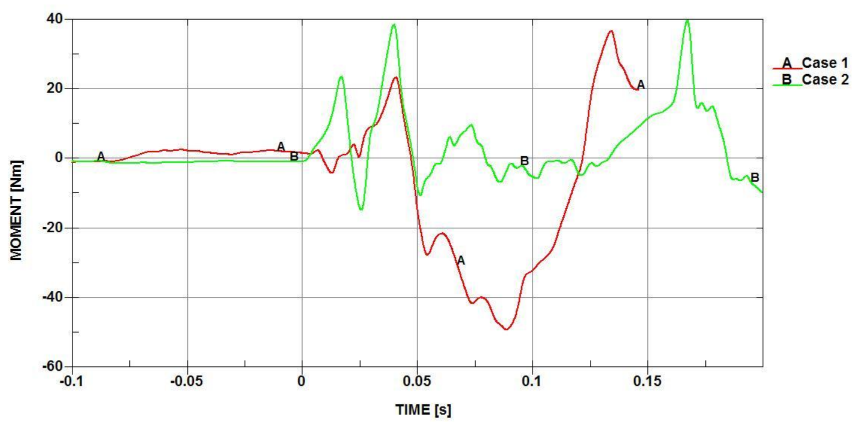


Figure 7.11: Comparison of the neck moment histories for LSTC fast dummy and variable initial conditions.

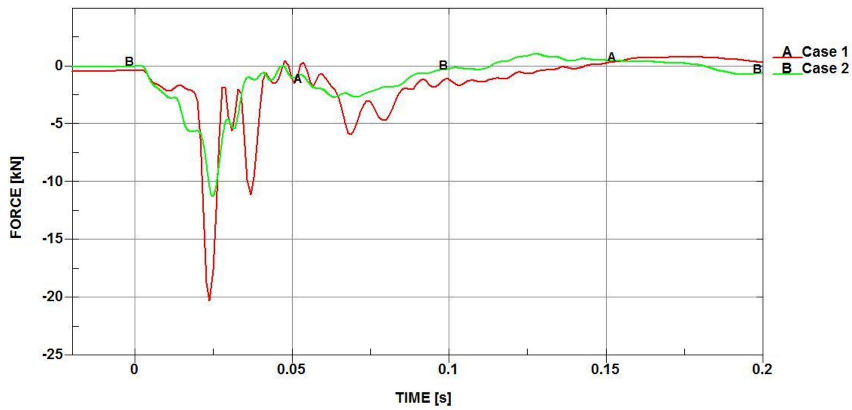


Figure 7.12: Comparison of the neck force histories for NCAC detailed dummy and variable initial conditions.

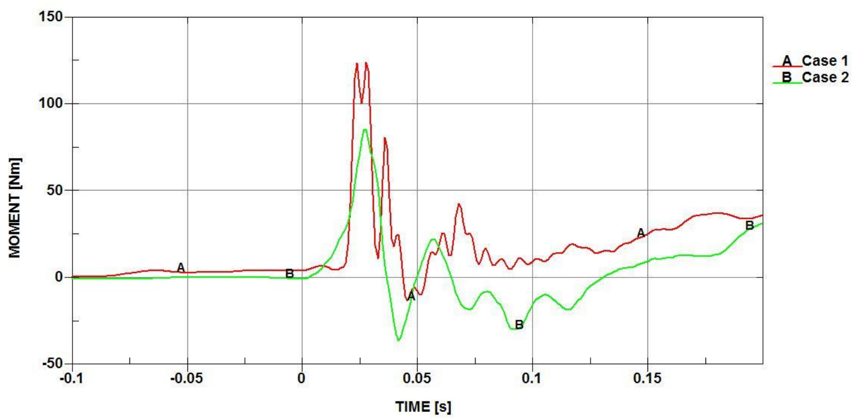


Figure 7.13: Comparison of the neck moment histories for NCAC detailed dummy and variable initial conditions.

8. Summary

This report presents a first attempt to model a rollover experimental test using LS-DYNA to model both the automobile and the full-scale anthropomorphic test device – in this case, the Hybrid III 50^{th} Male dummy. The test that the simulations are to be compared to is CRIS Test 51502, which was performed by Exponent Failure Analysis Associates using a production 1999 Ford Crown Victoria. Because a finite element model is not available for the Crown Victoria, a developmental finite element model for a 2001 Ford Taurus was obtained from the National Crash Analysis Center. A TRACC adjusted version of this model was used in the analysis as the surrogate for the Crown Victoria.

The finite element models used within this study were for the 2001 Ford Taurus and the Hybrid III 50th dummy. The latest Taurus finite element model under development at the NCAC was made available to TRACC researchers. The model did not match the inertial properties of the Crown Victoria used in the CRIS test. A small literature/Web review and teleconference with NHTSA produced representative values that could be used in this initial feasibility study. Subsequently, these inertia values can be changed when actual values become known.

Two Hybrid III dummy models were used: LSTC Hybrid III 50th FAST and NCAC Hybrid III 50th. Both of these models are distributed by LSTC. The FAST dummy model was developed at LSTC and has 4,310 elements and a computational time step of 1 μsec. The main purpose of this dummy – as its name implies – is for performing fast scoping studies. The NCAC model is a much more refined model with 397,491 elements and a computational time step of 0.5 sec. Both dummy models were independently positioned to fit into the driver's seat of the NCAC 2001 Ford Taurus model for their respective simulations.

It was discovered that using the initial conditions from CRIS Test 51502 did not produce results close to the experimental response reported by Ridella [1]. The initial conditions were reversed engineered from result files (*d3plots*) provided by NHTSA [3]. Apparently, these were approximately the actual initial conditions used in NHTSAs coupled LS-DYNA/MADYMO analysis.

Preliminary comparisons between the results obtained from the two dummy models (LSTC FAST and NCAC) showed that the more refined NCAC dummy, as expected, produced better results, especially for predicting neck moment. However, because the NCAC dummy had more than ninety times as many elements and required a time step half the size of the LSTC dummy, it required about three times as much CPU time.

To gain some understanding of the sensitivity of the neck's response to the neck's position relative to the roof at impact, a small study was performed. The following initial neck positions were investigated: maximum-allowed-backward position, neutral position and maximum-allowed-forward position. Looking at the LSTC dummy, there were no significant differences in neck force histories among the three cases. However, there were significant differences in neck moment response. Examining the results for the NCAC dummy, there were no significant differences in the general shape of neck force histories, but the peak magnitude for the "maximum-allowed-forward" case was 50% larger than the "maximum-allowed-backward" case. In contrast, the neck moments showed significant differences in shape, magnitude and sign between the three cases. The detailed NCAC dummy is less sensitive to variation of this parameter than the LSTC fast dummy. This may suggest that changing the initial neck position could be used to calibrate the model for parametric studies.

Finally, a list of unresolved issues has been generated that would be needed before additional simulations could be performed. The bulk of these issues will be resolved with the receipt of detailed data from CRIS Test 51502.

9. Conclusions

A feasibility study was performed to see if both LS-DYNA vehicle and dummy finite element models could be used to simulate CRIS test and assess the response of the Hybrid III 50th dummy – in particular, the head and neck response. Based on available but limited information for building the current simulation model, it appears that this approach will work well. Two metrics were defined by NHTSA for judging the model performance: neck force and neck moment. Comparison between simulation and experimental results showed favorable agreement in peak magnitude and shape. However, these agreements were obtained with an adjusted roll angular velocity. The roll angular velocity in CRIS Test 51502 was given as 223 deg/sec and the roll angular velocity used in the simulation was 165 deg/sec. The smaller roll angular velocity of 165 deg/sec was the apparent value used in a LS-DYNA-MADYMO analysis performed by NHTSA that produced similar neck force and moment responses.

Using LS-DYNA models for both the vehicle and Hybrid III 50th dummy eliminates the need for coupling LS-DYNA to MADYMO with associated numerical inefficiencies and dealing with two simulation software vendors.

The next step is to resolve the issues defined in Chapter 7 and obtain data from CRIS Test 51502. Then the current models can be refined and used to perform the parameter studies that will be defined by NHTSA.

10. References

[1] Ridella, Stephen A. and Barsan-Anelli, Aida, *Validation of Occupant Motion in a Finite Element Model of the Controlled Rollover Impact System*

[2] 4N6XPRT Systems, www.4n6xprt.com/screens.pdf

[3] Barsan-Anelli, Aida, Email transmittal, 03/08/2012

Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 222
Argonne, IL 60439

www.anl.gov

Argonne National Laboratory is a U.S. Department of Energy
laboratory managed by UChicago Argonne, LLC